BEFORE THE
ILLINOIS POLLUTION CONTROL BOARD

IN THE MATTER OF: ILLINOIS POWER GENERATING COMPANY Petitioner, v. ILLINOIS ENVIRONMENTAL PROTECTION AGENCY, Respondent.	PCB 2024-043 (Petition for review – Alternative Source Demonstration)

NOTICE OF FILING

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PLEASE TAKE NOTICE that today I have electronically filed with the Office of the Clerk of the Illinois Pollution Control Board the attached **EXPERT REPORT OF MELINDA HAHN**, along with a certificate of appeal, copies of which are herewith served upon you.

Dated: August 1, 2024

Respectfully submitted,

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CERTIFICATE OF SERVICE

I, the undersigned, certify that on this 1st Day of August, 2024:

I have electronically served true and correct copies of this Notice of Filing, Certificate of Service, and the attached EXPERT REPORT OF MELINDA HAHN by electronically filing with the Clerk of the Illinois Pollution Control Board and by e-mail upon the following persons:

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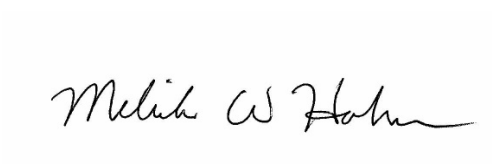
EXPERT REPORT OF MELINDA HAHN, PhD

ALTERNATIVE SOURCE DEMONSTRATION AND AGENCY RESPONSE – NEWTON PRIMARY ASH POND



Prepared on behalf of:
Illinois Power Generating Company, LLC

Prepared by:
Ramboll Americas Engineering Solutions, Inc.
Chicago, Illinois

Project Number:
1940106159

Date:
August 1, 2024

RAMBOLL

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ATTACHMENTS

Attachment A: Curriculum Vitae

Attachment B: Extra-Record Documents Relied Upon

ACRONYMS AND ABBREVIATIONS

ASD	Alternate Source Demonstration
ASTM	American Society for Testing and Materials
CCR	coal combustion residuals
COPC	contaminants of potential concern
EPA	U.S. Environmental Protection Agency
FALCON	Fingerprint Analysis of Leachate Contaminants
FGD	flue-gas desulfurization
ft	feet
ft/sec	feet per second
IEPA	Illinois Environmental Protection Agency
IPGC	Illinois Power Generation Company
ISGS	Illinois State Geological Survey
ISWS	Illinois State Water Survey
LEAF	Leaching Environmental Assessment Framework
LOE	line of evidence
L/S	liquid to solid
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
MLE	multiple lines of evidence
PAP	Primary Ash Pond
PE	professional engineer
Ramboll	Ramboll Americas Engineering Solutions, Inc.
RCRA	Resource Conservation and Recovery Act
SI	surface impoundment
TCLP	Toxicity Characteristic Leaching Procedure
TDS	total dissolved solids
USGS	United States Geological Survey
XRF	X-Ray Fluorescence

EXECUTIVE SUMMARY

Illinois Power Generation Company (IPGC) conducted groundwater monitoring for Newton Power Plant's Primary Ash Pond (PAP) in the 2nd quarter of 2023. That monitoring found some exceedances of the groundwater protection standards contained in 35 Ill. Adm. Code 845. IPGC concluded that the PAP may have contributed to most of those exceedances. However, IPGC prepared an Alternative Source Demonstration (ASD) under 35 Ill. Adm. Code 845.650(e) for one of the exceedances of the groundwater protection standards (chloride at APW15). The Illinois Environmental Protection Agency (IEPA) issued a denial of the ASD based on three perceived "data gaps."

The ASD contains scientifically supported conclusions based on facts and evidence demonstrating that the chloride exceedance at APW15 was being caused by source other than the PAP and that the PAP did not contribute to the exceedance. The ASD was prepared by a qualified Professional Engineer, who used professional judgment to develop multiple lines of evidence that support the ASD's conclusions, a commonly used, scientifically sound method used for this type of forensic analysis. The multiple lines of evidence included evaluating local hydrogeology (the presence of a low-permeability till that separates the surface impoundment [SI] from the aquifer), contaminant fingerprinting (APW15 did not exhibit expected ratios of chloride and other key coal combustion residuals (CCR) indicator parameters as observed in the SI porewater and in wells carried forward for corrective measure assessment), and contaminant transport/conservation of mass (chloride concentrations were significantly higher in APW15 than potential source concentrations in porewater). IPGC also presented evidence from the Illinois State Geological Survey and published peer-reviewed literature demonstrating that the alternative source was bedrock underlying the screened interval at APW15 with an upward gradient causing a flux of elevated chloride. No additional information is necessary to conclude that the chloride exceedance is caused by another source and is not being contributed to by the PAP.

The IEPA did not concur with the ASD, citing perceived data gaps including total solids sampling in the CCR, and characterization of the alternative source in terms of hydraulic conductivity and chemistry. IEPA's denial letter is sparse on details. None of the perceived data gaps listed in IEPA's denial letter are needed to support the ASD for the PAP. However, in deposition testimony, an IEPA witness who drafted the data gaps in the denial letter suggested that the principle of conservation of mass necessitated the requirement for total solids analysis (a mass balance analysis, in effect) and indicated that a significant field sampling plan consisting of ten borings with three solid samples each were necessary as a first step to characterize the CCR source for any ASD. Part 845 does not include specific sampling and analysis requirements for either the permitting process or the ASD. The requested solid sampling data (either analyzed as total or leachable concentrations) are not necessary and would not add useful information to the ASD because total constituent data (in units of mass of contaminant over mass of solid such as milligrams per kilogram [mg/kg]) are not an input to equations of contaminant transport in groundwater (source concentration is in units of mass contaminant over volume of groundwater such as milligrams per liter [mg/L]). SI porewater data are the best representation of potential water entering groundwater (compared to total or leach test data from CCR solid samples). By itself, total solids sampling of the CCR at the PAP will not provide helpful evidence regarding what has or may have reached the groundwater. While not explicit in IEPA's noted data gaps, those solids could be analyzed for leachability; however, that would require analysis of small amounts of CCR under idealized laboratory conditions that are not reflective of real world conditions to estimate potential leaching. Porewater data are superior in demonstrating what is actually leaching from the PAP, and is the superior method to use in transport modeling and forensic analysis of the potential impact to groundwater from a CCR SI. IPGC completed its demonstration

consistent with the EPA's preferred approach for evaluating a CCR SI's impact to groundwater. Further, from a technical basis, explicit identification of an alternative source is unnecessary to determine that a source other than the PAP is causing the chloride exceedance and that the PAP did not cause or contribute to the exceedance. This demonstration can be accomplished by ruling out the SI as a source. IPGC's submitted ASD ruled out the PAP as a source to APW15 with its three lines of evidence, therefore, it demonstrated that the CCR SI did not contribute to the exceedance and that another source was the cause. Regardless, the ASD presents the best available facts and evidence demonstrating that the source of the chloride exceedance is naturally occurring chloride from underlying bedrock.

Finally, I note that several documents in IEPA's Record are irrelevant to or further support the ASD. Additionally, the IEPA's data gaps would be impossible to collect during the short time period that was available to complete the ASD.

1. INTRODUCTION

Ramboll Americas Engineering Solutions, Inc. (Ramboll) was retained by ArentFox Schiff on behalf of Illinois Power Generation Company (IPGC) to review relevant documents and data and to prepare expert opinions regarding the Alternate Source Demonstration (ASD) for the Newton Power Plant Primary Ash Pond (PAP) located near Newton, Illinois (the "Site") and the Illinois Environmental Protection Agency's (IEPA) denial of this demonstration.

The qualifications of Melinda Hahn, Ph.D. are provided as Attachment A. Dr. Hahn has formed opinions as stated herein to a reasonable degree of scientific and technical certainty. This report includes a discussion of opinions and a discussion of the underlying bases for these opinions. Ramboll reserves the right to supplement or modify this report and its opinions to respond to any new or additional information that may become available after the date of this report, to add additional opinions and to rebut, as necessary, any opinions offered by witnesses in this case. In addition, all opinions provided in my December 15, 2023 Declaration are incorporated herein.

A list of documents relied upon in this report is included in Section 3. Documents relied upon for this report and my December 15, 2023 Declaration not included in the IEPA's Record are provided in Attachment 2.

2. BACKGROUND

This section provides background on basic concepts relevant to IPGC's ASD and IEPA's denial.

2.1 Environmental Sampling and Analysis

Environmental sampling and analysis are fundamental activities that support environmental site investigation, risk assessment, remediation, and environmental regulation. Reliable and reproducible data are necessary for each endeavor. Samples of soil, rock, sediment, or solid waste are considered "solid samples," and samples of groundwater, surface water, leachate, porewater, or wastewater are considered liquid or "aqueous samples."

- A "total" constituent analysis of a solid sample (or what IEPA appears to call a "total solids sample" in its ASD denial letter) yields results in units of mass of constituent over mass of solid (e.g., mg-constituent/kg-solid), usually on a dry weight basis.
- An analysis of contaminant concentration in an aqueous sample yields results expressed as mass of contaminant over volume of water (e.g., mg-contaminant/L-water).
- "Leaching tests" are performed on a solid sample in an effort to predict the chemical quality of water that has been in contact with the solid and received constituent mass transfer from the solid (the "leachate"). A leach test cannot represent all aspects of real world conditions, but is a laboratory simulation where conditions or parameters are selected to attempt to predict the chemical quality of interstitial porewater in a solid under land disposal conditions. Parameters of the leach tests that can impact final results include the liquid-to-solid ratio (L/S ratio), the starting chemistry of the water contacting the solid, or the eluent, the geometry of the system (including either "batch" or "column"), and the contact style and time. After completion of the leach test, the resulting water is called the eluate.
- A "porewater sample" (discussed further below) is a liquid sample of the interstitial water (porewater) within the void space of a solid.

The U.S. Environmental Protection Agency (EPA) has developed a compendium of laboratory analytical tests for solid and liquid samples and procedures for field and laboratory quality control, sampling, for the determination of hazardous constituents in waste, determination of hazardous characteristics of waste, and for the determination of physical properties of wastes. The compendium also contains guidance on how to select appropriate analytical methods. EPA often recommends these methods, collectively known as Test Methods for Evaluating Solid Waste, Physical/Chemical Methods (SW-846), for compliance with the Resource Conservation and Recovery Act (RCRA).[1] However, as stated in the SW-846 abstract and disclaimer, any reliable analytical method may be used to meet RCRA requirements unless Subtitle C of RCRA explicitly requires specific methods for certain applications. Importantly, SW-846 is neither a comprehensive set of procedures nor the only valid procedures used for environmental sample collection and analysis. For example, Clean Water Act methods are not included in SW-846,[2] and EPA has a number of validated methods that have been through extensive review, but are not included in the in the SW-846 Compendium. EPA encourages the use of validated

[1] U.S. EPA, Test Methods for Evaluating Solid Waste, Physical/Chemical Methods (SW-846), Abstract, https://www.epa.gov/hw-sw846/abstract-test-methods-evaluating-solid-waste-physicalchemical-methods-compendium-sw-846

[2] U.S. EPA Q&A for SW-846, https://www.epa.gov/hw-sw846/frequent-questions-about-sw-846-compendium-and-related-documents

methods as they represent the most current method versions.[3] The American Society for Testing and Materials (ASTM) and the United States Geological Survey (USGS) both publish test methods for analysis of solid and liquid samples. The USGS has used many of its own methods in its studies of properties of both coal and coal ash.

2.2 The Composition of Coal and Coal Combustion Residuals

Coal is formed from peat which consists of loosely consolidated layers of plant and mineral matter. Peat accumulates in wetlands, or peat swamps. Peat swamps are wetlands with appropriate conditions for peat to accumulate over time, including consistent moisture, a stable to slowly sinking land surface, deposition of waterborne or windborne inorganic sediments, and protection from erosional forces. Over millions of years, this peat decomposition and burial under inorganic sediments (compression) with the addition of heat from volcanic sources causes the formation of coal, a complex mixture of organic and inorganic matter with the appearance of well-bedded sedimentary rock.[4] As peat decomposes, it releases elements such as iron, calcium and magnesium that combine with other elements to form minerals such as pyrite (FeS_2) or calcite ($CaCO_3$) in the resulting coal.

Components of coal are primarily carbon and oxygen, but elements of potential environmental concern such as arsenic, cadmium, molybdenum and selenium are often present at trace levels (i.e., part per million).[5] Coal also contains elements known as halogens, including chlorine and bromine. The mean concentration of chlorine (Cl) in U.S. coals is 614 mg/kg.[6]

The behavior of trace elements of coal in pulverized-coal-fired boilers is dependent on relative element volatilities. Highly volatile elements such as mercury are released to air, others remain in the ash, but most have more intermediate behavior and are both emitted and retained within ash to some degree.[7] The materials that remain are called coal combustion residuals or CCR. Types of CCR include fly ash, bottom ash, boiler slag, and flue-gas desulfurization (FGD) materials. Fly ash is a product of burning finely ground coal that is removed from the exhaust gases. It is a fine, powdery material. Bottom ash is CCR that is too large to be entrained with flue gas and is collected from the bottom of the furnace. Bottom ash typically has grain sizes similar to sand or gravel. Boiler slag is molten bottom ash that has been quenched with water. It has hard, black angular particles that have a smooth, glassy appearance. FGD material is a byproduct of emission control equipment designed to reduce sulfur dioxide emissions from the boiler. The state of this material (wet sludge or dry powdered material) depends on the process. CCRs that are not reused are managed in wet or dry disposal systems. In wet systems, CCRs are sluiced to a surface impoundment (SI). In dry systems, CCRs are transported to landfills for disposal.[8]

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[3] U.S. EPA, Basic information about how to use SW-846, https://19january2017snapshot.epa.gov/hw-sw846/basic-information-about-how-use-sw-846_.html

[4] U.S. Geological Survey, Coal – A Complex Natural Resource, United States Government Printing Office, 2003, p. 8.

[5] U.S. Geological Survey, Coal – A Complex Natural Resource, United States Government Printing Office, 2003, p. 8.

[6] Mercury Control for Coal Derived Gas Streams, Wiley Vch, Edited by Evan Granite, Henry Pennline, and Constance Senior, 2015, p. 30.

[7] U.S. Geological Survey, Topics in Coal Geochemistry – Short Course, Open File Report 2018-1145, 2018 p. 7

[8] EPA, 75 FR 35128, June 21, 2010, p. 35137.

2.3 CCR Surface Impoundments and Migration of CCR Constituents into Groundwater

A CCR SI is a facility or part of a facility that is a natural topographic depression, man-made excavation, or diked area, which is designed to hold an accumulation of CCR and liquids, and the SI treats, stores, or disposes of CCR.[9] CCR SIs are used to receive CCRs that have been sluiced (flushed or mixed with water to facilitate movement) or wastes from wet air pollution control devices often in addition to other related solid and liquid wastes such as coal pile runoff, coal mill rejects, boiler blowdown, cooling tower wastes, storm water, etc.[10] Solids tend to sink to the bottom over time and become consolidated due to the pressure of the overlying materials.[11] A conceptual cross section of a CCR SI is shown in Figure 1.

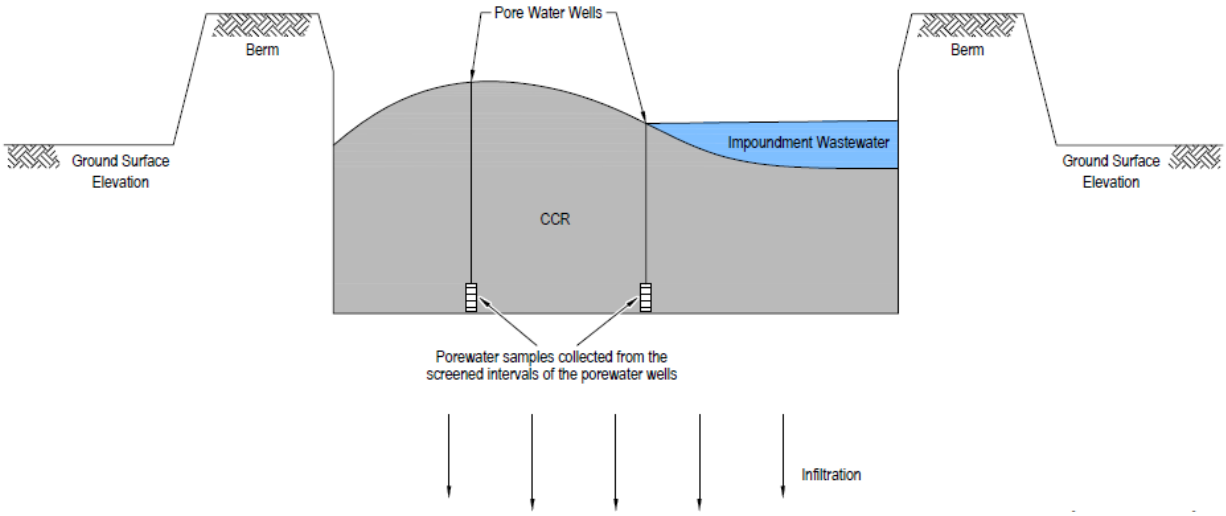

Figure 1: Conceptual Model Cross Section View of CCR Surface Impoundment

Chemical constituents are primarily released from unlined SIs through the leaching of constituents from CCR particles into the interstitial water (i.e., water in the CCR pore space, also known as porewater) and subsequent migration of the porewater to native material. Leaching is dependent on the porewater pH and the local L/S ratio within the impoundment. The L/S ratio represents the cumulative amount of water passing through the total mass of CCR subject to leaching (L-water/kg-CCR) and depends on many factors including the initial concentration of the disposed slurry, the addition of new materials, evaporation, precipitation, and runoff, decanting or dewatering, and settling of solids and consolidation or compaction of solids at the base. Porewater pH depends on the chemical nature of the CCR and comanaged materials and the L/S ratio. Both pH and L/S ratio can vary with time and space in a CCR SI. The L/S ratio begins relatively high in the disposed slurry and decreases as solids settle and consolidate. LS is lower at the base of the SI where compressed CCR has less pore space for water to occupy. A leach test requires selecting an eluent pH and an L/S ratio for the test system. Given the variation of pH and L/S ratio at a CCR SI over time and space, laboratory leach tests have limited value in estimating actual leaching from a CCR SI.

[9] 35 Ill. Adm. Code 845.120.

[10] See IPGC Initial Operating Permit Application, IEPA Record Doc. 10 at R000625-000640 (description of waste streams at Newton PAP).

[11] U.S. EPA, Human and Ecological Risk Assessment of Coal Combustion Wastes, August 2007, p. 3-15.

Porewater at a CCR SI is sampled with monitoring wells set in the CCR (Figure 1 shows monitoring wells set at the base of the SI). Typically, low-flow sampling techniques are used to collect porewater samples to reduce the turbidity of the samples. It is important to reduce turbidity to collect a sample that is representative of the water that may migrate rather than the CCR solids that may have been disturbed in the process of collecting a water sample. Porewater has the potential to percolate (migrate) downward into the subsurface soil and mix with groundwater. The CCR constituents can then be transported underground through the groundwater in the direction of groundwater flow, thus potentially causing a CCR SI to contribute to groundwater contamination. Exposures to CCR constituents could potentially occur if contaminated groundwater migrates to a downgradient well used as a source of drinking water, or to a downgradient surface water body where human receptors may be exposed through the ingestion of fish and ecological receptors may be exposed to contaminated water or sediment.[12]

A witness for IEPA has suggested that the principle of conservation of mass logically triggers sampling requirements for total constituents in CCR for an ASD.[13] However, the governing equations for models of contaminant transport in groundwater that are derived from the principle of conservation of mass do not depend on the total constituents in a solid such as CCR. Instead, the principle of conservation of mass in a groundwater system evaluates the rate of change of mass as an aqueous unit volume (i.e., mass of contaminant per groundwater volume or concentration) and reflects the balance between aqueous inputs and outputs from physical and chemical processes such as advection, dispersion, diffusion, decay and chemical reaction. Groundwater contaminant transport models can be complex and solve the governing equation describing the physical and chemical processes for contaminant concentration within a groundwater plume in three dimensions and time, or simplifying assumptions can be made to allow an analytic solution with a simple equation. Illinois uses one such simplification of the solution to this equation (the "Domenico" equation, or R26 in 35 IAC 742) as adopted in the ASTM Risk-Based Corrective Action Standard[14] to describe one-dimensional groundwater contaminant transport downgradient from a source (additional simplifying assumptions include steady state and no chemical reactions or processes other than decay) for sites seeking regulatory closure in its Site Remediation Program.[15] This equation is shown below:

$$C_{(x)} = C_{source} \bullet \exp\left[\left(\frac{X}{2\alpha_x}\right) \bullet \left(1 - \sqrt{1 + \frac{4\lambda \bullet \alpha_x}{U}}\right)\right] \bullet erf\left[\frac{S_w}{4 \bullet \sqrt{\alpha_y \bullet X}}\right] \bullet erf\left[\frac{S_d}{2 \bullet \sqrt{\alpha_z \bullet X}}\right]$$

where C(x) is the contaminant concentration in groundwater at location x (in mg/L), C_{source} is the source concentration in groundwater (mg/L), x is the distance downgradient along the center line of the plume, Sw and Sd are source widths and depths in cm, U is the specific discharge (contaminant velocity) in cm/d, the α's are dispersivity values in units of cm, and λ is the decay constant in units of d^{-1}. The mass of the contaminant in an associated soil or solid source is *not* an input to this equation.

[12] EPA, Human and Ecological Risk Assessment of Coal Combustion Residuals, Final Report, December 2014, p. 2-3.

[13] Lauren Hunt deposition, May 28, 2024, pp. 43-44, 119-121, 126.

[14] Connor et al, Parameter Estimation Guidelines for RBCA Modeling, NGWA Petroleum Hydrocarbons Conference, 1996, p. 7; ASTM E-1739 Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites.

[15] Illinois Title 35 Part 742 Tiered Approach to Corrective Action Objectives, Appendix C, Table C, Equation R26.

The source concentration and the downgradient concentrations at "x" distances are all concentrations in groundwater.

Evaluation of this equation and the resulting contaminant concentrations reveals that downgradient concentrations of contaminants in groundwater are greatest along the primary axis of the groundwater plume (in the downgradient direction) and lower in off-axis locations (cross-gradient). Also, downgradient concentrations are always lower than the source concentration in groundwater (C_{source}) due to attenuating processes such as dispersion, diffusion, decay and adsorption. This observed attenuation is a direct consequence of the principle of conservation of mass.

Constituents in groundwater that are not subject to decay, adsorption, or other chemical processes will travel in groundwater at approximately the same speed as the groundwater itself. These are known as conservative solutes. Sodium and chloride are examples of conservative solutes. Conservative solutes, like all solutes, exhibit decreasing concentrations moving downgradient from a source due to dispersion and diffusion. Conservative solutes can be useful in tracing groundwater flow direction and speed.

2.4 Characterizing Potential Leaching of CCR Contaminants

EPA has done extensive work to characterize both total and leachable concentrations for contaminants of potential concern (COPCs) in CCR in preparation for rulemakings over many decades. Through this work, EPA has created a model for pathway of migration of COPCs from CCR SIs that is consistent with the approach contained within IPGC's ASD. EPA's work has led the Agency to conclude that porewater sampling is the most appropriate method to characterize the potential impact of a CCR SI upon groundwater.

In the 1980s and 1990s, EPA collected leach test data to evaluate whether CCR should be regulated as a hazardous waste. EPA's 1988 Report to Congress contained data from multiple leach testing procedures including Extraction Procedure Toxicity test (EP Tox), Toxicity Characteristic Leaching Procedure (TCLP), ASTM leach tests, and column tests (early precursors of Leaching Environmental Assessment Framework, or LEAF tests) for multiple types of CCR, primarily fly ash and FGD material. The results supported EPA's determination that CCR is not subject to RCRA Subtitle C regulation. In 1999, EPA updated its report to Congress, this time addressing CCR and other low volume waste streams that are often co-disposed in SIs and landfills, such as coal pile runoff, coal mill rejects, boiler blowdown, cooling tower wastes, etc. These low-volume comanaged wastes and high-volume CCR wastes will generally have the characteristics of the high-volume fraction, but differences can be apparent in localized areas of a waste management unit.[16] Based on data from pore waters and TCLP data, EPA determined that comanaged wastes do not exhibit the characteristics of hazardous waste. EPA again concluded that CCR reuse or disposal of comanaged CCR wastes should not be regulated under RCRA Subtitle C.

EPA did not conclude from the leach test results and porewater data, however, that comanaged waste are incapable of mobilizing constituents at levels of concern. To assess potential risks to human health and the environment, EPA used porewater data from some comanaged wastes to model migration from CCR SIs to groundwater. Porewater data were used instead of TCLP data for fate and transport modeling and in turn risk assessment purposes because "(1) they represent actual leachate conditions

[16] EPA, Report to Congress: Wastes. from the Combustion of Fossil Fuels, Vol. 1 – Executive Summary, March 1999, EPA 530-S-99-010m p. 3-15

at the sampled sites, and (2) a larger and more representative database exists for pore water analyses than for TCLP analyses."[17] Early EPA risk assessment results indicated that of CCR constituents, only arsenic had the potential to migrate from CCR SIs to drinking water wells above health-based levels.

In support of a more comprehensive multi-pathway human health and ecological risk assessment of land disposal of CCR in 2007, EPA assembled a source characterization database of total and leachate sample results for 41 CCR constituents taken from more than 140 CCR disposal sites, including SIs and landfills around the country.[18] The constituents evaluated are shown in the table below. Waste streams included both conventional fly ash, bottom ash, mixed ash, and comanaged materials. Leachate data included actual porewater sample results for SIs and TCLP data for landfills (available data for landfills were mainly TCLP).[19] This data set was an improvement over that used in the 1990s as it included data on the major ions in CCR leachate such as calcium, chloride, sulfate and pH.[20]

Table 2-2. Toxicity Assessment of CCW Constituents

Constituent	CAS ID	HHB[a]	EcoB[b]	Constituent	CAS ID	HHB[a]	EcoB[b]
Metals				*Inorganic Anions*			
Aluminum	7429-90-5	✔	✔	Chloride	16887-00-6		
Antimony	7440-36-0	✔	✔	Cyanide	57-12-5	✔	
Arsenic	7440-38-2	✔[c]	✔	Fluoride	16984-48-8	✔	
Barium	7440-39-3	✔	✔	Nitrate	14797-55-8	✔	
Beryllium	7440-41-7	✔[d]	✔	Nitrite	14797-65-0	✔	
Boron	7440-42-8	✔	✔	Phosphate	14265-44-2		
Cadmium	7440-43-9	✔[d]	✔	Silicon	7631-86-9		
Chromium	7440-47-3	✔[c]	✔	Sulfate	14808-79-8		
Cobalt	7440-48-4	✔	✔	Sulfide	18496-25-8		
Copper	7440-50-8	✔[°]	✔	*Inorganic Cations*			
Iron	7439-89-6			Ammonia	7664-41-7	✔	
Lead	7439-92-1	✔[°]	✔	Calcium	7440-70-2		
Magnesium	7439-95-4			pH	12408-02-5		
Manganese	7439-96-5	✔		Potassium	7440-09-7		
Mercury	7439-97-6	✔	✔	Sodium	7440-23-5		
Molybdenum	7439-98-7	✔	✔	*Nonmetallic Elements*			
Nickel	7440-02-0	✔	✔	Carbon	7440-44-0		
Selenium	7782-49-2	✔	✔	Sulfur	7704-34-9		
Silver	7440-22-4	✔	✔	*Measurements*			
Strontium	7440-24-6	✔		Total Dissolved Solids	none		
Thallium	7440-28-0	✔	✔	Total Organic Carbon	none		
Vanadium	7440-62-2	✔	✔	Dissolved Organic Carbon	none		
Zinc	7440-66-6	✔	✔				

[a] HHB = human health effect benchmark
[b] EcoB = ecological benchmark
[c] Known carcinogen (for chromium VI, inhalation only); although arsenic can act as both a carcinogen and a noncarcinogen, the cancer risk exceeds the noncancer risk at any concentration, so we used the more protective cancer benchmark for human health throughout this assessment.
[d] Probable carcinogen
[°] Safe Drinking Water Act Action Level only

[17] EPA, Report to Congress: Wastes. from the Combustion of Fossil Fuels, Vol. 1 – Executive Summary, March 1999, EPA 530-S-99-010m p. 3-18.

[18] EPA, Human and Ecological Risk Assessment of Coal Combustion Wastes, Draft, 2007, p. 2-4.

[19] EPA, Human and Ecological Risk Assessment of Coal Combustion Wastes, Draft, 2007, p. 4-41.

[20] EPA, Human and Ecological Risk Assessment of Coal Combustion Wastes, Draft, 2007, p. 2-2.

Increasing use of air pollution control systems at U.S. coal-fired power plants and the need for evaluation of comanaged residues in land applications and beneficial reuse prompted EPA to further characterize the nature and leaching potential of comanaged CCR in a range of field conditions in 2009.[21] EPA tested both total and leachate constituent concentrations for CCR samples from multiple facilities with different types/ranks of coal and air pollution control processes and came to the following conclusions:[22]

> The major conclusions from this research include:
>
> - There is great variability in both the range of total constituent concentration values and in leaching values (orders of magnitude). In comparing there results to health indicator values such as the maximum concentration limit or toxicity characteristic, there are multiple COPCs of potential concern.
> - Distinctive patterns in leaching behavior have been identified over a range of pH values that would plausibly be encountered for CCR management.
> - Total constituent content is not a good indicator of leaching which has been found to be a function of the characteristics of the material (pH) and field conditions in which the material is managed.
> - The maximum eluate concentration from leaching test results varies over a wide range in pH and is different for different CCR types and elements. This indicates that there is not a single pH for which testing is likely to provide confidence in release estimates over a wide range of disposal and beneficial use options, emphasizing the benefit of multi-pH testing. Furthermore, for CCRs, the rate of constituent release to the environment is affected by leaching conditions (in some cases dramatically so), and that leaching evaluation under a single set of conditions will, in many cases, lead to inaccurate conclusions about expected leaching in the field.

EPA analyzed total metal content of CCR samples using ICP-MS or ICP-AES SW-846 methods or by X-Ray Fluorescence (XRF) Spectroscopy. CCR total chloride content was measured by XRF and found to range between approximately 80 to 10,000 mg/kg in concentration.[23] Leach test results were found to vary by orders of magnitude with eluent pH and L/S ratio. Leachate concentrations are greatest at the lowest L/S ratios and decrease with increasing L/S ratio.[24] One question that EPA sought to answer in this study was whether or not total content of an element in a CCR sample (e.g., mg-COPC/kg-CCR) is a useful indicator of potential environmental impact by leaching. The results showed: (1) there is poor correlation between leachate concentration and total content of any of the elements considered, (2) a wide range of total content values (over more than an order of magnitude) can result in the same or very similar eluate concentrations, and (3) a wide range of eluate concentrations (over more than an order of magnitude) are observed for CCRs with similar total content values. If leaching were correlated closely with total concentration, the data would have

[21] EPA, Characterization of Coal Combustion Residues from Electric Utilities- Leaching and Characteristic Data, 2009, p. 1

[22] EPA, Characterization of Coal Combustion Residues from Electric Utilities- Leaching and Characteristic Data, 2009, p. ii.

[23] EPA, Characterization of Coal Combustion Residues from Electric Utilities- Leaching and Characteristic Data, 2009, p. 74.

[24] EPA, Characterization of Coal Combustion Residues from Electric Utilities- Leaching and Characteristic Data, 2009, p. 52.

shown strong linearity, rather than significant scatter. This indicates that constituent leaching is better characterized by collecting porewater samples than by estimating based on total constituent concentration alone or with use of linear Kd partitioning values.

In 2014, EPA updated and finalized its probabilistic risk assessment of land disposal of CCR to human and ecological receptors from CCR disposal practices. The final assessment built on its prior assessments of CCR disposal in SIs and landfills in that it incorporated new data and addressed comments received by independent external peer reviewers and public commenters on the methodology, data sources, and assumptions used by the Agency. By this time, EPA had expanded its database to include data from 384 facilities with on-site CCR WMUs for a total of 953 SIs and 431 landfills.[25] For the groundwater pathway screening analysis, EPA used the 90th percentile of SI porewater concentrations to represent the source concentration of each constituent, and applied a dilution attenuation coefficient to account for reduction in concentration associated with migration to a downgradient receptor.[26] For the full probabilistic analysis, EPA used the porewater data distributions from its database for each waste type to represent the source concentration release from a SI as porewater samples best reflect leachate as it is released into underlying soils.[27] "Pore water data were collected from core samples both in and beneath SIs. Since the cores take leachate directly from the field, these data are known to represent field conditions and no further comparison is necessary."[28]

In its response to comments on the federal CCR disposal final rule in 2015, EPA stated that, even with the advent of the LEAF methods for leach testing, the use of porewater data is still considered the most appropriate approach to estimate constituent fluxes to groundwater for CCR SIs. This is because sufficient site-specific pH data was not available to probabilistically assign LEAF data to modeled units, and because there was no way to account for partitioning of the leachate into wastewater versus porewater.[29]

2.5 The Newton PAP ASD and Denial

The Newton PAP is an unlined CCR SI that was constructed in 1977 and has a design capacity of approximately 9,715 acre-feet. It currently receives bottom ash, fly ash, storm water runoff and low-volume wastewater from the plant's two coal-fired boilers. IPGC submitted to IEPA a Hydrogeological Characterization Report for the PAP in October 2021 that contains aquifer characterization information, leachate quality data, and upgradient and downgradient monitoring well data. IPGC also submitted an operating permit application for the PAP in October 2021 that includes additional information including waste types disposed and waste characterization data (as total concentration). Currently, IPGS is conducting quarterly monitoring of groundwater wells about the PAP.

In the second quarter of 2023, IPGC reported several groundwater protection standard exceedances at the PAP, including chloride at well APW15, and lithium, sulfate, and total dissolved solids (TDS) at

[25] EPA, Human and Ecological Risk Assessment of Coal Combustion Residuals, Final Report, December 2014, p. 2-7.

[26] EPA, Human and Ecological Risk Assessment of Coal Combustion Residuals, Final Report, December 2014, p. 3-18.

[27] EPA, Human and Ecological Risk Assessment of Coal Combustion Residuals, Final Report, December 2014, p. 4-5.

[28] EPA, Human and Ecological Risk Assessment of Coal Combustion Residuals, Final Report, December 2014, p. 5-47

[29] EPA, 80 FR 21302 40 CFR Parts 257 and 261 Hazardous and Solid Waste Management System: Disposal of Coal Combustion Residuals from Electric Utilities, Final Rule April 17, 2015, p. 21442.

several other wells.[30] The lithium, sulfate and TDS exceedances were carried forward for evaluation of corrective measures under Part 845, but an ASD was prepared for the chloride exceedance at well APW15. Evidence demonstrated that the Newton PAP was likely contributing to the lithium, sulfate, and TDS exceedances. Groundwater chemistry at the wells with those exceedances was similar to porewater chemistry, but concentrations did not exceed porewater concentrations, and the wells with those exceedances were also located closer to the PAP both horizontally and vertically than APW15. These observations suggested that the exceedance wells carried forward for a corrective measures evaluation under Part 845 would benefit from corrective measures at the SI, but APW15 would not.

The three lines of evidence (LOEs) supporting the ASD for chloride in APW15 presented in the October 3, 2023 ASD report are as follows:

i) LOE 1: The thick layer of low permeability till that separates the PAP from the screened aquifer in APW15 prevents vertical migration of CCR constituents;

ii) LOE 2: Primary CCR indicators, boron and sulfate, do not exceed background limits and are not increasing at APW15; and

iii) LOE 3: Concentrations of chloride at APW15 are greater than PAP porewater concentrations.

The ASD report also noted that concentrations of chloride at APW15 are consistent with published data for regional bedrock aquifer quality and the observation of a saline spring (that establishes the presence of an upward hydraulic gradient) within approximately 10 miles of the Newton Power Plant, suggesting that the underlying bedrock aquifer is the alternative source of chloride in well APW15.

In its November 7, 2023 letter, the IEPA denied the ASD due to the following perceived data gaps:

i) Source characterization of the CCR at the PAP must include total solids sampling in accordance with SW-846.

ii) Hydraulic conductivities from laboratory or in-situ testing must be collected, analyzed, and presented with hydrogeologic characterization of the bedrock unit.

iii) Characterization to include sample and analysis in accordance with 35 IAC 845.640 of alternative source must be provided with the ASD.[31]

[30] Ramboll, Groundwater Monitoring, Data and Detected Exceedances, Quarter 2, 2023, August 7, 2023.

[31] In deposition testimony, Ms. Lauren Hunt of the IEPA stated that the third data gap refers only to 35 IAC845.640(a). This section states that the CCR SI owner or operator must develop a sampling and analysis plan for its groundwater monitoring program that includes procedures for sample collection, preservation and shipment, analytical procedures, chain of custody and quality assurance/quality control. Ms. Hunt suggested that this documentation, including laboratory reports, are required for any sampling of the alternative source and the CCR SI. (May 28, 2024 deposition transcript at pp. 88-93). This data gap only references the alternative source. Regardless, and without agreeing it is required, I note that this documentation was provided to IEPA for the porewater samples of the Newton PAP. Ramboll, Groundwater Monitoring, Data and Detected Exceedances, Quarter 2, 2023, August 7, 2023.

3. OPINIONS

3.1 Alternative Source Demonstration Requirements

Opinion 1: The ASD requirement (Part 845.650(e)) can be met by ruling out a SI as a source of contamination to the exceeding well.

Illinois promulgated regulations regarding disposal of CCR in SIs in 2021. Among those provisions is, in the event of an exceedance of a groundwater protection standard at a monitored compliance well, that the owner or operator must either begin the assessment of corrective measures process, or within 60 days, submit a demonstration to the Agency that a source other than the CCR SI caused the contamination and the CCR SI did not contribute to the contamination, or that the exceedance of the groundwater protection standard resulted from error in sampling, analysis, statistical evaluation, natural variation of groundwater quality, or a change in the potentiometric surface and groundwater flow direction (i.e., an ASD).[32] I am not providing a legal opinion here regarding the interpretation of Part 845.650(e); however, from a scientific basis, the requirement to determine that "a source other than the CCR SI caused the contamination" can be met by ruling out the CCR SI as a source of the contamination. Notably, Part 845 is not a site-wide remediation program and does not contain provisions requiring corrective action or remediation concerning any source other than CCR SIs. It is designed to address risks associated with CCR SIs and if the CCR SI is not a source of the contamination, then the groundwater corrective measures requirements of Part 845 are inapplicable. If Part 845 is a site-wide remediation program, it would be appropriate to read into 845.650(e) a requirement to identify with specificity an alternative source because a site-wide remediation program is intended to address all sources, not one specific source. As it stands, Part 845 does not build in a timeline or process for such identification.

Opinion 2: Determining whether or not a potential source is a contributing source of observed environmental contamination requires engaging in the process of environmental forensic analysis. A multiple lines of evidence analysis is a commonly used, scientifically supported method by which to conduct an environmental forensic analysis.

Environmental forensic analysis seeks to make causal determinations regarding the source of observed contamination, and often relies on a multiple lines of evidence (MLE) approach as a standard practice.[33,34,35,36,37] The MLE approach involves analysis of multiple independent sets of data or information and analysis to test whether an identified source can explain observed data. Information

[32] 35 IAC 845.650(e).

[33] Miller, J. Methods and Advances in the Forensic Analysis of Contaminated Rivers, E3S Web of Conferences Vol. 125, 2019, p. 3.

[34] U.S. EPA, U.S. Navy SPAWAR Systems Center, GeoChem Metrix Inc., and Battelle Memorial Institute, A Handbook for Determining the Sources of PCB Contamination in Sediments, Technical Report, TR-NAVFAC EXWC-EV-1302, October 2012, p. 13.

[35] U.S. EPA, Office of the Science Advisor, Risk Assessment Forum, Weight of Evidence in Ecological Assessment, EPA/100/R-16/001, December 2016.

[36] U.S. EPA, Office of Solid Waste and Emergency Response, OSWER Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor in Indoor Air, June 2015, pp. xv-xvii, 17-18, 38-40, 60-61, 117-123.

[37] EPRI, Guidelines for Development of Alternative Source Demonstrations at Coal Combustion Residual Sites, 2017 Technical Report, p. viii.

to consider can be site-specific, regional, or from the literature.[38,39] These independent lines of evidence are developed until sufficient confidence is achieved to either confirm or rule out a source.[40] Rarely is an environmental remediation professional required to collect all of the quantitative data necessary to perform a complex conservation of mass analysis.

Instead, environmental remediation professionals use their judgment and rely on commonly accepted lines of evidence to identify or rule out sources. Typical lines of evidence can include but are not limited to diagnostic ratios of key contaminant concentrations, multivariate contaminant fingerprinting (use of multiple relative abundances, or concentration ratios, of key source constituents), hydrogeologic information such as aquifer hydraulic conductivities and gradients, the spatial distribution of contamination and consistency with models and concepts of contaminant migration, historical evidence from documents, maps or photos, and isotopic analysis for age dating or identification. Diagnostic constituent ratios and fingerprinting analysis are most often used because they rely on commonly collected data. EPA has developed its own contaminant fingerprinting tool: Fingerprint Analysis of Leachate Contaminants (FALCON) in response to the need for identifying the source of groundwater contaminant plumes.[41] FALCON relies on differences in relative abundances of key chemical parameters to develop a distinctive graphical fingerprint or multi-parameter chemical signature. These fingerprint patterns can be used to identify the source of a contaminant plume, differentiate the contaminant plume from background conditions at the source, and monitor the migration of leachate into the environment.[42] None of these accepted forensic methods of data analysis require the calculation of a mass balance with constituent concentration data from solid samples of the potential sources and impacted groundwater.

Opinion 3: There is no "cookie cutter" data set for conducting an ASD. It requires independent professional judgment.

Conducting a forensic analysis for an ASD requires gathering and evaluating available facts and evidence, based on site characteristics within the time-period provided for conducting the ASD. Deposition testimony from an IEPA employee involved in reviewing the ASD and drafting the "data gaps" included statements suggesting the type of data included in the purported "data gaps," characterizing the CCR source and the alternate source (i.e., solids sampling of the CCR source and direct sampling of the alternate source) are necessary as a baseline to begin an ASD.[43] This is not true. Based on my technical experience and review, I am aware of no requirements for such baseline data to be presented with an 845.650(e) ASD, including through Illinois regulations or guidance. Rather, in my experience, an ASD (and similar forensic analyses) will typically include multiple lines of

[38] U.S. EPA, Office of the Science Advisor, Risk Assessment Forum, Weight of Evidence in Ecological Assessment, EPA/100/R-16/001, December 2016, p. 20 et seq.

[39] U.S. EPA, U.S. Navy SPAWAR Systems Center, GeoChem Metrix Inc., and Battelle Memorial Institute, A Handbook for Determining the Sources of PCB Contamination in Sediments, Technical Report, TR-NAVFAC EXWC-EV-1302, October 2012, p. 30.

[40] Miller, J. Methods and Advances in the Forensic Analysis of Contaminated Rivers, E3S Web of Conferences Vol. 125, 2019, p. 3.

[41] U.S. EPA, Technical Support Center Issue, Fingerprint Analysis of Contaminant Data: A Forensic Tool for Evaluating Environmental Contamination, EPA/600/5-04/054, May 2004.

[42] U.S. EPA, Technical Support Center Issue, Fingerprint Analysis of Contaminant Data: A Forensic Tool for Evaluating Environmental Contamination, EPA/600/5-04/054, May 2004.

[43] Lauren Hunt deposition, May 28, 2024, pp. 66-68.

evidence that rely on available data.[44] There is a wide variety of chemical and hydrogeologic data (including background groundwater quality, porewater data, the geometry of the system, hydrogeologic data such as hydraulic conductivities and gradients) and analytical techniques (including fingerprinting, contaminant fate and transport modeling, isotopic comparisons, etc.) that could be used in the assessment and the process is dependent on the professional judgment of the professional engineer (PE) tasked with completing the ASD. As discussed further below, the Newton PAP ASD's conclusions are sound and the ASD analysis was conducted using the best available data and analytical techniques available for the site and circumstances.

Significantly, 845.650(e) does require that the ASD include a report that contains the factual, evidentiary, and logical basis for any conclusions and a certification of accuracy prepared by a qualified PE. A PE has satisfied educational requirements in collegiate engineering, gained sufficient experience, and has passed a licensing exam. Section 845.650(e) does not specify any particular data or analytical requirements necessary to complete an ASD, so some amount of professional judgment is required. Consistent with standard scientific practice for forensic analysis, the PE must draw conclusions based on reliable data using standard analytical techniques to a reasonable degree of scientific certainty such that a reasonable engineer or scientist would agree.

3.2 IPGC's ASD is Sufficient to Exclude the PAP as a Source of Chloride to APW15

Opinion 4: The lines of evidence presented in the PAP ASD are sufficient to conclude that coal ash in the PAP is not a source of the chloride concentrations observed in monitoring well APW15, and that those concentrations are consistent with adjacent natural groundwater quality.

Opinion 5: LOE 1 is based on appropriate supporting facts and evidence and is sufficient to establish that there is not a viable migration pathway between the PAP and APW15.

LOE 1 stated that the thick layer of low permeability till between the base of the PAP and the screen of APW15 would prevent vertical migration of CCR leachate to APW15. In order for the PAP to contribute to chloride concentrations in APW15, a pathway needs to exist for chloride from the PAP to reach APW15. For this LOE, IPGC relied upon the boring and well log for APW15 from the PAP construction permit application that shows approximately 60 feet of till separating the PAP from the screened interval of APW15, and hydraulic conductivity data that shows a vertical conductivity of 10^{-8} cm/s from the PAP's Hydrogeologic Site Characterization Report. This low hydraulic conductivity (consistent with an aquitard rather than an aquifer) means that any vertical seepage would occur at such a slow rate that the potential porewater travel time through the 60-foot layer would be much greater than the age of the SI, thereby ruling out the PAP as the source of the exceedance.

None of IEPA's perceived data gaps relate to the collection of facts or evidence that would further support or disprove LOE 1. If the information requested in IEPA's perceived data gaps was collected it could not disprove the evidence or conclusions contained within this LOE. None of IEPA's requested data could change the conclusion that there is no viable migration pathway between the PAP and APW15.

Opinion 6: LOE 2 is based on appropriate supporting facts and evidence and is sufficient to establish that the groundwater chemistry at APW15 is inconsistent with an impact from the PAP.

[44] U.S. EPA, Office of the Science Advisor, Risk Assessment Forum, Weight of Evidence in Ecological Assessment, EPA/100/R-16/001, December 2016, p. 1.

LOE 2 states that primary CCR indicator constituents boron and sulfate are not present above background limits and are not increasing in APW15. IPGC relied on multiple rounds of groundwater data from upgradient and compliance wells around the PAP, and multiple porewater samples from four monitoring wells installed at the base of the CCR within the PAP (porewater wells) using low-flow sampling techniques in support of this conclusion.[45] The porewater wells are installed at four locations along a cross-section of the PAP in order to capture variability across the SI. The porewater data are representative of the range of leachate quality potentially leaving the PAP because they were collected at the base of the SI (where L/S ratios should be lowest and leachate concentrations highest) in multiple locations over multiple sampling events. The groundwater and porewater data and the background analysis are included in the Hydrogeological Characterization Report, Groundwater Monitoring Plan, and the 2nd Quarter Groundwater Monitoring Report for the PAP referenced in IPGC's ASD.

As discussed above, the relative abundances (or concentration ratios) of key waste constituents can be used as a fingerprint in forensic analysis. The CCR fingerprint for groundwater impact can be defined by the relative abundances of boron, sulfate, and chloride in the porewater as these analytes all behave conservatively in groundwater (i.e., they are likely to travel together at a similar rate in groundwater without being influenced by chemical processes or decay thereby maintaining similar concentration ratios). In its final rulemaking for CCR land disposal, EPA identified the following CCR constituents as indicator parameters for CCR detection monitoring: boron, chloride, fluoride, pH, sulfate and TDS. These parameters are commonly observed in CCR leachate. Out of all constituents in CCR and CCR leachate, EPA determined that these parameters would behave most conservatively (flow with groundwater) in an aquifer, and when observed together in monitoring wells, might signal a CCR release is impacting that well.[46] Also, EPA determined that, out of all the coal ash constituents modeled, boron has the fastest travel time, meaning that boron is likely to reach potential receptors (or a well that is being impacted) before any other constituents, [47] although this difference is likely to be small for other constituents that behave like conservative solutes in groundwater such as sulfate and chloride.

The evidence presented in LOE 2 shows that the boron, sulfate, and chloride fingerprint at APW15 is marked by only background levels of boron and sulfate, but significantly elevated chloride. On the other hand, the CCR porewater data have elevated concentrations of boron and sulfate, but concentrations of chloride consistent with background. In other words, the ratio of chloride to boron and chloride to sulfate is much lower in APW15 than the ratios that exist in PAP porewater. The CCR SI is not a source of chloride at APW15 because it is not accompanied by either boron or sulfate. On the other hand, the CCR indicator concentrations in wells with exceedances attributed to the PAP have ratios similar to the porewater.[48] The ASD further reported that the boron and sulfate concentrations at APW15 are not increasing with time, as one would expect if CCR leachate was migrating to APW15. The lack of an increasing trend of boron and sulfate further supports that the PAP is not contributing

[45] Ramboll, Hydrogeologic Site Characterization Report, Primary Ash Pond, Newton Power Plant, October 25, 2021, Figure 2-8.

[46] EPA, 80 FR 21302 40 CFR Parts 257 and 261 Hazardous and Solid Waste Management System: Disposal of Coal Combustion Residuals from Electric Utilities, Final Rule April 17, 2015, p. 21342.

[47] EPA 83 FR 11584, Hazardous and Solid Waste Management system: Disposal of Coal Combustion Residuals from Electric Utilities; Amendments to the National Minimum Criteria (Phase one); Proposed Rule, March 15, 2018, p. 11588.

[48] Ramboll, Hydrogeologic Site Characterization Report, Primary Ash Pond, Newton Power Plant, October 25, 2021, Table 4-1.

to the chloride exceedance in APG15. This line of evidence is consistent with EPA's own FALCON fingerprinting method, discussed above, because both methods rely on a comparison of the relative concentrations of key constituents in sources and impacted groundwater.[49]

None of IEPA's perceived data gaps relate to the collection of facts or evidence that would further support or disprove LOE 2. If the information requested in IEPA's perceived data gaps was collected it could not disprove the evidence or conclusions contained within this LOE i.e. none of IEPA's requested data could change the conclusion that the concentrations and concentration trends of chloride, boron and sulfate in APW15 indicate that the Newton PAP is not contributing to the chloride exceedance in that well and that it is, thus, being caused by an alternate source.

Opinion 7: LOE 3 is based on appropriate facts and evidence sufficient to establish that the chloride concentrations observed could not have come from the PAP SI.

LOE 3 provides evidence that the concentration of chloride in APW15 is significantly (four to ten times) greater than chloride in the porewater data. This LOE is based on the same underlying data as LOE 2 above. As discussed in Section 3.3, contaminants being transported in groundwater experience decreasing concentrations moving away from the source due to the principle of conservation of mass (contaminant transport equations are derived from this principle). Porewater represents the maximum source concentration to underlying groundwater. Meaning, if chloride is leaching from the Newton PAP, its maximum concentration would be expected to be found in the porewater samples gathered from the base of the PAP (as that is the last possible input of mass from the CCR to the porewater that could leach from the PAP). Chloride concentrations would then decrease moving vertically from the base of the SI downward to the uppermost aquifer (assuming such a pathway existed, though evidence suggests it does not given the 60 feet of low permeability till), and would continue to decrease moving horizontally downgradient within the uppermost aquifer to APW15 due to dilutive processes such as dispersion and diffusion.

Therefore, it follows from the principle of conservation of mass (and the resulting equations for contaminant transport in groundwater such as R26 from TACO) that, in the event of a release from a CCR SI, the CCR constituent concentration in groundwater at a downgradient monitoring well would necessarily be less than the porewater (source) concentration. For the PAP, the maximum chloride concentration at well APW15 is four times the maximum porewater concentration, and the median APW15 chloride concentration is more than an order of magnitude higher than the median porewater concentration in the PAP. This indicates that the PAP is not the source of elevated chloride at APW15.

None of IEPA's perceived data gaps relate to the collection of facts or evidence that would further support or disprove LOE 3. If the information contained in IEPA's perceived data gaps was collected it could not disprove the evidence or conclusions contained within this LOE i.e. none of IEPA's requested data could change the conclusion that chloride concentrations at APW15 are much higher than chloride concentrations in Newton PAP porewater and that the chloride in APW15 is therefore not from the Newton PAP but, rather, is from an alternative source.

Opinion 8: Given the three strong LOEs (consistent with EPA's practice of modeling potential groundwater impacts from CCR SIs using porewater concentrations) presented in the ASD – including the lack of a viable vertical pathway, the lack of corroborating CCR indicator parameters at APW15 as

[49] U.S. EPA, Technical Support Center Issue, Fingerprint Analysis of Contaminant Data: A Forensic Tool for Evaluating Environmental Contamination, EPA/600/5-04/054, May 2004.

observed in porewater, and chloride concentrations at APW15 greater than is physically possible from a release of the observed porewater – a reasonable scientist or engineer would conclude that the Newton PAP is not causing or contributing to the observed chloride exceedance at APW15. Since the Newton PAP can be ruled out as a source, then the chloride must be coming from an alternate source.

Opinion 9: The ASD identified an alternative source using best available information.

IPGC's ASD also provided evidence that the underlying bedrock aquifer is the source of the chloride exceedance in APW15. This included providing facts and evidence demonstrating the close proximity (within approximately 10 to 15 feet vertically) of the screened interval at APW15 to underlying bedrock based on PAP boring logs, the naturally occurring elevated concentrations of chloride in the underlying bedrock aquifer, and the local upward gradients based on the presence of a saline spring within approximately ten miles of the PAP. IPGC's ASD relied on two key documents for this information.[50] The first is an article published by the National Groundwater Association called "Groundwater" (the "Panno article").[51] This article provides information regarding the chloride content of bedrock aquifers in southern Illinois. Chloride content of the uppermost bedrock aquifer as presented in the Panno article does not show significant variability across southern Illinois, so site-specific data are not necessary to identify the bedrock as an alternative source. The figure below[52] shows chloride concentrations in bedrock aquifers along a west-to-east cross section in southern Illinois, including Jasper County, where the Newton Power Plant is located. The plotted chloride isoconcentration line (a line through which concentrations are the same value) shows that chloride concentrations at 1,000 mg/L are present at the top of the Pennsylvanian shale (uppermost bedrock) across seven counties from Washington County in Illinois to Vigo County in Indiana. This includes Jasper County. The consistency in the data (i.e., lack of variability in the data) suggests that future sampling would yield very similar results.

[50] Additional supported documents cited in the ASD that I also reviewed include: Cartwright, K., Groundwater Discharge in the Illinois Basin as Suggested by Temperature Anomalies, Water Resources Research, Vol. 6, No. 3, 1970. pp. 912-918, Panno and Hackley, Geologic Influences on Water Quality, In Geology of Illinois, ed. Kolata and Nimz, Illinois State Geological Survey, 2010, pp. 337-350, Siegel, Geochemistry of the Cambrian-Ordovician Aquifer System in the Northern Midwest, U.S. Geological Survey Professional Paper 1405-D, 1989, and Willman et al, Geologic Map of Illinois: Illinois State Geological Survey Map, scale 1:500,000, 1967.

[51] Panno, S.V et al, Recharge and Groundwater Flow Within and Intracratonic Basin, Midwestern Unites States, Groundwater, Vol. 56, Jan/Feb 2018, pp. 32-45. (originally published online in July 2017).

[52] Panno, V.P. et al, Recharge and Groundwater Flow Within an Intracratonic Basis, Midwestern United States, Groundwater, 2017, Vol. 56, No. 1, p. 41.

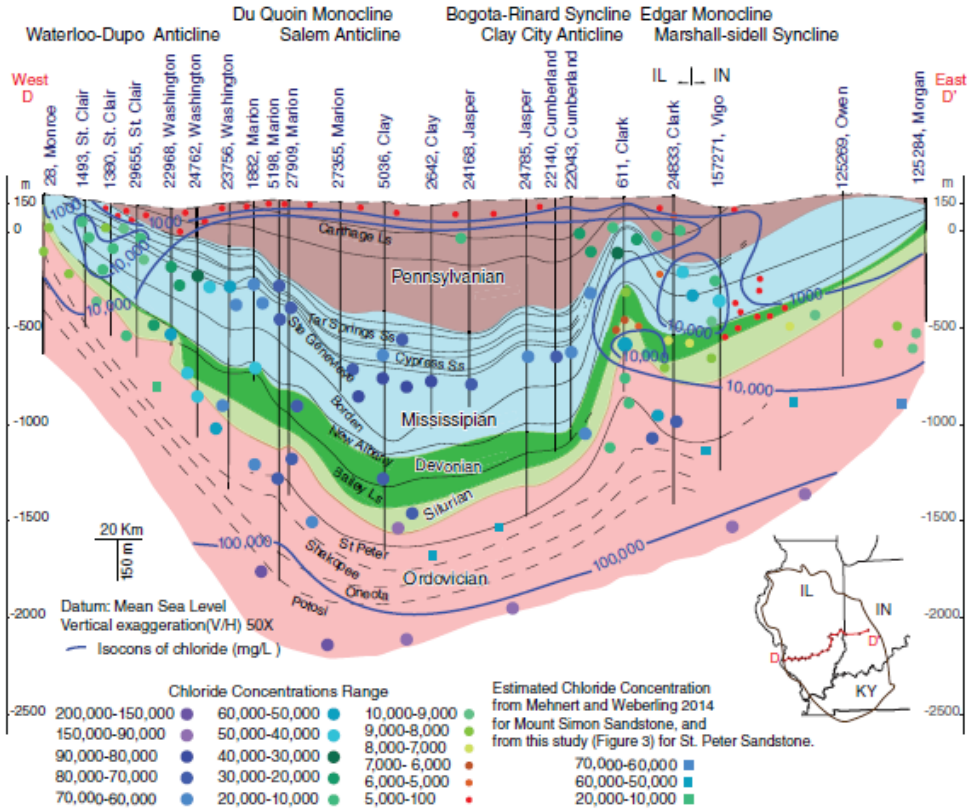

Figure 7. Cross section D–D′ extending east-west across southern Illinois and southern Indiana. Freshwater recharge affects the western and eastern margins of the basin, but not to the extent seen in cross sections farther north. Brines are also diluted along the LaSalle Anticlinorium (groundwater movement toward the reader). Again, the most concentrated brines are present in the Cambrian strata.

The second key document is a report jointly prepared by the Illinois State Water Survey (ISWS), the Illinois State Geological Survey (ISGS), and the Prairie Research Institute at the University of Illinois at Urbana-Champaign that shows a saline spring in close proximity to the PAP.[53] The primary author of the Panno article is an employee of the Illinois State Geological Survey. As a governmental agency document and a document published in a peer-reviewed journal, both documents were subject to peer review, and are reliable for the purposes of the ASD. It therefore should not be necessary to request documentation of field procedures and laboratory data packages from the ISWS and ISGS for their official publications to present as attachments to the Newton PAP ASD.

The facts and evidence provided in the ASD show that there is a pathway for chloride to migrate from the bedrock to APW15 (in contrast to the lack of pathway from the PAP to APW15). This includes evidence from PAP boring logs demonstrating the short distance between the well screen and underlying bedrock,[54] the elevated chloride concentrations from published ISGS data, and the presence of a saline spring based in ISGS observation. This supporting information establishes a viable

[53] Kelley, et al (ISWS, ISGS, and University of Illinois at Urbana-Champaign), The Sources, Distribution and Trends of Chloride in the Waters of Illinois, March 2012.

[54] Ramboll, Hydrogeologic Site Characterization Report, Primary Ash Pond, Newton Power Plant, October 25, 2021, Figure 2-7.

pathway for chloride migration from the underlying bedrock to APW15, whereas the 60-foot thick low permeability till between the PAP and APW15 precludes a pathway from the PAP.

In my opinion, the ASD concludes that elevations of chloride in APW15 are naturally occurring due to the underlying bedrock based on the best available information available to IPGC at the time it was putting together the ASD.

3.3 The "Data Gaps" in IEPA's Denial Letter Are Unnecessary for the Newton ASD

Opinion 10: The information in IEPA's data gap #1 is not necessary to support the conclusions of the ASD. This data would not change the conclusions in the ASD.

Data gap #1, "source characterization of the CCR at the Primary Ash Pond must include total solids sampling in accordance with SW-846," is not entirely clear in its meaning. Most directly, it appears to mean collect additional CCR solid samples[55] and analyze those samples for total chlorine or chloride content in units of mg/kg by an SW-846 method.[56] IEPA's Record does not cite to any specific SW-846 analysis method for a solid sample that it believes should have been used. Notably, there is no EPA SW-846 method that includes chloride or chlorine as an analyte in a solid sample so the request for "total solids sampling" using an SW-846 method for chloride or chlorine is not possible as written.

Regardless, any total solid analysis, irrespective of methodology, is unnecessary to support the Newton ASD and will not provide useful information regarding whether the PAP is impacting groundwater in APW15 without further assumptions or estimations of leaching concentrations because total constituent data are not a direct input to the equations of contaminant transport in groundwater as discussed in Section 3.3. As explained above, total solids analysis provides information regarding constituents that are currently within the solids in a CCR SI. It does not provide information regarding the concentrations of constituents in porewater that are potentially leaving a CCR SI and entering into groundwater. Meaning, if solids sampling and total constituent analysis was conducted at the Newton PAP (regardless of the methodology or number of borings and samples) it would not, by itself, provide useful information for an ASD to determine whether contaminants leaching from a CCR SI are contributing to contamination in groundwater.

As discussed in Section 2.4, after extensive testing, EPA found that the total concentrations of CCR constituents are not correlated with the leachable concentrations and elected to use CCR SI porewater concentrations as the basis to model contaminant migration in groundwater from a hypothetical SI in support of its risk assessment.[57] The input to a contaminant transport equation in groundwater such as R26 in TACO is a source concentration in groundwater (e.g., mg/L), not a mass or a total solids concentration in CCR (mg/kg). IEPA's total solids sampling is not relevant to understanding the potential for migration in groundwater and would not add any helpful information to the ASD. The leachate concentration from the source is the only relevant factor for understanding potential migration to groundwater. Total solids sampling and associated total mass calculation would be

[55] Total concentration of SW-846 analytes in Newton CCR samples expressed as mg/kg were provided in the Site Hydrogoelogic Characterization Report at Table 2-2.

[56] In deposition, IEPA witness Ms. Hunt suggested the data gap is intended to mean that ten borings throughout the CCR surface impoundment are necessary and three solid samples from each boring must be collected and analyzed to characterize the CCR source. Notably, Part 845 would be impossible for owners and operators to comply with if the Agency has significant internal data requirements that are not spelled out in the rule.

[57] EPA, Human and Ecological Risk Assessment of Coal Combustion Residuals, Final Report, December 2014, p. 5-47

relevant to an estimation of the total leaching lifetime of a SI, but that is not needed or relevant for an ASD, which is focused on whether a SI contributed to a particular exceedance.

Opinion 11: Porewater data is the better indicator of groundwater impact from a SI, compared to leach test data.

Total solid sampling could have some value if it the sample is analyzed by a leach test method. However, porewater data is superior to leach testing data to characterize whether a CCR SI is impacting groundwater. While not explicitly clear from the language in IEPA's ASD denial letter, it is also possible IEPA intended data gap #1 to mean collect CCR solid samples and analyze them for leachable concentrations using one of the SW-846 leach test methods. If IEPA intended to request SW-846 leaching analysis of Newton CCR, that information would not be superior to the existing porewater data set for the PAP for purposes of performing an ASD. After extensive research on the topic, as described above in Section 3.4, EPA found that actual porewater data for CCR SIs are best to represent the source term for risk assessment for the pathway of migration to groundwater because they are direct measurements, rather than estimates or simulations, of actual leachate quality at the CCR SIs,[58] and are best representation of field conditions such that no further data are necessary.[59] Differences between lab and field conditions include the size, scale and geometry of the leaching vessel, the particle size of the solid sample, the pH of the beginning eluent (rainwater is slightly acidic), the variability CCR placed over time, the variability of L/S ratios within the SI, and codisposal with additional wastes and wastewaters that are important in leachate generation and cannot be replicated in a laboratory. In contrast, SW-846 leach test methodologies such as LEAF tests are conducted under laboratory conditions and require selection of test L/S ratios and eluent pH that may not align with real world field conditions. The LEAF tests will generate multiple potential leachate concentrations (i.e., groundwater source terms) based upon laboratory selection of eluent pH, L/S ratio, and scenario (flow through or flow around). EPA does not provide guidance that addresses how to select a representative result. EPA documents not included in the IEPA Record indicate that field-measured, site-specific data are preferable to laboratory simulations or probabilistic estimates from multiple laboratory simulations.[60] Other research has corroborated that porewater is a better indicator of potential groundwater impact than leach test data.[61]

Why choose to simulate or predict data that can be directly measured? The Newton PAP ASD's method of characterizing what is leaching from the Newton PAP is more appropriate because it reflects real

[58] EPA, Report to Congress: Wastes. from the Combustion of Fossil Fuels, Vol. 1 – Executive Summary, March 1999, EPA 530-S-99-010m p. 3-18.

[59] EPA, Human and Ecological Risk Assessment of Coal Combustion Residuals, Final Report, December 2014, p. 5-47

[60] EPA Technical Manual on Solid Waste Disposal Facility Criteria, EPA530-R-93-017, pp. 124-125; and EPA, Leaching Tests to Develop Source Terms to Evaluate Potential Leaching from Waste, Beneficial Use, Land Disposal, and Treatment, Presentation dated October 29, 2021, p. 41.

[61] Electric Power Research Institute (EPRI), 2020. Leaching, Geotechnical, and Hydrologic Characterization of Coal Combustion Products from a Closed Coal Ash Impoundment: Capped Unit. EPRI, Palo Alto, CA:2020. 3002017363; Electric Power Research Institute (EPRI), 2021. Leaching, Geotechnical, and Hydrologic Characterization of Coal Combustion Products from an Active Coal Ash Management Unit: Plant 42197. EPRI, Palo Alto, CA: 2021. 3002018780.; Electric Power Research Institute (EPRI), 2022. Evaluation and Comparison of Leach Test and Porewater Variability for Multiple Coal Combustion Product Management Units. EPRI, Palo Alto, CA: 2022.

world data and collects porewater samples in areas of highest concentration using a method that is less likely to collect excessive and unrepresentative solids.

Opinion 12: Neither PAP porewater data nor PAP CCR solids sampling and total constituent analysis or leach testing will represent leachate quality from the distant past. However, porewater data are still the best representation for potential groundwater impact. Past porewater concentrations at the base of an unlined SI were not likely higher in concentration than those observed after decades of operation.

Basis: All sampling methodologies will necessarily reflect leachate quality at the current time. However, as CCR leaches constituents, the total constituent concentrations necessarily decrease over time as mass is lost to the fluid phase. Current porewater data represents mass lost from CCR in the past, while data from solid CCR samples would reflect future leachate that is likely lower in concentration than current porewater. Further, porewater CCR constituent concentrations at the base of a CCR SI are likely to increase over the lifetime of a CCR SI due to the high L/S ratio of original sluiced materials, the over time of total volume of materials managed, the increased migration path (and CCR contact time) that the porewater must follow vertically through the SI, and decreasing L/S ratio as materials at the bottom of the SI are compressed by an overlying materials. Over time, the mass available for leaching increases and the L/S ratio decreases, thereby increasing the leachate and porewater concentrations until these the SI is mature and the volume and L/S ratio are no longer changing significantly.

Opinion 13: Conducting a mass balance of all the chloride in the CCR SI and nearby groundwater is not necessary for the ASD.

While not clear or explicit from IEPA's denial letter, in deposition, Ms. Hunt seemed to suggest that a mass balance between the CCR SI and the groundwater must be calculated in order to apply the contaminant transport equation in groundwater.[62] This is simply not true. As explained in Section 3.3 above, porewater with dissolved solids or solutes, rather than gross solids, can potentially migrate to groundwater and create a groundwater plume.[63] The porewater data can be used as an input for source concentration to the contaminant transport equation in groundwater. Mass or total solids concentration cannot be used as an input to the equation without further manipulation or assumption. The leachable concentration must be modeled with a partition coefficient or simulated in a laboratory from a solid sample. Further, a mass balance cannot be completed when there is an exchange of materials from outside the system (e.g., chloride coming into the system from deeper groundwater). As discussed above in Section 3.4 and as practiced by EPA in its risk assessment of CCR SIs, the porewater concentrations represent the best estimate of source strength potentially migrating to groundwater. The contaminant transport equation predicts groundwater concentrations downgradient from a groundwater source concentration. These units are mg/L, not mass or mg/kg as in totals samples.

Opinion 14: Data gaps #2 and #3, bedrock hydraulic conductivity and alternate source characterization data (and underlying documentation), are not needed for the ASD, and would not have been possible to collect in the time allowed to submit an ASD.

[62] Lauren Hunt deposition, May 28, 2024, p. 44, 77, 78, 91, 92,118-121

[63] Fetter et al, Contaminant Hydrogeology, Third Edition, Waveland Press, 2018, p. 61.

Basis: Data gap #2, collecting, analyzing and presenting hydraulic conductivities from laboratory or in-situ testing with hydrogeologic characterization of the bedrock unit, is also not necessary. Fulfilling this request would require substantial drilling and well installation in the bedrock that would be very time consuming and expensive, based on my professional experience and the testimony of Cynthia Vodopivec. [64] It could not be done in the 60-day timeframe for submitting an ASD required by the regulation. It is also unnecessary because there are regional and local data available in the literature, which, as discussed in Opinion 8, was included with the ASD.

Data Gap #3, characterization to include sample and analysis in accordance with 35 IAC 845.640 of alternative source, is confusing based on subsequent IEPA witness testimony. It is unclear whether IEPA is requesting well installation and sampling in the bedrock aquifer with field procedures and laboratory data packages for the well installation and sampling of the bedrock aquifer, or provision of field procedures, and laboratory data packages for data published in the government and peer-reviewed professional journal articles that were relied upon. Again, in my professional experience bedrock drilling and sampling would be prohibitively time-consuming and could not be conducted within the ASD filing time limit required by 35 IAC 845. It is also unnecessary because there are regional and local data available in the literature, which, as discussed in Opinion 8, was included with the ASD.

While direct drilling and well installation and sampling was an impossibility, IPGC's ASD did use the best available facts and evidence available to determine that the chloride exceedance was naturally occurring, caused by bedrock underlying APW15. As discussed in Opinion 8, this included a wide array of reliable, peer-reviewed documents demonstrating the presence of elevated chloride levels in the bedrock underlying APW15 and demonstrating a potential pathway/connection between the bedrock and APW15. Given the evidence in the ASD, if the information in data gap #2 and #3 were collected, I would expect it to support the conclusion that the bedrock is the source of the chloride exceedance in APW15. Additionally, even if the information in data gap #2 and #3 were collected, it would never support a conclusion that the Newton PAP is contributing to the chloride exceedance or that it is not being caused by an alternative source.

Opinion 15: The documents included in IEPA's Record do not support the denial of the ASD.

I conducted a review of the scientific and technical documents contained within IEPA's Record. This included a review of the following documents:

- Drever, James I. The Geochemistry of Natural Waters: Surface and Groundwater Environments. Prentice Hall. Third Edition. 1997, Select pages (Record Document 1)
- Faybishenko, Boris, Paul A. Witherspoon and Sally M. Benson Editors. Dynamics of Fluids in Fractured Rock. American Geophysical Union. 2000, select pages (Record Document 2)
- Eby, G. Nelson. Principles of Environmental Geochemistry. Brooks/Cole, Cengage Learning. 2004, select pages (Record Document 3)
- United States Environmental Protection Agency (USEPA). SW-846 Test Method 1314: Liquid-Solid Partitioning as a Function of Liquid-Solid Ratio for Constituents in Solid Materials Using An Up-Flow Percolation Column Procedure. July, 2017 (Record Document 4)
- United States Env SW-846 Test Method 1316: Liquid-Solid Partitioning as a Function of Liquid-to-Solid Ratio in Solid Materials Using a Parallel Batch Procedure. July, 2017 (Record Document 6)

[64] Record Document 33 at R002213-R002214.

- ironmental Protection Agency (USEPA). SW-846 Test Method 1315: Mass Transfer Rates of Constituents in Monolithic or Compacted Granular Materials Using a Semi-Dynamic Tank Leaching Procedure. July, 2017 (Record Document 5)
- United States Environmental Protection Agency (USEPA) Region I. Low Stress (Low Flow) Purging And Sampling Procedure For The Collection Of Groundwater Samples From Monitoring Wells. September 19, 2017 (Record Document 7)
- Fetter, C.W., Thomas Boving, and David Kreamer. Contaminant Hydrogeology. Waveland Press. Third Edition. 2018, Chapters 1-9. (Record Document 8)
- United States Environmental Protection Agency (USEPA). Pore Water Sampling. USEPA Publication, No. LSASDPROC-513-R5. (Record Document 11)
- Handwritten notes of Heather Mullenax October 19, 2023 (Record Document 15)
- Handwritten notes of Heather Mullenax October 31, 2023 (Record Document 24)
- Handwritten notes of Heather Mullenax November 6, 2023 (Record Document 31)

Many of the documents in IEPA's Record are general textbooks, excerpts from textbooks or USEPA guidance that are not directly relevant. Other documents included by the IEPA support concepts in the ASD such as the fact that chloride has both natural and anthropogenic sources, and behaves as a conservative solute in groundwater.[65] Others describe the laboratory methods and limitations of LEAF test methods.

IEPA included three documents from SW-846, each related to LEAF testing methods. None are useful to the ASD. LEAF Testing Method 1314 documentation notes,[66] "This method provides eluate solutions considered indicative of leachate under field conditions only where the field leaching pH is controlled by the alkalinity or acidity of the solid material and the field leachate is not subject to dilution or other attenuation mechanisms." The test would not be representative of field conditions at the PAP due to codisposal of wastewaters. Further, in contrast to field conditions, LEAF tests use small volumes of solid samples and reagent grade water rather than rainwater that is naturally acidic. These shortcomings of rather idealized laboratory conditions highlight the fact that these tests merely provide estimates of potential leachate quality, and that direct measurement of porewater quality is much more accurate in terms of understanding the actual source concentration of contaminant available for transport from the SI because it is the integral result of lifetime variability of the L/S and spatial variability of the CCR itself. Further, multiple porewater samples can give a picture of the field-scale variability in leaching potential due to differences in CCR chemistry of all placed materials.

Documentation for other LEAF methods, Methods 1315[67] and 1316,[68] in IEPA's Record have similar statements regarding their lack of representation of field leaching conditions. This is consistent with EPA's decision to select field porewater data over laboratory leachate tests to model the potential migration of CCR constituents to groundwater. Method 1315 further relates to monolithic and

[65] Eby, G. Nelson. Principles of Environmental Geochemistry. Brooks/Cole, Cengage Learning. 2004, p. 366.

[66] United States Environmental Protection Agency (USEPA). SW-846 Test Method 1314: Liquid-Solid Partitioning as a Function of Liquid-Solid Ratio for Constituents in Solid Materials Using An Up-Flow Percolation Column Procedure. July, 2017, pp. 1314-2 to 1314-3.

[67] United States Environmental Protection Agency (USEPA). SW-846 Test Method 1315: Mass Transfer Rates of Constituents in Monolithic or Compacted Granular Materials Using a Semi-Dynamic Tank Leaching Procedure. July, 2017, Section 1.5.

[68] SW-846 Test Method 1316: Liquid-Solid Partitioning as a Function of Liquid-to-Solid Ratio in Solid Materials Using a Parallel Batch Procedure. July, 2017, Section 1.7.

compacted granular material. In my opinion CCR in a SI behaves more like a porous medium than a monolithic or compacted granular material.

The IEPA Record includes select pages from a textbook by Drever.[69] This document discusses certain constituents, but does not include a discussion of chlorine or chloride. It also, includes a description of geochemical modeling and redox reactions using software. This description and modeling applies to non-conservative solutes and does not apply to a conservative solute like chloride.

The IEPA Record includes select pages from a book by Nelson.[70] This text identifies chloride as a conservative solute that has both natural and anthropogenic sources. This text supports the conclusions in the ASD which relies upon chloride's role as a conservative solute to support the fact that the chloride in APW15 is not from the Newton PAP. It further supports the idea that chloride can come from natural sources, such as bedrock.

The IEPA Record includes much of a classic textbook in Contaminant Hydrogeology by Fetter et al.[71] Chapter 2 of this text discusses mass or solute transport in groundwater. As discussed above, the governing equations describe concentration in groundwater (e.g., mg/L), not on mass (kg) or total solid concentration (mg/kg) of a source. Fetter also states that the derivation of the advection-dispersion equation for solute (mg/L in groundwater) transport (similar to the TACO R26 Domenico equation) is based on the conservation of mass of solute flux into a unit volume of groundwater.[72] This does not mean that one must complete an actual mass balance of a solute in the system of interest in order to use the equation, so this document does not support IEPA's data gap #1, to characterize total solids in the CCR source. Instead of attempting to reinvent the wheel on the characterization of leachable constituents, IEPA should have relied upon the decades of work that EPA has completed in order to characterize CCR, CCR leachate, and the potential for migration of CCR constituents from porewater to groundwater in support of its rulemaking process. These include documents referenced in the ASD and comment letter, my declaration, and this expert report.

The record also contains a USEPA porewater sampling guidance document for sediment. While none of IEPA's data gaps appear to refer to the porewater sampling IPGC conducted to characterize what might be leaching from the Newton ASD, the document in IEPA's record is not relevant to the analysis of CCR SI porewater because it describes sampling of porewater in a shallow water body with a hand-held direct push device and a mechanism to collect a grab sample of porewater from relatively shallow depths, typical of shallow rivers or streams. This is not relevant to a CCR SI because SI porewater samples representative of liquid that may migrate to groundwater is typically collected using monitoring wells. The presence of this document in the record may suggest that IEPA misunderstands how porewater data were collected at the Newton PAP and are typically collected for a CCR SI. The Newton PAP porewater samples were collected from wells with screens set at the base of the CCR (in the zone where CCR would be most consolidated with a lower L/S ratio and higher leachate concentration) using low-flow sampling techniques. This is an appropriate methodology for collecting

[69] Drever, James I. The Geochemistry of Natural Waters: Surface and Groundwater Environments. Prentice Hall. Third Edition. 1997, select pages.

[70] Eby, G. Nelson. Principles of Environmental Geochemistry. Brooks/Cole, Cengage Learning. 2004, select pages.

[71] Fetter, C.W., Thomas Boving, and David Kreamer. Contaminant Hydrogeology. Waveland Press. Third Edition. 2018

[72] Fetter, C.W., Thomas Boving, and David Kreamer. Contaminant Hydrogeology. Waveland Press. Third Edition. 2018, p. 66.

porewater samples from a CCR SI because saturated CCR is effectively a porous medium, similar to natural sands, gravels and silts, with interstitial water that may be sampled with a monitoring well.

I did not see any facts or evidence, including a scientific or technical document, in IEPA's record supporting the idea that total solids sampling of the Newton PAP is necessary to support an ASD for chloride at APW15. I did not see any facts or evidence, including a scientific or technical document, in IEPA's record suggesting that direct sampling of an alternative source is needed or required to support an ASD for chloride at APW15.

Opinion 16: The Newton ASD uses all available and appropriate data to determine the strongest forensic lines of evidence in the limited time period provided to submit the ASD report, and these lines of evidence clearly rule out the Newton PAP as a source of or contributor to chloride at APW15, and provide evidence that chloride is coming from an alternative source. The 60-day deadline does not provide adequate time to collect the information requested by IEPA in its denial or in explanations provided by IEPA employees in depositions. As a practical matter, the ASD can only be completed with data already collected or that can be collected analyzed and included in a report within the 60-day window to complete the ASD.

As discussed above, neither the ten boring CCR solid characterization nor the bedrock aquifer characterization could have been completed before the 60-day ASD deadline. In fact, simply completing the ASD can fill the time requirement. The tasks that need to be completed to provide an ASD within the 60-day timeframe include contracting with a PE, having him/her gather and review the relevant data, conduct an analysis, draft a report, complete necessary reviews, and finalize the report. Each of these tasks can take a week or more to complete, so the baseline timeframe is approximately 6 weeks. There is simply insufficient time to add the tasks of develop a field sampling plan, safety plan, data objectives plan, engage with contractors, collect the data, and wait for analysis for any significant field investigation. These additional tasks can each take a week or more to complete as well. Typical laboratory turn-around-times are two weeks, so that single task pushes the project beyond 60 days. IEPA's source and alternate source data requirements are simply not possible to comply with in the allowed 60-day window.

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ATTACHMENT A

CURRICULUM VITAE

Electronic Filing: Received, Clerk's Office 08/1/2024

ENVIRONMENT & HEALTH

RAMBOLL

MELINDA W. HAHN, PH.D.

Senior Managing Consultant

Dr. Hahn's practice areas include site investigation and remediation, contaminant fate and transport modelling, statistics of environmental data, forensic analysis, and litigation support, including primarily environmental liability and cost allocation. Regulatory areas include RCRA, CERCLA, TSCA, and Voluntary Cleanup/Risk-Based Corrective Action. Dr. Hahn has experience in the following industry categories: energy (electric utilities, petroleum dispensing, pipeline operations, former manufactured gas plant sites), industrial equipment manufacturing, metal working and metal recycling, automobile manufacturing, ink and chemical manufacturing, wood treating, mining, cement manufacturing, milling and smelting operations, secondary aluminum production, and dry cleaning.

EDUCATION

1995
PhD, Environmental Engineering
The Johns Hopkins University

1990
BS, Physics
The University of Texas at Austin

1990
BS, Mathematics
The University of Texas at Austin

ACADEMIC HONORS

1992-1995
Graduate Fellow, National Science Foundation

1995
Most Distinguished Environmental Engineering Dissertation, Association of Environmental Engineering Professors

CAREER

1998-Present
Senior Managing Consultant, ENVIRON/Ramboll

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Consultant, Roy Ball, PC

1995-1997
Senior Project Engineer, Environmental Resources Management-North Central, Inc.

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ATTACHMENT B

EXTRA-RECORD DOCUMENTS RELIED UPON

Electronic Filing: Received, Clerk's Office 08/1/2024

Document 1

Cartwright, K., 1970. Groundwater discharge in the Illinois Basin as suggested by temperature anomalies. Water Resources Research 6, No. 3: 912-918.

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Groundwater Discharge in the Illinois Basin as Suggested by Temperature Anomalies

KEROS CARTWRIGHT

Illinois State Geological Survey, Urbana, Illinois 61801

Abstract. Areas where ground water in the Illinois basin is moving vertically should be reflected by temperature anomalies. To test this hypothesis, an isothermal map for a depth of 500 feet was constructed, based on bottom hole temperatures of deep wells. This map was compared with a theoretical isothermal map for a depth of 500 feet that was made by projecting temperature gradients (calculated from the thermal conductivities of the rock) downward from the surface where mean annual air temperatures were known. The residual temperature map that was made on the basis of this comparison (calculated minus observed temperature) shows several warm and cool anomalies that are postulated to be discharge and recharge areas, respectively. Analysis of the curvature of the earth's thermal profile calculated for the basin suggests that approximately 59,000 acre-feet of ground water per year are discharged upward from the deep rocks in the Illinois basin. This figure is of the same magnitude as an estimated excessive groundwater discharge into the region's streams of 43,000 acre-feet, based on comparison of unit-area discharge of streams in the basin with streams in similar areas outside the basin. From a simplified model of the basin, a groundwater inflow of about 36,500 acre-feet from the surrounding highlands is estimated. A significant portion of this discharge must be through fracture zones associated with faults and anticlines in the basin, inasmuch as this amount of flow would require that the shales have a vertical permeability from one to three orders of magnitude higher than is generally observed. One such discharge area in southwestern Illinois is suggested by field data.

INTRODUCTION

Movement of ground water within the lithosphere has long been known to affect the flux of heat within the earth. *Van Orstrand* [1934] suggested that the movement of ground water caused variations in the geothermal gradient in the Salt Creek oil field, Wyoming. The effect of groundwater movement is significant because the natural heat flux density from the earth is small.

Stallman [1960] presented the basic equation for the simultaneous transfer of heat and water within the earth and suggested they might be used to measure the rates of groundwater movement. *Bredehoeft and Papadopulos* [1965] and *Stallman* [1965] presented solutions of the basic equations applied to the vertical movement of water for certain boundary conditions. The Bredehoeft and Papadopulos solution is used in this paper to estimate the quantity of ground water discharge from the Illinois basin.

The general differential equation for simultaneous nonsteady flow of heat and fluid through fully saturated, isotropic, homogeneous, porous medium was developed [*Stallman*, 1960] from consideration of a unit volume of the medium. The equation is

$$\frac{\delta^2 T}{\delta x^2} + \frac{\delta^2 T}{\delta y^2} + \frac{\delta^2 T}{\delta z^2} - \frac{c_w \rho_w}{k} \left[\frac{\delta(v_x T)}{\delta x} + \frac{\delta(v_y T)}{\delta y} + \frac{\delta(v_z T)}{\delta z} \right] = \frac{c\rho}{k} \frac{\delta T}{\delta t} \quad (1)$$

where

- v, velocity of fluid flow; direction of flow specified by subscripts x, y, z;
- T, temperature at any point at time t;
- t, time since flow started;
- c, specific heat of rock fluid complex;
- c_w, specific heat of fluid;
- ρ, density of rock fluid complex;
- ρ_w, density of fluid;
- k, thermal conductivity of rock fluid complex;
- x,y,z, Cartesian coordinates.

For steady one-dimensional (vertical) flow of

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heat and fluid, equation 1 according to *Bredehoeft and Papadopulos* [1965] becomes

$$k\frac{\delta^2 T}{\delta z^2} - v_z c_w \rho_w \frac{\delta T}{\delta z} = 0 \qquad (2)$$

which when solved subject to the boundary conditions

$$T_z = T_0 \text{ at } z = 0 \qquad (3)$$

$$T_z = T_L \text{ at } z = L \qquad (4)$$

where T_z is the temperature measurement at any depth z, T_0 is the uppermost temperature measurement, T_L is the lowermost temperature measurement, and L is the length of vertical section over which temperature is measured, yields

$$\frac{(T_z - T_0)}{(TL - T_0)} = f(\beta, z/L) \qquad (5)$$

where

$$f(\beta, z/_L) = \frac{[\exp(\beta z/L) - 1]}{[\exp(\beta) - 1]} \qquad (6)$$

and

$$\beta = \frac{c_w \rho_w v_z L}{k} \qquad (7)$$

β is a dimensionless parameter that is positive or negative depending on whether v_z is downward or upward. *Bredehoeft and Papadopulos* [1965] presented a table and type curves for the solution of equation 6.

ILLINOIS BASIN

The Illinois basin is an oval-shaped structural and topographic depression with over 9000 feet of maximum relief in the granite basement [*Bell et al.*, 1964] and 1000 feet maximum topographic relief. Definition of the exact limits of the basin vary. However, at its broadest defined limits the basin extends from the Ozark uplift on the southwest to the Cincinnati and Kankakee arches on the east and northeast.

Very little is known of the distribution of hydrostatic head within the rocks of the basin. The difference in head between the rocks on the periphery of the basin and the water table at the center is 100 to at least 500 feet [*Bredehoeft et al.*, 1963]. Theoretical analyses by *Toth* [1963] and *Freeze and Witherspoon* [1966; 1967; 1968], and work by *Hitchon* [1969] in the Western Canadian sedimentary basin suggest that basins of this general shape should be discharging water upward from the deep, basin-wide flow system.

A mechanism for the concentration of the highly saline brine found in the basin was suggested by *Bredehoeft et al.* [1963]. The character and origin of these brines were further discussed in a series of papers by *Clayton et al.* [1966] and *Graf et al.* [1965; 1966]. The consensus of these studies is that the water in the deep formations of the basin is in motion and that some upward discharge of ground water is taking place through the clay shales that act as an osmotic membrane.

This study estimates the quantity of water being discharged, and where and how the major portion of discharge may be taking place. Most, if not all, of the fluid being discharged is in areas of high vertical permeability associated with the structural features of the basin.

TEMPERATURE ANOMALY

To test the hypothesis of upward flow of water and its effect on the geothermal gradients, an isothermal map for a depth of 500 feet was constructed from recorded bottom hole temperatures of deep wells. The wells are not evenly distributed throughout the mapped area (Figure 1). The first six wells (maximum of two per section where many datum points are available) for each Congressional township were selected from the mineral resource records of the Illinois State Geological Survey. Only wells over 1000-feet deep were chosen and records of obviously poor quality were eliminated from the sample. About 2000 well records were used. The temperature at 500 feet was calculated for each well by assuming that a linear gradient existed between the bottom hole temperature and the mean annual air temperature [*Jones*, 1966]. The mean of the temperature at 500 feet for all the selected wells was calculated for each township and plotted as a single point in the township. The inaccuracies of this type of temperature data are well known, but the fairly high degree of internal consistency in the data suggests the approach is valid.

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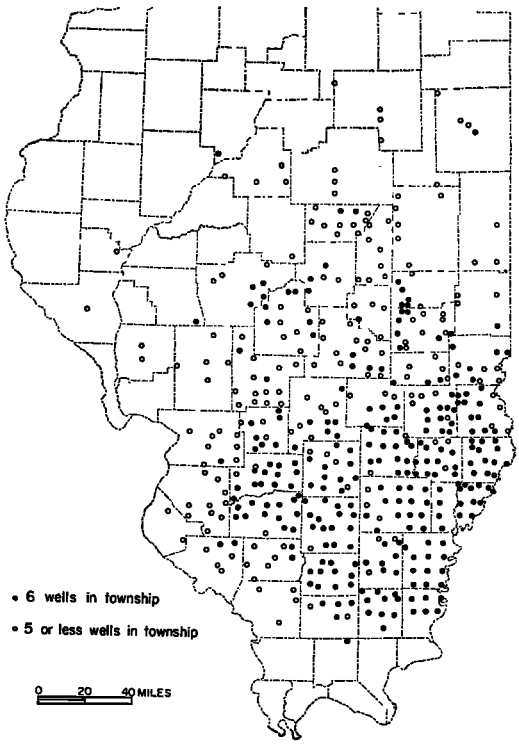

Fig. 1. Distribution of deep wells used in compiling isothermal map for 500-foot depth.

The resulting isothermal map (Figure 2) is a reasonable representation of the distribution of temperatures at the 500-foot depth. Two striking features appear on the map: (1) a general decrease in temperature from south to north reflects the trend of the mean annual air temperatures, and (2) the warm areas generally coincide with anticlinal areas and fault zones in the Illinois basin, which are also the principal oil producing areas in the state.

A theoretical isothermal map for the 500-foot depth was prepared (Figure 3) for comparison with the map based on well temperatures. For the theoretical map, temperatures at the 500-foot depth were calculated by estimating temperature gradients (based on assumed thermal conductivities of the rocks and geothermal gradient given below), and projecting the gradients downward from the surface where mean annual air temperatures were known. The air temperature data were from weather stations in the state [*Jones,* 1966]. The following thermal conductivities and geothermal gradients were used [*Cartwright,* 1968]:

Glacial sediments	0.0025 cgs units (cal/cm sec °C)
Pennsylvanian rocks	0.005 cgs units
Deep carbonate rocks	0.007 cgs units (and 1°F per 100 ft temperature gradient)

The thickness of the glacial drift in wide areas around the various weather stations was averaged.

A residual map (Figure 4) was then made to show the difference between the two isothermal maps by subtracting the observed temperature data from the calculated temperature data. The warm (negative) areas were assumed to be zones of upward movement (discharge) of water from deep aquifers in the basin, and the cool (positive) areas are zones of downward movement (recharge). Temperature anomalies in the northern third of the map probably are of little significance inasmuch as the data are sparse, and the thickness

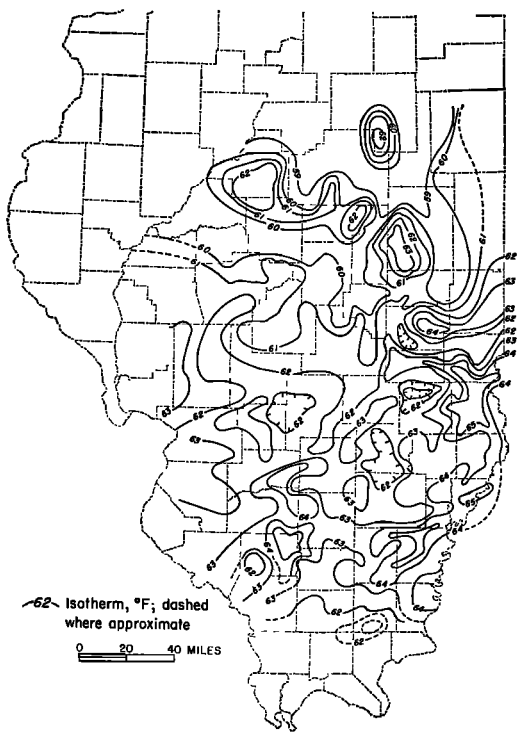

Fig. 2. Isothermal map for the 500-foot depth, based on temperature data from deep wells.

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of glacial drift, which has the greatest effect on the calculated temperature values, varies greatly. The Mahomet buried bedrock valley [*Horberg*, 1950], for instance, which contains 300 to 400 feet of fill, is reflected on the map as a cool area. This could be the result of the permeable drift's acting as a recharge zone, but it is probably due to not taking the effect of the thick drift when the temperature was calculated completely into account.

The residual map (Figure 4) also reflects some of the structural features of the area. The Wabash valley fault zone and the DuQuoin-Louden anticlinal belt are anomalously warm and probably are the principal discharge areas. In the latter area, saline waters too brackish for human consumption immediately underlie the water table. The area along the Shawnee hills to the south and the Mississippi river area to the west are both cool areas, and data suggest that recharge is probably occurring.

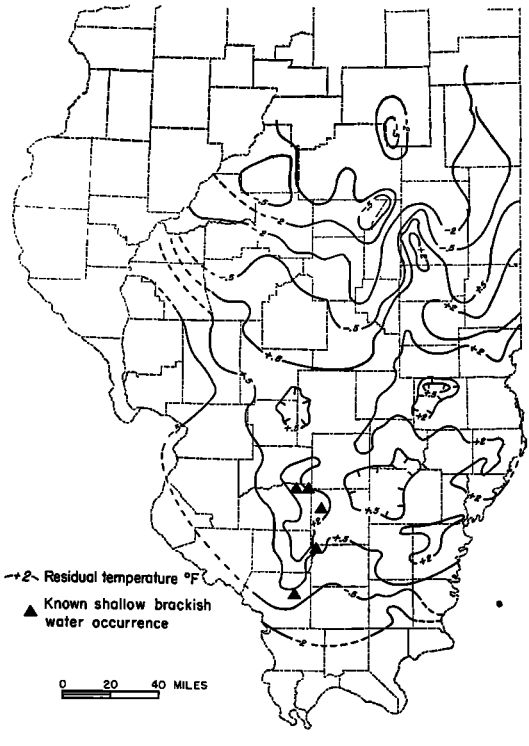

Fig. 4. Residual temperature map (calculated temperature minus observed temperature), showing anomalously warm (positive) and cool (negative) areas.

VOLUME OF DISCHARGE

The mean velocity of upward movement of water in the Illinois basin was calculated from the temperature data with equation 5. The average temperature in the warm discharge areas was determined at intervals of 300 feet for depths between 500 and 3500 feet, the range of depth that includes most oil wells in Illinois. At each 300-foot interval all points that fell within 50 feet of that depth were averaged to obtain a single value. The temperatures for 500 and 800 feet were determined by an upward extrapolation of the temperature data. The plotted temperature curve (Figure 5) compared with the type curves of *Bredehoeft and Papadopulos* [1965] yielded a velocity of 0.16×10^{-8} feet per second. The very small velocity can be detected because of the relatively large vertical distance over which the temperature is observed.

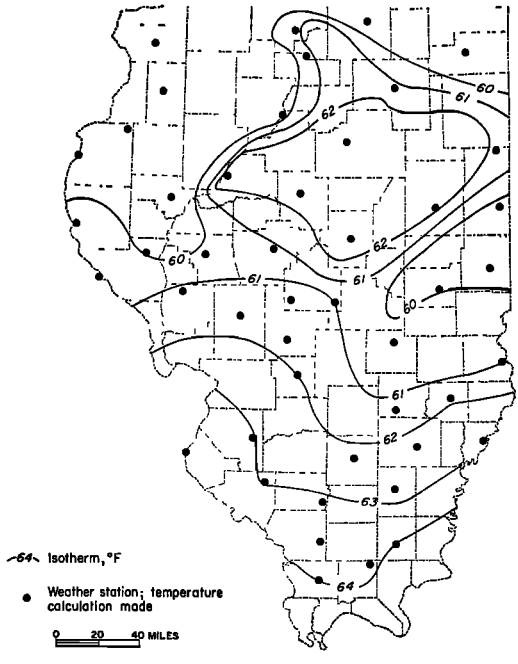

Fig. 3. Isothermal map calculated for 500-foot depth on basis of mean annual surface temperatures and thermal conductivity of the rocks.

Most of the discharge probably takes place in the anomalously warm areas within a radius of 100 miles from the center of the basin. This is approximately 1800 square miles. The quantity of water discharged was calculated by using

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$$Q = V_s A \quad (8)$$

where Q is the quantity of fluid discharge per unit of time, V_s is the velocity of fluid flow (upward), and A is the area over which discharge takes place. The discharge amounts to 59,000 acre-feet per year.

The quantity of water flowing into the Illinois basin was estimated by using the simplest model of *Bredehoeft et al.* [1963], which assumes the change of head over distance is linear (2.8×10^{-4} feet per feet). According to the model, all the water would pass through the sandstone aquifers (principally the Mt. Simon, St. Peter, Chesterian, and basal Pennsylvanian), which were assumed to average 3000 feet thick and have the permeability of the Mt. Simon sandstone of northern Illinois (1.34 feet per day according to *Walton and Csallany* [1962]). The discharge would be equal to the water that passes into the basin through the circumference of a circle with a radius of 100 miles, the center of which is the center of the basin. From this model it was calculated that 36,500 acre-feet of water per year moves into the basin.

Streams and rivers presently draining the central part of the Illinois basin have a normal annual groundwater runoff of about 2,670,000 acre-feet per year [*Walton,* 1965] exclusive of flow in the Wabash River which crosses the eastern part of the basin. The 59,000 acre-feet of discharge from the deeper rocks of the basin is only 2.2% of the total groundwater runoff, and only 0.7% of the total average stream discharge of 8.26 million acre-feet per year [*Mitchell,* 1957].

To determine whether streams of the Illinois basin have different discharge characteristics,

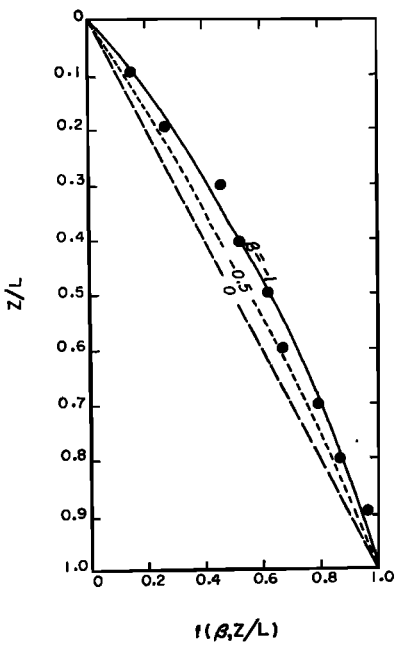

Fig. 5. Temperature profile (dots) in the Illinois basin compared with type curves of *Bredehoeft and Papadopulos* [1965]. The depth and temperatures of the profile are plotted as the ratios

$$\frac{z - Z_0}{L} \quad \text{and} \quad \frac{T_z - T_0}{T_L - T_0} \quad \text{(equation 5)}$$

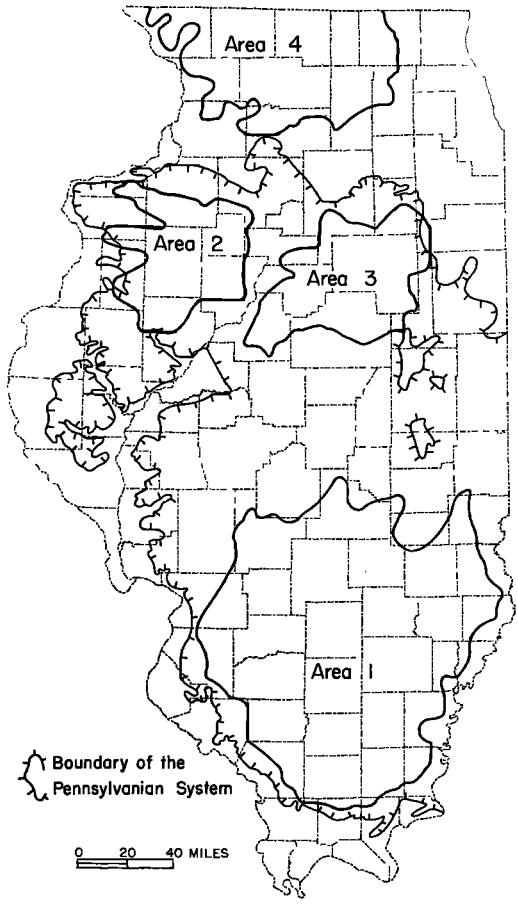

Fig. 6. Drainage areas studied for comparison of the groundwater discharge characteristics between years of normal and below normal precipitation.

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TABLE 1. Average Annual Groundwater Runoff

Region	Precipitation, inches	Runoff in Year of Normal Precipitation, cfs/mi²	Runoff in Year of Below Normal Precipitation, cfs/mi²	Percent of Below Normal Year's to Normal Year's Runoff	Area of Drainage Basin, mi²
1	35 to 45	0.19	0.11	57.9	10,161
		0.23*	0.14	60.9	6,609
2	34 to 37	0.19	0.09	44.3	4,731
3	33 to 37	0.16	0.06	37.5	2,984
4	33 to 34	0.31	0.21	67.7	9,663

* Stream with high drought period flow only.

a comparison was made of the annual groundwater runoff or base flow of streams, for four regions of the state [*Walton,* 1965]. The regions are shown in Figure 6. Region 1 is the area where discharge from the Illinois basin occurs. Regions 1, 2, and 3 are geologically similar and contain generally thin glacial tills [*Piskin and Bergstrom,* 1967] overlying rocks of the Pennsylvanian system, principally shale. Region 4 is different and has generally thin glacial tills overlying permeable Ordovician and Silurian carbonates. The evapotranspiration in the four regions varies in a pattern similar to the variation in precipitation [*Jones,* 1966] (Table 1). The variability in precipitation is slightly greater in region 1 than in the other three areas [*Huff and Changnon,* 1963].

The figures in the table suggest that the groundwater runoff characteristics of region 1 resemble those of region 4 rather than those of regions 2 and 3, even though region 1 is more similar geologically to the latter two.

Region 1 had a higher groundwater runoff in drought years in comparison to the other three regions and at least part of it must be discharge of deep basin waters. All areas except region 1 have 0.10 cfs/mi² differences between below-normal and normal years; area 1 has only a 0.08 cfs difference or a 0.09 cfs difference if we consider only streams with more than 55% of below-normal to normal discharge. This may be merely fortuitous; nevertheless, I assumed that the 0.01 cfs extra groundwater runoff of the streams with high flow during drought years is the result of discharge of water from the deep basin groundwater flow system. This amounts to 43,000 acre-feet of water per year.

If the shale of the Illinois basin has the same permeability of 0.13×10^{-4} feet per day found in the Ordovician shales of northern Illinois [*Walton,* 1960] and 100 feet of hydraulic head, the possible leakage upward would be only 2000 acre-feet per year. Thus, possibly as much as 95% of the discharge must be moving upward through vertical fractures. Concentration of fractures are present within the main structural features of the basin and therefore saline water discharges in the area of these features.

Regions where naturally brackish water is encountered immediately below the water table are shown on Figure 4. Brackish water also is found elsewhere, but from data presently available, it cannot be determined with certainty whether those occurrences are natural or related to the activities of man. The brackish water occurs within the areas of anomalously warm temperatures (Figure 4) near the main structural features of the basin. Furthermore, the anomalously cool area along the southern edge of the map coincides with the region of recharge to the thick basal Pennsylvanian sandstones that dip steeply toward the center of the basin.

DISCUSSION

Hydrogeologists working in the Illinois basin area have long believed that ground water is circulating in the basin. Lack of data on the fluid potentials in the water transmitting zone has necessitated reliance on chemical data and the theoretical explanation of these data. Theoretical calculations supported by chemical data suggest hydrodynamic rather than hydrostatic conditions. This paper further corroborates this hypothesis, and suggests that the quantity of

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groundwater discharge is about 40,000 to 60,000 acre-feet per year.

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Document 2

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Parameter Estimation Guidelines for Risk-Based Corrective Action (RBCA) Modeling

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Abstract

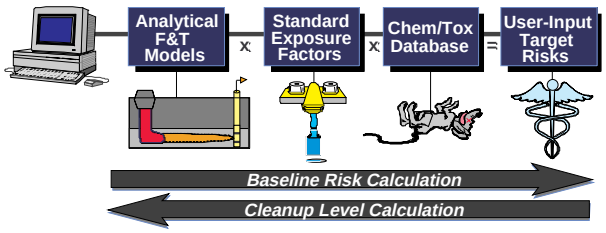
For use in risk-based corrective action (RBCA) analyses, simple analytical fate-and-transport models can provide a cost-effective means of estimating exposure concentrations and developing risk-based soil and groundwater remediation standards. Under ASTM E-1739 "Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites," such models are recommended as a conservative first step under Tiers 1 and 2 of the site evaluation process, prior to use of more complex numerical modeling methods under Tier 3. However, the reliability of an analytical model as a conservative predictor of chronic exposure levels depends upon proper characterization of key physical and chemical parameters.

This paper reviews a system of analytical fate-and-transport models compiled expressly for use with the ASTM RBCA Standard and provides practical guidelines for measurement and/or estimation of key input parameters for each model. Contaminant transport pathways addressed in this paper include soil-to-air volatilization, soil-to-groundwater leaching, lateral air transport, and lateral groundwater transport. Parameter selection guidelines discussed in this paper relate specifically to the analytical expressions listed in Appendix X.2 of ASTM E-1739. However, these guidelines are generally applicable to a broad range of soil, air, and groundwater transport models.

RBCA Spreadsheet System

The RBCA Spreadsheet System, developed by Groundwater Services, Inc. (GSI), is designed to complete all calculations required for Tiers 1 and 2 of the ASTM RBCA planning process (Connor et al, 1995). Based upon site-specific data supplied by the user, the RBCA software combines fate-and-transport modeling and risk characterization functions to complete the following tasks:

- Exposure Concentrations
- Average Daily Intake
- Baseline Risk Levels
- Risk-Based Media Cleanup Levels



Using a system of ten analytical models linked to internal libraries of standard exposure factors and chemical/ toxicological data for 90 compounds, the RBCA Spreadsheet can calculate either baseline risk levels or cleanup standards for each complete exposure pathway identified by the user. Key calculation steps are as follows:

- **Exposure Concentrations:** Based on representative concentrations of constituents of concern (COCs) present in the affected source media, maximum steady-state concentrations likely to

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occur at the point of exposure (POE) are calculated using the steady-state analytical fate-and-transport models identified in Appendix X.2 of ASTM E-1739. To perform these calculations, the system evaluates cross-media partitioning (e.g., volatilization from soil to air) and lateral transport from the source to the POE (e.g., contaminant transport via air or groundwater flow). The source media and optional exposure pathways included in the software as as follows:

SOURCE MEDIA	EXPOSURE PATHWAYS
Surface Soils	• Inhalation of Volatiles and Particulates • Dermal Contact with Soil • Ingestion of Soil and Dust • Leaching to Groundwater/Ingestion
Subsurface Soils	• Inhalation of Volatiles • Leaching to Groundwater/Ingestion
Groundwater	• Ingestion of Potable Water • Inhalation of Volatiles

- **Average Daily Intake:** Based upon the exposure factors selected by the user, the average daily chemical intake for each receptor along each selected pathway is calculated in accordance with EPA guidelines (see Connor et al, 1995). These values are used in baseline risk calculations for each complete pathway.

- **Baseline Risk Characterization:** Human health risks associated with exposure to COCs are calculated by the spreadsheet on the basis of average daily intake rates and the corresponding toxicological parameters for carcinogenic and non-carcinogenic effects. For each complete pathway, the system output provides both individual and additive constituent results for carcinogens and non-carcinogens.

- **Media Cleanup Values:** The RBCA Spreadsheet System has the ability to i) compare site data to Tier 1 Risk-Based Screening Levels (RBSLs), computed using default parameter values as listed in ASTM E-1739, or ii) calculate Tier 2 Site-Specific Target Levels (SSTLs) based on user-supplied site characterization information. For each source medium (i.e., affected soil and groundwater), the software reports target concentrations for all complete pathways and identifies the applicable (i.e., minimum) value for source remediation.

Fate and Transport Modeling Methods

The RBCA Spreadsheet System contains a series of fate and transport models for predicting COC concentrations at the point of exposure (POE) for each of the optional exposure pathways listed above. Under Tier 2 of the RBCA process, relatively simple analytical models are to be employed for this calculation, representing a minor incremental effort relative to Tier 1. The spreadsheet modeling system is consistent with Appendix X.2 of ASTM E-1739, although selected algorithms and default parameters have been updated to reflect advances in evaluation methods.

The idealized schematic shown on Figure 1 illustrates the steps for predicting transport of contaminants from the source zone to the POE for air and groundwater exposure pathways. Each element in Figure 1 represents a step-specific attenuation factor, corresponding to either a cross-media transfer factor (CM) or a lateral transport factor (LT). The effective natural attenuation factor (NAF) for each COC on each pathway is then calculated as the arithmetic product of the various attenuation factors occurring along the flow path from source to receptor. These steady-state NAF values are then used for calculation of baseline risks and back-calculation of Site-Specific Target Levels (SSTLs), as discussed above. Please note that fate and transport modeling is *not* required for exposure via direct contact with the source medium, such as soil ingestion or dermal contact,

where the source and exposure concentrations are equal (i.e., NAF = 1). Analytical models used for conservative estimation of each transport factor per ASTM E-1739 are described below.

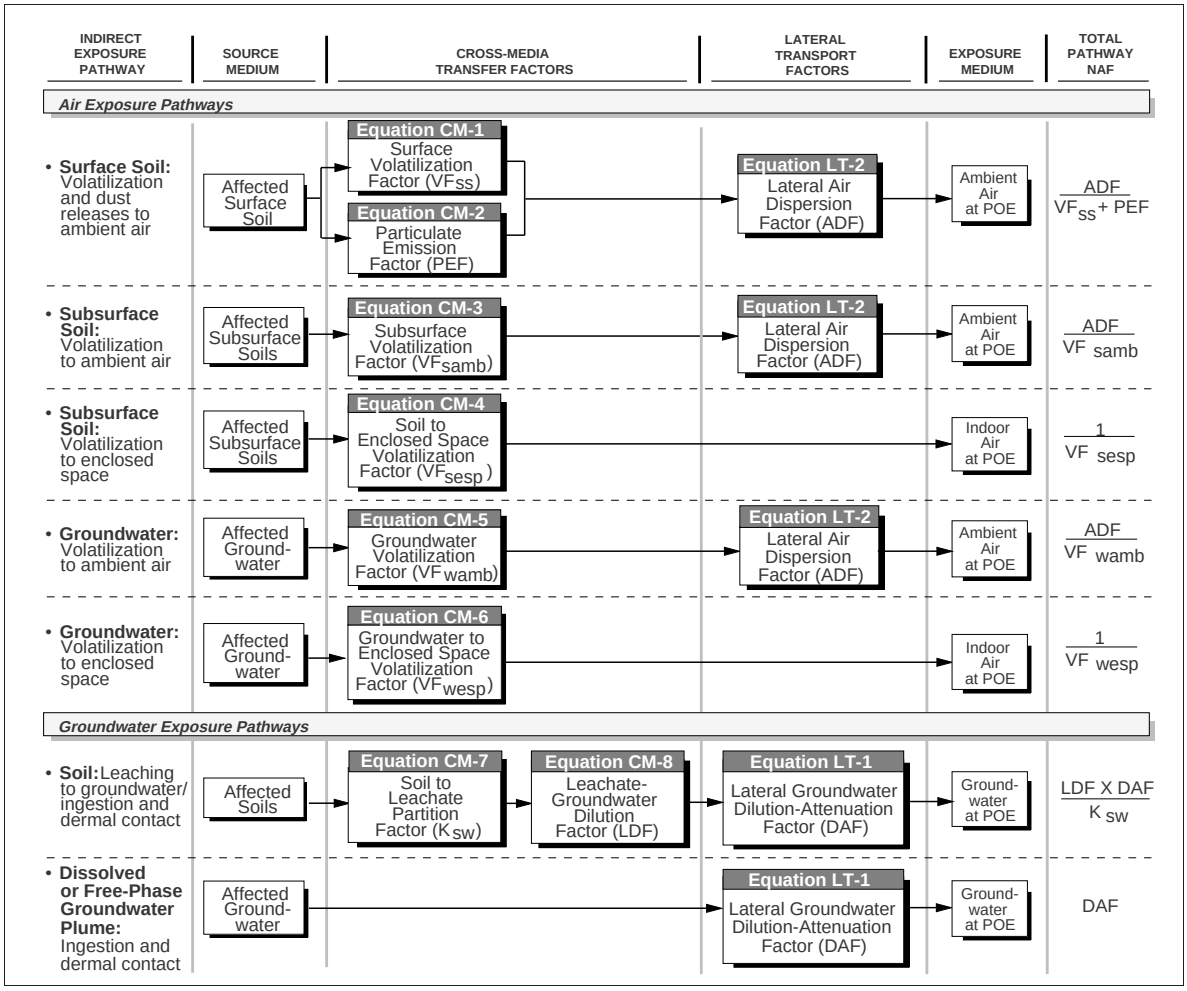
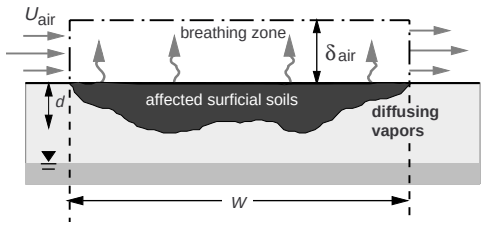


FIGURE 1. NAF CALCULATION SCHEMATIC FOR EXPOSURE PATHWAYS IN RBCA SPREADSHEET SYSTEM

CROSS-MEDIA TRANSFER FACTORS

Exposure pathways involving transport of COCs from one medium to another (e.g., soil-to-air, soil-to-groundwater) require estimation of the corresponding cross-media transfer factor. Various analytical expressions are available for estimating soil-to-air *volatilization factors* as a function of site soil characteristics and the physical/chemical properties of volatile organic COCs. *Leaching factors* for organic and inorganic constituent releases from soil to groundwater can similarly be estimated as a function of COC characteristics, soil conditions, and annual rainfall infiltration. Cross-media transfer equations incorporated in the RBCA Spreadsheet System are presented in Figure 2. Detailed discussion of each of these cross-media factors is provided in the Tier 2 RBCA Guidance Document (Connor et al, 1995).

Equation CM-1: Surface Soil Volatilization Factor (VFss)



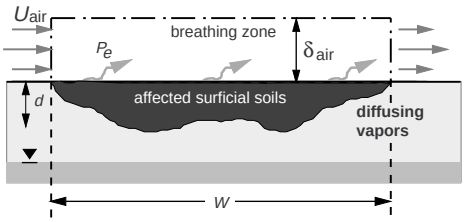
CM-1a:

$$VF_{ss}\left[\frac{(mg/m^3-air)}{(mg/kg-soil)}\right]=\frac{2W\rho_s}{U_{air}\delta_{air}}\sqrt{\frac{D_s^{eff}H}{\pi\tau(\theta_{ws}+k_s\rho_s+H\theta_{as})}}\times10^3$$

or CM-1b: $$VF_{ss}\left[\frac{(mg/m^3-air)}{(mg/kg-soil)}\right]=\frac{W\rho_s d}{U_{air}\delta_{air}\tau}\times10^3$$

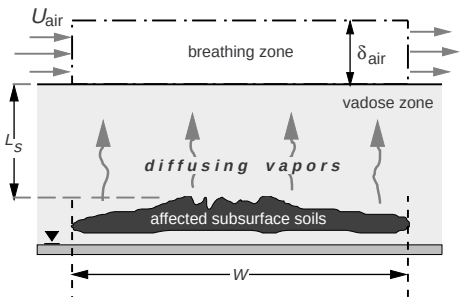
whichever is less

Equation CM-2: Soil Particulate Emission Factor (PEF)



$$PEF\left[\frac{(mg/m^3-air)}{(mg/kg-soil)}\right]=\frac{P_eW}{U_{air}\delta_{air}}\times10^3$$

Equation CM-3: Subsurface Soil Volatilization Factor (VFsamb)



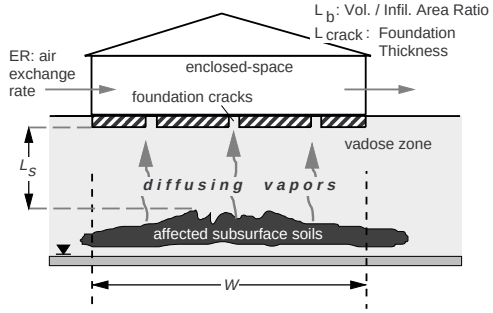
CM-3a:

$$VF_{samb}\left[\frac{(mg/m^3-air)}{(mg/kg-soil)}\right]=\frac{H\rho_s}{[\theta_{ws}+k_s\rho_s+H\theta_{as}]\left[1+\frac{U_{air}\delta_{air}L_s}{D_s^{eff}W}\right]}\text{x}10^3$$

or CM-3b: $$VF_{samb}\left[\frac{(mg/m^3-air)}{(mg/kg-soil)}\right]=\frac{W\rho_s d_s}{U_{air}\delta_{air}\tau}\text{x}10^3$$

whichever is less

Equation CM-4: Subsurface Soil to Enclosed Space Volatilization Factor (VFsesp)



CM-4a:

$$VF_{sesp}\left[\frac{(mg/m^3-air)}{(mg/kg-soil)}\right]=\frac{\frac{H\rho_s}{[\theta_{ws}+k_s\rho_s+H\theta_{as}]}\left[\frac{D_s^{eff}/L_s}{ER\ L_B}\right]}{1+\left[\frac{D_s^{eff}/L_s}{ER\ L_B}\right]+\left[\frac{D_s^{eff}/L_s}{(D_{crack}^{eff}/L_{crack})\eta}\right]}\text{x}10^3$$

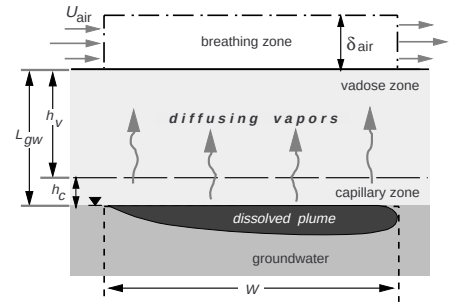
or CM-4b: $$VF_{sesp}\left[\frac{(mg/m^3-air)}{(mg/kg-soil)}\right]=\frac{\rho_s d_s}{L_B ER\tau}\text{x}10^3$$

whichever is less

FIGURE 2. CROSS-MEDIA PARTITIONING EQUATIONS IN THE RBCA SPREADSHEET SYSTEM ***Continued***

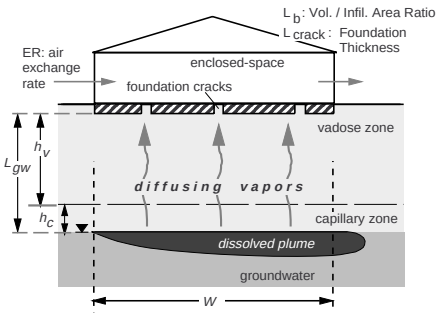
Continued

Equation CM-5: Groundwater Volatilization Factor (VFwamb)



$$VF_{wamb}\left[\frac{\left(mg/m^3-air\right)}{\left(mg/L-H_2O\right)}\right]=\frac{H}{1+\left[\frac{U_{air}\delta_{air}L_{GW}}{WD_{ws}^{eff}}\right]}\text{x}10^3$$

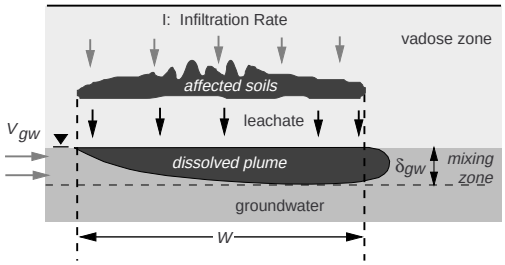
Equation CM-6: Groundwater to Enclosed Space Volatilization Factor (VFwesp)



$$VF_{wesp}\left[\frac{\left(mg/m^3-air\right)}{\left(mg/L-H_2O\right)}\right]=\frac{H\left[\frac{D_{ws}^{eff}/L_{GW}}{ER\ \ L_B}\right]}{1+\left[\frac{D_{ws}^{eff}/L_{GW}}{ER\ \ L_B}\right]+\left[\frac{D_{ws}^{eff}/L_{GW}}{\left(D_{crack}^{eff}/L_{crack}\right)\eta}\right]}\text{x}10^3$$

Equation CM-7: Soil Leachate Partition Factor(Ksw)

Equation CM-8: Leachate-Groundwater Dilution Factor (LDF)



$$K_{sw}\left[\frac{\left(mg/L-H_2O\right)}{\left(mg/kg-soil\right)}\right]=\frac{\rho_s}{\theta_{ws}+k_s\rho_s+H\theta_{as}}$$

$$LDF\left[dimensionless\right]=1+\frac{V_{gw}\delta_{gw}}{IW}$$

FIGURE 2. CROSS-MEDIA PARTITIONING EQUATIONS IN THE RBCA SPREADSHEET SYSTEM ***Continued***

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Continued

Definitions for Cross-Media Transfer Equations

D_s^{eff} Effective diffusivity in vadose zone soils:

$$D_s^{eff}\left[\frac{cm^2}{s}\right] = D^{air}\,\frac{\theta_{as}^{3.33}}{\theta_T^2} + \left[\frac{D^{wat}}{H}\right]\left[\frac{\theta_{ws}^{3.33}}{\theta_T^2}\right]$$

D_{ws}^{eff} Effective diffusivity above the water table:

$$D_{ws}^{eff}\left[\frac{cm^2}{s}\right] = \left(h_{cap} + h_v\right)\left[\frac{h_{cap}}{D_{cap}^{eff}} + \frac{h_v}{D_s^{eff}}\right]^{-1}$$

d	Lower depth of surficial soil zone (cm)
d_s	Thickness of affected subsurface soils
D^{air}	Diffusion coefficient in air (cm^2/s)
D^{wat}	Diffusion coefficient in water (cm^2/s)
ER	Enclosed-space air exchange rate (l/s)
f_{oc}	Fraction of organic carbon in soil (g-C/g-soil)
H	Henry's law constant (cm^3-H_2O)/(cm^3-air)
h_{cap}	Thickness of capillary fringe (cm)
h_v	Thickness of vadose zone (cm)
I	Infiltration rate of water through soil (cm/year)
k_{oc}	Carbon-water sorption coefficient (g-H_2O/g-C)
k_s	Soil-water sorption coefficient (g-H_2O/g-soil)
L_B	Enclosed space volume/infiltration area ratio (cm)
L_{crack}	Enclosed space foundation or wall thickness (cm)
L_{GW}	Depth to groundwater = $h_{cap} + h_v$ (cm)
L_s	Depth to subsurface soil sources (cm)
P_e	Particulate emission rate (g/cm^2-s)
U_{air}	Wind speed above ground surface in ambient mixing zone (cm/s)
V_{gw}	Groundwater Darcy velocity (cm/s)

D_{crack}^{eff} Effective diffusivity through foundation cracks:

$$D_{crack}^{eff}\left[\frac{cm^2}{s}\right] = D^{air}\,\frac{\theta_{acrack}^{3.33}}{\theta_T^2} + \left[\frac{D^{wat}}{H}\right]\left[\frac{\theta_{wcrack}^{3.33}}{\theta_T^2}\right]$$

D_{cap}^{eff} Effective diffusivity in the capillary zone:

$$D_{cap}^{eff}\left[\frac{cm^2}{s}\right] = D^{air}\,\frac{\theta_{acap}^{3.33}}{\theta_T^2} + \left[\frac{D^{wat}}{H}\right]\left[\frac{\theta_{wcap}^{3.33}}{\theta_T^2}\right]$$

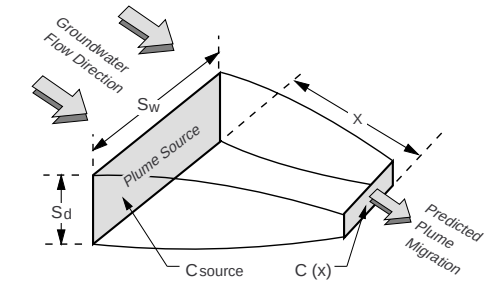
W	Width of source area parallel to wind, or groundwater flow direction (cm)
δ_{air}	Ambient air mixing zone height (cm)
δ_{gw}	Groundwater mixing zone thickness (cm)
η	Areal fraction of cracks in foundations/walls (cm^2-cracks/cm^2-total area)
θ_{acap}	Volumetric air content in capillary fringe soils (cm^3-air/cm^3-soil)
θ_{acrack}	Volumetric air content in foundation/wall cracks (cm^3-air/cm^3 total volume)
θ_{as}	Volumetric air content in vadose zone soils (cm^3-air/cm^3-soil)
θ_T	Total soil porosity (cm^3-pore-space/ cm^3-soil)
θ_{wcap}	Volumetric water content in capillary fringe soils (cm^3-H_2O/cm^3-soil)
θ_{wcrack}	Volumetric water content in foundation/wall cracks (cm^3-H_2O)/cm^3 total volume)
θ_{ws}	Volumetric water content in vadose zone soils (cm^3-H_2O/cm^3-soil)
ρ_s	Soil bulk density (g-soil/cm^3-soil)
τ	Averaging time for vapor flux (s)

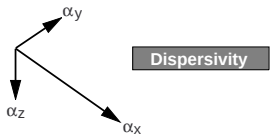
FIGURE 2. CROSS-MEDIA PARTITIONING EQUATIONS IN THE RBCA SPREADSHEET SYSTEM

LATERAL TRANSPORT FACTORS

During lateral transport within air or groundwater, COC concentrations in the flow stream will be diminished due to mixing and attenuation effects (see Figure 1). Site-specific attenuation factors characterizing COC mass dilution or loss during lateral transport can be estimated using the air dispersion and groundwater transport models provided in the RBCA Spreadsheet System. Equations for the steady-state analytical transport models incorporated in the RBCA spreadsheet are shown on Figure 3. Equations LT-1 and LT-2 correspond to the Domenico 3-D groundwater solute transport model and the standard gaussian air dispersion model, respectively. The user must provide information regarding COC properties and transport parameters (flow velocities, dispersion coefficients, retardation factors, decay factors, etc.), as required for the selected contaminant transport model. Procedures for definition of the contaminant source term for the groundwater solute model (Equation LT-1) are illustrated on Figure 4. Key assumptions of these lateral transport models are detailed in the Tier 2 RBCA Guidance Manual (Connor et al, 1995).

Equation LT- 1: Lateral Groundwater Dilution Attenuation Factor





LT-1a: Solute Transport with First-Order Decay:

$$\frac{C(x)_i}{Csi} = \exp\left(\frac{x}{2\alpha_x}\left[1-\sqrt{1+\frac{4\lambda_i\alpha_x R_i}{\nu}}\right]\right) erf\left(\frac{S_w}{4\sqrt{\alpha_y x}}\right) erf\left(\frac{S_d}{4\sqrt{\alpha_z x}}\right)$$

where: $\nu = \dfrac{K \cdot i}{\theta_e}$

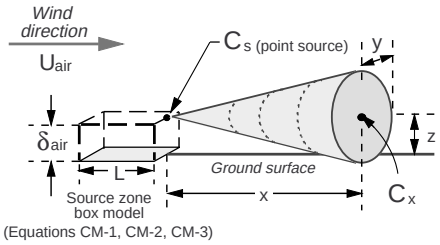
LT-1b: Solute Transport with Biodegradation by Electron-Acceptor Superposition Method:

$$C(x)_i = \left[\left(C_{si} + BC_i\right) erf\left(\frac{S_w}{4\sqrt{\alpha_y x}}\right) erf\left(\frac{S_d}{4\sqrt{\alpha_z x}}\right)\right] - BC_i$$

where: $BC_i = BC_T \text{ x} \dfrac{C_{si}}{\sum C_{si}}$ *and* $BC_T = \Sigma\ \dfrac{C(ea)_n}{UF_n}$

[Note: For Equations LT-1a and LT-1b, NAF = $Cs_i / C(x)_i$]

Equation LT-2: Lateral Air Dispersion Factor



(Equations CM-1, CM-2, CM-3)

$$\frac{C(x)_i}{C_{si}} = \frac{Q}{2\pi U_{air}\sigma_y\sigma_z} \text{ x } \exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left(\exp\left(-\frac{(z-\delta_{air})^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+\delta_{air})^2}{2\sigma_z^2}\right)\right)$$

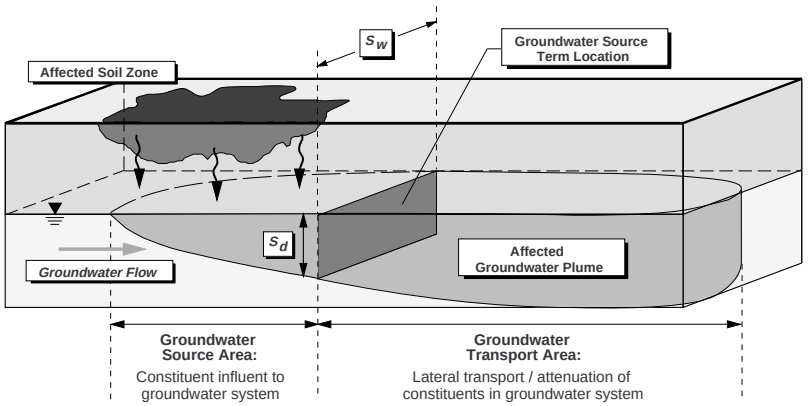
where: $Q = \dfrac{U_{air}(\delta_{air})(A)}{L}$

[Note: For Equation LT-2, NAF = $Cs_i / C(x)_i$]

Definitions for Lateral Transport Equations

$C(x)_i$	Concentration of constituent *i* at distance x downstream of source (mg/L) or (mg/m^3)
C_{si}	Concentration of constituent *i* in Source Zone (mg/L) or (mg/m^3)
BC_i	Biodegradation capacity available for constituent *i*
BC_T	Total biodegradation capacity of all electron acceptors in groundwater
$C(ea)_n$	Concentration of electron acceptor *n* in groundwater
UF_n	Utilization factor for electron acceptor *n* (i.e., mass ratio of electron acceptor to hydrocarbon consumed in biodegradation reaction)
x	Distance downgradient of source (cm)
α_x	Longitudinal groundwater dispersivity (cm)
α_y	Transverse groundwater dispersivity (cm)
α_z	Vertical groundwater dispersivity (cm)
θ_e	Effective Soil Porosity
λ_i	First-Order Degradation Rate (day^{-1}) for constituent *i*
υ	Groundwater Seepage Velocity (cm/day)
K	Hydraulic Conductivity (cm/day)
R_i	Constituent retardation factor
i	Hydraulic Gradient (cm/cm)
S_w	Source Width (cm)
S_d	Source Depth (cm)
δ_{air}	Ambient air mixing zone height (cm)
Q	Air volumetric flow rate through mixing zone (cm^3/s)
U_{air}	Wind Speed (cm/sec)
σ_y	Transverse air dispersion coefficient (cm)
σ_z	Vertical air dispersion coefficient (cm)
y	Lateral Distance From source zone (cm)
z	Height of Breathing Zone (assumed equal to δ_{air}) (cm)
A	Cross Sectional Area of Air Emissions Source (cm^2)
L	Length of Air Emissions source (cm) parallel to wind direction

FIGURE 3. LATERAL TRANSPORT EQUATIONS IN THE RBCA SPREADSHEET SYSTEM



SELECTION OF GROUNDWATER MODEL INPUT PARAMETERS

For use of Domenico groundwater solute transport model (see Equations LT-1a and LT-1b, Figure 3), select source term location, dimensions, and concentration as follows:

1) Groundwater Source Term Location

The source term corresponds to a vertical source plane, normal to the direction of groundwater flow, located at the downgradient limit of the area serving as the principal source of constituent release to groundwater (e.g., affected unsaturated zone soils, NAPL plume, land disposal unit, spill area, etc.). In the absence of such data, the source term should be located at the point of the maximum measured plume concentration(s). Distances to downgradient points of exposure (POEs) should then be measure from this location along the principal direction of groundwater flow.

2) Groundwater Source Term Width, S_W

The width of the source term should be matched to the **greater** of the following dimensions:

i) the measured groundwater plume width, (as defined by Tier 1 limits) normal to the principal direction of groundwater flow at the designated source term location.

ii) the maximum width of the affected soil zone, normal to the principal groundwater flow direction.

3) Groundwater Source Term Thickness, S_d

The thickness of the source term should be matched to **either**:

i) the measured vertical extent of the affected groundwater plume, at the designated source term location.

ii) in the absence of actual site measurements establishing the vertical extent of the affected groundwater plume, the full saturated thickness of the water-bearing unit at this location.

4) Groundwater Source Term Concentration, C_S

To calculate baseline risk levels, the user must also provide a groundwater source concentration for each constituent of concern (COC). The vertical plane source functions as a constant source term, applying these input concentrations to all groundwater flowing through the source location. Under a Tier 2 evaluation, the source concentration of each COC may be defined as follows:

i) use the maximum concentration of each COC detected at the source location or

ii) if multiple sampling locations are available to characterize plume concentrations across the source term width Sw, calculate a weighted average source concentration for each constituent across this plume transect based on time-consistent measurements.

FIGURE 4. DEFINITION OF SOURCE TERM FOR USE IN DOMENICO SOLUTE TRANSPORT MODEL

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Parameters Selection Guidelines

For purpose of parameter value selection, the input parameters required for each of the fate-and-transport models identified above can be grouped in the following categories:

- **Site-Specific Parameter Measurements**: Required for parameters which i) exhibit a wide range of site-specific variability (e.g., orders of magnitude) that may significantly impact model predictions and ii) are amenable to characterization based upon limited site-specific measurements. Examples include hydraulic conductivity, flow gradient, source dimensions, etc.

- **Reasonable Parameter Estimates**: Suitable for parameters which i) exhibit a moderate degree of site-specific variability (e.g., less than 1X) and ii) may be characterized on the basis of generic estimates without significantly impacting model predictions. Examples include soil porosity, soil unit weight, and volumetric air and water content, etc.

- **Chemical-Specific Parameter Values**: Physical properties of chemical constituents which must be characterized on the basis of published laboratory values. Examples include Henry's Law constant, air and water diffusion coefficients, and carbon-water sorption coefficients, etc.

For each of the analytical fate-and-transport models identified in Appendix X.2 of ASTM E-1739 and incorporated in the RBCA Spreadsheet System, practical guidelines for appropriate selection of input parameters per these general categories are outlined below. Please note that, although these recommendations relate to the modeling equations listed on Figures 1-3, these guidelines are generally applicable to various analytical models used for characterization of chronic exposure conditions.

VOLATILIZATION MODELS: Equations CM-1 through CM-6

The volatilization models provided in Equations CM-1 thorugh CM-6 (see Figure 2) define the steady-state ratio of the concentration in air at the POE to the source concentration in the underlying soil (Equations CM-1 through CM-4) or groundwater (Equations CM-5 and CM-6). Guidelines for selection of input parameters, grouped according to the three categories noted above, are summarized on Table 1.

SOIL-TO-GROUNDWATER LEACHING MODELS: Equations CM-7 and CM-8

Per the approach outlined in Appendix X.2 of ASTM E-1739, a soil-to-groundwater DAF value can be calculated as the product of: i) a leachate-groundwater dilution factor (Equation CM-8), divided by ii) a soil-leachate partition factor (Equation CM-7), providing a steady-state ratio between the concentration of a constituent on the affected soil mass to the resultant concentration in the underlying groundwater mixing zone. The model is applicable to both organic and inorganic constituents; however, as noted on Table 2, care must be taken to employ the appropriate equation for estimation of the soil-water sorption coefficient (k_s). Guidelines for selection of each input parameter required for Equations CM-7 and CM-8 are summarized on Table 2.

LATERAL GROUNDWATER TRANSPORT MODEL: Equation LT-1

To account for attenuation of affected groundwater concentrations between the source and POE, the Domenico analytical solute transport model has been incorporated into the RBCA software. This model uses a partially or completely penetrating vertical plane source, perpendicular to groundwater flow, to simulate the release of organics from the mixing zone to the moving groundwater (see Figure 4). Within the groundwater flow regime, the model accounts for the effects of advection, dispersion, sorption, and biodegradation. Given a representative source zone concentration for each COC, the model can predict steady-state plume concentrations at any point (x, y, z) in the downgradient flow system. In Equation LT-1 (see Figure 3), the model is set to

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predict centerline plume concentrations at any downgradient distance x, based on 1-D advective flow and 3-D dispersion. The receptor well is assumed to be located on the plume centerline, directly downgradient of the source zone at a location specified by the user. Note that the model incorporates biodegradation of organic constituents, based on use of a first-order decay function (LT-1a) or an electron-acceptor superposition algorithm (LT-1b). Inorganic constituents are assumed to be conservative ($\lambda = 0$), with no resultant sorption or bioattenuation under steady-state conditions. Guidelines for selection of key input parameters are outlined on Table 3.

LATERAL AIR TRANSPORT MODEL: EQUATION LT-2

The RBCA software includes a 3-dimensional gaussian dispersion model to account for transport of air-borne contaminants from the source area to a downwind POE (see Equation LT-2 on Figure 3). The model incorporates two conservative assumptions: i) a source zone height equivalent to the breathing zone and ii) a receptor located directly downwind of the source at all times. As indicated on Figure 3, an effective pathway NAF value is calculated as the steady-state ratio between the source concentration in the on-site affected soil zone and the ambient organic vapor or particulate concentration at the downwind POE. The model requires input data for the affected soil zone dimensions and concentrations, wind speed, and horizontal and vertical air dispersion coefficients to compute the resulting COC concentrations in ambient air at the POE. Guidelines for defining key input parameters are provided on Table 4.

Summary

As demonstrated by the RBCA Spreadsheet System, a system of simple analytical fate-and-transport models can be used for comprehensive evaluation of chronic exposure levels associated with potential soil, air, and groundwater exposure pathways. However, as with all predictive modeling efforts, reliable results require proper characterization of the input parameters, particularly those requiring site-specific measurement as noted on Tables 1-4. In all cases, model predictions must be shown to be consistent with the actual constituent distributions observed at the site. Use of the Tier 1 and Tier 2 calculation methods discussed in ASTM E-1739 and incorporated in the RBCA Spreadsheet System can significantly reduce the time and effort required for estimation of baseline risk levels or calculation of site-specific, risk-based soil and groundwater remediation goals. However, proper scientific and/or engineering expertise is required for both characterization of input parameters and assessment of model results.

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Biographical Information

- **John A. Connor, P.E**., is President of Groundwater Services, Inc. He received an M.S. in Civil Engineering from Stanford University and has over 16 years of professional experience in geotechnical and environmental engineering, with specialization in corrective action design and risk-based corrective action. Mr. Connor is the principal author of the "Tier 2 RBCA Guidance Manual", the "RBCA Spreadsheet System", and the "RBCA State Risk Policy Issues Workbook". He is a certified ASTM RBCA trainer. *Groundwater Services, Inc., 5252 Westchester, Suite 270, Houston, Texas 77005. (713) 663-6600.*
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TABLE 1. PARAMETER SELECTION GUIDELINES: VOLATILIZATION MODELS

Input Parameter		Typical Range	Parameter Measurement or Estimation Guidelines	Reference
Symbol	**Description**			
SITE-SPECIFIC PARAMETER MEASUREMENTS				
W	Soil source zone dimension parallel to wind direction (cm)	Site-specific	Measure lateral extent of soil zone serving as source of vapor release (e.g., zone exceeding Tier 1 limits). For on-site POE, use maximum lateral source dimension. For off-site POE, use dimension measured along line passing from source zone to nearest downwind off-site POE location.	Connor et al, 1995
L_{GW}	Depth to groundwater	Site-specific	For unconfined unit, measure depth to static water level. For confined unit, measure depth to top of water-bearing stratum.	Connor et al, 1995
L_S	Depth to subsurface soil source (cm)	Site-specific	Measure depth from ground surface to top of affected source zone.	Connor et al, 1995
d or d_S	Thickness of affected soil zone	Site-specific	Measure average vertical dimension from top to base of affected soil zone over lateral area corresponding to W.	Connor et al, 1995
h_V	Thickness of vadose zone (cm)	Site-specific	Measure from ground surface to depth of static water level in unconfined unit. In confined unit, measure from ground surface to depth of soil saturation (often corresponding to potentiometric surface elevation).	Connor et al, 1995
f_{OC}	Fraction of organic carbon in soil (g-C/g-soil)	0.001 - 0.03	Conduct lab analyses on representative unaffected soil samples over depth interval of vertical vapor migration or use generic value of 0.01 for vadose zone.	LaGrega, 1994
REASONABLE PARAMETER ESTIMATES				
U_{air}	Windspeed above ground surface in ambient mixing zone (cm/s)	45 - 450 cm/sec	Match to average annual windspeed for site area, based on published climatic data.	Connor et al, 1995
δ_{air}	Ambient air mixing zone height (cm/s)	200 cm	Match to typical height of human breathing zone (6 ft or 2m).	Connor et al, 1995
k_S	Soil-water sorption coefficient (g-H_2O/g-soil)	-----	For organics, estimate as: $k_S = k_{OC} \times f_{OC}$. For ionizing organics (e.g., chlorophenols), estimate k_S based on published pH-dependent partitioning coefficients for ionized and neutral forms. For inorganics, estimate k_S per published pH-dependent isotherms, based on measured groundwater pH. Detailed guidelines provided in U.S. EPA SSL Background Document (1996).	U.S. EPA, 1996
ρ_S	Soil bulk density (g-soil/cm^3-soil)	1.6 - 1.75	Use median soil value of 1.7 g/cm^3.	ASTM, 1995
Θ_T	Total soil porosity (cm^3-pore space/cm^3-soil)	35 - 55%	Estimate based on predominant soil type as follows: Uniform Sand: 40% Soft Clay: 55% Mixed-Grain-Sand: 35% Stiff Clay: 37% Silt: 50%	Peck et al, 1974
Θ_{ws}	Volumetric water content in vadose zone soils (cm3-H_2O/cm^3-soil)	13 - 52%	Estimate based on predominant soil type as follows: Uniform Sand: 13% Soft Clay: 52% Mixed-Grain-Sand: 16% Stiff Clay: 34% Silt: 42% NOTE: Typical Θ_{ws} values approximated as saturated water content minus specific yield of soil.	Peck et al, 1974 Todd, 1980
Θ_{as}	Volumetric air content in vadose zone soils (cm^3-air/cm^3-soil)	3-27%	Calculate as $\Theta_{as} = \Theta_T - \Theta_{ws}$, where Θ_{ws} and Θ_T estimated per predominant soil type as above.	Peck et al, 1974 Todd, 1980
NOTE: See Equation CM 1 through CM 6 on Figure 2 regarding use of the above parameters for estimation of steady-state volatilization factors for affected soils. Detailed discussion of these volatilization models is provided in the Tier 2 RBCA Guidance Manual (see Connor et al, 1995).				

continued

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TABLE 1. PARAMETER SELECTION GUIDELINES: VOLATILIZATION MODELS *continued*

Input Parameter				
Symbol	**Description**	**Typical Range**	**Parameter Measurement or Estimation Guidelines**	**Reference**
REASONABLE PARAMETER ESTIMATES (CONT'D)				
h_{cap}	Thickness of capillary fringe (cm)	2 - 200 cm	Estimate based on predominant soil type, as follows: Medium Samd: 25 cm Clayey Silt: 200 cm Fine Sand: 43 cm Silt: 105 cm	Todd, 1980
P_e	Particulate emission rate (g/cm^2-s)	-----	Use generic upperbound value (e.g., 6.9 x 10^{-14} g/cm^2-sec)) or estimate reasonable site-specific value using method outlined in U.S. EPA SSL guide.	ASTM, 1995 EPA, 1996
z	Averaging time for vapor flux (s)	-----	Match to assumed exposure duration (in seconds).	ASTM, 1995
ER	Enclosed space air-exchange rate (L/s)	-----	Use generic lowerbound value (e.g., 0.00014 L/s for residential, 0.00023 L/s commercial) or match to minimum allowable indoor air ventilation rate per local building code.	ASTM, 1995
L_B	Ratio of enclosed space volume to infiltration area (cm)	-----	Use generic lowerbound value (e.g., 200 cm) or develop reasonable estimates based on size (no. of floors) and area (foundation outline) of typical residential or commercial structures in site area.	ASTM, 1995
L_{crack}	Enclosed space foundation or wall thickness (cm)	-----	Use generic upperbound value (e.g., 15 cm) or match to local building code specifications for residential or commercial structures.	ASTM, 1995
Z	Areal fraction of cracks in foundations /walls (cm^2-cracks/cm^2-total area)	-----	Use generic upperbound value (e.g., 1%) or estimate based on observed site conditions.	ASTM, 1995
CHEMICAL-SPECIFIC PARAMETER VALUES				
H	Henry's Law Constant (cm3-H_2O/cm^3-air)	-----	Use median value reported for each constituent of concern in published chemical reference.	Connor et al, 1995 a
k_{oc}	Carbon-water sorption coefficient (g-H_2O/g-C)	-----	Use median value reported for each constituent of concern in published chemical reference.	Connor et al, 1995 a
D^{air}	Diffusion coefficient in air (cm^2/s)	-----	Use median value reported for each constituent of concern in published chemical reference.	Connor et al, 1995 a
D^{wat}	Diffusion coefficient in water (cm^2/s)	-----	Use median value reported for each constituent of concern in published chemical reference.	Connor et al, 1995 a
D_s^{eff}	Effective diffusivity in vadose zone soils (cm^2/s)	-----	Estimate as shown on Figure 2.	-----
D_{ws}^{eff}	Effective diffusivity above the water table (cm^2/s)	-----	Estimate as shown on Figure 2.	-----

NOTE: See Equation CM 1 through CM 6 on Figure 2 regarding use of the above parameters for estimation of steady-state volatilization factors for affected soils. Detailed discussion of these volatilization models is provided in the Tier 2 RBCA Guidance Manual (see Connor et al, 1995).

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TABLE 2. PARAMETER SELECTION GUIDELINES: SOIL-TO-GROUNDWATER LEACHATE MODELS (EQUATIONS CM-7 AND CM-8)

Input Parameter		Typical Range	Parameter Measurement or Estimation Guidelines	Reference
Symbol	**Description**			
SITE-SPECIFIC PARAMETER MEASUREMENTS				
W	Soil source zone dimension parallel to groundwater flow direction (cm)	Site-specific	Measure lateral extent of soil zone serving as source of leachate release to underlying groundwater (e.g., exceeding Tier 1 limits) along line parallel to natural groundwater flow.	Connor et al, 1995
f_{oc}	Fraction of organic carbon in soil (g-C/g-soil)	0.001 - 0.03	Measure on representative unaffected soil samples over vertical depth interval of vapor migration or use generic lowerbound value of 0.01 for vadose zone.	La Grega, 1994
V_{gw}	Groundwater Darcy velocity (cm/w)	Site-specific	Estimate as follows: $V_{gw} = K \bullet i$ where K and i are defined as noted below.	Bedient et al, 1994
K	Hydraulic conductivity of water-bearing unit (cm/sec)	Site-specific	Measure K values vased upon either i) rising-head slug tests or ii) constant-rate aquifer pumping tests conducted on wells properly installed and developed in water-bearing unit. Re-evaluate test results if measured values fall outside typical range for predominant soil type, as follows: Clays: $<1x10^{-6}$ cm/s Silts: $1x10^{-6}$ - $1x10^{-3}$ cm/s Silty Sands: $1x10^{-4}$ - $1x10^{-2}$ cm/s Clean Sands: $1x10^{-1}$ - 1 cm/s Gravels: >1 cm.s	Bedient et al, 1994
i	Lateral hydraulic flow gradient of water-bearing unit (cm/cm)	0.001 - 0.1	Measure lateral flow gradient in area beneath soil source zone based on triangulation among 3 or more monitoring wells or piezometers screened within water-bearing unit.	Newell et al, 1996
δ_{gw}	Groundwater mixing zone thickness (cm)	Site-specific	Measure vertical extent of affected groundwater zone within water-bearing unit in area underlying soil source zone. If vertical plume extent undetermined at this location, use lowerbound estimate (e.g., 200 cm).	ASTM, 1995
REASONABLE PARAMETER ESTIMATES				
I	Infiltration rate of water through soil (cm/year)	------	Estimate I as function of annual rainfall (P) in site area, depending on predominant surface soil type, as follows: Clayey Soils: I = (1 - 2%) x P Sandy Soils: I = (5 - 10%) x P Paved Site: I = (0.1 - 1%) x P	(NOTE: Values are preliminary. Supporting guidelines under development.)
P_s	Soil bulk density (g-soil/cm^3-soil)		Use median soil value of 1.7 g/cm^3.	ASTM, 1995
Θ_{ws}	Volumetric water content in vadose zone soils (cm3-H_2O/cm^3-soil)		Estimate based on predominant soil type as follows: Uniform Sand: 13% Soft Clay: 52% Mixed-Grain-Sand: 16% Stiff Clay: 34% Silt: 42% NOTE: Typical Θ_{ws} values approximated as saturated water content minus specific yield of soil.	Peck et al, 1974 Todd, 1980
Θ_{as}	Volumetric air content in vadose zone soils (cm^3-air/cm^3-soil)		Calculate as $\Theta_{as} = \Theta_T - \Theta_{ws}$, where Θ_{ws} and Θ_T estimated per predominant soil type as above. NOTE: Values correspond to drained conditions. Dry weather may increase Θ_{as} in near-surface silts and clays (< 6 ft depth).	Peck et al, 1974 Todd, 1980
NOTE: See Equations CM-7 and CM-8 on Figure 2 regarding use of the above parameters for estimation of soil-to-groundwater leaching factor for affected soils. Detailed discussion of this soil leachate model is provided in the Tier 2 RBCA Guidance Manual (Connor et al, 1995).				

continued

TABLE 2. PARAMETER SELECTION GUIDELINES: SOIL-TO-GROUNDWATER LEACHATE MODELS (EQUATIONS CM-7 AND CM-8) *continued*

Input Parameter		Typical Range	Parameter Measurement or Estimation Guidelines	Reference
Symbol	**Description**			
REASONABLE PARAMETER ESTIMATES (CONT'D)				
k_S	Soil-water sorption coefficient (g-H_2O/g-soil)	-----	For organics, estimate as: $k_S = k_{OC} \times f_{OC}$. For ionizing organics (e.g., chlorophenols), estimate k_S based on published pH dependent partitioning coefficients for ionized and neutral forms. For inorganics, estimate k_S as published pH-dependent isotherms, based on measured groundwater pH.	U.S. EPA, 1996
CHEMICAL-SPECIFIC PARAMETERS				
H	Henry's Law Constant (cm3-H_2O/cm^3-air)	-----	Use median value reported for each constituent of concern in published chemical reference.	Connor et al, 1995a
k_{oc}	Carbon-water sorption coefficient (g-H_2O/g-c)	-----	Use median value reported for each constituent of concern in published chemical reference.	Connor et al, 1995a
NOTE: See Equations CM-7 and CM-8 on Figure 2 regarding use of the above parameters for estimation of soil-to-groundwater leaching factor for affected soils. Detailed discussion of this soil leachate model is provided in the Tier 2 RBCA Guidance Manual (Connor et al, 1995).				

TABLE 3. PARAMETER SELECTION GUIDELINES: LATERAL GROUNDWATER TRANSPORT MODEL (EQUATION LT-1)

Input Parameter		Typical Range	Parameter Measurement or Estimation Guidelines	Reference
Symbol	**Description**			
SITE-SPECIFIC PARAMETER MEASUREMENTS				
υ	Groundwater seepage velocity (cm./sec)	Site-specific	Calculate site-specific value based on the following equation: $\upsilon = \frac{K \bullet i}{\theta_e}$ where K, i, and θ_e are determined as specified below..	Bedient et al, 1994
K	Hydraulic conductivity of water-bearing unit (cm/sec)	Site-specific	Measure K values based upon either i) rising-head slug tests or ii) constant-rate aquifer pumping tests conducted on wells properly installed and developed in water-bearing unit. Re-evaluate test results if measured values fall outside typical range for predominant soil type, as follows: Clays: <$1x10^{-6}$ cm/s Silts: $1x10^{-6}$ - $1x10^{-3}$ cm/s Silty Sands: $1x10^{-4}$ - $1x10^{-2}$ cm/s Clean Sands: $1x10^{-1}$ - 1 cm/s Gravels: >1 cm.s	Bedient et al, 1994
i	Lateral hydraulic flow gradient of water-bearing unit (cm/cm)	0.001 - 0.1	Measure lateral flow gradient in area beneath soil source zone based on triangulation among 3 or more monitoring wells or piezometers screened within water-bearing unit.	Newell et al, 1996
R_i	Constituent retardation factor	Site-specific	Calculate site-specific values based on the following equation: $R = 1 + \frac{k_s \bullet \rho_s}{\theta_e}$ where k_s, ρ_s, and θ_e are determined as specified below.	Newell et al, 1996

continued

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TABLE 3. PARAMETER SELECTION GUIDELINES: LATERAL GROUNDWATER TRANSPORT MODEL (EQUATION LT-1) *continued*

Input Parameter		Typical Range	Parameter Measurement or Estimation Guidelines	Reference
Symbol	**Description**			
SITE-SPECIFIC PARAMETER MEASUREMENTS (CONT'D)				
k_S	Soil-water sorption coefficient (g-H_2O/g-soil)		For organics, estimate as: $k_S = k_{OC} \times f_{OC}$. For ionizing organics (e.g., chlorophenols), estimate k_S based on published pH dependent partitioning coefficients for ionized and neutral forms. For inorganics, estimate k_S as published pH-dependent isotherms, based on measured groundwater pH. See EPA SSL Guidance for detailed information.	U.S. EPA, 1996
f_{oc}	Fraction of organic carbon in soil (g-C/g-soil)	0.001 - 0.03	Measure depth from ground surface to top of affected source zone. Measure average vertical dimension from top to base of affected soil zone over area corresponding to W. Generic lowerbound value of 0.001.	La Grega, 1994
BC_i	Biodegradation capacity for constituent i	Site-specific	If using electron-acceptor superposition form of Domenico model (Equation LT-1b), calculate BC_i value as indicated on Figure 3. Detailed instructions for BC_i and BC_T estimation are provided in BIOSCREEN user's manual (Newell et al, 1996). Calculation must be based on site-specific measurement of principal electron acceptor concentrations in site groundwater.	Newell et al, 1996 Connor et al, 1995
X	Distance from source to downgradient POE (cm)	Site-specific	Measure from source term location to downgradient POE location along line of groundwater flow.	Connor et al, 1995
S_w	Groundwater source term width (cm)	Site-specific	See Figure 4 for guidelines regarding site-specific determination of source width of water-bearing unit.	Connor et al, 1995
S_d	Groundwater source term thickness (cm)	Site-specific	See Figure 4 for guidelines regarding site-specific determination of source thickness in water-bearing unit.	Connor et al, 1995
REASONABLE PARAMETER ESTIMATES				
θ_e	Effective porosity of water-bearing unit (cm^3-pore/cm^3-soil)	0.001 - 0.1	Match to representative value for predominant soil type in water-bearing unit, as follows: Clay = 0.01 - 0.20 Silt = 0.01 - 0.30 Fine Sand = 0.10 - 0.30 Med. Sand = 0.15 - .30 Coarse Sand = 0.20 - 0.33 Gravel = 0.10 - 0.35	Domenico et al, 1990 Walton, 1988

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TABLE 3. PARAMETER SELECTION GUIDELINES: LATERAL GROUNDWATER TRANSPORT MODEL (EQUATION LT-1) *continued*

Input Parameter		Typical Range	Parameter Measurement or Estimation Guidelines	Reference
Symbol	**Description**			
REASONABLE PARAMETER ESTIMATES (CONT'D)				
α_x α_y α_z	Groundwater dispersivity coefficients in longitudinal (x), transverse (y), and vertical (z) dimensions	-----	For use with biodegradation functions in Domenico model (LT-1a or LT-1b), reasonable dispersivity estimates may be derived as follows: **Longitudinal Dispersivity**: $\alpha_x = 3.28 \bullet 0.83 \bullet \left[\log_{10}\left(\frac{X}{3.28}\right)\right]^{-2.414}$ **Transverse Dispersivity**: α_y = 0.10 alpha x (*based on high reliability points from Geihar et al, 1992*) **Vertical Dispersivity**: α_z = very low (i.e., 1 x 10^{-99} ft) (*based on conservative estimate*)	Xu and Eckstein, 1995 Gelhar et al, 1992 Newell et al, 1996
			Other commonly used relationships include: $\alpha_x = 0.1 \bullet X$ $\alpha_y = 0.33 \bullet \alpha_x$ α_z = 0.025 to 0.1 $\bullet \alpha_x$ [Note: If used with electron-acceptor superposition version of Domenico model (Equation LT-1b), these later relationshipos may result in overestimation of biodegradation effects.]	Pickens and Grisak, 1981 ASTM, 1995 EPA, 1986
λ_e	First-order degradation rate for constituent i (sec^{-1})	------	Optional methods for selection of appropriate decay coefficients for each constituent of concern are as follows: **Calibrate to Existing Plume Data**: If the plume is in a steady-state or diminishing condition, the BIOSCREEN or FATE II models can be used to determine first-order decay coefficients that best match the observed site concentrations. This site-specific calibration effort will require representative measurements of each constituent along the centerline of the groundwater plume. Detailed instructions are provided in the BIOSCREEN and FATE II User's Guides. **Literature Values**: If the plume is in an expanding condition or if a preliminary estimate of biodegradation effects is desired, decay half-life values for hydrolysis and biodegradation from published references (e.g., see Howard et al, 1991). Note that many references report the half-lives; these values can be converted to the first-order decay coefficients using k = 0.693/$t_{1/2}$ (see dissolved plume half-life). In the absence of site-specific calibration data, minimum values (maximum half-life values) should be used. The selected values should correspond to the half-life for full constituent decay to non-hazardous progeney. For inorganics, λ = 0.	Newell et al, 1996 Connor et al, 1995 Connor et al, 1994

NOTE: See Equation LT-1 on Figure 3 regarding use of the above parameters for estimation of steady-state groundwater dilution attenuation factor for dissolved groundwater plume. Detailed discussion of this groundwater solute transport model is provided in the Tier 2 RBCA Guidance Manual (see Connor et al, 1995).

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TABLE 4. PARAMETER SELECTION GUIDELINES: LATERAL AIR TRANSPORT MODEL (EQUATION LT-2)

Input Parameter		Typical Range	Parameter Measurement or Estimation Guidelines	Reference
Symbol	**Description**			
SITE-SPECIFIC PARAMETER MEASUREMENTS				
L	Length of affected soil zone parallel to wind direction (cm)	Site-specific	Determine lateral extent of affected soil zone serving as source of vapor release (e.g., zone exceeding Tier 1 limits) measured along line passing from source zone to downwind off-site POE.	Connor et al, 1995
A	Lateral area of affected soil zone (cm^2)	Site-specific	Measure areal extent of affected soils serving as source of vapor release (e.g., zone exceeding Tier 1 limits).	Connor et al, 1995
X	Lateral distance downwind of source zone (cm)	Site-specific	For most conservative evaluation, measure as distance from edge of affected soil zone to nearest off-site POE location (in some direction as L above). For typical case, measure this distance along line of predominant annual wind direction.	Connor et al, 1995
REASONABLE PARAMETER ESTIMATES				
$\mathbf{U_{air}}$	Windspeed above ground surface in ambient mixing zone (cm/s)	45 - 450 cm/sec	Match to average annual windspeed for site area, based on published climatic data.	Connor et al, 1995
δ_{air}	Ambient air mixing zone height (cm/s)	200 cm	Match to typical height of human breathing zone (6 ft or 2m).	ASTM, 1995
y	Transverse distance off air plume centerline (cm)	-----	To evaluate exposure concentrations along plume centerline, y is set equal to zero.	Connor et al, 1995
z	height of breathing zone (cm)	-----	Assume equal to δ_{air} above.	Connor et al, 1995
σ_y, σ_z	Air dispersion coefficients (cm) in the transverse (y) and vertical (z) directions	-----	For average annual climatic conditions, characterize σ_y, σ_z based on Stability Class C (slightly unstable) using the following relationships: $\sigma_y = 10^{(\text{Log (x)} \bullet 0.941 - 0.861)}$ $\sigma_z = 10^{(\text{Log (x)} \bullet 0.927 - 1.01)}$ If Stability Class C determined to be inapplicable, estimate air dispersion coefficient values using Pasquill-Gifford system as discussed in DeVaull et al, 1994.	Connor et al, 1995 Devaull et al, 1994 U.S. EPA, 1988
C_{si}	Concentration of constituent i in ambient air at point source	-----	Estimate based on appropriate soil-to-air volatilization model (see Equations CM-1 through CM-3 on Figure 2) or conduct site-specific measurements in breathing zone air overlying affected soil source area.	Connor et al, 1995
NOTE:	See Equation LT-2 on Figure 3 regarding use of the above parameters for estimation of lateral air dispersion factor for wind-borne contaminant transport to downwind receptor. Detailed discussion of this air dispersion model is provided in the Tier 2 RBCA Guidance Manual (see Connor et al, 1995).			

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Document 3

Deposition of Lauren Hunt, May 28, 2024.

BEFORE THE
ILLINOIS POLLUTION CONTROL BOARD

IN THE MATTER OF:

ILLINOIS POWER GENERATING COMPANY,

Petitioner

-vs- No. PCB 2024-043

ILLINOIS ENVIRONMENTAL PROTECTION AGENCY,

Respondent.

DEPOSITION OF LAUREN HUNT
May 28, 2024
2:00 PM
133 S. Fourth Street
Springfield, IL 62706

Reported In Person By:

Deann K. Parkinson: CSR 84-002089

APPEARANCES IN PERSON:

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* * * *

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DISCOVERY DEPOSITION

The deposition of LAUREN HUNT taken on behalf of the Petitioner at 133 South 4th Springfield, IL on May 28th, 2024, before Deann K. Parkinson, Certified Shorthand Reporter of the State of Illinois. Deposition taken pursuant to the discovery provisions of the Illinois Code of Civil Procedure and the Rules of the Supreme Court promulgated pursuant thereto.

(The time is 1:54 p.m.)

LAUREN HUNT,

the deponent herein, called as a witness, after having been first duly sworn, testified as follows:

EXAMINATION BY

MS. JOSHI:

Q. Good morning. I'm Bina Joshi from Arentfox Schiff representing Illinois Power Generating Company in this matter. Thank you very much for your time and for being here today. Would you mind starting by stating your name and current business address for the record.

A. Lauren Hunt. 1021 North Grand Avenue something. South Grand Avenue. I don't know.

Q. That's okay.

A. I live in Peoria. I'm really not familiar with Springfield. So --

Q. You currently work for the Illinois Environmental Protection Agency?

A. Yes.

Q. I'm going to start by going over some ground rules, just so that everyone is on the same page for this deposition. So, as you just saw,

you will be giving testimony under oath today. Is there anything that might impact your ability to answer truthfully today?

A. No.

Q. Are you aware of anything that would preclude your ability to understand any of my questions this afternoon?

A. Not that I'm aware of.

Q. I'd ask that you just give verbal answers to any of my questions because we have the court reporter here, and unfortunately the transcript can not pick up head nods.

A. Okay.

Q. Let me know if you don't understand a question that I ask, and I will try my best to clarify. Let me know if you, or let us know if you need a break at any point, and we can stop and take a break. Just if we're in the middle of a question and answer, I would ask that you finish the answer before we take the break, okay?

A. Okay.

Q. Do you understand these instructions?

A. Yes.

Q. Any questions about those?

A. No.

Q. Okay. I'm just going to go over some shorthand so we're on the same page. As you know, we live in a world of acronyms. When I refer to Illinois Power, IPGC, during this deposition, I'm going to be referring to Illinois Power Generating Company. Newton means the Newton Power Plant. The PAP or Newton PAP will refer to the Newton Primary Ash Pond that was the subject of the Alternative Source Demonstration at issue in this appeal.

When I use the term ASD, I'm referring to the Newton Alternative Source Demonstration, again, that's the subject of this proceeding. When I refer to IEPA, or the agency, I'm referring to the Illinois Environmental Protection Agency. And when I refer to part 845, I'm referring to the regulations located at Title 35 Illinois Administrative Code Part 845. Does all of that make sense to you?

A. Yes.

Q. I'm going to start by just asking a few questions about your background and experience. So, where did you get your bachelor's degree?

A. Western Illinois University.
Q. And in what subject did you get your degree in?
A. Geology.
Q. Do you have any other bachelor's degrees?
A. No.
Q. Do you have a Master's degree?
A. Yes.
Q. In what subject?
A. Hydrogeology.
Q. And where did you get that Master's degree?
A. Illinois State University.
Q. Do you have any other degrees at the collegiate or post-collegiate level?
A. No.
Q. Let's talk briefly about your employment history. What's your current position at IEPA?
A. Environmental protection geologist three.
Q. How long have you held that position?
A. The three, or can you clarify? The three or just been at the agency?

Q. The three?
A. Okay. Since February of 2022.
Q. Can you describe your, just generally, your responsibilities in that role?
A. Generally, we review documents from various responsible parties and citizens. We provide approvals where required by, or comments and approvals or reviews for documents where it's required by the regulations.
We work with the coal combustion residuals rule, part 620. And mines and permits where we're asked to help out with permit reviews.
Q. Would you consider your role a managerial position?
A. No.
Q. Do you have a direct superior?
A. I do.
Q. Who is that?
A. I am currently reporting to Joey Logan-Pugh.
Q. And were you reporting to anyone before Joey Logan-Pugh while you were in this position?
A. Yes.
Q. Who was that?

A. Mike Brown.
Q. Anyone else?
A. Mike Summers.
Q. When did you report to Mike Summers?
A. From basically since the end of 2020 until he left the agency at the end of 2023.
Q. Other than Mike Summers, were any of your other sort of direct superiors, Mike Brown or Joey Logan-Pugh, involved in reviewing the Newton PAP ASD?
A. No.
Q. So, prior to your current position at IEPA, did you hold any previous positions at IEPA?
A. Yes, environmental protection geologist one and environmental protection geologist two.
Q. And during what time period was that?
A. Starting in February of 2020, until 2021 I was an environmental protection geologist one. And then in 2021 to 2022 I was an environmental protection geologist two.
Q. And what were your responsibilities in those roles generally?
A. Generally the same as they are now.
Q. So what difference from going to a two

to a three, for example?

A. There's not much. I came to the agency with previous experience, so -- it was -- it's all kind of been the same.

Q. Okay. In terms of your responsibilities, it's been similar?

A. Yes.

Q. Did you hold employment prior to starting at IEPA?

A. Yes.

Q. Okay. And so where were you directly before you came to the agency?

A. CH2M Hill. Which it's formerly CH2M Hill. It's now owned by Jacobs Engineering.

Q. And how long were you there?

A. From 2005 to 2020.

Q. What were your responsibilities when you were at CH2M Hill?

A. A great many things. So, I was a geologist. I worked as a field team leader, construction manager, construction supervisor, construction quality manager. Subject matter expert. I guess an engineering geologist in the field. Site characterization site manager. Site

manager. A number of things; a lot, yeah.
Q. If I can ask you a little bit about a couple of those. You said you served as a Site characterization site manager. Can you elaborate on the kind of work that you did as a site characterization site manager?
A. As a site characterization site manager, I was in charge of reviewing and insuring the implementation of site characterization in the field for two projects while I was in the Middle East that are covered by an NDA.
Q. So I won't get into the details. So you were in the field hoping to implement this site characterization, is that correct?
A. Representing the client and checking that it's being implemented appropriately and accurately.
Q. Did you develop the method by which the sites would be characterized?
A. No.
Q. If you are able to talk about it, and if it's confidential, please feel free to let me know. What types of methodology -- you mentioned two sites in the Middle East, is that correct?

A. Uh-huh.
Q. Okay. Let's just start with the earliest of the two that you worked on?
A. They were concurrent.
Q. Okay. So, for the two site characterizations that you helped implement, what methodology was being used to characterize the sites?
A. What's I guess like overall subjects, is that what you're asking? That we're looking at? 'Cuz I was looking at geotechnical engineering, hydrogeology, geology, biology, meteorology, were all things that were being characterized at the time that I was there and I was reporting on. And possibly more.
Q. Okay. Are you a -- well, were you anywhere before CH2M Hill?
A. Yes.
Q. Where was that?
A. I worked at Whitney & Associates as an intern while I was in undergrad. And then after undergrad. And then I worked at Nicor while I was in grad school. And I did an internship for them in the summer.

Q. Okay. What kind of work did you do at Nicor?
A. Basically I worked on my thesis. They paid me to work on my thesis.
Q. Which was?
A. Basically setting the gas migration pathways from the gas storage field at Torrey Grove gas storage field here in Illinois to the surface.
Q. And then so was it Whitney the other place that you worked?
A. Yes.
Q. And what did you do there?
A. It would be engineering geology and construction materials testing. It was a geotechnical engineering firm that does third party inspections of construction sites.
Q. Are you licensed as a professional engineer?
A. No.
Q. Are you licensed as a professional geologist?
A. No.
Q. So, in all of that experience that

you've had, have you ever performed total solid sampling for CCR surface impoundment?

A. Not for CCR surface impoundment.

Q. Have you performed it for another type of source?

A. Yes.

Q. What type of source?

A. Various. First things that comes to mind is chromium ore process residuals. Various sites in Illinois. Like the Elgin O'Hare had a lot of solids collected for characterization for movement of the soil along the Elgin O'Hare western access when they, I guess managed the soil and put it in different places.

Q. Okay. And so was the source itself sort of the byproduct of the chromium ore processing facility?

A. Correct.

Q. And the source itself was then -- what was it? Was it a landfill or was it an impoundment? Or what, I guess --

A. It was Dundalk Marine Terminal in Baltimore, Maryland. It underlies all of the Port of Baltimore.

Q. Okay. So was it like fill underneath the port?
A. They mud waved the chromium ore process residuals into the Chesapeake Bay and created the port on top of it.
Q. So, what types of total solid sampling did you perform on the site?
A. We soil sampled, we tested it in the field. We tested to see if there was hex chrom in the solids, in the groundwater. Installed wells. Collected soil. Collected groundwater. I set up the geotechnical lab. We performed geotechnical testing at the site as well.
Q. Can you describe for me what geotechnical testing is?
A. Geotechnical testing would be like soils testing, such as we did Atterberg Limits. Moisture contents. Just various soil characterization methods, probably specific to specific gravity and dry densities. And, yeah.
Q. Did your testing involve any testing related to potential leaching from the source?
A. Yes. We collected groundwater samples and studied the groundwater to see what was

actually making it offsite. They also collected groundwater in catch basins and treated it on site to keep it from going offsite.

Q. Were there any pore water samples that were collected?

A. No.

Q. Was there any leach testing that was conducted?

A. No.

Q. Have you ever worked on a site where --

A. Not to my knowledge that I can remember.

Q. Have you ever worked on a site where pore water samples were collected?

A. Yes.

Q. Where was that?

A. Waukegan, it was the Waukegan Harbor area. One of the USEPA Superfund sites. No, it's not a Superfund site. Sorry. I take that back. It's not a Superfund site. So, when I was at Jacobs or CH2M Hill we were a USEPA contractor, so we did third-party oversight on the part of the USEPA. There are a number of sites along the Waukegan Harbor area that were being monitored. One of those included pore water sampling. But it

was in the hyporheic zone.

Q. And for this non engineer here, and I'm pointing to myself, can you explain what that zone is?

A. It is the -- between where the lake water and the groundwater come together; that zone where the sediment, and it's partial surface water and it's partial groundwater.

Q. So this was in the harbor itself?

A. Yes. On a barge.

Q. You accessed it through a barge?

A. Yes.

Q. And were you personally involved in collecting the pore water samples?

A. No.

Q. Did you oversee the process?

A. We watched.

Q. You watched as it was conducted?

A. Yeah.

Q. Okay. Did you analyze the pore water samples afterwards?

A. No, I wasn't involved in that.

Q. Any other sites with the experience with pore water sampling?

A. Not that I know of.
Q. Okay. I understand I'm asking you to reach into your memory here.
And any other sites where you might have conducted leach testing?
A. No.
Q. Have you ever performed a characterization of bedrock as part of your experience?
A. Yes.
Q. When was that?
A. When was the last time or when was --
Q. Yeah, let's start with the most recent.
A. So, I guess that would be -- I believe, I believe, and there could be others, but the last major site that I was on was in the Simi Hills. I'm trying to think if this was also covered by an NDA? As for -- but it was characterizing Simi Hills for fractures and what had gone on previously. It was a federal site.
Q. Okay. Can you explain, first of all, is that Simmi Hills? S-I-M-M --
A. No, S-I-M-I. Like Simi Valley, LA area here. The Simi Hills or the mountains around

there.

Q. And why was a characterization of bedrock occurring there?

A. Because the site was in the mountains.

Q. And what kind of site was it?

A. A NASA site.

Q. Under what program was it being -- was it being characterized under a particular regulatory program?

A. I am not 100 percent sure what regulatory program it was under. But yes, it was under one. I'm not sure if it was just a part of like DOD general work, or if it was CERCLA or specifically RECRA or Superfund. I'm not sure.

Q. Did the characterization include installing monitoring wells?

A. Correct. Yes.

Q. What else did the characterization include?

A. Packer testing.

Q. Anything else?

A. Groundwater sampling. This was ten years ago. So --

Q. Was the waste source that you were

trying to characterize located in the bedrock?
A. Yes. Well, no, wait a second; sorry.
The waste source? The plume, yes.
Q. So, the plume from the source had, or
had entered into the bedrock?
A. Yes.
Q. Or rather were you characterizing to see
sort of how far the plume had gotten into the
bedrock?
A. Yes.
Q. And how long did that process take?
A. Well, I am just a hydrogeologist, and I
was a subject matter expert for it. But I had,
like, I guess there were lead technologists on the
project as well. So, I'm not really sure. It's
probably still ongoing right now. But, I was only
involved for a few years.
Q. Okay. I got it. Thank you.
Have you ever prepared an alternative
source demonstration?
A. Do you mean an alternative source
demonstration like under regulation that says
specifically the alternative source demonstration?
Or do you mean just in general like determined an

alternative source?

Q. Let's go with the latter. And have you ever had experience determining whether a particular exceedance was coming from an alternative source?

A. Yes.

Q. And when was that?

A. 2009-2010.

Q. And what were the circumstances?

A. There was TCE in the bedrock. And not in the soil at the site.

Q. What kind of site was it?

A. A FUD site.

Q. A Superfund site?

A. FUDS.

Q. FUDS? What is a FUDS site?

A. A federal something defense systems. I'd have to look it up. It's a FUD site.

Q. Was it like an old like weapons manufacturing site?

A. Old World War II radar school.

Q. Okay. And there was TCE found in a well, is that right?

A. In the public water well.

Q. In a public water well. Okay. And you were helping to determine whether that TCE might have a source other than this FUD site? Is that right?

A. Correct. Well, we were determining where it was coming from, and whether it was coming from the soil at the actual site; if it was from the radar school or if it was from somewhere else offsite.

Q. And what type of process did you engage in to try to figure that out?

A. We installed bedrock wells. We installed -- and then we packer tested. We also sampled through the packers before we packer tested for TCE. We did flow meters in the holes to see, and a number of downhill geophysics to see how the groundwater was flowing in the bedrock when it was opened up.

And then once we had done that, we were able to take those results and match them with the results that had been previously taken of the soil and show that there was in fact no TCE at the site. It was coming in, in the bedrock from offsite. Much deeper than previously recognized.

Q. And did you have evidence showing that the TCE wasn't coming from the site?
A. Yes.
Q. What kind of evidence was that?
A. The TCE was highest at the lowest -- or deepest interval in the wells.
Q. And was it generally getting lower as you got --
A. Higher in the well and closer to the surface, yeah.
Q. Was there any other evidence that showed that it wasn't coming from the site?
A. We had known responsible parties offsite.
Q. Okay. When you were doing that, it sounds like your task was to figure out what the actual source was, is that right? Or was it just to show that it --
A. My task was to characterize what is going on. And then we can make a decision on what the data was telling us.
Q. Okay. Including whether there was another responsible party --
A. Correct.

Q. -- perhaps? When did you decide you had gathered enough data for your characterization?

A. I guess -- so, I came in and just designed the last bedrock investigation to determine where the groundwater was going to and coming from in the bedrock. And after that, like, we had collected enough samples that it showed conclusively that there was TCE coming in from offsite. And so at that point we were done. And under CERCLA rules, yeah, we were -- done.

Q. When you say it was coming from offsite, was the source the bedrock or was it something else?

A. The source was -- again, the likely a BP liquids terminal two miles away.

Q. When you say likely, why do you use the term likely?

A. Because we did not actually sample over there. But, we knew, it was a known fact that Naperville had TCE in their public water supply while between us and the BP terminal. And then we had an on-site well that was a public water supply well, that it was 80 years old that had TCE as well but at lower concentrations. And so now you

had five more wells installed, or six more wells installed that showed that it was coming from the specific direction offsite.

Q. And do you agree that was kind of enough information so that you guys were confident that it was not the FUD site, and it was likely the BP site?

A. It was enough information to say that it was definitely not the FUD site. Because the on-site groundwater flow was up the bore holes, and you had artesian wells in the bedrock.

Q. What are artesian wells?

A. Wells that have hydraulic head above the upper limit of that unit.

Q. And you said there was some other circumstances in the past as well where you've done sort of alternative source type of demonstration or characterization?

A. It's possible. But, not as significant as that one was all of my design.

Q. Okay. And have you ever conducted an alternative source demonstration like under a landfill program?

A. No.

Q. Have you ever conducted one under the Federal CCR rules part 257?
A. No.
Q. And considering the rule was promulgated after you started working at IEPA, I assume the answer is no. But have you ever conducted one personally under part 845?
A. No.
Q. And when did you first review an alternative source demonstration as part of your professional career?
A. Review --
Q. An actual alternative source demonstration that's required under regulatory program?
A. That would be Newton.
Q. And other than, you may have already answered this, but I'll just ask one more time to clarify. Other than that FUD site, have you ever done any sort of forensic analysis to identify the source of an exceedance?
A. I mean, technically almost all environmental assessments or site characterizations fall under that. So yes, many.

Q. And in that circumstance, what do you typically decide? Or how do you typically decide what information to look at?

A. Well, you have to determine what media is present. And then you determine what needs to be characterized from there, depending on what kind of data is available already.

Q. And how do you decide what information not to look at?

A. If the media is not present, then you wouldn't look at it because you wouldn't be able to collect it.

Q. Let's go back to the FUD site for a second. Was there additional data that could have been collected as part of that analysis?

A. They had already done several previous investigations going in to that. So it became a -- we had already singled it out to be bedrock that needed to be investigated further. So, the soil and the shallow groundwater and all of that was well understood and characterized, if that makes sense.

Q. But no one ever did a direct characterization of what was coming off of the BP

site, correct?

A. No. That's not correct.

Q. Okay. Did someone then?

A. At some point, yes.

Q. Okay. Was there other information --

A. I was conflicted out of that, so I have no information on it. And I was not able to be involved in any kind of proposals or any data that came across as part of any kind of RFP or anything having to do with the investigation of it because of that.

Q. Okay. So you were only involved in a piece of the overall investigation, it sounds like?

A. Correct.

Q. Do you believe in those types of investigations that it's typical to look at every single source of data, even if you're already convinced of what the source of the exceedance might be?

A. Can you restate the question? Sorry. I'm getting lost on this.

Q. Okay. So, let's see. Let me phrase it in a way that's maybe a little bit better here.

So, if you're in a situation where a professional engineer or someone else has determined that they have collected sufficient data to support a conclusion, but there's still additional data that they could collect to further support that conclusion, do you believe that additional data should be collected?

A. It depends on the circumstances.

Q. Okay. So you think that there are circumstances where even if you're convinced based on existing data of a particular conclusion, you would still collect additional data?

A. Yes, because people can get lost in confirmation bias.

Q. Okay. What do you mean by that?

A. So, like we are tasked and most regulations are regulating like soil and/or groundwater. If you haven't fully -- like if you haven't collected all of that data, if you hadn't collected the soil, you wouldn't know how the groundwater could be impacted because of a flood or storm water infiltration or whatever. You don't know until you've actually collected those pieces.

So even if you see something in the groundwater, and you say you believe this is what's happening, you have to fully characterize it. So it just depends.

Q. Do you agree that there's a certain amount of professional judgment that's involved in the process?

A. Yeah.

Q. And how would you describe professional judgment? Like, what does that mean to you?

A. It would be I guess based on -- obviously it's based on your experience. But also if your peers and your senior technical review are in agreement, then, yeah.

Q. So taking a step back, just in preparation for this deposition today did you talk to anyone to help prepare for the deposition today?

A. I mean, we discussed that we were having a deposition, the general rules.

Q. Did you review any documents?

A. Yes.

Q. What documents did you review?

A. 845.

Q. The regulations?
A. Uh-huh.
Q. Did you review anything else?
A. No, not really.
Q. All right. I'm going to hand you a document that's been marked as exhibit 1. Have you seen this document before?
A. Is this the filing?
Q. Yeah, this is the subpoena for the deposition today.
A. Okay. Yeah.
Q. And could I ask you to turn to the second to last page.
A. Okay.
Q. Do you see, is this the subpoena that was directed to you?
A. Yes.
Q. Did you read the document request that were contained in the subpoena?
A. Okay. So --
Q. So the first request asks for any documents containing or referring to notes taken during any meetings, phone calls or discussions related to the review of the alternative source

demonstration.

A. Yeah, I didn't take any notes.

Q. All right. Then so you don't have any documents in response to the first request, is that correct?

A. Correct.

Q. All right. And I'll allow you a moment to review the second request. Just let me know when you're done.

A. Okay. So the number two, we had already submitted those as a part of the administrative record. I don't have anything else other than that.

Q. Okay. I'm going to hand you a document that's been, or Sam is going to hand you a document that's been labeled as Exhibit 2. This is record document number 12. I'll give you a moment to just take a look at what the document is. Do you recognize this document?

A. Yes.

Q. And what is it?

A. The Alternative Source Demonstration for Newton Power Plant.

Q. The one that they submitted on October

6th of 2023?

A. Yes.

Q. I'm just going to start with some baseline setting so that we're on the same page here today.

Do you agree that this document in the Alternative Source Demonstration presented with it relates to chloride in the well designated as APW15?

A. Yes.

Q. And do you agree that that well, APW15, was screened in the upper aquifer?

A. Is that included in here, because I do not know that.

Q. Okay. Well, if you would like, you can refer to the top of page five, or their well log starting on page 22 of the document.

A. Is that AP --

Q. W15?

A. I really, I can't see an actual boring ID on here.

Q. Well, why don't I refer you to the top of page five then of the document. So, at the top of the page the Bates number will read R0001613.

A. Okay.
Q. Do you see the description of the upper aquifer there?
A. Yeah.
Q. Okay. And the second sentence there reads, the top of the UA is highest in elevation in the north and east portions and then it slopes downward towards APW15. Do you see that statement?
A. Yeah.
Q. Okay. And the top of unit elevations range from approximately 482 feet in APW05 and APW10, to 425 feet (APW15); do you see that statement?
A. Yes.
Q. Do you believe this is indicating that APW15 is in the uppermost aquifer?
A. It's possible.
Q. Okay. Do you agree that the uppermost aquifer is made up of sand, silty sand, clay sand and gravel?
A. I am not really that familiar with Newton specifics, to be honest.
Q. Would the location of the well be

relevant to performing an Alternative Source Demonstration?

A. Yes.

Q. Have you heard of the term peer reviewed?

A. Yes.

Q. How do you define that term?

A. So, peer review would be like review with -- from peers that are independently, like, they're not I guess associated with you. So, yeah.

Q. Would it be fair to say when something has been reviewed by like independent experts?

A. Yeah.

Q. Are you, beyond what we just discussed, are you aware of any standards for what makes a document peer reviewed?

A. Um, being published I would say in a journal that's a peer reviewed by practice. It's objective and independent.

Q. Do you believe the EPA issues documents are peer reviewed?

A. By definition we wouldn't have that capability.

Q. What do you mean by that?
A. So we don't have one, we don't have that, like, ability to have independent review.
Q. Pardon me. I was talking about EPA, the United States Environmental Protection Agency. Are you aware, do you agree that the United States Environmental Protection Agency issues documents that are peer reviewed?
A. It's possible. I don't know what their process is. But, yes. I would believe that, it's a government agency. So --
Q. Is it always clear from the face of the document whether it's peer reviewed?
A. In what context? Because in a government document if they're following their quality procedures, they would have the signatures of the management and the peer review that happened. Versus a journal that's published is going to have peer review, but it's not going to be like signed off on like that.
But there is a whole quality management sign off on the government documents 'cuz that's a part of the quality management plan that we have to have one as well.

Q. Would that be located with the actual document?
A. Yeah. When it says issued with a document number, yeah.
Q. Sorry?
A. When it's issued with a document number, so there's a document control number. Then, yes. It would usually. Yeah.
Q. Okay. And with the journal articles you were just mentioning?
A. That's a separate process. So that's the difference between the government, versus like journals.
Q. Do you believe that there can be papers that are peer reviewed even if they don't come from an academic journal or from a governmental organization like USEPA?
A. I guess it's possible.
Q. I want to show you a document which we are going to mark as exhibit 18. It's record document number 1.
(Whereupon, Deposition Exhibit No. 18 was marked for identification.)
Q. Are you familiar with this document?

A. This is Fedder, I believe, is it? Or no.

Q. I believe if you're asking about the author, I believe it was listed in the table of contents of the record as coming from James Drevr, D-R-E-V-R.

A. Yeah.

Q. So are you familiar with this document?

A. Yes.

Q. And what is it?

A. I would need the actual, do we have the list of like what the names of them are? I believe this is the -- it's the groundwater resource, right, that we used?

Q. Well, I can give you a list of the table of contents if that's helpful. Unfortunately, I don't have copies of this. But it's the table of contents?

A. Specifically, yes, I am familiar with this. I am just double-checking that, yeah.

Q. Sure. No worries. Let me just pull this out for you.

A. Okay. Geochemistry of natural waters.

Q. Okay. So was this document provided

with Illinois Power's ASD submittal for Newton?

A. No.

Q. Was it provided to the agency by Illinois Power at all?

A. No.

Q. Where did this document come from?

A. This is in my, I guess professional collection of references that we have at the office.

Q. Is it like a hard copy reference?

A. Yeah.

Q. So, the first page has a heading -- well, first of all, do you agree that this is an excerpt from a larger document?

A. Yes.

Q. Okay. So the first page has a heading, it looks like the "B" is cut off. But it appears to say, Behavior of Specific Elements. Do you see that?

A. Yes.

Q. Is chloride among the elements discussed in this document?

A. It's not in the first section, but may be part of the contaminant transport in

groundwater and chemical evolution of groundwater, reaction path modeling and that kind of thing. Yeah. It may be part of that.

Q. Okay. All right. So it's not in that first part discussing the behavior of specific elements. Let's talk about that second part you were just talking about. The reaction path modeling?

A. Uh-huh.

Q. So, generally what is this dissection of this document talking about?

A. Groundwater modeling and specific groundwater model software.

Q. All right. So, are there specific modeling software packages that are discussed in the document?

A. Yeah.

Q. And have you ever used any of these groundwater modeling softwares?

A. No. Not, like, extensively. If I did touch on them, it would have been in grad school.

Q. Are you generally familiar with these groundwater modeling softwares?

A. Yeah.

Q. Are you aware of whether you would ever use any of these ground water modeling softwares for chloride?

A. I am looking at what would be R00008 or whatever. And it looks like that is --- chloride is a part of what was being evaluated in the model. But, I mean, that's an example.

So, this is basically giving bigger concepts, and that's what we use it for is just the bigger picture concepts then to back up the mass transport equation needs.

So, big picture, when we review these, the law of conservation of mass, which is in Fedder Chapter One, which is -- so, it is document eight, Fedder contaminant hydrogeology, Chapter One, I think it's Section 1.8, goes over the law of conservation of mass. So -- which is what drives the bigger or the greater need for source characterization and waste characterization that's required under 845.

So, that's kind of -- these are all supporting documents to that bigger concept that it has to be.

Q. So what's that law again? The law of

concentration in mass?

A. Law of conservation of mass.

Q. Law of conservation and mass?

A. "Of" mass.

Q. Okay. And what is that concept?

A. Basically what goes in either sticks or leaves. And so -- but mass doesn't actually change. So, you have, for instance, a good example would be that if you had a very low pH and it leached out metals from a specific like volume, you would still have the certain specific mass there. But also you would have this coming out. And this is a whole -- I guess what's coming in has specific qualities that will impact what goes out.

And so, yeah. It's -- it gets into very, very specifics. If you go, I'm sure you have it over there printed; the 268 pages of Fedder. So yes, so that's just the basics of it. It's just, what goes in must come out. Yeah.

Q. Okay. So, talking about chloride specifically, what chemical reactions would you expect chloride to undergo in groundwater?

A. Specifically, chloride is a known

corrosive. So there's many. So, I don't know that we can go into that.

Q. Would you expect it to precipitate?

A. I mean, I think there's conditions for any chemical or element to precipitate given the right conditions. But it just depends.

Q. And what conditions might impact chloride's ability to precipitate?

A. We would have to go look at what probably the USGS says about that.

Q. Okay. Would you expect chloride to dissolve?

A. It does.

Q. Are you familiar with the term redox reaction?

A. Yes.

Q. What does that mean to you?

A. It's the reduction of oxidation or reduction or oxidation of a specific thing. So, yeah.

Q. Does chloride undergo redox reactions?

A. Yes.

Q. Are you familiar with the term conservative solute?

A. I am. But not that familiar.
Q. Okay.
A. Geochemistry is not my thing.
Q. Do you have any understanding of like what the term conservative solute refers to?
A. It's been a long time.
Q. Okay. So, if I were to define it for you and say that a conservative solute means one where its mobility in water would be similar to that of water, meaning that it would be expected to move as the water moves with no extra complexities sort of impeding the transport of the constituent, with that sort of definition would you agree that chloride is a conservative solute?
A. I, again, I'm not a geochemist so --
Q. So you don't feel comfortable answering?
A. No.
Q. Beyond what you've already explained, is there any other way in which the agency relied upon this document in reaching its decision regarding the Newton ASD?
A. Not that I'm aware of.
Q. Let's move on to another document. This is record document number 4, which we will mark as

exhibit 19.

(Whereupon, Deposition Exhibit No. 19 was marked for identification.)

Q. Are you familiar with this document?

A. Somewhat.

Q. What is it?

A. It is the SW846 test method for liquid, solid partitioning as a function of liquid solid ratio for constituents in solid material using an upflow percolation column procedure.

Q. When you say you're somewhat familiar with the document, what do you mean by somewhat?

A. Somewhat in that, like, we as a team we're not as familiar with pore water because it is not a regulated, I guess, media because it's already a part of groundwater. And so there wasn't specific standards for it.

So we pulled that method of sampling and the other documents five, six and -- five and six to basically show what we could find as far as like what procedures were out there in SW846 on the methods that were provided under SW846, which is incorporated by reference in 845.

Q. Methods for what?

A. Sampling or analyzing.
Q. For analyzing what?
A. Pore water. Or pulling the pore water out of the material.
Q. Do you agree that this is a laboratory test?
A. Uh-huh.
Q. Referring still to this document that is marked exhibit 19?
A. Yes.
Q. It's not a method to directly sample pore water from a source, correct?
A. Correct.
Q. So what's your understanding of how this method in exhibit 19 is used to predict pore water source concentrations in a CCR surface impoundment?
A. I don't know that that has been fully vetted. And we were, again, just pulling the known test methods that were available for analyses. And then there is the -- so, there is the method for field sampling is also in our document list for pore water.
So, between the two, we were just

basically showing these are what we know to be the established procedures and methods for analyzing or collecting pore water. But, we do not have, I guess, a great deal of knowledge. Or I don't have a great deal of knowledge of what this method is about. And I could say that about pretty much any method in SW846 'cuz I've never worked in a lab.

Q. Sure. Okay. So that document, Exhibit No. 19, refers to something called a liiquid-to-solid ratio. Are you familiar with that term?

A. I mean, I understand what you're saying. But --

Q. Okay.

A. I understand ratios. And liquid and solid, yes.

Q. Okay. Are you familiar with the term eluate, which is used in that document?

A. No.

Q. So, going back to the liiquid-to-solid ratio term, does or do you, have you heard from anyone at the agency an opinion on what an appropriate liiquid-to-solid ratio would be for testing a CCR surface impoundment?

A. I don't know, and I don't know that that's been established.
Q. Does the CCR surface impoundment liiquid-to-solid ratio change over time to your knowledge?
A. I guess the liiquid-to-solid ratio would depend on the degree of dewatering that's occurred.
Q. Do you believe that the liiquid-to-solid ratio is the same across the entirety of the CCR surface impoundment?
A. I don't -- probably not, based on there's higher piles of CCR in certain areas, versus others, and over burden is going to squeeze it out more than places where there isn't any over burden.
Q. Do you agree that pH in field conditions may vary from pH in laboratory conditions?
A. Yeah.
Q. Are you familiar with the pH of rain water?
A. No. Again, I am not a geochemist, so sorry.
Q. No. Are you familiar with whether the

test methodology reflected in exhibit 19 accounts for any ponding of water?

A. I have no idea.

Q. Are you aware of whether the test method reflected in document 19 accounts for incoming groundwater?

A. I don't know.

Q. Are you aware of whether the test method reflected in document 19 accounts for any conditions that could dilute the leachate?

A. I don't know.

Q. Are you familiar with what volume of material is collected for a sample evaluated through the test method reflected in Exhibit No. 19?

A. I'm sure it says somewhere in here. But no, I'm not.

Q. Would you expect it to be a fairly small amount of material compared to the overall size of the source?

A. Typically, I would expect that. Yes.

Q. All right. Let's move on to another document. I'm going to mark this as exhibit 20.

(Whereupon, Deposition Exhibit No. 20

was marked for identification.)

Q. This is document number five in the record. We're going to take a break.

(A break was taken at 2:58 p.m.)

(The time is 3:04 p.m.)

CONTINUED EXAMINATION BY

MS. JOSHI:

Q. Going to give you a document which is marked as record document number 5 and exhibit 20.

And are you familiar with this document?

A. I am semi familiar with this document.

Q. What is it, to your knowledge?

A. It is the SW846 Method 1315 Mass Transfer Rates of Constituents in Monolithic Or Compacted Granular Materials Using a Semi-Dynamic Tank Leaching Procedure.

Q. Would you agree that this document describes a methodology for leach testing?

A. Yes.

Q. Can I direct your attention to the page where the top is marked as R000065?

A. Okay.

Q. Section 1.1 of the document. It says, this method is designed to provide the mass

transfer rates (release rates) of inorganic analytes contained in monolithic or compacted granule -- pardon me; granular material under diffusion controlled release conditions as a function of leaching time.

I want to direct your attention to the term, monolithic. Do you believe that the material contained in the Newton PAP is a monolithic material?

A. I can not speak to that.

Q. Why not?

A. Because I am not as familiar with Newton, and I -- or this document. And I did a broader review as the technical reviewer for this ASD.

Q. Okay. Do you understand what, or to you, what does monolithic material mean?

A. Potentially I'm thinking -- I'm not 100 percent sure, but I'm thinking it's consolidated basically bedrock. It's a solid piece.

Q. And what does the term, compacted granular material mean to you?

A. Compacted granular material is just granular material such as sand or gravel that's

been compacted, I guess, artificially. So with a compactor, or has consolidated over time.

Q. Do you believe the material in the Newton PAP is a compacted granular material as defined in this document?

A. Some of it may be, yes. Just by the fact that it's been there for so long.

Q. And how so? Just because it's been there for a long time? Or is there anything more to that assumption of yours?

A. So, the deeper the material, it has more over burden. So there is compaction over time from consolidation because of that over burden weight. So I'm saying it's possible.

Q. Do you believe that CCR surface impoundment generally behaves more like a porous medium or a monolithic compacted granular material?

A. I'm not actually sure.

Q. And to your knowledge, does the method discussed in this document marked as exhibit 20 simulate water movement through a porous medium?

A. Compacted granular material would still be a potentially porous media in some cases. So,

it could be.

Q. Do you believe this test method is meant to address water movement through a porous medium?

A. It could be.

Q. Why did the agency include this document in the record?

A. For the same reasons I stated before. That it was a way of testing the liquids that came out of a solid or pore water. Or to our understanding at the time. But we had very little time to get things together as far as these documents go. So, that would also apply to document six.

Q. Okay. Great. Let's talk about document six then next. This is going to be marked as Exhibit 21 for the deposition.

(Whereupon, Deposition Exhibit No. 21 was marked for identification.)

Q. Are you familiar with this document?

A. Somewhat.

Q. Okay. Do you agree that that document describes a methodology for leach testing?

A. I am not sure. It doesn't seem to be necessarily very specific up front. And, yeah.

It doesn't seem to be necessarily very specific, so I'm not sure.

Q. Why did the agency include this document in the record?

A. Basically because it seems like it had to do -- it was a method that had to do with the testing or analyzing of the liquids that were within a solid material, and what comes out of it.

Q. Is what comes out of that material usually called leachate?

A. That depends on how I guess you're looking at it. Sometimes that can be interpreted as pore water, and we do pore water extraction in situ, and sometimes it's leachate because for whatever reason I think that's a different -- I don't know the specifics of why they make that determination.

Q. Okay. Do you agree that the methodology reflected in Exhibit 21 is a methodology that's conducted within a lab?

A. Yes.

Q. Again, if you go to, say, page two of this document at the top that's Bates numbered 4000103. And just look at, say, Section 1.1,

you'll see the term liquid-to-solid ratio there. Do you see that term?

A. Yes.

Q. All right. Again, how do you determine an appropriate liquid-to-solid ratio for a particular CCR surface impoundment under this methodology?

A. I don't know.

Q. Do you have any understanding of what type of pH might exist under the laboratory conditions used for this method?

A. No.

Q. Does this test methodology in Exhibit 21 to your knowledge account for any ponding of water?

A. I don't know.

Q. To your knowledge, does the test methodology in Exhibit 21 account for incoming groundwater?

A. I don't know.

Q. To your knowledge, does the test method reflected in Exhibit 21 account for any other conditions that could dilute the leachate?

A. I don't know.

Q. Are you familiar with the volume of material that's conducted for sampling under this method?
A. No.
Q. So for the last three documents that we just talked about, which have been marked as exhibits 19, 20 and 21, do you agree that they all reflect different SW846 methodologies?
A. Yes.
Q. Do you agree that each of the methodologies are conducted under laboratory conditions?
A. Yes.
Q. Do you believe that any of these methodologies are representative of field conditions of a CCR surface impoundment?
A. I wouldn't know.
Q. Do you agree that there's variability that could impact leaching of the unit over time? For example, weather conditions like rainfall?
A. It's possible. Yes.
Q. Could the topography of a unit impact leaching?
A. Yes.

Q. Could different permeability in different areas of the unit impact leaching?
A. Yes.
Q. Do you believe that any of the methods discussed in exhibits 19, 20 and 21 are a better indication of current impacts on groundwater than actual in-field pore water sampling?
A. I don't know.
Q. Did IEPA conduct any investigation into whether the methodologies reflected in documents 19, 20 and 21 are appropriate for a CCR surface impoundment?
A. No, we didn't have time.
Q. Did the agency look into any drawbacks or flaws from these methodologies as they might be applied to CCR surface impoundment?
A. No.
Q. All right. I'm going to give you another document that's been marked as exhibit 5.
Are you familiar with this document?
A. Yes.
Q. What is it?
A. The USEPA pore water sampling procedure.
Q. Is this a document that the agency

independently pulled in its review of the Newton ASD?

A. Yes.

Q. Did you review it in connection with the Newton ASD?

A. We reviewed the basics of it, and then looked for evidence in the ASD that these methods were followed. But we did not see that information.

Q. And generally do you consider USEPA to be a trustworthy source?

A. Yes.

Q. Does the agency regularly pull and review USEPA documents?

A. Um, with respect to some procedures, yes, we do.

Q. Do you believe that the pore water sampling methodology represented in that document is appropriate for CCR surface impoundments?

A. I do.

Q. Why so?

A. Because you can use these push points very easily in the field, and there are methods to be able to reshift load to be able to move out

into the CCR surface impoundments to get samples. So, yes. And I've used the hydropunch, which would fall under the push point or similar sampler, prior to my time at the agency. So we weren't collecting pore water though. That's not what we would call it though, I don't think. Again, this is a whole new thing that's not even in our regulation; pore water, the term.

Q. So, you're just saying you use a particular instrument that they refer to in that document?

A. Yeah.

Q. But you've never used it to collect pore water?

A. When you read this document and the way that it's supposed to be collected, it looks like what we were saying was a groundwater grab from a hydropunch or a push sampler way back in the day.

Q. Okay. A hydro what?

A. Hydropunch.

Q. Punch. Okay.

A. So, I guess I'm not sure what the difference is between a groundwater grab where you are just opening the slot and you're letting the

water come in from the pores, versus, and we were calling it groundwater at the time, versus now we want to call it pore water. But, groundwater is what's regulated. So we had to stick with that.

Q. Is pore water sampling in a stream sediment to your knowledge the same as pore water sampling for a CCR surface impoundment?

A. It would be very similar, honestly.

Q. Okay. And what would be the similarities?

A. In a stream, the sediment is laid down by active flow of water. In a CCR surface impoundment the CCR was laid there by active flow of the fluids into that impoundment and the settling of that sediment. So, which is the CCR. So, it's -- one is manmade and the other is natural. But it's the same process of settlement.

Q. Okay. And earlier in the deposition you referred to observing some pore water sampling, was it in a bay?

A. Yeah, it was in the Waukegan Harbor.

Q. Or harbor. Pardon me. Do you believe that pore water sampling of a CCR surface impoundment is similar to pore water sampling of a

harbor?

A. I feel like -- I'm not really, really 100 percent sure on the whole sediment in a harbor versus sediment in a CCR surface impoundment, to be honest. I have no idea.

Q. But you do believe that this document is relevant to pore water sampling of CCR surface impoundments?

A. I do.

Q. Let's move on to record document number 19. We're going to mark this as Exhibit 22.

(Whereupon, Deposition Exhibit No. 22 was marked for identification.)

Q. All right. Are you familiar with this document?

A. Yes.

Q. What is it?

A. It's an e-mail from myself to Lynn, Heather, Justin, Matt and I cc'd Mike Summers. And it is regarding the ASD for Newton and the ASD for JOPPA. And a list of what we needed to discuss.

Q. Okay. Are there three items listed there for discussion?

A. Yes.
Q. What's that first item that's listed?
A. Geochemistry.
Q. What is that intended to mean?
A. So, this e-mail, because it's addressed to our junior staff, was meant to bring everybody together to have a discussion on the general subjects that they were going to be encountering as they reviewed ASDs, because I'm the only one with a master's in hydrogeology and Heather is the only one with a master's in geochemistry. And the two other folks have a bachelor's and a collective three years of experience between the two of them.

So, we were trying to get people more familiar with just the basics of these items since they're coming up. So, it was less about specifically Newton, and I guess JOPPA, and more of like a training.

Q. Okay. So, is the geochemistry on here meant to reflect anything about geochemistry at the Newton PAP?
A. If we were talking about it, it would be Heather talking about it; the geochemistry, if that makes sense. So, and the specifics of that.

And like walking people through like what you -- how we would look at it or analyze it.

Q. Okay. So as an agenda item, to your recollection you did not intend to discuss anything specific to the Newton PAP geochemistry?

A. I was intending to have Heather walk through the Newton PAP geochemistry as an example and explain.

Q. Okay. And explain what?

A. What was being presented. Like she understands from her professional experience and understanding; that kind of thing.

Q. Okay. The second item on here reads, alternative source data submittal requirements. Do you see that?

A. Yes.

Q. What is that intended to mean?

A. That is intended to mean the agreed-upon data requirements that we needed for alternative source demonstrations to be considered complete.

So, we needed source characterization of the actual CCR source. And then also CCR surface impoundment of the alternative source.

Q. Was the discussion of alternative source

data submittal requirement general to all ASDs, or specific to the Newton and JOPPA ASDs?

A. Generally to all.

Q. And did the agency reach any conclusions at this meeting or at any other time on what is required for an alternative source data submittal?

A. Not necessarily at this meeting. But yes, we did. Because -- so, I basically asked if there was source characterization, both of the alternative source and then also of the CCR at Newton, so that was because it was the first one -- it was the first one that got discussed. And I took that to Mike Summers. And he said correct; if there's no source characterization of both, then we do not concur.

And so that was kind of the end of that.

Q. Okay. And what is the scope of source characterization that would be needed of let's start with the CCR surface impoundment?

A. So, according to Mike Summers, it was determined that we needed a ten percent source characterization of the CCR surface impoundment. So, that was basically ten borings with a sample in the upper one-third of the boring, the middle

one-third of the boring, and the lower one-third of the boring. And that's -- yeah.

Q. And did you have a discussion as to why that was needed?

A. We had a discussion about the fact that source characterization needed to occur. We had thrown out -- I had thrown out ideas on what we could do, or to just establish a baseline for all of them. And that is what management decided.

Q. And did you discuss what method had to be used for that source characterization?

A. Well, it was source characterization per the rule, which is that the solids have to be characterized.

Q. And when you say, per the rule?

A. 845.

Q. And what portion of 845 are you referring to?

A. Hold it. I have it marked. Okay. So, source characterization is required in 845.230(a)15. That's all initial operating permits.

Q. Does it -- are there any -- is there any specificity in 845.230(a)15 on what needs to be

done for source characterization?

A. No. Not in 230, no.

Q. All right. So, what regulation, guidance or other document to your knowledge was the agency relying upon in reaching the conclusion that it needed this ten percent source characterization that you referred to?

A. That was the professional judgment of Mike Summers.

Q. And then going to the second piece of characterization that you were talking about, the characterization of the alternate source, are you aware of whether the agency concluded what information would be required for characterization of that alternate source?

A. Well, our management has agreed that one sample is not sufficient to characterize any media because SW846 specifies that you must have a sampling rationale and that must include more than one sample.

Our interpretation as an agency is that you have to have sampling of the alternative source here, and it's in 845.650(e), right, is it? Yeah, 650(e).

Q. Can you point me to where in 845.650(e) it discusses requiring sampling of the alternate source?

A. So, we are interpreting, the agency interpreted the submit a demonstration to the agency that a source other than CCR surface impoundment caused the contamination, and CCR surface impoundment did not contribute to the contamination to mean that you had to have data to substantiate that claim that it came from an alternative source. So that would require an analysis of samples from the alternative source.

Q. So --

A. Because without data, you're making -- you're just making -- it's just an opinion.

Q. Do you agree that there can be data other than direct sampling that could support the conclusion that something is coming from an alternative source?

A. There has to be data. Now, the media that gets sampled for the alternative source may depend on availability of the media or field conditions.

Q. Going back to that FUD site where you

were investigating TCE, you said you came in sort of towards the end of that process?

A. Uh-huh.

Q. Okay. Do you have any idea how long it took to try to figure out the source there as part of that process that you were involved in?

A. It was upwards of ten years likely.

Q. Going back to the document, Exhibit 22, going back to Exhibit 22, that item number three reads, other items the team is curious about or needs to brush up on. Do you see that?

A. Uh-huh.

Q. What is that referring to?

A. That's just an open, like, dialogue for any other things that have come up in any of their work, if they needed to have that conversation while we're having a conversation about data and geochemistry. So --

Q. Did any of that discussion relate to the Newton ASD?

A. I'm sure some of it did. But, I don't know about number three though. Yeah, I don't recall.

Q. Okay. Going to move on to another

document that's already been marked as Exhibit No. 7.

Are you familiar with this document?

A. Yes.

Q. What is it?

A. It is the ASD nonconcurrence letter from the agency.

Q. Were you involved in drafting this letter?

A. Yes.

Q. What portions of it did you draft?

A. I helped draft one, two and three.

Q. So, do you mean the items that are listed here as one, two and three?

A. Uh-huh. Yes.

Q. Okay. Did anyone else help you draft items one, two and three?

A. I -- in what manner? Because I asked questions, and then they told me. Like, we had an open dialogue. Basically I was like, here's what we need for an ASD. And then, yeah. Then we got that approval from Mike. And then had the conversation about what was there and what wasn't.

Q. And who did you have the conversation

with, other than Mike Summers?

A. Heather Mullenax.

Q. And did Mr. Summers sign off on the language in here before he signed the letter?

A. Yeah.

Q. Did he do any editing to the portion that you wrote prior to sending the letter?

A. I don't recall.

Q. Is this generally consistent with what you presented, though, or originally drafted?

A. Generally, yes.

Q. What was the scope of discussion that you had with Mr. Summers about whether or not to include each of these data gaps in this letter?

A. So, the first one, source characterization, he agreed that the mass transport equation has to be answered. We have to have waste characterization or source characterization to be able to talk about whether or not the CCR surface impoundment has or does not have the potential to provide or contribute to the contamination as specified here in 650(e).

Additionally, it was our agency position that they had to have sampling from the

alternative source of some kind.

And then for number two, hydraulic conductivities from the laboratory or in-situ testing. We felt that there needed to be better characterization of the bedrock unit, that's fracture flow. If you're -- yeah; bedrock wells can not be installed in just solid rock. And not have a hydraulic conductivity and be used to say that there is nothing going on without substantial bedrock characterization showing there is not actual -- the secondary flow path, which is the primary flow path really of fracture flow. And those have to be captured. Does that make sense? Am I making sense?

Q. Let's talk about this. Let's take a step back and talk about them one at a time, all right?

So, for number one, it says source characterization of CCR at the Primary Ash Pond must include total solid sampling in accordance with SW846, right?

A. Yes.

Q. Okay. First off, what do you mean by source characterization in accordance with SW846?

A. Okay. So, SW846 has methods for testing or analyzing a solid sample. It's incorporated by reference in 845. We're saying source characterization of the CCR must be total solids based on what is required in 230, what's required for the corrective action modeling for closure modeling, which is FATE and transport. For transport modeling calculations, you're going to need that source characterization or the waste characterization as it's stated in 845.230.

Q. Okay. So --

A. Go ahead.

Q. I was just going to ask a follow-up question there. So 845.230, that relates to what goes into your operating permit application, right?

A. Correct.

Q. And you're saying that that's useful information for sort of the life of the unit?

A. Correct.

Q. As it's closing and maybe needs to undergo corrective action?

A. Yes.

Q. How is it specifically helpful for

determining whether a particular exceedance from a particular quarter is being caused by the CCR surface impoundment?

A. So, the source characterization or the waste characterization of the solids will show what metals are actually present in the CCR.

If, say, chloride was not present in the total CCR solids, but it was still in your well, and you're saying it's there because it's from an alternative source, but there's no existence of it in the source, then we could say okay, yeah. That's like an example. It's like, any constituent that's not in the CCR, because not all CCR is going to have the same metals in it because it depends on the parent coal that was used and burned, plus the processes that they go through to -- yeah, utilize the coal for energy.

Q. Okay. Do you agree that a way to find that out is also by doing pore water sampling?

A. No.

Q. Why not?

A. Pore water sampling is a snapshot in time of a very specific portion of the groundwater. It does not fully characterize the

groundwater. It does not fully characterize the total solids. And -- yeah.

Q. Again, so, I guess what I'm trying to get is what's the difference between the life of the unit versus what's happening right now? And for an ASD, do you need to be worried about what's going to happen over the whole life of the unit, or do you need to worry about what's happening right now?

A. So, the source characterization provides what is the actual potential for that CCR?

If you don't have that, then you can't say even what's happening right this second is accurate except for that one second, I guess. And not even that when it comes to pore water because it's not actually like the whole groundwater, if it's being collected as a groundwater graph. So we didn't have the documentation with the ASD to say this was done low flow and it's actually groundwater, and etc. If it's a groundwater grab, that's even less accurate.

Q. Do you agree that if there was -- leach testing would also just be discrete samples collected from around the CCR surface impoundment?

A. It's possible, but leach testing, again, wouldn't replace the total solid source characterization that needs to be done to be able to start that mass transport equation conversation. And that's where you -- that's a missing link.

Q. Okay. So, taking a step back then, when you're talking about total solid sampling in data gap one, what method are you referring to?

A. So, any of that are appropriate for total solids of those metals constituents, and I know that metals has a number of different analyses that are approved depending on the constituent. So we just said SW846 instead of parsing which methods.

Q. Okay. Did you mean to refer -- was this meant to refer to the SW846 methodologies we discussed earlier in this deposition?

A. No.

Q. Okay. It was meant to refer to something other than that, is that right?

A. Correct.

Q. Okay. Do you agree that pore water collection and sampling is a way to characterize

the source?

A. I don't think that it characterizes, fully characterizes the source adequately for the mass transport equation.

Q. Again, can you refer me to any specific method in SW846 that the agency would be looking for when it comes to the total solid sampling characterization?

A. I would have to go through SW846 and pull up the various constituents that are being tested to make sure all of them are covered. Because heavy metals has one, and generally speaking I know mercury is always separate and has a different test method. So there's a number of test methods under SW846 for solid sampling that you would have to do to do all of the constituents under 845.600.

Q. And you're not referring to other leach testing methods like, what is it? SPLP? I don't know if I'm saying that --

A. SPLP would be something that you do after you've done the total solid sampling. So you would do total solid sampling. You would see what's there. Then if you want to know if it's

leaching, then you would see for those specific constituents that are detected what they actually leach at.

Q. Okay. So, again, going back to data gap one, is the agency just looking for that initial total solid sampling? Or is it looking for anything further than that such as that second step of conducting a leach test?

A. I think that you will likely need the leach test to say for the things that are present this is not going to leach. You're going to have to do a leach test to make sure that it's not leaching.

Q. Okay. And do you believe that that leach test would be more accurate than a pore water test?

A. Yes, because you can adjust the pH in the lab to simulate various scenarios.

Q. But don't you agree that pore water sampling is conducted in, in-field conditions, which would be reflective of in-field PH?

A. Yes. But, other pHs could occur, or could have occurred in the past that created this down gradient plume.

Q. Going to refer you to what's been marked as Exhibit 8.

This is an excerpt from record document number 33. Have you ever reviewed this document before?

A. What is this document? I mean, it's possible that I've seen it.

Q. Sure.

A. I'm not sure.

Q. This is an excerpt from record document 33, which is Illinois Power's petition in this case.

A. Okay. No, I have not been able to get that far into that.

Q. Okay. Can I direct your attention to, please, paragraph four of that declaration.

And would you just take a moment to review that paragraph and just let me know when you're done.

A. Okay.

Q. So, the first sentence there says, performing source characterization of the CCR at the Newton Primary Ash Pond using total solid sampling techniques under SW846 would require

drilling within the Newton Primary Ash Pond up to ten borings using specialized equipment to collect 20 samples. Do you agree with that statement?

A. Well, it would be 30 samples; if you do one-third in the upper, one-third in the middle, one-third at the bottom. That's 30, not 20. But generally, yes.

Q. And why are you saying -- are you saying 30 samples is what the agency believes is appropriate?

A. Yeah. We were saying 30 samples, not 20. But yeah, ten borings with three samples at each one.

Q. The next sentence reads, it would further require complete laboratory analyses, data evaluation and reporting for these samples.

Do you agree that it would involve that process?

A. Yeah. Yes.

Q. The next sentence reads, assuming a driller is readily available, which is not always the case, this process would likely take approximately 21 to 42 weeks to complete.

Based on your experience, do you agree

with that statement?

A. Yeah.

Q. All right. Moving back to exhibit 7. Let's talk about that second listed data gap. Can you describe what information this data gap is referring to?

A. In our review, we determined that the hydraulic conductivity of the bedrock unit had not been presented with ASD.

Q. So, what hydraulic conductivities is this referring to? Just the bedrock unit?

A. It is, yeah.

Q. What type of in-situ hydraulic tests are you thinking would be necessary?

A. In-situ hydraulic tests can be anything from a spinner or some kind of down hole geophysical method that engages flow within the bedrock, or you can also do packer testing. There's -- yeah, there's various methods.

Q. Do you believe any of those methods you just listed would be appropriate?

A. It's possible, but it would depend on the conditions after it was properly logged with discontinuities logged and understood better.

Q. Why are you asking for a hydrogeologic characterization of the bedrock unit?

A. Okay. So, at the time I believe we're thinking that it was connected to the unit. And so we were looking at that as well.

Q. When you say, at the time, why do you use that phrase, "at the time"?

A. Because I don't recall the specifics of what went into the specific decision. It has been and primarily was and is a source characterization issue in the mass transport equation that went into the reason for the letter.

Q. And what regulation, guidance or other document leads you to believe that this type of characterization presented in data gap two is necessary to prove that the PAP is not the source of the chloride exceedance?

A. Hydraulic conductivities to bedrock is required as a part of 845.620, I believe. Yeah. 620. And so which is supposed to be -- so, if this was all working the way that it should, we would have an initial operating permit and the ASD would be requested after you had this piece that is supposed to be submitted with the operating

permit and approved by the agency.

So yes, it would be one of those pieces that all go into the bigger picture setting. So that when we're making these more minute decisions that are very specific, like we have all of the background data. But that is not the case here.

Q. So you agree here that IPGC has started to conduct monitoring under its ground water monitoring programming, correct?

A. Yes.

Q. Okay. And that was due to a request from the agency to start monitoring before the operating permit was approved?

A. Correct.

Q. Okay. And so as a result, the agency doesn't necessarily have the benefit of all of the information that would be in like an approved operating permit, is that correct?

A. Correct.

Q. And how long does it take, or how long did an owner/operator have to submit an operating permit application to the agency if you recall, or just generally?

A. Like a year and a half I think after the

rule was enacted. Somewhere around there.
Q. And how many rounds of sampling were typically conducted before an owner/operator submitted a ground water monitoring plan under its operating permit application?
A. At least eight.
Q. And how much time does an owner/operator have to put together an ASD?
A. Very little. It's something like 60 days, I believe. Or 90.
Q. I'll let you refer to 845.650, and I have a copy if you'd like a copy here.
A. Yes, it is 60 days after confirmed detected exceedance of the groundwater protection standard.
Q. Okay. Are you familiar with what a confining layer or aquatard is?
A. Yes.
Q. What is it?
A. It is a unit that impedes, stops, or slows the flow of ground water down into a lower aquifer.
Q. How is it different from an aquifer?
A. An aquifer has a hydraulic conductivity

that is conducive to ground water flow, and the aquatard or confining unit, again, slows down the flow of ground water or stops it.

Q. As part of your professional life, have you ever installed a well or wells for purposes of investigating hydraulic conductivity?

A. Yes.

Q. Have you ever done so for purposes of investigating hydraulic conductivity of a confining layer?

A. Yes.

Q. Can you please describe when you did that?

A. Yes. As a part of nuclear siting licensing here in the United States, we were required to install wells per whatever plan that we had exactly the way that we said. And if you said it was 15 feet, then it was going in 15 feet regardless. And so we ended up with some dry wells.

Q. So, that project involved drilling for purposes of investigating hydraulic conductivity in an aquifer?

A. Yeah.

Q. Did it involve drilling for purposes of investigating hydraulic conductivity in the confining layer?
A. They wanted to know flow, yes. In the confining units, in the aquifer, and -- yeah.
Q. Did you run into any issues by drilling into the confining layer?
A. I mean, yeah.
Q. What kind of issues?
A. Dry wells. No samples. Yeah.
Q. As part of that experience, did you ever install a well screen into a confining layer?
A. Because it was required by the NRC, yes.
Q. Okay. Did it have any usefulness?
A. No. Other than you had a dry point. So I guess it is data.
Q. Have you ever conducted in-situ hydraulic conductivity testing of a confining layer?
A. Potentially perc tests, just to see what was going on.
Q. Perc tests?
A. Yes.
Q. That is the procedure that you used?

A. Uh-huh.
Q. Anything else?
A. No.
Q. Have you ever drilled through a confining layer such that the aquifers above and below became connected hydraulically?
A. No.
Q. Moving on to the third data point here on exhibit 7.

What is the scope of characterization this data point is seeking?

A. 845.640(a) 1, 2, 3, 4 and 5.

So, if you go back to 640(a)1, at sample collection you basically have documentation reading sample collections, sample preservation, and shipment. Again, that's documented on your chain of custody. Your analytical procedures generally are in your laboratory report and your chain of custody. Quality assurance and quality control again are in there.

So, this would basically look like a laboratory report that includes your chain of custody, and also field documentation of your purge procedures, etc. And whatever field

procedures you used to collect the sample. Which was not in the actual submittal.

Q. Okay. So, the only portion of 845.640 this is meant to refer to is 845.640(a)?

A. Yeah.

Q. And what sampling is it referring to?

A. The sampling that was being provided. So, the sample collection that was presented in the ASD didn't have this documentation.

Q. Okay. So, for example, the pore water samplings that were conducted?

A. Yeah; so, whatever is being presented as a part of the ASD should have -- whatever data should be substantiated by the laboratory reports and the field collection procedures documentation.

Q. Okay. Data gap three only refers to the alternative source. Is it meant to refer to the alternative source?

A. Yes. I mean, because, again, ideally source characterization would have already occurred under an initial operating permit and you would already have that in the record. And we could just say, we would have already have said that that was acceptable and documented

appropriately, etc.

Q. Okay. Data gap three does not refer back to any other sampling results provided in the ASD, does it?

A. I don't know what you mean.

Q. Well, you were saying that it's meant to refer to samples that were provided with the ASD, is that right?

A. Yeah.

Q. Okay. I guess my question to you is, does it say that in your opinion? And if so, how?

A. So, yes, it does. And --

Q. Where?

A. It says that you have to have the characterization per 640. Well, it should be 640(a). For the alternative source, which is what would -- what was presented in the ASD was the alternative source data. But we didn't see the laboratory reports and we didn't see the documentation for how it was collected.

Q. So when data gap three refers to alternative source, what is it referring to?

A. Excuse me, what?

Q. When data gap three refers to

alternative source, what is that term referring to?

A. Your guys's proposed alternative source.

Q. Okay. So that's referring to the bedrock unit?

A. Whatever you were proposing was the alternative source.

Q. Okay. So, is it saying sample and analysis in accordance with 845 of what they were proposing, or what Illinois Power was proposing as the alternative source?

A. Correct.

Q. Is this referring in any way, or can you show me how it's referring in any way to sampling and analysis of the CCR surface impoundment?

A. Well, like I already said, the source characterization would have optimally already been completed and approved, but it wasn't so we needed that to actually go into the -- to feed into the mass transport equation or that whole discussion.

But, and that would have been sampled, again, per 845.640 as well. But, this point is specific to the data that was presented in the ASD, that it didn't come with laboratory reports

or field documentation.

Q. Okay. But, you just said that there wasn't data provided or sampling data provided related to the alternative source in the ASD?

A. No. I said that it didn't -- so, you have -- source characterization has to have -- for the mass transport equation you have to have the source characterization done so you can say that in fact this CCR surface impoundment doesn't have the ability to contribute to that contamination. And then you had this alternative source information that then says okay, yes, you have found the alternative source.

Q. Okay.

A. So, that's, yeah. You have to have both.

Q. Okay. So, data gap three, is it meant to refer to one of those two things or both of those two things?

A. It is meant to refer to the data that was presented in the ASD submittal.

Q. Okay. Can we take a short break?

(The time is 4:07 p.m.)

(The time is 4:17 p.m.)

CONTINUED EXAMINATION BY

MS. JOSHI:

Q. All right. So, going back to Exhibit No. 7, which is the denial letter, data point, or data gap three, it reads characterization to include sample and analysis in accordance with 35 I.A.C. 845.640 of alternative source must be provided with the ASD, correct?

A. Correct.

Q. It does not say characterization to include sample and analysis in accordance with 35 I.A.C. 845.640 of the CCR surface impoundment must be provided with the ASD, correct?

A. That's correct.

Q. I'd like to direct your attention back to Exhibit 8. And refer you to paragraph five. Give you a moment to review that, just let me know when you're done.

A. I'm done.

Q. The first sentence there says, conducting a characterization of the bedrock surrounding the Newton Primary Ash Pond in accordance with 35 Illinois Admin Code 845.640 would require drilling to bedrock, well

installation, solids and ground water sampling and analyses, and data evaluation and reporting.

Did I read that correctly?

A. You did read it correctly.

Q. Okay. Do you agree with the information in that sentence?

A. Typically you would not collect solids below the water table if you're not in like a source material that needs to be characterized.

Q. Okay. So, you would say that solid sampling and analysis perhaps would not be required for characterizing the bedrock?

A. If it's not a part of the source, correct.

Q. And is there anything else in that statement you disagree with?

A. Taken as a whole, the paragraph suggests that you would not actually be characterizing the bedrock in a manner that would be adequate to characterize fractures.

Q. Okay. So, do you think additional steps would be required?

A. Yeah.

Q. Okay. What additional steps?

A. Fracture analysis. Typically a bedrock well, and this is literally almost 15 years ago, costs 100 grand. So $150,000 would be one well. So no, it would not be sufficient to characterize bedrock. If you were going to have some kind of a monitoring network you would want to install the wells in the fractures. And again, that would require drilling where you could see where the fractures are, or doing some kind of down hole geophysics. So, it would cost more than that.

Q. So you are referring to the second sentence right now when you refer to the 150,000?

A. Yeah, I'm saying the second sentence suggests that the first sentence does not actually include everything; if that makes sense.

Q. It does not? Can you clarify what you mean?

A. So, $150,000 does not cover more than one well. And would not necessarily characterize a bedrock network if it's needed for Newton. So, I feel like the data evaluation and the bedrock characterization that would occur with drilling in the bedrock and well installation would not capture the fracture network.

Q. Okay. So, you're saying that the scope of --

A. At first glance, that was what came to me.

Q. I think you just said something along the lines of, if it's needed for Newton. What did you mean by that?

A. If, and again I did not do the initial operating permit review, and I'm not -- have not done that. So, I'm not familiar with whether or not they would need a network, a monitoring network for the bedrock. So, I'm saying that is not sufficient for the bedrock network.

Q. So, it may require drilling multiple wells?

A. Potentially.

Q. You are saying, and conducting ground water sampling of those multiple wells?

A. But I can't really say that right now.

Q. You can't say that right now. But it would require at least more than one?

A. I'm not sure. It suggests that -- yeah.

Q. It would require at least one though?

A. Yes.

Q. Okay. And going back to that second sentence, it reads assuming a driller is readily available, which is not always the case, this process would take approximately 20 to 30 weeks. Do you agree with that statement if we were talking about, say, one well?

A. Potentially, yes.

Q. Okay. And if we were talking about more wells than one, would you agree with that statement?

A. No.

Q. Okay. And do you believe it would require more time?

A. Yeah.

Q. Okay. And going back to confirm, you would also agree that the costs would probably be greater than the $150,000 represented in this document?

A. Yes, that's an extremely low number.

Q. Okay. All right. I'm going to hand you a document that's been marked as exhibit 9. This is an excerpt of record document number ten, which is the operating permit application that was submitted for the Newton PAP.

A. What document is Attachment C a part of?
Q. The operating permit itself.
A. Okay.
Q. So this is Attachment C of the operating permit. I'd like to refer you to the first page of Attachment C.
A. Okay.
Q. The first sentence reads, in accordance with 35 I.A.C. 845.230(d)(2)(C). Do you see that language?
A. Where?
Q. I'm sorry?
A. Am I supposed to be on 622?
Q. Yes. The page with 622 at the top.
A. All right. Okay.
Q. Do you see that language at the top that says, in accordance with 35 I.A.C. 845.230(d)(2)(C) IPGC is submitting available/existing analyses of the chemical constituents of all streams, chemical additives and sorbent materials entering or contained in the CCR surface impoundment on the Ash Pond.
A. Yes, I see that it says that.
Q. Can you turn to the next page, which has

a title that says Appendix A?

A. Okay.

Q. Do you agree that Appendix A provides information regarding the chemical constituents contained in the Newton PAP?

A. So, it has -- this is 845 and 620 constituents, first of all. And it is liquids or surface free liquids concentrations, and not totals.

Q. What do you mean by not totals?

A. Not total solids, sorry.

Q. Okay. But this includes for pollutants, total and dissolved results, right? Total for some, and dissolved for others? In the pollutant list?

A. Yes.

Q. Okay. And the third column says surface free liquids average concentration. Do you see that?

A. Yeah.

Q. What do you understand that to be referring to?

A. I have no idea what that means.

Q. Okay. And going to the next column, it

says subsurface free liquids average concentration. Do you see that?

A. Yeah.

Q. Do you understand what that means?

A. I don't know what it refers to, no.

Q. Okay. Did you review this document in connection, or rather did you review this Appendix A of Attachment C of the initial operating permit application as part of your review of the Newton PAP ASD submittal?

A. We did take a look at it. However, we need the actual data laboratory reports for the constituents that were collected for it to be considered. But it was still not total solids as agreed upon with management approval. So we were unable to accept it as source characterization.

Q. Okay. But you do agree that this provides some information about the chemical constituents contained in the Ash Pond?

A. I agree that it provides information about chemical constituents of the water in the Ash Pond.

Q. Moving on to Appendix B. All right. Do you agree the first table of Appendix B provides a

list of chemical additives that are located in the Newton PAP?

A. I agree that that is what is presented.

Q. Do you agree that the second table in Appendix B presents a list of waste streams that are in the Newton PAP?

A. I agree that that's what is presented.

Q. I'm going to refer you to another document that's been marked as exhibit 10.

This is another excerpt from record document number 10, the operating permit application. This is Attachment H to the operating permit application, and it is excerpts from Attachment H. And the cover pages are included in the exhibit for your reference.

A. Okay.

Q. Are you familiar with this document?

A. No, I have not seen this one.

Q. Okay. I'd like to refer you to the page with the record Bates number 696 at the top. Do you see that?

A. Okay.

Q. All right. So, do you see that this is the cover page of the hydrogeologic

characterization report for the Newton PAP?
A. Yes.
Q. Going to the very last page of this exhibit, table 2-2?
A. Yes.
Q. To confirm, you haven't seen this table before?
A. I don't believe so.
Q. Looking at this table now then, do you agree that it reflects solid sampling conducted of the Newton PAP?
A. I would agree that it potentially does, but it doesn't have laboratory reports or sample collection in accordance with 845.640. So, that would be a comment that we would have provided or will provide on the initial operating permit that this would be submitted with.
Q. Assuming that there are -- sorry; you just said the laboratory reports and what else?
A. The field collection documentation.
Q. Okay. So, assuming there was laboratory results and field collection data to back this information up, would you agree that this presents solid sampling conducted of the Newton PAP?

A. Yes.
Q. I'm going to provide you with a document that has been marked as exhibit 15.
Does the agency consider -- well, to go back for a moment. The agency considers documents outside of those just provided by Illinois Power in connection with the Newton ASD submittal, correct?
A. To an extent, yes.
Q. So, for example, you looked at EPA guidance?
A. Yes.
Q. Okay. You looked at some maybe academic references? Is that a fair characterization?
A. Yeah, possibly.
Q. How did you determine what other documents to review and consider?
A. So, I basically had the conversation with Heather Mullenax and asked her for the specifics that go into source characterization.
So, I asked her if there was any source characterization. And then we went through like what was missing. And so these pieces that are in the letter are not actually in the submittal. And

so we just, yeah, we went through that process of just asking those questions.

Q. So, referring to this document that's in front of you right now; have you ever seen this document before?

A. Yes.

Q. Okay. What is it?

A. It's 40 CFR part 257. The USEPA CCR rule, or at least the preamble, it looks like. I'm not sure. Or the proposed rules. I'm not really sure.

Q. Okay.

A. How you, like, interpret all of that. But, yes, it goes -- this seems to go through 107, 257, 107, I don't know.

Q. So do you agree it's an EPA rule making?

A. Yes.

Q. Or it's a proposed rule from the United States Environmental Protection Agency, agreed?

A. Yes.

Q. You agree it's authored by EPA?

A. Yes.

Q. Would you have this document in your possession when you were reviewing the Newton ASD

submittal?

A. Do you mean did I look at this specifically during my review?

Q. Could you have looked at it?

A. I could have, yes.

Q. Did you consider this document in connection with the Newton ASD submittal?

A. Indirectly, yes. Directly, no.

Q. Okay. Can you go to page 11588 of this document.

A. 115 what?

Q. 88. It's like a few pages in.

A. Okay.

Q. Do you see highlighted language in the third column there?

A. Yes.

Q. Okay. I'm going to read the first sentence of the highlighted language: Quote, "out of all the coal ash constituents modeled by EPA, boron has the fastest travel time, meaning boron is likely to reach potential receptors before other constituents." End quote.

Do you agree with that statement?

A. Yes.

Q. I'm going to read the second sentence that's highlighted there. Quote, "therefore, boron is expected to be one of the earliest constituents detected if releases to groundwater are occurring." The sentence then continues, "consequently, EPA reasoned that retaining boron on Appendix III was more appropriate as it would function as a signal constituent that would ensure that assessment monitoring was quickly triggered in response to any release."

Did I read that correctly?

A. Yes.

Q. Do you agree that boron is expected to be one of the earliest constituents detected if releases to groundwater are occurring?

A. Yes.

Q. Do you agree that boron can serve as a, or that boron would function as a signal constituent?

A. Yes, it could.

Q. Okay. And what do you understand the term signal constituent to mean as it's used here?

A. Basically, it's one of the first to appear, which is why it's Appendix III, and in the

detection monitoring versus assessment monitoring for this part.

Q. Were there exceedances to your recollection at Newton, at the Newton PAP other than the chloride exceedance that's the subject of this ASD?

A. I don't know. We'd have to look at that. I think there was ones that you've submitted in there, wasn't there?

Q. Let's look at Exhibit 2, which is the ASD submittal.

And if you could just turn to the page that has R0001611 at the top.

A. Okay.

Q. All right. And then going maybe two-thirds of the way down the page. Do you see the paragraph starting, "the most recent quarterly sampling event"?

A. Yes.

Q. Okay. The last sentence of that paragraph reads, "the statistical determination identified the following GWPS exceedances at compliance groundwater monitoring wells." Do you see that language?

A. Yes.
Q. Okay. And so does that then list several wells at which there were groundwater protection standard exceedances?
A. Yes.
Q. Okay. So, do you see the listing for chloride in APW15?
A. Yes.
Q. And are there other listings on there?
A. Other listings of what?
Q. Other wells where there were exceedances of groundwater protection standards?
A. For chloride or for others?
Q. For anything?
A. Yes.
Q. Okay. So, do you see a listing here for lithium at well APW02?
A. Yes.
Q. And then do you see sulfate exceedances listed for four different wells?
A. Yes.
Q. And then do you see TDS, or total dissolved solids, listed as exceedances in three other wells?

A. Yes.
Q. Okay. And then I would like to point your direction to the last sentence on that page, which says lithium, sulfate and TDS exceedances will be addressed in accordance with 35 I.A.C. 845.660.
A. Okay.
Q. Do you see that sentence?
A. Yes.
Q. What do you understand that to mean?
A. That means that only chloride is being addressed here.
Q. Okay. And what does that mean for the other exceedances?
A. That they're going to assessment of corrective measures.
Q. Do you have any understanding of what boron concentrations were in the wells that are undergoing an assessment of corrective measures?
A. No.
Q. Do you have an understanding of what sulfate concentrations were in the wells that are undergoing --
A. No.

Q. -- an assessment of corrective measures?
A. No.
Q. I'm going to direct your attention to another document, which has been marked as exhibit 16.
Are you familiar with this document?
A. I am familiar with the part 257, not 261.
Q. Okay. Do you agree that this is a final rule making related to part 257?
A. It seems to be.
Q. Okay. Have you reviewed this document before?
A. I have reviewed part 257. I, again, am not familiar with 261.
Q. Okay. Would you have reviewed the portions of this document related to part 257?
A. To some extent, but not in total.
Q. Okay. Do you agree this document is authored by EPA?
A. Yes.
Q. And when I say EPA, I mean the United States Environmental Protection Agency?
A. Yes.

Q. Is this a document that IEPA would have had access to when it was reviewing the Newton ASD?
A. Yes.
Q. Did you consider this document in connection with the Newton ASD?
A. Indirectly, yes. Directly, no.
Q. Indirectly how so?
A. Indirectly, the 845 is written to be as protective as or more protective than 257. So --
Q. Is part 845 meant to address similar risks as 257 is meant to address?
A. To my understanding, yes.
Q. I'd like to refer you to page 21441 of this document. And it's a bit of a ways through the document. All right. In the third column at the very top of the third column do you see a section starting, EPA response?
A. Yeah.
Q. Okay. The first sentence there reads, "the use of pore water data is still considered the most appropriate approach to estimate constituent fluxes to groundwater for CCR surface impoundments." Did I read that correctly?

A. Yes.
Q. Do you agree with that statement?
A. Yes.
Q. The second sentence reads, "this is because pore water better represents the leachate seeping from the bottom of the impoundment than impoundment water samples." Do you see that sentence?
A. Yes.
Q. Did I read it correctly?
A. Yes.
Q. Do you agree with that statement?
A. Yes.
Q. Okay. Are you aware of any EPA or other documents that state that LEAF testing or other leach tests are better than measurements taken in the field?
A. I am not familiar with LEAF testing enough to make a statement on that.
Q. I'm going to show you a document that's been marked as exhibit 17.
Are you familiar with this document?
A. Yes.
Q. What is it?

A. It's the Human and Ecological Risk Assessment of Coal Combustion Residuals From December 2014 done by the USEPA.
Q. Have you reviewed this document before?
A. Yes.
Q. In what context?
A. Just in general, how it pertains to CCR and --
Q. Do you agree that it's authored by the United States Environmental Protection Agency?
A. Yes.
Q. Is this a document that IEPA had in its possession when reviewing the Newton ASD?
A. Yes.
Q. Did you consider this document in connection with the Newton ASD?
A. Indirectly, yes.
Q. And indirectly how so?
A. In that I have reviewed it. I agree with what it says in respect to -- well, in total. But also, like, it doesn't contradict the mass transport equation and does still require source characterization is what we were asking for. So, it doesn't contradict what our request is. So,

yes.

Q. Okay. Can I refer your attention to page 4-5 of this document?

A. Okay.

Q. Do you see the section that's listed as 4.2.1?

A. Yes.

Q. All right. I'm going to read the first sentence there: It says, "similar to the screening analysis described in Section 3, EPA relied on pore water concentrations to characterize leaching from impoundments." Do you see that sentence?

A. Yes.

Q. Do you agree I read it correctly?

A. Yes.

Q. Do you agree with that statement?

A. Yes.

Q. Do you agree that under the risk assessment presented in this document, EPA relied upon pore water concentrations to characterize leaching from CCR surface impoundments?

A. Yes.

Q. The second sentence reads: "These

concentrations are collected from the interstitial water between the waste particles in surface impoundments as it occurs in the field, and best reflect leachate as it is released into underlying soils." Did I read that sentence correctly?

A. Yes.

Q. Do you agree with that statement?

A. Yes.

Q. Going to direct your attention to page 5-17 of this document.

All right. Let's turn it around here. Can you read the first sentence there under Section 5.1-3. Do you see the section titled, representativeness?

A. Yes.

Q. Could you read the first sentence there:

A. "Pore water data were determined to be the most representative data available for impoundments because these data are field-measured concentrations of leachate present at the bottom of these WMUs."

Q. First off, are you familiar with the acronym WMUs?

A. No.

Q. Okay. Do you agree that it might be referring to waste management units?
A. It's possible, yeah.
Q. All right. Assuming that WMUs is referring to waste management units, do you agree with the statement in the sentence you just read?
A. Yes.
Q. All right. I'm going to go back to Exhibit 2, which is the original ASD submittal.
Actually, can we take a short break?
(The time is 4:52 p.m.)
(The time is 4:58 p.m.)
CONTINUED EXAMINATION BY
MS. JOSHI:
Q. All right. So, I'd like to refer you back to what's been marked as Exhibit 2. And I'd like to refer you to the third page of the document, which has the record Bates number 1608 at the top.
All right. Do you agree that this page includes a certification from a professional engineer?
A. Yes.
Q. Do you agree that this page includes a

certification from a professional geologist?
A. Yes.
Q. If you could move to page three of the actual document, meaning the actual substance of the document. So, page title Introduction. Do you see that? It's R1611?
A. Okay.
Q. The second to last paragraph says, "pursuant to 35 I.A.C. 845.650(e) the lines of evidence (LOEs) presented in Section 3 demonstrate that sources other than the PAP are the cause of the chloride GWPS exceedance listed above." Do you see that sentence?
A. Yes.
Q. What do you understand the terms, lines of evidence analysis to mean?
A. It means this is the lines of evidence being presented, the data that's being presented; and analysis.
Q. Are you familiar with the lines of evidence analysis generally?
A. Not really, actually.
Q. Okay. Have you ever performed a lines of evidence analysis?

A. No.
Q. Have you reviewed the lines of evidence provided in this document?
A. Briefly in more of a big picture overview of whether or not there was a -- whether or not the data inputs into the mass transport equation were there or not.
Q. Okay. Like to refer you to the page that's numbered 1615 at the top right-hand corner.
And Section 3.1, do you agree that Section 3.1 sets forth the first line of evidence presented in this document?
A. I'm sorry, come again?
Q. Sure. You've reviewed this document, yes?
A. In a brief overview.
Q. Okay. Did you take a look at section 3.1 as part of your review?
A. I believe that, it's been several months, that I more focused on whether or not the source characterization of the total solid was included in this document. And therefore the mass transport equation was being implemented adequately to be able to start these lines of

evidence.

Q. What do you mean by, to be able to start these lines of evidence?

A. Going back to the law of mass conservation, the mass transport equation is basically that you have X amount of mass, and then on the other end of the equation is the same mass. And so if you don't have the one side, you can't say what's on the other side of that equation.

And so it's kind of what I've been saying the whole time. So we're back to, it's -- we have to have the total amount potential that's going into this, or could be leachable to be able to say what's actually potential and what's not.

Q. Potential, correct? Is the term you just used?

A. Yeah.

Q. So you did not review the first line of evidence in any detail?

A. Not in any detail, because again, it had to comply with 845.650(e).

Q. And in what way does the first line of evidence not comply with 845.650(e)?

A. Go back to 650(e). Again, the ASD task

is that you have to show that the CCR surface impoundment did not contribute to the contamination. And if you do not have that adequately characterized, thus the source characterization, mass transport equation, on the one side, then you can't say what's on the other side of that equation.

Q. Does 845.650(e) specifically refer to a source characterization?

A. In my technical interpretation, yes.

Q. Where?

A. Again, in the first sentence where it says, "and the CCR surface impoundment did not contribute to the contamination."

Q. Okay.

A. If you don't have the data, then you can't make the assumption.

Q. Okay. But again, what data are you talking about there?

A. The total solids data.

Q. And does 845.650(e) refer to total solid sampling anywhere?

A. It doesn't have to. The technical, the law of mass conservation and the mass transport

equation are the technical bases of making those statements. And without that data, you can't make this jump.

Q. Is that your opinion?

A. No, it's the law of conservation of mass. But --

Q. Is the law of conservation of mass a theoretical principle?

A. Yes.

Q. So it's a scientific principle?

A. Yes.

Q. Okay. So, you are saying that it should apply in this circumstance, correct?

A. Yes; and management agree.

Q. And by management, to whom are you referring?

A. Mike Summers.

Q. Anyone else?

A. No, he's the one that signed off on this.

Q. Okay. So, let's look at 845.650(e), and I actually have a copy we can enter into the record as an exhibit. We are on exhibit 23.

(Whereupon, Deposition Exhibit No. 23

was marked for identification.)

Q. Okay. So first of all, do you agree that this, looking at 845.650(e), all right? You agree that this section refers to alternative source demonstration?

A. Yes.

Q. Do you agree that this section requires an ASD submittal within 60 days after the detection of an exceedance of a groundwater protection standard?

A. Yes.

Q. Do you agree that it requires a submission of a demonstration to the agency?

A. Yes.

Q. And do you agree that that demonstration has to -- that that demonstration is that a source other than the CCR surface impoundment caused the contamination, and the CCR surface impoundment did not contribute to the contamination?

A. Yes.

Q. Okay. I want to -- well, I want to refer you to the last sentence of this Section e.

A. Okay.

Q. It says, "either type of ASD must

include a report that contains the factual or evidentiary basis for any conclusions and a certification of accuracy by a qualified professional engineer." Do you see that?

A. Yes.

Q. Okay. Did Illinois Power provide a report for the Newton PAP ASD submittal?

A. They provided a report, but they did not provide the data required under SW846 Chapter 1 to make regulatory decision, which is why the nonconcurrence letter said the source characterization was not complete.

Q. Okay. Going back to 845.650(e), does it make any reference to SW846?

A. No, SW846 is incorporated by reference, and it applies to all of 845.

Q. You believe that SW846 applies to all of 845?

A. In that all of our regulatory decisions have to be based on data, yes.

Q. Okay. Are there specific sections of 845 that specifically mention SW846?

A. The incorporation is by reference.

Q. So, for example, can you turn to 845.640

in your regs there?
A. Okay.
Q. And the very last section of 845.640?
A. Okay.
Q. Is that subsection, what is that j?
A. Yeah.
Q. Okay. Does that refer to SW846?
A. Yeah.
Q. Okay. Does 845.650 refer to SW846 anywhere?
A. So, j refers to 845 -- SW846 test methods, not to Chapter One.
Q. Okay.
A. 650 -- hold on. 650 does not refer to it directly, but Chapter One applies to across-the-board regulatory decisions.
Q. And what is your basis for saying that?
A. Because S40 -- S846 Chapter One in the first, like, introduction it says that all regulatory decisions must be supported by environmental data.
Q. Okay. Is SW846 law in Illinois?
A. No, but you can't just make decisions on opinions.

Q. Okay. Well, let's go back to this last sentence of Subsection e. So, you agree that a report was submitted?

A. Correct.

Q. It may not have included the information you wanted to see, but you agree that a report was submitted?

A. Correct.

Q. Do you agree that that report contained facts?

A. I agree that that report contained what was stated to be fact. However, the laboratory result, like laboratory reports and the field documentation substantiating that it is fact, were not provided.

Q. Okay. Did you ask for that data during your discussions?

A. I believe so, but I am not entirely sure.

Q. Okay. Do you agree that the report includes an evidentiary basis for the conclusions in the report?

A. I feel that if you do not have the substantial, like, evidence that this is in fact

data that is fact, then it undermines the whole entire document.

So, I don't agree that it would be evidence if it's not substantiated as fact. So, if you don't have the facts, then you don't have the evidence. One can not be by itself.

Q. Are there any facts presented in Exhibit 2 that you can point to, and tell me that you disagree with?

A. I did not review it enough to give an opinion on that specifically agree or disagree on the geochemistry; because again, I am not the geochemist. I was just agreeing based on the mass transport equation and the law of conservation of mass.

Q. So because there was no -- they didn't do those two things, you disagree with the ASD?

A. Correct.

Q. And you did not review any of these lines of evidence in detail?

A. Not in detail. I am not a geochemist.

Q. And sitting here today, you couldn't tell me whether you disagree with any of the facts in this ASD?

A. Well, if in fact they are substantiated as facts by the laboratory reports documentation.
Q. Sitting here today, do you disagree with any of the information presented in the ASD?
A. I can't say whether or not I do.
Q. Can we break really quick? I want to check on time.
(The time is 5:13 p.m.)
(The time is 5:13 p.m.)
CONTINUED EXAMINATION BY
MS. JOSHI:
Q. I'd like to refer you to page ten of Exhibit 2, the top is R0001618.
Did you review this section of the ASD submittal?
A. No, I did not.
Q. Did you review any of the references listed in the reference section of this document, which is on this page and also the following page, just so you know?
A. No.
Q. Why did you not review any of these documents?
A. Again, I was leading the technical

review and asking the questions of Heather Mullenax.

Q. Are you familiar with whether anyone from IEPA reviewed any of the reference documents listed here in connection with the Newton ASD?

A. I don't know that.

Q. All right. I'm going to refer you to one last document here, exhibit number -- it's been marked as Exhibit No. 14.

Are you familiar with this document?

A. I am not necessarily. Yeah, I'm not familiar.

Q. Did you review this document in connection with the Newton PAP ASD?

A. No.

Q. I'm going to refer you to R001941 of the document.

A. Okay.

Q. Do you see that section entitled, references?

A. Yes.

Q. Again, can you take a look at the references listed there, and let me know whether you reviewed any of the documents listed there in

connection with the Newton ASD submittal?

A. Not in particular.

Q. What do you mean by, not in particular?

A. I didn't review this page. But yes, I mean, I think I reviewed a few of these documents potentially for other purposes. But --

Q. Okay. Which of those documents would you have reviewed for other purposes?

A. Inasmuch as I've already said the initial operating permit, if I have done any review of that specific part of the document that we were looking at earlier that was part of the initial operating permit. And, I mean, the USEPA monitoring natural attenuation of Superfunds -- I may have reviewed that at a past time, but not in the course of this. So, otherwise none of this looks familiar.

Q. Okay.

A. Well, 846, yeah, obviously. But, yeah.

Q. And then turning back a couple pages from this reference section to page 1938.

Just want to confirm whether, did you look at this particular letter and the information contained within it as part of your review of the

Newton ASD?

A. I do not believe that I looked at this.

Q. Okay. Can we pause?

(The time is 5:19 p.m.)

(The time is 5:23 p.m.)

MS. JOSHI: We're all set. No more questions. Thank you.

THE WITNESS: Thank you.

MS. MEADE: No questions from us. Reserve signature.

(The time is 5:24 p.m.)

STATE OF ILLINOIS)
) SS
COUNTY OF CHAMPAIGN)

I, DEANN K. PARKINSON, a Notary Public in and for the County of Champaign State of Illinois, do hereby certify that LAUREN HUNT, the deponent herein, was by me first duly sworn to tell the truth, the whole truth and nothing but the truth in the aforementioned cause of action.

That the foregoing deposition was taken on May 28, 2024.

That said deposition was taken down in stenographic notes and afterwards reduced to typewriting under my instruction and said transcription is a true record of the testimony given; and that it was agreed by and between the witness and attorneys that said signature on said deposition would be not waived.

I do hereby certify that I am a disinterested person in this cause of action; that I am not a relative of any party or any attorney of record in this cause, or an attorney for any party herein, or otherwise interested in the event of this action, and am not in the employ of the attorneys for either party.

In witness whereof, I have hereunto set my hand and affixed my notarial seal June 2, 2024.

_____
DEANN K. PARKINSON, CSR
NOTARY PUBLIC

DEPOSITION ERRATA SHEET

Our Assignment No. J11288877
Case Caption: ILLINOIS POWER GENERATING COMPANY
vs. ILLINOIS ENVIRONMENTAL PROTECTION AGENCY

DECLARATION UNDER PENALTY OF PERJURY

I declare under penalty of perjury that I have read the entire transcript of my Deposition taken in the captioned matter or the same has been read to me, and the same is true and accurate, save and except for changes and/or corrections, if any, as indicated by me on the DEPOSITION ERRATA SHEET hereof, with the understanding that I offer these changes as if still under oath.

Signed on the _____ day of _____, 2024.

_____

LAUREN HUNT

DEPOSITION ERRATA SHEET

Page No._____Line No._____Change to:_____

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LAUREN HUNT

DEPOSITION ERRATA SHEET

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LAUREN HUNT

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Signed on the 10th day of July, 2024.

Lauren Hunt
_____

LAUREN HUNT

DEPOSITION ERRATA SHEET

Page No. 9 Line No. 20-21 Change to: Environmental Protection Geologist III

Reason for change: Title should be capitalized and Roman numerals for the number.

Page No. 11 Line No. 14-15 Change to: Environmental Protection Geologist I; Environmental Protection Geologist II

Reason for change: Title should be capitalized and roman numerals

Page No. 11 Line No. 18 Change to: Environmental Protection Geologist I

Reason for change: Title should be capitalized and Roman numerals

Page No. 11 Line No. 19-20 Change to: Environmental Protection Geologist II

Reason for change: Title should be capitalized and Roman numerals

Page No. 15 Line No. 6 Change to: determining

Reason for change: setting is not the correct word.

Page No. 15 Line No. 7 Change to: Troy Grove

Reason for change: Torrey is not the correct spelling.

Page No. 17 Line No. 9 Change to: hexavalent chromium

Reason for change: changed from abbreviated format.

SIGNATURE: Lauren Hunt DATE: 7/10/24

LAUREN HUNT

DEPOSITION ERRATA SHEET

Page No. 21 Line No. 14 Change to: RCRA

Reason for change: Acronym for Resource Conservation and Recovery Act.

Page No. 23 Line No. 18 Change to: FUDS

Reason for change: Acronym for Formerly Used Defense Site(s)

Page No. 24 Line No. 3 Change to: FUDS

Reason for change: Acronym for Formerly Used Defense Site(s)

Page No. 27 Line No. 6 Change to: FUDS

Reason for change: Acronym for Formerly Used Defense Site(s)

Page No. 27 Line No. 9 Change to: FUDS

Reason for change: Acronym for Formerly Used Defense Site(s)

Page No. 28 Line No. 19 Change to: FUDS

Reason for change: Acronym for Formerly Used Defense Site(s)

Page No. 29 Line No. 13 Change to: FUDS

Reason for change: Acronym for Formerly Used Defense Site(s)

SIGNATURE: Lauren Hunt DATE: 7/10/24

LAUREN HUNT

DEPOSITION ERRATA SHEET

Page No. 40 Line No. 1 Change to: Fetter

Reason for change: Spelling correction

Page No. 43 Line No. 14 Change to: Fetter

Reason for change: Spelling correction

Page No. 43 Line No. 15 Change to: Fetter

Reason for change: Spelling correction

Page No. 82 Line No. 17 Change to: gauges or gages

Reason for change: wrong word usage, spelling above is correct either way.

Page No. 85 Line No. 17 Change to: aquitard

Reason for change: spelling correction

Page No. 86 Line No. 2 Change to: aquitard

Reason for change: spelling correction

Page No. Line No. Change to:

Reason for change:

SIGNATURE: Lauren Hunt DATE: 7/10/24

LAUREN HUNT

Document 4

Deposition of Heather Mullenax, May 28. 2024.

BEFORE THE
ILLINOIS POLLUTION CONTROL BOARD

IN THE MATTER OF:

ILLINOIS POWER GENERATING COMPANY,

Petitioner

-vs- No. PCB 2024-043

ILLINOIS ENVIRONMENTAL PROTECTION AGENCY,

Respondent.

DEPOSITION OF HEATHER MULLENAX
May 28, 2024
9:00 AM
133 S. Fourth Street
Springfield, IL 62706

Reported In Person By:

Deann K. Parkinson: CSR 84-002089

APPEARANCES IN PERSON:

FOR THE PETITIONER:

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* * * *

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(Federal Register document page 21302)

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(Human and Ecological Risk Assessment of Coal Combustion Residuals article)

DISCOVERY DEPOSITION

The deposition of HEATHER MULLENAX taken on behalf of the Petitioner at 133 South 4th Springfield, IL on May 28th, 2024, before Deann K. Parkinson, Certified Shorthand Reporter of the State of Illinois. Deposition taken pursuant to the discovery provisions of the Illinois Code of Civil Procedure and the Rules of the Supreme Court promulgated pursuant thereto.

(The time is 8:57 a.m.)

HEATHER MULLENAX,

the deponent herein, called as a witness, after having been first duly sworn, testified as follows:

EXAMINATION BY

MS. JOSHI:

Q. Hello, good morning. My name is Bina Joshi from Arentfox Schiff LLP representing Illinois Power Generating Company in this matter. Ms. Mullenax, would you please state your name and business address for the record?

A. My name is Heather Mullenax. I work over at the Illinois EPA, which is on North Grand Avenue in the Bureau of Water.

Q. So Ms. Mullenax, you're giving testimony under oath today. I'm going to start by just going over a few sort of ground rules and like basis setting for the deposition before we kind of get into questions.

So, first of all, you are giving testimony under oath today as you know, by the fact that you were just sworn in by Ann here.

Is there anything that might impact your

ability to answer truthfully today?
A. No, ma'am.
Q. Are you aware of anything that would preclude your ability to understand my questions this morning?
A. No, ma'am.
Q. Are you aware of anything that might affect your memory?
A. No, ma'am.
Q. Could you please, you probably already know this, but give verbal answers to my questions, since we'll have a transcript, and they can't pick up head nods and things like that.
A. Yes, ma'am.
Q. Please, let me finish my questions before you answer a question. Let me know if you don't understand a question that I ask this morning, and I will do my best to try to rephrase it or to clarify.
Let me know or let us know if you need a break at any time. If there is a question pending, you will need to complete the response before we take the break. But, if you just need a minute, need to use the restroom, whatever, please

just speak up and we can take a break.

Do you understand these instructions?

A. Yes, I do.

Q. And I'll also start by going over some shorthand for this morning. So, I may refer to Illinois Power Generating Company this morning as Illinois Power or IPGC. I may refer to the Newton Power Plant as Newton. I may refer to the Newton Primary Ash Pond that was the subject of the alternative source demonstration at issue in this appeal as the PAP, or the Newton PAP.

When I use the term ASD, I'm referring to, again, Newton Alternative Source Demonstration for chloride that's the subject of this proceeding.

When I refer to IEPA, or the agency, I'm referring to Illinois EPA. And when I refer to part A45, I'm referring to the regulations located at Title 35 Illinois Administrative Code part 845. Does that all make sense to you?

A. Yes.

Q. I'm sure those are acronyms that you are very familiar with.

A. I understand.

Q. All right. So I'll start by asking you just a few questions about your background. Where did you get your bachelor's degree?

A. I received my bachelor's of arts in earth science at the Western Kentucky University. It was in earth science. And a minor in environmental science and sustainability.

Q. Do you have a Master's degree?

A. I do.

Q. And in what subject is your Master's degree?

A. My Master's of science is in earth science from the University of Memphis.

Q. Do you have any other degrees of a collegiate level or higher?

A. No, I do not.

Q. And then I'd like to talk briefly about your employment history. So, what, you said you currently work in the Bureau of Water at IEPA?

A. Yes.

Q. What is your position in the Bureau of Water?

A. My current position is the environmental protection geologist two.

Q. And what are your responsibilities just generally in your current role?
A. My current responsibilities are to overall look at coal combustion residuals, otherwise known as CCR. I look over bacteria results of other sites. And primarily look at chemistry of exceedances with other water qualities as sites.
Q. What types of other water quality sites?
A. They are usually spray irrigation sites, or usually like waste management sites. They submit water quality info to the agency to test for exceedances.
Q. And sort of in what way do you review those submittals? Just to make sure they're accurate?
A. Yes. To make sure they're accurate with the regulation of whatever class they are under; whether it's 620 class one, class two, or 845.
Q. Did you hold any positions at IEPA prior to your current position?
A. No, I did not.
Q. Did you hold any employment prior to starting at IEPA?

A. I did have prior employment.
Q. And what was that?
A. I was a substitute teacher back in Paducah, Kentucky.
Q. Did you have any other employment prior to that?
A. No, I did not.
Q. Are you licensed as a professional engineer?
A. No.
Q. Are you licensed as a professional geologist?
A. No.
Q. Are you a hydrogeologist?
A. I'm in earth sciences.
Q. Okay. Have you yourself ever performed total solid sampling of CCR surface impoundment?
A. No.
Q. Have you ever coordinated the schedule for performing total solid sampling for a CCR surface impoundment?
A. No.
Q. Have you yourself ever performed a characterization of bedrock?

A. No.
Q. Have you ever coordinated a schedule to conduct a bedrock characterization?
A. No.
Q. Have you ever prepared an alternative source demonstration?
A. No.
Q. Have you ever assisted in preparing an alternative source demonstration?
A. No.
Q. When did you first review an alternative source demonstration or an ASD?
A. The Newton Primary Ash Pond was the first one.
Q. Have you ever done a forensic analysis to identify the source of an exceedance in any context?
A. Yes.
Q. Okay. And when so?
A. It was back in 2022 when I was a research assistant with the University of Memphis. I looked at the source characterization or the -- for exceedances in a well field.
Q. Okay. And what kind of well field? Can

you give me a little more description of what the circumstance was of the characterization?

A. Yes. It was a water treatment plant looking at modern water leakage.

Q. And what was the scope of the source characterization that you did?

A. Modern water leakage.

Q. Can you explain to me, a non-geologist, what that means?

A. It is to determine whether new water is coming in to the well field, and therefore contaminating or causing exceedances in the well field.

Q. Okay. And what methods did you use for this characterization?

A. We use the EPA low flow sampling methodology. And we use radioactive isotopes. So, I'm not exactly sure of the EPA number for that sampling.

Q. Okay. And what was the scope of sampling that was conducted for this investigation?

A. To determine if there was modern water leakage in the well field using cation and anion

sampling.

Q. So, when you say -- sorry, can you repeat that?

A. Cation, C-A-T-I-O-N, and anion, A-N-I-O-N.

Q. And by scope, I mean how many wells were installed for the purposes of the sampling, do you recall?

A. I do not recall.

Q. And over how many sampling events occurred for the characterization, do you recall that?

A. I do not recall.

Q. When you were doing this characterization, how did you decide what information to look at?

A. I was asked by my adviser to look at the chemistry of the site. And that is looking at the, what I mentioned before, cation and anion elements. And compared them over a period of time to understand the exceedances.

Q. Compared them to what?

A. Previous historical data.

Q. And where was the historical data from?

A. From the University of Memphis.
Q. Okay. And was it historical data from that same site?
A. Yes.
Q. And you said over a period of time; what was that period of time, do you know?
A. Over a couple of years.
Q. So you were working on this project over a couple of years?
A. I was working on it a total of two years.
Q. So, it sounds like your professor sort of gave you direction on what to look at; how did, I guess how did you guys come to a conclusion on the process that you would use in order to do the comparison of conditions then, versus the historical conditions?
A. We looked at, we came to the conclusion, based on previous other well fields in Memphis, Tennessee, who have also done the same research. And my previous, the well field that I was under, had not gone through that historical comparison.
Q. And did you determine that it was being influenced by other sources?

A. We did not.
Q. And what led to that conclusion?
A. This was due to faulting in the Memphis, Tennessee, area, which did not allow for modern water to enter the well field.
Q. How did you know that faulting was occurring?
A. Based on historical data.
Q. And that historical data was what exactly?
A. It was maps made by USGS and the University of Memphis when they used geographical information systems; GIS.
Q. Moving on, did you do anything to prepare for the deposition today Ms. Mullenax?
A. Besides reviewing the submittal.
Q. Okay. So, by reviewing the submittal, what do you mean by the submittal?
A. The record that was submitted to everyone here.
Q. Okay. So, you reviewed the record prior to coming here today?
A. Yes.
Q. Okay. Did you review the entire record

or were you focused on particular documents in the record?

A. I focused on the alternative source demonstration. My notes that were submitted. And the meetings that were submitted in the -- as invites.

Q. And did you have discussions with anyone prior to your deposition today regarding the deposition?

A. No.

Q. I'm going to hand you a document, which we're going to mark as Exhibit 1.

(Whereupon, Deposition Exhibit No. 1 was marked for identification.)

Q. If you could pass the copy over there. Have you seen this document before?

A. Yes.

Q. If you could turn the page and look at the section where you were asked to bring certain documents to this deposition. I believe that would be page four of the document. Try to keep this double sided.

Did you review these requests for documents before you came here today?

A. Yes.
Q. Do you have any documents to provide in response to that first request for documents?
A. No.
Q. Do you have any documents to provide in response to the second request for documents?
A. No.
Q. Have you provided any correspondence you had internally or externally regarding the Newton ASD as part of the record in this proceeding?
A. Yes.
Q. Have you provided any notes that you made regarding the Newton ASD in the record in this proceeding?
A. Yes.
Q. I'm going to hand you another document here. This is record document number 12. Which is the original ASD submittal.
(Whereupon, Deposition Exhibit No. 2 was marked for identification.)
Q. Which I'm going to mark as Exhibit 2. Are you familiar with this document?
A. Yes.
Q. Okay. I'm going to start with just some

baseline setting for our discussion today. Do you agree that the ASD that's at issue in this proceeding relates to chloride in a well designated as APW15?

A. Yes.

Q. And do you agree that this well was screened in the upper aquifer?

A. Yes.

Q. Do you agree that the upper aquifer where this well was screened is made up of unconsolidated materials, such as sands, silts and clays?

A. Yes.

Q. Ms. Mullenax, have you heard of the term peer review before?

A. Yes.

Q. How do you define that term?

A. I define peer reviewed as journals or articles that are reviewed by multiple people or multiple organizations, and are backed by scientific records before.

Q. And where does your understanding of that definition come from?

A. From what I learned in my degree.

Q. Would you consider documents published by EPA to be peer reviewed?
A. Yes.
Q. Do you agree that a document may be peer reviewed even if it's not published in an academic journal?
A. I would say it would depend if it's clearly marked or clearly stated being peer reviewed.
Q. Can you always tell from the face of a document whether it's been peer reviewed?
A. No.
Q. So, what did you mean by your last statement about whether it was clearly marked as peer reviewed?
A. What I mean is, usually in a summary or a conclusion I have seen where they have stated, it has been peer reviewed by X number of people, or by whoever the, or by multiple out source.
Q. Is that statement always in a peer-reviewed article?
A. No.
Q. All right. I'm going to move on and show you another document. This is marked as

record document number three, and I'm going to mark it as Exhibit 3 for your deposition here.

(Whereupon, Deposition Exhibit No. 3 was marked for identification.)

Q. I'll give you a moment to take a look at the document. Are you familiar with this document?

A. Yes.

Q. All right. What is it?

A. This is my textbook called Geochemistry, the Principles of Geochemistry.

Q. When you say my textbook, do you mean that you own this textbook?

A. Yes.

Q. Do you agree this document was submitted with the ASD submittal?

A. Yes.

Q. Or included with the ASD record?

A. Yes.

Q. And do you agree that the pages that are included in the record consist of excerpts from a larger document?

A. Yes.

Q. I'd like to direct your attention to

page 366 of this document. Towards the end. Do you see on the left side of the page down at the bottom there's a section that starts, Cl and Br.

A. Yes.

Q. Do you agree that Cl stands for chlorine there?

A. It stands for chloride.

Q. Oh, chloride?

A. Yes.

Q. Okay. So, and just so we can also base that here, what is the difference between chlorine and chloride?

A. Chlorine is -- all right, let me -- chlorine is what would be considered what chloride is a part of. Chloride is what I would consider a small section of a chemical equation.

Q. So, would you agree chlorine is like an atom, while chloride is like an ion?

A. Yes.

Q. So, I want to read the first sentence of that section there. It says chlorine and bromine both have natural and anthropogenic sources. Do you see that language?

A. Yes.

Q. Okay. Do you agree with that statement?
A. Yes.
Q. And do you agree that the statement is true for both chlorine and chloride?
A. Yes.
Q. I want to direct your attention to some language that starts about halfway through that same paragraph. Do you see the sentence starting, hydrochemical characteristics?
A. Yes.
Q. Okay. I'm going to read that statement as well. Hydrochemical characteristics of both compounds are one, low concentration in most rock forming materials. Two, high solubility of most nonsilicate compounds. Three, virtually no absorption by particles. Four, lack of volatile compounds. And five, generally low bioconcentrations in aqueous systems.

Because of these characteristics, both elements behave as conservative species and they have been widely used as tracers in hydrological systems. Do you see that language?
A. Yes.
Q. Do you agree I read it correctly?

A. Yes.
Q. What do you understand the term, conservative species to mean as used in that statement?
A. They can be used to define a characteristic of a site or an exceedance.
Q. And why can a conservative species be used to help, to do that?
A. They're considered to be nonreactive. They, while other elements would be more reactive in a situation, conservative ones allow things to be easier to define.
Q. So, do you agree that chlorine is a conservative species?
A. Yes.
Q. And do you agree that chloride is also a conservative species?
A. Yes.
Q. Okay. I'm going to move on to another document. This is record document number 24. Which I'm going to mark as exhibit 4.
(Whereupon, Deposition Exhibit No. 4 was marked for identification.)
Q. Ms. Mullenax, are you familiar with this

document?
A. Yes.
Q. And what does it reflect?
A. This is my notes during a meeting.
Q. And notes regarding what?
A. A meeting with the IEPA and Illinois Power.
Q. And what was that meeting regarding?
A. This meeting was regarding the IEPA's decision on what was considered to be missing in the alternative source demonstration. And that we would be nonconcurring. And the response of what they would have to do.
Q. What do you mean by, the response of what they would have to do?
A. It stated either they would appeal, or go through corrective measures.
Q. If you look on these notes, the second to last bullet point there; could you read that for me. The one that starts, "use of"?
A. Use of aerial photos in order to determine pore water.
Q. Okay. Can you explain what you meant by this bullet point?

A. This was an explanation that was given through Illinois Power that they used aerial photos to determine their pore water samples.
Q. And why did you make note of that fact?
A. Because this was something the IEPA would have to discuss further based on what pore water was, and whether we would accept.
Q. Did IEPA discuss further?
A. Yes.
Q. And what did they conclude?
A. The conclusion was based on the IEPA pre water -- or my apologies; the USEPA pore water, and we could not accept the use of pore water.
Q. Can you explain that further? What do you mean by, it was based on the use of USEPA pore water?
A. USEPA had a guidance document that was stating of what pore water was. And because part 845 does not have standards for pore water, we were unsure of the validation with the chemistry.
Q. What do you mean by you were unsure of the validation with the chemistry?
A. Part 845 lines out groundwater standards in part 600. And because pore water is not a part

of that, we would have to -- we did not have a standard to look at.

Q. Again, when you say you did not have a standard to look at, you meant that 845 -- I'm just trying to understand what you are saying. Are you saying that 845 doesn't have a standard for sampling pore water?

A. Yes.

Q. And so then you were looking at USEPA standards for sampling pore water?

A. We used the USEPA guidance document to understand what pore water was.

Q. What guidance document is that?

A. It's a recent document from 2019, I believe. I did not find this document. This was -- I did not find this document.

Q. Is this a document that was provided with the record?

A. Yes.

Q. Okay. I'm going to hand you a document I'm marking as exhibit 5.

(Whereupon, Deposition Exhibit No. 5 was marked for identification.)

Q. Can you tell me if this is the document

to which you are referring to?
A. Yes.
Q. Okay. And do you believe that that document applies to pore water sampling of CCR surface impoundments?
A. That was my understanding.
Q. Okay. And how did you use this document to review the Newton alternative source demonstration?
A. This was our background document of what pore water was because we did not understand how the sampling of pore water does occur.
Q. Okay. And then again, after reviewing this document did you come to any conclusions regarding the Newton -- the pore water sampling that was conducted for the Newton alternative source demonstration?
A. No.
Q. Okay.
MR. HENDERSON: I'm sorry, would it be possible to get a read back of that last question?
(At this point the court reporter read the requested portion of the record.)
BY MS. JOSHI:

Q. What was your -- so, beyond understanding how pore water sampling occurs, did the agency use what has been marked as exhibit 5 for any purposes in reviewing the Newton ASD?

A. Would that be, besides coming to our conclusion to not use pore water overall in alternative source demonstrations?

Q. How did the agency use what's been marked as Exhibit No. 5 to come to the conclusion that pore water sampling could not be used in alternative source demonstrations?

A. It was our understanding that pore water had a specific sampling regimen that we did not see provided in the ASDs. And that because pore water has a specific sampling method, that we would need to see how that was done in the alternative source demonstration.

Q. Did the denial of the alternative source demonstration include the lack of information regarding the pore water sampling regime as a basis for denial?

A. No.

Q. And again, I just want to understand and clarify. Are you saying that the agency could not

accept the pore water sampling as a way of conducting source characterization of the CCR?

A. Yes.

Q. And the reason the agency couldn't do that is because the pore water sampling that was conducted differed from the regime that's in this particular USEPA guidance document?

A. We did not have that provided to us. That's why it was a data gap.

Q. But, we just established that wasn't listed as a data gap, right?

A. Yes.

Q. Okay. So, and what information was it that you did not have, that you would have liked to have seen regarding the pore water sampling?

A. This would be a documentation of the sampling, whether this was laboratory documents or the sampling methodology.

Q. And what kind of information would you have liked to have seen related to the sampling methodology?

A. This is for both the characterization and the groundwater that was provided, just an explanation of how the sampling occurred, and what

steps were provided. Plus, field methods.
Q. Did you review any other resources for how pore water sampling is conducted to inform your decision?
A. We looked at the USEPA LEAF guidance.
Q. LEAF testing is a type of leach testing, do you agree?
A. Yes.
Q. It's not a method of pore water sampling?
A. No.
Q. Sorry. Let me phrase that in a way so it's clear on the record.
Is LEAF testing a method of pore water sampling?
A. No.
Q. All right. I'm going to hand you another document, which is record document number 31. Which we will mark as exhibit 6.
(Whereupon, Deposition Exhibit No. 6 was marked for identification.)
Q. Are you familiar with this document?
A. Yes.
Q. And what is it?

A. My notes on the additional information that was provided during public comment from Illinois Power.
Q. Did you take these notes during the meeting?
A. No.
Q. What did you take these notes based off of?
A. The PDF document that was given as additional information from Illinois Power.
Q. So, this is based on additional information from Illinois Power that was provided during the public comment period?
A. Yes.
Q. And what is your understanding of why Illinois Power provided that information?
A. This was during our meeting from October 31st of the data gaps they did have. And what else could be provided.
Q. Okay. So, do you think -- so, again, I won't ask you to speculate why Illinois Power did something. But was it your understanding that they were providing this information in response to that earlier meeting regarding additional

information the agency wanted to see?
A. Yes.
Q. Okay. On the first line here there's -- well, not the first line. But do you see that first star that's listed on the document? Okay.
Can you read what that first star says?
A. Provided hydraulic conductivities for GW, groundwater, wells.
Q. I think you missed one part there?
A. It's ten to the negative eight.
Q. And what is that, provided hydraulic conductivities ten to the negative eight, intended to mean?
A. It is to the bullet point that is at the very bottom; the ten to the negative eight for the confining unit.
Q. Yes, but what does that ten to the negative eight, I guess, reflect? Or let me take this back. Why did you make note of that?
A. It was our understanding that a confining unit such as bedrock would have this hydraulic conductivity or be around this.
Q. And when you say "this", what are you referring to? The ten to the negative eight?

A. The ten to the negative eight, yes.
Q. The second star here says, no bedrock well logs. Correct?
A. Yes.
Q. What is that referring to?
A. There were no bedrock well logs that went directly into bedrock.
Q. Do you believe that bedrock well logs were needed with the ASD submission?
A. Yes.
Q. Why?
A. Because the alternative source was given as bedrock. And to understand how the bedrock is used in Newton, having the bedrock well log would help us understand if there is a bedrock unit, and how the -- how it reacts to the nearby geology.
Q. Can you tell me what is written on the line that starts, need for explanation?
A. Need for explanation and proof.
Q. So that's an "and" symbol there?
A. Yes.
Q. And then there is what appears to be an arrow to that note? Do you see that?
A. Yes.

Q. And I guess, what was your point of -- well, I guess first of all, what is that arrow referring back to?

A. This arrow is referring to the, because there was no bedrock, there's no lab reports that would be needed for an explanation to the alternative source or proof.

Q. Okay. So it's referring back to the no bedrock well logs bullet there and the no geochem lab reports bullet?

A. Yes.

Q. And first of all, is geochem short for geochemical?

A. Or geochemistry.

Q. Or geochemistry. Okay. Do you believe that geochemistry lab reports were needed for the ASD submission?

A. Yes.

Q. Why?

A. This is to prove the summary charts that were provided in the alternative source, just for validation purposes and quality control so that we can check the groundwater analytical report.

Q. And what summary charts are you

referring to?

A. I am referring to the alternative source demonstration submittal that was provided as one of the attachments that was in the alternative source.

Q. Which attachment are you referring to? And if you want to take a look at I believe what's been marked as Exhibit 2, feel free to go ahead and take a look.

A. This was marked as Appendix C.

Q. So, you believe that the geochemical lab reports were needed to provide additional data in support of the information in that appendix?

A. The validation of what was submitted into Appendix C.

Q. So you believe that the geochemical lab reports were necessary to -- the geochemistry lab reports were necessary to validate the information that's in that appendix?

A. Yes.

Q. Outside of the lack of perhaps what you consider validation, is there anything -- sorry; you said that was Appendix C?

A. Appendix C.

Q. Okay. Beside perhaps what you consider the lack of validation, is there any information that would lead you to disagree with the information that's in Appendix C?

A. By having the lab reports, it is to double check that the information provided was correct.

Q. So you didn't believe you had the information to double check that information?

A. Yes.

Q. But do you have any other reason to disagree with the information?

A. Could you clarify that?

Q. Sure. Yeah. Is there anything, other than perhaps the fact that you didn't have the information to double check the information that's in that appendix, did you see any information or evidence that would lead you to believe that that information is incorrect?

A. No.

Q. All right. Let's move on. I'm going to hand you another document. This is record document number 32, which we will mark as exhibit 7.

(Whereupon, Deposition Exhibit No. 7 was marked for identification.)

Q. It's double sided.

Are you familiar with this document?

A. Yes.

Q. What is it?

A. This is our letter to Illinois Power of the nonconcurrence to the Newton alternative source demonstration.

Q. Were you involved in drafting this document?

A. Yes.

Q. Okay. And what role did you take in drafting it?

A. To write the letter.

Q. Did you write all of the letter?

A. No.

Q. Okay. What portions did you write?

A. The portion of the first paragraph stating the purpose of the correspondence, the paragraph that is, "if you have any questions, please contact." And then the address and titles of what is stated on the document.

Q. Okay. So, you did not draft the three

data gaps that are located in the middle of that document?

A. No.

Q. Who drafted that?

A. Lauren Hunt.

Q. Okay. As you can see, this document is signed by someone named Michael Summers. Do you see that?

A. Yes.

Q. Did you have any discussions with Mr. Summers regarding the document?

A. Yes. We did.

Q. What discussions did you have?

A. The discussion with what data gaps we should move forward with.

Q. And how did you decide to move forward with these three data gaps?

A. During our groundwater meeting, Lauren came up with these data gaps, and we discussed with Mike Summers, or Michael Summers, who is our manager, and he agreed with these data gaps to be put in the letter.

Q. Was there any information presented in that meeting for learning the data gaps?

A. The Newton alternative source submittal.
Q. Did Mr. Summers offer any opinion, other than agreeing with including these three data gaps during that meeting?
A. He agreed that, of those submittals.
Q. And again, Lauren Hunt is the person who drafted these three data gaps that are in this document, correct?
A. Yes.
Q. And to clarify, is Lauren Hunt the person who determined that these three data gaps -- let me take a step back.
Is she the one who suggested that these three data gaps be included in this letter as part of that meeting that you had with Mr. Summers?
A. Yes.
Q. Did Mr. Summers have any role in drafting this document?
A. He reviewed the letter to make sure it matched with our, the data gaps we discussed, but that was it.
Q. Was there anyone else who had to weigh in on these, on this letter, prior to it being sent out?

A. Lauren also looked at this for the majority of edits.

Q. Was there anyone else who had to sign off on the data gaps presented in this letter before the letter was sent out?

A. No.

Q. Okay. So, to be clear, Lauren reviewed it, Lauren Hunt, and Michael Summers reviewed it; was there anyone else who reviewed this letter before it went out?

A. Lynn Dunaway did minor edits.

Q. Anyone else?

A. No.

Q. The first data gap listed on this letter states, source characterization of the CCR at the primary ash pond must include total solid sampling in accordance with SW846.

What does this mean?

A. This is, with the response to the alternative source, that it does not come from the CCR in the surface impoundment. And the characterization would provide that; would provide the explanation of it not coming from the CCR impoundment.

Q. Can you clarify what you mean by that? So, was IEPA looking for any particular type of source characterization through this first data gap?

A. No particular.

Q. Okay. So, what information is IEPA looking for?

A. In 845 it asks for characterization of CCR in waste streams under 230. And which would be provided. We would ask for this type of documentation to be given in the ASD as well.

Q. Okay. Did IEPA have a copy of the Newton PAP operating permit application when it reviewed this ASD?

A. Yes.

Q. And does 845-230, that section you just referred to, is that a section that relates to information that needs to be provided with an operating permit application?

A. Yes.

Q. Is there any section of 845 that requires this information being provided as part of an alternative source demonstration?

A. No.

Q. And when you say that IEPA was looking for a discussion of waste streams in accordance with 845-230, what kind of information related to waste streams?

A. This would be the channels that would be going in or out of the surface impoundment.

Q. What do you mean by channels?

A. This would be the way that CCR would flow into the impoundment, or the water from the CCR would flow out of the surface impoundment.

Q. Do you understand that any CCR is flowing into this impoundment?

A. We -- to be honest, I do not recall.

Q. Do you agree that pore water collection is a way to characterize waste that is flowing out of an impoundment?

A. Yes.

Q. So is there any particular type of method of investigation that IEPA was looking for the source characterization that's listed in data gap one?

A. We, in accordance with SW846.

Q. Any particular SW846 method?

A. I do not remember the exact chapter that

we would refer to.
Q. Okay. Was the intention, was IEPA's intention to suggest that leach testing in accordance with SW846 was required?
MR. HENDERSON: I'm going to object to foundation.
Q. You can answer the question.
A. For SW846 was incorporated into 845. We just see that as a methodology to be used for sampling.
Q. Do you agree that SW846 includes a lot of different types of methodologies?
A. Yes.
Q. And in this particular data gap in this letter, are you aware of whether IEPA was referring to any specific methodology in SW846?
A. I do not recall.
Q. Do you understand the difference between leach testing data and pore water sampling data?
A. I do.
Q. Do you believe that leach testing data is superior to pore water sampling data?
A. I'm not sure how you want me to answer that 'cuz --

Q. In your opinion, is leach testing data superior to pore water sampling data?
A. I find them equal ways of sampling.
Q. I would like to show you a document that is part of record document number 33, which we will mark as Exhibit 8.
(Whereupon, Deposition Exhibit No. 8 was marked for identification.)
Q. Are you familiar with this document?
A. Yes.
Q. Okay. I'd like to refer you to paragraph four of this document. Well, first of all, what is it, if you have reviewed it? What is it?
A. It was a declaration of Cynthia, who was over the Newton Primary Ash Pond alternative source demonstration.
Q. So, is Cynthia Vodopivec, do you agree she prepared this declaration on behalf of Illinois Power Generating Company?
A. Yes.
Q. And this declaration was attached to the petition that was filed in this matter?
A. Yes.

Q. Okay. So, if you could just take a moment to review paragraph four of this document to refresh your recollection on it.

A. Okay.

Q. In paragraph four, Cynthia states that using total solid sampling techniques under SW846 would require drilling within the Newton primary ash pond with up to ten borings using specialized equipment to collect 20 samples.

Do you agree that that would be required in order to conduct solid sampling in accordance with SW846?

A. Yes.

Q. And that next sentence reads, it would further require complete laboratory analyses, data evaluation and reporting for those samples. Do you agree that solid sampling under SW846 would require those steps?

A. Yes.

Q. The next sentence reads, assuming a driller is readily available, which is not always the case, this process would likely take approximately 21 to 42 weeks to complete. Do you agree with that statement?

A. I would -- yeah, I would agree.
Q. All right. Let's go back to what I believe has been marked as Exhibit 7, which is the denial letter.
Referring to the second data point on here. Can you please describe what information the agency is looking for through the second data gap?
A. This is the data reports of hydraulic conductivity within the wells, which would include bedrock wells.
Q. Okay. Let's break this down a little. What hydraulic conductivities is this referring to? Conductivity of what unit or units?
A. This would look at multiple units with the primary focus of bedrock.
Q. Okay. Any other units?
A. No.
Q. So just bedrock?
A. Yes.
Q. So, this is looking for the hydraulic conductivity of the bedrock?
A. Yes.
Q. And what type of in-situ hydraulic test

is the agency thinking is necessary for data gap two?

A. I do not know the specific.

Q. And what is the agency asking for through the phrase, hydrogeologic characterization of bedrock units?

A. This would include the bedrock well logs, and the well construction logs.

Q. Anything else?

A. No.

Q. Why do you believe such a characterization is necessary?

A. This is for our full understanding of how the bedrock is reacting in the Newton area.

Q. And what regulation, guidance or other documents leads you to believe this type of characterization is necessary to prove that the Newton PAP is not the source of the chloride exceedance?

A. This would overall be the alternative source, the characterization of that. But, it would refer back to 620 being the hydrogeologic characterization of the site.

Q. Sorry, when you say 620, what are you

referring to?

A. 845-620. Apologize.

Q. And when you refer to the 845-620 hydrogeo characterization of the site, are you referring to the hydrogeologic characterization that an owner/operator is expected to provide with its groundwater monitoring plan?

A. Yes.

Q. Okay. Is there a requirement to provide a hydrogeologic characterization with an alternative source demonstration in the regulations?

A. Not specifically.

Q. Moving on to the third listed data gap, or the third point here on this letter.

Characterization to include sample and analysis in accordance with 35IAC845640 of alternative source must be provided with the ASD.

What characterization is this meant to refer to?

A. This is to refer to the geochemical lab reports and the chain of custodies.

Q. And geochemical lab reports for what?

A. The data that was provided with Appendix

C.

Q. And chain of custody for what?

A. Appendix C.

Q. Is this meant to refer to anything else?

A. No.

Q. So, to confirm, was the agency seeking any additional sampling through this data gap?

MR. HENDERSON: I'm just going to repeat my previous objection.

Q. You can answer.

A. Could you repeat the question?

Q. Sure. Data gap three says, characterization to include sample and analysis in accordance with 35 I.A.C. 845.640 of alternative source must be provided with the ASD.

So, was the agency looking for any sampling through this data gap? I'm just trying to understand what this data gap means.

A. I -- to my understanding, as this was Lauren who made this, the additional sampling would refer to item number one, not item number three.

Q. Okay. All right. So, is there any information outside of the geochemical lab reports

and chain of custody that you believe the agency was looking for through data gap three?

A. I do not believe so.

Q. Okay. And just based on your understanding. Okay. Thanks.

All right. If we could turn back to what I believe is marked as Exhibit 8.

Cynthia Vodopifec's declaration. Could I refer you to paragraph five of that declaration?

A. Okay.

Q. And I'll give you a moment to review if you want to read over that paragraph, just let me know when you're done.

A. Okay.

Q. All right. You had a moment to read paragraph five. Is the agency looking for what she has stated in this paragraph through this third data gap?

A. Not with the third data gap.

Q. No? Okay. Was the agency looking for the information in this paragraph in connection with its denial of the Newton ASD?

A. Yes, with the second data gap.

Q. Oh, the second data gap.

A. Yes.
Q. Okay. All right. Well, then looking at paragraph five, do you agree that conducting a characterization of the bedrock surrounding the Newton Primary Ash Pond in accordance with 35 Illinois admin code 845.640 would require drilling to bedrock, well installation, solids and groundwater sampling and analyses and data evaluation and reporting?
A. Yes.
Q. Then that next sentence reads, assuming a driller is readily available, which is not always the case, this process would take approximately 20 to 30 weeks. Do you agree with that statement?
A. Yes. And I would also like to rephrase to your question; it would be for data gap two, and then would conjoin with data gap three. It's not, I guess my understanding was specifically just data gap three.
Q. Would you agree that data gap two and data gap three both are referring back to like characterization of the bedrock unit?
A. Yes.

Q. Okay. And through both those data gaps we're looking for ground water sampling, geochemical lab reports, and chain of custody, as well as perhaps some other things?
A. Yes.
Q. Are you familiar with 845640 generally?
A. Generally, yes.
Q. Okay. How many rounds of sampling would the agency have wanted to see for the bedrock unit?
A. Usually, it's eight quarters.
Q. And do you agree that eight quarters of sampling usually provides you with enough data to determine whether an exceedance is statistically significant?
A. Yes.
Q. And if I may just ask the question; if they were to drill wells for the bedrock unit, say, even when doing this initial ASD for the Newton PAP, there's no way they could have had eight rounds of sampling data before they had to submit the ASD. Do you agree with that?
A. Yes.
Q. Is it your understanding that an owner

and operator always has to identify the alternative source in connection with an alternative source demonstration?

A. Yes.

Q. Is this true even if there's clear evidence that the CCR surface impoundment is not contributing to the exceedance?

A. It is my understanding it would either -- it would not be the CCR impoundment, and there would be an alternative source.

Q. Right. So if there's clear evidence that the CCR surface impoundment is not contributing to the exceedance in a particular well, then does an owner/operator still need to identify what the alternative source is?

A. Yes, with an exceedance.

Q. Okay. And what's your basis for this understanding?

A. The alternative source would show that an exceedance is not with the impoundment, and therefore the owner/operator might not have to do corrective measures for the --

Q. What's your basis for the understanding that even if it's clear that a CCR surface

impoundment is not contributing to an exceedance, that the owner/operator still has to identify what the alternative source is?

A. My understanding is that's how 845 was regulated. Beyond that, I am not sure.

Q. Okay. Are you basing it on any particular provision or guidance?

A. No.

Q. And what is your understanding of the degree of provision -- sorry. What is your understanding of the degree of precision with which the alternative source must be identified?

A. My understanding is there is clear proof that it is not coming from the impoundment, and then the alternative source is proven--whatever the source may be--is proven through different methods.

Q. Okay. And what methods would be required for identifying the alternative source?

A. I believe that's up to the owner and operator because it's not clearly stated in to the alternative source.

Q. So, it wouldn't necessarily always mean testing the alternative source?

A. The 845 regulation says they have to, if they do an alternative source, they have to show that it is the alternative source. So my understanding would be there is, there would have to be testing or an explanation to that.

Q. Okay. And what section of 845 were you just referring to? Or was it 845.650 that you were referring to?

A. Yes. I believe so.

Q. Okay.

A. Also, can I get a water? That would be great.

Q. Can we take a quick break.

(The time is 10:10 a.m.)

(The time is 10:17 a.m.)

CONTINUED EXAMINATION BY

MS. JOSHI:

Q. So we were just talking about whether or not an owner/operator always has to characterize an alternative source and the extent to which characterization is required.

So, going back I just want to clarify. So, is it your position that the owner/operator has discretion to decide for themselves, sort of

the scope of characterization that might be needed for the alternative source?

A. Yes.

Q. All right. Let's move on to another document. This is an excerpt from record document number 10, which is the operating permit application, and is very large so we're only going to provide an excerpt here. This is going to be marked as exhibit 9.

(Whereupon, Deposition Exhibit No. 9 was marked for identification.)

Q. The first few pages are just the cover pages for document number ten. And then you'll see a few pages in there is the start of something called Attachment C. Do you see that?

A. Yes.

Q. Are you familiar with this document?

A. Yes.

Q. Have you reviewed this document before?

A. Yes.

Q. I'd like to refer you to Appendix A of Attachment C. Do you see that?

A. Yes.

Q. Do you agree that this Appendix A

provides information regarding the chemical constituents contained in the Newton Primary Ash Pond?

A. Yes.

Q. And then on Appendix A, you'll see there's a table. The first column reads pollutant, agreed?

A. Yes.

Q. The second column reads units, agreed?

A. Yes.

Q. The third column reads surface free liquids average concentration; do you agree?

A. Yes.

Q. Okay. What do you understand that to mean?

A. These are what is at the surface level of the impoundment. This is what would be considered liquid that is just at the top of the impoundment.

Q. Okay. And then the next column, or final column here reads, subsurface free liquids average concentration. Do you agree?

A. Yes.

Q. And what do you understand that to mean?

A. That could be the liquids that would be found under the subsurface of the impoundment, or what is beneath the impoundment.

Q. Okay. And so what is reflected then in the final column of this chart?

A. This would be the -- what would be considered in the surface impoundment, or like the state of the chemicals in the surface impoundment.

Q. So it's a reflection of the chemicals in the surface impoundment?

A. Yes.

Q. And if you could flip over two pages to the chart that's marked Appendix B. Do you see that?

A. Yes.

Q. Okay. Do you agree that the first table of Appendix B provides a list of chemical additives that are located in the Newton PAP?

A. Yes.

Q. And do you agree that the second table in Appendix B provides a list of waste streams that are in the Newton PAP?

A. Yes.

Q. I'd like to refer you to another

document which we will mark as exhibit 10.

(Whereupon, Deposition Exhibit No. 10 was marked for identification.)

Q. This is another excerpt from that same document that's in the record. The operating permit application. Are you familiar with this document?

A. Yes.

Q. All right. What is it?

A. This is the hydrogeologic site characterization of the Newton Primary Ash Pond.

Q. And that hydrogeologic characterization was provided with the Newton Primary Ash Pond's operating permit application?

A. Yes.

Q. And you've reviewed this document before?

A. Yes.

Q. If you could go to the last page of this document, you'll see that there's a table there marked 2-2. Are you familiar with this table?

A. Yes.

Q. What is it?

A. This is sampling of, or I should say, a

summary of the sampling analytes for the ash in the impoundment.

Q. Do you agree that that table reflects solid sampling conducted of the Newton PAP?

A. Yes.

Q. Going to move on to another document. This is record document number 16. Which I will mark as exhibit 11.

(Whereupon, Deposition Exhibit No. 11 was marked for identification.)

Q. Give you a moment to just look at it. Are you familiar with this document?

A. Yes.

Q. What is it?

A. The JOPPA East Ash Pond Alternative Source Demonstration.

Q. Why was this document included in the record for the Newton ASD?

A. We were reviewing both the Newton ASD and the JOPPA one at the same time.

Q. Did the agency rely upon or consider this document in any way when reaching its decision on the Newton ASD denial?

A. No.

Q. All right. Going to hand you record document number 22, which I will mark as exhibit 12.

(Whereupon, Deposition Exhibit No. 12 was marked for identification.)

Q. Are you familiar with this document?

A. Yes.

Q. What is it?

A. The IEPA's letter for the JOPPA ASD nonconcurrence.

Q. Why was this document included in the record?

A. Since they were, since Newton and JOPPA were viewed at the same time, we had them both in the record.

Q. Did the agency rely upon this document at all in reaching its decision for the Newton ASD?

A. No.

Q. And did the agency consider this document at all in reaching its decision on the Newton ASD?

A. No.

Q. One last document for this line of

questions. This is record document number 26. Which we will mark as exhibit 13.

(Whereupon, Deposition Exhibit No. 13 was marked for identification.)

Q. Are you familiar with this document?

A. Yes.

Q. What is it?

A. This is an e-mail correspondence with Lauren about the JOPPA West Ash Pond adjusted standards.

Q. And are you copied on this e-mail?

A. Yes.

Q. Okay. Why was this document included in the record?

A. This was included as the documentation of what the IEPA would request as the CCR characterization.

Q. Okay. Can you point me to what portion of this document you're referring to when you say that this reflects what IEPA would sort of rely upon for a CCR source characterization?

A. Yes, I can. This would -- the line that is stated, IEPA also asks for CCR characterization. JOPPA provided the six CCR

samples, analyses. Would you want me to read the entire paragraph?

Q. Or you could just show me where it ends, if it is easier.

A. It would end where the SPLP analysis is in accordance with SW846 using the lowest pH of the site of frequent five.

Q. So, you just read the term SPLP. What do you understand that to mean?

A. I understand that as a leaching test that was brought up as an example to be used.

Q. Okay. So, again, before when we were talking about CCR source characterization, you said that there wasn't any one particular method that would be required, correct?

A. Yes.

Q. Okay. But, is the agency looking for a leaching type test, like SPLP for source characterization?

A. I believe this is a suggestion that as one of the ways to do this. And this is how we would analyze the characterization.

Q. Okay. And the information in this paragraph that you just referred me to here, in

that second paragraph starting, please provide further CCR solids. Do you see that language?

A. Yes.

Q. Okay. It goes on to read, please provide further CCR solid sampling and analysis to include a minimum of: One sample location per ten percent of the total cubic yards of CCR, with three samples collected from each location. This language regarding one sample per ten percent of the total cubic yards of CCR; is that meant to refer to a leach type of test, or a leach test?

A. I believe so.

Q. Okay. Do you believe that the number of samples required might differ based on the type of testing that is occurring?

A. Yes.

Q. Do you believe that the number of samples would differ if it was a different method of leach testing that was occurring?

A. I would believe so.

Q. The last sentence says: The SPLP analysis in accordance with SW846 using the lowest pH on site of 3.5. Is it your opinion that a leach test would typically be done using the

lowest pH that's been found at the site?

A. Yes, that's my understanding.

Q. So, in what way did the agency, if at all, rely upon this document in reaching its decision on the Newton PAP ASD?

A. This is our understanding of what source characterization for CCR would be at most sites. This was kind of a general consensus with the groundwater section for this type of explanation when talking to the companies.

Q. When you say companies, who are you referring to?

A. Owners and operators of CCR surface impoundments.

Q. Does that include owner and operators other than IPGC?

A. Yes.

Q. Let's go back to Exhibit 2, which is the ASD, the original ASD submittal.

It's document 12 marked as Exhibit 2.

A. Yes.

Q. And to confirm, you have reviewed this document before, correct?

A. Yes.

Q. Okay. Can I refer you to the third page of the document? The one that has certifications at the top? Do you see that?
A. Yes.
Q. Okay. Sorry, I meant the third physical page of the document, not the page marked page three.
All right. Do you agree that this page includes a certification from a professional engineer?
A. Yes.
Q. Do you agree that that page includes a certification from a professional geologist?
A. Yes.
Q. Now, if you could move on to the actual page three of the document, which is at the top. The Bates number for the record is R001611.
Do you see that?
A. Yes.
Q. I'd like to refer you to the second to last paragraph of this page that says, pursuant to 35 I.A.C. 845.650(e), the lines of evidence (LOEs) presented in Section 3 demonstrate that sources other than the PAP were the cause of the chloride

GWPS exceedance listed above. Do you see that sentence?

A. Yes.

Q. Did I read that correctly?

A. Yes.

Q. Okay. So, I just referred to something called a lines of evidence evaluation. Are you familiar with lines of evidence evaluations?

A. Well, do you mean prior to, or just overall?

Q. Just -- well, sure. Prior to reviewing the Newton ASD, were you familiar with the concept of a lines of evidence evaluation?

A. No, I was not.

Q. Did you become familiar with it after?

A. Yes.

Q. Okay. What do you understand a lines of evidence analysis to mean?

A. I understand lines of evidence to be the explanation of evidence that would be for, in this case, an alternative source, and the reason of why it would not be the surface impoundment.

Q. Okay. Are you familiar with the fact that a lines of evidence analysis is used in

various different circumstances for a forensic analysis?

A. I did not know.

Q. Okay. You said you engaged in sort of a forensic analysis before, right, to determine whether outside water was impacting a particular site?

A. Yes.

Q. Okay. In that type of situation, if you reached a point where you had data that supported your conclusion, but there was still additional data you could collect to further support your conclusion, did you end up collecting that additional data?

A. We just stated what -- we stated what additional data could have been had.

Q. Okay.

A. If it was not readily available.

Q. Have you reviewed the lines of evidence that are in this document?

A. Yes.

Q. Okay. Let's go to page seven of the document.

Do you agree that this is the start of

the more in depth discussion of the lines of evidence in this document?

A. Yes.

Q. Okay. I'm going to refer you first to the information related to the first line of evidence in section 3.1. Do you see that?

A. Yes.

Q. Okay. Do you agree that header reads, LOE number one: The PAP is separated from the UA at APW15 by a thick layer of low permeability glacier till. And then you've got the term in parentheses (UCU)?

A. Yes.

Q. Did you review the information that's contained here within this first line of evidence?

A. Yes.

Q. Is there any information presented here in this first line of evidence that you disagree with?

A. No, not disagree.

Q. Can I point you to the second line of evidence there at section 3.2. Have you reviewed the second line of evidence?

A. Yes.

Q. Is there any information presented here in the second line of evidence that you disagree with?
A. The need of laboratory data as just validation would make me unsure.
Q. Can you clarify what you mean by that?
A. For this line of evidence, by having the laboratory data, it validates the issue of giving a summary chart to make sure it matches with the laboratory reports, just as validation.
Q. So, outside of maybe not having that laboratory data, do you agree that the evidence provided showed that boron concentrations in APW15 are below background?
A. Yes.
Q. And do you agree that the information in here shows that sulfate concentrations in APW15 are below background concentrations?
A. Yes.
Q. And if CCR was the source of the chloride exceedance in APW15, how would you explain a lack of boron above background?
A. My understanding is looking at the chemistry of the impoundment, while boron is a

main constituent that would be used to identify the CCR, if there are other issues such as chloride being really high, while pH is very low, then CCR could flow through the impound -- flow through more quickly than usual.

Q. But wouldn't that CCR contain boron?

A. Yes.

Q. All right. Let's go to the third point of evidence, which is on the next page, page eight, section 3.3.

Have you reviewed this third line of evidence?

A. Yes.

Q. Is there any information presented in the third line of evidence that you disagree with?

A. No.

Q. Do you believe that the data set forth in IEPA's denial letter would have changed the ultimate determination of the Newton PAP ASD?

A. Yes.

Q. How so?

A. By having the full scope of the three data gaps that were provided would help the understanding of the entire CCR, versus what would

be the alternative source. And have a, I would say, a more complete understanding for the IEPA and for the public.

Q. You would believe it would provide a more fullsome picture?

A. Yes.

Q. Do you believe that any of that data would end up changing the ultimate conclusion that the Newton PAP is not the source of the chloride exceedance?

A. It would depend on the -- the characterization of the CCR, and the laboratory data. If it did show that the characterization was low, and the laboratory data that is given validates or is the same as the analytical data that was given, then yes.

Q. Then "yes" what?

A. Then yes, we could see that as the -- that the surface impoundment was not the cause of the chloride exceedance.

Q. I'm going to refer you to page ten of this document.

Do you see that section titled, references?

A. Yes.
Q. All right. Did you review this page of the document?
A. Yes.
Q. Did you review any of the references listed in this document?
A. No.
Q. Did you search for any of the references listed in this document?
A. No, I did not.
Q. Did you ask Illinois Power for any of the documents listed in this reference section?
A. No. I didn't.
Q. But, let's just go down, let's say, to the fourth item from the bottom. Do you see that Ramboll Americas Engineering Solutions 2021 Hydrogeologic Site Characterization Report. Correct me if I'm wrong, but you have reviewed that document?
A. Yes, I have.
Q. Can I give you a moment to just review this list and let me know what it is that you have reviewed and haven't reviewed?
A. Yes. Okay.

Q. Go ahead. Could you now walk me through what it is you have reviewed and have not reviewed? Why don't we just go with what you have reviewed.

A. Yes. The AECOM 2016 drawing that was included in the construction permit application. The HDR 2022 closure drawing that was also included in the construction permit application.

And then the Ramboll Hydrogeologic Site characterization, the groundwater monitoring plan that were also included into the operating permit. And those were the ones that I reviewed during the ASD.

Q. And did you review any after the ASD denial letter was issued?

A. The Ramboll detected exceedances quarter to Primary Ash Pond.

Q. Right above the Ramboll Engineering Solutions there's a document called Panno, do you see that? It starts with Panno SV 2018?

A. Yes.

Q. Have you ever reviewed this document?

A. I believe that I have heard. I did not review it.

Q. Okay. And if I could just have you flip the page because there are three more citations on the next page. If you could take a look, and again let me know whether you have reviewed any of these documents.

A. No, I did not review these.

Q. And did you ask for any of these documents from Illinois Power?

A. No.

Q. Did you independently go and look for or obtain these documents?

A. No.

Q. I'm going to hand you another document, which we will be marking as exhibit 14.

(Whereupon, Deposition Exhibit No. 14 was marked for identification.)

Q. This is record document number 29. Are you familiar with this document?

A. Yes, I am.

Q. What is it?

A. This is the additional information that Illinois Power provided us before the -- or on November 3rd.

Q. And additional information related to

what?

A. The alternative source demonstration data gaps.

Q. Did you review this document prior to IEPA issuing the denial of Newton's ASD?

A. Yes.

Q. I'm going to ask you to turn to, and just so you know this is towards the back of the document. The page that is Bates numbered with the number R001941.

Would you have reviewed this page as part of your review of this document?

A. Yes.

Q. Did you review any of the references listed on this page?

A. I have reviewed the Burns & McDonnell operating permit. The Ramboll Hydrogeologic Site Characterization. The USEPA LEAF document. And that is it.

Q. Okay. The USEPA LEAF document, you mean the USEPA 2019 Leaching Environmental Assessment Framework, how-to guide document?

A. Yes.

Q. Thank you. Did you ask for any of these

documents to review as part of your review of the Newton ASD?

A. No.

Q. And did you seek out or review any of these documents as part of your review of the Newton ASD?

A. There was a discussion with Mike Summers and Lauren Hunt about the Electric Power Research Institute that we had a discussion on that. But I did not go out and look for these references.

Q. And so there was a discussion regarding the Electric Power Research Institute; which document? The 2017 document that's listed here?

A. The 2022 document.

Q. Okay. And that discussion was in relation to the Newton ASD submittal?

A. The Newton ASD, and ASDs going forward with this reference.

Q. And do you recall the scope of that discussion?

A. The discussion was on the validation of EPRI, our Electric Power Research Institute, between Lauren and Mike Summers.

Q. What do you mean by the validation of --

A. According to Mike Summers, there were articles of EPRI that are not peer reviewed, and that was his position to me and Lauren.

Q. Did you confirm whether or not this EPRI reference or any of the other EPRI references listed here were in fact peer reviewed?

A. I did not confirm them.

Q. The agency considered documents outside of those provided with, or referenced in IPGC's ASD submittal when reviewing the Newton PAP ASD, correct?

A. Can you please repeat that?

Q. So, for example, earlier we talked about a textbook that you referenced when reviewing the Newton PAP ASD, correct?

A. Yes.

Q. Okay. So, you didn't just look at references that were cited to you in the Newton ASD when reviewing and considering the ASD submittal, correct?

A. Yes, that's correct.

Q. Okay. You also referenced EPA pore water sampling guidance that you reviewed to, correct?

A. Yes.
Q. How did you determine what documents to review?
A. These were given as our background documentation of my understanding or, like, well the documents that I reviewed are my background documentation. So --
Q. Okay. You started by saying these documents were given; what do you mean by given?
A. Well, my textbook was one that I have already had. The pore water documentation was found by Lauren Hunt.
Q. Why did you decide to refer to that particular textbook?
A. That, the geochemistry textbook is my background in my Master's degree. And to document the basis of my understandings.
Q. Okay. And when you say, and the textbook we're talking about, can you confirm that's the document that's been marked as Exhibit 3 on the record?
A. Yes. That's correct.
Q. Okay. Did you ever think about pulling any other reference materials?

A. Not at the time of the Newton ASD.
Q. Have you pulled any additional reference materials for ASDs you've reviewed since the Newton ASD submittal?
A. Yes.
Q. Can you provide me with examples?
A. We've pulled more like recent guidance documents instead of ones that are in 2017. We're looking more at the 2022 or 2023.
And then that's typically with the other ASDs, what we've done.
Q. Recent guidance related to what?
A. The USEPA typically, yes.
Q. And what is the subject matter of the guidance?
A. The pore water or leaching testing, just so we have the most up to date.
Q. Do you happen to recall specifically what any of these documents are right now?
A. No, I do not recall.
Q. But, they are guidance documents from USEPA, correct?
A. Yes.
Q. And they relate to pore water or leach

testing?
A. Yes.
Q. And were they available at the time you reviewed the Newton PAP ASD?
A. I believe so.
Q. Do you review federal rule makings related to CCR surface impoundments as part of your job?
A. Yes.
Q. And it sounds like yes, but do you review EPA guidance documents as part of your job?
A. Yes.
Q. I'd like to direct your attention to a document which I will mark as exhibit 15.
(Whereupon, Deposition Exhibit No. 15 was marked for identification.)
Q. Are you familiar with this document?
A. No. I'm not familiar.
Q. Okay. Do you see the title of the document there, Hazardous and Solid Waste Management System: Disposal of Coal Combustion Residuals From Electric Utilities: Amendments to the National Minimum Criteria, Phase One, Proposed Rule?

A. Yes.
Q. Okay.
A. I see that.
Q. Do you agree that this is a rule making related to coal combustion residuals from electric utilities?
A. Yes.
Q. Is this the type of rule making document from EPA you might review as part of your job?
A. Yes.
Q. Do you have any recollection of actually reviewing this document as part of your job ever?
A. No.
Q. Okay. I'd like to refer you to page 11588 of this document.
It's the fifth page of the document. You'll see some highlighted language there. So, this document in the third column here, the highlighted language; well, first of all, do you agree there's some highlighted language there?
A. Yes.
Q. Do you see it?
A. Yes. I do.
Q. So, it reads, out of all the coal ash

constituent modeled by EPA, boron has the fastest travel time, meaning that boron is likely to reach potential receptors before their constituent. Do you agree with that statement?

A. Yes.

Q. The next sentence reads, therefore, boron is expected to be one of the earliest constituents detected if releases to groundwater are occurring. Do you agree with that statement?

A. Yes.

Q. And then that sentence continues to say, consequently, EPA reasoned that retaining boron on Appendix III was more appropriate as it would function as a signal constituent that would insure that assessment monitoring was quickly triggered in response to any release. Do you agree with the portion of that statement that says that boron can function as a signal constituent?

A. Yes.

Q. So, generally, do you agree that boron can serve as a signal constituent?

A. Generally, yes.

Q. And what do you understand the term, signal constituent to mean?

A. I understand that as to be a primary indicator when it comes to CCR, or the coal combustion.

Q. And could you explain what you mean by primary indicator?

A. The boron would be generally noticed first as an exceedance, or a large amount of it, in groundwater.

Q. Did you review or consider this document in connection with the ASD?

A. I did not.

Q. Did anyone else you're aware of review this document in connection with the ASD?

A. I'm not sure.

Q. Is this a document that IEPA would have had in its possession when reviewing the Newton ASD?

A. We would have had the final rule of 257. I am not 100 percent sure if we have this one.

Q. Okay. Do you typically review proposed rules related to CRR? You or other folks at IEPA?

A. I believe so.

Q. I'd like to refer you to another document. This will be marked as exhibit 16.

(Whereupon, Deposition Exhibit No. 16 was marked for identification.)

Q. Give you a second to look at it. Are you familiar with this document?

A. I am not.

Q. So, over there, do you agree that it's a USEPA rule making?

A. Yes, I do.

Q. Do you agree that it's a rule making that was published in the Federal Register?

A. Yes.

Q. Do you agree that the title of this rule making is Hazardous and Solid Waste Management System Disposal of Coal Combustion Residuals From Electric Utilities?

A. Yes.

Q. Do you agree that this is a final rule?

A. Yes.

Q. Have you ever reviewed this document?

A. I do not believe so. Not this document.

Q. Do you agree that it's authored by EPA?

A. Yes.

Q. I would like to direct your attention to page 21441 of this document. Apologize, it's

long.

Just let me know when you're there.

A. 21441.

Q. Yes. Okay. In the third column of 21441 do you see at the top section that starts with EPA response, colon.

A. Yes.

Q. The first sentence there after EPA response says: The use of pore water data is still considered the most appropriate approach to estimate constituent fluxes to groundwater for CCR surface impoundments. Do you see that sentence?

A. I do.

Q. Do you agree with that sentence?

A. I do.

Q. The second sentence there reads: This is because pore water better represents the leachate seeping from the bottom of the impoundment than impoundment water samples. Do you see that sentence?

A. Yes, I do.

Q. Do you agree with that sentence?

A. I do.

Q. And if I were to just tell you generally

that this is the 2015 Federal CCR rule, would that refresh your recollection as to whether you've ever reviewed this document before?

A. I would still say I believe I have not reviewed this one.

Q. Okay. So, again, did you consider this document at all when reviewing the Newton ASD submittal?

A. No.

Q. Is this a document that IEPA would have had in its possession when reviewing the Newton ASD submittal?

A. I believe so.

Q. Are you aware of whether anyone else at IEPA reviewed this document in connection with the Newton ASD submittal?

A. I am not aware.

Q. I'd like to direct your attention to an additional document which I will mark as exhibit 17.

(Whereupon, Deposition Exhibit No. 17 was marked for identification.)

Q. Are you familiar with this document?

A. I have heard of it. I have not

reviewed.

Q. Okay. When you say you've heard of it, in what context?

A. Lauren Hunt had mentioned about the human and ecological risk assessments. And that there was documentation. I did not see this, I should say.

Q. Okay. Do you have familiarity generally with what this is?

A. A very general --

Q. Sure. How would you describe what it is?

A. Whether the coal combustion residuals are at risk to the human health or the ecological health.

Q. Do you agree that this is a document authored by the United States Environmental Protection Agency?

A. Yes.

Q. So, would it be fair to categorize this as a risk assessment conducted by the United States Environmental Protection Agency related to coal combustion residuals?

A. Yes.

Q. So, I would like to direct your attention to page 4-5 of this document. At the bottom right-hand corner of the page. Do you see the section that starts, surface impoundments? Section 4.2.1?

A. Yes.

Q. Okay. The first sentence of that section reads, similar to the screening analysis described in section three, EPA relied on pore water concentrations to characterize leaching from impoundments. Do you agree that this sentence is saying that EPA was relying on pore water data to characterize CCR surface impoundment leaching?

A. Yes.

Q. The second sentence reads: These concentrations are collected from the interstitial water between waste particles and surface impoundments as it occurs in the field, and best reflect leachate as it is released into underlying soils. Do you see that sentence?

A. Yes, I do.

Q. Do you agree with that sentence?

A. Yes.

Q. Do you agree with the fact that pore

water concentrations best reflect leachate as it's released into underlying soils from a CCR surface impoundment?

A. I do.

Q. I'd like to refer you to page 5-17 of this document.

There's some highlighted language there. Do you see that?

A. I do.

Q. Okay. The highlighted language reads: Pore water data were determined to be the most representative data available for impoundments because these data are field measured concentrations of leachate present at the bottom of these WMUs. Do you see that sentence?

A. I do.

Q. What do you understand the term WMUs to mean?

A. I understand that as a waste management unit.

Q. Do you agree with the statement in that sentence that I just read?

A. I do.

Q. Did you review or consider this document

in connection with the Newton ASD submittal?
A. I did not.
Q. Are you aware of whether anyone else at IEPA reviewed or considered this document in connection with the Newton ASD submittal?
A. I am not aware.
Q. Would this document have been in IEPA's possession prior to its review of the Newton ASD submittal?
A. I would guess so.
Q. Can we take a short break?
(The time is 11:16 a.m.)
(The time is 11:25 a.m.)
CONTINUED EXAMINATION BY MS. JOSHI:
Q. Ms. Mullenax, can you refer back to what's been marked as Exhibit 2 in this deposition. It's the Newton ASD submittal, record document number 12.
And go to Appendix C of this document. I think you had referred to this appendix previously, correct?
A. Yes.
Q. What do you understand this appendix to

reflect?

A. I see this appendix as a summary of the groundwater in there, specifically the boron chloride sulfate in the Newton Primary Ash Pond.

Q. Do you agree that it reflects pore water sampling of the Newton Primary Ash Pond?

A. This is groundwater sampling, as this is the groundwater analytical data.

Q. So let's go, if you go to the very first page of the document, or you'll see that the first column is titled well ID. Do you agree with that?

A. Yes.

Q. Okay. Then the second column is titled, well type.

A. Yes.

Q. Okay. Do you see sort of the first set of well types, let's say maybe until two-thirds of the way down in the document, it says, compliance. Do you see that?

A. Yes, I do.

Q. Okay. And then eventually, and the well ID associated with those well types are all APW15, do you agree with that?

A. Yes, that is.

Q. Okay. And then about two-thirds of the way down in the document, do you see where well ID XPW01 starts?
A. Yes, I do.
Q. What type of well type is listed for that?
A. Pore water.
Q. And do you agree that this document -- so, sort of looking there, let's just start with that very first line for XPW01. Pore water. Do you see the date of 2-17-2021?
A. I do.
Q. Okay. The fourth column down that is titled parameter, agreed?
A. Yes.
Q. Okay. And what does parameter appear to be referring to?
A. The analyte that is being sampled.
Q. Okay. So for that 2-17-2021 data that we were just looking at, what is the parameter that is being sampled for?
A. Boron.
Q. Okay. And then going down the page a little bit more; do you see the next entry for

2-17-2021 on that page?

A. Yes. I do.

Q. Okay. Again, is that for well ID XPW01?

A. It is.

Q. And is that for pore water well type?

A. Yes, that's correct.

Q. Okay. And is the parameter listed there chloride?

A. Yes. That's correct.

Q. Okay. And going down through the rest of the entries on this first page, are those all, do those all have the same well ID?

A. Yes.

Q. Are they all listed as pore water for the well type?

A. Yes.

Q. Do you agree that they all have different date listed?

A. Yes.

Q. Okay. And then do you agree that the parameters for all of them are chloride?

A. Yes.

Q. Okay. And then the fifth column titled results? Do you see that?

A. Yes.
Q. What do you understand that to reflect?
A. This would be whatever the analytes total is in being sampled.
Q. And the very last column unit, what do you understand that to reflect?
A. This is the measurement of the unit, this one being in milligrams per liters.
Q. And going on to the second page of the document, or this appendix, second page of Appendix C. Do you agree that that page contains additional data regarding pore water for various well IDs?
A. Yes.
Q. Okay. And do you agree that it includes data under the parameters for chloride, sulfate and boron?
A. Yes.
Q. Okay. Going on to the next page of this appendix, page three. Do you agree, again, that this page contains various well IDs on it? It looks like XPW03 and XPW04 might be reflected on this page. Do you agree?
A. Yes.

Q. Do you agree that the well type listed on this page all consists of pore water?
A. Yes.
Q. And then do you agree that parameters listed on this page include boron, chloride and sulfate?
A. Yes.
Q. Moving on to the very last page of this appendix, page four. Do you agree that the first column reflects the well ID, and in this case this is for well ID XPW04?
A. Yes.
Q. Do you agree that the second column again indicates the well type as pore water?
A. Yes.
Q. And do you agree that the fourth column includes sulfate as a parameter?
A. Yes.
Q. Okay. And again, the parameters, the constituent being sample four, do you agree?
A. Yes.
Q. Going back to something you had mentioned earlier today, you had mentioned wanting information to validate the data provided in

Appendix C, is that correct?

A. Yes.

Q. And what kind of information were you looking for there again to validate the data here?

A. In supporting this, would be the laboratory documentation and the chain of custodies.

Q. And what laboratory documentation?

A. Whatever lab that Ramboll or Illinois Power sampled or went with.

Q. So, just the name of the lab or something more than that?

A. The documentation that the lab provides, which would describe the analytes and the result.

Q. If IEPA had received that information related to Appendix C, meaning one, the laboratory documentation as you just described it. And two, the chain of custody information, do you believe IEPA would have still included data gap number one in its denial letter? And if you need to refresh your recollection on data gap number one, please feel free to do so. That would be in exhibit 7.

A. I would believe so. I'm not sure.

Q. Okay. Why are you not sure?

A. This, again, the first data gap was not my decision. It was Lauren Hunt's. So, that's where I don't know exactly what she would --

Q. And to confirm, was Lauren Hunt sort of the final decision maker for all three of the data gaps?

A. Yes. Before Mike Summers.

Q. Okay. And Mike Summers then signed off on the three data gaps that Lauren presented, correct?

A. Yes.

Q. Okay. No further questions. Thank you very much for your time today.

MR. HENDERSON: Just a couple of questions.

EXAMINATION BY
MR. HENDERSON:

Q. So, we've just been discussing, or we were just a moment discussing Exhibit 2, which is the alternative source demonstration submittal. So I'm just going to stay with that, and direct your attention to page R0001616. Which is page eight of the ASD.

And it says, I'll read from the bottom;

analytical data to support summary statistics presented in Table A are included in Appendix C.

So, is it your understanding from reviewing this document that the pore water statistics that you've just reviewed with opposing counsel are summarized in Table A on this page?

A. Yes.

Q. Okay. So these include composite pore water readings, or composite pore water concentrations for chloride, is that correct?

A. Yes. That's correct.

Q. Can you explain -- well, I'm sorry. And it was Illinois EPA's position that these were not sufficient, correct?

A. Yes, that's correct.

Q. So, can you explain why that was, those pore water concentrations were not sufficient?

A. We would need the data or the laboratory documentation, with the statistical information that what is being summarized in Appendix C and Table A were valid in Illinois Power's submittal.

MR. HENDERSON: No further questions.

MS. JOSHI: May I ask one clarifying question? You just referenced statistical

information that you would need which I don't think you had referenced before. What do you mean by statistical information?

THE WITNESS: This, as a data gap, it is kind of the analyses information of statistics, which usually is a company's -- how they do statistics for a more further explanation.

MS. JOSHI: Is that reflected anywhere in the denial letter?

THE WITNESS: No.

MS. JOSHI: Nothing further. Thanks.

MR. HENDERSON: We would not waive signature.

(The time is 11:38 a.m.)

STATE OF ILLINOIS)
) SS
COUNTY OF CHAMPAIGN)

I, DEANN K. PARKINSON, a Notary Public in and for the County of Champaign State of Illinois, do hereby certify that HEATHER MULLENAX, the deponent herein, was by me first duly sworn to tell the truth, the whole truth and nothing but the truth in the aforementioned cause of action.

That the foregoing deposition was taken on May 28, 2024.

That said deposition was taken down in stenographic notes and afterwards reduced to typewriting under my instruction and said transcription is a true record of the testimony given; and that it was agreed by and between the witness and attorneys that said signature on said deposition would be not waived.

I do hereby certify that I am a disinterested person in this cause of action; that I am not a relative of any party or any attorney of record in this cause, or an attorney for any party herein, or otherwise interested in the event of this action, and am not in the employ of the attorneys for either party.

In witness whereof, I have hereunto set my hand and affixed my notarial seal June 2, 2024.

_____
DEANN K. PARKINSON, CSR
NOTARY PUBLIC

DEPOSITION ERRATA SHEET

Our Assignment No. J11288877
Case Caption: ILLINOIS POWER GENERATING COMPANY
vs. ILLINOIS ENVIRONMENTAL PROTECTION AGENCY

DECLARATION UNDER PENALTY OF PERJURY

I declare under penalty of perjury that I have read the entire transcript of my Deposition taken in the captioned matter or the same has been read to me, and the same is true and accurate, save and except for changes and/or corrections, if any, as indicated by me on the DEPOSITION ERRATA SHEET hereof, with the understanding that I offer these changes as if still under oath.

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HEATHER MULLENAX

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Page No. 78 Line No. 22 Change to: or

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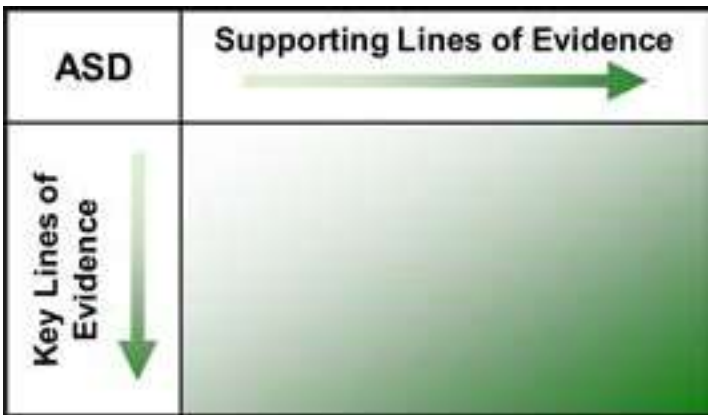
Document 5

Electric Power Research Institute (EPRI), 2017. Guidelines for Development of Alternative Source Demonstrations at Coal Combustion Residual Sites. EPRI, Palo Alto, CA: 2017. 3002010920.

EPRI ELECTRIC POWER RESEARCH INSTITUTE

2017 TECHNICAL REPORT

Guidelines for Development of Alternative Source Demonstrations at Coal Combustion Residual Sites



Guidelines for Development of Alternative Source Demonstrations at Coal Combustion Residual Sites

3002010920

Final Report, October 2017

EPRI Project Manager
B. Hensel

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ABSTRACT

EPRI's guidance for alternative source demonstrations (ASDs) was developed to provide environmental managers at electric utilities with a list of alternative sources to check as well as a standardized, defensible approach for building and documenting an ASD when there are exceedances of one or more benchmarks established within a groundwater monitoring program. This guidance is designed for statistical benchmarks, in specific, statistically significant increases (SSIs) or statistically significant levels (SSLs) for groundwater monitoring under the federal Coal Combustion Residuals (CCR) rule and/or state regulations, but the guidance also applies to exceedances of other types of benchmarks such as groundwater quality standards.

The guidance provides information to help identify when a cause other than a release from the facility is the likely source of an SSI during detection monitoring or an SSL during assessment monitoring along with a checklist-based framework for developing a defensible ASD. The guidance covers ASDs developed in response to sampling causes, laboratory causes, statistical evaluation causes, natural variation, and alternative anthropogenic sources, with emphasis on development of an ASD when an SSI, SSL, or other exceedance is due to natural variation or an alternative anthropogenic source.

Keywords

Alternative source demonstration (ASD)
CCR Rule
Coal combustion residuals
Groundwater monitoring
Statistically significant increase (SSI)
Statistically significant level (SSL)

Deliverable Number: 3002010920

Product Type: Technical Report

Product Title: Guidelines for Development of Alternative Source Demonstrations at Coal Combustion Residual Sites

PRIMARY AUDIENCE: Electric utility environmental managers interpreting and responding to groundwater data collected under the Coal Combustion Residuals (CCR) rule and/or state rules

SECONDARY AUDIENCE: Consultants working for electric utilities with responsibility for responding to potential exceedances of benchmarks or criteria established for utility groundwater monitoring programs

KEY RESEARCH QUESTION

Groundwater monitoring programs developed for compliance with the federal CCR rule, and some state rules, use statistical analysis to determine whether or not individual results represent exceedances, which are often termed statistically significant increases (SSIs) over background in detection monitoring or statistically significant levels (SSLs) relative to a groundwater protection standard in assessment monitoring. However, the statistical methods are subject to false positive results, where a value that is not a true exceedance is flagged as such. Furthermore, there are literally dozens of causes related to sampling, laboratory analysis, natural variation, and other anthropogenic sources that can trigger an exceedance that is not due to a release from the monitored unit. When an exceedance is triggered due to a cause other than a release from the facility, federal and state regulations allow for an alternative source demonstration (ASD). At present, however, there are no criteria for how to develop and document an ASD.

RESEARCH OVERVIEW

This research provides guidance for identifying when an ASD is needed, evaluation techniques that can be used to support the demonstration, and a standardized checklist-driven approach for documenting a defensible ASD. The guidance is based on experience developing ASDs in states that have long used statistical analysis to determine compliance with groundwater quality benchmarks and is tailored for application in CCR monitoring programs.

KEY FINDINGS

- Potential sampling, laboratory, and statistical causes that can trigger an exceedance that is not due to a release from the CCR facility are described in Section 2. Checklist 1 outlines a methodology for demonstrating these causes.
- Natural variation can trigger an exceedance if there are changes in mineralogy along a groundwater flow path, changes in pH and/or redox over time or along a flow path, changes in groundwater elevation over time, and/or changes in groundwater flow direction over time (Section 4).
- Potential anthropogenic sources at a power plant that can trigger an exceedance at one or more monitoring locations include, but are not limited to, spills of petroleum or other materials, road salt, leakage of runoff from coal management areas, overspray of leachate used for dust control, accumulation of blowing dust near monitoring wells, leakage from leachate conveyance pipelines or tanks, and releases from other CCR units (Section 5).

- Potential off-site anthropogenic sources include, but are not limited to, agricultural activities, road salt, coal mining, brines associated with oil and gas production, leaking underground pipes, pumping-induced brackish water, septic systems, and industrial or municipal waste management (Section 5).
- An ASD due to natural variation or an off-site or on-site anthropogenic source will be strongest if multiple lines of evidence are developed. Key lines of evidence include a lack of exceedances and a lack of increasing trends for primary indicators of the CCR, leachate concentrations for the affected constituent that are lower than concentrations observed in groundwater, major ion chemistry in the affected monitoring well that does not represent mixing of leachate with background groundwater, tritium age-dating showing that the groundwater is older than the CCR unit, and isotopic data showing that the groundwater at the affected monitoring well is not a mixture of background groundwater and leachate (Section 6).

WHY THIS MATTERS

False identification of an SSI can trigger assessment monitoring, and false identification of an SSL can trigger corrective action, either of which can increase the cost and manpower resources needed for groundwater compliance at CCR sites. An ASD can be used to demonstrate that these incremental increases in resource allotment are not necessary if the statistical exceedance is not due to a release from the facility. ASDs may be reviewed by state regulators and the public, and this guidance provides a standardized, checklist-driven approach for documenting a strong ASD.

HOW TO APPLY RESULTS

Users of this guidance can begin by reviewing Sections 2, 4, and 5 to determine whether or not an ASD is appropriate, and if so, the potential alternative causes that may explain the ASD. Section 3 describes evaluation techniques that can be used to support the ASD. The user can then use the checklists described in Section 6 and provided at the end of the document in Appendix B to build the ASD.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- Statistical analysis used in CCR groundwater monitoring programs is described in *Groundwater Monitoring Guidance for the Coal Combustion Residuals Rule*. EPRI, Palo Alto, CA: November 2015. 3002006287.
- Techniques for evaluating groundwater quality data are described in *Groundwater Quality Signatures for Assessing Potential Impacts from Coal Combustion Product Leachate*. EPRI, Palo Alto, CA: October 2012. 1017923.
- Methodologies for application and evaluation of isotopic analysis are provided in *Application of Isotopic Methods to Coal Combustion Residual Groundwater Quality Investigations*. EPRI, Palo Alto, CA: December 2017. 3002010911.

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PROGRAM: Coal Combustion Products – Environmental Issues, P49

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ACRONYMS AND ABBREVIATIONS

ASD	Alternative Source Demonstration
CCR	Coal Combustion Residual
CCR Rule	Coal Combustion Residuals Rule (40 CFR 257 Subpart D)
CFR	Code of Federal Regulations
EPRI	Electric Power Research Institute
FR	Federal Register
GWPS	Groundwater Protection Standard
LCL	Lower Confidence Limit
MCL	Maximum Contaminant Level
MDL	Method Detection Limit
ORP	Oxidation Reduction Potential
PQL	Practical Quantitation Level
RL	Reporting Level
UCL	Upper Confidence Level
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
SSI	Statistically Significant Increase
SSL	Statistically Significant Level
TDS	Total Dissolved Solids
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey

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1
INTRODUCTION

Scope of Guidance

This guidance for alternative source demonstrations (ASDs) was developed to provide environmental managers at electric utilities with a list of alternative sources to check, and a standardized, defensible approach for building and documenting an ASD when there are exceedances of one or more benchmarks established within a groundwater monitoring program. The guidance is designed for statistical benchmarks, specifically statistically significant increases (SSIs) or statistically significant levels (SSLs) for groundwater monitoring under the Coal Combustion Residuals Rule (CCR Rule)[1] and/or state regulations, but the guidance is also applicable to exceedances of other types of benchmarks such as groundwater quality standards.[2]

The guidance provides information to help identify when a cause other than a release from the facility is the likely cause of an SSI during detection monitoring or an SSL during assessment monitoring, and a framework for developing a defensible ASD.

As provided for in the CCR Rule,[3] an alternative source demonstration can have a variety of causes:

- Sampling causes (ASD Type I)
- Laboratory causes (ASD Type II)
- Statistical evaluation causes (ASD Type III)
- Natural variation not accounted for in the basic detection monitoring or assessment monitoring statistics (ASD Type IV)
- Potential alternative sources (ASD Type V)
  - Anthropogenic impacts
  - Natural sources

Potential alternative sources, both anthropogenic and due to natural environmental influences, are the main focus of this report.

The scope of this document does not include guidance for performing a site investigation or establishing a groundwater monitoring system. Readers can refer to EPRI (2015) and a variety of other documents, many of which are listed in EPRI (2015), for such information.

[1] 40 CFR 257 Subpart D; published in 80 FR 21302-21501, April 17, 2015.

[2] The remainder of this document will primarily reference exceedances of SSIs or SSLs even though the methodology applies to exceedances of all types of benchmarks.

[3] 40 CFR 257.94(e)(2) for detection monitoring; 40 CFR 257.95(g)(3)(ii) for assessment monitoring.

2
TYPES OF ALTERNATIVE SOURCES

As stated in the CCR Rule at 40 CFR 257.94(e)(2), "The owner or operator may demonstrate that a source other than the CCR unit caused the statistically significant increase over background levels for a constituent or that the statistically significant increase resulted from error in sampling, analysis, statistical evaluation, or natural variation in groundwater quality. The owner or operator must complete the written demonstration within 90 days of detecting a statistically significant increase over background levels to include obtaining a certification from a qualified professional engineer verifying the accuracy of the information in the report." This section describes the five types of ASDs, provides example causes, and presents examples for how those causes might be identified.

Potential causes or investigation paths associated with each of the alternative source categories identified in the CCR Rule are listed in Table 2-1 and are discussed below. Anthropogenic sources are further discussed in Section 5, and natural variation is discussed in Section 4.

Table 2-1
ASD Types and Causes

Sampling Causes (ASD Type I)	Laboratory Causes (ASD Type II)	Statistical Evaluation Causes (ASD Type III)	Natural Variation (ASD Type IV)	Alternative Sources (ASD Type V - Natural and Anthropogenic)
• Sample mislabeling • Contamination • Change in technique • Excessive suspended solids or turbidity • Other sampling anomalies	• Analytical method • Calibration • Analytical technique • Contamination • Interference • Recording • Dilution errors • Digestion methods	• Lack of statistical independence • Outliers • Trends • Non-detect processing • False positives • New background data	• Geology • Precipitation • Seasonality • Water level • Changes in pH and/or ORP • Biological activity • Time of travel	• See Tables 2-2 and 2-3

Sampling Causes (ASD Type I)

- Sample mislabeling: One form of sample mislabeling is sample switching. Sample switching can be identified by sudden changes in concentration for the same constituent at two monitoring wells (Figure 2-1). Multiple constituents will be affected when this occurs, although it would only be evident for constituents with large differences in concentration

between the two monitoring wells. The multiple constituents will come from the same type of sample bottle (e.g., metals, IC analysis) if only one sample bottle is switched, and can come from multiple bottles if all bottles for two samples are switched. If analysis results suddenly differ from normal for a particular well, look for similar anomalies at other wells for patterns that could indicate swapped identification.

Another form of mislabeling can occur if the sample is taken from a different monitoring well than listed on the label (e.g., MW-01b instead of MW-01a), when the other monitoring well is not in the sampling program. In this case, only one monitoring well will show an anomaly for multiple constituents. This anomaly should affect all sampled constituents, although it will only be evident for constituents where concentration is different in the sampled well, relative to the well that should have been sampled. This case is more difficult to identify and demonstrate than the case of the switched sample. If all concentrations in a resample return to previous levels, then it is a possible explanation.

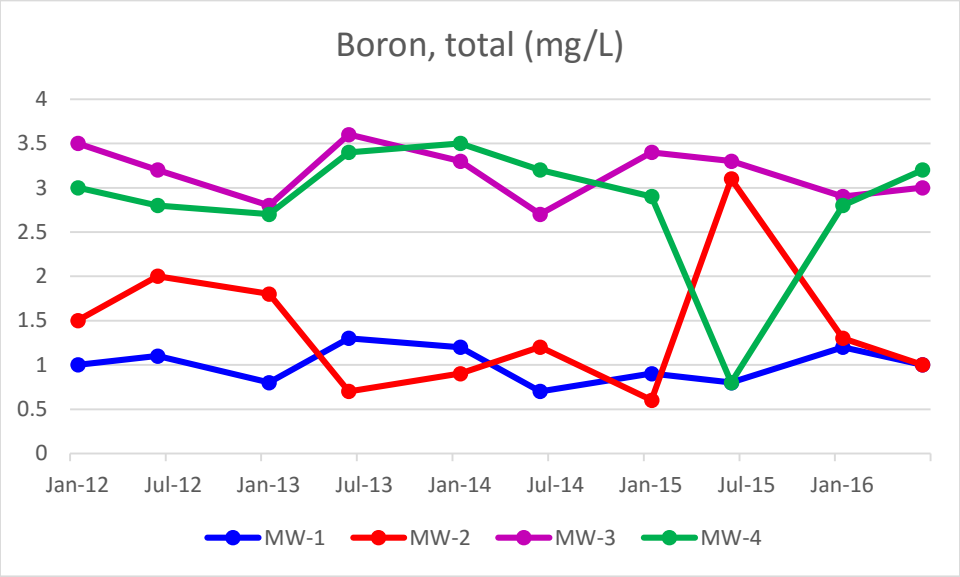

Figure 2-1
Time series plot showing potential sample mislabeling (switching)

- Contamination: If non-dedicated sampling devices are used to collect samples, contamination from the sampling equipment could potentially cause unrepresentative, elevated concentrations that could trigger an SSI/SSL. This type of sampling error is more likely to affect trace elements such as those found in Appendix IV of the CCR Rule than higher concentration elements such as those listed in Appendix III of the CCR Rule. An equipment blank (also called a rinsate blank) is a field quality control sample consisting of the rinsate from equipment used to collect the sample. Check the equipment blank analytical results to assess the potential for cross contamination, which will be evident by elevated concentration in the equipment blank. A field blank is a sample of deionized water from the laboratory that is opened in the field to assess the potential for field contamination. Field blanks are not always used for groundwater sampling at CCR sites. If field blank analytical results are available, check to assess the potential for field contamination unrelated to the sampling equipment.

- Sampling technique: A change in sampling technique, whether planned or due to an error, can have an influence on resulting concentrations if it affects the amount of sediment, as measured by turbidity, in the sample. See the next bullet for turbidity effects.
- Turbidity: Sudden increases in total dissolved solids and/or trace element concentrations can sometimes be associated with an increase in suspended solids/turbidity in a sample, relative to previous samples. Because the CCR Rule requires collection and analysis of unfiltered samples, elements comprising or attached to the particulate matter that causes turbidity are digested and analyzed along with the dissolved elements in the sample. Therefore, a turbid sample can yield higher concentrations for the elements that make up or are attached to the particulate matter. Evaluate the sampling technique used and the field analytical results, particularly the turbidity value if available, to assure that low-flow sampling procedures were properly followed. If the field analytical results do not indicate that stabilization of the field parameters (pH, temperature, specific conductance, dissolved oxygen, redox potential, and turbidity) was achieved, then sampling technique may be a defensible cause for an SSI/SSL. Some facilities establish sampling protocols that include collection of replicate filtered samples whenever a sample location has a turbidity greater than 10 to 20 NTU to allow comparison of analytical results between filtered and unfiltered samples. If filtered results are available, and are considerably lower than the unfiltered results, then turbidity resulting from differences in sampling technique, a screen failure in the monitoring well, or a need for redevelopment may be defensible alternative causes.
- Sampling anomalies: Review field documents (chain of custody form, calibration logs for field equipment, field notes, and field data) to see if any issues were encountered during the sampling event that could potentially affect the sample integrity. Potential anomalies may include improper bottles or preservation, inadequate calibration of field instruments, failure to achieve stabilized field parameters prior to sampling, use of non-dedicated or improperly cleaned equipment, improper labeling, etc.

Laboratory Causes (ASD Type II)

There are opportunities for potential contamination or errors associated with laboratory procedures, equipment decontamination and calibration, and sample handling and analysis. In addition to the analytical results, laboratory reports include documentation of methods and data qualifier flags to indicate potential issues that may affect the accuracy of results. The following are common data qualifiers for inorganic constituents sanctioned by USEPA:

- U = Reading was less than the method detection limit (MDL).
- J = Reading was less than the contract required quantitation limit but greater than or equal to the MDL.
- B = Analyte was found in the method blank as well as in the sample. Indicates possible/probable blank contamination.
- E = Reported value is estimated due to the presence of an interference. Look for comments.
- N = Spiked sample recovery not within control limits.
- * = Duplicate analysis not within control limits.
- D = The reported value is from a dilution.

The B, E, N, *, and D flags all indicate potential for laboratory errors that may have triggered an SSI/SSL, and warrant a closer look at the results to determine if the reported results may be invalid and if resampling and/or an ASD should be considered.

Potential errors associated with laboratory handling and analysis include:

- Calibration: Use of poorly or inadequately calibrated instruments may cause elevated analytical results that are not representative of the water quality at the sampling location. If results for a particular analyte in multiple samples, particularly if all were analyzed on the same day (laboratories typically recalibrate their instrumentation daily), are higher than the norm, then poor calibration of analytical equipment may be a potential cause. Consider reviewing instrument calibration records to see if poor calibration is a defensible alternative source for the SSI or SSL.
- Contamination: One or more samples may be contaminated by improperly cleaned and/or prepared sample bottles, analytical equipment, calibration standards, reagents, or preservatives. This type of error is more likely to be evident for trace elements such as those found in Appendix IV of the CCR Rule than for higher concentration constituents such as those listed in Appendix III of the CCR Rule. If sample contamination is suspected, evaluate the analytical results for trip blanks (if available) and method blanks. Trip blanks are sample bottles filled with laboratory-prepared deionized water that accompany the samples to and from the field, without being opened. If trip blank results show detection of analytes, it is possible that the sample bottles may not have been properly cleaned or the deionized water may have been contaminated. Method blanks are analyte-free laboratory quality control samples subjected to the entire analytical process used to demonstrate that the analytical system did not introduce contamination. The method blank results should be below the method reporting limits. If they are not, then the analytical process may have introduced contamination. Look for "B" data qualifiers to determine if the analytes were detected in the method blank.
- Digestion Methods: Use of more aggressive digestion methods using hydrofluoric acid for total digestion rather than concentrated nitric and/or hydrochloric acids for "total recoverable metals" may result in higher trace element concentration results compared to results using "total recoverable metals" methods. USEPA requires digestion consistent with "total recoverable metals" methods under the CCR Rule. If more aggressive digestion methods were used, reanalysis (if there is any remaining undigested sample) or resampling is warranted to determine if the SSI/SSL result persists when total recoverable digestion methods are used.
- Dilution Corrections: If dilutions were necessary to overcome matrix interferences, then review analytical results to ensure that the analytical results were properly corrected and that the resulting detection levels are low enough to detect increases over background levels. Look for the "D" data qualifiers to determine if dilutions were used. If a sample result is suddenly higher (especially if it is close to an order of magnitude higher) than the norm at a sample location and dilution was used, it is possible that the sample results were not corrected for the dilution ratio (Figure 2-2). Use of dilution ratios typically increases the MDL. If the sample results are non-detect but the MDL is higher than the norm, erroneous statistical identification of increasing trends may occur, depending on how non-detects are handled in the statistical analysis.

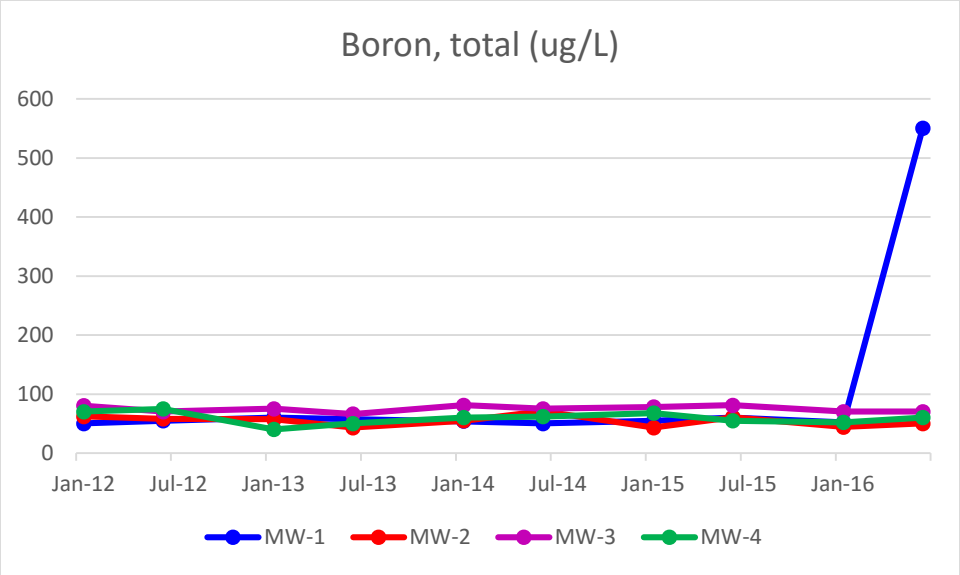

Figure 2-2
Time series plot showing potential dilution error

- Interference: Elevated analytical results may occur due to interference from other constituents present in the sample. If the laboratory identified interferences, the analytical report should include "E" data qualifiers. If interference was a problem, consider reanalyzing if there is sufficient remaining sample, and/or resampling and analyzing using methods that are less sensitive to interference from constituents of concern.
- Methods: Use of inappropriate methods or methods with reporting levels (RLs) or practical quantitation levels (PQLs) that are higher than background or maximum contaminant levels (MCLs) can result in erroneous analytical results or use of elevated non-detect values that can result in erroneous statistical determination of increasing trends. If use of inappropriate methods is suspected, verify that the methods used match those specified in the sampling and analysis plan, and are appropriate for the objectives of the groundwater monitoring program. Table 3-1 of EPRI (2015) shows methods, typical MDL and PQL capabilities, potential for interferences, and relative costs of test options for the CCR Rule Appendix III and Appendix IV constituents. This information can be very helpful in selecting and verifying that appropriate analytical methods were used.
- Technique: Poor analytical technique or use of poorly calibrated instruments (lack of quality control) can result in erroneous sample results. Check the laboratory report for data qualifiers ("B", "E", "N", "*") indicating that quality control may have been a problem.
- Transcription: Improper recording of results or mixing up results between samples can cause erroneous identification of SSI or SSL trends. If analytical results for two sampling locations are suddenly out of the norm, it's possible that the analytical results were transcribed to the wrong sampling locations. If a single location is suddenly out of the norm by an order of magnitude or more, it is possible that a transcription error such as inconsistency in units may have occurred.

Statistical Evaluation Causes (ASD Type III)

A primary challenge in statistical analysis is maintaining adequate statistical power while minimizing the false positive rate. While a detailed discussion of statistical methods and associated false positive rates is beyond the scope of this text, it is important to be aware that false positives can occur and are inherent in the statistical methods used for evaluation of groundwater quality data. See EPRI (2015) for guidance on statistical methods and recommendations for statistical approach under detection monitoring, assessment monitoring, and corrective action monitoring.

The following types of statistical errors could potentially falsely identify an SSI/SSL:

- Lack of statistical independence: The statistical comparison tests to determine if an SSI/SSL has occurred assume that the results are statistically independent. If samples are collected from the same well before the groundwater can flow through the well and be replaced with a fresh sample, then the samples are not physically independent and the comparison is not valid. As stated in the USEPA Unified Guidance (USEPA, 2009), the aquifer may "exhibit pockets or sub-zones of higher or lower concentration, perhaps due to location-specific differences in natural geochemistry or the dynamics of contaminant plume behavior over time." Generally, lack of statistical independence may be of concern if the groundwater velocity is less than 5-10 ft/yr. This type of statistical error is more likely to trigger an SSI during detection monitoring if a resampling protocol is included in the statistical plan, because the resample is collected more quickly after the original sample than the next regularly scheduled sample, and is therefore more likely to lack independence. This can be avoided by factoring groundwater flow rates into the timeframe calculation for resampling in a statistical analysis plan. Lack of independence is less likely to trigger an SSL during assessment monitoring due to the multiple sample design inherent with confidence intervals that are used in assessment monitoring statistics.
- Outliers: An outlier is a result that falls outside the typical range of values due to causes *other than* natural variability or a true change in concentration, and as such is not representative of groundwater quality. An analytical result that is suddenly much higher or lower than historical values represents a potential outlier, and there are graphical and statistical methods to identify such values. An SSI/SSL could be the result of an outlier due to transcription or typographical error, contamination, analytical interference, or other cause described under ASD Types I and II. Potential outliers need to be evaluated by reviewing sampling and laboratory documentation, and sometimes professional judgement needs to be applied to determine a) if the result is valid and should be included in the statistical analysis, b) if the result is due to an error and should be replaced with a corrected value, or c) if the value should be flagged and maintained in the database but not used in statistical calculations. If an outlier is confirmed, recalculation of the comparison to background or groundwater protection standard (GWPS) without the outlier can be performed to determine if the SSI or SSL determination was dependent on the outlier.
- False positives: A false positive is not an error per se; however, by statistical design, false positives can be expected to trigger a certain number of SSIs or SSLs under any statistical analysis plan. A false positive, also referred to as a Type I error, occurs when an SSI/SSL is falsely determined for a constituent at a compliance monitoring well relative to background groundwater quality (for SSIs) or a GWPS (for SSLs). The USEPA Unified Guidance

(USEPA, 2009) recommends that a statistical program be designed so that the site-wide false positive rate (SWFPR), which is the potential for one or more false positives on a site-wide scale, be 10% or less per year (5% per semi-annual sample event). See EPRI (2015) for a detailed discussion of statistical options and recommendations for balancing statistical power with false positive rates. Proving a false positive for an ASD may be challenging, and may require a weight of evidence approach as described in Section 6.

- Non-detect processing: Method detection limits change over time, although usually downward, or can suddenly increase by a factor of 10 or more when a laboratory dilution is used. If there is a dilution, or if MDLs increase (Figure 2-3), then an SSI could result if MDLs are used in statistical analyses. Potential for this type of statistical cause can be minimized by using set reporting limits for non-detect results and by using the double quantification rule when all background results are lower than the reporting limit.

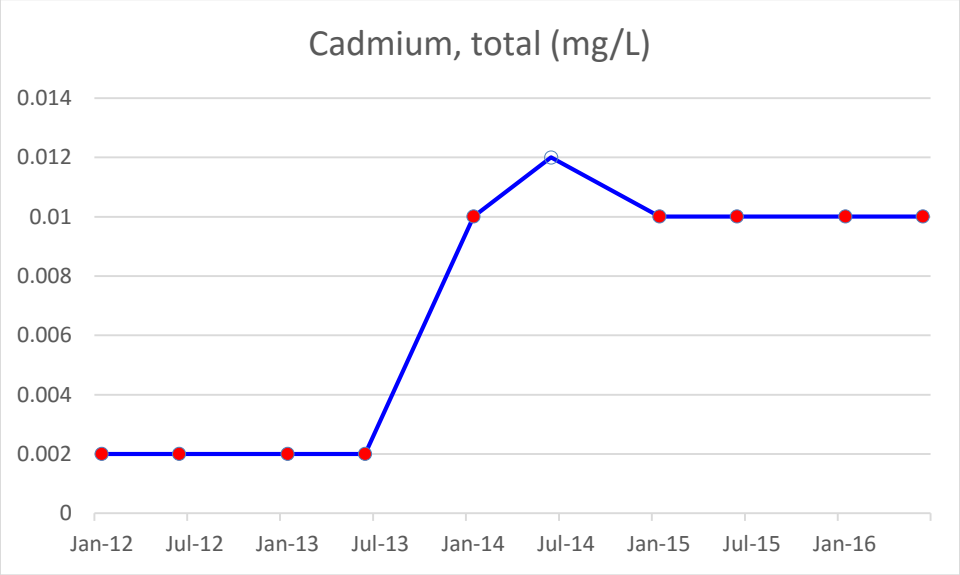

Figure 2-3
Time series plot of showing increasing trend associated with changing detection limits. Red markers indicate sample results below the minimum detection level associated with each respective sampling event.

Background Data: In the initial stages of detection monitoring, if there are numerous SSIs in the absence of a suspected release from the facility (e.g., a new lined landfill), then it is possible that background groundwater is not representative of downgradient groundwater due to spatial or temporal variability. The Unified Guidance (USEPA, 2009) states that a "high quality background dataset is the single most important key to a successful statistical groundwater monitoring program" and recommends a minimum of at least 8 to 10 independent samples for the initial background dataset before running most statistical tests.

Later on, apparent SSIs or SSLs can be triggered when new background data are added to an existing background dataset if that addition results in a change in statistical analysis method. This is particularly relevant if new data changes the distribution of the background dataset from parametric to non-parametric (Figure 2-4), because most non-parametric tests used in

groundwater analysis use the highest value as the upper limit (for detection monitoring) or GWPS (for assessment monitoring), and have a higher false-positive rate than their parametric counterparts.

Refer to Chapter 5 of the Unified Guidance (USEPA, 2009) for a thorough discussion of establishing background, reviewing and updating background, and effects of spatial and temporal variability on background.

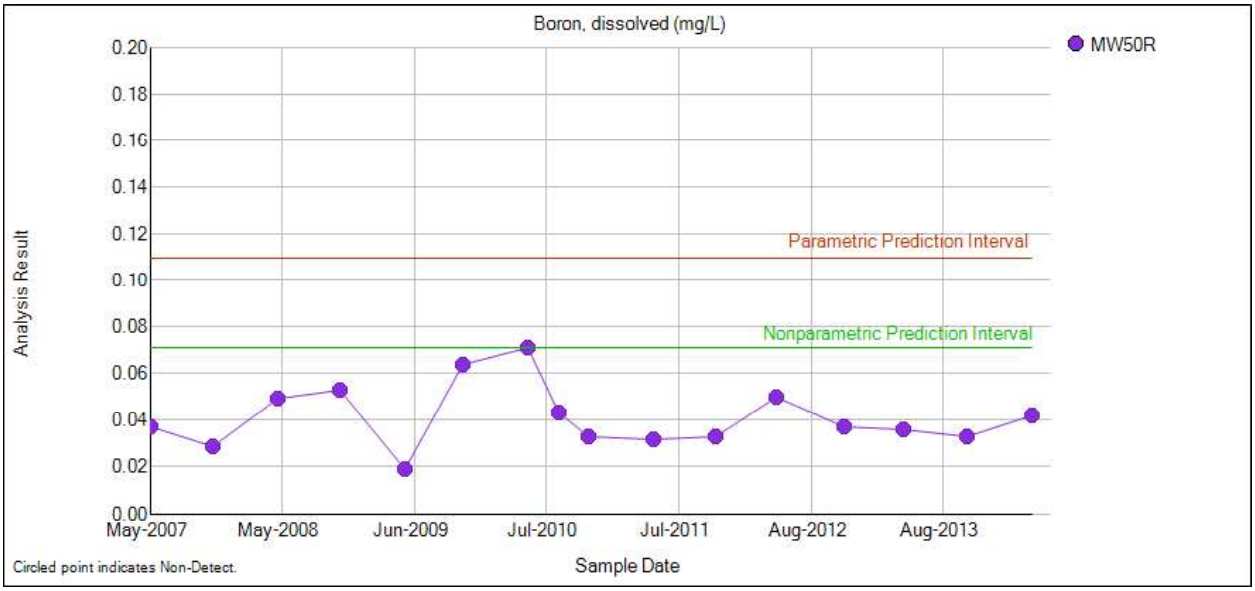

Figure 2-4
Background dataset illustrating the difference between a parametric and non-parametric upper prediction interval

Natural Variation (ASD Type IV)

Natural variation is recognized as a potential alternative cause of SSIs and SSLs under the CCR Rule. This category encompasses variability due to geologic influences such as dissolution of geomedia and natural ion exchange, changes in groundwater quality related to precipitation, seasonal changes in groundwater level or flow direction such as groundwater recharge and discharge fluctuations near surface water bodies, changing water levels in monitoring wells, time-of-travel for monitoring wells to detect upgradient changes, and influences related to changes in pH, oxidation reduction potential, and biological activity. These interactions and how they may affect groundwater quality are discussed in more detail in Section 4.

Alternative Sources (ASD Type V)

Sources for constituents dissolved in groundwater may come from both natural and anthropogenic sources. Natural sources include constituents present in groundwater from dissolution of minerals from the geomedia the groundwater has passed through. Anthropogenic sources can be complex and are too numerous to completely categorize, as many of them are likely to have source-specific signatures.

Table 2-2 provides information on natural and anthropogenic occurrence and typical behavior in groundwater for Appendix III and IV constituents as well as other constituents that may be helpful for identification of potential alternative sources. This table also identifies the relevance of the constituent as a CCR indicator for coal ash and FGD gypsum leachate.[4]

Table 2-3 provides an overview of common constituents that may be present in groundwater from a variety of anthropogenic sources. This information is intended to stimulate thought regarding constituents that *may be* present in groundwater, absent a release from the CCR site, if one of these activities is upgradient and has experienced its own release. Table 2-3 is not definitive; the information may be incomplete or not representative of actual anthropogenic sources near a particular site under evaluation. Site-specific investigation of nearby activities and history can be performed to verify groundwater impacts if an anthropogenic alternative source is suspected.[4]

A more detailed discussion of common groundwater impacts and contaminants associated with some of the more likely alternative sources is provided in Section 5.

[4] Tables 2-2 and 2-3 are also provided in Appendix A for easy reference with the ASD checklists.

Table 2-2
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25th / 50th / 75th Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
CCR Rule Appendix III Detection Monitoring Constituents								
Boron	Key Indicator	Yes if unwashed	17 / 35 / 82 ug/L	No	Very mobile	Boron-containing rocks (especially marine shales and clays), seawater, volcanic and geothermal activities, mined in arid regions of the United States (and other countries)	Fly ash leachate, may also be present in FGD leachate; sewage sludge, boron-containing fertilizers or herbicides, manufacture of glass, fiberglass, ceramics, soaps, detergents, bleach, fire retardants, and lubricants; used in control rods of nuclear reactors, and to produce a green color in pyrotechnics and flames; also used in the aerospace industry	Micronutrient for plants but may be toxic to some plant species in high concentrations. Boron deficiencies are more common than toxicities. Mobile in most hydrogeological environments, particularly sandy materials. Sorption to clay reaches a maximum in the pH range of 8-10.
Calcium	No	Yes	21 / 43 / 70 mg/L	CEC	Slightly mobile	Calcium carbonate rocks, limestone, calcium clay; fifth most common element in Earth's crust	Water softening wastes, soil acidity neutralization (lime additions to soil), calcium road salt, deicing, agriculture, cement and concrete, drying agents	Calcium carbonate is one of the most common calcium minerals. The concentration in groundwater may be limited by the solubility of calcium carbonate or calcium sulfate (gypsum). May be sorbed by ion exchange in soil and sediments but tends to be a reversible reaction.

Table 2-2 (continued)
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25th / 50th / 75th Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
CCR Rule Appendix III Detection Monitoring Constituents								
Chloride	No	Yes if unwashed	3.1 / 8.6 / 23 mg/L	No	Very mobile	Salt water and brackish water sources; chloride anion is the most abundant element (other than hydrogen and oxygen) in Earth's oceans	Road salt, deicing, water softening wastes, sewage, septic effluent, livestock waste, oil-field brines, salt water intrusion (oil and gas well production), industrial emissions, incinerator ash, landfill leachate, aerospace industry, automobile industry, soaps and detergents, drying agents, flame retardants, flocculants, pharmaceutical and medical waste	
Fluoride	Yes for some coal ash	Yes for some FGD gypsum	<0.1 / 0.2 / 0.4 mg/L	No	Mobile	Natural weathering of fluoride-containing minerals	Steel, brick, and aluminum manufacturing; waste incineration, municipal water treatment	Occurs as fluoride anion at pH > 3, hydrofluoric acid at pH < 3. Can be sorbed by amorphous aluminum and iron oxides under strongly acidic conditions.
pH	No	No	6.9 / 7.3 / 7.6 SU	- -	- -	Oxidation/weathering of naturally occurring pyritic soils due to well installation or other excavation may cause low pH	Low pH: Oxidation/weathering of pyrite in coal or coal ash, leaking batteries High pH: Certain coal ash leachates may have high pH; cement and concrete manufacturing and use, soaps and detergents	Fly ash leachate pH may be acidic or basic depending on coal type. Bituminous coals tend to produce more acidic leachate, especially if comanaged with pyritic mill rejects, and subbituminous coals tend to produce more basic leachate. Important due to impact of pH on leachability of many trace elements.

Table 2-2 (continued)
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25^{th} / 50^{th} / 75^{th} Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
CCR Rule Appendix III Detection Monitoring Constituents								
Sulfate	Yes for most coal ash	Key Indicator	4.7 / 14 / 36 mg/L	No	Very mobile	Sulfur is the 14th most abundant element in the Earth's crust; oxidation/ weathering of naturally occurring pyritic soils (such as iron sulfide)	Fly ash and FGD leachate, lead acid batteries, algaecides, gypsum mines, wood pulp production (paper mills), textile mills, tanneries, coal pyrite oxidation/weathering from mining or storage, industrial emissions and effluents, soaps and detergents, drying agents, flocculants, petroleum refining	Sulfate may precipitate with calcium, barium, and strontium. Not usually sorbed due to negative charge, but can be sorbed under acidic conditions by soils and sediments containing iron, aluminum, and manganese oxides with positive charges. May precipitate from solution as sulfides under strongly reducing conditions.
Total Dissolved Solids (TDS)	No	No	146 / 254 / 381 mg/L	- -	- -	TDS is largely based on concentration of major ions in groundwater (Ca, Mg, Na, K, carbonates, Cl, SO_4)		Refer to primary components.

Table 2-2 (continued)
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25^{th} / 50^{th} / 75^{th} Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
CCR Rule Appendix IV Assessment Monitoring Constituents								
Antimony	No	No	<1 ug/L	No	Very mobile		Flameproof retardants, batteries, lead shot; metal and glass manufacturing	Usually soluble but may be sorbed by iron, aluminum and manganese oxides under acidic conditions (EPRI, 1987).
Arsenic	No	No	0.23 / 0.79 / 3.0 ug/L	Yes, pH and redox	Variable	May be present in sulfide minerals and in organic forms; concentrations can be naturally higher than typical under reduced conditions or if sulfide minerals are oxidized	Wood preservatives (chromated copper arsenate), feed additives, pharmaceuticals, electronic devices, metallurgical applications, metal mining and smelting, cemeteries; pesticides/herbicides/ insecticides (prior to 1960)	Arsenic occurs in the 5+ oxidation state as arsenate (AsO_4^{3-}) under relatively neutral pH and oxidized conditions, and as 3+ arsenite (AsO_3^{3-}) under reduced conditions. Arsenic fate and transport is complex due to sensitivity to pH and redox. Sorption usually increases with decreasing pH.
Barium	No	No	24 / 54 / 120 ug/L	Yes	Mobile	Weathering of sedimentary rocks	Well drilling mud or fluid, mining; manufacture of glass, paint, and rubber	Usually present as relatively insoluble barium sulfate in fly ash. Most barium compounds have limited solubility. Sorbed by clay, soils, and sediment.
Beryllium	No	No	<1 ug/L	Yes, pH	Immobile	Relatively scarce in Earth's crust	Electronic and electrical components, telecommunications and computer components, defense applications	Strong tendency to sorb at neutral to alkaline pH. Sorption may be reduced in the presence of humic acids.

Table 2-2 (continued)
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25th / 50th / 75th Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
CCR Rule Appendix IV Assessment Monitoring Constituents								
Cadmium	No	No	<1 ug/L	Yes, pH	Slightly mobile	Minor component in Earth's crust, occurs in zinc minerals	Batteries, waste incineration, sewage sludge disposal, paint pigments, phosphate fertilizers, automobiles, electroplating and metal fabricating	Can be sorbed by clay, soil, and sediment at pH less than 8, but sorption decreases at low pH.
Chromium	No	No	0.68 / 1.2 / 3.0 ug/L	Yes, pH and redox	Variable	Primarily occurs as Cr(III) in soils and rocks	Electroplating, leather tanning, wood pulp production (paper mills), metal ore refining, wood preservatives, steel manufacturing, automobiles, electroplating and metal fabricating, paint and coatings	The solubility of Cr(III) generally increases at pH levels <6.5 and >11. Cr(III) is the predominant dissolved species under reducing to mildly oxidizing conditions. Cr(IV) is more soluble than Cr(III) at neutral to alkaline pH. Cr(VI) is soluble at alkaline pH and mildly to strongly oxidizing conditions.
Cobalt	No	No	0.063 / 0.17 / 0.48 ug/L	Yes	Variable	Relatively scarce in Earth's crust; usually occurs in combination with arsenic and sulfur in nature	Rechargeable battery electrodes, radial tires, drying agents, catalysts, paint pigments, medical wastes, automobiles	May be sorbed by mineral oxides (e.g., Fe and Mn), crystalline materials such as aluminosilicate, and natural organic substances in soil.
Lead	No	No	0.018 / 0.070 / 0.27 ug/L	Yes pH	Variable	Rare in Earth's crust	Smelting and mining, batteries, waste incineration, leaded gasoline (before 1996), lead-containing paint, glass manufacturing, ammunition, firing ranges, plumbing, automobiles	Sorption usually increases with pH.

Table 2-2 (continued)
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25th / 50th / 75th Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
CCR Rule Appendix IV Assessment Monitoring Constituents								
Lithium	Yes for some coal ash	No	2.0 / 6.0 / 18 ug/L	No	Mobile	Rare in Earth's crust, dissolution of lithium-containing minerals	Glass and ceramics production, lubricants, greases, batteries, salt water intrusion	Reacts with sulfate ions to form lithium sulfate anion.
Mercury	No	No	NR	No	Slightly mobile	Occurs as HgS in nature; can be converted to methylated forms by anaerobic microbes	Waste incineration, mercury mining, metal recycling, fungicides, fluorescent lamps, batteries, thermometers/ thermostats/switches (electronic equipment), automobiles	Can be sorbed by iron, magnesium, silicon oxides, and organic matter.
Molybdenum	Yes for some coal ash	No	0.32 / 1.0 / 3.3 ug/L	No	Very mobile	Usually combined with sulfur or oxygen in natural minerals	Steel production, catalysts, lubricants, pigments, fertilizers, animal feed	Micronutrient for plants and animals; may be in fertilizers or animal feed. Peak sorption at pH <5 and limited sorption above pH 8. Phosphate and other oxyanions will depress sorption.

Table 2-2 (continued)
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25^{th} / 50^{th} / 75^{th} Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
CCR Rule Appendix IV Assessment Monitoring Constituents								
Radium 226 + 228	No	No	NR / 0.28 / 1.2 pCi/L	Yes, CEC	No data	Natural decay product of uranium and thorium ores	Uranium mines, nuclear power, nuclear fuel and weapons manufacturing, uranium in coal	Radium decays to radon gas, so it is prevalent in locations where radon gas is a concern.
Selenium	No	No	0.12 / 0.34 / 1.0 ug/L	Yes, pH and redox	Variable	Usually occurs with silver, copper, lead, and nickel sulfide minerals; may exist in a variety of organic compounds	Metal mining and milling, industrial waste water, sewage effluent, waste incineration, saline agricultural waste waters	May exist as selenate (SeO_4^{2-}), selenite (SeO_3^{2-}), elemental selenium (Se^0), and selenide (Se^{2-}) in groundwater (shown in order from most to least oxic species). Since anionic selenium is the dominant form in groundwater, sorption typically is not significant. However, selenite can be sorbed by iron and aluminum oxides.
Thallium	No	No	<1 ug/L	Yes, redox	Mobile	Occurs in combinations with oxygen, sulfur, and halogens	Glass and electronic industries, iron and steel production, cement factories	May be immobilized under reducing conditions.

Table 2-2 (continued)
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25th / 50th / 75th Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
Other Constituents								
Aluminum	No	No	0.98 / 3.0 / 4.9 ug/L	Yes, pH	Slightly mobile	Most abundant metal in Earth's crust; weathering of aluminosilicate minerals	Mining and industrial emissions and effluents; most abundant metal in coal ash, cement and concrete, drying agents, well drilling, flocculants, abrasives, aluminum manufacturing	Most soluble in water under acidic and alkaline solutions, essentially insoluble in near neutral water. May be sorbed by soils, sediments, and organic matter.
Bromide	Possible for certain coal ash	Yes if unwashed	0.02 / 0.04 / 0.09 mg/L	No	Mobile	Brackish groundwater and sea water, relatively rare in Earth's crust	CCR fly ash and emission control wastes, particularly if bromide compounds were used to facilitate mercury capture; drinking water disinfection, flame retardants	
Copper	No	No	0.47 / 1.0 / 3.0 ug/L	Yes, pH and redox	Variable	Relatively common in Earth's crust	Manufacture of bronzes, brass, electrical conductors, and ammunition; sewage sludge wastes, municipal solid wastes, copper-containing fertilizers, cemeteries, electronics, plumbing, wood preservatives, automobiles, electroplating and metal fabricating	Solubility may be controlled by solubility of copper hydroxide. May sorb to organic matter, clay, aluminum, manganese, and iron oxides.
Iron	No	No	0.81 / 7.9 / 93 ug/L	Yes, pH and redox	Variable	Commonly has high concentration in groundwater under reduced conditions; Weathering of iron-containing minerals (dissolution of iron oxides under reducing conditions), 4th most common element in Earth's crust	Industrial emissions, pyrite oxidation/acid mine drainage from coal mining or storage, flocculants	Iron oxides my dissolve and become mobile under reducing conditions. Occurs as ferrous (+2) and ferric (+3) iron. Ferric iron can be sorbed by silica, clay, and iron and manganese oxides.

Table 2-2 (continued)
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25th / 50th / 75th Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
Other Constituents								
Magnesium	No	No	4.4 / 11 / 23 mg/L	CEC	Slightly mobile	Eighth most abundant element in the Earth's crust, abundant in sea water; dissolution of magnesium carbonates and clay minerals	Aluminum fabrication and welding (alloying agent), flares and pyrotechnics, fire retardants, heat-resistant bricks, animal feed, fertilizers, drying agents	Solubility may be limited under alkaline conditions. May be removed from solution by ion exchange in soils and sediments via reversible reactions.
Manganese	No	No	0.85 / 7.0 / 84 ug/L	Yes, pH and redox	Variable	Commonly has high concentration in groundwater under reduced conditions; 13th most abundant element in the Earth's crust	Production of steel and aluminum alloys, glass production, use as an additive in gasoline	
Nickel	No	No	0.35 / 1.1 / 2.5 ug/L	No	Variable	Commonly combined with iron or sulfur	Manufacture of steels, other metal alloys, and electronic applications; automobiles, electroplating and metal fabricating, petroleum	Sorbs to iron and manganese oxides, and clay to a lesser extent.
Nitrogen	No	No	0.07 / 0.55 / 2.4 (NO_3 as N) mg/L	Nitrification/ denitrifi-cation, redox	Very mobile as NO_3	In nature, nitrogen is converted from one redox state to another by abiotic reactions and microbial catalysis in oxic conditions: $NH_4OH \rightarrow NO_2 \rightarrow NO_3$; under reducing conditions: $NO_3 \rightarrow NO_2 \rightarrow N_2$	Fertilizers, livestock wastes, wastewater treatment plants, sewage and septic effluent, rubber manufacturing; ammonia sources include CCRs from sources using SNCR or SCR technology, coke production, flame retardants	NO_2 and NO_3 are not significantly sorbed by most soils, sediments, or clays, but NH_4OH is.

Table 2-2 (continued)
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25^{th} / 50^{th} / 75^{th} Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
Other Constituents								
Phosphate	No	No	<0.01 / 0.02 / 0.04 mg/L	Yes, pH	Variable	Phosphorus is the 11th most abundant element in the Earth's crust	Fertilizers, wastewater treatment plants, sewage and septic effluents, industrial effluents, soaps and detergents, flame retardants	Can be sorbed by iron, aluminum, and manganese oxides, and by clay under acidic conditions.
Potassium	Yes for some coal ash	No	0.9 / 1.7 / 3.5 mg/L	CEC	Mobile	7th most abundant element in the Earth's crust; Weathering of potassium-containing minerals	Water treatment, fertilizers, sea water intrusion, soaps and detergents, drying agents	May be removed from groundwater by reversible ion exchange with soils and sediments.
Silicon	No	No	12 / 19 / 31 mg/L	Yes	Very mobile	2nd most abundant element in the Earth's crust; usually in the form of SiO_2	Glass, ceramics, abrasives, electronic devices, metal alloying, water filtration, insulation, cement, concrete, paper, rubber, lubricants, flocculants	Can be sorbed by iron and aluminum oxides, and by clay minerals.
Silver	No	No	<1 ug/L	Yes, pH	Variable		Textile plant wastewater, photographic materials, sewage sludge, medical wastes, electronics, electroplating and metal fabricating	Can be sorbed by soils but affected by pH, clay content, particle size, organic content, and free iron and manganese oxide content.
Sodium	Yes for some coal ash	No	5.2 / 11 / 29 mg/L	CEC	Mobile	6th most abundant element in Earth's crust; brackish groundwater and surface water, sea water, weathering of sodium-containing minerals	Road salt, deicing, septic effluent, sodium hydroxide water treatment wastes, water softening, salt water intrusion (gas and oil well production), sewage and septic effluent, soaps and detergents, drying agents	Most sodium compounds are soluble but may be sorbed by reversible ion exchange in soils or sediments.

Table 2-2 (continued)
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25^{th} / 50^{th} / 75^{th} Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
Other Constituents								
Strontium	No	No	100 / 270 / 680 ug/L	Yes	Slightly mobile		Glass and ceramics production, pyrotechnics, phosphate fertilizers	Reacts with sulfate ions to form $SrSO_4^0$.
Vanadium	No	No	0.30 / 1.4 / 11 ug/L	Yes, pH and redox	Variable		Crude oil, oil shale, tar sands, phosphate fertilizers, wastes from steel production, petroleum	Can be sorbed by iron, aluminum, and manganese oxides; sorption decreases as pH increases.
Zinc	No	No	1.6 / 4.8 / 18 ug/L	Yes, pH	Variable		Fertilizers, protective coatings to reduce corrosion of metal surfaces, dry-cell batteries, castings, automobiles, lubricating oils and greases, plumbing/piping, electroplating and metal fabricating	Sorption increases with increasing pH but is also affected by clay content, particle size, organic content, and iron, aluminum, and manganese oxide content.

Notes:

1. Based on EPRI (2012). "No" indicates that the constituent it is not considered an indicator due to low concentration in CCR leachate relative to typical background, low mobility, and/or potential for reactivity.

2. Concentration ranges in ug/L from USGS (2011), Table 4; concentration ranges in mg/L or SU from USGS (2008), Tables 2 and 6; radium 226+228 from Szabo et. al (2012) supplemental table S-3; NR indicates that the concentration was not reported in any of these three documents.

3. Reactivity and mobility, while separate geochemical processes, are often interrelated. Reactivity descriptions in this table refer to chemical reactions, primarily precipitation and dissolution, that can change the concentration or mobility of the element in solution under typical aquifer conditions. Yes indicates that the constituent is subject to precipitation, coprecipitation, and/or dissolution reactions. In addition, pH and redox are indicated if they have a strong influence on the environments under which reactions occur and/or mobility. CEC is listed for constituents that are subject to cation exchange.

4. The mobility classification is based on the classification system of van Loon and Duffy (2000). See Table 2-2 of EPRI (2012) for corresponding K_d values.

5. Refer to Appendix B in EPRI (2012) for brief summaries of geochemical factors affecting reactivity and sorption. Detailed information can be found for selected constituents in the following EPRI reports:

- Arsenic
  1015550 | Chemical Constituents in Coal Combustion Product Leachate: Arsenic | Profile | 2008
  1021212 | Arsenic in Coal Combustion Products | Tech Brief | 2010
- Beryllium
  1012583 | Chemical Constituents in Coal Combustion Product Leachate: Beryllium | Profile | 2006
- Boron
  1005258 | Chemical Constituents in Coal Combustion Product Leachate: Boron | Profile | 2005
  1023737 | Boron in Coal Combustion Products | Tech Brief | 2012
- Chromium
  1022143 | Chromium in Coal Combustion Products | Tech Brief | 2011
- Lithium
  In Prep | Chemical Constituents in Coal Combustion Products: Lithium | Profile | 2018
- Molybdenum
  1021815 | Chemical Constituents in Coal Combustion Products: Molybdenum | Profile | 2011
  In Prep | Molybdenum in Coal Combustion Products | Tech Brief | 2017
- Selenium
  3002001237 | Chemical Constituents in Coal Combustion Product Leachate: Selenium | Profile | 2013
  3002003761 | Selenium in Coal Combustion Products | Tech Brief | 2014
- Thallium
  1016801 | Chemical Constituents in Coal Combustion Product Leachate: Thallium | Profile | 2008
  3002001155 | Thallium in Coal Combustion Products | Tech Brief | 2013

Table 2-3
Constituents Potentially Associated with Alternative Anthropogenic Sources

Potential Source	Constituents That May Be released to Groundwater*
Abrasives	**Silicon, aluminum**
Acid mine drainage	**Low pH, sulfate, iron**, dissolved solids, metals (aluminum, cadmium, calcium, chromium, cobalt, copper, magnesium, manganese, nickel, zinc, and others); can travel along mine shafts and tunnels and show up in unexpected locations (sometimes across aquifers) (notes 1, 26, 51, 54)
Aerospace industry	**Boron, perchlorate, chloride, cyanide, cadmium**, beryllium, solvents (trichloroethane, methylene chloride, trichloroethylene, toluene, methylethylketone), metals, oils (notes 2, 3, 4, 5, 51)
Aging infrastructure (leaking sewage, urban runoff)	Nitrate, phosphorus, sodium, chloride, organic substances, bacteria, pesticides, miscellaneous chemicals, cadmium, copper, iron, lead, selenium, zinc, and other elements (note 6)
Agriculture - animal feed lots	**Nitrates, ammonia, other nitrogen compounds, phosphorus/phosphate, chloride**, **arsenic**, **magnesium, molybdenum, selenium** and other elements, organic substances, bacteria/viruses (notes 7, 22, 51, 52, 54)
Agriculture - fertilization	**Nitrates, ammonia, other nitrogen compounds, phosphorus/phosphate**, **boron**, **cadmium, calcium**, chloride, cobalt, **copper**, cyanide, **magnesium**, **molybdenum, potassium, selenium, strontium, vanadium, zinc**, and other elements (notes 7, 22, 51, 52, 54)
Agriculture - irrigation	**Nitrates, ammonia, other nitrogen compounds, phosphorus/phosphate,** arsenic, boron, cadmium, calcium, chloride, cobalt, copper, cyanide, magnesium, mercury, molybdenum, potassium**, selenium**, sodium, sulfate, and other elements (notes 7, 8, 9, 22, 52)
Agriculture - lime addition	**Calcium** (note 22)
Agriculture - pesticides, herbicides, and insecticides	Aldicarb, Aldrin, alachlor, atrazine, carbofuran, chlordane, dacthal, DDT, dieldrin, bibromo-chloropropane, 1,2-dichloropropane, dinoseb, endrin, endosulfan, ethylene dibromide, heptachlor, hexachlorobenzene, lindane, mirex, PCBs, prometon, simazine, toxaphene, trifluralin; **arsenic** (prior to 1960), chloride, **mercury, boron**, **sulfate** (notes 10, 51, 52, 54)
Airport runways	**Sodium, potassium**, acetate, formate, urea (note 11)
Aluminum manufacturing	**Aluminum, fluoride, sodium**, magnesium, manganese, perfluorocarbons, polycyclic aromatic hydrocarbons (notes 12, 13)
Ammunition, firearms	**Lead, antimony, copper,** other heavy metals, nitrate, perchlorate, potassium, sulfur/sulfate, chloride (notes 14, 15, 22)
Asphalt plants	Oils, greases, PAHs, other hydrocarbons (note 16)
Automobile production	**Chloride, sulfate, phosphate,** oil and grease, solvents, ethylene glycol. Potential for heavy metals: aluminum (auto bodies), **cadmium** (tires and batteries), **cobalt** (radial tires), **chromium** (brakes, coolants, engine parts), **copper** (brake linings), iron (auto bodies), **lead** (batteries, lube oil and grease, bearings, brakes), **mercury** (batteries), **nickel** (lube oil, brakes), **zinc** (tires, fuel oil, lubricants) (notes 17, 18, 22)
Automobile repair shops	Gasoline, diesel fuel, oil, degreasing solvents (toluene, xylene, chlorinated solvents, MEK), ethylene glycol, lead, sulfate (notes 19, 44)

Table 2-3 (continued)
Constituents Potentially Associated with Alternative Anthropogenic Sources

Potential Source	Constituents That May Be released to Groundwater*
Batteries	**Sulfate, lead, antimony**, **cadmium, cobalt, lithium, mercury, zinc, low pH** (notes 22, 51)
Bleach manufacturing	**Boron** (bleaches containing sodium perborate) (notes 20, 31)
Brick manufacturing	**Aluminum, silicon, iron**, calcium, **fluoride**, **magnesium,** chromium (notes 21, 22, 52)
Catalysts	Aluminum, chromium, **cobalt**, copper, iron, **molybdenum**, titanium, tungsten, vanadium, zinc, and other metals (depends on catalyst manufactured or used) (note 22)
CCR - ash	**Boron, sulfate**, molybdenum, lithium, bromide, potassium, sodium, fluoride, selenium; may contain ammonia (nitrogen) if SCR or SNCR technology was used at the power plant (note 22)
CCR - FGD gypsum	**Sulfate**, fluoride, calcium, boron, bromide, chloride, selenium (note 22)
CCR - FGD fixated sludge	**Boron, sulfate**, calcium, chloride, molybdenum, lithium, bromide, potassium, sodium, fluoride, selenium (note 22)
Cemeteries	**Formaldehyde**, **copper, arsenic,** mercury, pesticides, fertilizers, weed killers (note 23)
Cement and concrete manufacturing and use	**High pH, aluminum, calcium, silicon, thallium,** chromium and other elements (notes 22, 24, 51)
Ceramics production	Oxides of carbon, **silicon, boron**, and nitrogen; may include aluminum, antimony, barium, copper, fluoride, iron, **lithium**, **strontium**, and other elements (notes 21, 22, 51)
Coal mining	**Sulfate, low pH, iron**, dissolved solids, trace elements (aluminum, beryllium, cadmium, chromium, cobalt, copper, lead, magnesium, manganese, mercury, nickel, selenium, **uranium (decays into radium 226+228)**, zinc and others); Oxidation of pyrite in coal can form sulfuric acid. The low pH increases solubility of many metals. (notes 1, 26, 51, 54)
Coatings	VOCs, solvents (halogenated solvents and non-halogenated solvents such as acetone, cresols, cresylic acid, nitrobenzene, benzene, toluene, xylene, methyl ethyl ketone, methylene chloride, etc.); trace elements may include barium, cadmium, **chromium**, cobalt, lead, mercury, molybdenum, nickel, titanium, and **zinc** (note 27)
Coke production (from coal)	**Phenols, ammonia (nitrogen), polycyclic aromatic hydrocarbons, cyanide**, benzene, naphthalene, anthracene, cresols, metals (see metals in "coal piles or coal waste piles") (note 28)
Computer and telecommunications components (electronics)	Trace elements may include aluminum, arsenic, barium, **beryllium**, cadmium, chromium, cobalt, **copper**, gallium, gold, iron, lead, manganese, mercury, palladium, platinum, selenium, **silver**, and zinc; solvents may include benzene, xylene (dimethylbenzene), trichloroethane, tetrachloroethane, ethylene glycol, methyl cellosolve; **silicon** (notes 29, 30, 32)

Table 2-3 (continued)
Constituents Potentially Associated with Alternative Anthropogenic Sources

Potential Source	Constituents That May Be released to Groundwater*
Defense applications	**Beryllium** (note 22)
Detergent or soap manufacturing	**Sodium, potassium, sulfates and sulfonates, high pH, phosphate**, **chloride, boron**, phenol, aluminosilicate, sodium citrate, nitrilotriacetate, alcohol ethoxylates, fats, oil and grease, lead, hexane, methyl alcohol, trichloroethane, perchloroethylene, benzene, toluene (notes 22, 34, 35)
Deicing	**Sodium, chloride**, **calcium**, magnesium, urea (notes 44, 51)
Drying agents	**Aluminum, calcium, sodium, potassium, magnesium, sulfate, chloride,** cobalt, lithium, phosphorus, silicon and/or other substances (notes 22, 36, 37)
Electronic equipment manufacturing and disposal	**Copper, silver, gold, palladium**, **arsenic, beryllium, copper, mercury, nickel,** selenium, **silicon, thallium** and other trace elements, chloride, fluoride, solvents (benzene, xylene, 1,1,1-trichloroethane, tetrachloroethane, methanol), ethylene glycol, hydrogen chloride, hydrogen fluoride (notes 22, 29, 30, 33, 51)
Electroplating and metal fabricating	**Cadmium, chromium, copper, nickel, silver**, sodium, tin, **zinc**, spent solvents, paints, spent acidic and alkaline solutions, cyanide, waste oils (notes 17, 22, 44, 51, 52, 56)
Explosives manufacturing and testing	**Nitroglycerin and nitro-aromatic compounds**, nitrate, perchlorate, ammonia, lithium, sodium, potassium, sulfur/sulfate, aluminum, chloride, **lead**, antimony, **copper**, nickel, silver (notes 38, 39, 40, 51)
Fertilizers	See Agriculture - fertilization
Fiberglass manufacturing	Aluminum, silicon, calcium, magnesium, **boron**, polyester or epoxy resin, styrene, solvents, volatile organic compounds, formaldehyde, urea, phenol, vinyl acetate (notes 31, 41)
Firearms, ammunition	See Ammunition, firearms
Firing ranges	**Lead**, antimony (notes 14, 22)
Fireworks manufacturing or use	Aluminum, antimony, arsenic, barium, **boron**, chloride, copper, lead, **magnesium**, nitrate, perchlorate, potassium, sulfur/sulfate, **strontium** (notes 31, 38, 39, 40, 51)
Flame retardant manufacturing or use	**Bromine, phosphate, nitrogen/nitrate, chloride**, **antimony, boron**, **magnesium**, polybrominated diphenyl ethers (PBDEs), PCBs (notes 22, 42, 43, 51)
Flocculants	**Sulfate, chloride, aluminum, iron**, ammonium, calcium, silica, polyamines (note 45)
Fluorescent lamps/bulbs	**Mercury**, PCBs in ballasts (note 47)
Fracking	See Oil and gas wells / production

Table 2-3 (continued)
Constituents Potentially Associated with Alternative Anthropogenic Sources

Potential Source	Constituents That May Be released to Groundwater*
Fungicides	See Pesticides
Furniture (wood stripping and refinishing)	Methylene chloride, methanol, isopropyl alcohol, acetone, perchloroethylene, toluene, acidic and alkaline solutions, metals, other solvents, petroleum distillates, resins, halogenated hydrocarbons, glycol ether (note 44)
Gasoline stations	**Benzene, ethylbenzene, toluene, xylene, MTBE**, ethylene dichloride, naphthalene, other organic compounds, lead (prior to 1996), **manganese**; trichloroethylene, perchloroethylene, methylene chloride, carbon tetrachloride, oils, ethylene glycol, hydraulic fluid, detergents, and acids (notes 22, 49, 51, 52)
Glass manufacturing	**Silicon**, antimony, **barium, boron, lead**, iron, **lithium**, **manganese**, nickel, potassium, **strontium**, **thallium**, tin, zinc, fluoride (notes 22, 31, 50, 51)
Industrial emissions	**Chloride, sulfate, iron,** wide variety of other elements and chemical substances (notes 22, 51, 54)
Irrigation	See Agriculture – irrigation
Junk and scrap yards	Used oil, gasoline, antifreeze, lead, sulfuric acid, agricultural chemicals/pesticides/other chemicals, metals (note 44)
Lamp manufacturing and disposal	**Mercury**, bromide, chloride, fluoride, iodide, PCBs, sodium (notes 22, 47)
Landfills - industrial	Wide range of trace metals, acids, **chloride**, sulfate, organic substances and pesticides (notes 51, 53, 54)
Landfills - municipal	Salts (sodium, calcium, magnesium, **chloride**, etc.), metals (iron, copper, zinc, other heavy metals), nitrate, organic compounds, solvents, pesticides (notes 22, 51, 54)
Laundry - dry cleaning	**Perchloroethylene (tetrachloroethylene)**, camphor oil, turpentine spirits, benzene, kerosene, white gasoline, petroleum solvents (petroleum naphtha), chloroform, carbon tetrachloride, trichloroethylene, 1,1,2-trichlorotrifluoroethane, glycol ethers, 1,1,1-trichloroethane, decamethylcyclopentasiloxane, n-propyl bromide, liquid carbon dioxide, fluorocarbon-113, antimony, cadmium, copper, lead, sulfate, zinc (notes 20, 31, 44, 52)
Leather tanning	**Chromium**, **cyanide**, **tannins**, chlorinated phenols including PCB, azodyes, cadmium, cobalt, copper, antimony, barium, lead, selenium, mercury, zinc, arsenic, nickel, formaldehyde, pesticides, salts, lime, acids, sodium sulfide, hydrogen sulfide, sulfate (notes 22, 55, 56)
Lubricants and greases	**Zinc**, polyaromatic hydrocarbons, arsenic, **boron**, cadmium, lead, **lithium**, **molybdenum**, PCBs, **silicon**, and other elements (note 22)
Medical supplies or wastes	Chloride, formaldehyde, **arsenic**, cadmium, **cobalt**, lead, mercury**, silver**, other heavy metals, radioactive waste, infectious or pathological waste, dioxins and furans from incineration; Also see Pharmaceutical industry (notes 22, 51, 57, 58, 59, 62)

Table 2-3 (continued)
Constituents Potentially Associated with Alternative Anthropogenic Sources

Potential Source	Constituents That May Be released to Groundwater*
Metal manufacturing - smelting	**Aluminum**, **antimony**, **arsenic**, beryllium, cadmium, **chromium**, **copper**, cyanide, iron, **lead**, **magnesium** (aluminum manufacturing), **manganese** (steel and aluminum manufacturing), mercury, **molybdenum** (steel manufacturing), **nickel** (steel and other metal manufacturing), **selenium**, silver, **thallium** (iron and steel manufacturing), zinc and other elements, **fluoride** (steel and aluminum manufacturing), **silicon, vanadium** (steel manufacturing), **zinc** (notes 22, 44, 51, 52)
Metal mining	Aluminum, antimony, **arsenic**, beryllium, cadmium, **chromium**, **copper, cyanide**, iron, **lead, manganese**, **mercury, nickel, selenium**, silicon, silver, thallium, tungsten, zinc and other elements (notes 22, 51, 52, 54, 56)
Metal plating	Spent solvents, paints, spent acidic and alkaline solutions, waste oils, heavy metal sludges, metal dust, chromium, copper, nickel, selenium, **zinc** and other elements (notes 22, 44, 51, 52)
Metal recycling	Iron, copper, **mercury**, nickel, zinc, and other elements (note 22)
Mining - unspecified	Depends on contents of ore; may include aluminum, antimony, arsenic, beryllium, cadmium, chromium, copper, iron, lead, manganese, mercury, nickel, selenium, silver, **sulfate** (gypsum mines), thallium, zinc, other minerals, hydraulic oils; **radium 226+228 (uranium mines)** (notes 22, 51)
Natural gas pipelines	**Methane, PCBs** (notes 60, 61)
Nuclear power	**Tritium**, **strontium 90, radium 226+228,** boron, beryllium (notes 31, 51, 54)
Oil and gas wells / production	Produced water may contain high **TDS, chloride, sodium**, sulfate, barium, boron, bromide, iodide, lithium, potassium, radionuclides, **vanadium** and other minerals, methane, volatile organic compounds (notes 52, 60, 63)
Ore refining / smelting	Aluminum, antimony, arsenic, beryllium, cadmium, chromium, copper, cyanide, iron, lead, manganese, mercury, nickel, selenium, silver, thallium, zinc and other elements (notes 22, 44, 51)
Paint and pigment manufacturing	VOCs, solvents (halogenated solvents, non-halogenated solvents such as acetone, cresols, cresylic acid, nitrobenzene, benzene, toluene, xylene, methyl ethyl ketone, methylene chloride, etc.); metals may include **barium**, **cadmium, cobalt**, **chromium**, **lead**, mercury, **molybdenum**, titanium, and zinc (notes 22, 44, 51, 52, 64)
Paper and pulp manufacturing	Organic and inorganic compounds including lignin, cellulose, phenols, mercaptans, **chromium**, nitrates, phosphates, **silicon, sulfides/sulfates**, chlorinated compounds including chloroform and dioxin (notes 22, 65)
Petroleum facilities and refining	Benzene, ethylene, toluene, xylene, methane, other organic compounds, hydrogen sulfide, **sulfate, nickel, vanadium** and other elements; some refineries use deep-injection wells to dispose of highly contaminated wastewater that could potentially contaminate groundwater (note 51)
Pharmaceutical industry	Wide variety of organic solvents; **arsenic, cobalt**, ammonia, chloride, cobalt, **silver** and other elements; Also see Medical supplies or wastes (notes 22, 51, 57, 62)
Photographic materials/photography	**Silver,** sodium, potassium (notes 22, 51)

Table 2-3 (continued)
Constituents Potentially Associated with Alternative Anthropogenic Sources

Potential Source	Constituents That May Be released to Groundwater*
Pigments	See Paint and pigment manufacturing
Plastic manufacturing	Cadmium, cyanide, benzene, vinyl hydrochloride, phthalates, trichloroethane, acetone, methylene chloride, methyl ethyl ketone, styrene, toluene, trichloroethane, sulfate, methanol, ethylene oxide, volatile organic compounds, sodium, caustic, nickel, lead, cadmium, mercury (notes 51, 66)
Plumbing	**Copper, lead, zinc** (note 51)
Road salting	**Chloride, sodium**, **calcium**, other salts (notes 22, 44)
Rubber manufacturing	**Ammonia, amines**, acetic acid, **barium**, cobalt, formic acid, sodium, **silicon**, sulfite/sulfate, organics, nitrogen compounds (notes 22, 69)
Salt or brackish water intrusion (from well drilling)	**High TDS, chloride**, boron, bromide, calcium, **lithium**, magnesium, **potassium, sodium**, sulfate, and other minerals (notes 22, 51, 54)
Salvage and junk yards	Grease, oil, solvents, lead and acid from batteries, metals (notes 44, 54)
Semiconductor manufacturing	Copper, silver, gold, palladium, arsenic, beryllium, copper, mercury, nickel, selenium, silicon, thallium and other elements, chloride, fluoride, solvents (benzene, xylene, 1,1,1-trichloroethane, tetrachloroethane, methanol), ethylene glycol, hydrogen chloride, hydrogen fluoride (notes 22, 29, 30, 33, 51)
Septic effluent	**Nitrate, phosphorus, chloride, sodium**, organic substances, bacteria and viruses, detergents, oils, heavy metals including cadmium, copper, lead, **selenium**, salts, septic tank cleaners such as trichloroethane or methylene chloride, and a wide variety of other chemicals (notes 22, 51, 52, 53)
Sewage	**Nitrate, phosphorus, chloride, sodium**, organic substances, bacteria and viruses, detergents, oils, **boron**, **cadmium**, **copper**, lead, **selenium, silver**, salts, and a wide variety of other chemicals (notes 22, 51, 52)
Soap or detergent manufacturing or use	See Detergent and soap manufacturing
Soil acidity neutralization	**Calcium**
Steel (including stainless) and iron manufacturing	Iron, chromium, manganese, nickel, ammonia, cyanide, chloride, copper, fluoride, molybdenum, sulfate, tin, thallium, zinc, hydraulic oils
Textiles	Polyvinyl chloride, chlorine bleach, benzidine, toluidine, cyanide, formaldehyde, hydrocarbons, ammonia, nitrate, organic solvents, chloride, sodium, fluoride, silicon, **sulfate**, phosphate, boron, bromide, chromium, copper, aluminum, antimony, potassium, aluminum, **silver**, titanium, zinc, copper, insecticides (notes 22, 51, 56, 67, 68)
Thermometers, thermostats, switches	**Mercury** (note 51)

Table 2-3 (continued)
Constituents Potentially Associated with Alternative Anthropogenic Sources

Potential Source	Constituents That May Be released to Groundwater*
Underground storage tanks (USTs leaking petroleum products such as gasoline)	Benzene, toluene, xylene, other organic compounds (notes 49, 51, 53)
Urban runoff	Oils, heavy metals, salts, copper, zinc, and other chemicals (notes 6, 18, 54)
Waste incineration	**Chloride, cadmium**, chromium**, fluoride, lead, mercury**, selenium, dioxins and furans (note 22)
Water treatment - flocculants	See Flocculants (note 45)
Water treatment - industrial effluents	Wide variety of metals, aluminum, **chloride**, **phosphate**, **potassium, sulfate**, nitrate, **selenium, silicon**, **sodium**, organics depending on industry (notes 22, 46)
Water treatment - municipal supply	Bromide, **chlorine, fluoride** (notes 22, 51)
Water treatment - treated sewage effluent	May contain **nitrates and other nitrogen compounds, phosphates, sodium, chloride**, **selenium, silicon**, and a variety of other elements (notes 22, 51, 52)
Water treatment - water softening	**Sodium, chloride**, **calcium**, magnesium, iron, other salts and metals (note 22)
Water treatment - cooling water	Chromium, zinc (notes 51, 52)
Well drilling (mud or fluid)	Constituents of bentonite clay and the natural geomedia including **aluminum, barium**, calcium, potassium, sodium and other minerals (note 22)
Wood preservatives and treatments	**Pentachlorophenol (PCP), creosote**, **copper, chromium, arsenic** (chromated copper arsenic, ammoniacal copper arsenate) (notes 22, 44, 48, 51)

* Bold indicates likely key indicators; list will vary by site-specific source; list may be incomplete or may not accurately represent a particular source.

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3
ASD EVALUATION TECHNIQUES

Primary Indicators for Coal Combustion Residual Leachate

A key line of evidence in any ASD will be whether or not there is an SSI/SSL for one or more primary CCR leachate indicator constituents. For ASD purposes, a primary indicator is:

- a constituent that typically has high concentration in leachate, relative to background, such that it is expected to have elevated concentration in the event of a release, *and*
- is not reactive, and has high mobility in groundwater such that it is expected to be at the leading edge of the plume, meaning that it will have elevated concentrations relative to background across the entire area of the plume.

Boron (B) and sulfate (SO_4) are primary indicators for coal ash leachate (EPRI 2012). The association of both boron and sulfate with CCP leachate was established during the late 1970s (EPRI 1979, Cherkauer 1980). Based on the EPRI CPInfo database, boron concentrations in fly ash leachate range between 1.1 and 109 mg/L with an average concentration of 8.3 mg/L; sulfate concentrations range from 89 to 6,070 mg/L with an average concentration of 1,370 mg/L (EPRI 2012). For FGD gypsum, sulfate is a primary indicator constituent. Sulfate concentrations for FGD leachate range from 437 to 1,549 mg/L with average concentrations around 1,300 mg/L (EPRI 2012).

There may be other primary indicators for a given CCR site depending on a variety of factors (Table 3-1). For example, molybdenum may be a primary indicator for landfilled fly ash derived from bituminous coal, and boron, bromide, and chloride may be primary indicator constituents for unwashed FGD gypsum. When determining primary indicator constituents, the optimal approach is to start with field-measured leachate concentrations. If field data are not available, published sources provide an alternative source of data. EPRI (2016) provides landfill leachate data ranges for a variety of CCRs and source coals.

Table 3-1
Potential Indicator Constituents for Coal Ash and FGD Gypsum

Potential Indicators for Coal Ash		Potential Indicators for FGD Gypsum	
Constituent	**Advantages and Caveats**	**Constituent**	**Advantages and Caveats**
Boron	Typically present in leachate, non-reactive and mobile in common hydrogeologic environments, and not a common anthropogenic contaminant.	Sulfate	High concentrations expected in both washed and unwashed FGD gypsum (EPRI, 2011). Commonly analyzed. Very mobile in all hydrogeologic environments. Less useful in strongly reducing environments where sulfate can be reduced to hydrogen sulfide gas.
Molybdenum	Most useful for dry-managed coal ash. May be less mobile than boron in some hydrogeologic environments. Concentrations may be too low in impoundment leachate to be useful if background groundwater has detectable concentrations.	Fluoride	Assure that leachate concentration is higher than background, particularly for washed gypsum. Mobile in common hydrogeologic environments, although precipitation as CaF_2 is possible.
Lithium	Useful for coal ash management sites where the power plant burned bituminous coal. Leachate concentrations are typically low in coal ash derived from subbituminous and lignite coal (EPRI, 2006).	Calcium	High concentrations expected in both washed and unwashed FGD gypsum (EPRI, 2011). Understanding of carbonate chemistry necessary to assure that precipitation or dissolution does not affect downgradient concentrations.
Sulfate	Commonly analyzed and very mobile in all hydrogeologic environments. Concentration in impoundment leachate may in some cases be too low relative to background to be useful. Less useful in strongly reducing environments where sulfate can be reduced to hydrogen sulfide gas.	Boron	Mobile indicator constituent for unwashed FGD gypsum. Concentrations for washed gypsum may be too low to be useful (EPRI, 2011).
Bromide	May have high concentration in coal ash leachate at power plants where brominated powdered activated carbon (Br-PAC) or calcium bromide is used for mercury control. Leachate concentrations for coal ash generated absent use of these technologies may be too low to be useful. Mobile and non-reactive in typical groundwater environments.	Bromide	Mobile indicator constituent for unwashed FGD gypsum, especially if Br-PAC or CaBr used for mercury controls. Concentrations for washed gypsum may be too low to be useful (EPRI, 2011).

Table 3-1 (continued)
Potential Indicator Constituents for Coal Ash and FGD Gypsum

Potential Indicators for Coal Ash		Potential Indicators for FGD Gypsum	
Constituent	**Advantages and Caveats**	**Constituent**	**Advantages and Caveats**
Potassium	Commonly analyzed, although may be less mobile than boron and sulfate. Assure that leachate concentration is higher than background and that there are no anthropogenic sources such as agricultural fields where potassium may be applied in fertilizers.	Chloride	Mobile indicator constituent for unwashed FGD gypsum. Concentrations may be very high if transport water is recirculated. Concentrations for washed gypsum may be too low to be useful (EPRI, 2011).
Sodium	Useful for coal ash management sites where the power plant injects trona or sodium bicarbonate, or burned subbituminous coal. Absent dry sorbent injection, leachate concentrations are considerably lower in coal ash derived from bituminous coal, particularly at impoundments (EPRI, 2006). Assure that leachate concentration is higher than background and that there are no anthropogenic sources such as agricultural fields, or major highways in northern climates where sodium may be applied as road salts.		
Fluoride	Mobile and non-reactive in common hydrogeologic environments. Assure that leachate concentration is higher than background.		
Source: EPRI, 2012			

Site-Specific Leachate Analysis

Collection of site-specific field leachate data is useful for ASDs because it identifies 1) whether or not particular constituents that can cause an exceedance have higher concentration in leachate than in background groundwater, and 2) the leachate signature or fingerprint.

Where possible, leachate samples from landfills and impoundments can be collected using leachate wells, lysimeters, and/or leachate collection systems. These collection methods are preferred because the samples collected are representative of interstitial porewater. Because leachate characteristics will change with coal types and sources as well as changes in emission control technology, it is important to collect leachate samples representative of the spectrum of CCR materials placed into the CCR unit. Samples of pond water, sluice water, and runoff water are less useful than porewater samples for groundwater fingerprint analysis because their chemistry is affected by the composition of the source water used for sluicing as well as the leachate. Laboratory samples do not always represent actual leaching conditions (pH, redox, and liquid-to-solid ratio) and therefore, are less representative of actual field leachate composition than field samples. They are also more likely to provide only a snapshot of leachate chemistry based on the coal type and technologies used at the time of generation.

Water Quality Analyses for an ASD

The constituents included in a groundwater monitoring plan may not provide all data needed to evaluate certain lines of evidence for an ASD. The list below will typically provide the information needed for all except specialized lines of evidence.[5] Some of these constituents may already be part of the monitoring plan, while others may represent extra or special analyses.

- The constituents listed in Table 3-1, depending on the CCR managed in the site, in order to identify primary indicators for the leachate. All of these could be analyzed in leachate samples, and those with elevated concentration could be analyzed in groundwater samples.
- Major ion concentrations (alkalinity, chloride, sulfate, calcium, magnesium, potassium, and sodium) in leachate and groundwater. These concentrations can be used to evaluate whether downgradient groundwater chemistry remains representative of background groundwater chemistry. Major ion chemistry can also be used to evaluate natural variability due to seasonal changes or other causes.
- Field turbidity in groundwater is an indicator of the presence of suspended solids that may contribute to elevated concentrations of constituents monitored in unfiltered samples under the CCR Rule.
- pH in leachate and groundwater because it provides information on chemical reactions and mobility in groundwater.
- Dissolved oxygen (DO), oxidation reduction potential (ORP), and iron and manganese in groundwater are all indicators of redox conditions. Changes in redox can affect the chemical state and solubility of sulfate in addition to trace elements including arsenic and selenium. For example, under strongly reduced conditions, sulfate can be reduced to form hydrogen sulfide or it can precipitate as iron sulfide, arsenic reduces to the more mobile arsenite species, and selenium reduces to the low-mobility selenite species.

Water Quality Signatures

Natural surface water and groundwater may contain literally thousands of other substances (USGS, 2003). In fact, water is often referred to as the universal solvent because it dissolves more substances than any other solvent. Sources of these dissolved constituents or solutes include dust and gases collected as precipitation falls to the earth, dissolution of minerals in the soil and rocks, infiltration of contaminants from anthropogenic sources, etc. Groundwater monitored at a CCR unit for compliance with the CCR Rule is a compilation of the history of all sources of water comingling at that particular monitoring well. Different sources may contribute some of the same solutes, making source identification challenging. The identification and use of water quality "signatures" can be used as a tool for deciphering the similarity between potential sources and the water quality at a specific monitoring point.

EPRI (2012) describes three tiers of investigation for evaluation of water quality signatures to determine if elevated concentrations represent a release from a CCR facility. Conversely, these

[5] Specialized lines of evidence include geochemical modeling, isotopic signatures, and tritium age dating. Refer to EPRI (2017).

tools can also be used to evaluate whether or not sources other than CCR are contributing to groundwater quality degradation. The three tiers defined by EPRI (2012) are:

- Tier I: Trend Analysis and Statistics
- Tier II: Advanced Geochemical Evaluation Methods
- Tier III: Isotopic Analyses

This section provides guidance for interpretation of results using these evaluation techniques for an ASD.

Tier I Evaluation

By requiring determination of statistically significant increases/levels, the CCR Rule essentially requires Tier I statistical analysis under detection monitoring and under assessment monitoring. Many of the indicator constituents listed in Table 3-1 are included in constituent lists for these monitoring programs, including the primary constituents boron and sulfate. As discussed next, if there is an SSI/SSL without a corresponding increase in a primary indicator constituent (boron and usually sulfate[6] for coal ash), then this is a key line of evidence for an alternative source demonstration.

As previously introduced, an ideal primary indicator is a constituent that has concentrations in leachate greater than concentrations in background/upgradient groundwater, is mobile, and is relatively non-reactive in the hydrogeologic environment. Boron and sulfate are the most common primary indicators for coal ash leachate (EPRI, 2012). This is the first line of evidence to investigate for an ASD. If a constituent other than boron and/or sulfate is identified as an SSI/SSL but boron and/or sulfate are not also identified as elevated over background, it is unlikely that leakage from the CCR unit is the source of the SSI/SSL. This relationship holds for other potential indicators identified in Table 3-1, such as fluoride and sodium, if they have elevated concentration in site leachate relative to background.

If the site-specific leachate signature has not been determined, the potential indicators identified for fly ash and FGD gypsum in Table 3-1 can be considered. All of these potential indicators are naturally occurring and may be present in background groundwater. If any of these potential indicators are elevated over background but boron and/or sulfate are not, that provides a line of evidence for an ASD. Conversely, if any of these constituents have been identified as an SSI/SSL in addition to boron and sulfate, then temporal trends can be compared to determine if the constituents are trending together in the same direction. The more this "fingerprint" matches, the more strongly the monitoring results point to a release from the CCR unit. The trends in Figure 3-1 for boron, lithium, and sulfate indicate that lithium concentrations tend to rise and fall with boron and sulfate concentrations indicating that lithium may be an additional indicator parameter for a release from this site.

[6] Sulfate concentration increases may not be evident if groundwater is strongly reduced.

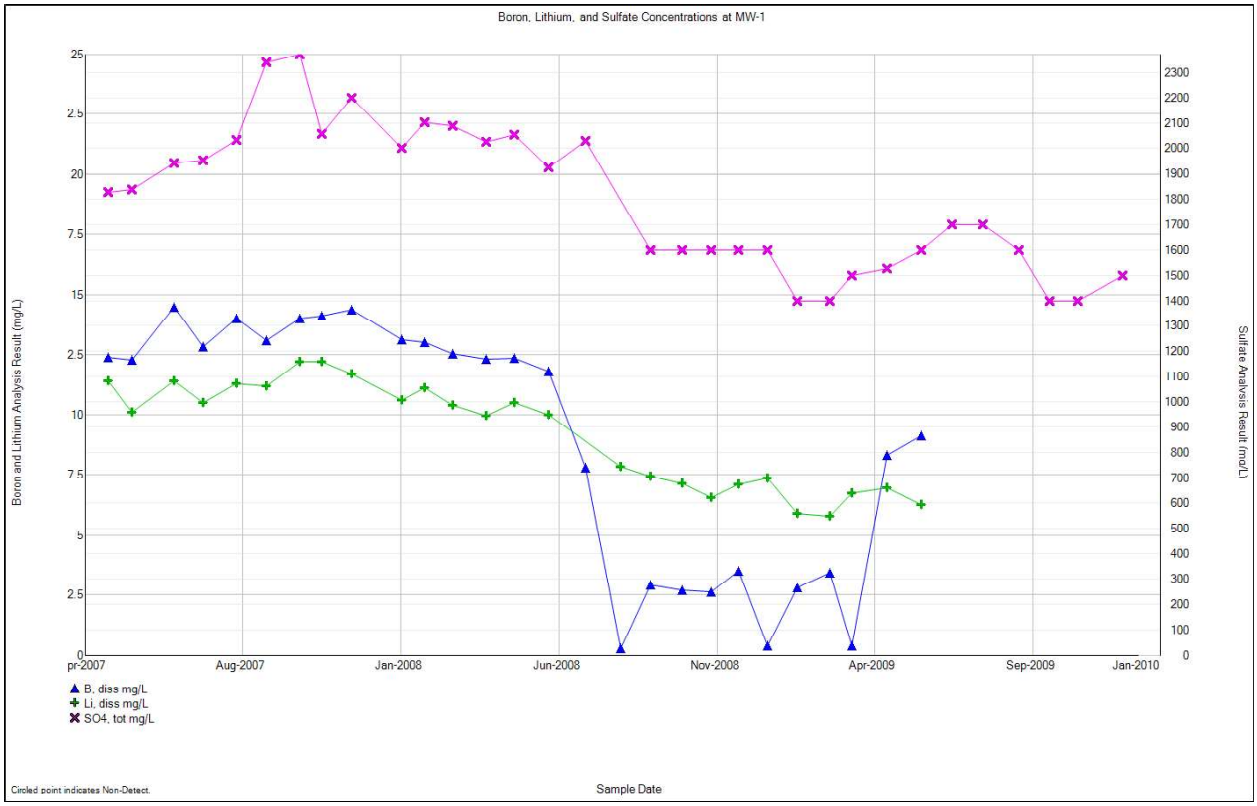


Figure 3-1
Time series plot showing potential correlation for lithium with boron and sulfate concentration changes indicating that lithium may be an indicator parameter for this site.

Scatter plots are another useful technique for identifying or refuting indicator parameters and identifying the presence of alternative sources. This technique plots one constituent on the X axis against another constituent on the Y axis. It can be used to show the relationship between two constituents. If the pattern of dots slopes from the lower left to the upper right portion of the graph, the two constituents are positively related (as one increases the other also increases). In this case, they are both likely related to the same source. If the pattern of dots slopes from the upper left to the lower right portion of the graph, the two constituents are negatively related and not from the same source. Figure 3-2 shows that arsenic and boron are not positively related. Therefore, even though the elevated boron concentrations suggest that a release has occurred, the lack of correlation suggests that the highest arsenic concentrations have a different source than the boron, which becomes a line of evidence in an ASD *specific to the arsenic*.

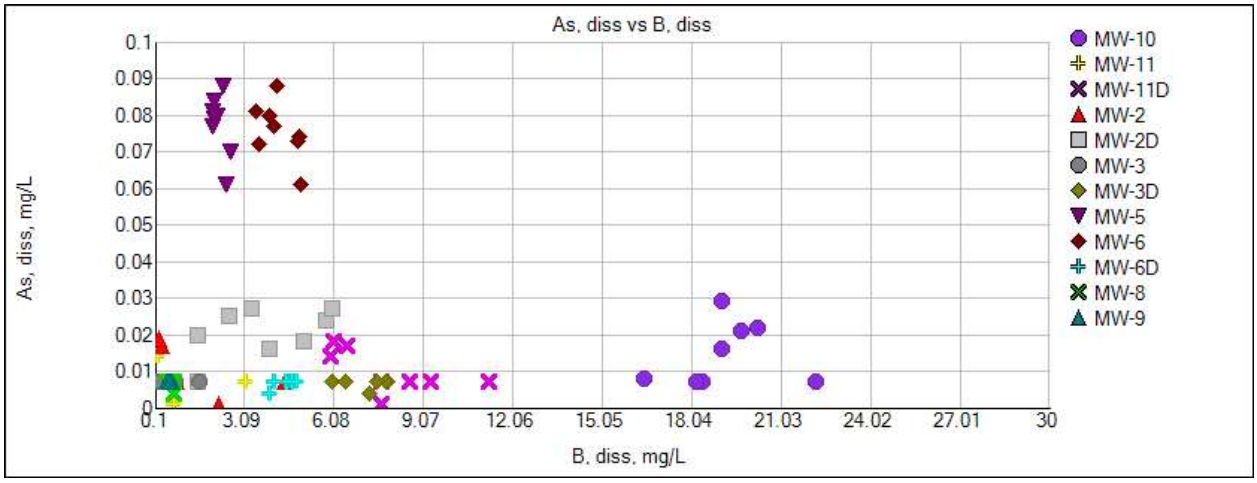


Figure 3-2
Scatter plot of arsenic versus boron, showing no correlation

Tier II Evaluation – Advanced Geochemical Evaluation Methods

Analysis of indicator constituents may not provide the lines of evidence needed for a strong ASD. More sophisticated methods may be needed at sites that have high concentrations of naturally occurring indicator constituents, multiple CCR sources, or upgradient sources of indicator constituents not related to the monitored unit, or where groundwater is brackish or saline. Furthermore, as groundwater travels through the environment, the composition may change due to geochemical interactions such as pH and ORP changes, influences from microbial activity, mixing with recharging surface water or other aquifers, or contamination from a variety of other anthropogenic or natural sources. The methods described below are useful for evaluating and visualizing the differences in water chemistry between upgradient and downgradient sampling locations.

Five Tier II methods were recommended in EPRI (2012) for multi-parameter comparison of water chemistry at multiple locations:

1. Ion ratios
2. Piper diagrams
3. Durov diagrams
4. Stiff diagrams
5. Fingerprint Analysis of Leachate Contaminants (FALCON)

This section adds a geochemical modeling and multivariate statistics to the EPRI (2012) list.

Ion Ratios and FALCON

The ion ratio method is the simplest approach from the list above and, unlike items 2 through 5, does not require analytical data for all major cations (calcium, magnesium, sodium, and potassium) and anions (chloride, sulfate, carbonate and bicarbonate or total alkalinity). Ion ratios are calculated by dividing the concentration of one constituent (usually the higher concentration constituent) by the concentration of another constituent from the same sample. Any units may be

used as long as the units are the same, because the ratio calculation is dimensionless. Ion ratios can be used to identify different source waters, or to determine that an additional source water is being added along a flow path. The method is based on the premise that if two constituents with similar mobility are released to groundwater, they will travel in groundwater at the same relative concentration or ratio unless they are mixed with water from other sources that have significantly different ratios of the same constituents. In other words, if leachate is released, then the relative concentration (ion ratio) in downgradient wells should be similar to the relative concentration in the leachate even if the concentration is diluted due to mixing with background groundwater. EPRI 2012 recommends that mobile, non-reactive constituents such as boron, chloride, lithium, molybdenum, and sulfate are the best candidates for this approach.

Table 3-2 illustrates the use of ion ratios as a line of evidence that downgradient well MW-3 is not impacted by ash leachate. In this example, MW-3 has higher sulfate concentrations than the two background wells, indicating that it may be impacted by CCR leachate. Boron concentrations at MW-3 are similar to upgradient well MW-1, whereas boron was not detected at upgradient well MW-2. Field leachate data indicate that chloride may be a CCR leachate indicator for this site in addition to boron and sulfate. Ion ratios for sulfate/chloride and boron/chloride were calculated and are provided in the chart (note that the boron/chloride ratios were multiplied by 1000 for enhanced visual representation). Since boron, sulfate, and chloride are all non-reactive in groundwater, ion ratios (boron/chloride and sulfate/chloride) representative of the leachate should remain consistent as leachate disperses and is diluted in groundwater unless there is another source of these constituents. In this case, the ion ratios at MW-3 are more representative of those at background wells MW-1 and MW-2, providing a line of evidence that CCR leachate is not the source of these constituents at MW-3.

Table 3-2
Use of Ion Ratios to Show that Groundwater Concentrations Are Not Caused by a CCR Release

		Background Wells		Downgradient Well	Field Leachate Concentration
Constituent	**Units**	**MW-1**	**MW-2**	**MW-3**	**LH-1**
B, tot	mg/L	0.02	<0.01	0.02	29
Cl, tot	mg/L	15	8	34	2,500
SO4, tot	mg/L	33	31	130	3,294
SO4/Cl Ratio		2.2	3.9	3.8	1.3
B/Cl Ratio	*1000	1.3	1.2	0.59	12

Ion ratios are also the basis of the Fingerprint Analysis of Leachate Contaminants (FALCON) method that was developed by the U.S. EPA. The FALCON method is more robust than simple ion ratios because it utilizes multiple constituents including all major cations and anions, as well as selected indicator constituents representative of the leachate signature. Regression analysis is used to mathematically represent the correlation between monitoring well, leachate, and background well signatures. EPRI (2012) provides a step-by-step procedure for the application of FALCON.

Piper, Durov, and Stiff Diagrams

Piper, Durov, and Stiff diagrams use graphical methods to group groundwater data to evaluate major ion chemistry. For an ASD, these methods are used to determine whether or not downgradient groundwater quality is a mixture of background groundwater and leachate. Interpretation of these plots can be subjective due to variation in the quality of various water groups. However, with Piper and Durov diagrams, a mixture is evident when downgradient groundwater quality plots at a point between leachate and background groundwater quality, and little or no mixing is determined if downgradient points plot with background, or at a point that is not between background and leachate. For a Stiff diagram, mixing is determined if the downgradient point evolves along a flow path to look less like background and more like leachate, where little or no mixing can be concluded if the shape of the downgradient point remains similar to background. These methods can also be used to evaluate whether or not an alternative source is affecting downgradient groundwater quality.

Common to each method is the necessity to conduct chemical analyses of the leachate and groundwater samples that include major cations and anions. Major cations present in natural water sources are calcium, magnesium, sodium, and potassium. Major anions are chloride, sulfate, bicarbonate, and carbonate. Bicarbonate and carbonate can be analyzed and reported together as total alkalinity. Prior to using graphical analysis for evaluation of major ion chemistry, it is good practice to calculate the charge balance in the sample. If the charge balance is not within an acceptable criterion (typically ±10%), it indicates that analytical results may be missing significant constituents, or there may be errors in the reported results. EPRI (2012) provides the equation and describes how to calculate and interpret the charge balance error for a water sample.

A Piper diagram is a graphical technique used to classify types of groundwater. It consists of two ternary plots (one for cations, and one for anions) linked to a diamond plot that is a combination of cations and anions. The Piper diagram below (Figure 3-3) shows an example where mixing is evident between leachate and groundwater, as denoted by the yellow-shaded area; however, the lysimeter chemistry does not indicate mixing of groundwater and leachate (primarily based on the cation triangle).

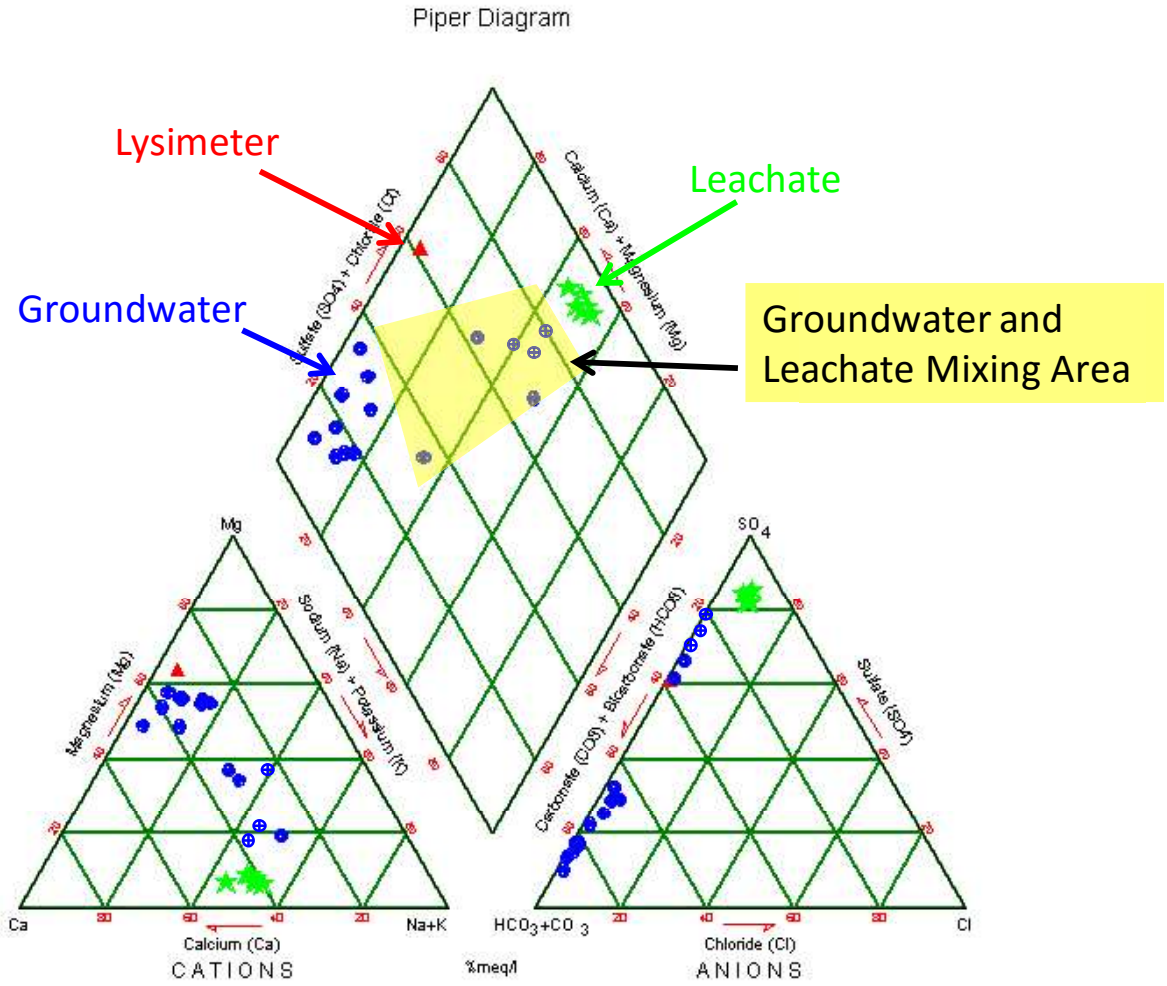


Figure 3-3
Example Piper diagram (from EPRI, 2012)

A Durov diagram is a combination of two ternary plots attached to a square-shaped plot. It displays data similar to a Piper diagram in different format. An example is provided in Figure 3-4. This diagram shows that bituminous coal ash leachate can be characterized as calcium-magnesium-sulfate water type, leachate from subbituminous coal ash can be characterized as sodium-calcium-sulfate water type, and background groundwater in this illustration can be characterized as calcium-magnesium-bicarbonate type.

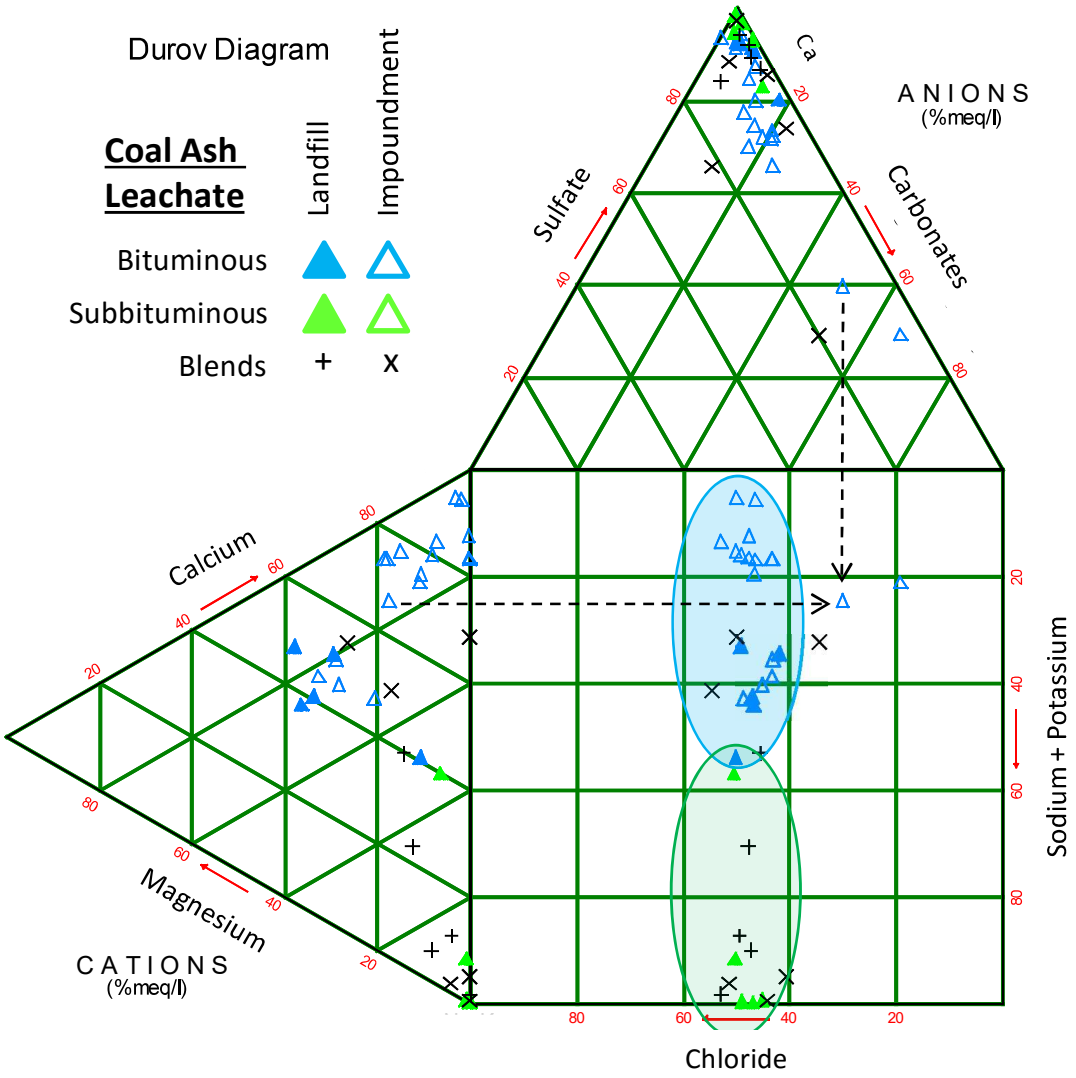


Figure 3-4
Durov diagram showing coal ash leachate derived from bituminous coal compared to subbituminous-lignite coal (From EPRI, 2012)

A Stiff diagram (Figure 3-5) is a multi-sided figure that compares the major cations in solution with the major anions. The resulting polygon can be placed in cross-sections or maps to show how the composition of the groundwater changes spatially.

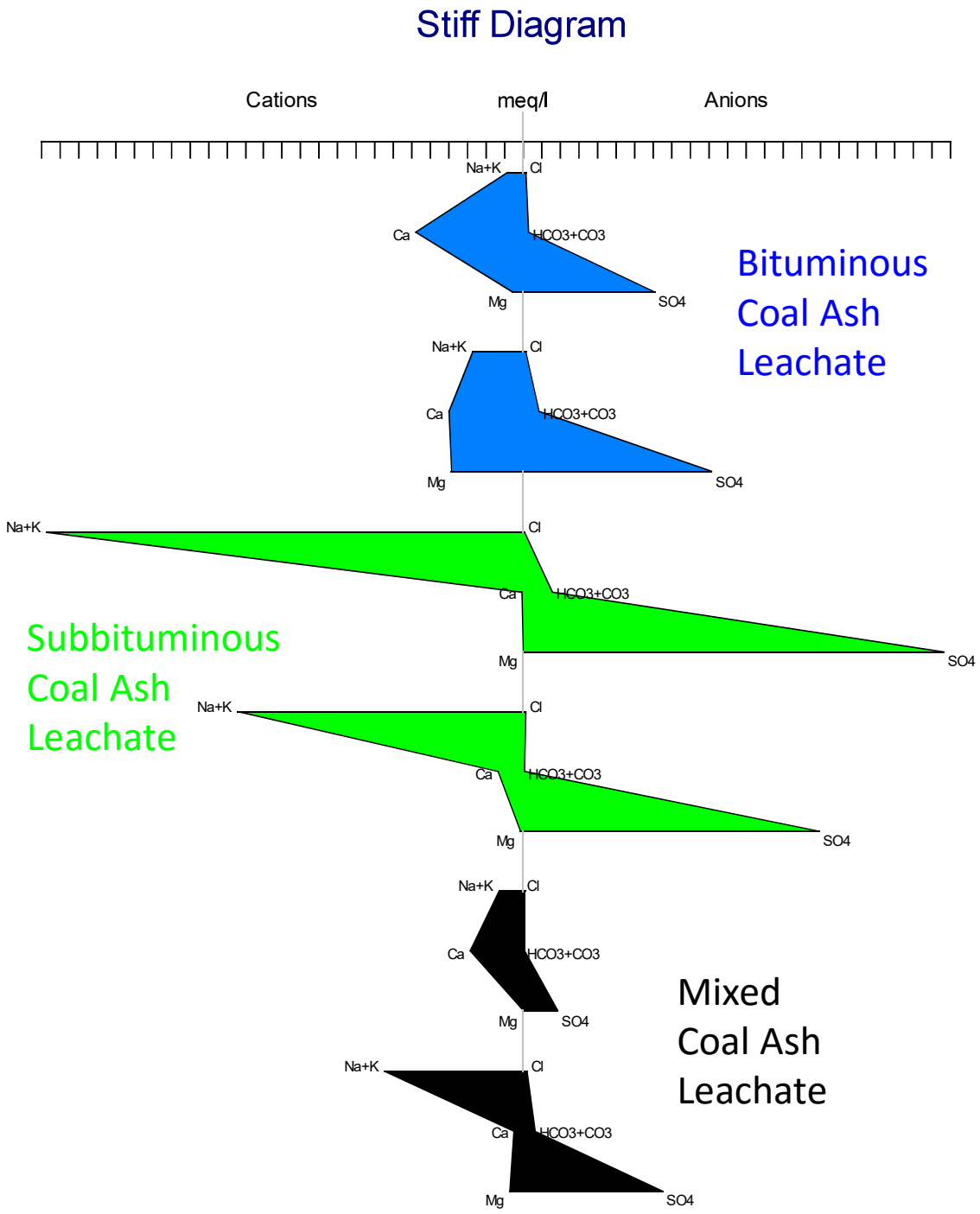


Figure 3-5
Stiff diagram showing six coal ash leachate samples (From EPRI, 2012)

Geochemical Modeling

Geochemical modeling is an additional Tier II geochemical method that can be used to evaluate the mobility of leachate or groundwater constituents based on chemical equilibrium and to potentially differentiate sources of groundwater contamination. Computer-assisted geochemical modeling has been used for many years to investigate the chemical equilibria of laboratory

extracts and field groundwater-leachate samples. EPRI (2017) discusses use of geochemical modeling to evaluate whether or not observed concentrations in a downgradient monitoring well can be a result of a groundwater flow path that includes mixing with CCR leachate.

Geochemical modeling can be used to identify the solid mineral phases that are controlling the solubility of dissolved cations and anions. Modeling can be used to identify whether dissolved constituents are thermodynamically favored to precipitate or remain in solution. Kinetic modeling attempts to identify the rate of chemical reactions. Such information is potentially useful for predicting the fate of dissolved constituents in a timeframe beyond the monitoring period. Kinetic modeling, however, may require additional information about the chemical and physical characteristics of the geomedia of the area under study.

Use of geochemical computer models requires entry of chemical characterization data for the groundwater sample(s) being evaluated. Analytical data, such as total sulfate or boron, are entered into the model, which will estimate the concentrations of several ionic forms (speciation) of each parameter. The model then calculates the degree of saturation of the liquid sample for hundreds of solid mineral phases. For example, if the liquid sample appears to be supersaturated with respect to a specific mineral, then that mineral is thermodynamically poised to precipitate from solution. Chemical precipitation may limit the movement of CCR constituents off-site.

The data required for chemical modeling are more extensive than those typically collected during a groundwater monitoring program. Most geochemical models require data for pH, ORP, alkalinity, and all the major anions and cations to ensure that the liquid sample is electrically balanced. In addition, solids data are often collected and used in the model to enhance confidence in results.

Multivariate Statistics

Multivariate statistics encompasses statistical analysis methods for evaluating more than two variables simultaneously and to determine how those variables relate to each other. Multivariate statistical techniques can be paired with geochemical modeling to determine the main sources of groundwater impacts in an aquifer, whether from a CCR leachate source, a naturally occurring source, or an anthropogenic source. Hydrogeological factors can also be co-evaluated with water quality data, including isotopic data from Tier III evaluations, using multivariate statistical methods. Although multivariate statistics is a powerful analysis tool for evaluating more complex datasets, it requires robust datasets, an experienced statistician, and a conceptual understanding of the input variables and their potential correlations. Computer software to perform multivariate statistical analysis relevant to environmental data is readily available.

Multivariate statistical methods utilized in the environmental field are typically correlation analysis, principal components analysis (PCA), and cluster analysis (CA). However, there are numerous other statistical methods available. Detailed explanations of the various multivariate methods available for statistical analysis are found in the following references:

- Anderson, T.W., 2003. An Introduction to Multivariate Statistical Analysis, Third Edition, John Wiley and Sons, Inc.
- Johnson, T.W. and D.W. Wichern, 2007. Applied Multivariate Statistical Analysis, Sixth Edition, Pearson Prentice Hall.

The scientific objectives identified by Johnson and Wichern (2007) for which multivariate statistics might be used include the following:

- **Data reduction or structural simplification**. To represent the information or conceptual model as simply as possible to aid in interpretation.
- **Sorting and grouping**. Groups of similar objects or variables are created based upon measured characteristics.
- **Investigation of dependence among variables**. Relationships between variables are evaluated to determine which variables might be independent and what two or more variables are dependent. From that information, the investigator might determine how the variables are related or what factor or feature they are related to.
- **Prediction**. Predicting the values of one or more variables based on observations of other variables. This is not a typical objective for an ASD evaluation.
- **Hypothesis construction and testing**. Testing of statistical hypotheses about multivariate populations to validate assumptions or reinforce other lines of evidence.

A brief description of a few of the more commonly used multivariate statistical methods pertinent to evaluation of groundwater and hydrogeologic data during an ASD is provided here, with the caveat that there are numerous other methods available.

Correlation Analysis can be performed on multiple variables, such as water quality constituents, to determine how much the variance of each constituent can be explained by the relationship with other constituents. Table 3-3 shows the Pearson product moment correlation matrix between pairs of variables measured in groundwater in background monitoring wells at a site. The correlation coefficients range between -1 and 1 and measure the strength of the linear relationship between the variables. The number of pairs of data values used to compute each coefficient was 60 (6 observations of each chemical parameter in groundwater per well for 10 wells). In the case of this dataset, correlations greater than 0.50 or less than -0.50 indicate statistically significant non-zero correlations at the 95 percent confidence level. Positive numbers indicate that the parameters are directly proportional, and negative numbers indicate that the parameters are inversely proportional. Bold-face numbers within highlighted boxes in the sample table indicate a high level of correlation between two parameters. Typically, correlation coefficients are rated as “high”, “medium”, and “low” (or “strong”, “moderate”, and “weak”) for values > 0.75, 0.75 to 0.50, and 0.50 to 0.30, respectively.

Table 3-3
Example Correlation Analysis Table

	Boron	Barium	Calcium	Chloride	Iron	Potassium	Lithium	Magnesium	Manganese	Sodium	Sulfate	TDS
Boron		0.13	-0.20	0.65	-0.02	0.25	0.47	-0.10	-0.04	0.63	-0.19	0.61
Barium			-0.11	0.77	**0.87**	0.38	0.28	-0.04	-0.16	0.73	-0.23	0.72
Calcium				-0.30	0.06	0.18	0.01	**0.98**	**0.81**	-0.34	**0.86**	0.00
Chloride					0.55	0.32	0.48	-0.17	-0.23	**0.94**	-0.37	**0.88**
Iron						0.40	0.31	0.11	0.10	0.58	0.06	0.62
Potassium							0.67	0.15	0.07	0.37	0.06	0.42
Lithium								0.05	0.08	0.45	-0.08	0.47
Magnesium									**0.86**	-0.21	**0.86**	0.14
Manganese										-0.18	**0.91**	0.15
Sodium											-0.29	**0.93**
Sulfate												0.01
TDS												

Principal Components Analysis (PCA) is used to reduce data to a small number of significant factors (i.e., components) for analyzing relationships among variables. PCA can be performed to evaluate the spatial variations of groundwater quality data and determine possible sources of specific contaminants. An analysis of principal components may reveal relationships between variables that were not readily apparent or suspected (Johnson and Wichern, 2007), or may assist in removing variables from an analysis that have no bearing on the objectives of an investigation. PCA analysis may serve as an intermediate step to determining what factors to focus on in an investigation and to assist in developing multiple lines of evidence in an ASD.

Cluster Analysis (CA) is a descriptive statistical analysis method used to identify groupings (i.e., clusters) of samples or other variables. CA is used to reveal the latent structure within a data set and is an exploratory tool only. For example, the data from a site can be analyzed using cluster analysis to demonstrate the following:

- Groupings of samples from wells into clusters based on water quality as defined by the major cations and anions
- Groupings of samples from wells into clusters based on water quality of minor and trace elements
- Groupings of wells into clusters based on selected water quality parameters and/or hydrogeologic variables

CA analysis results can be presented in several ways. To visually interpret how the data have been categorized, a graphical depiction of the clusters can be shown with a dendrogram. The dendrogram is a linkage tree that first links those samples or parameters that have the greatest similarity. Each subsequent linkage (or cluster) is less similar than earlier linkages. The greater the distance on the y-axis between linkages, the lower the significance between the linked samples or variables. In the example dendrogram displayed below (Figure 3-6), the first clusters of trace elements in groundwater upgradient from a CCR unit are between barium and iron, and the next cluster is aluminum and lithium. The correlation coefficient {R} calculated for barium and iron is strong at R = 0.87. The R value for aluminum and lithium is moderate at 0.63. Next, barium-iron is clustered with strontium (R = 0.54 and 0.56, respectively) and aluminum-lithium

is clustered with boron (R = -0.02 and 0.47, respectively). Manganese concentrations in groundwater at the study site are very poorly correlated with all the other minor/trace elements, and there is no cluster formed with any other parameters.

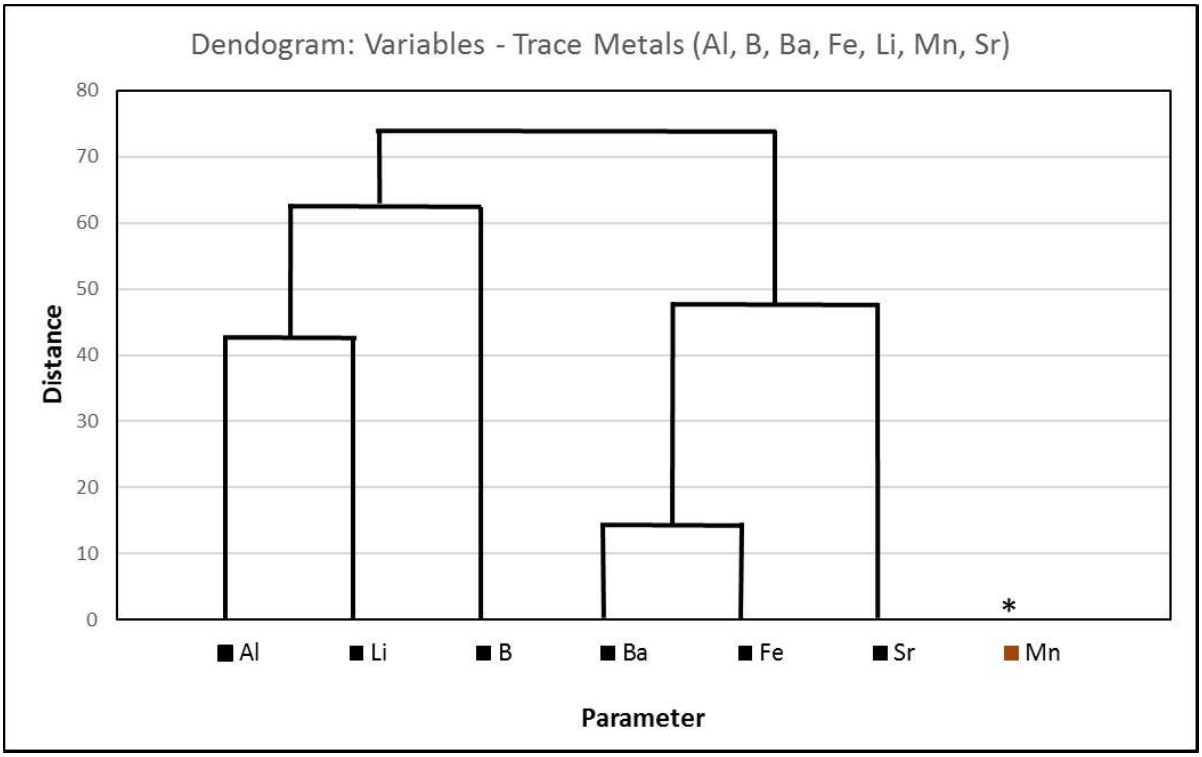


Figure 3-6
Example Cluster analysis dendrogram

Tier III Evaluation – Isotopic Analyses

Tier III uses isotopic analyses as a method to determine a groundwater signature. As described in EPRI (2017), isotopes have the same number of protons, but each form has a different number of neutrons. Because of this difference in atomic mass (neutrons plus protons), the isotopes will react differently with geomedia as they migrate in groundwater. These differences can be expressed as isotopic ratios, and can be used as diagnostic tools.

The application of isotopes as groundwater signatures is a relatively new technique, but boron isotopes are particularly relevant to CCR. Boron-11 is heavier than boron-10, and the heavier isotope is preferentially precipitated or sorbed from solution. Changes in the ratio of these two isotopes can yield information about the source of boron in the groundwater. Available data suggest that CCR leachate is often isotopically light, while groundwater may be isotopically heavy. Other isotopes that may be useful include strontium, oxygen, and hydrogen. EPRI (2012 and 2017) provides a comprehensive review on the use of boron and selected other isotopes as groundwater signatures.

Another form of isotopic analysis is tritium age dating. As discussed in EPRI (2017), tritium has a relatively short half-life of 12.3 years. Furthermore, there was an accumulation of tritium in the atmosphere in the early 1960s due to atmospheric atomic bomb testing. These two observations

enable use of tritium data to determine whether or not groundwater recharged prior to atmospheric testing of atomic bombs (i.e., prior to the 1960s) or since that time. If a CCR site was built during or after the 1960s, but the groundwater does not have detectable levels of tritium (meaning it recharged prior to the 1960s), that provides a line of evidence that an SSI/SSL is not due to a release from that site because the leachate from such a site would have detectable levels of tritium that should be evident in the downgradient groundwater.[7]

Hydrogeologic Scenario Evaluation

Hydrogeologic scenario evaluation is another line of evidence that can be used in an ASD. The premise is that if a mobile and non-reactive constituent is released to groundwater, it will travel in groundwater with a predictable concentration profile unless mixed with water from other sources that have significantly different concentrations of the same constituent. Following the ion ratio approach discussed above, the downgradient concentration of the mobile, non-reactive constituent of concern should be proportional to the mixing ratio of the relative volumes and concentrations of all sources combined and collected at the downgradient monitoring point.

Figure 3-7 presents a variety of hydrogeologic scenarios comparing leachate concentration of a mobile, non-reactive constituent to the concentrations observed in upgradient and downgradient wells. Groundwater flow directions are also considered to point out that some downgradient monitoring wells may be in a side-gradient or partial intercept path rather than in the direct path of the monitored upgradient groundwater. Each column in Figure 3-7 presents two to three hydrogeologic scenarios as follows:

- Column 1 – Scenarios providing a line of evidence that a CCR facility is the source of an SSI/SSL.
- Column 2 – Scenarios providing a line of evidence that both a CCR facility and a possible alternative source are the source of an SSI/SSL.
- Column 3 – Scenarios providing a line of evidence that an alternative source is causing an SSI/SSL.

The basis for these scenarios is fairly straightforward:[8]

- If leachate concentration is less than background, leachate cannot cause downgradient concentrations to be higher than background, and an alternative source is indicated.
- If downgradient concentrations are greater than leachate concentrations, an alternative source (natural or anthropogenic) must be present.

These scenarios, particularly those shown in columns 2 and 3 of Figure 3-7, demonstrate the benefit of multiple upgradient monitoring wells. This benefit is also realized for intrawell statistical programs if there is any potential for naturally occurring or anthropogenic changes in groundwater quality upgradient of the monitored unit.

[7] This line of evidence may not be valid in the case of a pond where "old" groundwater, for example from a deep aquifer, was used for sluice water.

[8] Assuming that leachate and background concentrations are well-characterized.

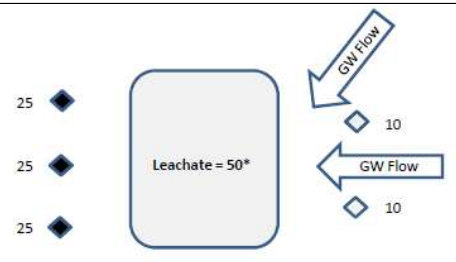
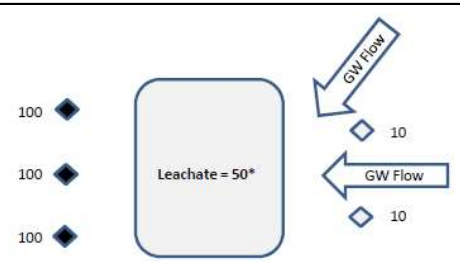
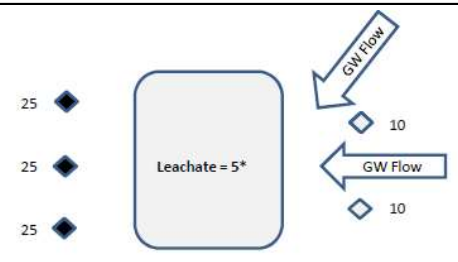
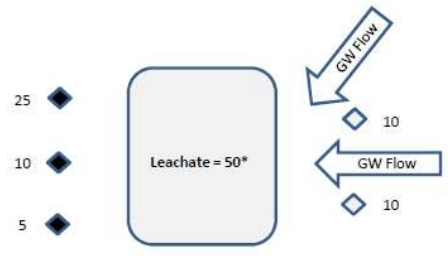
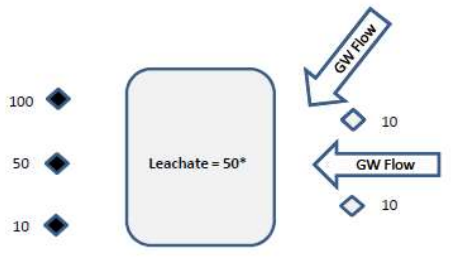
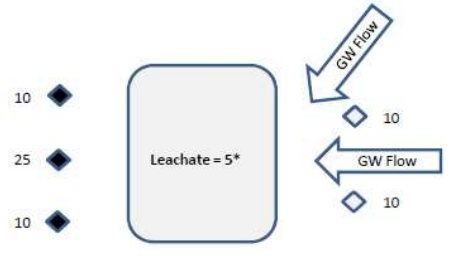
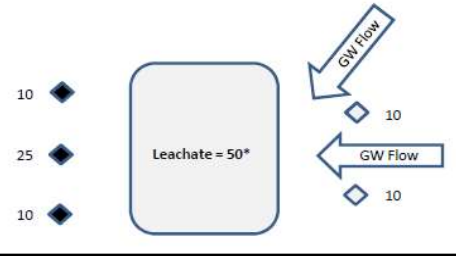
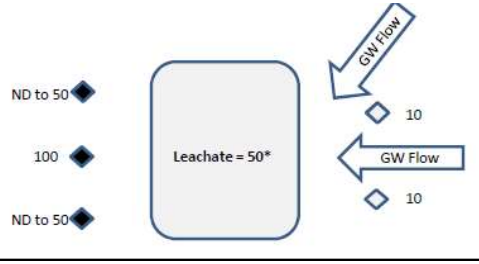
	Line of Evidence for:		
	CCR Leachate Release	**Possible CCR Leachate Release + Possible Alternative Source**	**Alternative Source Release**
	Column 1	**Column 2**	**Column 3**
Row a			
Row b			
Row c			
	1. Leachate concentration is higher than upgradient/background. 2. One or more downgradient concentrations are higher than upgradient/background but lower or equal to leachate concentration.	1. Leachate concentration is higher than upgradient/background. 2. One or more downgradient concentrations are higher than the leachate concentration.	1. Leachate concentration is less than upgradient/background.

Figure 3-7
Example hydrogeologic lines of evidence

Time-of-Travel Evaluation

Time-of-travel for a mobile and non-reactive source constituent to a downgradient monitoring well can also be considered as a potential line of evidence for connecting a source to an elevated result at a downgradient monitoring location. It takes time for a source constituent to travel downward to reach the aquifer and then travel within the aquifer to the downgradient monitoring location. For example, if groundwater velocity is 50 ft/year, assuming minimal dispersion, it would take about two years for a release to reach a monitoring well 100 feet from the waste boundary *if* the release occurred at the waste boundary, and *assuming* a relatively thin unsaturated zone. It would take more than two years if the release occurred toward the center of the facility as opposed to the waste boundary of a lined facility, or if there was a thick unsaturated zone. Since the permeability of different geological media such as sand, gravel, clay, silt, and fractured bedrock can vary considerably, time-of-travel evaluation requires knowledge of site and regional hydrogeology. If this information is available, it can be used to identify or discredit potential sources. Horizontal groundwater flow velocity through a uniform (homogeneous) water-bearing unit with no preferential flow direction (i.e., anisotropic), is calculated as follows:

$$V = K i / n_e$$

V = Groundwater Velocity
K = Hydraulic Conductivity
i = Hydraulic Gradient (unitless value)
n_e = Effective Porosity

Simple analytical models such as MYGRT (EPRI, 2005), or more advanced fate and transport models, can also be used for this evaluation. Models can account for dispersivity, which is not accounted for in the equation above.

4
NATURAL VARIATION

Natural variation encompasses natural variation in background levels and variability due to geologic influences such as dissolution of geomedia and natural ion exchange, changes in groundwater quality and/or flow related to precipitation such as changing water levels in monitoring wells, groundwater recharge and discharge fluctuations near surface water bodies, and time-of-travel for monitoring wells to detect upgradient changes, as well as influences related to changes in pH, oxidation reduction potential, and biological activity. These interactions, and how they may affect groundwater quality, are discussed below.

Changes in Mineralogy Along a Groundwater Flow Path

The mineralogy of soils and rocks near the monitored CCR unit can affect the natural chemistry of groundwater. For example:

- Geomedia such as limestones and certain sand units that are rich in carbonates can add calcium to the groundwater.
- Geomedia with little carbonates lack buffering capability that can enable changes in chemistry if low-pH recharge from precipitation reduces the overall pH of the aquifer along the flow path.
- Geomedia that contain reactive clay minerals can alter the chemical composition of groundwater by dissolution-precipitation reactions, and by either removing (by sorption) or adding (by desorption) solutes along the flow path.

The extent of the reactions can be pH-dependent, which may depend on changes in mineralogy. These examples underscore the importance of placing background monitoring wells in the same geomedia as compliance monitoring wells. If background and compliance wells are in different geomedia,[9] then SSIs/SSLs due to this natural variation and unrelated to a release from the facility are possible, and even likely. An ASD in this case would highlight the mineralogical differences between the geomedia and constituents expected to be affected.

Changes in pH Along a Flow Path or over Time

If pH is different between background and compliance wells, and/or changes over time, it can cause chemical changes capable of triggering an SSI/SSL. Examples of concentration changes that can occur due to a change in pH are illustrated in Figure 4-1 and the text that follows. For the purposes of an ASD, if there is an SSI/SSL at a monitoring well where pH is different from

[9] It is not always possible to screen background wells in the same geomedia as compliance wells. In these cases, intrawell statistical analysis can avoid this form of natural variation; however, intrawell analysis may not be an option in certain detection monitoring plans if monitoring wells have already been affected by a release.

or has changed from background (SSI) or baseline (SSL), and the constituent with the SSI/SSL is sensitive to changes in pH, then the pH difference can be a line of evidence in an ASD.

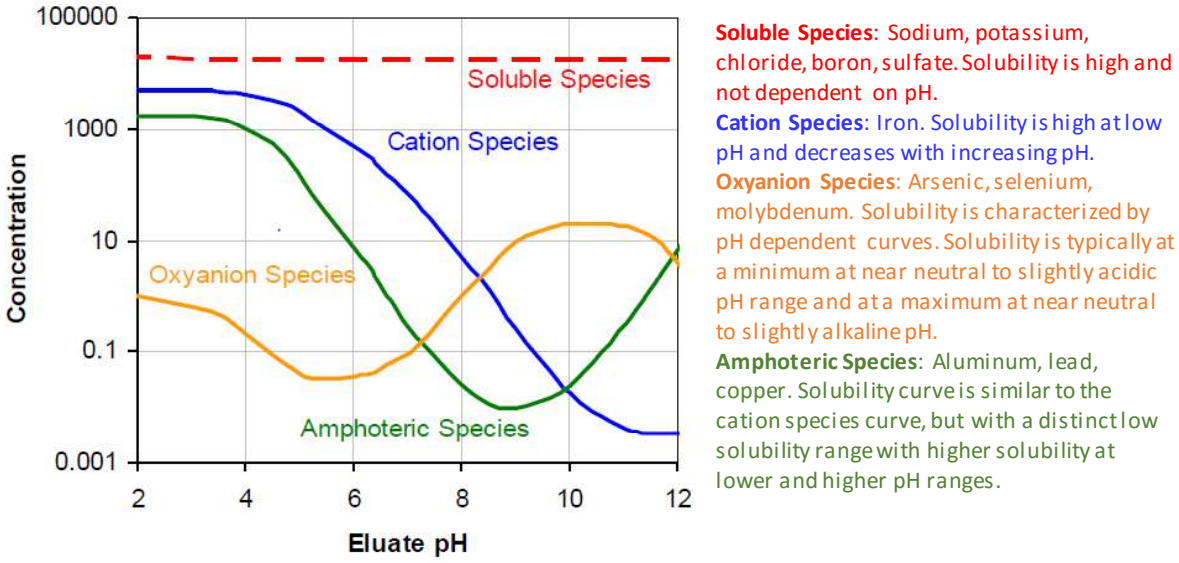


Figure 4-1
Typical solubility behavior of various constituents as pH changes (EPRI, 2007)

Soluble species such as sodium, potassium, chloride, boron, and sulfate tend to have relatively high solubility that is not affected by changes in pH. Cation species such as iron usually have higher solubility at low pH and minimum solubility at high pH.

Oxyanion species include elements such as arsenic, selenium, and molybdenum that react with oxygen or hydroxide to form anions. The solubility of oxyanion species varies with pH and often ORP because their chemical form changes as these two variables change. For example, the specific form of arsenic in solution depends on both pH and ORP. Under highly alkaline conditions (pH > 11), the dominant form of arsenic is AsO_4^{3-}. In relatively acidic groundwater (pH < 7), the dominant form is $H_2AsO_4^-$ under oxidized conditions, and $As(OH)_3$ under reduced conditions. The solubility curves of oxyanions characteristically have minimum solubility at near neutral to slightly acidic pH and maximum solubility at slightly alkaline pH.

Amphoteric species such as aluminum, lead, and copper have solubility curves similar to the cation species; however, they typically exhibit a range of minimum solubility, with higher solubility at lower and higher pH ranges.

Changes in Redox

Similar to a change in pH, a change in the redox state of the groundwater can have a significant impact on the concentration of some constituents in groundwater. If there is an SSI/SSL at a monitoring well where there is indication that redox is different from or has changed from background (SSI) or baseline (SSL), and the constituent with the SSI/SSL is sensitive to changes in redox, then the redox change can be a line of evidence in an ASD (Figure 4-2).

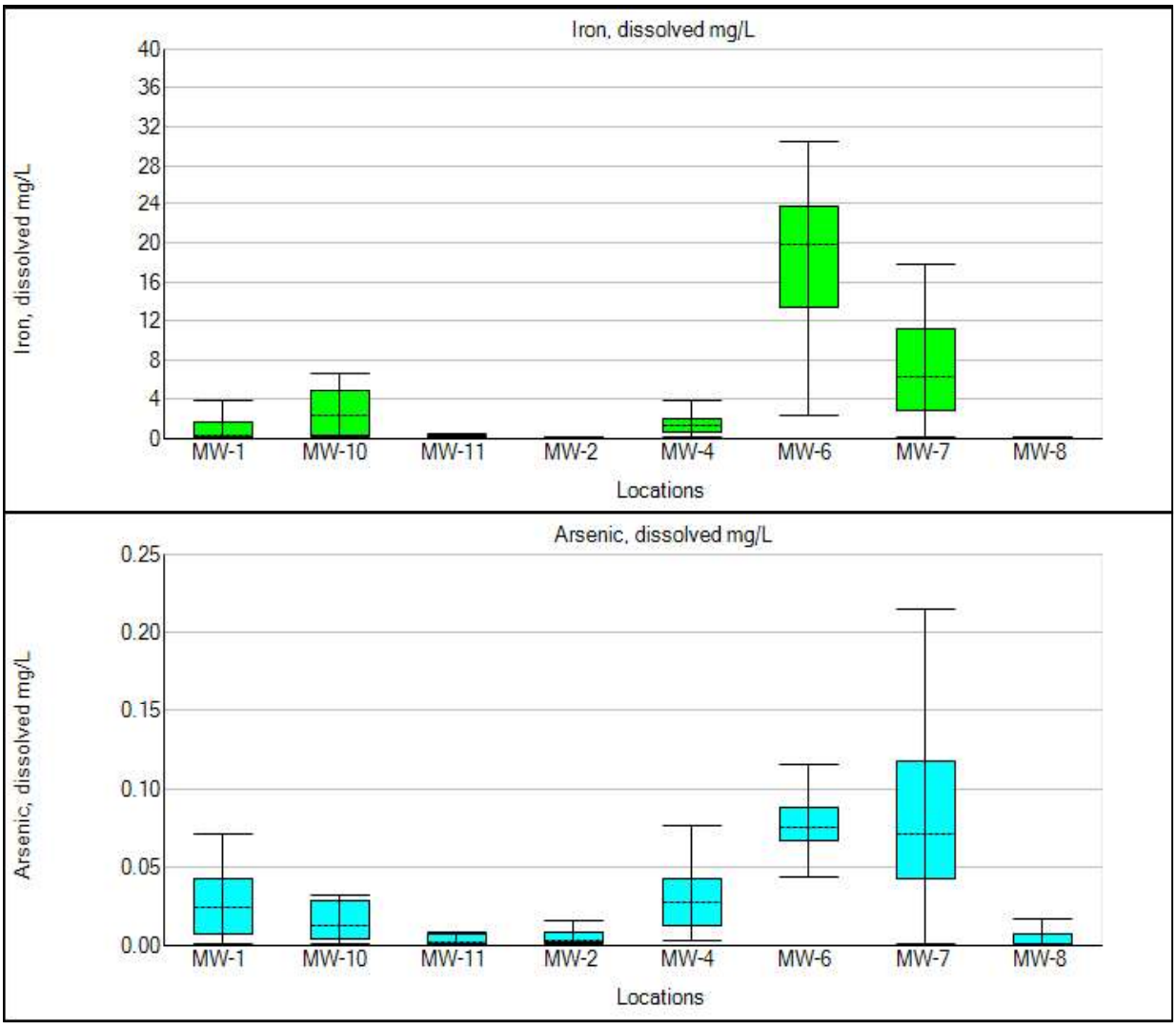


Figure 4-2
Example ASD line of evidence where elevated arsenic concentrations occur in monitoring wells with elevated iron, indicative of reduced conditions

The term redox refers to reduction-oxidation. Oxidation is the loss of electrons or an increase in the oxidation state of an ion or molecule. Reduction is the gain of electrons or a decrease in the oxidation state of an ion or molecule. In a more practical sense, the redox potential of groundwater reflects the dissolved oxygen content. Oxic water has higher levels of oxygen—if an element has multiple oxidation states in groundwater, then the species with a higher electrical charge will be prevalent in an oxic environment. Reduced groundwater typically has low dissolved oxygen content—the species with a lower electrical charge will be prevalent in a reduced environment. Redox potential, Eh, ORP, and pE are all measures of redox state. In addition, concentrations of iron and manganese can be used as indicators of redox state in groundwater because these constituents tend to have low concentration in oxic groundwater and high concentration in reduced groundwater.

Examples of redox-sensitive constituents include, but are not limited to the following:

- Naturally occurring sulfide minerals in reduced soils may form soluble sulfate if exposed to oxygen—which can occur when a monitoring well is installed, resulting in a naturally occurring increase in sulfate concentration in that monitoring well. Conversely, under strongly reducing conditions, sulfur in groundwater can convert from sulfate to hydrogen sulfide gas, with a corresponding reduction in sulfate concentration.
- Under oxidized conditions, arsenic in groundwater occurs in the 5+ oxidation state as arsenate (AsO_4^{3-}), but under reducing conditions it occurs in the 3+ oxidation state as arsenite (AsO_3^{3-}) and is more soluble and mobile. It is not uncommon to see naturally occurring arsenic in reduced groundwater. Conversely, if arsenic-containing sulfide minerals are present in an aquifer under reduced conditions, introduction of oxygen, for example by installing a monitoring well, can result in release of arsenic to groundwater in the vicinity of the monitoring well.
- The solubility and speciation of selenium in groundwater is dependent on the pH and ORP of the solution. In highly oxidized solutions, selenium exists as highly mobile selenate. Over a relatively large range in pH and ORP, selenium occurs in the selenite forms as $HSeO_3^-$ and SeO_3^{2-}. Under oxygen-poor conditions, the concentration of selenium in groundwater (as HSe^-) may be controlled by the solubility of ferroselite ($FeSe_2$). Because anionic selenium is the dominant form of the element in groundwater, sorption may not be significant by many types of geologic media.
- Boron, molybdenum, lithium, and cobalt concentrations are not significantly impacted by the range of redox commonly observed in groundwater.

Influence of Biological Activity

The potential for biologically mediated chemical reactions should not be overlooked. Some of the redox reactions described above, particularly release of naturally occurring arsenic, can be biologically mediated. For example, when pyrite (ferrous sulfide) deposits (commonly present in coal) are exposed to air by mining operations, oxidation and release of ferric iron, sulfate, and sulfuric acid can be accelerated by bacteria that thrive in a low-pH sulfuric acid environment, accelerating the reaction and increasing the release of sulfuric acid and other minerals present in the geomedia that are more soluble in low pH and/or oxidizing environments, such as arsenic. Another example of natural microbial redox activity in geomedia is oxidation of ammonia nitrogen to nitrate and/or nitrite compounds. As discussed in Section 5, the presence of ammonia, nitrate, or nitrite in CCR monitoring wells is typically related to agricultural activities; however, it may also be due to leaching of ammonia compounds deposited on fly ash or FGD solids due to the use of ammonia in selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) emission control technology for reduction of nitrogen oxide emissions.

Changes in Groundwater Elevation at Compliance Wells

In some cases, groundwater can be naturally stratified, for example if shallow groundwater is oxic and deeper groundwater is reduced. Stratification may also occur near groundwater discharge points where upwelling of deep groundwater, which may have higher dissolved solids content than shallow groundwater, may be occurring. Stratification is also common near oceans

where saltwater wedges form beneath fresh water due to the higher density of seawater. When there is a natural stratification of groundwater quality, changes in groundwater elevation can trigger a naturally occurring SSI/SSL if the deeper water rises and intersects the monitoring well screen.

Such changes in groundwater elevation can be due to precipitation/recharge events, or changes in elevation at nearby groundwater discharge points such as rivers (which can also affect flow direction as described next). Changing groundwater elevation can be a line of evidence for an ASD if there is evidence that the groundwater is naturally stratified. A hydrograph showing a change in groundwater elevation (up or down) that corresponds with the SSI/SSL may be useful in supporting this cause.

Changes in Groundwater Flow Direction at Compliance Wells

Groundwater flow direction naturally exhibits variability. For many sites, this variability may not be significant; however for some sites, flow direction can vary by as much as 180 degrees. Inland locations may have relatively narrow ranges of variability, such that groundwater flow is usually in one broad direction. Sites along rivers can exhibit very large ranges of variability, including complete flow reversals, that are dependent on river stage. Much of this variability will be accounted for during the background monitoring period. However, if the background monitoring was performed during a period of little variation, or if there is an extreme hydrologic event such as a 100-year (or larger) flood, then groundwater flow can change in a way that was not accounted for during the background monitoring period, and if there is aerial variability in groundwater chemistry, then this change in flow direction can trigger an SSI/SSL due to natural variation in groundwater flow direction.

If groundwater flow direction at the time of, or prior to, sampling for an SSI/SSL is different than flow directions that occurred during the background monitoring period, then that is a line of evidence for a naturally occurring ASD. Groundwater flow direction is not typically monitored between sampling events, so a change in flow direction prior to a sampling event may need to be demonstrated based on indirect evidence such as river hydrographs showing that a particular river stage was not representative of the background monitoring period.

Another ASD consideration with changes in groundwater flow direction is detection of an alternative anthropogenic source that had not previously been detected. While the cause of the SSI/SSL in this case is not natural variation, the detection of the alternative source is due to natural variation.

Time-of-Travel Consideration for Natural Variation

As noted in Section 3, there will be a time lag between the time that a change in concentration affects background groundwater and when that same change is detected in downgradient groundwater. Just as it takes time for somebody to walk from point A to point B, it takes time for water to travel through geomedia. Methods for calculating that time lag are presented at the end of Section 3.

If a change in concentration is noted at an upgradient monitoring location, and a similar change at a downgradient well triggers an SSI/SSL at a later date, then a line of evidence for an ASD can be developed if it can be demonstrated that the detected constituents are the same as detected in

the upgradient well, and the time lag is consistent with groundwater velocity between the upgradient and downgradient locations.

This line of evidence applies to both natural variability and upgradient anthropogenic sources. A natural variability example would be a case where pH changes in groundwater chemistry affect upgradient locations before downgradient locations.

5
ANTHROPOGENIC IMPACTS TO GROUNDWATER

When considering alternative sources that may be contributing to an SSI/SSL, it is important to investigate the site and surrounding area for current and historical land uses. Mapping descriptions and locations of current and historical land uses near the CCR unit, along with groundwater flow direction and locations of surface water bodies, can narrow the list of likely alternative anthropogenic sources and identify constituents to look for that may point to an alternative source (Figure 5-1).

If the CCR unit is on or near a power plant, note the past and current locations of coal piles, impoundments, landfills, underground and aboveground oil storage tanks, known oil and chemical spill areas, CCR transport routes (i.e., haul roads and sluice lines) and processing areas, and areas where ash or other fill material has been used as structural fill. This information may help identify on-site activities that may be contributing to an SSI/SSL.

Understanding the area surrounding the CCR unit can guide the ASD investigation, because the groundwater signature often reflects the combined local land uses. Land uses and/or features that may be near coal-fired power plants are discussed below. Tables A-3 and A-4 in Appendix A list activities that can affect the groundwater concentrations of constituents monitored at CCR management facilities by constituent and by activity, respectively.[10]

[10] Tables A-3 and A-4 are also presented in Section 2 as Tables 2-2 and 2-3.

Figure 5-1
Examples of anthropogenic activities near a CCR unit with potential to affect groundwater quality in one or more monitoring wells, depending on the direction and variability of groundwater flow.

Power Plant Land Use and Operations

Power plant operations including other CCR impoundments and landfills, as well as historical land uses, can be reviewed as potential alternative sources, depending on their location relative to groundwater flow at the CCR unit with the SSI/SSL and the water quality signature. Areas to evaluate during the ASD include areas of coal or coal ash spillage, coal piles and coal pile runoff conveyance structures, underground storage tanks, underground piping, locations of past chemical spills, and other CCR management facilities.

Preparation of subgrades to achieve favorable power plant building conditions may have required low areas to be filled with structural fill. Historical requirements for fill material were not as strict as current standards for leachability and therefore, materials such as fly ash, bottom ash, construction debris, demolition debris, dredge spoils, and/or incinerator residue may have been used as fill material, particularly at older power plant sites. If these types of materials are present, they may contribute leachate to groundwater from random, non-point source locations. If historical fill practices are a potential concern, consider researching fill locations and material types and quality by reviewing historical fill maps and aerial photographs, reviewing historical fill records with sampling data and/or fill material descriptions, reviewing information available on neighboring properties, and interviewing knowledgeable persons and neighbors.

Historical ash management practices may have included on-site use of fly ash and/or bottom ash for fill, road base, berm construction, and other structural applications. Ash may also have been piled in various areas for dewatering or temporary storage or transfer to trucks. Former ash ponds and/or landfills may have been covered and closed on-site, or may have a residual contribution to groundwater contamination.

Current or past ash handling practices may also have allowed for dispersion of ash and subsequent accumulation in plant sumps, storm water swales and ponds, and other low-lying areas. In particular, wind-blown ash may accumulate in ditches, or leachate sprayed for dust control on an active landfill face may be blown off the lined area where it can infiltrate. Such conditions can contribute to localized, elevated groundwater concentrations with ash leachate signatures. It is important to be aware of these activities and their locations because their presence can result in SSIs/SSLs, but from sources other than a release from the liner/base of the monitored CCR unit.

Contaminants from underground storage tank (UST) leaks, aboveground tank and transformer leaks, underground oil piping leaks, or oil and/or chemical spills may also cause groundwater impacts, the extent of which depends on the severity and duration of the leak or spill. Oil-based contamination primarily involves organic constituents; however, trace elements may also be of concern. For example, biological activity associated with a petroleum plume may result in biologically mediated arsenic release from minerals in the aquifer. Therefore, it is important to be aware of site history as it relates to major oil and chemical spills, and UST and underground piping leaks in case these issues may potentially be impacting CCR monitoring.

If an on-site anthropogenic source is suspected, consider testing for additional analytes such as organics (to diagnose oil-related contamination), and/or all major ions to enable use of Tier II geochemical analysis to help determine similarity and source of groundwater collected at the monitoring wells. Other constituents such as aluminum, iron, and manganese may also be helpful in fingerprinting potential alternative power-plant-related groundwater impacts. Perhaps most

importantly, knowledge of site history can be very helpful in determining whether or not alternative plant-related sources are positioned upgradient of wells where an SSI/SSL was determined.

Agricultural Activities

If the CCR unit is located in an area with upgradient farmlands or livestock, then groundwater impacts associated with these agricultural activities can be evaluated for an ASD. Agricultural impacts to groundwater are possible due to its prevalence and the use of irrigation water, fertilizers, and pesticides to support optimal plant growth. The most common constituents of concern include nitrogen compounds (nitrate, nitrite, and ammonium) and phosphorus compounds associated with fertilizers, runoff from animal feedlots, and the use of manure for crop fertilization; however, other inorganic constituents may also come from agricultural sources (refer to Table A-4).

Relatively high levels of nitrate, nitrite, and/or ammonium ions in groundwater are indicators of agricultural impacts. Consider analyzing for these constituents, particularly in upgradient wells, if groundwater degradation from surrounding agriculture is possible.

If the power plant that produced the CCR utilizes SCR or SNCR technology, ammonia compounds may have adsorbed onto the ash (usually as ammonium bisulfate or ammonium sulfate) and may subsequently be released to groundwater as ammonium ions. Biological activity may convert the ammonium ions into nitrate and/or nitrite. Nitrogen compounds also may occur naturally in soil due to fixation by bacteria in the root nodules of legume plants, such as soybeans and alfalfa. Therefore, when considering a potential alternative source demonstration related to nitrogen compounds, consider agricultural activities surrounding the CCR management unit, the potential for natural occurrence associated with legumes, and the processes used to produce the CCR. It may be difficult to distinguish between naturally occurring nitrates/nitrites and those present due to leaching from fertilizers, animal wastes, or ammoniated CCR. However, phosphorus is not a common constituent of CCR, so the presence of elevated concentrations of phosphorus in groundwater typically points towards agricultural sources.

In addition to nitrogen and phosphorus, agricultural activities may also contribute trace elements, salts, herbicides, pesticides, and pathogens to the groundwater. Because herbicides, pesticides, and pathogens are not monitored under the CCR Rule, they are not discussed in more detail here, but if they are known to be present, their presence indicates a source other than CCR.

Salts and trace elements may leach into groundwater as a result of agriculture, particularly in arid western regions of the United States that rely heavily on irrigation to support agricultural activity (Carter, 1980). This is particularly a concern if the native soils originated from marine mud and sediments that may contain elevated concentrations of arsenic, boron, calcium, chloride, magnesium, mercury, molybdenum, nitrate, potassium, selenium, sodium, and sulfate, and/or if the irrigation water is salty.[11] Selenium is a common constituent of concern in these environments (Fio et al., 1991). Use of salty irrigation water can result in salt deposition and the

[11] http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/docs/cmnt081712/cwin/cwinappendix_a.pdf

need for increased irrigation to flush salts from the root zone of the crops, resulting in increased leaching of these salts and trace elements to the receiving groundwater. Distinguishing between agricultural sources and CCR sources may be challenging in this situation. Evaluation of nitrogen and phosphorus compounds and/or use of Tier 2 geochemical methods can be used to try to distinguish between sources. Another evaluation option in this case is analysis for boron isotopes.

Road Salting

Use of salt or salt spray for road deicing can affect groundwater quality near roads in northern climates (Kelly et al., 2009). Common types of salt used for road deicing include sodium chloride, calcium chloride, magnesium chloride, and potassium chloride. High chloride concentrations in groundwater observed during detection monitoring may be due to road salting rather than a release from the monitored facility.

Leaking Underground Pipes

In large urban areas, liquid waste including household and commercial sewage, storm water runoff, and industrial wastewater, is transported to treatment facilities in underground pipes. Under certain conditions (i.e., leaks and outward flow) this underground infrastructure may serve as conduits to transport contaminants from their original source to other areas that may be difficult to connect with the source. If the groundwater quality signature indicates an anthropogenic source, but does not resemble CCR, and no other anthropogenic source is apparent, then it may be worthwhile to investigate whether or not leakage from underground pipes is a potential alternative source.

Gasoline (Gas) Stations

Leaking underground storage tanks (LUSTs) at gas stations containing gasoline, diesel, kerosene or oil are a common source of groundwater contamination. As of March 2012, over 504,000 leaks had been recorded from federally regulated LUSTs in the United States.[12] The associated groundwater contaminants include benzene, toluene, ethylbenzene, xylene, lead, MTBE (a gasoline additive), ethylene dichloride, and naphthalene. If the gas station included a service shop, other compounds that may be released include trichloroethylene, perchloroethylene, methylene chloride, carbon tetrachloride, oils, ethylene glycol, motor oil, hydraulic fluid, detergents, and acidic solutions. These compounds are not present in CCR leachate, so their presence in groundwater indicates a source other than CCR leachate.

Septic Systems

Septic systems are potential sources of nitrate, phosphorus, chloride, organic substances, bacteria and viruses, detergents, oils, salts, septic tank cleaners such as trichloroethane or methylene chloride, and a wide variety of other chemicals.[13] These systems rely on the capacity of the native soils to attenuate, and naturally occurring microbes to digest, elements and compounds

[12] http://earthrepair.ca/resources/scenarios/gas-stations/

[13] http://infohouse.p2ric.org/ref/01/00065.htm

contained in the sewage. If improperly located, designed, constructed, or maintained these systems may fail or inadequately treat the effluent. If spaced too closely due to residential population density, these systems may exceed the capacity of the local soil to assimilate the chemical loads. High concentrations of chloride, nitrate, phosphorus, and/or sodium provide a line of evidence for an ASD for monitoring wells downgradient of areas where septic systems are used.

Mineral and Oil Extraction

Mining (Non-Coal)

Leaching from slag piles and other mining-related activities can result in groundwater quality impacts. If the background monitoring does not fully characterize these impacts, then SSIs/SSLs are possible. The water quality signatures from mining sources are highly variable depending on the substance being mined and the composition of the local soils, but common constituents include phosphates, sulfates, fluorides, and trace elements. Furthermore, if pyrite (FeS_2) was exposed to oxygen and water from the mining process, the drainage may be acidic (low pH) and have high iron and sulfate concentrations, as discussed next.

Major ion chemistry may provide a line of evidence for an ASD in this case if groundwater at the monitoring well(s) with an SSI/SSL plots in a region of the Piper diagram that is not between leachate and background groundwater. Isotopic analysis may be also considered, although unless an isotopic signature is available for the suspected mining source, it would only demonstrate that the CCR is or is not the source of an SSI/SSL. As with all potential upgradient sources, a stronger line of evidence would be installation of an intermediate monitoring well if it is possible to install such a well downgradient of the suspected mining-related source *and* upgradient or side gradient of the CCR units.

Coal Mining

The coal mining process exposes underground coal, as well as stock piles of coal and coal refuse, to oxygen and moisture, which results in oxidation of the pyrite (iron and other sulfides). The resultant leachate has high concentrations of iron and is acidic due to high concentrations of sulfuric acid. As the acidic leachate moves through the natural environment, it breaks down clay, and silicate and carbonate minerals releasing silica, aluminum, calcium, magnesium, and manganese. Concentrations of trace elements including chromium, cobalt, copper, nickel, and zinc may also increase above background levels (USEPA, 1980). The solubility of most of these elements is higher under acidic conditions. If limestone is present near the mining site, the acidic water may be neutralized by the calcium carbonate alkalinity of the limestone, and the concentrations of these elements may decrease. If the soil does not have this inherent alkalinity, the acidic water, known as acid mine drainage, may migrate from the mine site as contaminated groundwater or surface water. Mine-impacted groundwater may travel to deeper or more distant aquifers along fractures, seams, mining tunnels, and other subsurface conduits, sometimes making it difficult to trace the source.

Building an ASD where coal mining impacts are the suspected source of an SSI/SSL may require multiple lines of evidence because the water quality signatures may be only slightly different from that of groundwater mixed with CCR leachate. An obvious line of evidence for an ASD

would be the presence of a coal mine in an upgradient position. Other lines of evidence may include pH differences if the CCR leachate is alkaline, since the coal mining leachate would be expected to be acidic; absolute concentrations if it can be demonstrated that groundwater has higher concentrations for some constituents than CCR leachate; and Tier II data comparison techniques such as geochemical modeling, multivariate statistics, and/or FALCON. Isotopic analysis would need to look at more than boron and strontium, since the coal may have similar isotopic ratios, and could also include hydrogen and oxygen isotopes to build an isotopic signature.

Oil and Gas Production

Hundreds of thousands of wells have been drilled in the United States for oil and gas exploration, production, and brine disposal. Brines with high concentrations of dissolved solids are extracted with oil and gas and separated from the oil and gas at the land surface. The brines, called produced water, are stored in tanks or surface impoundments until they are disposed, often by reinjecting back into the subsurface oil and gas formation. Mechanisms for brine release include leaks from tanks, impoundments (which are usually lined but were not always lined in the past) and piping. Oil field brines may also be released to groundwater if there is a leak in the casing of an injection well. In addition, abandoned oil and gas wells can act as direct conduits for vertical oil field brine migration if the seal is incomplete or has failed. Vertical migration via abandoned oil and gas wells can occur either up or down, depending on a variety of factors. Pressure-induced upwelling of brine from depth to shallow aquifers is most relevant for ASD purposes.

Multiple lines of evidence may be available for an ASD where impacts from oil field brines are suspected. Oil field brines can have elevated boron, chloride, and other constituent concentrations. The first line of evidence would be confirmation that oil and gas production occurred in the area of the CCR unit—such areas are commonly mapped by state geological surveys. Another line of evidence is major ion chemistry, because brines have high chloride concentrations while coal ash leachate has high sulfate concentration. Brines can have much higher total dissolved solids (TDS) than CCR leachate, and depending on the level of dilution in groundwater, absolute concentrations of constituents such as barium may be higher in the monitoring well than in the CCR leachate. Ion ratios may also yield a considerably different signature than CCR leachate (Figure 5-2).

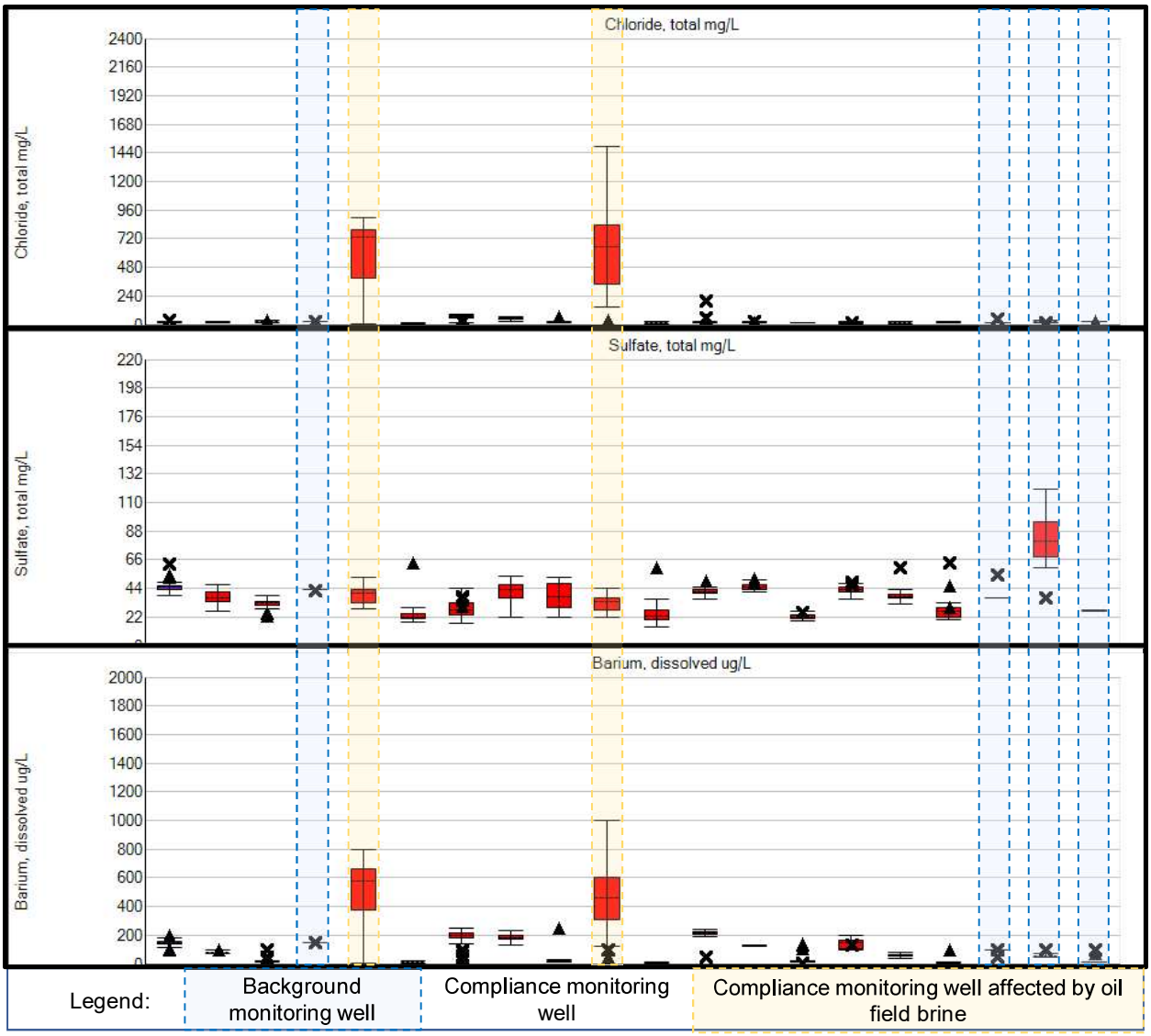


Figure 5-2
Box-whisker plots showing relatively high chloride and barium, and low sulfate concentrations, in brine-impacted groundwater monitored at a CCR management facility

Induced Salt Water Intrusion into Freshwater Aquifers

The water quality in shallow freshwater aquifers can be degraded by upwelling of deeper, naturally salty groundwater caused by heavy pumpage for anthropogenic activities such as mine dewatering, irrigation, or drinking water supplies if there is an underlying source of salt water. Salt water sources include seawater wedges and brackish groundwater that occurs naturally at depth in many areas of the United States.

Lines of evidence for an ASD based on induced pumping are similar to the lines of evidence when oil and gas brines are suspected as the cause of an SSI/SSL. First, there must be evidence for seawater or brackish water underlying the area where an SSI/SSL is observed. Additional lines of evidence can include major ion chemistry, because brackish groundwater and seawater have high chloride concentrations, while coal ash leachate has high sulfate concentration.

Brackish groundwater and seawater can also have higher TDS than CCR leachate, and depending on the level of dilution in groundwater, absolute concentrations of constituents such as barium may be higher in the monitoring well than in the CCR leachate. Ion ratios may also yield a considerably different signature than CCR leachate. Isotopic analysis could also be considered if other lines of evidence do not build a strong ASD, because boron in seawater and brines tends to be isotopically heavy ($\delta^{11}B > 0$), and boron in CCR leachate tends to be isotopically light ($\delta^{11}B < 0$) (Figure 5-3).

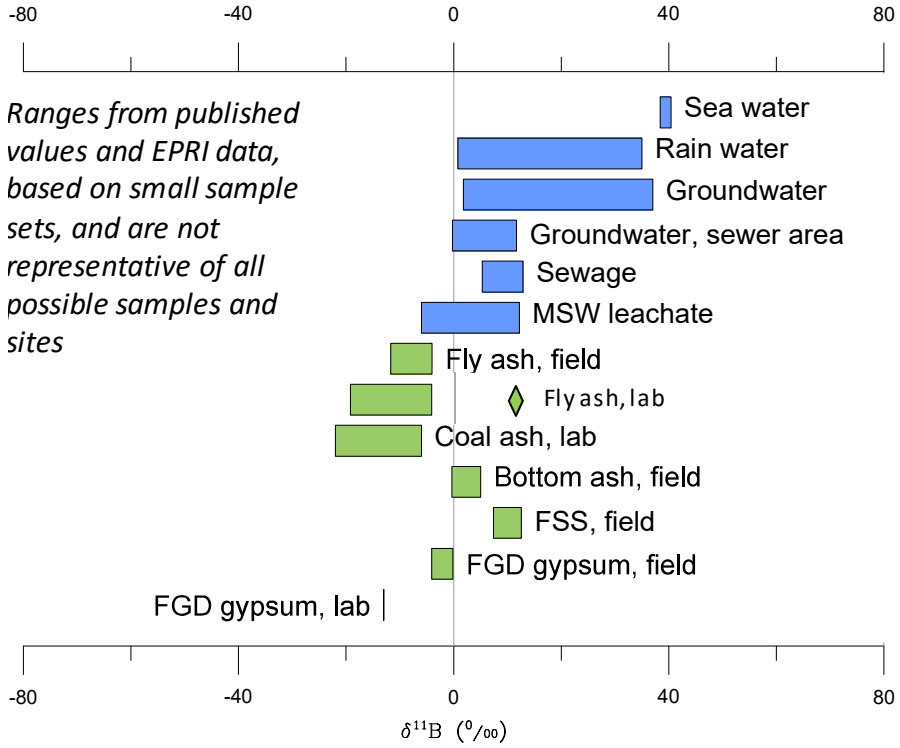


Figure 5-3
Boron isotope ranges, expressed as $\delta^{11}B$, based on EPRI (2012)

Industrial Land Use and Activities

Industrial activities produce liquid and solid waste containing a variety of inorganic constituents, organic compounds, acids, and chemicals that is too variable to cover in detail in this report. Environmental regulations now require treatment and proper disposal to prevent or minimize the risk of contamination to land and water resources, but this has not always been the case. Historical dumping, land application, seepage from unlined or poorly lined impoundments and landfills, and discharge of untreated or poorly treated waste may have contaminated the environment near areas with present or historical industrial activity.

If industrial impacts other than CCP leachate are suspected, the first line of evidence is to identify current and historical industrial activities and land use in the vicinity and upgradient of the monitored CCR unit. Identification of the types of industrial uses can help identify likely contaminants associated with these industrial activities. If these "industrial signatures" can be identified in the CCR program wells, they can be used as lines of evidence supporting an ASD.

Waste Disposal – Municipal and Industrial Landfills

State and federal regulations mandate liners and leachate collections for current landfills. However, prior to enactment and promulgation of implementing rules, waste disposal was often managed in open pits with minimal or no barriers to migration of leachate into groundwater. In the event of a release from a current or legacy solid waste landfill, potential constituents in the leachate include sodium and chloride, nitrate, organic compounds, and trace elements.

If a solid waste landfill is a suspected cause of an SSI/SSL, it may be possible to obtain leachate data from the agency that regulates the facility for use in a water quality signature evaluation. Groundwater monitoring data may also be available from the same agency, which could be used to document whether or not the solid waste landfill monitoring wells had elevated concentrations of the constituent(s) with an SSI/SSL. This assumes that the constituent is monitored at the solid waste landfill, because CCR indicators such as boron, lithium, and molybdenum are not always monitored at non-CCR sites. Otherwise, lines of evidence for an ASD can include major ion chemistry, ion ratio analysis, and perhaps isotopic analysis.

6
PREPARATION OF AN ALTERNATIVE SOURCE DEMONSTRATON

Overview

A combination of tables and checklists have been developed to guide development of an ASD. The following assumptions are inherent with this process:

- There has been an SSI, an SSL, or an exceedance of a groundwater quality standard or benchmark.[14]
- The SSI/SSL is not due to a release from the CCR unit. Note that in some situations, ASDs may apply to all SSI/SSLs at a site, for example at a lined landfill where background groundwater monitoring does not fully characterize the variability possible in groundwater quality. In other situations, ASDs may apply to some, but not all, SSIs/SSLs at a CCR unit, as may be the case for an unlined impoundment where boron and sulfate concentrations in downgradient groundwater may be elevated due to a release, while other constituents in groundwater may be due to naturally occurring or anthropogenic sources.
- ASDs based on sampling (ASD I), laboratory (ASD II), or statistical (ASD III) causes do not require a weight of evidence approach, provided that the cause is documented, or otherwise verified and defensible.
- For natural variation (ASD IV) or alternative sources (ASD V), it is assumed that there are sufficient data to build a weight of evidence case that the SSI/SSL is not due to a release from the CCR unit. If such data are not available, then the ASD process may identify additional data collection that could be used to build a stronger ASD.

The first step in an ASD is to determine if ASD Types I, II, or III explain the SSI/SSL. If not, then a weight of evidence approach is used for ASD Types IV and V. The weight of evidence approach outlined here is dependent on two types of lines of evidence (Figure 6-1):

- Key lines of evidence are based on relationships that must be observed in order for an SSI/SSL to be due to a release from a CCR unit. If these relationships are not observed, then they are critical to establishing an ASD. It is difficult to build a strong ASD without any key lines of evidence. It may be possible to build an ASD with a single key line of evidence, but the ASD will be stronger with additional key or supporting lines of evidence.
- Supporting lines of evidence provide additional information that supports the ASD. Supporting lines of evidence are generally not sufficient to build an ASD unless there is at least one key line of evidence, although it may be possible if there are many supporting lines of evidence.

[14] Throughout this document, and continuing into this chapter, this is referred to as an SSI/SSL.

		Supporting Lines of Evidence		
		None	**Few**	**Many**
Key Lines of Evidence	**None**	No ASD	Weak ASD	ASD possible
	One	Weak ASD	ASD possible	**Strong ASD**
	Multiple	ASD possible	**Strong ASD**	**Strong ASD**

Figure 6-1
Use of key and supporting lines of evidence for ASD Types IV and V

Reference tables for the ASD process are included in the text of this report, and are also provided in Appendix A for simplified reference. The ASD checklists are provided in Appendix B. Table 6-1 summarizes potential causes to consider under each of the ASD types.

Table 6-1
Potential Causes for an SSI/SSL

Sampling Causes (ASD Type I)	Laboratory Causes (ASD Type II)	Statistical Evaluation Causes (ASD Type III)	Natural Variation (ASD Type IV)	Alternative Sources (ASD Type V - Natural and Anthropogenic)
• Sample mislabeling • Contamination • Change in technique • Excessive suspended solids or turbidity • Other sampling anomalies	• Analytical method • Calibration • Analytical technique • Contamination • Interference • Recording • Dilution errors • Digestion methods	• Lack of statistical independence • Outliers • Trends • Non-detect Processing • False positives • New background data	• Geology • Precipitation • Seasonality • Water level • Changes in pH and/or ORP • Biological activity • Time of travel	• See Appendix A, Tables A-3 and A-4

ASD Evaluation Checklists

Checklist 1: ASD Types I, II, and III

The evaluation process starts with ASD Checklist 1 (Appendix B). This checklist is based on the discussion in Section 2 and lists potential sampling, laboratory, and statistical causes for an SSI/SSL. In some cases, the data record may contain sufficient information to document an ASD, but in some cases resampling may be required. If there is documentation, or a resample to demonstrate one of these types of ASD, or if there is irrefutable evidence that one of these ASDs

caused the SSI/SSL, then a weight of evidence approach is not needed. Examples of documentation and evidence include, but are not limited to:

- Laboratory reports showing qualifier flags, uncorrected dilution calculations, contamination in blanks, poor spike recovery, or other anomalies
- Field sampling notes describing difficulties or anomalies encountered while sampling
- High turbidity values in the unfiltered sample, accompanied by filtered sample showing low concentration
- Resample results showing low concentrations
- Graphs clearly showing reversed results (see Figure 2-1), or concentration spikes by a factor of 10 or more (see Figure 2-2)
- Graphs and calculations showing that new background data have triggered a change in background normality, while downgradient concentrations have not increased

If the ASD is not documented, and other evidence is not irrefutable, or if there is insufficient time for resampling, then ASD Checklist 2 could be used to build a weight of evidence approach that the SSI/SSL is not due to a release from the site.

Checklist 2: ASD Types IV and V Lines of Evidence Associated with the CCR Unit

Checklist 2 can be used to guide the evaluation of lines of evidence associated with the CCR unit. The checklist provides a template for recording answers to questions related to primary indicator constituents, secondary indicator constituents, other chemical evaluation techniques, and hydrogeological evaluation. The answers to each question can be recorded in columns that organize the evidence pointing to a release from the CCR Unit (Column A), evidence pointing to a natural or anthropogenic alternative source (Column B), or unknown or indeterminate evidence (Column C). Note that all key lines of evidence are contained in Checklist 2.

If most answers fall into Column B, and particularly if the line of evidence is identified as "key," then weight of evidence is developed that an alternative cause explains the SSI/SSL. Checklist 3 can then be used to guide further evaluation of alternative causes.

Checklist 3: ASD Types IV and V Lines of Evidence Associated with Alternative Natural and Anthropogenic Sources

Checklist 3 is designed to develop lines of evidence to identify alternative source(s) for an SSI/SSL. There are no key lines of evidence on Checklist 3. Rather, it provides for a methodical approach to documenting alternative sources if evaluation using Checklist 2 indicates that an ASD is likely.

ASD Reporting

An ASD requires both defensible lines of evidence and a well-organized presentation of the lines of evidence that clearly lead to the conclusion that the SSI/SSL is not due to a release from the monitored CCR facility. The following format, modified from one developed by Southern Company (2016), provides a viable approach for ASD documentation. Other formats may be equally effective.

Introduction and summary of the SSI/SSL

An example of language that could be used for introducing the SSI/SSL is: "Review of the statistical analysis indicates that the concentrations of the parameters were within the [specify statistical test used] limits for each constituent at each monitoring well except for the following statistically significant increases/levels (SSIs/SSLs): [List each well with SSI/SSL constituents and identify all constituents at each well location that were identified to have SSI or SSL trends.]

Cite the ASD language included in the CCR Rule (or state rule is applicable) using explicit language

For example: "40 CFR 257.94(e)(2) allows the owner or operator 90 days from the date of determination to demonstrate that a source other than the CCR unit caused the SSI or that the apparent SSI was from a source other than the CCR unit or resulted from errors in sampling, analysis, statistical evaluation, or natural variation in groundwater quality. Pursuant to 40 CFR 257.94(e)(2), the following text is provided as a demonstration that the listed SSIs are due to [identify the cause(s) applicable to the site-specific case]."

Present the ASD checklists

Identify all lines of evidence, and supporting data as needed, that the release is not from the CCR unit and is explained by alternative causes. Identify whether each line of evidence is key or supporting, and why. Also group and explain the evidence by well if multiple constituents have SSI trends at the same well(s). If the same constituent has SSI trends at multiple wells, explain how this is relevant to the ASD being presented. Include supporting data such as the checklists, maps, trend charts, geological factors, hydrogeological factors, and any geochemical data analysis tools used that support the conclusions.

Clearly state the conclusion and provide a closing statement

Example language for the closing statement if the ASD is for SSIs during detection monitoring: "The preceding information serves as the ASD prepared in accordance with 40 CFR 257.94(e)(2) and supports the position that the SSIs during [the monitoring period] are not due to a release from the CCR unit. Therefore, no further action (i.e., assessment monitoring) is warranted and [name the CCR unit] will remain in detection monitoring."

Certification by a PE (for ASDs developed under the CCR Rule)

An ASD developed under the CCR Rule requires certification by a Professional Engineer (PE). Including the PE early in the evaluation process can improve this individual's confidence in supporting the conclusions. Keep in mind that the PE may request time to review the data and the ASD report, and factor this time into schedules so that ASD compliance dates can be achieved (the demonstration must be completed and posted to the owner's CCR website within 90 days from the determination that an SSI or SSL has occurred under the CCR Rule). If the PE requires approval by a Professional Geologist (PG), ensure that a PG is also involved early in the evaluation. It may also be beneficial to develop a certification statement that passes management and legal approval.

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A
ASD REFERENCE TABLES

Table A-1
Potential Indicator Constituents for Coal Ash and FGD Gypsum

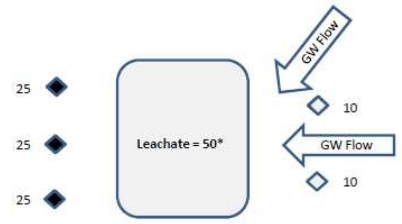
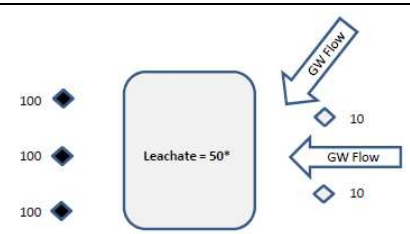
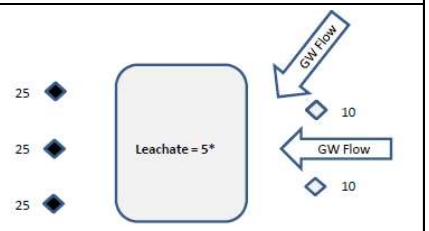
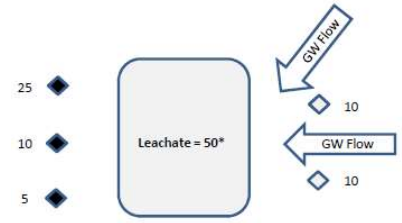
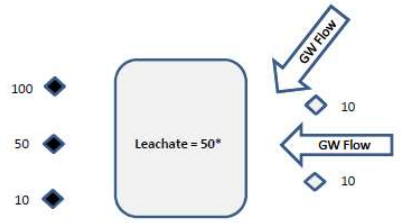
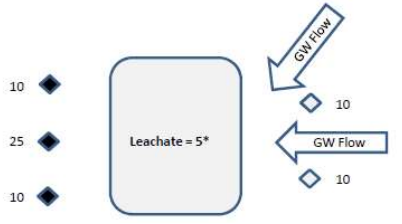
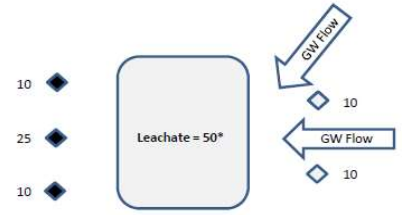
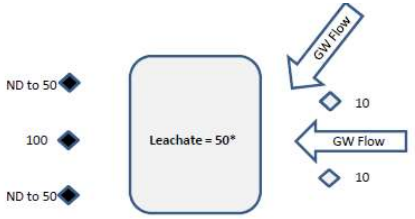
Potential Indicators for Coal Ash		Potential Indicators for FGD Gypsum	
Constituent	**Advantages and Caveats**	**Constituent**	**Advantages and Caveats**
Boron	Typically present in leachate, non-reactive and mobile in common hydrogeologic environments, and not a common anthropogenic contaminant.	Sulfate	High concentrations expected in both washed and unwashed FGD gypsum (EPRI, 2011). Commonly analyzed. Very mobile in all hydrogeologic environments. Less useful in strongly reducing environments where sulfate can be reduced to hydrogen sulfide gas.
Molybdenum	Most useful for dry-managed coal ash. May be less mobile than boron in some hydrogeologic environments. Concentrations may be too low in impoundment leachate to be useful if background groundwater has detectable concentrations.	Fluoride	Assure that leachate concentration is higher than background, particularly for washed gypsum. Mobile in common hydrogeologic environments, although precipitation as CaF_2 is possible.
Lithium	Useful for coal ash management sites where the power plant burned bituminous coal. Leachate concentrations are typically low in coal ash derived from subbituminous and lignite coal (EPRI, 2006).	Calcium	High concentrations expected in both washed and unwashed FGD gypsum (EPRI, 2011). Understanding of carbonate chemistry necessary to assure that precipitation or dissolution does not affect downgradient concentrations.
Sulfate	Commonly analyzed and very mobile in all hydrogeologic environments. Concentration in impoundment leachate may in some cases be too low relative to background to be useful. Less useful in strongly reducing environments where sulfate can be reduced to hydrogen sulfide gas.	Boron	Mobile indicator constituent for unwashed FGD gypsum. Concentrations for washed gypsum may be too low to be useful (EPRI, 2011).

Table A-1 (continued)
Potential Indicator Constituents for Coal Ash and FGD Gypsum

Potential Indicators for Coal Ash		Potential Indicators for FGD Gypsum	
Constituent	**Advantages and Caveats**	**Constituent**	**Advantages and Caveats**
Bromide	May have high concentration in coal ash leachate at power plants where brominated powdered activated carbon (Br-PAC) or calcium bromide is used for mercury control. Leachate concentrations for coal ash generated absent use of these technologies may be too low to be useful. Mobile and non-reactive in typical groundwater environments.	Bromide	Mobile indicator constituent for unwashed FGD gypsum, especially if Br-PAC or CaBr used for mercury controls. Concentrations for washed gypsum may be too low to be useful (EPRI, 2011).
Potassium	Commonly analyzed, although may be less mobile than boron and sulfate. Assure that leachate concentration is higher than background and that there are no anthropogenic sources such as agricultural fields where potassium may be applied in fertilizers.	Chloride	Mobile indicator constituent for unwashed FGD gypsum. Concentrations may be very high if transport water is recirculated. Concentrations for washed gypsum may be too low to be useful (EPRI, 2011).
Sodium	Useful for coal ash management sites where the power plant injects trona or sodium bicarbonate, or burned subbituminous coal. Absent dry sorbent injection, leachate concentrations are considerably lower in coal ash derived from bituminous coal, particularly at impoundments (EPRI, 2006). Assure that leachate concentration is higher than background and that there are no anthropogenic sources such as agricultural fields, or major highways in northern climates where sodium may be applied as road salts.		
Fluoride	Mobile and non-reactive in common hydrogeologic environments. Assure that leachate concentration is higher than background.		
Source: EPRI, 2012			

Note: This table is also presented in the body of the report as Table 3-1.

Table A-2
Hydrogeologic Scenarios

	Line of Evidence for:		
	CCR Leachate Release	**Possible CCR Leachate Release + Possible Alternative Source**	**Alternative Source Release**
	Column 1	**Column 2**	**Column 3**
Row a			
Row b			
Row c			
	1. Leachate concentration is higher than upgradient/background. 2. One or more downgradient concentrations are higher than upgradient/background but lower or equal to leachate concentration.	1. Leachate concentration is higher than upgradient/background. 2. One or more downgradient concentrations are higher than the leachate concentration.	1. Leachate concentration is less than upgradient/background.

This table is also presented in the body of the report as Figure 3-7.

Table A-3
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25th / 50th / 75th Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
CCR Rule Appendix III Detection Monitoring Constituents								
Boron	Key Indicator	Yes if unwashed	17 / 35 / 82 ug/L	No	Very mobile	Boron-containing rocks (especially marine shales and clays), seawater, volcanic and geothermal activities, mined in arid regions of the United States (and other countries)	Fly ash leachate, may also be present in FGD leachate; sewage sludge, boron-containing fertilizers or herbicides, manufacture of glass, fiberglass, ceramics, soaps, detergents, bleach, fire retardants, and lubricants; used in control rods of nuclear reactors, and to produce a green color in pyrotechnics and flames; also used in the aerospace industry	Micronutrient for plants but may be toxic to some plant species in high concentrations. Boron deficiencies are more common than toxicities. Mobile in most hydrogeological environments, particularly sandy materials. Sorption to clay reaches a maximum in the pH range of 8-10.
Calcium	No	Yes	21 / 43 / 70 mg/L	CEC	Slightly mobile	Calcium carbonate rocks, limestone, calcium clay; fifth most common element in Earth's crust	Water softening wastes, soil acidity neutralization (lime additions to soil), calcium road salt, deicing, agriculture, cement and concrete, drying agents	Calcium carbonate is one of the most common calcium minerals. The concentration in groundwater may be limited by the solubility of calcium carbonate or calcium sulfate (gypsum). May be sorbed by ion exchange in soil and sediments but tends to be a reversible reaction.

Table A-3 (continued)
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25th / 50th / 75th Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
CCR Rule Appendix III Detection Monitoring Constituents								
Chloride	No	Yes if unwashed	3.1 / 8.6 / 23 mg/L	No	Very mobile	Salt water and brackish water sources; chloride anion is the most abundant element (other than hydrogen and oxygen) in Earth's oceans	Road salt, deicing, water softening wastes, sewage, septic effluent, livestock waste, oil-field brines, salt water intrusion (oil and gas well production), industrial emissions, incinerator ash, landfill leachate, aerospace industry, automobile industry, soaps and detergents, drying agents, flame retardants, flocculants, pharmaceutical and medical waste	
Fluoride	Yes for some coal ash	Yes for some FGD gypsum	<0.1 / 0.2 / 0.4 mg/L	No	Mobile	Natural weathering of fluoride-containing minerals	Steel, brick, and aluminum manufacturing; waste incineration, municipal water treatment	Occurs as fluoride anion at pH > 3, hydrofluoric acid at pH < 3. Can be sorbed by amorphous aluminum and iron oxides under strongly acidic conditions.
pH	No	No	6.9 / 7.3 / 7.6 SU	- -	- -	Oxidation/weathering of naturally occurring pyritic soils due to well installation or other excavation may cause low pH	Low pH: Oxidation/weathering of pyrite in coal or coal ash, leaking batteries High pH: Certain coal ash leachates may have high pH; cement and concrete manufacturing and use, soaps and detergents	Fly ash leachate pH may be acidic or basic depending on coal type. Bituminous coals tend to produce more acidic leachate, especially if comanaged with pyritic mill rejects, and subbituminous coals tend to produce more basic leachate. Important due to impact of pH on leachability of many trace elements.

Table A-3 (continued)
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25^{th} / 50^{th} / 75^{th} Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
CCR Rule Appendix III Detection Monitoring Constituents								
Sulfate	Yes for most coal ash	Key Indicator	4.7 / 14 / 36 mg/L	No	Very mobile	Sulfur is the 14th most abundant element in the Earth's crust; oxidation/weathering of naturally occurring pyritic soils (such as iron sulfide)	Fly ash and FGD leachate, lead acid batteries, algaecides, gypsum mines, wood pulp production (paper mills), textile mills, tanneries, coal pyrite oxidation/weathering from mining or storage, industrial emissions and effluents, soaps and detergents, drying agents, flocculants, petroleum refining	Sulfate may precipitate with calcium, barium, and strontium. Not usually sorbed due to negative charge, but can be sorbed under acidic conditions by soils and sediments containing iron, aluminum, and manganese oxides with positive charges. May precipitate from solution as sulfides under strongly reducing conditions.
Total Dissolved Solids (TDS)	No	No	146 / 254 / 381 mg/L	- -	- -	TDS is largely based on concentration of major ions in groundwater (Ca, Mg, Na, K, carbonates, Cl, SO_4)		Refer to primary components.

Table A-3 (continued)
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25^{th} / 50^{th} / 75^{th} Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
CCR Rule Appendix IV Assessment Monitoring Constituents								
Antimony	No	No	<1 ug/L	No	Very mobile		Flameproof retardants, batteries, lead shot; metal and glass manufacturing	Usually soluble but may be sorbed by iron, aluminum and manganese oxides under acidic conditions (EPRI, 1987).
Arsenic	No	No	0.23 / 0.79 / 3.0 ug/L	Yes, pH and redox	Variable	May be present in sulfide minerals and in organic forms; concentrations can be naturally higher than typical under reduced conditions or if sulfide minerals are oxidized	Wood preservatives (chromated copper arsenate), feed additives, pharmaceuticals, electronic devices, metallurgical applications, metal mining and smelting, cemeteries; pesticides/herbicides/ insecticides (prior to 1960)	Arsenic occurs in the 5+ oxidation state as arsenate (AsO_4^{3-}) under relatively neutral pH and oxidized conditions, and as 3+ arsenite (AsO_3^{3-}) under reduced conditions. Arsenic fate and transport is complex due to sensitivity to pH and redox. Sorption usually increases with decreasing pH.
Barium	No	No	24 / 54 / 120 ug/L	Yes	Mobile	Weathering of sedimentary rocks	Well drilling mud or fluid, mining; manufacture of glass, paint, and rubber	Usually present as relatively insoluble barium sulfate in fly ash. Most barium compounds have limited solubility. Sorbed by clay, soils, and sediment.
Beryllium	No	No	<1 ug/L	Yes, pH	Immobile	Relatively scarce in Earth's crust	Electronic and electrical components, telecommunications and computer components, defense applications	Strong tendency to sorb at neutral to alkaline pH. Sorption may be reduced in the presence of humic acids.

Table A-3 (continued)
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25th / 50th / 75th Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
CCR Rule Appendix IV Assessment Monitoring Constituents								
Cadmium	No	No	<1 ug/L	Yes, pH	Slightly mobile	Minor component in Earth's crust, occurs in zinc minerals	Batteries, waste incineration, sewage sludge disposal, paint pigments, phosphate fertilizers, automobiles, electroplating and metal fabricating	Can be sorbed by clay, soil, and sediment at pH less than 8, but sorption decreases at low pH.
Chromium	No	No	0.68 / 1.2 / 3.0 ug/L	Yes, pH and redox	Variable	Primarily occurs as Cr(III) in soils and rocks	Electroplating, leather tanning, wood pulp production (paper mills), metal ore refining, wood preservatives, steel manufacturing, automobiles, electroplating and metal fabricating, paint and coatings	The solubility of Cr(III) generally increases at pH levels <6.5 and >11. Cr(III) is the predominant dissolved species under reducing to mildly oxidizing conditions. Cr(IV) is more soluble than Cr(III) at neutral to alkaline pH. Cr(VI) is soluble at alkaline pH and mildly to strongly oxidizing conditions.
Cobalt	No	No	0.063 / 0.17 / 0.48 ug/L	Yes	Variable	Relatively scarce in Earth's crust; usually occurs in combination with arsenic and sulfur in nature	Rechargeable battery electrodes, radial tires, drying agents, catalysts, paint pigments, medical wastes, automobiles	May be sorbed by mineral oxides (e.g., Fe and Mn), crystalline materials such as aluminosilicate, and natural organic substances in soil.
Lead	No	No	0.018 / 0.070 / 0.27 ug/L	Yes pH	Variable	Rare in Earth's crust	Smelting and mining, batteries, waste incineration, leaded gasoline (before 1996), lead-containing paint, glass manufacturing, ammunition, firing ranges, plumbing, automobiles	Sorption usually increases with pH.

Table A-3 (continued)
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25th / 50th / 75th Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
CCR Rule Appendix IV Assessment Monitoring Constituents								
Lithium	Yes for some coal ash	No	2.0 / 6.0 / 18 ug/L	No	Mobile	Rare in Earth's crust, dissolution of lithium-containing minerals	Glass and ceramics production, lubricants, greases, batteries, salt water intrusion	Reacts with sulfate ions to form lithium sulfate anion.
Mercury	No	No	NR	No	Slightly mobile	Occurs as HgS in nature; can be converted to methylated forms by anaerobic microbes	Waste incineration, mercury mining, metal recycling, fungicides, fluorescent lamps, batteries, thermometers/ thermostats/switches (electronic equipment), automobiles	Can be sorbed by iron, magnesium, silicon oxides, and organic matter.
Molybdenum	Yes for some coal ash	No	0.32 / 1.0 / 3.3 ug/L	No	Very mobile	Usually combined with sulfur or oxygen in natural minerals	Steel production, catalysts, lubricants, pigments, fertilizers, animal feed	Micronutrient for plants and animals; may be in fertilizers or animal feed. Peak sorption at pH <5 and limited sorption above pH 8. Phosphate and other oxyanions will depress sorption.

Table A-3 continued)
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25^{th} / 50^{th} / 75^{th} Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
CCR Rule Appendix IV Assessment Monitoring Constituents								
Radium 226 + 228	No	No	NR / 0.28 / 1.2 pCi/L	Yes, CEC	No data	Natural decay product of uranium and thorium ores	Uranium mines, nuclear power, nuclear fuel and weapons manufacturing, uranium in coal	Radium decays to radon gas, so it is prevalent in locations where radon gas is a concern.
Selenium	No	No	0.12 / 0.34 / 1.0 ug/L	Yes, pH and redox	Variable	Usually occurs with silver, copper, lead, and nickel sulfide minerals; may exist in a variety of organic compounds	Metal mining and milling, industrial waste water, sewage effluent, waste incineration, saline agricultural waste waters	May exist as selenate (SeO_4^{2-}), selenite (SeO_3^{2-}), elemental selenium (Se^0), and selenide (Se^{2-}) in groundwater (shown in order from most to least oxic species). Since anionic selenium is the dominant form in groundwater, sorption typically is not significant. However, selenite can be sorbed by iron and aluminum oxides.
Thallium	No	No	<1 ug/L	Yes, redox	Mobile	Occurs in combinations with oxygen, sulfur, and halogens	Glass and electronic industries, iron and steel production, cement factories	May be immobilized under reducing conditions.

Table A-3 (continued)
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25th / 50th / 75th Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
Other Constituents								
Aluminum	No	No	0.98 / 3.0 / 4.9 ug/L	Yes, pH	Slightly mobile	Most abundant metal in Earth's crust; weathering of aluminosilicate minerals	Mining and industrial emissions and effluents; most abundant metal in coal ash, cement and concrete, drying agents, well drilling, flocculants, abrasives, aluminum manufacturing	Most soluble in water under acidic and alkaline solutions, essentially insoluble in near neutral water. May be sorbed by soils, sediments, and organic matter.
Bromide	Possible for certain coal ash	Yes if unwashed	0.02 / 0.04 / 0.09 mg/L	No	Mobile	Brackish groundwater and sea water, relatively rare in Earth's crust	CCR fly ash and emission control wastes, particularly if bromide compounds were used to facilitate mercury capture; drinking water disinfection, flame retardants	
Copper	No	No	0.47 / 1.0 / 3.0 ug/L	Yes, pH and redox	Variable	Relatively common in Earth's crust	Manufacture of bronzes, brass, electrical conductors, and ammunition; sewage sludge wastes, municipal solid wastes, copper-containing fertilizers, cemeteries, electronics, plumbing, wood preservatives, automobiles, electroplating and metal fabricating	Solubility may be controlled by solubility of copper hydroxide. May sorb to organic matter, clay, aluminum, manganese, and iron oxides.
Iron	No	No	0.81 / 7.9 / 93 ug/L	Yes, pH and redox	Variable	Commonly has high concentration in groundwater under reduced conditions; Weathering of iron-containing minerals (dissolution of iron oxides under reducing conditions), 4th most common element in Earth's crust	Industrial emissions, pyrite oxidation/acid mine drainage from coal mining or storage, flocculants	Iron oxides my dissolve and become mobile under reducing conditions. Occurs as ferrous (+2) and ferric (+3) iron. Ferric iron can be sorbed by silica, clay, and iron and manganese oxides.

Table A-3 (continued)
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25^{th} / 50^{th} / 75^{th} Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
Other Constituents								
Magnesium	No	No	4.4 / 11 / 23 mg/L	CEC	Slightly mobile	Eighth most abundant element in the Earth's crust, abundant in sea water; dissolution of magnesium carbonates and clay minerals	Aluminum fabrication and welding (alloying agent), flares and pyrotechnics, fire retardants, heat-resistant bricks, animal feed, fertilizers, drying agents	Solubility may be limited under alkaline conditions. May be removed from solution by ion exchange in soils and sediments via reversible reactions.
Manganese	No	No	0.85 / 7.0 / 84 ug/L	Yes, pH and redox	Variable	Commonly has high concentration in groundwater under reduced conditions; 13th most abundant element in the Earth's crust	Production of steel and aluminum alloys, glass production, use as an additive in gasoline	
Nickel	No	No	0.35 / 1.1 / 2.5 ug/L	No	Variable	Commonly combined with iron or sulfur	Manufacture of steels, other metal alloys, and electronic applications; automobiles, electroplating and metal fabricating, petroleum	Sorbs to iron and manganese oxides, and clay to a lesser extent.
Nitrogen	No	No	0.07 / 0.55 / 2.4 (NO_3 as N) mg/L	Nitrification/ denitrifi-cation, redox	Very mobile as NO_3	In nature, nitrogen is converted from one redox state to another by abiotic reactions and microbial catalysis in oxic conditions: $NH_4OH \rightarrow NO_2 \rightarrow NO_3$; under reducing conditions: $NO_3 \rightarrow NO_2 \rightarrow N_2$	Fertilizers, livestock wastes, wastewater treatment plants, sewage and septic effluent, rubber manufacturing; ammonia sources include CCRs from sources using SNCR or SCR technology, coke production, flame retardants	NO_2 and NO_3 are not significantly sorbed by most soils, sediments, or clays, but NH_4OH is.

Table A-3 (continued)
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25^{th} / 50^{th} / 75^{th} Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
Other Constituents								
Phosphate	No	No	<0.01 / 0.02 / 0.04 mg/L	Yes, pH	Variable	Phosphorus is the 11th most abundant element in the Earth's crust	Fertilizers, wastewater treatment plants, sewage and septic effluents, industrial effluents, soaps and detergents, flame retardants	Can be sorbed by iron, aluminum, and manganese oxides, and by clay under acidic conditions.
Potassium	Yes for some coal ash	No	0.9 / 1.7 / 3.5 mg/L	CEC	Mobile	7th most abundant element in the Earth's crust; Weathering of potassium-containing minerals	Water treatment, fertilizers, sea water intrusion, soaps and detergents, drying agents	May be removed from groundwater by reversible ion exchange with soils and sediments.
Silicon	No	No	12 / 19 / 31 mg/L	Yes	Very mobile	2nd most abundant element in the Earth's crust; usually in the form of SiO_2	Glass, ceramics, abrasives, electronic devices, metal alloying, water filtration, insulation, cement, concrete, paper, rubber, lubricants, flocculants	Can be sorbed by iron and aluminum oxides, and by clay minerals.
Silver	No	No	<1 ug/L	Yes, pH	Variable		Textile plant wastewater, photographic materials, sewage sludge, medical wastes, electronics, electroplating and metal fabricating	Can be sorbed by soils but affected by pH, clay content, particle size, organic content, and free iron and manganese oxide content.
Sodium	Yes for some coal ash	No	5.2 / 11 / 29 mg/L	CEC	Mobile	6th most abundant element in Earth's crust; brackish groundwater and surface water, sea water, weathering of sodium-containing minerals	Road salt, deicing, septic effluent, sodium hydroxide water treatment wastes, water softening, salt water intrusion (gas and oil well production), sewage and septic effluent, soaps and detergents, drying agents	Most sodium compounds are soluble but may be sorbed by reversible ion exchange in soils or sediments.

Table A-3 (continued)
Potential Alternative Sources by Constituent

Constituent Name	Coal Ash Indicator? (note 1)	FGD Gypsum Indicator? (note 1)	Typical U.S. Groundwater Concentration at 25th / 50th / 75th Percentile (note 2)	Reactivity (note 3)	Mobility (note 4)	Natural Prevalence and Naturally Occurring Causes for Presence in Groundwater	Potential Anthropogenic Sources	Comments (note 5)
Other Constituents								
Strontium	No	No	100 / 270 / 680 ug/L	Yes	Slightly mobile		Glass and ceramics production, pyrotechnics, phosphate fertilizers	Reacts with sulfate ions to form $SrSO_4^0$.
Vanadium	No	No	0.30 / 1.4 / 11 ug/L	Yes, pH and redox	Variable		Crude oil, oil shale, tar sands, phosphate fertilizers, wastes from steel production, petroleum	Can be sorbed by iron, aluminum, and manganese oxides; sorption decreases as pH increases.
Zinc	No	No	1.6 / 4.8 / 18 ug/L	Yes, pH	Variable		Fertilizers, protective coatings to reduce corrosion of metal surfaces, dry-cell batteries, castings, automobiles, lubricating oils and greases, plumbing/piping, electroplating and metal fabricating	Sorption increases with increasing pH but is also affected by clay content, particle size, organic content, and iron, aluminum, and manganese oxide content.

Notes:

1. Based on EPRI (2012). "No" indicates that the constituent it is not considered an indicator due to low concentration in CCR leachate relative to typical background, low mobility, and/or potential for reactivity.

2. Concentration ranges in ug/L from USGS (2011), Table 4; concentration ranges in mg/L or SU from USGS (2008), Tables 2 and 6; radium 226+228 from Szabo et. al (2012) supplemental table S-3; NR indicates that the concentration was not reported in any of these three documents.

3. Reactivity and mobility, while separate geochemical processes, are often interrelated. Reactivity descriptions in this table refer to chemical reactions, primarily precipitation and dissolution, that can change the concentration or mobility of the element in solution under typical aquifer conditions. Yes indicates that the constituent is subject to precipitation, coprecipitation, and/or dissolution reactions. In addition, pH and redox are indicated if they have a strong influence on the environments under which reactions occur and/or mobility. CEC is listed for constituents that are subject to cation exchange.

4. The mobility classification is based on the classification system of van Loon and Duffy (2000). See Table 2-2 of EPRI (2012) for corresponding K_d values.

5. Refer to Appendix B in EPRI (2012) for brief summaries of geochemical factors affecting reactivity and sorption. Detailed information can be found for selected constituents in the following EPRI reports:

- Arsenic
  1015550 | Chemical Constituents in Coal Combustion Product Leachate: Arsenic | Profile | 2008
  1021212 | Arsenic in Coal Combustion Products | Tech Brief | 2010
- Beryllium
  1012583 | Chemical Constituents in Coal Combustion Product Leachate: Beryllium | Profile | 2006
- Boron
  1005258 | Chemical Constituents in Coal Combustion Product Leachate: Boron | Profile | 2005
  1023737 | Boron in Coal Combustion Products | Tech Brief | 2012
- Chromium
  1022143 | Chromium in Coal Combustion Products | Tech Brief | 2011
- Lithium
  In Prep | Chemical Constituents in Coal Combustion Products: Lithium | Profile | 2018
- Molybdenum
  1021815 | Chemical Constituents in Coal Combustion Products: Molybdenum | Profile | 2011
  In Prep | Molybdenum in Coal Combustion Products | Tech Brief | 2017
- Selenium
  3002001237 | Chemical Constituents in Coal Combustion Product Leachate: Selenium | Profile | 2013
  3002003761 | Selenium in Coal Combustion Products | Tech Brief | 2014
- Thallium
  1016801 | Chemical Constituents in Coal Combustion Product Leachate: Thallium | Profile | 2008
  3002001155 | Thallium in Coal Combustion Products | Tech Brief | 2013

Table A-4
Constituents Potentially Associated with Alternative Anthropogenic Sources

Potential Source	Constituents That May Be released to Groundwater*
Abrasives	**Silicon, aluminum**
Acid mine drainage	**Low pH, sulfate, iron**, dissolved solids, metals (aluminum, cadmium, calcium, chromium, cobalt, copper, magnesium, manganese, nickel, zinc, and others); can travel along mine shafts and tunnels and show up in unexpected locations (sometimes across aquifers) (notes 1, 26, 51, 54)
Aerospace industry	**Boron, perchlorate, chloride, cyanide, cadmium**, beryllium, solvents (trichloroethane, methylene chloride, trichloroethylene, toluene, methylethylketone), metals, oils (notes 2, 3, 4, 5, 51)
Aging infrastructure (leaking sewage, urban runoff)	Nitrate, phosphorus, sodium, chloride, organic substances, bacteria, pesticides, miscellaneous chemicals, cadmium, copper, iron, lead, selenium, zinc, and other elements (note 6)
Agriculture - animal feed lots	**Nitrates, ammonia, other nitrogen compounds, phosphorus/phosphate, chloride**, **arsenic**, **magnesium, molybdenum, selenium** and other elements, organic substances, bacteria/viruses (notes 7, 22, 51, 52, 54)
Agriculture - fertilization	**Nitrates, ammonia, other nitrogen compounds, phosphorus/phosphate**, **boron**, **cadmium, calcium**, chloride, cobalt, **copper**, cyanide, **magnesium**, **molybdenum, potassium, selenium, strontium, vanadium, zinc**, and other elements (notes 7, 22, 51, 52, 54)
Agriculture - irrigation	**Nitrates, ammonia, other nitrogen compounds, phosphorus/phosphate,** arsenic, boron, cadmium, calcium, chloride, cobalt, copper, cyanide, magnesium, mercury, molybdenum, potassium**, selenium**, sodium, sulfate, and other elements (notes 7, 8, 9, 22, 52)
Agriculture - lime addition	**Calcium** (note 22)
Agriculture - pesticides, herbicides, and insecticides	Aldicarb, Aldrin, alachlor, atrazine, carbofuran, chlordane, dacthal, DDT, dieldrin, bibromo-chloropropane, 1,2-dichloropropane, dinoseb, endrin, endosulfan, ethylene dibromide, heptachlor, hexachlorobenzene, lindane, mirex, PCBs, prometon, simazine, toxaphene, trifluralin; **arsenic** (prior to 1960), chloride, **mercury, boron**, **sulfate** (notes 10, 51, 52, 54)
Airport runways	**Sodium, potassium**, acetate, formate, urea (note 11)
Aluminum manufacturing	**Aluminum, fluoride, sodium**, magnesium, manganese, perfluorocarbons, polycyclic aromatic hydrocarbons (notes 12, 13)
Ammunition, firearms	**Lead, antimony, copper,** other heavy metals, nitrate, perchlorate, potassium, sulfur/sulfate, chloride (notes 14, 15, 22)
Asphalt plants	Oils, greases, PAHs, other hydrocarbons (note 16)
Automobile production	**Chloride, sulfate, phosphate,** oil and grease, solvents, ethylene glycol. Potential for heavy metals: aluminum (auto bodies), **cadmium** (tires and batteries), **cobalt** (radial tires), **chromium** (brakes, coolants, engine parts), **copper** (brake linings), iron (auto bodies), **lead** (batteries, lube oil and grease, bearings, brakes), **mercury** (batteries), **nickel** (lube oil, brakes), **zinc** (tires, fuel oil, lubricants) (notes 17, 18, 22)
Automobile repair shops	Gasoline, diesel fuel, oil, degreasing solvents (toluene, xylene, chlorinated solvents, MEK), ethylene glycol, lead, sulfate (notes 19, 44)

Table A-4 (continued)
Constituents Potentially Associated with Alternative Anthropogenic Sources

Potential Source	Constituents That May Be released to Groundwater*
Batteries	**Sulfate, lead, antimony**, **cadmium, cobalt, lithium, mercury, zinc, low pH** (notes 22, 51)
Bleach manufacturing	**Boron** (bleaches containing sodium perborate) (notes 20, 31)
Brick manufacturing	**Aluminum, silicon, iron**, calcium, **fluoride**, **magnesium,** chromium (notes 21, 22, 52)
Catalysts	Aluminum, chromium, **cobalt**, copper, iron, **molybdenum**, titanium, tungsten, vanadium, zinc, and other metals (depends on catalyst manufactured or used) (note 22)
CCR - ash	**Boron, sulfate**, molybdenum, lithium, bromide, potassium, sodium, fluoride, selenium; may contain ammonia (nitrogen) if SCR or SNCR technology was used at the power plant (note 22)
CCR - FGD gypsum	**Sulfate**, fluoride, calcium, boron, bromide, chloride, selenium (note 22)
CCR - FGD fixated sludge	**Boron, sulfate**, calcium, chloride, molybdenum, lithium, bromide, potassium, sodium, fluoride, selenium (note 22)
Cemeteries	**Formaldehyde**, **copper, arsenic,** mercury, pesticides, fertilizers, weed killers (note 23)
Cement and concrete manufacturing and use	**High pH, aluminum, calcium, silicon, thallium,** chromium and other elements (notes 22, 24, 51)
Ceramics production	Oxides of carbon, **silicon, boron**, and nitrogen; may include aluminum, antimony, barium, copper, fluoride, iron, **lithium**, **strontium**, and other elements (notes 21, 22, 51)
Coal mining	**Sulfate, low pH, iron**, dissolved solids, trace elements (aluminum, beryllium, cadmium, chromium, cobalt, copper, lead, magnesium, manganese, mercury, nickel, selenium, **uranium (decays into radium 226+228)**, zinc and others); Oxidation of pyrite in coal can form sulfuric acid. The low pH increases solubility of many metals. (notes 1, 26, 51, 54)
Coatings	VOCs, solvents (halogenated solvents and non-halogenated solvents such as acetone, cresols, cresylic acid, nitrobenzene, benzene, toluene, xylene, methyl ethyl ketone, methylene chloride, etc.); trace elements may include barium, cadmium, **chromium**, cobalt, lead, mercury, molybdenum, nickel, titanium, and **zinc** (note 27)
Coke production (from coal)	**Phenols, ammonia (nitrogen), polycyclic aromatic hydrocarbons, cyanide**, benzene, naphthalene, anthracene, cresols, metals (see metals in "coal piles or coal waste piles") (note 28)
Computer and telecommunications components (electronics)	Trace elements may include aluminum, arsenic, barium, **beryllium**, cadmium, chromium, cobalt, **copper**, gallium, gold, iron, lead, manganese, mercury, palladium, platinum, selenium, **silver**, and zinc; solvents may include benzene, xylene (dimethylbenzene), trichloroethane, tetrachloroethane, ethylene glycol, methyl cellosolve; **silicon** (notes 29, 30, 32)

Table A-4 (continued)
Constituents Potentially Associated with Alternative Anthropogenic Sources

Potential Source	Constituents That May Be released to Groundwater*
Defense applications	**Beryllium** (note 22)
Detergent or soap manufacturing	**Sodium, potassium, sulfates and sulfonates, high pH, phosphate**, **chloride, boron**, phenol, aluminosilicate, sodium citrate, nitrilotriacetate, alcohol ethoxylates, fats, oil and grease, lead, hexane, methyl alcohol, trichloroethane, perchloroethylene, benzene, toluene (notes 22, 34, 35)
Deicing	**Sodium, chloride**, **calcium**, magnesium, urea (notes 44, 51)
Drying agents	**Aluminum, calcium, sodium, potassium, magnesium, sulfate, chloride,** cobalt, lithium, phosphorus, silicon and/or other substances (notes 22, 36, 37)
Electronic equipment manufacturing and disposal	**Copper, silver, gold, palladium**, **arsenic, beryllium, copper, mercury, nickel,** selenium, **silicon, thallium** and other trace elements, chloride, fluoride, solvents (benzene, xylene, 1,1,1-trichloroethane, tetrachloroethane, methanol), ethylene glycol, hydrogen chloride, hydrogen fluoride (notes 22, 29, 30, 33, 51)
Electroplating and metal fabricating	**Cadmium, chromium, copper, nickel, silver**, sodium, tin, **zinc**, spent solvents, paints, spent acidic and alkaline solutions, cyanide, waste oils (notes 17, 22, 44, 51, 52, 56)
Explosives manufacturing and testing	**Nitroglycerin and nitro-aromatic compounds**, nitrate, perchlorate, ammonia, lithium, sodium, potassium, sulfur/sulfate, aluminum, chloride, **lead**, antimony, **copper**, nickel, silver (notes 38, 39, 40, 51)
Fertilizers	See Agriculture - fertilization
Fiberglass manufacturing	Aluminum, silicon, calcium, magnesium, **boron**, polyester or epoxy resin, styrene, solvents, volatile organic compounds, formaldehyde, urea, phenol, vinyl acetate (notes 31, 41)
Firearms, ammunition	See Ammunition, firearms
Firing ranges	**Lead**, antimony (notes 14, 22)
Fireworks manufacturing or use	Aluminum, antimony, arsenic, barium, **boron**, chloride, copper, lead, **magnesium**, nitrate, perchlorate, potassium, sulfur/sulfate, **strontium** (notes 31, 38, 39, 40, 51)
Flame retardant manufacturing or use	**Bromine, phosphate, nitrogen/nitrate, chloride**, **antimony, boron**, **magnesium**, polybrominated diphenyl ethers (PBDEs), PCBs (notes 22, 42, 43, 51)
Flocculants	**Sulfate, chloride, aluminum, iron**, ammonium, calcium, silica, polyamines (note 45)
Fluorescent lamps/bulbs	**Mercury**, PCBs in ballasts (note 47)
Fracking	See Oil and gas wells / production

Table A-4 (continued)
Constituents Potentially Associated with Alternative Anthropogenic Sources

Potential Source	Constituents That May Be released to Groundwater*
Fungicides	See Pesticides
Furniture (wood stripping and refinishing)	Methylene chloride, methanol, isopropyl alcohol, acetone, perchloroethylene, toluene, acidic and alkaline solutions, metals, other solvents, petroleum distillates, resins, halogenated hydrocarbons, glycol ether (note 44)
Gasoline stations	**Benzene, ethylbenzene, toluene, xylene, MTBE**, ethylene dichloride, naphthalene, other organic compounds, lead (prior to 1996), **manganese**; trichloroethylene, perchloroethylene, methylene chloride, carbon tetrachloride, oils, ethylene glycol, hydraulic fluid, detergents, and acids (notes 22, 49, 51, 52)
Glass manufacturing	**Silicon**, antimony, **barium, boron, lead**, iron, **lithium**, **manganese**, nickel, potassium, **strontium**, **thallium**, tin, zinc, fluoride (notes 22, 31, 50, 51)
Industrial emissions	**Chloride, sulfate, iron,** wide variety of other elements and chemical substances (notes 22, 51, 54)
Irrigation	See Agriculture – irrigation
Junk and scrap yards	Used oil, gasoline, antifreeze, lead, sulfuric acid, agricultural chemicals/pesticides/other chemicals, metals (note 44)
Lamp manufacturing and disposal	**Mercury**, bromide, chloride, fluoride, iodide, PCBs, sodium (notes 22, 47)
Landfills - industrial	Wide range of trace metals, acids, **chloride**, sulfate, organic substances and pesticides (notes 51, 53, 54)
Landfills - municipal	Salts (sodium, calcium, magnesium, **chloride**, etc.), metals (iron, copper, zinc, other heavy metals), nitrate, organic compounds, solvents, pesticides (notes 22, 51, 54)
Laundry - dry cleaning	**Perchloroethylene (tetrachloroethylene)**, camphor oil, turpentine spirits, benzene, kerosene, white gasoline, petroleum solvents (petroleum naphtha), chloroform, carbon tetrachloride, trichloroethylene, 1,1,2-trichlorotrifluoroethane, glycol ethers, 1,1,1-trichloroethane, decamethylcyclopentasiloxane, n-propyl bromide, liquid carbon dioxide, fluorocarbon-113, antimony, cadmium, copper, lead, sulfate, zinc (notes 20, 31, 44, 52)
Leather tanning	**Chromium**, **cyanide**, **tannins**, chlorinated phenols including PCB, azodyes, cadmium, cobalt, copper, antimony, barium, lead, selenium, mercury, zinc, arsenic, nickel, formaldehyde, pesticides, salts, lime, acids, sodium sulfide, hydrogen sulfide, sulfate (notes 22, 55, 56)
Lubricants and greases	**Zinc**, polyaromatic hydrocarbons, arsenic, **boron**, cadmium, lead, **lithium**, **molybdenum**, PCBs, **silicon**, and other elements (note 22)
Medical supplies or wastes	Chloride, formaldehyde, **arsenic**, cadmium, **cobalt**, lead, mercury**, silver**, other heavy metals, radioactive waste, infectious or pathological waste, dioxins and furans from incineration; Also see Pharmaceutical industry (notes 22, 51, 57, 58, 59, 62)

Table A-4 (continued)
Constituents Potentially Associated with Alternative Anthropogenic Sources

Potential Source	Constituents That May Be released to Groundwater*
Metal manufacturing - smelting	**Aluminum**, **antimony**, **arsenic**, beryllium, cadmium, **chromium**, **copper**, cyanide, iron, **lead**, **magnesium** (aluminum manufacturing), **manganese** (steel and aluminum manufacturing), mercury, **molybdenum** (steel manufacturing), **nickel** (steel and other metal manufacturing), **selenium**, silver, **thallium** (iron and steel manufacturing), zinc and other elements, **fluoride** (steel and aluminum manufacturing), **silicon, vanadium** (steel manufacturing), **zinc** (notes 22, 44, 51, 52)
Metal mining	Aluminum, antimony, **arsenic**, beryllium, cadmium, **chromium**, **copper, cyanide**, iron, **lead, manganese**, **mercury, nickel, selenium**, silicon, silver, thallium, tungsten, zinc and other elements (notes 22, 51, 52, 54, 56)
Metal plating	Spent solvents, paints, spent acidic and alkaline solutions, waste oils, heavy metal sludges, metal dust, chromium, copper, nickel, selenium, **zinc** and other elements (notes 22, 44, 51, 52)
Metal recycling	Iron, copper, **mercury**, nickel, zinc, and other elements (note 22)
Mining - unspecified	Depends on contents of ore; may include aluminum, antimony, arsenic, beryllium, cadmium, chromium, copper, iron, lead, manganese, mercury, nickel, selenium, silver, **sulfate** (gypsum mines), thallium, zinc, other minerals, hydraulic oils; **radium 226+228 (uranium mines)** (notes 22, 51)
Natural gas pipelines	**Methane, PCBs** (notes 60, 61)
Nuclear power	**Tritium**, **strontium 90, radium 226+228,** boron, beryllium (notes 31, 51, 54)
Oil and gas wells / production	Produced water may contain high **TDS, chloride, sodium**, sulfate, barium, boron, bromide, iodide, lithium, potassium, radionuclides, **vanadium** and other minerals, methane, volatile organic compounds (notes 52, 60, 63)
Ore refining / smelting	Aluminum, antimony, arsenic, beryllium, cadmium, chromium, copper, cyanide, iron, lead, manganese, mercury, nickel, selenium, silver, thallium, zinc and other elements (notes 22, 44, 51)
Paint and pigment manufacturing	VOCs, solvents (halogenated solvents, non-halogenated solvents such as acetone, cresols, cresylic acid, nitrobenzene, benzene, toluene, xylene, methyl ethyl ketone, methylene chloride, etc.); metals may include **barium**, **cadmium, cobalt**, **chromium**, **lead**, mercury, **molybdenum**, titanium, and zinc (notes 22, 44, 51, 52, 64)
Paper and pulp manufacturing	Organic and inorganic compounds including lignin, cellulose, phenols, mercaptans, **chromium**, nitrates, phosphates, **silicon, sulfides/sulfates**, chlorinated compounds including chloroform and dioxin (notes 22, 65)
Petroleum facilities and refining	Benzene, ethylene, toluene, xylene, methane, other organic compounds, hydrogen sulfide, **sulfate, nickel, vanadium** and other elements; some refineries use deep-injection wells to dispose of highly contaminated wastewater that could potentially contaminate groundwater (note 51)
Pharmaceutical industry	Wide variety of organic solvents; **arsenic, cobalt**, ammonia, chloride, cobalt, **silver** and other elements; Also see Medical supplies or wastes (notes 22, 51, 57, 62)
Photographic materials/photography	**Silver,** sodium, potassium (notes 22, 51)

Table A-4 (continued)
Constituents Potentially Associated with Alternative Anthropogenic Sources

Potential Source	Constituents That May Be released to Groundwater*
Pigments	See Paint and pigment manufacturing
Plastic manufacturing	Cadmium, cyanide, benzene, vinyl hydrochloride, phthalates, trichloroethane, acetone, methylene chloride, methyl ethyl ketone, styrene, toluene, trichloroethane, sulfate, methanol, ethylene oxide, volatile organic compounds, sodium, caustic, nickel, lead, cadmium, mercury (notes 51, 66)
Plumbing	**Copper, lead, zinc** (note 51)
Road salting	**Chloride, sodium**, **calcium**, other salts (notes 22, 44)
Rubber manufacturing	**Ammonia, amines**, acetic acid, **barium**, cobalt, formic acid, sodium, **silicon**, sulfite/sulfate, organics, nitrogen compounds (notes 22, 69)
Salt or brackish water intrusion (from well drilling)	**High TDS, chloride**, boron, bromide, calcium, **lithium**, magnesium, **potassium, sodium**, sulfate, and other minerals (notes 22, 51, 54)
Salvage and junk yards	Grease, oil, solvents, lead and acid from batteries, metals (notes 44, 54)
Semiconductor manufacturing	Copper, silver, gold, palladium, arsenic, beryllium, copper, mercury, nickel, selenium, silicon, thallium and other elements, chloride, fluoride, solvents (benzene, xylene, 1,1,1-trichloroethane, tetrachloroethane, methanol), ethylene glycol, hydrogen chloride, hydrogen fluoride (notes 22, 29, 30, 33, 51)
Septic effluent	**Nitrate, phosphorus, chloride, sodium**, organic substances, bacteria and viruses, detergents, oils, heavy metals including cadmium, copper, lead, **selenium**, salts, septic tank cleaners such as trichloroethane or methylene chloride, and a wide variety of other chemicals (notes 22, 51, 52, 53)
Sewage	**Nitrate, phosphorus, chloride, sodium**, organic substances, bacteria and viruses, detergents, oils, **boron**, **cadmium**, **copper**, lead, **selenium, silver**, salts, and a wide variety of other chemicals (notes 22, 51, 52)
Soap or detergent manufacturing or use	See Detergent and soap manufacturing
Soil acidity neutralization	**Calcium**
Steel (including stainless) and iron manufacturing	Iron, chromium, manganese, nickel, ammonia, cyanide, chloride, copper, fluoride, molybdenum, sulfate, tin, thallium, zinc, hydraulic oils
Textiles	Polyvinyl chloride, chlorine bleach, benzidine, toluidine, cyanide, formaldehyde, hydrocarbons, ammonia, nitrate, organic solvents, chloride, sodium, fluoride, silicon, **sulfate**, phosphate, boron, bromide, chromium, copper, aluminum, antimony, potassium, aluminum, **silver**, titanium, zinc, copper, insecticides (notes 22, 51, 56, 67, 68)
Thermometers, thermostats, switches	**Mercury** (note 51)

Table A-4 (continued)
Constituents Potentially Associated with Alternative Anthropogenic Sources

Potential Source	Constituents That May Be released to Groundwater*
Underground storage tanks (USTs leaking petroleum products such as gasoline)	Benzene, toluene, xylene, other organic compounds (notes 49, 51, 53)
Urban runoff	Oils, heavy metals, salts, copper, zinc, and other chemicals (notes 6, 18, 54)
Waste incineration	**Chloride, cadmium**, chromium**, fluoride, lead, mercury**, selenium, dioxins and furans (note 22)
Water treatment - flocculants	See Flocculants (note 45)
Water treatment - industrial effluents	Wide variety of metals, aluminum, **chloride**, **phosphate**, **potassium, sulfate**, nitrate, **selenium, silicon**, **sodium**, organics depending on industry (notes 22, 46)
Water treatment - municipal supply	Bromide, **chlorine, fluoride** (notes 22, 51)
Water treatment - treated sewage effluent	May contain **nitrates and other nitrogen compounds, phosphates, sodium, chloride**, **selenium, silicon**, and a variety of other elements (notes 22, 51, 52)
Water treatment - water softening	**Sodium, chloride**, **calcium**, magnesium, iron, other salts and metals (note 22)
Water treatment - cooling water	Chromium, zinc (notes 51, 52)
Well drilling (mud or fluid)	Constituents of bentonite clay and the natural geomedia including **aluminum, barium**, calcium, potassium, sodium and other minerals (note 22)
Wood preservatives and treatments	**Pentachlorophenol (PCP), creosote**, **copper, chromium, arsenic** (chromated copper arsenic, ammoniacal copper arsenate) (notes 22, 44, 48, 51)

* Bold indicates likely key indicators; list will vary by site-specific source; list may be incomplete or may not accurately represent a particular source.

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B
ASD CHECKLISTS

		Supporting Lines of Evidence		
		None	**Few**	**Many**
Key Lines of Evidence	**None**	No ASD	Weak ASD	ASD possible
	One	Weak ASD	ASD possible	**Strong ASD**
	Multiple	ASD possible	**Strong ASD**	**Strong ASD**

Figure B-1
Use of key and supporting lines of evidence for ASD Types IV and V

ASD Checklist 1: Sampling, Laboratory, or Statistical Causes

ASD Type	Potential Cause	Identify and Comment on Applicability of Potential Cause
Sampling Causes (ASD Type I)	Sample mislabeling	
	Contamination	
	Sampling technique	
	Turbidity	
	Sampling anomalies	
Laboratory Causes (ASD Type II)	Calibration	
	Contamination	
	Digestion methods	
	Dilution corrections	
	Interference	
	Analytical methods	
	Laboratory technique / qualifier flags	
	Transcription error(s)	
Statistical Evaluation Causes (ASD Type III)	Lack of statistical independence	
	Outliers	
	False positives	
	Non-detect processing	
	Background data / change in normality	

ASD Types I, II, and III do not require a weight of evidence approach. Refer to Section 2 for descriptions of potential causes.

ASD Checklist 2: Lines of Evidence Associated with the CCR Unit

		Column A	Column B	Column C				
	Line of Evidence (LOE)	**Points to release from the CCR unit if:**	**Points to alternative source if:**	**LOE is not applicable if:[1]**	**LOE Type[2]**	**Applies to[3]**	**Weight of Evidence Determination / Basis**	**Alternative Source Demonstration Approach**
	Primary CCR Indicators							
1a	If the CCR unit contains fly ash, is there an SSI/SSL for boron and sulfate?	Yes	No	ND	Key	Monitoring Point	The primary indicators for CCR leachate typically have high concentration in the leachate, are mobile, and are not reactive in groundwater, such that any groundwater affected by a leachate release will have elevated concentration for the indicator constituent. Boron and sulfate are primary indicators for coal ash leachate. Sulfate is a primary indicator for FGD gypsum leachate. Other potential indicators are identified in Table A-1. Leachate analysis can confirm site-specific primary indicators by identifying constituents present in leachate in concentrations higher than background. An SSI/SSL is unlikely to be due to release from the facility if the leachate concentration is not higher than background.	Demonstrate using graphical and statistical analysis. Special leachate sampling may be needed if not already routinely sampled.
1b	If the CCR unit contains FGD gypsum (only) is there an SSI/SSL for sulfate?	Yes	No	ND	Key	Monitoring Point		
1c	Are there other constituents in the groundwater that represent primary indicators? List the applicable constituents.	Yes	No	ND	Supporting	Monitoring Point		
1d	Is there an SSI/SSL for any of the other primary indicators?	Yes	No	ND	Key if No	Monitoring Point		
1e	Is the *leachate* concentration for any of the primary indicators (including boron and sulfate) with an SSI/SSL statistically higher than background? List the applicable constituents.	Yes	No	ND	Key if No	Constituent		
1f	Are concentrations for the primary indicators increasing?	Yes	No	ND	Supporting	Monitoring Point		
	Secondary Indicators							
2a	Are there other SSI(s) or SSL(s) of Appendix III or IV parameters? (These are potential secondary indicators. List the applicable constituents.)	Yes	No	ND	Supporting	Monitoring Point	Secondary CCR indicators are defined by high concentration in the CCR leachate, but they may be less mobile or more reactive in the environment, or they may be relatively common in groundwater due to natural or anthropogenic causes. Leachate analysis is used to determine site-specific secondary indicators. An SSI/SSL is not likely to be due to release from the facility if the leachate concentration is not higher than background. This line of evidence is secondary to LOE 1. If LOE 1 points to an alternative source, then the alternative sources may also explain SSI/SSLs for secondary indicators.	Demonstrate using graphical and statistical analysis. Special leachate sampling may be needed if not already routinely sampled.
2b	Are the constituents identified in 2a present *in leachate* in concentrations statistically higher than background?	Yes	No	ND	Key if No	Constituent		
2c	Are concentrations for any of the secondary indicators increasing? List the applicable constituents.	Yes	No	ND	Supporting	Monitoring Point		

		Column A	Column B	Column C				
	Line of Evidence (LOE)	**Points to release from the CCR unit if:**	**Points to alternative source if:**	**LOE is not applicable if:[1]**	**LOE Type[2]**	**Applies to[3]**	**Weight of Evidence Determination / Basis**	**Alternative Source Demonstration Approach**
	Other Chemistry							
3a	Are organic constituents present in concentrations statistically higher than background? If "yes," mark column B. (May not be relevant if the CCR unit is not a monofill.)	Not applicable	Yes	No	Supporting	Monitoring Point	Organic compounds are combusted in the power plant boiler. EPRI data [1987, 2016] has shown that organic compounds typically have non-detectable concentrations in CCR leachate. The presence of organic constituents in groundwater indicates that an alternative source has affected groundwater quality at that monitoring point, although it does not rule out the CCR unit as a source for inorganic constituents. Biologically mediated reactions within organic plumes can result in natural release from soil of redox-sensitive constituents such as arsenic.	Special analyses for organic compounds may be needed if there is reason to suspect that organic compounds are present in the groundwater. Demonstrate using graphical and statistical analysis.
3b	Is major ion chemistry similar to leachate?	Yes	No	ND	Key	Monitoring Point	If the SSI/SSL is due to a release from the facility, then the major ion chemistry of the groundwater sample should be a mixture of leachate and background groundwater.	Special sampling for all eight major ions may be necessary if not routinely analyzed as part of the groundwater monitoring program. This demonstration can be performed using Piper diagrams, Stiff charts, and ion ratios (see Section 3; Tier II analysis is also described in EPRI 2012).
3c	Does major ion chemistry suggest a mixture of leachate and background groundwater?	Yes	No	ND				
3d	Does tritium age dating indicate that the groundwater was recharged after the facility was first used?	Not applicable	No	Yes	Key if No	Monitoring Point	Tritium can be used to determine if groundwater recharged prior to atomic testing in the 1950s. The CCR unit is unlikely to be the cause of an SSI/SSL if groundwater is older than the unit.	Special analysis for tritium is required, refer to EPRI (2017) for more on this method.
3e	Does isotopic analysis show evidence of mixing with CCR leachate?	Yes	No	ND	Key	Monitoring Point	The CCR unit is unlikely to be the cause of an SSI/SSL if isotope ratios show no evidence of mixing between leachate and background groundwater.	Special analyses required for isotope testing, refer to EPRI (2017).

		Column A	Column B	Column C				
	Line of Evidence (LOE)	**Points to release from the CCR unit if:**	**Points to alternative source if:**	**LOE is not applicable if:[1]**	**LOE Type[2]**	**Applies to[3]**	**Weight of Evidence Determination / Basis**	**Alternative Source Demonstration Approach**
	Hydrogeology							
4a	Is the monitoring well with an SSI/SSL downgradient from CCR unit at any point during year?	Yes	No	ND	Key if No	Monitoring Point	The monitoring well must be downgradient for the SSI/SSL to be attributed to the CCR unit.	Demonstrate using maps or calculated vectors for groundwater flow direction.
4b	Review the Hydrogeological vs Leachate Scenario Table (Table A-2) and identify the most representative scenario for each SSI or SSL case. List cases and scenario numbers.	(Check here for cases indicating a possible CCR release.) (Scenario types from Table A-2, column 1 or 2)	(Check here for cases indicating a possible alternative source.) (Scenario types from Table A-2, column 2 or 3)	ND	Key	Monitoring Point	CCR Leachate Release (Table A-2, column 1 scenarios) - If the CCR unit is the only source and the leachate concentration is higher than background, the downgradient well concentration should be equal to or less than the leachate concentration due to mixing with groundwater. CCR Leachate Release and/or Alternative Source (Table A-2, column 2 scenarios) - If the leachate concentration is higher than background and a downgradient concentration is higher than the leachate concentration, both leachate and an alternative source may be contributing to downgradient concentrations. Alternative Source Release (Table A-2, column 3 scenarios) - If the leachate concentration is less than background, the leachate cannot cause downgradient concentrations to be higher than background, and an alternative source is indicated.	This LOE requires site-specific knowledge of leachate concentrations. Demonstrate by comparing site-specific flow and concentration maps to Table A-2.
4c	Is the CCR unit immediately underlain by clay, shale, or other geologic media with low hydraulic conductivity?	No	Yes	ND	Supporting	Unit	Clay and shale can provide a physical barrier to migration from a CCR unit; however, CCR indicator concentrations, particularly boron, can be naturally elevated in these formations.	Cross-sections developed from boring logs
4d	Is the monitoring point distant from the facility AND does the constituent with an SSI/SSL have low mobility in groundwater given the hydrogeologic environment at the monitoring location (see Table A-3)?	No	Yes	ND	Supporting	Case	The CCR unit is less likely to be the source of the SSI/SSL if the constituent has low mobility and is monitored at a distant point.	Groundwater modeling, accounting for sorption, can be used to determine whether or not migration to the monitoring location is possible.
4e	Are the background monitoring wells screened in the same hydrostratigraphic unit, and along the same groundwater flow path, as the monitoring location with the SSI?	Yes	No	ND	Supporting	Monitoring Point	If the background and downgradient wells are not along the same flow path and/or are not screened in the same hydrostratigraphic unit, the SSI/SSL may indicate a natural difference between formations or flow paths, rather than an anthropogenic release.	The site conceptual model, based on groundwater flow and hydrogeology, provides data that can be used for this determination. Geochemical modeling can be used to evaluate the naturally occurring geochemistry expected for different hydrostratigraphic units, and whether or not the observed evolution in groundwater quality is consistent with what is known about the geochemistry of each hydrostratigraphic unit.

		Column A	Column B	Column C				
	Line of Evidence (LOE)	**Points to release from the CCR unit if:**	**Points to alternative source if:**	**LOE is not applicable if:[1]**	**LOE Type[2]**	**Applies to[3]**	**Weight of Evidence Determination / Basis**	**Alternative Source Demonstration Approach**
	CCR Unit Design							
5a	Does the entire footprint of the monitored CCR unit have a liner?	No	Yes	ND	Supporting	Unit	The presence of a liner reduces the potential (relative to an unlined unit) for a release from the CCR unit, particularly if it is not underlain by a natural barrier material.	Review design documentation. The response to this question would be no if any portion of the monitored CCR unit is unlined.
5b	If the facility is lined, is it a composite liner?	No	Yes	ND	Supporting	Unit	A composite liner, consisting of a geosynthetic barrier material over clay, further reduces the potential for a release (relative to a clay liner) from a CCR unit.	Review design documentation. The response to this question would be no if any portion of the monitored CCR unit does not have a composite liner.
5c	Does the entire footprint of the CCR unit have a leachate collection system?	No	Yes	ND	Supporting	Unit	A leachate collection system further reduces the potential (relative to a unit with liner and no leachate collection) of a release from a CCR unit.	Review design documentation. The response to this question would be no if any portion of the monitored CCR unit does not have leachate collection.
5d	If the CCR unit is unlined, is it known to have or is it likely to have groundwater intersecting the CCR?	Yes	No	ND	Supporting	Unit	This LOE is indeterminate for active impoundments. This LOE is indeterminate for CCR units with engineered or natural liners. For cases that are not indeterminate, an intersecting water table increases the potential for a release to groundwater, relative to a facility where groundwater is below the CCR.	Water table elevation contours and engineering drawings can be compared to project whether or not the water table intersects the CCR. If engineering drawings are not available, and the facility is unlined, then borings can be performed to gauge CCR depth. Spring seepage into a CCR unit would be counted as intersecting groundwater.

Table Notes:

1. ND (not determined) indicates that this line of evidence was not tested or there are insufficient data to make a determination.
2. Line of Evidence (LOE) Types:
   Key lines of evidence are based on relationships that must be observed in order for an SSI/SSL to be due to a release from a CCR unit. If these relationships are not observed, then they are critical to establishing an ASD. It is difficult to build a strong ASD without any key lines of evidence. It may be possible to build an ASD with a single key line of evidence, but the ASD will be stronger with additional key or supporting lines of evidence.
   Supporting lines of evidence provide additional information that supports the ASD. Supporting lines of evidence are generally not sufficient to build an ASD unless there is at least one key line of evidence, although it may be possible if there are many supporting lines of evidence.
3. This LOE applies to:
   Constituent: An SSI/SSL for that constituent at any monitoring point
   Monitoring Point: All SSIs/SSLs at a specific monitoring point
   Case: An SSI/SSL for a specific constituent at a specific monitoring point
   Unit: All SSIs/SSLs at the monitored unit

ASD Checklist 3: Lines of Evidence Associated with Alternative Natural and Anthropogenic Sources

		Column A	Column B	Column C				
	Line of Evidence (LOE)	***Does not* point to alternative source if:**	**Points to alternative source if:**	**LOE is not applicable if:[1]**	**LOE Type[2]**	**Applies to[3]**	**Weight of Evidence Determination / Basis**	**Alternative Source Demonstration Approach**
General								
6a	Are there any known alternative sources for any of the constituents of concern on-site or off-site?	No	Yes	ND	Supporting	Unit	Identification of an alternative source for one or more constituents with an SSI/SSL, in an upgradient location, establishes potential for an ASD.	Consider answering the questions below first to help identify possibilities, and then come back to this set of questions. Refer to Tables A-3 and A-4 for common anthropogenic sources for various constituents in groundwater. List and draw locations with reference to the CCR unit on a map.
6b	Are any current or former potential alternative sources upgradient of the monitoring location?	No	Yes	ND	Supporting	Monitoring Point		
6c	Do monitoring locations between a potential upgradient source and CCR unit have concentrations at SSI/SSL levels?	No	Yes	ND	Supporting	Constituent	If a constituent has high concentration in groundwater, relative to background, both upgradient and downgradient from a CCR unit, then an alternative source is possible, regardless of whether or not the responses to 6a and 6b are yes. If the upgradient concentration is similar to or higher than the downgradient concentration, then an alternative source is likely.	Demonstrate using statistical and graphical methods.
On-Site Alternative Source								
7a	Is the monitoring point downgradient of or near a coal pile, or coal pile runoff, or coal pile leachate management area?	No	Yes	ND	Supporting	Monitoring Point	If yes, the coal pile may be a potential alternative source if it is unlined.	Use Tier II analysis to test for differences in leachate and groundwater signatures. May require special sample from coal pile runoff ditch or collection pond.
7b	Are there former coal mines, mine spoil, or conveyers near the CCR unit or upgradient from the facility?	No	Yes	ND	Supporting	Unit	If yes, these may be alternative sources.	pH may be lower, and concentrations of iron, manganese, and trace elements may be higher in groundwater impacted by a coal mine relative to CCR leachate.
7c	Does the site have other CCR units that are upgradient or side gradient of the affected monitoring location?	No	Yes	ND	Supporting	Monitoring Point	If yes, the other CCR units may be alternative sources, particularly if they are unlined impoundments or landfills.	For this case CCR indicator constituents should have an SSI/SSL or increasing trend at the monitoring location. If water quality signatures are not different, then intermediate monitoring points may be needed.
7d	Is the CCR unit built on top of a former CCR disposal area (i.e., has a lined impoundment been built on top of a former unlined impoundment, or has a lined landfill been built on top of a portion of an unlined impoundment)?	No	Yes	ND	Supporting	Unit	If yes, groundwater quality may be affected by leachate from the underlying CCR.	For this case CCR indicator constituents should have an SSI/SSL or increasing trend at the monitoring location. If the overfill CCR unit is lined and concentrations of CCR leachate indicators are decreasing, an ASD may be possible showing that the groundwater impacts are due to the former CCR disposal activities. The water quality signature and isotope ratios for a legacy site may be different than those for the overfill unit if there has been a coal switch.

		Column A	Column B	Column C				
	Line of Evidence (LOE)	***Does not* point to alternative source if:**	**Points to alternative source if:**	**LOE is not applicable if:[1]**	**LOE Type[2]**	**Applies to[3]**	**Weight of Evidence Determination / Basis**	**Alternative Source Demonstration Approach**
On-Site Alternative Source (continued)								
7e	Do the CCR unit or adjacent units have an active underdrain piping system or groundwater pumping system, or are there any groundwater pumping activities nearby, that could have localized influence on groundwater flow and quality?	No	Yes	ND	Supporting	Unit	If yes, consider potential effects on localized groundwater flow directions and quality.	Groundwater with CCR constituents can be pulled toward another CCR unit with an underdrain system or if CCR units are within the radius of influence of on-site production wells. For example, elevated CCR constituents from an unlined fly ash pond (e.g., boron) can occur in adjacent gypsum pond downgradient wells due to localized groundwater flow.
7f	Is there evidence that water used for dust suppression on uncovered CCR or coal piles flowed off the footprint of the liner or runoff containment system near the monitoring point?	No	Yes	ND	Supporting	Monitoring Point	Runoff water from dust control can contain many of the same constituents as CCR leachate. If wind or other issues cause a spray irrigation system to deposit leachate beyond the landfill boundary, then an SSI/SSL with a CCR leachate signature can result. These are examples of an ASD where management of the unit is responsible for the SSI/SSL, but the SSI/SSL is not due to a direct release of leachate to groundwater from the unit. A change in management can mitigate this SSI/SSL source.	Identify the source of dust suppression water (coal pile runoff water, leachate, reused water from other sources). Document, using photos or other evidence, potential pathways off the liner or beyond the runoff containment system. For these cases, CCR indicator constituents should have an SSI/SSL or increasing trend at the monitoring location. Concentrations should decrease after management improvements are implemented.
7g	Is leachate or sluice water used for dust control close to the monitoring location?	No	Yes	ND	Supporting	Monitoring Point		
7h	Is the monitoring point downgradient of or near a CCR handling area (silo, storage area, dewatering bin, sump, truck loading/unloading or washing area, etc.) or haul road?	No	Yes	ND	Supporting	Monitoring Point	These are examples of an ASD where CCR handling associated with the unit is responsible for the SSI/SSL, but the SSI/SSL is not due to a direct release of leachate to groundwater from the unit. Revisions to handling practices, or repairs to handling structures, can mitigate this SSI/SSL source.	Engineering investigation of CCR and leachate handling structures may be required to demonstrate these alternative sources. Documentation of spillage or leaks (by material type, source, and location) will support this ASD. For these cases, CCR indicator constituents should have an SSI/SSL or increasing trend at the monitoring location. This ASD is particularly effective if concentrations begin to decrease after the alternative source is mitigated (allowing for lag time due to slow-moving groundwater).
7i	Is the monitoring point downgradient of or near sluice water lines, handling equipment, or storage areas?	No	Yes	ND	Supporting	Monitoring Point		
7j	Is the monitoring point downgradient of or close to a leachate collection pipeline or leachate storage structure?	No	Yes	ND	Supporting	Monitoring Point		
7k	Have there been any documented spills of CCR or leachate or sluice water in upgradient or nearby locations?	No	Yes	ND	Supporting	Monitoring Point		
7l	Were CCRs ever drained or stockpiled in unlined areas and/or without run-off/leachate control in upgradient or nearby areas?	No	Yes	ND	Supporting	Monitoring Point		

	Line of Evidence (LOE)	Column A ***Does not* point to alternative source if:**	Column B **Points to alternative source if:**	Column C **LOE is not applicable if:[1]**	**LOE Type[2]**	**Applies to[3]**	**Weight of Evidence Determination / Basis**	**Alternative Source Demonstration Approach**
On-Site Alternative Source (continued)								
7m	Is there any history of on-site or upgradient oil or chemical spills or leaking underground storage tanks?	No	Yes	ND	Supporting	Monitoring Point	If yes, groundwater may be impacted by oil or chemical spills.	Documentation of spillage or leaks (by material type, source, and location) will support this ASD. For this case, look for constituents that are higher than background that are not primary indicators of the site-specific CCR leachate signature.
7n	Does a significant amount of road salting occur on-site? (also see 9b)	No	Yes	ND	Supporting	Monitoring Point	If yes, concentrations for chloride and other major ions (depending on the type of salt; see Table A-4) may have an SSI/SSL.	If yes, look for notably elevated concentrations of the cations and anions comprising the salts used. If these are elevated, then an ASD related to road salting may be possible.
7o	Are fertilizers being used on-site for cap vegetation or other uses?	No	Yes	ND	Supporting	Monitoring Point	Consider if groundwater impacts include nitrates or phosphates, or if the fertilizers include calcium, sulfate, or other minerals that are monitored under the CCR program.	Documentation of on-site use of fertilizers will help support this ASD.
7p	Is there any history of on-site or upgradient ash utilization (structural fill, landfill, road base, berm construction, soil stabilization, etc.)?	No	Yes	ND	Supporting	Monitoring Point	If yes, these may be on-site alternative sources.	Documentation of historical site structural fill activities, source information, and analytical data will help support this ASD.
7q	Was the power plant site subgrade prepared with CCR, dredge spoils, incinerator residue, construction debris, industrial waste, or non-native soils?	No	Yes	ND	Supporting	Monitoring Point		
Natural Variation								
8a	Are background wells screened in the same geomedia as the monitoring point?	Yes	No	ND	Supporting	Monitoring Point	If no, then one or more SSI/SSL may be a result of naturally occurring differences in groundwater quality.	Geochemical modeling can be used to evaluate whether or not observed concentrations are consistent with the geomedia.
8b	Is the aquifer comprised of poorly buffered media such as sand and gravel?	No	Yes	ND	Supporting	Unit	If yes, then pH may be evolving if the pH or precipitation water is different than the groundwater, which can cause desorption or dissolution of pH-sensitive constituents.	Investigate long-term data records for evidence of pH changes. Refer to Table A-3 to determine if this case applies to the constituent with an SSI/SSL. Geochemical modeling may be considered to fully document this effect.
8c	Is the pH at the monitoring point similar to the background pH?	Yes	No	ND	Supporting	Monitoring Point	If no, then background is not fully representative of downgradient groundwater. Concentrations may evolve over the groundwater flow path.	Refer to Table A-3 to determine if this case applies to the constituent with an SSI/SSL. Geochemical modeling may be considered to fully document this effect.

		Column A	Column B	Column C				
	Line of Evidence (LOE)	***Does not* point to alternative source if:**	**Points to alternative source if:**	**LOE is not applicable if:[1]**	**LOE Type[2]**	**Applies to[3]**	**Weight of Evidence Determination / Basis**	**Alternative Source Demonstration Approach**
Natural Variation (continued)								
8d	Is the monitoring point near a river?	No	Yes	ND	Supporting	Monitoring Point	If yes, then there may be changes in flow direction and/or groundwater elevations in response to changes in river stage that could result in monitoring different groundwater than during the background monitoring period. A yes response here also signifies potential for a redox change from oxic in upgradient areas where groundwater recharges, to reduced near the river where groundwater discharges.	Time-series plots can be used to see if there are correlations between river stage and concentration. Concentration distribution maps can be used to investigate effects of changes in flow direction. Check redox indicators to look for changes in redox.
8e	Is the constituent chemically reactive in groundwater, such that dissolution or desorption is possible (see Table A-3)?	No	Yes	ND	Supporting	Constituent	Reactive constituents can exhibit naturally occurring concentration changes if pH or redox conditions change along the flow path.	Refer to Table A-3 to determine if this case applies to the constituent with an SSI/SSL. Geochemical modeling can be used to test whether or not a change in geochemical conditions is causing a naturally occurring evolution of the groundwater.
8f	Is there a difference in redox indicators between background and compliance monitoring data?	No	Yes	ND	Supporting	Monitoring Point	This can affect redox-sensitive constituents, and can cause an SSI/SSL if the different redox environment only occurs at downgradient monitoring locations.	Compare background and compliance redox indicators to determine if this case applies. Refer to Table A-3 to determine if this case applies to the constituent with an SSI/SSL. Geochemical modeling may be considered to fully document this effect.
8g	Has there been a recent flood, recharge event, or dry period that caused groundwater elevation to rise or fall to elevations higher or lower than observed during the background monitoring period?	No	Yes	ND	Supporting	Unit	If yes, then there may be changes in groundwater elevation that could result in monitoring different groundwater than during the background monitoring period.	Time-series plots can be used to see if there are correlations between river stage and concentration.
8h	Does the aquifer contain saline water at depth?	No	Yes	ND	Supporting	Unit	If yes, monitoring wells close to the ocean, or that are deeper than background, may have higher concentrations of indicators for brine than background groundwater. Implementation of, or an increase in, groundwater withdrawals near the monitoring point could cause upwelling that would be a change over time.	The water quality signature for seawater and brines should be different than leachate, as described in Section 4.
8i	Was the direction of groundwater flow prior to or during the sample event different than observed during the background prior?	No	Yes	ND	Supporting	Monitoring Point	If yes, then the changes in flow direction could result in monitoring different groundwater than during the background monitoring period.	Concentration distribution maps can be used to investigate effects of changes in flow direction.

		Column A	Column B	Column C				
	Line of Evidence (LOE)	***Does not* point to alternative source if:**	**Points to alternative source if:**	**LOE is not applicable if:[1]**	**LOE Type[2]**	**Applies to[3]**	**Weight of Evidence Determination / Basis**	**Alternative Source Demonstration Approach**
Off-Site Anthropogenic								
9a	Are there former coal mines, mine spoil, or conveyers near the CCR unit or upgradient from the facility (also consider under "On-site")?	No	Yes	ND	Supporting	Unit	If yes, these may be alternative sources.	pH may be lower, and concentrations of iron, manganese, and trace elements may be higher, in groundwater impacted by a coal mine relative to CCR leachate.
9b	Does a significant amount of road salting occur off-site?	No	Yes	ND	Supporting	Unit	If yes, concentrations for chloride and other major ions (depending on the type of salt; see Table A-4) may have an SSI/SSL.	If yes, look for notably elevated concentrations of the cations and anions comprising the salts used. If these are elevated, then an ASD related to road salting may be possible.
9c	Does the surrounding land use include agriculture (crops)?	No	Yes	ND	Supporting	Unit	If yes, then concentrations of nitrates and other agricultural constituents (see Table A-4) may be elevated.	Use graphical or statistical analysis to demonstrate presence of agricultural indicators. This ASD is most effective if agricultural indicators are present in upgradient or intermediate monitoring points.
9d	Does the surrounding land use include agriculture (animal)?	No	Yes	ND	Supporting	Unit		
9e	Are there current or former underground or aboveground storage tanks that have had a release? (Consider gas stations and surrounding industrial activities.)	No	Yes	ND	Supporting	Unit	If yes, these may be alternative sources.	Identification of locations of underground and aboveground storage tanks, along with documented leak history (if known), will help support this ASD. Include locations of gas stations.
9f	Are there, or were there, oil and gas production wells in the vicinity of the site?	No	Yes	ND	Supporting	Unit	If yes, look for evidence of salt water intrusion, seepage of drilling fluid or additive chemicals, and organics.	Document locations of oil and gas wells.
9g	Are there existing or historical commercial and/or industrial sources of impacts, such as metal manufacturing, mining, landfills, Superfund or brownfield sites, wood treatment, etc.?	No	Yes	ND	Supporting	Unit	First determine if surrounding land use includes current or former industrial or commercial activity and identify types and locations. Then look for evidence of potential impacts to groundwater. Tables A-3 and A-4 provide information on potential impacts to groundwater related to common anthropogenic activities.	Review historical aerial photos, Sanborn maps, and available GIS data showing changing landscape and property use since the late 19th century. USGS topographic maps can be used to evaluate drainage patterns and topographic changes as well as locations of mines, quarries, and landfills. Review local, state, and federal information available through online databases or Freedom of Information Act requests related to brownfield sites and NPL listings. The local fire department and county health department may be good sources of information.
9h	Could any potential anthropogenic sources be causing changes to groundwater chemistry that would result in release of the constituent of concern through changes to pH, redox, etc.?	No	Yes	ND	Supporting	Unit	As noted, a change in pH or redox along a flow path or over time can cause concentrations for pH or redox-sensitive constituents to change.	Review field data to determine if a pH or redox change has occurred. Document the source of the pH or redox change. Refer to Table A-3 to verify that the SSI/SSL is for a constituent that is pH or redox-sensitive.
	Time-of-Travel Analysis							
10	Has groundwater flowing beneath potential sources had enough time to migrate to the affected monitoring well location?	No	Yes	ND	Supporting	Monitoring Point	Constituents must have time to travel downward to the aquifer and travel with the aquifer to the monitoring point. Sources must also be in upgradient or side gradient locations.	Use groundwater velocity calculation or simple analytical model to determine if there has been sufficient time for transport to the monitoring point.

Table Notes:

1. ND (not determined) indicates that this line of evidence was not tested or there are insufficient data to make a determination.
2. Line of Evidence (LOE) Types:
   Key lines of evidence are based on relationships that must be observed in order for an SSI/SSL to be due to a release from a CCR unit. If these relationships are not observed, then they are critical to establishing an ASD. It is difficult to build a strong ASD without any key lines of evidence. It may be possible to build an ASD with a single key line of evidence, but the ASD will be stronger with additional key or supporting lines of evidence.

Supporting lines of evidence provide additional information that supports the ASD. Supporting lines of evidence are generally not sufficient to build an ASD unless there is at least one key line of evidence, although it may be possible if there are many supporting lines of evidence.

3. This LOE applies to:
   Constituent: An SSI/SSL for that constituent at any monitoring point
   Monitoring Point: All SSIs/SSLs at a specific monitoring point
   Case: An SSI/SSL for a specific constituent at a specific monitoring point
   Unit: All SSIs/SSLs at the monitored unit

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Program:

Coal Combustion Products - Environmental Issues

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Leaching, Geotechnical, and Hydrologic Characterization of Coal Combustion Products from a Closed Coal Ash Impoundment

Capped Unit

2020 TECHNICAL REPORT

Leaching, Geotechnical, and Hydrologic Characterization of Coal Combustion Products from a Closed Coal Ash Impoundment

Capped Unit

3002017363

Final Report, June 2020

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ABSTRACT

The appropriate use of laboratory leaching tests to describe the leaching characteristics of disposed or beneficially used coal combustion products (CCPs) is an ongoing concern. Leaching tests can provide information to estimate the release of inorganic constituents for (i) comparison of the effects of environmental conditions on leaching characteristics of a material, (ii) evaluation of the effects that chemical changes over time may have on leaching, and (iii) comparison of leaching characteristics between different materials. However, the ability of leaching test results as a tool or input used to predict field porewater concentrations is dependent on the intended purpose of the leaching test, the applied test conditions, individual constituent geochemistry, and the ability of the test to address the principal conditions that control leaching in the field.

This report presents the results of geotechnical, hydrologic, and leaching characterization of samples collected from a closed and capped coal ash impoundment. The hydraulic conductivity of intact cores from the pond was measured in context of the distribution of particles in the coal ash samples and the overburden pressure associated with disposal at depth within the pond. The leaching test results for LEAF tests (i.e., EPA Methods 1313 and 1314) were compared to those for traditional tests (i.e., ASTM, TCLP, SPLP). In addition, concentrations derived from leaching tests were compared to porewater concentrations determined from field samples, and field-sampled porewater concentrations were compared to groundwater concentrations, to evaluate similarities and dissimilarities between these results.

Keywords

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Porewater
Leaching Environmental Assessment Framework (LEAF)
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PRIMARY AUDIENCE: Electric utility environmental professionals responsible for landfill and impoundment management of CCPs.

SECONDARY AUDIENCE: Researchers and regulators interested in CCP leaching and chemistry.

KEY RESEARCH QUESTION

The appropriate use of laboratory leaching tests to describe the leaching characteristics of disposed or beneficially used coal combustion products (CCPs) is an ongoing concern. Leaching tests can provide information to estimate the release of inorganic constituents for (i) comparison of the effects of environmental conditions on leaching characteristics of a material, (ii) evaluation of the effects that chemical changes over time may have on leaching, and (iii) comparison of leaching characteristics between different materials. However, the ability of leaching test results as a tool or input used to predict field porewater concentrations is dependent on the intended purpose of the leaching test, the applied test conditions, individual constituent geochemistry, and the ability of the test to address the principal conditions that control leaching in the field. The goals of this research were (i) to evaluate approaches for estimating porewater concentrations at CCP disposal facilities, and (ii) to explore potential connections between the CCP leaching performance of a disposal facility, based on porewater measurements or leaching tests, and monitoring of groundwater exterior to the facility.

RESEARCH OVERVIEW

Coal ash samples were collected at three locations from a closed and capped disposal impoundment. During field activities, porewater access and subsurface gas access points were established and monitored for 13 months. Collected solids were characterized for leaching and geotechnical/hydrologic properties. The hydraulic conductivity of intact cores was measured in context of the distribution of particle sizes in the coal ash samples and the overburden pressure associated with disposal at depth within the pond. The leaching test results for the Leaching Environmental Assessment Framework (LEAF) (i.e., EPA Methods 1313 and 1314) were compared to those for traditional tests (i.e., ASTM, TCLP, and SPLP). In addition, leaching test results were compared to porewater concentrations determined from field samples, and field-sampled porewater concentrations were compared to groundwater concentrations, to evaluate similarities and dissimilarities between these results.

KEY FINDINGS

- The hydraulic conductivity of intact ash samples is strongly dependent on the fraction of fines in the material. The measured hydraulic conductivity of finer, less permeable coal ash samples was lower (ranging from approximately $7x10^{-4}$ cm/s to $1x10^{-5}$ cm/s) than the hydraulic conductivity of coarser, more permeable samples (approximately $1x10^{-3}$ cm/s). In general, the measured hydraulic conductivity decreased with increasing effective stress, or overburden pressure; however, the hydraulic conductivity of coarser, more permeable coal ash samples decreased three times as much as that of finer, less permeable coal ash.

- The subsurface gas measurements and concentrations of redox-sensitive constituents in field porewater samples suggest that reduction-oxidation conditions of the closed disposal impoundment were more bio-chemically reduced than indicated by porewater analysis alone. Monitoring of subsurface gas concentrations shows the presence of hydrogen sulfide and methane, indicating strongly reducing conditions. Monthly data indicate that reducing conditions are spatially variable in extent and may be seasonally dependent. In addition, arsenic concentrations in the porewater are at the high end of previously reported ranges for coal ash. At intermediate reducing conditions, elevated concentrations of arsenic are likely due to loss of hydrous ferric oxides as ferric oxides are reduced and solubilized (conversion of insoluble Fe^{3+} to soluble Fe^{2+}). Under very low redox conditions, arsenic porewater concentrations decrease due to conversion of As(V) to As(III) and likely precipitation as sulfides. Conversely, the porewater concentrations of antimony and selenium in the reduced pond environment are suppressed due to formation of reduced species with lower solubility.
- Traditional leaching tests (i.e., TCLP, SPLP, and ASTM) are poor indicators of measured porewater concentrations. Low liquid-to-solid ratio (L/S) eluates from EPA Method 1314 were better indicators than the traditional tests for concentrations for available content-limited constituents (B, Ca, Cl, Mo, SO_4, Tl) because of the strong L/S-dependence. However, additional information (e.g., available content and porewater L/S) would be needed to provide a reasonable approximation of porewater concentrations. For constituents with solubility-controlled liquid-solid partitioning (Sb, As, Ba, Cr, F^-, Se, V, Zn), pH-dependence tests (e.g., EPA Method 1313) may provide valuable information for geochemical modeling, but, for this site, the natural or own pH responses did not reliably estimate field porewater concentrations, in part due to differences in redox as noted in the next bullet.
- When the field environment is highly reducing, laboratory leaching results for redox-sensitive elements (e.g., As, Cr, Sb, Se, and Fe) do not directly reflect the leaching anticipated in porewater. This is, in part, because reduced materials collected in the field are inevitably partially oxidized during sampling, handling, and testing.
- Porewater concentrations were not a reliable indicator for which constituents would have elevated concentrations, relative to background, in downgradient groundwater or for future prediction of downgradient concentrations at this site.

WHY THIS MATTERS

This research provides a unique opportunity to compare a field porewater sample set to laboratory leaching test results on samples collected from the same location and depth interval as the porewater sampling point and provides information to guide appropriate use of these tests. It also provides information on, and comparison of, the spatial and temporal/seasonal variability in both porewater quality and laboratory leachate quality at a CCP site. Data collected during this research will inform EPRI physical and geochemical modeling of leaching within coal ash landfills and impoundments.

HOW TO APPLY RESULTS

The results of this research are site-specific, yet when considered with known differences in L/S associated with different leaching tests, and geochemical differences between the field and laboratory environment, they provide information for generalizing the best uses of different leaching tests and porewater data. Companies interested in performing similar comparisons between leaching tests and porewater will be interested in the

field and laboratory methodologies described in Sections 2 and 3. Companies and stakeholders interpreting leaching test and porewater results will be interested in the results summarized in Sections 4 and 5, as well as the detail provided in Appendices C through G.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- A framework using geochemical modeling and porewater data to predict long-term leaching at CCP sites is being developed under EPRI Program 49A's hydrogeochemistry project. A series of reports published from 2018 through 2020 describe results of this research. These reports can be accessed by searching epri.com for "Hydrogeochemical Assessment of Long-Term Leaching Characteristics at Coal Combustion Product Sites."
- Stakeholders, including regulatory agencies, reviewing leaching test analyses may be interested in results of this research to understand the relationship between the different leaching tests, and the relationship between leaching tests and porewater within CCPs.

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PROGRAM: Coal Combustion Products—Environmental Issues, PS49A

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ABBREVIATIONS, ACRONYMS, AND SYMBOLS

Abbreviations and Acronyms

AMSL	above mean sea level
BGS	below ground surface
CCP(s)	coal combustion product(s)
CFR	Code of Federal Regulations
CH_4	methane gas
CO_2	carbon dioxide gas
DIW	deionized water
DIC	dissolved inorganic carbon
DO	dissolved oxygen
DOC	dissolved organic carbon
EC	electrical conductivity (mS/cm)
Eh	redox potential (mV)
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
GAP(s)	gas access point(s)
HDPE	high-density polyethylene
HFO	hydrous ferric oxides
HNO_3	nitric acid
HSA	hollow-stem auger
H_2S	hydrogen sulfide gas
H_2SO_4	sulfuric acid
IC	ion chromatography
ICP	inductively coupled plasma
ICP-MS	inductively coupled plasma – mass spectrometry
ICP-OES	inductively coupled plasma – optical emission spectroscopy

ID	internal diameter
KOH	potassium hydroxide
LEAF	Leaching Environmental Assessment Framework
LLOQ(s)	lower limit(s) of quantitation
LOI	loss on ignition
LSP	liquid-solid partitioning
L/S	liquid-to-solid ratio
MDL(s)	method detection limit(s)
NDIR	non-dispersive infrared
NH_3	ammonia gas
NIST	National Institute of Standards and Technology
OD	outer diameter
ORP	oxidation-reduction potential
O_2	oxygen gas
PAP(s)	porewater access point(s)
pe	electron concentration
PSD	particle size distribution
QA/QC	quality assurance/quality control
RCRA	Resource Conservation and Recovery Act of 1986
SU	standard unit(s)
TC	total carbon
UVA	University of Virginia (Charlottesville, VA)
VU	Vanderbilt University (Nashville, TN)
wt%	weight percent (percent by mass)
XRF	x-ray fluorescence

Groundwater/Porewater Sample Points

AD1	upgradient, background groundwater well
VB-1	porewater access point in the closed impoundment
VB-2	porewater access point in the closed impoundment
VB-3	porewater access point in the closed impoundment
6AR	downgradient compliance groundwater well

Leaching/Extraction Tests

ASTM	ASTM D3987: Practice for Shake Extraction of Solid Waste with Water
1313	EPA Method 1313: Liquid-Solid Partitioning as a Function of Eluate pH Using a Parallel Batch Procedure
1314	EPA Method 1314: Liquid-Solid Partitioning as a Function of Liquid-Solid Ratio Using an Up-Flow Percolation Column Procedure
1313_L/S=1	EPA 1313 modified for L/S=1 mL/g-dry and abbreviated to 5 target endpoint pH values about the own pH of the material
1313_3pt	EPA 1313 abbreviated to 3 target endpoint pH values (<2, natural pH, and 9)
SPLP	EPA Method 1312: Synthetic Precipitation Leaching Procedure
TCLP	EPA Method 1311: Toxicity Characteristic Leaching Procedure

Equation and Parameter Variables

F	Faraday constant (23,061 cal/(V mol))
MC	moisture content on a dry basis (%)
m_{wet}	mass of “wet” solid (g)
m_{dry}	mass of oven-dried solid (g-dry)
n	porosity (m^3_{pore}/m^3)
SC	solids content on a wet basis (%)
R	1.987 (cal/(K mol))
T	temperature (K)
ρ_d	dry density (mg-dry/m^3)
θ_s	saturated water content (m^3_{water}/m^3)

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1
INTRODUCTION

The appropriate use of laboratory leaching tests to describe the leaching characteristics of disposed or beneficially used coal combustion products (CCPs) is an ongoing concern. Leaching tests can provide information to estimate the release of inorganic constituents for (i) comparison of the effects of environmental conditions on leaching characteristics of a material, (ii) evaluation of the effects that chemical changes over time may have on leaching, and (iii) comparison of leaching characteristics between different materials. However, the ability of leaching test results as a tool or input used to predict field porewater concentrations is highly dependent on the intended purpose of the leaching test, the applied test conditions, individual constituent geochemistry, and the ability of the test to address the principal conditions that control leaching in the field. For example, traditional leaching tests, including EPA Method 1311: Toxicity Characteristic Leaching Procedures (TCLP), EPA Method 1312: Synthetic Precipitation Leaching Procedure (SPLP), and ASTM D3987: Shake Extraction of Solid Waste with Water (ASTM), provide only a snapshot of leaching performance under conditions that often deviate substantially from current conditions and anticipated future field conditions.

In 2012, the United States Environmental Protection Agency (EPA) published four leaching methods from the Leaching Environmental Assessment Framework (LEAF) as draft methods available for use. The four methods have since been validated (Garrabrants et al., 2012a; 2012b) and incorporated as final methods into the Agency's compendium of laboratory methods (SW-846). The four LEAF methods are:

- EPA Method 1313: Liquid-Solid Partitioning as a Function of Eluate pH Using a Parallel Batch Procedure
- EPA Method 1314: Liquid-Solid Partitioning as a Function of Liquid-Solid Ratio Using an Up-Flow Percolation Column Procedure
- EPA Method 1315: Mass Transport Rates of Constituents in Solid Materials Using a Tank Leaching Procedure
- EPA Method 1316: Liquid-Solid Partitioning as a Function of Liquid-Solid Ratio Using a Parallel Batch Procedure

The LEAF approach differs from traditional leaching assessment methodologies in that the leaching tests are designed to provide a series of eluates characteristic of leaching behavior dependent on one or more controlling factors rather than a single eluate that is representative of field leachate from a designed scenario. The EPA has provided a guide for how LEAF tests may be incorporated into common leaching assessment practices (EPA 2019, Garrabrants et al., 2019a, 2019b).

There remains uncertainty as to the selection of specific test methods to represent (i) the range of pH and liquid-to-solid ratio (L/S) within a waste mass and (ii) the current and long-term geochemical conditions of the porewater of CCP impoundments and landfills. Thus, leaching

tests have been widely applied, but often without consideration of their inherent limitations for providing information suitable for evaluation of long-term leaching performance. In addition, little information is available that directly compares measured field porewater concentrations at CCP disposal sites to the results of various leaching test results.

The Electric Power Research Institute (EPRI), Vanderbilt University (VU), and University of Virginia (UVA) collaborated on a study to evaluate relationships between the geochemistry of the disposed CCPs and the measured and predicted concentrations for inorganic constituents in the porewater of CCP disposal units. In addition, this study investigates the potential relationship between porewater concentrations and the concentrations in groundwater measured at adjacent monitoring wells. CCP materials were collected from two disposal sites. During field activities, porewater access and subsurface gas access points were established for eight to twelve months of monthly monitoring. Collected materials were characterized for leaching and geotechnical/hydrologic properties. A framework for integrating these data is being developed under a separate EPRI project. This report provides the methodology for sampling and characterization of disposed CCPs collected from a closed ash impoundment at Plant 42201, also referred to as "KSP." This report summarizes the results of leaching tests and monitoring data with respect to groundwater and impoundment porewater collected at the facility as well as vadose zone subsurface gas concentrations monitored within the impoundment.

Project Goals and Objectives

The goals of this research were (i) to evaluate approaches for estimating porewater concentrations at CCP disposal facilities, and (ii) to explore potential connections between the CCP leaching performance of a disposal facility, based on porewater measurements or leaching tests, and monitoring of groundwater exterior to the facility.

The specific objectives of this project include:

- Collecting field materials to qualify the spatial and temporal variability of materials disposed in the closed impoundment and to allow for characterization of leaching and geotechnical/hydrologic property determination.
- Correlating the characterization of leaching from bulk samples using traditional leaching tests (i.e., TCLP, SPLP, and ASTM) and LEAF pH- or L/S-dependence leaching tests with measured porewater concentrations monitored at the site.
- Assessing the ability of leaching tests (traditional or LEAF tests) to directly estimate porewater concentrations within the closed impoundment.
- Identifying the relationship, if any, between porewater concentrations within the closed impoundment and downgradient groundwater concentrations.

Site Description

The closed impoundment, represented in Figure 1-1a, is a triangular 25-acre area divided from a larger coal ash landfill constructed in the 1950s. The impoundment was used to collect storm water and process water from Plant 42201 before discharge into an adjacent river. Between 2012 and 2015, the impoundment received sluiced CCPs from the plant. In 2016, the inactive impoundment was closed, with the closure project completed approximately one month prior to

the field collection of field samples and establishment of groundwater sampling points. The closure project involved removal of free water from the impoundment, regrading of the coal ash to level the surface, and installation of a composite geosynthetic soil cover system as illustrated in Figure 1-1b. The cover is typically about 5 feet thick; however, the thickness of the cover system varies based on the ash layer elevations. At the time of the field investigation, phreatic porewater occurred approximately 6 feet below the surface of the ash layer. At the center of the impoundment, the ash layer is approximately 20 feet thick.

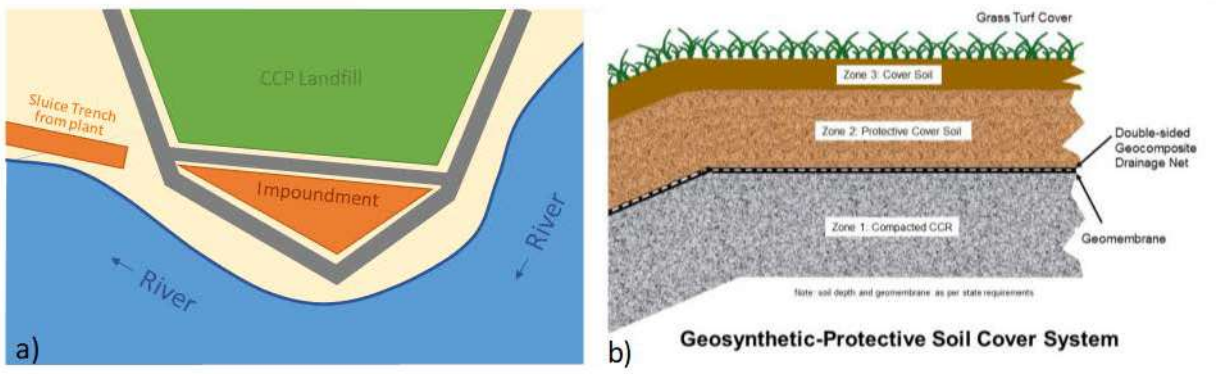

Figure 1-1
Schematic representations of the KSP closed impoundment: a) plan view of impoundment relative to the adjacent coal ash landfill and river; b) cross-section of typical geosynthetic soil cover

Sampling and Testing Approach

Fieldwork for this project included: (i) advancement of boreholes into the coal ash deposit to improve the understanding of stratigraphy and to sample contained solids (i.e., ash, cover fill, and native clay liner); (ii) installation of porewater access points (PAPs) and subsurface gas access points (GAPs) within boreholes in the ash deposit; and (iii) monthly sampling of groundwater and porewater and subsurface gas compositions. At each of three locations within the closed impoundment, bulk ash samples were collected from continuous split spoon sampling to evaluate the constituency of material in the ash deposit and leaching properties of the collected ash. In parallel, intact ash cores were collected to determine geotechnical characteristics and hydraulic conductivity of the disposed ash. At monthly intervals after the completion of initial field work, porewater was collected from each PAP along with groundwater collection at upgradient (background) and downgradient wells to provide points of comparison to porewater samples.

Characterization of leaching properties was carried out by personnel in the Department of Civil and Environmental Engineering at VU. Leaching characterization tests included EPA Method 1313 to determine leaching behavior as a function of eluate pH, EPA Method 1314 to evaluate L/S-dependent leaching from a percolation column, and a trio of single-batch extraction tests (i.e., TCLP, SPLP, and ASTM). For all leaching tests, the pH of all eluates was measured and recorded so that comparisons could be made between leaching evaluations. The reported constituents include most of those found in the Code of Federal Regulations, Title 40, Section 257 (40 CFR 257), Appendix III for detection monitoring and Appendix IV for assessment monitoring, as well as several additional constituents as listed in Table 3-3, Table 3-4, and Table

3-5 of this report. Relative to 40 CFR 257 App III and IV, a broader suite of approximately 40 constituents was quantified to provide a comprehensive basis for geochemical modeling of leaching test results. Although listed in 40 CFR 257 App III and IV, radium and total dissolved solids were not analyzed.

The geotechnical and hydrologic properties of intact core samples were determined at the School of Engineering at UVA. Hydraulic conductivity of intact samples was measured using flexible-wall permeameters following the methods in ASTM D5084. Tests were conducted over a range of effective stresses to evaluate how hydraulic conductivity varies with packing configuration and overburden found at depth. Particle size analysis was conducted on each sample using the methods in ASTM D6913 to understand how the hydraulic conductivity varies with the composition of the ash.

At UVA, a complementary series of tests to that of EPA Method 1314 was conducted on undisturbed samples collected in thin-wall sampling tubes for hydraulic conductivity testing in flexible-wall permeameters. Although the primary purpose of these tests was to measure the hydraulic conductivity of the coal ash samples, eluates collected from hydraulic conductivity testing served as a point of comparison to percolation leaching tests on composite samples according to EPA Method 1314. These tests on undisturbed samples in flexible-wall permeameters contrasted with conventional Method 1314 tests conducted on remolded (including partially oxidized) samples in rigid-wall columns, providing a direct assessment of the impacts of sample handling, column packing, and potential sidewall flow on percolation leaching. Additional discussion of these tests is included in the section on hydraulic conductivity test methods.

2
COLLECTION OF FIELD MATERIALS

Sample Locations

Ash, porewater, and gas samples were obtained at three boring locations (VB-1, VB-2, and VB-3). The approximate locations of these boreholes are shown in Figure 2-1 relative to the closed impoundment and the adjacent river. These locations were selected to be within the area of the closed impoundment and were considered to capture the vertical and horizontal heterogeneity of ash materials. When the impoundment was active, coal ash was sluiced from the main plant using process water into the impoundment near the location of VB-1. The water flowed toward VB-3 and onto the outfall to the river near location VB-2. Ash chemistry of the three locations is assumed representative of materials across the closed impoundment.

Figure 2-1
Schematic representation of the closed KSP ash impoundment, showing the approximate locations of three porewater access points (PAPs), VB-1, VB-2, and VB-3, and existing groundwater wells, 6AR and AD1 (out of frame).

Initial Site Sampling

The field sampling included continuous split spoon sampling to obtain bulk ash for leaching characterization and to provide an understanding of the ash deposit after closure, followed by discrete Osterberg sampling to obtain intact ash cores at approximate 5-ft intervals. All drilling

operations were conducted by a contracted drilling/engineering company. Prior to sampling, the top vegetation cover and geosynthetic cover in a 100-ft^2 area (10 ft by 10 ft) at each sampling location were removed by contractors. Bulk ash material was collected using 3-inch outside diameter (OD) x 24-inch long split spoons advanced through a 4.25-inch internal diameter (ID) hollow-stem auger (HSA) drilling a 9-inch diameter hole. Intact cores were collected at discrete depth intervals using thin-wall tube samplers pushed through an 8.25-inch ID HSA drilling a 13-inch hole. After the completion of the borings and installation of monitoring points, the geosynthetic cover was repaired and the cover fill replaced.

Bulk Material (Split Spoon Samples)

Split spoons were advanced from the upper cover-ash interface into the underlying native clay material (Table 2-1). Upon retrieval by the drilling contractor, each split spoon sample was opened and recorded by a licensed geologist and released to VU for documentation and collection. The borehole logs and an index with photographs of recovered split spoon material are provided in Appendix A and Appendix B, respectively. During field sampling, the activities included (i) preparation of ash extractions with de-oxygenated, deionized water (DIW) targeting an L/S of approximately 1 mL of water per estimated gram of dry ash and (ii) collection and preservation of bulk material for subsequent laboratory testing.

- L/S ≈ 1 Extractions: To protect the redox conditions of the sample and characterize the porewater composition for a screening analysis within each borehole, about 150-200 g of ash was placed into a certified, pre-tared 250-mL high-density polyethylene (HDPE) bottle (Nalgene I-Chem #N311-0250). The mass of the ash grab sample was measured and recorded. The bottle was filled with de-oxygenated DIW and weighed to quantify the mass of added water. The location of the ash grab sample within the split spoon was selected based on visual representativeness of ash.
- Bulk Ash Collection: Remaining ash from each split spoon was vacuum-sealed in plastic bags (Figure 2-2) and stored on ice for transport to the laboratory. To the extent possible, the bulk ash was maintained in its original split spoon shape and the top and bottom of the core were marked on the plastic bag.

Sample labels included “KSP” as a site identifier, the borehole number (VB-1, VB-2, or VB-3), and the depth below ground surface (BGS) from which the samples were taken. For example, the sample labeled “KSP_VB-3_15-17” in Figure 2-2 was collected from the split spoon at 15 to 17 feet BGS at borehole VB-3. For split spoons that penetrated an interface (e.g., between ash and the bottom native clay layer or between coal ash layers with visually different properties), the separate materials were collected as separate bulk samples in two vacuum-sealed bags. The upper portion was labeled with an “A” extension, while the lower portion was labeled with “B” at the same split spoon interval. All samples were preserved in coolers with ice and transported to the VU lab within 48 hours. During transport, the cooler temperature was monitored and recorded by an Elitech RC-5 USB temperature data logger. At the VU lab, all bulk materials were stored in an environmentally controlled room at 5 °C prior to processing for leaching tests.

a)

b)

Figure 2-2
Examples of split spoon cores: a) as recovered and photo-documented and b) vacuum-sealed bulk sample from borehole VB-3 (KSP_VB-3_15-17) preserved for testing

A schematic summary of the split spoon samples and the numbers of total samples preserved at each location are shown in Figure 2-3. In this figure, the depths BGS for each sample have been converted to elevations in feet above mean sea level (AMSL) after surveying of the PAP casings and ground elevations.

Intact Cores (Tube Samples)

Immediately following completion of the continuous split spoon borehole, the drilling rig was moved forward in its tracks 5 feet to advance an 8.25-inch HSA for push core sampling of ash. At each boring location, 3-inch OD by 36-inch long thin-wall tube samplers were pushed into the ash layer and obtained intact cores at intervals according to the observations from split spoon boring. The locations of the cores were targeted to collect samples across interfaces with the cover material and clay liner as well as major ash deposits within the ash column. Each recovered thin-walled tube was sealed at both ends using plastic expanding inserts, capped with plastic endcaps, and sealed with duct tape. The thin-walled tubes were vacuum-sealed in plastic bags and kept upright for transport. Sample identification was based on the interval BGS from which the samples were recovered. For example, the tube sampler recovered from the interval from 12 to 14.5 feet BGS at borehole VB-1 was labeled "VB-1_OST_12-14.5." The associated elevations for the three tube samples collected at each borehole are summarized in Table 2-1.

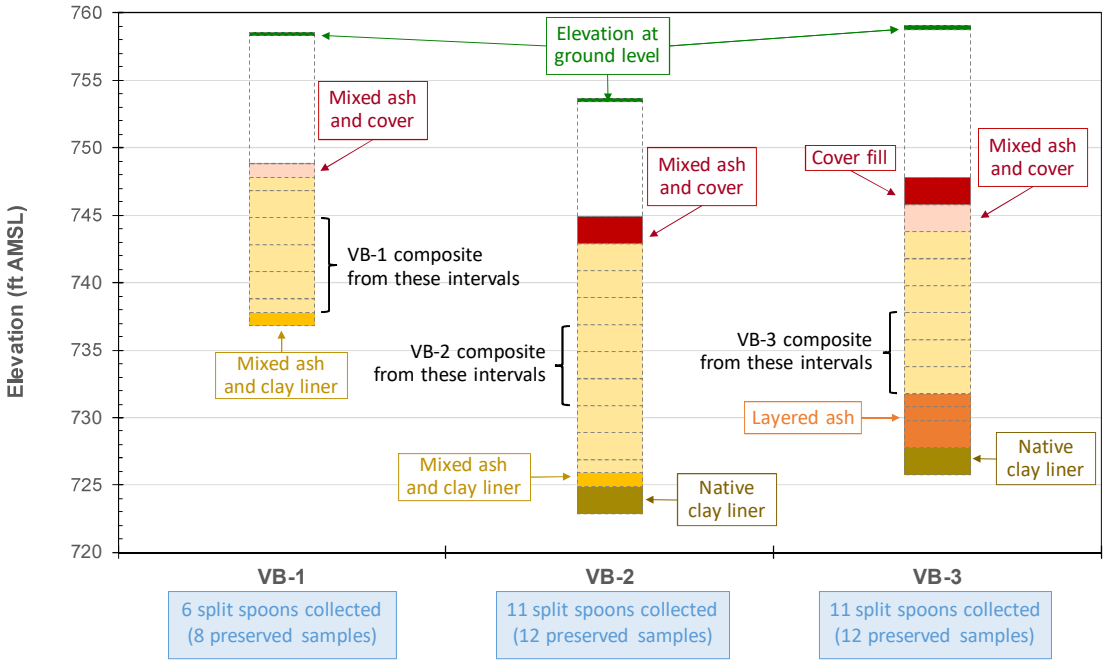

Figure 2-3
Collection of bulk material samples by split spoon, showing bulk samples composited around well screening levels

Porewater Access Points

Once the 8.25-inch ID HSA was advanced to the target depth for placement of the PAP, a 2-inch OD Schedule 40 PVC pipe was installed through the HSA. At each well location, the contractor installed a pre-packed, 2-foot screened section in agreement of the field team leads for VU, EPRI, and KSP after review of saturated zone observed for the continuous sampling borehole. Each 13-inch diameter borehole was backfilled with 1 foot of clean sand before the well screen was set, and after setting the screen, was backfilled with sand to 2 feet above the top of the well screen. The sand pack was sealed with bentonite clay pellets, and bentonite chips were used to backfill the borehole to within ½ foot of the GAP depth. Boring logs are presented in Appendix A.

Subsurface Gas Access Points

The composition of subsurface gas within the ash pond was sampled through GAPs set between 2 and 3 feet below the top of the ash deposit. Each GAP consisted of a ¼-inch diameter stainless steel tube set at depth within a 1-foot thick layer of round river rock and sealed from above and below with a 1-foot thick layer of expanded bentonite clay. The lower end of the GAP tubing was protected from rock, ash, and clay debris with an inverted steel cup. The stainless steel tubing was zip-tied to the PVC well and finished with a 2-way shutoff valve. The bed of river rock, nominal size of between ¾ inch and ¼ inch, ensures sufficient subsurface gas volume for measurement. A conceptual diagram and photograph are presented in Figure 2-4.

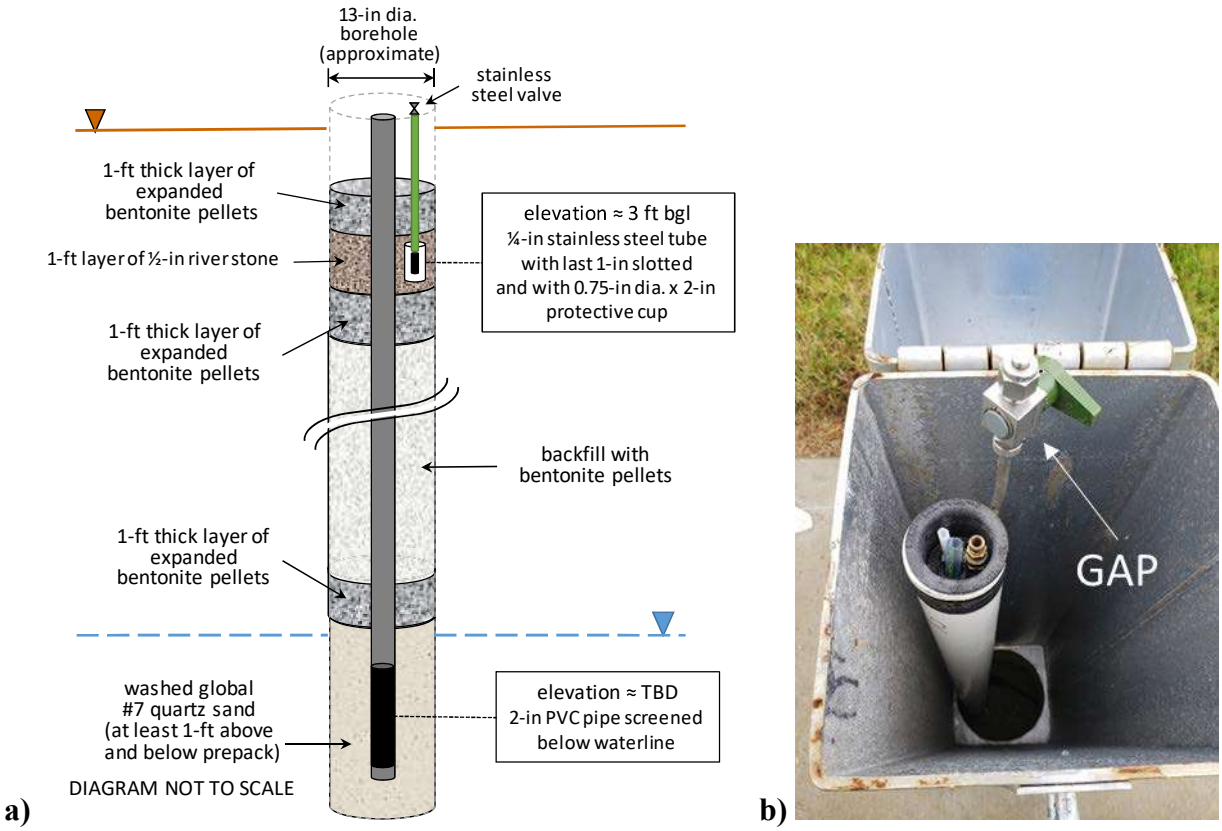

Figure 2-4
Porewater and gas access points: a) conceptual design of PAP and GAP installation and b) picture of installed PAP and GAP within a metal riser

Summary of Borehole Stratigraphy, Ash Collection, and PAP/GAP Installation

Within two weeks of field sampling, the drilling contractor installed dedicated pumps, developed the wells, and protected the borehole locations with a metal riser and concrete base. As part of this process, the horizontal location of the PVC riser, as well as the elevations of the well riser and ground level, were surveyed by a professional land surveyor. A summary of the elevation survey results and elevation of pertinent strata and sampling locations for the VB-1, VB-2, and VB-3 boreholes are tabulated in Table 2-1 and presented graphically in Figure 2-5 along with the stratigraphy for the upgradient background well (AD1) and downgradient compliance well (6AR).

Table 2-1
Elevations Above Mean Sea Level (AMSL) for KSP Boreholes Including the Range of Continuous Bulk Ash Sampling and Discrete Tube Samples

	VB-1	VB-2	VB-3
	Elevation (ft AMSL)	Elevation (ft AMSL)	Elevation (ft AMSL)
Top of Well Casing	761.60	756.78	762.04
Ground Level	758.3	753.4	758.8
Cover Fill Interface	748.8	744.9	753.8
Top of Ash Bed	748.8	743.9	745.4
GAP Placement	746.3	741.4	743.8
Water Level	742.3	741.9	738.8
PAP Well Screen	738.8 to 740.8	733.4 to 735.4	733.8 to 735.8
Bottom of Ash Bed	737.3	725.6	731.3
Clay Liner Interface	737.3	725.6	728.0
Bulk Ash Samples	737.8 to 747.8	725.9 to 744.9	731.8 to 747.8
Tube Sample #1	748.3 to 750.3	744.4 to 746.4	738.8 to 741.8
Tube Sample #2	743.8 to 741.3	737.9 to 739.9	731.8 to 734.8
Tube Sample #3	738.8 to 741.3	731.9 to 734.9	-

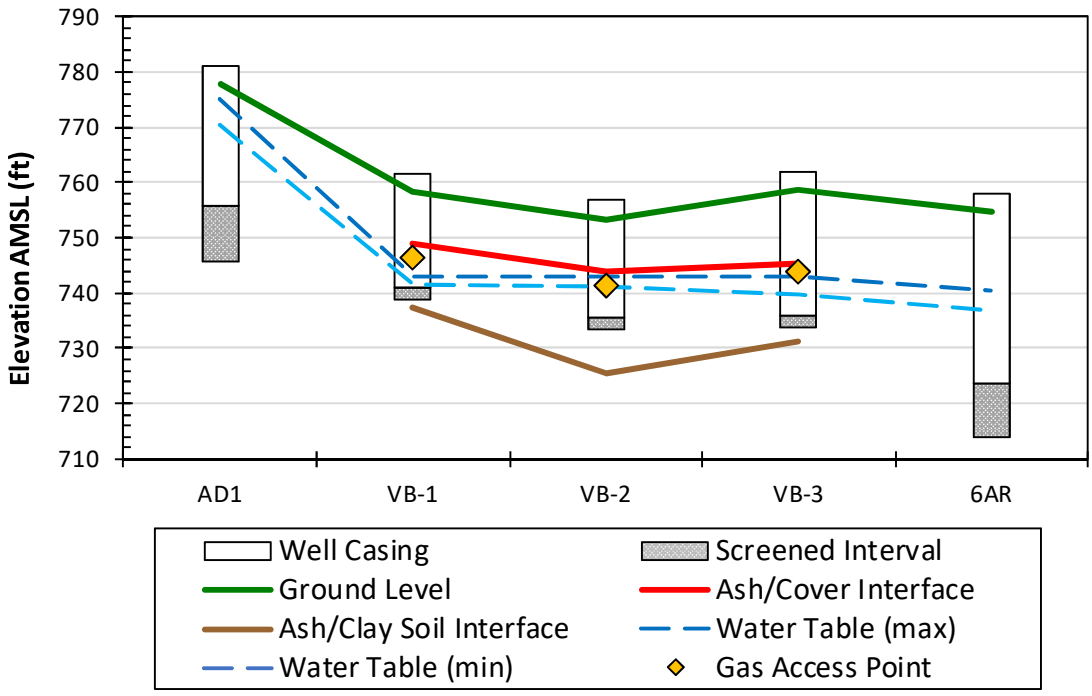

Figure 2-5
Summary of the groundwater well and PAP elevations including pond stratigraphy and location of GAPs

Monthly Field Monitoring

Porewater and subsurface gases were monitored monthly at each PAP location over a 13-month period from September 2018 through September 2019. In addition, groundwater samples were analyzed from one upgradient (AD1) and one downgradient (6AR) monitoring well.

Collection of Groundwater and Porewater

Figure 2-1 shows the relative locations for the three installed PAPs (VB-1, VB-2, and VB-3) and the two existing groundwater sampling wells. Although the location of the upgradient well (AD1) is out-of-frame relative to this figure, the general direction of the well is indicated. KSP field personnel accessed each well, stabilized the well using low-flow sampling techniques according to company standard operating procedures, and allowed the VU field team access to the effluent line for collection of groundwater and porewater samples. At no time did the site owners' personnel retain custody of any samples used for this analysis.

The sampling flowrates for groundwater wells averaged approximately 150 mL/min and 300 mL/min for AD1 and 6AR, respectively. Porewater was sampled at approximately 50 mL/min to minimize drawdown of the water level in each PAP. At 5-minute intervals, the pH, dissolved oxygen (DO), electrical conductivity (EC), oxidation-reduction potential (ORP), temperature, and turbidity of the sampled water were measured through a multi-parameter sonde and separate turbidity meter, while water level was measured with a portable electronic water level meter. All measured parameters were recorded by KSP field personnel. The criteria used to determine well stability were (i) turbidity less than 10 NTUs and (ii) pH stable within 0.1 standard unit over three consecutive 5-minute readings.

Groundwater and porewater samples were collected in 50-mL SCP Science Digitubes including duplicate samples collected for anion analysis via ion chromatograph (IC) and duplicate samples collected for metals and other cation analysis via inductively coupled plasma (ICP) techniques (see *Chemical Analysis of Eluates, Groundwater, and Porewater* for details). Samples for ICP analysis were preserved in the field by addition of 1.5 mL of Tracemetal® grade nitric acid (3% total acid addition) using a 100-1000 µL Oxford Benchmate manual pipette and disposable tips. A set of four samples was collected unfiltered followed by a set of samples passed through a Quickfilter, 609 cm^2, 0.45-mm inline filter. In total, eight 50-mL Digitubes were collected at each sampling location. All liquid samples were stored in a cooler of ice with an Elitech RC-5 USB temperature data logger to record the temperature within the cooler. Samples were transported by the field team to VU for immediate storage at 5 ºC prior to analysis.

Subsurface Gas Monitoring

A description of the monitoring process for subsurface gas and a picture of gas monitoring apparatus are provided in Section 3.

3
LABORATORY MATERIALS AND METHODS

The follow sections include brief descriptions of the laboratory test methods and analytical methods used in this study. Also included are the quality assurance/quality control (QA/QC) samples and criteria for each analytical method.

Collected Materials

Materials recovered during initial sample collection from the ash deposit included bulk samples from split spoons and intact cores contained in thin-wall tubes. Processing of bulk material for leaching tests included (i) homogenization within each split spoon sample and (ii) compositing samples near the screening level.

Subsampling and Homogenization of Bulk Samples

Homogenized split spoon samples were used to evaluate the vertical and horizontal variability of ash deposits and provide materials for developing a representative composite for characterization of leaching parameters to be compared to monthly porewater monitoring. Each recovered split spoon sample was removed from its vacuum-sealed bag and bisected along the longitudinal axis as shown in Figure 3-1a. If the structure of split spoon material was not intact, the preserved sample was bisected vertically along the axis of the plastic bag Figure 3-1b. One-half of the material was immediately vacuum-sealed into a plastic bag and stored in the environmentally controlled room at 5 ºC for future use.

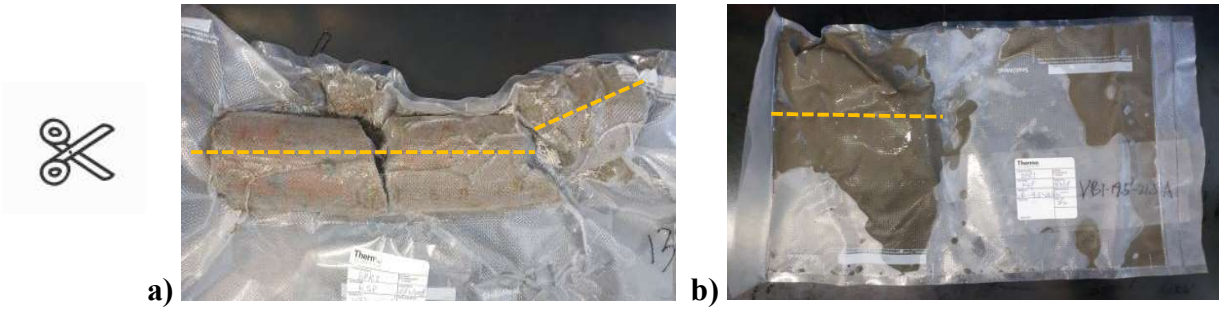

Figure 3-1
Schematic showing bisection of a) structurally sound split spoon material and b) bulk split spoon material

The remaining half of the split spoon material was placed in a plastic bag and sealed with lab tape to minimize exposure to air. This material was crushed with a rolling pin and homogenized by hand through the plastic bag until the contents were well mixed. This homogenized material was used as test material (i) in laboratory L/S=1 extractions for comparison to field L/S~1 extractions and (ii) for limited pH-dependence leaching methods to evaluate vertical heterogeneity within borehole samples.

Borehole Composite Materials

Homogenized split spoon material was used to develop a composite test material that would be representative of the bulk ash deposited near the screened interval of the PAP for each borehole. Table 3-1 shows the split spoon samples used to create each borehole composite sample. The selection of these intervals was based on the evaluation of laboratory L/S=1 extractions and considering the mass of composite that would be required to complete the testing program.

Table 3-1
Intervals (BGS) and Elevations (AMSL) of Split Spoon Samples Used in Borehole Composites

VB-1		VB-2		VB-3	
Interval (ft BGS)	**Elevation (ft AMSL)**	**Interval (ft BGS)**	**Elevation (ft AMSL)**	**Interval (ft BGS)**	**Elevation (ft AMSL)**
PAP Screen	740.8-738.8	PAP Screen	735.4-733.4	PAP Screen	735.8-733.8
13.5-15.5	744.8-742.8	16.5-18.5	736.9-734.9	21-23	737.8-735.8
15.5-17.5	742.8-740.8	18.5-20.5	734.9-732.9	23-25	735.8-733.8
17.5-19.5	740.8-738.8	20.5-22.5	732.9-730.9	25-27	733.8-731.8
19.5-21.5 (A)	738.8-737.3	-	-	-	-

The material was composited by mixing equal dry mass equivalents (i.e., the mass of "as received" material that equates to a prescribed mass of dry material) from each homogenized split spoon in a plastic bag. For VB-2 and VB-3 composites, each of three split spoons was used with 450 g-dry taken from each sample. However, for the VB-1 composite, there was not enough material in the three split spoons nearest the well screen, so a fourth split spoon was included with 250 g-dry taken from each homogenized split spoon sample. The plastic bag was sealed with lab tape to minimize air exposure and the composited material was homogenized by hand through the plastic bag until well mixed. This composited sample was used for total content analysis and characterization using LEAF leaching tests and traditional leaching tests (i.e., ASTM, TCLP, and SPLP).

Material Properties

Total Content by EPA Method 3052

The total elemental content of composite samples was determined by acid digestion following EPA Method 3052 with subsequent analysis of the digestate by Eurofins TestAmerica (Nashville, TN). According to the Method 3052, a solid sample of up to 0.5 g (wet) is digested in 9 mL of nitric acid and 3 mL of hydrofluoric acid for 15 minutes in a microwave to accelerate the digestion reactions. Addition acid and reagent combinations, including hydrochloric acid and hydrogen peroxide, are added to ensure that the solid is dissolved. The microwave temperature profile includes reaching 180 ± 5 ºC in approximately less than 5.5 minutes and remaining at 180 ± 5 ºC for 9.5 minutes for the completion of specific reactions. After cooling, the vessel contents were centrifuged and decanted. The small volume of remaining digestate was diluted to a volume of 100 mL and chemically analyzed. Inductively coupled plasma-optical emission

spectrometry (ICP-OES) following EPA Method 6010B was used to determine digestate concentrations for Ag, Al, As, Ba, Be, Ca, Cd, Cr, Co, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, Pb, Sb, Se, Sr, Ti, V, and Zn. Mercury in digestates was measured by using cold vapor atomic absorption following EPA Method 7470A. The total content (mg/kg) is calculated by multiplying the concentration measured in the digestate (mg/L) by the L/S of the extraction procedure (L/g). For this study, the resultant total content is effectively on a dry mass basis (mg/kg-dry) because the material submitted to the laboratory for testing was oven dried.

X-Ray Fluorescence Analysis

The elemental composition of coal ash samples was determined at UVA using x-ray fluorescence (XRF) quantitative analysis on an Epsilon 3X energy-dispersive XRF spectrometer (PANalytical, Malvern, UK) with a silver anode X-ray tube and 50-micron beryllium window. Five-gram subsamples of coal ash were taken from the undisturbed core samples, air-dried for 24 hours at room temperature, and ground by hand to less than 0.075 mm using an agate mortar and pestle. For analysis, ground samples were packed into an 18-mL sample cup (28 mm ID x 30 mm). Each subsample was analyzed in duplicate following ASTM 8064-16 for the XRF analytical method of silicate rocks.

Loss on Ignition

Loss on ignition (LOI) was measured at UVA for subsamples of undisturbed coal ash to quantify total organic matter content. LOI was conducted in accordance with ASTM D2974-14 by sintering a pre-weighed sample at 550 °C using a Lindberg/Blue M 1200 ºC box furnace (ThermoFisher Scientific, Waltham, MA). The mass lost during sintering was associated with the total organic matter.

Moisture Content

As part of the leaching test characterization using the LEAF methods, the moisture content of each study material was determined following ASTM D2216-19. Moisture content on a dry mass basis was calculated as the difference in the mass of a “wet” subsample compared to the sample after oven-drying to constant mass at 105 ± 5 ºC. The solids content is defined as the mass of solid material in an “as-tested” or “wet” subsample, measured on a “wet” basis. The determination of moisture content and solids content provides uniform bases for reporting of total content and leaching behavior results, allowing for comparison between moist and dry materials.

Porosity or Saturated Volumetric Water Content

Dry density (ρ_d) and porosity (n) of each material were determined at UVA using weight-volume computations, following the procedure in ASTM D7263-09. Under saturated conditions (i.e., when all voids are filled with water), the saturated volumetric water content (θ_s) equals the porosity.

Particle Size Distribution

Particle size distribution (PSD) of each coal ash sample was determined at UVA by a combination of mechanical analysis following ASTM D6913-17 and sedimentation analysis

following ASTM D7928-17. For mechanical analysis, a 100-g sample was oven-dried at 110±5 °C and passed through a series of US standard sieves: No. 10 (2 mm), No. 20 (0.85 mm), No. 60 (0.25 mm), No. 100 (0.15 mm), and No. 200 (0.075 mm). The fraction of the 100-g mass retained on each sieve was measured gravimetrically. Particle size distribution of the fraction coarser than the No. 200 sieve (0.075 mm) was calculated as the weight of solid retained on each sieve.

For sedimentation analysis, 50 g of dry solid that had passed the No. 200 (0.075 mm) sieve was soaked in 4% sodium metaphosphate, $(NaPO_3)_6$, solution for 12 hours and then transferred to a 1-L graduated cylinder. The graduated cylinder was capped, then agitated end-over-end for 60 seconds, and then settling of particles was monitored using a hydrometer. Stokes' law was used to compute the PSD from the hydrometer data for the fraction of particles finer than the No. 200 sieve.

Saturated Hydraulic Conductivity

Hydraulic conductivity tests were conducted in flexible-wall permeameters following the methods in ASTM D5084-16. Sections of undisturbed coal ash were extruded from the 73-mm ID, thin-wall sampling tubes (Figure 3-2) and cut into 76-mm long specimens. Non-woven geotextile disks and porous stones were placed on both ends of each coal ash specimen (Figure 3-3a) to ensure uniform flow distribution and to retain particles. Specimens were wrapped in a latex membrane and placed into a flexible-wall permeameter (Figure 3-3b).

In lieu of the more traditional tap water or 0.01 M $CaCl_2$ solution suggested in ASTM D5084, DIW was used as the permeant solution to ensure that the water entering the specimen had no ionic species that might alter the hydraulic conductivity or the leachable constituents in the coal ash. Effluent from the permeameter was collected following the procedure in ASTM D7100-11. Effluent samples were collected from the tests and stored in Teflon sample bottles with minimal headspace. Effluent samples were shipped under chain of custody to VU for chemical analysis.

The falling headwater-constant tailwater method was used with an average hydraulic gradient of 15. No backpressure was applied to simulate field conditions and to minimize alterations in geochemistry. All tests were conducted at an initial effective stress of 20 kPa and continued until the hydraulic conductivity reached hydraulic equilibrium as defined in ASTM D5084 (steady hydraulic conductivity, incremental outflow divided by inflow was constant within 1.0 ± 0.25). At the conclusion of the test, weight-volume calculations were used to determine that all specimens were fully saturated during testing.

After testing at 20 kPa was complete, three specimens, representing coarser, finer, and mid-range particle size distributions, were consolidated to 100 kPa and permeated again until hydraulic equilibrium was established (steady hydraulic conductivity, steady flow ratio 1.0 ± 0.25). The initial stress (20 kPa) was selected to replicate the stress condition of the coal ash with a burial depth of 1 m in the basin. The consolidation/permeation procedure was repeated at consolidation pressures of 250, 400, and 500 kPa to simulate stress at greater depths within the basin. The highest stress (500 kPa) corresponded to a depth of approximately 35 m. Effluent samples from these higher-stress experiments were not collected or chemically analyzed.

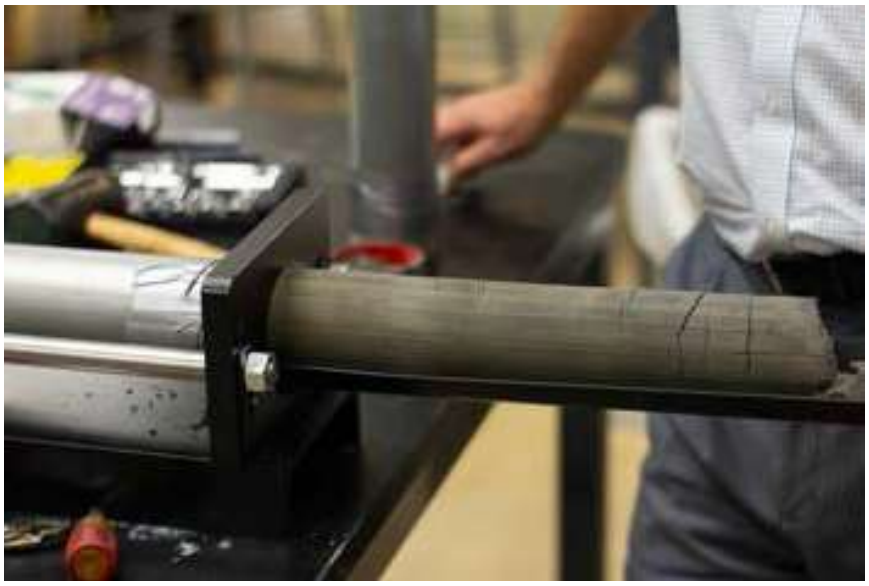

Figure 3-2
Extrusion of undisturbed coal ash sample from a thin-wall sampling tube conducted at UVA

a)

b)

Figure 3-3
Hydraulic conductivity test specimen and permeameter setup: a) test specimen (brown, gray cylinder) between two geotextile filter disks (thin black disks) and two porous stones (blue-gray disk on each end); b) test specimen installed in flexible-wall permeameter

Traditional Extraction Tests

EPA Method 1311 – Toxicity Characteristic Leaching Procedure

EPA Method 1311, or TCLP, is a single-point batch leaching test used to determine the toxicity characteristic of a material and the disposal options for a material under the Resource Conservation and Recovery Act of 1986 (RCRA). At the time of test development, TCLP was designed to simulate eluate concentrations for a plausible mismanagement scenario where hazardous waste is disposed in a municipal solid waste landfill. Thus, a solution of acetic acid in DIW is the extraction fluid to represent the primary acidity in municipal solid waste landfill leachate. Selection of an extraction fluid is based on a pretest of the buffering capacity of a test sample for acetic acid. Extraction Fluid #1 is dilute acetic acid buffered at a pH of 4.93 ± 0.05 with sodium hydroxide, while Extraction Fluid #2 is dilute acetic acid at a pH of 2.88 ± 0.05 without added base. The test-specific L/S of 20 mL/g is based on a filtered sample after pressure filtration at 15 psi. Since the filtered solid may still contain moisture, the final dry-basis extraction L/S is typically greater than 20 mL/g-dry. The filtrate from pressure filtration was preserved and chemically analyzed in parallel to TCLP extracts.

For this study, 80 grams of filtered solid was mixed with 160 mL of Extraction Fluid #1 and tumbled at 28 ± 2 rpm for 18 ± 2 hours. Although not specified in the method, the pH of the final eluate was measured and recorded so that test results could be compared to other leaching methods. The eluate from the extraction was pressure-filtered through a 0.22-µm borosilicate glass fiber filter and preserved for analysis. Filtrate from pressure filtration and the extraction eluate were analyzed separately and an "effective" extraction concentration was calculated for each constituent as a volume-weighted average concentration of the two liquids. For QA/QC purposes, a method blank, with the filter paper and extraction fluid only, and a duplicate sample for VB-2 were conducted in parallel using the same reagents.

EPA Method 1312 – Synthetic Precipitation Leaching Procedure

EPA Method 1312, or SPLP, is a single-batch leaching test used to evaluate the leaching behavior of a waste material in contact with acidic rain. The test is performed in the same manner as in the TCLP, but with extraction fluids of 60/40 weight percent (wt%) sulfuric acid (H_2SO_4) and nitric acid (HNO_3) in DIW (Extraction Fluids #1 and #2) or DIW (Extraction Fluid #3). The selection of extraction fluid depends on the location of the site under investigation and the constituents being tested. Extraction Fluid #1 is used for sites east of the Mississippi River, Extraction Fluid #2 is used for sites west of the Mississippi River, and Extraction Fluid #3 is used only when cyanides or volatiles are to be analyzed.

For these tests, 100 grams of filtered solid was mixed with 160 mL of Extraction Fluid #1 and tumbled at 28±2 rpm for 18±2 hours. Although not specified in the method, the pH of the final eluate was measured and recorded so that test results could be compared to other leaching methods. The eluate from the extraction was pressure-filtered through a 0.22-µm borosilicate glass fiber filter and preserved for analysis. Filtrate from pressure filtration and the extraction eluate were analyzed separately and an "effective" extraction concentration for each constituent was calculated as a volume-weighted average of the two liquids. A method blank—extraction fluid with no solid carried through the test process—and a duplicate sample for VB-2 were analyzed.

ASTM D3987 – Shake Extraction of Solid Waste with Water

ASTM D3987-12, or ASTM, is a single-point extraction test that is used to estimate leaching concentrations when no acid or base is added to the extraction. Since the method is patterned after TCLP, the procedure is similar to the EPA method; however, DIW is used as the extraction fluid.

For these tests, a subsample of ash (70±0.1 g) was tumbled at 28±0.2 rpm with DIW at an L/S of 20 mL/g for 18±0.25 hours. After tumbling, the extract was separated from the solid by vacuum filtration through a 0.45-m polypropylene membrane and the pH of the final eluate was measured and recorded. Reagent and method blanks were analyzed, and a duplicate test was conducted on the VB-3 sample.

Leaching Environmental Assessment Framework (LEAF) Test Methods

EPA Method 1313 – Liquid-Solid Partitioning as a Function of Eluate pH Using a Batch Extraction Procedure

EPA Method 1313 is standardized, parallel batch extraction method used to evaluate the liquid-solid partitioning (LSP) of inorganic constituents as a function of eluate pH. The general procedure consists of nine batch extractions of a particle-size reduced subsample material that is contacted with leaching solution at an L/S of 10 mL/g-dry material and tumbled end-over-end over a specified contact interval. The leaching solution is DIW with additions of HNO_3 or potassium hydroxide (KOH) to adjust the final pH of the eluate to a target of nine specific pH values (i.e., pH values of 2, 4, 5.5, 7, 8, 9, 10.5, 12, and 13). An additional extraction without addition of acid or base was carried out to measure constituent leaching at the natural pH of the material.[1] After 24 hours of tumbling, the contact time associated with a sample particle size of 85 wt% less than 300 µm, the solid and liquid phases were separated by settling or centrifugation, and the pH, EC, and ORP of the clarified eluate were measured. The remaining slurry was vacuum-filtered through 0.45-µm pore size membranes prior to chemical analysis by ICP-OES, IC, and carbon analysis.

EPA Method 1313 provides (i) a titration curve of the pH response to additions of acid or base, (ii) the available content of constituents in the solid material, and (iii) the LSP curve for constituents over the tested pH range. Furthermore, the results of EPA Method 1313 are suitable for use in geochemical speciation modeling for the estimation of the solid phase mineralogy and surface chemistry that controls constituent release.

Variants of EPA 1313 Methods

In this program, the full EPA 1313 method and variants of EPA 1313 were carried out on ash materials for different purposes:

- An abbreviated, 3-point EPA 1313 (1313_3 pt) was conducted on two homogenized samples of individual split spoon samples from each borehole. Since the natural pH of the CCP

[1] The "natural pH," sometimes referred to as "own pH," is defined as the eluate pH in response to extraction in deionized water (i.e., no acid or base added) at an L/S of 10 mL/g-dry. To distinguish the natural pH at L/S=10 mL/g-dry (Method 1313 or 1313_3pt) from the pH response to DIW at L/S of 1 mL/g-dry measured using 1313_L/S=1, the former will continue to be called with "natural pH" while latter will be referred to as "own pH."

materials was expected to be near neutral, the pH targets selected included $1.5 \leq pH \leq 2$, the natural pH, and pH=9.0±0.5. The pH targets near pH 2.0 and 9.0 are useful for determining the available contents of cationic and oxyanionic constituents, respectively. The results of these 3-point pH-dependence tests on individual split spoon samples were compared to the full-range EPA 1313 of composite samples as an indicator of vertical heterogeneity within a borehole.

- EPA 1313 was carried out on composited ash samples from each borehole but using an L/S of 1 mL/g-dry and abbreviated to the natural pH and two pH targets on either side of the natural pH, for five pH values in total. This modified 1313 test, referred to as 1313_L/S=1, was used to evaluate how changes in L/S may influence LSP concentrations and to provide verification data for development of geochemical speciation models.

EPA Method 1314 – Liquid-Solid Partitioning as a Function of Liquid-Solid Ratio Using a Percolation Column Procedure

EPA Method 1314 is a standardized, up-flow column procedure used to evaluate release of inorganic constituents from percolating solid materials as a function of cumulative L/S (i.e., the volume of liquid that passes through the column relative to the dry mass of material in the column). In this study, EPA 1314 was used to characterize the L/S-dependent leaching of constituents in 250-400 g-dry composited ash samples (e.g., VB-1, VB-2, and VB-3). A 5-cm diameter by 30-cm glass column was packed with coal ash in a series of five lifts with moderate tamping between lifts. DIW was used as the eluent solution since CCPs in general have relatively low organic carbon and clay contents compared to soils. The eluent was pumped at a flow rate of 0.75±0.25 L/S per day through the column in an up-flow direction to minimize air entrapment and flow channeling. Eluates were collected at predetermined cumulative L/S values (i.e., 0.2, 0.5, 1, 1.5, 2, 2.5, 4.5, 5, 9.5 and 10 mL/g-dry). For each eluate fraction, the pH and conductivity were recorded prior to filtration and preservation for chemical analysis. To present the results, the concentrations of constituents in the eluates (mg/L) as well as the cumulative release through the end of each eluate fraction (mg/kg-dry) were plotted as functions of L/S in separate graphs.

Comparison of Leaching Test Parameters and Conditions

All leaching tests conducted for this program are designed to measure the LSP of constituent release from a material under the specified test conditions shown in Table 3-2. TCLP, SPLP, and ASTM are single-batch leaching tests. Similarly, the EPA 1313 test and its variants are batch procedures, but with parallel extractions to provide data over a range of test conditions. These batch tests, however, differ in the chemical makeup of extraction fluid as well as in the specified L/S. Moving from left to right in Table 3-2, the leaching test conditions are presented in order of decreasing L/S from left to right. In the last column are the test conditions for EPA 1314, designed to measure LSP as a function of cumulative L/S.

Table 3-2
Leaching Test Parameters and Test Conditions

Parameter	TCLP	SPLP	ASTM	1313	1313_3-pt	1313_L/S=1	1314
Method Type	Single-batch	Single-batch	Single-batch	Parallel batch	Parallel batch	Parallel batch	Column
Number of Eluates	1	1	1	9	3	5	9
Extraction Fluid	Acetic acid in DIW	H_2SO_4/HNO_3 in DIW	DIW	HNO_3 or KOH in DIW	HNO_3 or KOH in DIW	HNO_3 or KOH in DIW	DIW
Extraction Fluid pH	#1: 4.93 ± 0.05* #2: 2.88 ± 0.05	#1: 4.20 ± 0.05* #2: 5.00 ± 0.05 #3: DIW	-	-	-	-	-
L/S	20 mL/g-filtered	20 mL/g-filtered	20 mL/g-wet	10 mL/g-dry	10 mL/g-dry	1 mL/g-dry	0.2-10 mL/g-dry (cumulative)
Eluate pH	-	-	-	<2, 4, 5.5, 7, 8, 9, 10.5, 12, 13, natural pH	<2, 9, natural pH	5.5, 7, 8, 9, own pH	based on solid buffering capacity
Eluate Filtration	0.22-µm via pressure	0.22-µm via pressure	0.45-µm via vacuum	0.45-µm via vacuum	0.45-µm via vacuum	0.45-µm via vacuum	0.45-µm via vacuum
Eluate Measurements	pH, EC	pH, EC	pH, EC	pH, EC, ORP	pH, EC, ORP	pH, EC, ORP	pH, EC, ORP
Reagent Blank	No	No	Yes	No	No	No	Yes
Method Blank	Yes	Yes	Yes	Yes	Yes	Yes	No
Duplicate Test	VB-2	VB-2	VB-2	None	None	None	None
Chemical Analysis	ICP-OES/MS DIC/DOC IC	ICP-OES/MS DIC/DOC IC	ICP-OES/MS DIC/DOC IC	ICP-OES/MS DIC/DOC IC	ICP-OES/MS	ICP-OES/MS DIC/DOC IC	ICP-OES/MS DIC/DOC IC
Samples Tested	VB-1, VB-2, VB-3 composites	VB-1, VB-2, VB-3 composites	VB-1, VB-2, VB-3 composites	VB-1, VB-2, VB-3 composites	2 individual split spoons per borehole	VB-1, VB-2, VB-3 composites	VB-1, VB-2, VB-3 composites

Note: * indicates the TCLP and SPLP extraction fluids used for these tests.

Chemical Analysis of Eluates, Groundwater, and Porewater

Eluate pH

Eluate pH was measured on all aqueous extracts following EPA Method 9040C using an Accumet XL20 meter and a combined pH electrode on approximately 5 mL of eluate. Prior to testing, the electrode was calibrated with two National Institute of Standards and Technology (NIST) traceable pH buffer solutions that bounded the anticipated range of pH to be measured. A third mid-range NIST buffer was used to verify the calibration.

Specific Conductance

Specific conductance, or EC, is a measure of the ability of an aqueous solution to carry an electrical current. The property is dependent on (i) the presence of ions; (ii) total concentration, mobility, and variance of ions in solutions; and (iii) the temperature of the measurement. Conductivity of all leaching test eluates was determined following EPA Method 9050A using a standard conductivity probe calibrated to an appropriate standard conductivity solution for the conductivity range of concern.

Oxidation-Reduction Potential

ORP is a voltage differential related to the redox state of a solid-liquid solution and its effect on chemical composition (e.g., reduced/oxidized iron, dissolved oxygen, biological activity). ORP voltage of all eluate solutions was measured with a probe, consisting of a platinum electrode and a reference electrode, placed in contact with the soil solution. In laboratory tests, the ORP voltage reading was converted to redox potential (Eh) by addition of a probe-specific correction factor of 228 mV at 25 °C. In field measurements, however, the probe correction factor was automatically compensated for by the instrument and are output as Eh values.

Since, redox reactions vary with pH and the mineral species present, redox is parameterized in geochemical modeling as the pH+pE, where pE is the negative logarithm of the free electron concentration, or –log([e^-]). The corrected Eh values of leachates and eluates were converted to a pE value using the following equation:

$$pE = \frac{F}{2.303RT}(Eh/1000)$$

where F is the Faraday constant (23,061 cal/(V mol)),

Eh is the redox potential of the solution (mV),
2.303 is a conversion (ln[e^-]/2.303 log[e^-]),
R is the gas constant (1.987 cal/(K mol)),

T is the temperature (K), and

1000 is a unit conversion (1,000 mV = 1 V).

Inductively Coupled Plasma Spectrometry

The eluate concentrations of trace elements and material major species (e.g., Al, Ca, Si) were determined using a combination of ICP-OES and inductively coupled plasma – mass

spectrometry (ICP-MS). The choice of instrumentation was determined based on detection limits, expected concentrations, and environmental threshold values. Table 3-3 provides the method detection limits (MDLs) and lower limits of quantitation (LLOQs) used in this project along with the working ranges for each constituent.

Major species and trace elements present at higher concentrations were determined using a Varian Model 720-ES ICP-OES (Agilent Technologies, Santa Clara, CA) following EPA Method 6010D. The ICP-OES was calibrated to a 5-point standard curve with an analytical range of 25 to 25,000 µg/L. For some high-concentration trace elements, the standard curve was extended up to 500,000 µg/L using a 7-point standard curve. For low-level trace analysis, concentrations were determined by ICP-MS using a Perkin Elmer Elan DRC II (Perkin Elmer, Waltham, MA) following EPA Method 6020A. The ICP-MS was calibrated to a 5-point standard curve with range between approximately 1 and 250 µg/L and extended with a 7-point curve to 1,000 µg/L for some constituents.

Analytical QA/QC included initial and continuing calibration checks and blanks, matrix spikes, and method blanks. Calibration check standards and matrix blanks were evaluated every 10 to 20 samples with the requirements that check standards were within 15% of the specified value and blanks were below LLOQs. Matrix spikes were required to have recoveries within 20% of the calculated concentration considering the spiked mass. Initial and continuing calibration check standards for ICP-OES and ICP-MS were 0.5 mg/L and 0.050 mg/L, respectively. Analyte concentrations measured at less than the MDL were reported as <MDL and graphed at one-half the MDL values to indicate that the measurement was conducted. Analytical results measured at less than the LLOQ but greater than the MDL are estimated values.

Table 3-3
Methods, MDLs, and LLOQs for Analysis of Eluates by ICP-OES and ICP-MS

Analyte	Symbol	Method	MDL (mg/L)	LLOQ (mg/L)
Aluminum	Al	ICP-OES	0.0034	0.025
Antimony	Sb	ICP-MS	0.00008	0.001
Arsenic	As	ICP-MS	0.00057	0.001
Barium	Ba	ICP-OES	0.0016	0.005
Beryllium	Be	ICP-MS	0.00042	0.001
Boron	B	ICP-OES	0.0023	0.025
Cadmium	Cd	ICP-MS	0.00019	0.001
Calcium	Ca	ICP-OES	0.0065	0.025
Chromium	Cr	ICP-MS	0.00047	0.001
Cobalt	Co	ICP-MS	0.00041	0.001
Copper	Cu	ICP-MS	0.00054	0.001
Iron	Fe	ICP-OES	0.0022	0.025
Lead	Pb	ICP-MS	0.00022	0.001
Lithium	Li	ICP-OES	0.0047	0.025
Magnesium	Mg	ICP-OES	0.0035	0.025
Manganese	Mn	ICP-OES	0.001	0.05
Molybdenum	Mo	ICP-MS	0.00059	0.001
Nickel	Ni	ICP-MS	0.00047	0.001
Phosphorus	P	ICP-OES	0.0068	0.025
Potassium	K	ICP-OES	0.0032	0.025
Selenium	Se	ICP-MS	0.00051	0.001
Silicon	Si	ICP-OES	0.0038	0.025
Sodium	Na	ICP-OES	0.0056	0.025
Strontium	Sr	ICP-OES	0.0037	0.025
Sulfur	S	ICP-OES	0.0058	0.025
Thallium	Tl	ICP-MS	0.00047	0.001
Titanium	Ti	ICP-OES	0.0023	0.025
Uranium	U	ICP-MS	0.00026	0.001
Vanadium	V	ICP-MS	0.00032	0.001
Zinc	Zn	ICP-MS	0.000647	0.001

Ion Chromatography

The concentrations of anions in leaching test eluates were determined by IC using a Metrohm 881 Compact IC Pro (Metrohm USA, Riverview, FL) with a Metrosep A Supp 5 column and a conductivity detector following EPA Method 9056A. A 7-anion calibration standard was diluted to form a 5-point calibration curve with the MDLs and LLOQs shown in Table 3-4. Since the calibration standards are diluted from a bulk multi-analyte standard, the calibration range differs for each analyte (e.g., 0.050-50 mg/L for Cl^- and 0.150-150 mg/L for SO_4^{-2}). Calibration check standards were required to be within 15% of the specified value, while acceptable analytical blanks were measured below the quantitation limits.

Table 3-4
MDLs and LLOQs for Analysis of Eluates by IC

Analyte	Symbol	MDL (mg/L)	LLOQ (mg/L)
Bromide	Br^-	0.0064	0.025
Chloride	Cl^-	0.0101	0.05
Fluoride	F^-	0.0063	0.02
Nitrate	NO_3^-	0.0112	0.1
Nitrite	NO_2^-	0.0108	0.05
Phosphate	PO_4^{-3}	0.0247	0.15
Sulfate	SO_4^{-2}	0.0254	0.15

Carbon Analysis

Carbon analysis for eluate samples included analyses for dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC). Carbon analysis was conducted using a Shimadzu TOC-V CPH/CPN (Shimadzu Scientific Instruments, Inc., Columbia, MD) by catalytic oxidation/non-dispersive infrared detection (NDIR) following EPA Method 9060A. Total carbon (TC) in the eluate is converted to carbon dioxide via oxidation or decomposition, carried by a zero-CO_2 air stream into the NDIR. For analysis of DIC, liquid samples are acidified with 2-molar hydrochloric acid to liberate carbonates and other forms of inorganic carbon from solution as carbon dioxide, which is sparged from the liquid sample into the NDIR by the zero-CO_2 carrier gas. DOC is determined by measuring the TC of a sample after purging of IC. The instrument was calibrated using sodium hydrogen carbonate and potassium hydrogen phthalate over a 5-point calibration curve for DIC and DOC, respectively. The resultant analytical range was between 0.1 and 100 mg/L, with MDL and LLOQ values shown in Table 3-5. Checks on QA/QC at a frequency of every 10 analytical samples included calibration checks with a required recovery within 15% of the specific value, and method blanks with a requirement that the concentration was less than quantifiable limits.

Table 3-5
MDLs and LLOQs for Eluate Analysis for Carbon

Analyte	Symbol	MDL (mg/L)	LLOQ (mg/L)
Inorganic carbon	DIC	0.15	0.50
Organic carbon	DOC	0.18	0.50

Subsurface Gas Analysis

The composition of subsurface gas was monitored monthly from September 2018 through September 2019. Subsurface gas was monitored for oxygen (O_2), carbon dioxide (CO_2), methane (CH_4), ammonia (NH_3), and hydrogen sulfide (H_2S) using a hand-held field meter (Figure 3-4a). Table 3-6 shows the measurement units and calibration ranges for the five gases. To avoid any moisture from subsurface gas fouling the vacuum pump, the subsurface gas was drawn through a 250-mL syringe filled with desiccant (Figure 3-4b).

a) b)

Figure 3-4
Subsurface gas monitoring apparatus: a) field meter and b) connected tubing and desiccant syringe

Table 3-6
Calibration Ranges for Subsurface Gas Monitoring

Analyte	Symbol	Units	Calibration Range	
Ammonia	NH_3	ppm	0	500
Hydrogen sulfide	H_2S	ppm	0	500
Carbon dioxide	CO_2	%	0	5
Methane	CH_4	%	0	5
Oxygen	O_2	%	0	30

Data Management with LeachXS™

Information on how leaching tests were conducted was recorded by the laboratory technician in Microsoft Excel® spreadsheets specifically designed for each test for use as templates for data collection and archiving. Analytical data documenting concentrations of constituents from each leaching test were entered into the same spreadsheets. These data templates were used as the interface for loading laboratory and analytical data into LeachXS™ (VU, 2019), a database-driven data management and reporting software program. LeachXS was used to (i) archive the laboratory and analytical data from leaching tests; (ii) compare test results between composite materials (e.g., VB-1, VB-2, or VB-3) or test results (e.g., TCLP, SPLP, ASTM, and LEAF); and (iii) generate the Excel plots used for this report.

4
TEST RESULTS AND DISCUSSION

A large volume of data was generated during this research. The discussion that follows presents representative example figures that illustrate observations based on all data. Graphs and data tables reflecting all data are provided in the appendices. In addition, key observations within subsections are denoted by underscored text.

Physical and Hydraulic Properties

Physical properties of the fly ash samples used for measurement of hydraulic properties are summarized in Table 4-1, composition of the solids is summarized in Table 4-2, and the hydraulic conductivities are summarized in Table 4-3.

Particle size distributions of the coal ash samples are shown in Figure 4-1. All samples contained a broad range of particle sizes ranging from those associated with coarse-to-fine sand, silt, and clay-size (<2 μm) particles. Each has a broadly graded distribution with relatively comparable fractions of all sizes and no gaps. The fines content (i.e., silt and clay-size particles finer than 75 μm) ranges from 36.6 to 92.2%, and the clay-size (i.e., finer than 2 μm) ranges from 5.2 to 19.8%. No particles coarser than sand-size were observed.

Table 4-1
Physical Properties of Coal Ash Samples Used for Hydraulic Conductivity Assessment

Sample ID	Sample Elevation at Bottom (ft AMSL)	Sample Elevation at Top (ft AMSL)	Water Content (%)	Dry Unit Weight (mg/m^3)	Particle Size Fractions			
VB-1_OST_12-14.5	743.8	746.3	41.5	1.14	0.0	15.5	84.5	15.1
VB-1_OST_17-19.5	738.8	741.3	52.0	1.00	0.0	25.2	74.8	10.0
VB-2_OST_13.5-15.5	737.9	739.9	37.5	1.11	0.0	64.4	36.6	5.2
VB-2_OST_18.5-21.5	731.9	734.9	28.7	1.35	0.0	23.1	76.9	12.6
VB-3_OST_17-20	738.8	741.8	36.3	1.28	0.0	34.5	65.5	14.0
VB-3_OST_24-27	731.8	734.8	27.9	1.26	0.0	7.8	92.2	19.8

Sample VB-2_OST_13.5-15.5 was notably coarser than the other samples and was classified as silty sand (SM) in ASTM D2487. This classification is characteristic of bottom ash mixed with fly ash. All other samples were classified as fine-grained “elastic silt” (ML) as defined in ASTM D2487, which is characteristic of fly ash.

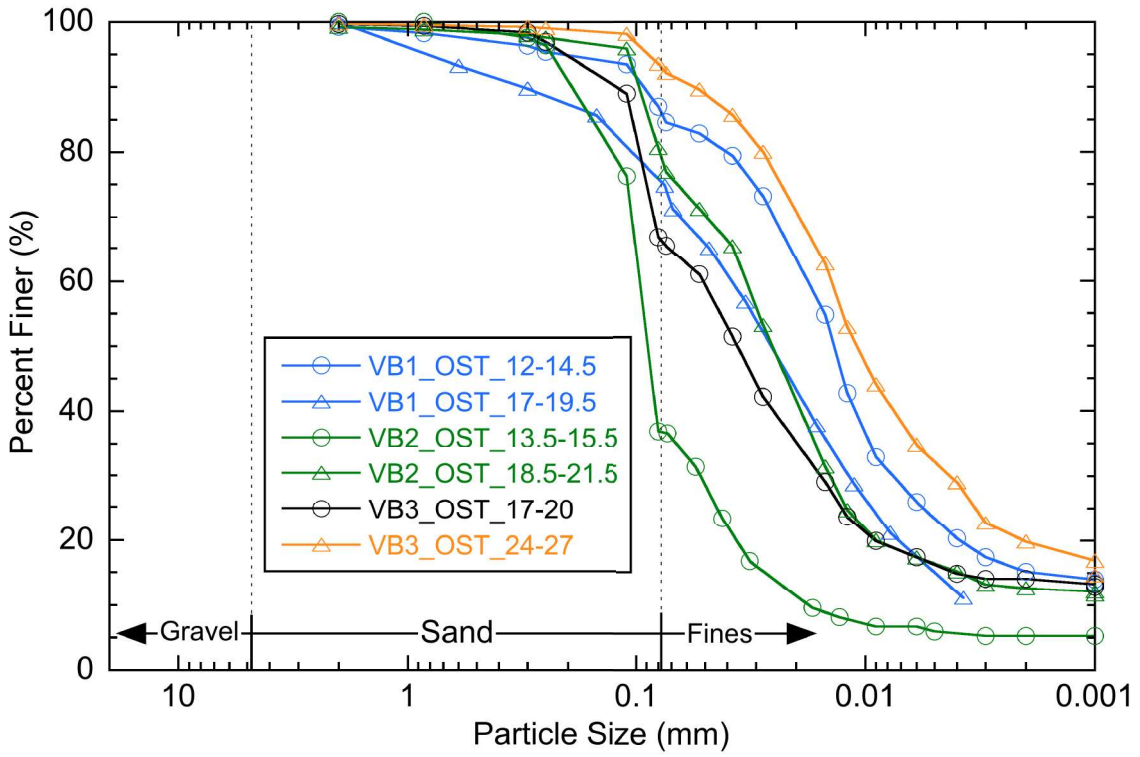

Figure 4-1
Particle size distribution of coal ash samples

Table 4-2 indicates that all of the ash samples are predominantly composed of Al and Si oxides, which reflects the predominant alumino-silicate mineral structure of the particulate. All samples contain modest amounts of Ca, K, Fe, and Ti. The VB-2 series samples are richer in iron than the other samples. The LOI varies considerably, from 0.50 to 11.83%.

Table 4-2
Composition of Solids (%) from LOI and XRF of Coal Ash Samples Used for Hydraulic Conductivity Assessment (elements exceeding 1.0%)

Composition	VB-1		VB-2		VB-3
	12-14.5	17-19.5	13.5-15.5	18.5-21.5	17-20
LOI	0.98	1.89	0.50	11.83	4.95
Al_2O_3	26.19	26.69	24.26	19.88	26.79
CaO	1.35	1.44	1.36	1.32	1.50
Fe_2O_3	16.14	11.34	22.99	19.45	12.61
K_2O	5.70	3.66	4.78	3.79	3.74
SiO_2	45.42	51.10	41.86	39.74	46.87
TiO_2	2.04	1.48	1.99	1.64	1.59

The hydraulic conductivities fall into two groups: the coarser, more permeable samples (VB-1_OST_17-19.5, VB-2_OST_13.5-15.5, and VB-3_OST_17-20) and the finer, less permeable samples (VB-1_OST_12-14.5, VB-2_OST_18.5-21.5, and VB-3_OST_24-27). The coarser samples have hydraulic conductivities in the range of 10^{-4} to 10^{-3} cm/s and fines content less than 75%, whereas the finer samples have hydraulic conductivities closer to 10^{-5} cm/s and fines content greater than 75%. There is a strong relationship between the hydraulic conductivity and fines content (Figure 4-2), with hydraulic conductivity diminishing as the fines content increases. The hydraulic conductivities also align well with hydraulic conductivities generally associated with the geotechnical classifications.

Table 4-3
Hydraulic Conductivity of Coal Ash Samples

Sample ID	Percent Fines (%)	Effective Stress (kPa)	Hydraulic Conductivity (cm/s)
VB-1_OST_12-14.5	84.5	20	2.0×10^{-5}
		100	2.0×10^{-5}
		250	1.4×10^{-5}
		400	1.3×10^{-5}
		500	1.3×10^{-5}
VB-1_OST_17-19.5	74.8	20	3.6×10^{-4}
VB-2_OST_13.5-15.5	36.6	20	1.3×10^{-3}
VB-2_OST_18.5-21.5	76.9	20	4.2×10^{-5}
		100	4.1×10^{-5}
		250	3.0×10^{-5}
		400	2.7×10^{-5}
		500	1.2×10^{-5}
VB-3_OST_17-20	65.5	20	6.3×10^{-4}
		100	6.9×10^{-4}
		250	2.5×10^{-4}
		400	2.3×10^{-4}
		500	9.7×10^{-5}
VB-3_OST_24-27	92.2	20	2.7×10^{-5}
		100	2.7×10^{-5}
		250	2.6×10^{-5}
		400	2.4×10^{-5}
		500	2.3×10^{-5}

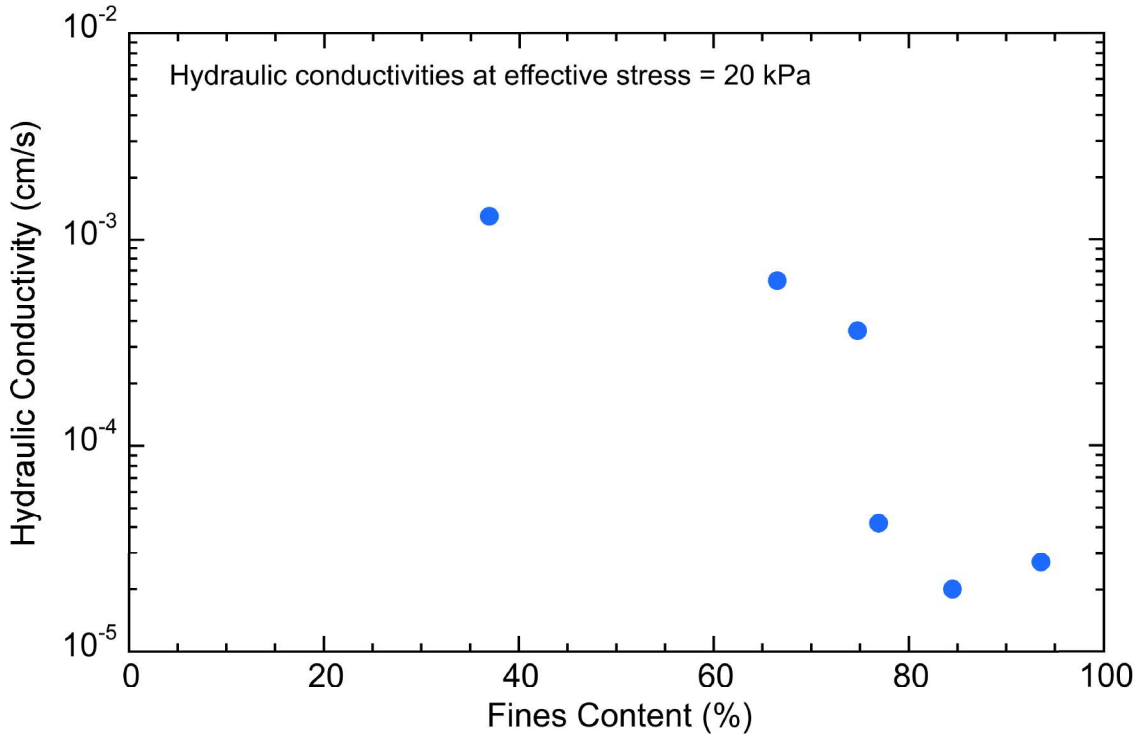

Figure 4-2
Hydraulic conductivity of coal ash at 20 kPa effective stress as a function of fines content

The hydraulic conductivity of the coal ash samples as a function of confining stress is shown in Figure 4-3. In general, the hydraulic conductivity decreases modestly with increasing effective stress. The hydraulic conductivity of the coarser, more permeable sample (VB-3_OST_17-20) is more sensitive to effective stress than the finer, less permeable samples. As the stress increased from 20 to 500 kPa, the hydraulic conductivity of the coarser sample decreased by a factor of 6.5. In contrast, the hydraulic conductivity of the finer, less permeable samples decreased by a factor of 2.1 on average over the same range of stresses. The greater sensitivity to stress for VB-3_OST_17-20 may reflect closure of larger pores between the sand-size particles, with the finer particles filling the remaining pores and resulting in lower hydraulic conductivity.

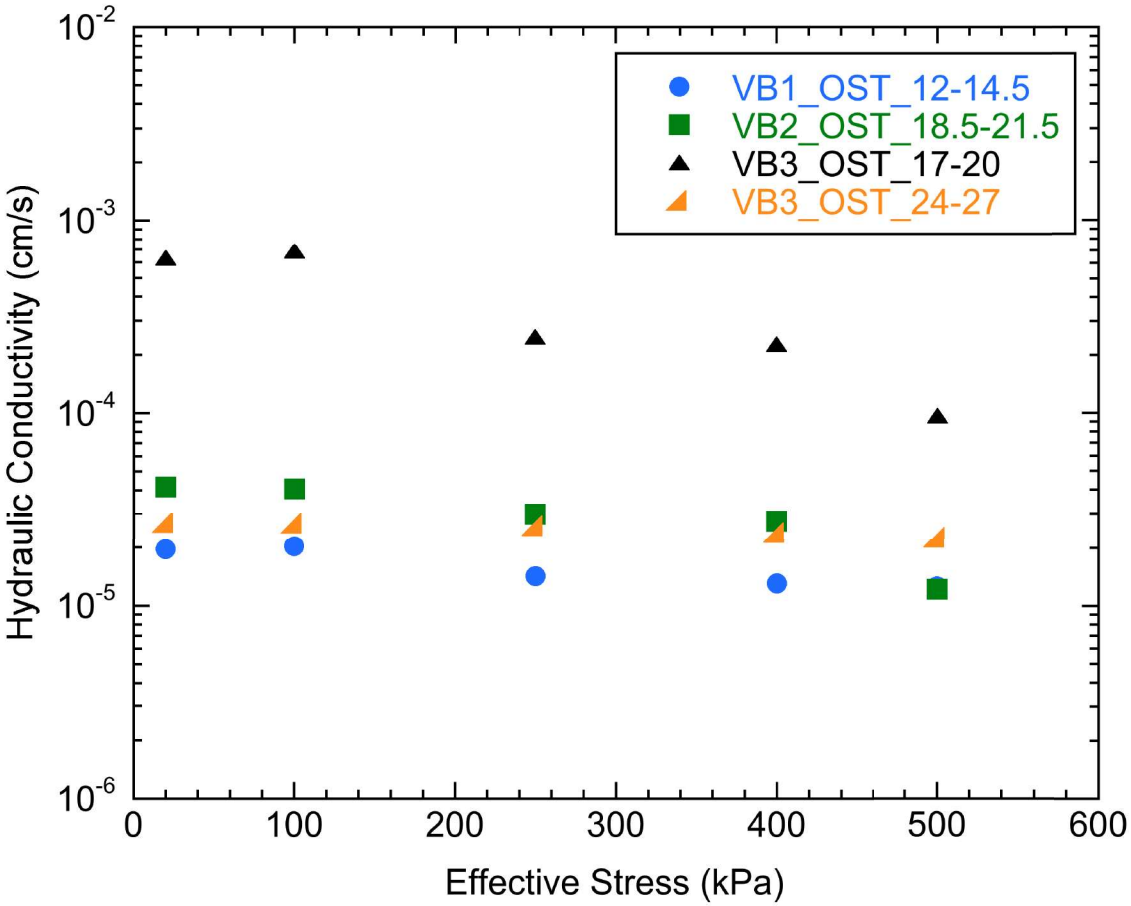

Figure 4-3
Hydraulic conductivity of coal ash samples as a function of effective stress

Individual Split Spoon Sample Testing

Evaluation of Field Extractions (L/S~1 vs. L/S=1)

During field sampling, extractions of split spoon materials were conducted using de-oxygenated water at an L/S~1. For each extract, approximately 150-g grab samples of recovered material from the center of the split spoon were contacted with approximately 150 mL of DI water that had been deoxygenated with nitrogen prior to field operations. If the split spoon indicated an interface between dissimilar materials (e.g., across the ash-cover or ash-liner interfaces or in layered ash), two extractions were conducted on grab samples of distinctive material types. Because the moisture content of the split spoon material varied with depth and texture, the resultant L/S of field extractions varied between 1.7 and 3.3 mL/g-dry.

The variation in L/S of field-extracted materials confounds the comparison of material within a borehole or between boreholes based on concentrations. Therefore, extractions at a constant L/S ratio were conducted in the laboratory. Collected bulk materials that had been vacuum-sealed to preserve the redox conditions of split spoon samples were homogenized within each split spoon. 100-g subsamples of homogenized material were extracted with DI water at an L/S=1 mL/g-dry. Figure 4-4 shows a comparison between field extractions (L/S~1) and laboratory extractions (L/S=1) as a function of pH and L/S. Comparisons of field and laboratory extraction data for all constituents are presented in Appendix C.1.

In these figures, the color of the data points indicates the borehole (e.g., VB-1 in blue, VB-2 in green, and VB-3 in orange), with lighter colors indicating field extractions and darker colors indicating laboratory extractions. The shape of the data point refers to the primary type of material used in the extraction (ash samples are shown as dots, cover material as squares, and liner material as diamonds). Solid data points are confirmed material types that fall within the material classification provided in the bore logs by the licensed geologist, while open data points indicate materials near interfaces that are likely to be a blend of two or more material types (e.g., open squares indicate blended samples of the ash and cover materials while open diamonds refer to blends of ash, layered ash, and liner material).

The data in Figure 4-4 show that the primary difference between laboratory tests is L/S ratio, which is most noticeable in the L/S-dependence plot. The pH range for the laboratory extractions is primarily the same as that of the field extractions.

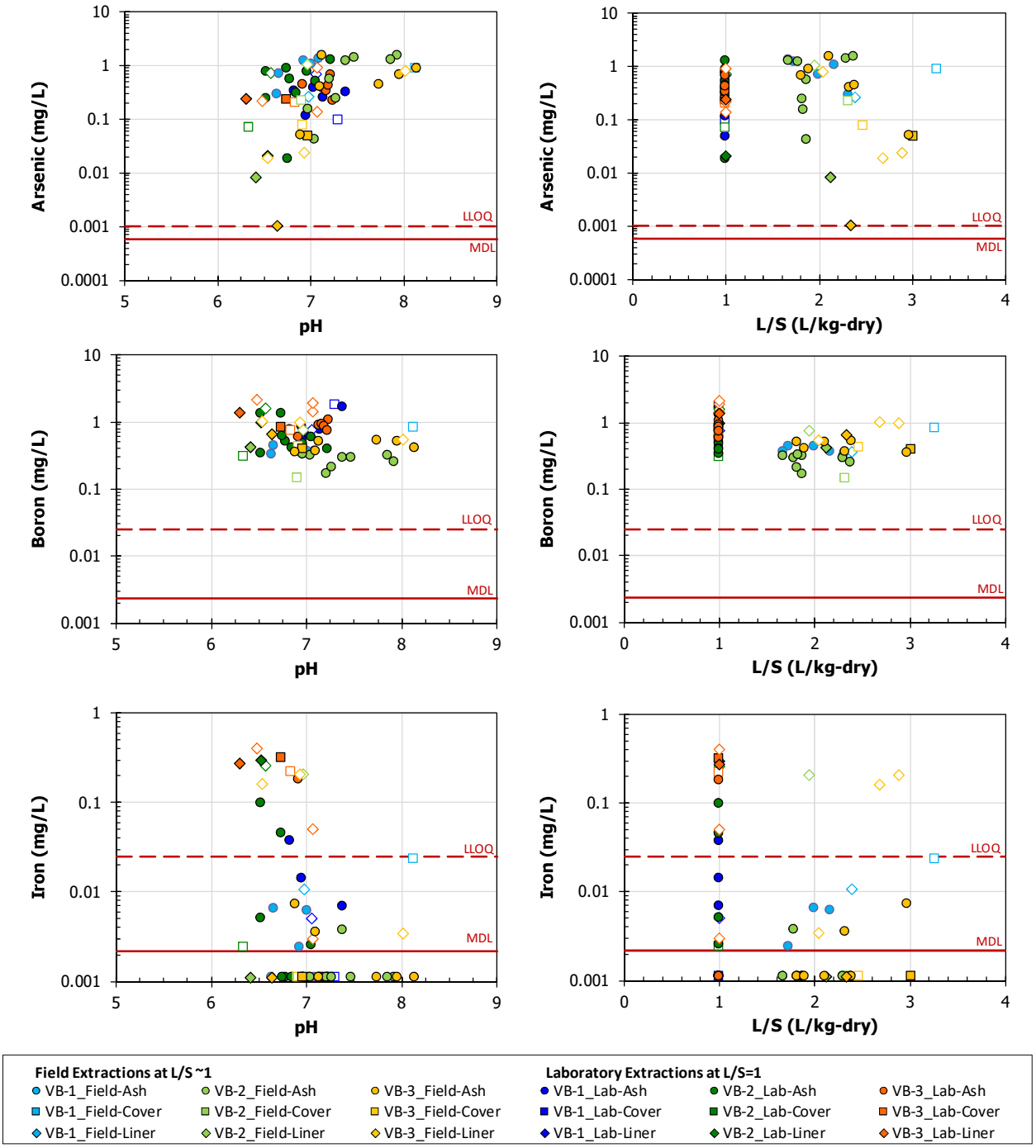

Figure 4-4
Comparison of field extractions at L/S~1 (lighter colors) to laboratory extractions at L/S=1 (darker colors) for individual split spoon materials shown as a function of pH (left) and L/S (right)

Vertical Heterogeneity Within and Between Boreholes

Profile Plots of Field and Laboratory Extraction Data

After surveying of the borehole and PAP locations and elevations, depths below grade that were monitored during sample recovery were converted to elevations ASML. The concentrations from field extractions (L/S~1) and laboratory extractions (L/S=1) of individual split spoon materials were plotted as a function of elevation to provide a visual metric of material heterogeneity with depth within a borehole. An example of these borehole profile plots is presented in Figure 4-5.

Each line of the figure represents the concentration profiles for a measured constituent in the laboratory extractions (L/S=1) for VB-1 in blue, VB-2 in green, and VB-3 in orange. The concentration is plotted along the x-axis, while the elevation for the center of the split spoon is plotted on the y-axis. The red horizontal line shows the elevation at the interface between cover material and the ash deposit, while the brown horizontal line indicates the elevation where the main ash deposit ended either at an interface with the underlying native clay liner material or in layers of different ash textures above the clay liner. The 2-foot wide shaded area indicates the screening interval for the PAP in each borehole. The 3 to 4 light-colored data points in each profile indicate the intervals from which material was taken to create the composite ash sample for each borehole used in detailed characterizations.

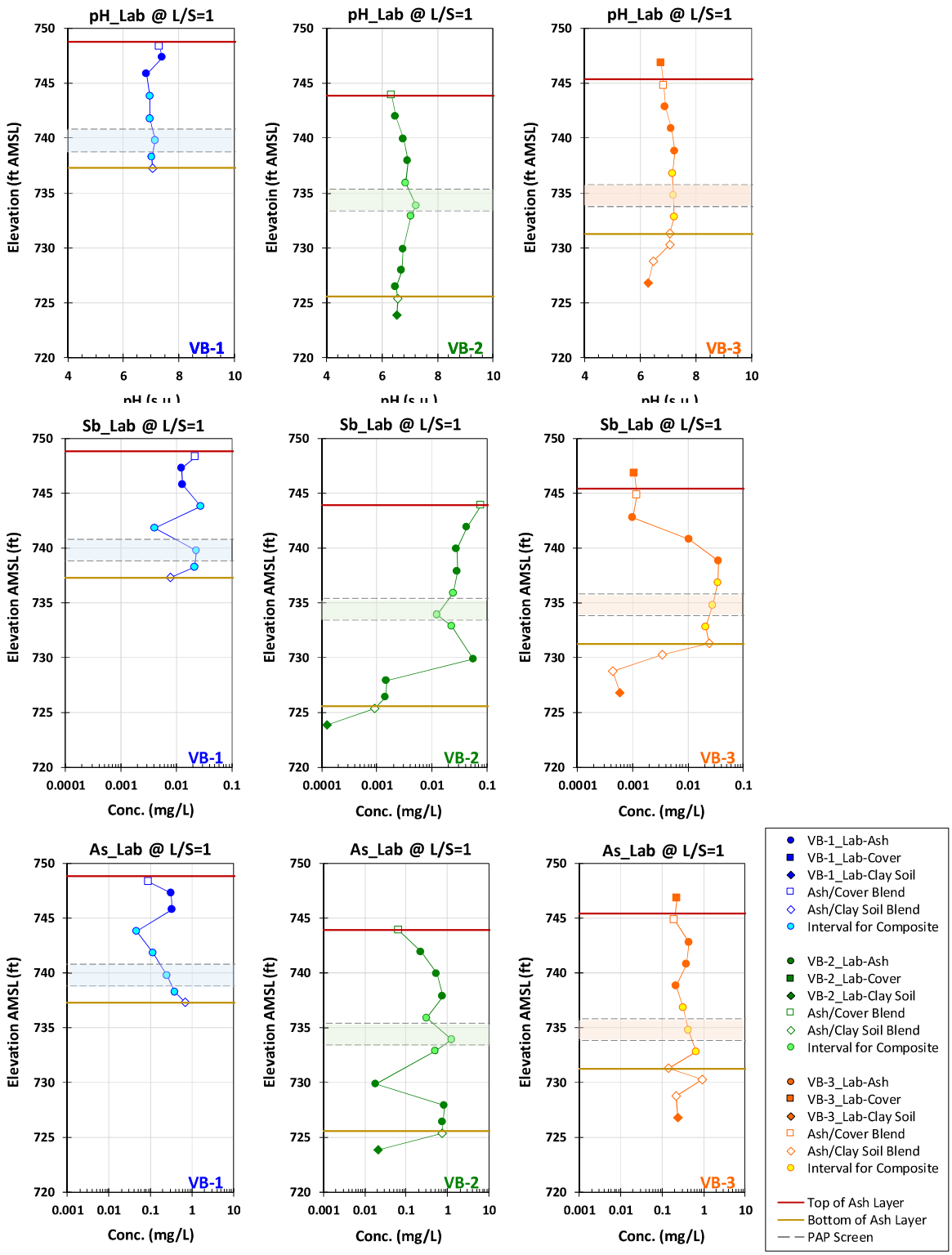

Figure 4-5
Laboratory extraction (L/S=1) concentration profiles within boreholes (VB-1, VB-2, VB-3) based on eluate concentration (SU or mg/L) for pH, antimony, and arsenic

Standardized Borehole Profiles of Laboratory Extraction (L/S=1) Concentrations

The concentration data for laboratory extractions of homogenized split spoon material were converted to standardized profile plots using the global mean and standard deviation for "known ash samples" in all boreholes based on geologist notes. The standardized concentration is calculated as:

$$\frac{x - \bar{x}}{s}$$

where x is the parameter (e.g., pH, concentration) from the extraction test,
$\bar{x}$ is the global mean of all "known ash samples" for all boreholes, and
s is the global standard deviation of all "known ash samples."

The standardized concentration provides a measure of the difference between the measured concentration and the mean as a number of standard deviations from the mean concentration. A homogenous material, for example, may have measurements within 2 standard deviations of the mean while measurements greater than 4 standard deviations may have more than random variations such as influence from cover or underlying material. Justification for use of ash sample global statistics, rather than within-borehole statistics, was based on the results of t-test results for pair-wise comparisons assuming unequal variances, which showed no statistical difference in means between boreholes. In addition, the use of global statistics in standardized concentration profiles allows for comparison between boreholes on the same basis.

Examples of the resulting standardized borehole profiles are shown in Figure 4-6 for major constituents and in Figure 4-7 for trace constituents. The standardized profiles for all constituents are presented Appendix C.2. The global mean and standard deviation for all constituents are tabulated in Table 4-4.

The process for collection of split spoon samples at boreholes VB-2 and VB-3 was designed to capture the interfaces at the cover and underlying materials, whereas the collection of split spoons at borehole VB-1 was centered on the ash material only. These sampling schemes are reflected in the results of the standardized profiles. Figure 4-6 shows that the concentration profiles for aluminum and iron from laboratory extractions (L/S=1) show very consistent response within the ash deposit, with clear influences from overlying and underlying materials. The profiles for antimony, arsenic, and boron in Figure 4-7 show more variation within the ash layers, with little to no influence from cover or underlying materials. Overall, the samples used in the composite materials for all boreholes were relatively consistent and are considered representative of the global mean of the stored ash.

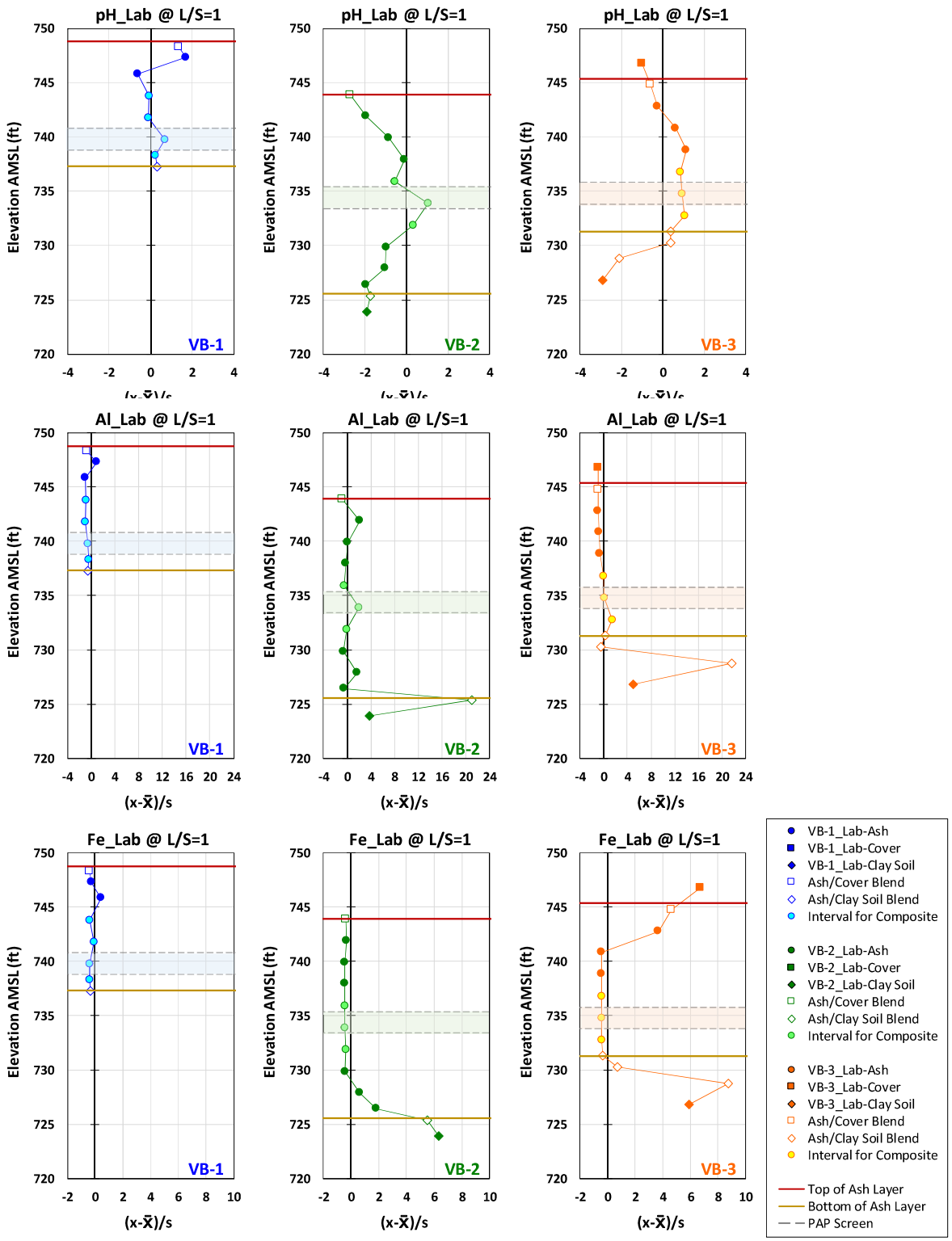

Figure 4-6
Laboratory extraction (L/S=1) concentration profiles within boreholes (VB-1, VB-2, and VB-3) standardized to the global mean (x̄) and standard deviation (s) of known ash samples for pH, aluminum, and iron

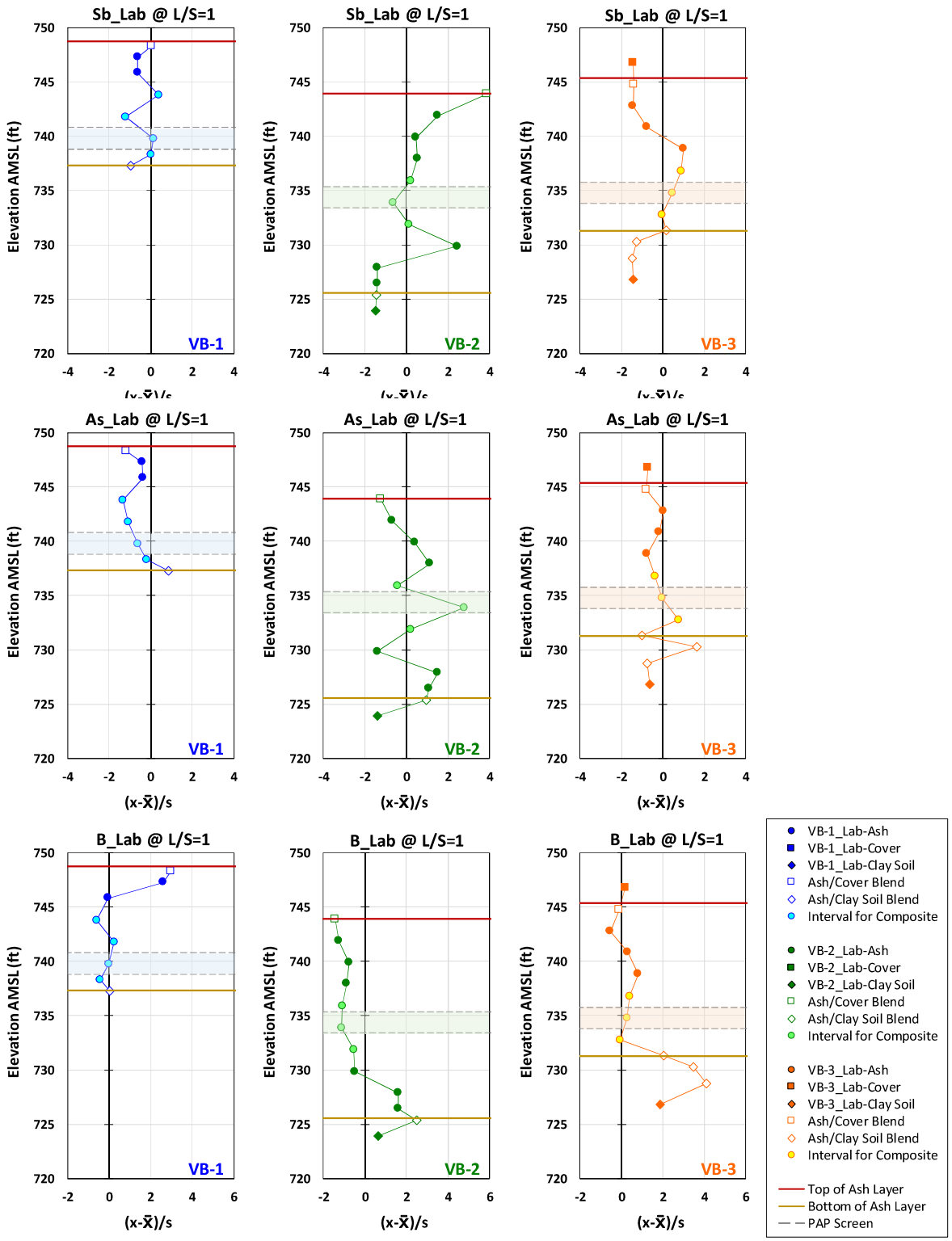

Figure 4-7
Laboratory extraction (L/S=1) concentration profiles within boreholes (VB-1, VB-2, and VB-3) standardized to the global mean (X̄) and standard deviation (s) of known ash samples for antimony, arsenic, and boron

Table 4-4
Global Mean and Standard Deviation of Laboratory Extractions (L/S=1) Concentrations

Analyte	Units	Global Statistics	
		Mean	Std. Dev.
EC	mS/cm	0.38	0.24
IS	Mol/L	0.0057	0.0036
pH	S.U.	6.98	0.23
ORP	mV	97.95	19.58
pE	-	5.51	0.33
pH+pE	-	12.49	0.42
Aluminum	mg/L	0.093	0.095
Antimony	mg/L	0.022	0.014
Arsenic	mg/L	0.44	0.30
Barium	mg/L	0.15	0.06
Beryllium	mg/L	<MDL	<MDL
Boron	mg/L	0.77	0.33
Cadmium	mg/L	<MDL	<MDL
Calcium	mg/L	73.69	57.83
Chromium	mg/L	0.0052	0.0022
Cobalt	mg/L	<MDL	<MDL
Copper	mg/L	0.0022	0.0015
DOC	mg/L	21.03	9.11
Iron	mg/L	0.02	0.04
Lead	mg/L	<MDL	<MDL
Lithium	mg/L	<MDL	<MDL
Magnesium	mg/L	14.37	12.89
Manganese	mg/L	0.41	1.03
Molybdenum	mg/L	0.79	1.46
Nickel	mg/L	<MDL	<MDL
Phosphorus	mg/L	0.19	0.11
Potassium	mg/L	7.79	3.80
Selenium	mg/L	0.21	0.23

Table 4-4 (continued)
Global Mean and Standard Deviation of Laboratory Extractions (L/S=1) Concentrations

Analyte	Units	Global Statistics	
		Mean	Std. Dev.
Silicon	mg/L	3.01	1.50
Sodium	mg/L	5.81	2.60
Strontium	mg/L	1.57	0.54
Sulfur	mg/L	38.81	57.03
Thallium	mg/L	<MDL	<MDL
Titanium	mg/L	<MDL	<MDL
Vanadium	mg/L	0.11	0.11
Zinc	mg/L	0.03	0.09

Notes: <MDL indicates all or most of the L/S=1 concentrations were less than the MDL

Comparison of Standardized Borehole Profiles for Field and Laboratory Extractions Based on Mass Release (mg/kg)

The standardized borehole variability graphs can be used to examine the differences between field extractions at L/S ~1 and laboratory extractions at L/S=1. Example comparisons for selected major and trace constituents are shown in Figure 4-8 and Figure 4-9, respectively, while the complete results for all measured constituents are presented in Appendix C.3.

In general, the variability of laboratory and field extraction are similar; however, the laboratory extractions are somewhat less variable than the field extractions. This observation is due to the homogenization within a split spoon sample that was conducted on the material used for laboratory extractions, especially for trace species where blending would matter most (see Figure 4-9). A secondary cause for lesser variability in the laboratory extraction data may be a result of redox changes between the laboratory and field extraction conditions.

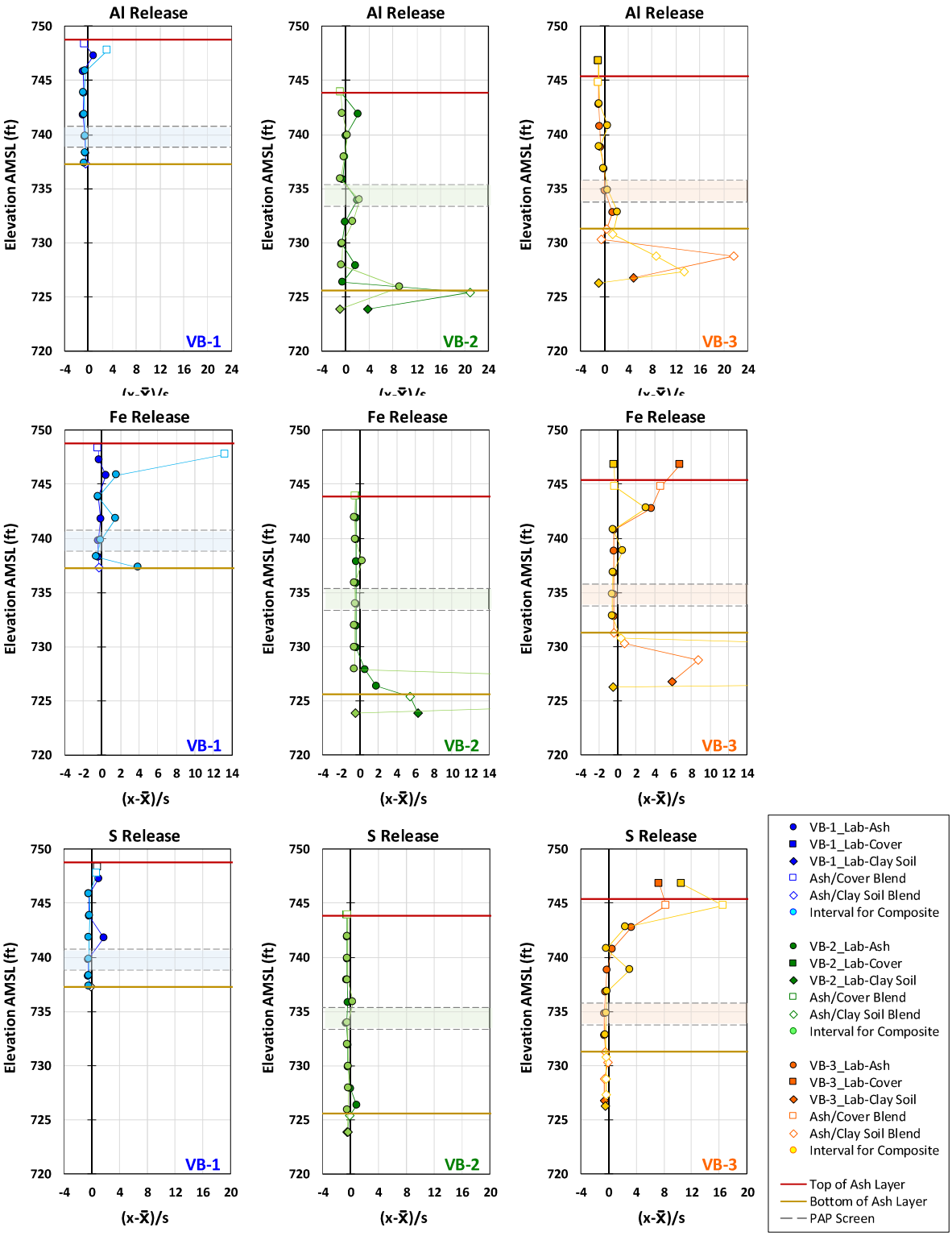

Figure 4-8
Comparison of standardized mass release profiles for field extractions (L/S~1) and laboratory extraction (L/S=1) of major constituents from VB-1, VB-2, and VB-3 for aluminum, iron, and sulfur

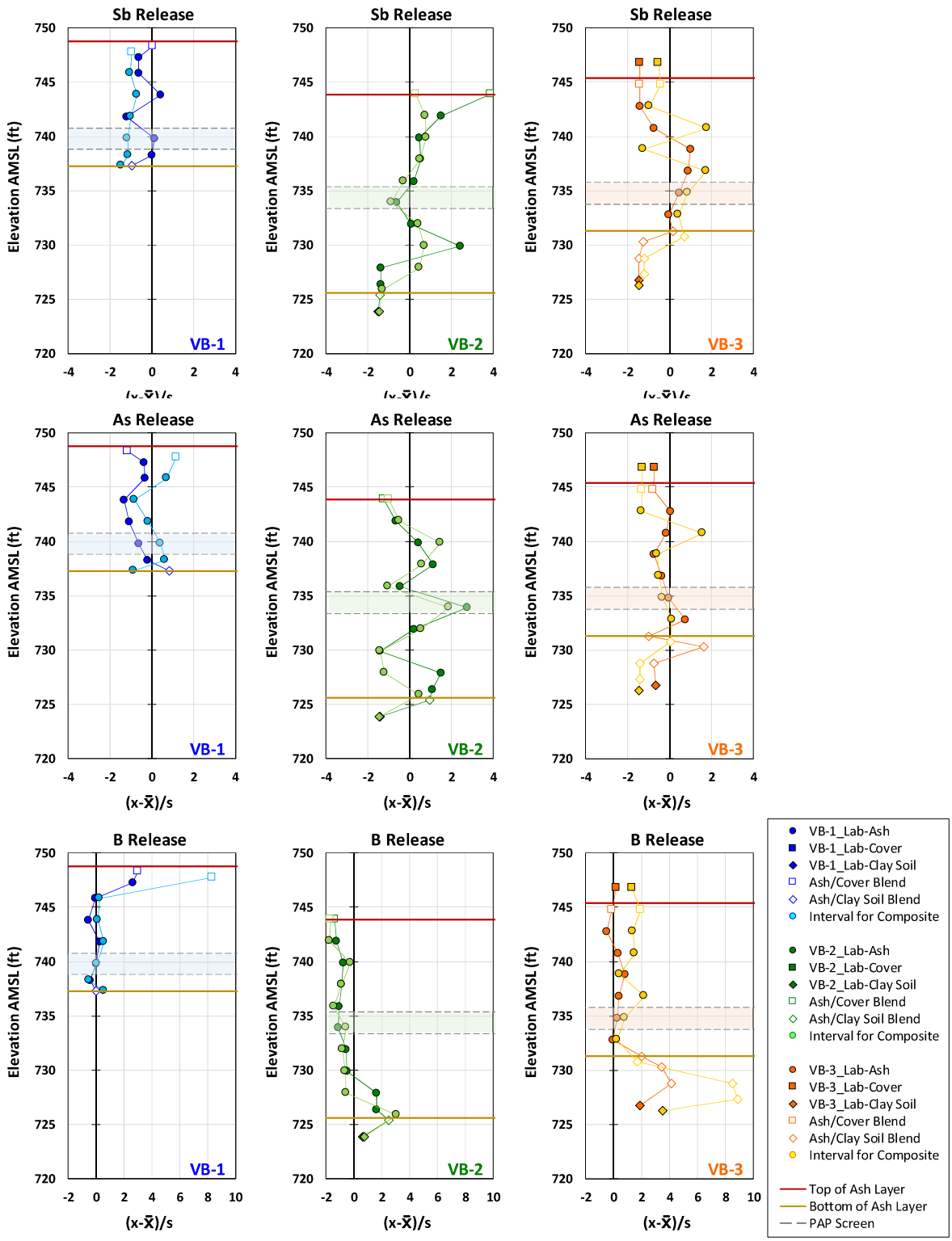

Figure 4-9
Comparison of standardized mass release profiles for field extractions (L/S~1) and laboratory extraction (L/S=1) of trace constituents from VB-1, VB-2, and VB-3 for antimony, arsenic, and boron

Composite Ash Sample Test Results

Subsamples of bulk material collected from split spoon sampling were homogenized within each bulk storage packet and then composited by equal mass over intervals around the PAP screening intervals. These composites were subject to detailed investigation of total and available content, leaching characteristics as a function of pH and L/S, and comparison between leaching tests and to porewater concentrations. The complete set of pH- and L/S-dependent results for all measured constituents is presented in Appendix D.1.

Total Content

In preparation for EPA Method 3052, ash samples were dried under nitrogen and ground to pass a No. 100 (150 μm) sieve. Therefore, although the EPA method is based on "as received" solid sample, which can include the inherent moisture within the material, the results presented on an "as received" mass (mg/kg) are, in this case, based on dry-mass (mg/kg-dry) like the LEAF tests. The total content reported for samples of the three composite materials is shown in Table 4-5. Of the 27 constituents analyzed, Sb, Mg, Hg, Se, Ag, and Tl were reported to have a total content less than the commercial laboratory's reporting limit shown in the table. Furthermore, the total content of thallium was not detected at a value greater than the shown MDL value. Based on the low total content and low eluate concentrations of initial leaching test results, Ag and Hg were not considered in the analysis of test leachates or the comparison to groundwater concentrations. The remaining constituents were retained because preliminary testing indicated that leaching concentrations were low, but quantifiable for most leaching tests.

Table 4-5
Total Content for Composite Samples VB-1, VB-2, and VB-3 Based on EPA Method 3052

Analyte	Symbol	MDL (mg/kg)	RL (mg/kg)	VB-1 (mg/kg)	VB-2 (mg/kg)	VB-3 (mg/kg)
Aluminum	Al	3.1	40	13,000	13,000	13,000
Antimony	Sb	2.0	6.0	3.5 J	3.3 J	4.5 J
Arsenic	As	1.4	10	92 B	110 B	110 B
Barium	Ba	0.24	1.0	370	360	400
Beryllium	Be	0.015	1.0	6.4	5.9	6.8
Cadmium	Cd	0.32	1.0	2.2	1.1	1.7
Calcium	Ca	11	500	930	980 F1	970
Chromium	Cr	0.14	1.5	140	140	150
Cobalt	Co	3.0	25	40	34	35
Copper	Cu	1.5	5.0	130	130	200
Iron	Fe	28	40	11,000	77,000	57,000
Lead	Pb	1.1	7.5	53	46	61
Lithium	Li	0.29	5.0	170	170	190

Table 4-5 (continued)
Total Content for Composite Samples VB-1, VB-2, and VB-3 Based on EPA Method 3052

Analyte	Symbol	MDL (mg/kg)	RL (mg/kg)	VB-1 (mg/kg)	VB-2 (mg/kg)	VB-3 (mg/kg)
Magnesium	Mg	3.7	500	110 J	110 J, F1	120 J
Manganese	Mn	0.11	1.5	250	210	170
Mercury	Hg	0.062	0.2	0.098 J	0.093 J	0.083 J
Molybdenum	Mo	0.16	4.0	8.2	4.5	5.0
Nickel	Ni	0.16	20	100	89	90
Potassium	K	100	1,000	12,000	15,000	15,000
Selenium	Se	1.7	7.5	6.1 J	4.4 J	5.3 J
Silver	Ag	0.11	3.0	1.8 J	1.7 J	1.9 J
Sodium	Na	260	500	1,400	1,700	1,800
Strontium	Sr	0.058	5.0	140	100 F1	120
Thallium	Tl	10	17	ND	ND	ND
Titanium	Ti	1.0	25	7,500	7,800	8,200
Vanadium	V	0.12	5.0	240	240	260
Zinc	Zn	2.0	12	120	110	120

Notes: B the compound was found in the blank and sample.

F1 the matrix spike recovery is outside of acceptance limits

J the result is less than the LLOQ but greater than or equal to the MDL; estimated concentration.

ND the compound was not detected at a concentration above the MDL.

pH-Dependent Leaching Tests

Titration curves from EPA 1313 and 1313_L/S=1 conducted on the VB-1, VB-2, and VB-3 composite samples are presented in Figure 4-10. The titration curve indicates the amount of acid or base (shown as acid additions less than zero) required to provide a specific eluate pH. This is sometimes referred to as the acid/base neutralization capacity of the material. Also shown in Figure 4-10 is the natural pH response for each composite material when no acid or base is added.

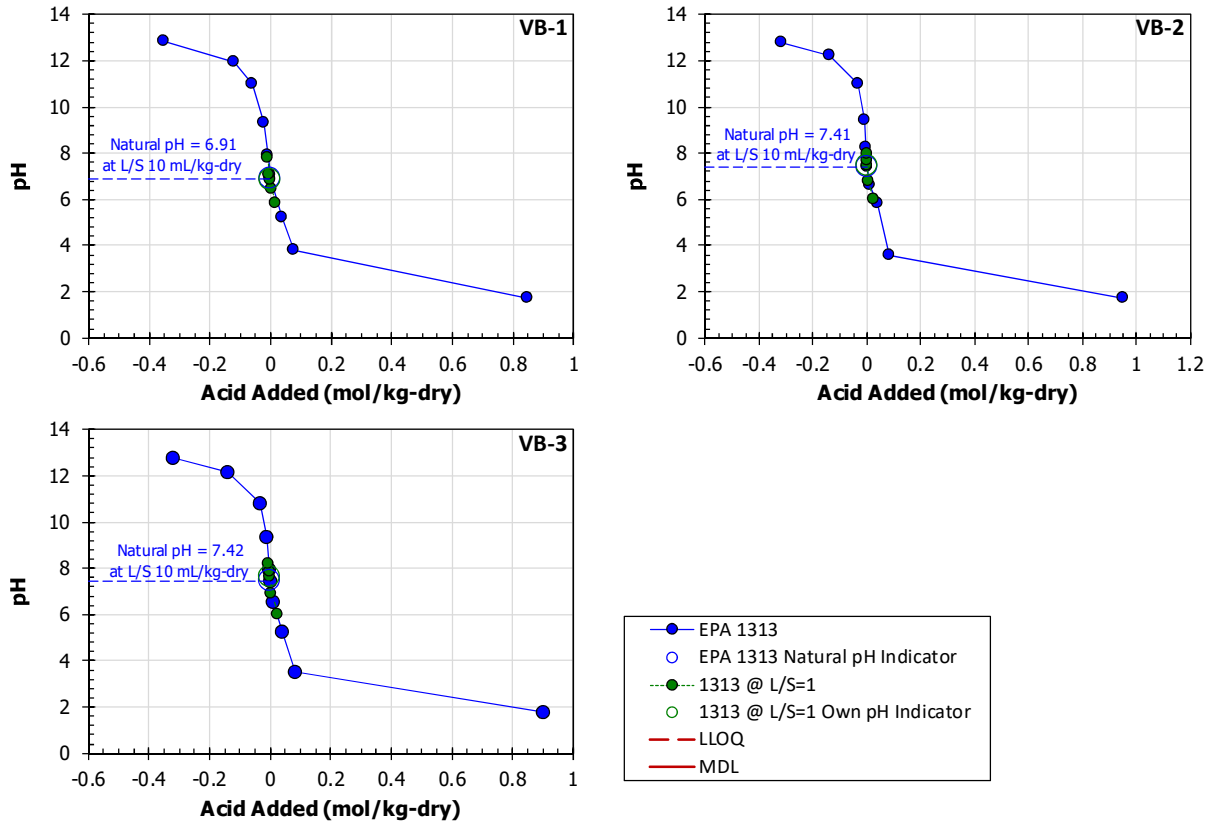

Figure 4-10
Titration curves from EPA 1313 test results from composite testing of VB-1, VB-2, and VB-3

The natural pH values for the three composites are presented in Table 4-6 along with the "own pH" values measured during 1313 testing at an L/S=1 mL/g-dry. Although the natural pH values for all composites are generally neutral, VB-1 is slightly more acidic (pH_{nat}=6.91) than the composites at VB-2 (pH_{nat}=7.41) or VB-3 (pH_{nat}=7.42). The different L/S ratios between natural pH and own pH had little effect on overall pH (less than 0.2 SU).

Table 4-6
Natural pH (EPA 1313) and Own pH (1313_L/S=1) of Composite Samples

	Method	L/S (mL/g-dry)	pH (SU) VB-1	pH (SU) VB-2	pH (SU) VB-3
Natural pH	EPA 1313	10	6.91	7.41	7.42
Own pH	1313_L/S=1	1	6.84	7.45	7.59

Constituent Concentrations

The concentration of a constituent in each eluate of a pH-dependent leaching test (i.e., EPA 1313 and 1313_L/S=1) is indicative of the LSP in equilibrium with the L/S, pH, EC, and ORP of the contacting fluid. Eluate concentrations are typically plotted as a function of eluate pH to indicate how LSP changes over a broad range of pH values. Example test results from EPA 1313 and

1313_L/S=1 are shown in Figure 4-11 through Figure 4-13 as pH-dependent eluate concentration (mg/L) and mass release (mg/kg-dry).

The pH-dependent leaching behavior of a constituent is useful when disposed materials may be contacted with water containing significant amounts of acid or base (e.g., pyrite-impacted groundwater or alkali process wastewaters). These data can be used to parameterize controlling mineral sets in geochemical speciation models, for example, LeachXS™/ORCHESTRA (Meeussen, 2015), to create a source term for fate and transport modeling.

Solubility-Controlled LSP vs. Available Content-Limited LSP

In addition, comparison of the effects of changing pH (e.g., within an EPA 1313 test) to the effects of changing L/S (e.g., between EPA 1313 and 1313_L/S=1 or EPA 1314) can be used to distinguish constituents with "solubility-controlled LSP" behavior from those with "available content-limited LSP." The following classifications are based on comparison of EPA 1313 test results to those of 1313_L/S=1 testing and, thus, the classifications are limited to a relatively narrow pH range about the natural pH. Outside of those bounds, constituents that were classified as available-content limited may show solubility-controlled LSP.

- Solubility-Controlled LSP – When the eluate concentrations are limited by mineral solubility and precipitation/dissolution, the LSP behavior is considered "solubility-controlled" and pH is a controlling factor for leaching. Eluate concentrations for these behaviors are often a strong function of pH. However, unless pH changes significantly when L/S is changed, eluate concentrations are a weak function of L/S. The pH-dependent results for Ba (Figure 4-11, top) as well as Cr, F^-, Sb, Se, V, and Zn (in Appendix D.1) are good examples of solubility-controlled LSP. For these constituents, eluate concentrations change by orders-of-magnitude as a function of pH but do not change when the L/S is reduced from L/S=10 mL/g-dry (EPA 1313) to L/S=1 mL/g-dry (1313_L/S=1).
- Similarly, adsorption/desorption processes can be highly pH-dependent and often can be classified along with solubility-controlled LSP. For example, the LSP behavior of arsenic (Figure 4-11, bottom) with regard to changes in pH and L/S has similar trends to the solubility-controlled LSP behavior of Ba; however, the primary mechanism for the pH-dependent LSP of arsenic is likely adsorption to hydrous ferric oxides (HFO) rather than solubility of arsenic species.

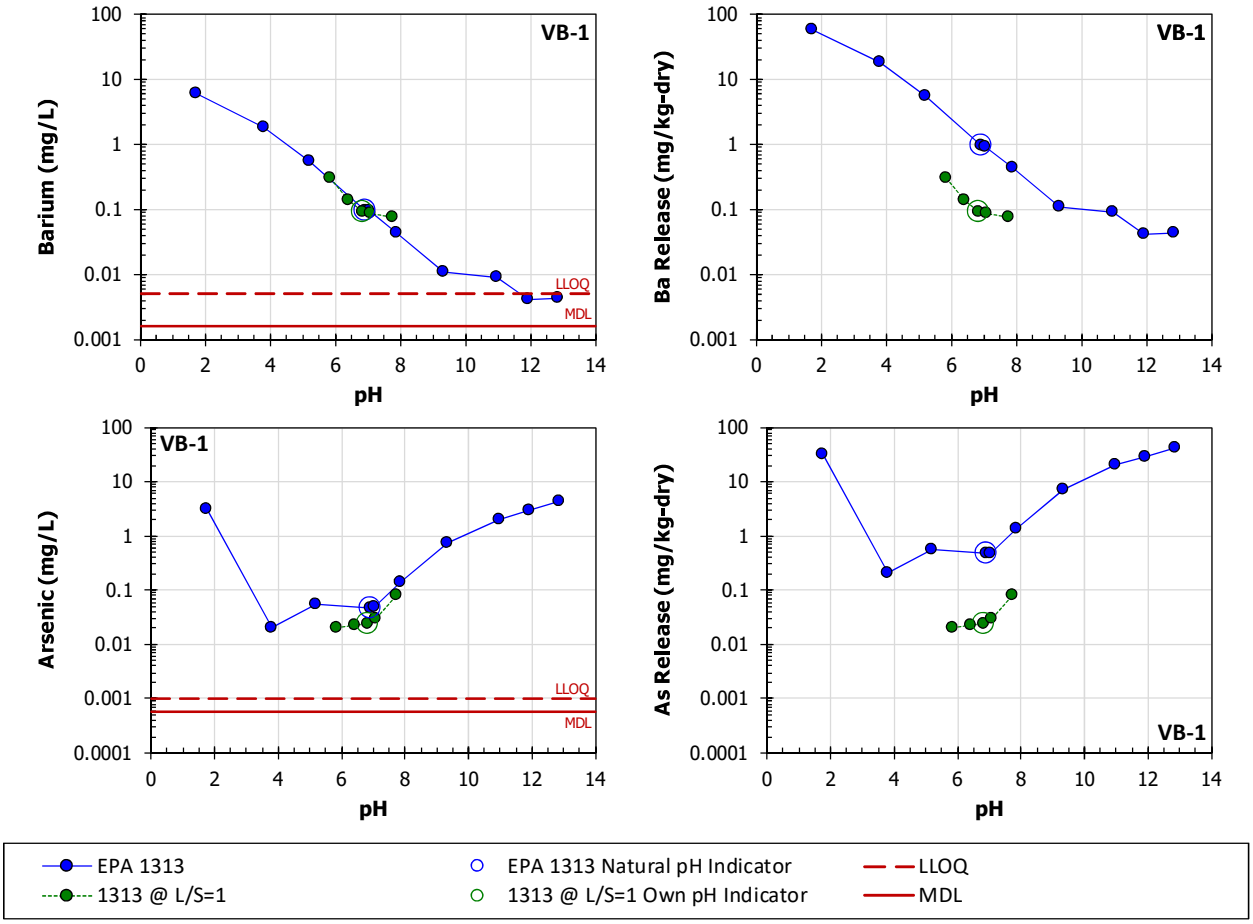

Figure 4-11
Example pH-dependent (EPA 1313) test results showing solubility-controlled LSP (barium) and adsorption-dominated LSP (arsenic)

- Available Content-Limited LSP – The concentration of some highly soluble constituents is not limited by the conditions of the eluate but by the amount of leachable mass in the solid. The characteristic pH-dependent behavior of these "available content-limited LSP" constituents is that eluate concentration curve is a weak function of pH but a strong function of L/S. Figure 4-12 presents examples of available content-limited LSP for B and SO_4^{-2} results from EPA 1313 and 1313_L/S=1. These figures show that pH-dependent concentrations within a test vary by approximately an order-of-magnitude across the entire pH range. However, when the L/S changes from L/S=10 mL/g-dry to L/S=1 mL/g-dry, the eluate concentration changes accordingly. Because the L/S effect is correlated to the magnitude of the L/S, the mass release (i.e., the eluate concentration multiplied by the L/S) is the same for both tests. Available content-limited LSP was observed for B, Ca, Cl^-, Mo, SO_4^{-2}, and Tl in VB-1, VB-2, and VB-3 composites (Appendix D.1).

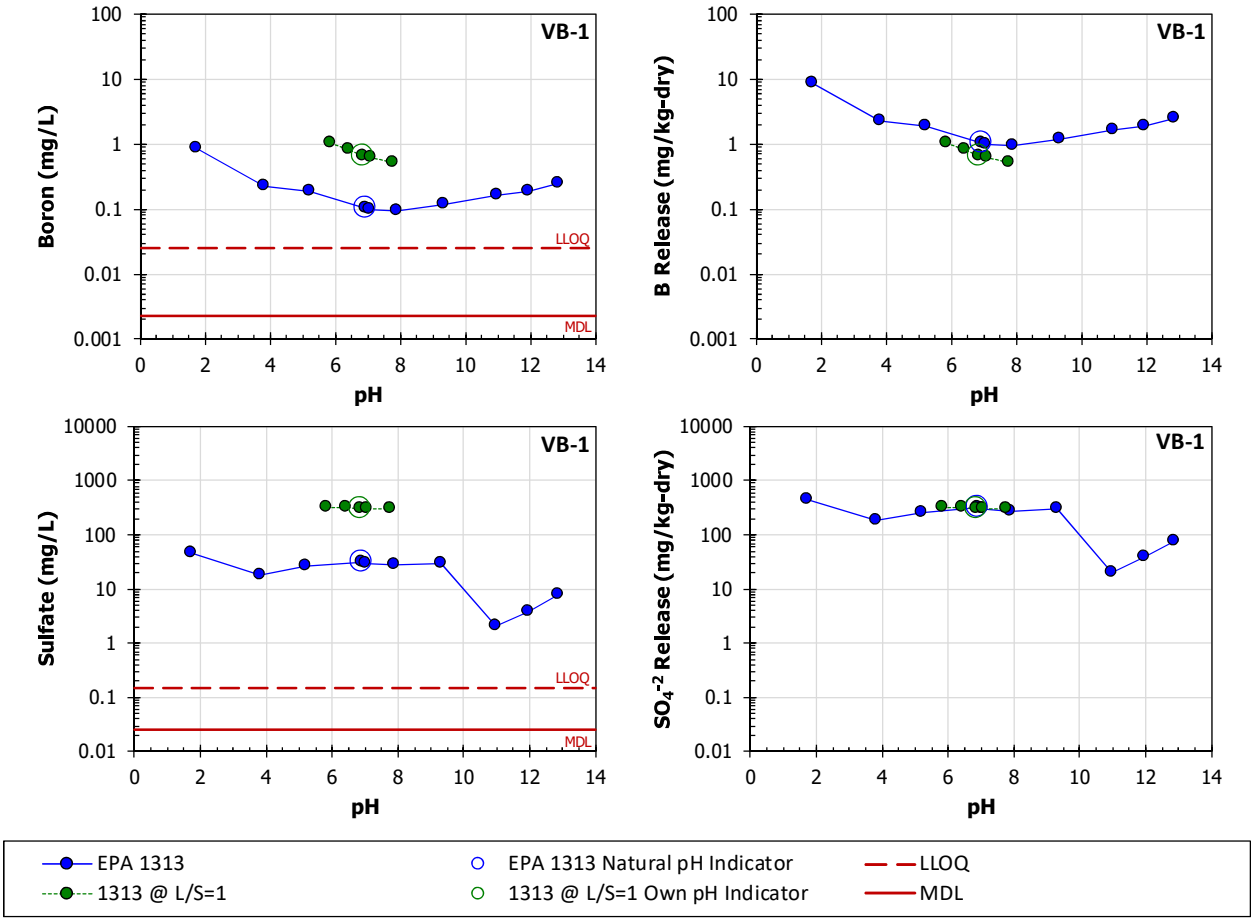

Figure 4-12
Example pH-dependent (EPA 1313) test results showing available content-limited LSP

For some constituents, the pH-dependent leaching data does not support the determination of LSP behavior, because eluate concentrations are less than the MDL for the analytical method. Figure 4-13 presents examples for Be and Li. Similar behavior was shown for Cd, Co, Cu, Fe, Ni, and Pb (Appendix D.1).

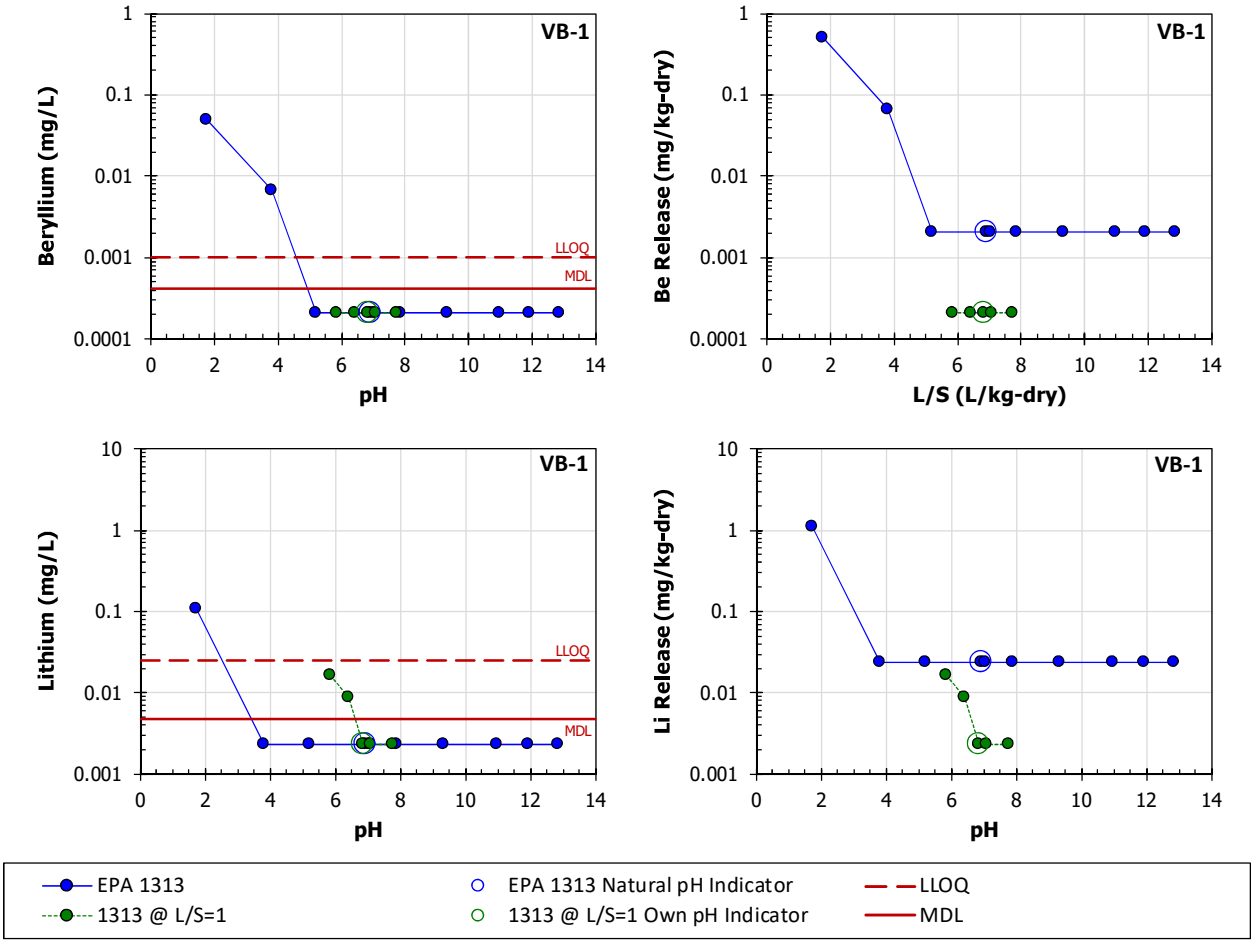

Figure 4-13
Example pH-dependent (EPA 1313) test results for constituents where LSP type could not be determined based on measured concentrations

Available Content Determination Using EPA 1313

The available content of the three borehole composites was determined from the maximum concentration over the pH range $2 \leq pH \leq 13$ from EPA 1313 testing. The available content values and pH locations for the maximum 1313 concentration are shown in Table 4-7. In Table 4-8, comparison of available content (mg/kg-dry) to the total content (mg/kg) shown in Table 4-5 indicates that only a small fraction of most constituents is leachable over a broad pH range. The high ratios of available Ca and Mg to their total content suggest either that digestion by EPA 3052 was not complete or that there is inherent error associated with multiplying a relatively small digestate concentration by a large effective L/S of 500 or more.

Table 4-7
Available Content for Composite Samples VB-1, VB-2, and VB-3 Based on the Maximum Concentration from EPA Method 1313

Analyte	Symbol	VB-1 (mg/kg-dry)	@ pH	VB-2 (mg/kg-dry)	@ pH	VB-3 (mg/kg-dry)	@ pH
Aluminum	Al	2,200	2	2,300	2	2,500	2
Antimony	Sb	0.22	13	0.15	13	0.20	13
Arsenic	As	43	13	46	13	51	13
Barium	Ba	59	2	75	2	74	2
Beryllium	Be	0.50	2	0.48	2	0.55	2
Boron	B	8.5	2	13	2	16	2
Bromide	Br^-	<0.064	NA	<0.064	NA	<0.064	NA
Cadmium	Cd	0.23	2	0.20	2	0.21	2
Calcium	Ca	1,500	2	1,800	2	1,700	2
Carbon, Inorganic	DIC	950	13	580	13	560	13
Carbon, Organic	DOC	160	13	93	13	130	13
Chloride	Cl^-	<0.064	4	<0.064	9	<0.064	7
Chromium	Cr	6.8	2	2.7	2	3.2	2
Cobalt	Co	2.2	2	0.36	2	0.35	2
Copper	Cu	12	2	11	2	52	2
Fluoride	F^-	19	2	20	2	28	2
Iron	Fe	110	2	110	2	110	2
Lead	Pb	3.6	2	0.82	2	0.99	2
Lithium	Li	1.1	2	1.3	2	1.6	2
Magnesium	Mg	290	2	280	2	320	2
Manganese	Mn	50	2	19	2	14	2
Molybdenum	Mo	3.6	13	0.48	13	0.55	13
Nickel	Ni	3.6	2	0.85	2	0.86	2
Nitrate	NO_3^-	11	12	8.3	9	3.3	9
Phosphate	PO_4^{-3}	470	2	140	2	130	2
Phosphorus	P	110	2	200	2	210	2
Potassium	K	140	2	200	2	220	2
Selenium	Se	1.4	13	0.87	13	1.5	13

Table 4-7 (continued)
Available Content for Composite Samples VB-1, VB-2, and VB-3 Based on the Maximum Concentration from EPA Method 1313

Analyte	Symbol	VB-1 (mg/kg-dry)	@ pH	VB-2 (mg/kg-dry)	@ pH	VB-3 (mg/kg-dry)	@ pH
Silicon	Si	1,400	2	1,500	2	1,400	2
Sodium	Na	31	2	36	2	35	2
Strontium	Sr	59	2	56	2	62	2
Sulfate	SO_4^{-2}	450	2	160	2	160	2
Sulfur	S	770	13	39	13	46	13
Thallium	Tl	0.74	2	0.21	2	0.27	2
Titanium	Ti	18	2	46	2	50	2
Uranium	U	1.3	2	0.38	2	0.41	2
Vanadium	V	24	2	17	2	19	2
Zinc	Zn	5.1	2	4.4	2	5.5	2

Notes: NA the target pH not available since all concentrations are less than MDL.

Table 4-8
Ratio of Available Content (EPA 1313) to Total Content (EPA 3052) for Composite Samples VB-1, VB-2, and VB-3

		Available Content / Total Content (-)		
Analyte	**Symbol**	**VB-1**	**VB-2**	**VB-3**
Aluminum	Al	0.17	0.18	0.19
Antimony	Sb	0.06 J*	0.05 J*	0.04 J*
Arsenic	As	0.47 B*	0.42 B*	0.46 B*
Barium	Ba	0.16	0.21	0.19
Beryllium	Be	0.08	0.08	0.08
Cadmium	Cd	0.10	0.18	0.12
Calcium	Ca	1.6	1.8 F1*	1.8
Chromium	Cr	0.049	0.019	0.021
Cobalt	Co	0.055	0.011	0.010
Copper	Cu	0.092	0.085	0.26
Iron	Fe	0.010	0.001	0.002
Lead	Pb	0.068	0.018	0.016
Lithium	Li	0.006	0.008	0.008
Magnesium	Mg	2.6 J*	2.5 J, F1*	2.7 J*
Manganese	Mn	0.20	0.090	0.082
Molybdenum	Mo	0.44	0.11	0.11
Nickel	Ni	0.036	0.010	0.01
Potassium	K	0.012	0.013	0.015
Selenium	Se	0.23 J*	0.20 J*	0.28 J*
Sodium	Na	0.022	0.021	0.019
Strontium	Sr	0.42	0.56 F1*	0.52
Titanium	Ti	0.002	0.006	0.006
Vanadium	V	0.10	0.071	0.073
Zinc	Zn	0.043	0.040	0.046

Notes:
- * total content data indicated an analytical anomaly (see error codes below).
- B the compound was found in the blank and sample of the total content analysis extract.
- F1 the matrix spike recovery for the total content analysis extract is outside of acceptance limits.
- J the total content result was less than the LLOQ but greater than or equal to the MDL; estimated value.

Comparison of pH-Dependent Leaching from Individual Split Spoon Samples to Composite Samples for Each Borehole

pH-dependent leaching data (EPA 1313) from composite samples was compared to laboratory extractions of individual split spoon materials to illustrate how the composite samples represented the strata of ash materials. Bulk materials collected by split spoon were homogenized within the vacuum-sealed bag prior to testing using a modified, 3-point version of EPA 1313. The 3-point version of EPA 1313 that was applied to individual split spoon samples included extractions at $1.5 \leq pH \leq 2$, the natural pH, and $pH = 9 \pm 0.5$, and the results were used as comparators to the full-range testing conducted on the composite samples. Example results are provided in Figure 4-14 and Figure 4-15 for major and trace constituents, respectively. The complete set of testing results are presented in Appendix D.2.

The data in these figures indicate the extent of agreement between individual split spoon data (individual points) and EPA 1313 testing of composites (continuous lines). The variability in leaching properties within a borehole (individual split spoons) is consistent with the laboratory and field extraction variability discussed above regarding variability of extraction tests within a borehole. The variability between composites and individual samples for trace constituents is dominated by the variability of composition for these constituents within the individual grab samples. When analyses approach quantitation limits (e.g., for trace constituents or LSP curves near the LLOQ), the variability is likely attributed to the measurement uncertainty.

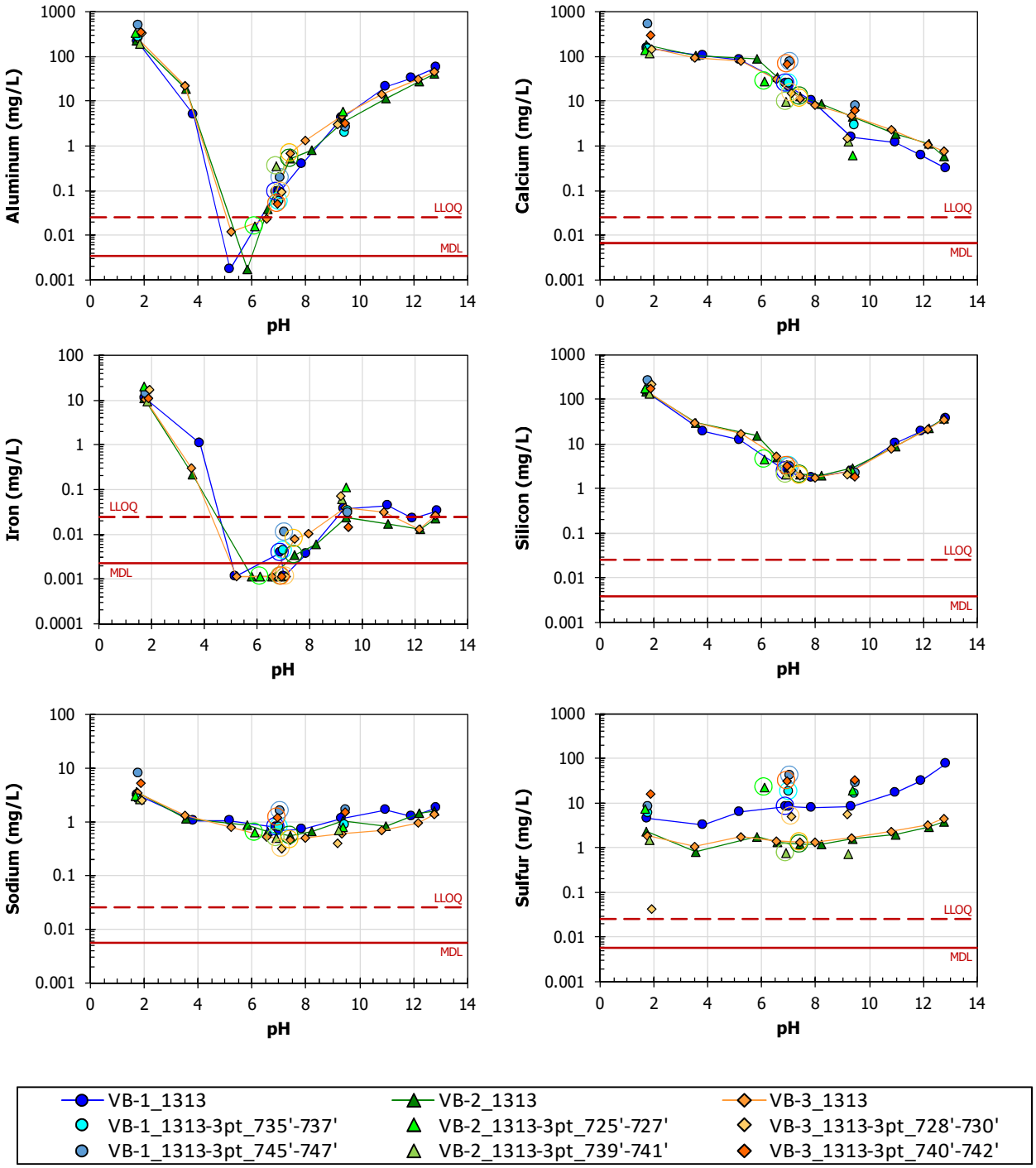

Figure 4-14
Comparison of pH-dependent leaching data for major constituents using individual split spoon samples (3-pt EPA 1313) and borehole composite materials (EPA 1313)

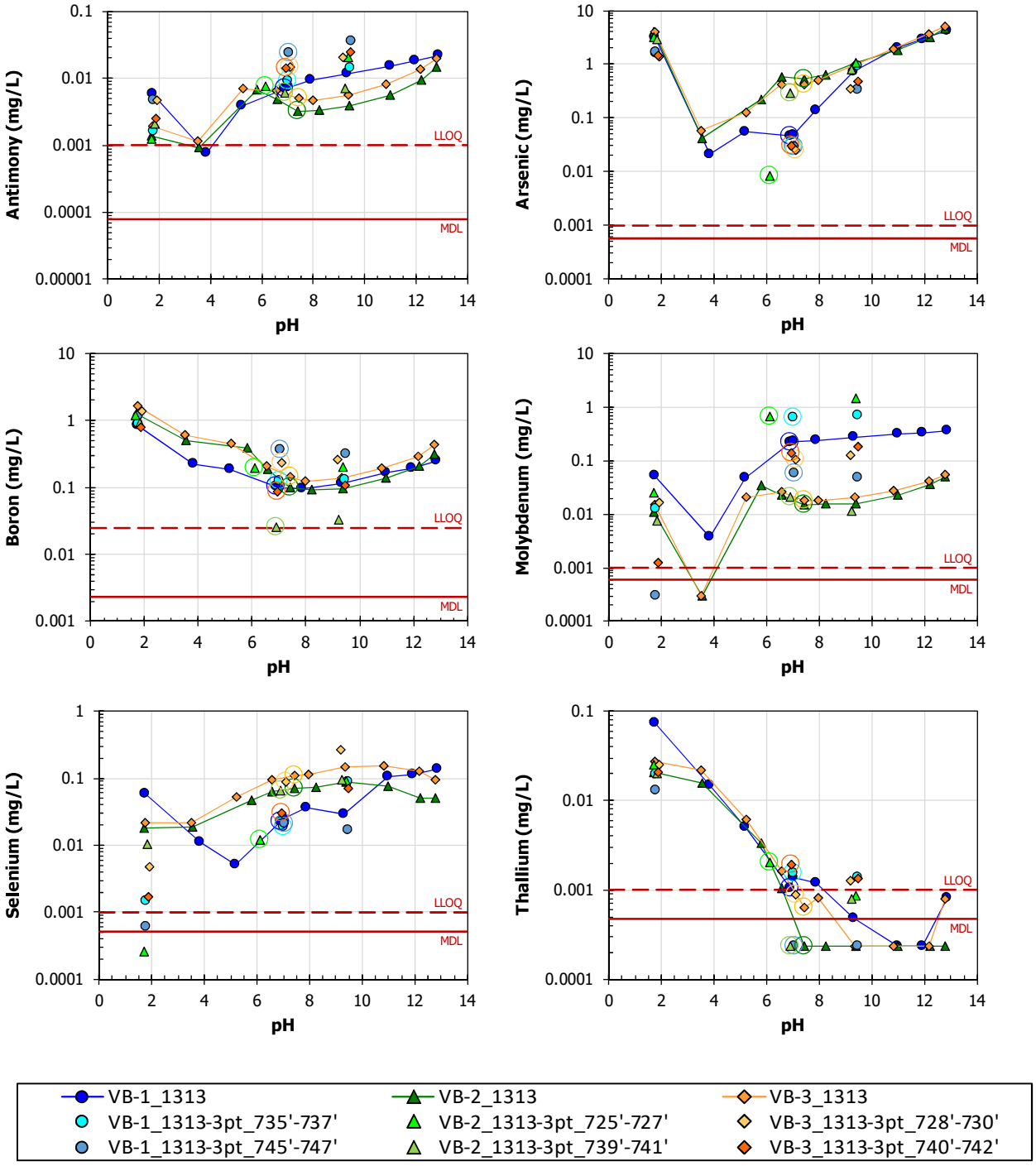

Figure 4-15
Comparison of pH-dependent leaching data for trace constituents using individual split spoon samples (3-pt EPA 1313) and borehole composite materials (EPA 1313)

L/S-Dependent Leaching Test Results

When conducted at low flow rate, the results of column tests (e.g., EPA 1314) indicate how the LSP of constituents changes as the cumulative L/S (i.e., the total amount of water passing through a column to the mass of solid in the column) increases. As soluble minerals dissolve and constituents are eluted from the material, different minerals control the release of constituents and the ionic strength of the eluate changes. In scenarios where L/S can be related to the rate of infiltration, column test data can provide an estimate of leaching concentration as a function of time (Garrabrants et al., 2019a; b).

Examples of typical L/S-dependent behavior from EPA 1314 conducted on the VB-1 composite are shown in Figure 4-16. In this figure, eluate concentration (mg/L) is presented in the left column while mass release (mg/kg-dry), determined by the accumulated interval mass released up through a cumulative L/S value, is shown in the right column. Interval mass release is calculated by multiplying the eluate concentration by the associated interval L/S value. In mass release graphs, the gray dashed line indicates the mass release proportional to the cumulative L/S expected if concentration is controlled by constant solubility.

- The eluate concentrations for Ba (Figure 4-16, top) are constant as a function of L/S and, thus, the mass release is proportional to the cumulative L/S and the mass release curve follows the solubility indicator line. This L/S-dependent behavior is consistent with a constituent that has solubility-controlled LSP. In the composites, As, F^-, Li, Sb, and V show the similar solubility-controlled LSP based on EPA 1314 data as Ba.
- For many constituents in the composite samples (Cd, Co, Cr, Ni, Se, Tl, and Zn), the L/S-dependent leaching data indicated that the constituent is quickly depleted from the matrix. For Tl (Figure 4-16, middle), the eluate concentration is a strong function of L/S but drops below the MDL when L/S increases beyond approximately L/S=3 L/kg-dry. This behavior is characteristic when the available content has been depleted.
- The L/S-dependent leaching of Cl^- (Figure 4-16, bottom) is an example of rapid release of a soluble fraction of the available content without depletion. This differs from the example behavior of Cd in that, after an initial "wash off" of a highly soluble fraction, leaching concentrations are detectable and relatively constant, suggesting a solubility-controlled fraction. Similar behavior was observed for B, Ca, Mo, and SO_4^{-2} in composite samples.
- Elements where EPA 1314 eluate concentrations were not detected include Be, Br^-, Cu, Fe, and Pb.

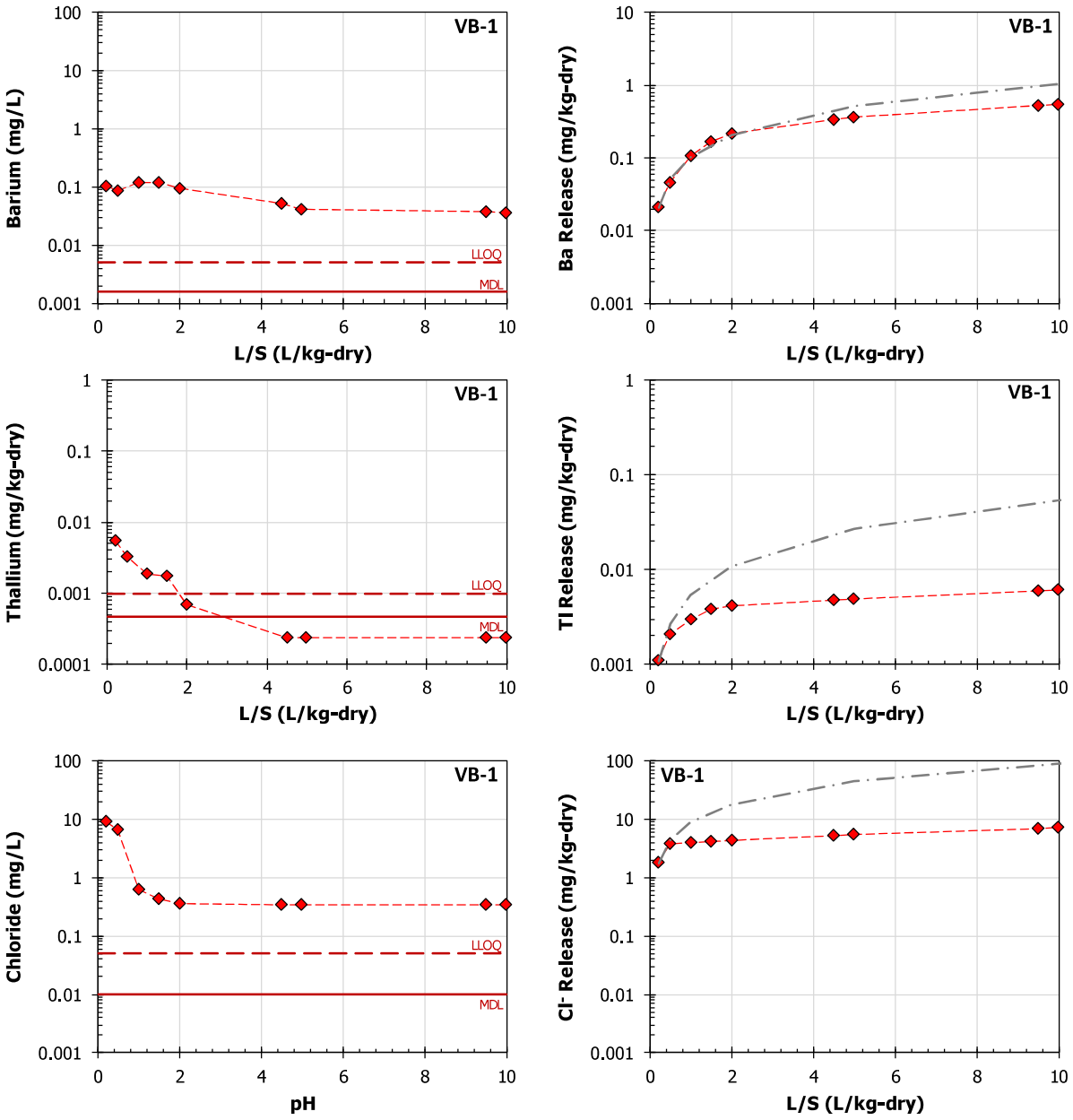

Figure 4-16
Example EPA 1314 test results from VB-1, showing a solubility-controlled constituent (barium), depletion of the available content (thallium), and wash-off of a soluble constituent fraction without depletion (chloride)

Traditional Extraction Test Results

The calculated L/S and measured pH from the extractions using the traditional leaching tests (TCLP, SPLP, and ASTM) are presented in Table 4-9.

Table 4-9
Liquid-to-Solid Ratio and Measured Extraction pH for Traditional Leaching Tests

Material	TCLP		SPLP		ASTM	
	L/S (mL/g-dry)	pH	L/S (mL/g-dry)	pH	L/S (mL/g-dry)	pH
VB-1	22.9	4.99	22.9	6.39	27.3	6.71
VB-2	22.1	5.00	22.1	6.89	28.1	7.27
VB-3	23.2	4.95	23.2	6.94	26.9	7.17

The amount of extraction fluid for ASTM is determined as the mass of the "as received" test material in grams divided by the test-specific L/S of 20 mL/g. The resultant L/S on a dry basis is greater than 20 because of the water inherent in the pores of the "as received" material. The procedures for TCLP and SPLP require a pressure filtration preconditioning of the test sample to remove excess liquid, which is analyzed separately. The extraction fluid is based on the mass of pressure-filtered solid material in grams divided by the same L/S of 20 mL/g. Therefore, the calculated L/S for TCLP and SPLP is lower than the L/S for the ASTM test that includes extra water.

The measured pH for ASTM, which uses DIW as an extraction fluid, is consistent with the natural pH (1313) and own pH (1313_L/S1) of the composites at VB-1, VB-2, and VB-3 reported in Table 4-6. The slight decrease in ASTM extraction pH compared to the natural pH (e.g., VB-1 pH_{ASTM}=6.71 versus pH_{Nat}= 6.91) may be attributed to the higher ASTM extraction L/S. For SPLP, the measured pH is slightly lower than the ASTM pH, consistent with the small amount of acid used in the extraction fluid. The stability of the measured pH for TCLP extracts across different composites reflects the buffering provided by the organic acetic acid.

The eluate constituent concentrations for TCLP, SPLP, and ASTM tests are presented in Table 4-10, Table 4-11, and Table 4-12, respectively. Since pH is an important factor for solubility-controlled LSP, these tables also include the final eluate pH. Recording of eluate pH allows for comparison of the results of these traditional tests to the pH- and L/S-dependent LEAF test results. In general, SPLP and ASTM concentrations were comparable to each other but were lower than TCLP concentrations due to the lower pH of TCLP eluates. Exceptions for this site (which may not be generalizable) include As, Mo, and SO_4^{-2}, where similar concentrations were measured in all three procedures, and PO_4^{-2}, Se, and V, where SPLP and ASTM eluates had higher concentration than TCLP eluates. All of these observations are consistent with the pH-dependent LSP curves discussed above.

Table 4-10
TCLP (EPA Method 1311) Eluate Concentrations

Analyte	Symbol	VB-1 (mg/L)	VB-2 (mg/L)	VB-3 (mg/L)
	pH	**4.99**	**5.00**	**4.95**
Aluminum	Al	0.90	0.78	0.89
Antimony	Sb	0.0038	0.0033	0.0047
Arsenic	As	0.055	0.18	0.17
Barium	Ba	2.0	2.1	2.0
Beryllium	Be	0.0015	0.00085 J	0.00084 J
Boron	B	0.37	0.47	0.48
Bromide	Br^-	ND	ND	ND
Cadmium	Cd	0.0039	0.0035	0.0040
Calcium	Ca	47	57	40
Carbon, Inorganic	DIC	0.19	0.24	0.22
Carbon, Organic	DOC	2,600	2,600	2,600
Chloride	Cl^-	640	640	630
Chromium	Cr	0.0026	0.0063	0.0085
Cobalt	Co	0.029	0.0066	0.0054
Copper	Cu	0.36	0.093	0.93
Fluoride	F^-	ND	ND	ND
Iron	Fe	0.028	0.0047 J	0.0028 J
Lead	Pb	ND	ND	ND
Lithium	Li	ND	ND	ND
Magnesium	Mg	7.6	5.0	3.2
Manganese	Mn	1.6	0.48	0.32
Molybdenum	Mo	0.024	0.0075	0.0084
Nickel	Ni	0.021	0.0042	0.0061
Nitrate	NO_3^-	1.9	2.0	1.8
Phosphate	PO_4^{-3}	ND	ND	ND
Phosphorus	P	0.030	0.15	0.13
Potassium	K	2.8	2.7	2.9
Selenium	Se	0.0033	0.011	0.019

Table 4-10 (continued)
TCLP (EPA Method 1311) Eluate Concentrations

Analyte	Symbol	VB-1 (mg/L)	VB-2 (mg/L)	VB-3 (mg/L)
	pH	**4.99**	**5.00**	**4.95**
Silicon	Si	7.0	11	10
Sodium	Na	590	580	590
Strontium	Sr	1.0	1.2	1.4
Sulfate	SO_4^{-2}	10	8.4	7.9
Sulfur	S	2.2	0.84	1.3
Thallium	Tl	0.0072	0.0059	0.0087
Titanium	Ti	ND	ND	0.015 J
Uranium	U	0.0061	0.0028	0.0054
Vanadium	V	0.010	0.012	0.020
Zinc	Zn	0.36	0.39	0.40

Notes: J the result is less than the LLOQ but greater than or equal to the MDL; estimated concentration.

ND the compound was not detected at a concentration above the MDL.

Table 4-11
SPLP (EPA Method 1312) Eluate Concentrations

COPC	Symbol	VB-1 (mg/L)	VB-2 (mg/L)	VB-3 (mg/L)
	pH	**6.39**	**6.89**	**6.94**
Aluminum	Al	0.0080 J	0.23	0.20
Antimony	Sb	0.0020	0.0015	0.0025
Arsenic	As	0.027	0.21	0.16
Barium	Ba	0.19	0.12	0.13
Beryllium	Be	ND	ND	ND
Boron	B	0.084	0.097	0.11
Bromide	Br^-	ND	ND	ND
Cadmium	Cd	ND	ND	ND
Calcium	Ca	13	11	9.2
Carbon, Inorganic	DIC	2.2	3.9	3.4
Carbon, Organic	DOC	2.1	3.6	2.9
Chloride	Cl^-	1.9	1.8	2.2
Chromium	Cr	ND	ND	ND

Table 4-11 (continued)
SPLP (EPA Method 1312) Eluate Concentrations

COPC	Symbol	VB-1 (mg/L)	VB-2 (mg/L)	VB-3 (mg/L)
	pH	**6.39**	**6.89**	**6.94**
Cobalt	Co	ND	ND	ND
Copper	Cu	ND	ND	ND
Fluoride	F^-	ND	ND	ND
Iron	Fe	ND	ND	ND
Lead	Pb	ND	ND	ND
Lithium	Li	ND	ND	ND
Magnesium	Mg	0.65	0.54	0.57
Manganese	Mn	0.015 J	0.0044 J	0.0067 J
Molybdenum	Mo	0.038	0.0077	0.0091
Nickel	Ni	ND	ND	ND
Nitrate	NO_3^-	6.0	5.9	6.5
Phosphate	PO_4^{-3}	ND	0.32	0.18
Phosphorus	P	0.019 J	0.083	0.052
Potassium	K	0.32	0.33	0.34
Selenium	Se	0.20	0.042	0.056
Silicon	Si	1.5	1.2	1.2
Sodium	Na	0.64	0.58	0.34
Strontium	Sr	0.37	0.40	0.42
Sulfate	SO_4^{-2}	13	4.7	7.1
Sulfur	S	4.4	1.6	2.0
Thallium	Tl	ND	ND	ND
Titanium	Ti	ND	ND	ND
Uranium	U	ND	ND	ND
Vanadium	V	0.016	0.038	0.042
Zinc	Zn	ND	ND	ND

Notes: J the result is less than the LLOQ but greater than or equal to the MDL; estimated concentration.
ND the compound was not detected at a concentration above the MDL.

Table 4-12
ASTM (ASTM D3987) Eluate Concentrations

COPC	Symbol	VB-1 (mg/L)	VB-2 (mg/L)	VB-3 (mg/L)
	pH	**6.71**	**7.27**	**7.17**
Aluminum	Al	ND	0.24	0.26
Antimony	Sb	0.0019	0.0011	0.0022
Arsenic	As	0.029	0.17	0.15
Barium	Ba	0.19	0.11	0.12
Beryllium	Be	ND	ND	ND
Boron	B	0.041	0.046	0.060
Bromide	Br^-	ND	ND	ND
Cadmium	Cd	ND	ND	ND
Calcium	Ca	11	8.3	7.2
Carbon, Inorganic	DIC	5.7	6.7	6.6
Carbon, Organic	DOC	2.5	3.9	3.5
Chloride	Cl^-	0.40	0.513	ND
Chromium	Cr	ND	ND	ND
Cobalt	Co	ND	ND	ND
Copper	Cu	ND	ND	ND
Fluoride	F^-	ND	ND	ND
Iron	Fe	ND	ND	ND
Lead	Pb	ND	ND	ND
Lithium	Li	ND	ND	ND
Magnesium	Mg	0.81	0.65	0.66
Manganese	Mn	0.014 J	0.0038 J	0.0061 J
Molybdenum	Mo	0.041	0.0058	0.0089
Nickel	Ni	ND	ND	ND
Nitrate	NO_3^-	0.12	0.15	0.17
Phosphate	PO_4^{-3}	0.082 J	0.26	0.16
Phosphorus	P	0.021 J	0.068	0.045
Potassium	K	0.37	0.34	0.36
Selenium	Se	0.024	0.029	0.050

Table 4-12 (continued)
ASTM (ASTM D3987) Eluate Concentrations

COPC	Symbol	VB-1 (mg/L)	VB-2 (mg/L)	VB-3 (mg/L)
	pH	**6.71**	**7.27**	**7.17**
Silicon	Si	1.5	1.0	1.2
Sodium	Na	0.67	0.50	0.46
Strontium	Sr	0.36	0.33	0.37
Sulfate	SO_4^{-2}	19	5.1	4.5
Sulfur	S	15	1.8	1.6
Thallium	Tl	ND	ND	ND
Titanium	Ti	ND	ND	ND
Uranium	U	ND	0.00056 J	0.00052 J
Vanadium	V	0.017	0.030	0.038
Zinc	Zn	ND	ND	ND

Notes: J the result is less than the LLOQ but greater than or equal to the MDL; estimated concentration.

ND the compound was not detected at a concentration above the MDL.

Comparison of Traditional and LEAF Test Results

When the pH and L/S of leaching tests are recorded, the test results from different leaching tests can be compared based on pH- or L/S-dependence. An example comparison is shown in Figure 4-17 for SO_4^{-2} leaching from the VB-1 composite. Similar comparisons for all constituents are presented in Appendix E.

Figure 4-17 presents data as a function of pH on the left and as a function of L/S on the right. For a constituent with available content-limited LSP, for example sulfate, the traditional leaching test data are consistent with LEAF test results considering the shift in pH (TCLP) and the higher L/S for the traditional tests.

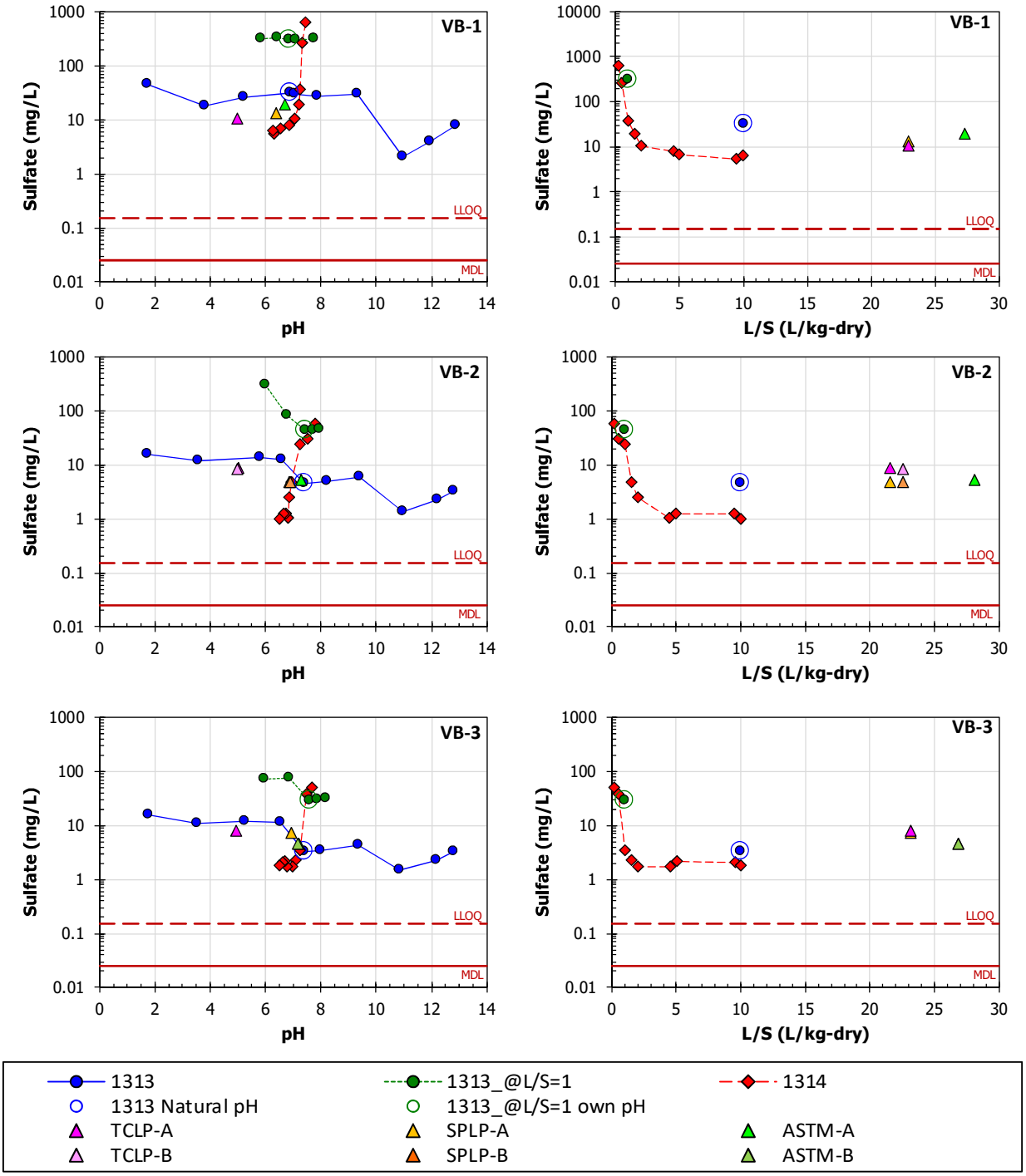

Figure 4-17
Comparison of sulfate concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

Groundwater, Porewater, and Subsurface Gas Monitoring

Measured field parameters for groundwater and porewater sampling as well as graphical presentation of groundwater and porewater concentrations are provided in Appendix F.1. These data represent the sampling period from September 2018 through September 2019.

Groundwater and Porewater Field Parameters

Plots of field measurements are shown in Figure 4-18 and Figure 4-19. Within each bar chart, data for groundwater sampled at the upgradient well (AD1) and downgradient well (6AR) are shown in light and dark gray, respectively, while data for porewater from the PAPs (VB-1, VB-2, and VB-3) are shown as blue, green, and gold bars, respectively.

The data in Figure 4-18 show that the water table elevation, pH, and electrical conductivity remain relatively constant over time at each sample point. No samples were collected in November due to a scheduling conflict. The mean water table at the upgradient well (773.4 ft AMSL) is approximately 30 feet higher in elevation than the mean water table of the three PAPs (741.6 ft AMSL) or the mean water table at the downgradient well (738.5 ft AMSL). The pH of the groundwater at the upgradient well is somewhat more alkaline ($pH_{ave\text{-}AD1}$=8.6±0.2) than the porewater in the PAPs ($pH_{ave\text{-}VB\text{-}1}$=8.1±0.1, $pH_{ave\text{-}VB\text{-}2}$=7.8±0.5, $pH_{ave\text{-}VB\text{-}3}$=7.7±0.4) and considerably more alkaline than in the downgradient well ($pH_{ave\text{-}6AR}$=4.8±0.1).

Figure 4-19 presents measured values of water temperature, ORP, and DO. Of these, water temperature and ORP show a seasonal trend. The decrease in ORP in the late summer and fall months may indicate an increase in biological activity. Although there is significant variability in the measured value, the mean dissolved oxygen in the downgradient well ($DO_{ave\text{-}6AR}$=1.0±0.5 mg/L) is somewhat lower than in the PAPs ($DO_{ave\text{-}VB\text{-}1}$=1.4±0.7 mg/L, $DO_{ave\text{-}VB\text{-}2}$=1.4±0.4 mg/L, $DO_{ave\text{-}VB\text{-}3}$=1.7±0.3 mg/L) and notably lower than in the upgradient well ($DO_{ave\text{-}AD1}$=2.6±0.5 mg/L). The expected value for dissolved oxygen at equilibrium with atmospheric oxygen at a temperature of 20 ºC is approximately 9.1 mg/L (USGS, 1998).

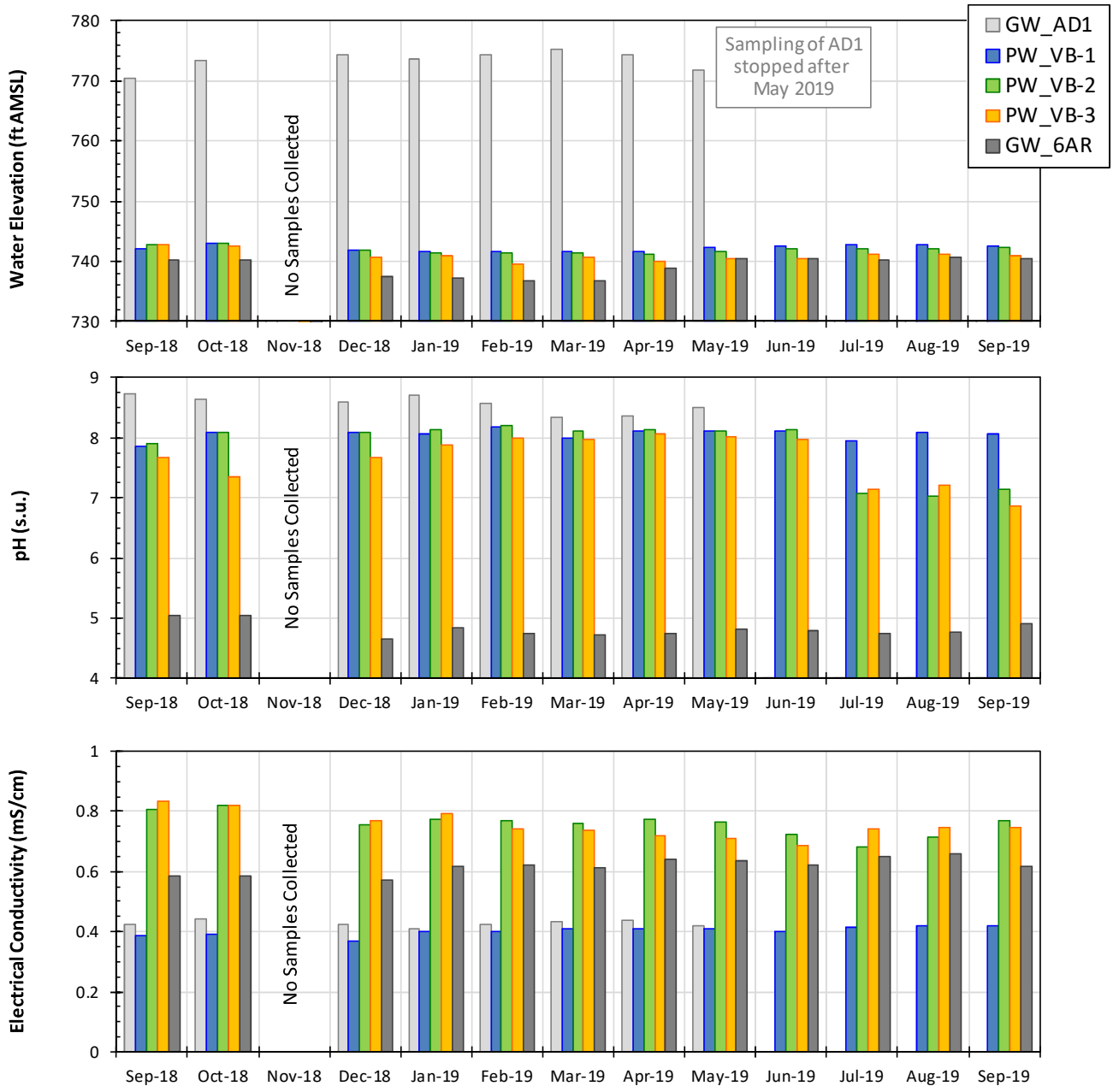

Figure 4-18
Groundwater and porewater field parameters from monthly sampling (elevation, pH, and EC)

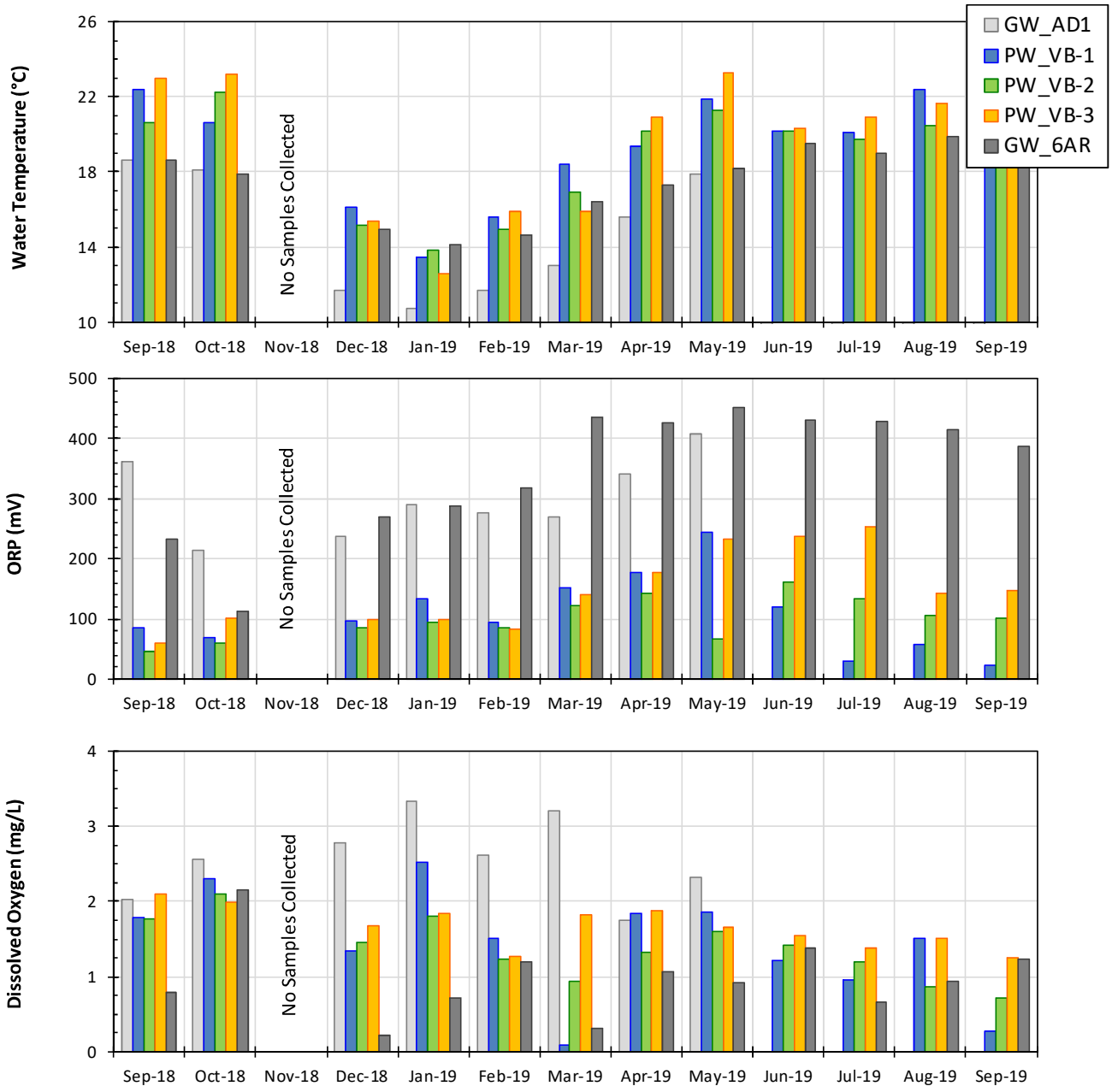

Figure 4-19
Groundwater and porewater field parameters from monthly sampling (temperature, ORP, and DO)

Concentrations in Groundwater and Porewater

Monthly analysis of groundwater wells and PAPs focused on 22 constituents, including 17 from 40 CFR 257 (As, B, Ba, Be, Ca, Cd, Cl^-, Co, Cr, F^-, Li, Mo, Pb, Sb, Se, SO_4^{-2} and Tl). Five additional constituents that were analyzed were Cu, Fe, Ni, V, and Zn. Examples of the results for selected constituents are presented in Figure 4-20 and Figure 4-21, while the graphical results for all 22 constituents are presented after the field parameter data tables in Appendix F.1.

Overall, concentrations in the downgradient groundwater well at 6AR are relatively low. A comprehensive review of impacts to groundwater based on one downgradient well (6AR) and one upgradient well (AD1) is not sufficiently robust to determine with confidence whether or not the groundwater quality at 6AR represents a release from the closed impoundment. Therefore, the discussion that follows allows for either possibility as the relationship between porewater and downgradient groundwater is explored. Table 4-13 groups the observed concentrations from monthly analysis to express the relationships between groundwater across the site (6AR vs. AD1) and porewater concentrations relative to downgradient groundwater (PAPs vs. 6AR). Of the 22 constituents analyzed, Pb, Sb, Tl, and V are not included in the table because the concentrations of these constituents were below the MDL in both porewater and groundwater.

Table 4-13
Relationships Between Upgradient Groundwater (AD1), Downgradient Groundwater (6AR), and Porewater at PAPs (VB-1, VB-2, and VB-3)

	Downgradient > Upgradient	Downgradient ≤ Upgradient
Porewater < Downgradient	Be**, Cd, Cr, Co, Fe,Ni, Se**, SO_4^{-2}, Zn	none
Porewater > Downgradient	B, Ca, Cl^-, Li	As*, Ba, Cu*, F^-, Mo*

Notes
* Indicates that groundwater concentrations mostly below the MDL
** Indicates that porewater concentrations all below the MDL

The following are observations from this review.

- Nine constituents (Be, Cd, Cr, Co, Fe, Ni, Se, SO_4^{-2}, and Zn) have higher concentrations in the downgradient monitoring well than in the upgradient background well, suggesting that there is a source for these constituents affecting the downgradient groundwater. However, these nine constituents also have higher concentrations in the downgradient well than in the porewater (e.g., Cd, Co, and Se in Figure 4-20), suggesting that porewater from the dewatered impoundment is not the primary source of the observed downgradient groundwater concentration. These observations suggest limited relationship between the recent porewater concentration and the downgradient groundwater concentrations at this site.
- Five constituents (As, Ba, Cu, F^-, and Mo) have higher concentration in porewater than in the downgradient monitoring well, suggesting that porewater has the potential to affect downgradient groundwater quality. However, the downgradient monitoring well has a concentration that is similar to or lower than concentrations in the upgradient monitoring well (e.g., As and F^- in Figure 4-21), indicating no change in groundwater quality for these constituents. Furthermore, porewater concentrations for As, F^-, and Mo are orders-of-magnitude higher than in the upgradient monitoring well, yet there is no increase in downgradient concentration relative to the upgradient well. These data suggest limited relationship between porewater and downgradient concentrations at this site.
- Four constituents (B, Ca, Cl^-, Li) have higher concentration in porewater than in downgradient groundwater, and higher concentrations in downgradient groundwater than in upgradient groundwater (e.g., B in Figure 4-21), suggesting a possible relationship between

the concentration in the ash deposit porewater and the concentration of groundwater in the downgradient well for these constituents. Furthermore, all four of these constituents may be considered indicators of coal ash leachate, but only B and Cl^- can be considered reasonably non-interacting with materials underlying the ash deposit.

The overall temporal means of porewater concentrations for B and Cl^- were calculated and compared to the difference in the temporal means of groundwater concentrations (i.e., temporal mean at 6AR minus temporal mean at AD1). If porewater concentrations can be used as an indicator of downgradient groundwater concentrations, this ratio should be similar between constituents. At VB-2, the closest PAP to the downgradient well at 6AR,[2] the ratios for B and Cl^- were both 2.8, indicating a potential relationship. In contrast, the same ratio for Ca was lower (1.4), while the ratio for Li was significantly higher (12). Increased Ca in the downgradient groundwater monitoring well relative to the upgradient well may be a consequence of the change in groundwater pH from ca. 8.5 to 4.5 and equilibrium with aquifer solids and/or influence from the ash porewater in conjunction with cation exchange and sorption within the aquifer. Similarly, increased Li concentrations may be a result of the change in groundwater pH or other influences, as well as uncertainty because the lithium concentrations in downgradient groundwater are near, and in some samples below, analytical method quantitation limits.

Overall, these observations indicate that porewater concentrations are unreliable as an indicator of whether or not a constituent will have an elevated downgradient concentration relative to upgradient groundwater. B and Cl^- are considered conservative ions, and the similar ratios suggest that these constituents can be tracers for evaluation of porewater migration into groundwater. However, porewater concentrations are not predictors of future groundwater concentrations because of the potential for rapid attenuation in proximity to the boundary of the disposal unit.

[2] These ratios do not vary significantly if all three PAPs are averaged.

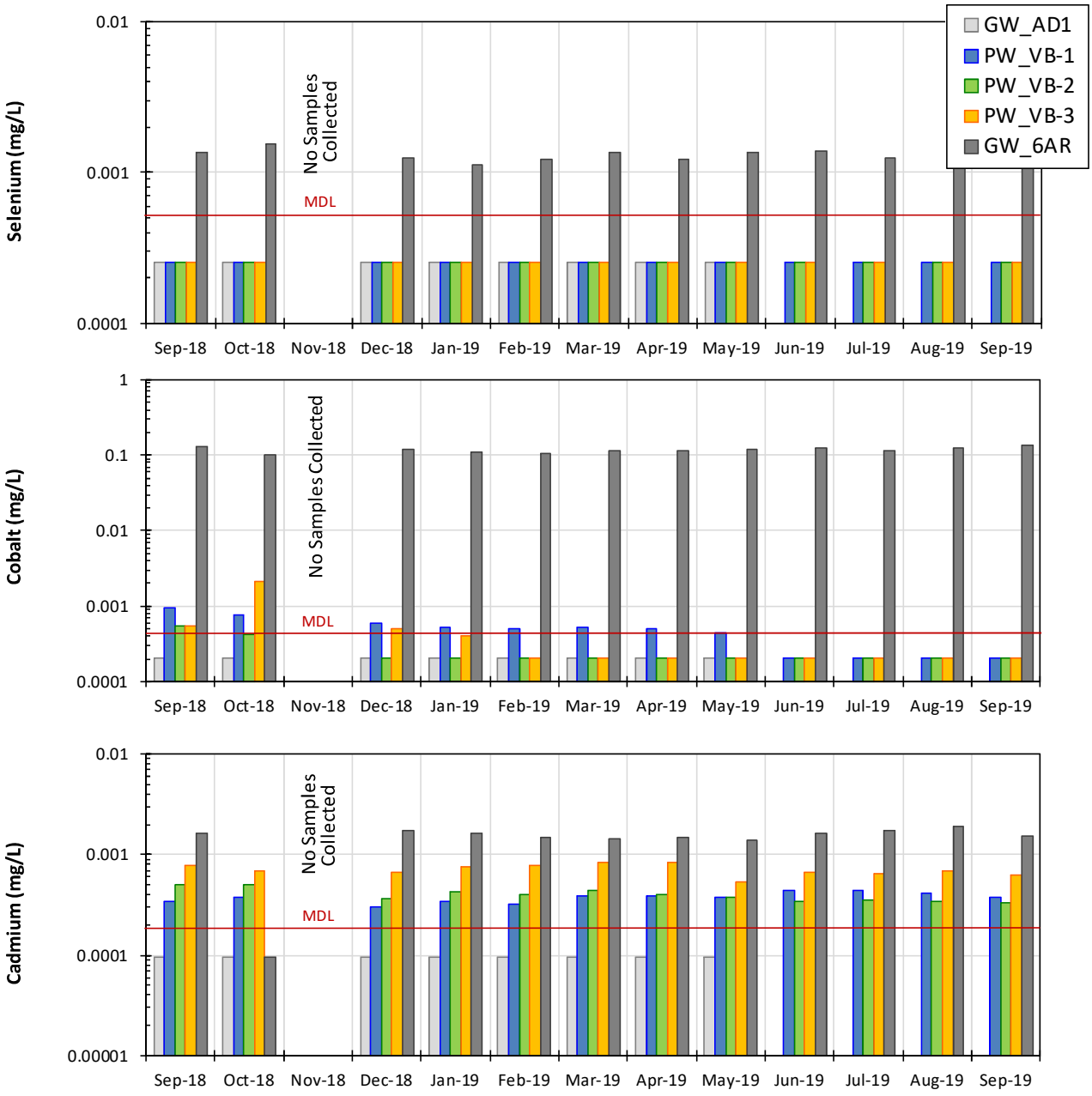

Figure 4-20
Groundwater and porewater monitoring from monthly sampling showing lower concentrations in ash deposit porewater (VB-1, VB-2, and VB-3) than in downgradient groundwater (6AR) (monitoring at AD1 was discontinued after May 2019)

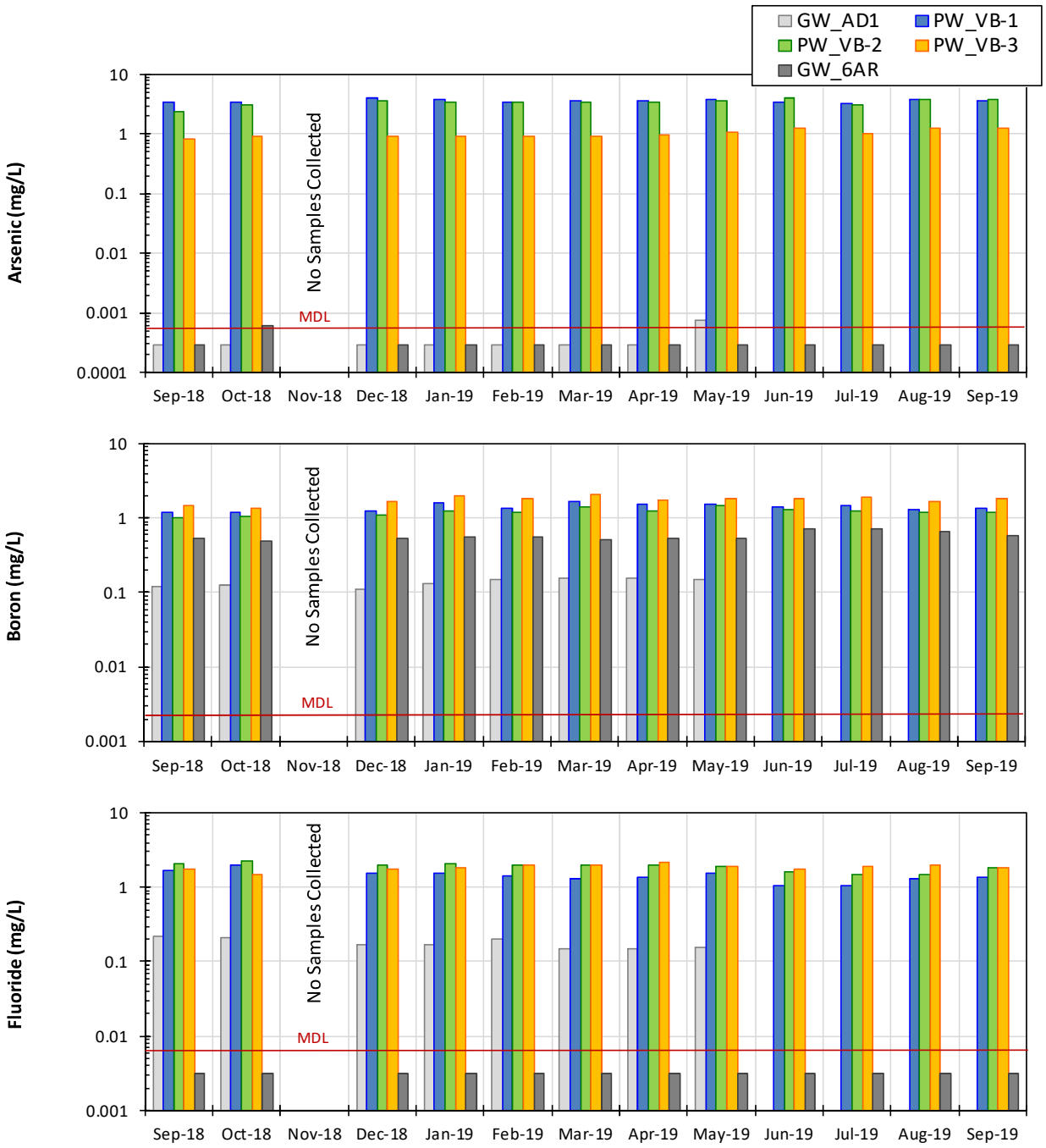

Figure 4-21
Groundwater and porewater monitoring from monthly sampling showing relatively higher concentrations in ash deposit porewater (VB-1, VB-2, and VB-3) than in groundwater (AD1 and 6AR) (monitoring at AD1 was discontinued after May 2019)

Variability in Porewater Concentrations

The temporal variability data for porewater parameters from monthly monitoring are presented as time-series plots as a function of date. The shapes of the time series show which porewater properties are relatively constant over the 13 months of sampling and which samples vary with

time. Time-series graphs for porewater parameters and constituents are presented in Appendix F.2. Examples of parameters showing temporal variability are presented in Figure 4-22 and Figure 4-23. In these figures, variability may be preliminarily attributed to one or more of several factors including (i) seasonal changes (e.g., temperature, redox conditions as seen by pH+pE; Figure 4-22), (ii) groundwater level changes due to infiltration and river intrusion (e.g., porewater level, decrease in pH of VB-2 and VB-3 during late summer 2019; Figure 4-22), and (iii) changing conditions shortly after closure of the impoundment (e.g., variability in cobalt, copper, iron, nickel, and zinc in VB-3 porewater during the summer of 2018; Appendix F.2). In comparison, many parameters remain relatively constant throughout this brief monitoring period (e.g., As, B, and Mo; Figure 4-23).

Concentrations from a PAP were deemed higher than other PAPs if consistently higher by a factor of 3 to 5 or more during all sample events. Overall, there was no pattern to spatial variability that applied to all monitored constituents, and concentrations between PAPs were usually within a factor of 10. However, there were patterns that were evident by element as listed below:

- No variability, all non-detect: Sb, Be, Pb, Se, Tl, V
- Little variability between PAPs: Ba, B, Ca, Cl, Cr, Co, Cu, F^-
- VB-1 and VB-2 consistently higher than VB-3: As, Li
- VB-3 consistently higher than VB-1 and VB-2: Cd, Fe, Mo, Ni, Zn
- VB-2 and VB-3 consistently higher than VB-1: SO_4

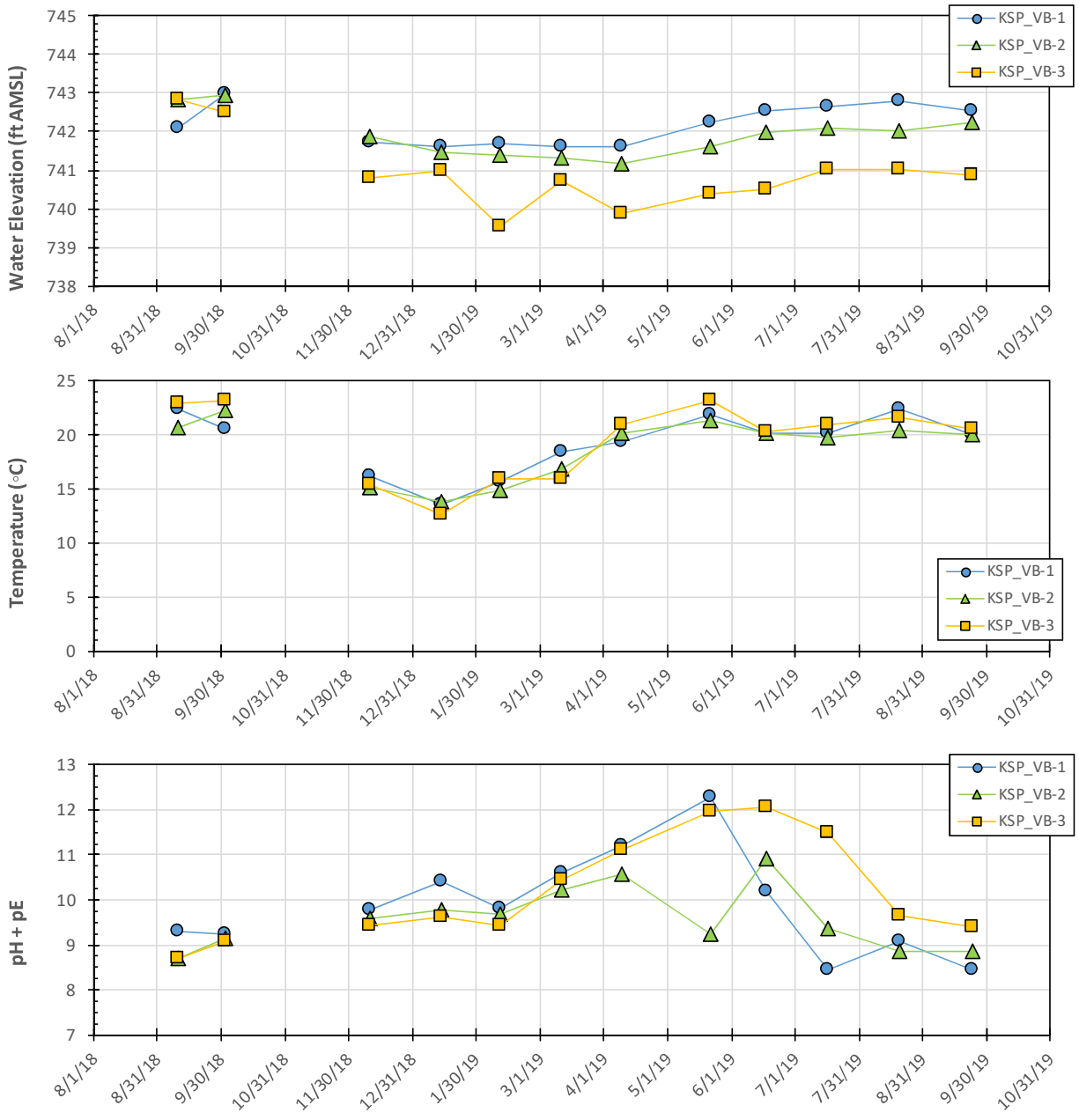

Figure 4-22
Example temporal porewater data showing seasonal or other variability: elevation, temperature, and pH+pE

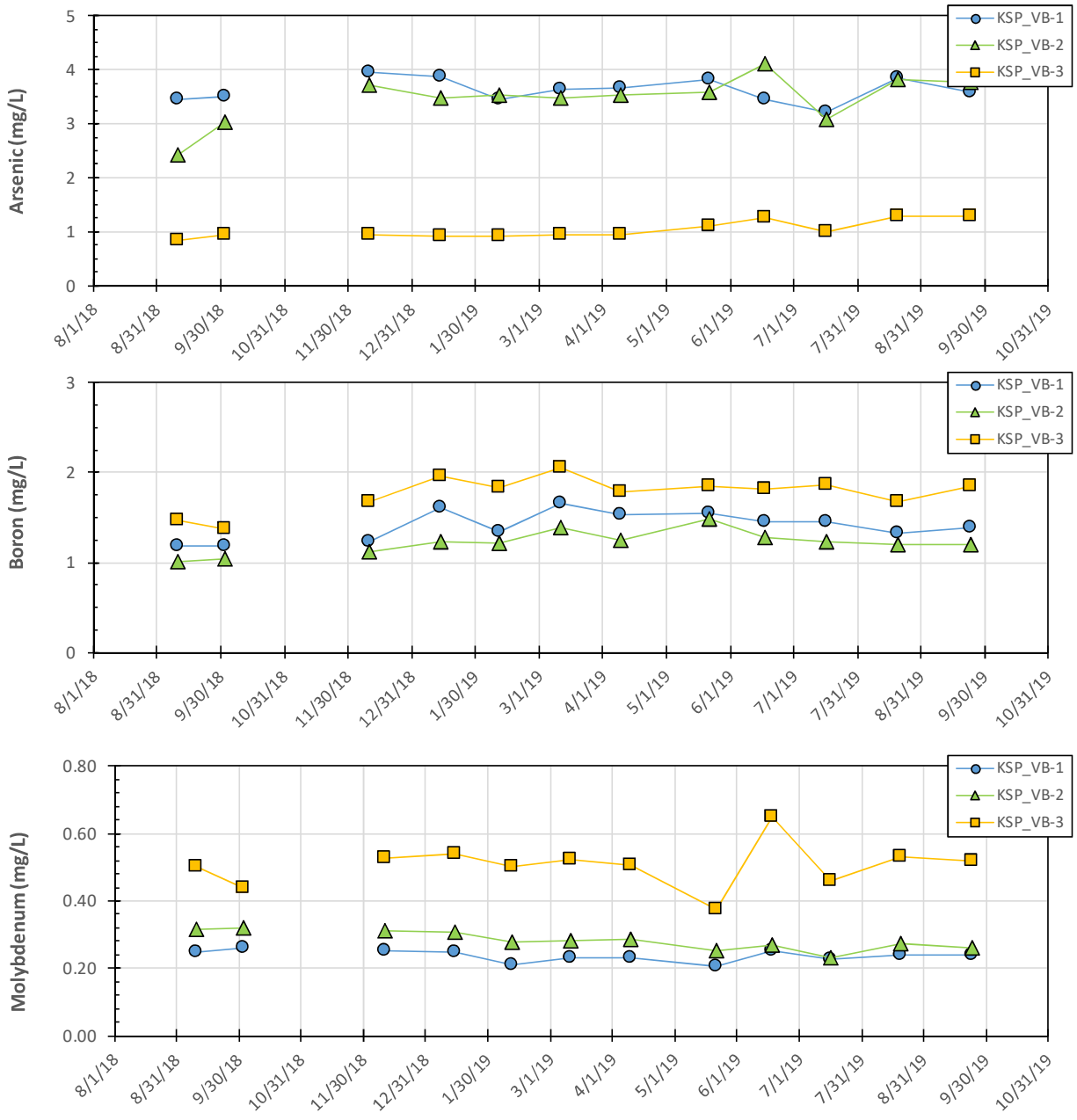

Figure 4-23
Example temporal porewater data showing relatively constant conditions: arsenic, boron, and molybdenum

Subsurface Gas Monitoring

The O_2, CO_2, CH_4, NH_4, and H_2S concentrations were measured in the three GAPs as presented in Figure 4-24 and Figure 4-25. Full tabular data for subsurface monitoring are presented along with graphical comparisons in Appendix F.3. Oxygen levels in the closed impoundment have been typically much less than in air, while CO_2 and CH_4 concentrations are often greater than the calibration limit of 5%. The concentrations of NH_4 and H_2S are sporadic but indicate elevated

concentrations up to 5 ppm for NH_4 and 30 ppm for H_2S. In general, these subsurface gas measurements imply a significant amount of biological activity that results in a stronger chemical reducing environment than indicated by the DO and ORP of the porewater samples.

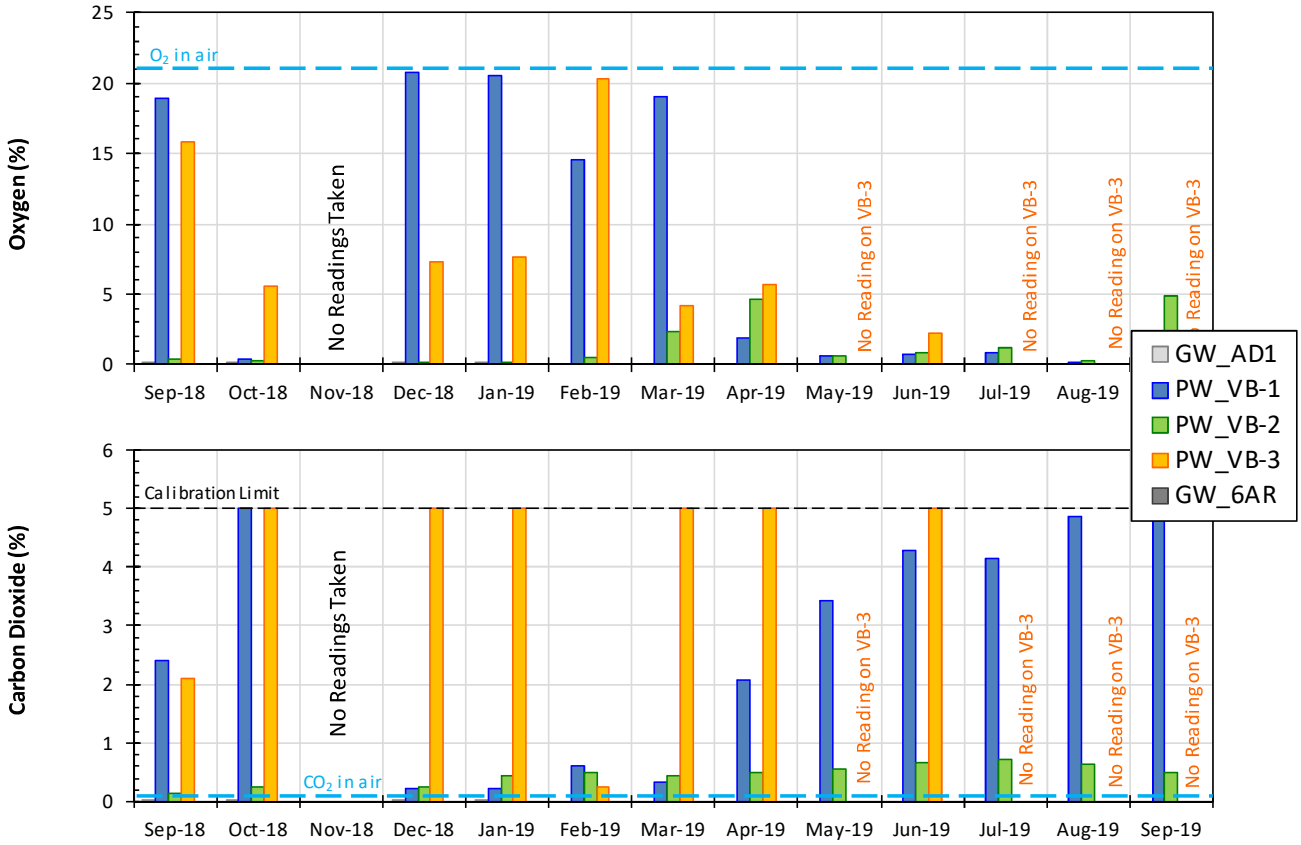

Figure 4-24
Concentration (%) of oxygen (O_2) and carbon dioxide (CO_2) from GAPs (VB-1, VB-2, and VB-3) in the subsurface of the closed ash impoundment

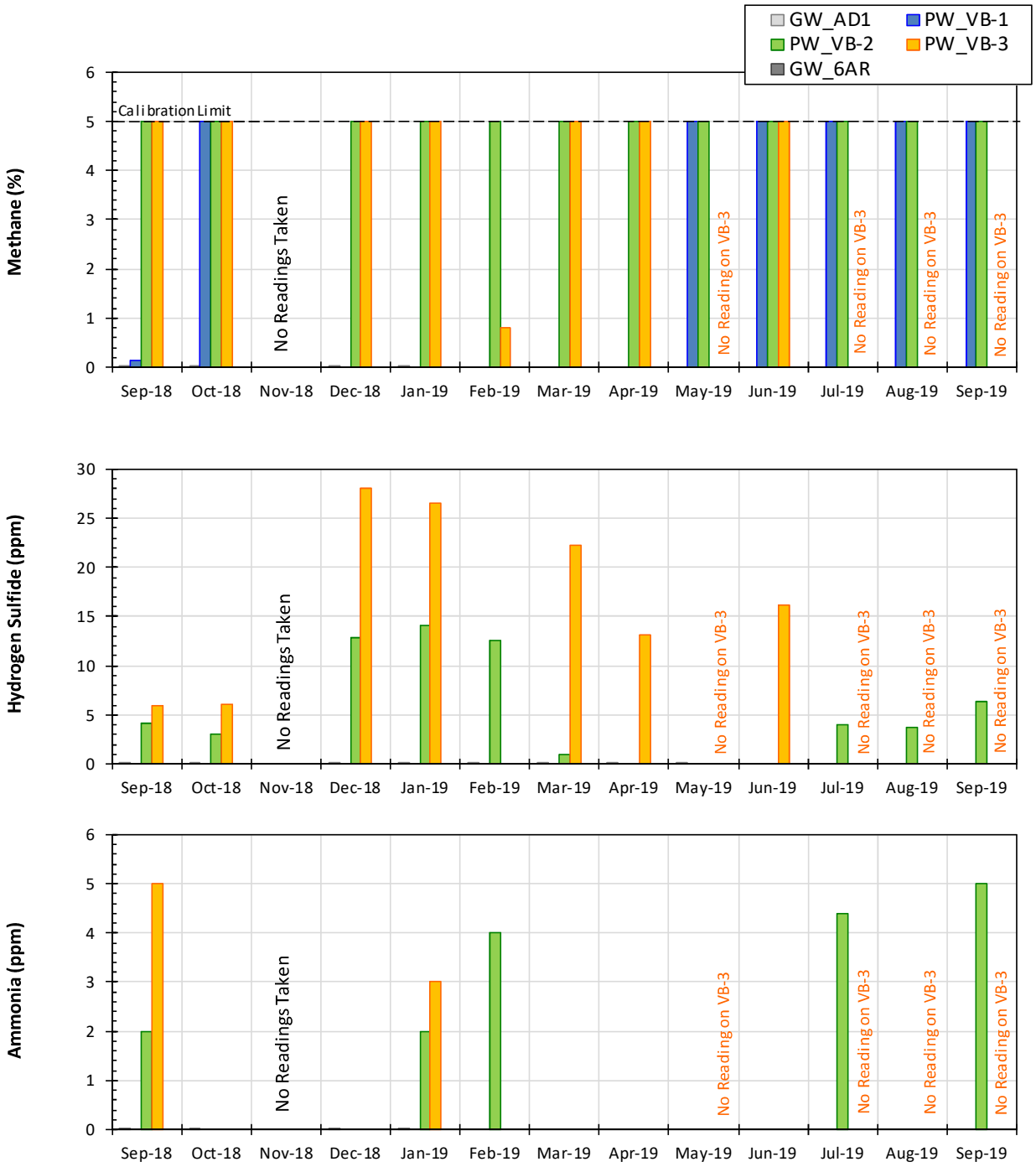

Figure 4-25
Concentrations of methane (CH_4), hydrogen sulfide (H_2S) and ammonia (NH_4) from GAPs (VB-1, VB-2, and VB-3) in the subsurface of the closed ash impoundment

Speciation of Arsenic, Iron, and Selenium Under Low Redox Conditions

At moderately low redox conditions, arsenic release can be associated with loss of HFO sorption sites as Fe(III) is reduced to Fe(II) at a pH+pE value of approximately 7 to 8. At these conditions, there would be a corresponding increase in the concentration of iron (Fe^{2+}) in solution. At lower values of pH+pE, sulfate is reduced to sulfide, and arsenic may be precipitated with sulfidic minerals. At these same redox conditions, biological activity would convert carbon dioxide to methane as observed for VB-2 and VB-3 (see top of Figure 4-25). These processes are consistent with the temporal dissolved arsenic and iron concentrations observed for VB-1, VB-2, and VB-3 (Figure 4-26), where increased dissolved iron in VB-3 was also accompanied with much lower dissolved arsenic concentration (ca. 3.5 vs. 1.0 mg/L) compared to VB-1 and VB-2. Considering the presence of methane, iron reduction appears to have been an intermediary step concurrent with sulfate reduction and methanogenesis, resulting in arsenic precipitation and lower solubility.

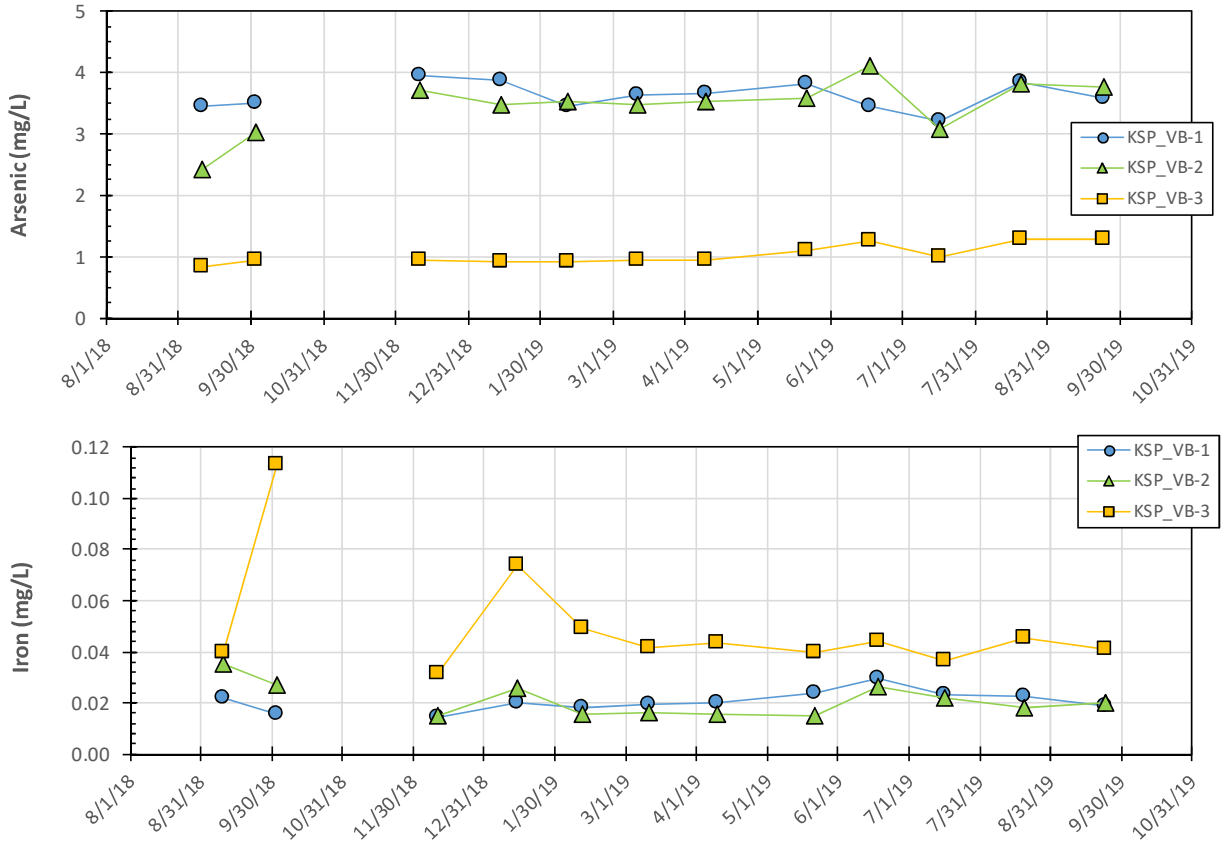

Figure 4-26
Temporal porewater data for arsenic and iron collected at boreholes VB-1, VB-2, and VB-3

Uncertainties in Redox Analysis and Impacts on Porewater Concentrations

Figure 4-27 presents a typical redox ladder for electron donors (e.g., O_2, $Fe(OH)_{3(am,\ s)}$, SO_4^{2-}, $CO_{2(g)}$) and products of biochemical reduction (e.g., CO_2, Fe^{2+}, HS^-, $CH_{4(g)}$).

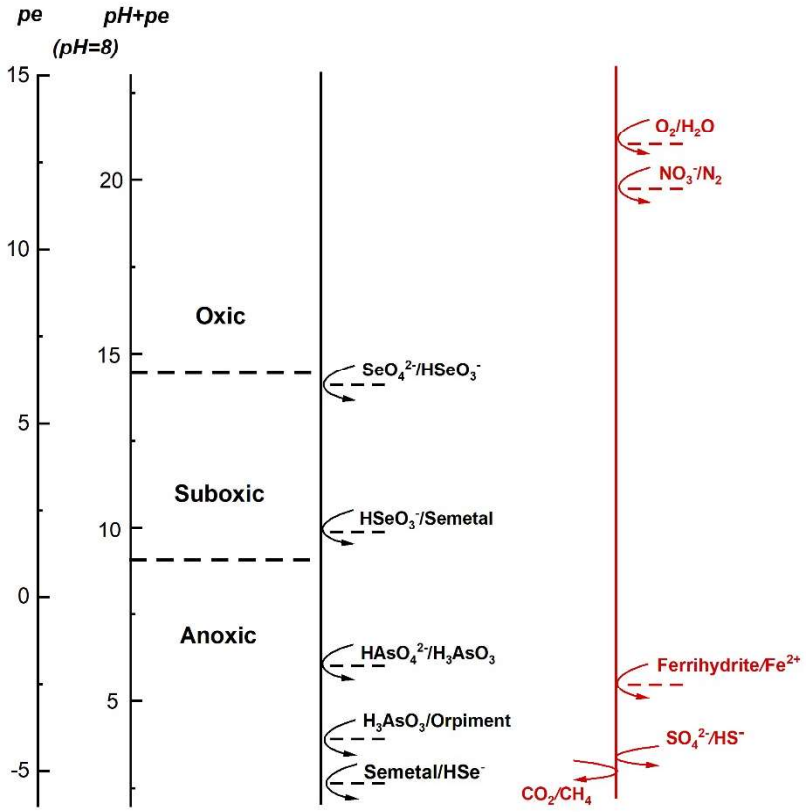

Figure 4-27
Redox ladder for relevant redox reactions (after Borch et al., 2010)

Porewater ORP measurements indicated suboxic to anoxic conditions, while subsurface gas measurements and porewater measurements of pH and dissolved constituents indicated mildly anoxic ($Fe(OH)_{3(am,\ s)}$ conversion to Fe^{2+}) to strongly anoxic and reducing (HS^- and robust CH_4 formation)[3] conditions in the ash deposit. Furthermore, porewater measured redox trended toward less reducing/more oxidizing conditions during warmer months, which is contrary to increased microbial activity, inducing more reducing conditions, at warmer temperatures. There is no clear explanation for the observed discrepancy between field-measured ORP and the redox state as deduced from gas measurements and porewater concentration data; however, the latter are generally considered more reliable indicators of redox conditions. There are several possible causes for the observed inconsistency:

- Integration Areas – Porewater reflects leaching in response to infiltration and possibly mixing with groundwater influx in response to changes in hydraulic heads (e.g., groundwater responses to changes in river elevation are evident in VB-3). In contrast, subsurface gas

[3] Hydrosulfide ion (HS^-) is a weak acid (pKa ≈6.9) resulting in a solution equilibrium with hydrogen sulfide (H_2S) gas, which was detected intermittently during subsurface gas analysis.

measurements integrate over a much larger area by diffusion and convection driven by barometric pressure changes. Gases released from the saturated zone in the coal ash can also be reflected in the gas monitoring. It is well established that the localized zones of microbially active/induced aerobic, suboxic, and highly reduced anoxic conditions can co-exist in close physical proximity (e.g., in biofilms).

- Sampling Effects – Porewater samples reflect integration over the zone of influence around the porewater access point during pumping for sampling.[4] Porewater sampling requires low-flow pumping of the porewater monitoring points, while the monitoring well remains uncapped and in exchange with the atmosphere. During initial monitoring point purging, porewater in the monitoring point can partially aerate and oxidize by oxygen exchange at the air-porewater interface within the monitoring point and the sand packing around the well screen if it is partially unsaturated.
- ORP Readings – Field monitoring instrumentation and the process of data documentation normally do not measure extremely low reducing conditions and, therefore, some negative instrument readings may have been misrepresented as positive readings. In order to examine this possibility, ORP based on sonde measurements (mV) at boreholes VB-1, VB-2, and VB-3 and resultant pH+pE values (Figure 4-28) are compared with the bounding case results if some sonde ORP measurements were actually negative values with the same absolute value (Figure 4-29). This figure indicates more reducing conditions during the warmer months and redox conditions (pH+pE) consistent with the subsurface gas measurements.

[4] For this project, porewater and groundwater sampling was conducted using low-flow sampling techniques that result in negligible drawdown.

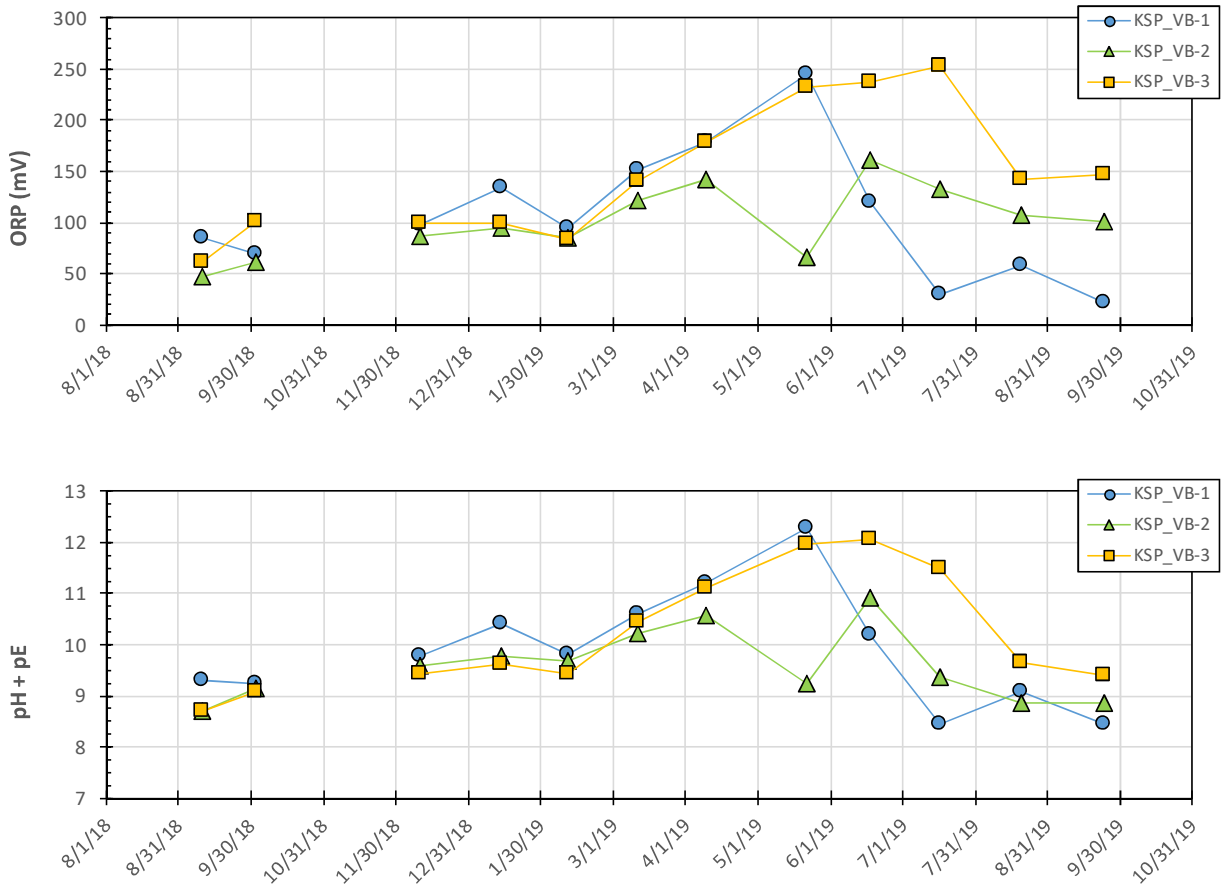

Figure 4-28
Oxidization reduction potential based on sonde measurements at boreholes VB-1, VB-2, and VB-3 and resultant pH+pE values

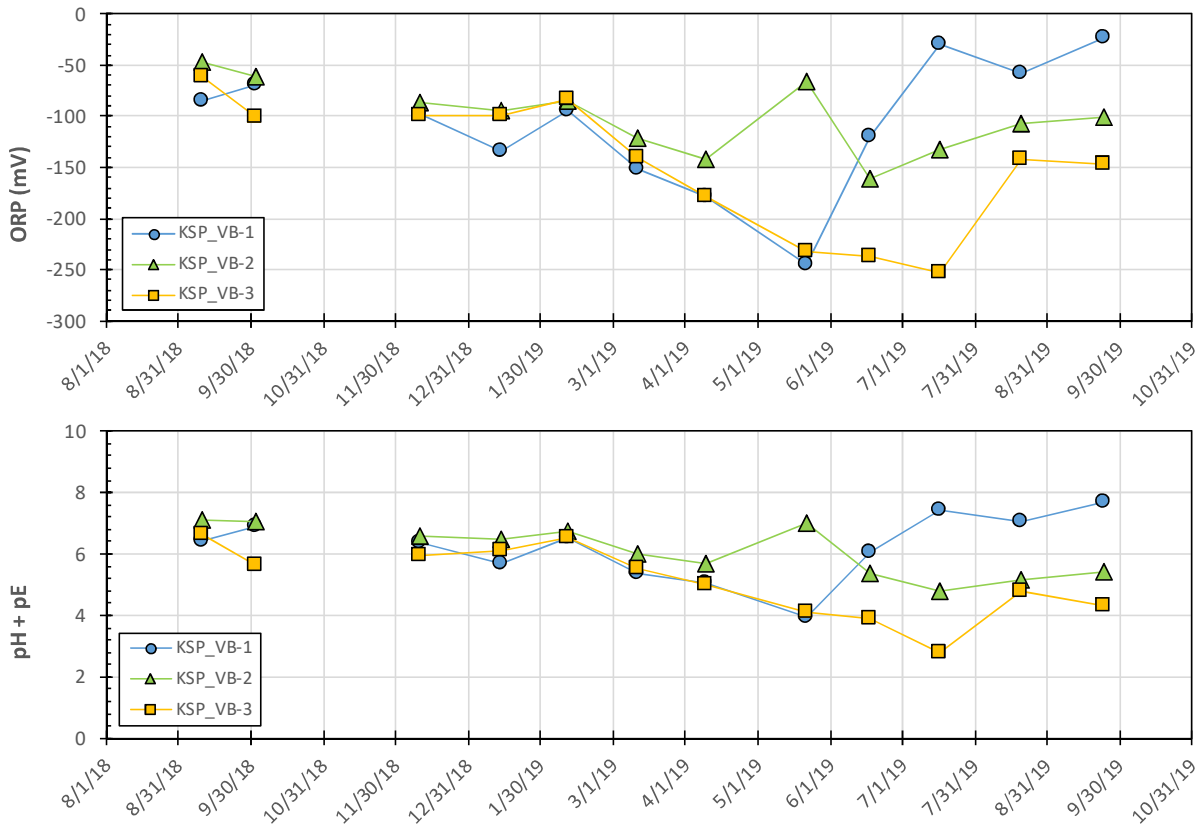

Figure 4-29
Oxidization reduction potential and resultant pH+pE values if recorded ORP measurements were negative for boreholes VB-1, VB-2, and VB-3

Comparison of Leaching Tests to Monthly Porewater Samples

The results of LEAF leaching tests and traditional tests (TCLP, SPLP, and ASTM) were plotted as a function of pH along with the porewater concentrations measured at the corresponding borehole (VB-1, VB-2, or VB-3). Examples of these comparisons are shown in Figure 4-30 through Figure 4-32, while a full set of results is presented in Appendix G. In the pH-dependence graphs, monitored porewater data are presented both as data points representing monthly measured porewater concentrations and as dashed lines representing the mean pH and mean concentration of all measured values.

To the right of each pH-dependence graph, bar charts show the ratio of the leaching test concentration to the mean porewater concentration. The seven ratios are shown in increasing order of L/S, including:

- The 1st eluate from EPA 1314 at L/S=0.2 mL/g-dry,
- The 2nd eluate from 1314 at L/S=0.3 mL/g-dry (cumulative L/S=0.5 mL/g-dry),
- The 1313_L/S=1 concentration at own pH at L/S=1 mL/g-dry,
- The 1313 concentration at natural pH at L/S=10 mL/g-dry,
- TCLP conducted at an average L/S of 23 mL/g-dry,
- SPLP conducted at an average L/S of 22 mL/g-dry, and
- ASTM at an average L/S of 27 mL/g-dry.

The eluate-to-porewater-concentration ratios indicate how closely leaching test concentrations can predict measured field concentrations. For example, Figure 4-30 shows that B porewater concentrations are reasonably predicted by low L/S leaching test data (EPA 1314 and 1313_L/S=1) while being under-predicted by at least an order-of-magnitude at higher L/S ratios. This is consistent with available content-limited LSP where eluate concentration is a strong function of L/S. However, arsenic is under-predicted in all leaching test approximations at VB-1 and VB-2 (Figure 4-31), most likely because of oxidation of solid materials with experiments conducted under laboratory conditions. This observation is consistent with the reducing conditions observed through subsurface gas monitoring and explains why arsenic concentrations are different in the field than in laboratory samples, possibly due to the loss of HFO as adsorption sites and precipitation as arsenic sulfides. Due to the effects of oxidation of laboratory samples, the leaching tests tend to over-predict the porewater concentrations of other oxyanions including Sb (Figure 4-32), Se, and V.

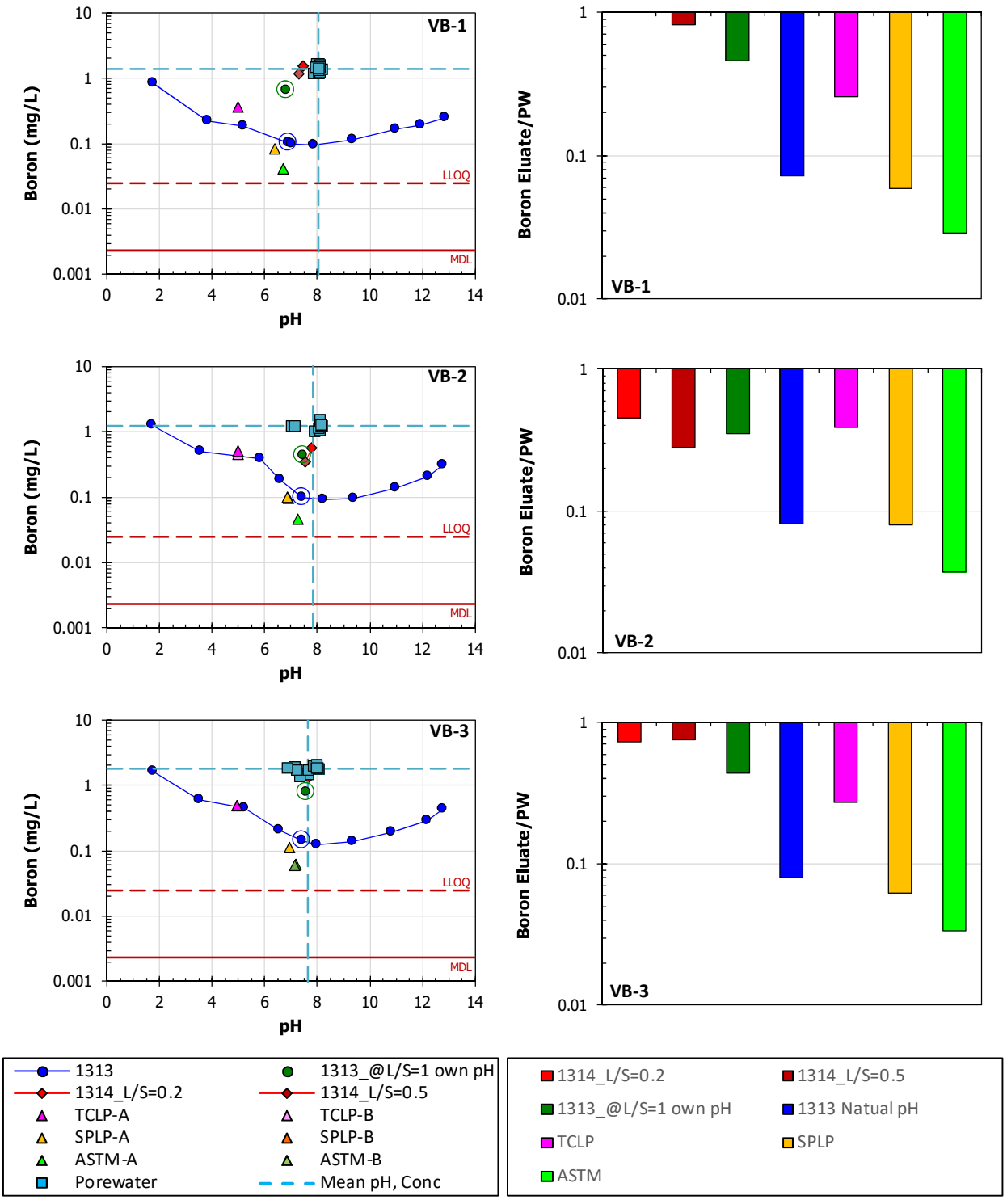

Figure 4-30
Boron concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right)

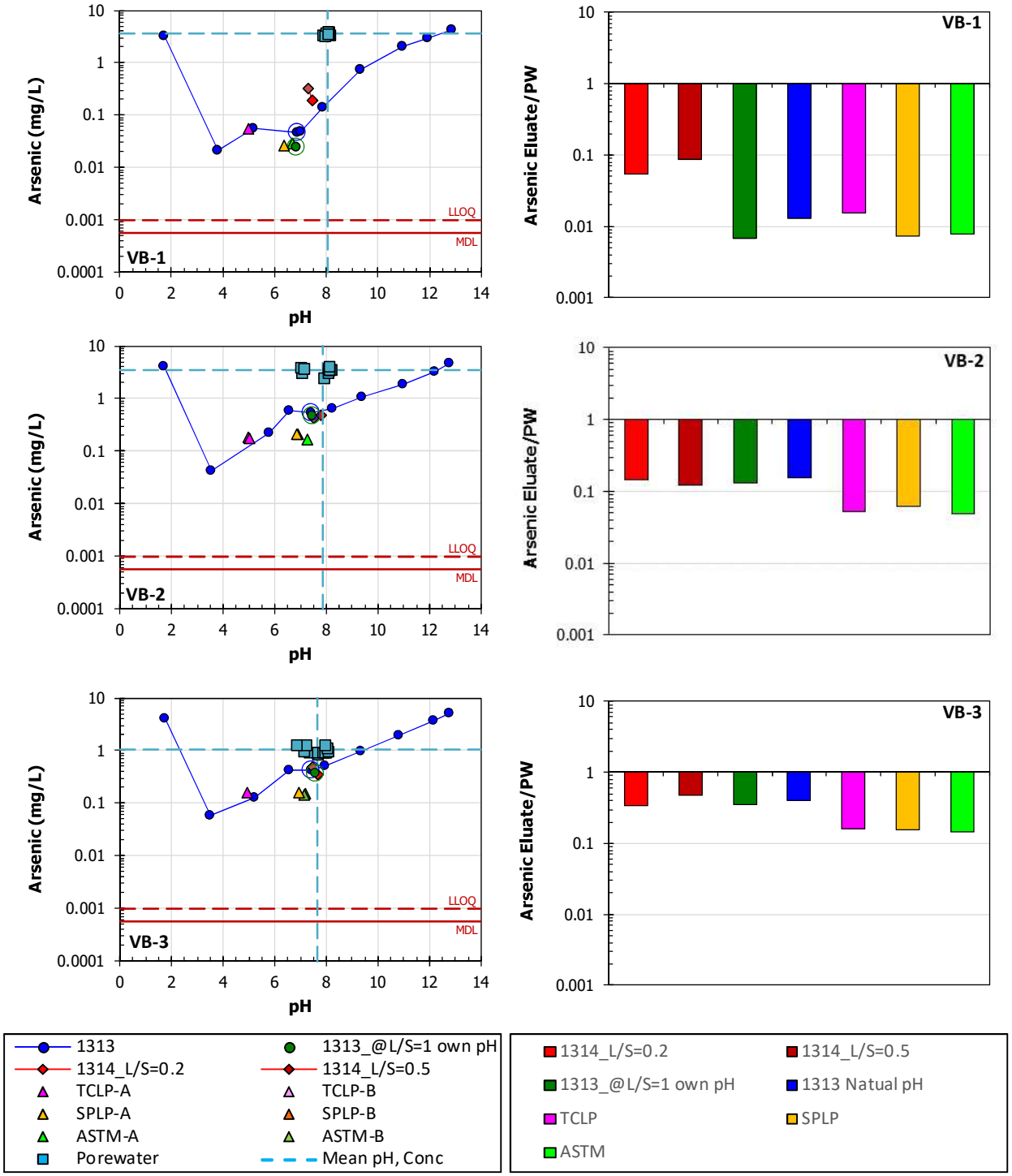

Figure 4-31
Arsenic concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right)

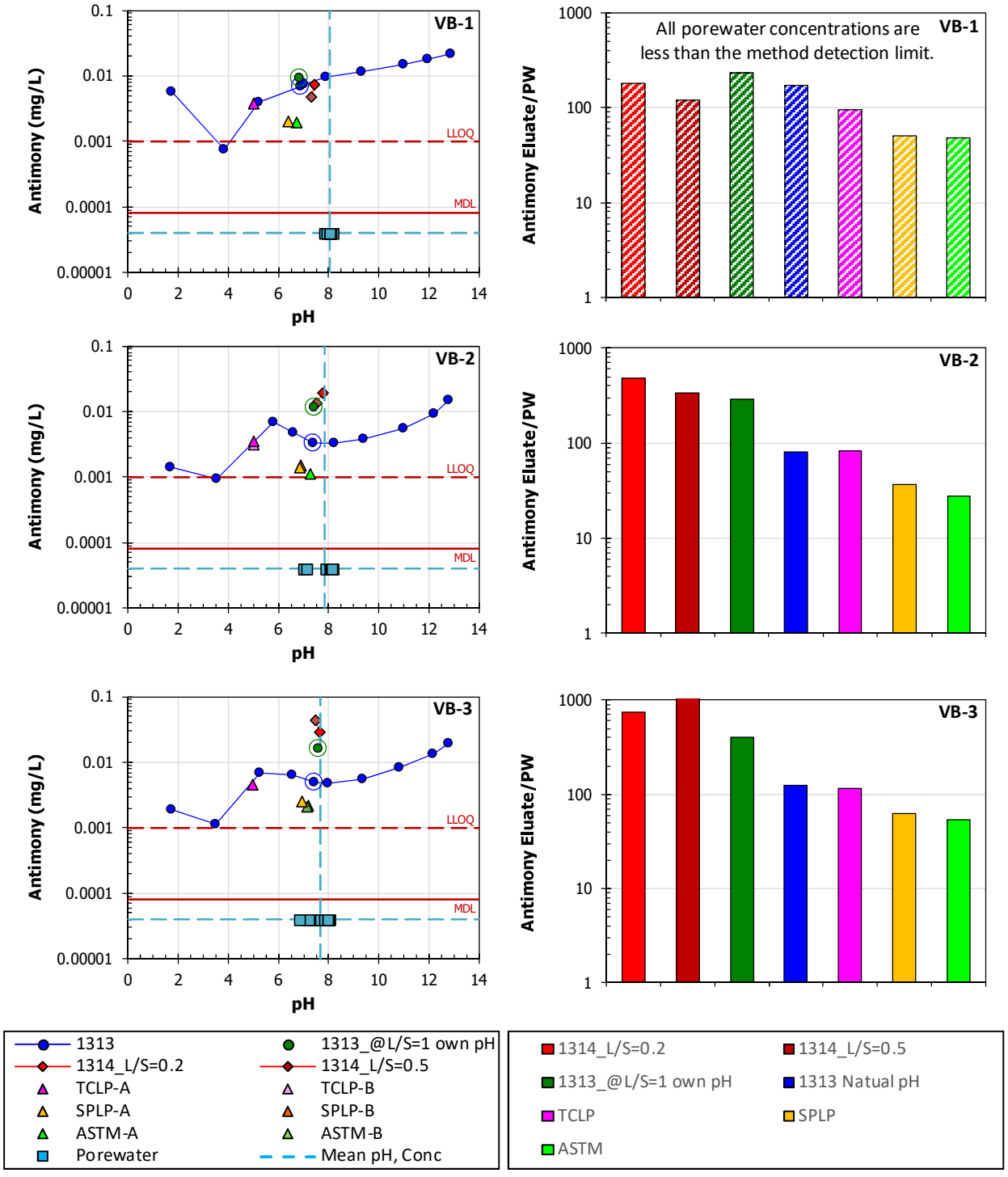

Figure 4-32
Antimony concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right); crosshatched ratio results indicate estimates based on at least one MDL value

A qualitative summary of the ability of different leaching tests to estimate the measured porewater concentrations at each of the PAPs is shown in Table 4-14 for constituents with solubility-controlled LSP, Table 4-15 for constituents with available content-limited LSP, and Table 4-16 for constituents where the LSP could not be determined. In those tables, shading is used to indicate if the leaching test estimate is within 25% of the mean groundwater concentration (green), within an order-of-magnitude of the mean porewater concentration (orange), or greater than an order-of-magnitude from the mean porewater concentration (red). When "GW <MDL" appears in the Notes column, the mean porewater concentration was less than the analytical MDL. Within the field of the table, an asterisk is used to indicate that the leaching test results were less than the MDL.

Table 4-14, Table 4-15, and Table 4-16 provide an overview of the ability of leaching tests, conducted on materials collected from a highly reducing environment and tests at mildly oxidizing conditions in a laboratory setting, to estimate porewater concentrations. The results of this qualitative summary should not be used without consideration of the redox conditions of the field and should always be shown along with the graphical data (e.g., Figure 4-30 through Figure 4-32) that preserve the pH result for the tests. For example, the table indicates that TCLP would provide a good estimate of porewater concentration for Ca; however, this is somewhat of a coincidence because the pH of TCLP is more than two pH units less than the natural pH of the ash.

Table 4-14
Summary of Leaching Tests to Predict Porewater Concentrations – Constituents with Solubility-Controlled LSP

Constituent		1314 L/S=0.2	1314 L/S=0.5	1313 L/S=1 Own pH	1313 L/S-10 Nat pH	TCLP	SPLP	ASTM	Notes
Antimony	VB-1								GW <MDL
	VB-2								
	VB-3								
Arsenic[5]	VB-1								
	VB-2								
	VB-3								
Barium	VB-1								
	VB-2								
	VB-3								
Chromium	VB-1						*	*	
	VB-2						*	*	
	VB-3				*		*	*	
Fluoride	VB-1					*	*	*	
	VB-2					*	*	*	
	VB-3					*	*	*	
Selenium	VB-1								
	VB-2								GW <MDL
	VB-3								GW <MDL
Vanadium	VB-1								GW <MDL
	VB-2								GW <MDL
	VB-3								GW <MDL
Zinc	VB-1						*	*	GW <MDL
	VB-2						*	*	GW <MDL
	VB-3						*	*	

	Estimate within 25% of porewater (±25%)
	Estimate within order of magnitude (±10x)
	Estimate more than order of magnitude (>±10x)
GW <MDL	Mean porewater concentration < MDL
*	Test concentration <MDL

[5] Although the liquid-solid partitioning (LSP) for arsenic appears to be solubility-controlled, arsenic LSP is likely a result of adsorption onto hydrous ferric oxides (HFO) and not solubility of arsenic-bearing minerals.

Table 4-15
Summary of Leaching Tests to Predict Porewater Concentrations – Constituents with Available Content-Limited LSP

Constituent		1314 L/S=0.2	1314 L/S=0.5	1313 L/S=1 Own pH	1313 L/S-10 Nat pH	TCLP L/S=20+	SPLP L/S=20+	ASTM L/S=20+	Notes
Boron	VB-1								
	VB-2								
	VB-3								
Calcium	VB-1								
	VB-2								
	VB-3								
Chloride	VB-1								
	VB-2								
	VB-3								
Molybdenum	VB-1								
	VB-2								
	VB-3								
Sulfate	VB-1								
	VB-2								
	VB-3								
Thallium	VB-1						*	*	GW <MDL
	VB-2				*		*	*	GW <MDL
	VB-3						*	*	GW <MDL

	Estimate within 25% of porewater (±25%)
	Estimate within order of magnitude (±10x)
	Estimate more than order of magnitude (>±10x)
GW <MDL	Mean porewater concentration < MDL
*	Test concentration <MDL

Table 4-16
Summary of Leaching Tests to Predict Porewater Concentrations – Constituents with no LSP Designation

Constituent		1314 L/S=0.2	1314 L/S=0.5	1313 L/S=1 Own pH	1313 L/S-10 Nat pH	TCLP L/S=20+	SPLP L/S=20+	ASTM L/S=20+	Notes
Beryllium	VB-1	*	*	*	*		*	*	GW <MDL
	VB-2	*	*	*	*		*	*	GW <MDL
	VB-3	*	*	*	*		*	*	GW <MDL
Cadmium	VB-1				*		*	*	
	VB-2			*	*		*	*	
	VB-3			*	*		*	*	GW <MDL
Cobalt	VB-1				*		*	*	
	VB-2	*	*	*	*		*	*	GW <MDL
	VB-3	*	*	*	*		*	*	
Copper	VB-1	*	*		*		*	*	GW <MDL
	VB-2	*	*	*	*		*	*	
	VB-3								GW <MDL
Iron	VB-1	*	*	*			*	*	
	VB-2	*	*				*	*	
	VB-3	*	*	*			*	*	
Lead	VB-1	*	*	*	*	*	*	*	GW <MDL
	VB-2	*	*	*	*	*	*	*	GW <MDL
	VB-3	*	*	*	*	*	*	*	GW <MDL
Lithium	VB-1			*	*	*	*	*	
	VB-2			*	*	*	*	*	
	VB-3			*	*	*	*	*	
Nickel	VB-1				*		*		
	VB-2			*	*		*	*	
	VB-3			*	*		*	*	

	Estimate within 25% of porewater (±25%)
	Estimate within order of magnitude (±10x)
	Estimate more than order of magnitude (>±10x)
GW <MDL	Mean porewater concentration < MDL
*	Test concentration <MDL

5
SUMMARY OF OBSERVATIONS

The data presented in this report represent the results of geotechnical, hydrologic, and leaching characterization of samples of coal ash collected from the closed and capped impoundment at Plant 42201. The hydraulic conductivity of intact cores from the ash deposit was measured in context of the distribution of particles in the coal ash samples and the overburden pressure associated with disposal at depth within the pond. The leaching test results for LEAF tests (i.e., EPA Methods 1313 and 1314) were compared to those for traditional tests (i.e., ASTM, TCLP, and SPLP). In addition, leaching test results were compared to porewater concentrations determined from field samples, and field-sampled porewater concentrations were compared to groundwater concentrations, to evaluate similarities and dissimilarities between these results.

Based on the presented data and analysis, the following general observations can be made:

- The hydraulic conductivity of intact ash samples is dependent on the fraction of fines in the material. The measured hydraulic conductivity of finer, less permeable coal ash was lower (ranging from approximately $7x10^{-4}$ cm/s to $1x10^{-5}$ cm/s) than the hydraulic conductivity of coarser, more permeable coal ash (approximately $1x10^{-3}$ cm/s). In general, the hydraulic conductivity decreases modestly with increasing effective stress.
- The subsurface within the closed impoundment was more bio-chemically reducing than indicated by porewater analysis. Monitoring of subsurface gas concentrations shows the presence of hydrogen sulfide and methane, indicating strongly reducing conditions. Monthly data indicate that the extent of reducing conditions is spatially variable and may be seasonally dependent. In addition, arsenic concentrations in the porewater are at the high end of previously reported ranges for coal ash (EPRI, 2019) in some areas. At intermediate reducing conditions (e.g., at VB-1), elevated concentrations of arsenic (ca. 3 mg/L) are likely due to loss of HFO when ferric oxides are reduced and solubilized (conversion of insoluble Fe^{3+} to soluble Fe^{2+}). Under very low redox conditions, as observed by subsurface gas monitoring at VB-2 and VB-3 by the presence of methane, arsenic porewater concentrations decrease due to conversion of As(V) to As(III) and likely precipitation as sulfides. Conversely, the porewater concentrations of Sb and Se in the reduced pond environment are suppressed due to formation of reduced species with lower solubility.
- Some constituents in the porewater samples exhibited temporal variability due to factors such as (1) seasonal changes in pH and redox, (2) changes that appeared to be related to seasonal groundwater elevation changes, and (3) changing conditions shortly after closure of the impoundment. However, some constituents such as, B, and Mo remained relatively constant within each porewater access point throughout the 13-month monitoring period.
- The data collected suggest that porewater concentration is an unreliable indicator for which constituents will have elevated groundwater concentrations or for prediction of downgradient concentrations at this site.

- Traditional leaching tests (TCLP, SPLP, and ASTM) are poor indicators of measured porewater concentrations. Low liquid-to-solid ratio (L/S) eluates from EPA Method 1314 are better indicators than the traditional tests for concentrations for available content-limited constituents (B, Ca, Cl, Mo, Tl) because of the strong L/S-dependence. However, additional information (e.g., available content and porewater L/S) is needed to provide a reasonable approximation of porewater concentrations. For constituents with apparent solubility-controlled liquid-solid partitioning (Sb, As, Ba, Cr, F^-, Se, SO_4, V, Zn), pH-dependence tests (e.g., EPA Method 1313) may provide valuable information for geochemical modeling, but, for this site, the natural or own pH responses did not reliably estimate field porewater concentrations, in part due to differences in redox as noted in the next bullet.
- When the field environment is highly reducing, laboratory leaching results for redox sensitive elements (e.g., As, Cr, Sb, Se, and Fe) do not directly reflect the leaching anticipated in porewater. This is, in part, because reduced materials collected in the field are inevitably partially oxidized during sampling, handling, and testing.

6
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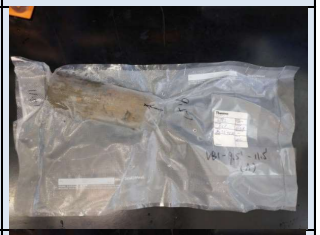
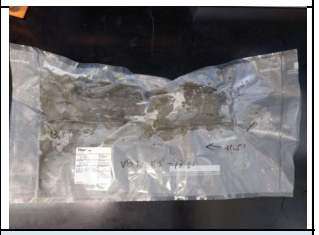
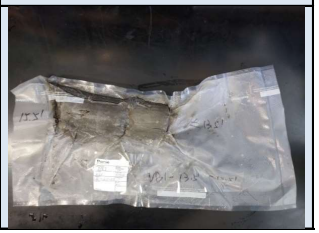
A
BORE LOGS AND WELL STRATIGRAPHY

Borehole reports are maintained as electronic files available upon request to EPRI.

B
MATERIAL COLLECTION SAMPLE INDEX

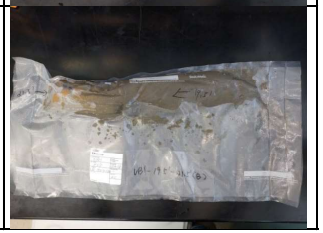
INVENTORY OF FIELD-COLLECTED ASH SAMPLES
KSP_VB-1
Collection Date June 19, 2018

Granular Ash Sampling

Depth Below Ground Level (ft)	Sample ID	Material Type	Sample Type	Container & Size	Mass of Ash (g)	Mass of Water Added (g)	Bottle Mass Without Lid (g)	Collected Sample Picture	Saved Sample Picture
9.5'-11.5'	EPRI_VB1_9.5'-11.5'	Fly Ash	L/S ~ 1	250-mL bottle	160.03	194.93	26.82		
	EPRI_VB1_9.5'-11.5'_A	Fly Ash (upper portion near interface)	Bulk	1-gal. vacuum-seal bag	865.8				
	EPRI_VB1_9.5'-11.5'_B	Fly Ash (lower portion)	Bulk	1-gal. vacuum-seal bag	1395				
11.5'-13.5'	EPRI_VB1_11.5'-13.5'	Fly Ash	L/S ~ 1	250-mL bottle	156.01	195.87	26.88		
	EPRI_VB1_11.5'-13.5'	Fly Ash	Bulk	1-gal. vacuum-seal bag	1431.2				
Note: Starting with EPRI_VB1_13.5'-15.5', the driller add ed water to prevent back flow into auger.									
13.5'-15.5'	EPRI_VB1_13.5'-15.5'	Fly Ash	L/S ~ 1	250-mL bottle	157.52	204.29	26.86		
	EPRI_VB1_13.5'-15.5'	Fly Ash	Bulk	1-gal. vacuum-seal bag	1145.4				

INVENTORY OF FIELD-COLLECTED ASH SAMPLES
KSP_VB-1
Collection Date June 19, 2018

Granular Ash Sampling

Depth Below Ground Level (ft)	Sample ID	Material Type	Sample Type	Container & Size	Mass of Ash (g)	Mass of Water Added (g)	Bottle Mass Without Lid (g)	Collected Sample Picture	Saved Sample Picture
15.5'-17.5'	EPRI_VB1_15.5'-17.5'	Fly Ash	L/S ~ 1	250-mL bottle	167.00	200.00	26.73		
	EPRI_VB1_15.5'-17.5'	Fly Ash	Bulk	1-gal. vacuum-seal bag	682.4				
17.5'-19.5'	EPRI_VB1_17.5'-19.5'	Fly Ash	L/S ~ 1	250-mL bottle	193.13	181.38	26.69		
	EPRI_VB1_17.5'-19.5'	Fly Ash	Bulk	1-gal. vacuum-seal bag	2038.0				
19.5'-21.5'	EPRI_VB1_19.5'-21.5'	Fly Ash	L/S ~ 1	250-mL bottle	195.47	181.19	26.83		
	EPRI_VB1_19.5'-21.5'(M)	Fly Ash	Moisture	250-mL bottle	33.95	-	26.82		
	EPRI_VB1_19.5'-21.5'_N	Native Clay	L/S ~ 1	250-mL bottle	152.48	220.16	26.85		
	EPRI_VB1_19.5'-21.5'_A	Fly Ash (upper portion)	Bulk	1-gal. vacuum-seal bag	957.5				
	EPRI_VB1_19.5'-21.5'_B	Fly Ash (lower portion near clay liner)	Bulk	1-gal. vacuum-seal bag	1408.9				

INVENTORY OF FIELD-COLLECTED ASH SAMPLES

KSP_VB-1

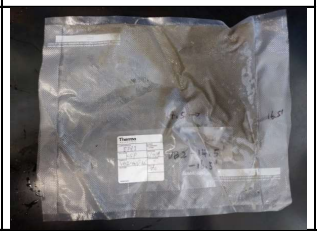
Collection Date June 19, 2018

Minimally-Disturbed Core Sampling (Osterberg Sampler)

Depth Below Ground Level (ft)	Sample ID	Material Type	Tube Recovery	Container & Size	Saved Sample Picture
8'-10'	EPRI_VB1_OST_8'-10'	Upper Interface	17" recovered from 24" push	36"-long tube	
12'-14.5'	EPRI_VB1_OST_12'-14.5'	Fly Ash	24.5" recovered from 30" push	36"-long tube	
17'-19.5'	EPRI_VB1_OST_17'-19.5'	Fly Ash	24" recovered from 30" push	36"-long tube	
20'-22'	none	Lower Interface	0" recovered from 30" push (no recovery)		

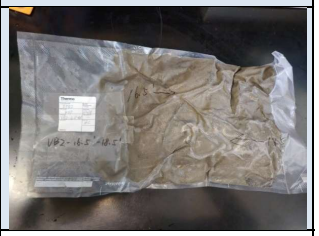
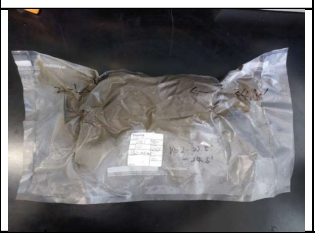
INVENTORY OF FIELD-COLLECTED ASH SAMPLES
KSP_VB-2
Collection Date June 14, 2018

Granular Ash Sampling

Depth Below Ground Level (ft)	Sample ID	Material Type	Sample Type	Container & Size	Mass of Ash (g)	Mass of Water Added (g)	Bottle Mass Without Lid (g)	Collected Sample Picture	Saved Sample Picture
8.5'-10.5'	EPRI_VB2_8.5'-10.5'	Fly Ash	L/S ~ 1	250-mL bottle	153.1	96.58	26.73		
	EPRI_VB2_8.5'-10.5'	Fly Ash	Bulk	1-gal. vacuum-seal bag	1294.8				
10.5'-12.5'	EPRI_VB2_10.5'-12.5'	Fly Ash	L/S ~ 1	250-mL bottle	170.64	78.75	26.97		
	EPRI_VB2_10.5'-12.5'	Fly Ash	Bulk	1-gal. vacuum-seal bag	1592.2				
Note: Starting with EPRI_VB2_12.5'-14.5', the driller add ed water to prevent back flow into auger.									
12.5'-14.5'	EPRI_VB2_12.5'-14.5'	Fly Ash	L/S ~ 1	250-mL bottle	173.03	76.3	26.98		
	EPRI_VB2_12.5'-14.5'	Fly Ash	Bulk	1-gal. vacuum-seal bag	925.3				
14.5'-16.5'	EPRI_VB2_14.5'-16.5'	Fly Ash	L/S ~ 1	250-mL bottle	181.97	67.49	26.97		
	EPRI_VB2_14.5'-16.5'	Fly Ash	Bulk	1-gal. vacuum-seal bag	380.6				

INVENTORY OF FIELD-COLLECTED ASH SAMPLES
KSP_VB-2
June 19, 2018

Granular Ash Sampling

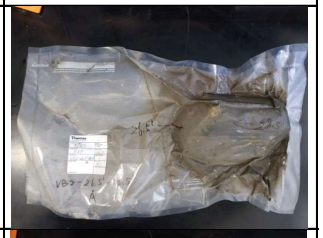
16.5'-18.5'	EPRI_VB2_16.5'-18.5'	Fly Ash	L/S ~ 1	250-mL bottle	182.77	67.02	26.87		
	EPRI_VB2_16.5'-18.5'	Fly Ash	Bulk	1-gal. vacuum-seal bag	1918.7				
18.5'-20.5'	EPRI_VB2_18.5'-20.5'	Fly Ash	L/S ~ 1	250-mL bottle	165.76	84.14	26.97		
	EPRI_VB2_18.5'-20.5'	Fly Ash	Bulk	1-gal. vacuum-seal bag	1165.7				
20.5'-22.5'	EPRI_VB2_20.5'-22.5'	Fly Ash	L/S ~ 1	250-mL bottle	191.86	58.12	26.78		
	EPRI_VB2_20.5'-22.5'	Fly Ash	Bulk	1-gal. vacuum-seal bag	1372.3				
22.5'-24.5'	EPRI_VB2_22.5'-24.5'	Fly Ash	L/S ~ 1	250-mL bottle	173.86	75.77	26.72		
	EPRI_VB2_22.5'-24.5'	Fly Ash	Bulk	1-gal. vacuum-seal bag	1105.9				

INVENTORY OF FIELD-COLLECTED ASH SAMPLES

KSP_VB-2

Collection Date June 14, 2018

Granular Ash Sampling

24.5'-26.5'	EPRI_VB2_24.5'-26.5'	Fly Ash	L/S ~ 1	250-mL bottle	180.21	69.42	26.98		
	EPRI_VB2_24.5'-26.5'	Fly Ash	Bulk	1-gal. vacuum-seal bag	2908.6				
26.5'-28.5'	EPRI_VB2_26.5'-28.5'	Fly Ash	L/S ~ 1	250-mL bottle	180.69	69.13	26.97		
	EPRI_VB2_26.5'-28.5'_A	Fly Ash	Bulk	1-gal. vacuum-seal bag	1034.6				
	EPRI_VB2_26.5'-28.5'_B	Fly Ash	Bulk	1-gal. vacuum-seal bag	1243.6				
28.5'-30.5'	EPRI_VB2_28.5'-30.5'_N	Fly Ash	L/S ~ 1	250-mL bottle	149.41	100.63	26.98		
	EPRI_VB2_28.5'-30.5'(M)	Fly Ash	Moisture	250-mL bottle	51.59	-	26.72		
	EPRI_VB2_28.5'-30.5'	Fly Ash	Bulk	1-gal. vacuum-seal bag	1076.8				

INVENTORY OF FIELD-COLLECTED ASH SAMPLES

KSP_VB-2

Collection Date June 14, 2018

Minimally-Disturbed Core Sampling (Osterberg Sampler)

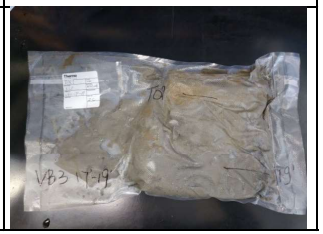
Depth Below Ground Level (ft)	Sample ID	Material Type	Tube Recovery	Container & Size	Saved Sample Picture
7'-9.5'	EPRI_VB2_OST_7'-9'	Upper Interface	28" recovered from 30" push	36"-long tube	
13.5'-15.5'	Osterberg-13.5'-15.5'	Fly Ash	23" recovered from 30" push	36"-long tube	
18.5'-21.5'	Osterberg-18.5'-21.5'	Fly Ash	30" recovered from 30" push	36"-long tube	
23.5'-26.5'	none	Fly Ash	0" recovered from 30" push (no recovery)	none	
27'-29'	none	Lower Interface	0" recovered from 30" push (no recovery)	none	

INVENTORY OF FIELD-COLLECTED ASH SAMPLES

KSP_VB-3

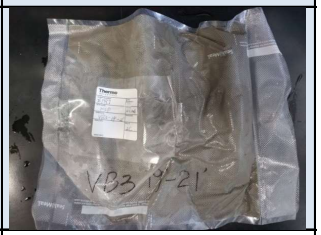
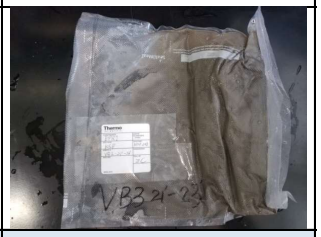
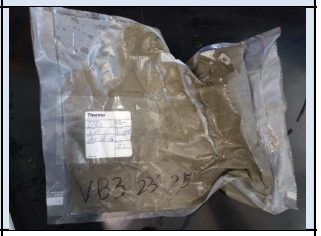
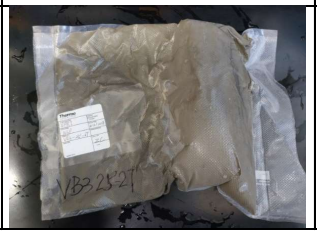
Collection Date June 12, 2018

Granular Ash Sampling

Depth Below Ground Level (ft)	Sample ID	Material Type	Sample Type	Container & Size	Mass of Ash (g)	Mass of Water Added (g)	Bottle Mass Without Lid (g)	Collected Sample Picture	Saved Sample Picture
11'-13'	EPRI_VB2_11'-13'	Fly Ash	L/S ~ 1	250-mL bottle	147.66	143.22	26.99		
	EPRI_VB3_11'-13'	Fly Ash (portion below clay cover)	Bulk	1-gal. vacuum-seal bag	1543.9				
13'-15'	EPRI_VB3_13'-15'	Fly Ash	L/S ~ 1	250-mL bottle	165.67	125.32	26.89		
	EPRI_VB3_13'-15'	Fly Ash	Bulk	1-gal. vacuum-seal bag	1885				
15'-17'	EPRI_VB3_15'-17'	Fly Ash	L/S ~ 1	250-mL bottle	157.18	134	26.9		
	EPRI_VB3_15'-17'	Fly Ash	Bulk	1-gal. vacuum-seal bag	2025.5				
17'-19'	EPRI_VB3_17'-19'	Fly Ash	L/S ~ 1	250-mL bottle	173.83	117.37	26.88		
	EPRI_VB3_17'-19'	Fly Ash	Bulk	1-gal. vacuum-seal bag	2871				

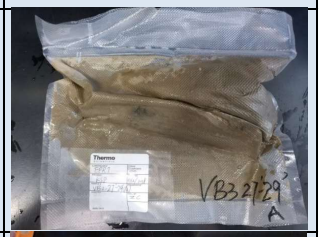
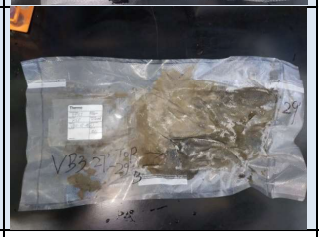
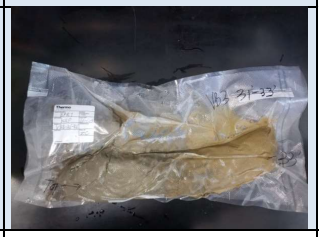
INVENTORY OF FIELD-COLLECTED ASH SAMPLES
KSP_VB-3
Collection Date June 12, 2018

Granular Ash Sampling

Depth Below Ground Level (ft)	Sample ID	Material Type	Sample Type	Container & Size	Mass of Ash (g)	Mass of Water Added (g)	Bottle Mass Without Lid (g)	Collected Sample Picture	Saved Sample Picture
19'-21'	EPRI_VB3_19'-21'	Fly Ash	L/S ~ 1	250-mL bottle	152.71	138.71	26.98		
	EPRI_VB3_19'-21'	Fly Ash	Bulk	1-gal. vacuum-seal bag	601.2				
Note: Starting with EPRI_VB2_21'-23', the driller add ed water to prevent back flow into auger.									
21'-23'	EPRI_VB3_21'-23'	Fly Ash	L/S ~ 1	250-mL bottle	183.03	108.44	26.77		
	EPRI_VB3_21'-23'	Fly Ash	Bulk	1-gal. vacuum-seal bag	966.5				
23'-25'	EPRI_VB3_23'-25'	Fly Ash	L/S ~ 1	250-mL bottle	189.81	101.78	26.98		
	EPRI_VB3_23'-25'	Fly Ash	Bulk	1-gal. vacuum-seal bag	1213.3				
25'-27'	EPRI_VB3_25'-27'	Fly Ash	L/S ~ 1	250-mL bottle	179.18	112.43	26.79		
	EPRI_VB3_25'-27'	Fly Ash	Bulk	1-gal. vacuum-seal bag	2365.5				

INVENTORY OF FIELD-COLLECTED ASH SAMPLES
KSP_VB-3
Collection Date June 12, 2018

Granular Ash Sampling

Depth Below Ground Level (ft)	Sample ID	Material Type	Sample Type	Container & Size	Mass of Ash (g)	Mass of Water Added (g)	Bottle Mass Without Lid (g)	Collected Sample Picture	Saved Sample Picture
27'-29'	EPRI_VB3_27'-29'	Fly Ash	L/S ~ 1	250-mL bottle	187.39	104.21	26.86		
	EPRI_VB3_27'-29'(M)	Fly Ash	Moisture	250-mL bottle	60.18				
	EPRI_VB3_27'-29'_A	Fly Ash (upper portion)	Bulk	1-gal. vacuum-seal bag	981.2				
	EPRI_VB3_27'-29'(B)	Fly Ash (portion below clay layers)	Bulk	1-gal. vacuum-seal bag	1435.5				
29'-31'	EPRI_VB3_29'-31'	Fly Ash	L/S ~ 1	250-mL bottle	164.03	127.98	26.79		
	EPRI_VB3_29'-31'	Fly Ash	Bulk	1-gal. vacuum-seal bag	3009.5				
31'-33'	EPRI_VB3_31'-33'ASH	Fly Ash	L/S ~ 1	250-mL bottle	153.89	138.28	26.89		
	EPRI_VB3_31'-33'_N	Native Clay	L/S ~ 1	250-mL bottle	168.19	123.83	26.9		
	EPRI_VB3_31'-33'	Fly Ash (portion above native clay liner)	Bulk	1-gal. vacuum-seal bag	2438.7				
33'	EPRI_VB3_33'	Native Clay	Moisture	250-mL bottle	60.29				

INVENTORY OF FIELD-COLLECTED ASH SAMPLES

KSP_VB-3

Collection Date June 12, 2018

Minimally-Disturbed Core Sampling (Osterberg Sampler)

Depth Below Ground Level (ft)	Sample ID	Material Type	Tube Recovery	Container & Size	Saved Sample Picture
17'-20'	EPRI_VB3_OST_17'-20'	Fly Ash	23.5" recovered from 30" push	36"-long tube	
20'-23'	EPRI_VB3_OST_20'-23'	Fly Ash	0" recovered from 30" push (no recovery)	none	
24'-27'	EPRI_VB3_OST_24'-27'	Fly Ash	12" recovered from 30" push	36"-long tube	

C
INDIVIDUAL SPLIT SPOON SAMPLE ANALYSIS

Table of Appendices

C.1 Field Extractions (L/S~1) and Laboratory Extractions (L/S=1) as Functions of pH and L/S

C.2 Standardized Concentration Profiles from Laboratory Extractions (L/S=1) Using the Global Ash Mean and Standard Deviation

C.3 Comparison of Standardized Release Profiles

C.1 Field Extractions (L/S~1) and Laboratory Extractions (L/S=1) as Functions of pH and L/S

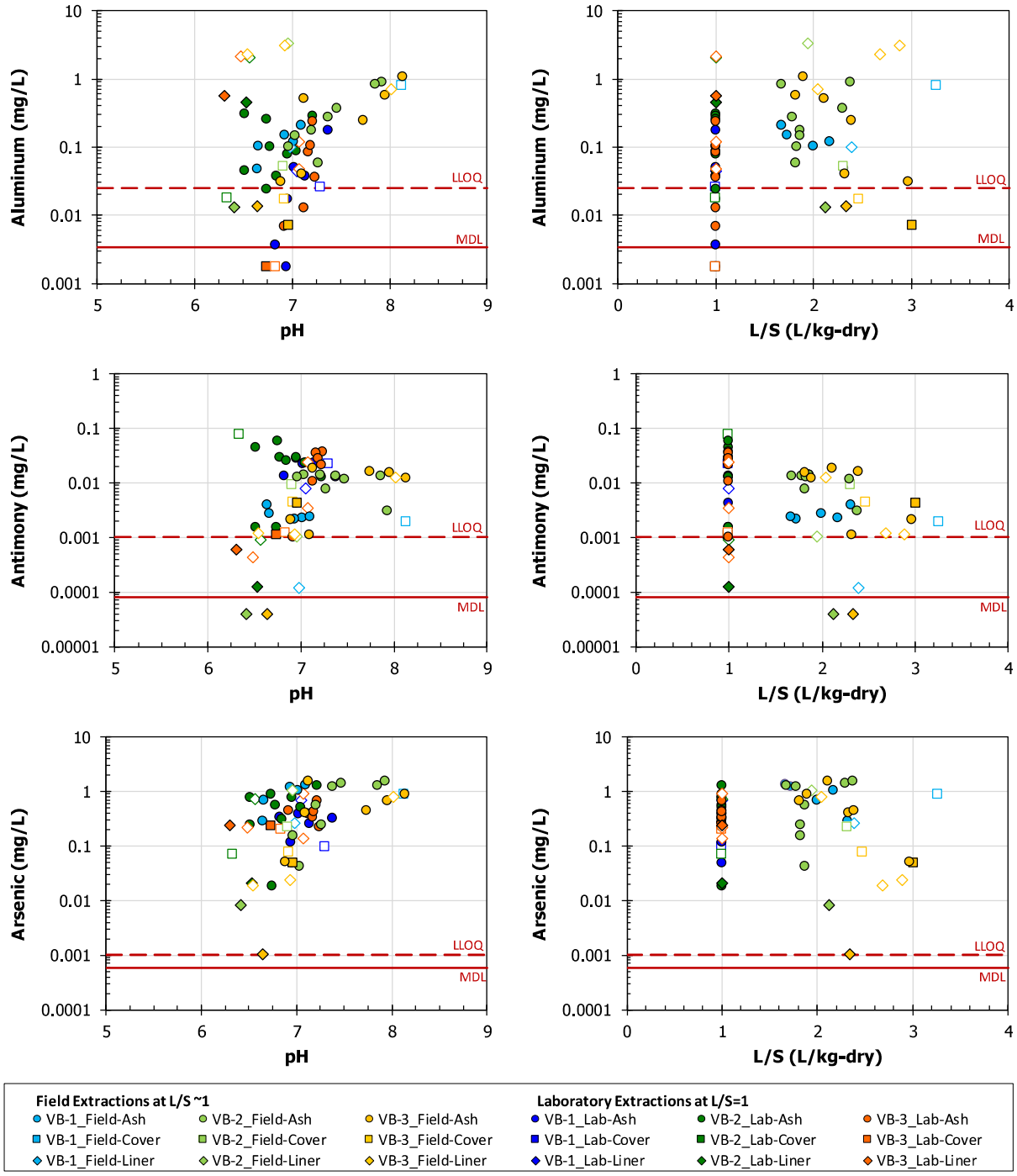


Figure C-1
Comparison of field extractions at L/S~1 (lighter colors) to laboratory extractions at L/S=1 (darker colors) for individual split spoon materials shown as a function of pH (left) and L/S (right): aluminum, antimony, and arsenic.

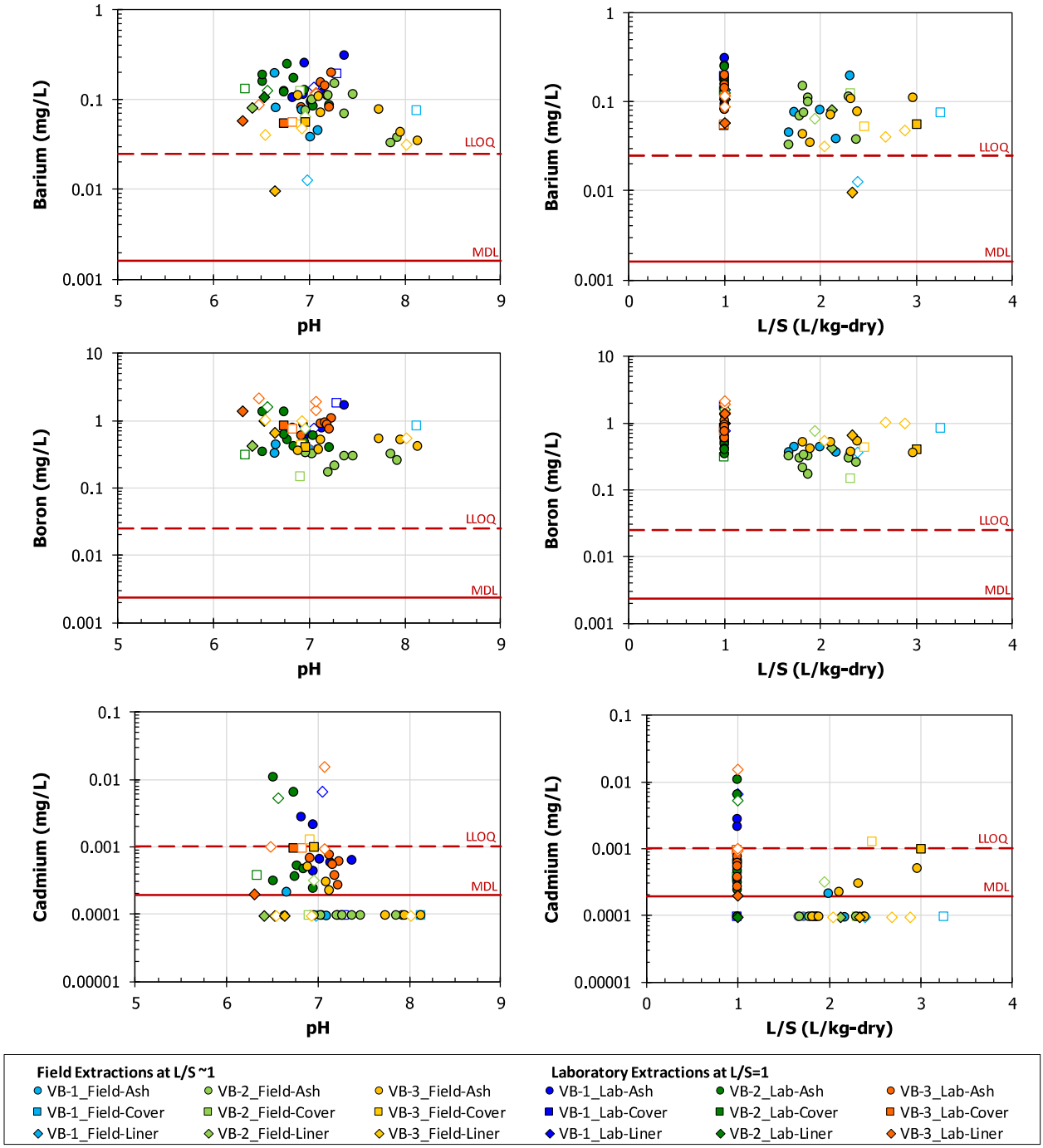


Figure C-2
Comparison of field extractions at L/S~1 (lighter colors) to laboratory extractions at L/S=1 (darker colors) for individual split spoon materials shown as a function of pH (left) and L/S (right): barium, boron, and cadmium.

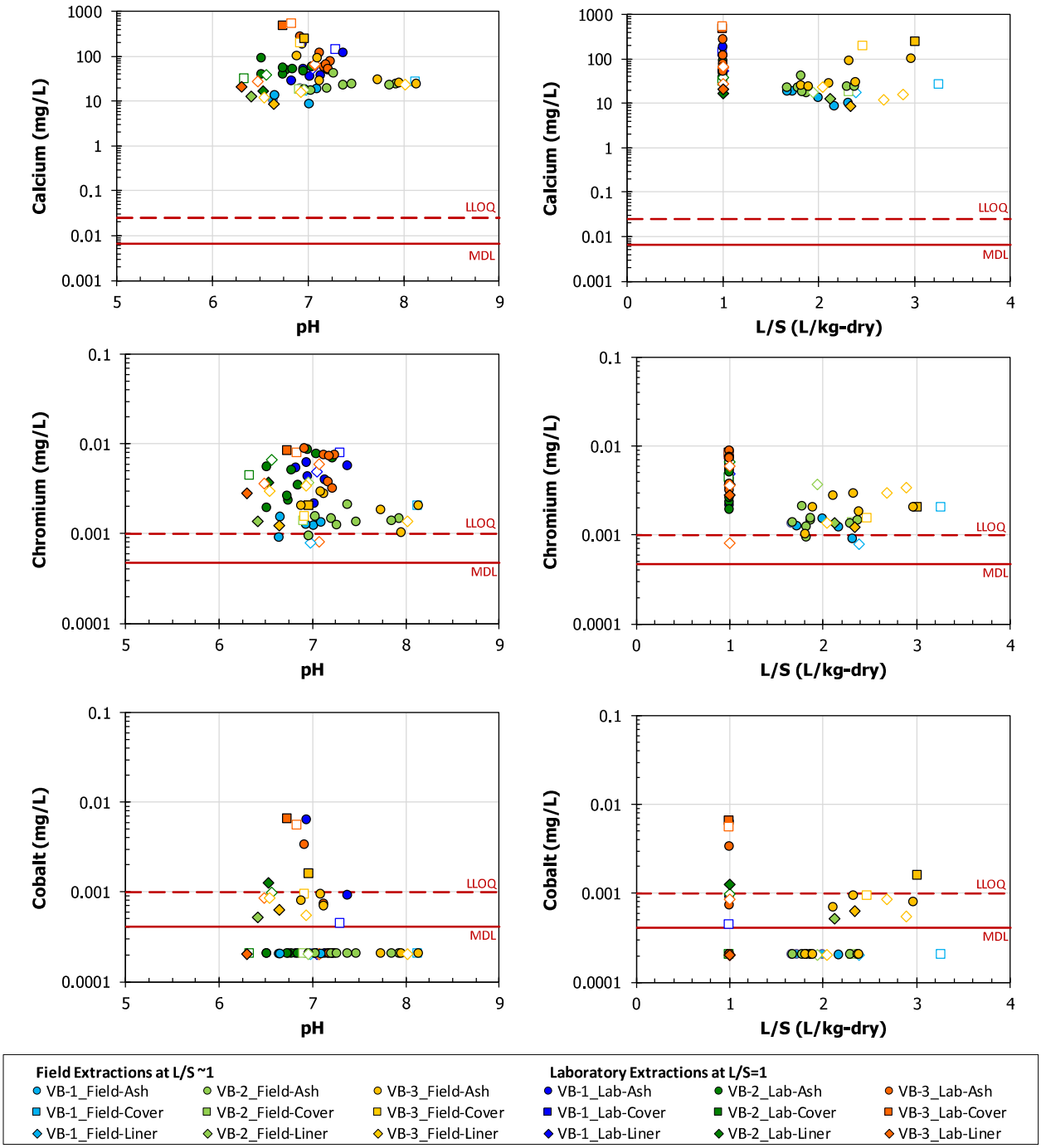


Figure C-3
Comparison of field extractions at L/S~1 (lighter colors) to laboratory extractions at L/S=1 (darker colors) for individual split spoon materials shown as a function of pH (left) and L/S (right): calcium, chromium, cobalt.

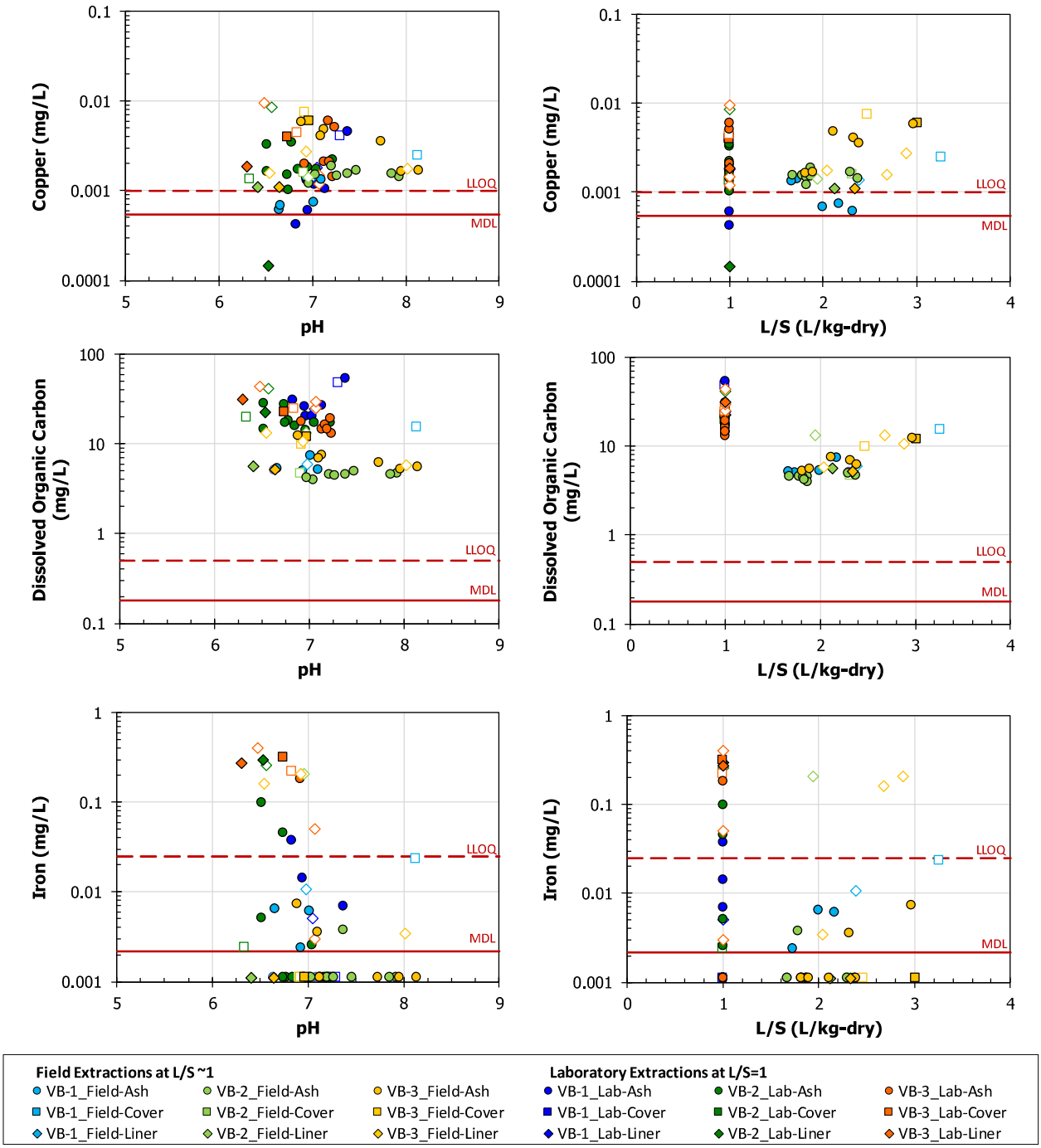


Figure C-4
Comparison of field extractions at L/S~1 (lighter colors) to laboratory extractions at L/S=1 (darker colors) for individual split spoon materials shown as a function of pH (left) and L/S (right): copper, dissolved organic carbon, and iron.

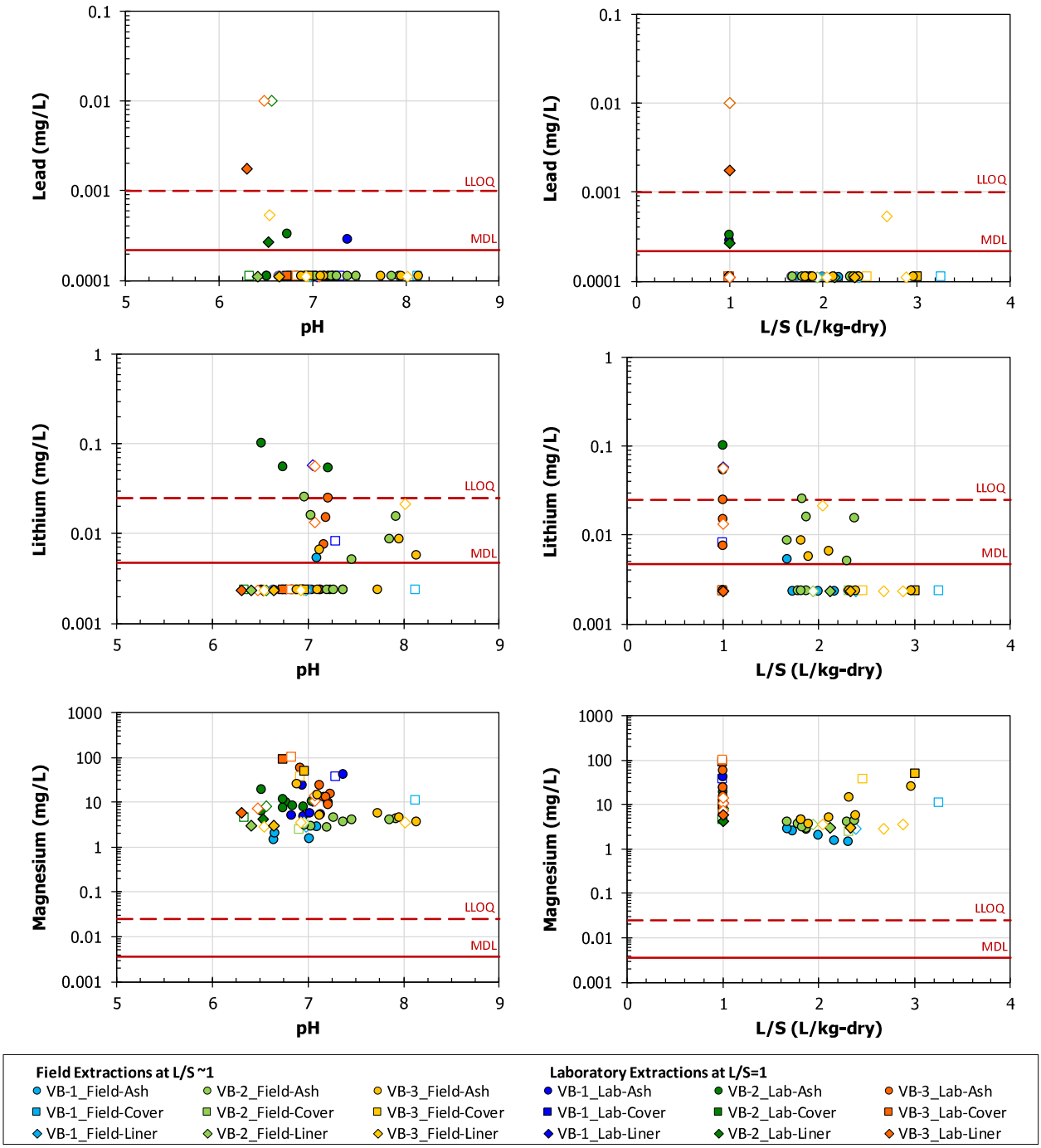


Figure C-5
Comparison of field extractions at L/S~1 (lighter colors) to laboratory extractions at L/S=1 (darker colors) for individual split spoon materials shown as a function of pH (left) and L/S (right): lead, lithium and magnesium.

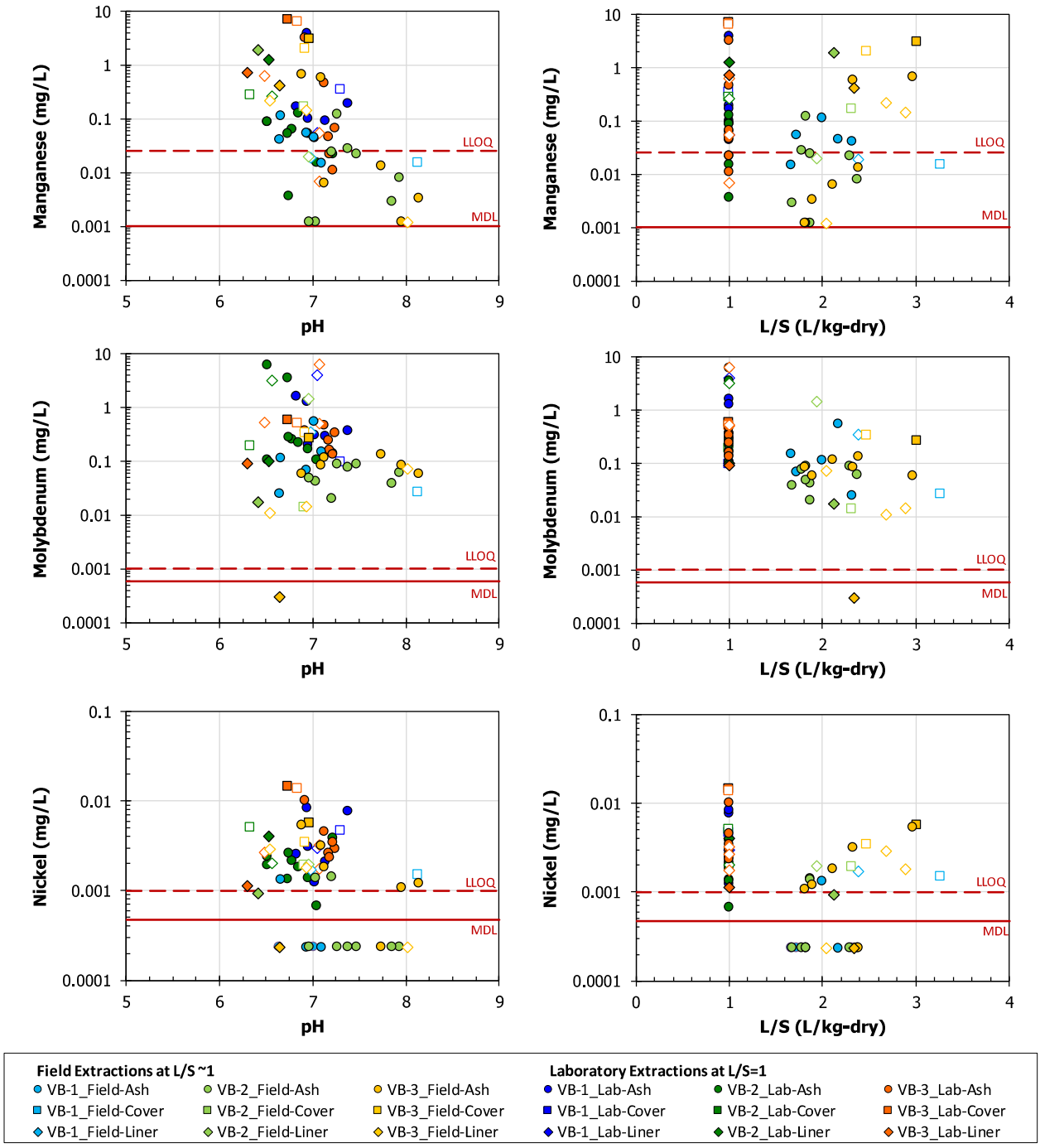


Figure C-6
Comparison of field extractions at L/S~1 (lighter colors) to laboratory extractions at L/S=1 (darker colors) for individual split spoon materials shown as a function of pH (left) and L/S (right): manganese, molybdenum, and nickel.

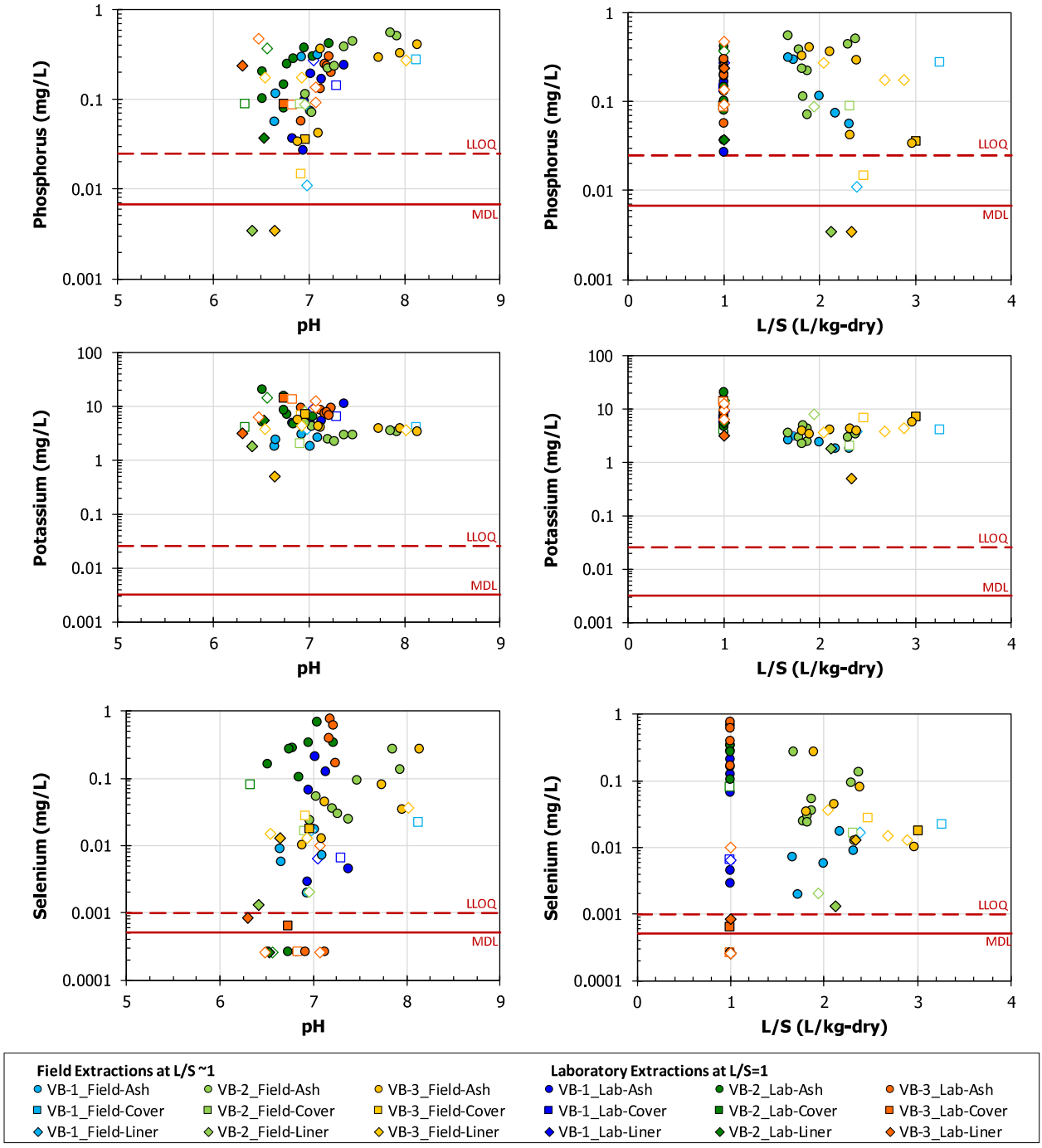


Figure C-7
Comparison of field extractions at L/S~1 (lighter colors) to laboratory extractions at L/S=1 (darker colors) for individual split spoon materials shown as a function of pH (left) and L/S (right): phosphorus, potassium, and selenium.

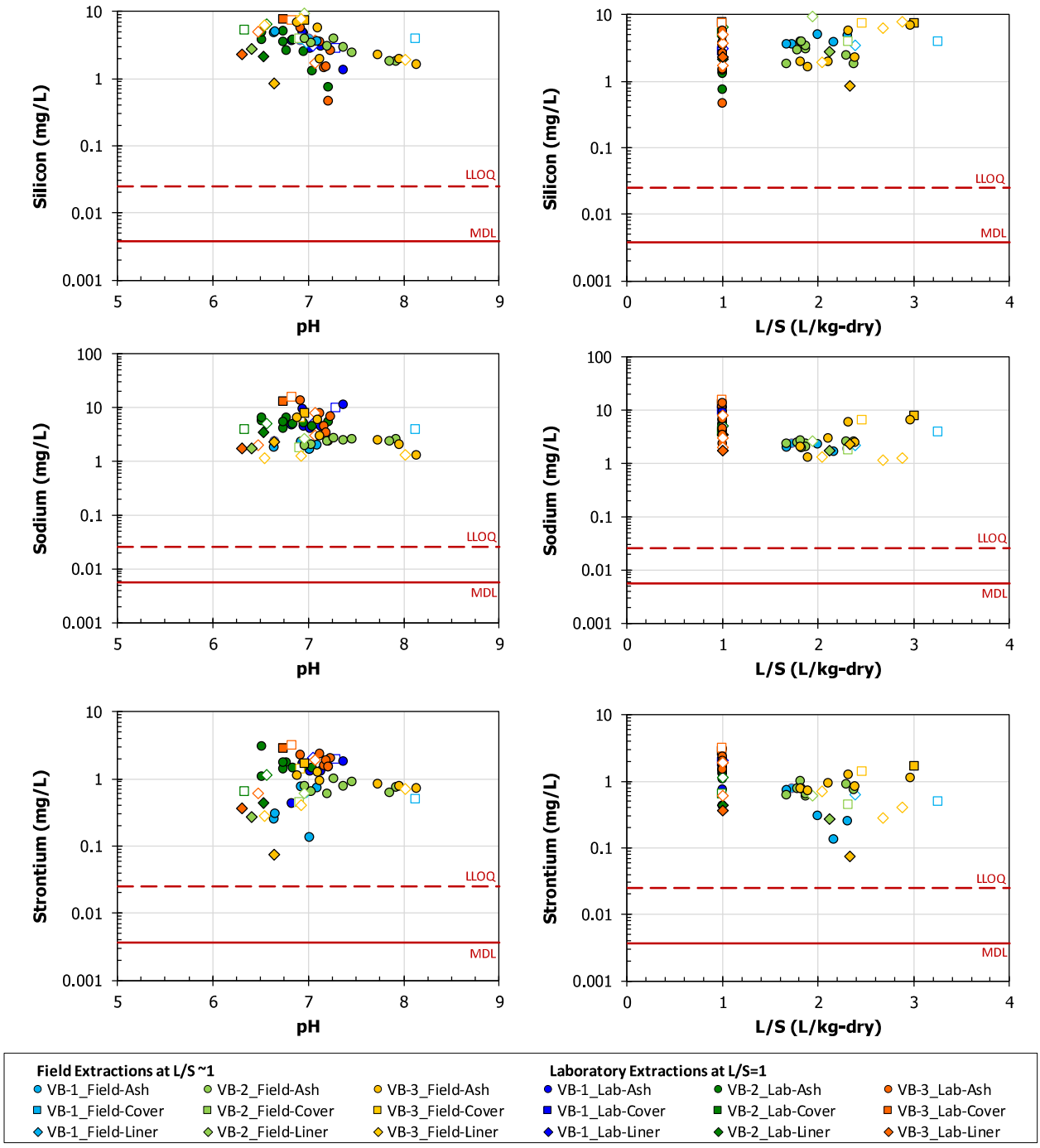


Figure C-8
Comparison of field extractions at L/S~1 (lighter colors) to laboratory extractions at L/S=1 (darker colors) for individual split spoon materials shown as a function of pH (left) and L/S (right): silicon, sodium, and strontium.

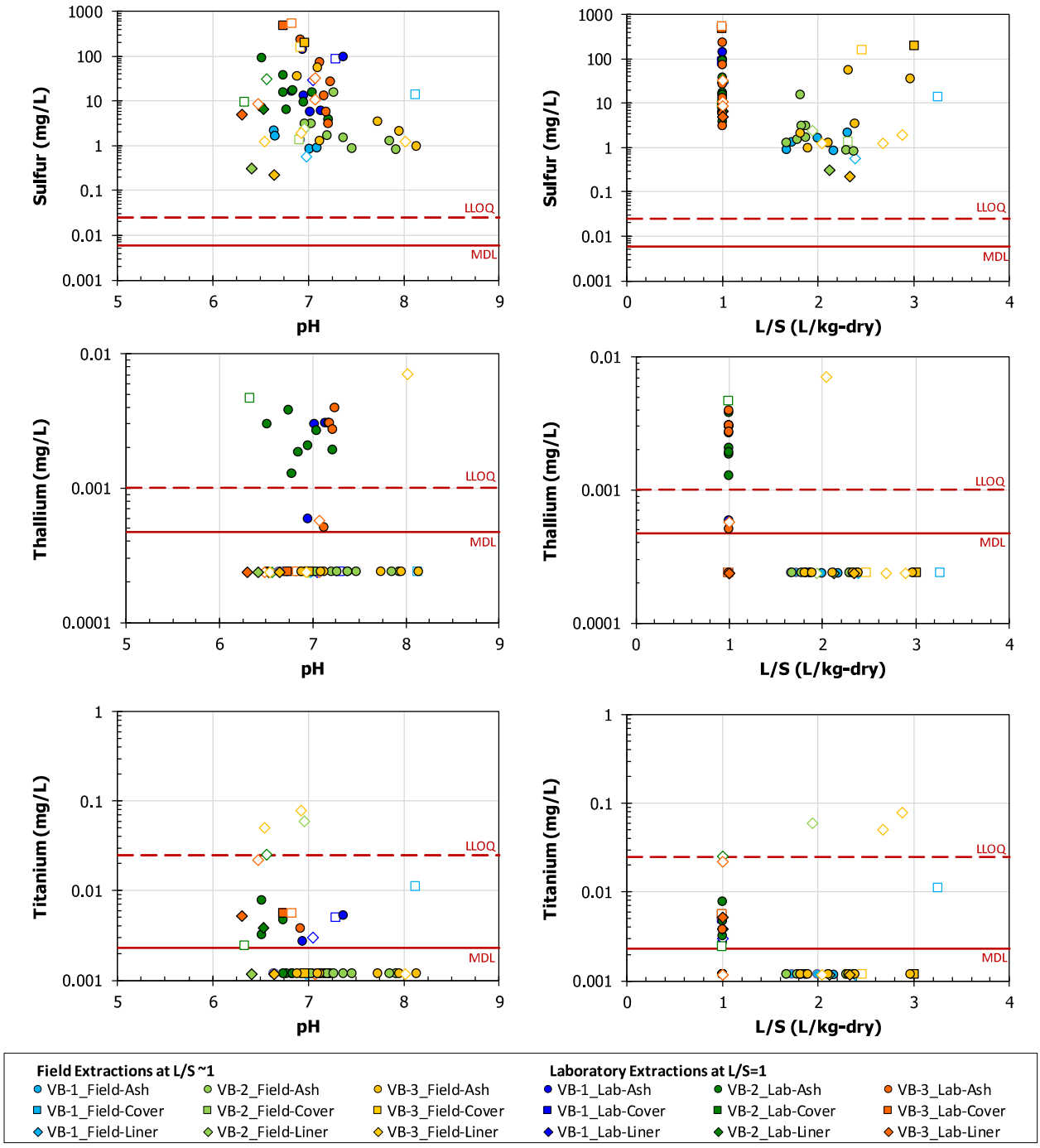


Figure C-9
Comparison of field extractions at L/S~1 (lighter colors) to laboratory extractions at L/S=1 (darker colors) for individual split spoon materials shown as a function of pH (left) and L/S (right): sulfur, thallium, and titanium.

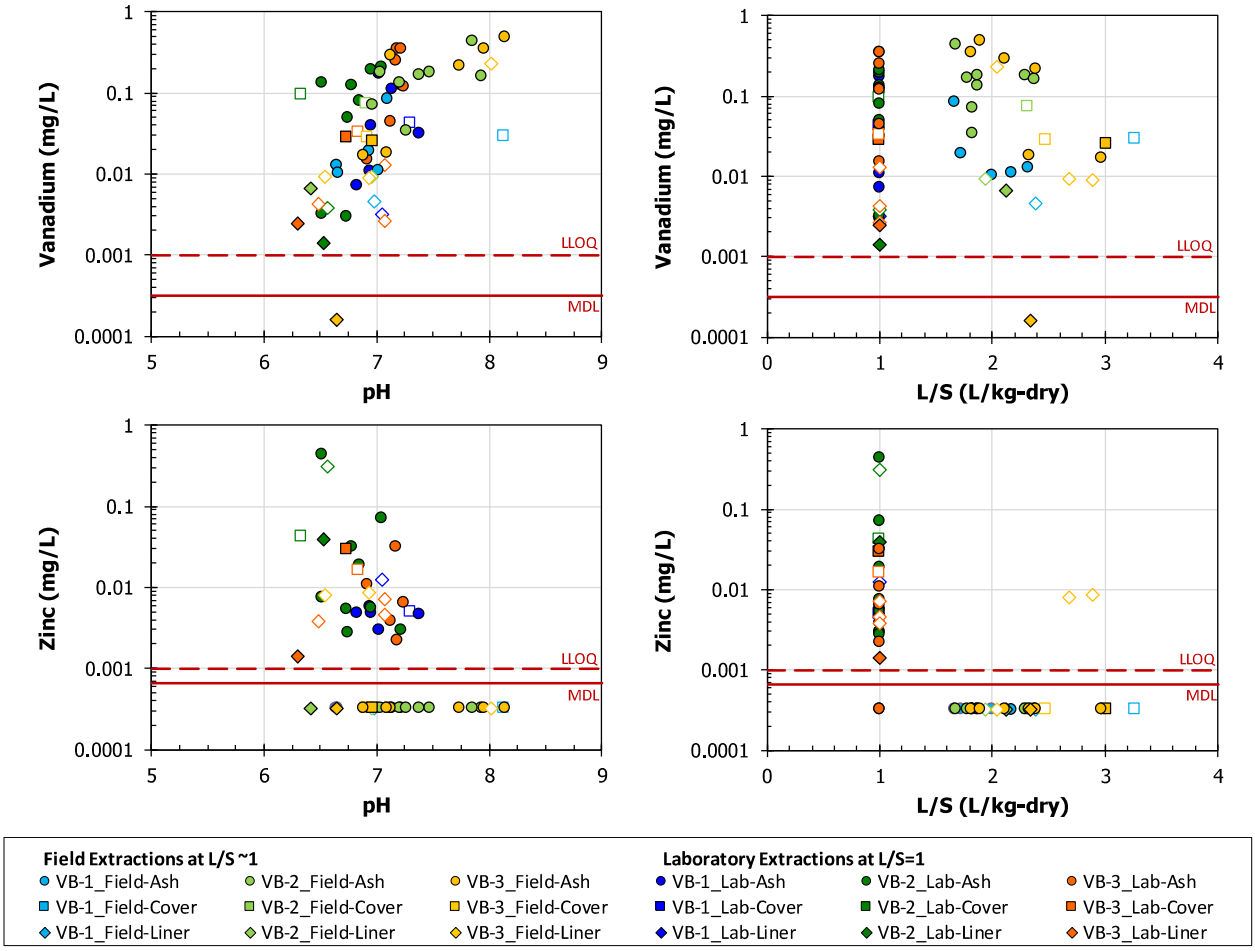


Figure C-10
Comparison of field extractions at L/S~1 (lighter colors) to laboratory extractions at L/S=1 (darker colors) for individual split spoon materials shown as a function of pH (left) and L/S (right): vanadium and zinc.

C.2 Standardized Concentration Profiles from Laboratory Extractions (L/S=1) Using the Global Ash Material Mean and Standard Deviation

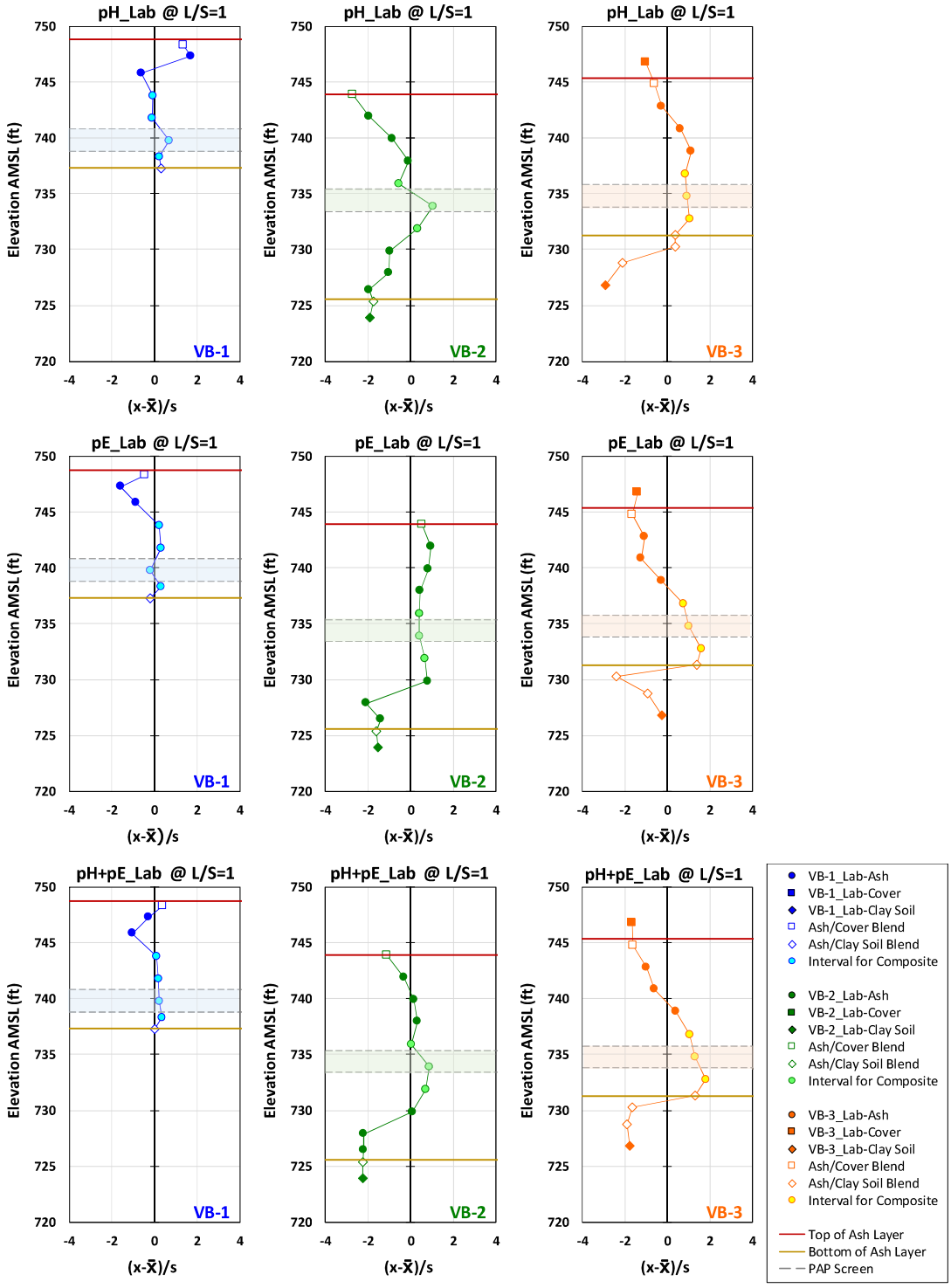


Figure C-11
Concentration profiles from laboratory extractions (L/S=1) standardized using the global ash material mean and standard deviation: pH, pE, and pH+pE.

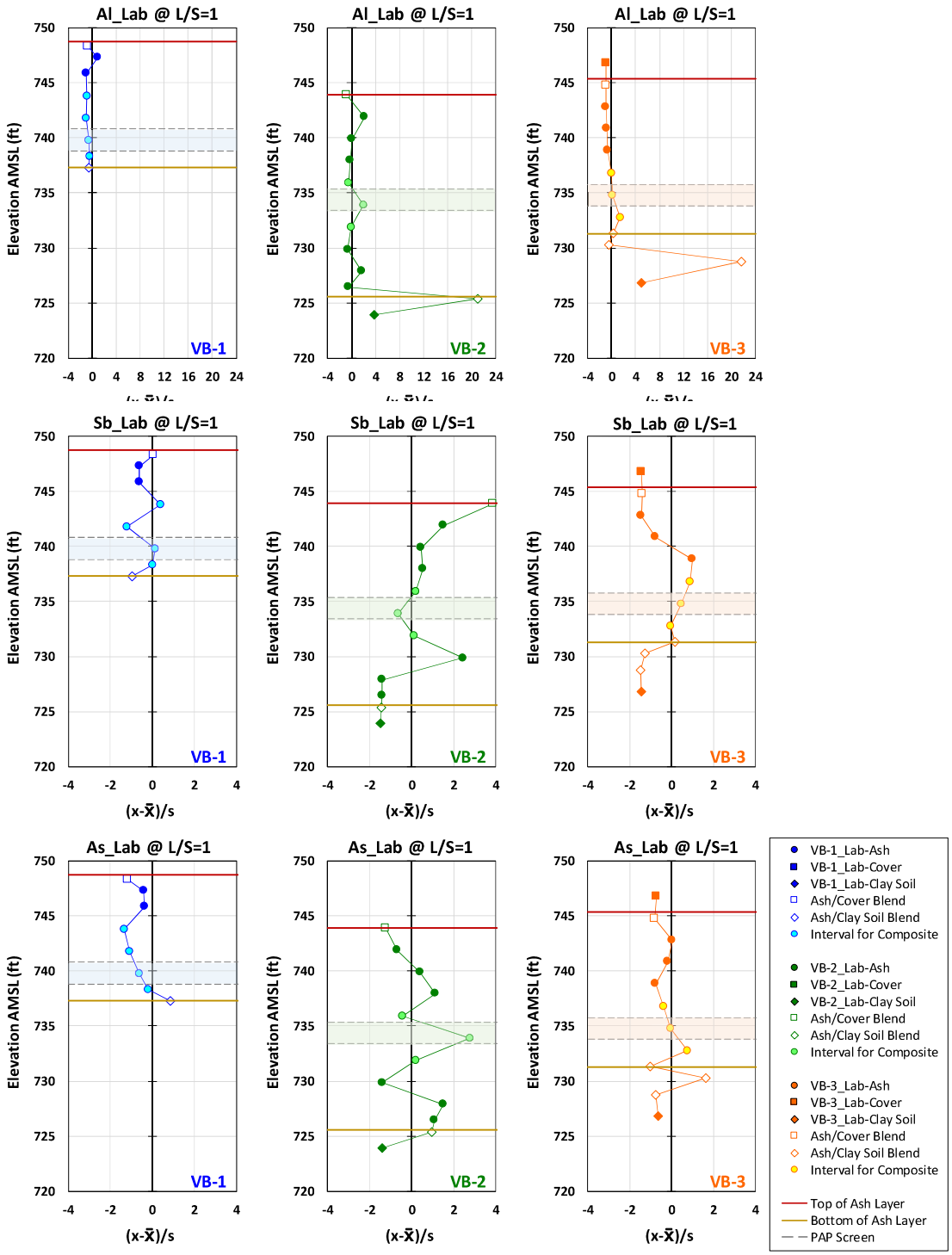


Figure C-12
Concentration profiles from laboratory extractions (L/S=1) standardized using the global ash material mean and standard deviation: aluminum, antimony, and arsenic.

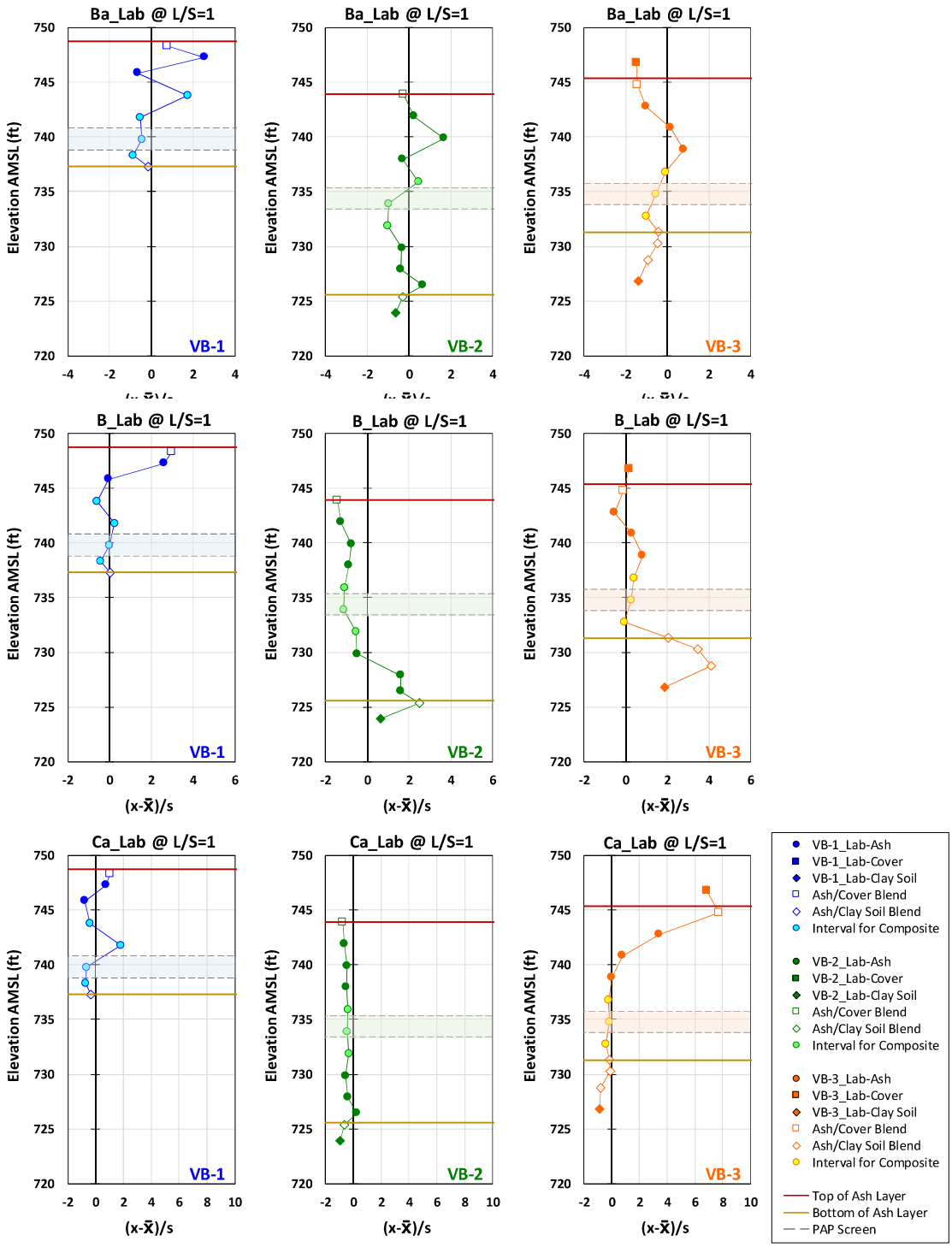


Figure C-13
Concentration profiles from laboratory extractions (L/S=1) standardized using the global ash material mean and standard deviation: barium, boron, and calcium.

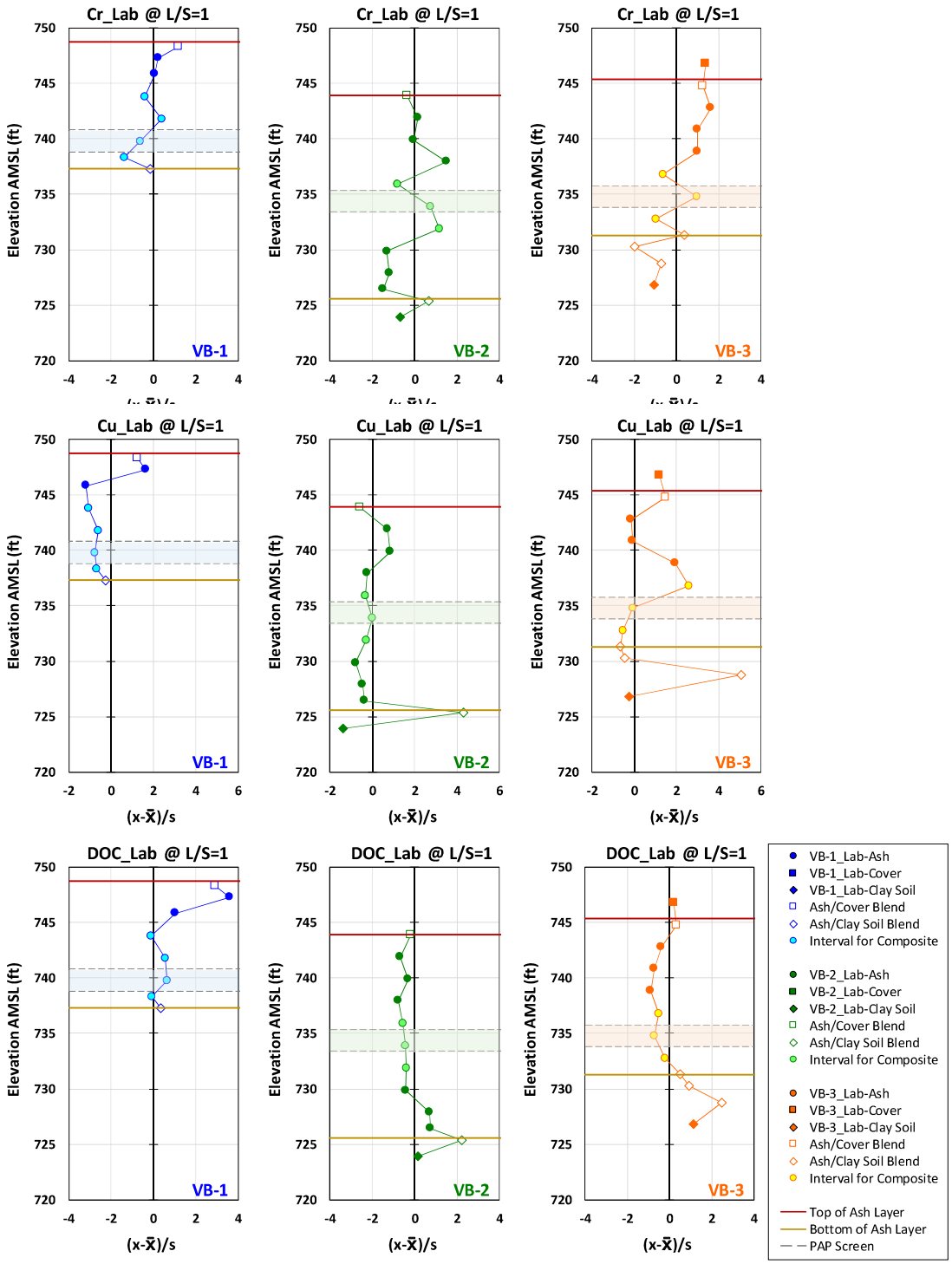


Figure C-14
Concentration profiles from laboratory extractions (L/S=1) standardized using the global ash material mean and standard deviation: chromium, copper, and dissolved organic carbon.

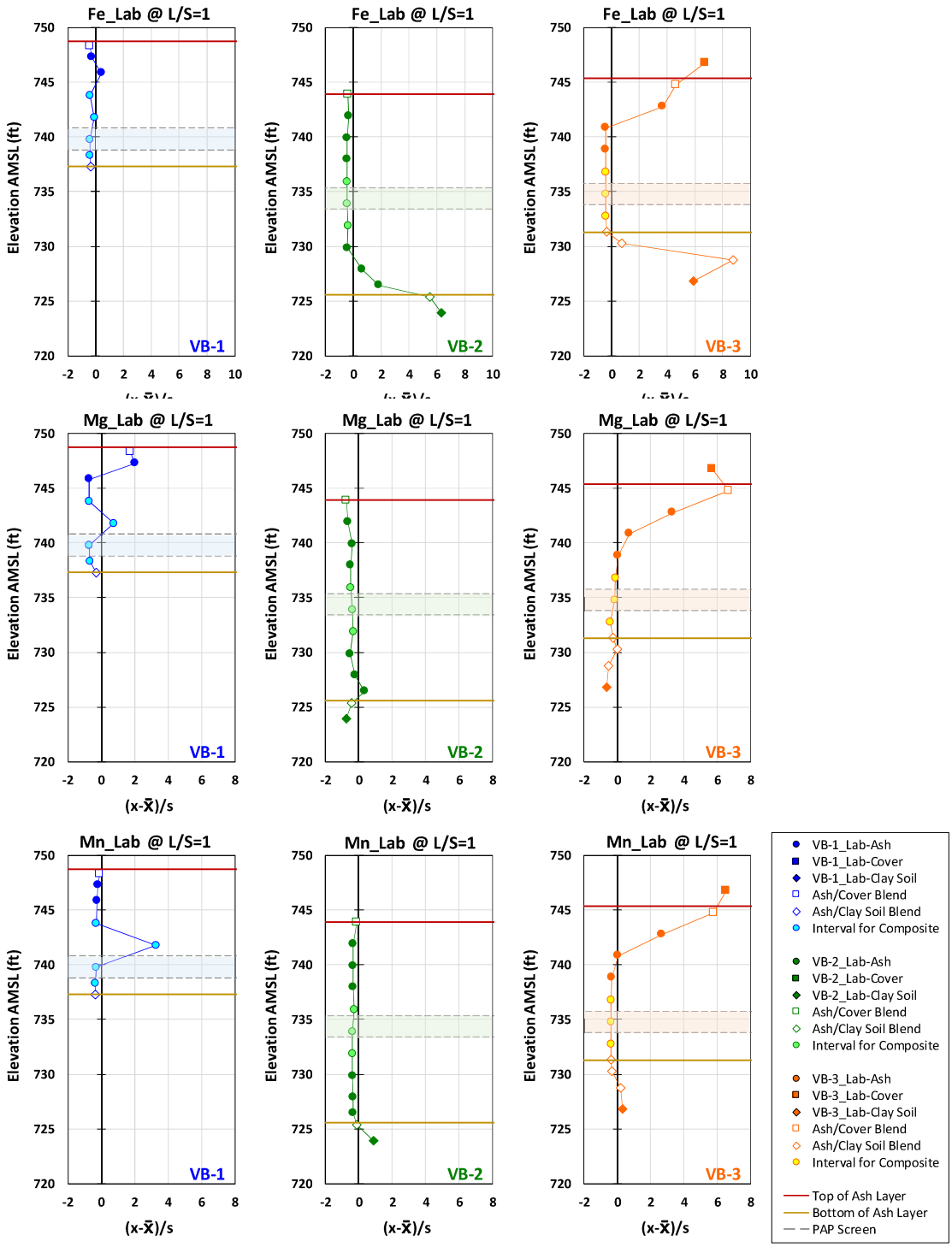


Figure C-15
Concentration profiles from laboratory extractions (L/S=1) standardized using the global ash material mean and standard deviation: iron, magnesium, and manganese.

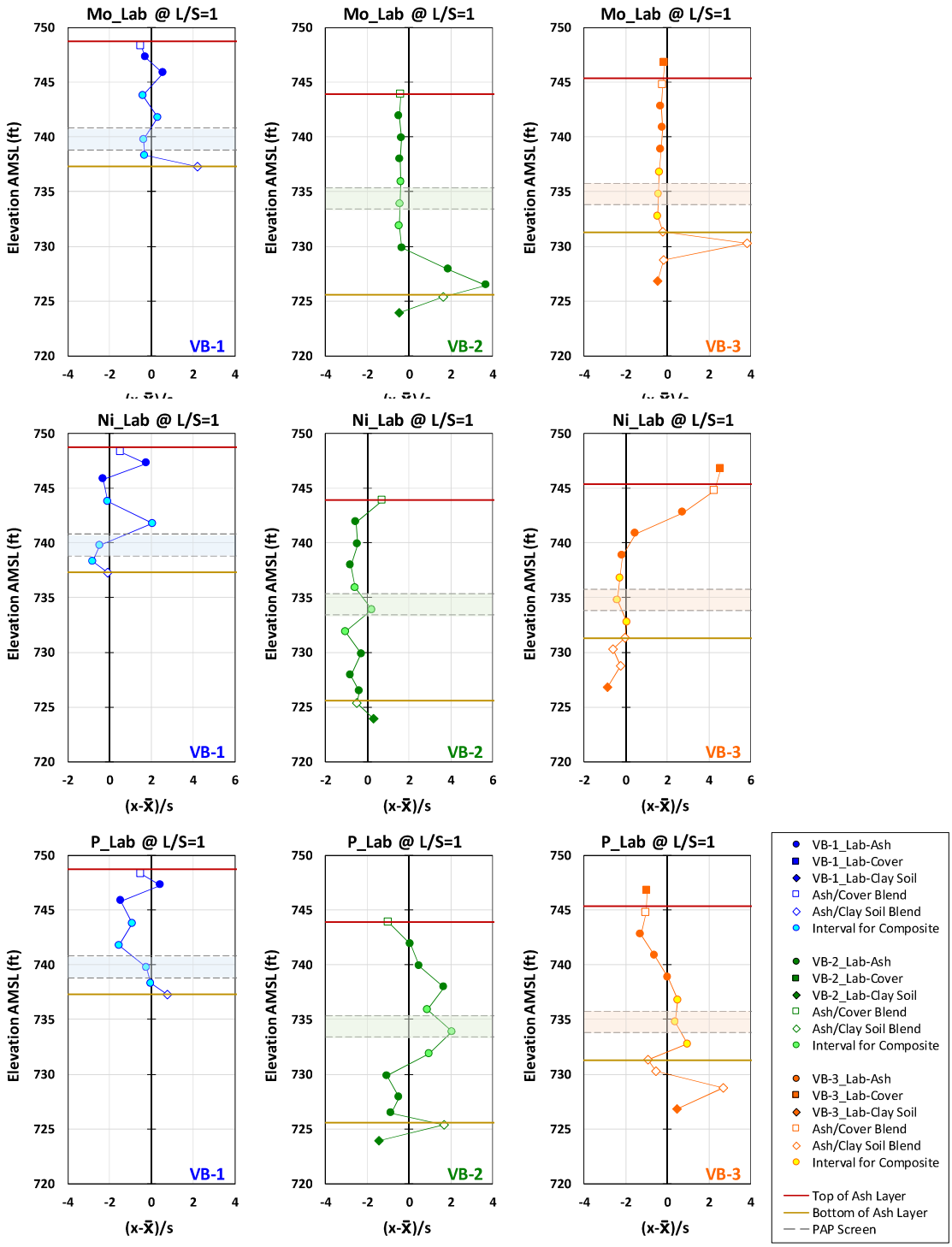


Figure C-16
Concentration profiles from laboratory extractions (L/S=1) standardized using the global ash material mean and standard deviation: molybdenum, nickel, and phosphorus.

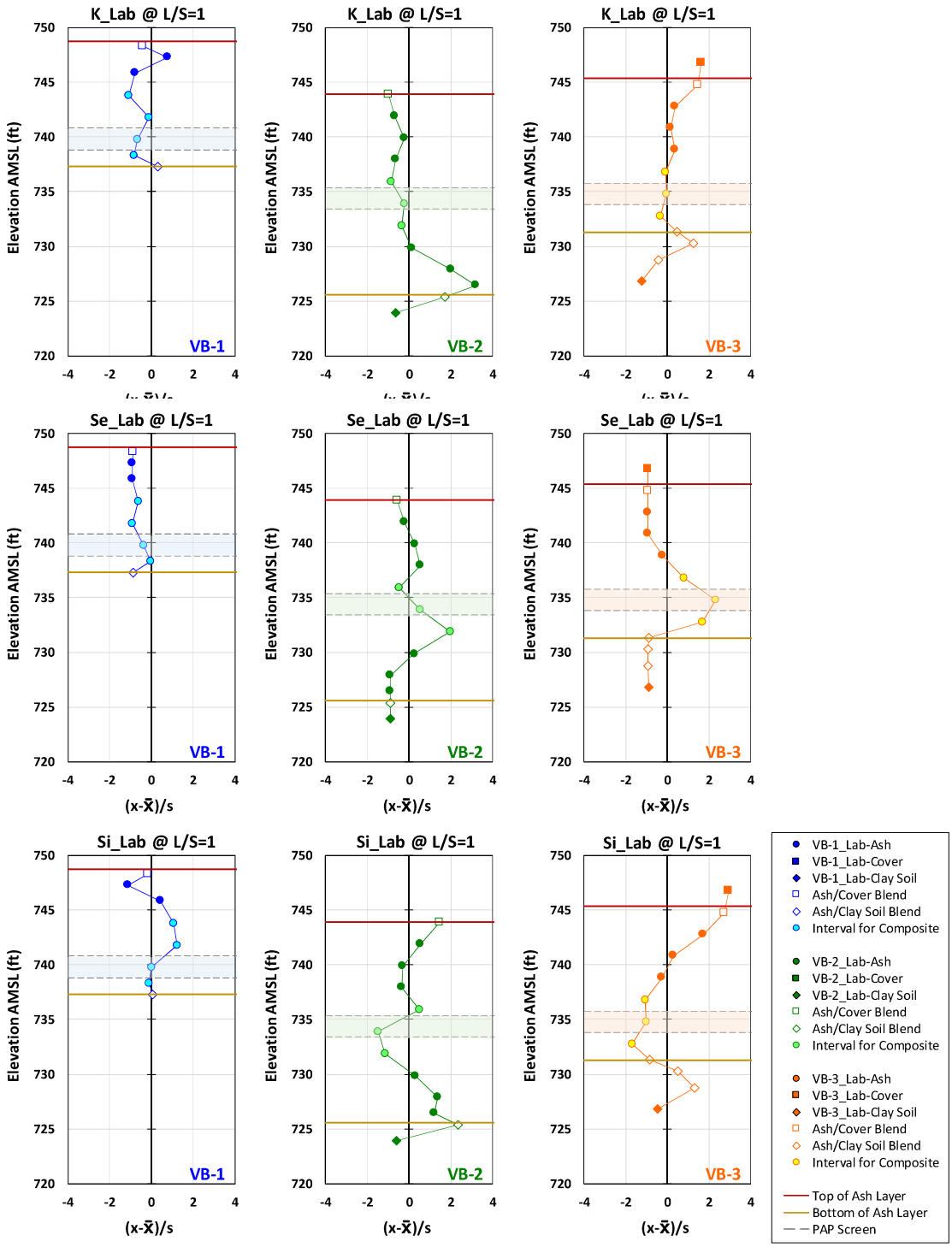


Figure C-17
Concentration profiles from laboratory extractions (L/S=1) standardized using the global ash material mean and standard deviation: potassium, selenium, and silicon.

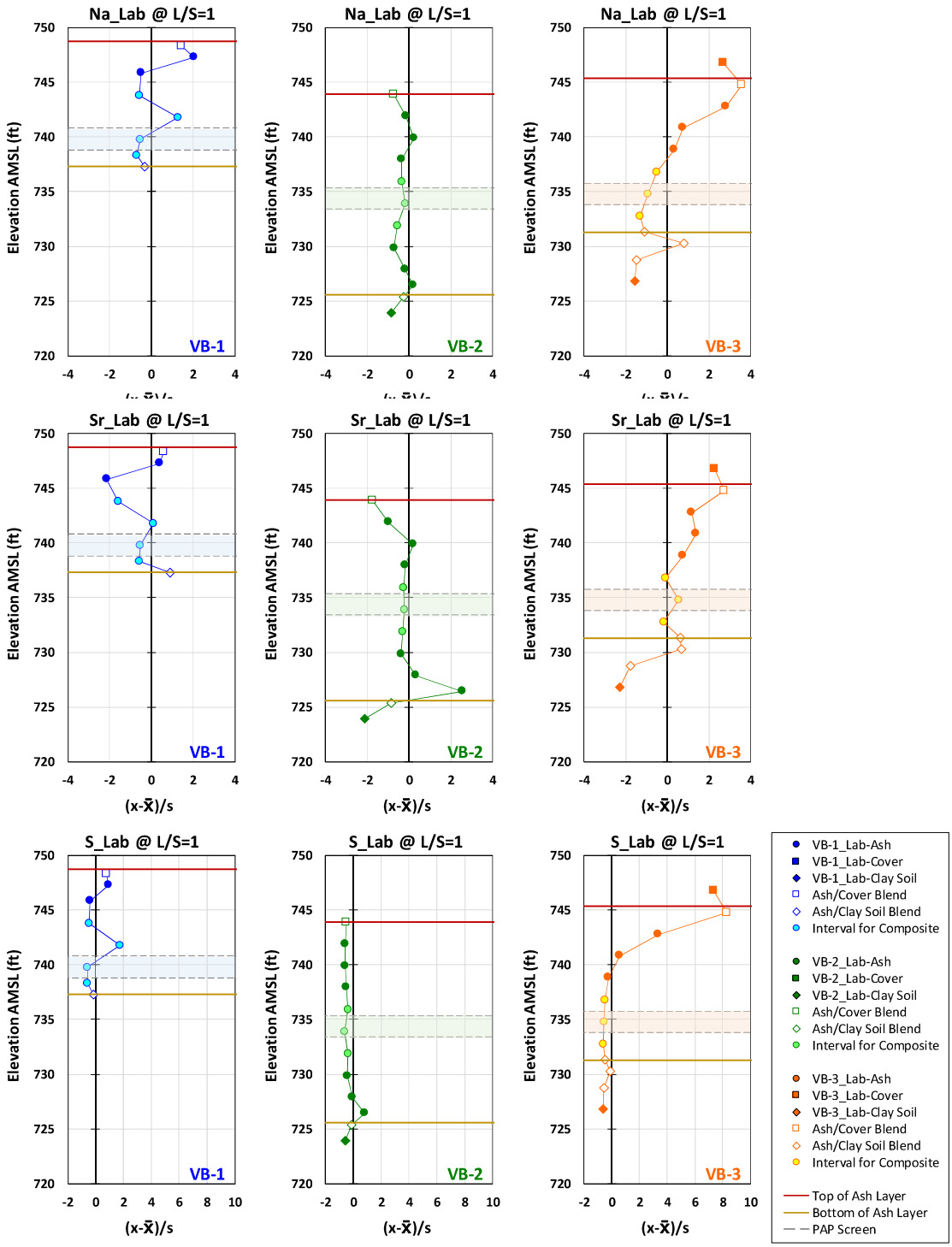


Figure C-18
Concentration profiles from laboratory extractions (L/S=1) standardized using the global ash material mean and standard deviation: sodium, strontium, and sulfur.

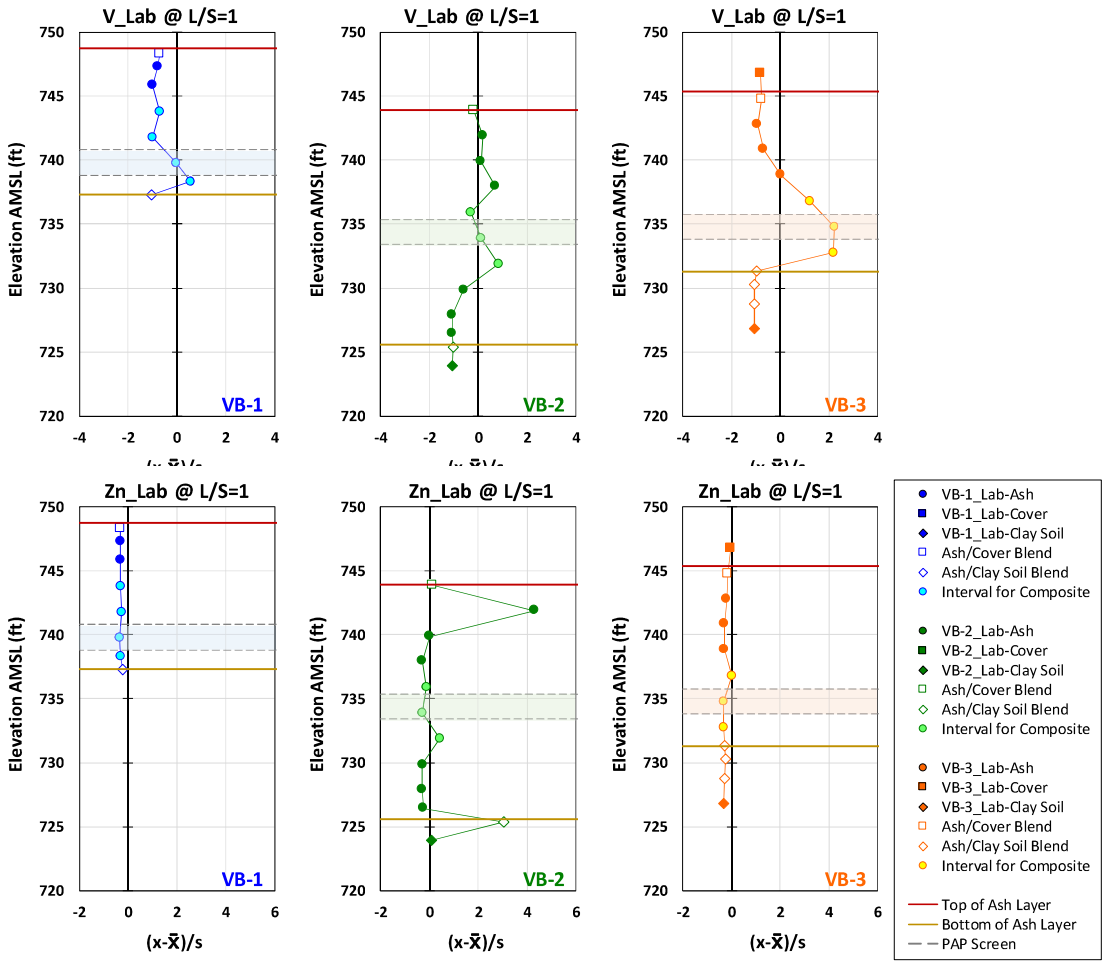


Figure C-19
Concentration profiles from laboratory extractions (L/S=1) standardized using the global ash material mean and standard deviation: vanadium and zinc.

C.3 Comparison of Standardized Release Profiles

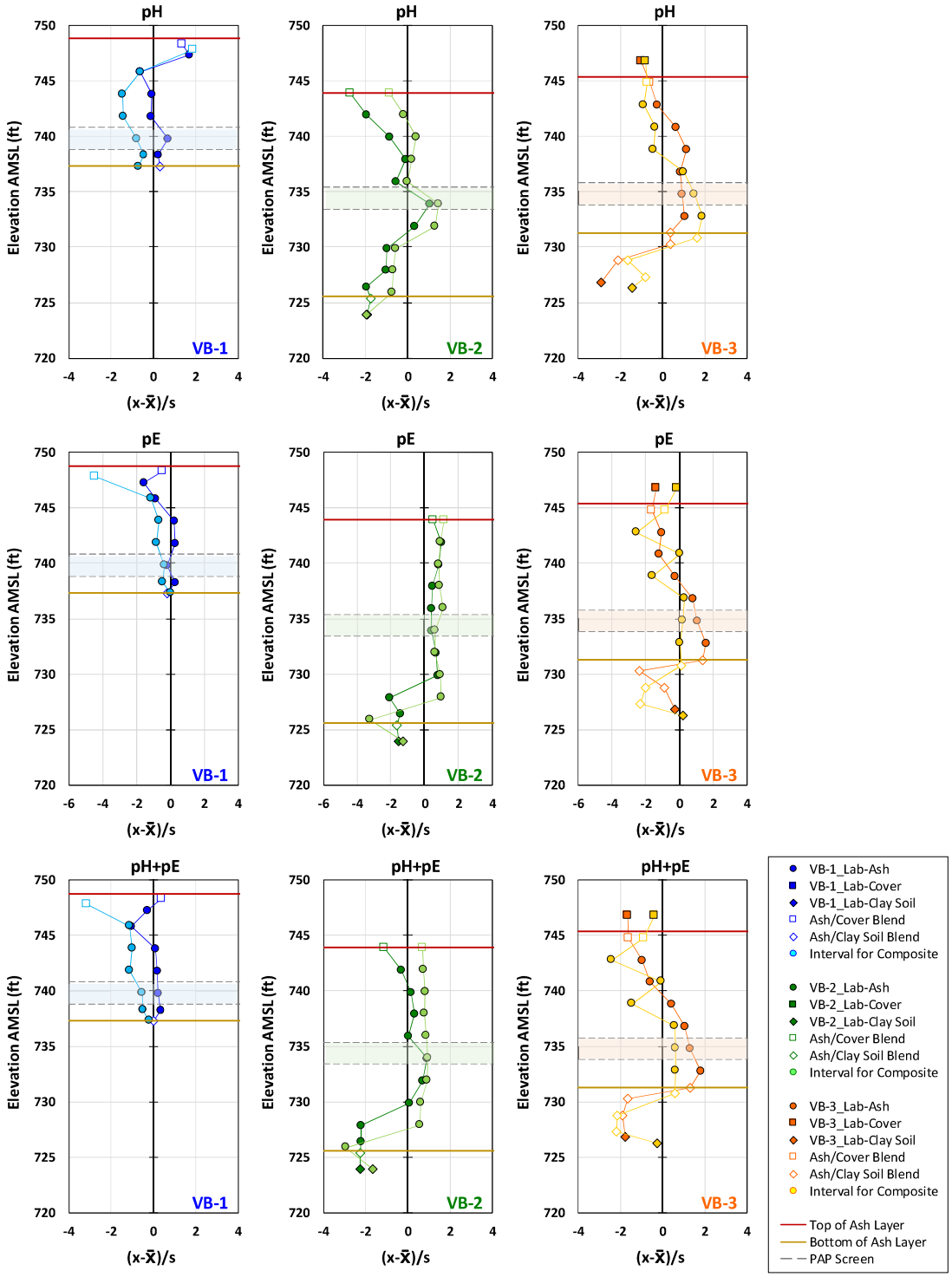


Figure C-20
Comparison of standardized profiles from field extractions (L/S~1) and laboratory extractions (L/S=1): pH, pE, and pH+pE.

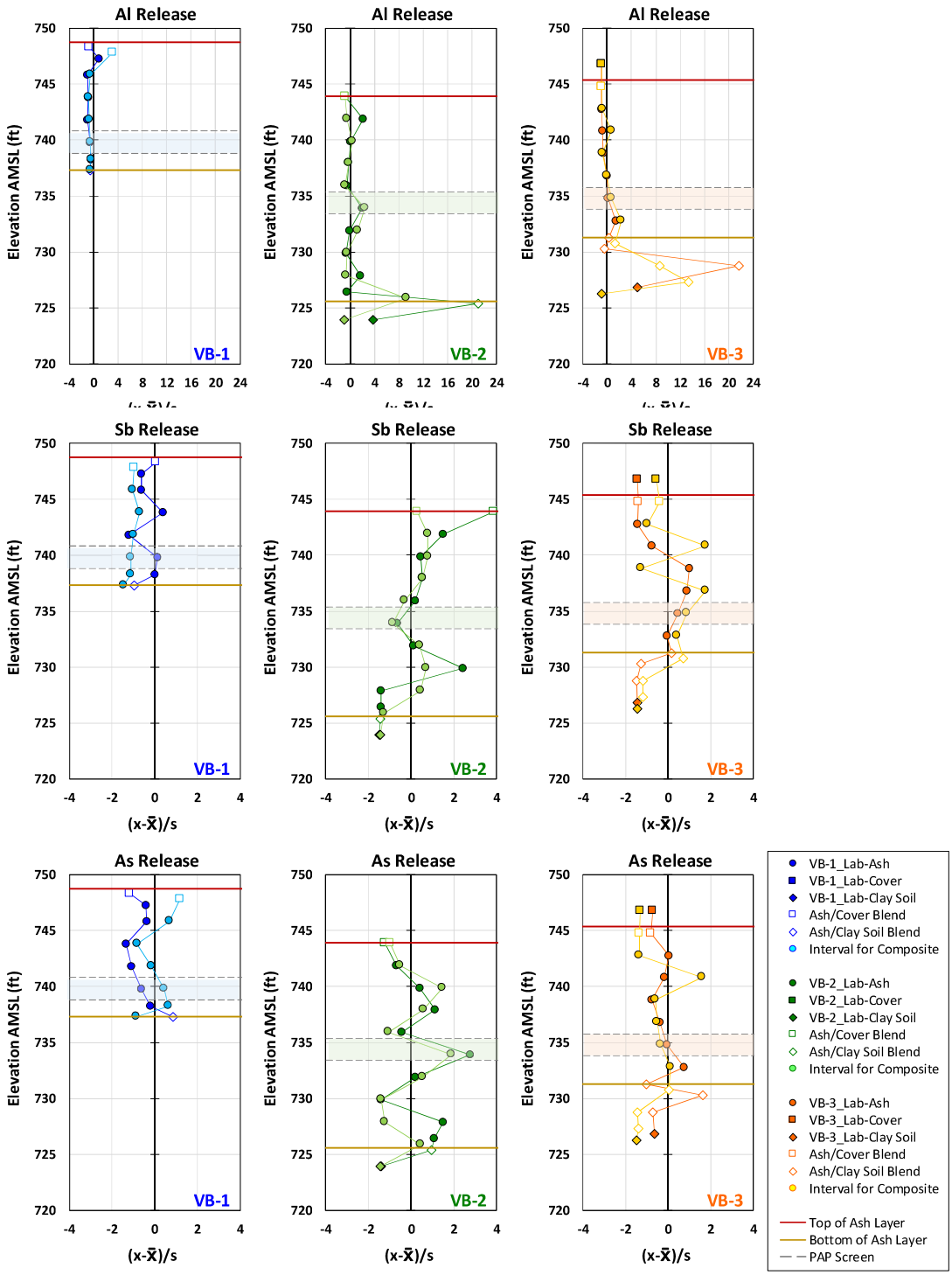


Figure C-21
Comparison of standardized mass release profiles (mg/kg) from field extractions (L/S~1) and laboratory extractions (L/S=1): aluminum, antimony, and arsenic.

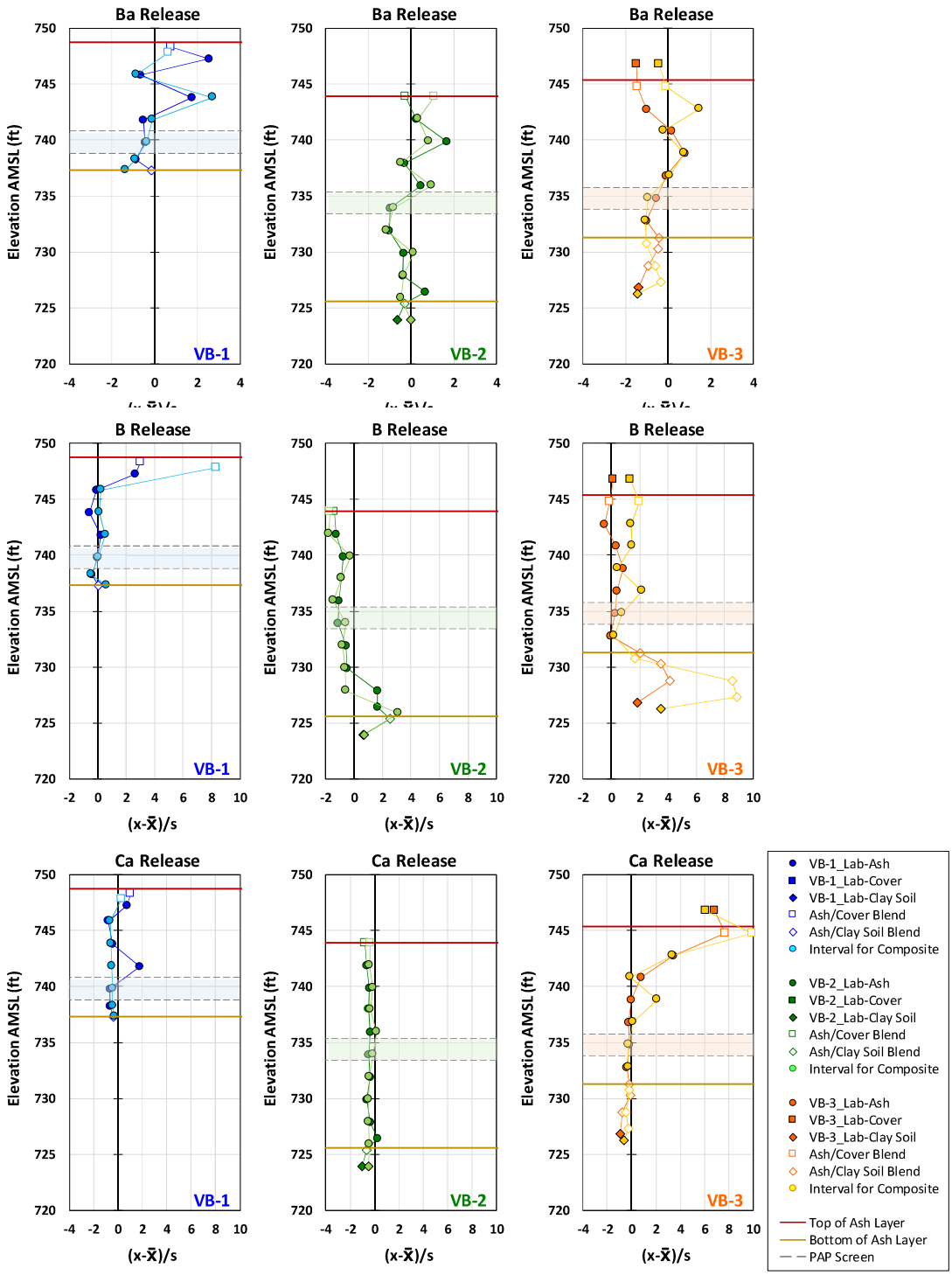


Figure C-22
Comparison of standardized mass release profiles (mg/kg) from field extractions (L/S~1) and laboratory extractions (L/S=1): barium, boron, and calcium.

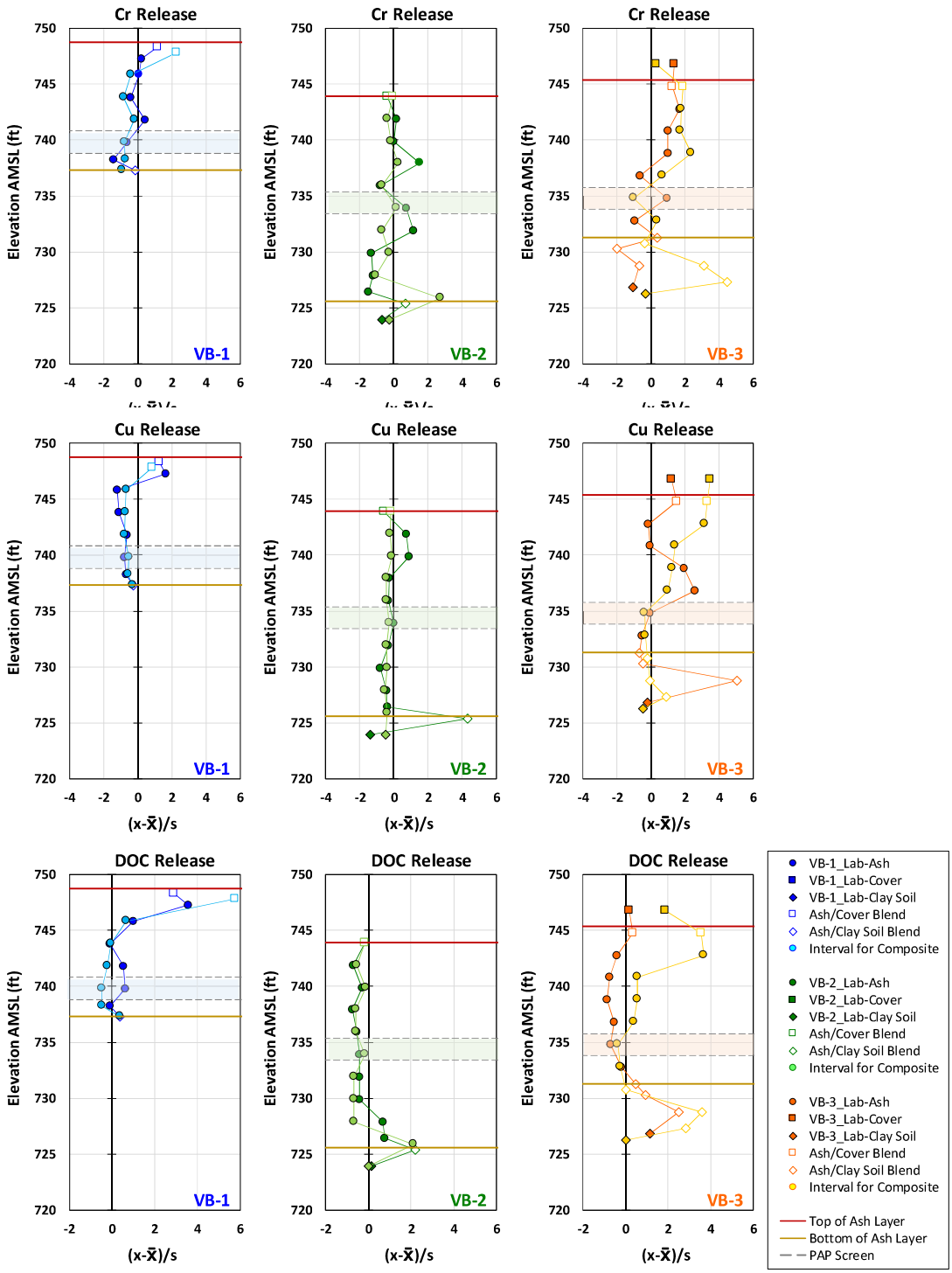


Figure C-23
Comparison of standardized mass release profiles (mg/kg) from field extractions (L/S~1) and laboratory extractions (L/S=1): chromium, copper, and dissolved organic carbon.

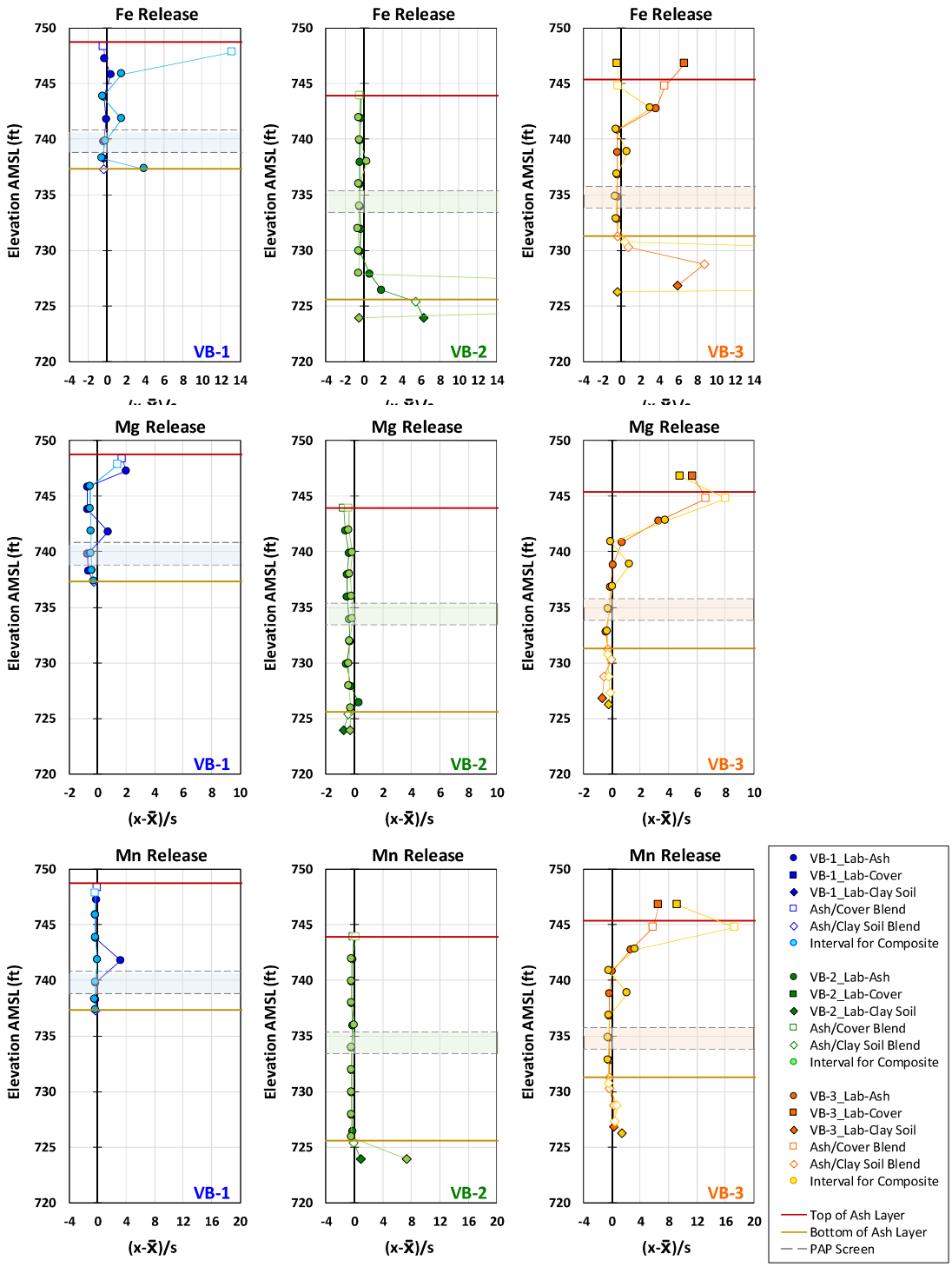


Figure C-24
Comparison of standardized mass release profiles (mg/kg) from field extractions (L/S~1) and laboratory extractions (L/S=1): iron, magnesium, and manganese.

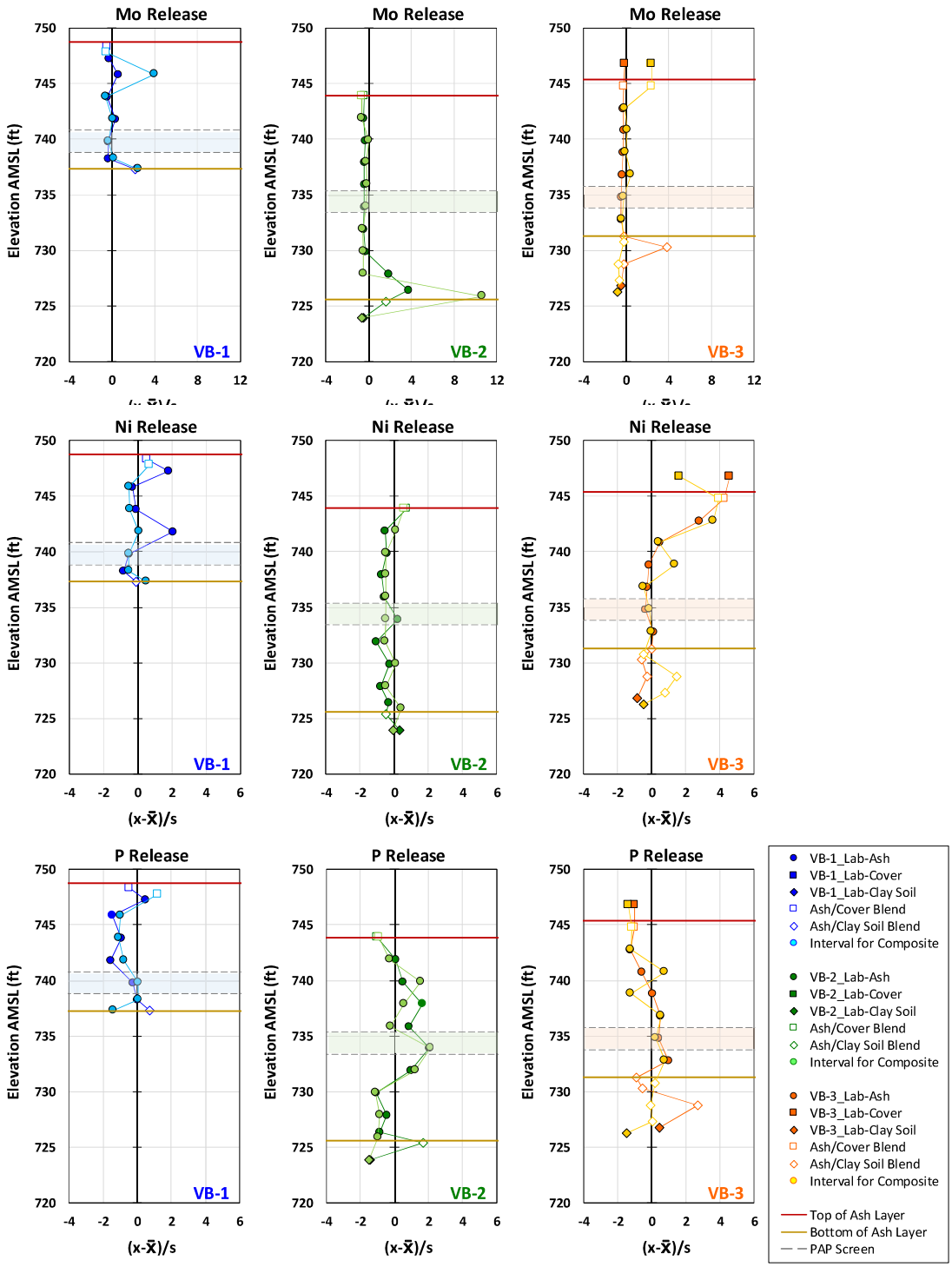


Figure C-25
Comparison of standardized mass release profiles (mg/kg) from field extractions (L/S~1) and laboratory extractions (L/S=1): molybdenum, nickel, and phosphorus.

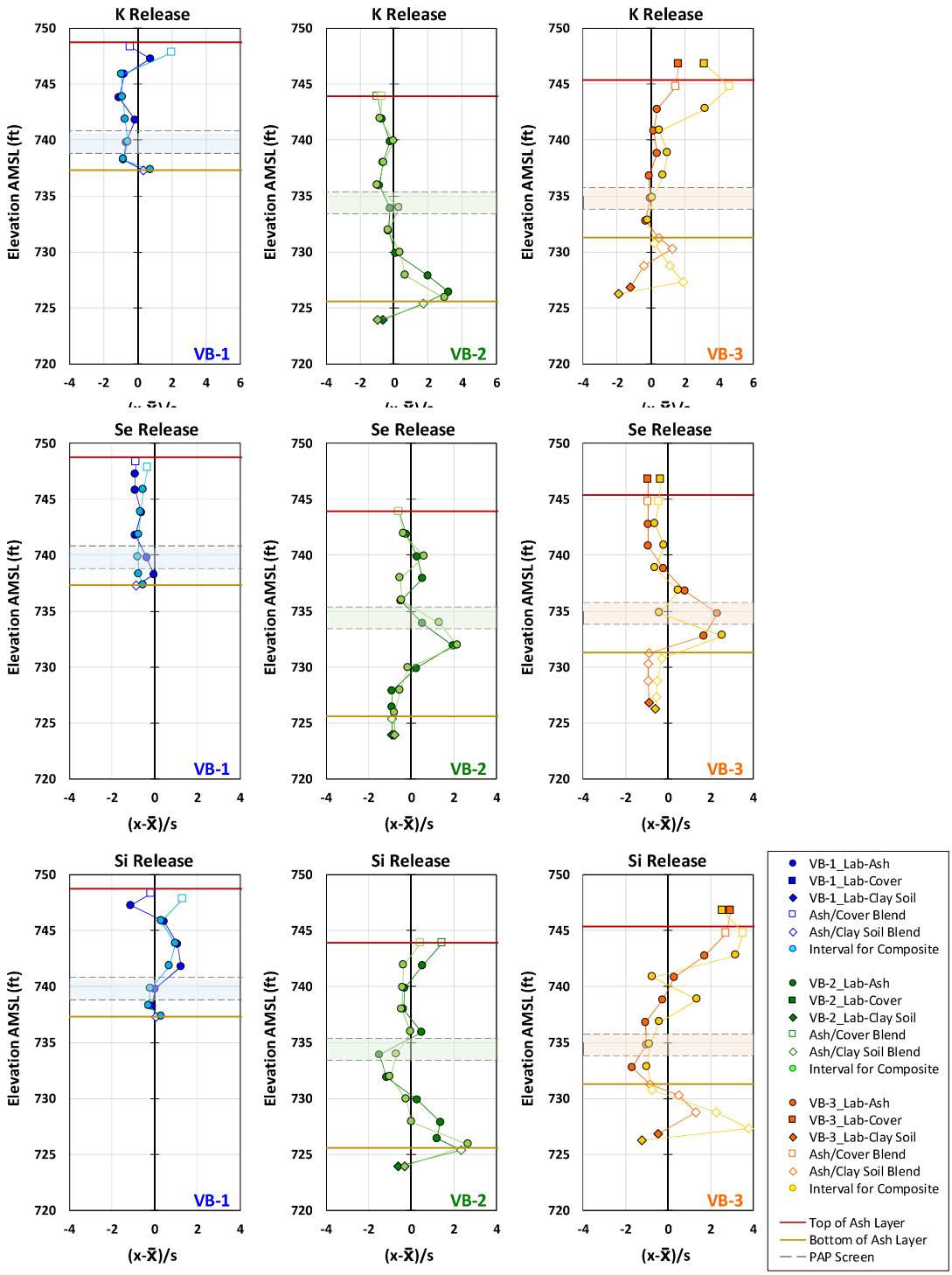


Figure C-26
Comparison of standardized mass release profiles (mg/kg) from field extractions (L/S~1) and laboratory extractions (L/S=1): potassium, selenium, and silicon.

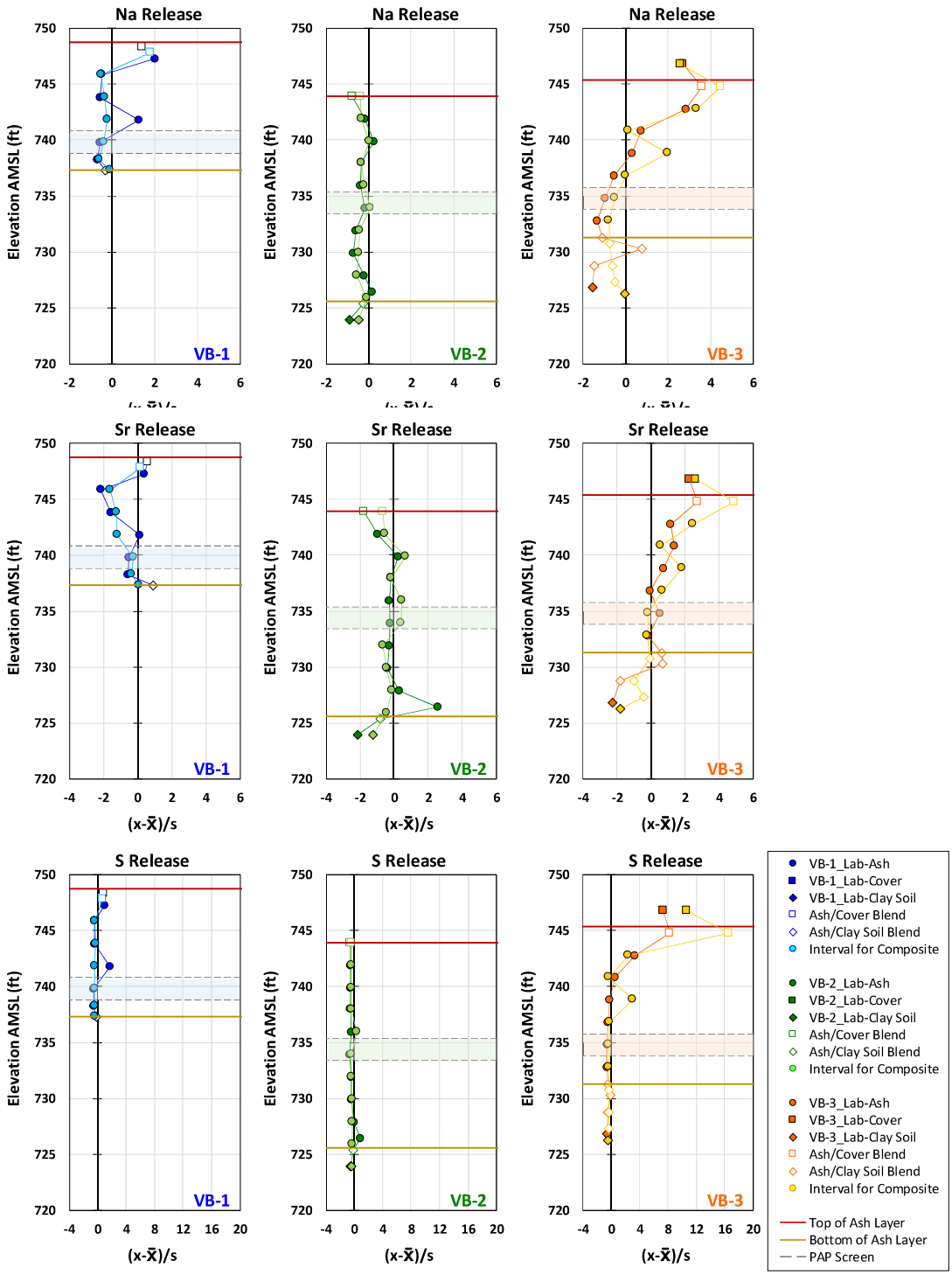


Figure C-27
Comparison of standardized mass release profiles (mg/kg) from field extractions (L/S~1) and laboratory extractions (L/S=1): sodium, strontium, and sulfur.

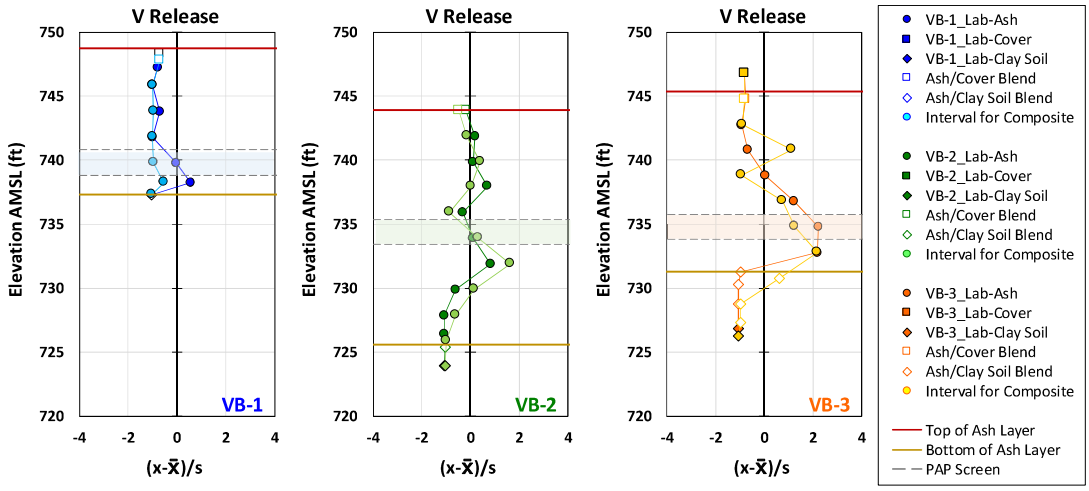


Figure C-28
Comparison of standardized mass release profiles (mg/kg) from field extractions (L/S~1) and laboratory extractions (L/S=1): vanadium.

D
LEAF TEST RESULTS ON COMPOSITE SAMPLES

Table of Appendices

D.1 pH- and L/S-Dependent Test Results

The following graphs present the results of pH-dependent tests (i.e., EPA Method 1313 and the low L/S-modified 1313) and L/S-dependent test (i.e., EPA Method 1314) on composite samples from split spoon samples taken from three boreholes at the closed KSP impoundment. These figures show the following data for three composites of coal ash:

a) eluate concentration in mg/L as a function of pH (top, left),

b) eluate concentration in mg/L as a function of L/S (top, right),

c) mass release in mg/kg-dry as a function of pH (middle, left) including available content, derived from the maximum concentration in the 1313 LSP curve,

d) cumulative mass release in mg/kg-dry as a function of cumulative L/S (middle, right),

e) acid/base neutralization capacity (ANC/BNC) of the composite material as a function of pH, and

f) evolution of eluate pH from the percolation column test.

D.2 Comparison of Individual Split Spoon and Composite Sample Data

D.1 pH- and L/S-Dependent Test Results

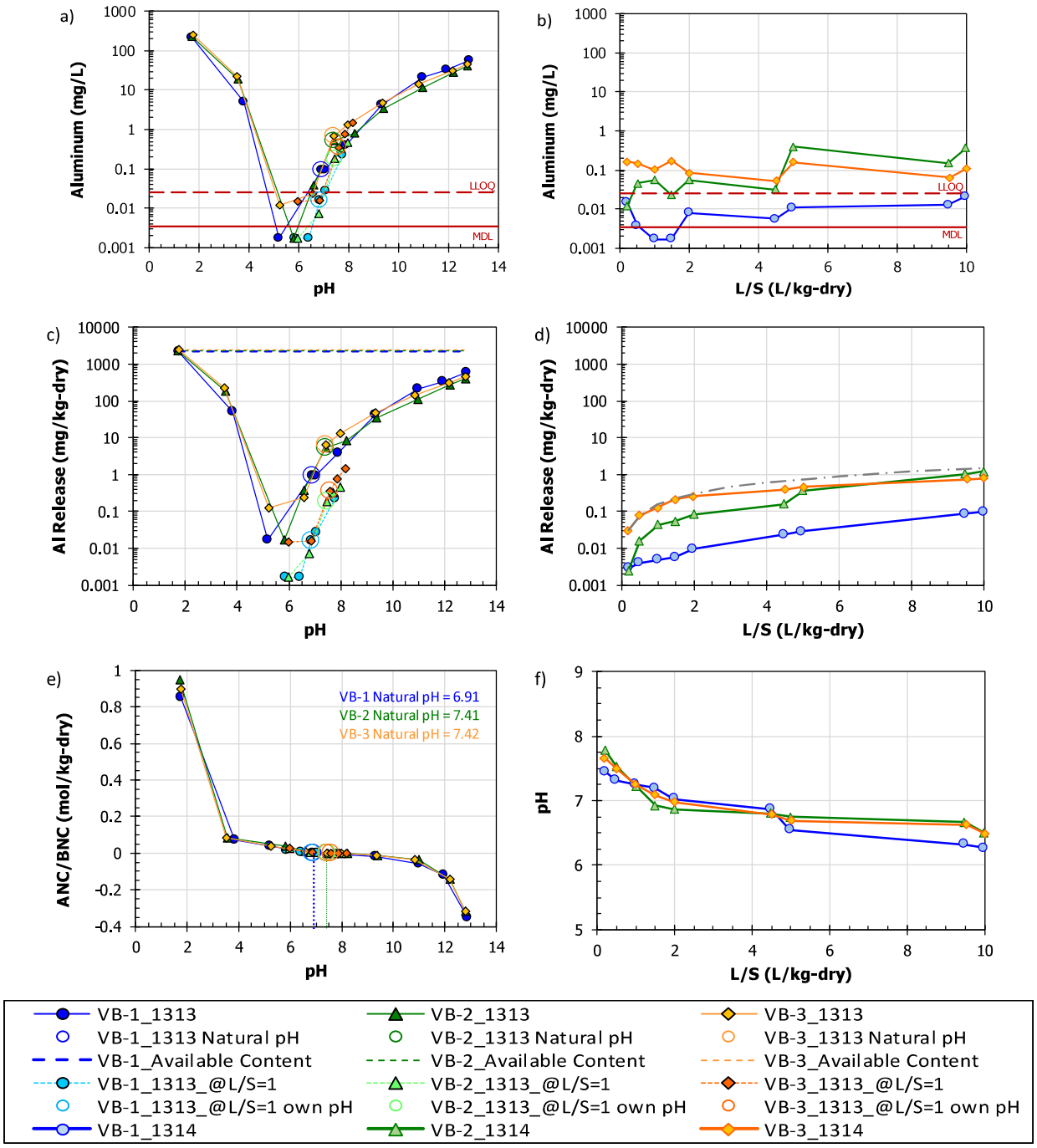


Figure D-1
Aluminum LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

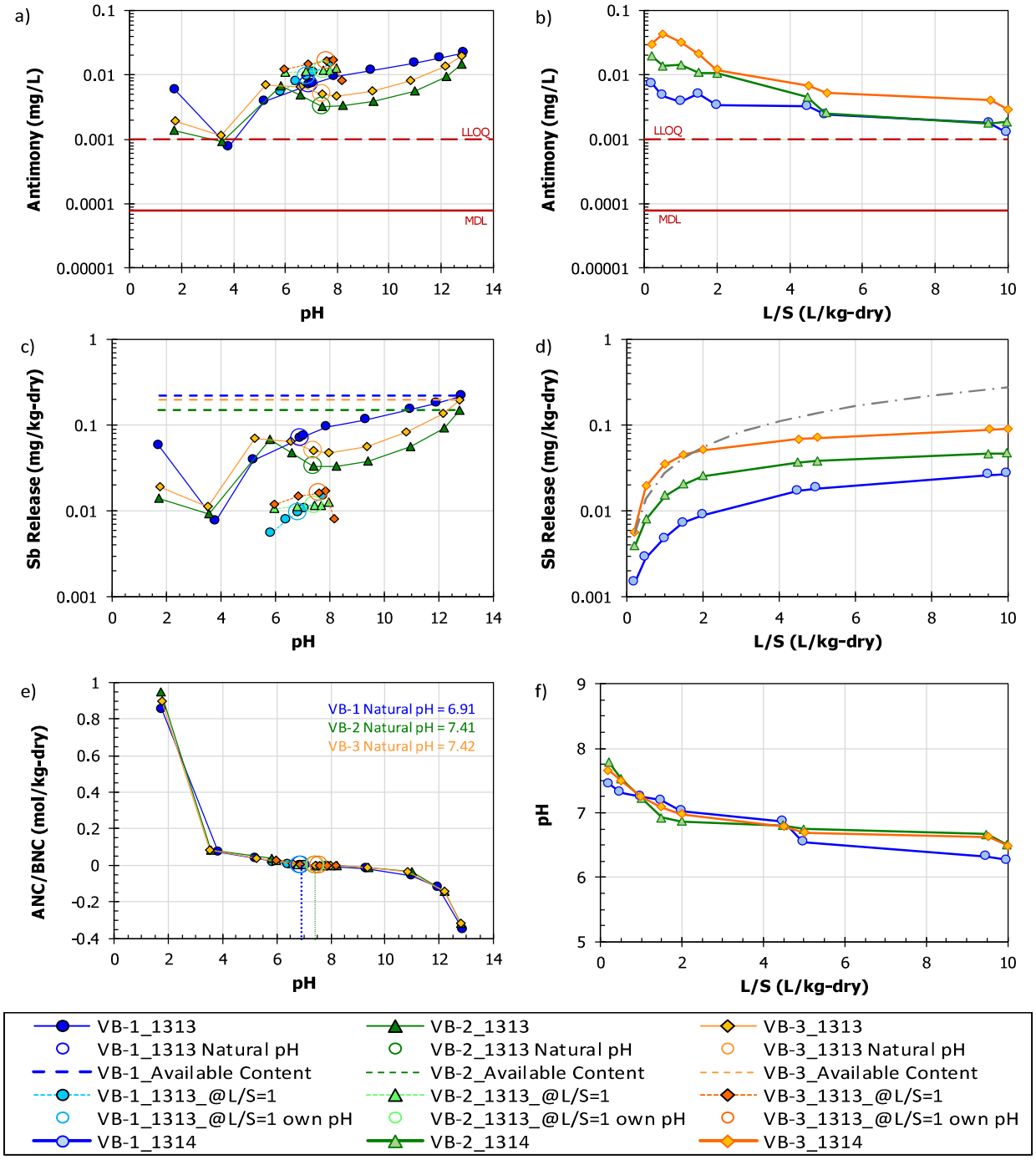


Figure D-2
Antimony LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

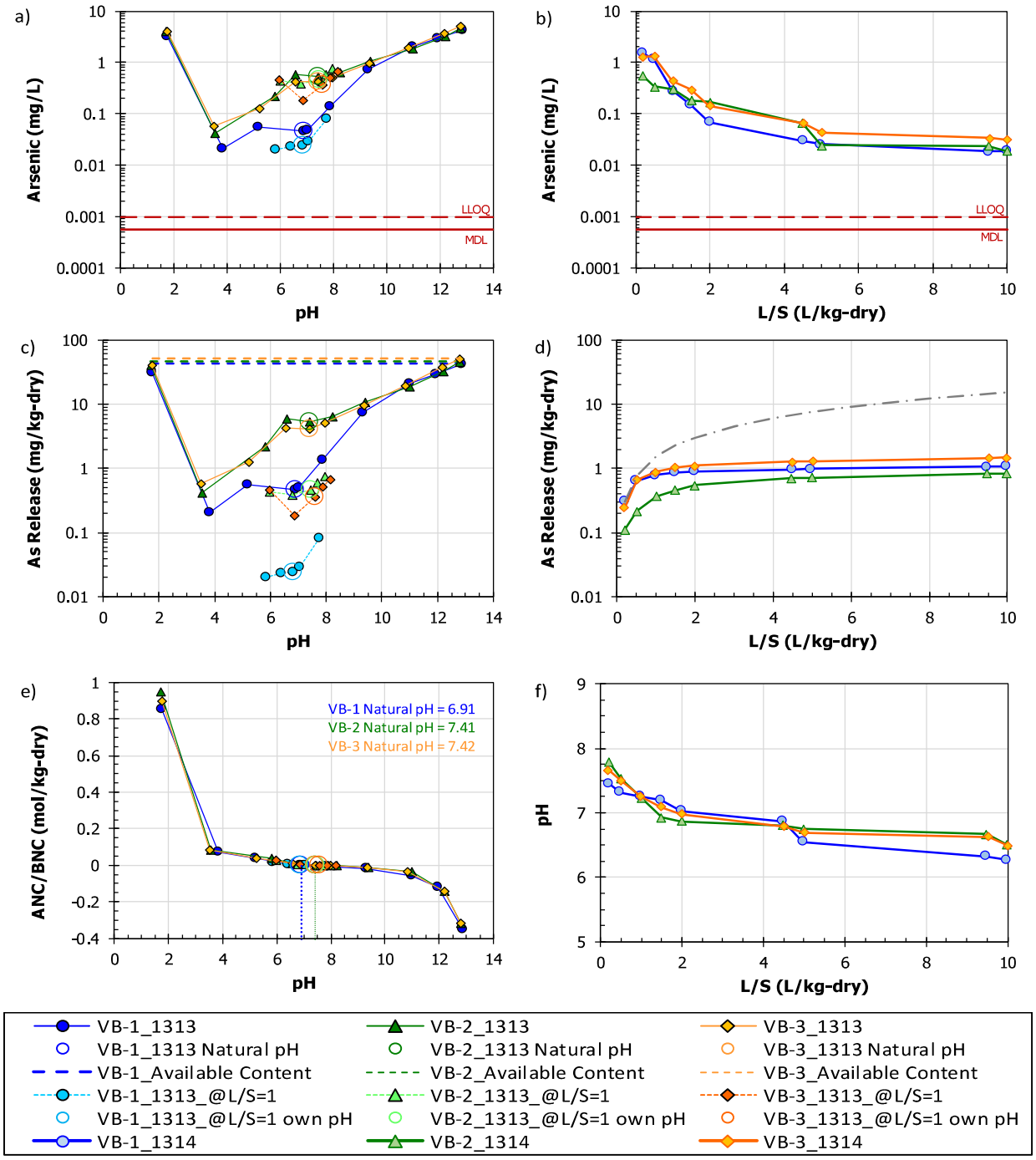


Figure D-3
Arsenic LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

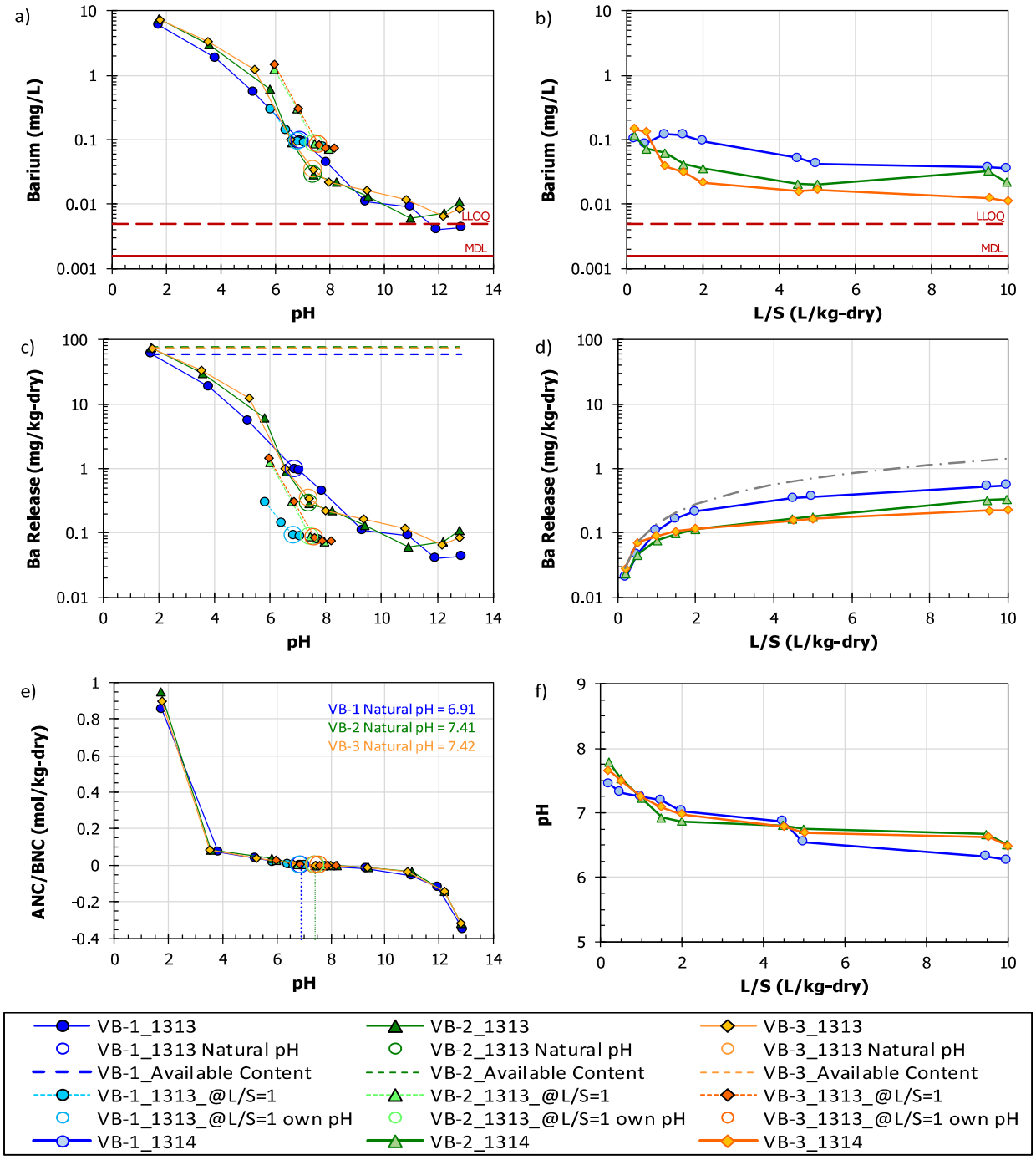


Figure D-4
Barium LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

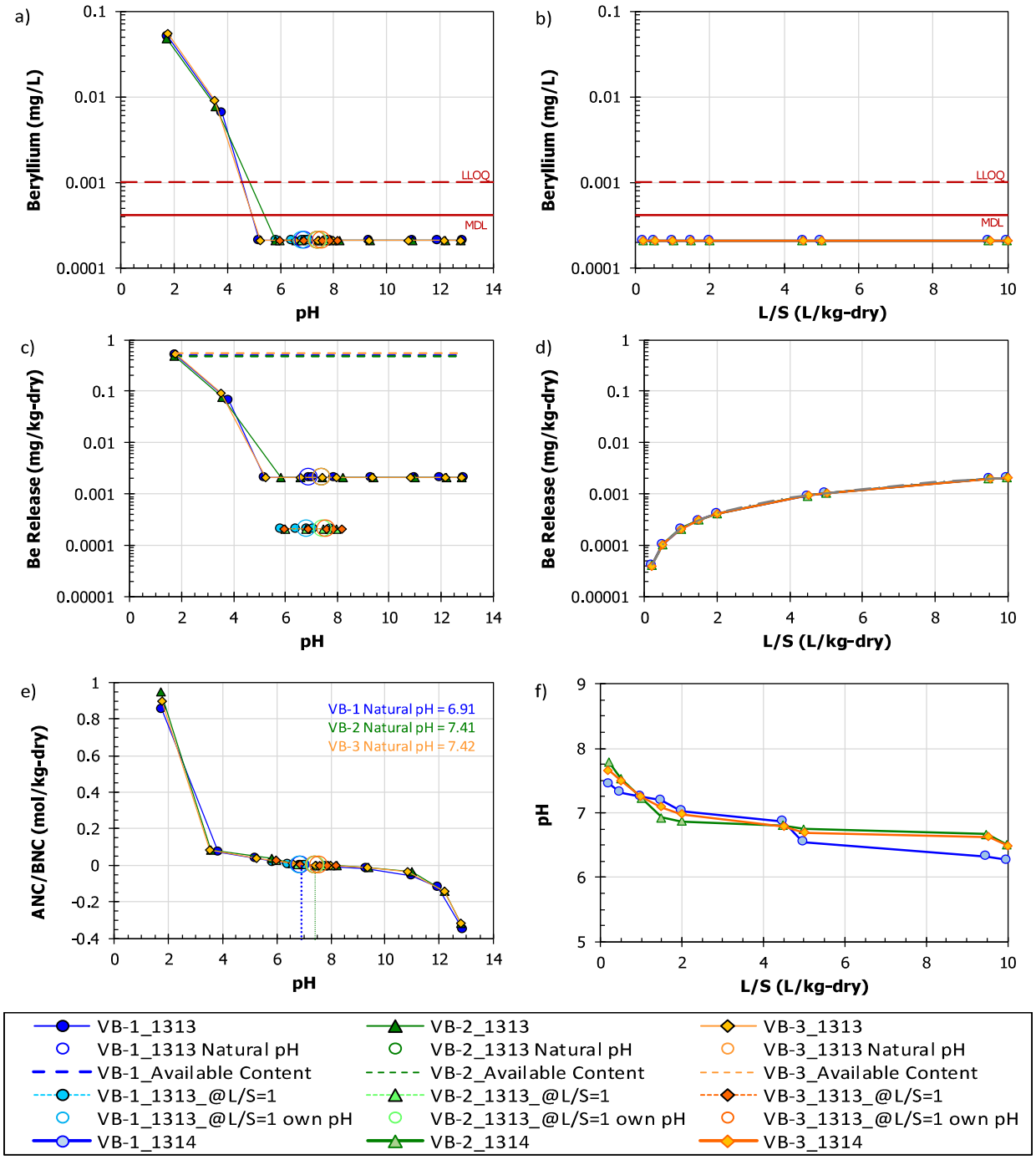


Figure D-5
Beryllium LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

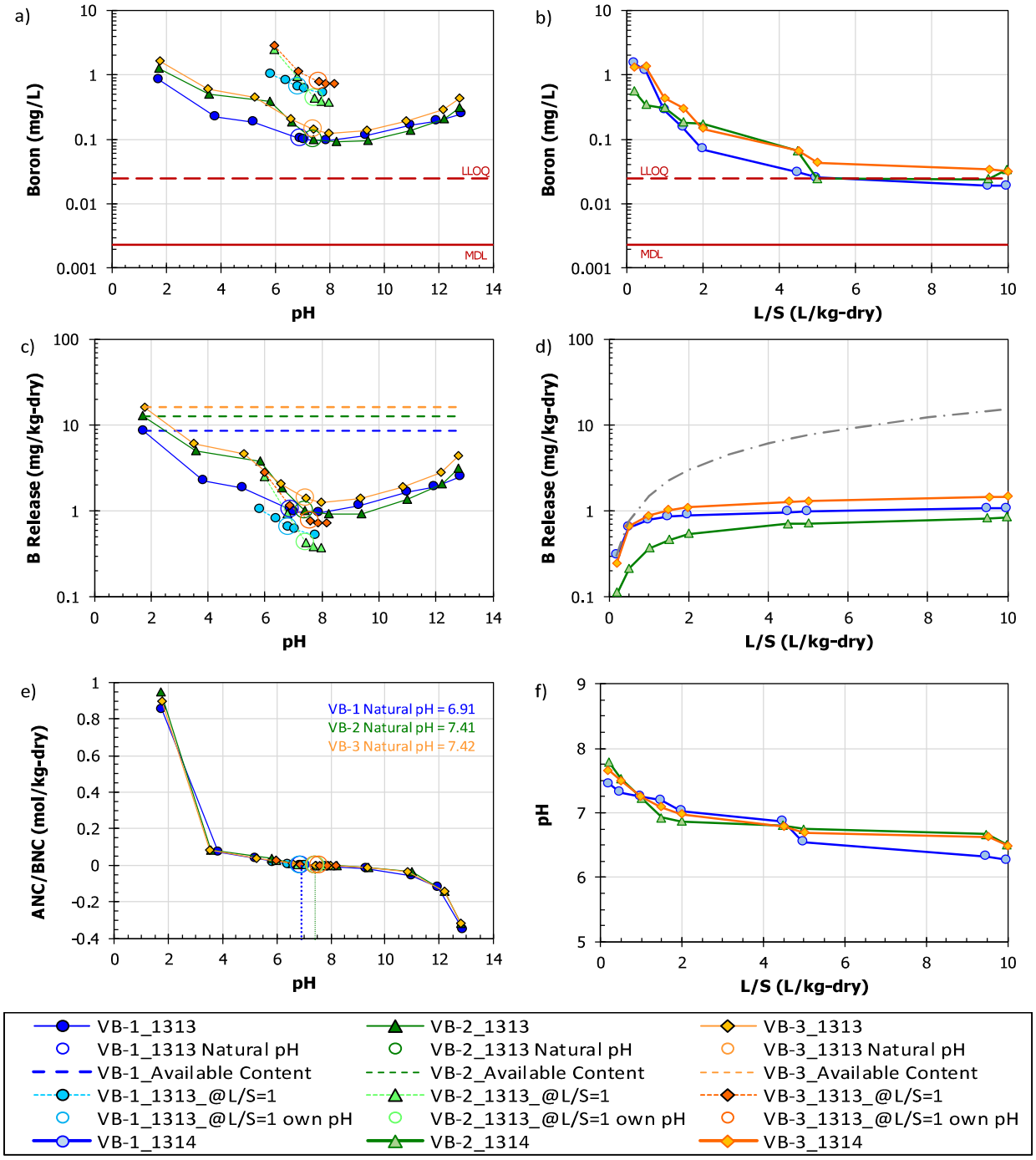


Figure D-6
Boron LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

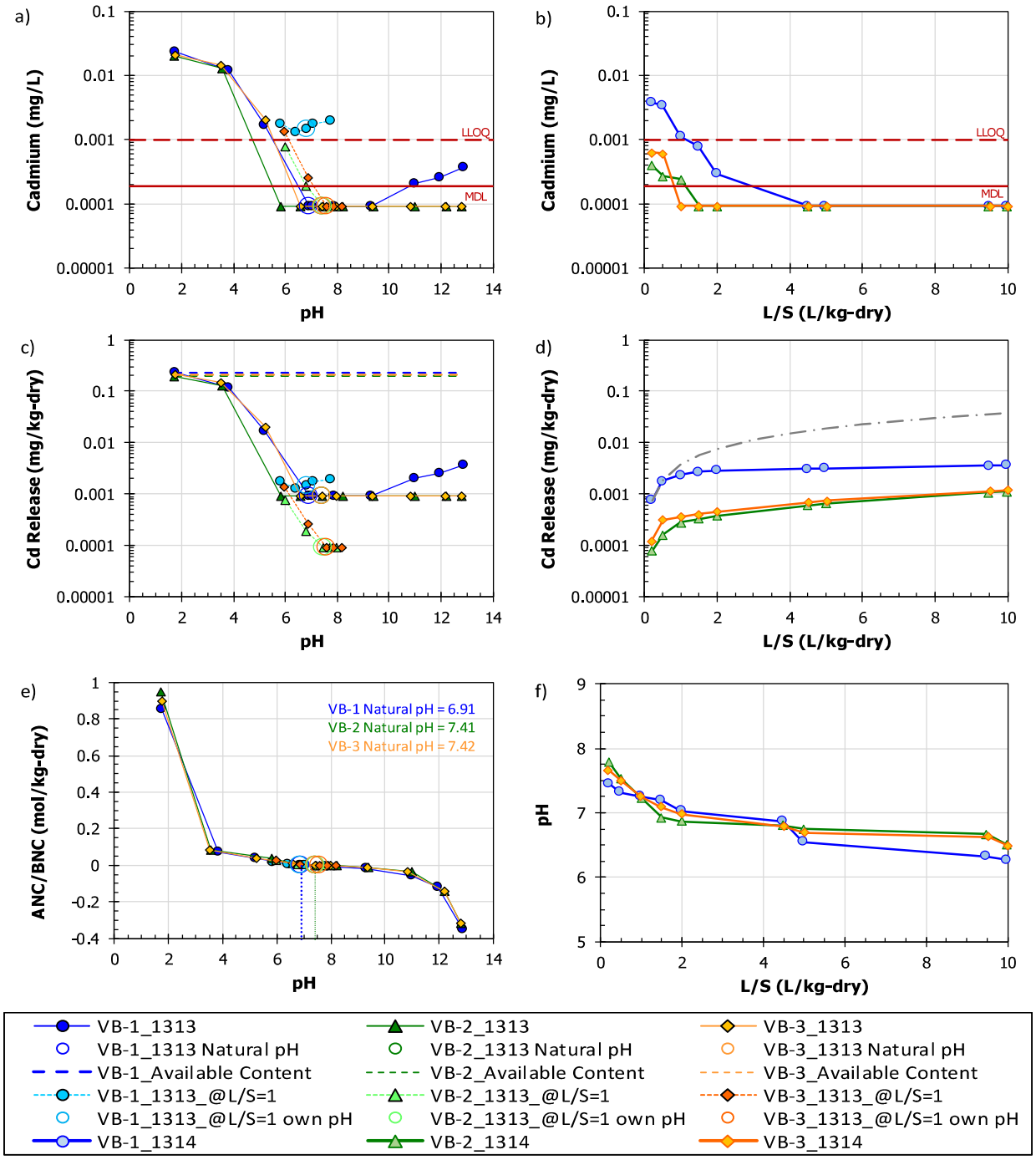


Figure D-7
Cadmium LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

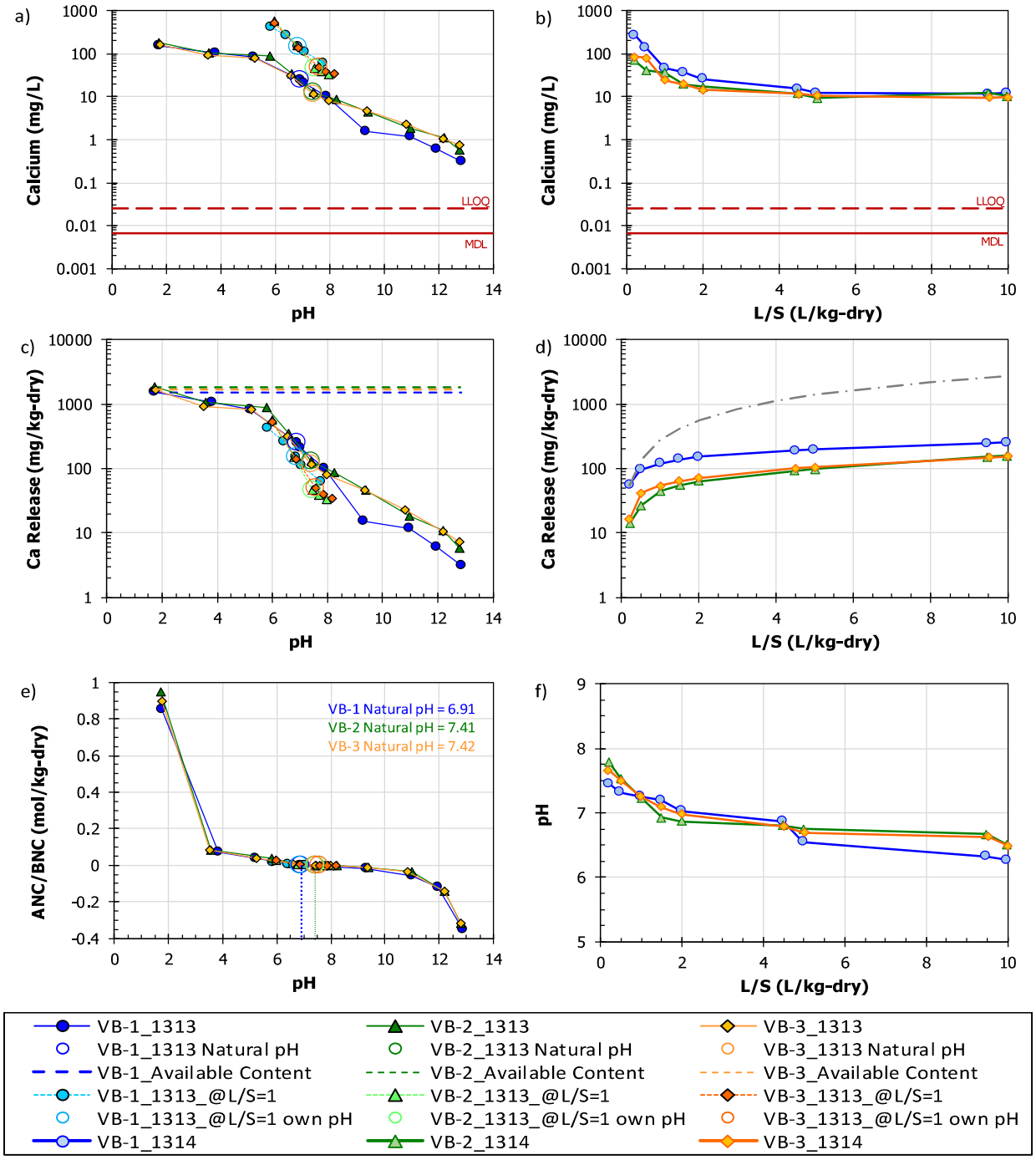


Figure D-8
Calcium LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S.

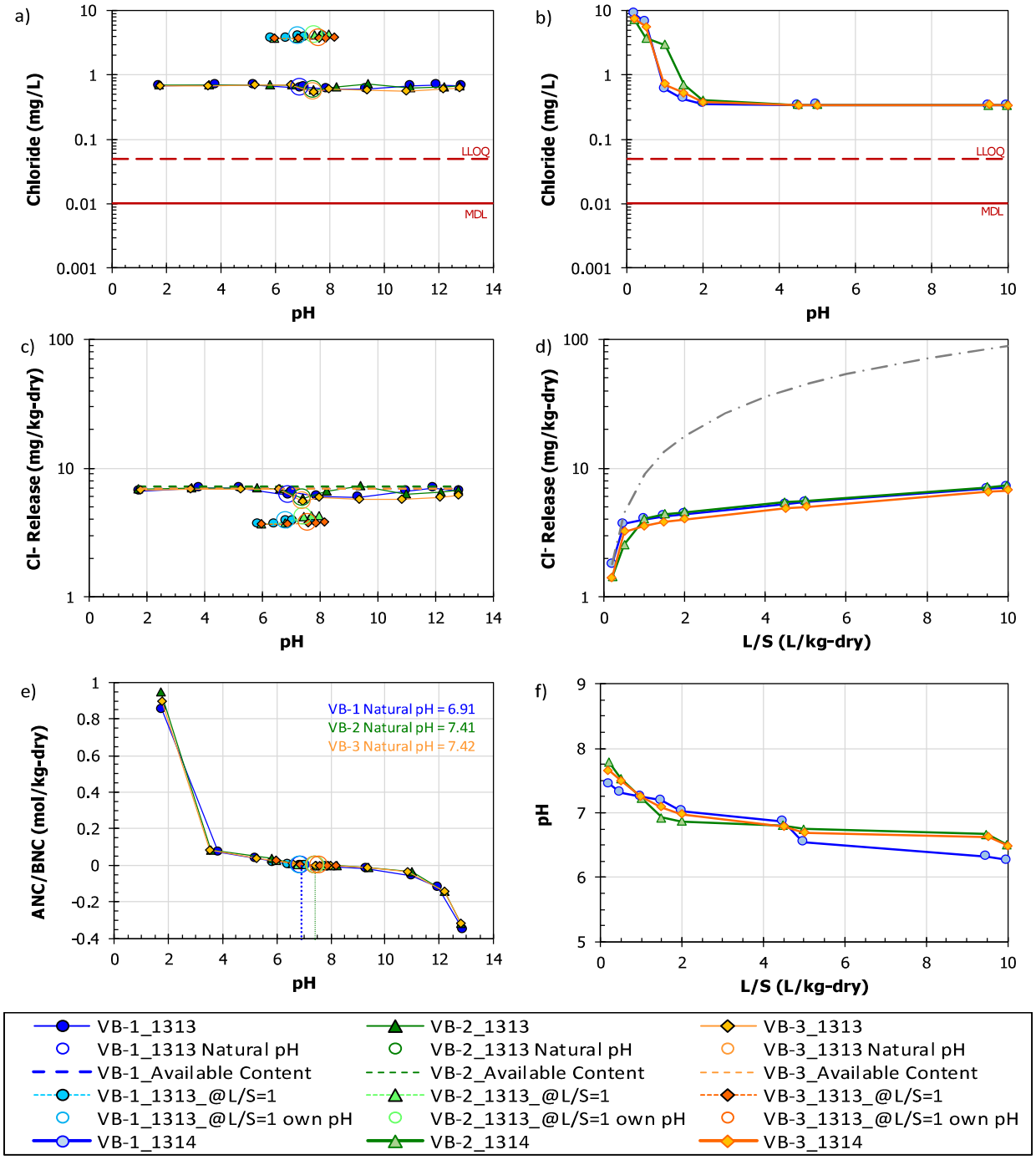


Figure D-9
Chloride LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S.

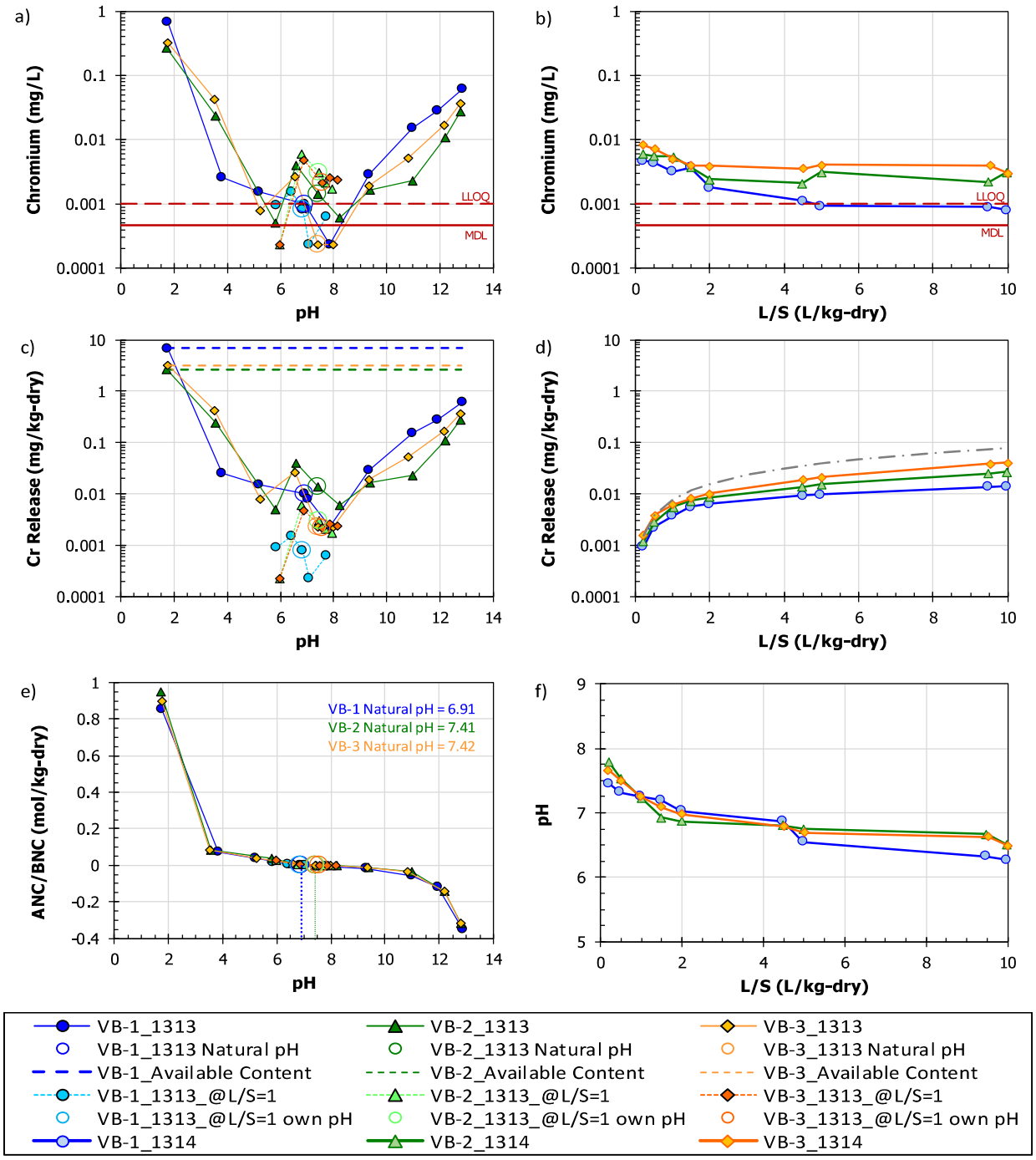


Figure D-10
Chromium LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

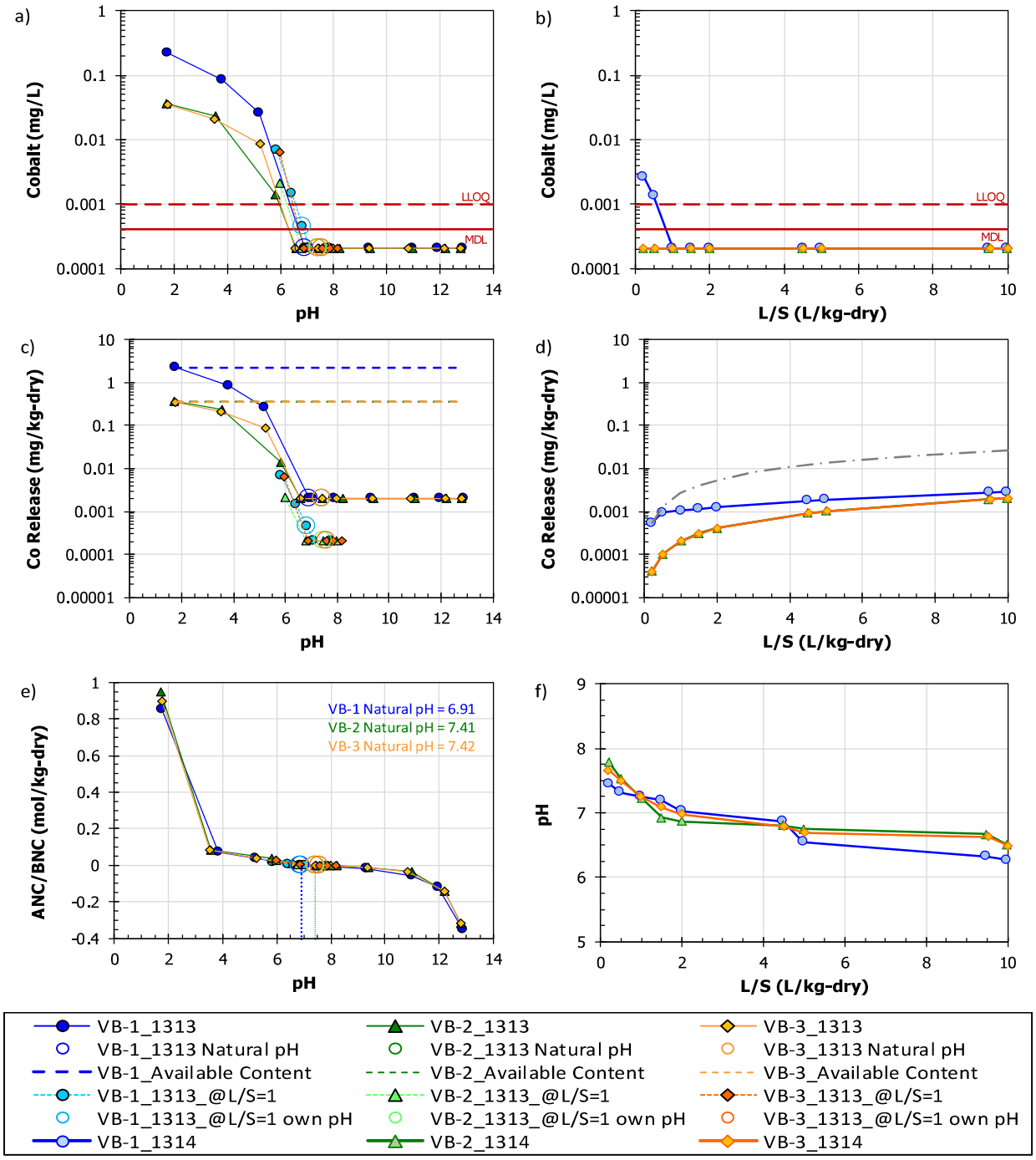


Figure D-11
Cobalt LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S.

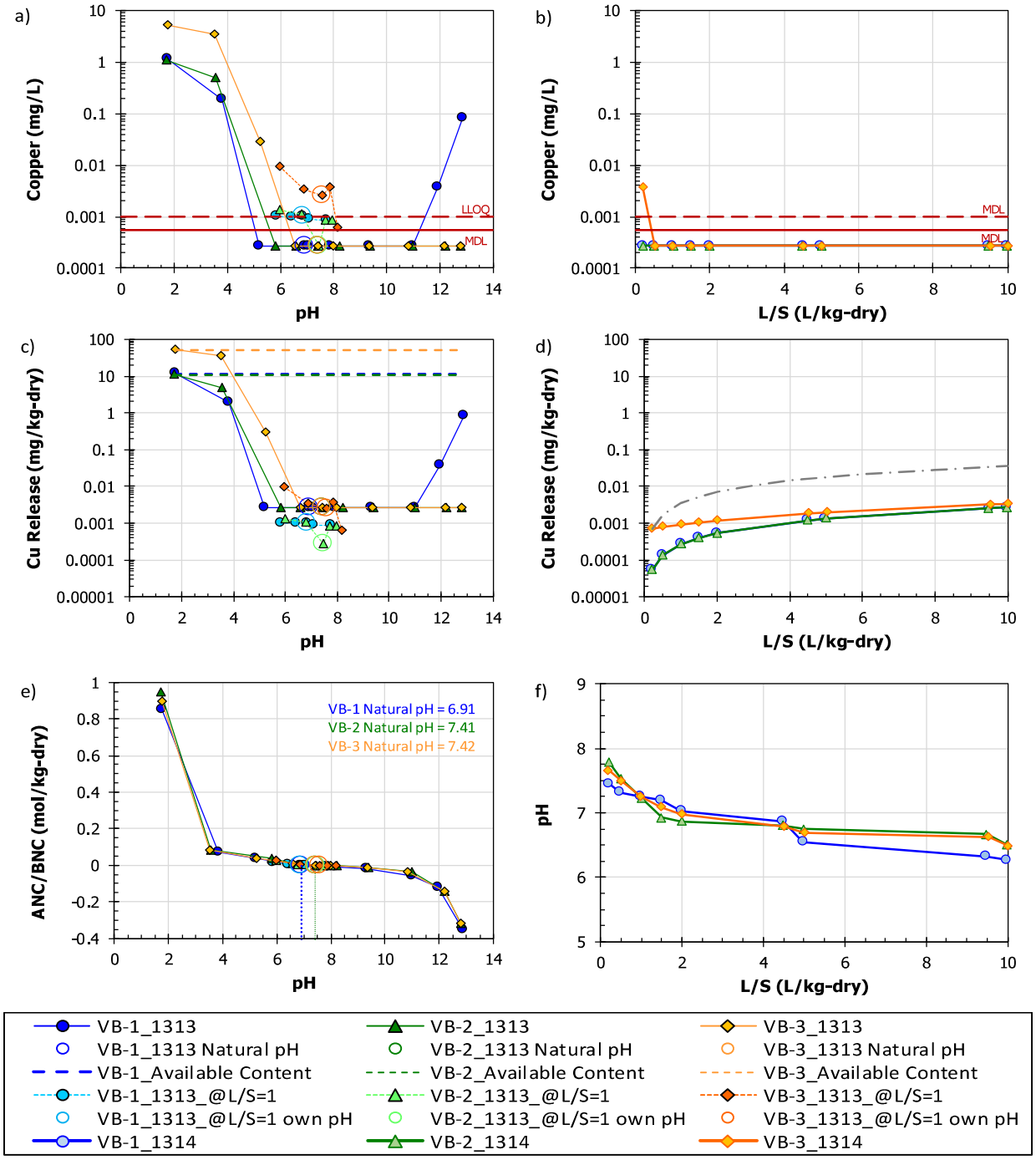


Figure D-12
Copper LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

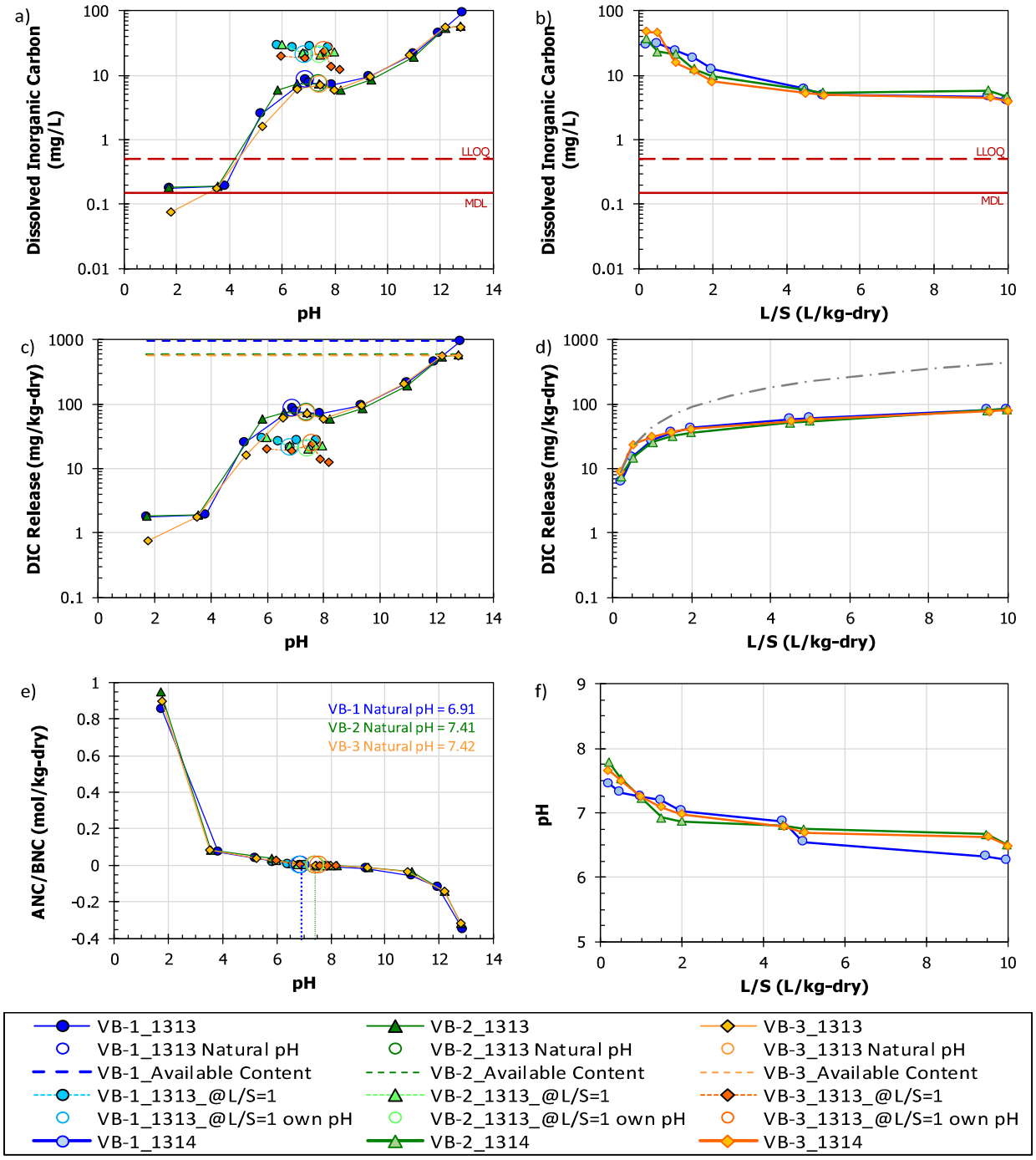


Figure D-13
Dissolved inorganic carbon LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

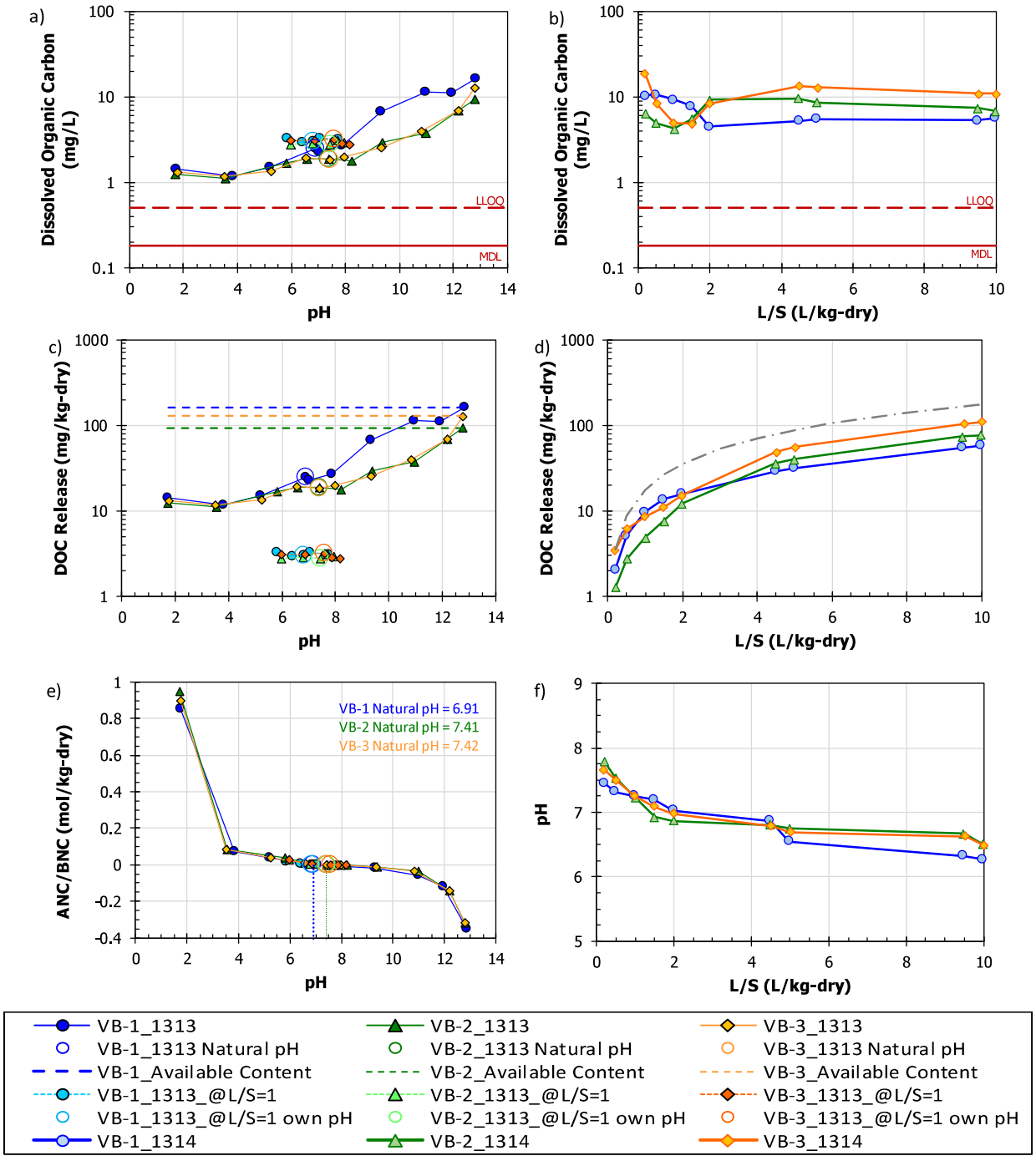


Figure D-14
Dissolved organic carbon LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

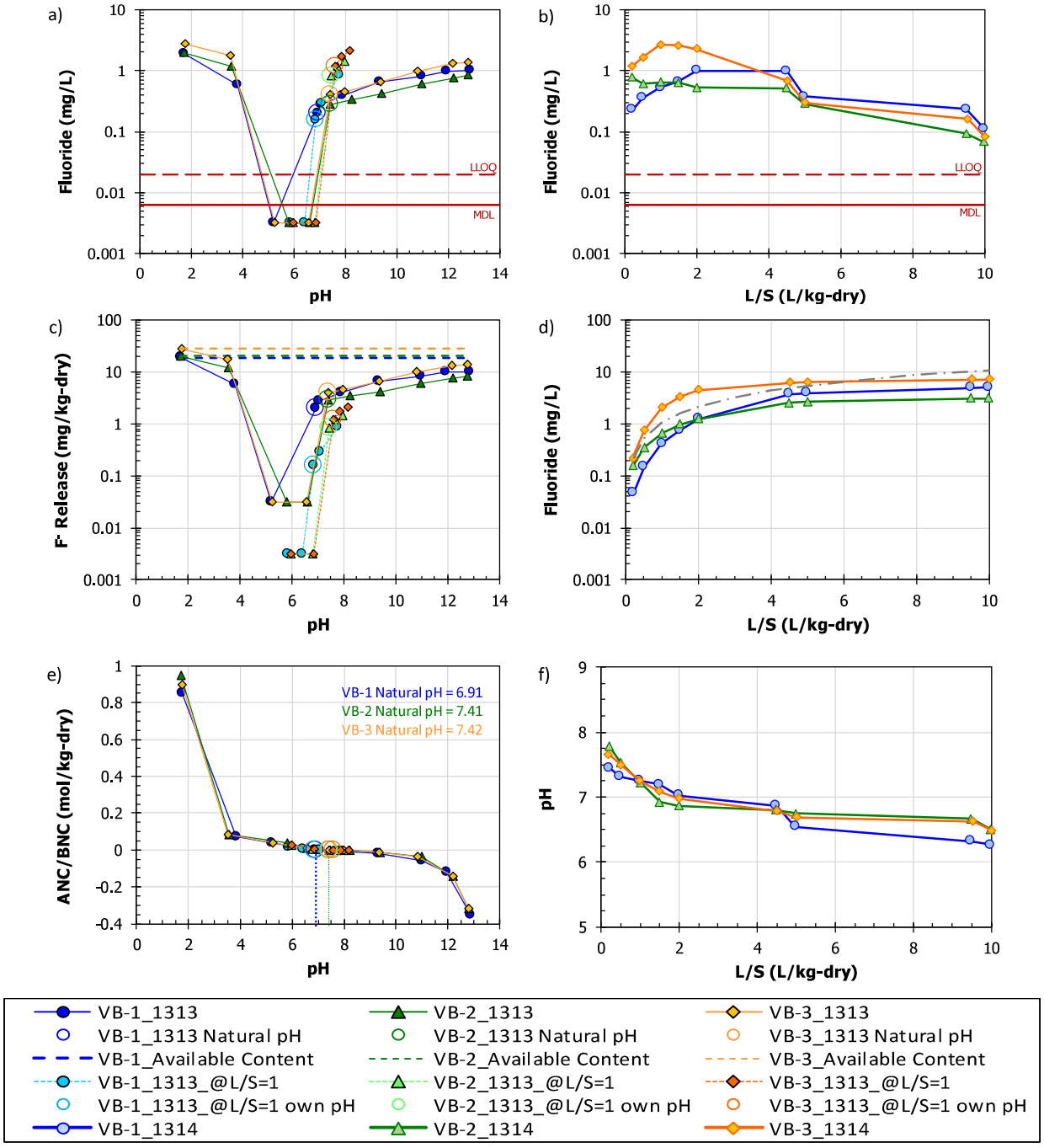


Figure D-15
Fluoride LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

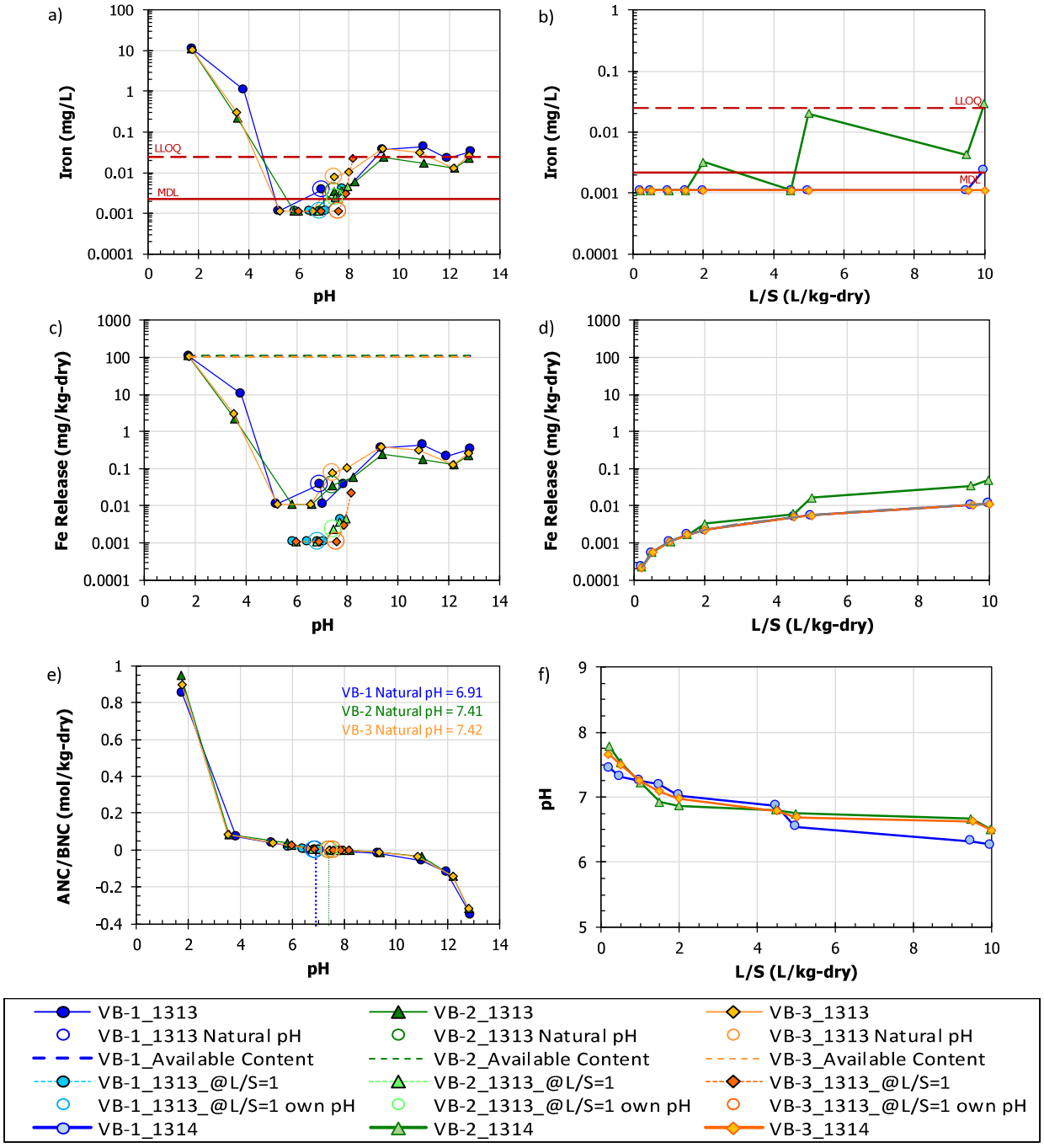


Figure D-16
Iron LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

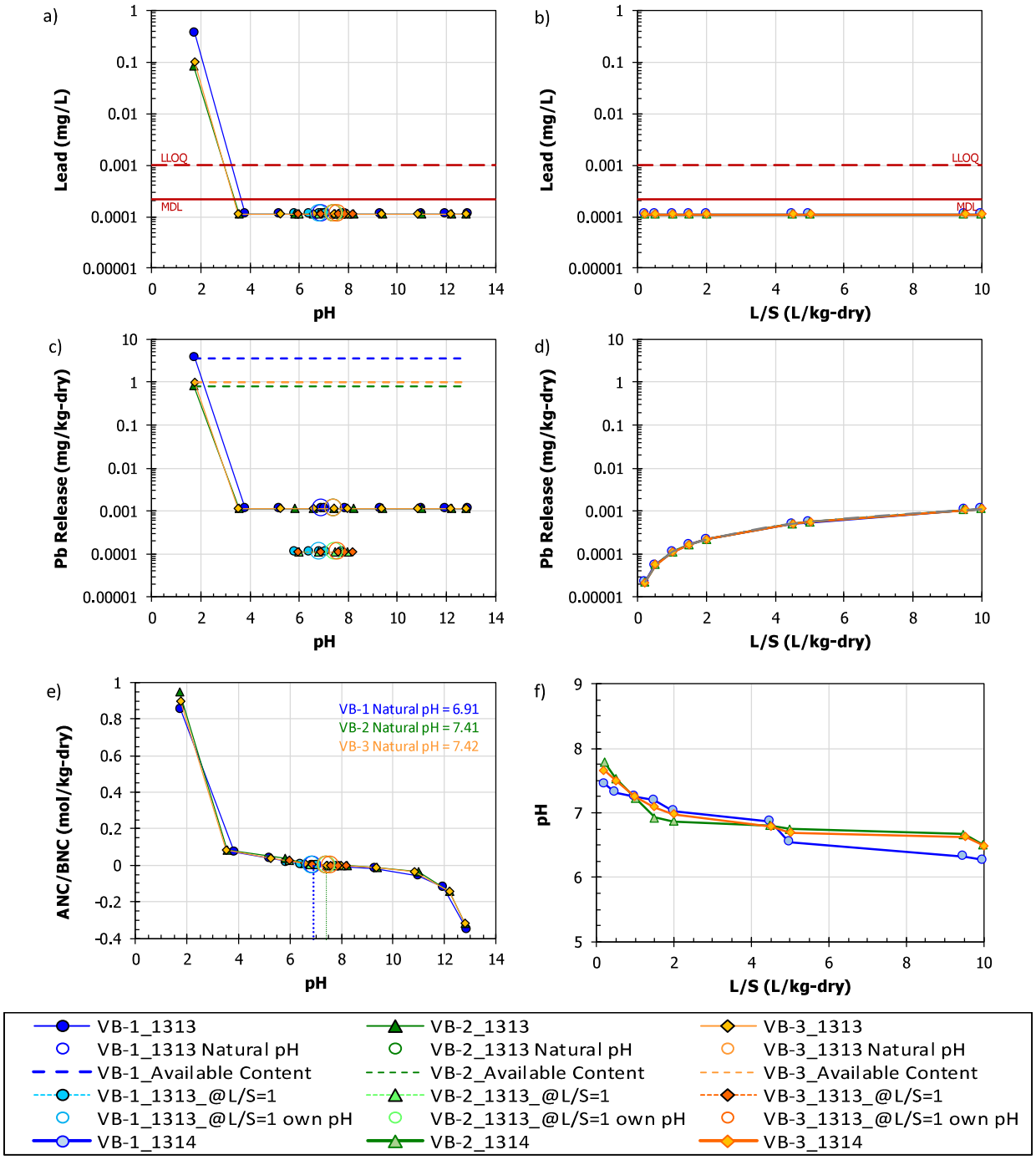


Figure D-17
Lead LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

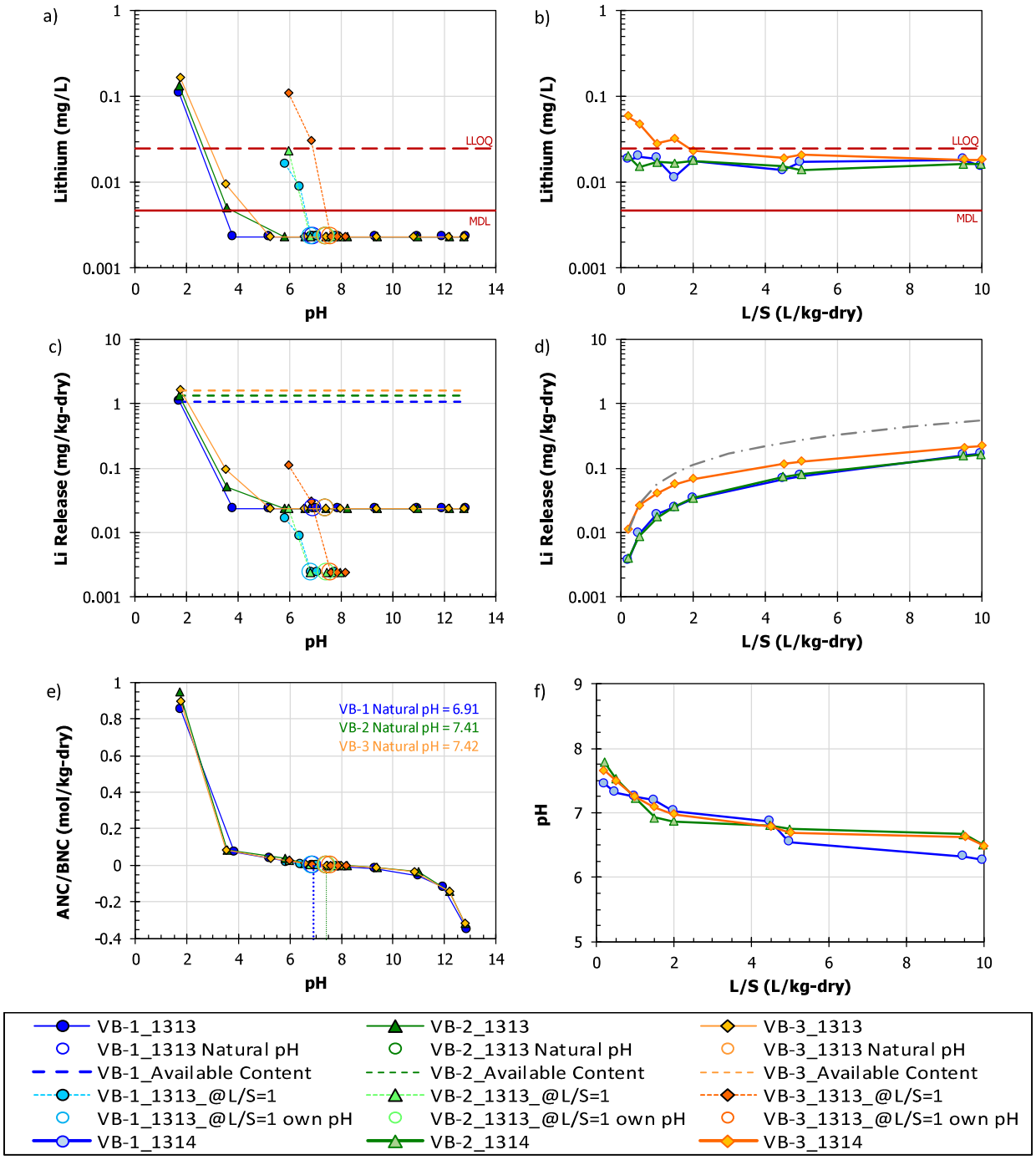


Figure D-18
Lithium LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

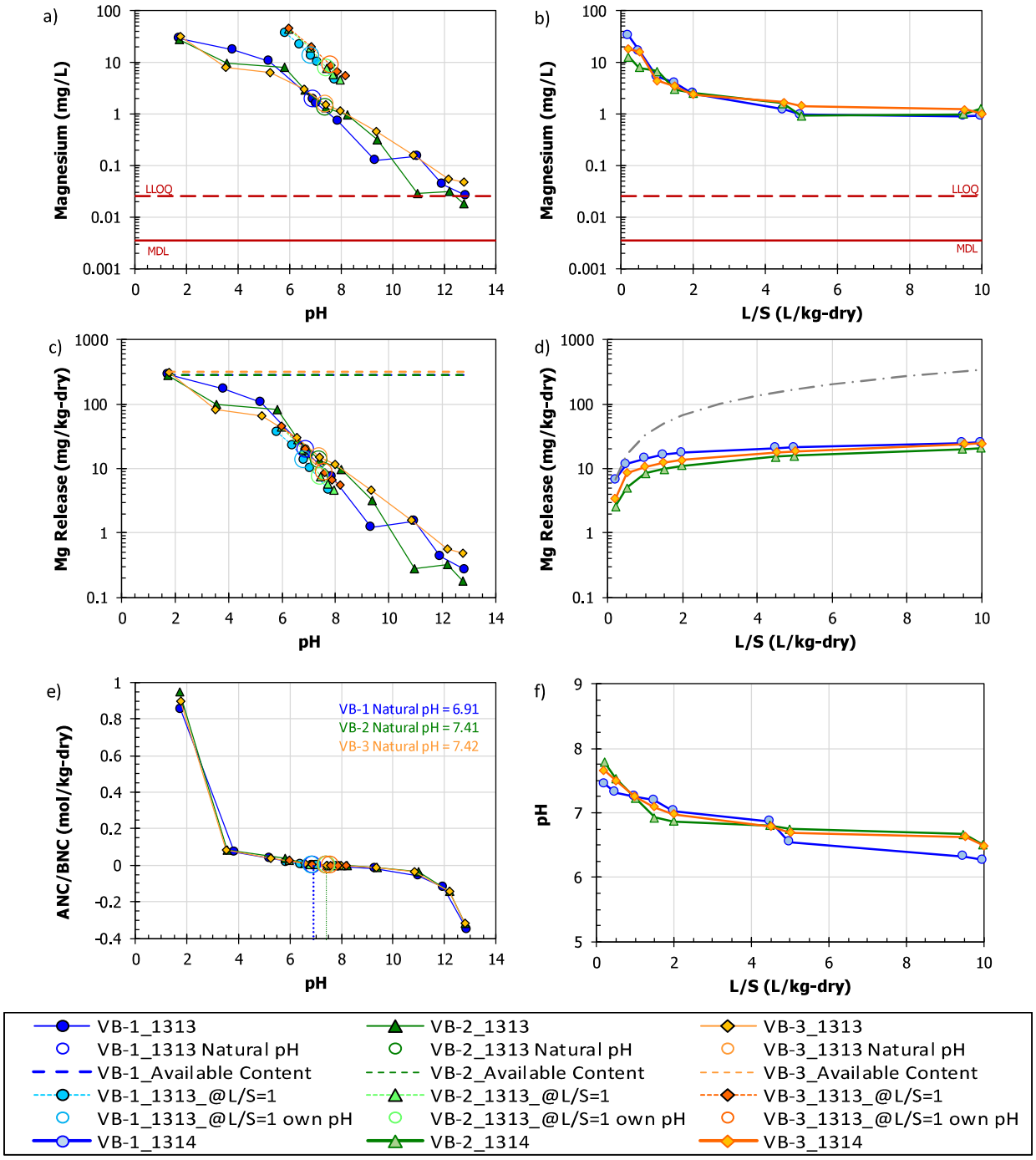


Figure D-19
Magnesium LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

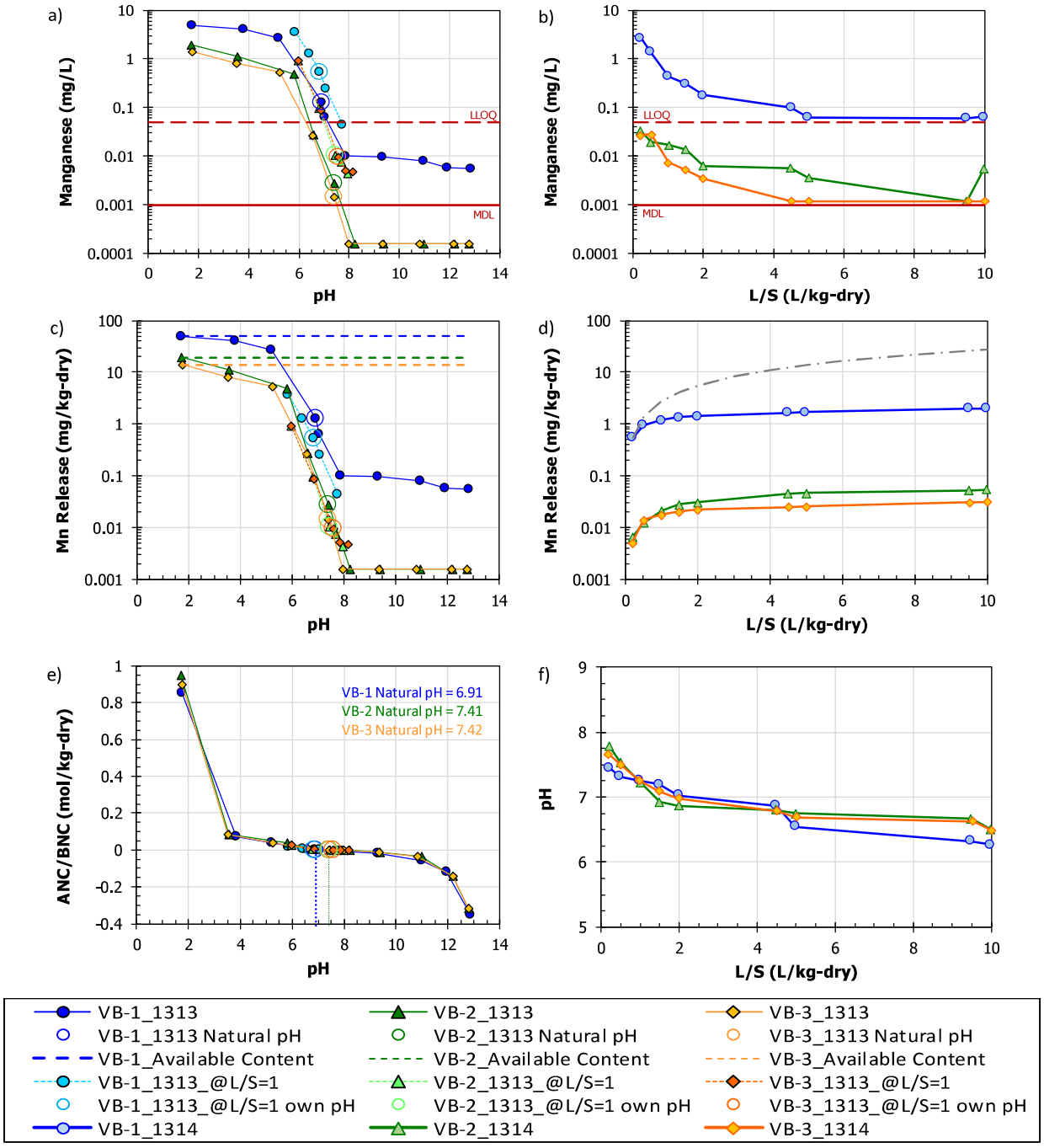


Figure D-20
Manganese LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

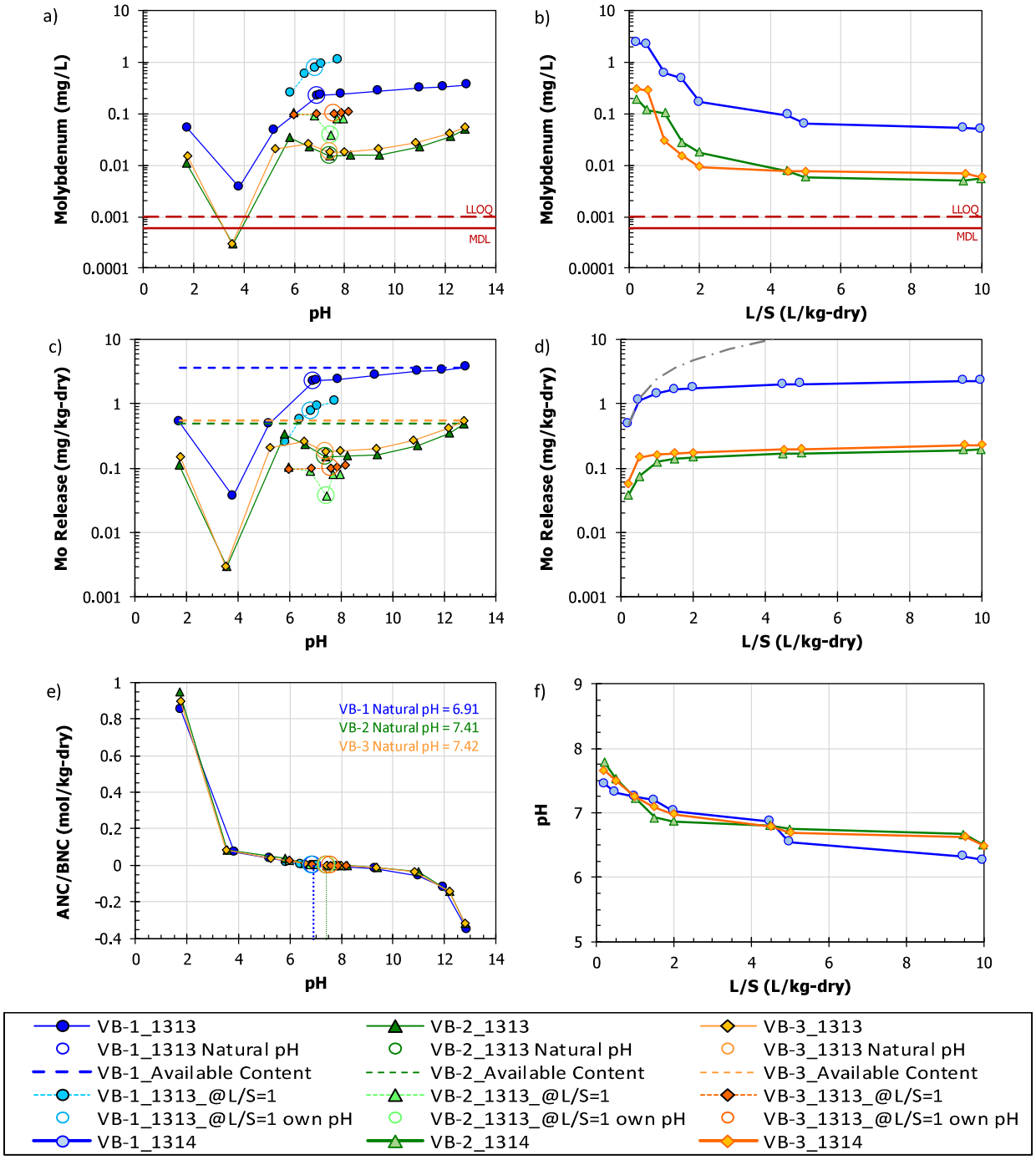


Figure D-21
Molybdenum LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

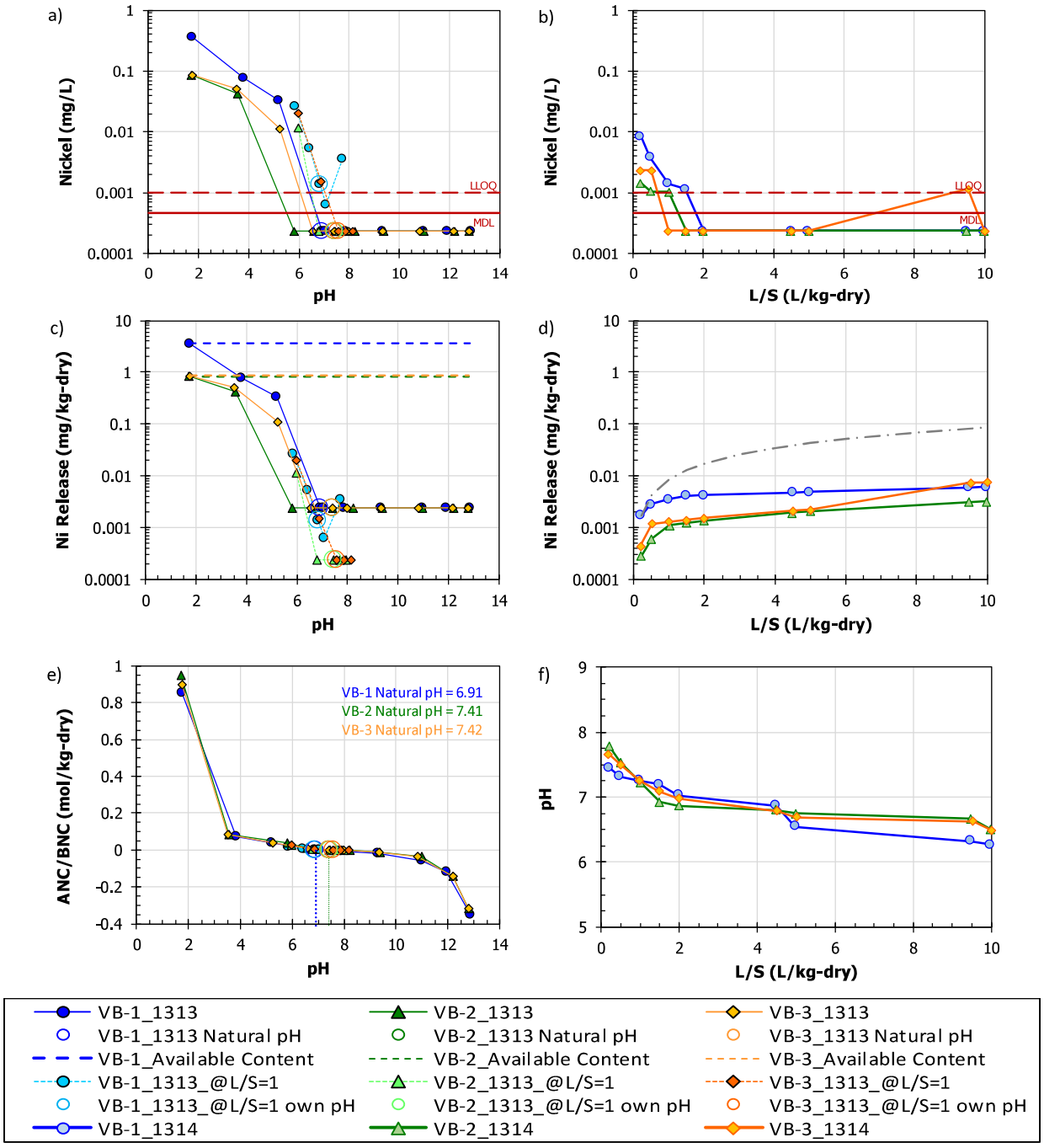


Figure D-22
Nickel LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

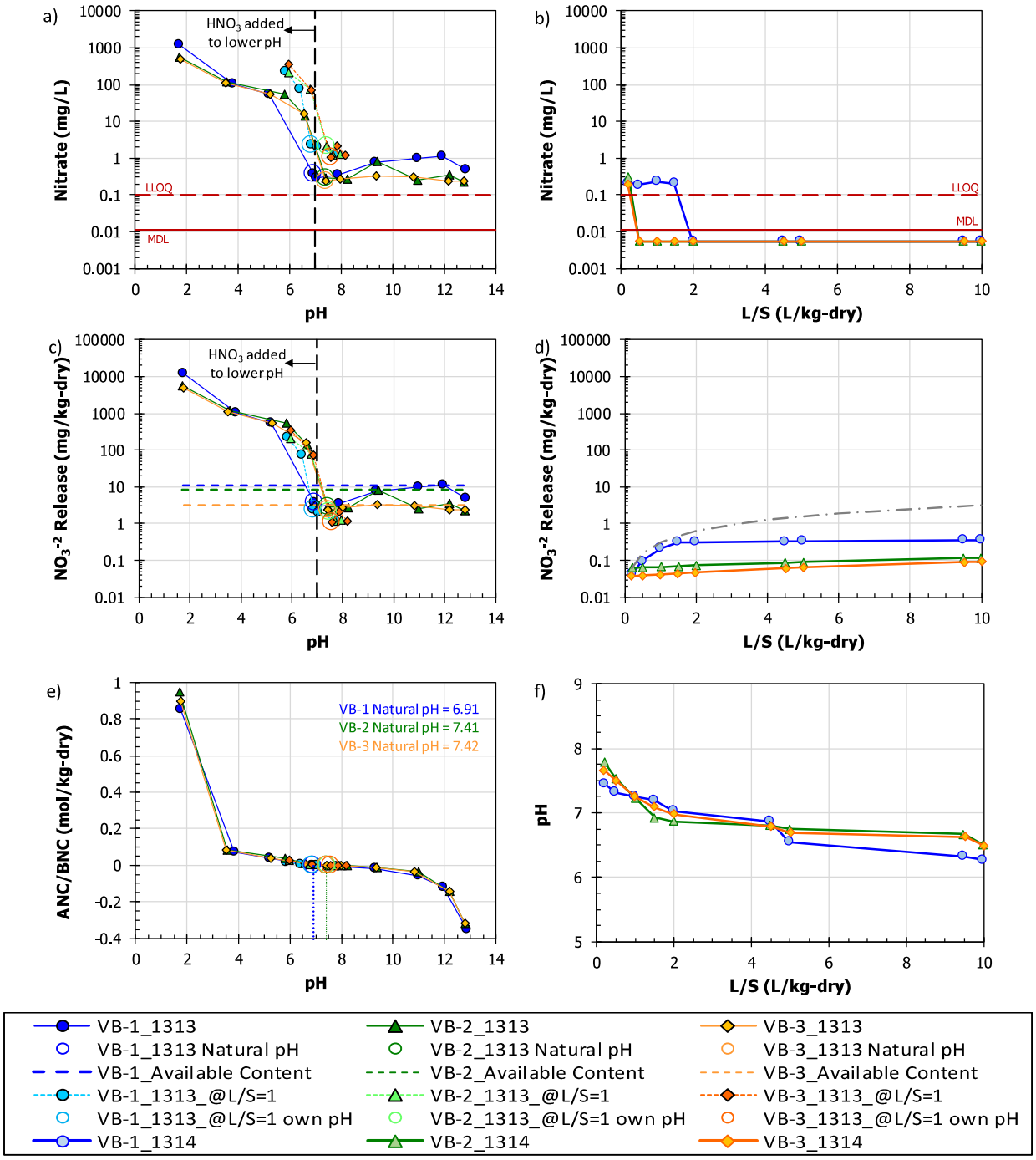


Figure D-23
Nitrate LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

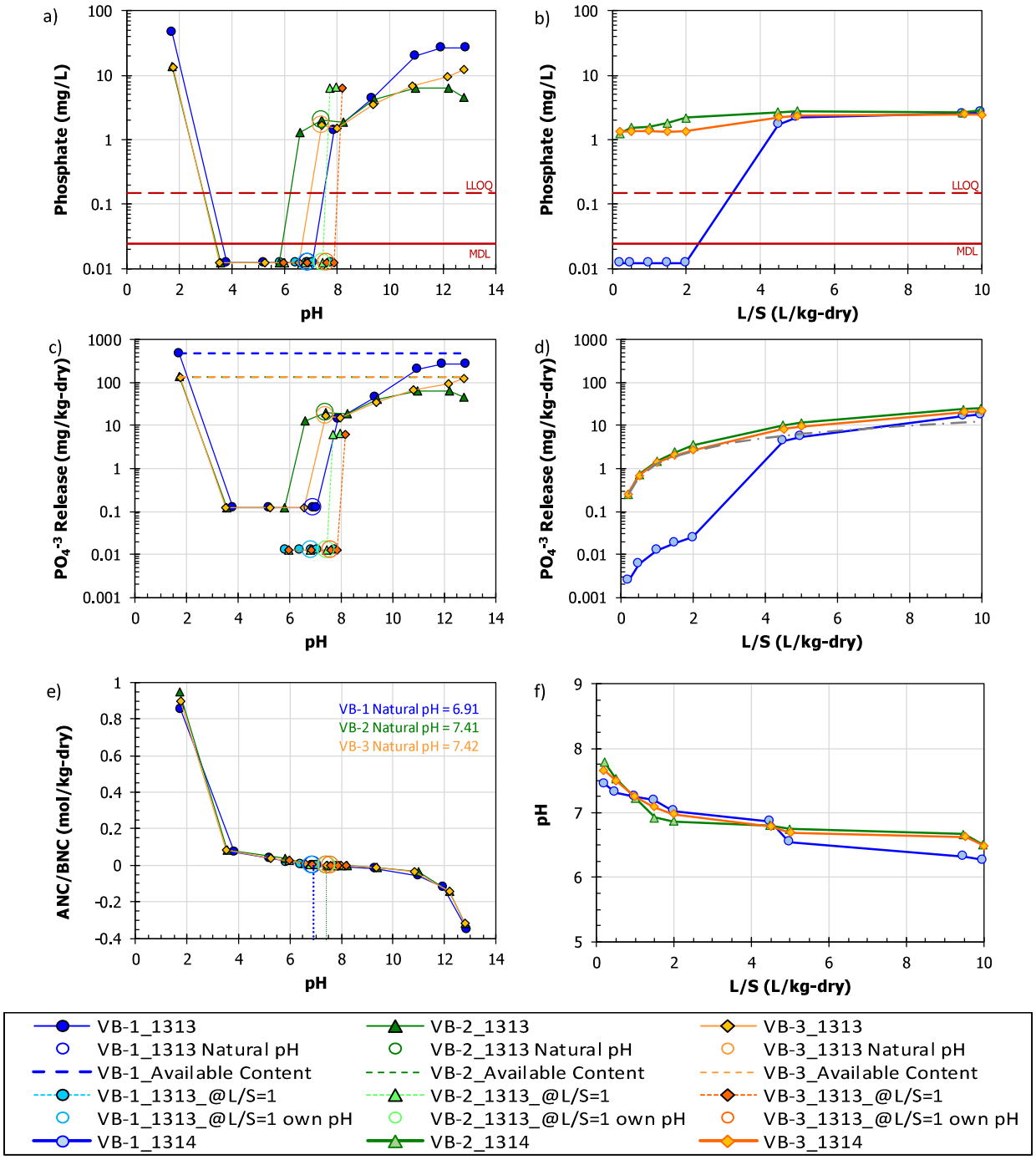


Figure D-24
Phosphate LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

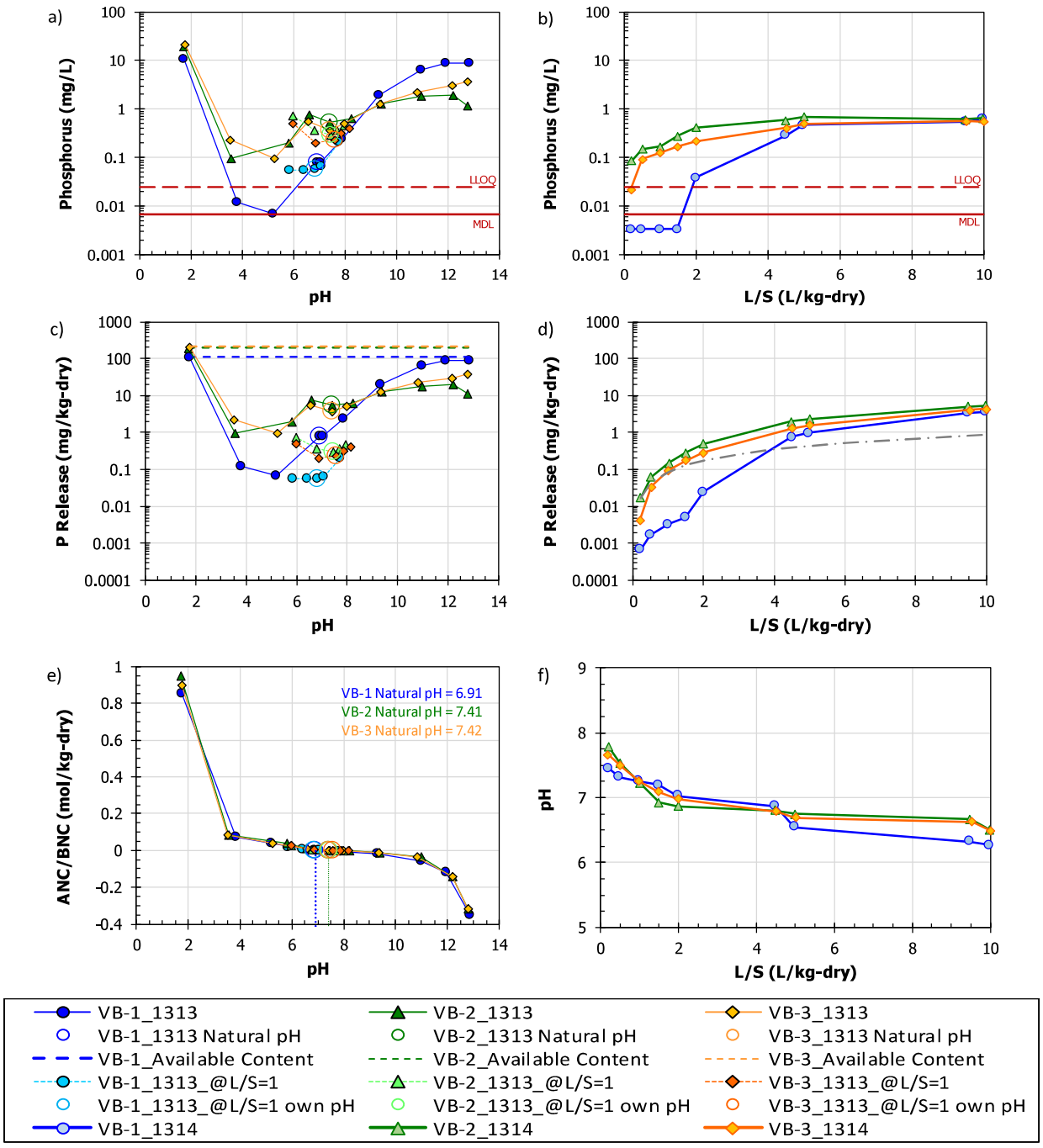


Figure D-25
Phosphorus LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

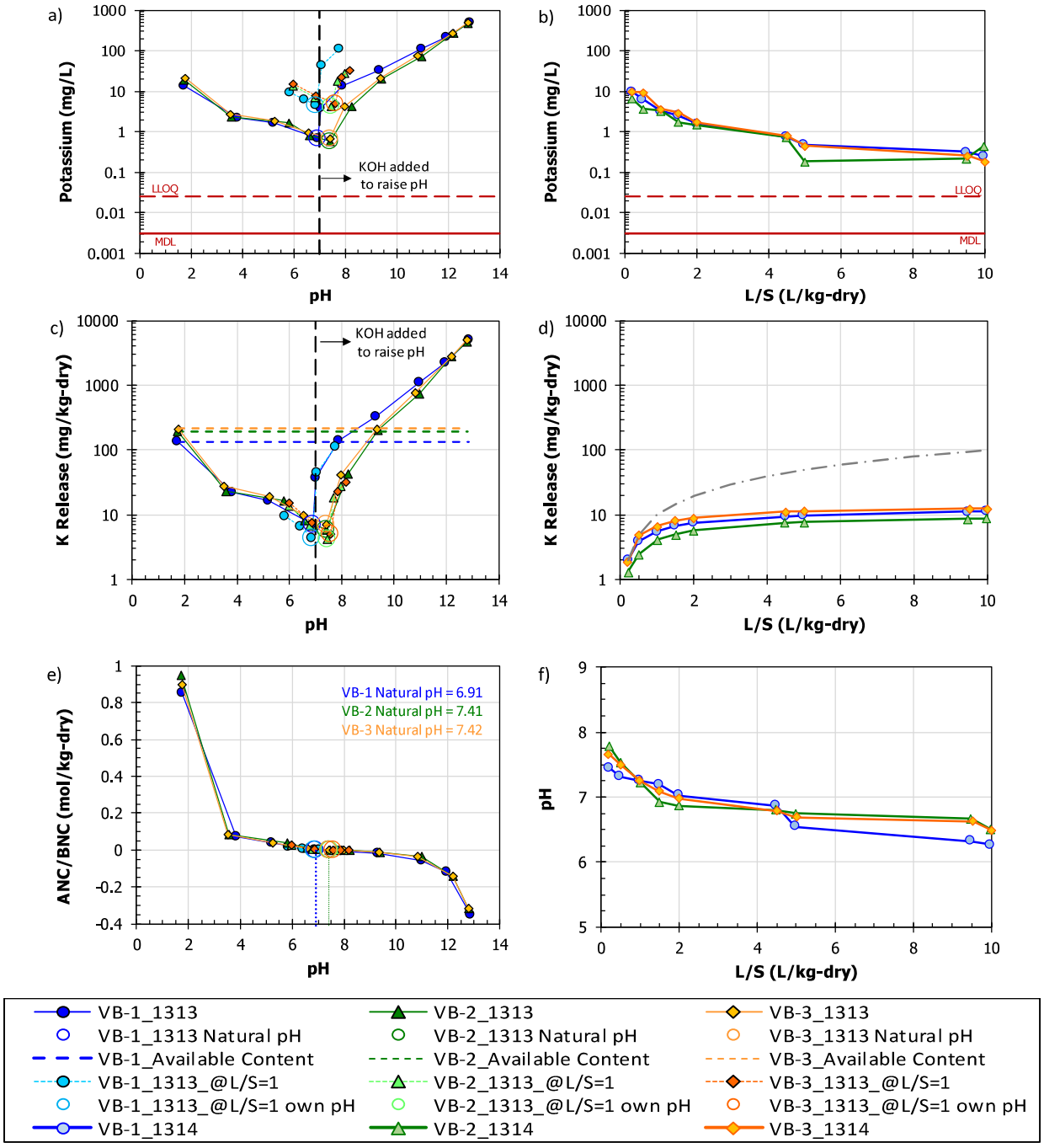


Figure D-26
Potassium LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

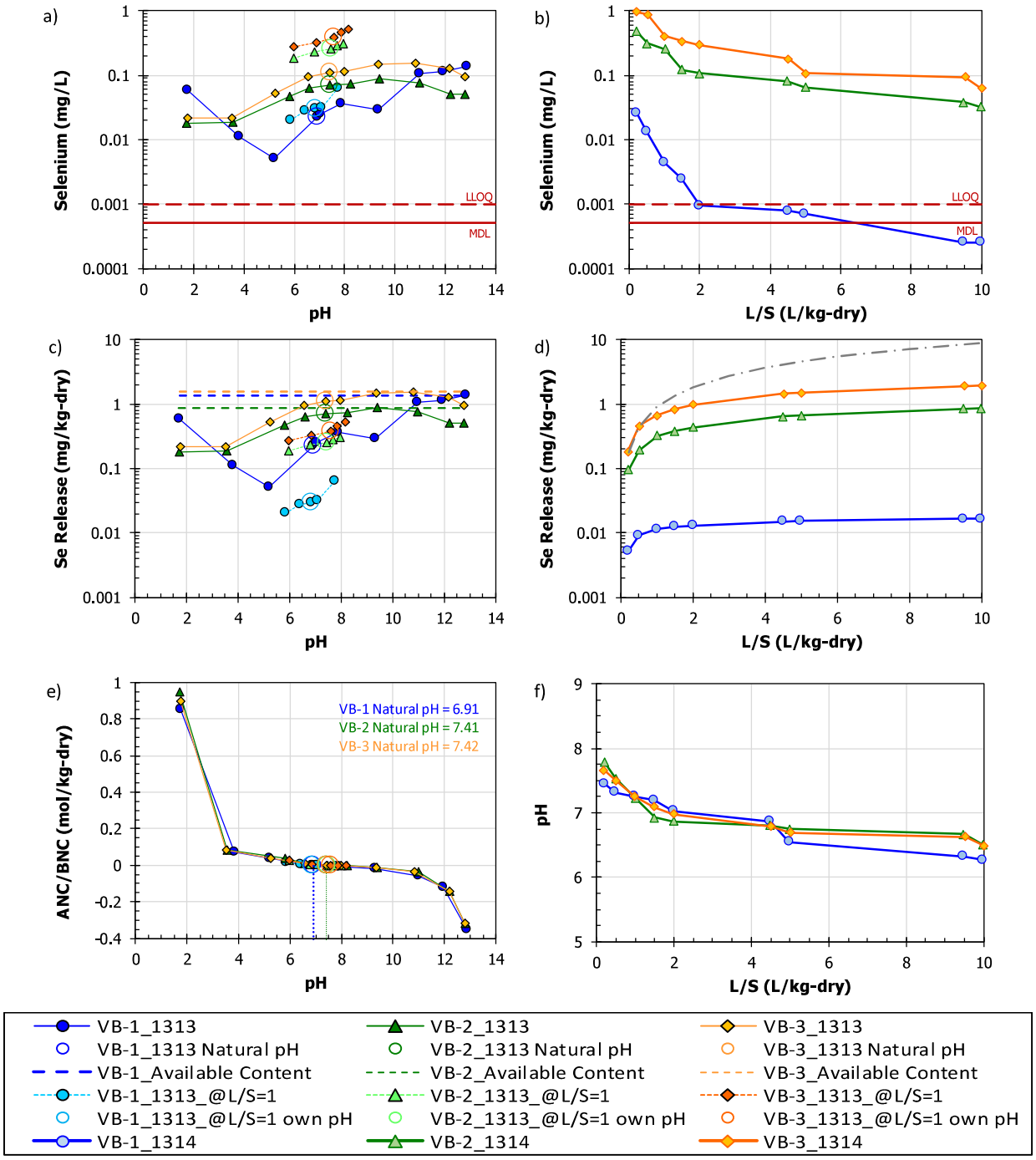


Figure D-27
Selenium LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

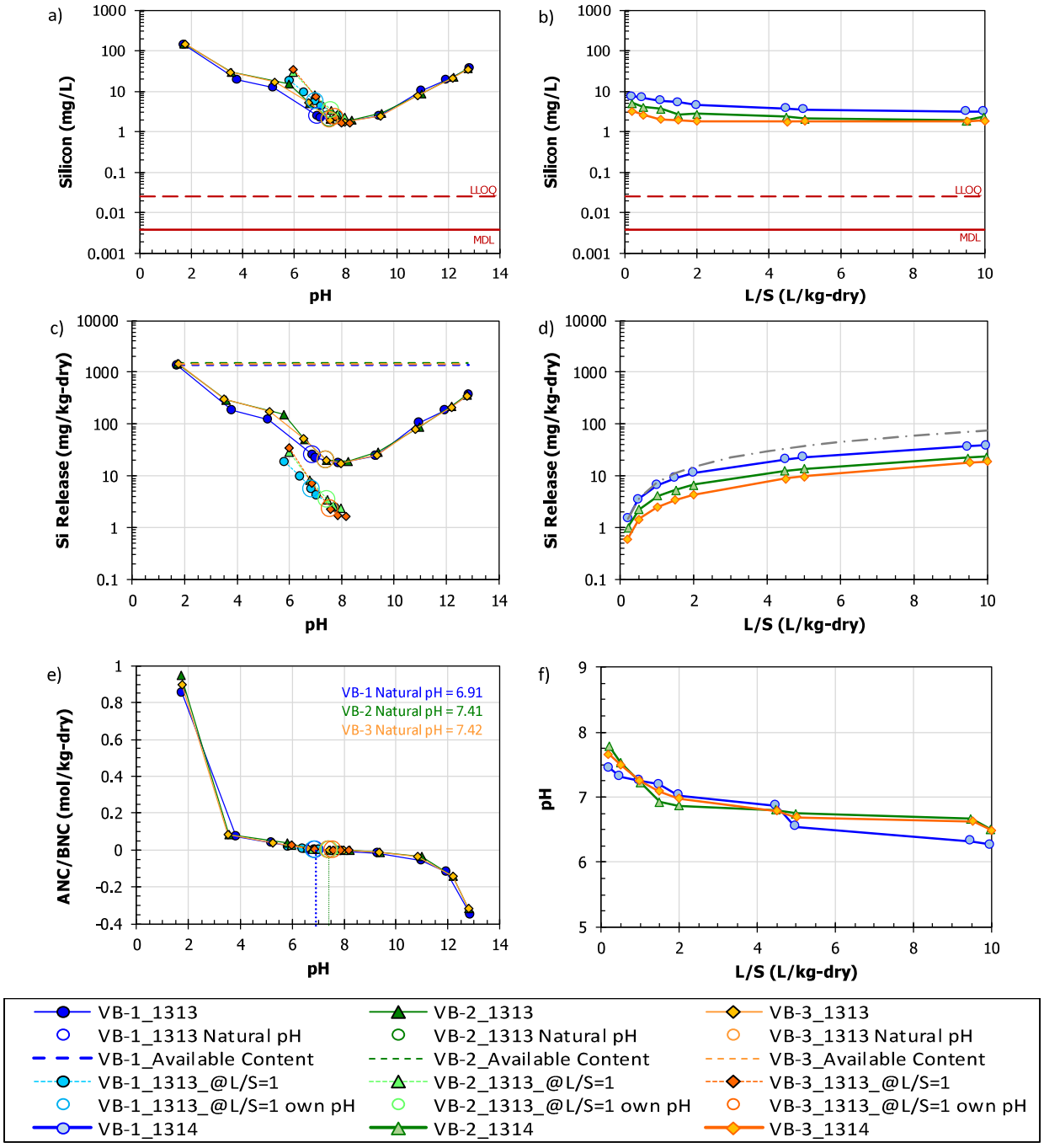


Figure D-28
Silicon LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

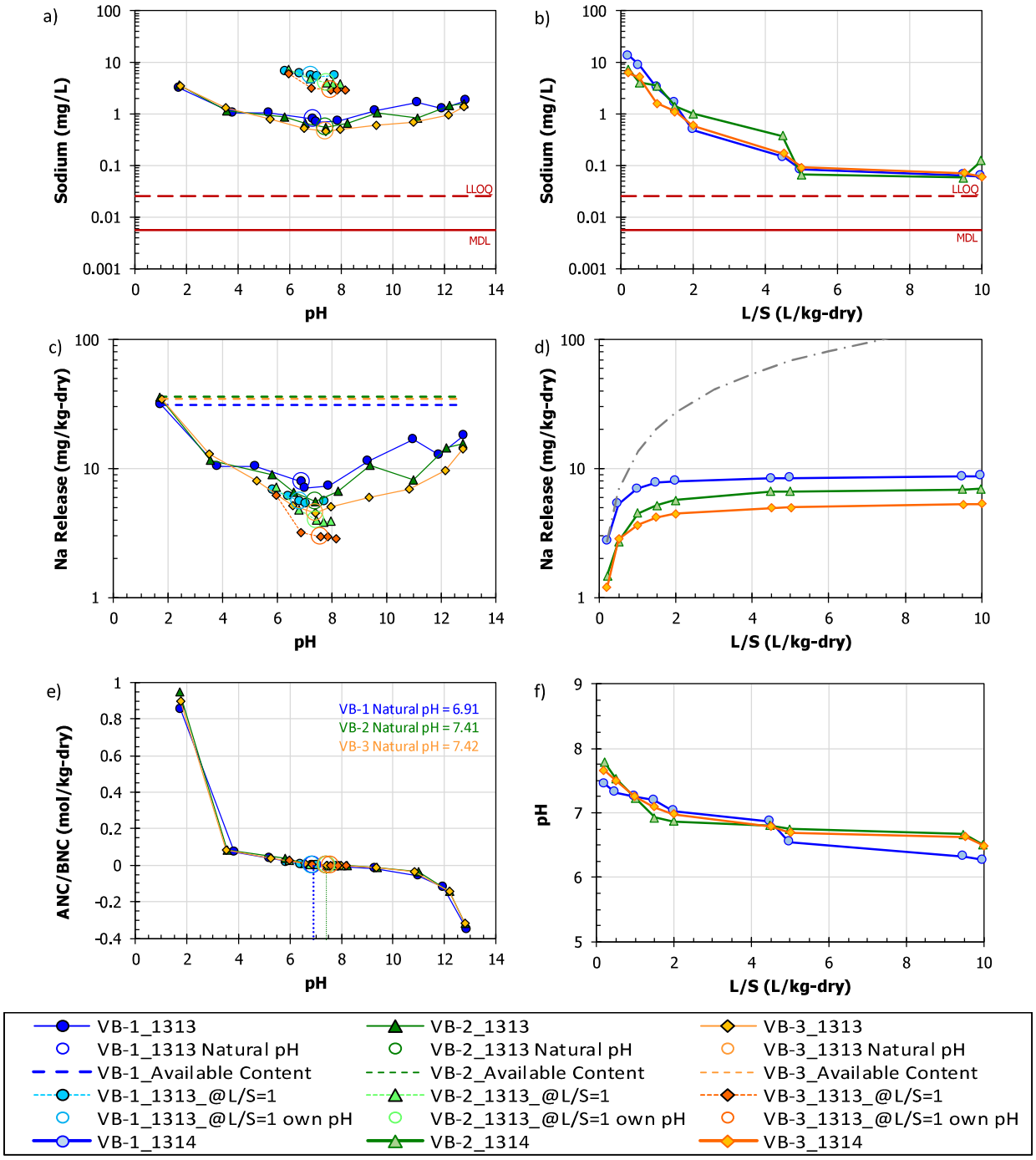


Figure D-29
Sodium LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

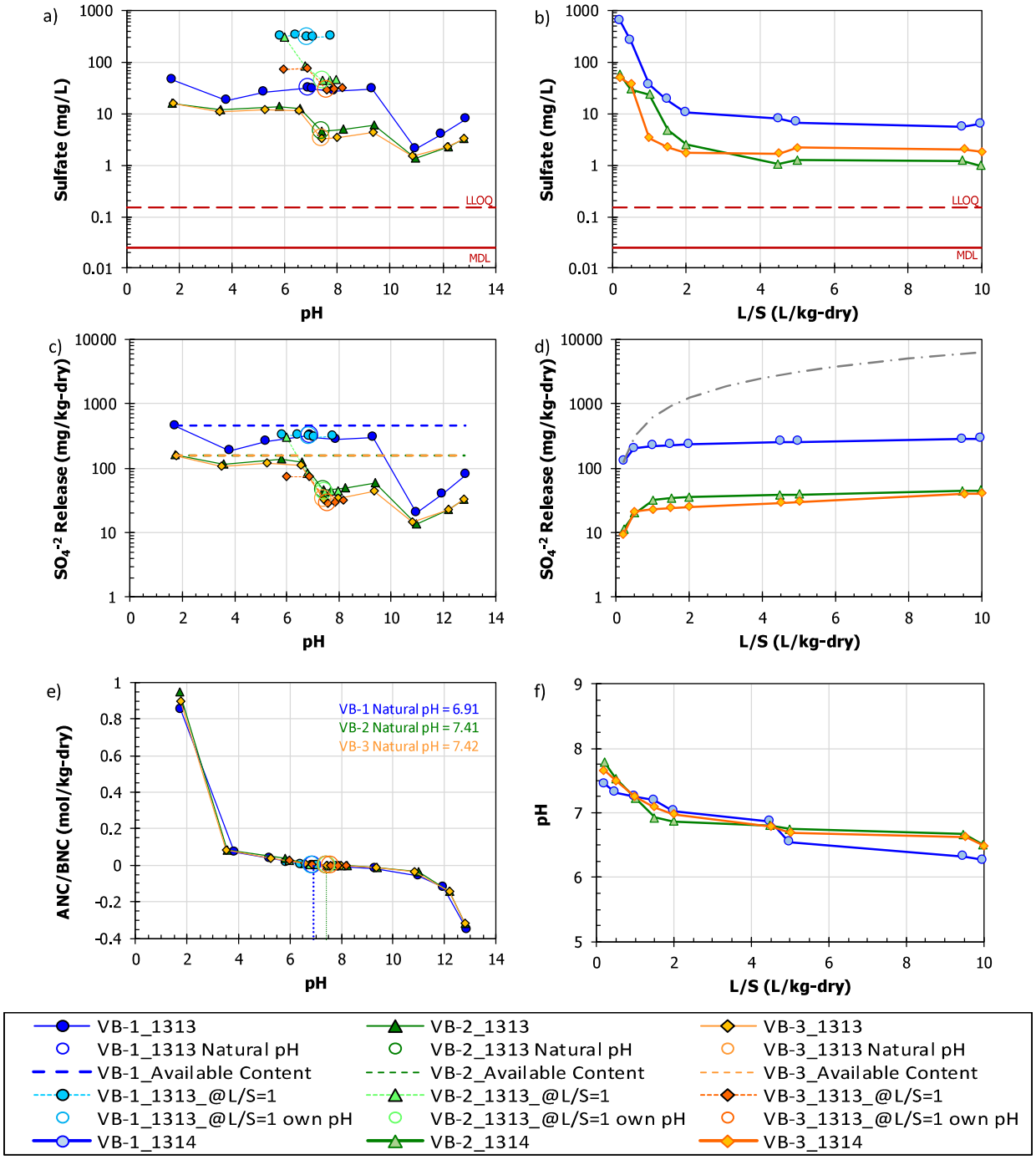


Figure D-30
Sulfate LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

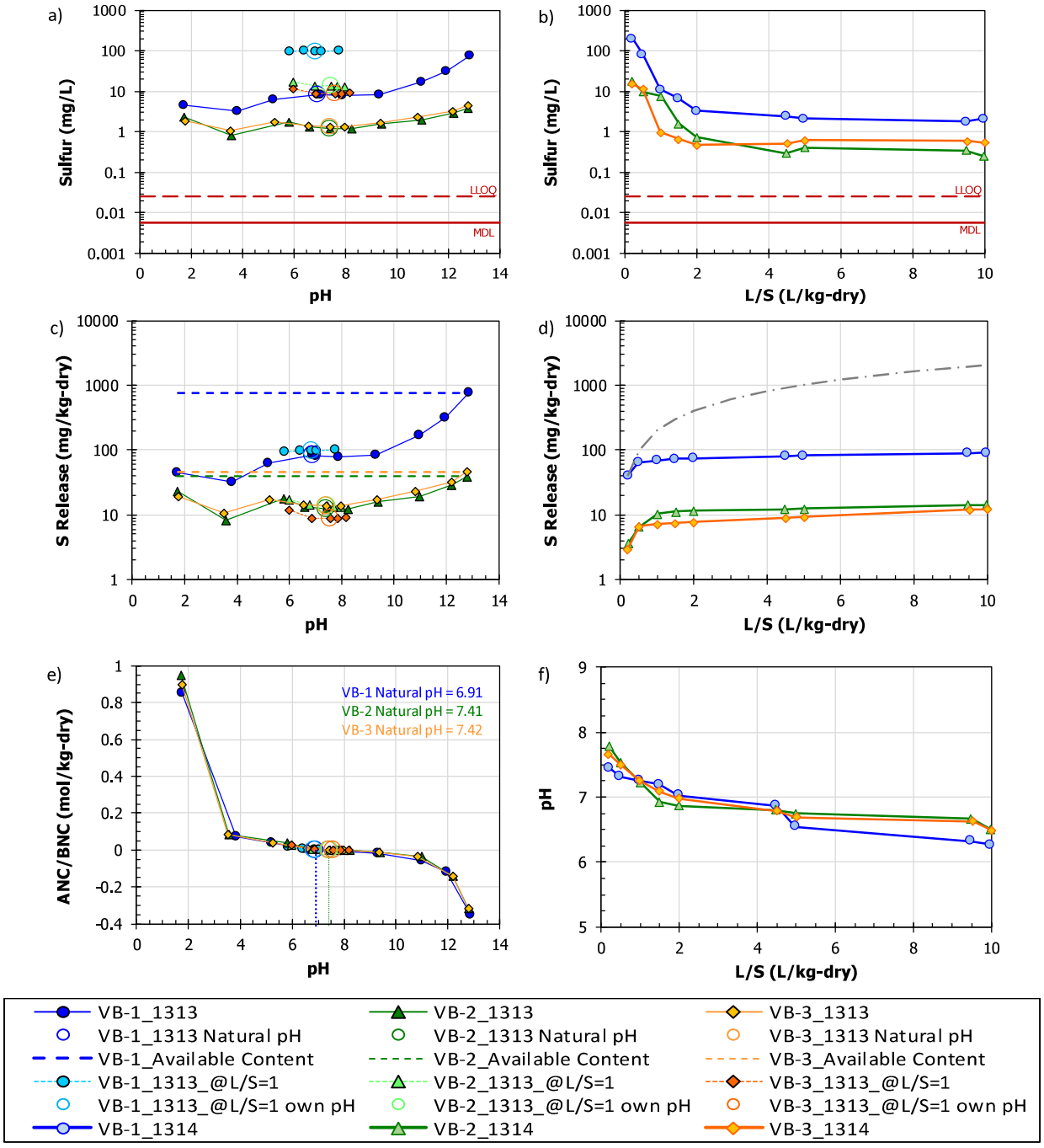


Figure D-31
Sulfur LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

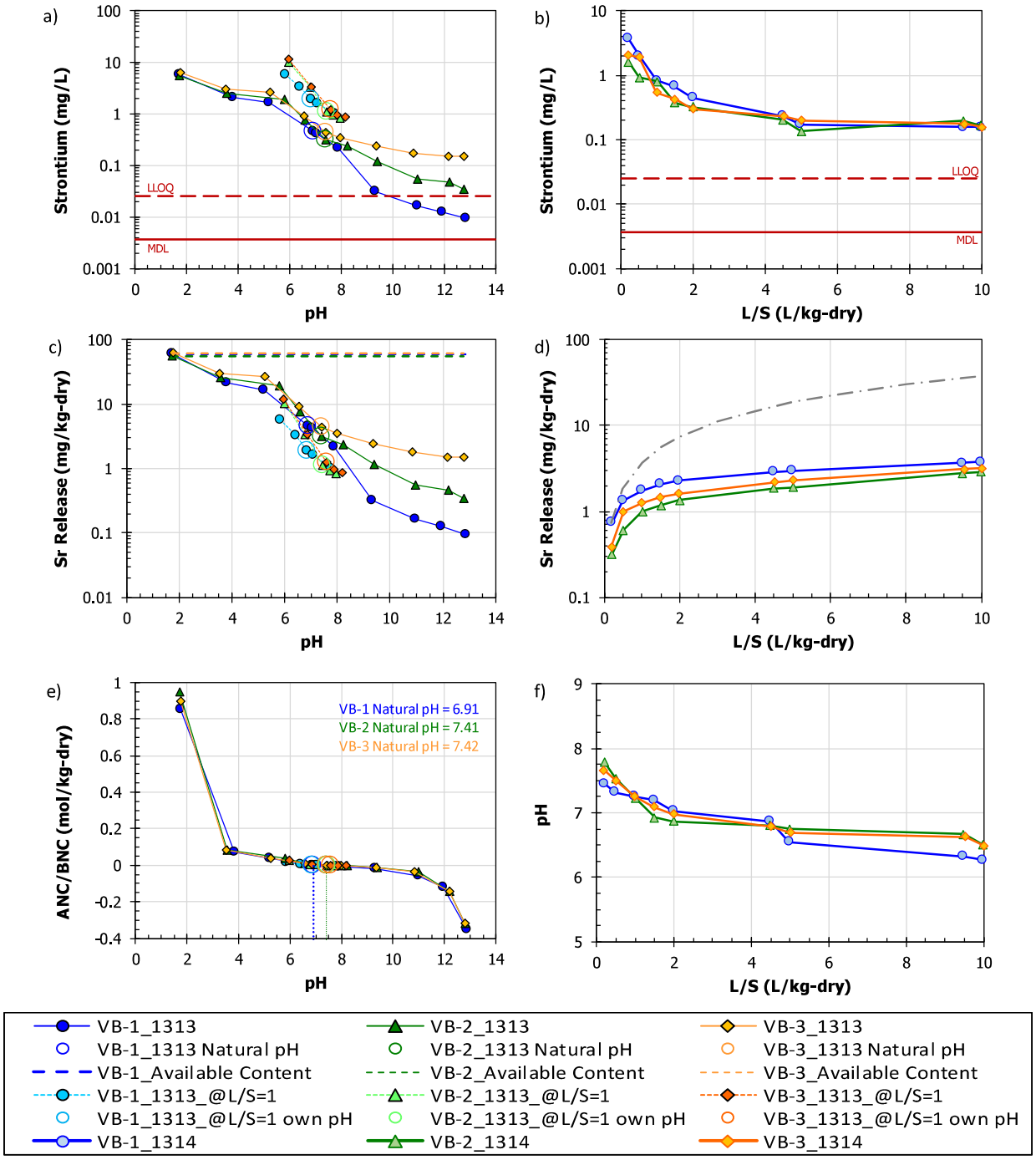


Figure D-32
Strontium LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

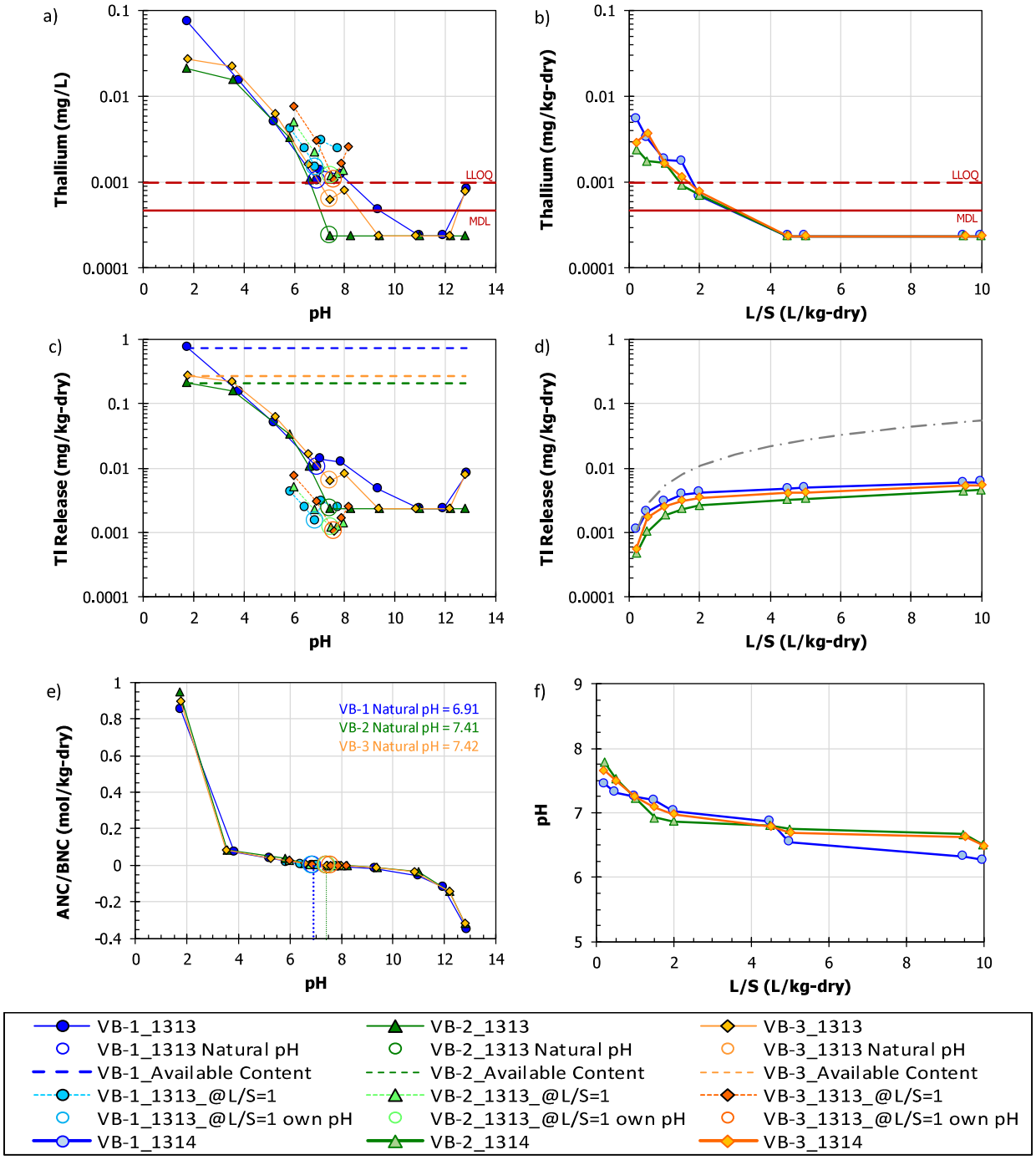


Figure D-33
Thallium LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

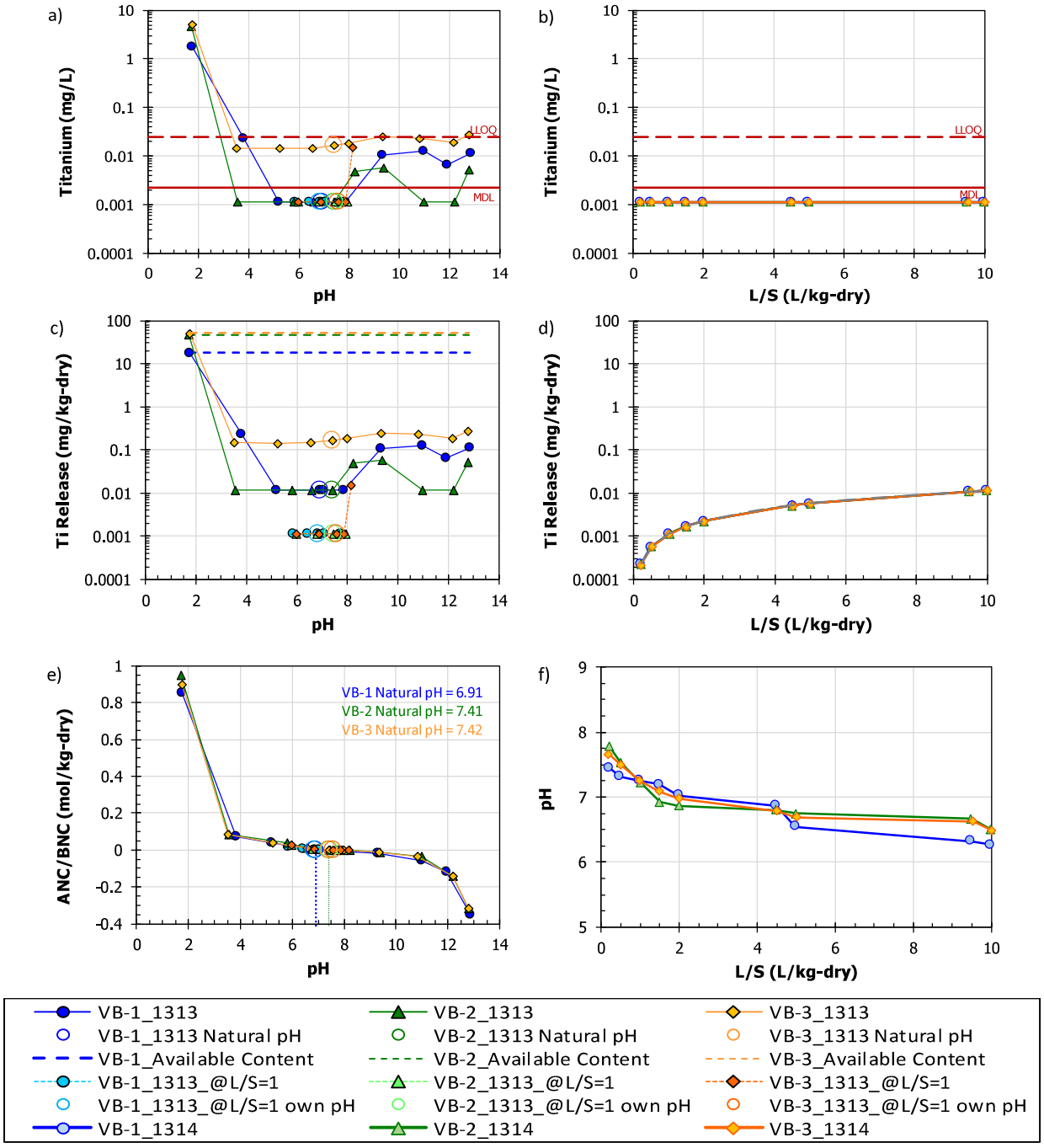


Figure D-34
Titanium LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

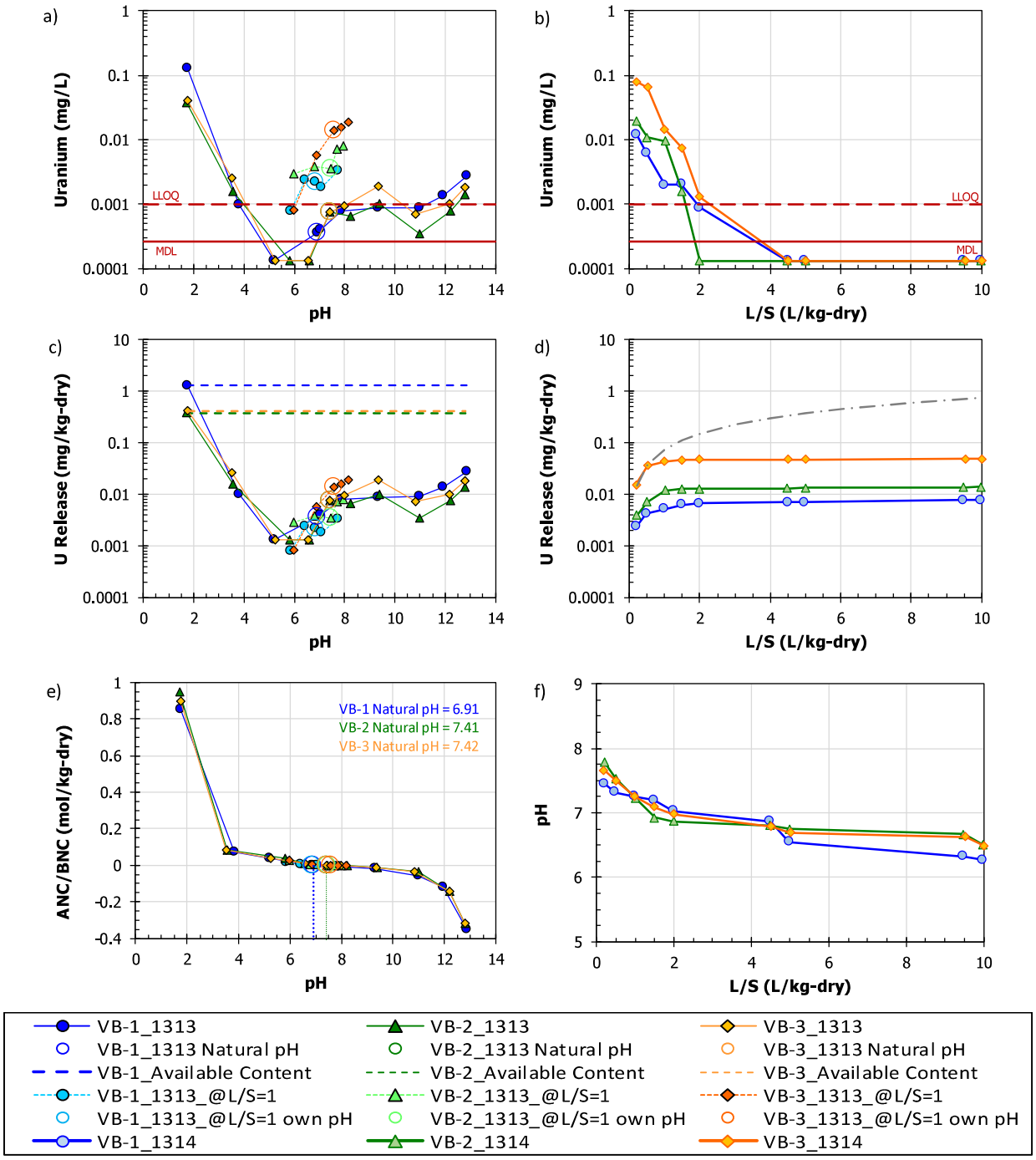


Figure D-35
Uranium LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

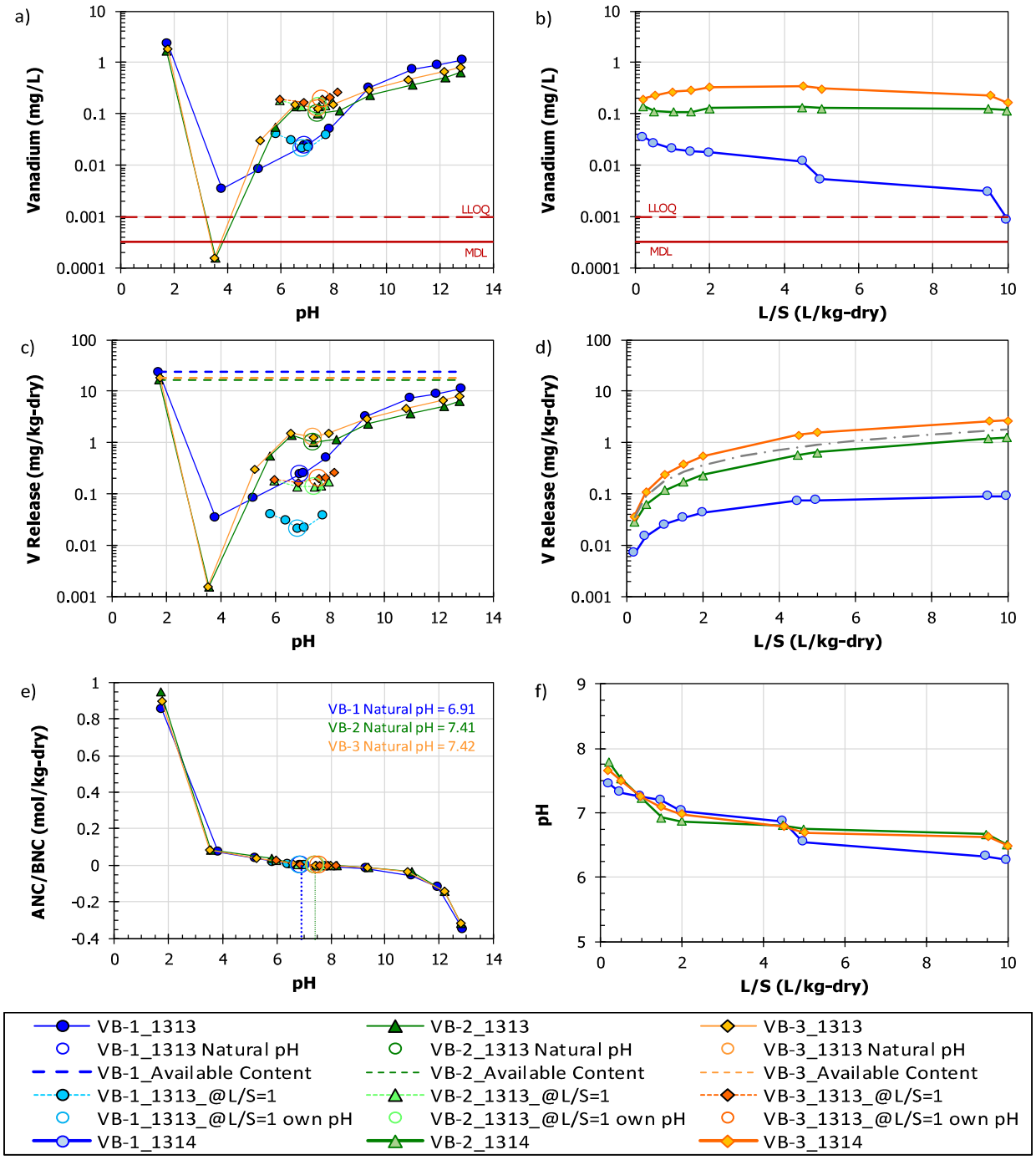


Figure D-36
Vanadium LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

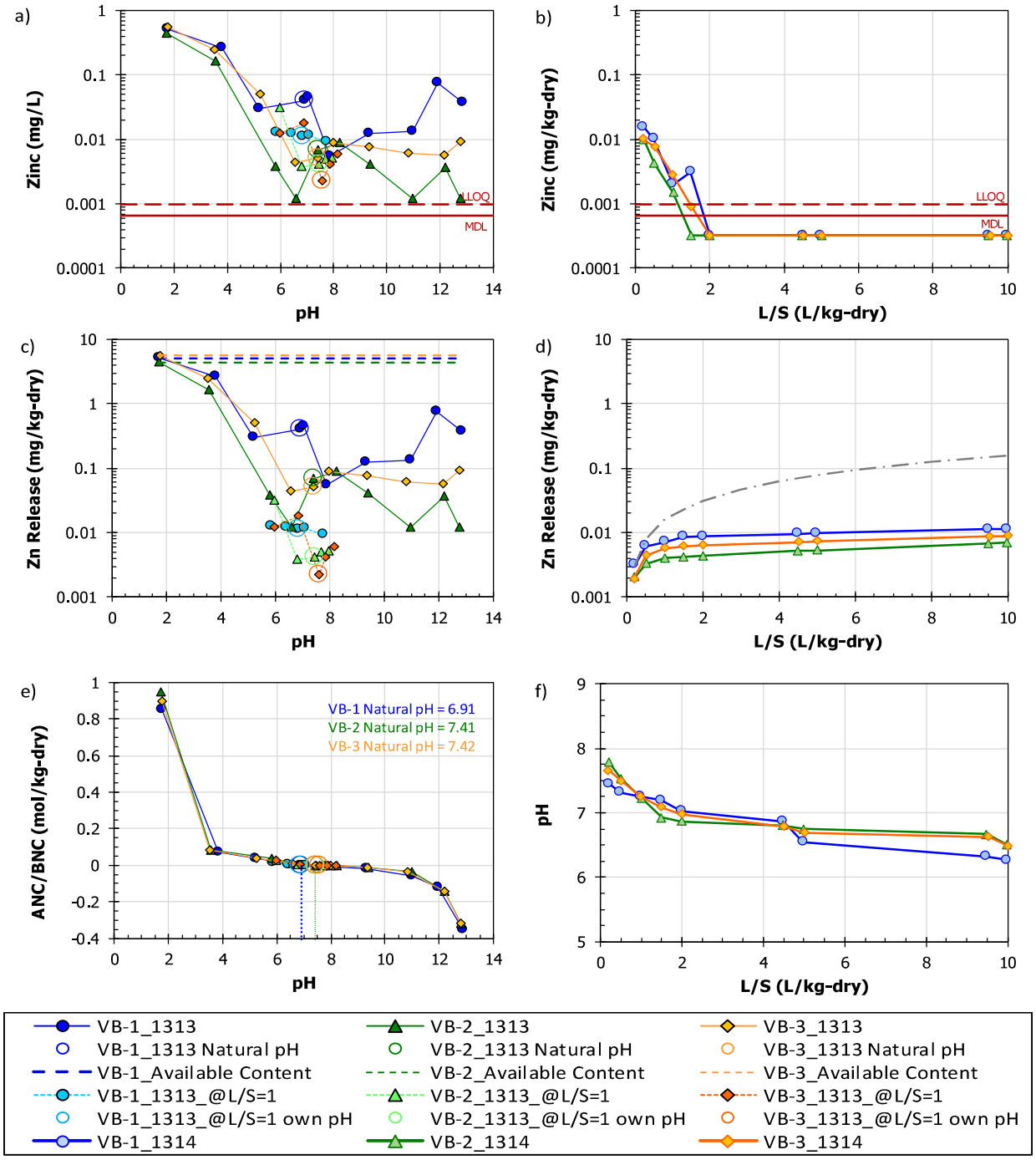


Figure D-37
Zinc LEAF test results from composite samples VB-1, VB-2, and VB-3: a) concentration as a function of pH, b) concentration as a function of L/S, c) mass release as a function of pH with available content, d) mass release as a function of L/S, e) acid/base neutralization capacity (ANC/BNC) as a function of pH, and f) column pH as a function of L/S

D.2 Comparison of Individual Split Spoon and Composite Sample Data

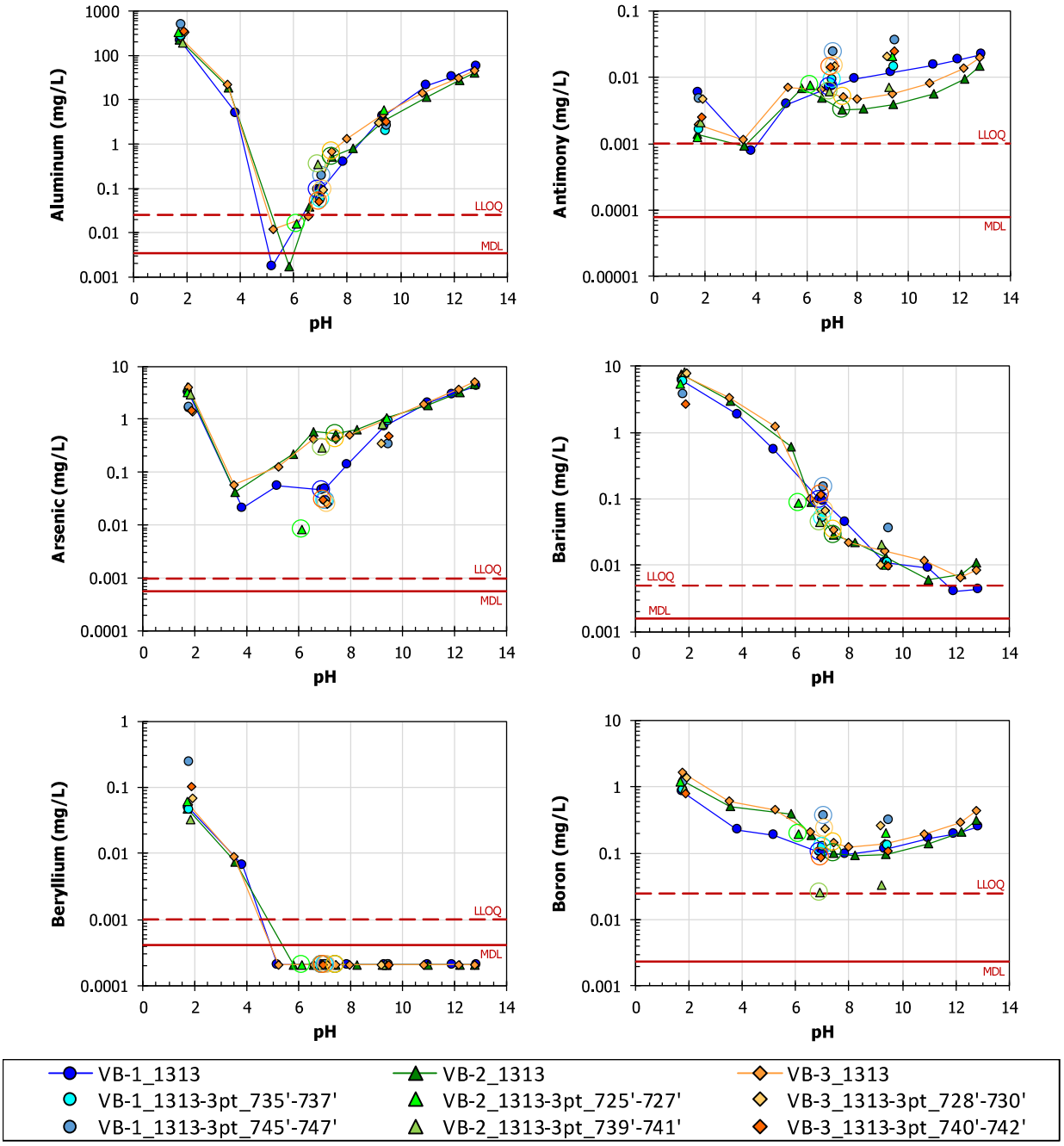


Figure D-38
pH-dependent concentration of composite samples (Method 1313) and discrete split spoon samples (Method 1313-3pt) from boreholes VB-1, VB-2 and VB-3: aluminum, antimony, arsenic, barium, beryllium, and boron

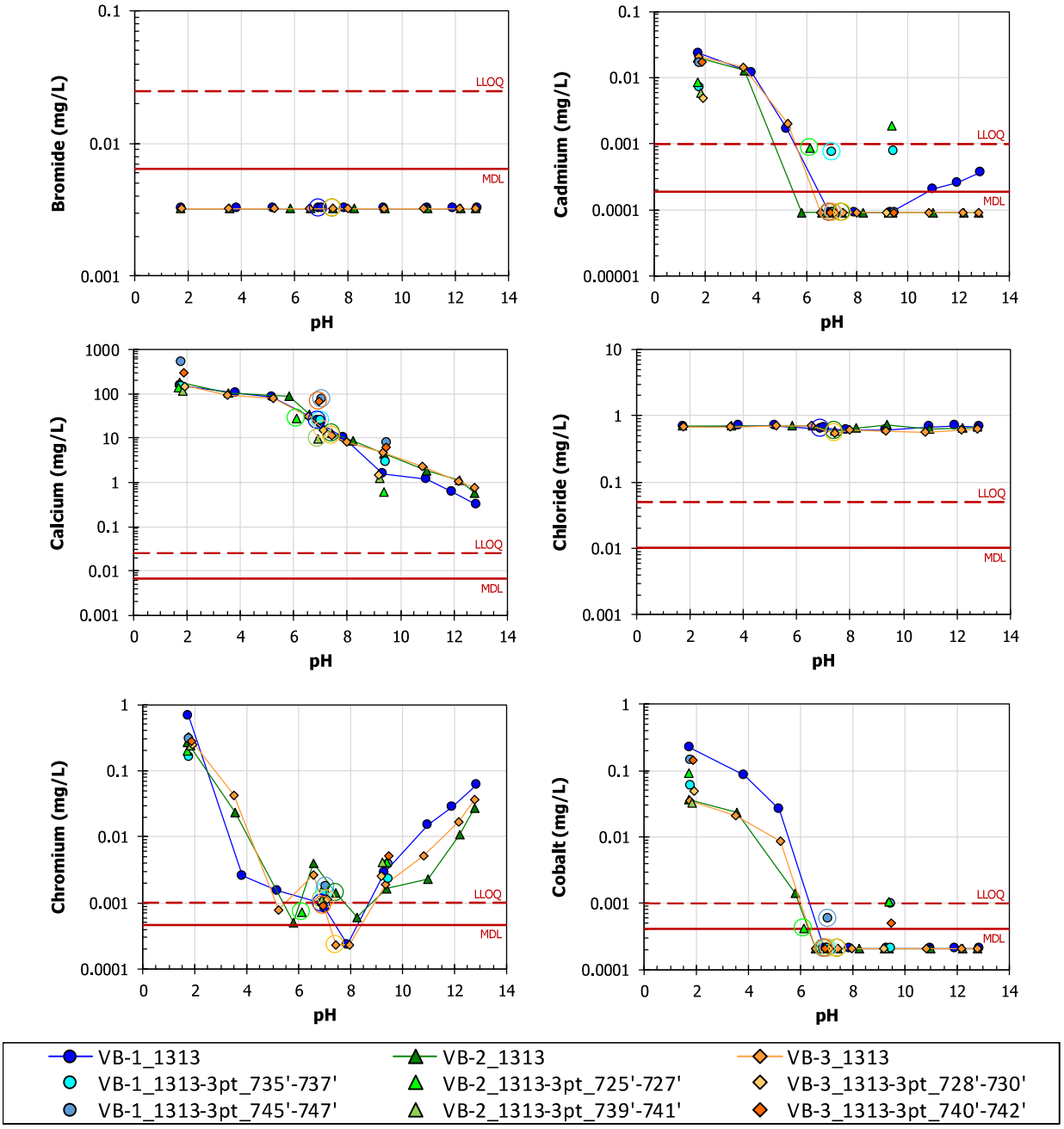


Figure D-39
pH-dependent concentration of composite samples (Method 1313) and discrete split spoon samples (Method 1313-3pt) from boreholes VB-1, VB-2 and VB-3: bromide, cadmium, calcium, chloride, chromium, and cobalt

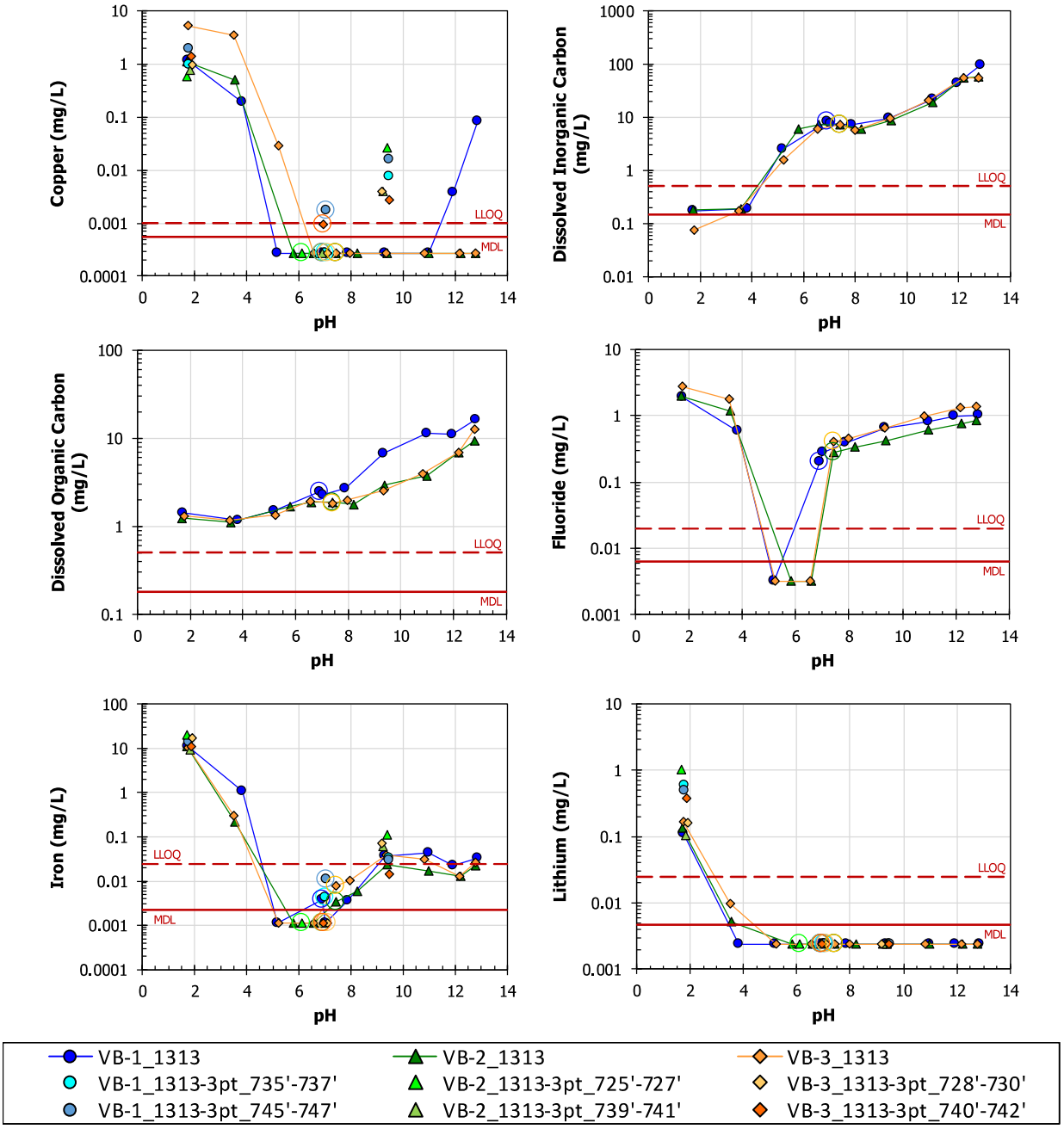


Figure D-40
pH-dependent concentration of composite samples (Method 1313) and discrete split spoon samples (Method 1313-3pt) from boreholes VB-1, VB-2 and VB-3: copper, dissolved inorganic carbon, dissolved organic carbon, fluoride, iron, and lithium

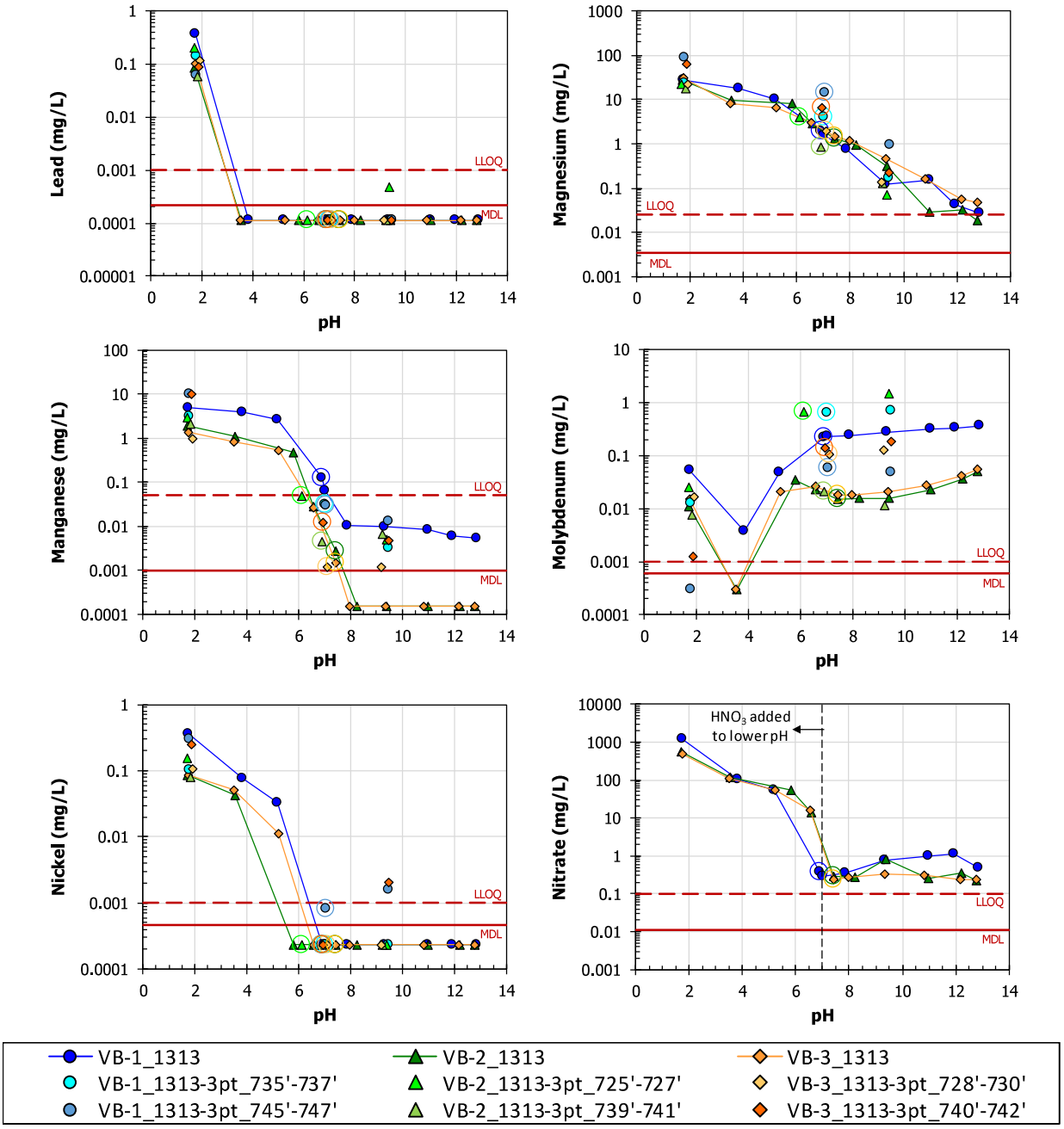


Figure D-41
pH-dependent concentration of composite samples (Method 1313) and discrete split spoon samples (Method 1313-3pt) from boreholes VB-1, VB-2 and VB-3: lead, magnesium, manganese, molybdenum, nickel, and nitrate

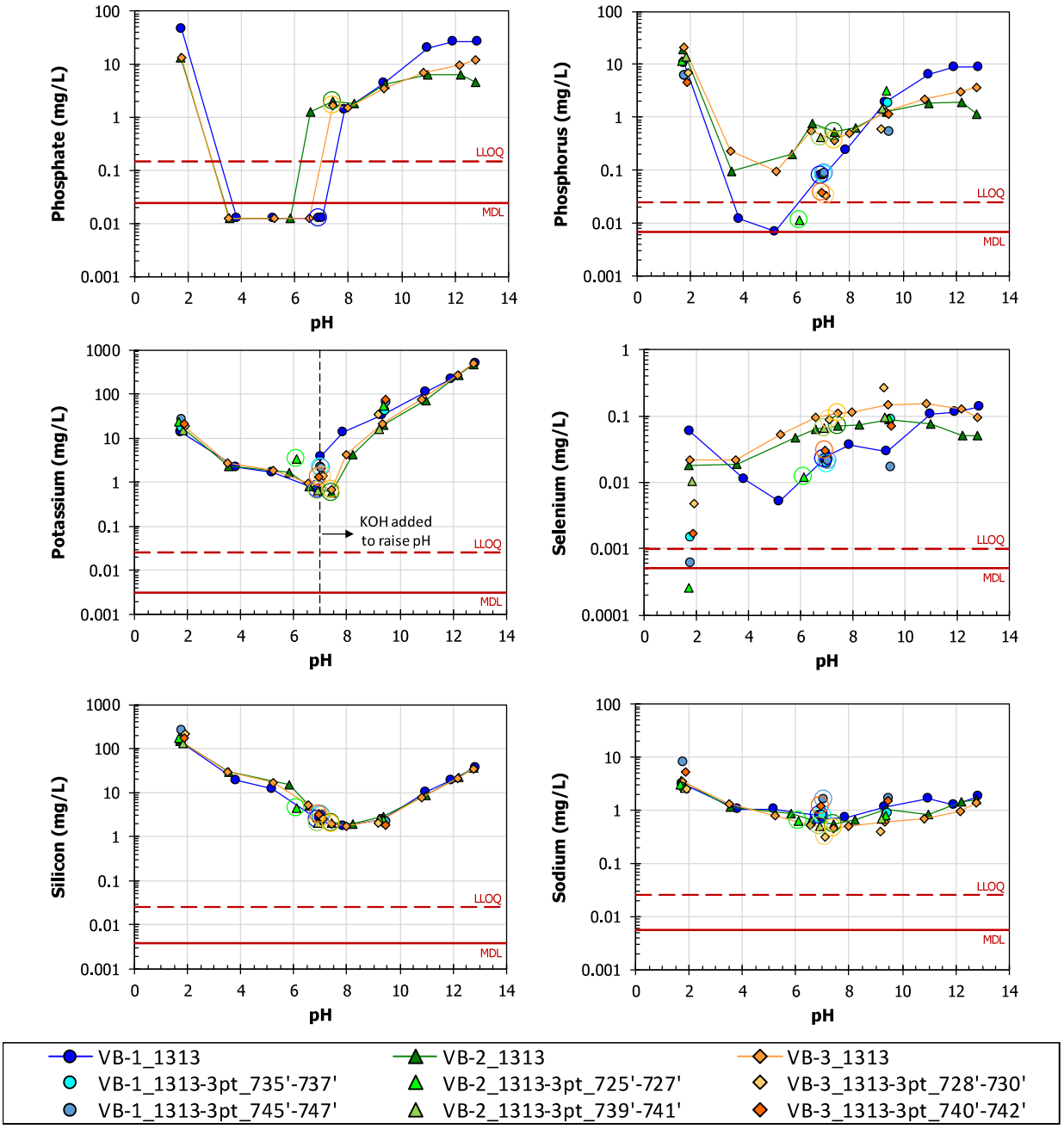


Figure D-42
pH-dependent concentration of composite samples (Method 1313) and discrete split spoon samples (Method 1313-3pt) from boreholes VB-1, VB-2 and VB-3: phosphate, phosphorus, potassium, selenium, silicon, and sodium

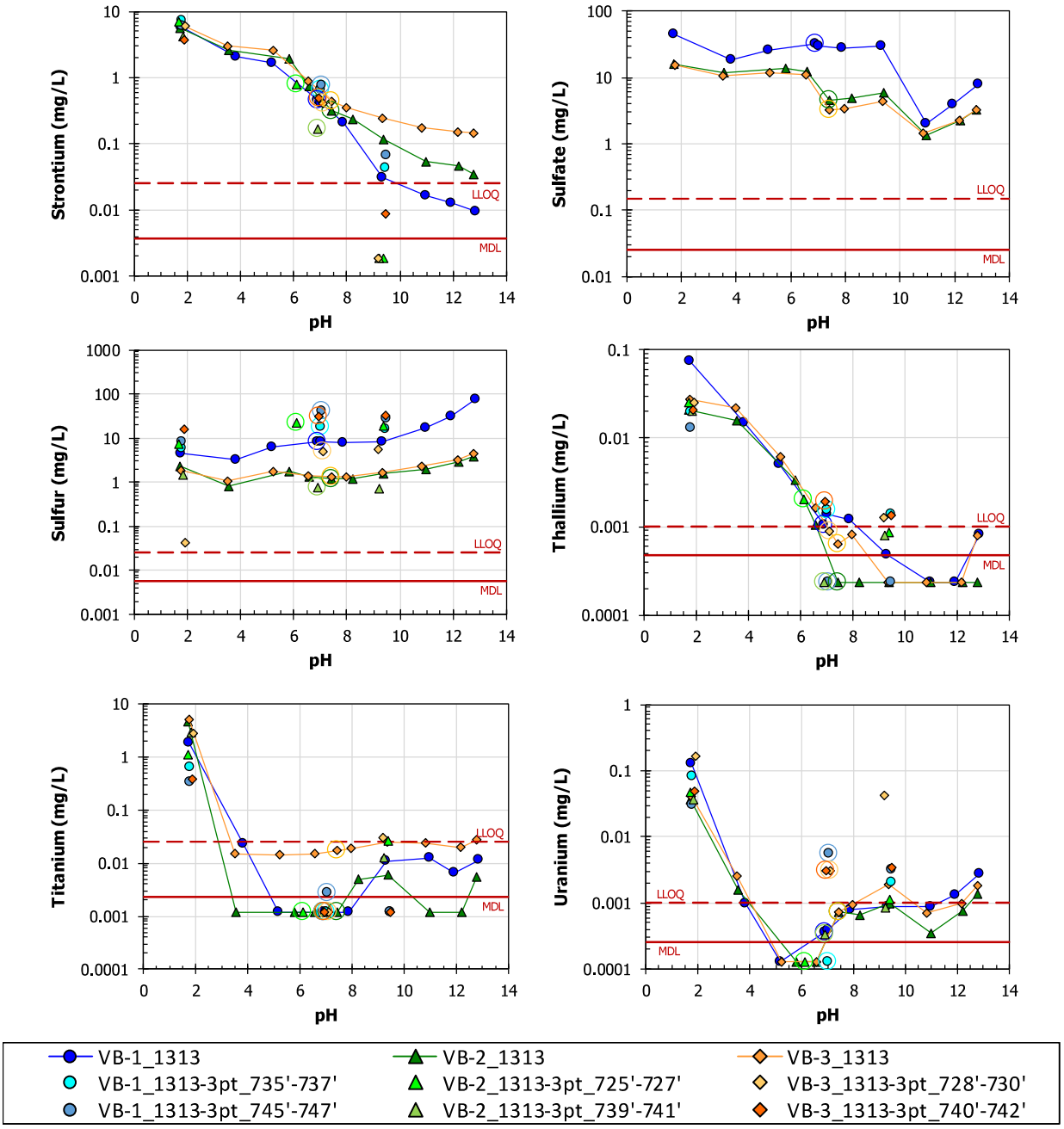


Figure D-43
pH-dependent concentration of composite samples (Method 1313) and discrete split spoon samples (Method 1313-3pt) from boreholes VB-1, VB-2 and VB-3: strontium, sulfate, sulfur, thallium, titanium, and uranium

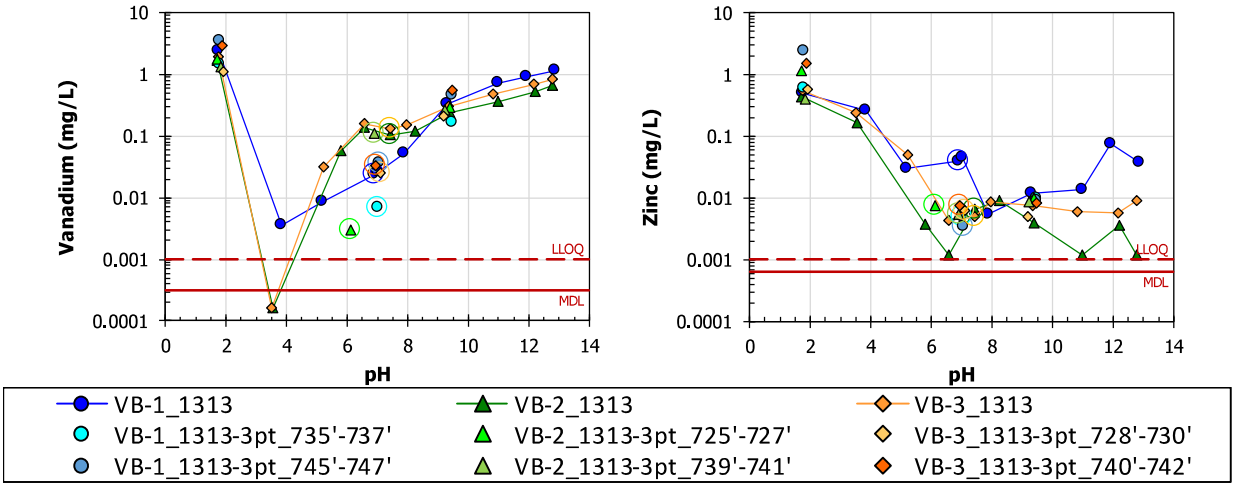


Figure D-44
pH-dependent concentration of composite samples (Method 1313) and discrete split spoon samples (Method 1313-3pt) from boreholes VB-1, VB-2 and VB-3: vanadium and zinc

E
COMPARISON OF TEST METHOD RESULTS

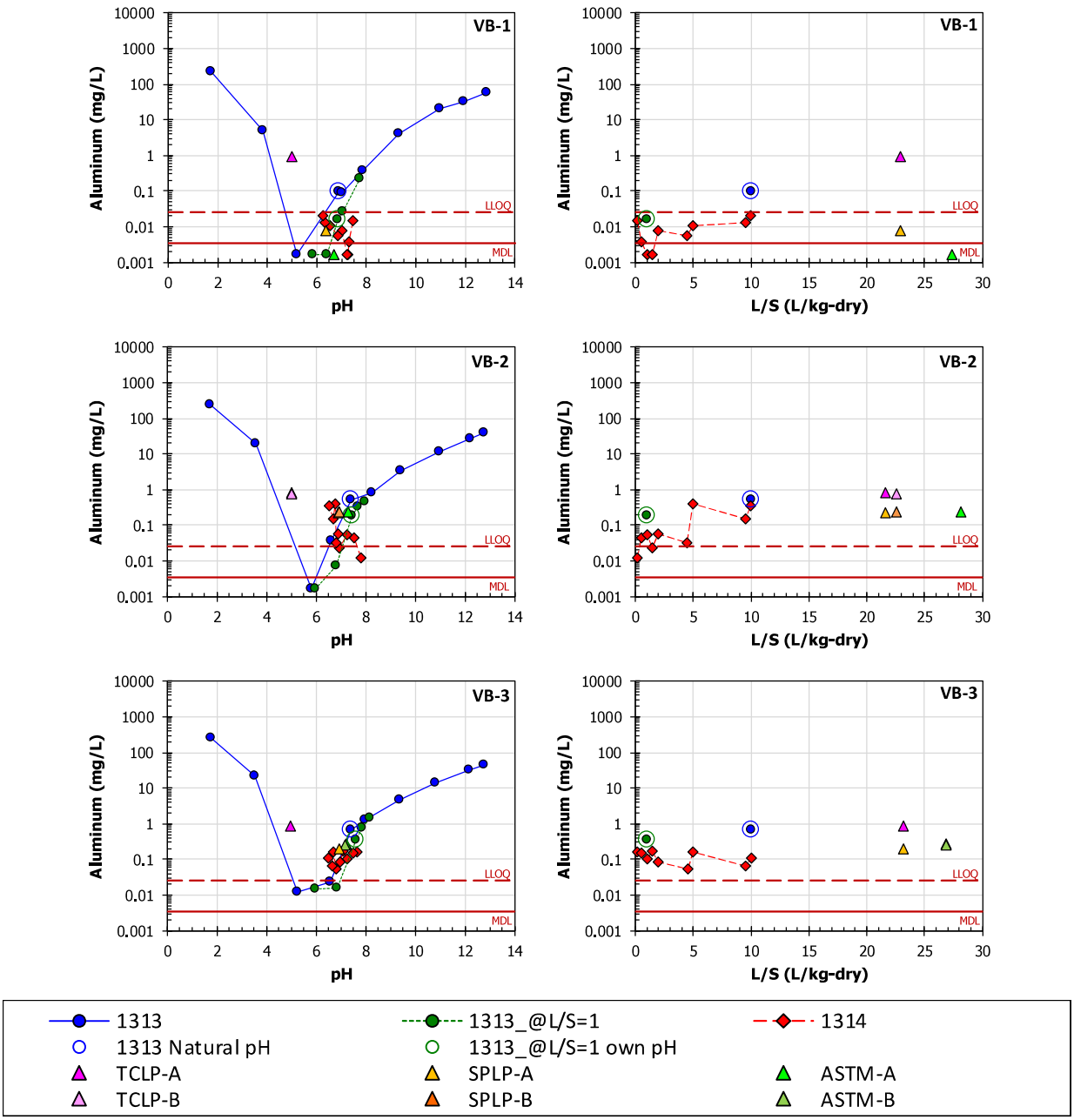


Figure E-1
Aluminum concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

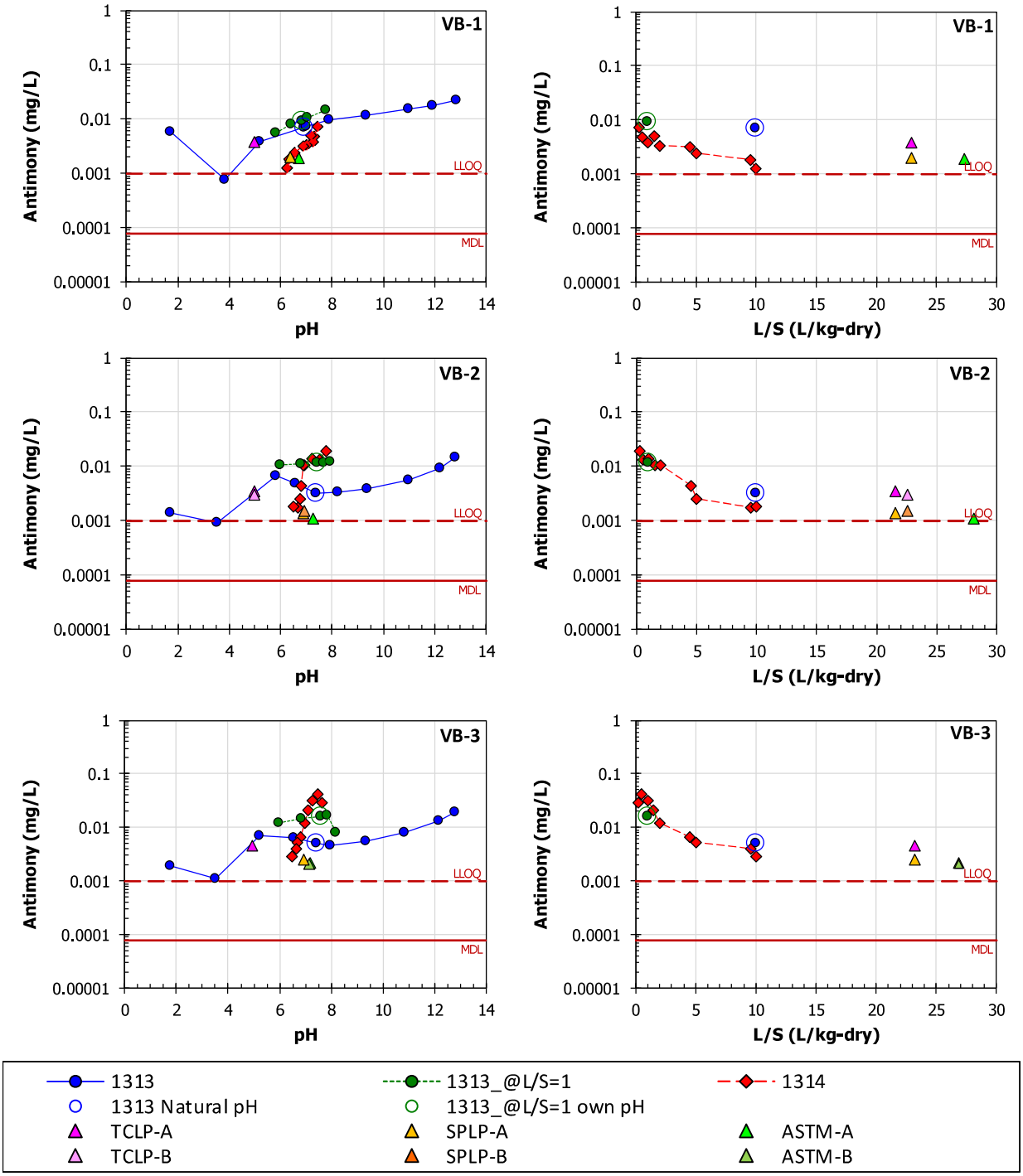


Figure E-2
Antimony concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

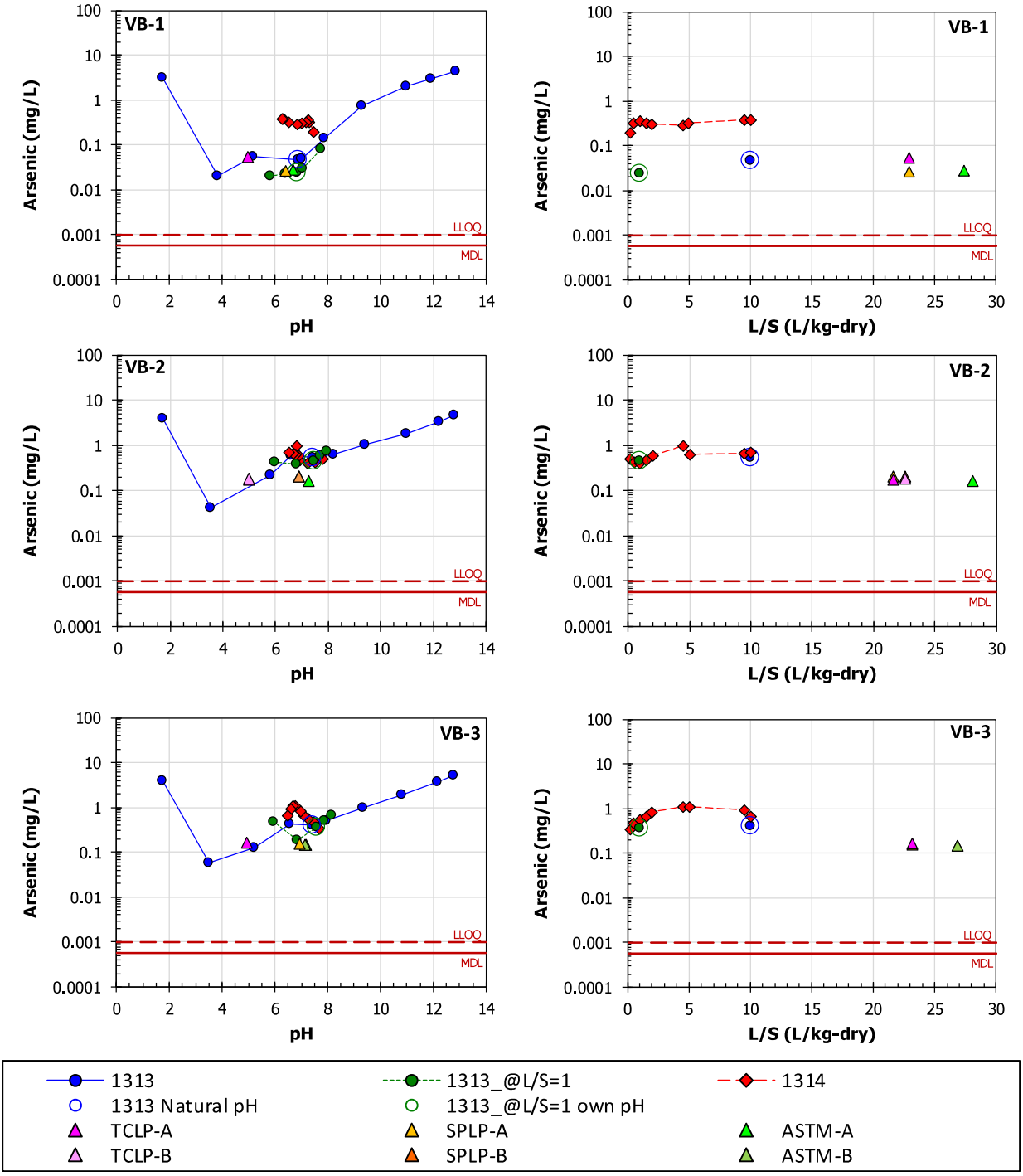


Figure E-3
Arsenic concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

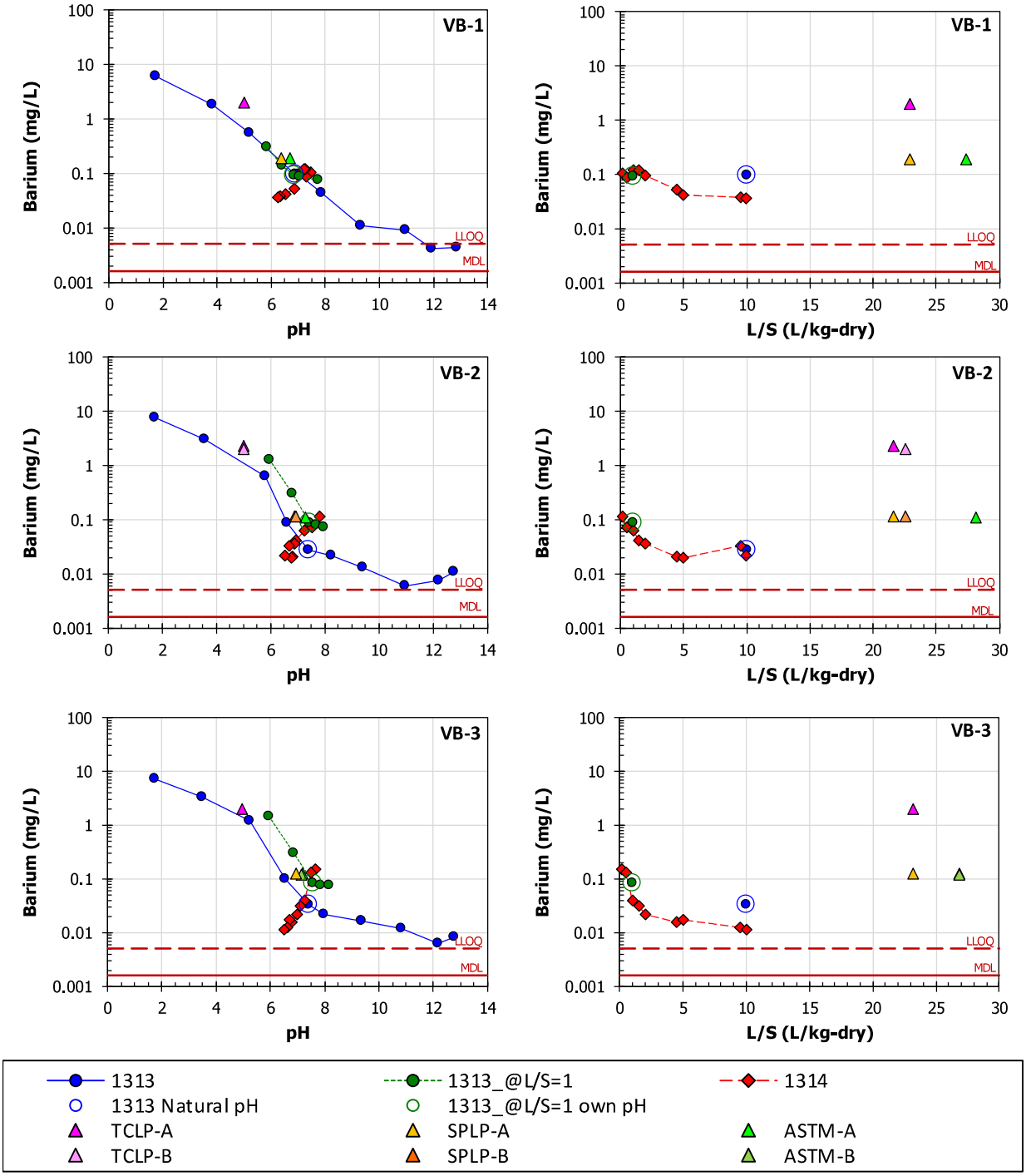


Figure E-4
Barium concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

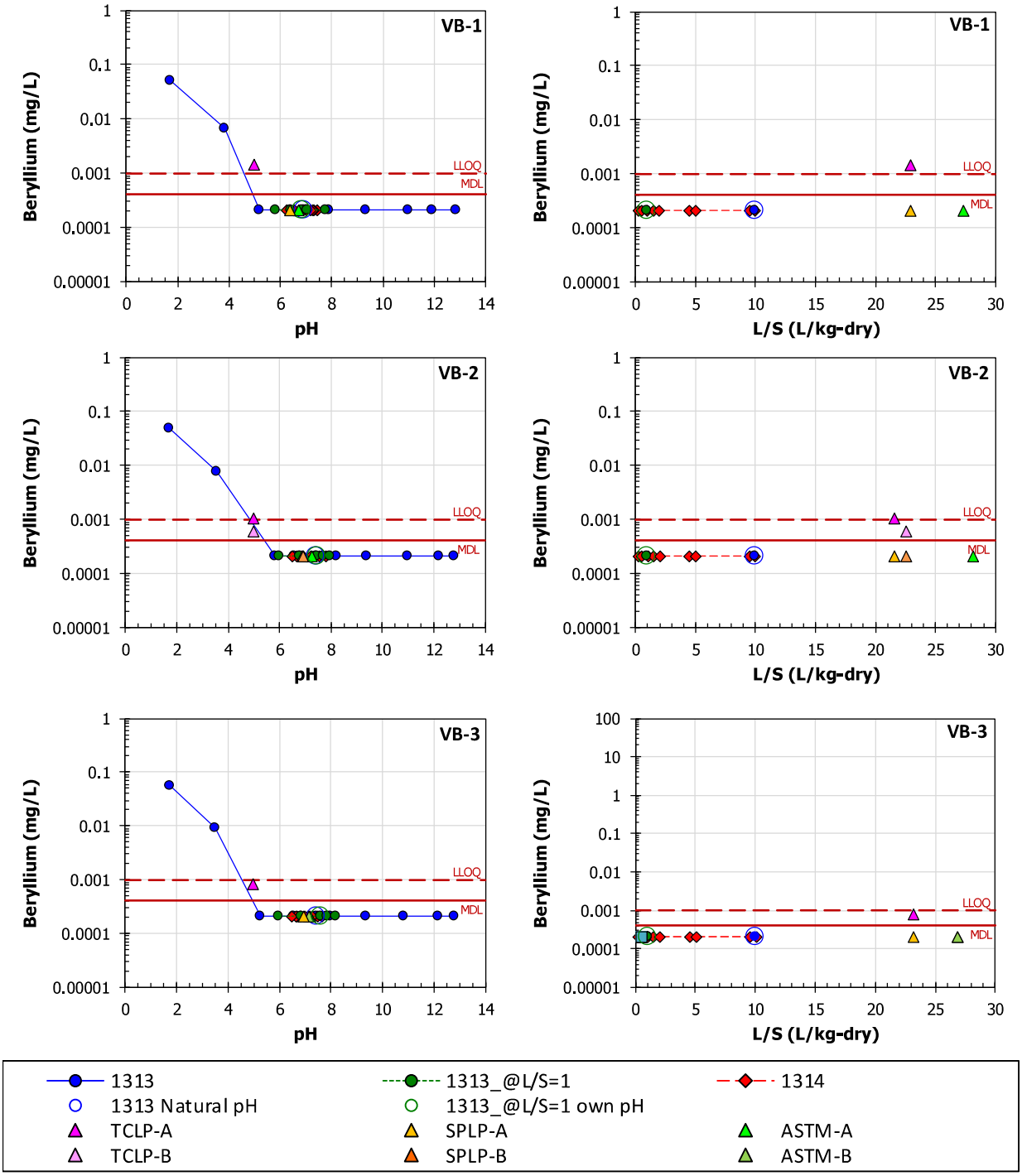


Figure E-5
Beryllium concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

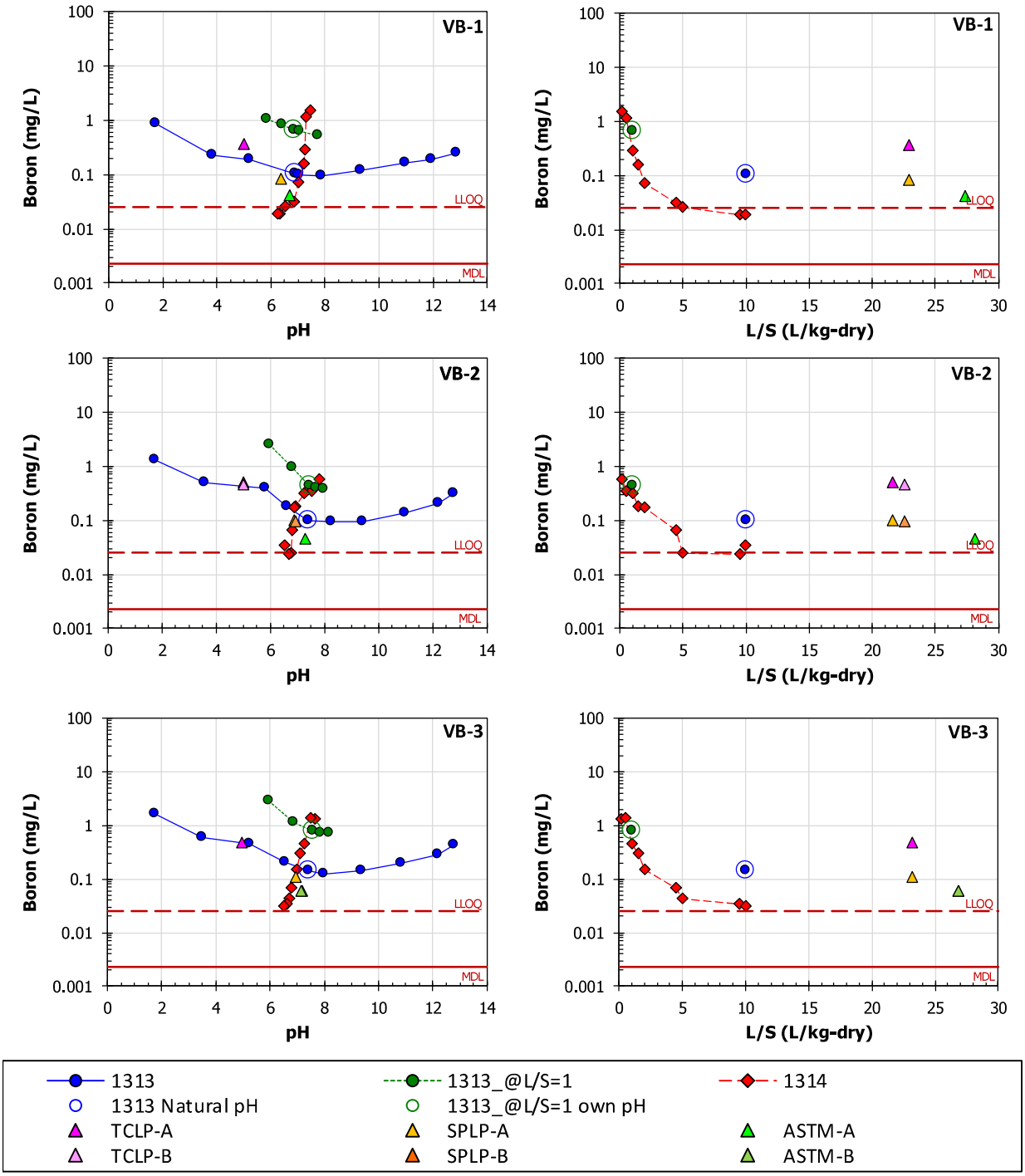


Figure E-6
Boron concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

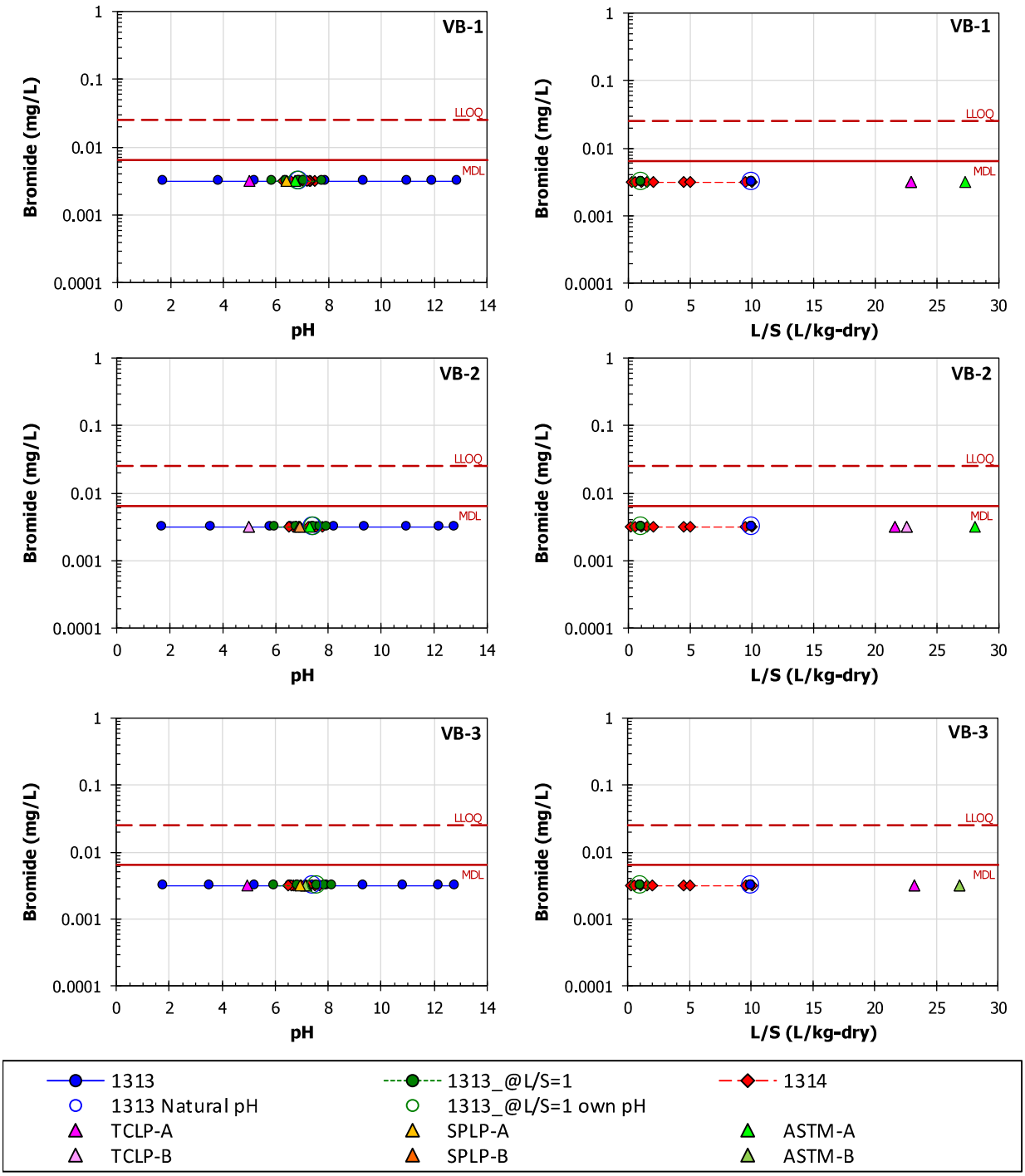


Figure E-7
Bromide concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

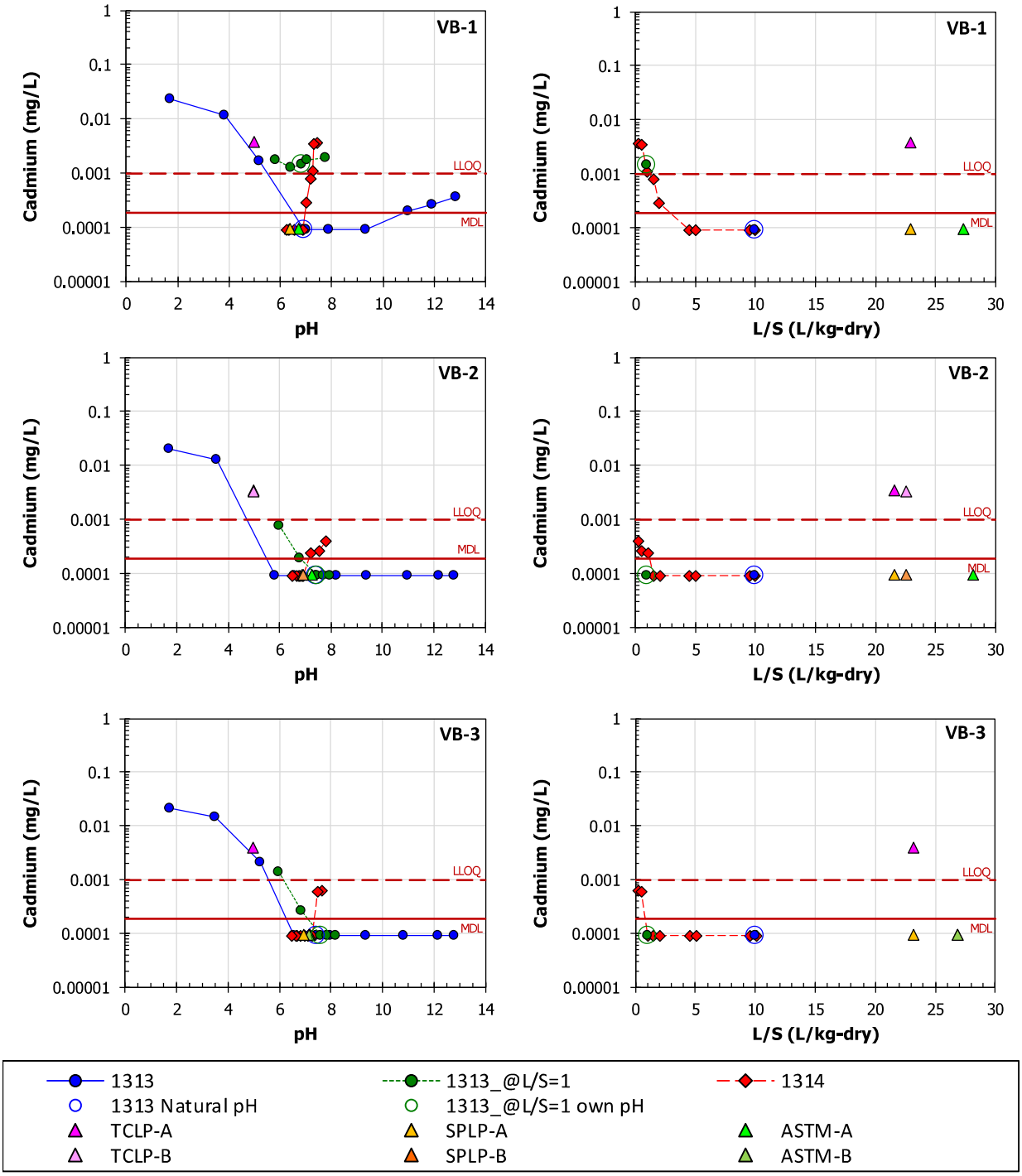


Figure E-8
Cadmium concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

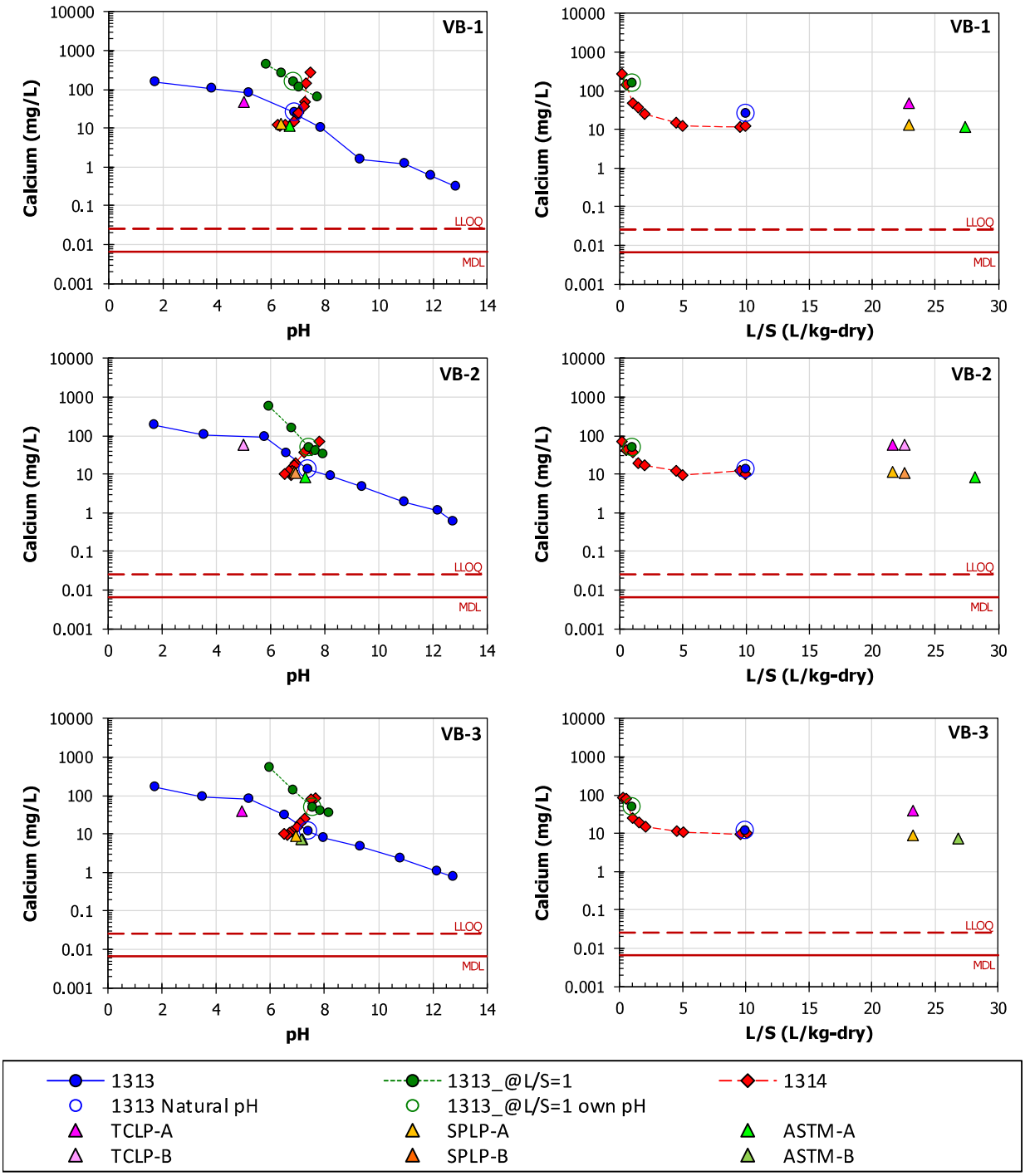


Figure E-9
Calcium concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

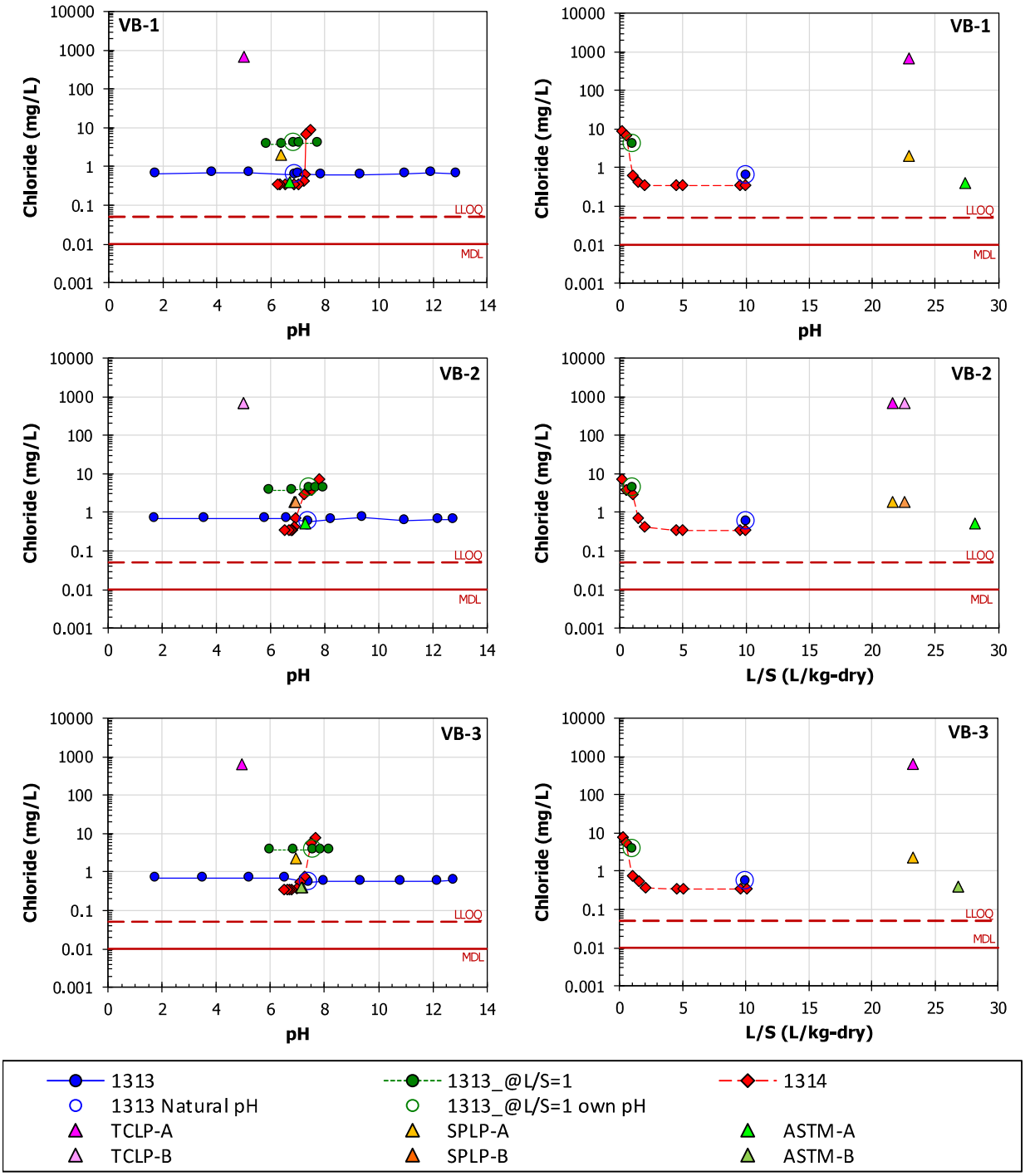


Figure E-10
Chloride concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

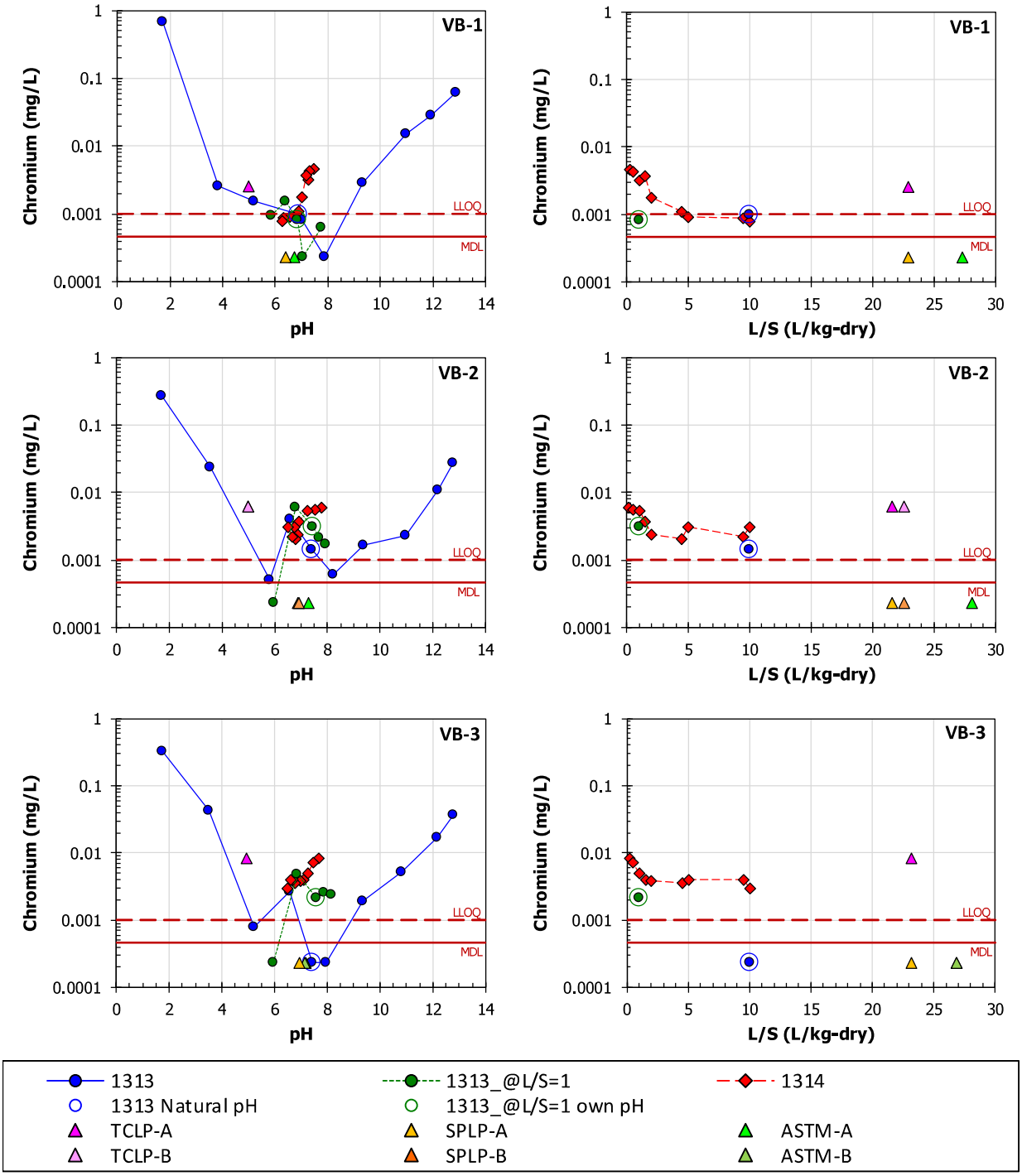


Figure E-11
Chromium concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

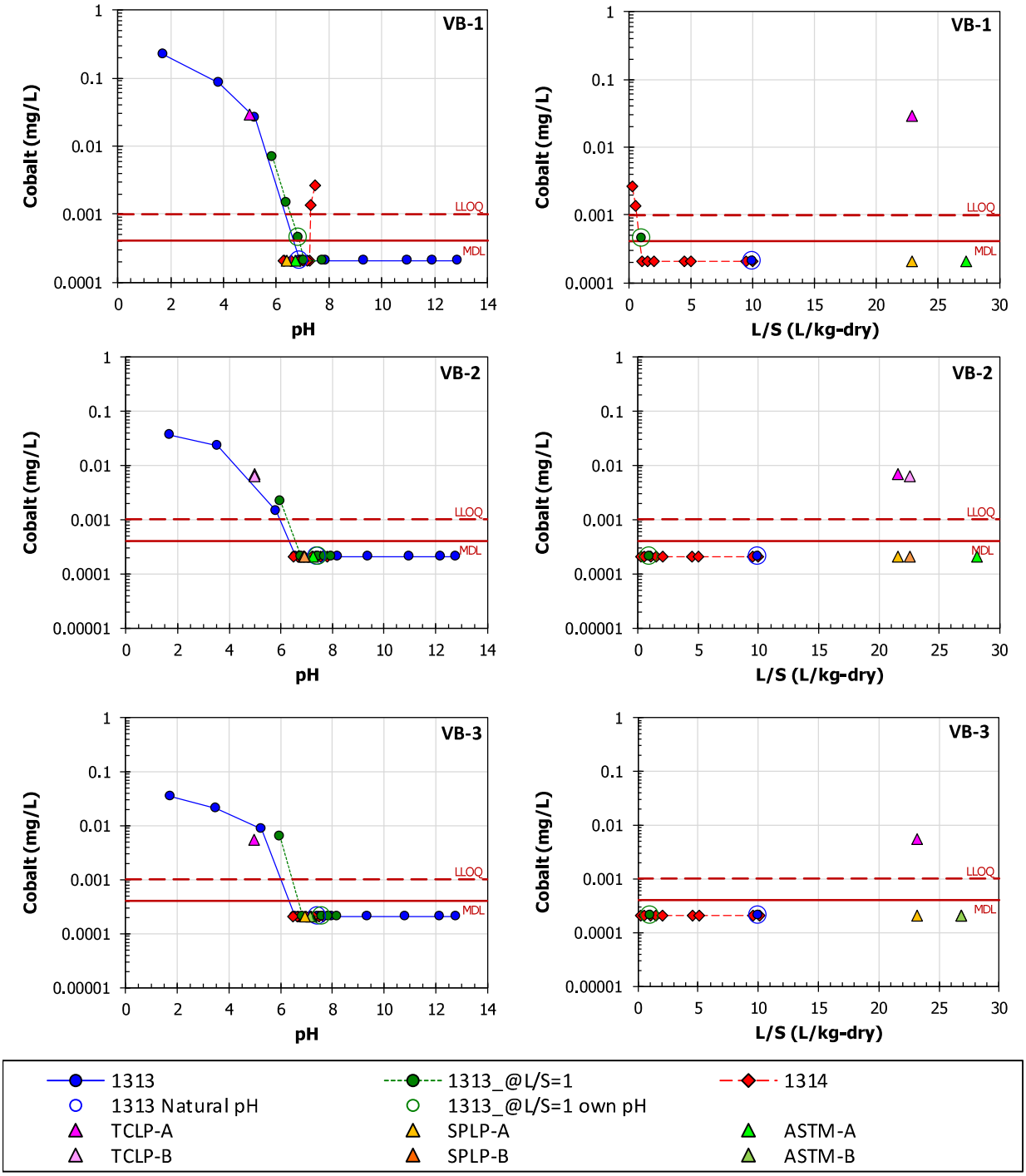


Figure E-12
Cobalt concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

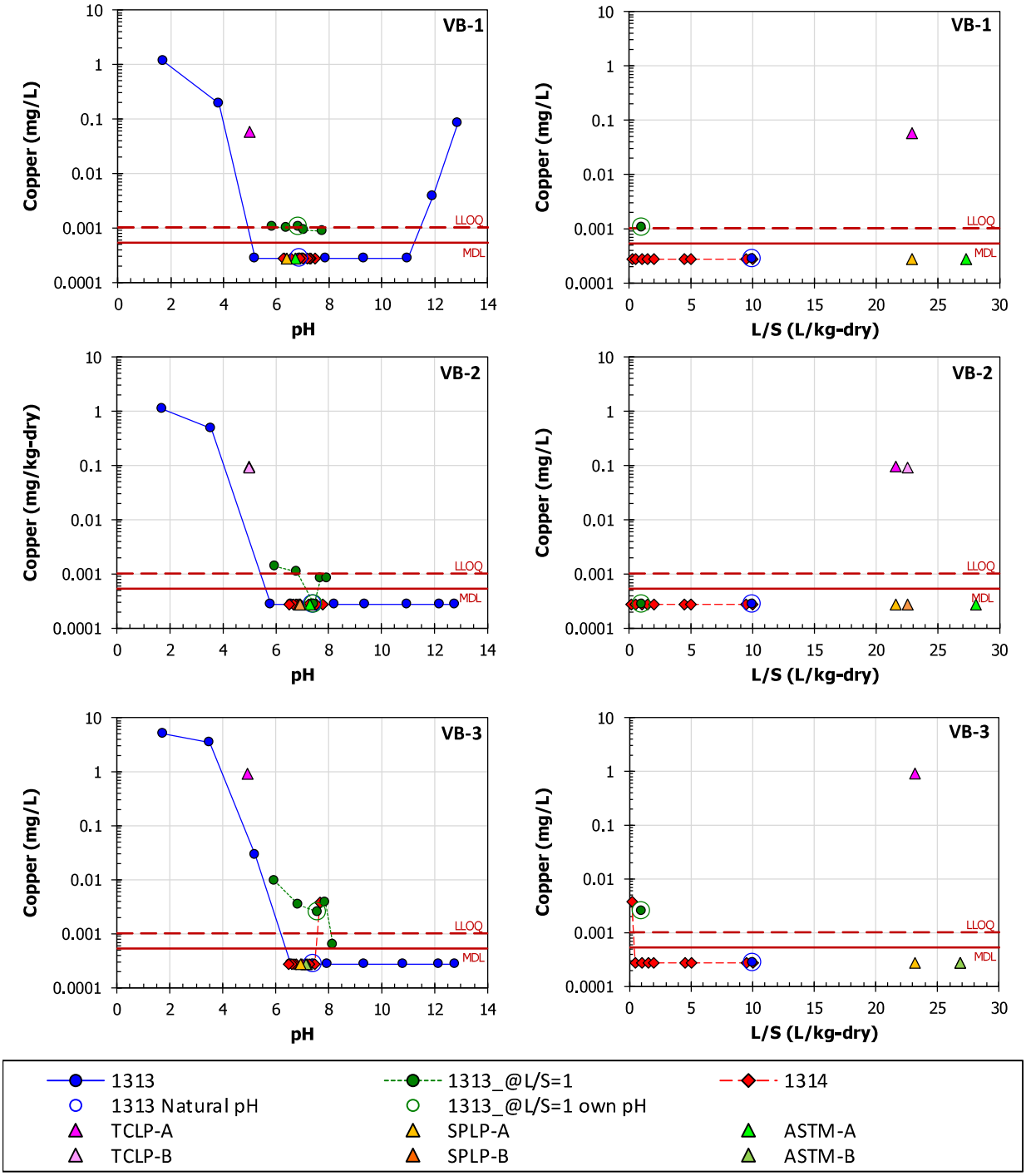


Figure E-13
Copper concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

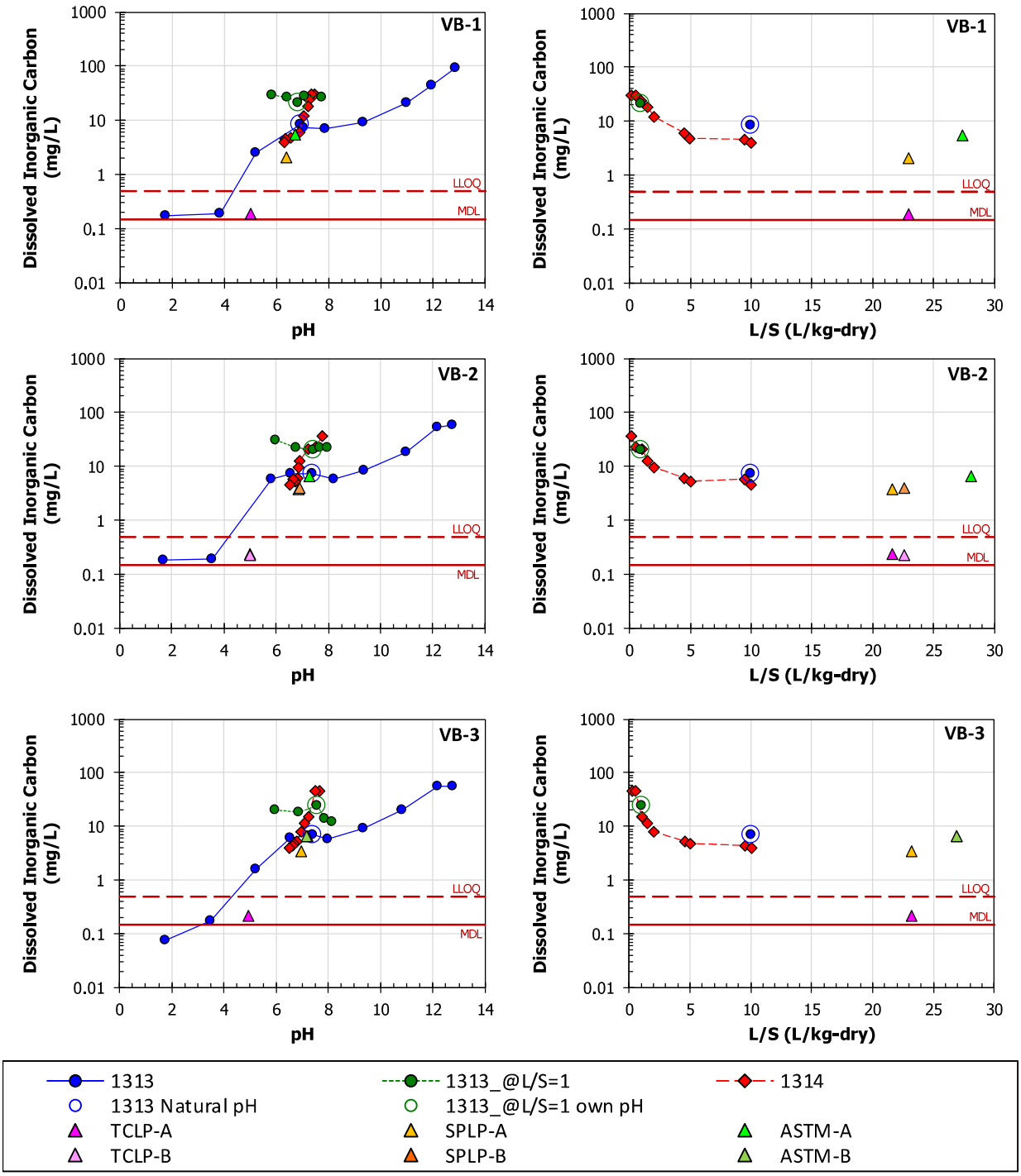


Figure E-14
Dissolved inorganic carbon concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

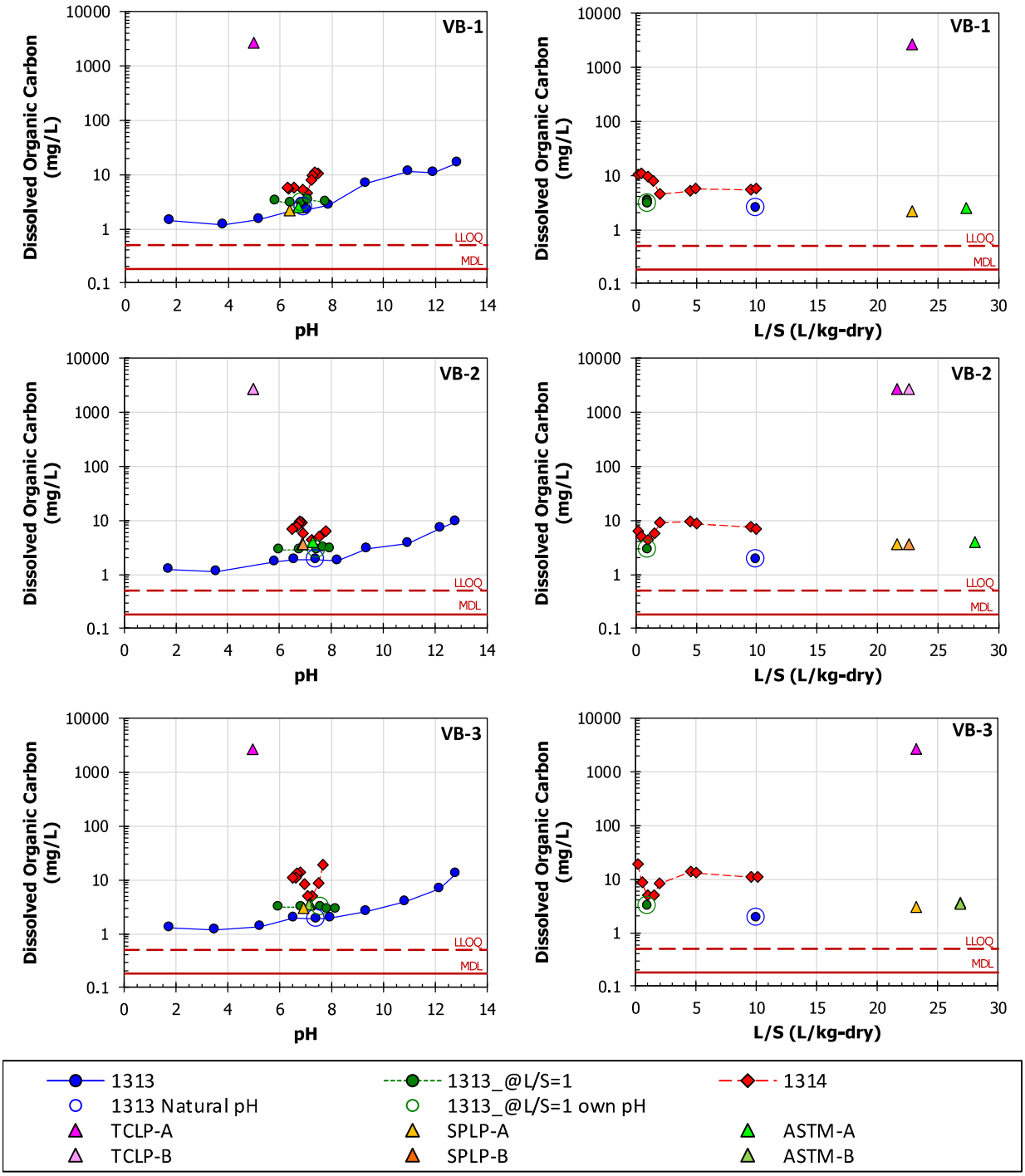


Figure E-15
Dissolved organic carbon concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

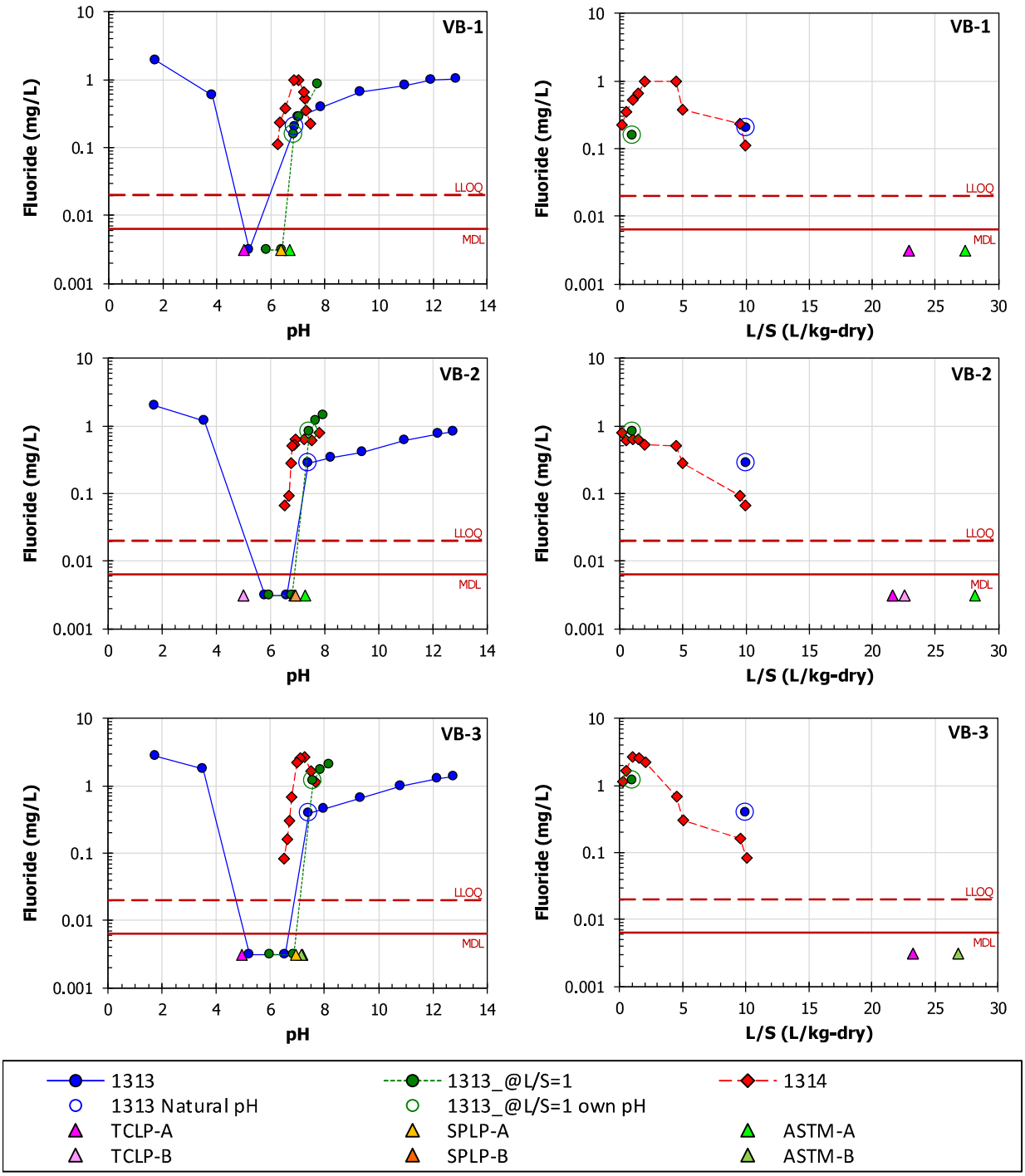


Figure E-16
Flouride concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

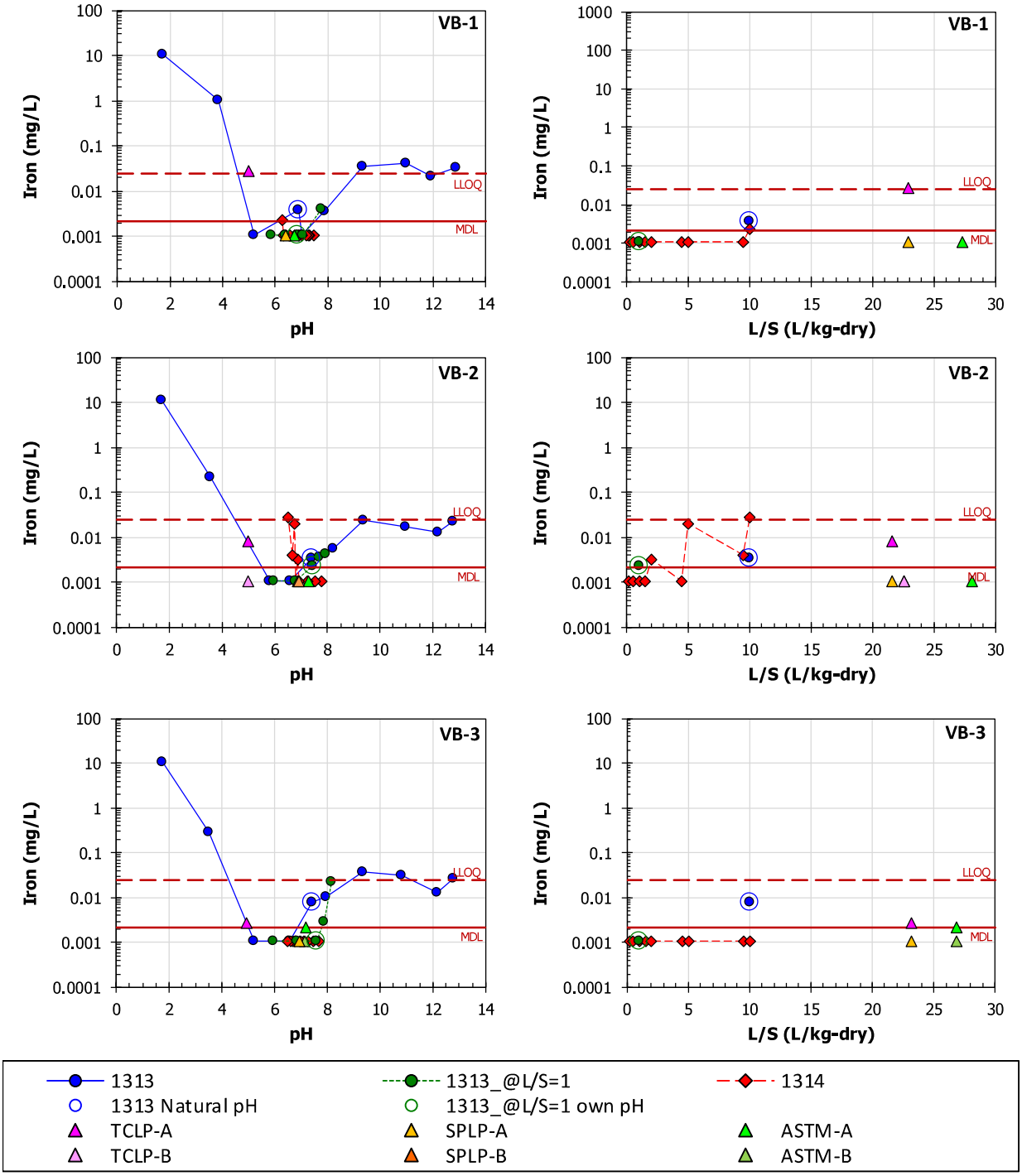


Figure E-17
Iron concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

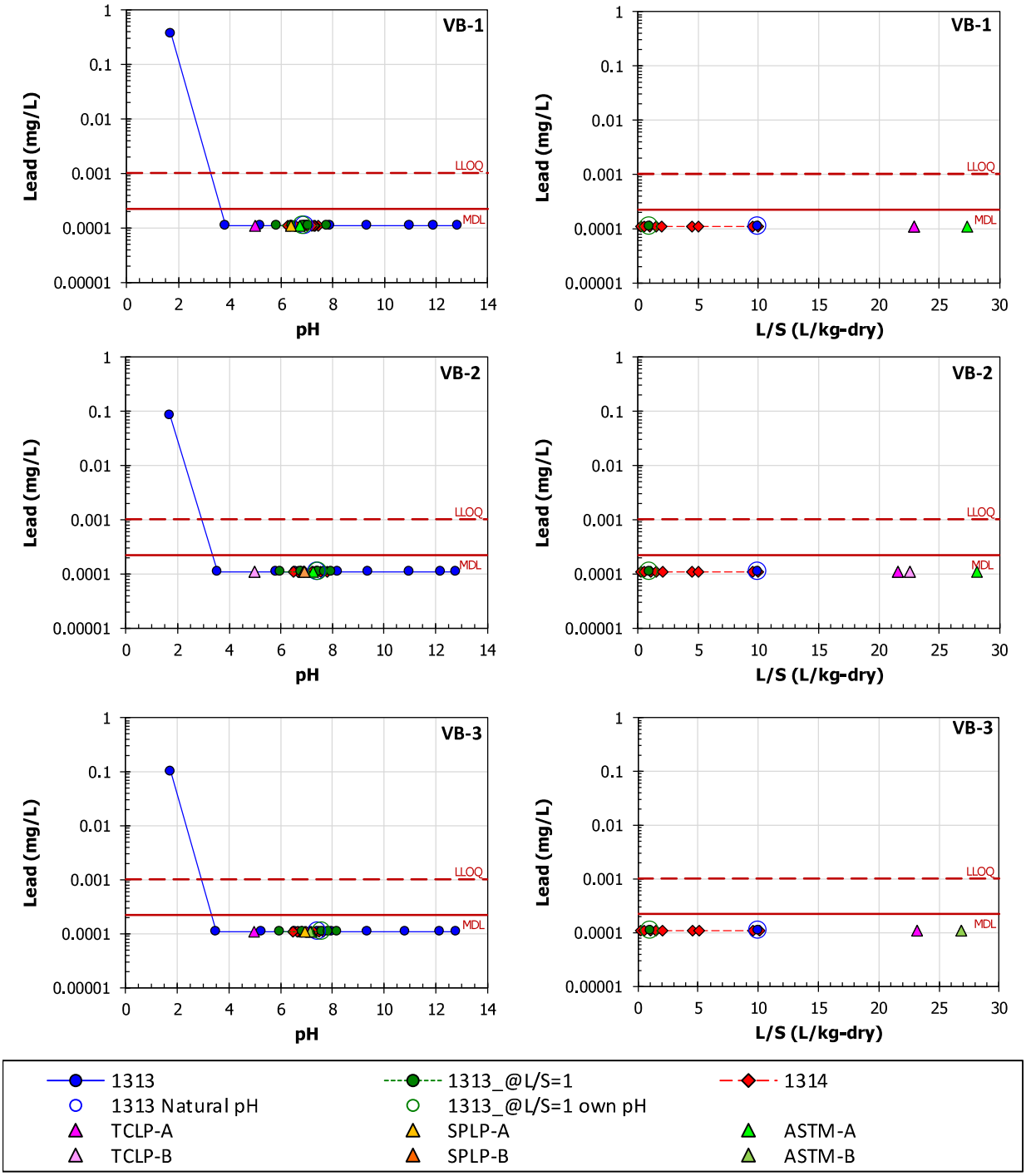


Figure E-18
Lead concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

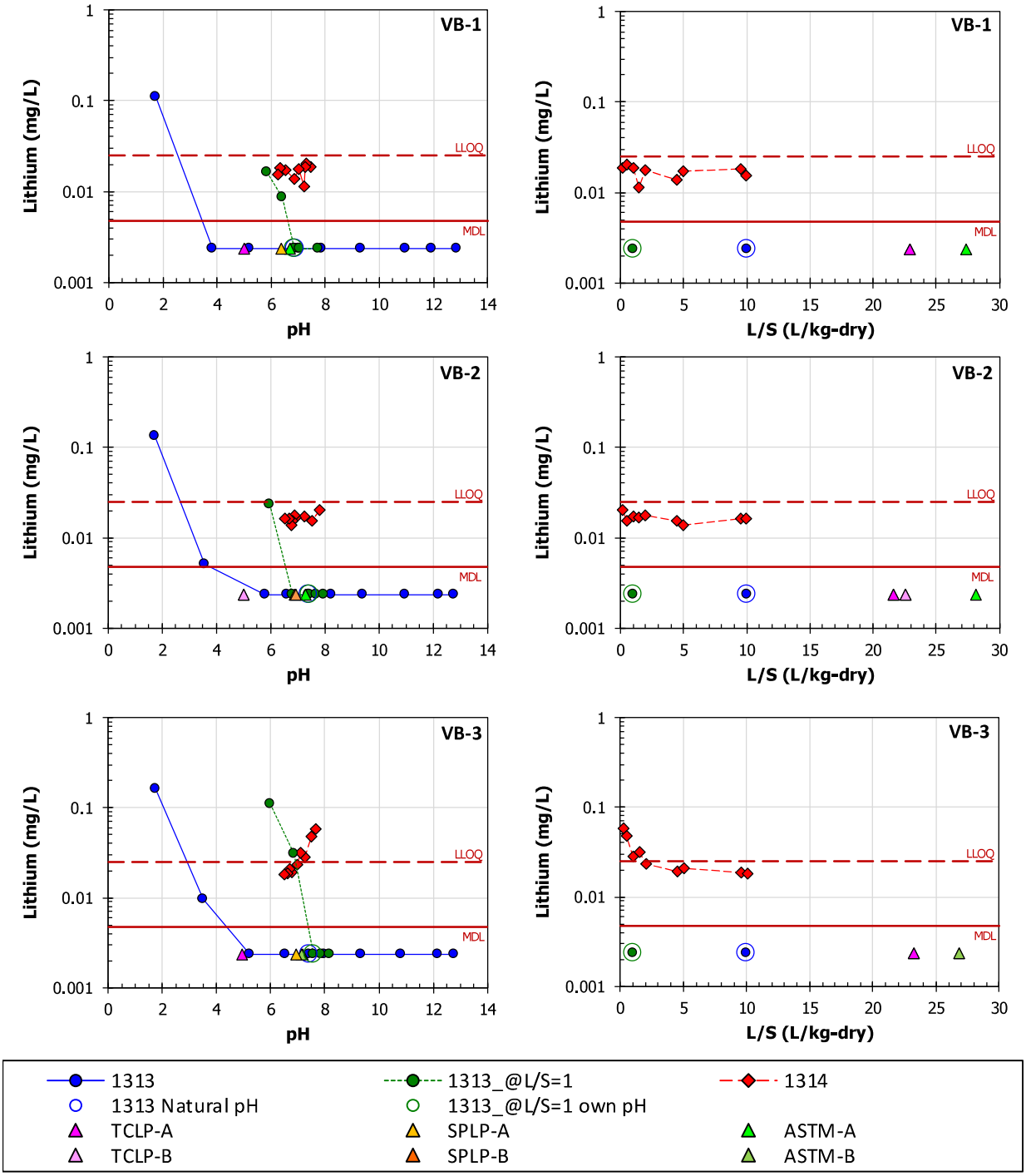


Figure E-19
Lithium concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

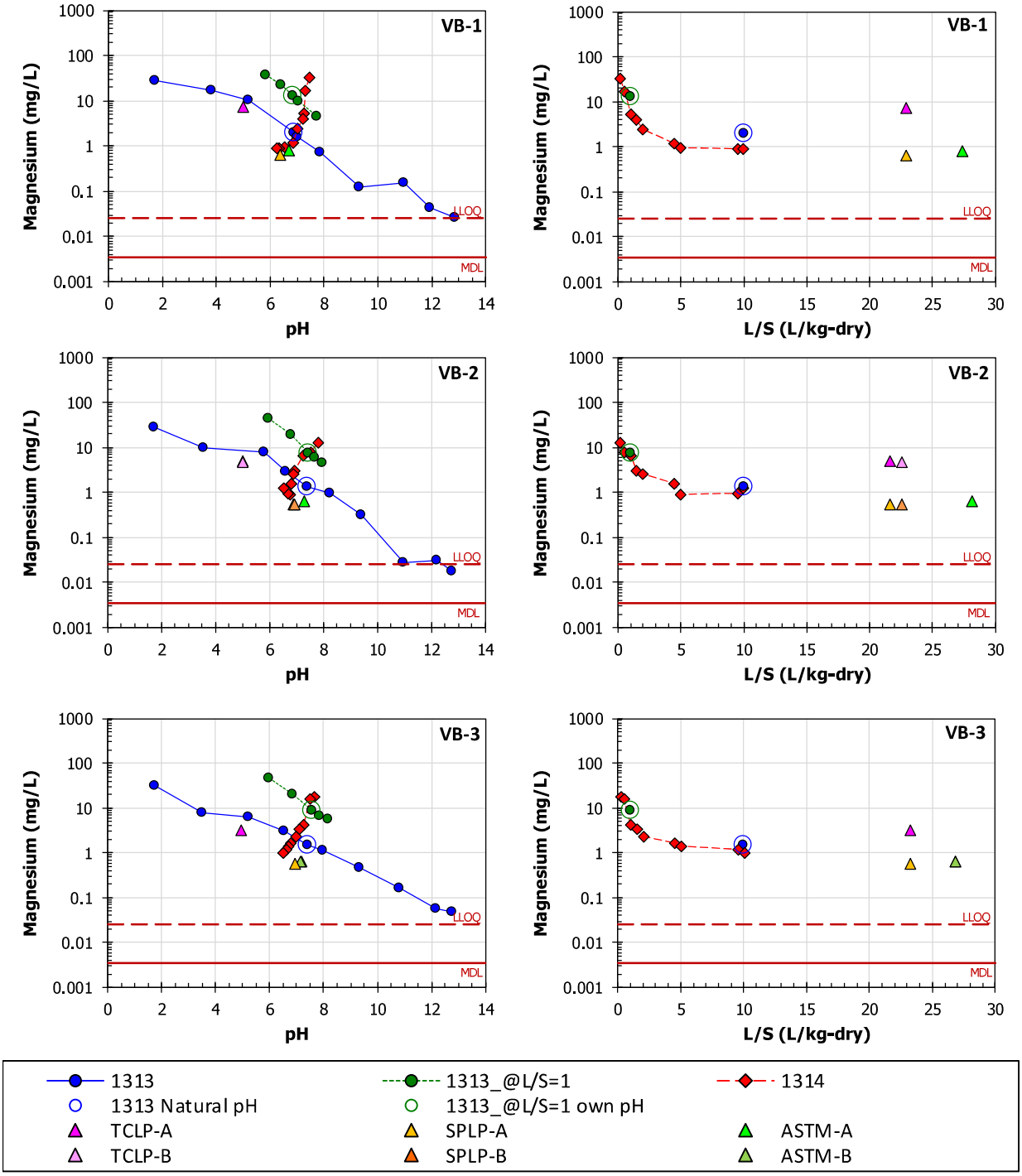


Figure E-20
Magnesium concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

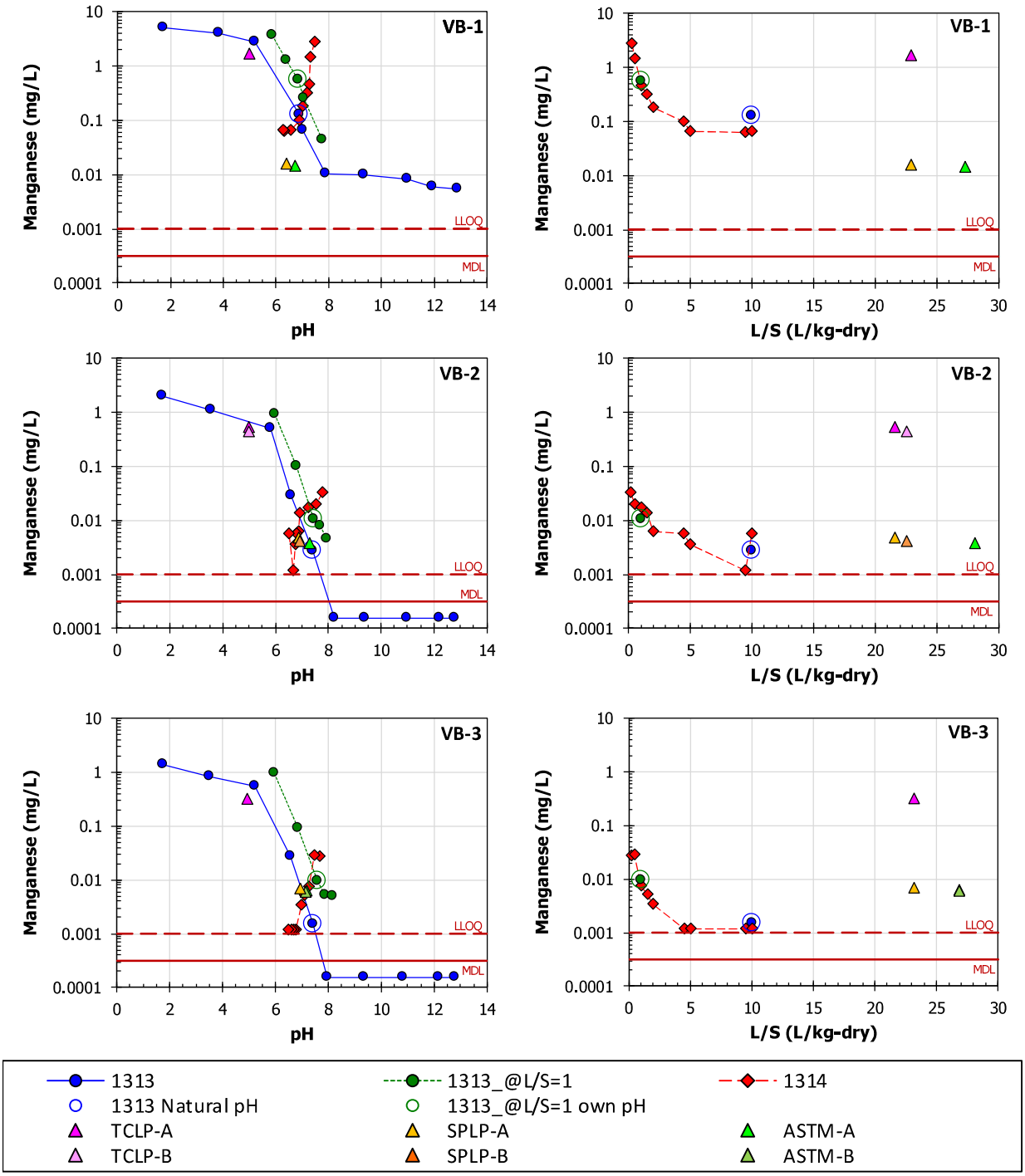


Figure E-21
Manganese concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

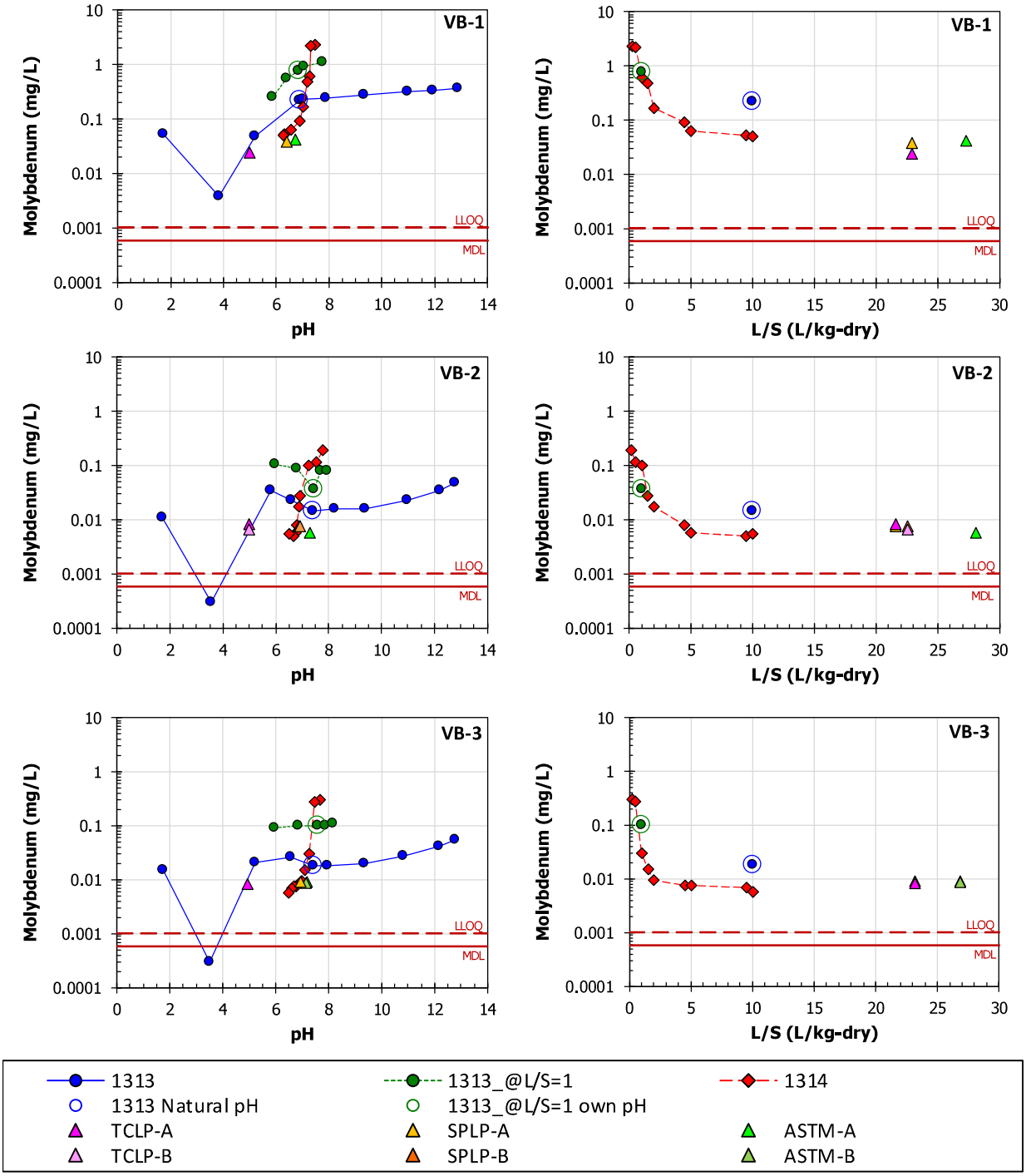


Figure E-22
Molybdenum concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

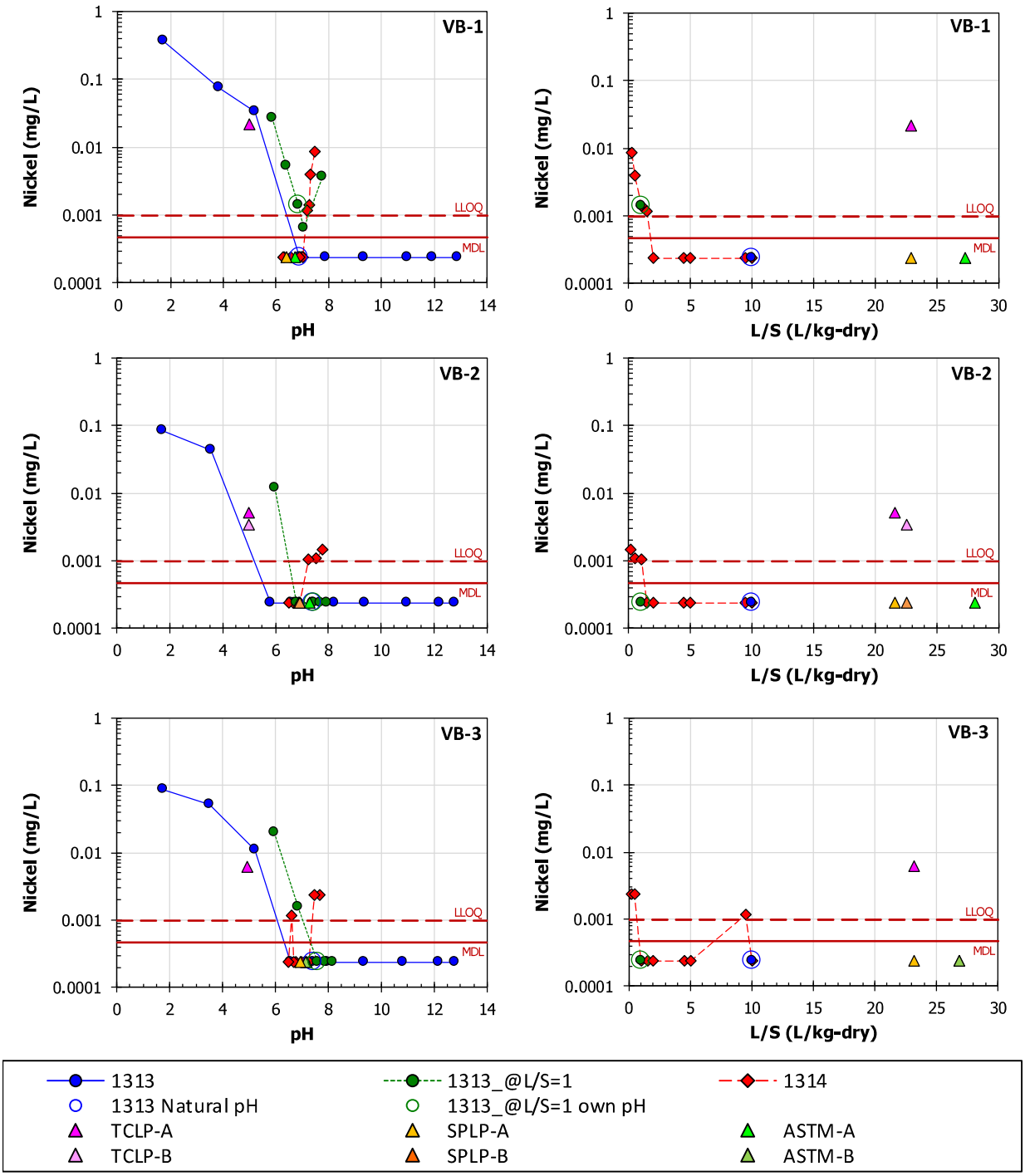


Figure E-23
Nickel concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

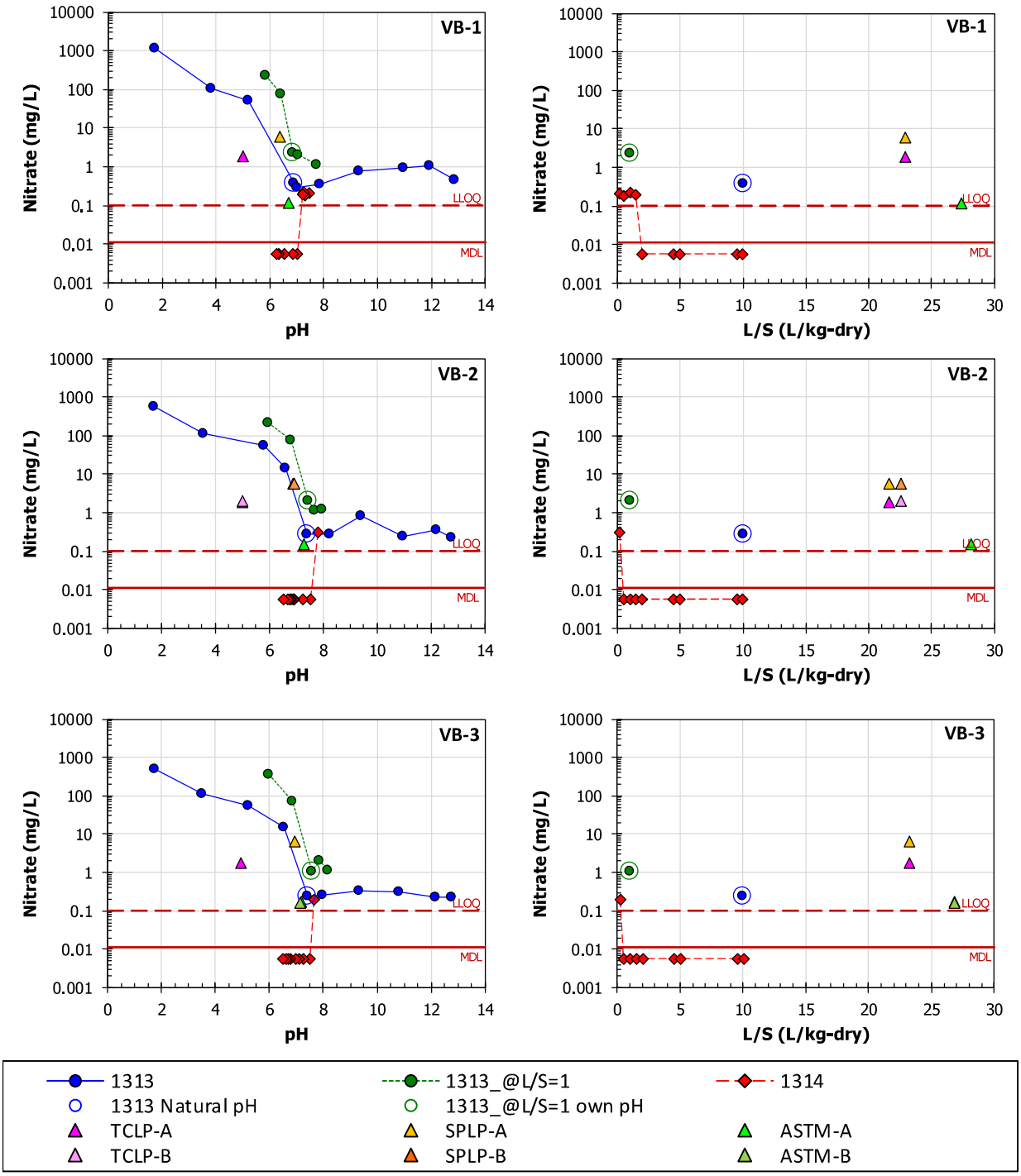


Figure E-24
Nitrate concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

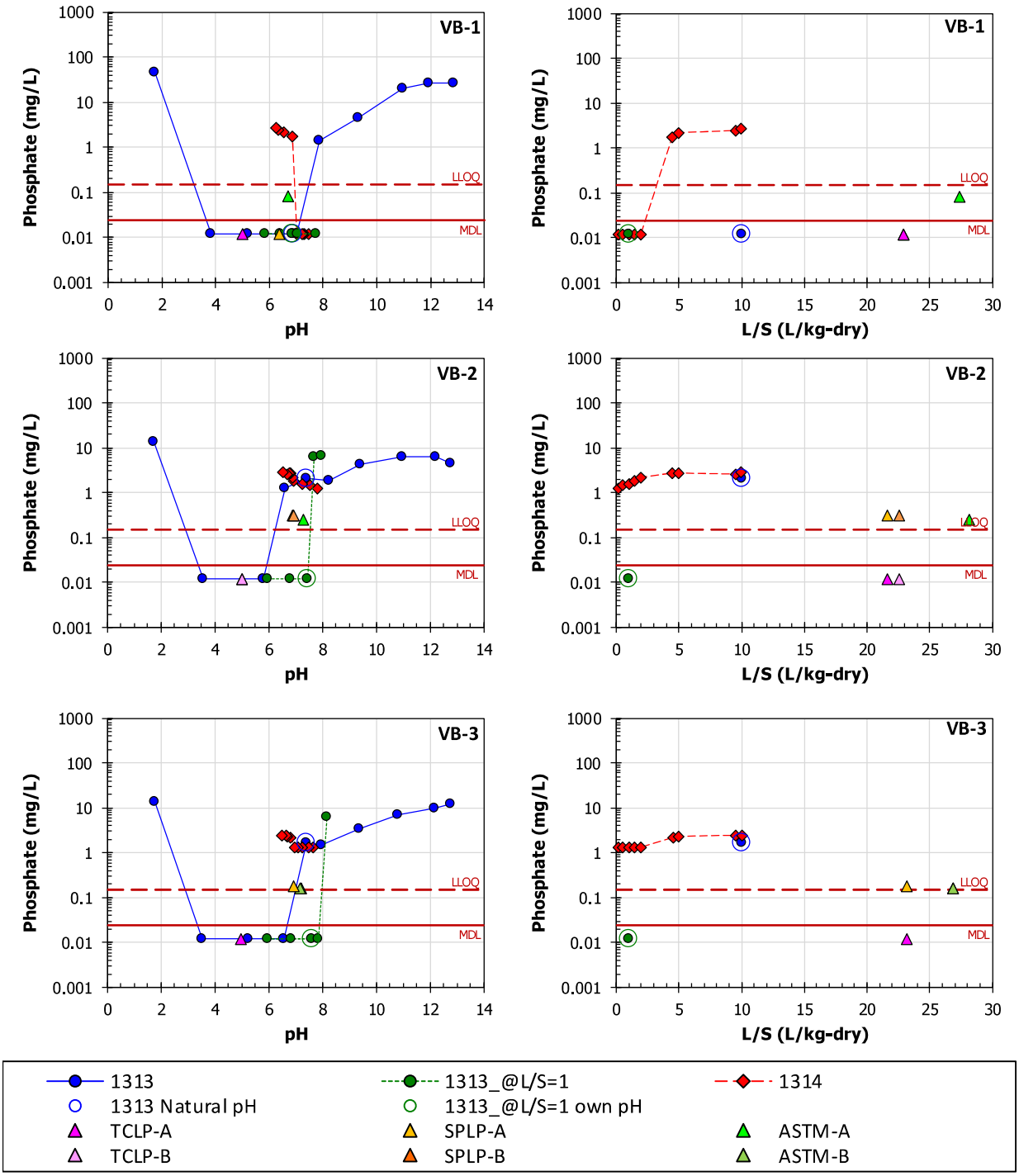


Figure E-25
Phosphate concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

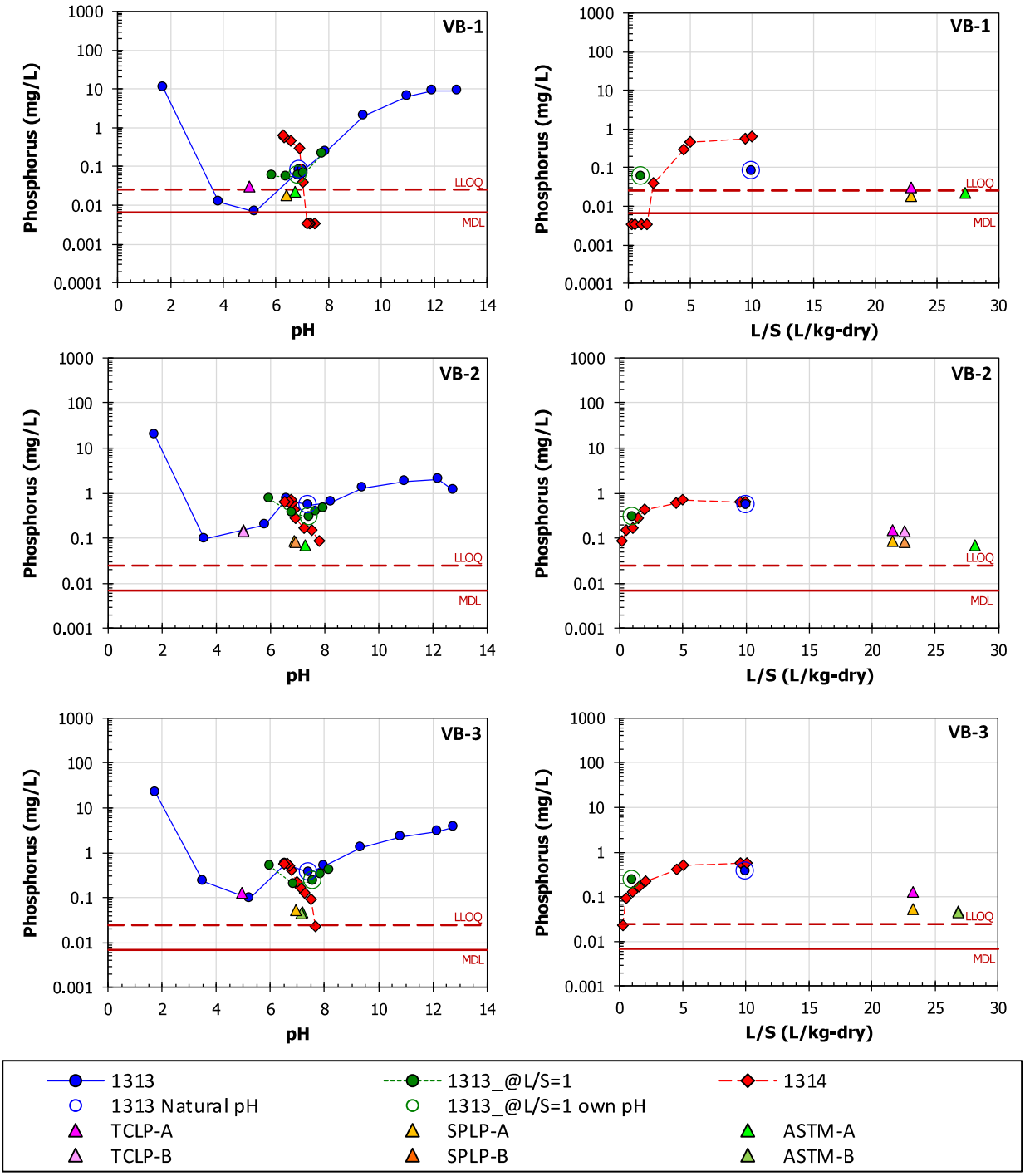


Figure E-26
Phosphorus concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

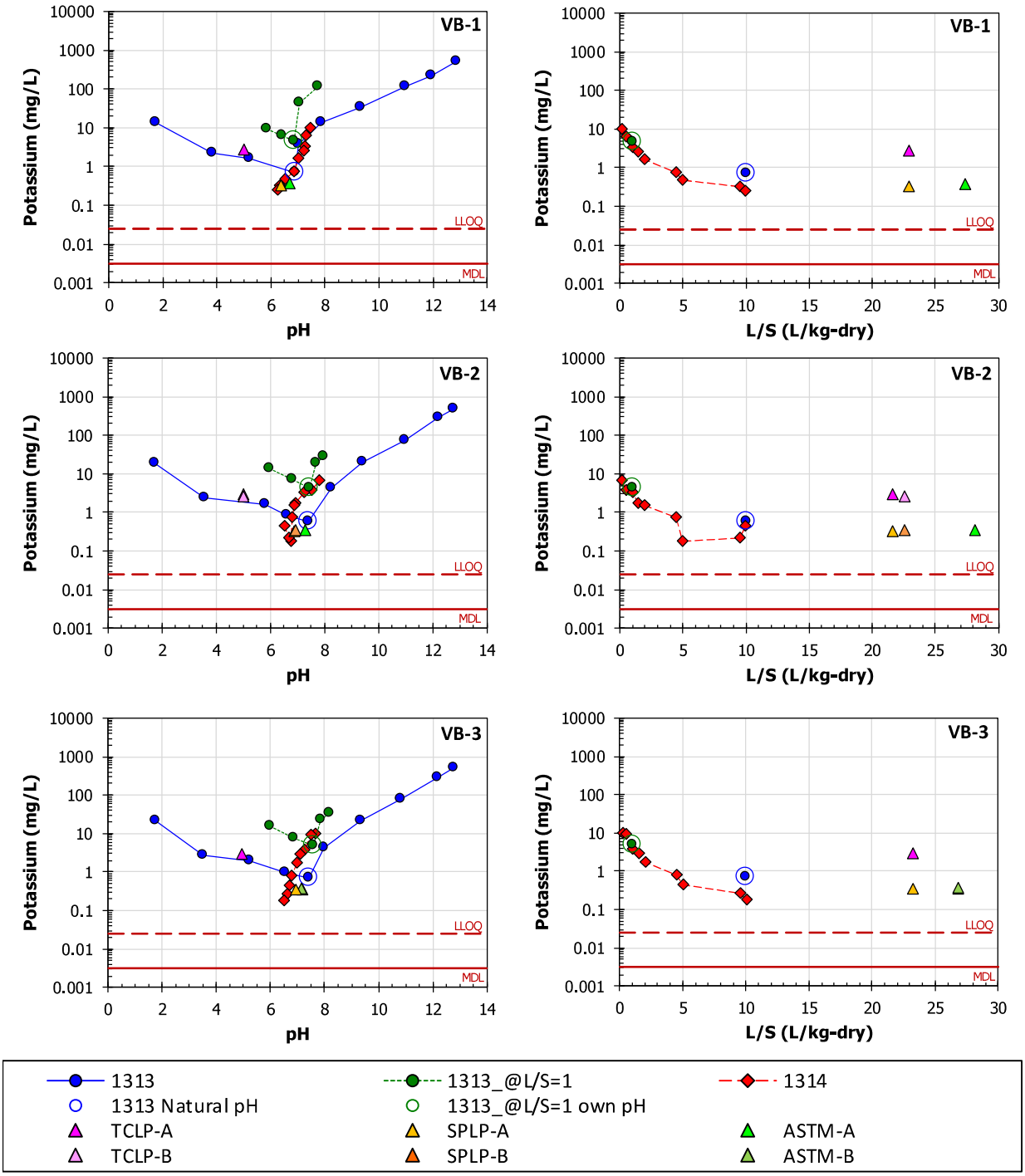


Figure E-27
Potassium concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

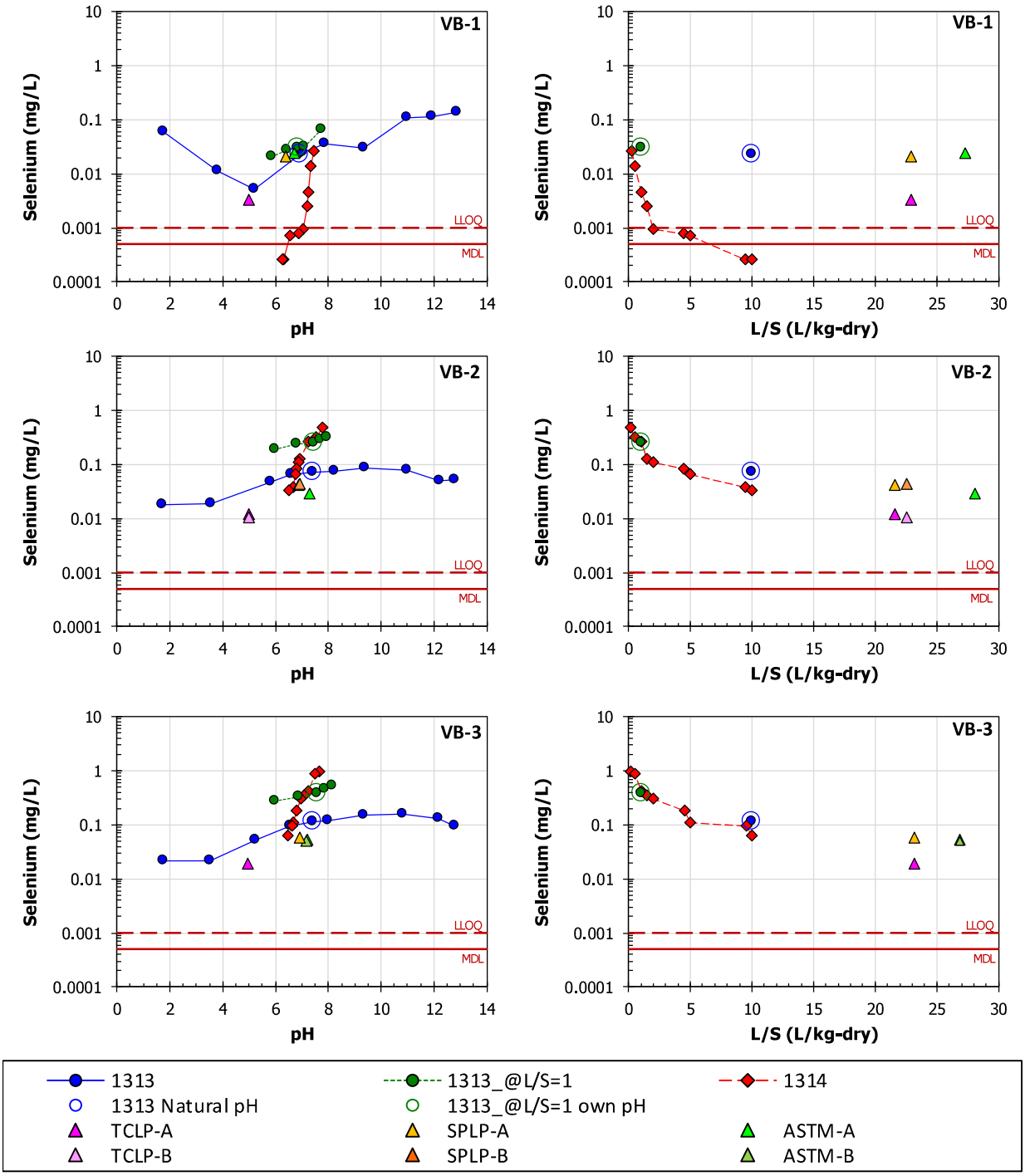


Figure E-28
Selenium concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

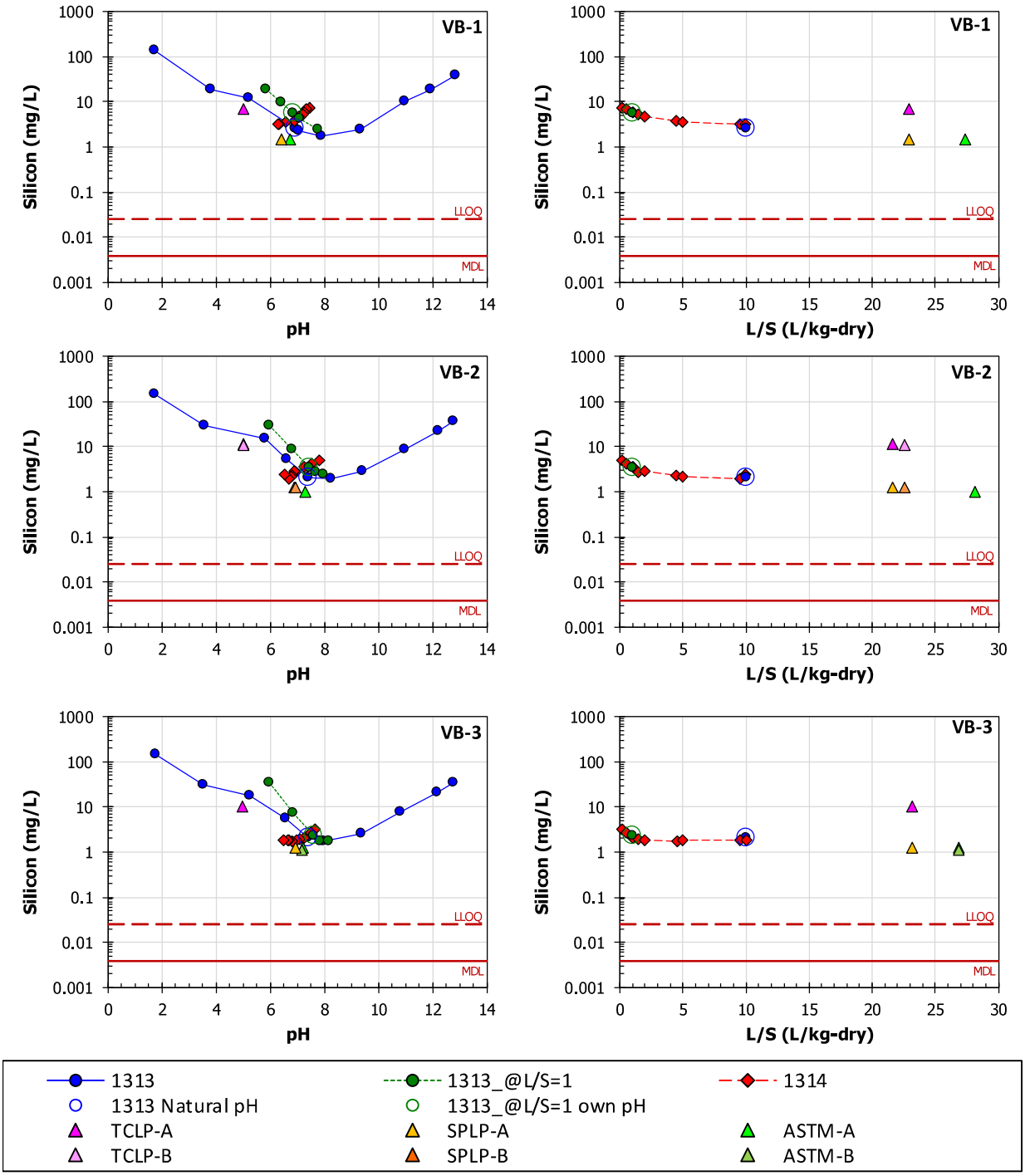


Figure E-29
Silicon concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

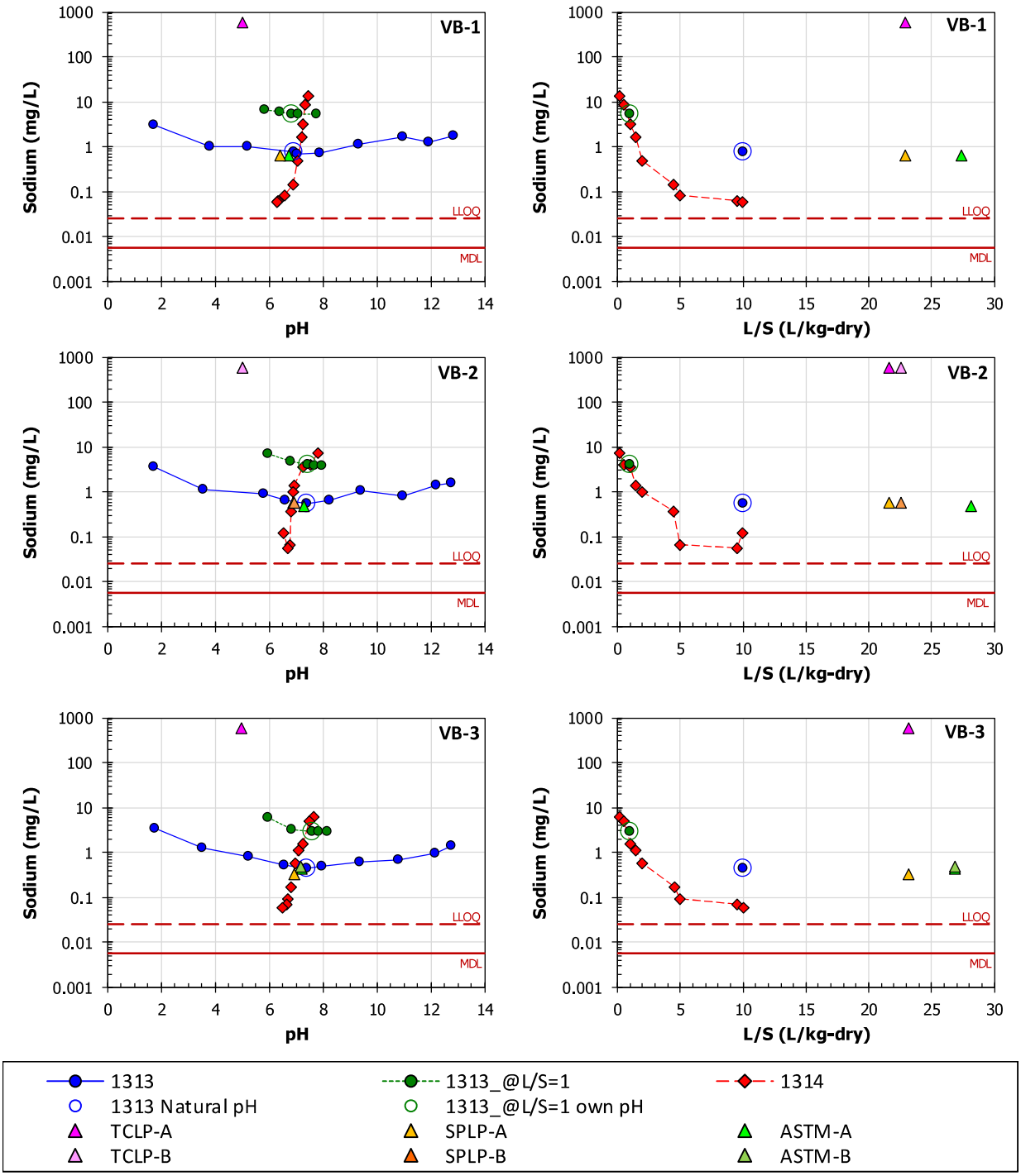


Figure E-30
Sodium concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

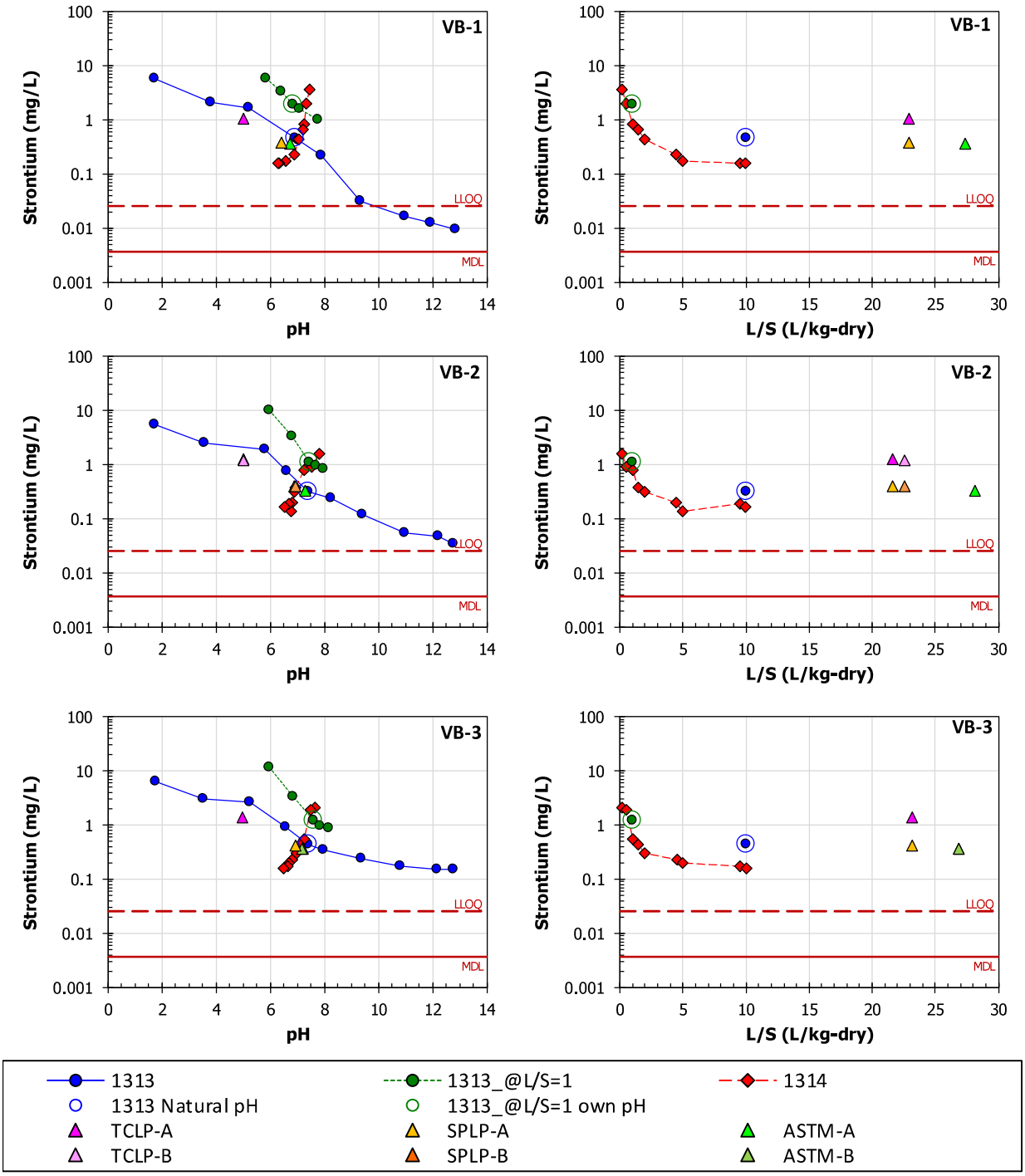


Figure E-31
Strontium concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

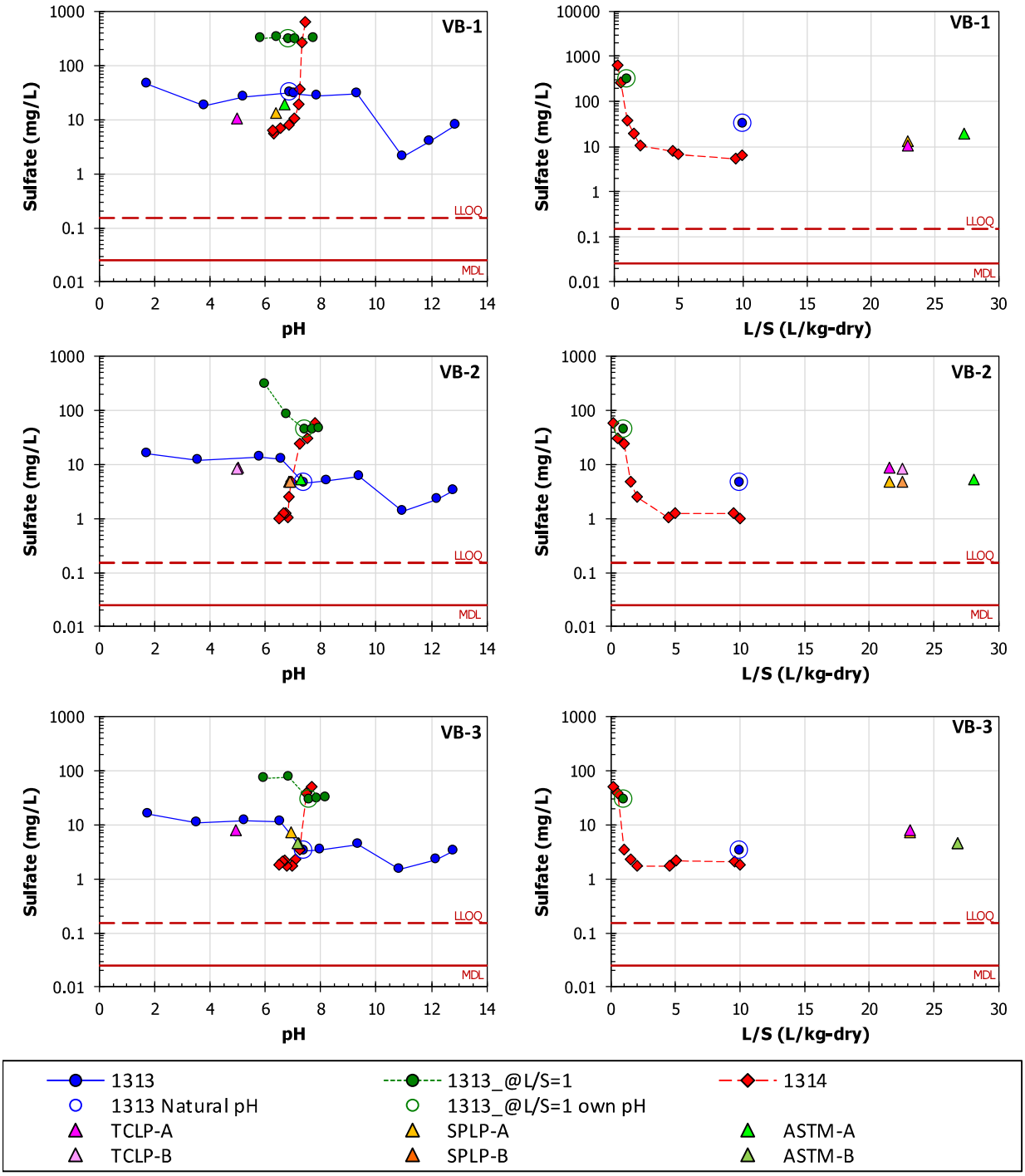


Figure E-32
Sulfate concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

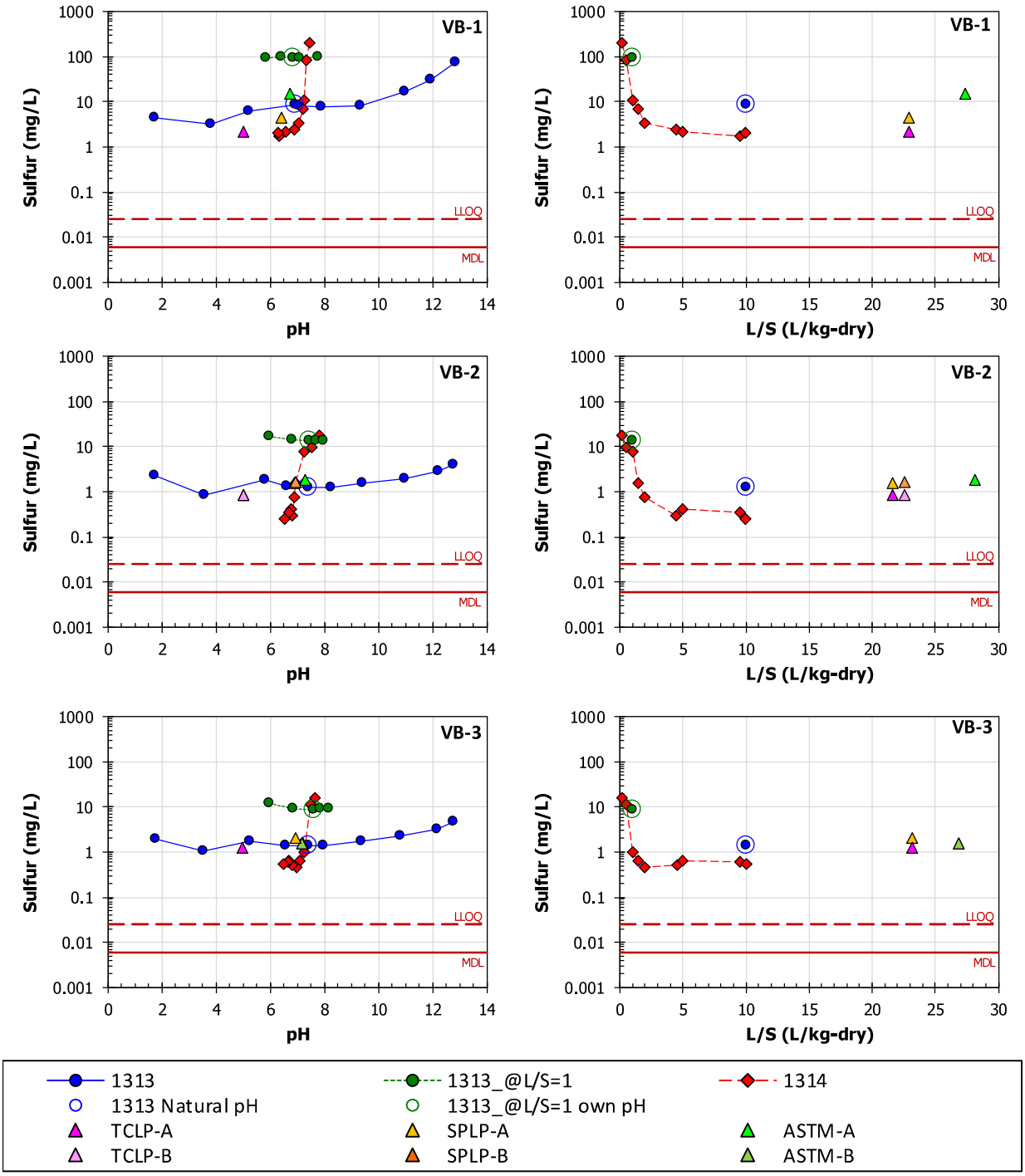


Figure E-33
Sulfur concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

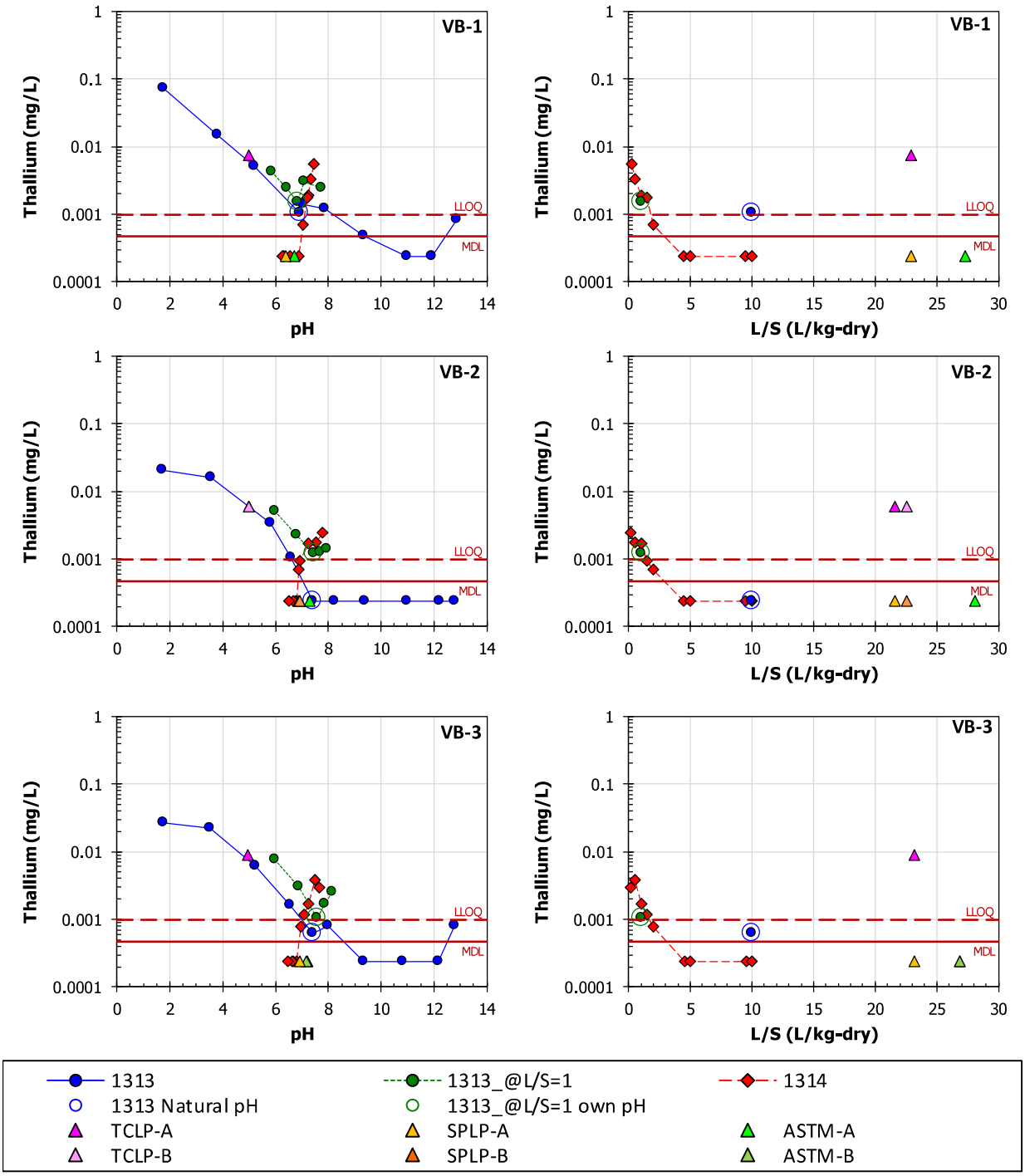


Figure E-34
Thallium concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

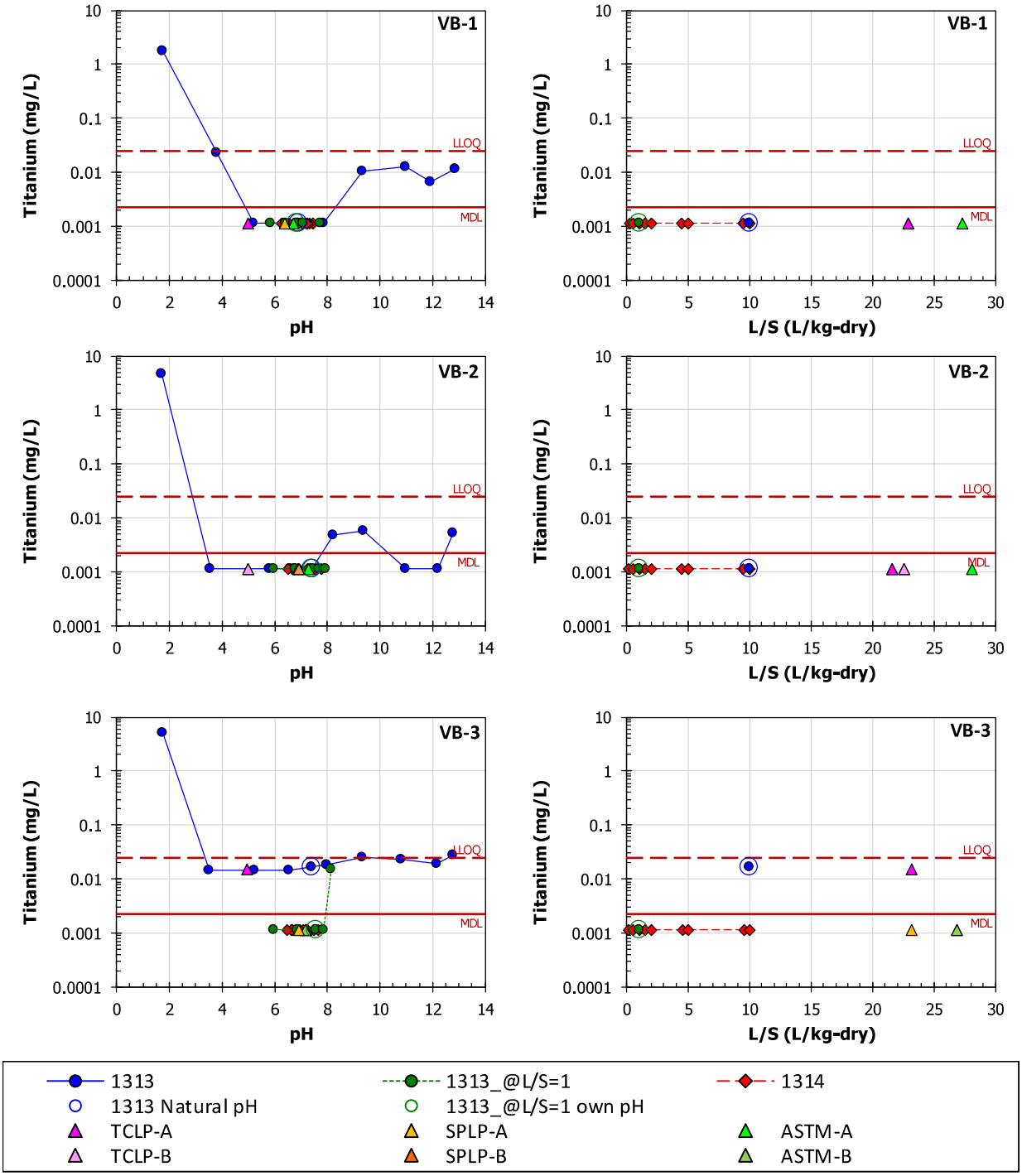


Figure E-35
Titanium concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

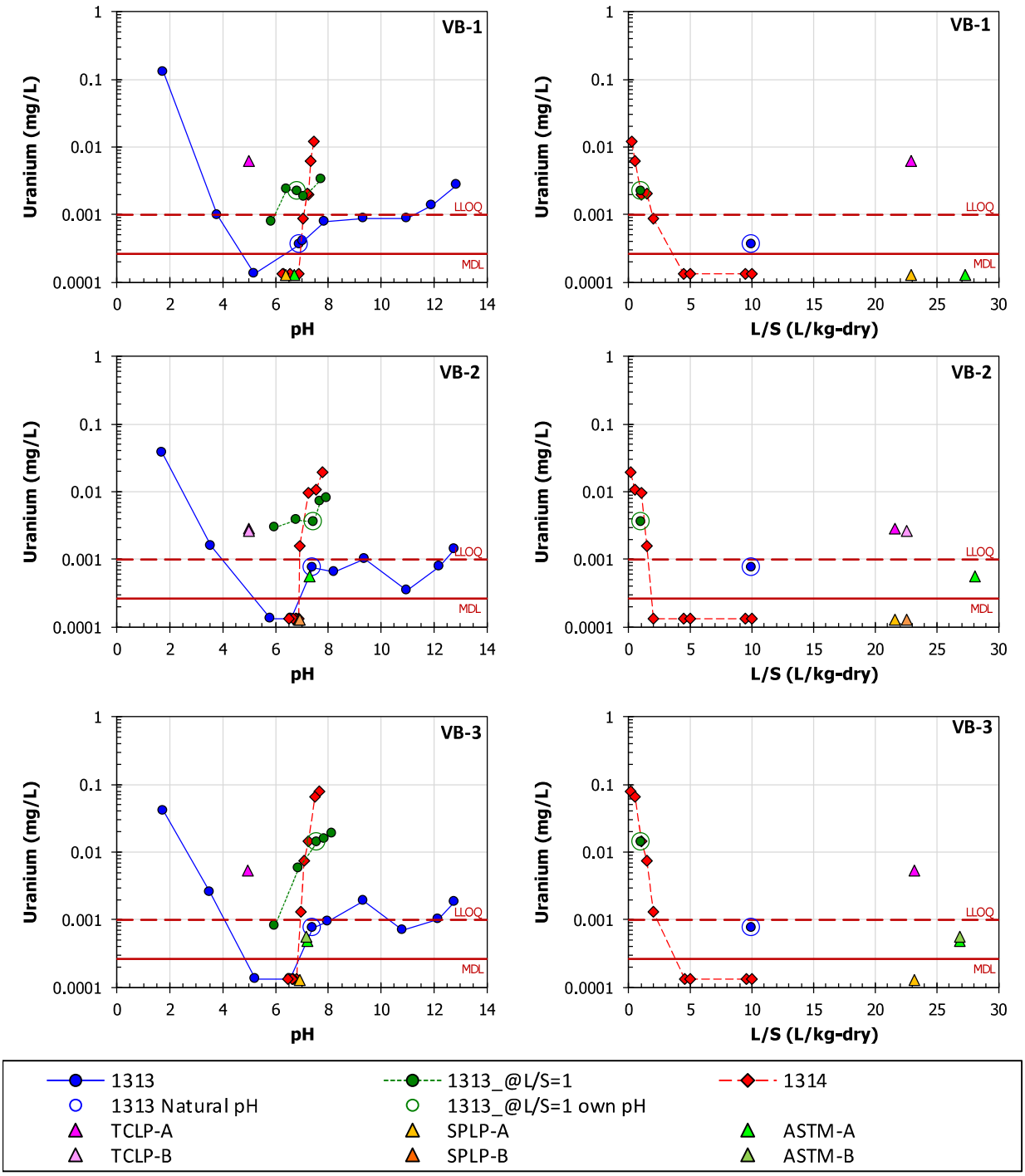


Figure E-36
Uranium concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

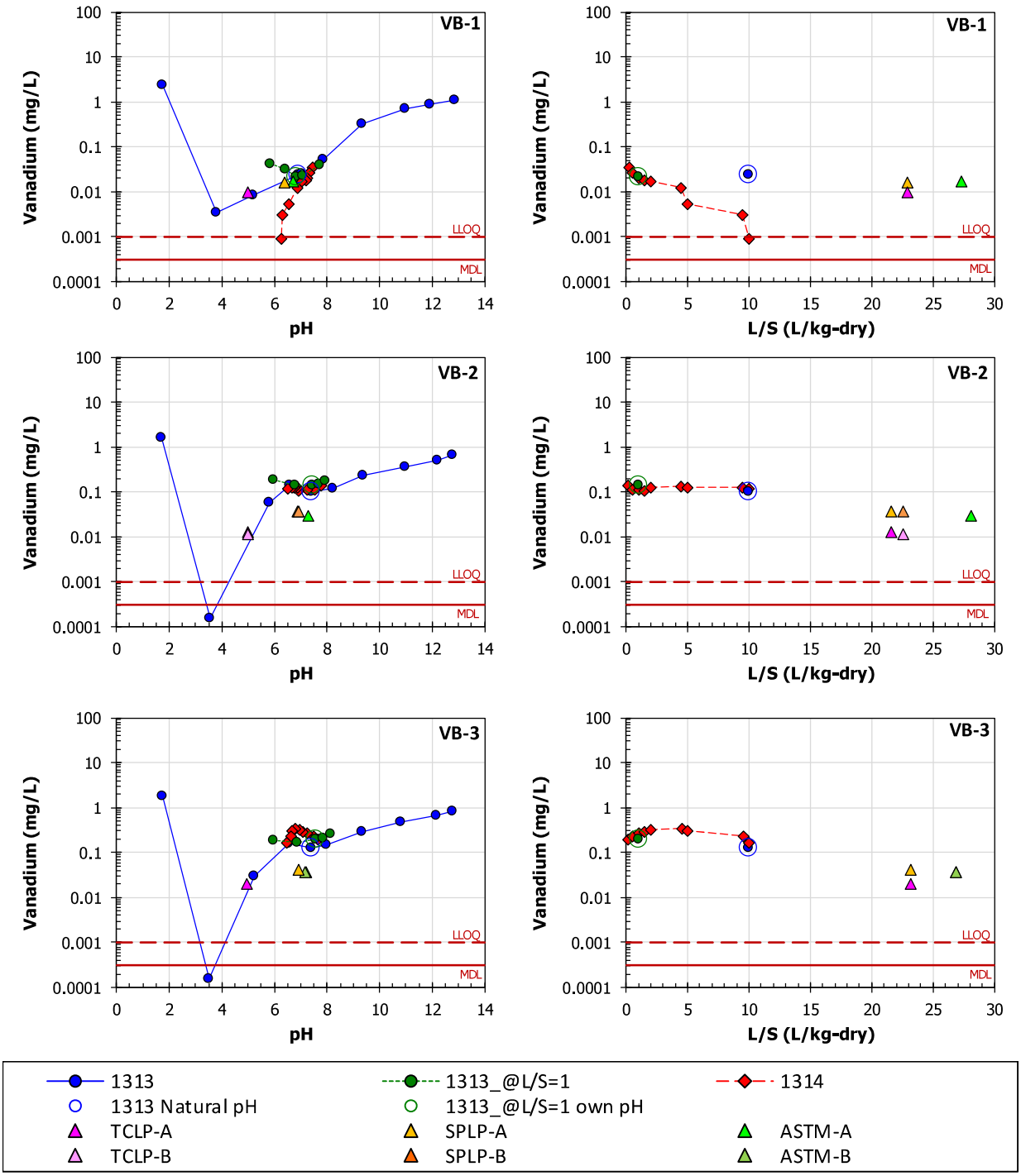


Figure E-37
Vanadium concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

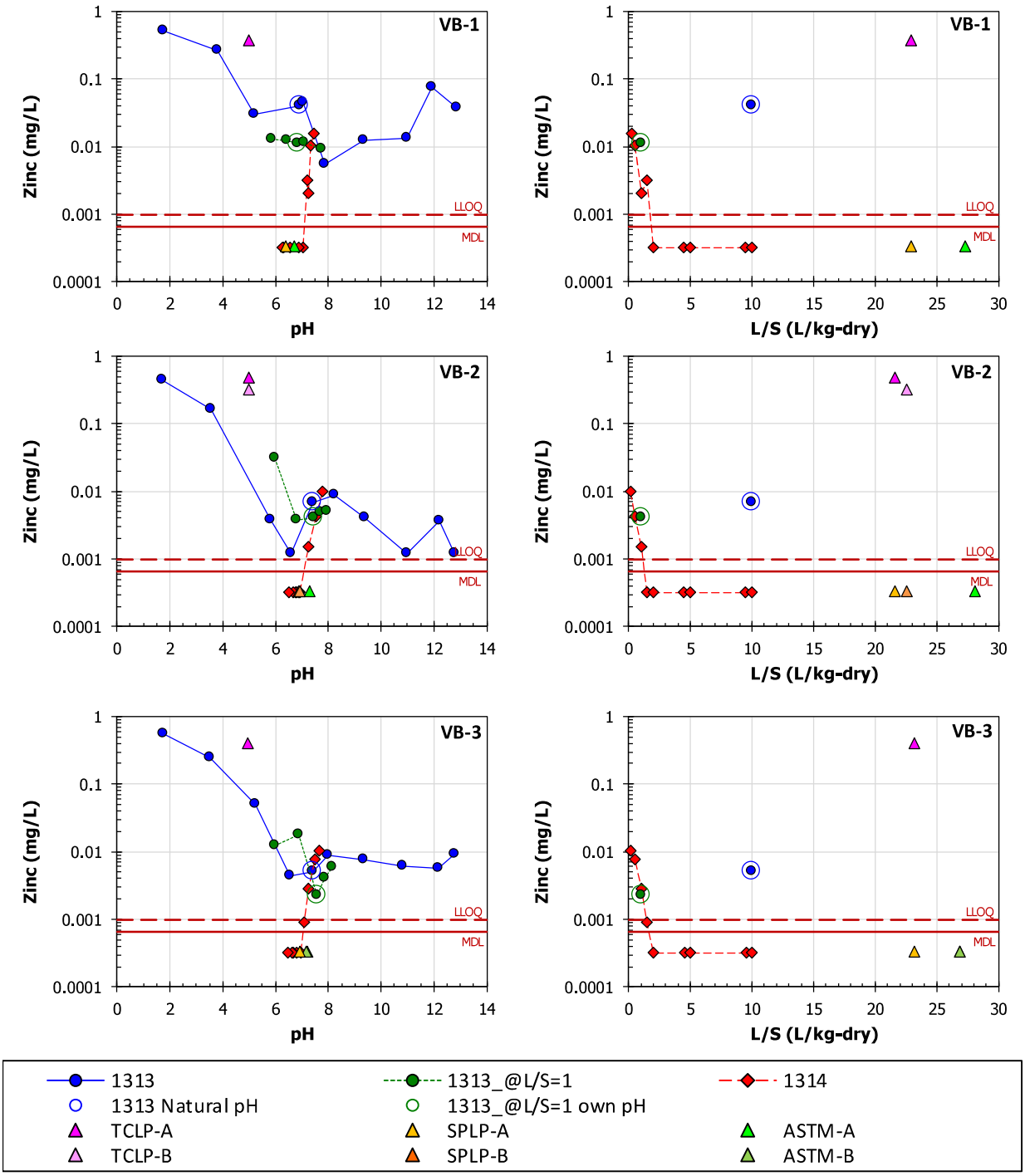


Figure E-38
Zinc concentrations from traditional leaching tests (TCLP, SPLP, and ASTM) compared to LEAF concentrations from composite samples VB-1, VB-2, and VB-3 shown as a function of pH (left) and L/S (right)

F
GROUNDWATER AND POREWATER DATA

Table of Appendices

F.1 Groundwater and Porewater Field and Analytical Data

F.2 Time Series Graphs for Porewater Data

F.3 Subsurface Gas Parameter Tables and Graphs

F.1 Groundwater and Porewater Field Measurement Tables and Graphs

AD1 (upgradient background groundwater well)

	Sep-18	Oct-18	Nov-18	Dec-18	Jan-19	Feb-19	Mar-19
Sampling Date	9/10	10/3	No Sample	12/12	1/14	2/11	3/12
Time at start	11:40	8:40	-	9:35	10:10	10:05	9:50
Water Table AMSL (ft)	770.4	773.3	-	774.3	773.5	774.2	775.2
Temperature (°C)	18.6	18.1	-	11.7	10.7	11.7	13.0
pH (s.u.)	8.72	8.63	-	8.60	8.71	8.57	8.33
DO (mg/L)	2.02	2.56	-	2.78	3.34	2.63	3.22
EC (mS/cm)	0.423	0.443	-	0.424	0.412	0.426	0.434
ORP (mV)	362	214	-	238	291	277	270
Turbidity (NTU)	3.39	1.73	-	2.68	1.46	1.55	1.44
Time at end	12:30	8:50	-	11:37	10:21	10:19	11:18

	Apr-19	May-19	Jun-19	Jul-19	Aug-19	Sep-19
Sampling Date	4/10	5/22				
Time at start	10:05	10:05				
Water Table AMSL (ft)	774.3	771.9				
Temperature (°C)	15.6	17.86				
pH (s.u.)	8.36	8.50				
DO (mg/L)	1.76	2.33				
EC (mS/cm)	0.438	0.422				
ORP (mV)	342	408				
Turbidity (NTU)	2.44	1.43				
Time at end	10:18	10.:19				

Sampling at AD1 discontinued after May 2019.

VB-1 (ash porewater borehole)

	Sep-18	Oct-18	Nov-18	Dec-18	Jan-19	Feb-19	Mar-19
Sampling Date	9/10	10/3	No Sample	12/11	1/14	2/11	3/12
Time at start	15:30	10:20	-	12:40	12:10	12:15	14:47
Water Table AMSL (ft)	742.1	743.0	-	741.7	741.6	741.7	741.6
Temperature (°C)	22.4	20.6	-	16.2	13.5	15.6	18.4
pH (s.u.)	7.86	8.08	-	8.09	8.06	8.17	8.00
DO (mg/L)	1.79	2.31	-	1.35	2.52	1.51	0.10
EC (mS/cm)	0.388	0.393	-	0.370	0.399	0.402	0.409
ORP (mV)	85	69	-	97	134	95	152
Turbidity (NTU)	3.13	0.80	-	1.02	0.99	0.35	0.25
Time at end	15:40	10:33	-	12:43	12:22	12:25	14:55

	Apr-19	May-19	Jun-19	Jul-19	Aug-19	Sep-19
Sampling Date	4/10	5/22	6/18	7/17	8/20	9/24
Time at start	12:40	12:40	13:10	14:05	13:25	11:55
Water Table AMSL (ft)	741.6	742.3	742.6	742.7	742.8	742.5
Temperature (°C)	19.4	21.9	20.2	20.1	22.4	20.0
pH (s.u.)	8.12	8.12	8.12	7.96	8.08	8.07
DO (mg/L)	1.84	1.87	1.22	0.96	1.52	0.27
EC (mS/cm)	0.408	0.412	0.400	0.416	0.422	0.418
ORP (mV)	179	245	121	30	59	23
Turbidity (NTU)	0.30	0.45	0.39	0.38	0.78	0.78
Time at end	12:49	12:54	13:19	14:17	13:38	12:02

VB-2 (ash porewater borehole)

	Sep-18	Oct-18	Nov-18	Dec-18	Jan-19	Feb-19	Mar-19
Sampling Date	9/11	10/3	No Sample	12/11	1/14	2/11	3/13
Time at start	10:25	11:15	-	14:10	14:50	14:00	10:50
Water Table AMSL (ft)	742.8	743.0	-	741.9	741.5	741.4	741.3
Temperature (°C)	20.7	22.2	-	15.2	13.9	14.9	16.9
pH (s.u.)	7.91	8.10	-	8.08	8.13	8.20	8.11
DO (mg/L)	1.77	2.11	-	1.47	1.81	1.24	0.94
EC (mS/cm)	0.809	0.820	-	0.754	0.776	0.770	0.759
ORP (mV)	47	61	-	86	95	85	122
Turbidity (NTU)	2.47	1.35	-	1.13	1.16	0.57	0.51
Time at end	10:50	11:26	-	14:15	15:03	14:14	11:02

	Apr-18	May-18	Jun-18	Jul-18	Aug-19	Sep-19
Sampling Date	4/10	5/22	6/18	7/17	8/20	9/24
Time at start	15:35	15:35	12:00	12:40	12:10	10:50
Water Table AMSL (ft)	741.2	741.6	742.0	742.1	742.0	742.2
Temperature (°C)	20.2	21.3	20.2	19.7	20.4	20.1
pH (s.u.)	8.13	8.12	8.13	7.08	7.02	7.14
DO (mg/L)	1.34	1.60	1.42	1.19	0.87	0.71
EC (mS/cm)	0.776	0.763	0.723	0.680	0.714	0.768
ORP (mV)	143	66	162	133	107	101
Turbidity (NTU)	0.47	0.39	0.40	0.36	0.65	0.66
Time at end	15:45	15:48	12:12	12:49	12:29	11:00

VB-3 (ash porewater borehole)

	Sep-18	Oct-18	Nov-18	Dec-18	Jan-19	Feb-19	Mar-19
Sampling Date	9/11	10/3	No Sample	12/11	1/14	2/11	3/13
Time at start	12:20	13:05	-	15:30	13:55	15:30	12:10
Water Table AMSL (ft)	742.8	742.5	-	740.8	741.0	739.6	740.7
Temperature (°C)	22.97	23.21	-	15.36	12.61	15.93	15.91
pH (s.u.)	7.68	7.34	-	7.68	7.87	7.99	7.98
DO (mg/L)	2.11	1.99	-	1.68	1.84	1.28	1.82
EC (mS/cm)	0.832	0.822	-	0.768	0.792	0.742	0.738
ORP (mV)	61	102	-	100	100	84	141
Turbidity (NTU)	1.33	1.89	-	1.07	1.56	0.86	0.41
Time at end	12:40	13:16	-	15:33	14:10	15:41	12:18

	Apr-19	May-19	Jun-19	Jul-19	Aug-19	Sep-19
Sampling Date	4/10	5/22	6/18	7/17	8/20	9/24
Time at start	14:20	14:25	10:50	10:15	10:10	9:55
Water Table AMSL (ft)	739.9	740.4	740.5	741.0	741.0	740.9
Temperature (°C)	20.89	23.3	20.3	20.9	21.7	20.5
pH (s.u.)	8.07	8.03	7.98	7.14	7.22	6.87
DO (mg/L)	1.88	1.66	1.55	1.38	1.52	1.26
EC (mS/cm)	0.720	0.711	0.688	0.743	0.747	0.745
ORP (mV)	178	232	237	254	142	148
Turbidity (NTU)	0.41	0.30	0.19	0.39	0.71	0.74
Time at end	14:32	14:41	11:04	10:31	10:27	10:08

6AR (downgradient groundwater well)

	Sep-18	Oct-18	Nov-18	Dec-18	Jan-19	Feb-19	Mar-19
Sampling Date	9/10	10/3	No Sample	12/11	1/14	2/11	3/12
Time at start	13:45	9:25	-	11:25	11:10	11:15	13:10
Water Table AMSL (ft)	740.3	740.2	-	737.4	737.2	736.8	736.8
Temperature (°C)	18.6	17.9	-	14.9	14.1	14.7	16.4
pH (s.u.)	5.05	5.05	-	4.66	4.84	4.75	4.73
DO (mg/L)	0.80	2.15	-	0.22	0.73	1.20	0.31
EC (mS/cm)	0.584	0.584	-	0.573	0.618	0.623	0.614
ORP (mV)	232	114	-	270	288	319	436
Turbidity (NTU)	0.92	0.65	-	0.58	0.80	0.50	0.63
Time at end	14:40	9:30	-	11:51	11:20	11:23	13:47

	Apr-19	May-19	Jun-19	Jul-19	Aug-19	Sep-19
Sampling Date	4/10	5/22	6/18	7/17	8/20	9/24
Time at start	11:25	11:20	14:20	15:15	14:50	13:30
Water Table AMSL (ft)	738.8	740.5	740.5	740.3	740.6	740.5
Temperature (°C)	17.3	17.5	19.5	19.0	19.9	20.2
pH (s.u.)	4.75	4.81	4.80	4.74	4.77	4.90
DO (mg/L)	1.08	0.92	1.39	0.67	0.95	1.24
EC (mS/cm)	0.641	0.638	0.624	0.651	0.658	0.617
ORP (mV)	427	451	431	428	416	388
Turbidity (NTU)	0.77	2.11	1.92	0.44	1.21	1.24
Time at end	11:32	11:34	14:50	15:21	15:01	13:38

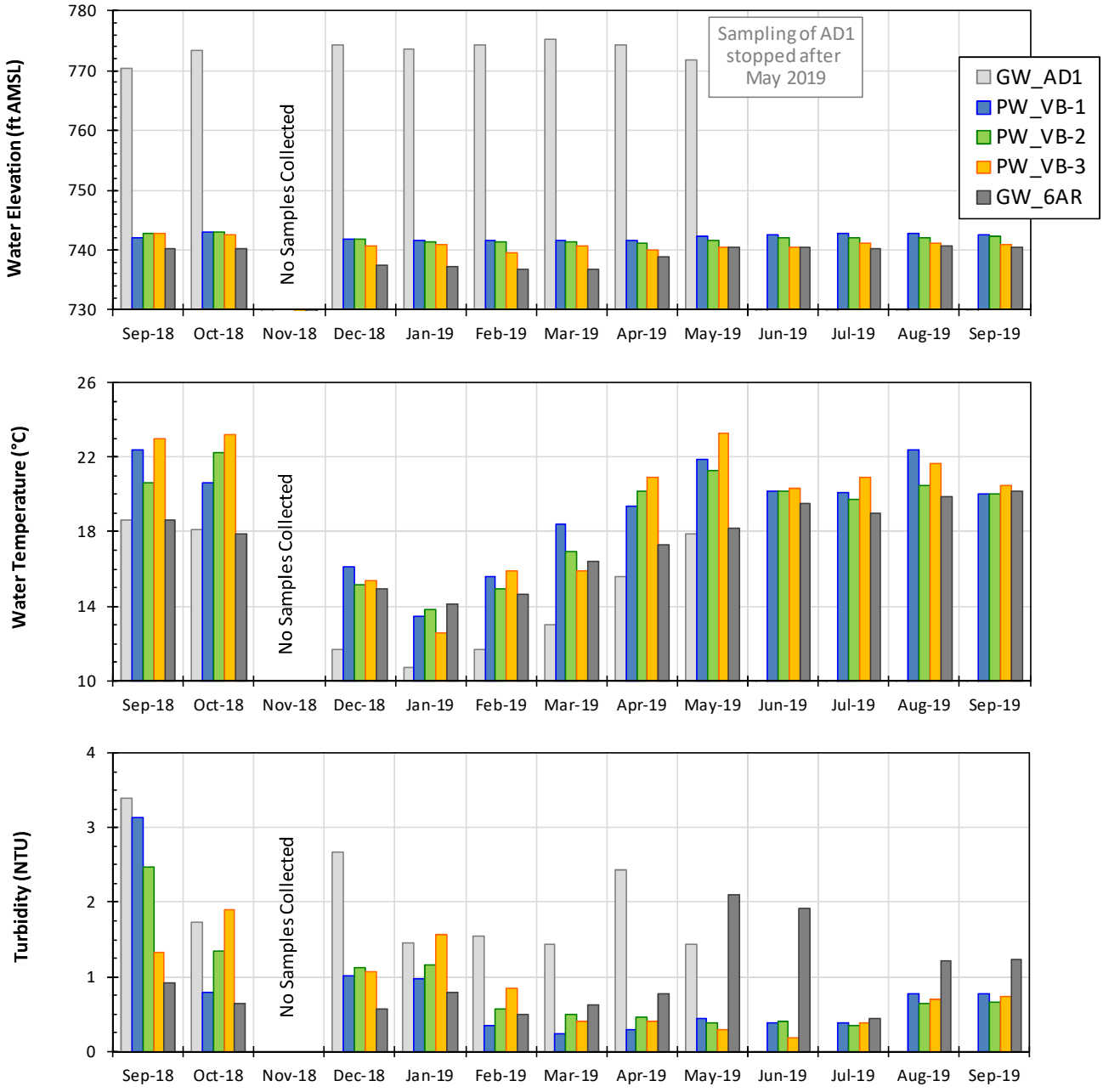


Figure F-1
Groundwater and porewater conditions during monthly sampling: water table elevation, water temperature, and turbidity

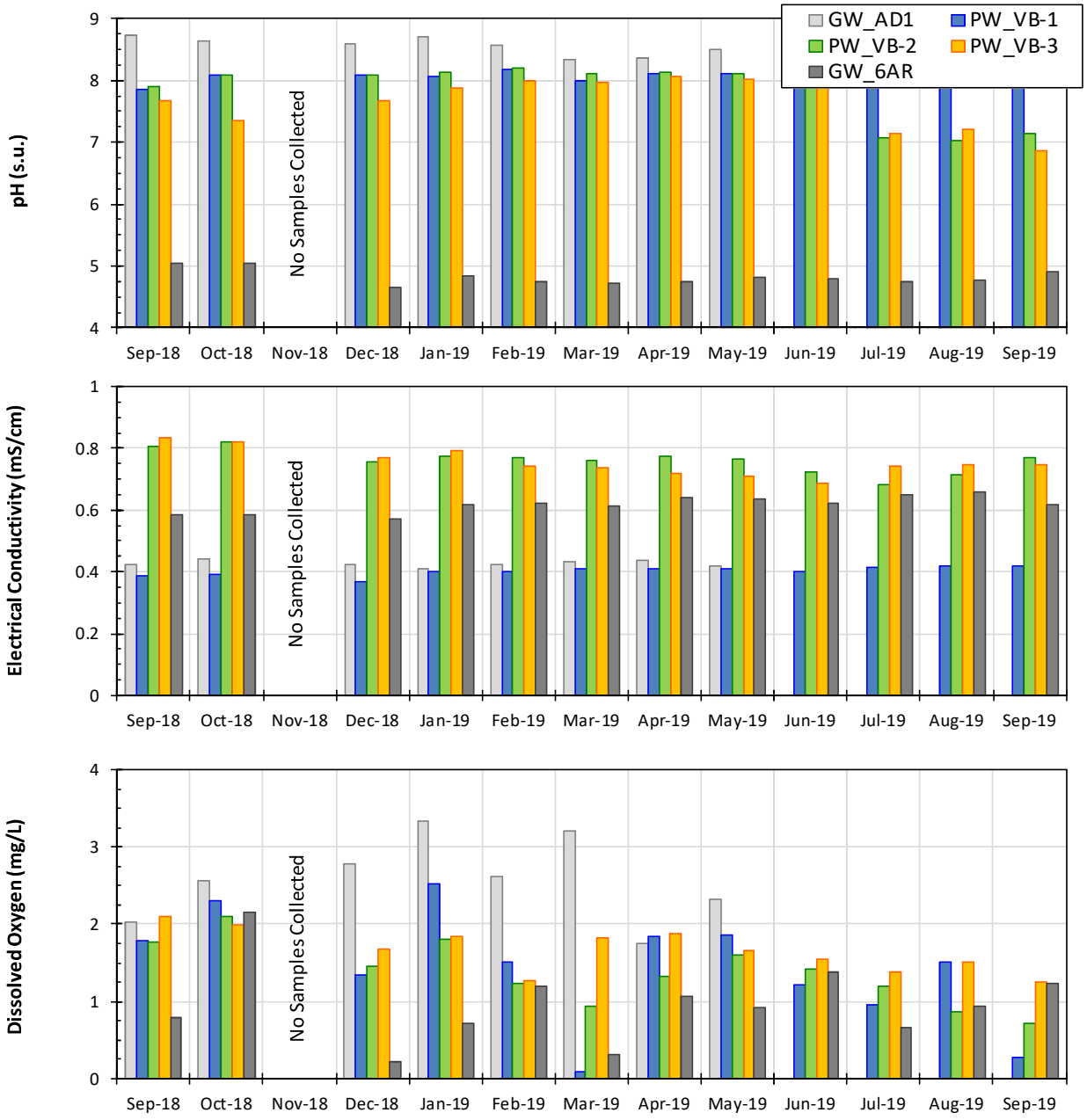


Figure F-2
Groundwater and porewater conditions during monthly sampling: pH, electrical conductivity, and dissolved oxygen

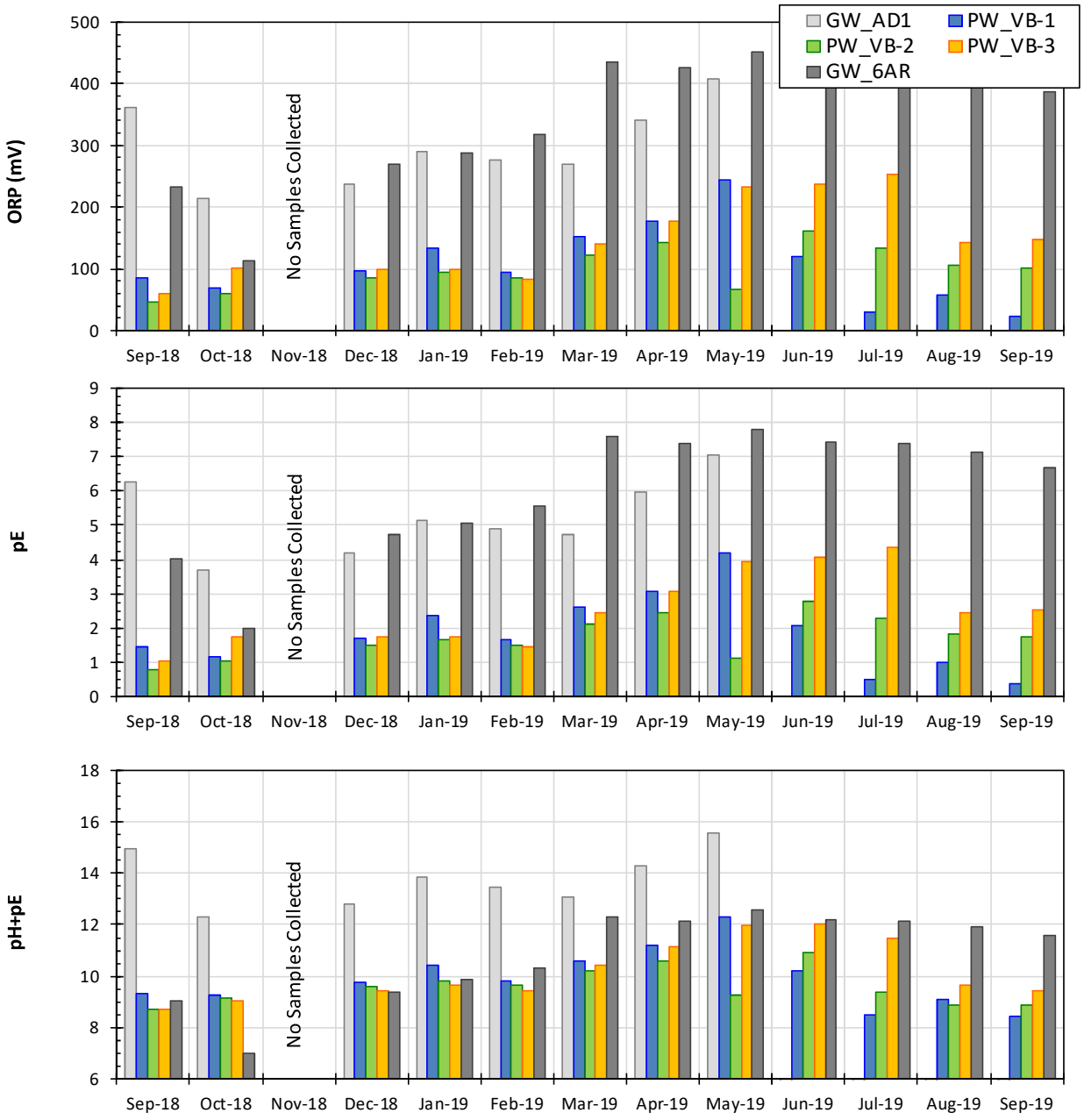


Figure F-3
Groundwater and porewater conditions during monthly sampling: ORP, pE (derived from ORP), and pH+pE (derived from ORP and pH)

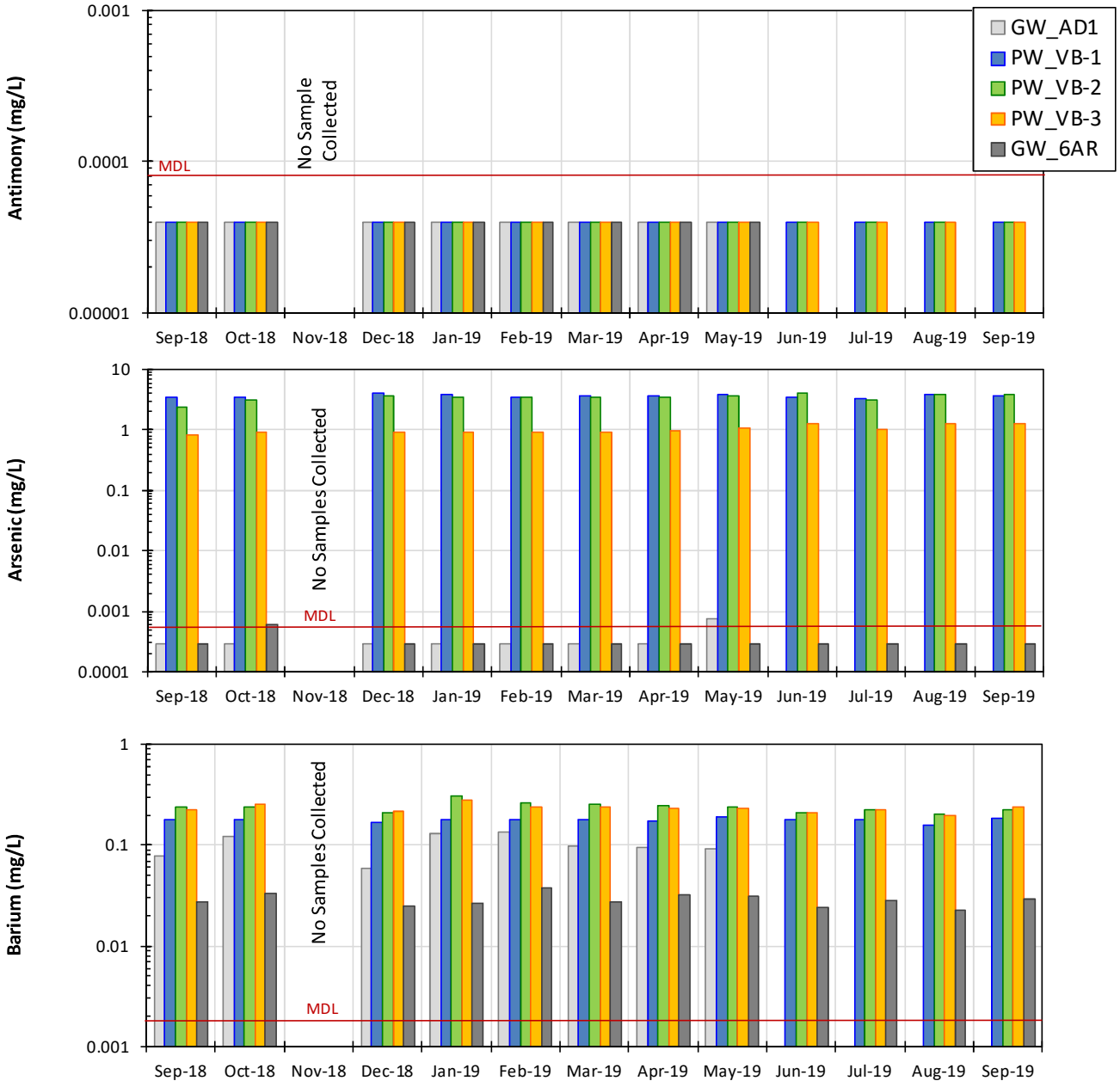


Figure F-4
Measured groundwater and porewater concentrations: antimony, arsenic, and barium; concentrations plotted on a logarithmic axis

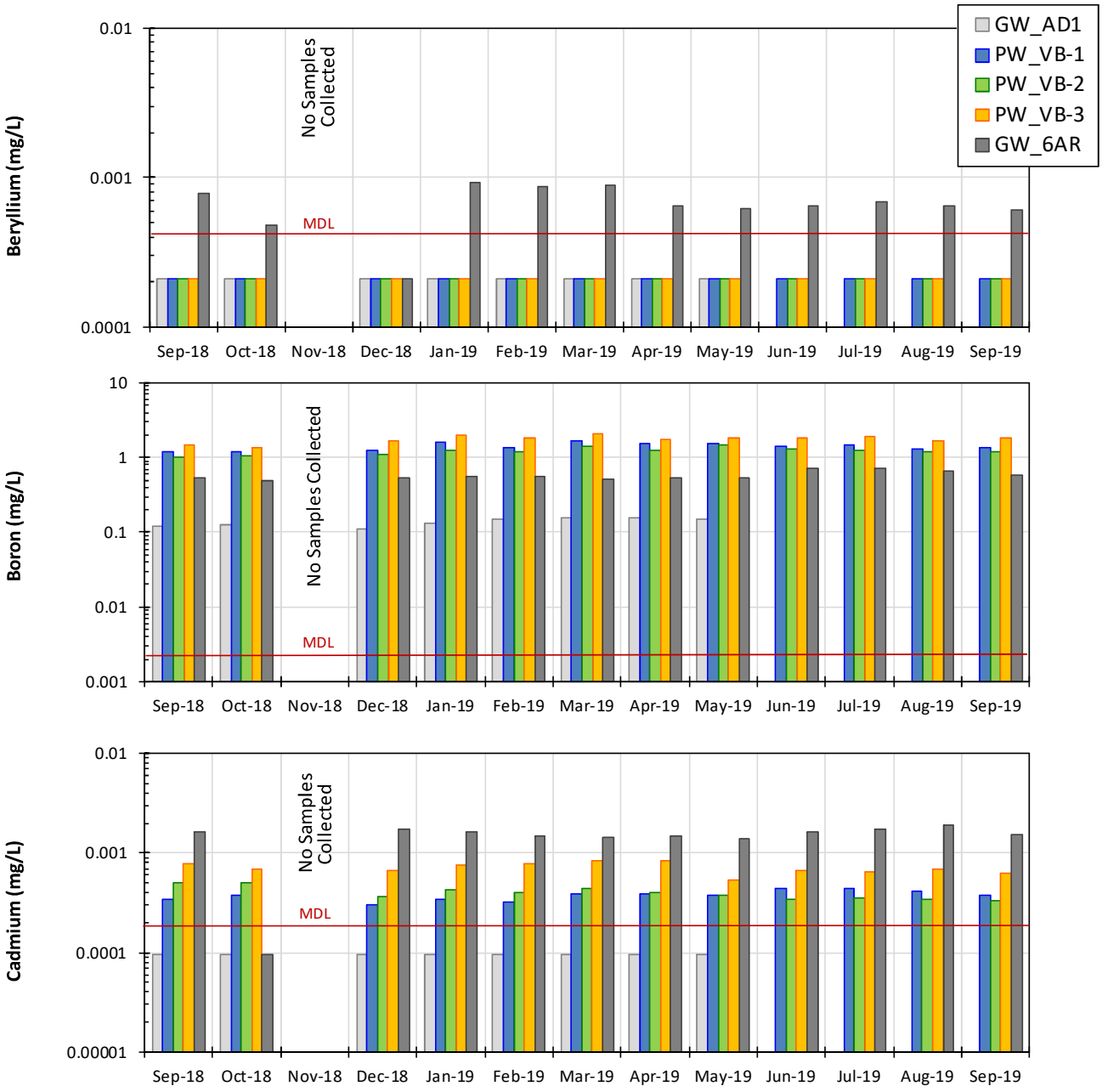


Figure F-5
Measured groundwater and porewater concentrations: beryllium, boron, and cadmium; concentrations plotted on a logarithmic axis

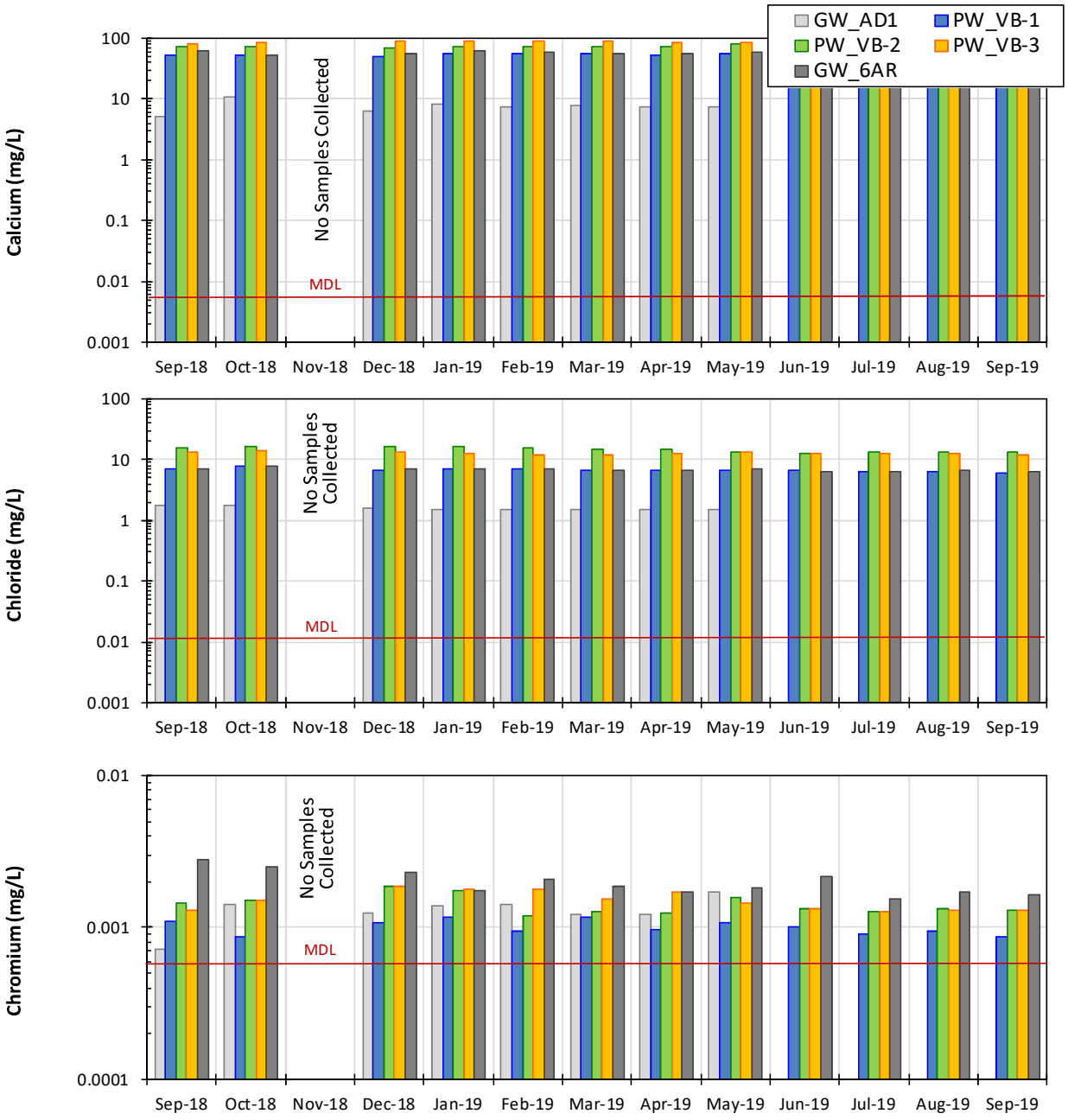


Figure F-6
Measured groundwater and porewater concentrations: calcium, chloride, and chromium; concentrations plotted on a logarithmic axis

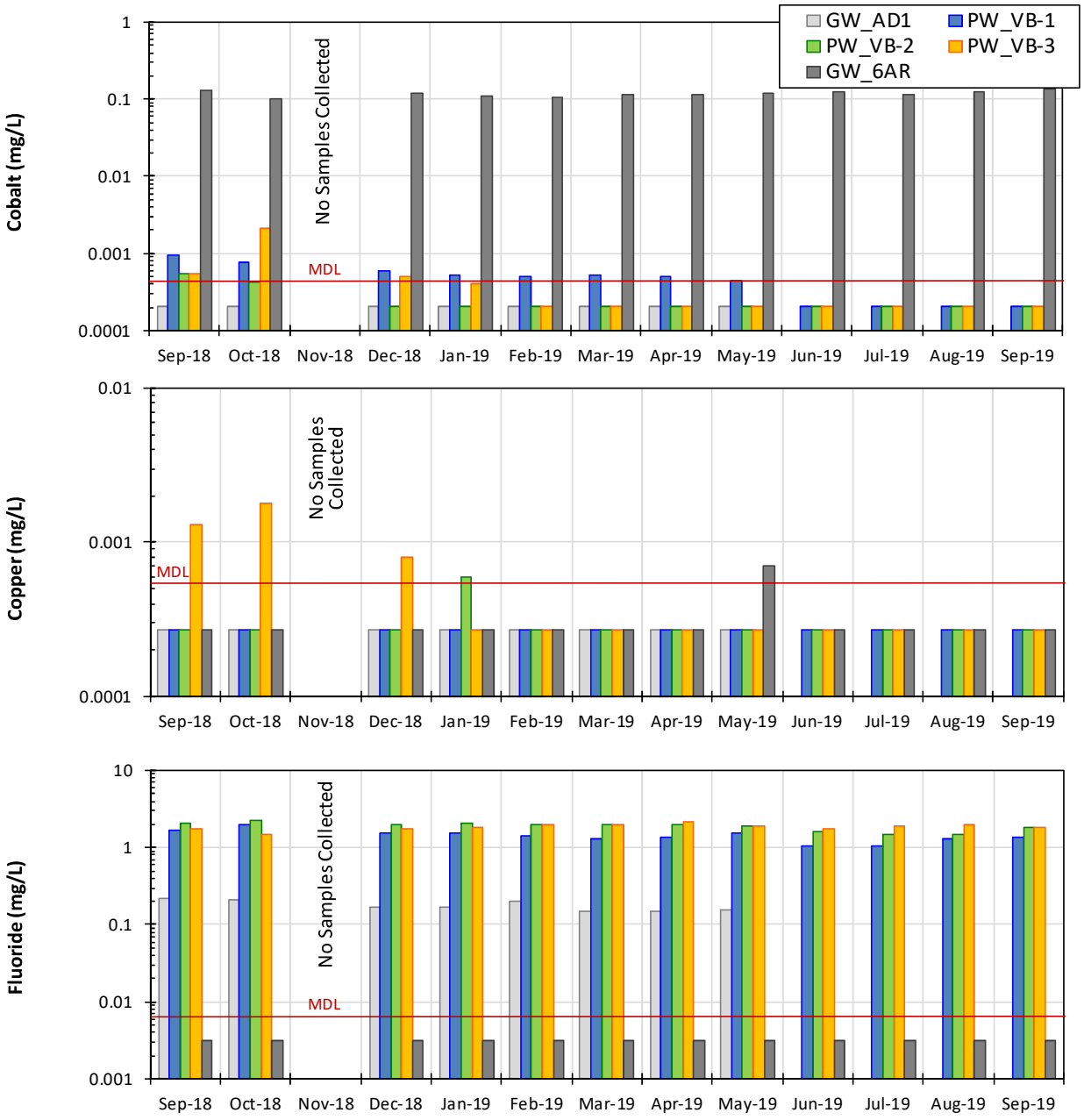


Figure F-7
Measured groundwater and porewater concentrations: cobalt, copper, and fluoride; concentrations plotted on a logarithmic axis

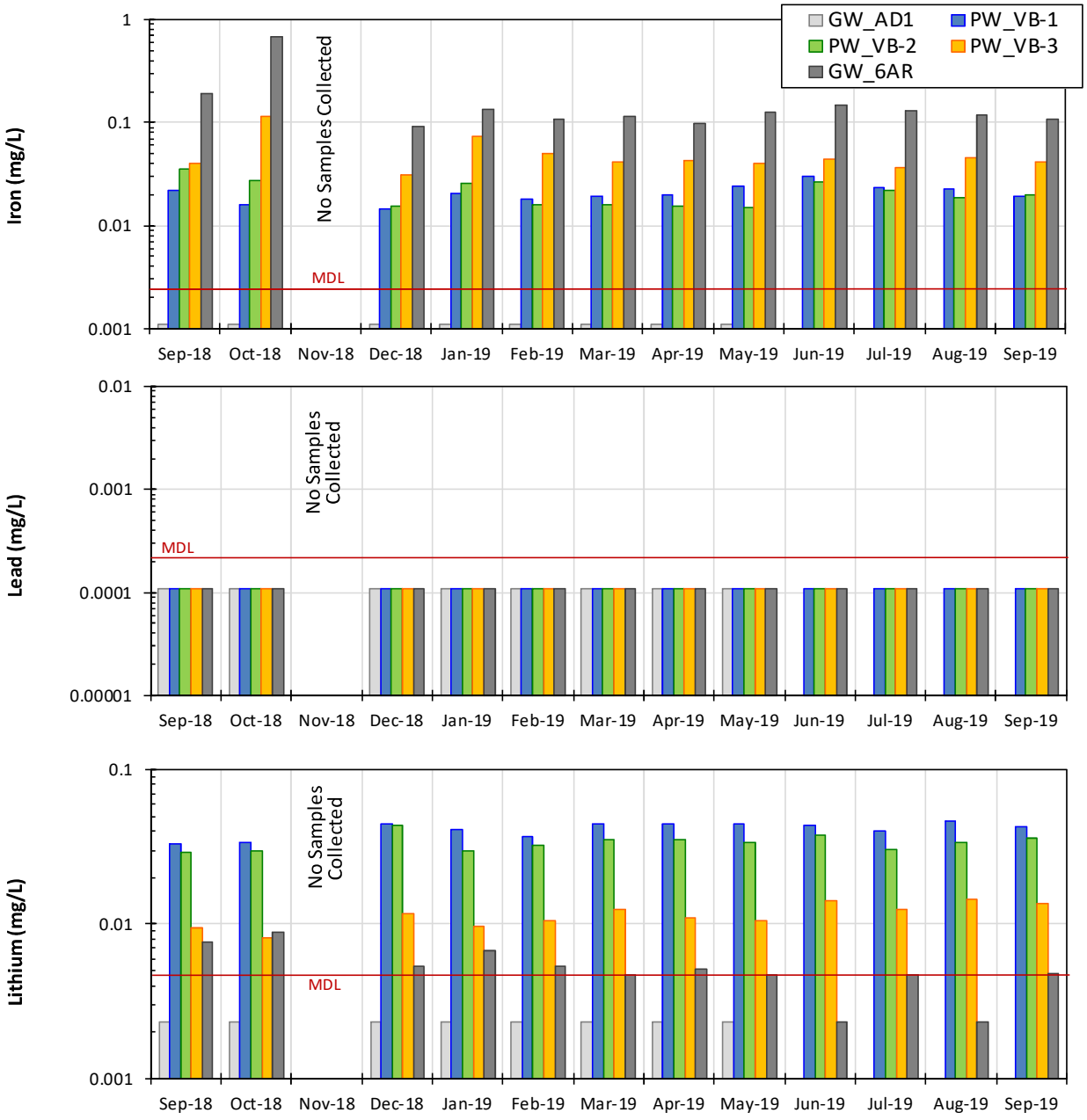


Figure F-8
Measured groundwater and porewater concentrations: iron, lead, and lithium; concentrations plotted on a logarithmic axis

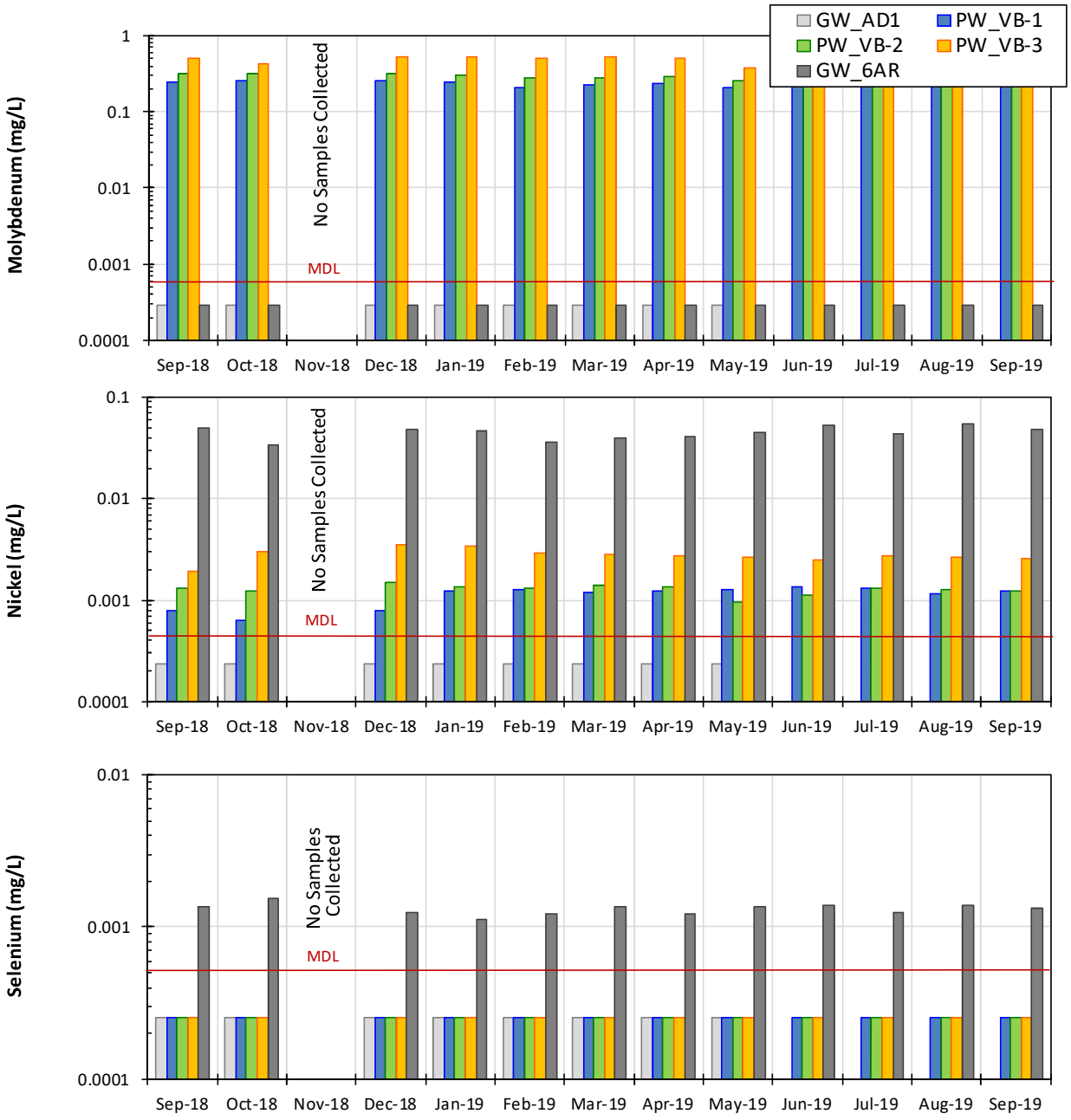


Figure F-9
Measured groundwater and porewater concentrations: molybdenum, nickel, and selenium; concentrations plotted on a logarithmic axis

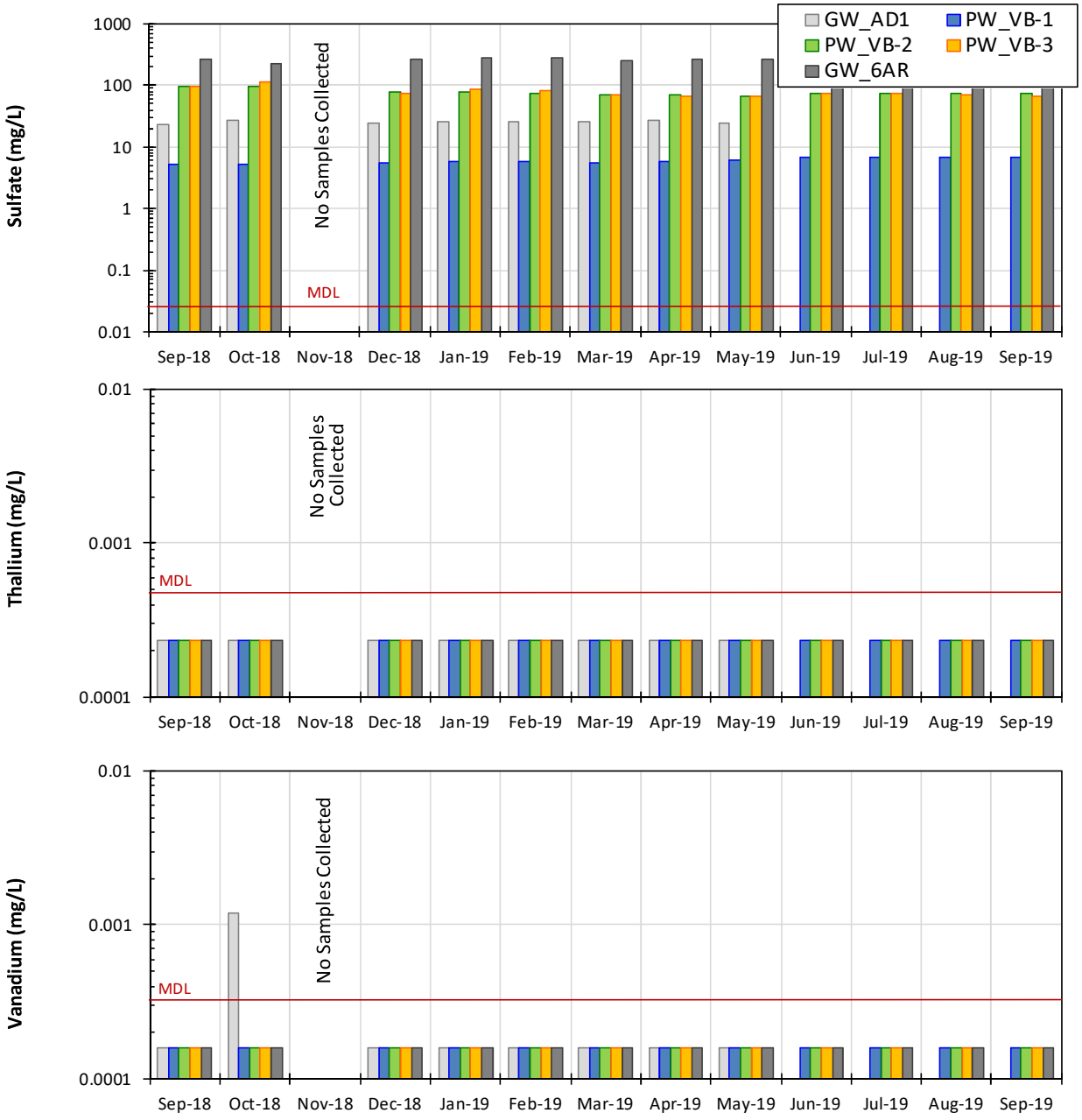


Figure F-10
Measured groundwater and porewater concentrations: sulfate, thallium, and vanadium; concentrations plotted on a logarithmic axis

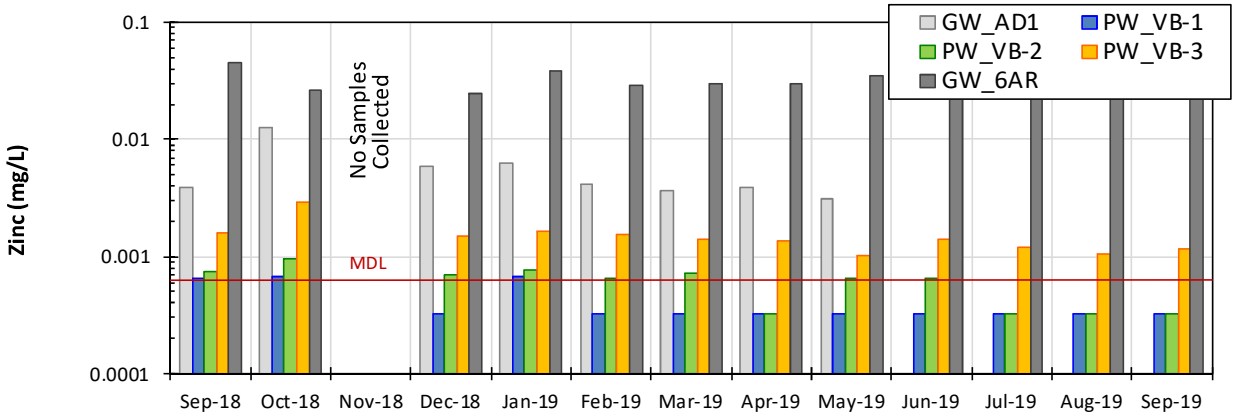


Figure F-11
Measured groundwater and porewater concentrations: zinc; concentrations plotted on a logarithmic axis

F.2 Time Series Graphs for Porewater Data

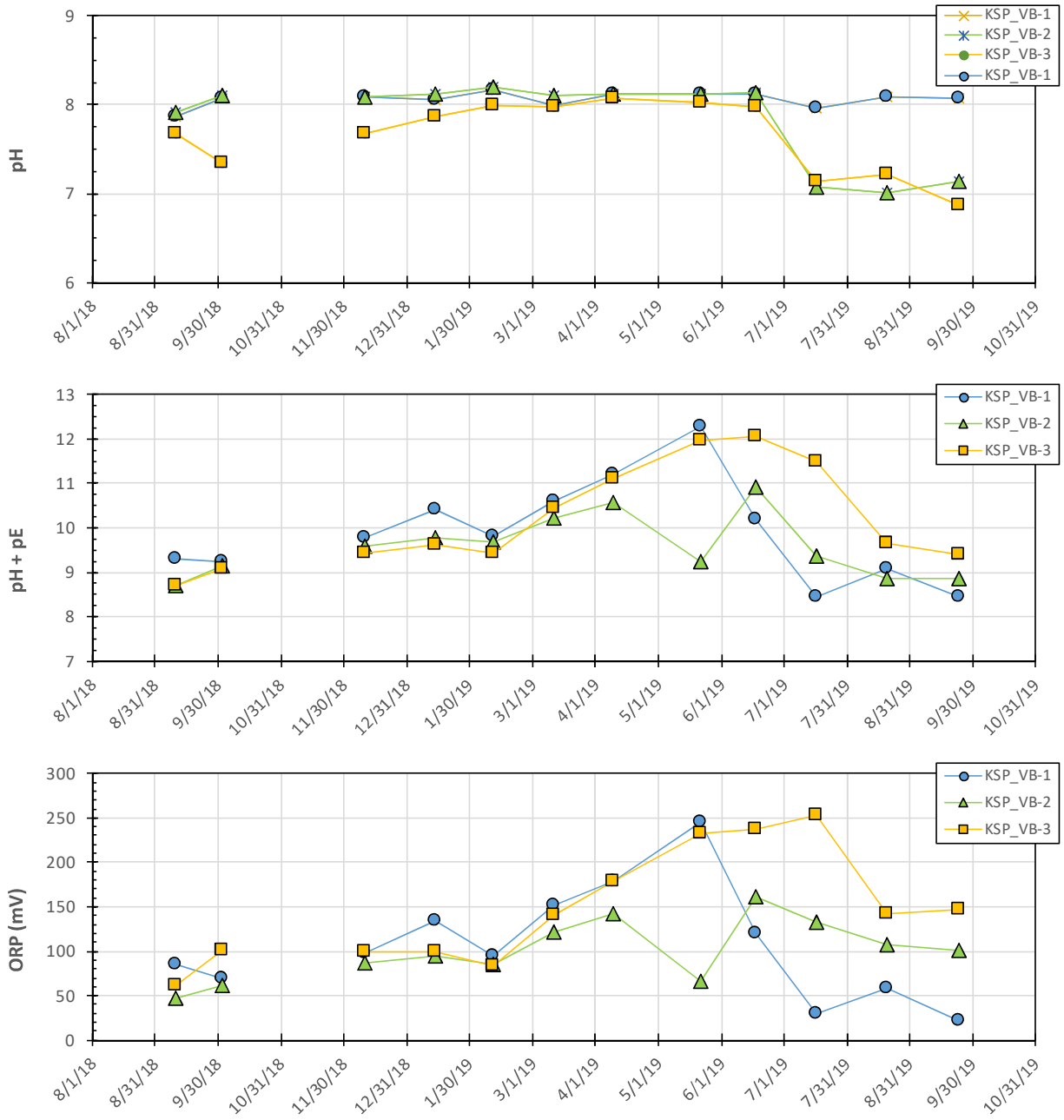


Figure F-12
Time-series plots of porewater conditions: pH, pH+pE, and ORP

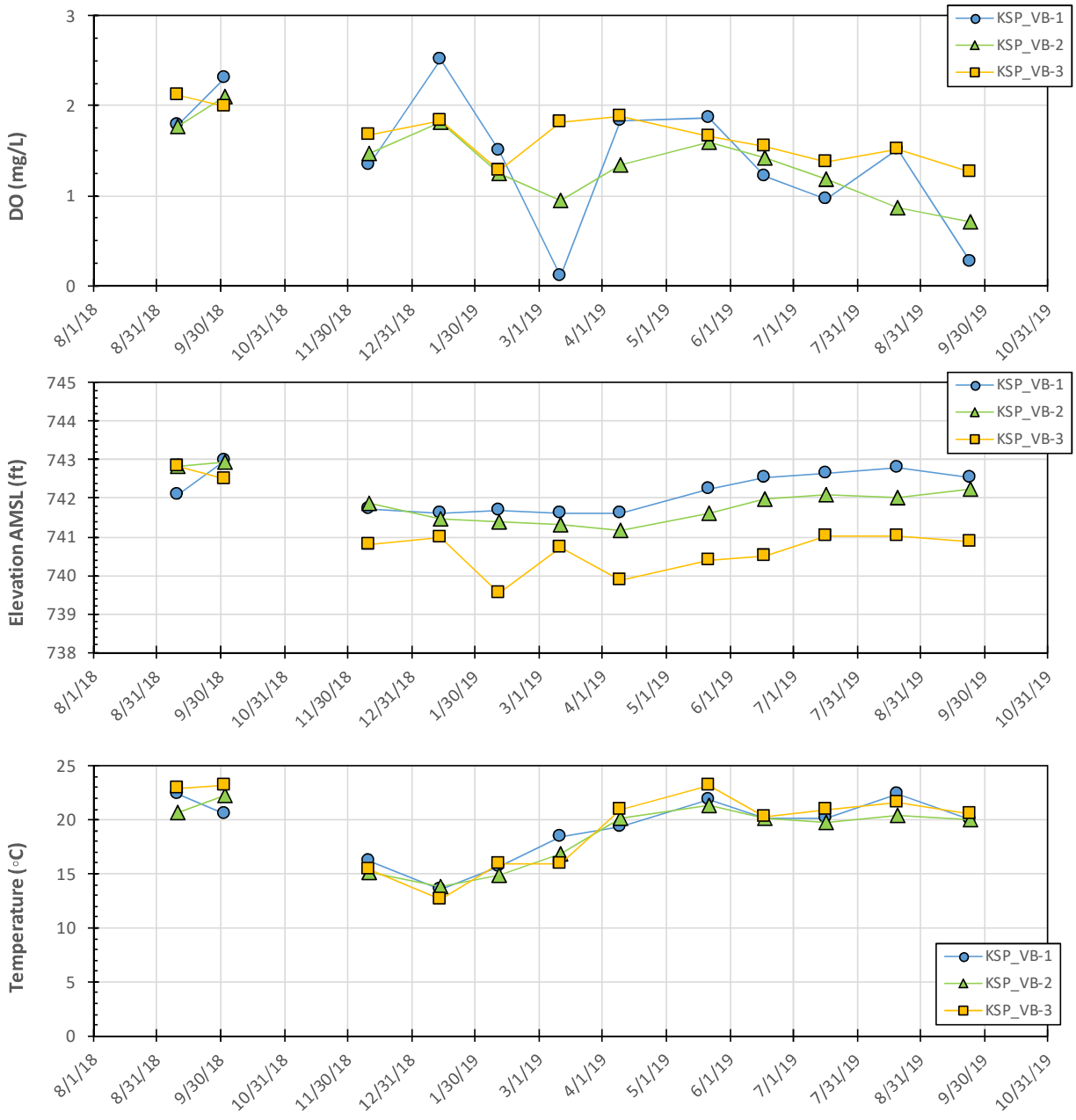


Figure F-13
Time-series plots of porewater conditions: dissolved oxygen (DO), water elevation, and temperature

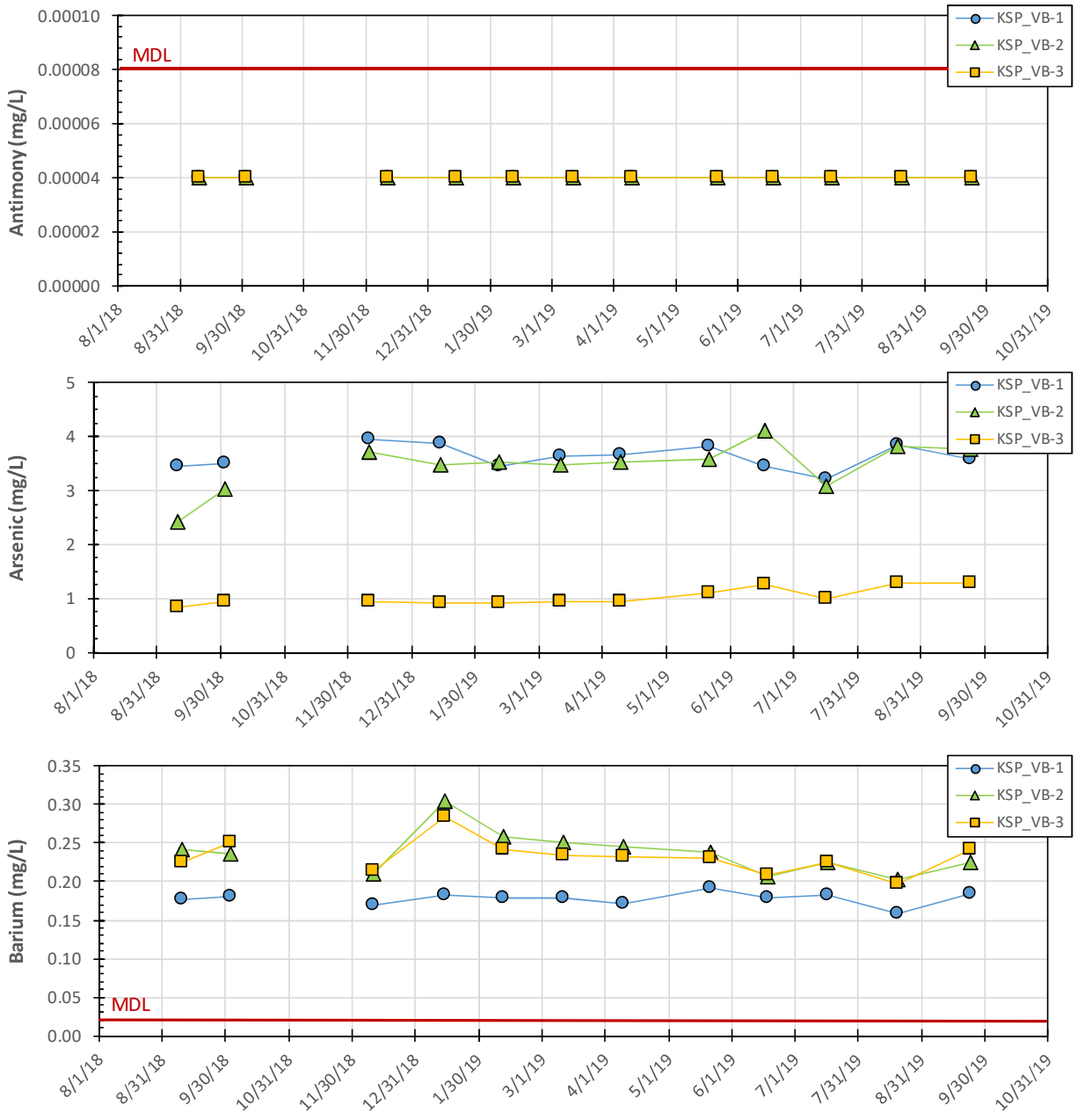


Figure F-14
Time-series plots of porewater concentrations: antimony, arsenic, and barium

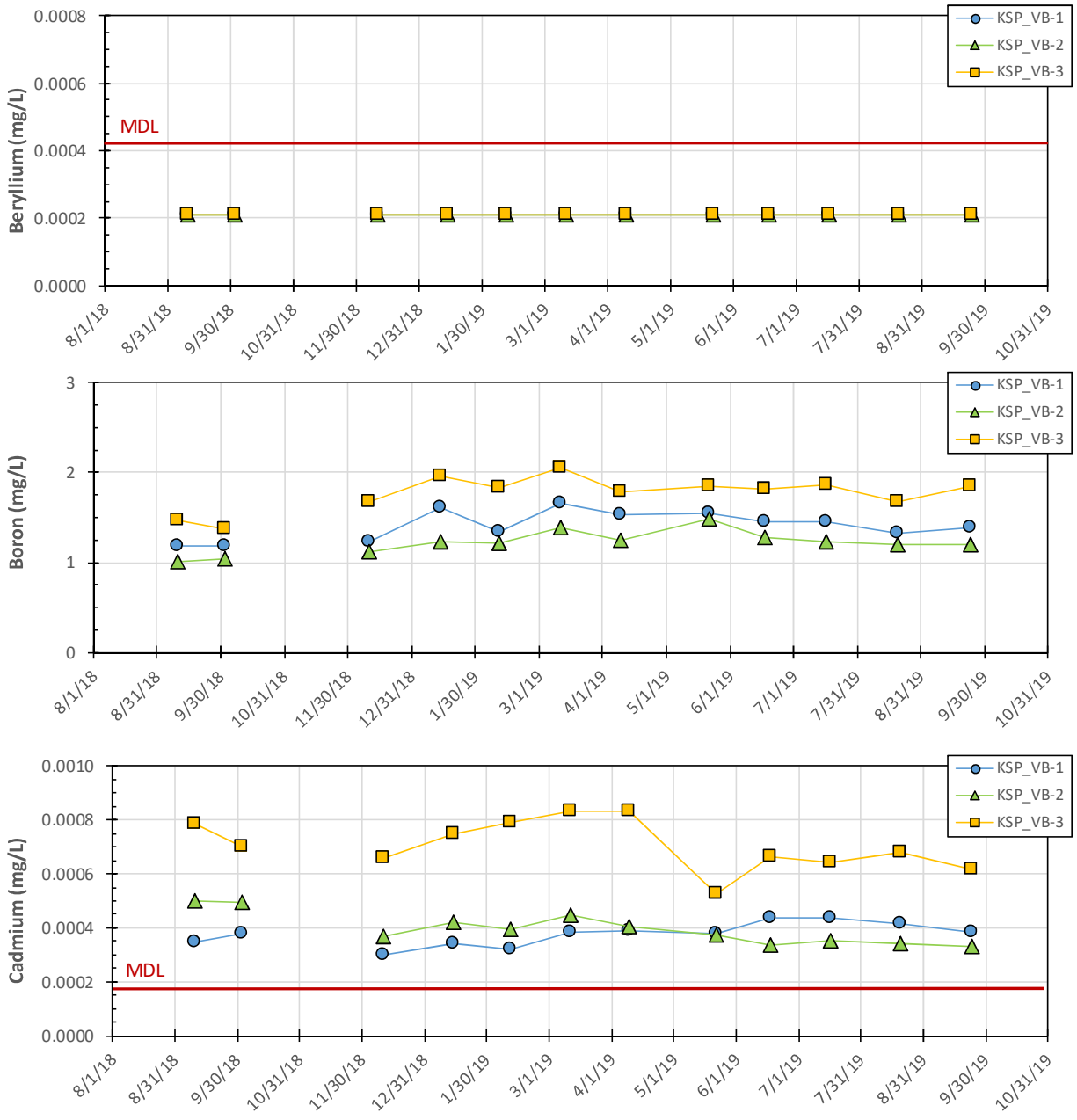


Figure F-15
Time-series plots of porewater concentrations: beryllium, boron, and cadmium

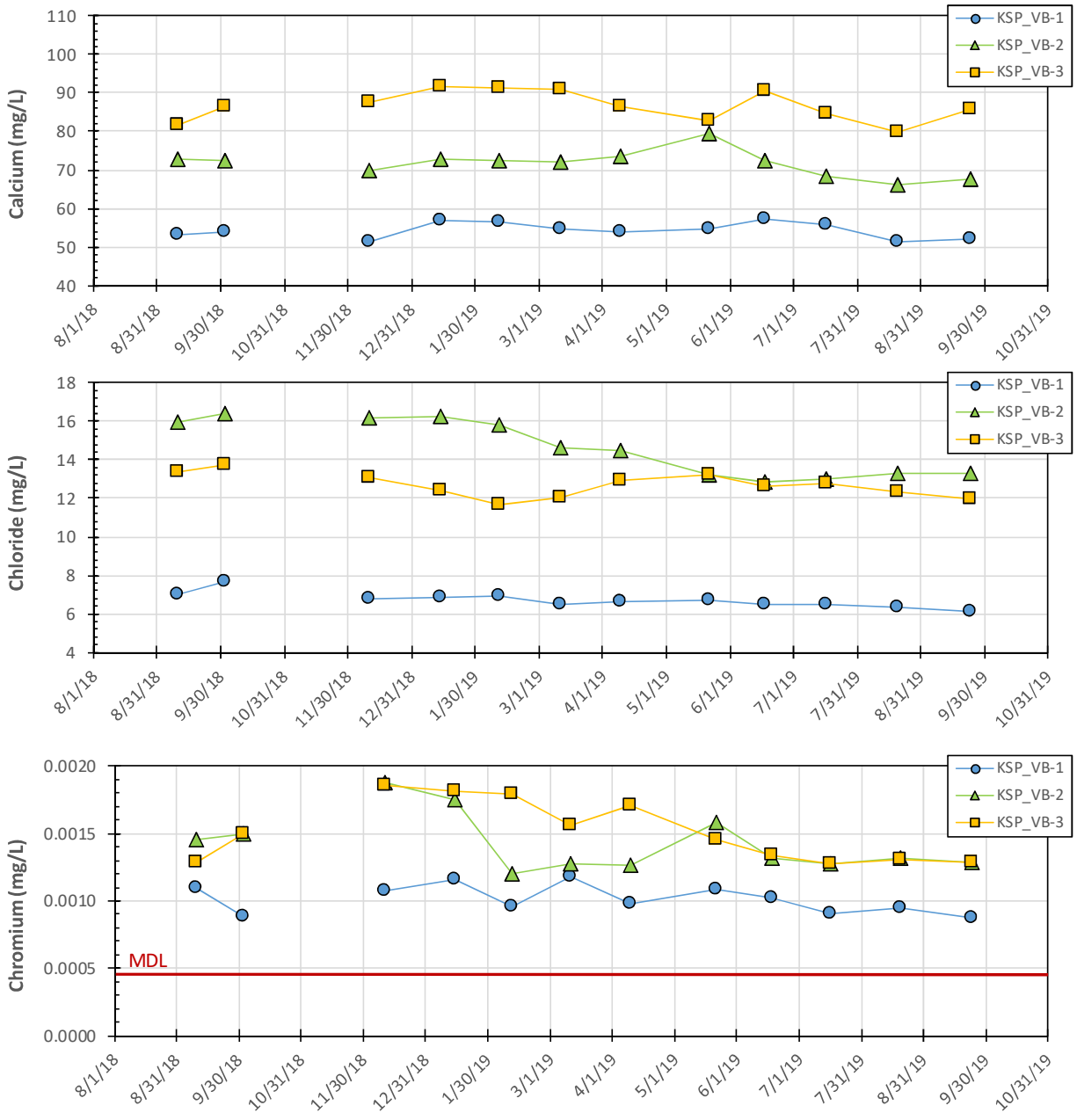


Figure F-16
Time-series plots of porewater concentrations: calcium, chloride, and chromium

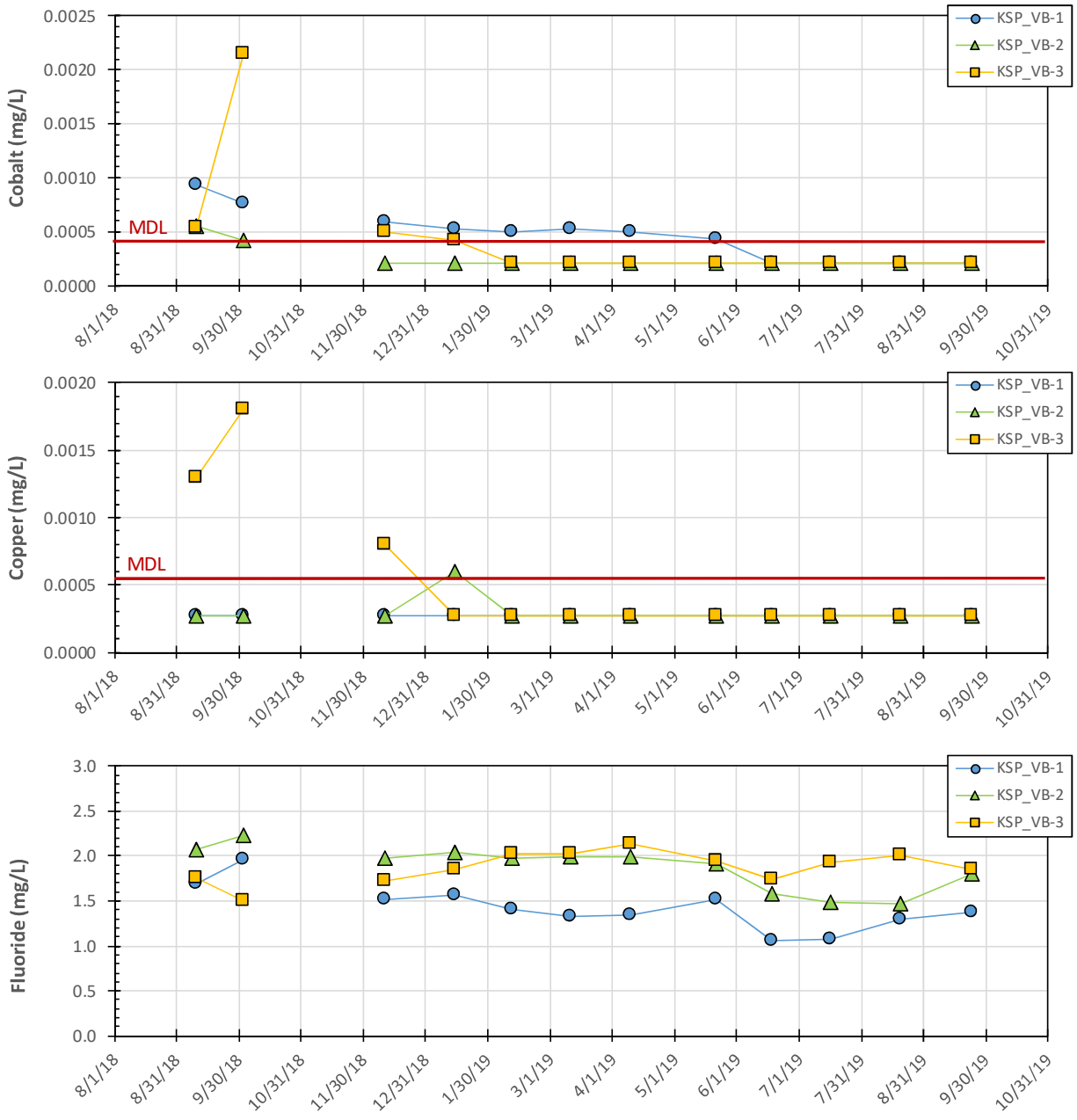


Figure F-17
Time-series plots of porewater concentrations: cobalt, copper, and fluoride

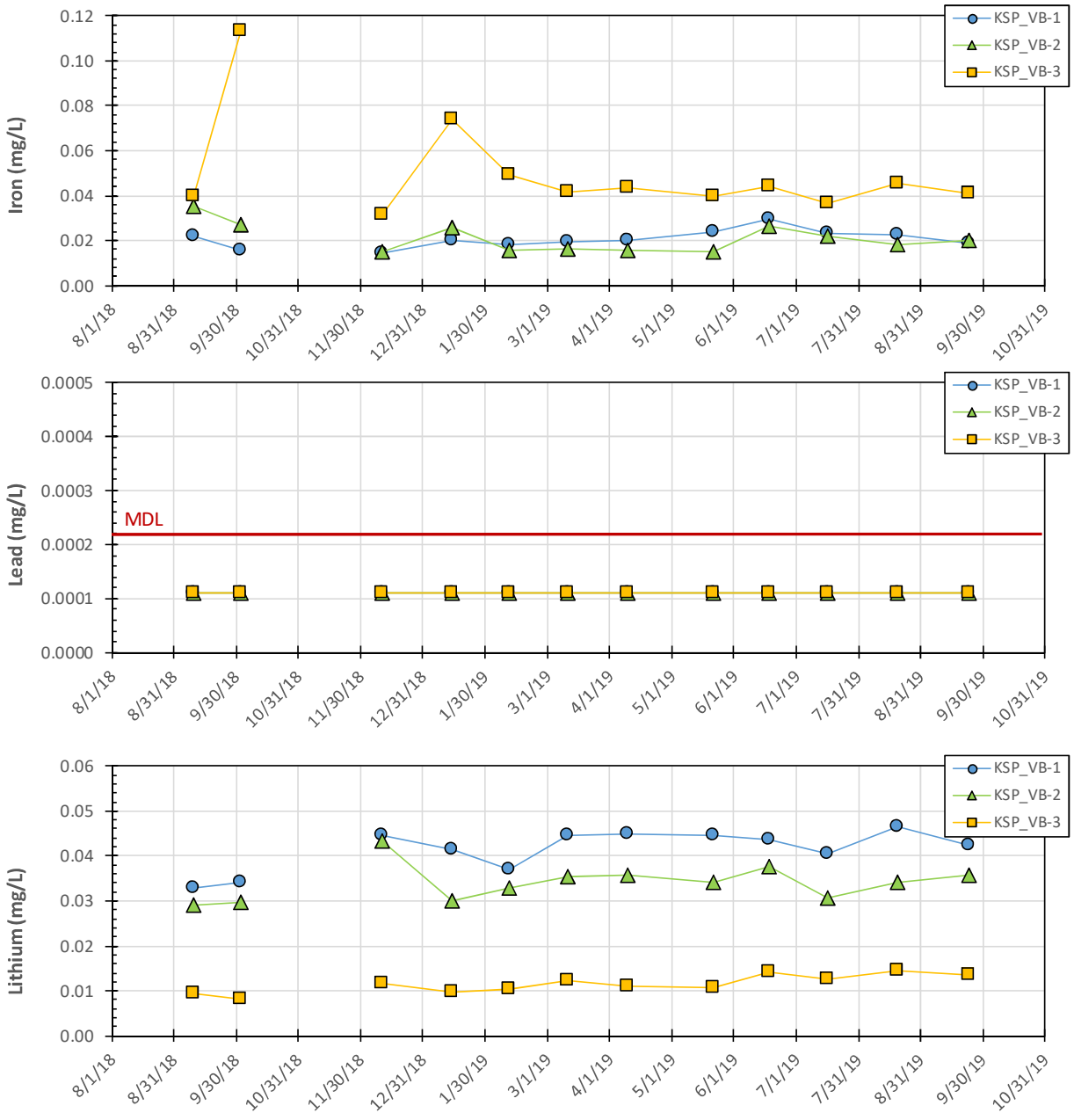


Figure F-18
Time-series plots of porewater concentrations: iron, lead, and lithium

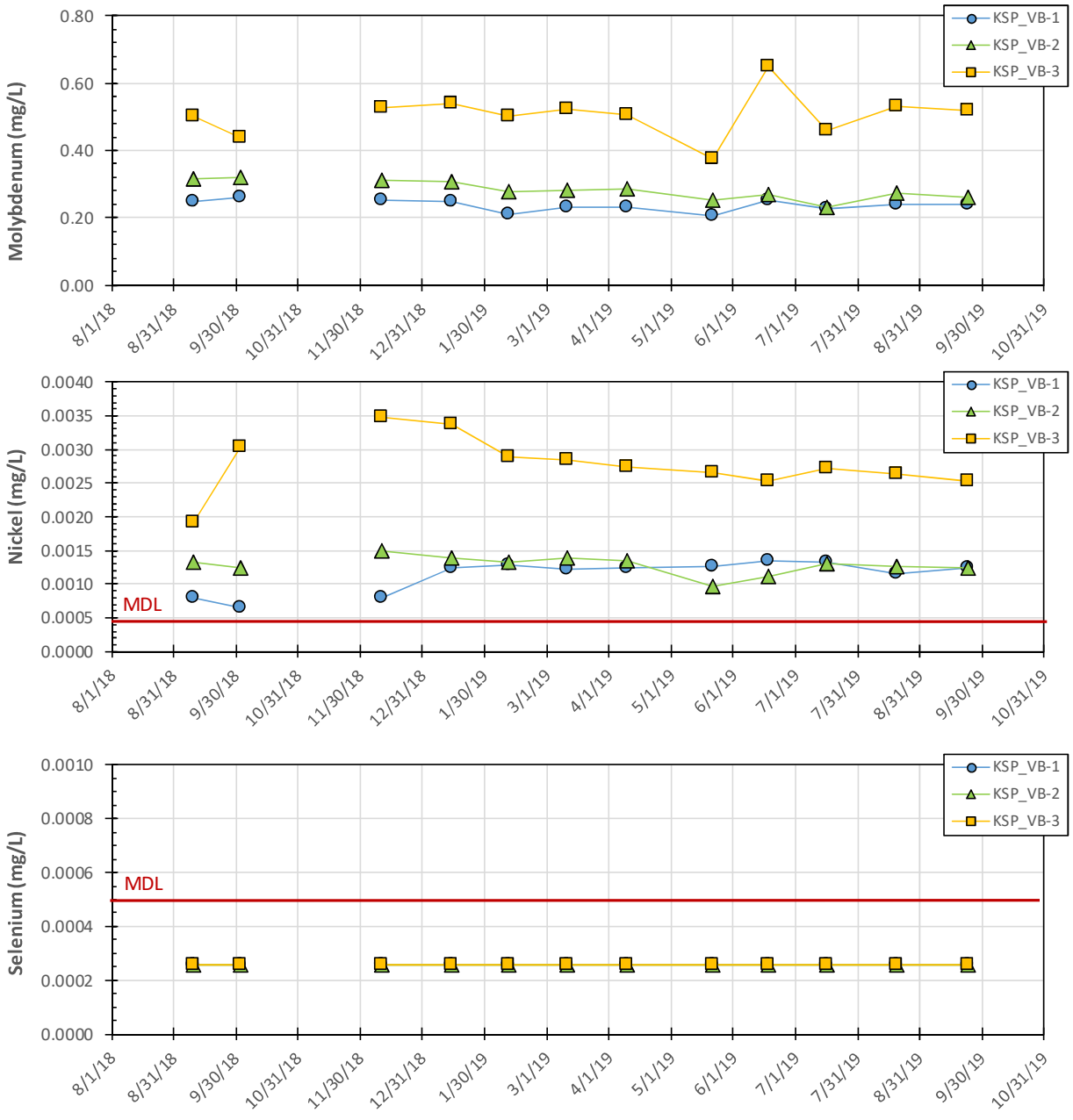


Figure F-19
Time-series plots of porewater concentrations: molybdenum, nickel, and selenium

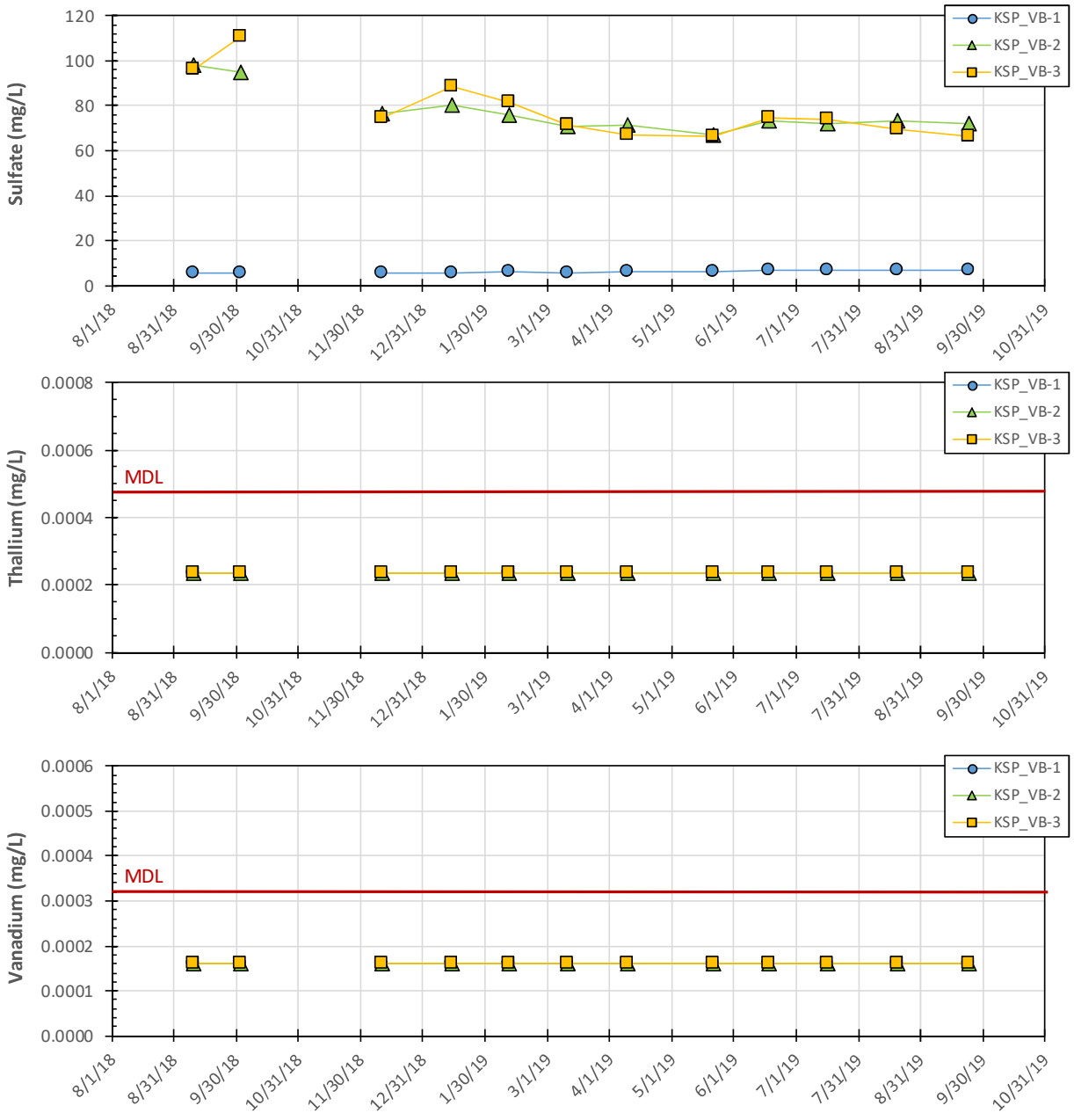


Figure F-20
Time-series plots of porewater concentrations: sulfate, thallium, and vanadium

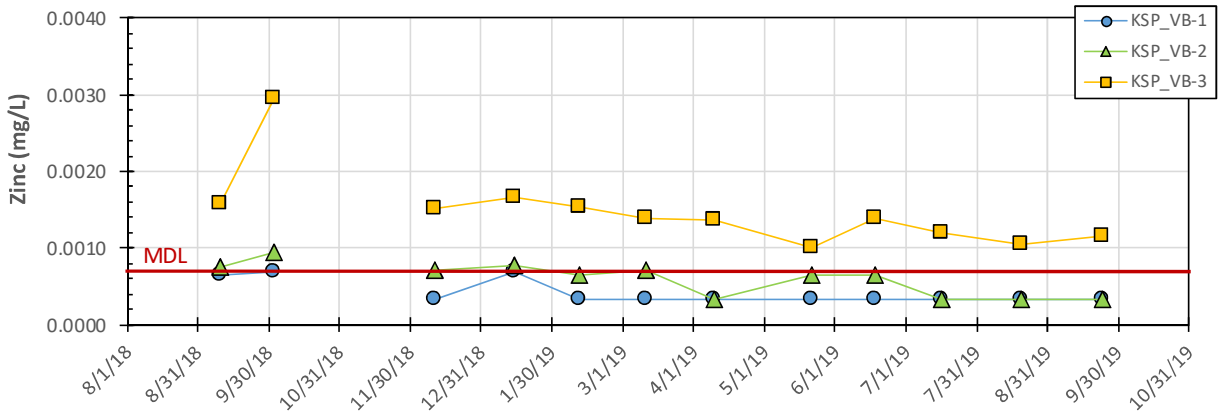


Figure F-21
Time-series plots of porewater concentrations: zinc

F.3 Subsurface Gas Parameter Tables and Graphs

VB-1 (ash porewater borehole)

	Sep-18	Oct-18	Nov-18	Dec-18	Jan-19	Feb-19	Mar-19
Sampling Date	9/10	10/3	No Sample	12/11	1/14	2/11	3/12
O_2 (%)	18.9	0.4	-	20.8	20.6	14.6	19.0
CO_2 (%)	2.4	>5	-	0.22	0.22	0.61	0.32
CH_4 (%)	0.13	>5	-	0	0	0	0
NH_3 (mg/L)	0	0	-	0	0	0	-
H_2S (mg/L)	0	0	-	0	0	0	0
Note	-	-	-	-	-	-	-

	Apr-19	May-19	Jun-19	Jul-19	Aug-19	Sep-19
Sampling Date	4/10	5/22	6/18	7/17	8/20	9/24
O_2 (%)	1.9	0.6	0.7	0.8	0.2	0.3
CO_2 (%)	2.08	3.42	4.29	4.14	4.86	5.00
CH_4 (%)	0	>5	>5	>5	>5	>5
NH_3 (mg/L)	0	0	0	0	0	0
H_2S (mg/L)	0	0	0	0	0	0
Note	-	-	-	-	-	-

VB-2 (ash porewater borehole)

	Sep-18	Oct-18	Nov-18	Dec-18	Jan-19	Feb-19	Mar-19
Sampling Date	9/11	10/3	No Sample	12/11	1/14	2/11	3/12
O_2 (%)	0.4	0.3	-	0.2	0.2	0.5	2.4
CO_2 (%)	0.14	0.26	-	0.24	0.45	0.51	0.45
CH_4 (%)	>5	>5	-	>5	>5	>5	>5
NH_3 (mg/L)	2.0	0	-	0	2.0	4.0	-
H_2S (mg/L)	4.1	3.0	-	12.8	14.1	12.6	0.9
Note	-	-	-	-	-	W @ 8 min	W @ 3 min

	Apr-19	May-19	Jun-19	Jul-19	Aug-19	Sep-19
Sampling Date	4/10	5/22	6/18	7/17	8/20	9/24
O_2 (%)	4.7	0.6	0.8	1.2	0.3	4.9
CO_2 (%)	0.51	0.55	0.65	0.71	0.63	0.50
CH_4 (%)	>5	>5	>5	>5	>5	>5
NH_3 (mg/L)	0	0	0	0	0	0
H_2S (mg/L)	0	0	0	0	0	0
Note	W @ 3 min	W @ 3 min				

Notes:

PF = pump fault (line blockage) occurred

W = water/ash mixture pumped from gas access line

VB-3 (ash porewater borehole)

	Sep-18	Oct-18	Nov-18	Dec-18	Jan-19	Feb-19	Mar-19
Sampling Date	9/11	10/3	No Sample	12/11	1/14	2/10	3/10
O_2 (%)	15.8	5.6	-	7.3	7.6	20.3	4.2
CO_2 (%)	2.1	>5	-	>5	>5	0.26	>5
CH_4 (%)	>5	>5	-	>5	>5	0.8	>5
NH_3 (mg/L)	>5	0	-	0	3.0	0	
H_2S (mg/L)	5.9	6.1	-	28.1	26.5	0	22.3
Note	-	PF @ 5 min	-	PF @ 6 min	-	W @ 5 min	PF @ 6 min

	Apr-19	May-19	Jun-19	Jul-19	Aug-19	Sep-19
Sampling Date	4/10	No Sample	6/18	7/17	8/20	9/24
O_2 (%)	5.7	-	2.2	-	-	-
CO_2 (%)	>5	-	>5	-	-	-
CH_4 (%)	>5	-	>5	-	-	-
NH_3 (mg/L)	0	-	0	-	-	-
H_2S (mg/L)	13.2	-	16.2	-	-	-
Note	PF @ 4 min	PF @ 0 min	PF @ 3 min	PF @ 0 min	PF @ 0 min	PF @ 0 min

Notes:

PF = pump fault (line blockage) occurred

W = water/ash mixture pumped from gas access line

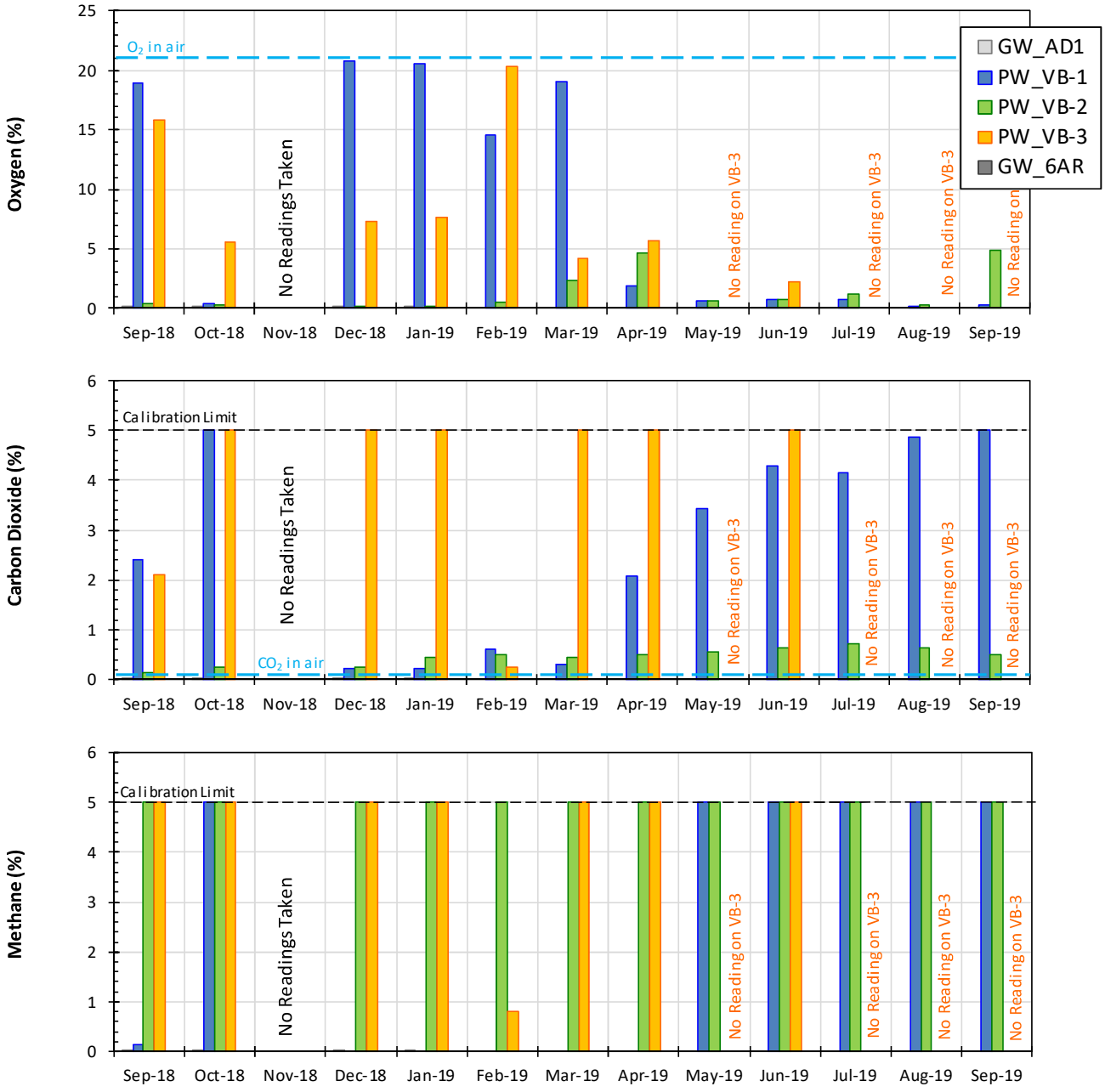


Figure F-22
Measured subsurface gas composition: oxygen, carbon dioxide, and methane

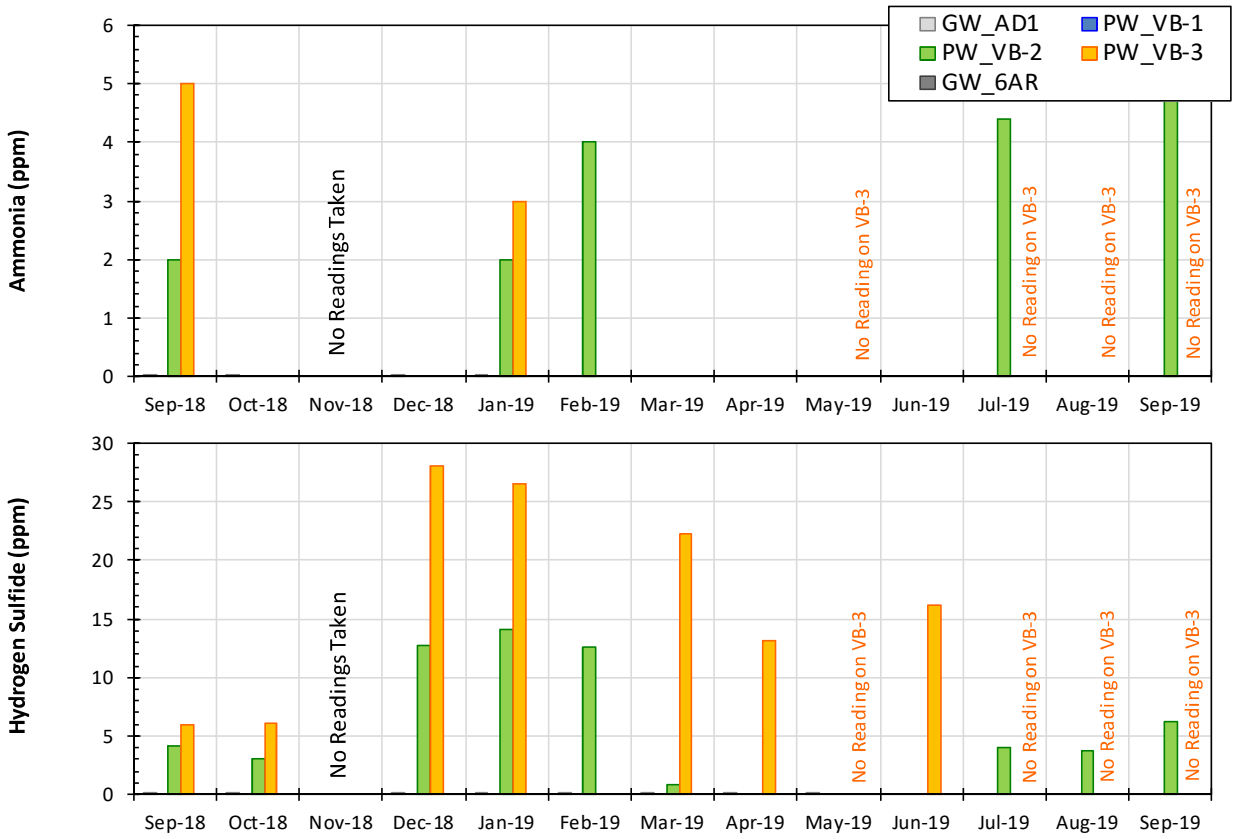


Figure F-23
Measured subsurface gas composition: ammonia and hydrogen sulfide

G

COMPARISON OF POREWATER ESTIMATES FROM LEACHING TESTS WITH MEASURED VALUES

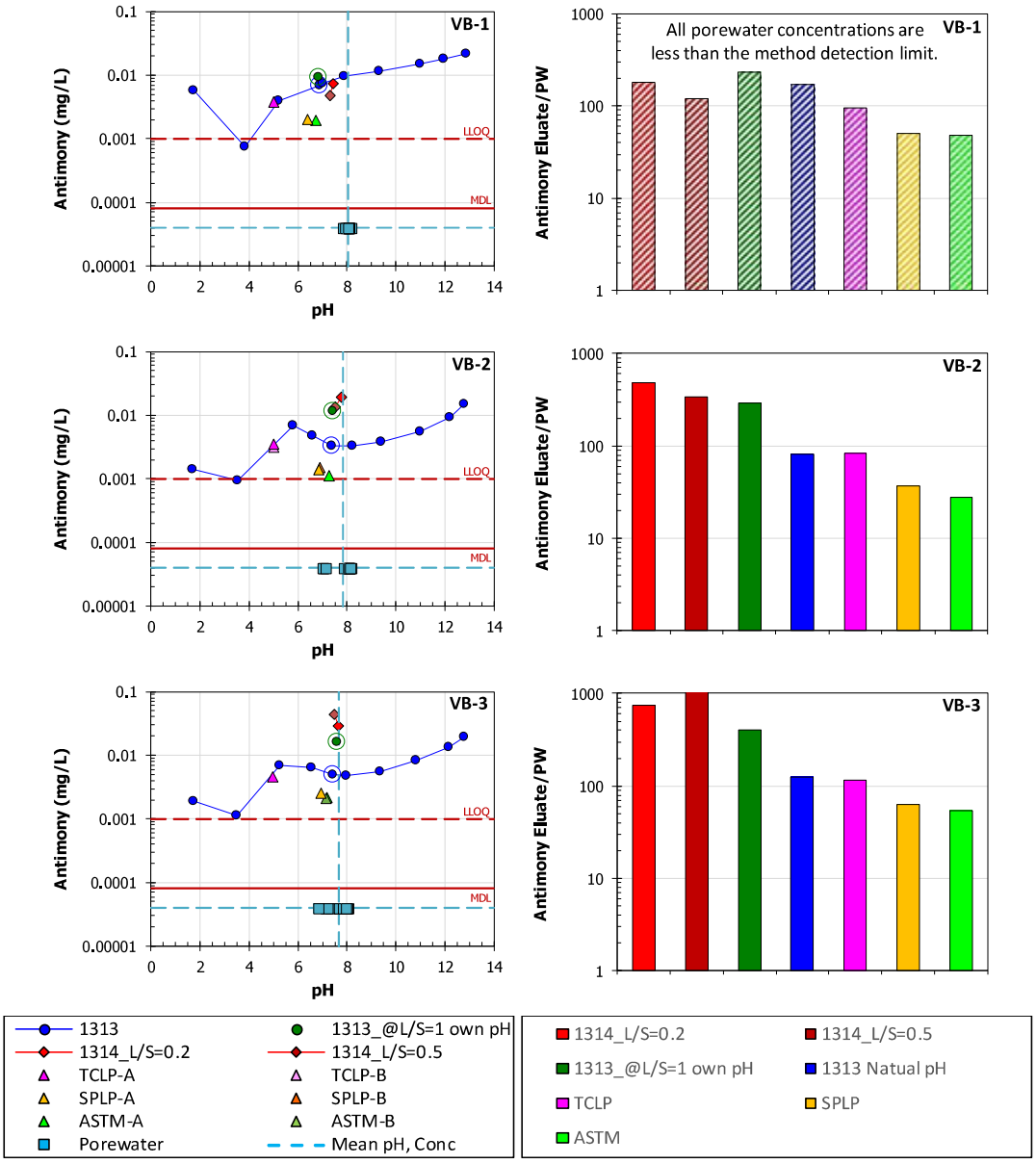


Figure G-1
Antimony concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate and porewater concentrations (right); crosshatched ratio results indicate estimates based on at least one MDL value

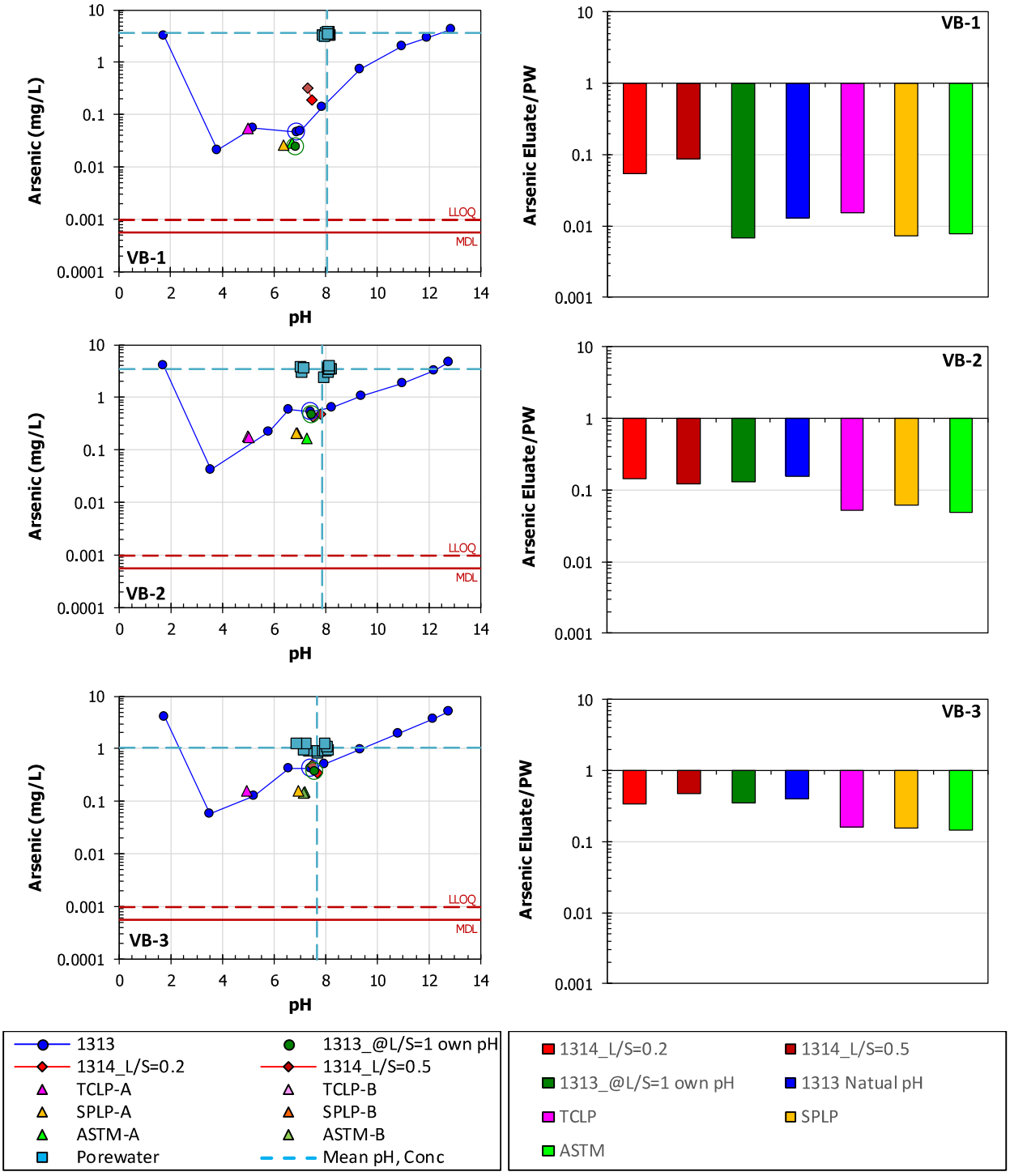


Figure G-2
Arsenic concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate and porewater concentrations (right)

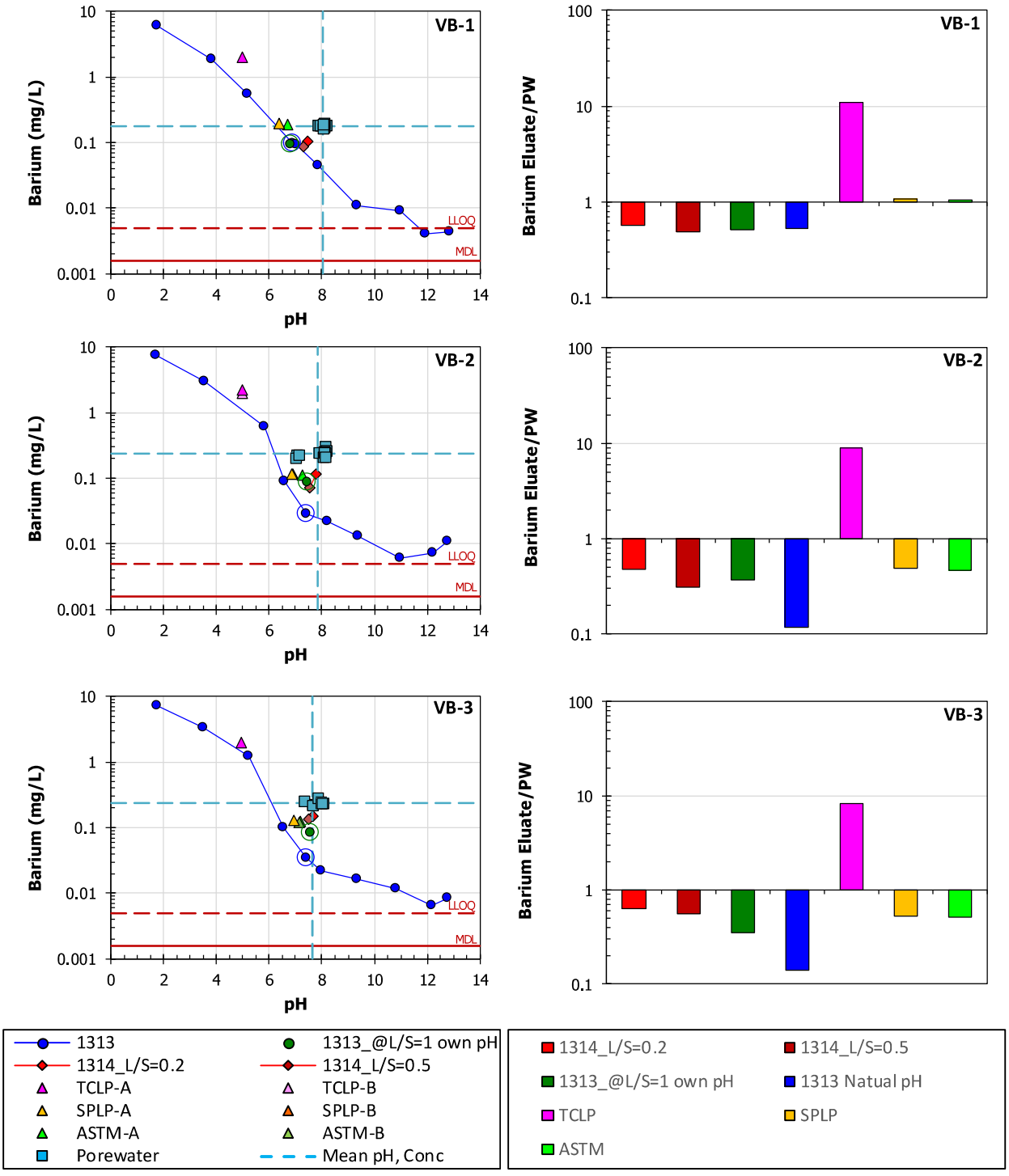


Figure G-3
Barium concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate and porewater concentrations (right)

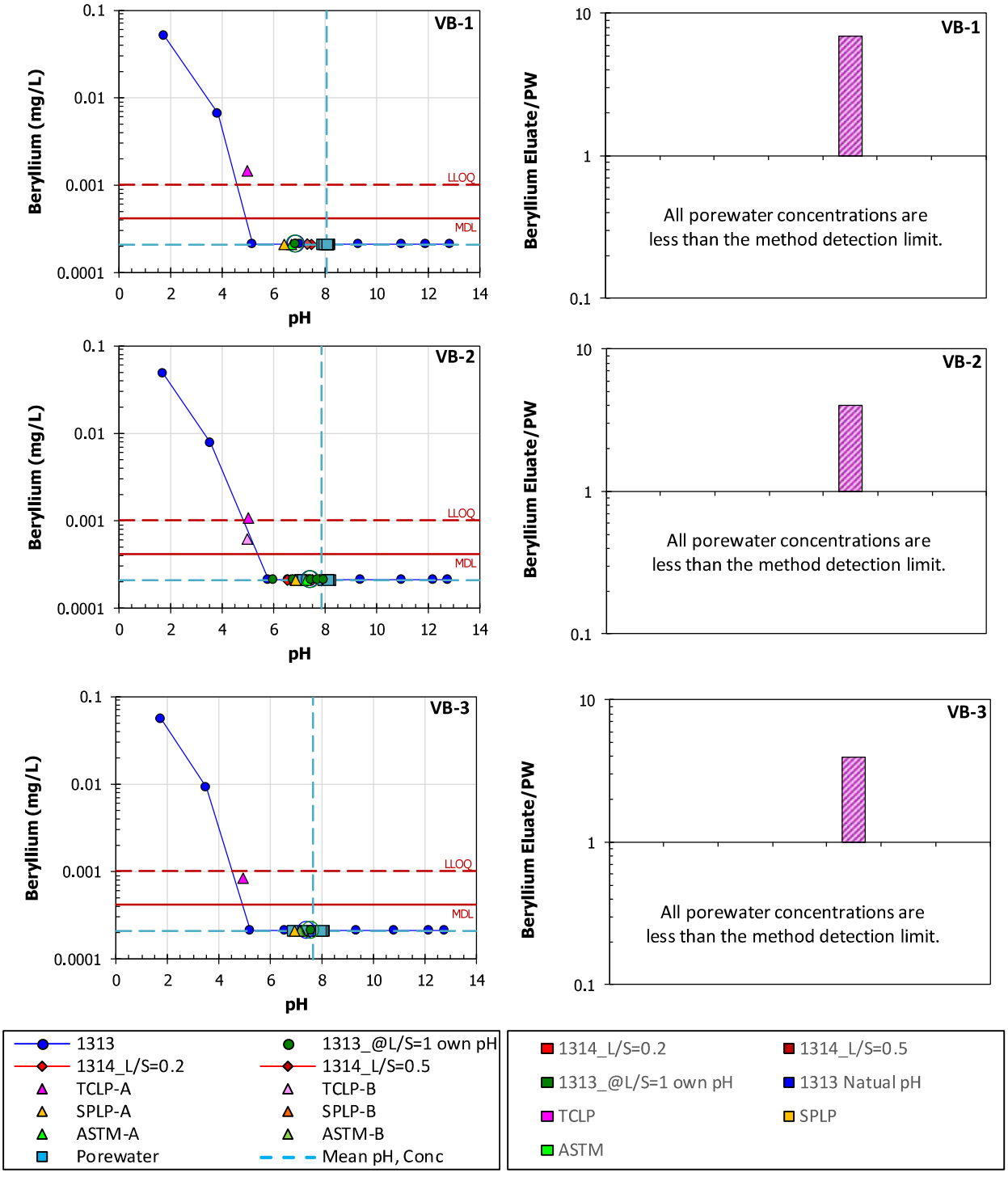


Figure G-4
Beryllium concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right); crosshatched ratio results indicate estimates based on at least one MDL value

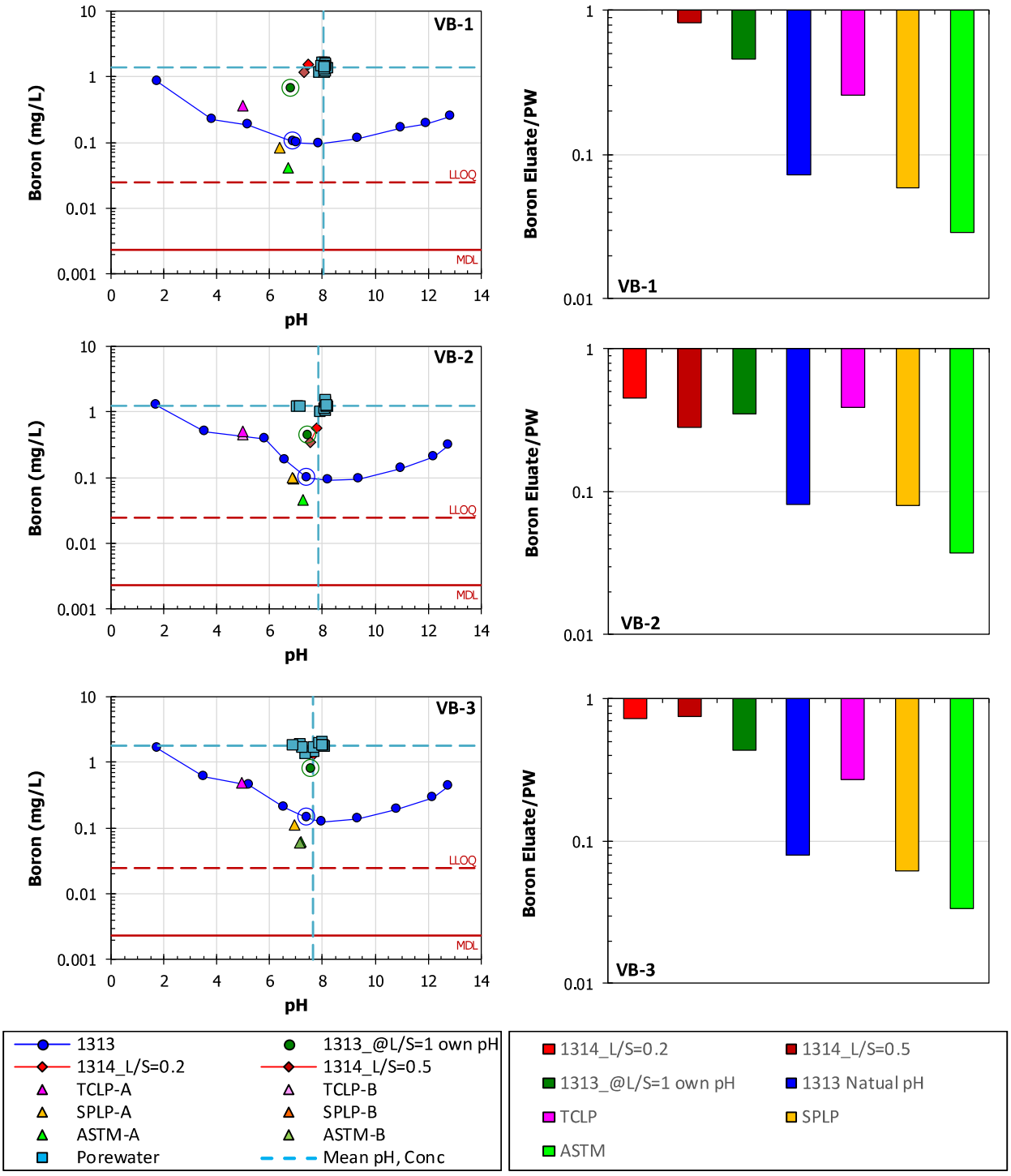


Figure G-5
Boron concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right)

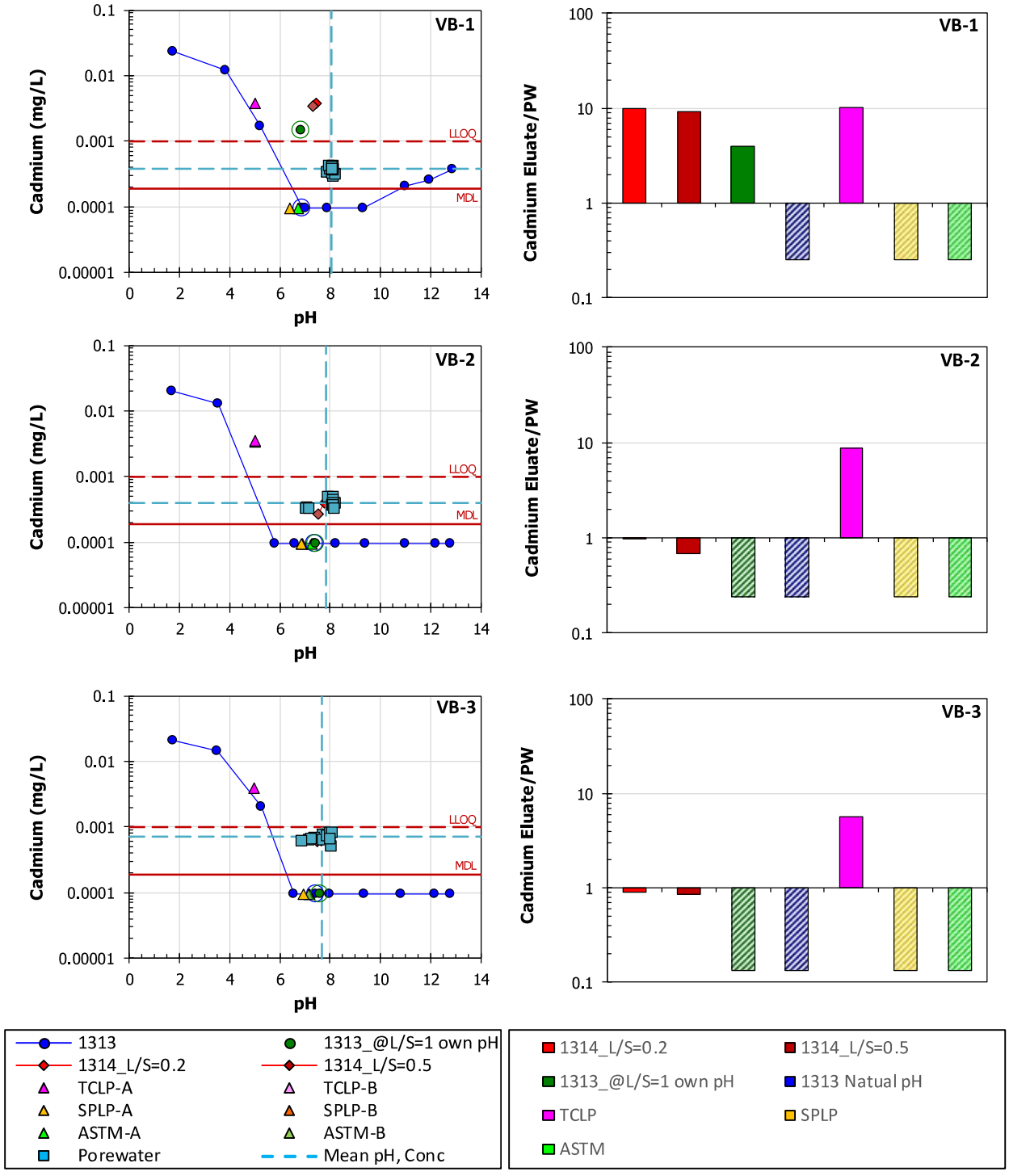


Figure G-6
Cadmium concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right); crosshatched ratio results indicate estimates based on at least one MDL value

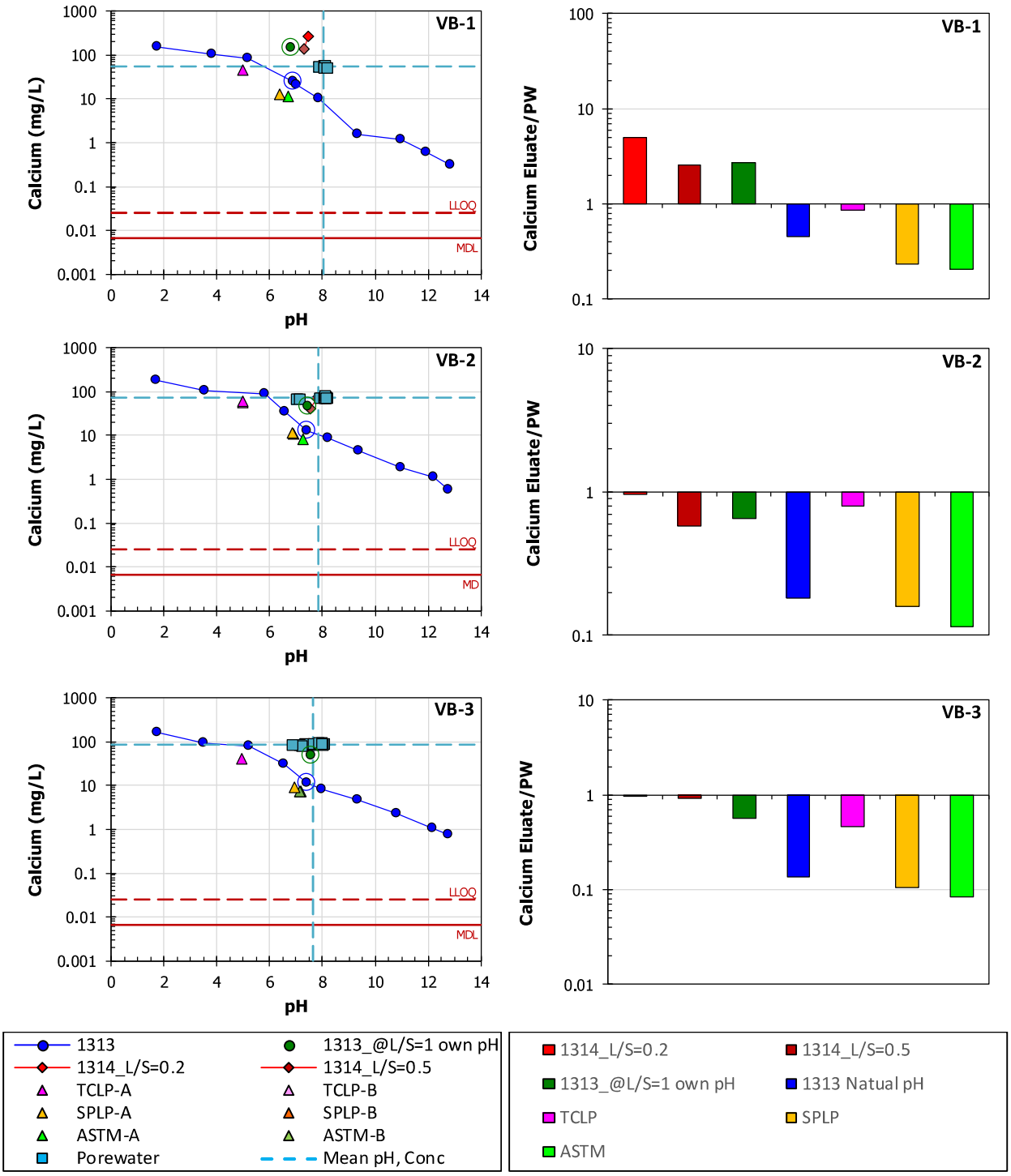


Figure G-7
Calcium concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right)

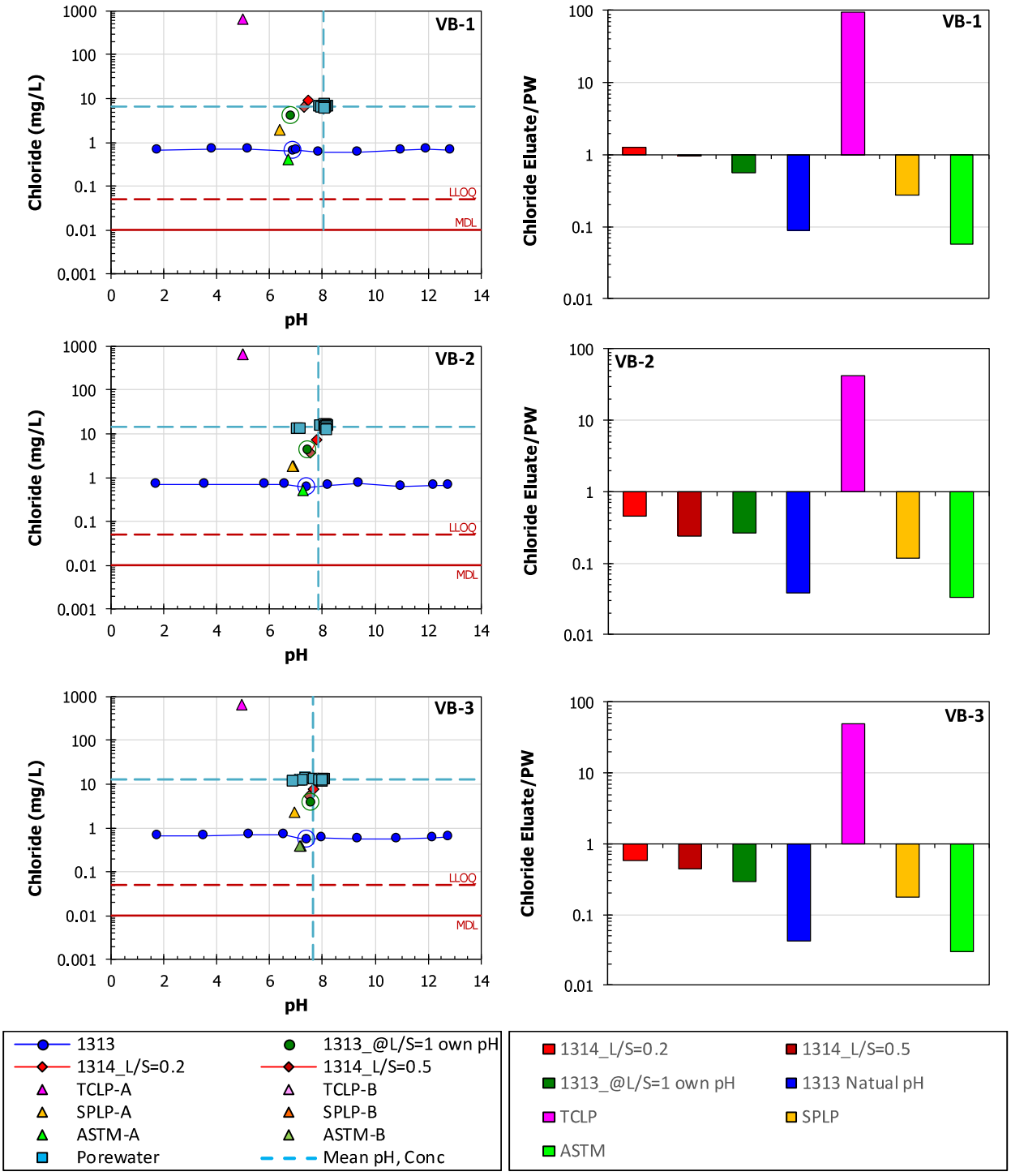


Figure G-8
Chloride concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right)

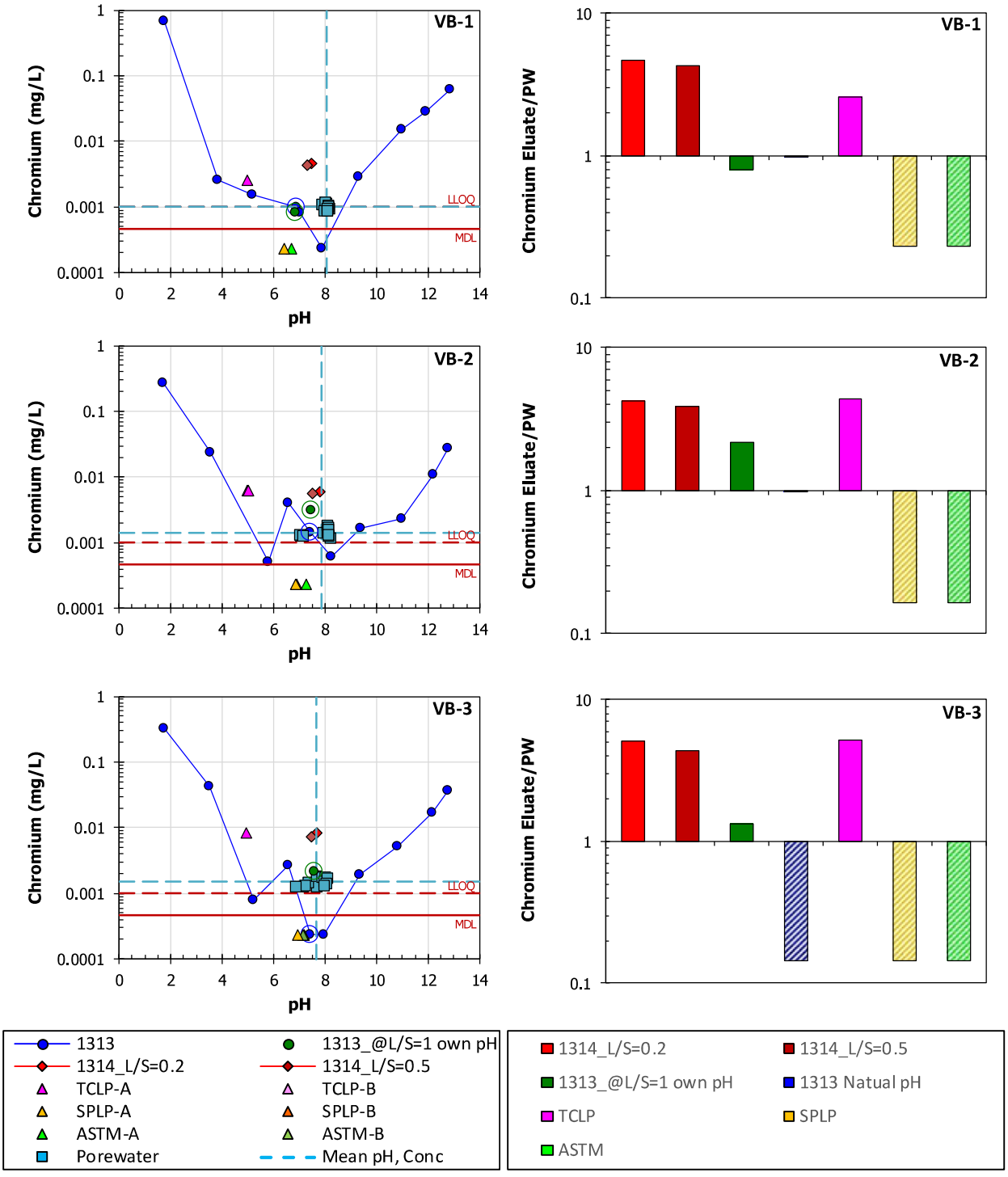


Figure G-9
Chromium concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right); crosshatched ratio results indicate estimates based on at least one MDL value

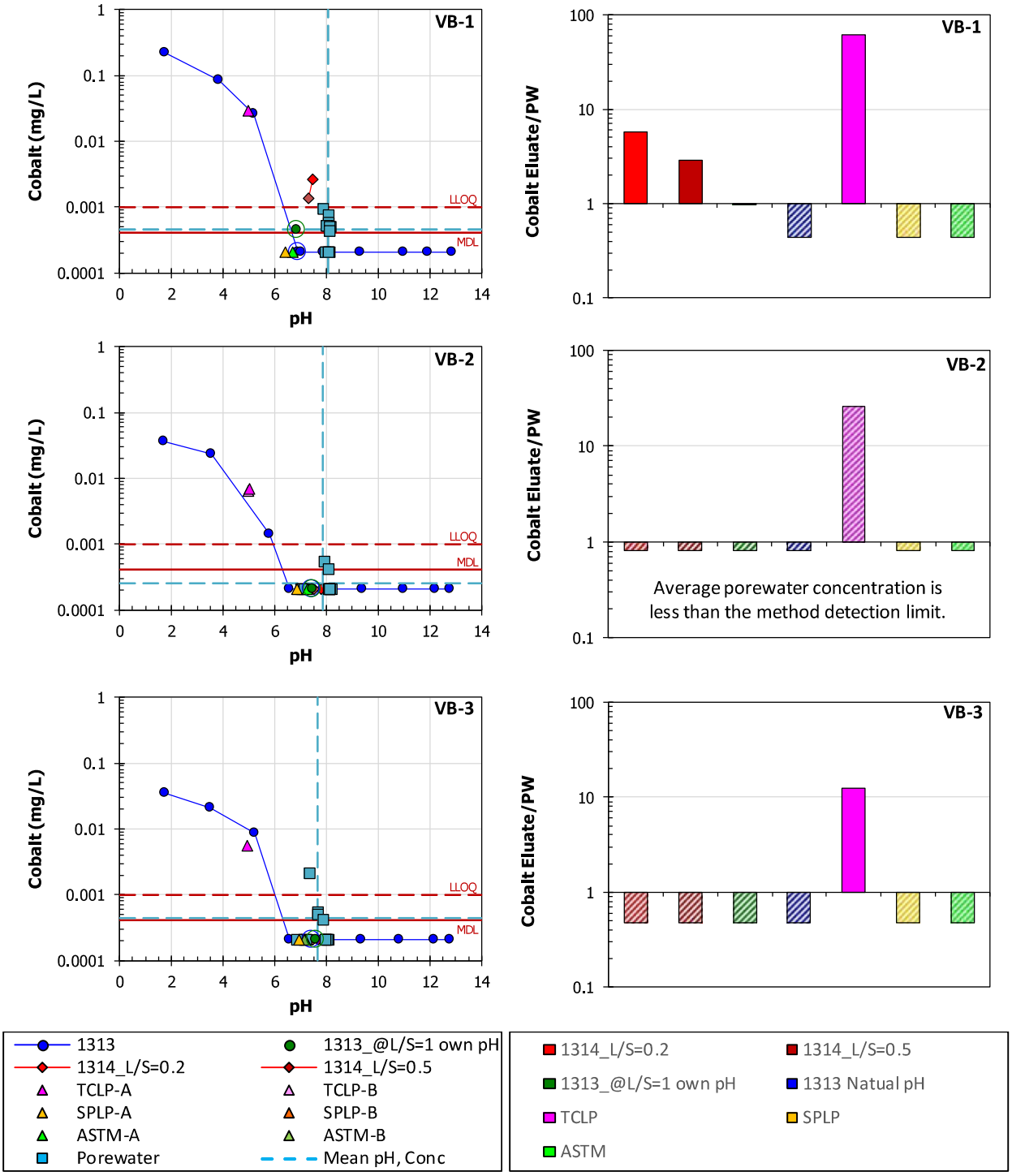


Figure G-10
Cobalt concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right); crosshatched ratio results indicate estimates based on at least one MDL value

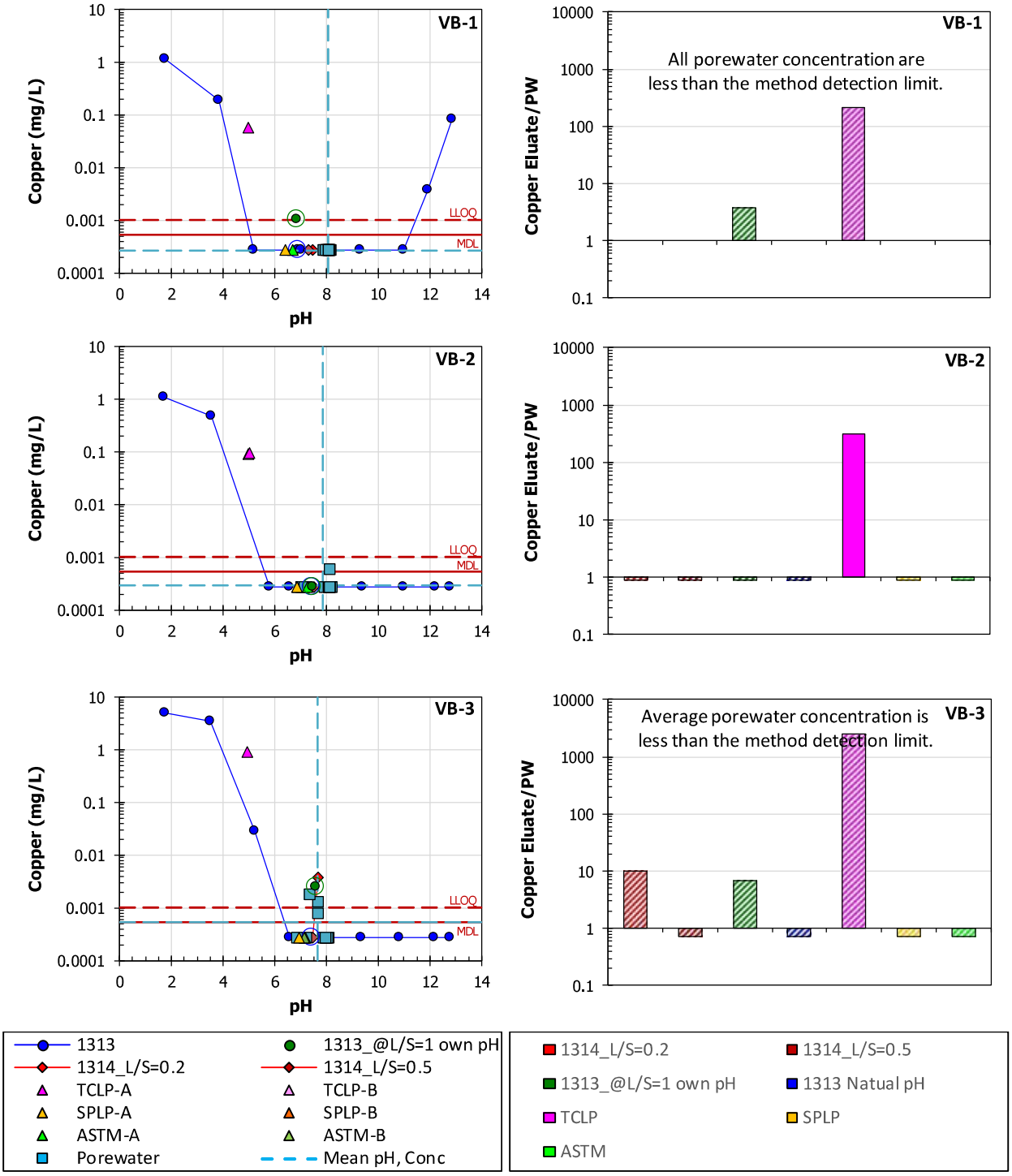


Figure G-11
Copper from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right); crosshatched ratio results indicate estimates based on at least one MDL value

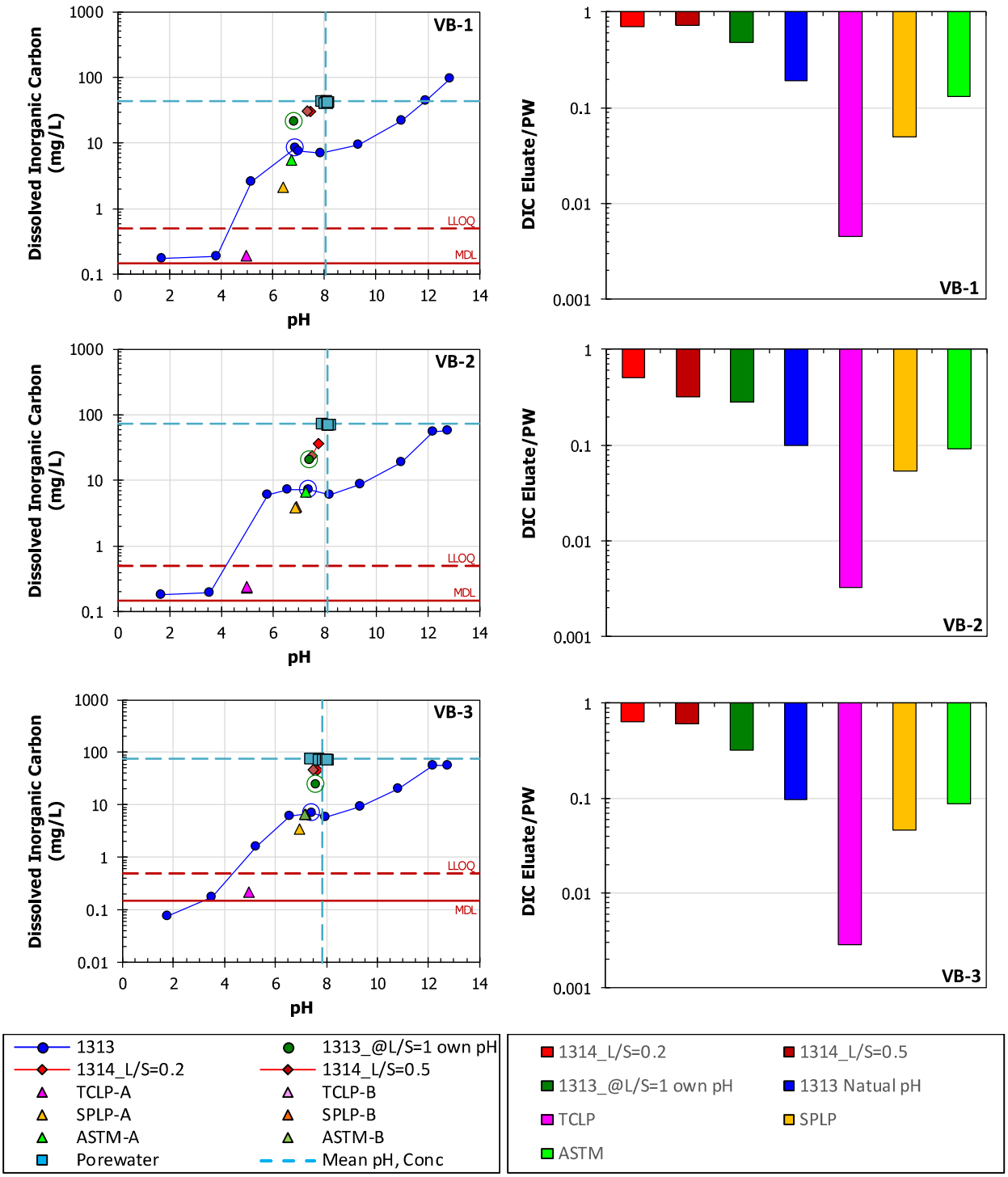


Figure G-12
Dissolved inorganic carbon concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right)

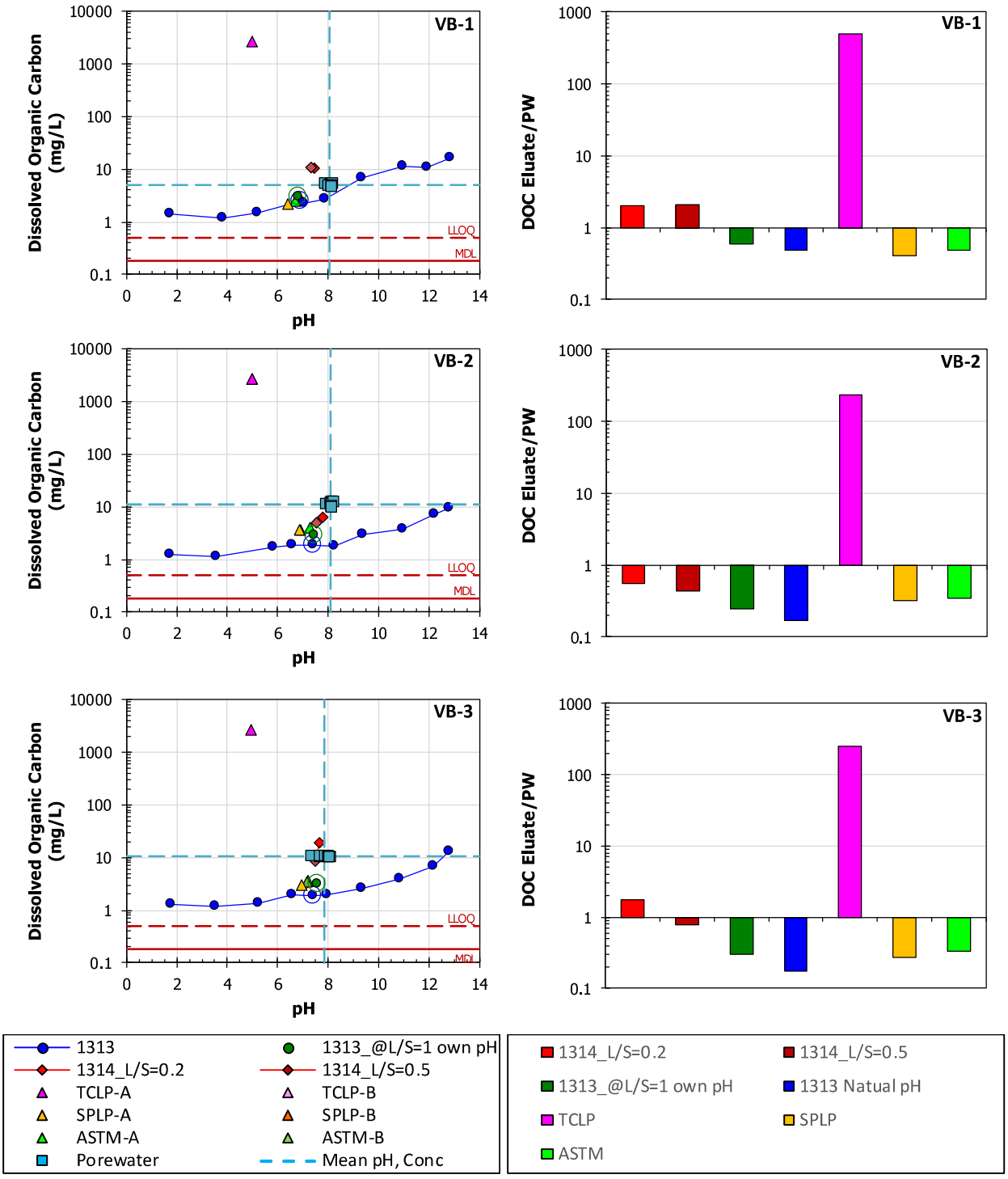


Figure G-13
Dissolved organic carbon concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right)

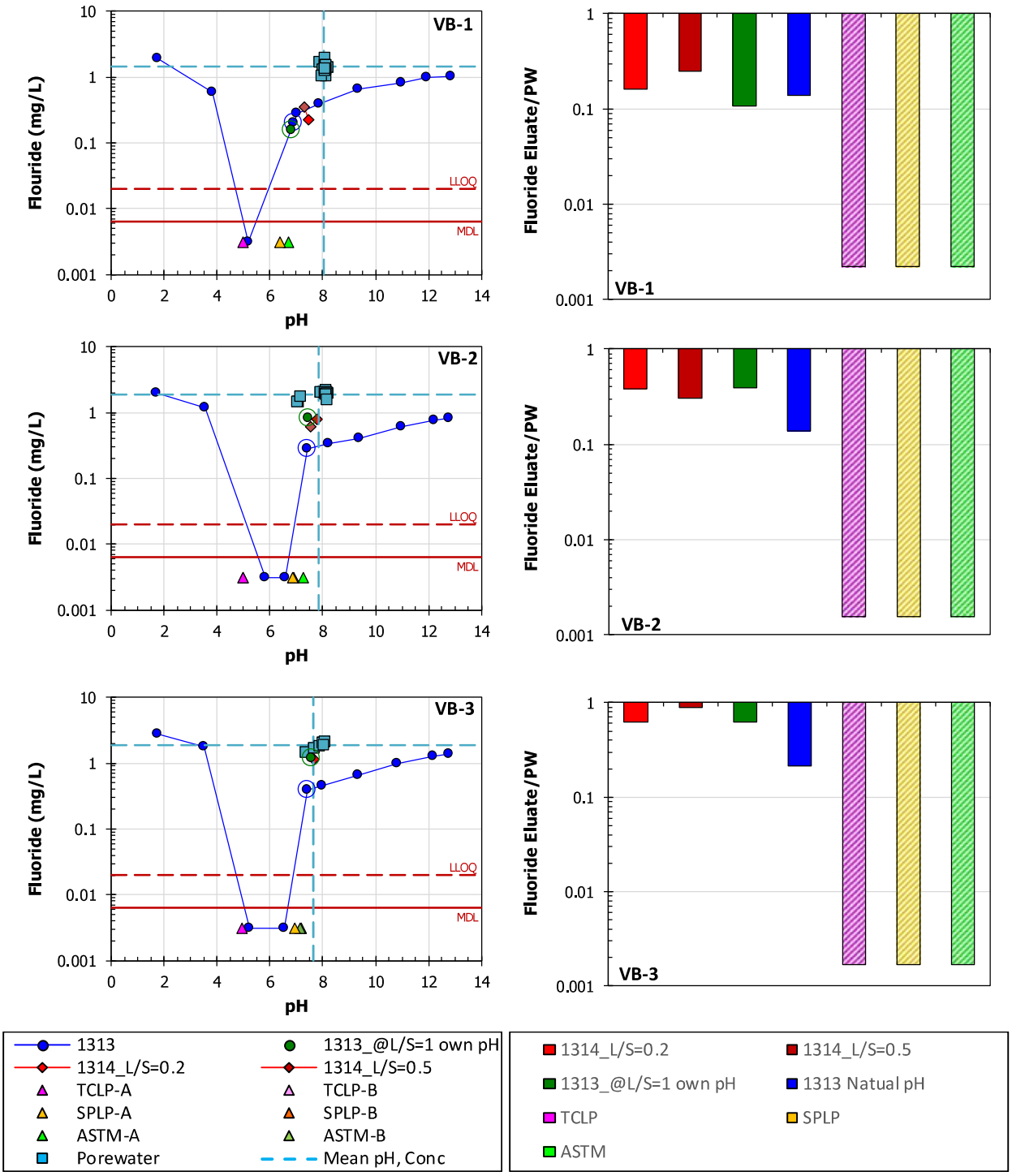


Figure G-14
Fluoride concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right); crosshatched ratio results indicate estimates based on at least one MDL value

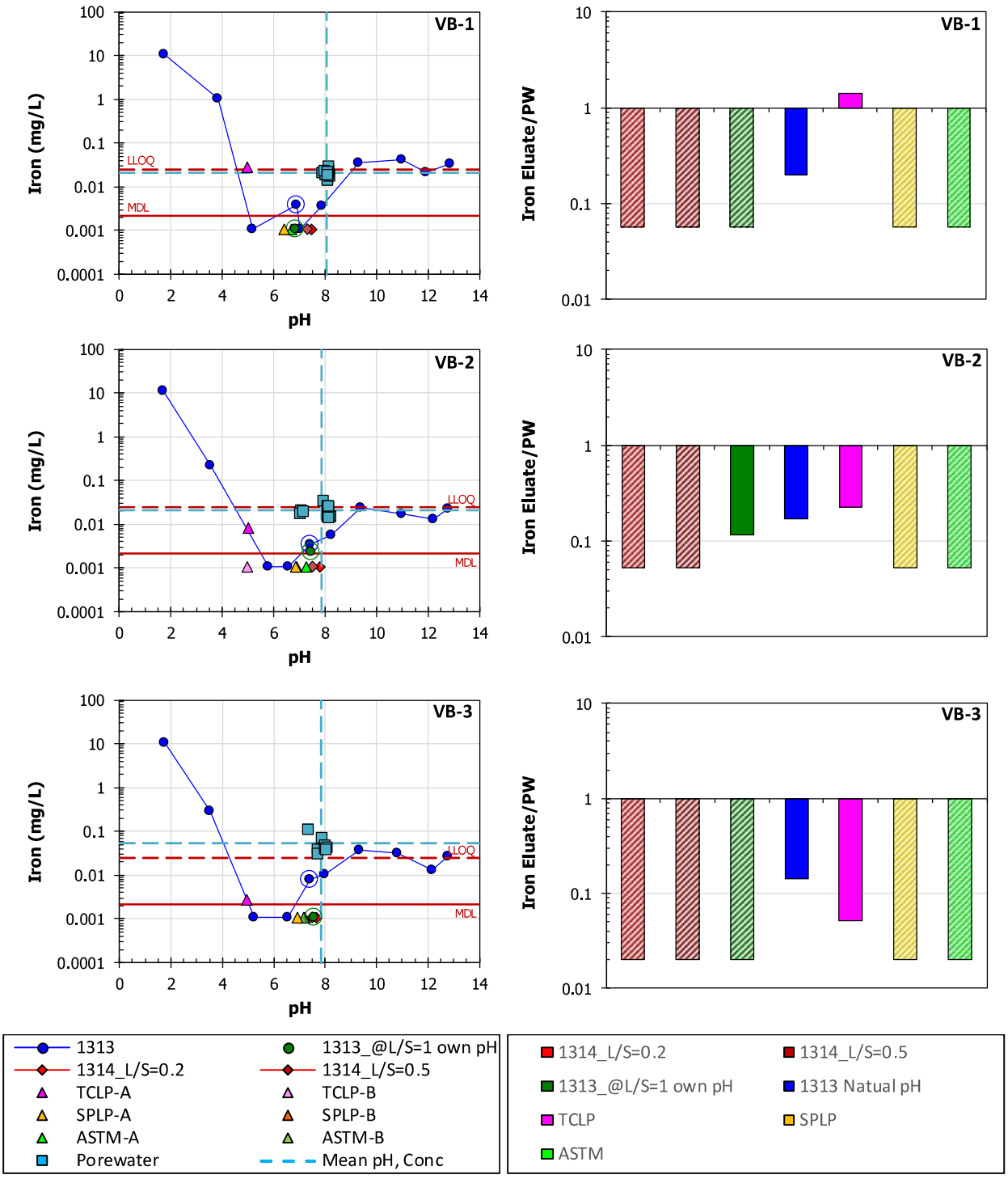


Figure G-15
Iron concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right); crosshatched ratio results indicate estimates based on at least one MDL value

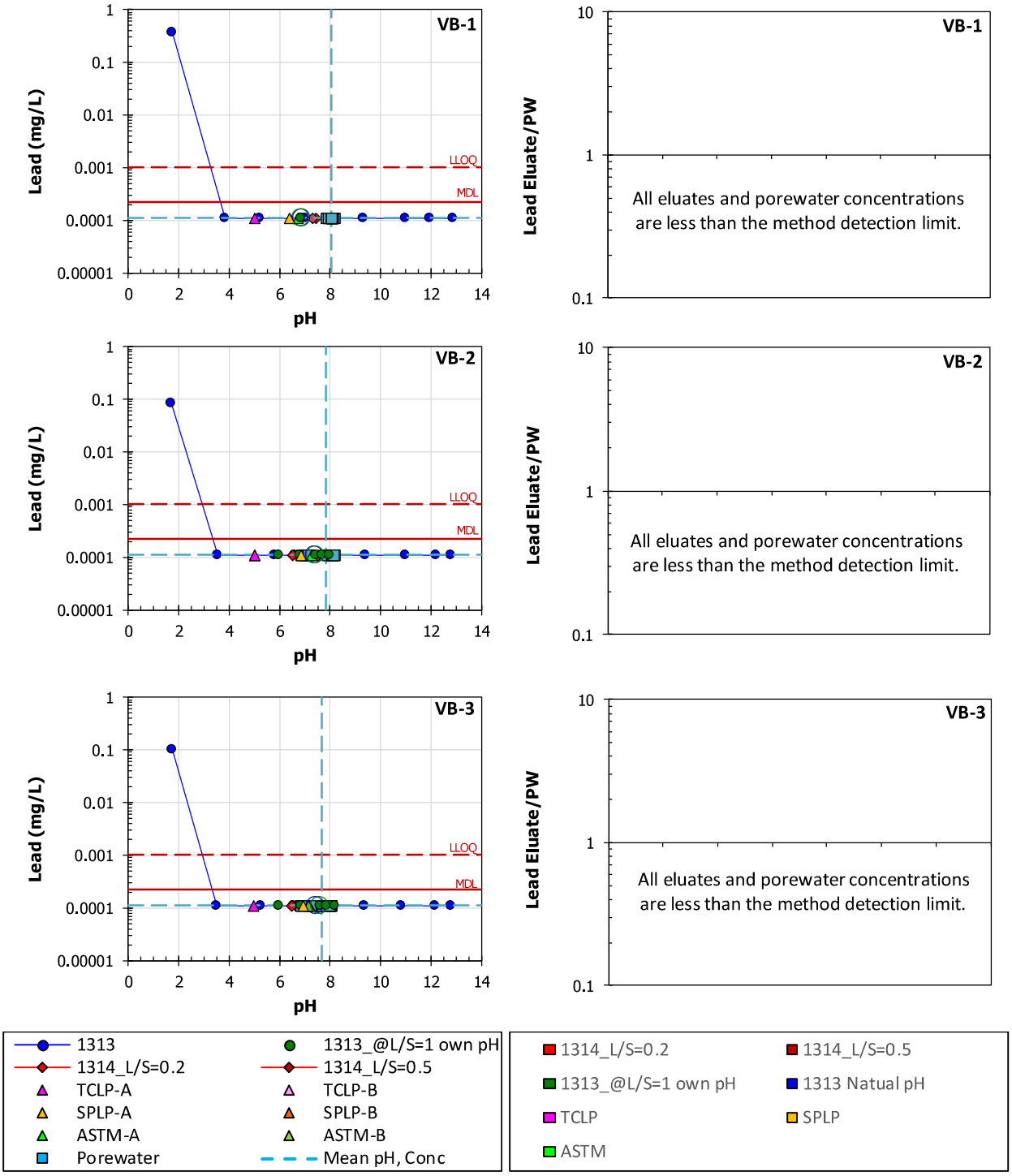


Figure G-16
Lead concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right)

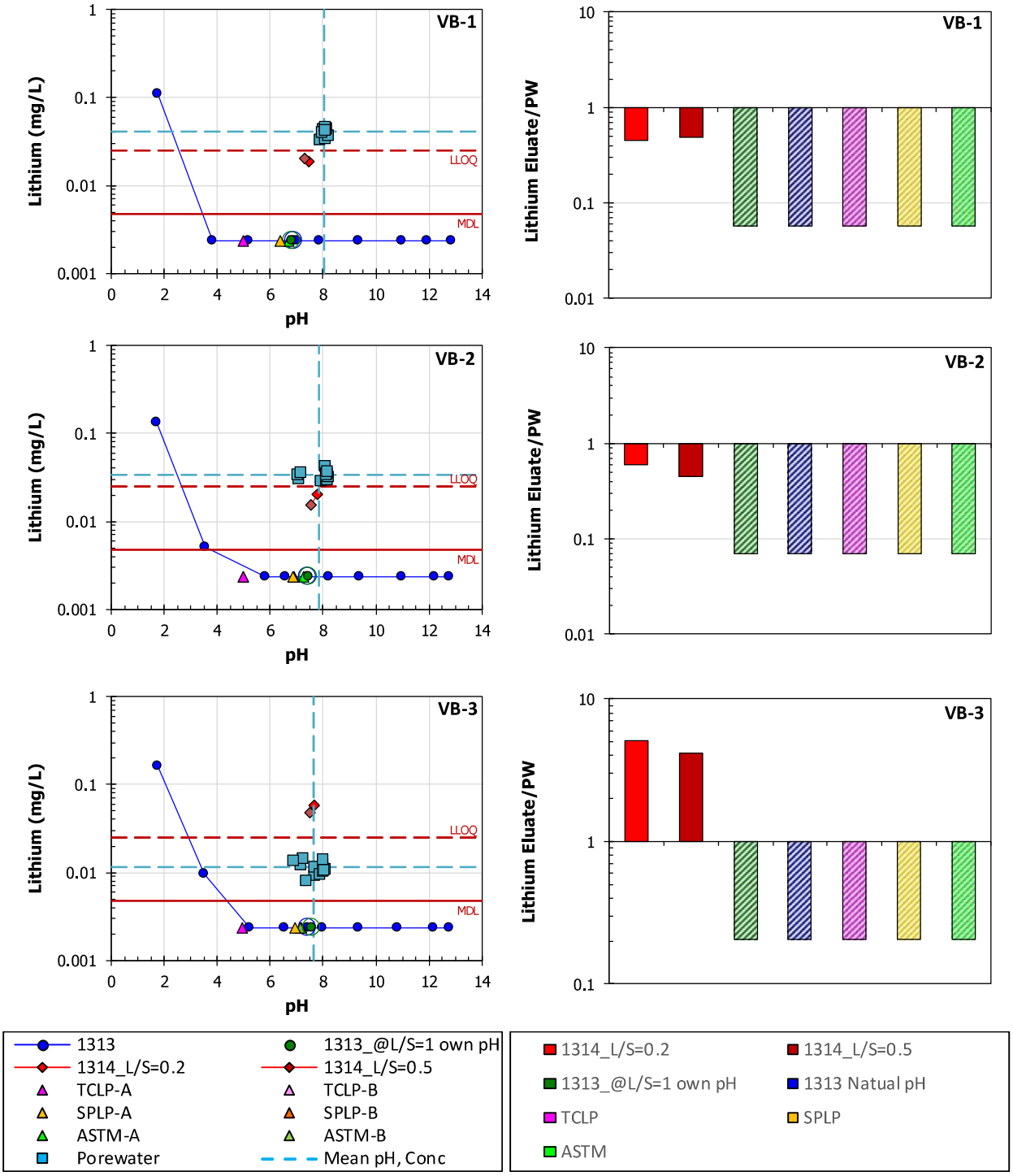


Figure G-17
Lithium concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right); crosshatched ratio results indicate estimates based on at least one MDL value

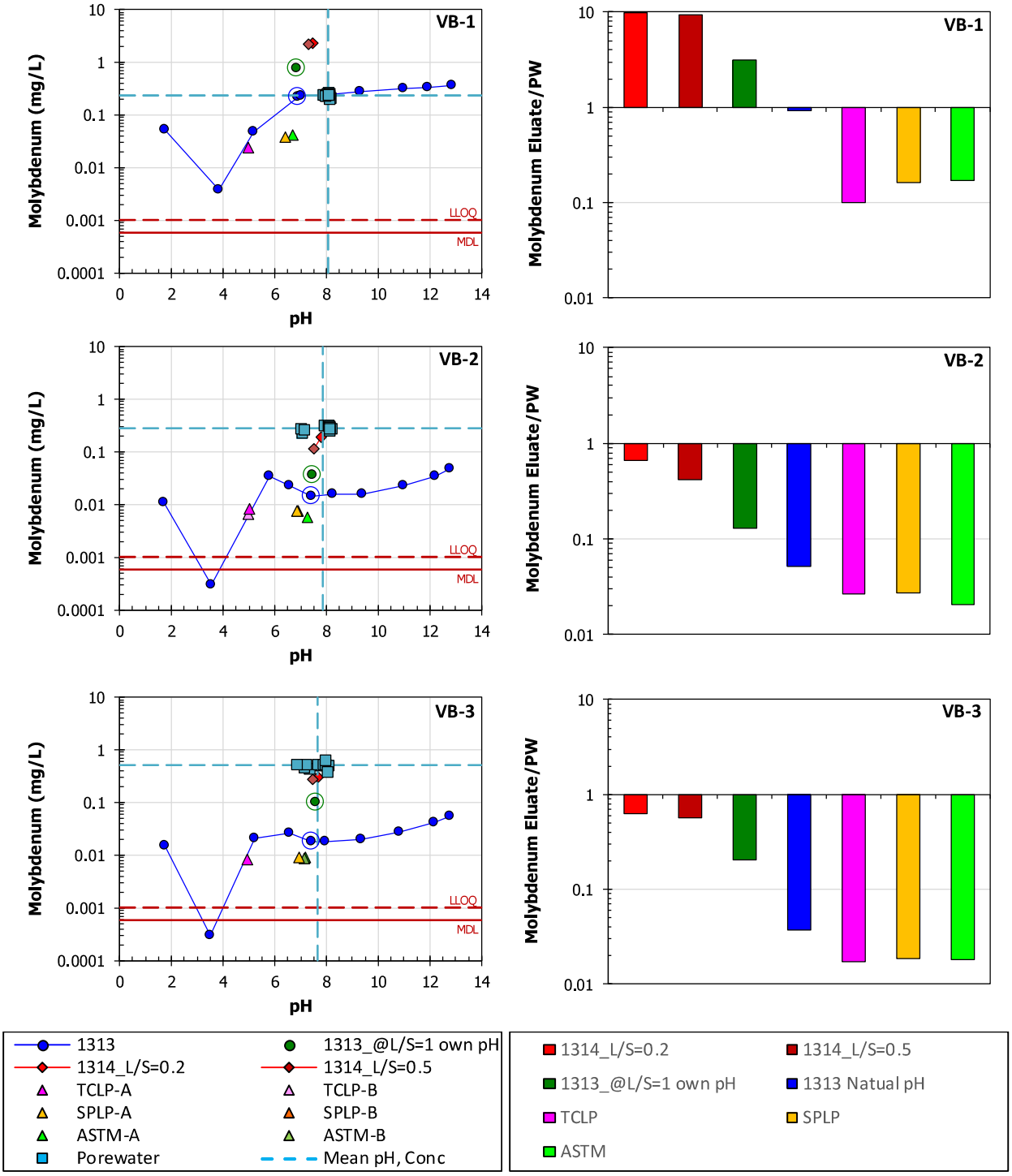


Figure G-18
Molybdenum concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right)

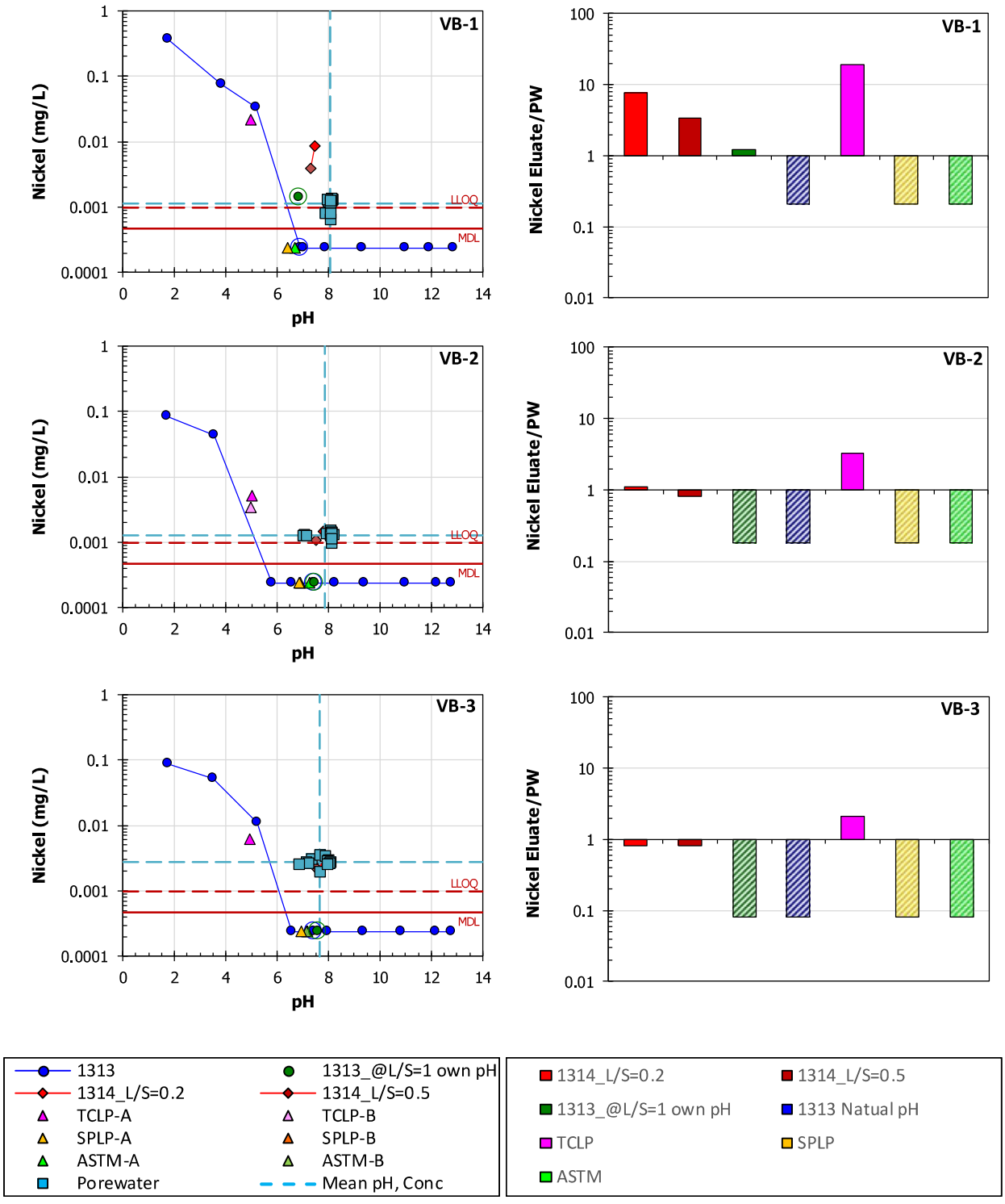


Figure G-19
Nickel concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right); crosshatched ratio results indicate estimates based on at least one MDL value

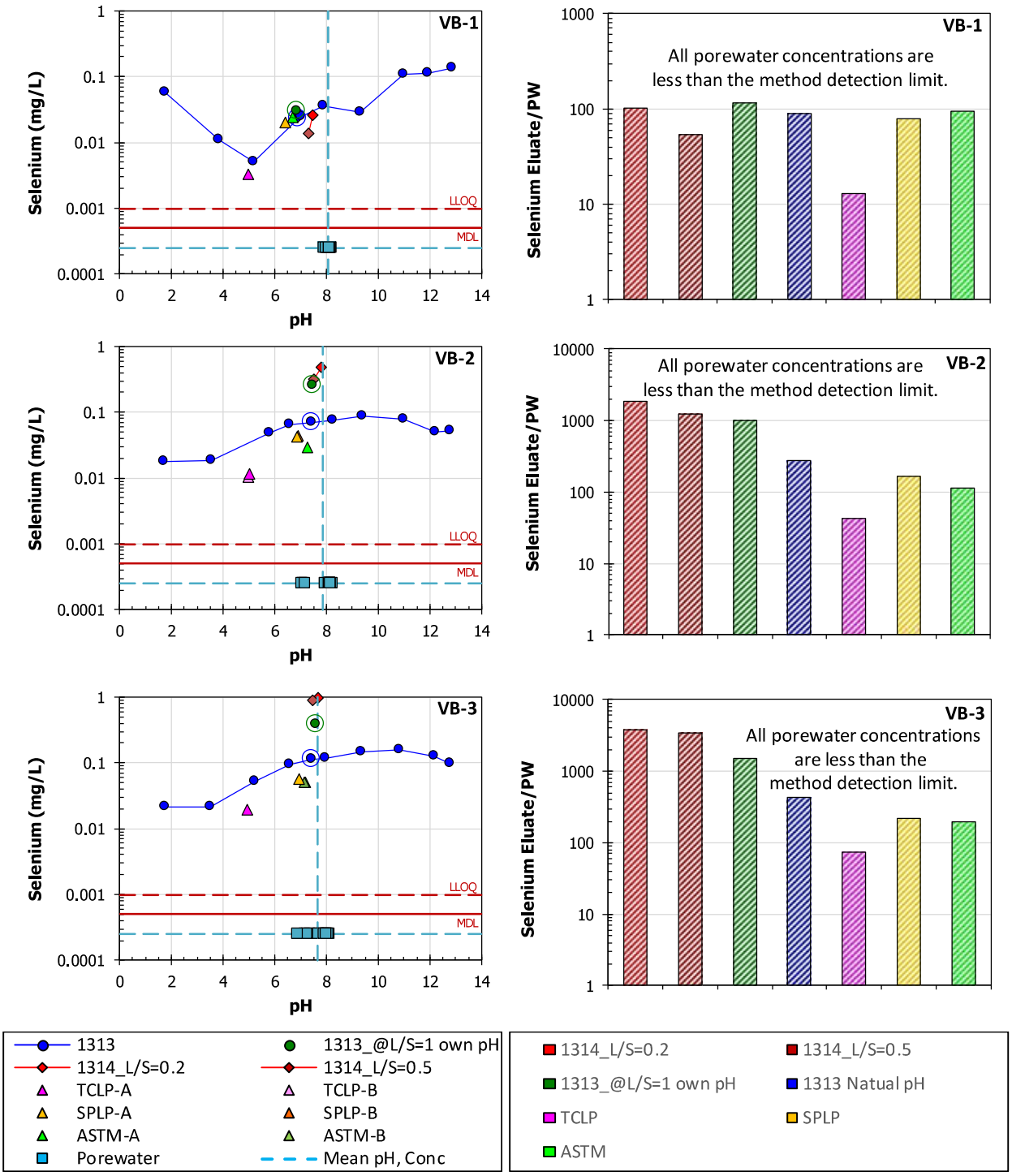


Figure G-20
Selenium concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right); crosshatched ratio results indicate estimates based on at least one MDL value

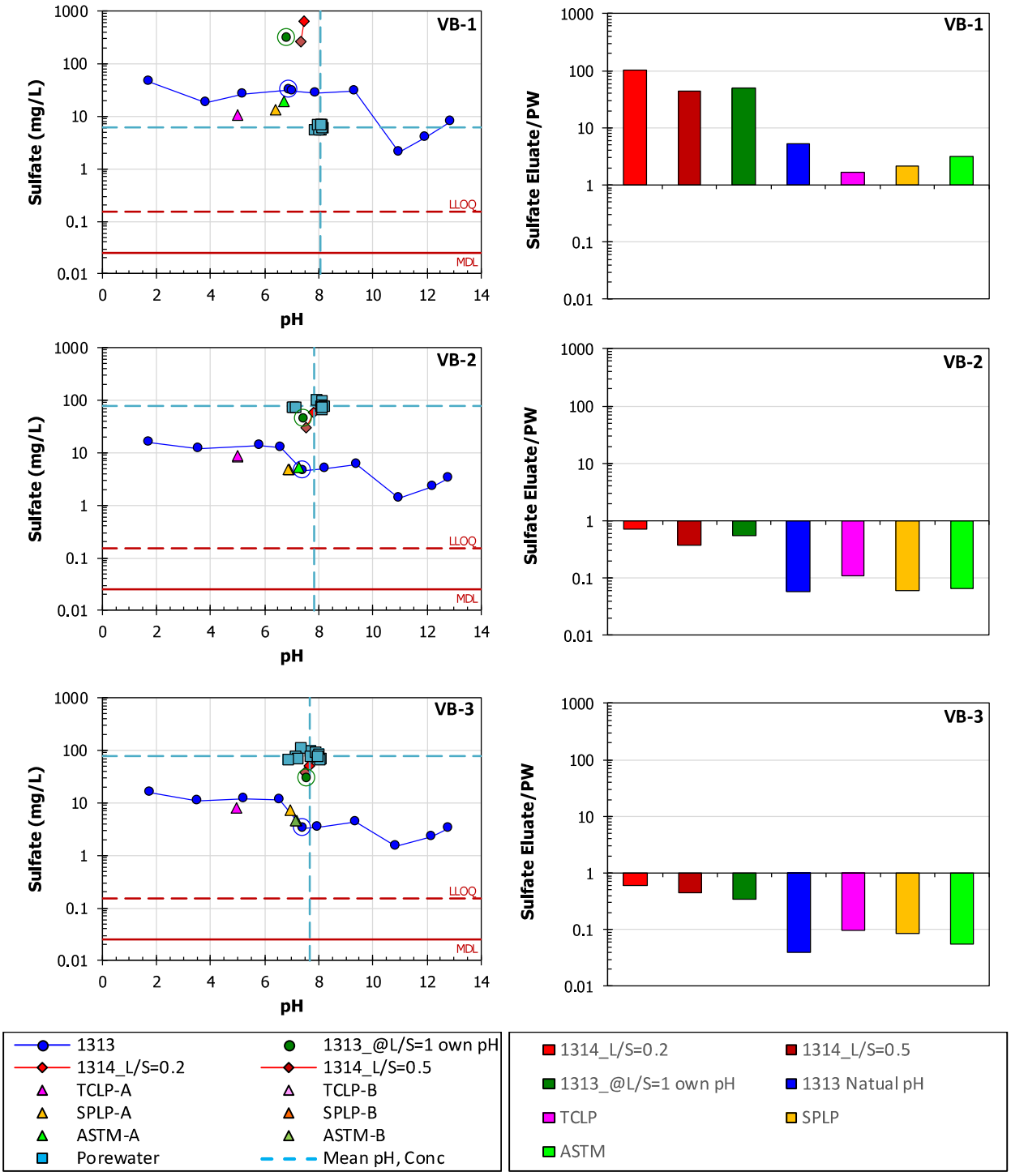


Figure G-21
Sulfate concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right)

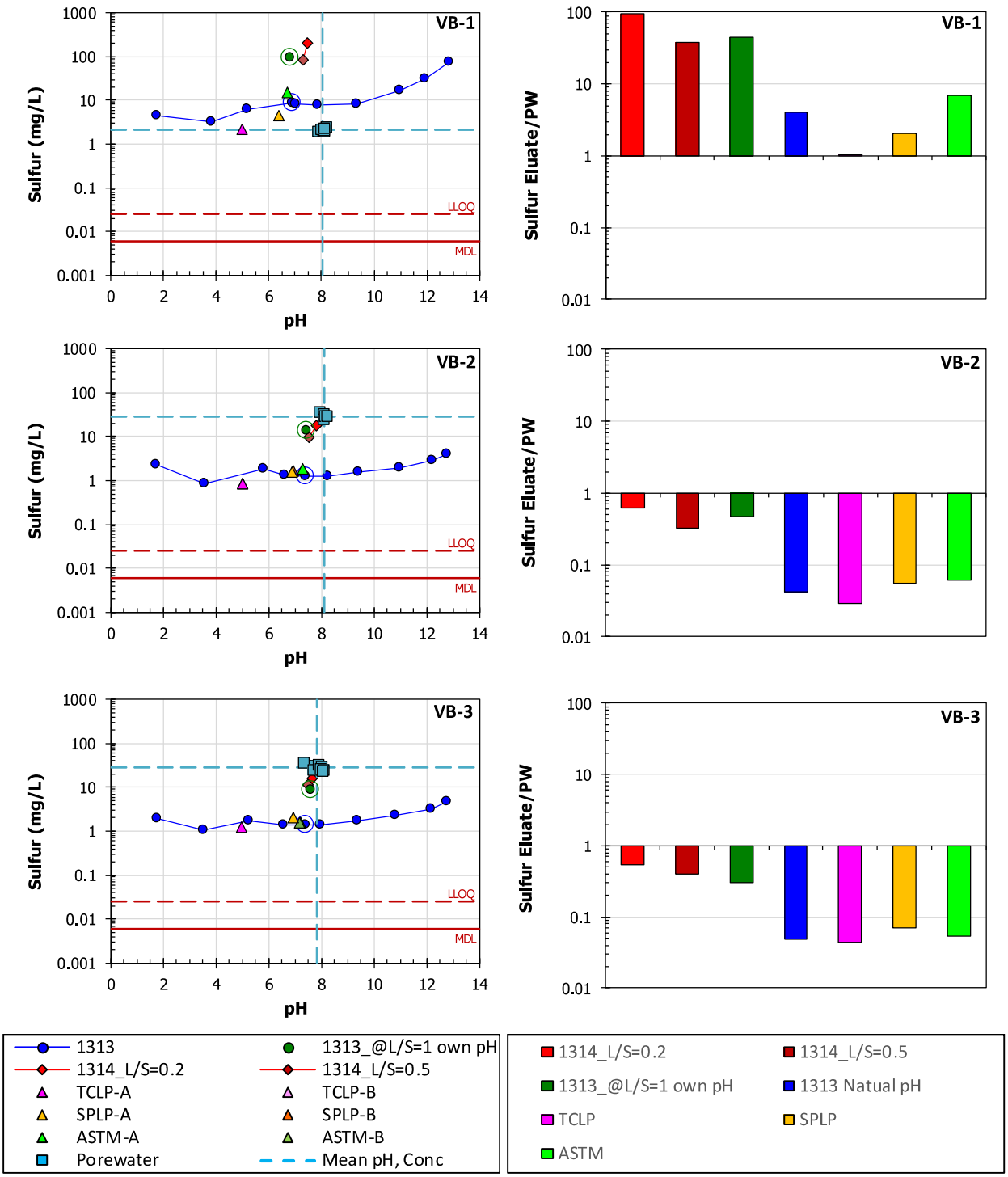


Figure G-22
Sulfur concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right)

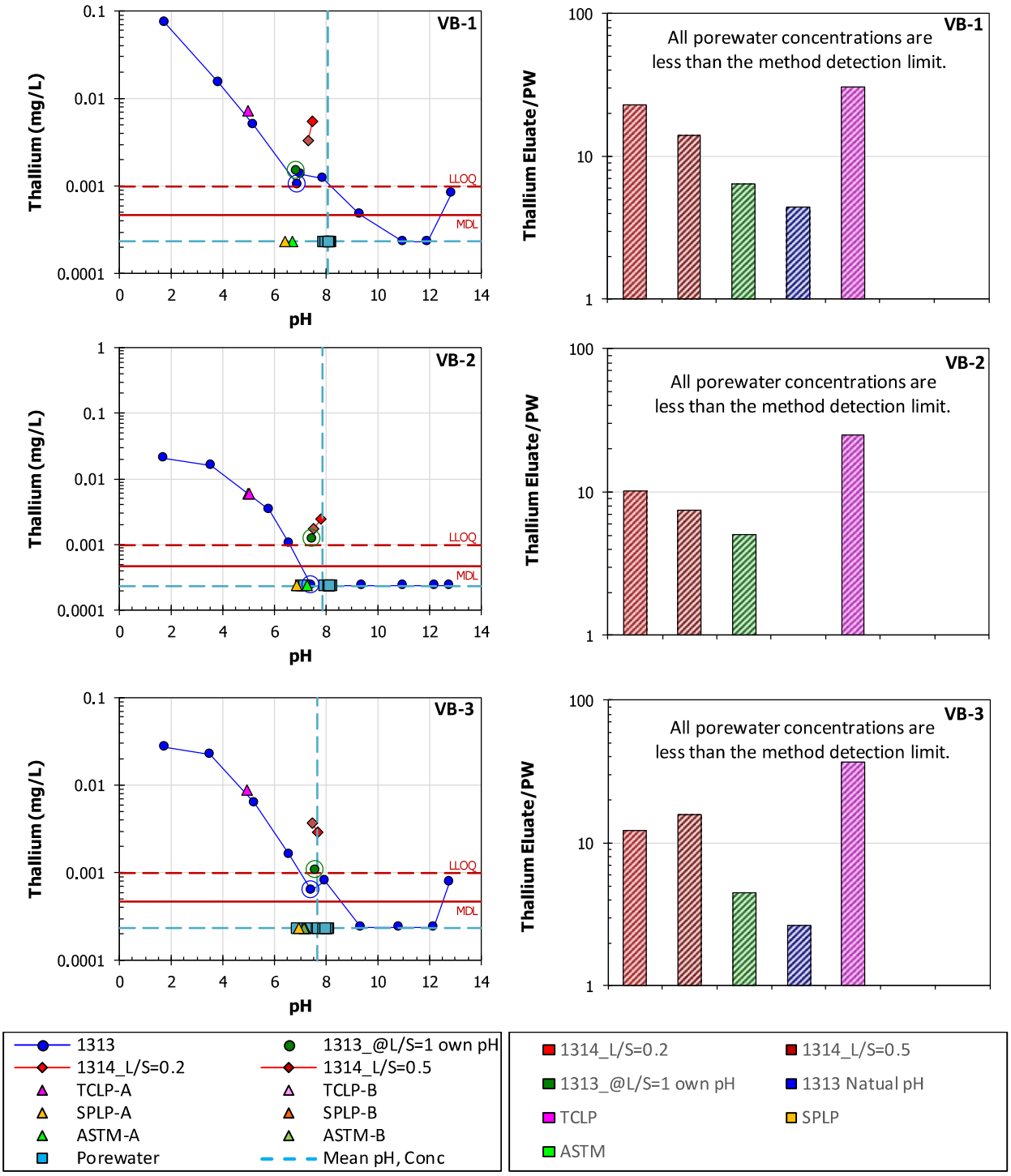


Figure G-23
Thallium concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right); crosshatched ratio results indicate estimates based on at least one MDL value

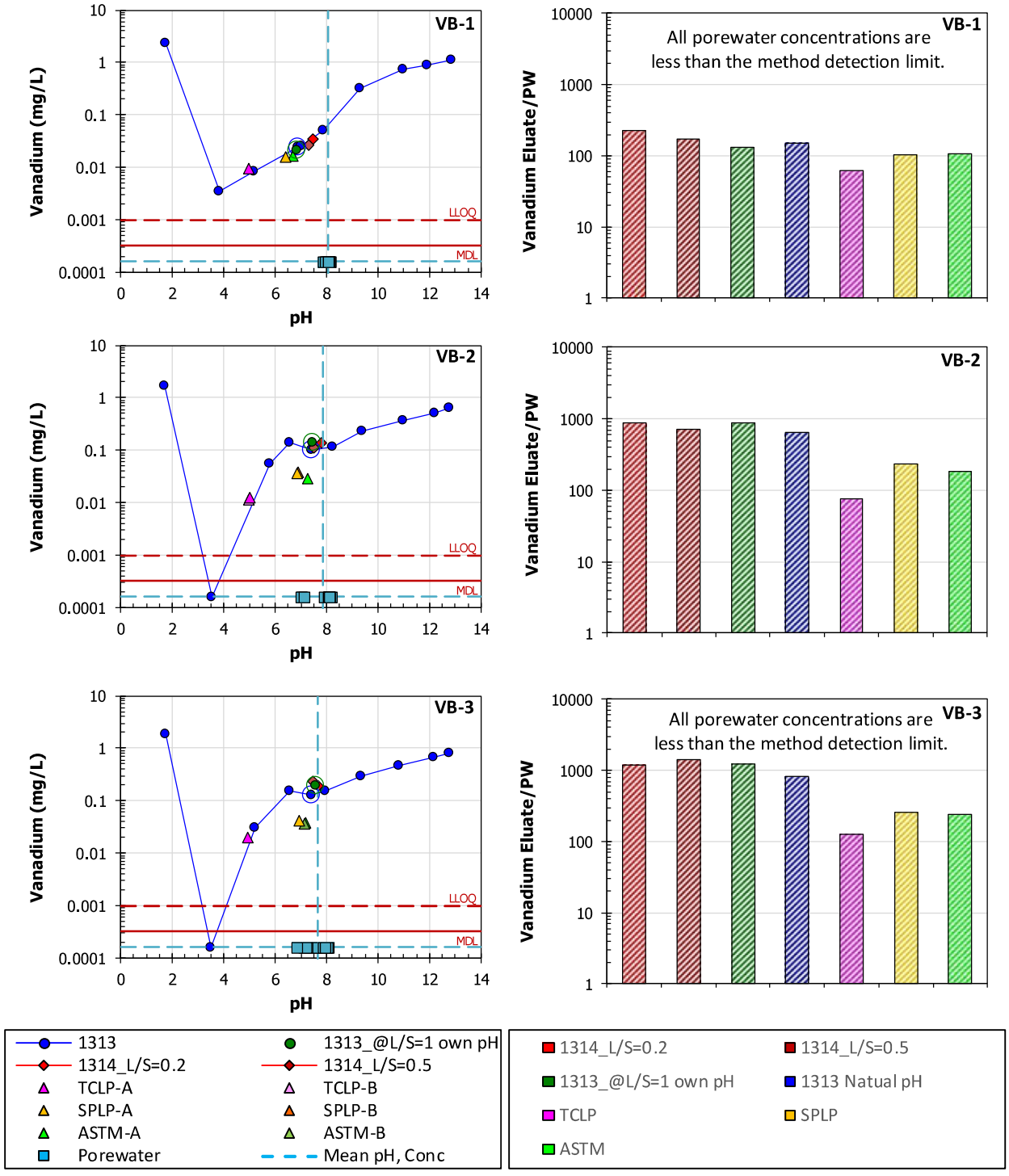


Figure G-24
Vanadium concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right); crosshatched ratio results indicate estimates based on at least one MDL value

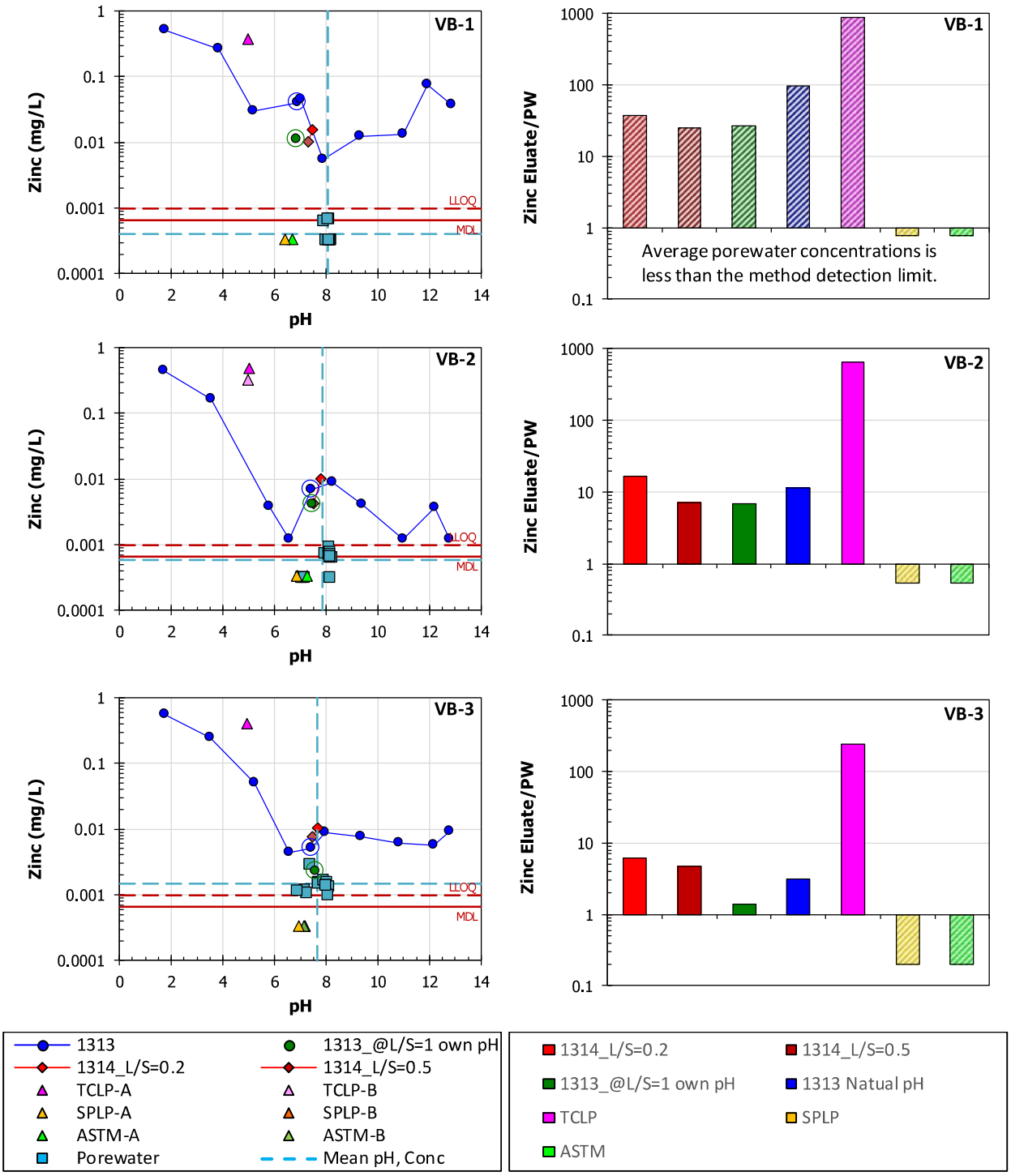


Figure G-25
Zinc concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right); crosshatched ratio results indicate estimates based on at least one MDL value

H
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Document 7

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Leaching, Geotechnical, and Hydrologic Characterization of Coal Combustion Products from an Active Coal Ash Management Unit

Plant 42197

2021 TECHNICAL REPORT

Leaching, Geotechnical, and Hydrologic Characterization of Coal Combustion Products from an Active Coal Ash Management Unit

Plant 42197

3002018780

Final Report, February 2021

EPRI Project Manager
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ABSTRACT

The appropriate selection and use of laboratory leaching tests to describe the leaching characteristics of disposed or beneficially used coal combustion products (CCPs) is an ongoing concern. Leaching tests can provide information to estimate the release of inorganic constituents for (i) comparison of the effects of environmental conditions on leaching characteristics of a material, (ii) evaluation of the effects that chemical changes over time may have on leaching, and (iii) comparison of leaching characteristics between different materials. However, the ability of leaching test results as a tool or input used to predict field porewater concentrations is highly dependent on the intended purpose of the leaching test, the applied test conditions, individual constituent geochemistry, and the ability of the test to address the principal conditions that control leaching in the field.

This report presents the results of geotechnical, hydrologic, and leaching characterization of samples of coal ash collected from an active coal ash disposal unit where dry-handled coal ash is placed over a portion of a former sluiced (i.e., wet-handled) coal ash deposit. The hydraulic conductivity of intact cores from the saturated coal ash was measured in context of the distribution of particles in the coal ash samples and the overburden pressure associated with disposal at depth within the facility. The leaching test results for LEAF tests (i.e., EPA Methods 1313 and 1314) were compared to the results for traditional tests (i.e., ASTM, TCLP, SPLP). In addition, porewater estimates derived directly from leaching tests were compared to measured porewater concentrations, and measured porewater concentrations were compared to groundwater concentrations.

Keywords
Coal ash
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PRIMARY AUDIENCE: Electric utility environmental professionals responsible for landfill and impoundment management of CCPs

SECONDARY AUDIENCE: Researchers and regulators interested in CCP leaching and chemistry

KEY RESEARCH QUESTION

The appropriate use of laboratory leaching tests to describe the leaching characteristics of disposed or beneficially used coal combustion products (CCPs) is an ongoing concern. Leaching tests can provide information to estimate the release of inorganic constituents for (i) comparison of the effects of environmental conditions on leaching characteristics of a material, (ii) evaluation of the effects that chemical changes over time may have on leaching, and (iii) comparison of leaching characteristics between different materials. However, the ability of leaching test results as a tool or input used to predict field porewater concentrations is highly dependent on the intended purpose of the leaching test, the applied test conditions, individual constituent geochemistry, and the ability of the test to address the principal conditions that control leaching in the field. The objectives of this research were (i) to determine the most appropriate approach for estimating porewater concentrations at CCP disposal facilities, and (ii) to highlight the potential connection between the CCP leaching performance of a disposal facility, based on porewater measurements or leaching tests, and sentinel monitoring of groundwater exterior to the disposed material.

RESEARCH OVERVIEW

The Electric Power Research Institute (EPRI), Vanderbilt University (VU), and University of Virginia (UVA) performed a study to develop relationships between the geochemistry of the disposed CCPs and the measured concentrations for inorganic constituents in the porewater of CCP disposal units. In addition, this study investigates the potential relationship between porewater concentrations and concentration in groundwater measured at adjacent monitoring wells.

CCP materials were collected at four locations from an active CCP disposal unit where coal ash was initially sluiced (wet-handled), and is now dry-handled. During field activities, porewater access points and subsurface gas access points were established for eight monthly sampling events. Collected materials were characterized for leaching and geotechnical/hydrologic properties. The hydraulic conductivity of intact cores from the ash deposit was measured in context of the distribution of particle sizes in the CCP samples and the overburden pressure associated with disposal at depth within the unit. The leaching test results for the Leaching Environmental Assessment Framework (LEAF) (i.e., EPA Methods 1313 and 1314) were compared to those for traditional tests (i.e., ASTM, TCLP, and SPLP). In addition, porewater estimates derived directly from leaching tests were compared to measured porewater concentrations, and measured porewater concentrations were compared to groundwater concentrations.

KEY FINDINGS

- Despite differences in coal ash placement (dry-handled ash in the upper portion and wet-handled ash in the lower portion), there was little observed variability in vertical concentration profiles. This observation suggest that infiltration moving through the unsaturated dry-handled ash (e.g., from precipitation, liquid dumps, water spray for dust management) results in migration of readily dissolved constituents from the dry-handled material into the underlying wet-handled coal ash. Downward movement of soluble constituents results in the pH and porewater composition within the saturated material being similar to the low L/S extraction fractions of composited dry material.
- The ratio of the available content to the total content shows that only a small fraction of total content of most trace constituents is leachable over a broad pH range.
- Suboxic to anoxic conditions are established at relatively shallow depths (> 5 m) below the surface of the dry-handled material.
- The high pH within the porewater of deposited material prevents development of significant microbial activity at depths greater than 5 m below the surface.
- Hydraulic conductivity of the ashes typically was within the range of 10^{-5} to 10^{-6} cm/s. Hydraulic conductivity diminished as the effective stress increased, but only modestly.
- Some parameters in the porewater (e.g., pH, temp, B, Co, Ni, and Zn) exhibited temporal variability due to factors such as seasonal changes or impacts of damage and repair of porewater access points. Other constituents (e.g., Cd, Ca, Cu, Mo, and Se) remained relatively constant within each porewater access point throughout the 8-month monitoring period. Spatial variability was observed for some constituents between porewater access points; however, no consistent pattern was observed.
- The limited data collected from downgradient monitoring wells and porewater access points suggest that porewater concentration alone is an unreliable indicator that a constituent has had an impact on elevated groundwater concentrations or for prediction of downgradient concentrations at this site.
- Traditional leaching tests, such as TCLP, SPLP, and ASTM, are poorer indicators of measured porewater concentrations than LEAF tests. Low liquid-to-solid ratio (L/S) eluates from EPA Method 1314 are better indicators than the traditional tests and EPA Method 1313 for concentrations for available content-limited constituents (e.g., B, Cd, Cl^-, Mo, Se, and SO_4^{-2}) because of the strong L/S-dependence. The data presented here showed that the traditional tests, with an L/S greater than 20 L/kg-dry, and EPA 1313 at L/S=10 L/kg-dry often under-predicted field porewater concentrations by an order of magnitude or more. These results indicate that additional information (e.g., available content and porewater L/S) is needed to provide a reasonable approximation of porewater concentrations. For constituents with solubility-controlled liquid-solid partitioning (e.g., As, Sb, and Tl), EPA 1313 tests at L/S=1 L/kg-dry provide an estimate of porewater concentrations generally within a factor of 2. The combination of pH-dependent leaching data (EPA 1313) with percolation column test results (EPA 1314) provides valuable information for geochemical modeling.

- For field environments that are oxidizing to slightly reducing, leaching test data approximated field porewater concentrations of solubility-controlled constituents within an order of magnitude. Because of the oxic to suboxic subsurface conditions at this site, sampling, laboratory handing, and testing conditions did not appear to significantly influence the redox condition of the field material. This in contrast to impoundments with highly reducing subsurface conditions, where material handling in the presence of oxygen during sampling and laboratory testing can significantly impact test results. The only constituent not well defined by any of the LEAF tests was chromium, the result for which may have been influenced by oxidization of materials during collection from a suboxic environment and testing in an oxic laboratory. The leaching results for chromium indicate that laboratory testing results for redox-sensitive elements (e.g., As, Cr, Sb, Se, V) may not directly reflect the leaching anticipated in porewater when the field environment is reducing, in part due to oxidation incurred during sampling, handling, and testing.

WHY THIS MATTERS

This research provides a unique opportunity to compare a statistically valid field porewater sample set to laboratory leaching test results on samples collected from the same location and depth interval as the porewater sampling point and provides information to guide appropriate use of these tests. It also provides information on, and comparison of, the spatial and temporal/seasonal variability in both porewater quality and laboratory leachate quality at a CCP site. Data collected during this research will inform EPRI physical and geochemical modeling of leaching within coal ash landfills and impoundments.

HOW TO APPLY RESULTS

The results of this research are site-specific, yet when considered with known differences in L/S associated with different leaching tests, and geochemical differences between the field and laboratory environment, they provide information for generalizing the best uses of different leaching tests and porewater data. Companies interested in performing similar comparisons between leaching tests and porewater will be interested in the field and laboratory methodologies described in Sections 2 and 3. Companies and stakeholders interpreting leaching test and porewater results will be interested in the results summarized in Sections 6 and 7.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- A framework using geochemical modeling and porewater data to predict long-term leaching at CCP sites is being developed under EPRI Program 242's hydrogeochemistry project. A series of reports published from 2018 through 2021 describe results of this research. These reports can be accessed by searching epri.com for "Hydrogeochemical Assessment of Long-Term Leaching Characteristics at Coal Combustion Product Sites."
- Stakeholders, including regulatory agencies, reviewing leaching test analyses may be interested in results of this research to understand the relationship between the different leaching tests, and the relationship between leaching tests and porewater within CCPs.

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PROGRAMS: Coal Combustion Products Management, P241, P242 and 2020 PS49A.

ABBREVIATIONS, ACRONYMS, AND SYMBOLS

Abbreviations and Acronyms

AMSL	above mean sea level
BGS	below ground surface
CCP(s)	coal combustion product(s)
CFR	Code of Federal Regulations
CH_4	methane gas
CO_2	carbon dioxide gas
DIW	deionized water
DIC	dissolved inorganic carbon
DO	dissolved oxygen
DOC	dissolved organic carbon
EC	electrical conductivity (mS/cm)
EPA	U.S. Environmental Protection Agency (Washington, DC)
EPRI	Electric Power Research Institute (Palo Alto, CA)
GAP(s)	gas access point(s)
HDPE	high-density polyethylene
HFO	hydrous ferric oxides
HNO_3	nitric acid
HSA	hollow-stem auger
H_2S	hydrogen sulfide gas
H_2SO_4	sulfuric acid
IC	ion chromatography
ICP	inductively coupled plasma
ICP-MS	inductively coupled plasma – mass spectrometry
ICP-OES	inductively coupled plasma – optical emission spectroscopy
ID	internal diameter
KOH	potassium hydroxide

LEAF	Leaching Environmental Assessment Framework
LLOQ(s)	lower limit(s) of quantitation
LOI	loss on ignition
LSP	liquid-solid partitioning
L/S	liquid-to-solid ratio (mL/g-dry)
MDL(s)	method detection limit(s)
NDIR	non-dispersive infrared
NH_3	ammonia gas
NIST	National Institute of Standards and Technology (Gaithersburg, MD)
NTU	nephelometric turbidity unit
OD	outer diameter
ORP	oxidation-reduction potential (mV)
O_2	oxygen gas
PAP(s)	porewater access point(s)
pe	electron concentration (-log mol e^-/L)
PSD	particle size distribution
QA/QC	quality assurance/quality control
RCRA	Resource Conservation and Recovery Act of 1986
SAP	sampling and analysis plan
SU	standard unit
TC	total carbon
UVA	University of Virginia (Charlottesville, VA)
VU	Vanderbilt University (Nashville, TN)
wt%	weight percent (percent by mass)
XRF	x-ray fluorescence
ΣL/S	cumulative liquid-to-solid ratio

Groundwater/Porewater Sample Points

VC-1	porewater access point in the CDL landfill
VC-2	porewater access point in the CDL landfill
VC-3	porewater access point in the CDL landfill
VC-4	porewater access point in the CDL landfill
209	downgradient groundwater monitoring well

931	downgradient groundwater monitoring well

Leaching/Extraction Tests

ASTM	ASTM D3987: Practice for Shake Extraction of Solid Waste with Water
1313	EPA Method 1313: Liquid-Solid Partitioning as a Function of Eluate pH Using a Parallel Batch Procedure
1314	EPA Method 1314: Liquid-Solid Partitioning as a Function of Liquid-Solid Ratio Using an Up-Flow Percolation Column Procedure
1313_L/S=1	EPA Method 1313 modified for L/S=1 mL/g-dry and abbreviated to 5 target endpoint pH values about the own pH of the material
SPLP	EPA Method 1312: Synthetic Precipitation Leaching Procedure
TCLP	EPA Method 1311: Toxicity Characteristic Leaching Procedure

Equation and Parameter Variables

AC	available content (mg/kg-dry)
$C_{1313(\max pH\ 2,9,13)}$	max concentration from EPA 1313 at pH 2, 9, or 13 (mg/kg-dry)
F	Faraday constant (23,061 cal/(V mol))
Eh	redox potential (mV)
L/S	liquid-to-solid ratio for fully saturated pores (L/kg-dry)
$(L/S)_{1313}$	liquid-to-solid ratio for EPA 1313 extractions
PW	mean porewater concentration from monthly PAP monitoring (mg/L)
R	1.987 (cal/(K mol))
s	global standard deviation of a profile parameter in all "known ash samples"
T	temperature (K)
WC	water content (%)
x	parameter measurement (e.g., pH, concentration) from the low L/S extraction test
$\bar{x}$	global mean of a profile parameter in all "known ash samples" for all boreholes
z	concentration of a constituent in a leaching test (mg/L)
%D	percentage difference between leaching and porewater concentrations
ρ_{dry}	dry unit density (kg-dry/m^3)
θ_s	saturated water content (m^3_{water}/m^3)

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1
INTRODUCTION

The appropriate use of laboratory leaching tests to describe the leaching characteristics of disposed or beneficially used coal combustion products (CCPs) is an ongoing concern. Leaching tests can provide information to estimate the release of inorganic constituents for (i) comparison of the effects of environmental conditions on leaching characteristics of a material, (ii) evaluation of the effects that chemical changes over time may have on leaching, and (iii) comparison of leaching characteristics between different materials. However, the ability of leaching test results as a tool or input used to predict field porewater concentrations is dependent on the intended purpose of the leaching test, the applied test conditions, individual constituent geochemistry, and the ability of the test to address the principal conditions that control leaching in the field. For example, traditional leaching tests, including EPA Method 1311: Toxicity Characteristic Leaching Procedures (TCLP), EPA Method 1312: Synthetic Precipitation Leaching Procedure (SPLP), and ASTM D3987: Shake Extraction of Solid Waste with Water (ASTM), provide only a snapshot of leaching performance under conditions that often deviate substantially from current or anticipated future field conditions.

In 2012, the United States Environmental Protection Agency (EPA) published four leaching methods from the Leaching Environmental Assessment Framework (LEAF) as draft methods available for use. The four methods have since been validated (Garrabrants et al., 2012a; 2012b) and incorporated as final methods into the Agency's compendium of laboratory methods for solid wastes (SW-846, 2019). The four LEAF methods are:

- EPA Method 1313: Liquid-Solid Partitioning as a Function of Eluate pH Using a Parallel Batch Procedure
- EPA Method 1314: Liquid-Solid Partitioning as a Function of Liquid-Solid Ratio Using an Up-Flow Percolation Column Procedure
- EPA Method 1315: Mass Transport Rates of Constituents in Solid Materials Using a Tank Leaching Procedure
- EPA Method 1316: Liquid-Solid Partitioning as a Function of Liquid-Solid Ratio Using a Parallel Batch Procedure

The LEAF approach differs from traditional leaching assessment methodologies in that the leaching tests are designed to provide a series of eluates characteristic of leaching behavior dependent on one or more controlling factors rather than a single eluate that is representative of field leachate from a designed scenario. The EPA has provided a guide for how LEAF tests may be incorporated into common leaching assessment practices (EPA, 2019; Garrabrants et al., 2020a; 2020b).

There remains uncertainty as to the selection of specific test methods and interpretation of testing results to represent (i) the range of pH and liquid-to-solid ratio (L/S) within a waste mass and (ii)

the current and long-term geochemical conditions of the porewater of CCP impoundments and landfills. Thus, leaching tests have been widely applied, but often without consideration of their inherent limitations for providing information suitable for evaluation of long-term leaching performance. In addition, little information is available that directly compares measured field porewater concentrations at CCP disposal sites to the results of various leaching test results.

The Electric Power Research Institute (EPRI), Vanderbilt University (VU), and University of Virginia (UVA) initiated a study to develop relationships between the geochemistry of the disposed CCPs and the measured and predicted concentrations for inorganic constituents in the porewater of CCP disposal units. In addition, this study investigates the potential relationship between porewater concentrations and the concentrations in groundwater measured at adjacent downgradient monitoring wells; although this evaluation was limited because there were no upgradient or background monitoring wells that could be used for comparison. This research was accomplished by collecting CCP materials from an active disposal unit where dry-handled coal ash overlies wet-handled ash. During field activities, subsurface materials were collected during borings, and porewater access and subsurface gas access points were installed and sampled for eight monthly monitoring events. Collected materials were characterized for leaching and geotechnical/hydrologic properties. A framework for integrating these data is being developed under a separate EPRI project. This report provides the methodology for sampling and characterization of disposed CCPs collected from an ash management unit at Plant 42197, also referred to as "CDL." The report summarizes the results of characterization CCP samples, including leaching tests and geotechnical/hydrologic data, and monitoring data with respect to groundwater and coal ash porewater collected at the facility as well as vadose-zone subsurface gas concentrations monitored within the coal ash deposit.

Project Goals and Objectives

The goals of this research are (i) to determine the most appropriate approach for estimating porewater concentrations at CCP disposal facilities, and (ii) to highlight the potential connection between the CCP leaching performance of a disposal facility and monitoring of groundwater exterior to the disposed material, based on porewater measurements and leaching tests.

The specific objectives of this project include:

- Collecting field materials to qualify the spatial variability of materials disposed in the management unit and measurements of spatial and temporal variability of porewater and pore gas composition, and to allow for characterization of leaching and geotechnical/hydrologic properties;
- Characterizing the hydraulic properties of coal ash for use in hydrologic/reactive transport modeling of CCP impoundments and landfills;
- Establishing the relationships between the characterization of leaching from bulk samples using traditional leaching tests (i.e., TCLP, SPLP, and ASTM) and LEAF pH- or L/S-dependence leaching tests with measured porewater concentrations monitored at the site;
- Assessing the ability of leaching tests (traditional or LEAF tests) to directly estimate coal ash porewater concentrations; and

- Identifying the relationship, if any, between porewater concentrations within the saturated zone of the management unit and downgradient groundwater concentrations.

Site Description

The active landfill at Plant 42197 covers a 110-acre area that was part of a larger 300-acre CCP management unit constructed around 1970 and used to collect storm water and process water from the plant. Starting in the mid-1990s, the unit was divided into sections for sluicing/consolidation of bottom ash, storage of gypsum, and landfilling of dry-handled fly and bottom ash. A 5-ft layer of bottom ash with a permeable geomembrane was laid as a capillary break over the lower wet-handled coal ash deposit to separate this older material from the landfill. Fly ash is collected in a dry state and conditioned with moisture prior to spreading and compacting the ash on the landfill. Bottom ash from the bottom ash settling area is deposited and compacted into the unit primarily to provide surface stability for transport and construction equipment. Starting in October 2019, approximately one-quarter of the surface area of the landfill was covered with 1-2 feet of topsoil and seeded for final cover.

Sampling and Testing Approach

Fieldwork for this project included: (i) advancement of boreholes into the coal ash deposit to improve the understanding of the ash stratigraphy and to obtain samples of the unsaturated and saturated ash layers; (ii) installation of porewater access points (PAPs) within the saturated ash layer and subsurface gas access points (GAPs) within the unsaturated ash; and (iii) sampling of groundwater and porewater and subsurface gas on a monthly basis.

Figure 1-1 shows the relative locations of four boreholes (VC-1, VC-2, VC-3, and VC-4) drilled into the coal ash for material sampling at the site and for installation of PAPs. Additionally, the figure indicates the locations of two groundwater monitoring wells (209 and 931) that allow for sampling of downgradient groundwater in the alluvium that extends beneath the management unit. No upgradient groundwater monitoring well was identified that would provide data on the condition of groundwater prior to reaching the disposal facility. At each of the four borehole locations, bulk ash samples were collected at approximately 10-foot intervals by split spoon sampling. This material was tested in the field and in the laboratory to evaluate the homogeneity of material in the disposal facility and to characterize the leaching properties of the collected ash. In parallel, intact ash cores were collected by tube sampling to determine geotechnical characteristics and hydraulic conductivity of the disposed ash. On a monthly basis for eight months following the completion of the initial fieldwork, samples were collected from each PAP and from the two downgradient groundwater monitoring wells to provide points of comparison to PAP porewater samples. During monthly sampling, the composition of subsurface gas was monitored.

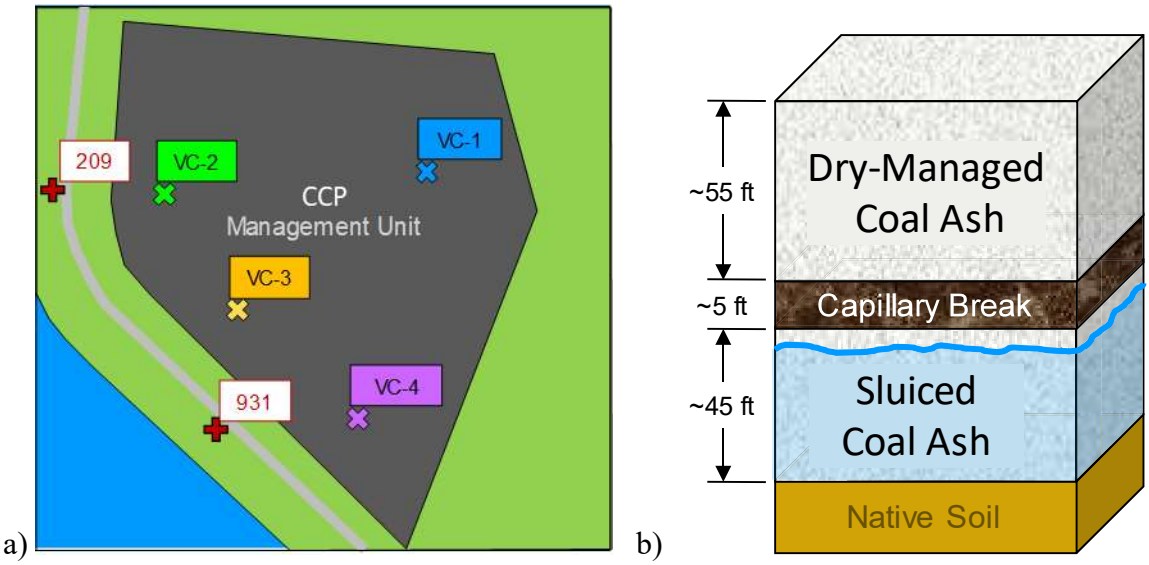

Figure 1-1
Schematic representations of the CDL management unit: a) plan view showing boreholes (VC-1 through VC-4) and groundwater monitoring wells; b) cross-section of disposal unit with approximate layer depths

Bulk samples of collected ash were shipped to the Department of Civil and Environmental Engineering at VU for characterization of leaching properties using the following tests:

- EPA Method 1313 to determine leaching behavior as a function of eluate pH at L/S values of 10 and 1 mL/g-dry,
- EPA Method 1314 to evaluate L/S-dependent leaching from a percolation column, and
- A trio of single-batch extraction tests (i.e., TCLP, SPLP, and ASTM) commonly used to estimate leaching concentrations.

The eluate pH for all leaching tests was measured and recorded so that comparisons could be made between leaching evaluations. The reported constituents include most of those found in the Code of Federal Regulations, Title 40, Section 257 (40 CFR 257), Appendix III for detection monitoring and Appendix IV for assessment monitoring, as well as several additional constituents. Although listed in 40 CFR 257 App III and IV, radium and total dissolved solids were not analyzed. Approximately 40 constituents were quantified in leachates and porewater/groundwater samples to provide a comprehensive basis for geochemical modeling of leaching test results.

The geotechnical and hydrologic properties of intact core samples were determined at the School of Engineering at UVA. Hydraulic conductivity of intact samples was measured using flexible-wall permeameters following the methods in ASTM D5084. Tests were conducted over a range of effective stresses to evaluate how hydraulic conductivity varies with packing configuration and overburden found at depth. Particle size analysis was conducted on each sample using the methods in ASTM D6913 to understand how the hydraulic conductivity varies with the composition of the ash.

2
COLLECTION OF FIELD MATERIALS

The locations of the four boreholes (VC-1, VC-2, VC-3, and VC-4) shown in Figure 1-1 were selected to be within the footprint of the saturated ash deposits, but out of the way of active ash placement. Thus, materials obtained from these boreholes were considered to capture the vertical and horizontal heterogeneity of ash materials above and below the water table. Prior to the 1990s, coal ash was sluiced from the main plant using process water to an outfall near the location of VC-1. Records indicate that the wet-handled ash is approximately 45-feet deep, covered by a 5-foot thick bottom ash capillary break, and, at the time of field sampling, approximately 55 feet of unsaturated dry-handled material consisting of fly ash mixed with bottom ash. The description of historical ash placement in this unit, and the lack of any significant known spatial variations in material types within the unit, indicated that the four locations would be representative of materials across the 110-acre disposal facility.

Initial Site Sampling

Field sampling included collection and testing of bulk ash samples from two to three consecutive split spoons interspersed with thin-wall tube sampling to obtain samples of undisturbed ash. This sequence was repeated at 10-foot intervals starting at five feet below ground surface (BGS). All drilling operations were conducted by a contracted drilling/engineering company. Boreholes were advanced using an 8.25-inch internal diameter (ID) hollow-stem auger (HSA) drilling a 13-inch diameter hole. Collected samples included small samples used in field-testing, bulk material preserved for leaching characterization at VU, and core samples for hydraulic property testing at UVA. Figure 2-1 shows a schematic of the samples collected at depth along with a summary of the number and type of samples collected at each borehole. In this figure, the depths BGS for each sample recorded during collection have been converted to elevations in feet above mean sea level (AMSL) after surveying of the PAP casings and ground elevations. An inventory of the collected samples is provided in Appendix A.

When the borehole depth reached a target level below the water table, prepacked PVC well screen was set in a sand layer for porewater recovery, and the borehole was sealed with bentonite pellets and then backfilled with bentonite chips to the target level for GAP placement. GAPs were set within a 1-foot interval of round river stone and sealed with a wetted and expanded bentonite cap (bentonite pellets) above and below the GAP layer. After the completion of initial site sampling (i.e., advancing borings and installation of monitoring points), the PAP wells were developed and readied for sampling. The finalized bore logs are maintained as electronic files available upon request.

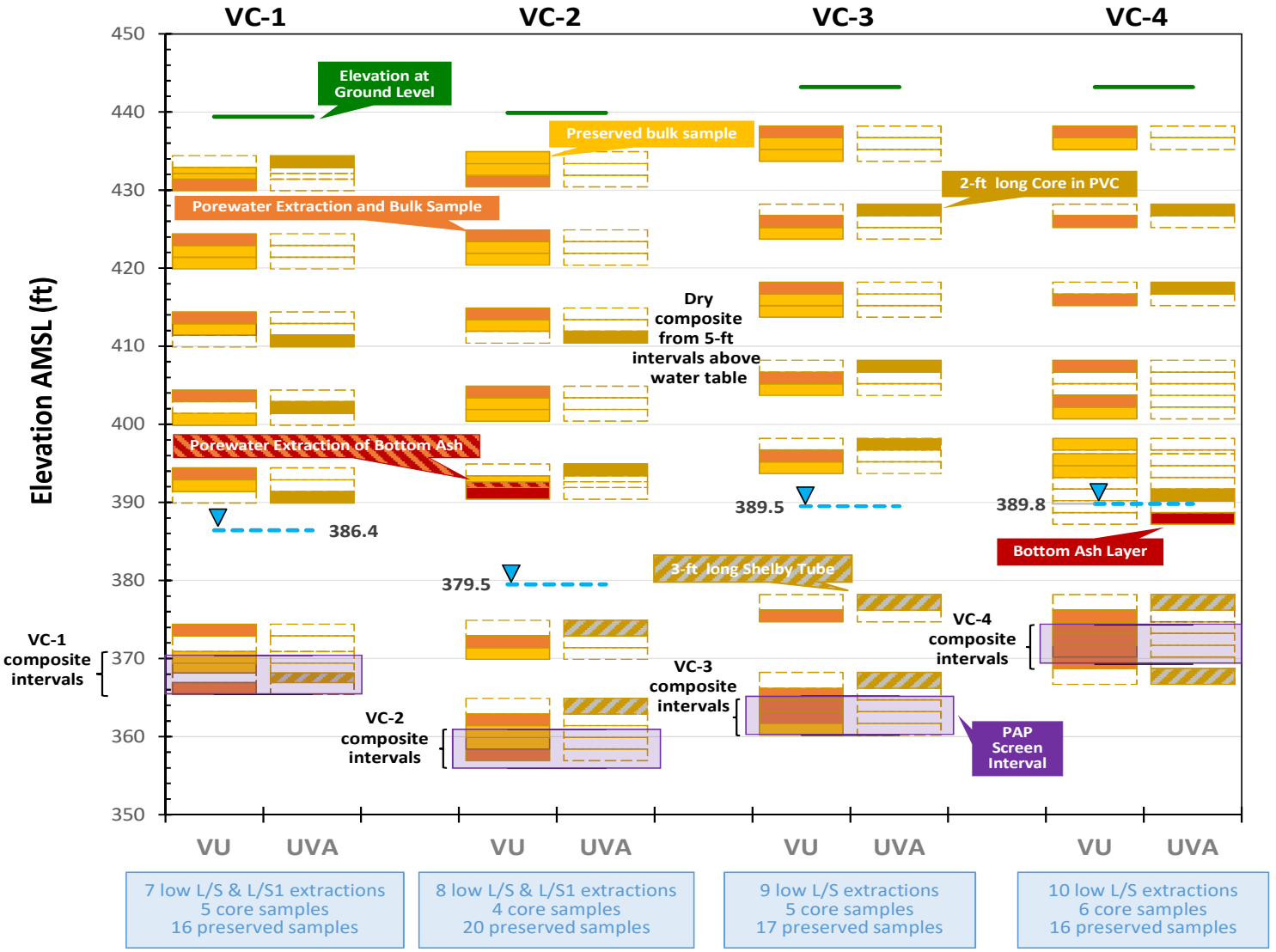

Figure 2-1
Ash sample collection and field testing for VC-1, VC-2, VC-3, and VC-4 boreholes

Bulk Material (Split Spoon Samples)

At each borehole location, 3-inch OD x 24-inch long split spoon samplers were advanced into the coal ash starting at 5 feet BGS (Figure 2-1). Upon retrieval by the drilling contractor, each split spoon sample was opened, recorded, and examined by a licensed geologist prior to release to VU for sample packaging, distribution, and laboratory analysis. VU field activities included preparation of samples for the following:

- Low L/S Field Extractions: Approximately 120 grams of ash from a split spoon was moderately packed into a 3.8-cm ID x 11-cm long acrylic cylinder equipped with a filtration stage and a 0.45-m polypropylene filtration membrane (Figure 2-2a). To ensure extractable moisture in visually dry samples, 10 to 20 mL of de-oxygenated, deionized water (DIW) was added to the cylinder prior to capping, sealing, and storage under an argon blanket (Figure 2-2b). In the laboratory, these samples were centrifuged at 1,000 revolutions-per-minute (rpm) for 5 minutes to extract the pore solution for analysis. During field operations, the porewater extraction tubes were stored in a pressure vessel that was purged with argon gas immediately after each sampling session. This unique field sampling and extraction technique was specifically designed for this project to optimize control of L/S ratio and maintenance of field reduction-oxidization (redox) conditions based on previous field sampling experience (EPRI, 2020).

a) b)

Figure 2-2
Low L/S Field Extraction: a) capped apparatus with sample and b) collected samples stored in pressure vessel prior to purging with argon

- Moisture Content Samples: In parallel to porewater testing, a known mass of ash (~20 g) was collected in a certified, pre-tared 125-mL high-density polyethylene (HDPE) bottle (Nalgene I-Chem #N311-0125) for moisture content analysis at VU.
- L/S≈1 Extractions: A known mass of ash (~150 g) from VC-1 and VC-2 split spoons was placed into a certified, pre-tared 50-mL HDPE DigiTube (SCP Science #010-500-253). The bottle was filled with de-oxygenated DIW and weighed to record the mass of added water. In the laboratory, these tubes were tumbled for 24 hours followed by filtration through 0.45-µm HDPE membrane and analysis of extracted fluid.

- Bulk Ash Collection: Remaining ash from each split spoon was vacuum-sealed in plastic bags (Figure 2-3) with oxygen scavenger packets (zero-valent iron) to preserve the redox conditions of the material. The preserved bulk material was maintained in its original cylindrical shape with the top and bottom of the core marked on the vacuum bag. Bulk samples were stored in coolers for shipment to VU.

Labels used for samples included "CDL" as a site identifier, the borehole number (VC-1, VC-2, VC-3, or VB-4), and the depth BGS from which the samples were taken. For example, the sample labeled "CDL_VC-3_16.5-18" in Figure 2-3 was collected from the split spoon at 16.5 to 18 feet BGS at borehole VC-3. For split spoons that penetrated an interface (e.g., between ash with visually different properties), the separate materials were collected as separate bulk samples in two vacuum-sealed bags. The upper portion was labeled with an "A" extension, while the lower portion was labeled with "B" at the same split spoon interval. All samples were stored at <5 °C and transported to the VU lab within 48 hours of collection, where they were stored in an environmentally controlled room at 5 °C prior to processing for leaching tests.

a)

b)

Figure 2-3
Examples of split spoon cores: a) as recovered and photo-documented in the field and b) as a vacuum-sealed bulk sample from borehole VC-3 (CDL_VC-3_16.5'-18') preserved for testing

Intact Cores (Tube Samples)

Thin-walled tube sampling of unsaturated ash was attempted, but the tubes would not penetrate the compacted unsaturated material without crumpling. Therefore, split spoon samples of unsaturated ash were extruded into 2-inch OD diameter x 24-inch long PVC tubes, maintaining the sample orientation, so that materials could be consolidated at UVA for testing. Oxygen scavenger packets were included within the tubes, and PVC endcaps were sealed to the tube with duct tape.

Below the water table, in the wet-handled ash, 3-inch OD by 36-inch long thin-wall tube samplers were pushed into the ash layer to obtain intact cores at locations targeted to collect samples near the PAP elevations. Each recovered thin-walled tube was sealed at both ends using plastic expanding inserts, capped with plastic endcaps, and sealed with duct tape. Oxygen scavenger packets were included in each thin-walled tube before sealing. Sample identification was based on the interval BGS from which the samples were recovered (e.g., the tube sampler recovered from the interval from 65 to 67 feet BGS at borehole VC-2 was labeled "CDL_VC-2_65-67").

Porewater Access Points

Once the 8.25-inch ID HSA was advanced to the target depth for placement of a PAP, a 2-inch OD Schedule 40 PVC pipe was installed through the HSA. At each well location, the contractor installed pre-packed, 5-foot screened section in agreement of the field team leads for VU, EPRI, and CDL. Each 13-inch diameter borehole was backfilled with 1 foot of clean sand before the well screen was set, and after setting the screen, was backfilled with sand to 2 feet above the top of the well screen. The sand pack was sealed with bentonite clay pellets, and bentonite chips were used to backfill the borehole to within ½ foot of the GAP depth.

Subsurface Gas Access Points

GAPs were established for monthly monitoring of subsurface gas at nominally 5-, 15-, and 50-feet BGS (50-foot deep GAPs were established at VC-1 and VC-3 only). Each GAP consisted of a ¼-inch diameter stainless steel tube set at depth within a 1-foot thick layer of round river rock and sealed from above and below with a 1-foot thick layer of expanded bentonite clay. The lower end of the GAP tubing was protected from rock, ash, and clay debris with an inverted steel cup. The stainless steel tubing was zip-tied to the PVC well and finished with a 2-way shut-off valve. The bed of river rock, nominal size of between ¾ inch and ¼ inch, ensures sufficient subsurface gas volume for measurement. A detail of the conceptual design of an installed GAP is illustrated in Figure 2-4.

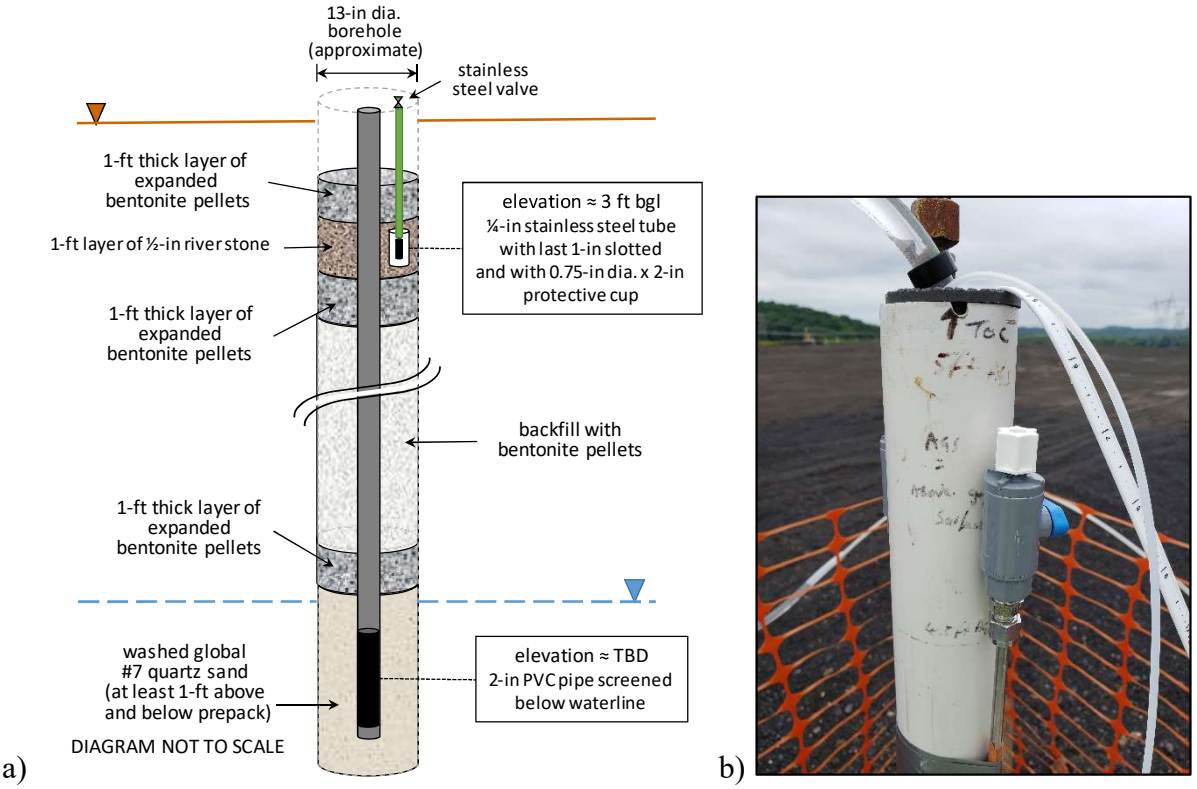

Figure 2-4
Porewater and gas access points: a) conceptual design of PAP and GAP installation and b) picture of installed PAP and GAP

Summary of Borehole and PAP/GAP Elevations

Within two weeks of field sampling, the drilling contractor installed dedicated pumps, developed the wells, and protected the borehole locations with a construction mesh. The horizontal location of the PAP and the elevations of the PVC tubing and ground surface level were surveyed by a professional land surveyor. A summary of the elevation survey results and elevation of pertinent sampling locations for the VC-1, VC-2, VC-3, and VC-4 boreholes is tabulated in Table 2-1. Figure 2-5 graphically shows the elevation relationships between the boreholes and the two downgradient monitoring wells (209 and 931), as well as porewater and groundwater elevations measured during the field study.

Table 2-1
Elevations Above Mean Sea Level (AMSL) for CDL Boreholes

	Elevations AMSL (ft)			
	VC-1	**VC-2**	**VC-3**	**VC-4**
Top of Well Casing	444.46	445.06	448.92	447.63
Ground Surface	439.4	439.9	443.2	443.2
GAP #1 (green)	434.4	435.0	438.4	438.1
GAP #2 (red)	424.4	425.0	427.7	428.3
GAP #3 (blue)	391.0	-	393.5	-
Water Level *	386.4	379.5	389.5	389.8
Top of PAP Well Screen	370.4	360.9	365.2	374.3
Bottom of PAP Well Screen	365.4	355.9	360.2	369.3

Note: (-) indicates that no GAP was placed adjacent to the water table at VC-2 or VC-4.

* water level measured on the date of well construction. Monthly water table elevations are provided in Figure 7-1.

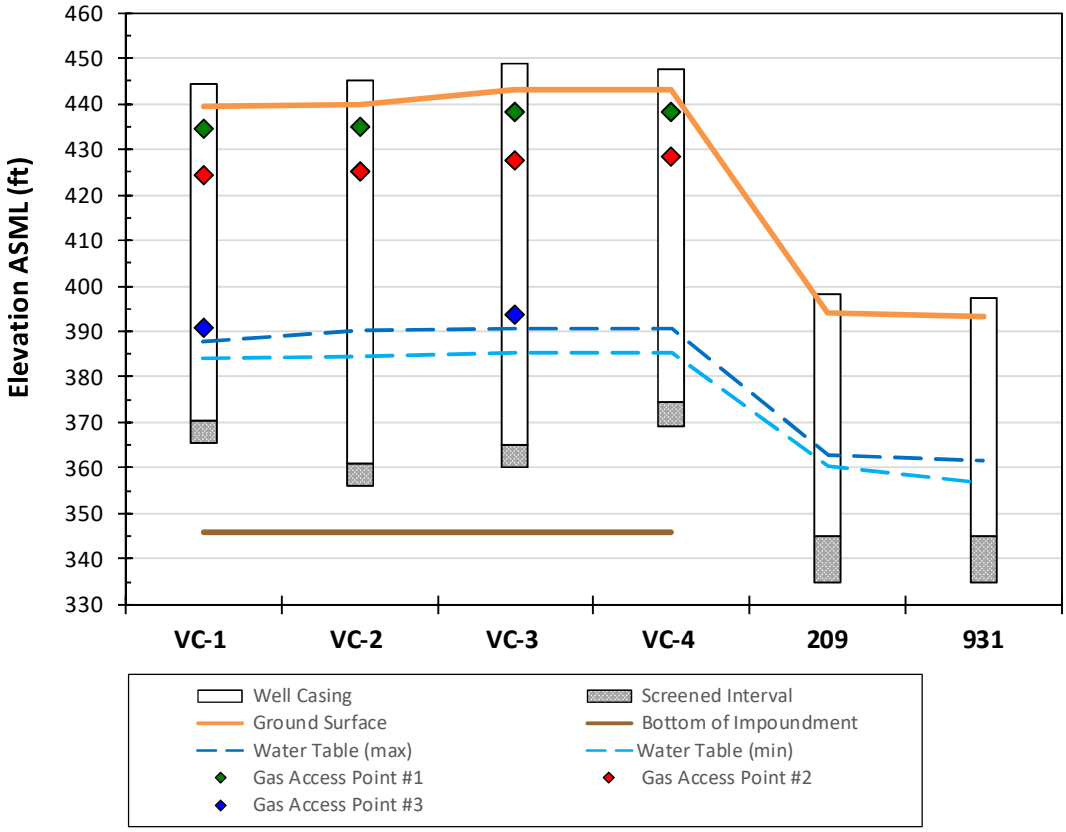

Figure 2-5
Summary of borehole and monitoring well elevations including screened intervals and GAPs. Maximum and minimum water table measurements from monthly measurements (Figure 7-1) are also shown. Figure does not depict horizontal monitoring point placement.

Monthly Field Monitoring

Porewater and subsurface gases were monitored monthly at each borehole location over eight months from June 2019 through January 2020. In addition, groundwater samples from monitoring wells 209 and 931 downgradient of the CCP landfill were collected.

Collection of Groundwater and Porewater

The relative locations of the four installed PAPs (VC-1, VC-2, VC-3, and VC-4) and the two existing groundwater sampling wells were shown previously in Figure 1-1. CDL field personnel accessed each well, stabilized the well using low-flow sampling techniques according to company standard operating procedures, and allowed VU field team access to the effluent line for collection of groundwater and porewater samples. At no time did the site owners' personnel retain custody of any samples used for this analysis.

The sampling flow rates for porewater and groundwater wells were approximately 150 mL/min and 50 mL/min, respectively. At 5-minute intervals, the pH, dissolved oxygen (DO), electrical conductivity (EC), oxidation-reduction potential (ORP), temperature, and turbidity of the sampled water were monitored using a flow-through multi-parameter sonde and separate

turbidity meter while water level was measured with a portable electronic water level meter. The criteria used to determine well stability were (i) turbidity less than 10 NTUs and (ii) pH stable within 0.1 standard unit over three consecutive 5-minute readings.

Groundwater and porewater samples were collected in 50-mL Digitubes including duplicate samples collected for anion analysis via ion chromatograph (IC) and duplicate samples collected for metals and other cation analysis via inductively coupled plasma (ICP) techniques (see *Chemical Analysis of Eluates, Groundwater, and Porewater* in Section 3 for details). Samples for ICP analysis were preserved in the field by addition of 1.5 mL of Tracemetal® grade nitric acid (3% total acid addition) using a 100-1000 µL Oxford Benchmate manual pipette and disposable tips. A set of four samples was collected unfiltered followed by a set of samples passed through a QuickFilter 609 cm^2, 0.45-mm inline filter. In total, eight 50-mL Digitubes were collected at each sampling location. All liquid samples were stored in a cooler of ice with an Elitech RC-5 USB temperature data logger to record the temperature within the cooler. Samples were transported by the field team to VU for immediate storage at 5 ºC prior to analysis. Analysis of the sample results showed negligible differences between the filtered and unfiltered samples, and the results from the unfiltered samples are used in the following analysis.

Subsurface Gas Monitoring

A description of the monitoring process for subsurface gas and a picture of gas monitoring apparatus are provided in Section 3.

3
MATERIALS AND METHODS

The following sections include brief descriptions of the test methods and analytical methods used in this study. Also described are the quality assurance/quality control (QA/QC) samples and criteria for each analytical method.

Collected Materials

Materials recovered during initial sample collection included bulk samples from split spoons and intact cores contained in PVC tubes or thin-wall stainless steel tubes. Laboratory processing of bulk material for leaching tests included (i) homogenization within each split spoon sample, (ii) compositing saturated ash samples from each borehole from materials collected near the screening level, and (iii) compositing unsaturated ash into one sample across the disposal facility.

Homogenization of Bulk Samples

Each recovered split spoon sample was crushed with a rolling pin and homogenized by hand through the plastic bag until the contents were well mixed. From this homogenized split spoon material, composite samples were created.

Material Composites

For each of four boreholes (VC-1, VC-2, VC-3, and VC-4), saturated ash homogenized from split spoons collected at the PAP screen elevation was used to develop a composite test material representative of the bulk ash deposited at the PAP. Table 3-1 shows the specific homogenized split spoon materials used to create each composite sample for the four boreholes. In addition, a fifth composite material of unsaturated ash was created by blending homogenized material above the water table from all boreholes collected; however, the intervals used in this composite, hereafter referred to as "Dry," varied with the intervals of unsaturated ash at each borehole.[1]

The composite material was created by mixing equal dry mass equivalents (i.e., the mass of "as received" material that equates to a prescribed mass of dry material) from each homogenized split spoon in a plastic bag under a N_2-purged environment in a Coy chamber (an anoxic glove box) to minimize air exposure. The composite material was homogenized by hand through the plastic bag until well mixed. This composited sample was used for total content analysis and characterization using LEAF leaching tests and traditional leaching tests (i.e., ASTM, TCLP, and SPLP).

[1] In other words, five composites are discussed in Section 4 – composites VC-1, VC-2, VC-3, and VC-4, which represent the lower wet-handled coal ash deposit and have corresponding PAP porewater samples, and the composite referred to as Dry, which represents the upper dry-managed coal ash deposit and does not have corresponding porewater samples.

Table 3-1
Below Ground Surface (BGS) and Top Elevations Above Mean Sea Level (AMSL) of Homogenized Split Spoon Intervals Used to Create Borehole Composites (VC-1, VC-2, VC-3, and VC-4)

VC-1		VC-2		VC-3		VC-4	
Interval BGS (ft)	Elevation AMSL (ft)	Interval BGS (ft)	Elevation AMSL (ft)	Interval BGS (ft)	Elevation AMSL (ft)	Interval BGS (ft)	Elevation AMSL (ft)
PAP Screen	367.9	PAP Screen	358.4	PAP Screen	362.7	PAP Screen	371.8
68.5-70.0	370.9	78.5-80.0	361.4	78.5-80.0	364.7	68.5-70.0	374.7
70.0-72.5	369.4	80.0-81.5	359.9	80.0-81.5	363.2	70.0-71.5	373.2
72.5-74.0	366.9	81.5-83.0	358.4	81.5-83.0	361.7	71.5-73.0	371.7
-	-	-	-	-	-	73.0-74.5	370.2

Notes: PAP Screen elevation to middle of 5-ft screen.
All elevations shown at the top of the 2-ft split spoon sample.

Material Properties

Total Content by EPA Method 3052

The total elemental content of composite samples was determined by acid digestion following EPA Method 3052, with subsequent analysis of the digestate by Eurofins TestAmerica (Knoxville, TN). According to the Method 3052, a solid sample of up to 0.5 g (wet) is digested in 9 mL of nitric acid and 3 mL of hydrofluoric acid for 15 minutes in a microwave to accelerate the digestion reactions. Additional acid and reagent combinations, including hydrochloric acid and hydrogen peroxide, are added to ensure that the solid is dissolved. The microwave temperature profile includes reaching 180±5 ºC in approximately less than 5.5 minutes and remaining at 180±5 ºC for 9.5 minutes for the completion of specific reactions. After cooling, the vessel contents were centrifuged and decanted. The small volume of remaining digestate was diluted to a volume of 100 mL and chemically analyzed. Inductively coupled plasma–optical emission spectrometry (ICP-OES) following EPA Method 6010A was used to determine digestate concentrations for 26 constituents (i.e., Al, Sb, As, Ba, Be, Cd, Ca, Cr, Co, Cu, Fe, Pb, Li, Mg, Mn, Hg, Mo, Ni, K, Se, Ag, Na, Sr, Tl, V, and Zn). Boron was not included in this total content analysis because metaborate is added to the digestion process for Method 3052. Mercury concentrations in the digestate were measured by using cold vapor atomic absorption following EPA Method 7470A. The total content (mg/kg) is calculated by multiplying the concentration measured in the digestate (mg/L) by the L/S of the extraction procedure (L/kg). For this study, the resultant total content is effectively on a dry mass basis (mg/kg-dry) because the material submitted to the laboratory for testing was oven-dried prior to submission to the laboratory.

X-Ray Fluorescence Analysis

The elemental composition of coal ash samples was determined at UVA using x-ray fluorescence (XRF) quantitative analysis on an Epsilon 3X energy-dispersive XRF spectrometer (PANalytical, Malvern, UK) with a silver anode X-ray tube and 50-micron beryllium window.

Five-gram subsamples of coal ash were taken from the undisturbed core samples, air-dried for 24 hours at room temperature, and ground by hand to less than 0.075 mm using an agate mortar and pestle. For analysis, ground samples were packed into an 18-mL sample cup (28 mm ID x 30 mm). Each subsample was analyzed in duplicate following ASTM D8064 (2016) for the XRF analytical method of silicate rocks.

Loss on Ignition

Loss on ignition (LOI) was measured at UVA for subsamples of undisturbed coal ash material to quantify total organic matter content. LOI was conducted in accordance with ASTM D2974-14 by heating a pre-weighed sample at 550 °C using a Lindberg/Blue M 1200 °C Box Furnace (ThermoFisher Scientific, Waltham, MA).

Moisture Content

As part of the leaching test characterization using the LEAF methods, the moisture content of each study material was determined following the ASTM D2216 (2010). Moisture content on a dry mass basis was calculated as the difference in the mass of a "wet" subsample compared to the sample after oven drying to constant mass at 105±5 °C. The solids content is defined as the mass of solid material in an "as-tested" or "wet" subsample, measured on a "wet" basis. The determination of moisture content and solids content provides uniform bases for reporting of total content and leaching behavior results, allowing for comparison between moist and dry materials.

Porosity or Saturated Volumetric Water Content

Dry density and porosity of each material were determined at UVA using weight-volume computations, following the procedure in ASTM D7263 (2018). Under saturated conditions (i.e., when all voids are filled with water), the saturated volumetric water content equals the porosity.

Particle Size Distribution

Particle size distribution (PSD) of each CCP sample was determined at UVA by a combination of mechanical analysis following ASTM D6913-17 and sedimentation analysis following ASTM D7928-17. For mechanical analysis, a 100-g sample was oven-dried at 110±5 °C and passed through a series of US standard sieves: No. 10 (2 mm), No. 20 (0.85 mm), No. 60 (0.25 mm), No. 100 (0.15 mm), and No. 200 (0.075 mm). The fraction of the 100-g mass retained on each sieve was measured gravimetrically. Particle size distribution of the fraction coarser than the No. 200 sieve (0.075 mm) was calculated as the weight of solid retained on each sieve.

For sedimentation analysis, 50 g of dry solid that had passed the No. 200 (0.075 mm) sieve was soaked in 4% sodium metaphosphate, $(NaPO_3)_6$, solution for 12 hours and then transferred to a 1-L graduated cylinder. The graduated cylinder was capped, then agitated end-over-end for 60 seconds, and then settling of particles was monitored using a hydrometer. Stokes law was used to compute the PSD from the hydrometer data for the fraction of particles finer than the No. 200 sieve.

Saturated Hydraulic Conductivity

Hydraulic conductivity tests were conducted in flexible-wall permeameters following the methods in ASTM D5084-16. Sections of undisturbed coal ash were extruded from thin-wall sampling tubes (Figure 3-1) and cut into 76-mm long specimens. Non-woven geotextile disks and porous stones were placed on both ends of each coal ash specimen (Figure 3-2a) to ensure uniform flow distribution and to retain particles. Specimens were wrapped in a latex membrane and placed into a flexible-wall permeameter (Figure 3-2b).

In lieu of the more traditional tap water or 0.01 M $CaCl_2$ solution suggested in ASTM D5084, DIW was used as the permeant solution to ensure that the water entering the specimen had no ionic species that might alter the hydraulic conductivity or the leachable constituents in the coal ash. Effluent from the permeameter was collected following the procedure in ASTM D7100-11. Effluent samples were collected from the tests, stored in Teflon® sample bottles with minimal headspace, and shipped under chain of custody to VU for chemical analysis.

The falling headwater-constant tailwater method was used with an average hydraulic gradient of 15. No backpressure was applied to simulate field conditions and to minimize alterations in geochemistry. All tests were conducted at an initial effective stress of 20 kPa and continued until the hydraulic conductivity reached hydraulic equilibrium as defined in ASTM D5084 (steady hydraulic conductivity, incremental outflow divided by steady inflow within 1.0±0.25). At the conclusion of the test, weight-volume calculations were conducted to confirm that all specimens were saturated during testing.

After testing at 20 kPa was complete, three specimens, representing higher, lower, and intermediate hydraulic conductivity, were consolidated to an effective stress of 100 kPa and permeated again until hydraulic equilibrium was established (steady hydraulic conductivity, steady flow ratio 1.0±0.25). This procedure was repeated at effective stresses of 250, 400, and 500 kPa. The initial stress (20 kPa) was selected to replicate the stress condition of shallow coal ash in the basin. The higher stresses represent conditions at greater depths. Effluent samples from the higher-stress tests were not collected for chemical analysis.

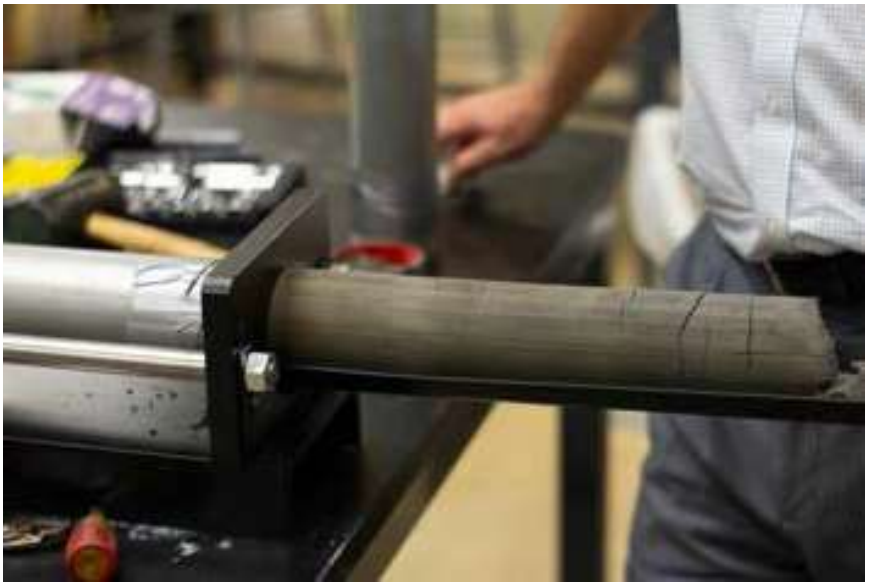

Figure 3-1
Extrusion of undisturbed coal ash sample from a thin-wall sampling tube conducted at UVA

a) b)

Figure 3-2
Hydraulic conductivity test specimen and permeameter setup: a) test specimen (brown, gray cylinder) between two geotextile filter disks (thin black disks) and two porous stones (blue-gray disk on each end); b) test specimen installed in flexible wall permeameter

Traditional Extraction Tests

EPA Method 1311 – Toxicity Characteristic Leaching Procedure

EPA Method 1311, or TCLP, is a single-point batch leaching test used to determine the toxicity characteristic of a material and the disposal options for a material under the Resource

Conservation and Recovery Act of 1986 (RCRA). TCLP was designed to simulate eluate concentrations for a plausible mismanagement scenario where hazardous waste is disposed in a municipal solid waste landfill. Thus, a solution of acetic acid in DIW is the extraction fluid to represent the primary acidity in municipal solid waste landfill leachate. Based on a pretest of the buffering capacity of test sample for acetic acid, either Extraction Fluid #1 (dilute acetic acid with a NaOH buffer at a pH of 4.93±0.05) or Extraction Fluid #2 (dilute acetic acid at a pH of 2.88±0.05) is selected for the test. Since the method allows for analysis of samples with filterable water (e.g., slurries), the specified L/S of 20 mL/g is based on the mass of moist sample recovered from pressure filtration at 15 lb/in^2 (103 kPa). The filtrate from pressure filtration was preserved and chemically analyzed in parallel to TCLP extracts. Therefore, the final dry-basis extraction L/S is typically greater than 20 mL/g-dry when filterable water is considered.

For TCLP analysis, 100 g of solid was pressure-filtered and the moist solid was mixed with Extraction Fluid #1 at an L/S of 20 mL/g-dry. The mixture was tumbled at 28±2 rpm for 18±2 hours. Although not specified in the method, the pH of the final eluate was measured and recorded so that test results could be compared to other leaching methods. The eluate from the extraction was pressure-filtered through a 0.22-µm borosilicate glass fiber filter and preserved for analysis. Filtrate from pressure filtration and the extraction eluate were analyzed separately, and an "effective" extraction concentration was calculated for each constituent as a volume-weighted average concentration of the two liquids. For QA/QC purposes, a method blank, with the filter paper and extraction fluid only, and duplicate samples for the composite at VC-3 were conducted in parallel using the same reagents.

EPA Method 1312 – Synthetic Precipitation Leaching Procedure

EPA Method 1312, or SPLP, is a single-batch leaching test used to evaluate the leaching behavior of a waste material in contact with acidic rain. The test is performed in the same manner as the TCLP, but with extraction fluids of 60/40 weight percent (wt%) sulfuric acid (H_2SO_4) and nitric acid (HNO_3) in DIW (Extraction Fluids #1 and #2) or DIW (Extraction Fluid #3). The selection of extraction fluid depends on the location of the site under investigation and the constituents being tested. Extraction Fluid #1 is used for sites east of the Mississippi River, Extraction Fluid #2 is used for sites west of the Mississippi River, and Extraction Fluid #3 is used only when cyanides or volatiles are to be analyzed.

Approximately 100 g of ash was pressure-filtered and the moist solid was mixed with Extraction Fluid #1 at an L/S of 20 mL/g. The mixture was tumbled at 28±2 rpm for 18±2 hours. Although not specified in the method, the pH of the final eluate was measured and recorded so that test results could be compared to other leaching methods. The eluate from the extraction was pressure-filtered through a 0.22-µm borosilicate glass fiber filter and preserved for analysis. Filtrate from pressure filtration and the extraction eluate were analyzed separately and an "effective" extraction concentration for each constituent was calculated as a volume-weighted average of the two liquids. A method blank, extraction fluid with no solid carried through test process, and duplicate samples for the composite at VC-4 were analyzed.

ASTM D3987 – Shake Extraction of Solid Waste with Water

ASTM D3987, or ASTM, is a single-point extraction test that is used to estimate leaching concentrations when no acid or base is added to the extraction. Since the method is patterned

after TCLP, the procedure is similar to the EPA method; however, DIW is used as the extraction fluid. A subsample of ash (70±0.1 g) was tumbled at 28±0.2 rpm with DIW at an L/S of 20 mL/g for 18±0.25 hours. After tumbling, the extract was separated from the solid by vacuum filtration through a 0.45-µm polypropylene membrane and the pH of the final eluate was measured and recorded. Reagent blanks, method blanks, and duplicate samples for the composite at VC-2 were analyzed.

Leaching Environmental Assessment Framework (LEAF) Methods

EPA Method 1313 – Liquid-Solid Partitioning as a Function of Eluate pH Using a Batch Extraction Procedure

EPA 1313 (SW-846, 2019) is a standardized, parallel batch extraction method used to evaluate the liquid-solid partitioning (LSP) of inorganic constituents as a function of eluate pH. The general procedure consists of nine batch extractions of a particle-size reduced subsample material contacted with leaching solution at an L/S of 10 mL/g-dry material and tumbled end-over-end over a specified contact interval. The leaching solution is DIW with additions of HNO_3 or potassium hydroxide (KOH) to adjust the final pH of the eluate to a target of nine specific pH values (i.e., pH values of 2, 4, 5.5, 7, 8, 9, 10.5, 12, and 13). An additional extraction without addition of acid or base was carried out to measure constituent leaching at the natural pH of the material.[2] After 24 hours of tumbling, the contact time associated with a sample particle size of 85 wt% less than 300 µm, the solid and liquid phases were separated by settling or centrifugation, and the pH, EC, and ORP of the clarified eluate were measured. The remaining slurry was vacuum-filtered through 0.45-µm pore size membranes prior to chemical analysis by ICP-OES, IC, and carbon analysis.

EPA 1313 provides (i) a titration curve of the pH response to additions of acid or base, (ii) the available content of constituents in the solid material, and (iii) the LSP curve for constituents over the tested pH range. Furthermore, the results of EPA Method 1313 are suitable for use in geochemical speciation modeling for the estimation of the solid-phase mineralogy and surface chemistry that controls constituent release.

Variants of EPA 1313 Methods

In this program, the full EPA 1313 method and variants of EPA 1313 were carried out on ash materials for different purposes:

- Full EPA 1313 was conducted on all composite samples (i.e., saturated ash composite from each borehole plus the site-wide unsaturated composite). The procedure was modified slightly to include an extra extraction filling the gap in pH between pH < 2.0 and pH = 4.
- For all composite materials, a variant of EPA 1313 was carried out using an L/S of 1 mL/g-dry and abbreviated to the natural pH and four other pH target values distributed over the range of pH 6 to 13 (i.e., five pH values in total). This modified 1313 test, referred to as

[2] The "natural pH," sometimes referred to as "own pH," is defined as the eluate pH in response to extraction in deionized water (i.e., no acid or base added) at an L/S of 10 mL/g-dry. To distinguish the natural pH at L/S=10 mL/g-dry (Method 1313 or 1313_3pt) from the pH response to DIW at L/S of 1 mL/g-dry measured using 1313_L/S=1, the former will continue to be called with "natural pH," while latter will be referred to as "own pH."

1313_L/S=1, was used to evaluate how changes in L/S may influence LSP concentrations and to provide verification data for development of geochemical speciation models.

EPA Method 1314 – Liquid-Solid Partitioning as a Function of Liquid-Solid Ratio using a Percolation Column Procedure

EPA 1314 (SW-846, 2019) is a standardized, up-flow column procedure used to evaluate release of inorganic constituents from percolating solid materials as a function of cumulative L/S (i.e., the volume of liquid that passes through the column relative to the dry mass of material in the column). In this study, EPA 1314 was used to characterize the L/S-dependent leaching of constituents in 250-400 g-dry composited ash samples (e.g., VC-1, VC-2, VC-3, VC-4, and Dry). A 5-cm diameter by 30-cm glass column was packed with coal ash in a series of five lifts with moderate tamping between lifts. DIW was used as the eluent solution since the coal ash had relatively low organic carbon and clay contents compared to soils. The eluent was pumped at a flowrate of 0.75±0.25 L/S per day through the material in an up-flow direction to minimize air entrapment and flow channeling. Eluates were collected at predetermined cumulative L/S values (i.e., 0.2, 0.5, 1.0, 1.5, 2.0, 4.5, 5.0, 9.5, and 10 mL/g-dry). For each eluate fraction, the pH and conductivity were recorded prior to filtration and preservation for chemical analysis. To present the results, the eluate pH, and concentrations of constituents in the eluates (mg/L), and the cumulative release through the end of each eluate fraction (mg/kg-dry) were plotted as functions of L/S in separate graphs.

Comparison of Leaching Test Parameters and Conditions

All leaching tests conducted for this program are designed to measure the LSP of constituent release from a material under the specified test conditions shown in Table 3-2. TCLP, SPLP, and ASTM are single-batch leaching tests that yield only one result; thus, test duplicates were conducted as shown in the table to ensure the quality of test results. The EPA 1313 test and its variants are batch procedures, but with parallel extractions to provide data over a range of test conditions. These batch tests, however, differ in the chemical makeup of extraction fluid as well as in the specified L/S. Moving from left to right in Table 3-2, the leaching test conditions are presented in order of increasing L/S. In the last column are the test conditions for EPA 1314, designed to measure LSP as a function of cumulative L/S.

Table 3-2
Leaching Test Parameters and Test Conditions

Parameter	TCLP	SPLP	ASTM	1313	1313_L/S=1	1314
Method Type	Single-batch	Single-batch	Single-batch	Parallel batch	Parallel batch	Column
Number of Eluates	1	1	1	11**	5	9
Extraction Fluid	Acetic acid in DIW	H_2SO_4/HNO_3 in DIW	DIW	HNO_3 or KOH in DIW	HNO_3 or KOH in DIW	DIW
Extraction Fluid pH	#1: 4.93±0.05* #2: 2.88±0.05	#1: 4.20±0.05* #2: 5.00±0.05 #3: DIW	-	-	-	-
L/S	20 mL/g-filtered	20 mL/g-filtered	20 mL/g-wet	10 mL/g-dry	1 mL/g-dry	0.2-10 mL/g-dry (cumulative)
Eluate pH	-	-	-	<2, 3**, 4, 5.5, 7, 8, 9, 10.5, 12, 13, natural pH	5.5, 7, 8, 9, own pH	based on solid buffering capacity
Eluate Filtration	0.22-µm via pressure	0.22-µm via pressure	0.45-µm via vacuum	0.45-µm via vacuum	0.45-µm via vacuum	0.45-µm via vacuum
Eluate Measurements	pH, EC	pH, EC	pH, EC	pH, EC	pH, EC	pH, EC
Reagent Blank	No	No	Yes	No	No	Yes
Method Blank	Yes	Yes	Yes	Yes	Yes	No
Duplicate Test	VC-3	VC-4	VC-2	None	None	None
Chemical Analysis	ICP-OES/MS DIC/DOC IC	ICP-OES/MS DIC/DOC IC	ICP-OES/MS DIC/DOC IC	ICP-OES/MS DIC/DOC IC	ICP-OES/MS DIC/DOC IC	ICP-OES/MS DIC/DOC IC
Samples Tested	VC-1, VC-2, VC-3, VC-4, Dry composites	VC-1, VC-2, VC-3, VC-4, Dry composites	VC-1, VC-2, VC-3, VC-4, Dry composites	VC-1, VC-2, VC-3, VC-4, Dry composites	VC-1, VC-2, VC-3, VC-4, Dry composites	VC-1, VC-2, VC-3, VC-4, Dry composites

Note: * indicates the TCLP and SPLP extraction fluids used for these tests.
** the 1313 procedure calls for 9 pH extractions + natural pH. An additional extraction at pH 3 was performed for this testing.

Chemical Analysis of Eluates, Groundwater, and Porewater

For each eluate from a leaching test, the following parameters were measured.

Eluate pH

Eluate pH was measured on all aqueous extracts following EPA 9040C (SW-846, 2019) using an Accumet XL20 meter and a combined pH electrode on approximately 5 mL of eluate. Prior to testing, the electrode was calibrated with two National Institute of Standards and Technology (NIST) traceable pH buffer solutions that bounded the anticipated range of pH to be measured. A third mid-range NIST buffer was used to verify the calibration.

Specific Conductance

Specific conductance, or EC, is a measure of the ability of an aqueous solution to carry an electrical current. The property is dependent on (i) the presence of ions; (ii) total concentration, mobility, and variance of ions in solutions; and (iii) the temperature of the measurement. Conductivity of all leaching test eluates was determined following EPA Method 9050A (SW-846, 2019) using a standard conductivity probe calibrated to an appropriate standard conductivity solution for the conductivity range of concern.

Oxidation-Reduction Potential

ORP is a voltage differential related to the redox state of a solid-liquid solution and its effect on chemical composition (e.g., reduced/oxidized iron, dissolved oxygen, biological activity). ORP voltage of all eluate solutions was measured with a probe, consisting of a platinum electrode and a reference electrode, placed in contact with the soil solution. In laboratory tests, the ORP voltage reading was converted to redox potential (Eh) by addition of a probe-specific correction factor of 228 mV at 25 °C. In field measurements, however, the probe correction factor was automatically compensated for by the instrument to produce output as Eh values.

Since redox reactions vary with pH and the mineral species present, redox is parameterized in geochemical modeling as the pH+pE, where pE is the negative logarithm of the free electron concentration, or –log([e^-]). The corrected Eh values of leachates and eluates were converted to a pE value using the following equation:

$$pE = \frac{F}{2.303RT}(Eh/1000)$$

where F is the Faraday constant (23,061 cal/(V mol)),
Eh is the redox potential of the solution (mV),
2.303 is a conversion (ln[e^-]/2.303 log[e^-]),
R is the gas constant (1.987 cal/(K mol)),
T is the temperature (K), and
1000 is a units conversion (1,000 mV = 1 V).

Inductively Coupled Plasma Spectrometry

The eluate concentrations of trace elements and material major species (e.g., Al, Ca, Si) were determined using a combination of ICP-OES and inductively coupled plasma–mass spectrometry (ICP-MS). The choice of instrumentation was determined based on detection limits, expected concentrations, and environmental threshold values. Table 3-3 provides the method detection limits (MDLs) and lower limits of quantitation (LLOQs) used in this project.

Major species and trace elements present at higher concentrations were determined using a Varian Model 720-ES ICP-OES (Agilent Technologies, Santa Clara, CA) following EPA Method 6010D (SW-846, 2019). The ICP-OES was calibrated to a 5-point standard curve with an analytical range of 25 to 25,000 µg/L. For some high-concentration trace elements, the standard curve was extended up to 500,000 µg/L using a 7-point standard curve. For low-level trace analysis, concentrations were determined by ICP-MS using a Perkin Elmer Elan DRC II (Perkin Elmer, Waltham, MA) following EPA Method 6020A (SW-846, 2019). The ICP-MS was calibrated to a 5-point standard curve with range between approximately 1 and 250 µg/L and extended with a 7-point calibration curve to 1,000 µg/L for some constituents.

Analytical QA/QC included initial and continuing calibration checks and blanks, matrix spikes, and method blanks. Calibration check standards and matrix blanks were evaluated every 10 to 20 samples with the requirements that check standards were within 15% of the specified value and blanks were below LLOQs. Matrix spikes were required to have recoveries within 20% of the calculated concentration considering the spiked mass. Initial and continuing calibration check standards for ICP-OES and ICP-MS were 0.5 mg/L and 0.050 mg/L, respectively. Analyte concentrations measured at less than the MDL were reported as <MDL and graphed at one-half the MDL values to indicate that the measurement was conducted. Analytical results measured at less than the LLOQ but greater than the MDL are estimated values.

Table 3-3
Methods, MDLs, and LLOQs for Analysis of Eluates by ICP-OES and ICP-MS

Analyte	Symbol	Method	MDL (mg/L)	LLOQ (mg/L)
Aluminum	Al	ICP-OES	0.0034	0.025
Antimony	Sb	ICP-MS	0.000013	0.001
Arsenic	As	ICP-MS	0.000036	0.001
Barium	Ba	ICP-OES	0.0016	0.025
Beryllium	Be	ICP-MS	0.000035	0.001
Boron	B	ICP-OES	0.0023	0.025
Cadmium	Cd	ICP-MS	0.00018	0.001
Calcium	Ca	ICP-OES	0.0065	0.025
Chromium	Cr	ICP-MS	0.000053	0.001
Cobalt	Co	ICP-MS	0.000023	0.001
Copper	Cu	ICP-MS	0.00004	0.001
Iron	Fe	ICP-OES	0.0022	0.025
Lead	Pb	ICP-MS	0.000027	0.001
Lithium	Li	ICP-OES	0.0047	0.025
Magnesium	Mg	ICP-OES	0.0035	0.025
Manganese	Mn	ICP-MS	0.000032	0.001
Molybdenum	Mo	ICP-OES	0.0018	0.025
Nickel	Ni	ICP-MS	0.000032	0.001
Phosphorus	P	ICP-OES	0.0068	0.025
Potassium	K	ICP-OES	0.0032	0.025
Selenium	Se	ICP-MS	0.000062	0.001
Silicon	Si	ICP-OES	0.0038	0.025
Silver	Ag	ICP-MS	0.000042	0.001
Sodium	Na	ICP-OES	0.0056	0.025
Strontium	Sr	ICP-OES	0.0037	0.025
Sulfur	S	ICP-OES	0.0058	0.025
Thallium	Tl	ICP-MS	0.000019	0.001
Vanadium	V	ICP-OES	0.0012	0.0025
Zinc	Zn	ICP-MS	0.000091	0.001

Ion Chromatography

The concentrations of anions in leaching test eluates were determined by IC using a Metrohm 881 Compact IC Pro (Metrohm USA, Riverview, FL) with a Metrosep A Supp 5 column and a conductivity detector following EPA Method 9056A (SW-846, 2019). A seven-anion calibration standard was diluted to form a 5-point calibration curve with the MDLs and LLOQs shown in Table 3-4. Since the calibration standards are diluted from a bulk multi-analyte standard, the calibration range differs for each analyte (e.g., 0.050-50 mg/L for Cl^- and 0.150-150 mg/L for SO_4^{-2}). Calibration check standards were required to be within 15% of the specified value, while acceptable analytical blanks were measured below the quantitation limits.

Table 3-4
MDLs and LLOQs for Analysis of Eluates by IC

Analyte	Symbol	MDL (mg/L)	LLOQ (mg/L)
Bromide	Br^-	0.0064	0.025
Chloride	Cl^-	0.0101	0.05
Fluoride	F^-	0.0063	0.02
Nitrate	NO_3^-	0.0112	0.1
Nitrite	NO_2^-	0.0108	0.05
Phosphate	PO_4^{-3}	0.0247	0.15
Sulfate	SO_4^{-2}	0.0254	0.15

Carbon Analysis

Carbon analysis for eluate samples included analyses for dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC). Carbon analysis was conducted using a Shimadzu TOC-V CPH/CPN (Shimadzu Scientific Instruments, Inc., Columbia, MD) by catalytic oxidation/non-dispersive infrared detection (NDIR) following EPA Method 9060A. Total carbon (TC) in the eluate is converted to carbon dioxide via oxidation or decomposition, carried by a zero-CO_2 air stream into the NDIR. For analysis of DIC, liquid samples are acidified with 2-molar hydrochloric acid to liberate carbonates and other forms of inorganic carbon from solution as carbon dioxide, which is sparged from the liquid sample into the NDIR by the zero-CO_2 carrier gas. DOC is determined by measuring the TC of a sample after purging of inorganic carbon. The instrument was calibrated using sodium hydrogen carbonate and potassium hydrogen phthalate over a 5-point calibration curve for DIC and DOC, respectively. The resultant analytical range was between 0.1 and 100 mg/L, with MDL and LLOQ values shown in Table 3-5. Checks on QA/QC at a frequency of every 10 analytical samples included calibration checks with a required recovery within 15% of the specific value, and method blanks with a requirement that the concentration was less than quantifiable limits.

Table 3-5
MDLs and LLOQs for Eluate Analysis for Carbon

Analyte	Symbol	MDL (mg/L)	LLOQ (mg/L)
Inorganic carbon	DIC	0.15	0.5
Organic carbon	DOC	0.18	0.5

Subsurface Gas Analysis

The composition of subsurface gas was monitored monthly from June 2019 through January 2020. Subsurface gas was monitored for oxygen (O_2), carbon dioxide (CO_2), methane (CH_4), ammonia (NH_3), and hydrogen sulfide (H_2S) using a Ventis Pro 5 meter (Figure 3-3a) rented monthly from Industrial Scientific, Pittsburgh, PA. Table 3-6 shows the measurement units and calibration ranges for the five gases. To avoid any moisture from subsurface gas fouling the vacuum pump, the subsurface gas was drawn through a 250-mL syringe filled with desiccant (Figure 3-3b).

a) b)

Figure 3-3
Subsurface gas monitoring apparatus: a) Ventis Pro 5 meter and b) connected tubing and desiccant syringe

Table 3-6
Calibration Ranges for Subsurface Gas Monitoring

Analyte	Symbol	Units	Calibration Range	
Ammonia	NH_3	ppm	0	500
Hydrogen sulfide	H_2S	ppm	0	500
Carbon dioxide	CO_2	%	0	5
Methane	CH_4	%	0	5
Oxygen	O_2	%	0	30

Data Management with LeachXS™

Laboratory and analytical information for leaching tests was recorded by the laboratory technician in Microsoft Excel® spreadsheets specifically designed for each test for use as templates for data collection and archiving. Analytical data documenting concentrations of constituents from each leaching test were entered into the same spreadsheets. These data templates were used as the interface for loading laboratory and analytical data into LeachXS™ (VU, 2019), a database-driven data management and reporting software program. LeachXS was used to (i) archive the laboratory and analytical data from leaching tests; (ii) compare test results between composite materials (e.g., VC-1, VC-2, VC-3, or VC-4) and between test types (e.g., TCLP, SPLP, ASTM, and LEAF); and (iii) generate the Excel plots used for this report. These data have also been added to EPRI's CPInfo database.

4
PHYSICAL AND HYDRAULIC PROPERTIES

Physical properties of the fly ash samples used for measurement of hydraulic properties are summarized in Table 4-1, composition of the solids is summarized in Table 4-2, and the hydraulic conductivities are summarized in Table 4-3.

Particle size distributions of the coal ash samples are shown in Figure 4-1. All of the ashes contained a broad range of particle sizes ranging from coarse-to-fine sand, silt, and clay-size (<2 μm) particles. Fines is the predominant fraction for all of the samples. Each has a broadly graded particle size distribution. The fines content (i.e., particles finer than 75 μm) ranges from 61.5% to 96.8%, and the clay-size (i.e., finer than 2 μm) ranges from 7.0% to 19.4%. No particles coarser than sand-size were observed.

Table 4-1
Physical Properties of Coal Ash Samples Used for Hydraulic Conductivity Testing

Sample ID	Sample Elevation at Top (ft AMSL)	Sample Elevation at Bottom (ft AMSL)	Water Content (%)	Dry Unit Weight (kg/m^3)	Pore L/S of Intact Cores (L/kg-dry)	Particle Size Fractions			
						% Gravel	% Sand	% Fines	% Clay
CDL-VC2-65	374.9	371.9	39.5	1,090	0.36	0	12.1	87.9	13.1
CDL-VC2-75	364.9	361.9	35.4	1,110	0.32	0	38.5	61.5	7.3
CDL-VC3-65	378.2	375.2	35.7	1,390	0.26	0	3.2	96.8	14.3
CDL-VC3-75	368.2	365.2	41.5	1,150	0.36	0	7.8	92.2	7.0
CDL-VC4-65	378.2	375.2	39.8	1,150	0.35	0	23.3	76.7	19.4
CDL-VC4-75	368.2	365.2	36.6	1,290	0.28	0	6.2	93.8	11.6

An estimate of the pore L/S ratio of intact cores was made from the water content and the dry unit density assuming a fully saturated 1 m^3 volume of ash:

$$L/S = \frac{WC/100}{\rho_{dry}} \times 1000$$

where L/S is the liquid-to-solid ratio for fully saturated pores (L/kg-dry);
WC is the water content (%) from Table 4-1;
ρ_{dry} is the dry unit density (kg-dry/m^3) from Table 4-1; and,
1000 is a unit conversion factor for volume (1000 L = 1 m^3).

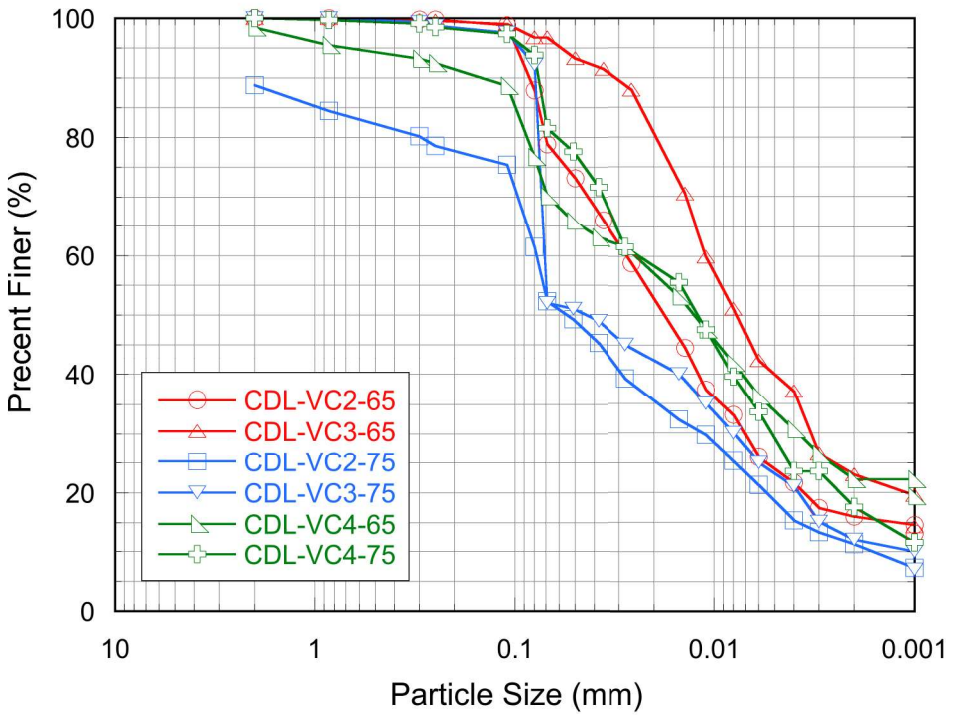

Figure 4-1
Particle size distribution of coal ash samples on which hydraulic conductivity tests were conducted

Table 4-2 indicates that all of the ash samples are predominantly composed of Al, Fe, and Si oxides, which reflects the predominant alumino-silicate mineral structure of the particulate. All samples contain modest amounts of Ca, K, and Ti. The LOI varies considerably, from 1.9% to 13.1%, with all but one sample having an LOI > 3.3%. The variability in composition of major elements appears to reflect the nature of the deposited ash as layers of fly ash and bottom ash.

Table 4-2
Composition of Solids (%) from LOI and XRF of Coal Ash Samples Used for Hydraulic Conductivity Assessment (elements exceeding 1.0%). Measurements were not conducted for CDL-VC3-65.

Composition	VC-2		VC-3		VC-4	
	65	75	65	75	65	75
LOI	2.0	2.7	-	1.9	13.1	3.3
Al_2O_3	15.8	16.1	-	17.2	15.6	17.5
CaO	7.9	8.9	-	6.6	8.4	5.3
Fe_2O_3	32.6	29.0	-	27.5	32.6	31.0
K_2O	3.7	4.2	-	4.5	3.7	4.0
SiO_2	35.2	36.4	-	39.2	34.6	37.3
TiO_2	1.3	1.3	-	1.4	1.2	1.4

The hydraulic conductivities fall into two groups (Table 4-3): more permeable samples (CDL-VC2-65, CDL-VC2-75, and CDL-VC3-75) and less permeable samples (CDL-VC3-65, CDL-VC4-65, and CDL-VC4-75). The more permeable ashes have hydraulic conductivities in the range of 10^{-5} cm/s, whereas the less permeable ashes have hydraulic conductivities in the range

of 10^{-6} cm/s. The differences in hydraulic conductivity between these groups cannot be attributed to particle size characteristics such as fines content or 2 -μm clay content (Figure 4-2). However, the less permeable ashes have higher dry density, and therefore lower void ratio (Figure 4-3).

Table 4-3
Hydraulic Conductivity of Coal Ash Samples

Sample ID	Effective Stress (kPa)	Hydraulic Conductivity (cm/s)
CDL-VC2-65	20	4.18×10^{-5}
	100	2.40×10^{-5}
	250	2.02×10^{-5}
	400	1.82×10^{-5}
	500	1.81×10^{-5}
CDL-VC2-75	20	2.43×10^{-5}
	100	1.90×10^{-5}
CDL-VC3-65	20	8.28×10^{-6}
	100	6.22×10^{-6}
	250	4.83×10^{-6}
	400	4.32×10^{-6}
	500	3.75×10^{-6}
CDL-VC3-75	20	1.54×10^{-5}
	100	1.26×10^{-5}
	250	1.09×10^{-5}
	400	8.15×10^{-6}
CDL-VC4-65	20	4.98×10^{-6}
	100	4.47×10^{-6}
CDL-VC4-75	20	2.07×10^{-6}
	100	1.96×10^{-6}

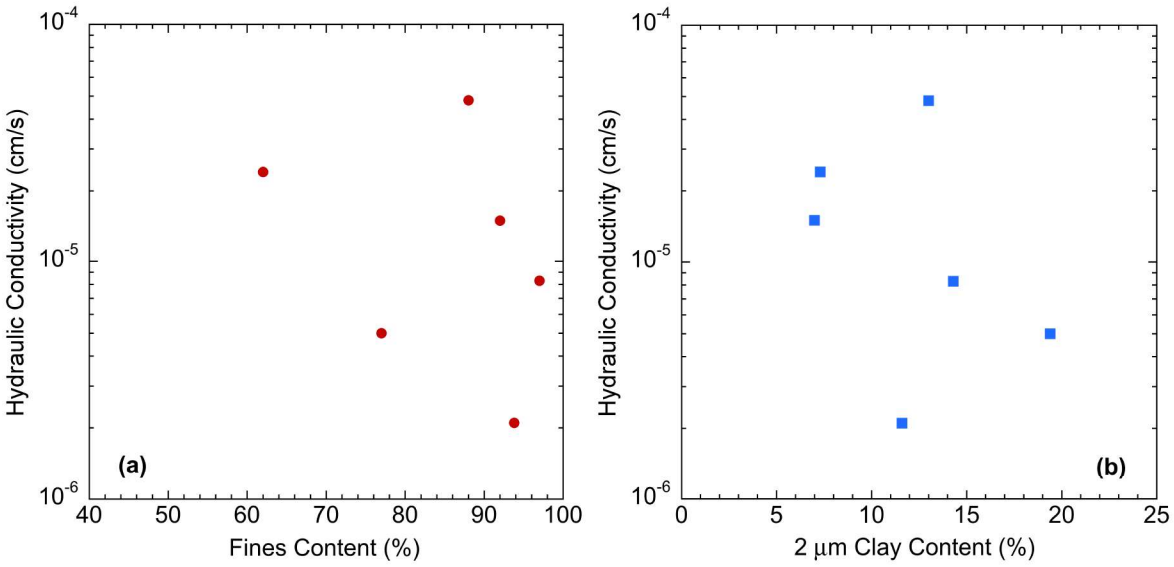

Figure 4-2
Hydraulic conductivity of coal ashes at 20 kPa effective stress as a function of (a) fines content and (b) 2-µm clay content

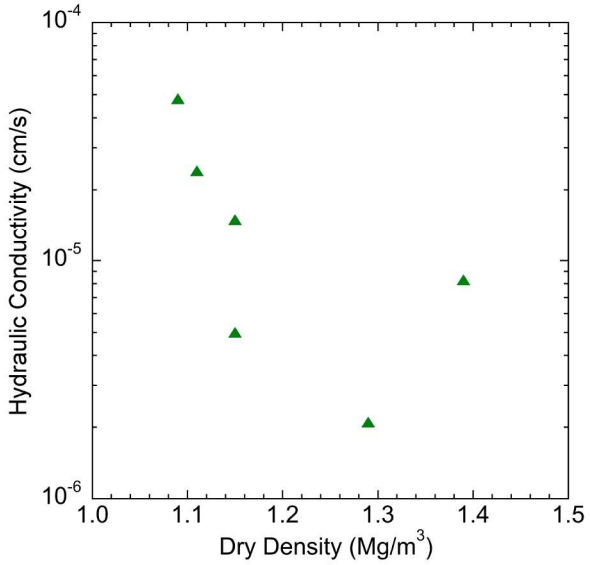

Figure 4-3
Hydraulic conductivity of coal ashes as a function of dry unit weight

Hydraulic conductivity of the coal ash samples as a function of confining stress is shown in Figure 4-4. The hydraulic conductivity diminishes only modestly with increasing stress, decreasing approximately by a factor of 2 as the effective stress is increased from 20 to 500 kPa. The insensitivity to stress is most likely due to the ash being predominantly comprised of silt-size and sand-size particles.

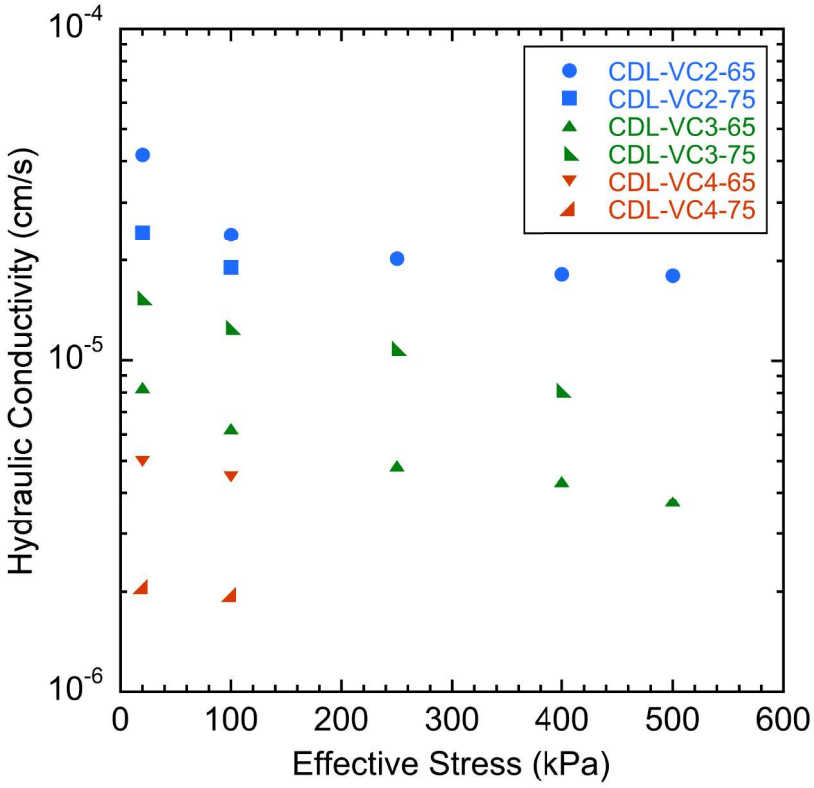

Figure 4-4
Hydraulic conductivity of coal ash samples as a function of effective stress

5
INDIVIDUAL SPLIT SPOON SAMPLE TESTING

Evaluation of Field Extractions (Low L/S and L/S ≈ 1)

During field sampling, grab samples of ash from each split spoon were extracted by centrifugation of the moisture content (i.e., Low L/S Field Extractions). Because the moisture content of the unsaturated split spoon material varied with depth and texture, a small amount of DIW was added to each extraction to ensure that a sufficient amount of liquid could be recovered and analyzed. The resultant L/S of Low L/S Field Extractions varied between 0.28 and 0.67 mL/g-dry, consistent with the L/S of porewater from intact core samples (Table 4-1).

Vertical Heterogeneity Within and Between Boreholes

Profile Plots of Field and Laboratory Extraction Data

After surveying of the borehole and PAP locations and elevations, depths BGS measured during sample recovery were converted to elevations ASML. The concentration from Low L/S Field Extractions of individual split spoon materials was plotted as a function of elevation to provide a visual indication of material heterogeneity with depth within a borehole. Examples of these borehole profile plots are presented in Figure 5-1 and Figure 5-2.

Each figure represents the concentration profiles for a measured constituent in the Low L/S Field Extractions for VC-1 (blue), VC-2 (green), VC-3 (orange), and VC-4 (purple). The constituent concentration is plotted along the x-axis, while the elevation for the center of the split spoon is plotted on the y-axis. The red horizontal line shows the surface elevation at the time of drilling. The 5-foot wide shaded area indicates the screening interval for the PAP in each borehole. The light-colored data points in each profile indicate the intervals from which material was taken to create the composite ash sample for each borehole used in detailed characterizations.

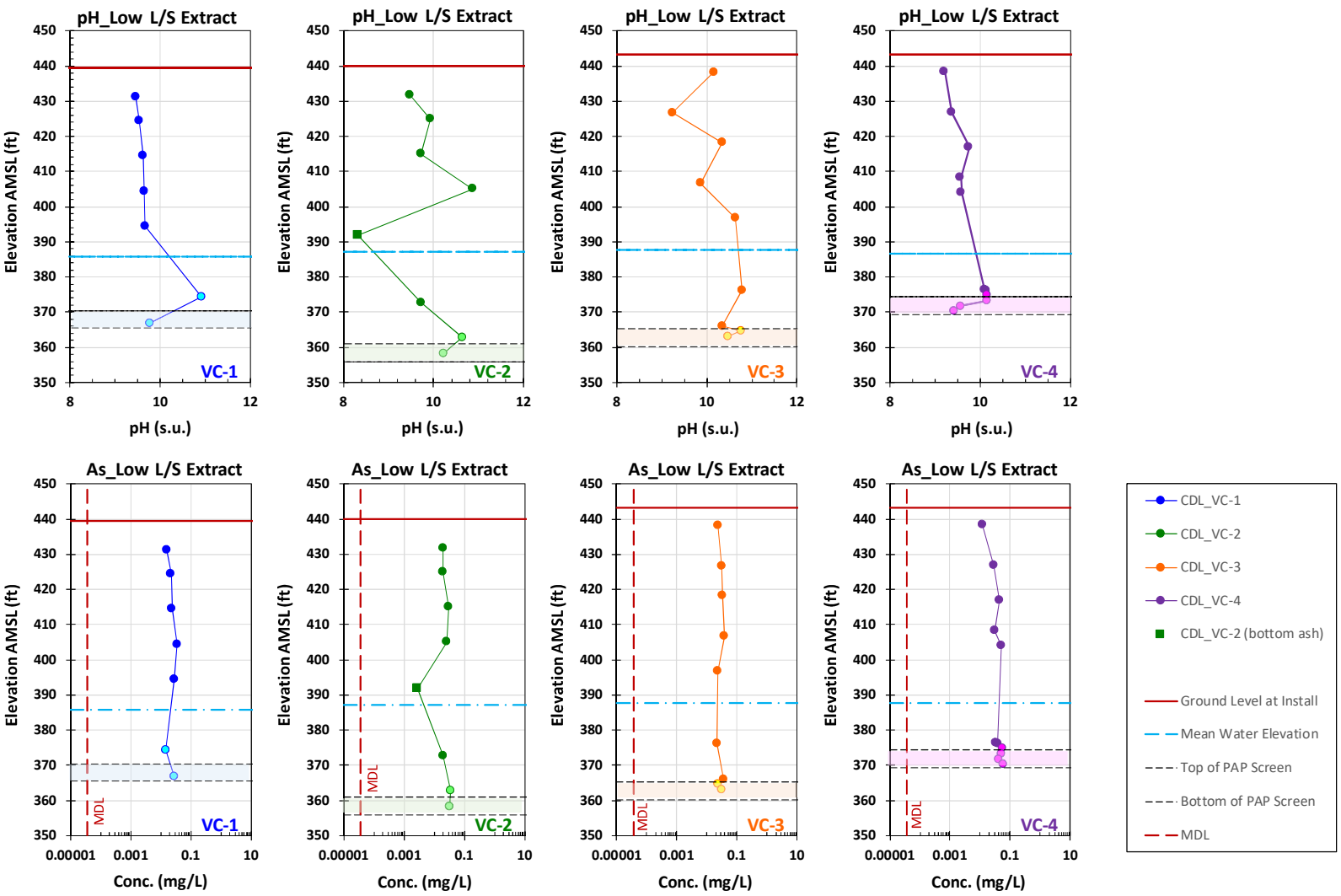

Figure 5-1
Low L/S Field Extraction concentration profiles within boreholes (VC-1, VC-2, VC-3, and VC-4): pH and arsenic; interface between dry- and wet-handled ash occurs at approximately 390 ft AMSL

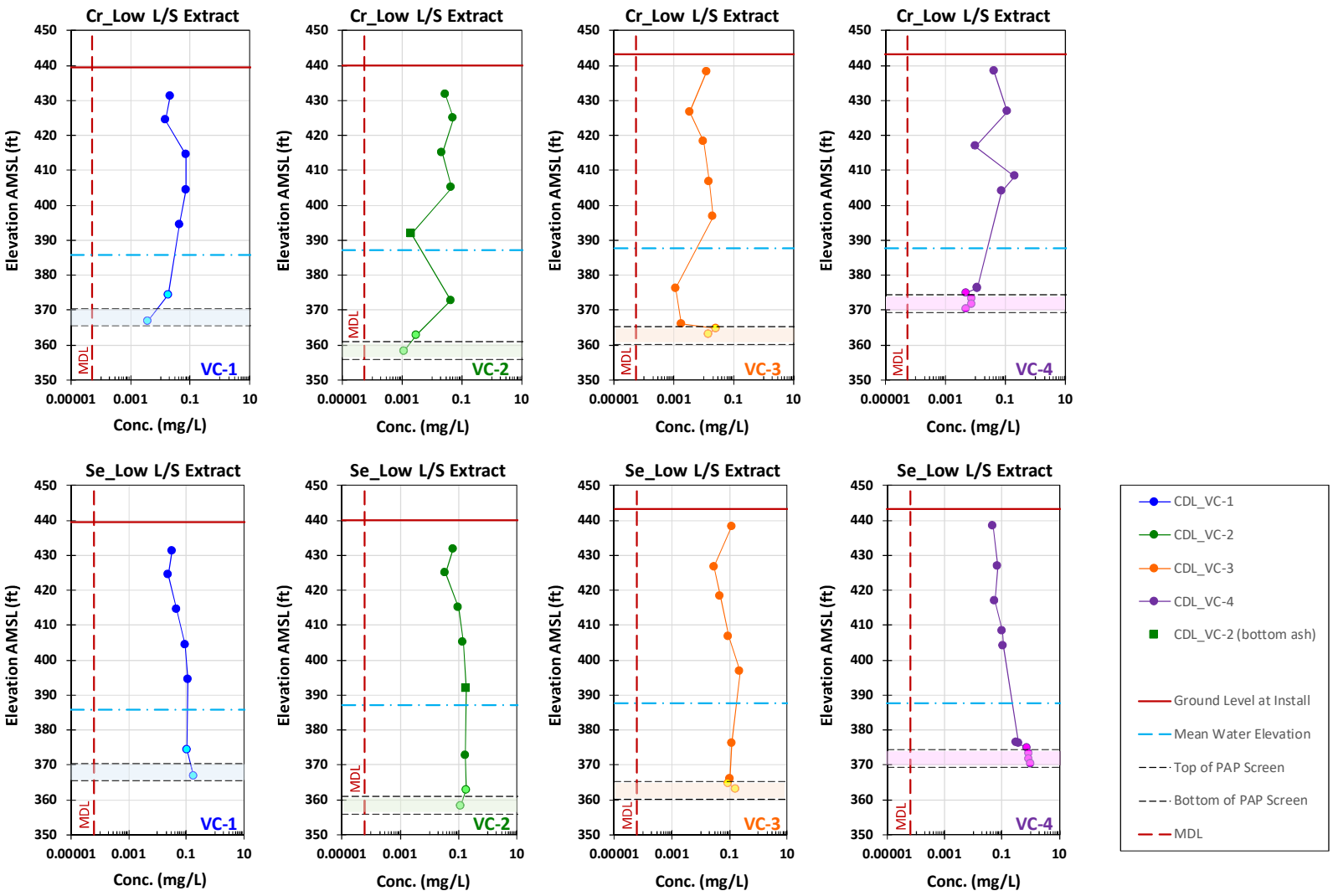

Figure 5-2
Low L/S Field Extraction concentration profiles within boreholes (VC-1, VC-2, VC-3, and VC-4): chromium and selenium; interface between dry- and wet-handled ash occurs at approximately 390 ft AMSL

Standardized Borehole Profiles of Low L/S Field Extractions

The concentration data for Low L/S Field Extractions were converted to standardized profile plots using the global mean and standard deviation for "known ash samples" in all boreholes as characterized by the geologist notes. The standardized concentration is calculated as:

$$\frac{x - \bar{x}}{s}$$

where x is the parameter (e.g., pH, concentration) from the extraction test,
$\bar{x}$ is the global mean of all "known ash samples" for all boreholes, and
s is the global standard deviation of all "known ash samples."

The global mean and standard deviation for all constituents are tabulated in Table 5-1. The standardized concentration provides a measure of the difference between the measured concentration and the mean as a number of standard deviations from the mean concentration. A homogenous material, for example, may have measurements within 2 standard deviations of the mean, while measurements greater than 4 standard deviations may have more than random variations such as influence from cover or underlying material. Justification for use of ash sample global statistics, rather than within-borehole statistics, was based on the results of t-test for pairwise comparisons assuming unequal variances, which showed no statistical difference in means between boreholes. In addition, the use of global statistics in standardized concentration profiles allows for comparison between boreholes on the same basis.

The standardized borehole profiles for the example constituents presented in Figure 5-1 and Figure 5-2 are presented in Figure 5-3 and Figure 5-4. The standardized profiles for all constituents are presented Appendix B-2. In general, the concentration profiles for most constituents are vertically consistent within the ash deposit and show no evidence of difference between the upper dry-handled coal ash and lower wet-handled coal ash.

Table 5-1
Global Mean and Standard Deviation of Laboratory Extractions (L/S=1) Concentrations

		Global "Ash" Statistics		
Analyte	**Units**	**Mean**	**Std. Dev**	**Coefficient of Variation**
Moisture Content	g_{H2O}/g	0.24	0.07	29%
EC	mS/cm	4.29	1.48	35%
pH	S.U.	9.96	0.49	4.9%
ORP	mV	78.4	23.3	30%
pH+pE	-	15.14	0.32	2.1%
Aluminum	mg/L	0.78	0.89	110%
Antimony	mg/L	0.002	0.001	50%
Arsenic	mg/L	0.03	0.01	33%
Barium	mg/L	0.11	0.05	46%
Beryllium	mg/L	ND	-	-
Boron	mg/L	16.1	15.8	98%
Cadmium	mg/L	0.02	0.01	50%
Calcium	mg/L	570	250	44%
Chromium	mg/L	0.31	0.04	13%
Cobalt	mg/L	0.0006	0.0002	33%
Copper	mg/L	0.011	0.001	9.1%
Iron	mg/L	0.01	0.02	200%
Lead	mg/L	ND	-	-
Lithium	mg/L	1.4	1.0	71%
Magnesium	mg/L	0.96	1.0	100%
Manganese	mg/L	0.0017	0.0011	65%
Molybdenum	mg/L	10.4	8.6	83%
Nickel	mg/L	0.0047	0.0012	26%
Phosphorus	mg/L	ND	-	-
Potassium	mg/L	300	88	29%
Selenium	mg/L	0.21	0.26	120%
Silicon	mg/L	4.1	2.2	54%
Silver	mg/L	ND	-	-
Sodium	mg/L	280	130	46%
Strontium	mg/L	3.2	2.0	63%
Sulfur	mg/L	590	280	48%
Thallium	mg/L	0.02	0.02	100%
Vanadium	mg/L	1.8	1.1	61%
Zinc	mg/L	0.01	0.01	100%

Notes: ND = all or most of the L/S=1 concentrations were less than the MDL

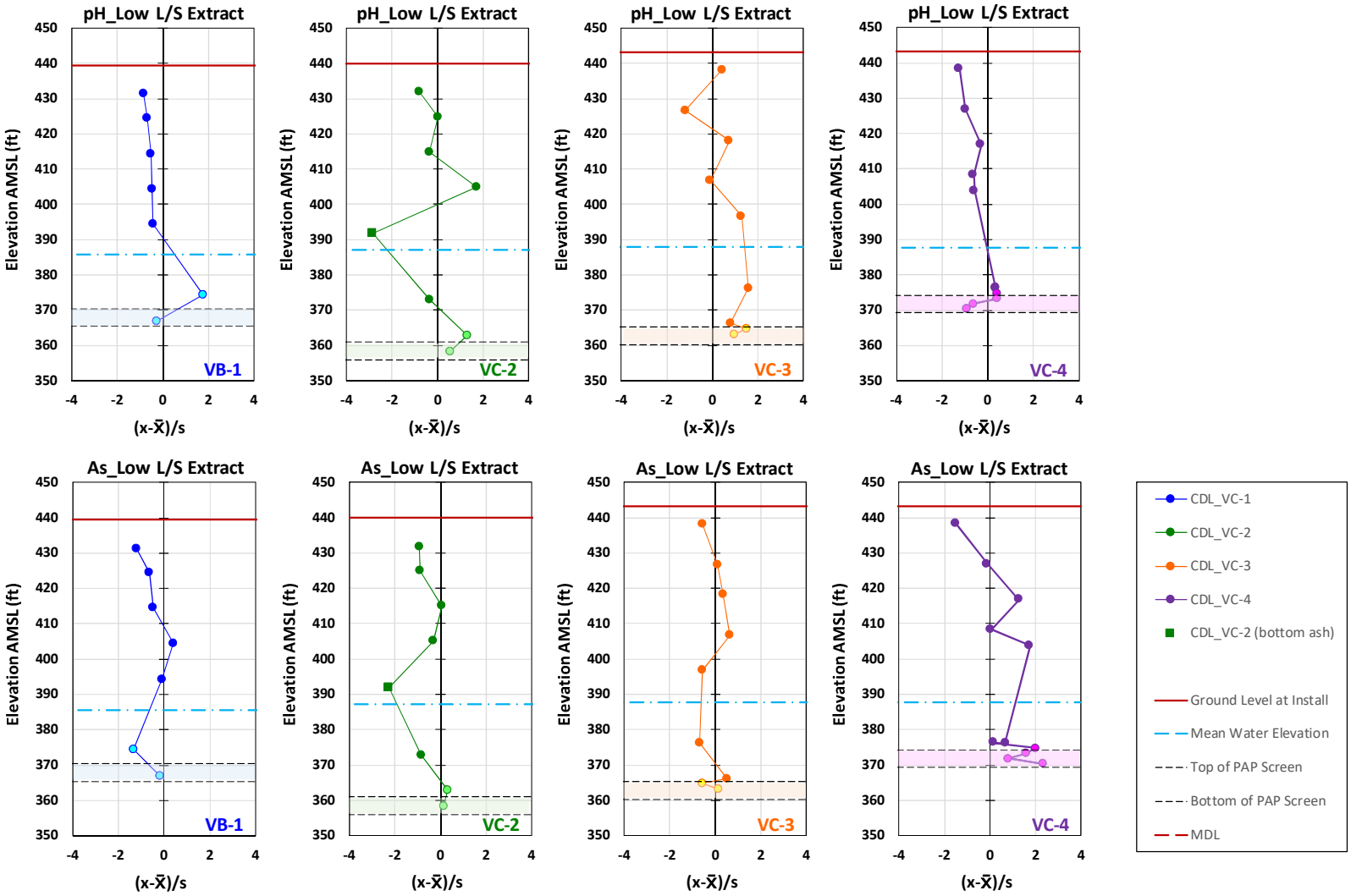

Figure 5-3
Standardized Low L/S Field Extraction profiles within boreholes (VC-1, VC-2, VC-3, and VC-4) standardized to the global mean (X̄) and standard deviation (s) of known ash samples: pH and arsenic; interface between dry- and wet-handled ash occurs at approximately 390 ft AMSL

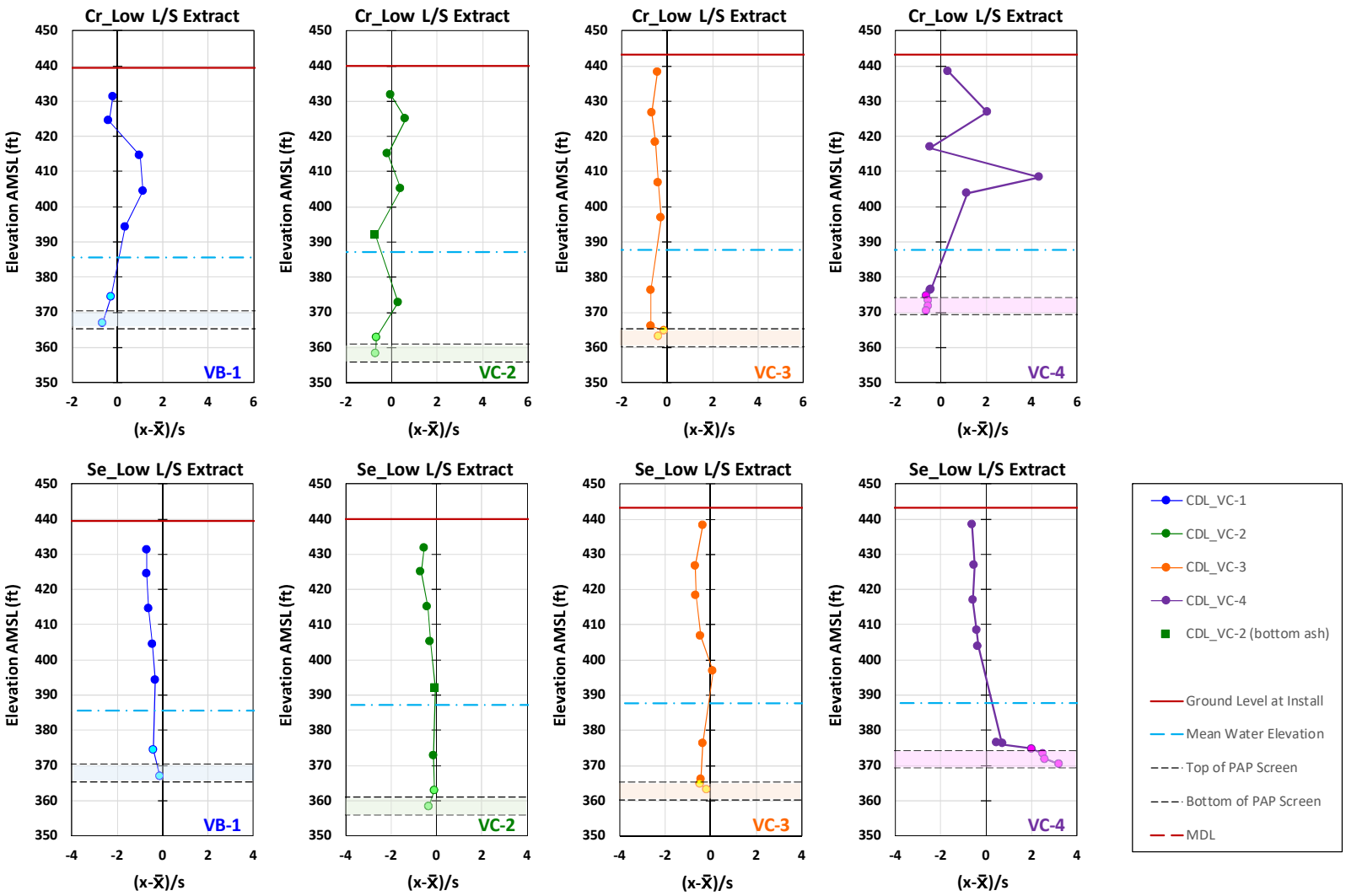

Figure 5-4
Standardized Low L/S Field Extraction profiles within boreholes (VC-1, VC-2, VC-3, and VC-4) standardized to the global mean (x̄) and standard deviation (s) of known ash samples: chromium and selenium; interface between dry- and wet-handled ash occurs at approximately 390 ft AMSL

Comparison of Standardized Borehole Profiles for Low L/S and L/S≈1 Field Extractions Based on Mass Release (mg/kg)

For boreholes VC-1 and VC-2, L/S≈1 Field Extractions were conducted as a comparator to the unique Low L/S Field Extractions. Example comparisons of standardized borehole variability graphs are presented in Figure 5-5 and Figure 5-6, while the complete results for all measured constituents are presented in Appendix B-3. In general, the variability between field extraction methods is negligible; however, the unique Low L/S Field Extraction technique provided data that are somewhat less variable than the L/S≈1 Field Extractions. The Low L/S extractions are considered to provide better control of redox conditions and L/S values that are more consistent with porewater values.

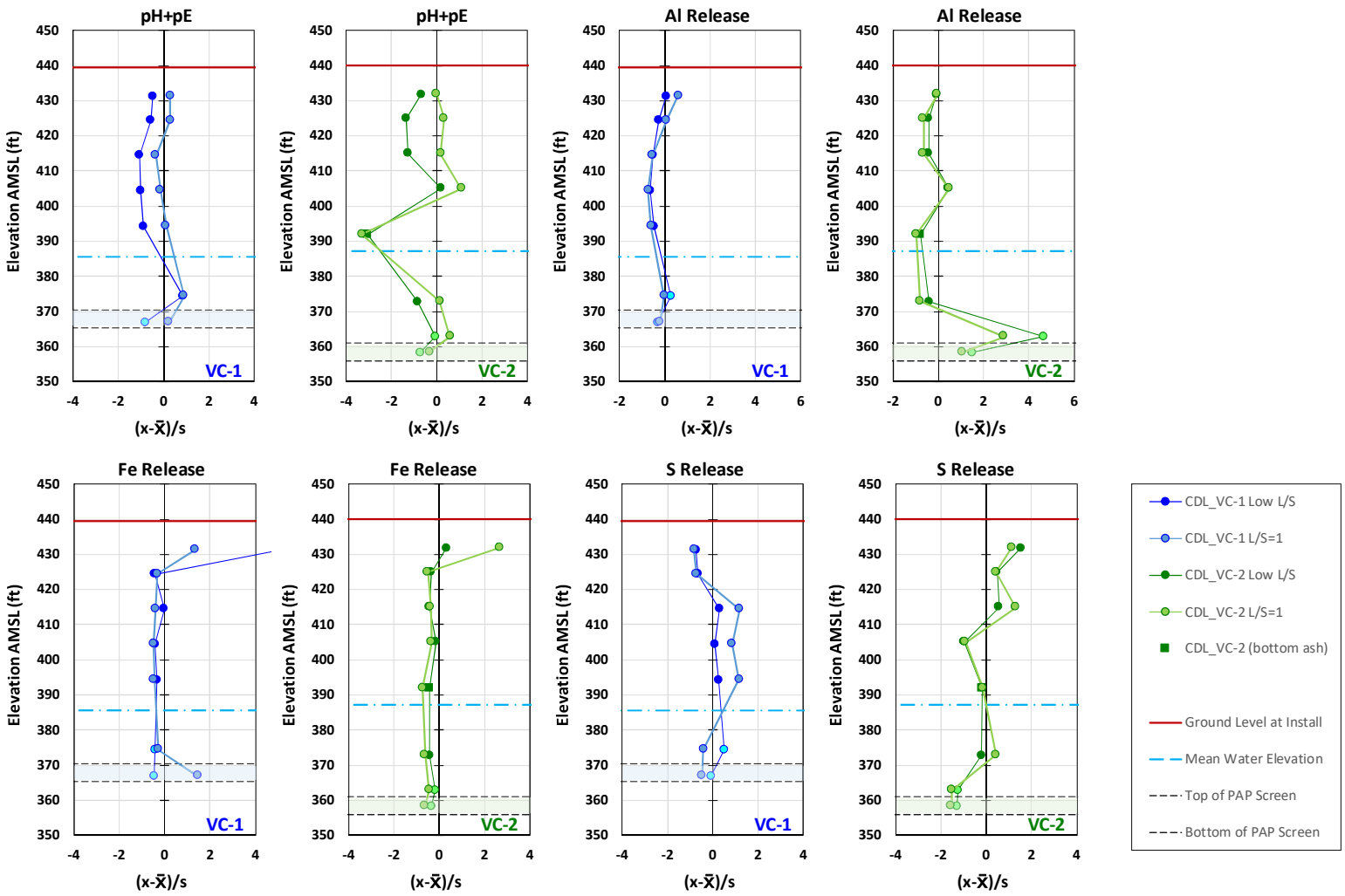

Figure 5-5
Comparison of standardized mass release profiles for Low L/S Field Extractions and L/S ≈ 1 Field Extractions of major constituents from VC-1 and VC-2: pH+pE, aluminum, iron, and sulfur; interface between dry- and wet-handled ash occurs at approximately 390 ft AMSL

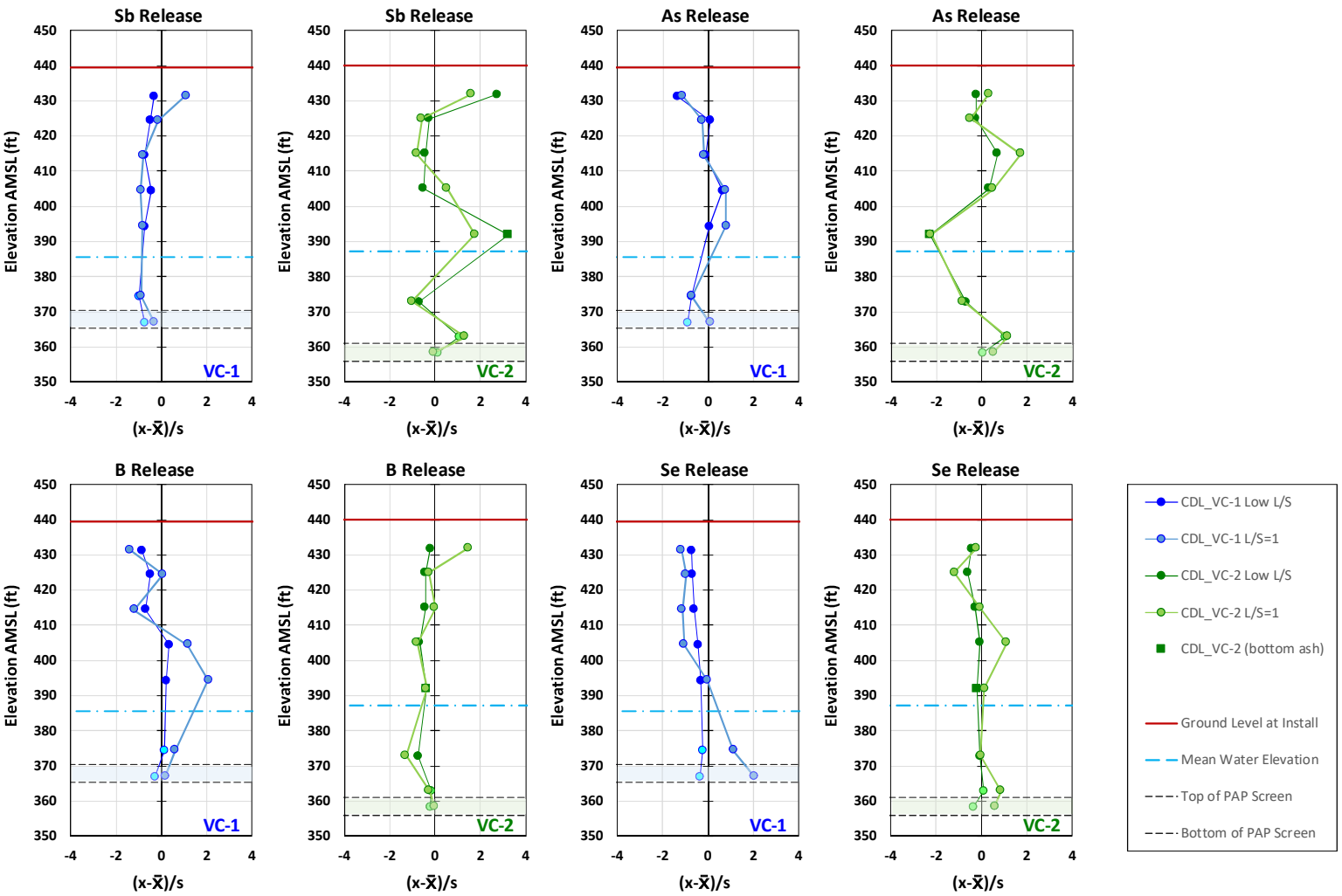

Figure 5-6
Comparison of standardized mass release profiles for Low L/S Field Extractions and L/S ≈ 1 Field Extractions of trace constituents from VC-1 and VC-2: antimony, arsenic, boron, and selenium; interface between dry- and wet-handled ash occurs at approximately 390 ft AMSL.

6
COMPOSITE ASH SAMPLE TEST RESULTS

Subsamples of bulk material collected from split spoon sampling were homogenized within each bulk storage packet. For borehole composites, the material in the storage packets around the PAP screening intervals was composited by equal dry mass from each packet as shown in Table 3-1. These composites of wet-handled ash were labeled for their respective borehole locations (i.e., VC-1 through VC-4). An additional site-wide composite of unsaturated material, labeled as "Dry," was created by equal mass from split spoon samples from dry-handled material in all boreholes collected above the water table. The five composites were subject to detailed investigation of total content, available content, and leaching characteristics as a function of pH and L/S.

Total Content

The total content analysis results for the five composite materials are shown in Table 6-1.[3] In preparation for EPA Method 3052, ash samples were dried under nitrogen and ground to pass a No. 100 (150 μm) sieve. Therefore, the total content results are reported on a dry-mass basis (mg/kg-dry), whereas typical EPA Method 3052 results would be based on "as received" solid sample (mg/kg), which can include the inherent moisture in the solid sample.

The coal ash composites are comprised mainly of Al, Ca, Fe, K, Na, and Si (not measured). Of the 26 constituents analyzed, Sb, Co, Mg, Mn, Hg, Ag, and Tl were reported for at least one of the five composites to have low total content relative to the commercial laboratory's reporting limit. Mercury was detected above reporting limit only in the "Dry" composite and, therefore, was not considered in the analysis of test leachates or the comparison to groundwater concentrations. The remaining low-concentration constituents were retained because preliminary testing indicated that leaching concentrations were low, but quantifiable in LEAF leaching tests.

For most elements analyzed (16 of 26), the dry-handled ash composite had a total content value within the range of values for the wet-handled composites. Only Pb, Hg, and Mo had a total content a factor of 1.5 or more higher than the highest wet-handled composite value within the range, while Cd, Li, Sr, and Zn had total contents slightly higher (within a factor of 1.0 to 1.5) than the highest wet-handled value. Total content values for Mn, K, and Na were slightly lower than the lowest wet-handled total content value.

[3] As noted in the test description in Section 3, boron was not analyzed for total content because metaborate is added to the digestion process for Method 3052.

Table 6-1
Total Contents for Composite Samples (VC-1, VC-2, VC-3, VC-4, and Dry) Based on EPA Method 3052

Analyte	Symbol	MDL (mg/kg)	VC-1 (mg/kg)	VC-2 (mg/kg)	VC-3 (mg/kg)	VC-4 (mg/kg)	Dry (mg/kg)
Aluminum	Al	2.9	21,000	17,000	27,000	18,000	27,000
Antimony	Sb	1.9	6.2	4.5 J	5.0 J	7.7	7.4
Arsenic	As	1.3	51	63	48	94	54
Barium	Ba	0.22	370	480	820	390	360
Beryllium	Be	0.014	11	7.9	5.9	13	9.5
Cadmium	Cd	0.74	4.4	3.5	5.1	3.8	6.0
Calcium	Ca	10	13,000	9,400	24,000	9,300	21,000
Chromium	Cr	0.13	170	140	130	180	160
Cobalt	Co	2.8	32	23 J	20 J	42	29
Copper	Cu	3.6	81	72	64	92	78
Iron	Fe	65	120,000	99,000	100,000	130,000	110,000
Lead	Pb	1.0	62	70	67	74	160
Lithium	Li	0.27	68	55	50	66	71
Magnesium	Mg	3.4	340 J	430 J	610	300 J	490 F1
Manganese	Mn	0.10	380 B	390 B	430 B	330 B	280 B
Mercury	Hg	0.058	ND	ND	ND	0.058 J	0.46
Molybdenum	Mo	0.15	27	26	18	37	62
Nickel	Ni	2.1	130	93	89	160	120
Potassium	K	240	12,000	16,000	14,000	12,000	11,000
Selenium	Se	1.6	14	10	9.3	17	16
Silver	Ag	0.10	1.2 J	1.0 J	0.93 J	1.3 J	1.1 J
Sodium	Na	240	5,400	5,200	4,900	5,100	3,800
Strontium	Sr	0.054	68	57	67	95	130 F1
Thallium	Tl	9.3	13 J	14 J	9.7 J	14 J	9.4 J
Vanadium	V	0.056	670	450	480	660	620
Zinc	Zn	4.6	410	430	410	420	460

Notes:
B the compound was found in the blank and sample.
F1 the matrix spike recovery is outside of acceptance limits
J the result is less than the reporting limit but greater than or equal to the MDL; estimated concentration.
ND the compound was not detected at a concentration above the MDL.

Leaching Test Results

For this project, leaching test results included LEAF test results (EPA 1313, 1313_L/S=1, EPA 1314) and traditional leaching tests (TCLP, SPLP, ASTM). All leaching data are presented in Appendix C for each composite sample as a function of pH and L/S. The graphs used in the following discussion of leaching test results were derived from the appendix figures either by combining data series (e.g., comparisons between composites) or by limiting axis domains. In

some cases, discussion graphs are presented as graphs of mass release (mg/kg-dry), which were derived from eluate concentrations (mg/L) multiplied by the associated L/S value (L/kg-dry). Mass release graphs are not presented in the appendix.

pH-Dependent Leaching Tests (EPA 1313, 1313_L/S=1)

Titration Curves

Titration curves from pH-dependent tests conducted on composite samples are presented in Figure 6-1. The titration curve indicates the amount of acid or base (shown as acid additions less than zero) required to provide a specific eluate pH, sometimes referred to as the acid/base neutralization capacity of the material. This data may be useful when leachates or materials from other processes or natural environments are introduced to a storage facility (e.g., pyritic tailings co-disposed with fly ash).

In LEAF nomenclature, the pH response when no acid or base is added to the extraction at an L/S of 10 mL/g-dry is referred to as the "natural pH" of the material. Because the natural pH is defined at an L/S of 10 mL/g, the term "own pH" will be used to differentiate the pH response at other L/S values (e.g., 1313_L/S=1) from the natural pH. The natural pH (EPA 1313) and own pH (1313_L/S=1) are tabulated for the five composite materials in Table 6-2 and represented in Figure 6-1 as large color-coded circles about a data point. The values for natural pH for the five composites are generally the same (average value of 10.41±0.18). The composite of the unsaturated ash (Dry) is the least alkaline (pH_{nat}=10.21), but not much more so than the composite of saturated ash at VC-2 (pH_{nat}=10.29). The most alkaline composite is the saturated ash composite at VB-3 (pH_{nat}=10.67). In comparison to natural pH, the own pH values are essentially the same as their associated natural pH values (within approximately 0.2 standard units).

Table 6-2
Natural pH (EPA 1313) and own pH (1313_L/S=1) of composite samples

	Method	L/S (mL/g-dry)	VC-1 pH (SU)	VC-2 pH (SU)	VC-3 pH (SU)	VC-4 pH (SU)	Dry pH (SU)
Natural pH	EPA 1313	10	10.44	10.29	10.67	10.43	10.21
Own pH	1313_L/S=1	1	10.66	10.64	10.71	10.29	10.01

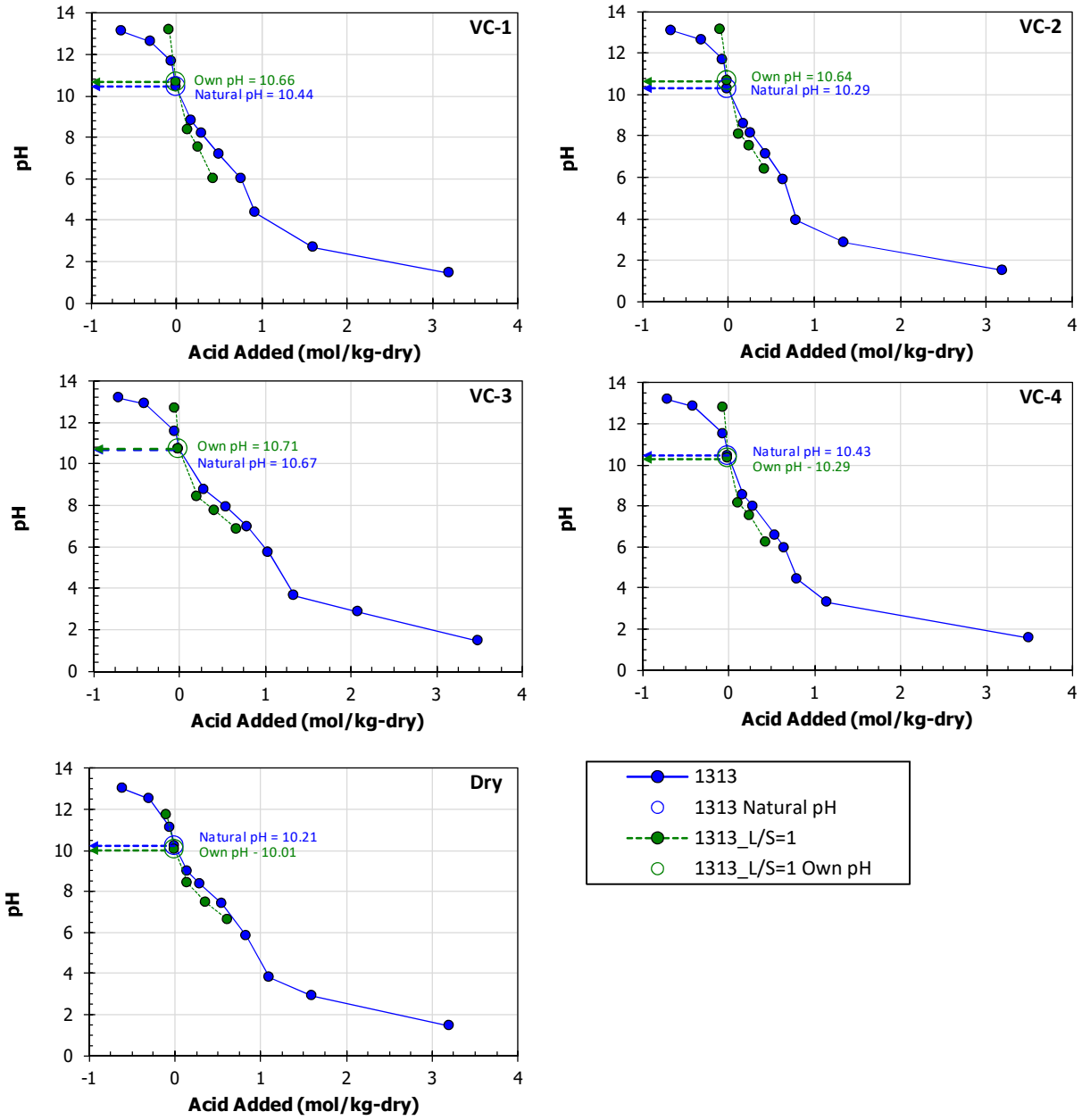

Figure 6-1
Titration curves from EPA 1313 test results from five composite samples (VC-1, VC-2, VC-3, VC-4, and Dry)

Constituent Concentrations

The concentration of a constituent in each eluate of a pH-dependent leaching test (i.e., EPA 1313 and 1313_L/S=1) is indicative of the speciation of the constituent and the LSP in equilibrium with the L/S, pH, EC, and ORP of the contacting fluid. Eluate concentrations are typically plotted as a function of eluate pH to indicate how LSP changes over a broad range of pH values. These data also can be used to parameterize controlling mineral sets in geochemical speciation models, for example, LeachXS™/ORCHESTRA (Meeussen, 2015), to create a source term for

fate and transport modeling. The pH-dependent leaching behavior of a constituent is useful when disposed materials may be contacted with water containing significant amounts of acid or base (e.g., pyrite-impacted groundwater or alkali process wastewaters).

However, for many field assessments, evaluation of LSP may be limited to an applicable pH domain. The applicable pH domain is typically centered about the natural pH of the material but should consider the potential for leachate pH values to shift with aging or external influences (EPA, 2019). For example, alkaline materials that may be exposed to the environment can carbonate, which neutralizes the pH toward the equilibrium pH of calcium carbonate (pH ~ 8.2). Therefore, an applicable pH domain that is inclusive of critical pH values and is based on target eluate pH values from EPA 1313 would be $8 \leq pH \leq 12$. Example test results from EPA 1313 are shown in Figure 6-2 with the applicable pH domain shaded. These examples show that LSP behavior can vary significantly between constituents (e.g., boron vs. lead) but that the behavior for a constituent is very consistent between composite samples. The concentrations within the applicable pH domain are often, but not always, considerably lower than the maximum concentration over the entire EPA 1313 test pH range.

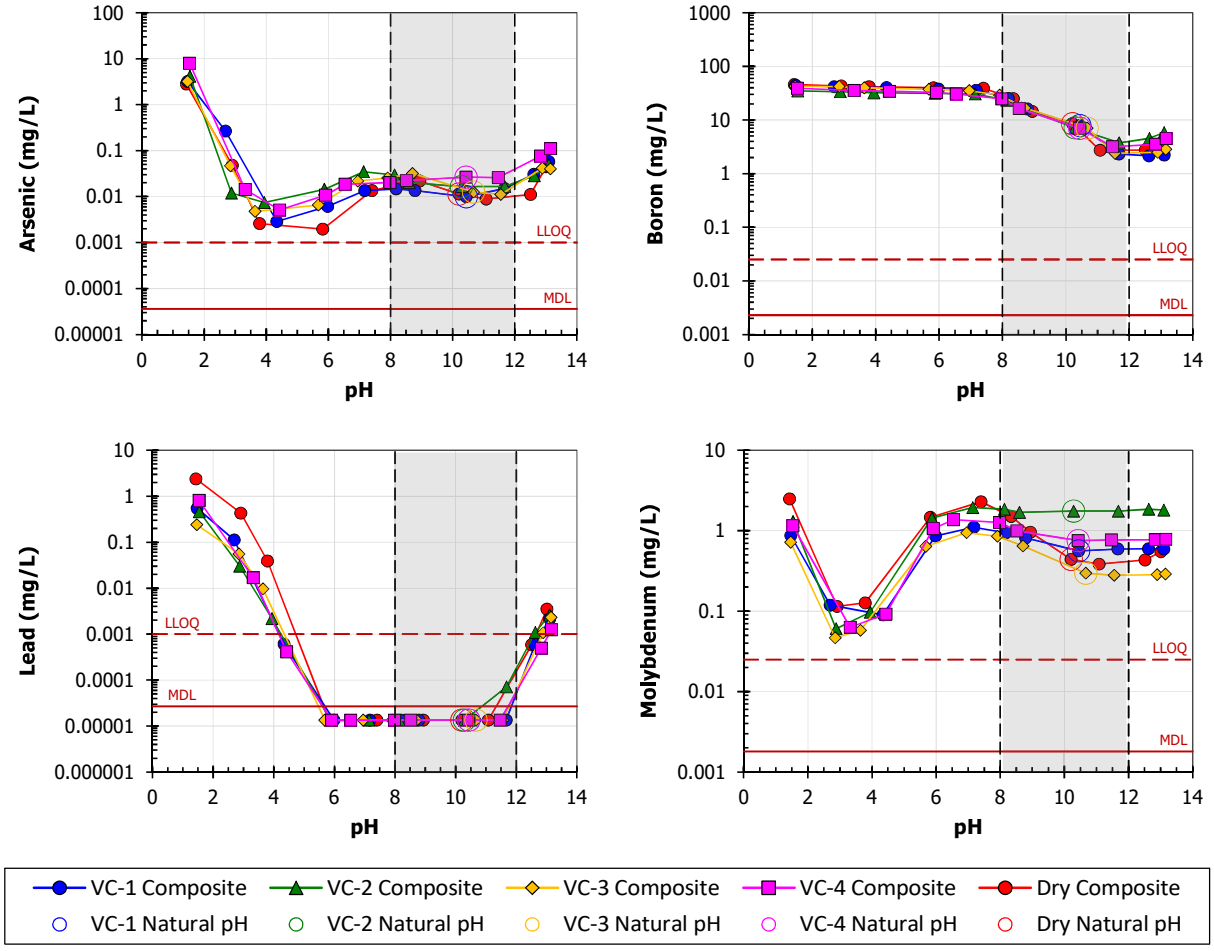

Figure 6-2
Example LSP behaviors from composite samples (VC-1, VC-2, VC-3, VC-4, and Dry) showing applicable pH range ($8 \leq pH \leq 12$) for alkaline materials

Available Content Determination Using EPA 1313

The broad pH range of data provided by EPA 1313 data allows for evaluation of content of leachable constituent, known as the available content (EPA, 2019). The standard EPA methodology (EPA, 2019) for determination of available content is to identify the maximum leaching concentration (mg/L) from EPA 1313 test results at pH value of 2, 9, and 13 and calculate the mass release (mg/kg-dry) at the maximum LSP concentration:

$$AC = C_{1313(\max pH\ 2,9,13)} \cdot (L/S)_{1313}$$

where AC is the available content (mg/kg-dry);
$C_{1313(\max pH\ 2,9,13)}$ is the maximum concentration from EPA 1313 data at pH 2, 9, or 13 (mg/kg-dry); and,
$(L/S)_{1313}$ is the liquid-to-solid ratio for the EPA 1313 extractions of 10 mL/g-dry (10 L/kg-dry).

Values for the available content of constituents for the five composite samples (VC-1, VC-2, VC-3, VC-4, and Dry) are reported in Table 6-3. The ratio of the available content to the total content (Table 6-4) indicates that for most constituents only a fraction (< 20%) is leachable over a broad pH range. In some cases, the available fraction is less than 1% of the total content. In Table 6-4, the high ratios (> 1) for Ca and Mg suggest either that digestion by EPA 3052 was not complete or that there is inherent error associated with multiplying a relatively small digestate concentration by a large effective L/S of 500 or more.

Table 6-3
Available Content for Composite Samples VC-1, VC-2, VC-3, VC-4, and Dry Based on the Maximum Concentration from EPA Method 1313

Analyte	Symbol	VC-1 (mg/kg-dry)	VC-2 (mg/kg-dry)	VC-3 (mg/kg-dry)	VC-4 (mg/kg-dry)	Dry (mg/kg-dry)
Aluminum	Al	4,900	4,900	6,200	4,700	5,100
Antimony	Sb	2.5	2.2	4.6	2.0	3.8
Arsenic	As	32	42	32	79	28
Barium	Ba	4.5	5.5	4.1	6.3	2.7
Beryllium	Be	2.1	1.4	1.3	2.5	1.9
Boron	B	440	350	430	390	460
Bromide	Br^-	< 0.064	< 0.064	< 0.064	< 0.064	< 0.064
Cadmium	Cd	2.5	1.5	2.7	2.3	3.4
Calcium	Ca	17,000	17,000	19,000	15,000	19,000
Chloride	Cl^-	620	460	360	620	470
Chromium	Cr	9.4	11	11	8.0	8.3
Cobalt	Co	1.1	1.5	1.5	2.0	1.9
Copper	Cu	3.5	4.2	2.2	3.8	7.5
Dissolved Inorganic Carbon	DIC	130	140	210	160	67
Dissolved Organic Carbon	DOC	190	180	240	170	24
Fluoride	F^-	< 0.063	83	68	< 0.063	77
Iron	Fe	2,200	2,100	2,200	2,200	2,100
Lead	Pb	5.5	4.6	2.4	8.1	24
Lithium	Li	1.8	1.0	1.7	1.1	3.4
Magnesium	Mg	490	580	760	410	710
Manganese	Mn	80	75	120	57	54
Molybdenum	Mo	8.7	19	9.0	14	25
Nickel	Ni	4.0	4.0	3.9	4.9	4.3
Nitrate	NO_3^-	< 0.11	0.2	< 0.11	< 0.11	< 0.11
Phosphate	PO_4^{-3}	780	1,300	600	830	750
Potassium	K	670	820	730	540	820
Selenium	Se	2.1	1.0	1.3	2.6	2.4
Silicon	Si	5,100	4,900	7,700	4,500	5,700
Silver	Ag	< 0.0004	< 0.0004	< 0.0004	< 0.0004	< 0.0004
Sodium	Na	430	330	260	440	300
Strontium	Sr	25	20	24	35	48
Sulfate	SO_4^{-2}	9,500	7,000	13,000	9,100	19,000
Thallium	Tl	5.1	4.2	3.6	6.3	5.6
Vanadium	V	190	140	150	190	150
Zinc	Zn	10	8.0	13	10	19

Notes: All available contents determined at a pH of 2 except DOC and DIC at pH 13.

Table 6-4
Ratio of Available Content (EPA 1313) to Total Content (EPA 3052) for Composite Samples VC-1, VC-2, VC-3, VC-4, and Dry

		Available Content / Total Content (-)				
Analyte	**Symbol**	**VC-1**	**VC-2**	**VC-3**	**VC-4**	**Dry**
Aluminum	Al	0.23	0.29	0.23	0.26	0.19
Antimony	Sb	0.40	0.49 J	0.92 J	0.26	0.051
Arsenic	As	0.63	0.67	0.67	0.84	0.52
Barium	Ba	0.012	0.012	0.0050	0.016	0.0075
Beryllium	Be	0.19	0.18	0.22	0.19	0.20
Cadmium	Cd	0.57	0.43	0.53	0.61	0.57
Calcium	Ca	1.3	1.8	0.79	1.6	0.91
Chromium	Cr	0.055	0.079	0.085	0.044	0.052
Cobalt	Co	0.034	0.065 J	0.075 J	0.048	0.066
Copper	Cu	0.043	0.058	0.034	0.041	0.096
Iron	Fe	0.018	0.021	0.022	0.017	0.019
Lead	Pb	0.089	0.066	0.036	0.11	0.15
Lithium	Li	0.026	0.018	0.034	0.017	0.048
Magnesium	Mg	1.4 J	1.3 J	1.2B	1.4 J	1.4 F1
Manganese	Mn	0.21 B	0.19 B	0.28 B	0.17 B	0.19 B
Molybdenum	Mo	0.41	0.73	0.50	0.38	0.40
Nickel	Ni	0.031	0.011	0.044	0.031	0.036
Potassium	K	0.056	0.051	0.052	0.045	0.075
Selenium	Se	0.15	0.10	0.14	0.15	0.15
Sodium	Na	0.080	0.063	0.053	0.086	0.079
Strontium	Sr	0.37	0.35	0.36	0.37	0.37 F1
Thallium	Tl	0.39 J	0.30 J	0.37 J	0.45 J	0.60 J
Vanadium	V	0.28	0.31	0.28	0.29	0.24
Zinc	Zn	0.024	0.019	0.031	0.022	0.041

Notes: B the compound was found in the blank and sample of the total content analysis extract.
F1 the matrix spike recovery for the total content analysis extract is outside of acceptance limits.
J the total content result is less than the LLOQ but greater than or equal to the MDL; estimated value.

Alternatively, the available content may be presented graphically as the maximum mass release from EPA 1313 data (Figure 6-3). These figures show that the maximum release for many constituents is often determined at pH $\leq$ 2, but that mass release may be similar at other pH values (see Mo). These figures also show that the absolute value determined for the available content may be dependent on the pH value used to determine the maximum concentration from EPA 1313. For example, the maximum mass release values for arsenic and boron are determined at a pH $\leq$ 2; however, the boron data plateaus in the acidic range, while the arsenic data is still on a steep increasing slope as pH decreases. Therefore, a minor change in the EPA 1313 eluate pH

will not significantly impact the available content determination for boron, while the same minor change may significantly alter the determined available content for arsenic.

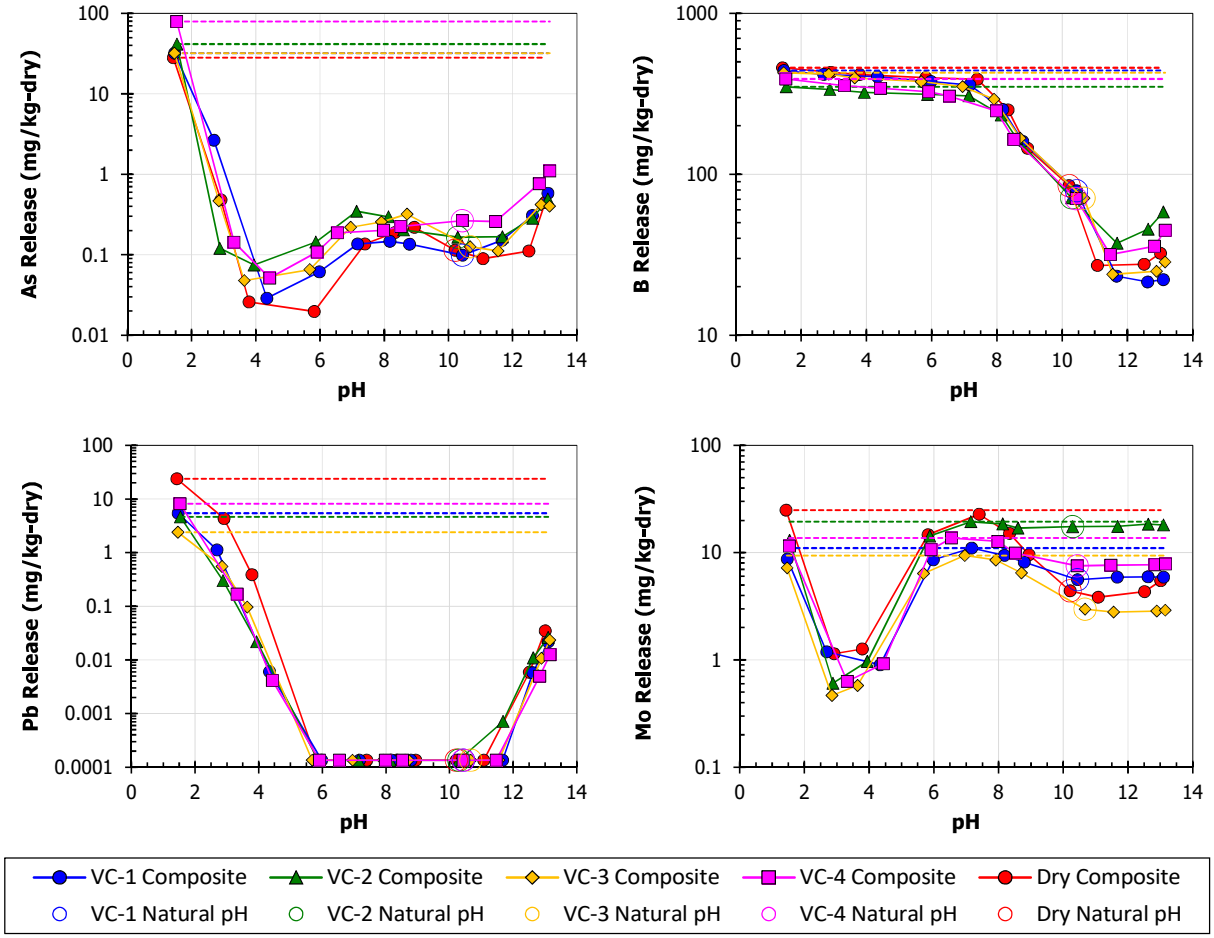

Figure 6-3
Example mass release from composite samples (VC-1, VC-2, VC-3, VC-4, and Dry) showing available content (dashed horizontal lines)

L/S-Dependent Leaching Test Results (EPA 1314)

The results of EPA 1314 indicate how the LSP of constituents changes as the amount of water passing through a bed of material increases (i.e., the cumulative L/S, or ΣL/S). In general, soluble minerals are dissolved and removed from the column at low ΣL/S values; therefore, different minerals and processes (e.g., dissolution vs. desorption) may control the release of constituents at various points along the percolation column elution curve. As leaching progresses, the ionic strength of the porewater decreases, leading to changes in controlling minerals and, in some cases, the controlling LSP mechanisms (e.g., a constituent with an LSP limited by the available content at high concentration may show signs of solubility-controlled LSP at low concentration). In cases where the ΣL/S can be related to the rate of field infiltration, column test data can provide an estimate of leaching concentration as a function of time (Kosson et al., 2014; Garrabrants et al., 2020a, 2020b; EPA, 2019).

pH in Column Eluates

The measured pH values of eluates from the column test (EPA 1314) for the five composite samples (VC-1, VC-2, VC-3, VC-4, and Dry) are presented in Figure 6-4. These graphs also indicate the natural pH (EPA 1313) and the own pH (EPA 1313_L/S=1) as dashed lines, and the range of pH values measured in the PAPs.

For the saturated composites (VC-1, VC-2, VC-3, and VC-4), the evolution of pH in the percolation column shows an initially increasing trend followed by a plateau at an approximate pH of 10, with the starting pH and the plateau varying slightly between composites. However, the evolution of pH for the Dry composite taken from samples above the water table shows a different trend, with an initially high pH that decreases by about 0.5 pH units to plateau at a pH of approximately 9.0. The increase in pH at low L/S for the saturated composites (VC-1 through VC-4) may be due to surficial oxidation or carbonation resulting from contact of moist, alkaline ash with air during sample handling.

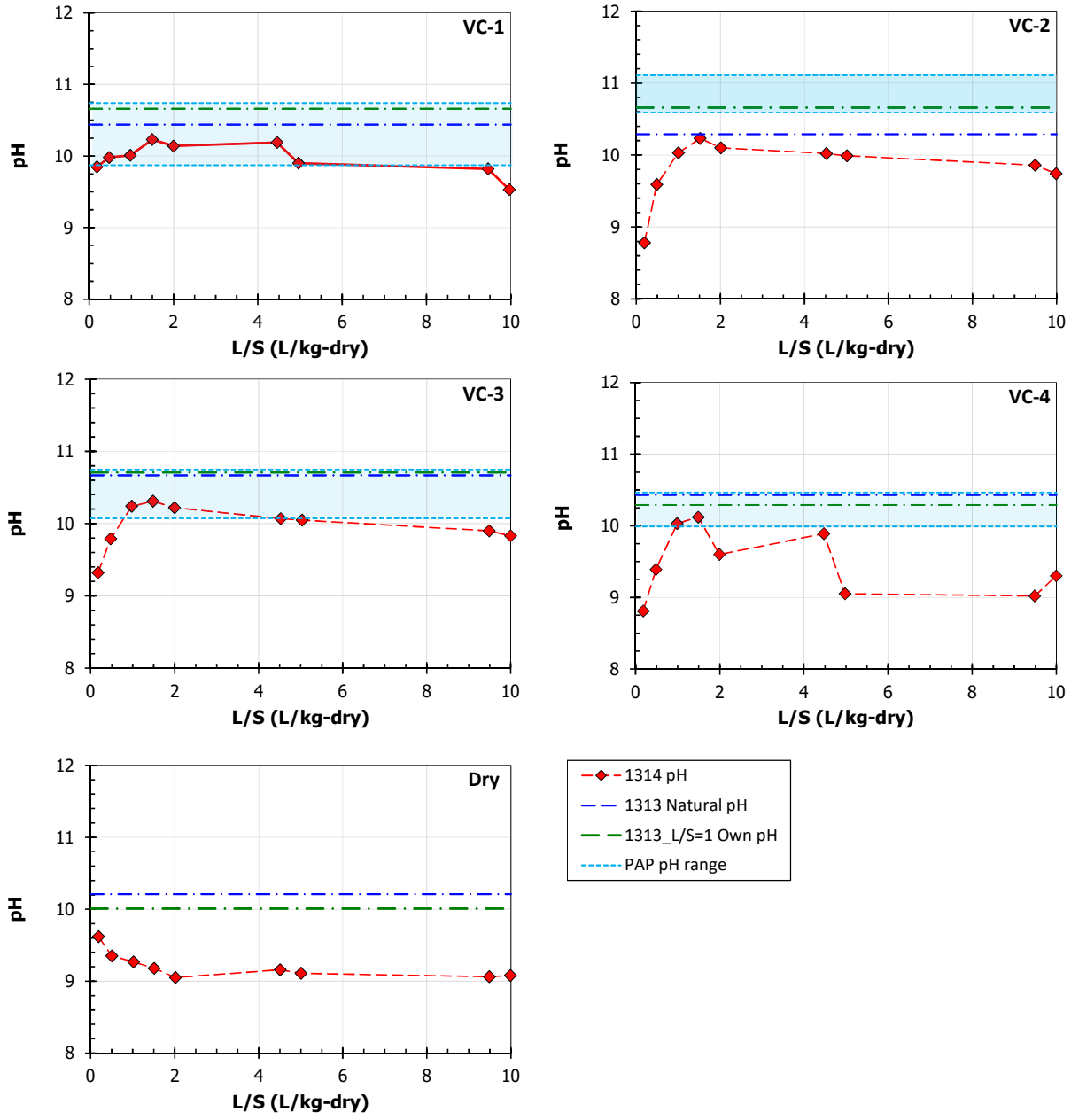

Figure 6-4
Evolution of pH in column eluates (EPA 1314) from five composite samples (VC-1, VC-2, VC-3, VC-4, and Dry) compared to natural pH (EPA 1313), own pH (EPA 1313_L/S1), and range of porewater pH measurements

Table 6-5 compares the eluate pH values from the lowest L/S fraction of EPA 1314 to the range of pH values at higher L/S values, to the natural pH and own pH measured in batch leaching tests (EPA 1313 and 1313_L/S-1), and to the range of pH in porewater samples from the PAPs. In general, column test eluates at low L/S are approximately 1.5 pH units lower than measured in batch leaching tests. The difference may be explained predominantly by ionic strength changes with increasing L/S and interactions with dissolved constituents in equilibrium at the L/S values.

Table 6-5
Comparison of Eluate pH from Low L/S Column Fraction (EPA 1314) to the Natural pH (EPA 1313) and Own pH (1313_L/S=1) of Composite Samples

	Method	L/S (mL/g-dry)	VC-1 pH (SU)	VC-2 pH (SU)	VC-3 pH (SU)	VC-4 pH (SU)	Dry pH (SU)
1st Fraction	EPA 1314	0.2	9.85	8.78	9.32	8.81	9.62
Range	EPA 1314	2-10	9.5-10.1	9.7-10.1	9.8-10.2	9.0-9.9	9.0-9.2
Own pH	1313_L/S=1	1	10.66	10.64	10.71	10.29	10.01
Natural pH	EPA 1313	10	10.44	10.29	10.67	10.43	10.21
Porewater	-	0.35	9.9-10.7	10.6-11.1	10.1-10.8	10.0-10.5	-

Note: Porewater L/S estimated from porosity and density of intact cores collected at the elevation of the PAP.

Constituent Results

The concentration of a constituent's percolation column eluates (EPA 1314) indicates how the LSP changes as water passes through the material. Eluate concentrations and mass release are typically plotted as a function of the cumulative L/S (i.e., the cumulative amount of eluent passing through the column relative to the mass of material in the column).

Examples of typical L/S-dependent behavior from EPA 1314 conducted on the VC-1 composite are shown in Figure 6-5, presented as eluate concentration (mg/L) on the left and cumulative mass release (mg/kg-dry) on the right. In mass release graphs, the gray dashed line indicates the mass release proportional to the cumulative L/S expected if concentration is controlled by constant solubility. The following behaviors are shown in Figure 6-5:

- The eluate concentrations for Sb (top) are essentially constant as a function of L/S and, thus, the mass release is proportional to the cumulative L/S and the mass release curve follows the solubility indicator line. This L/S-dependent behavior is consistent with ***solubility-controlled LSP***.
- EPA Method 1314 data indicate that the constituent concentration of Co (middle) decreases rapidly up to an L/S of 2 L/kg-dry, indicating an ***available content-limited LSP***. Eluate concentrations that are a strong function of L/S may decrease to less than quantitation limits within the test cumulative L/S range, indicating depletion of the available content.
- The L/S-dependent leaching of Se (bottom) is a good example of rapid release of a soluble fraction of the available content without depletion. This differs from the example behavior of Co because, after an initial "wash off" of a highly soluble fraction, leaching concentrations remain detectable and relatively constant, suggesting the constituent exists in ***both content-limited (highly soluble mineral phase) and solubility-controlled (low-solubility mineral phase) LSP*** fractions.

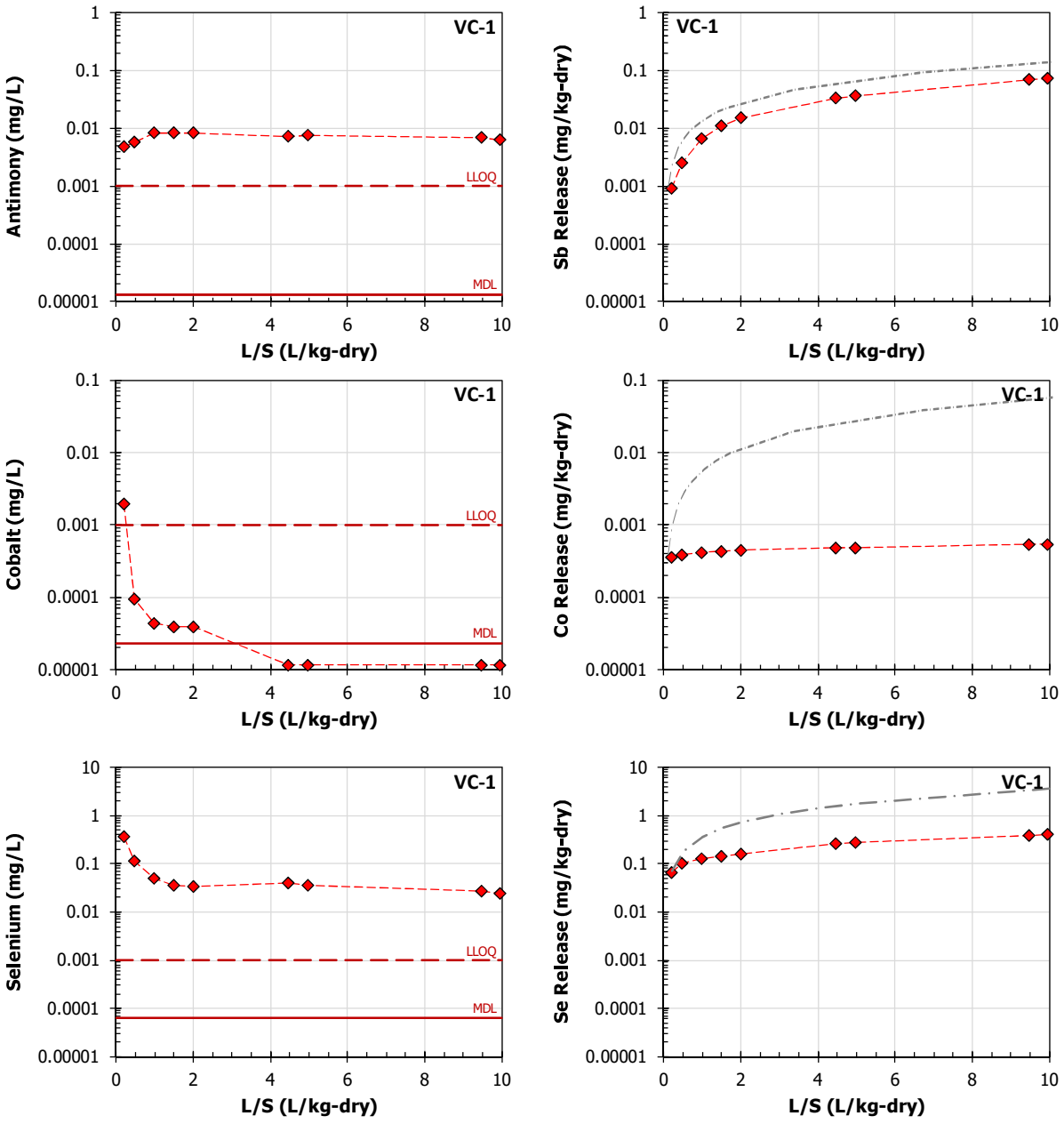

Figure 6-5
Example 1314 test results from VC-1 showing a solubility-controlled constituent (antimony) and depletion of the available content (cobalt) and wash-off of a soluble constituent fraction without depletion (selenium). The gray dot-dashed line indicates prototypical solubility-controlled release fitted to the first EPA 1314 data point.

Determining LSP Behavior

Solubility-Controlled LSP vs. Available Content-Limited LSP

Comparing the impacts of changing pH (e.g., within an EPA 1313 test) with the impact of changing L/S (e.g., within an EPA 1314 test) can be a helpful methodology for distinguishing

the LSP behavior of constituents. Often, the distinction of "solubility-controlled LSP" or "adsorption-controlled" behavior from those with "available content-limited LSP" is a useful classification for grouping large lists of constituents.

The following LSP leaching behaviors were observed from comparison of pH-dependent (EPA 1313) leaching data to L/S-dependent (EPA 1314) leaching data. The focus of the following classifications is limited to the applicable pH domain about the natural pH. Outside of those pH bounds, constituents that were classified as available content-limited may show solubility-controlled LSP or vice versa.

- Solubility-Controlled LSP – When the eluate concentrations are limited by mineral solubility, sorption to mineral phases, and precipitation/dissolution, eluate concentrations are considered ***solubility-controlled.*** Eluate concentrations are a strong function of pH and a weak function of L/S. The LSP for Sb (Figure 6-6) provide a good example of solubility-controlled LSP, as eluate concentrations change by orders-of-magnitude with pH (EPA 1313) but do not change with L/S over the range up to L/S=10 mL/g-dry (EPA 1314). However, the distinction between adsorption and solubility as a controlling mechanism within this classification may be unclear, as both mechanisms are strongly influenced by pH and the patterns for these mechanisms may look similar. Geochemical speciation modeling (not included in this scope) can be useful to discern specific pH-dependent mechanisms.
- Available Content-Limited LSP – When eluate concentrations are limited by the amount of leachable mass in the solid, the characteristic LSP behavior is considered ***available content-limited***. Eluate concentrations are a weak function of pH and a strong function of L/S. Over the applicable pH range ($8 \leq pH \leq 12$), the LSP behavior of Mo (Figure 6-6) presents a good example of available content-limited LSP, as the pH-dependent concentrations (EPA 1313) are relatively stable compared to the significant change in LSP (EPA 1314).
- Wash-Off with Depletion – When a percentage of a constituent is present in porewater or in an easily dissolvable form, there can be a significant initial flush of constituent from a column (i.e., orders-of-magnitude decrease through a $\Sigma L/S$ of 2 L/kg-dry). This behavior is typical for a ***wash-off release mechanism***. The pH-dependent leaching data alone may not indicate this behavior, and the L/S-dependent data become crucial. The endpoint of wash-off can result in depletion of the constituent from the material, evidenced by L/S-dependent concentrations below quantitation limits as presented for Mg in Figure 6-6.

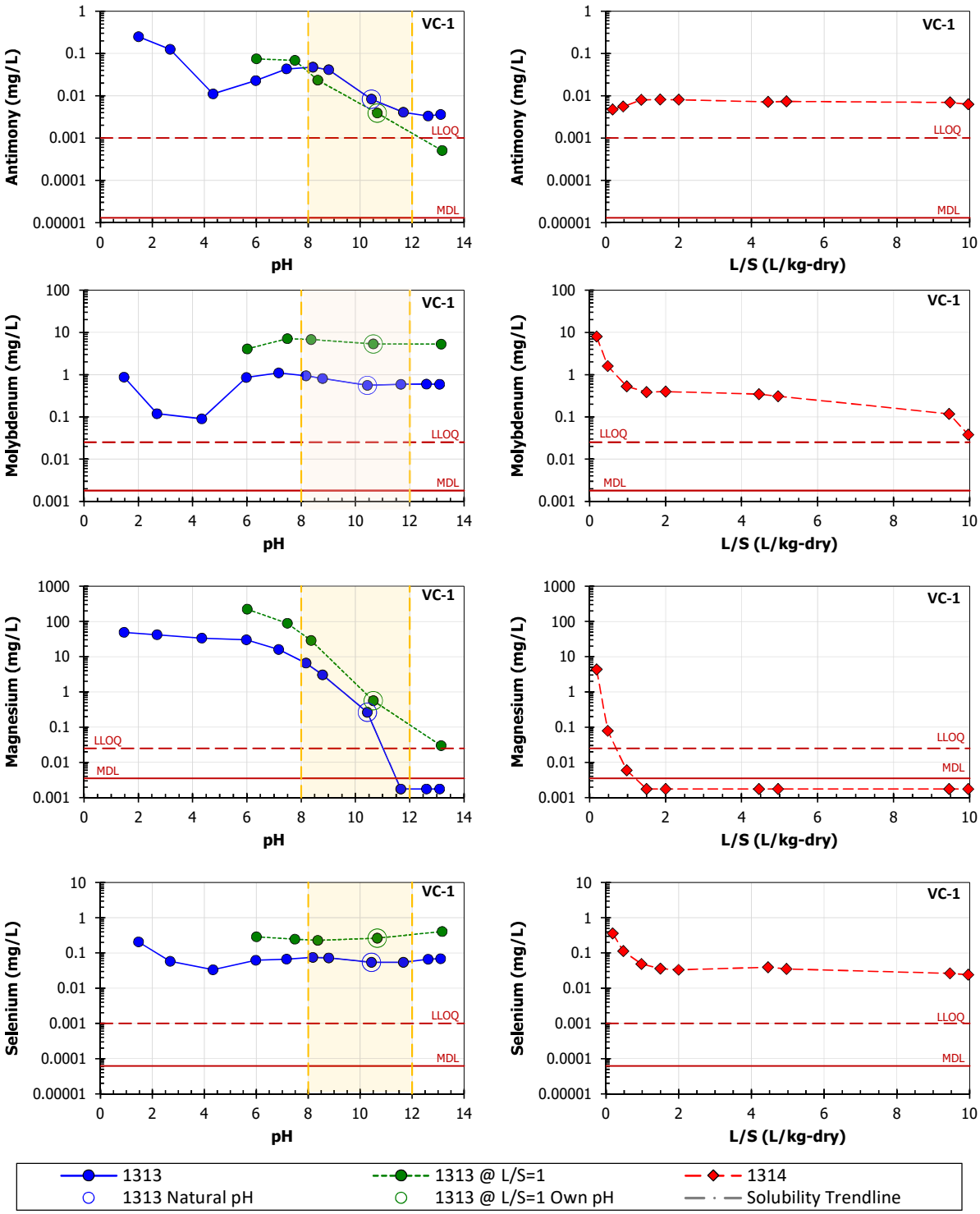

Figure 6-6
Examples of EPA 1313 and EPA 1314 data showing solubility-controlled LSP (antimony); available content-limited LSP (molybdenum); wash-off of soluble fraction leading to depletion (magnesium); and wash-off followed by solubility-controlled LSP (selenium)

- Wash-Off Followed by Solubility Control – In some cases, a secondary fraction of a constituent in the solid material may control eluate concentrations after the initial wash-off. This mechanism results in a relatively constant, detectable eluate concentration following wash-off. In Figure 6-6, Se LSP is a good example of this behavior.
- Non-Detected – For some constituents, eluate concentrations over the applicable pH domain ($8 \leq pH \leq 12$) are below the MDL of the analytical method. Therefore, LSP behavior cannot be determined.

The constituents that are included in each observed behavior are summarized in Table 6-6.

Table 6-6
LSP Behavior over Applicable pH Domain Based on Comparison of EPA 1313 and EPA 1314

LSP Behavior	Constituents
Available Content-Limited	Cl^-, Mo, K, Na
Wash-Off to Depletion	Mg, Mn, NO_3^-
Wash-Off Fraction/Solubility-Controlled	Ba, B, Cd, Cr, Cu, DOC, Li, Ni, Se, Si, Sr, SO_4^{-2}, V
Solubility-Controlled	Al, Sb, As, Ca, DIC, Tl
Non-Detect (values < MDL)	Be, Br^-, Co, F^-, Fe, Pb, PO_4^{-3}, Ag, Zn

The high number of constituents with wash-off followed by a low concentration of solubility-controlled LSP suggest a systematic controlling mechanism in the landfill. Figure 6-7 compares the L/S-dependent data between all composite samples. The data in this figure show that the eluate concentrations for the dry composite are often initially higher than the eluate concentrations of the saturated borehole composites (VC-1 through VC-4). In some cases (e.g., SO_4 in Figure 6-7), the LSP behavior in unsaturated ash is solubility-controlled whereas the LSP behavior in the saturated ash indicates a mobile constituent. These observations suggest that constituents leached from dry-handled ash penetrate into the saturated ash, providing the dissolved or easily solubilized fraction of a constituent in the observed wash-off behavior. Once the overburden constituents are released, the LSP behavior is controlled by the dissolution of more recalcitrant constituents in the saturated ash.

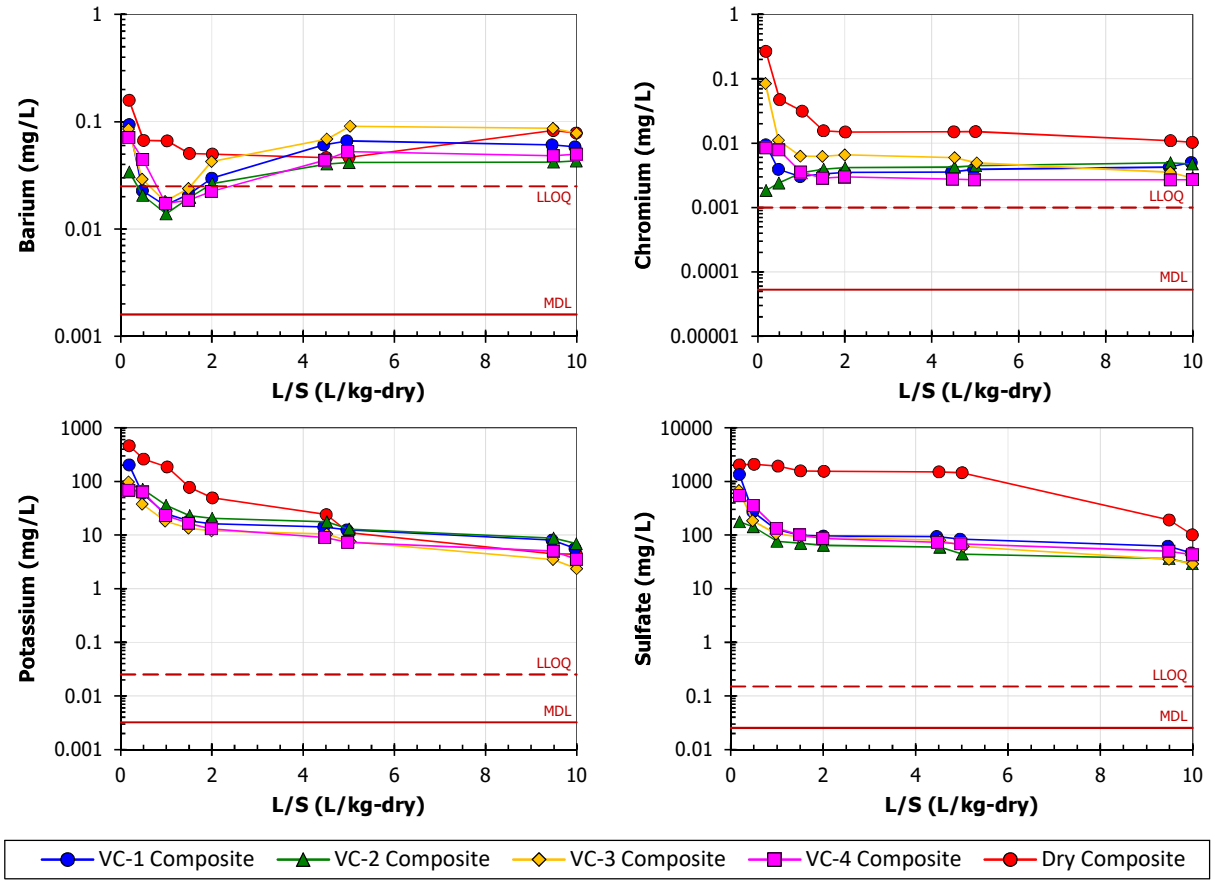

Figure 6-7
Comparison of L/S-dependent (EPA 1314) data showing influence of dry-handled ash (Dry composite) on eluate concentrations of wet-handled ash (VC-1, VC-2, VC-3, and VC-4)

Traditional Extraction Test Results

The L/S and measured pH from the extractions using the traditional leaching tests (TCLP, SPLP, and ASTM) are presented in Table 6-7.

Table 6-7
Liquid-to-Solid Ratio and Measured Extraction pH for Traditional Leaching Tests

Material	TCLP		SPLP		ASTM	
	L/S (mL/g-dry)	pH	L/S (mL/g-dry)	pH	L/S (mL/g-dry)	pH
VC-1	26.8	5.74	26.8	10.47	27.8	10.48
VC-2	28.8	5.39	28.8	10.40	30.0	10.51
VC-3	28.4	6.27	28.4	10.38	29.7	10.60
VC-4	26.9	5.47	26.9	10.32	28.1	10.51
Dry	24.8	5.78	24.8	10.04	24.8	10.20

The amount of extraction fluid for ASTM is determined as the mass of the "as received" test material in grams divided by the test-specific L/S of 20 mL/g. The resultant L/S on a dry basis is greater than 20 because of the water inherent in the pores of the "as received" material. The procedures for TCLP and SPLP require a pressure filtration preconditioning of the test sample to remove excess liquid, which is analyzed separately. The extraction fluid is based on the mass of the pressure-filtered solid material in grams divided by the same L/S of 20 mL/g. Therefore, the calculated L/S for TCLP and SPLP is lower than the L/S for the ASTM test that includes extra water. The measured pH for ASTM, which uses DIW as an extraction fluid, is consistent with the natural pH (1313) and own pH (1313_L/S=1) of the composites at VC-1, VC-2, VC-3, VC-4, and Dry reported in Table 6-2. For SPLP, the measured pH is slightly lower than the ASTM pH, consistent with the small amount of acid used in the extraction fluid. The stability of the measured pH for TCLP extracts across different composites reflects the buffering provided by the organic acetic acid.

The eluate constituent concentrations for TCLP, SPLP, and ASTM tests are presented in Table 6-8, Table 6-9, and Table 6-10, respectively. Since pH is an important factor for solubility-controlled LSP, these tables also include the final eluate pH. Recording of eluate pH allows for comparison of the results of these traditional tests to the pH- and L/S-dependent LEAF test results. In general, SPLP and ASTM concentrations were comparable to each other but were lower than TCLP concentrations, sometimes by orders-of-magnitude. In many cases, the increases in TCLP concentrations were caused by the lower pH of TCLP eluates. Exceptions for this site (which may not be generalizable) include As, Mo, and SO_4^{-2}, where similar concentrations were measure in all three procedures, and PO_4^{-2}, Se, and V, where SPLP and ASTM eluates had higher concentration than TCLP. All of these observations are consistent with the pH-dependent LSP curves discussed above.

Table 6-8
TCLP (EPA Method 1311) Eluate Concentrations

Analyte	Symbol	VC-1 (mg/L)	VC-2 (mg/L)	VC-3 (mg/L)	VC-4 (mg/L)	Dry (mg/L)
	pH	5.74	5.39	6.28	5.47	5.78
Aluminum	Al	1.7	1.8	0.41	2.1	1.1
Antimony	Sb	0.049	0.053	0.073	0.046	0.078
Arsenic	As	0.0056	0.012	0.0097	0.012	0.0064
Barium	Ba	0.55	0.085	0.40	0.84	0.14
Beryllium	Be	0.001 J	0.0019	0.0001 J	0.0023	0.0015
Boron	B	15	13	16	15	19
Bromide	Br^-	ND	ND	ND	ND	ND
Cadmium	Cd	0.019	0.013	0.010	0.018	0.032
Calcium	Ca	650	500	750	550	860
Carbon, Inorganic	DIC	4.5	5.5	13	8.1	2.1
Chloride	Cl^-	2.7	3.7	2.3	7.5	7.6
Chromium	Cr	0.037	0.081	0.13	0.048	0.0071
Cobalt	Co	0.017	0.014	0.010	0.028	0.029
Copper	Cu	0.018	0.021	0.013	0.022	0.017
Fluoride	F^-	ND	ND	ND	ND	ND
Iron	Fe	0.19	0.14	0.017 J	0.19	0.060
Lead	Pb	0.0002 J	0.0003 J	0.0001 J	0.0002 J	0.0009 J
Lithium	Li	0.009 J	0.011 J	0.012 J	0.008 J	0.014 J
Magnesium	Mg	4.8	5.7	8.5	6.2	13
Manganese	Mn	2.6	2.4	1.9	2.1	0.68
Molybdenum	Mo	0.32	0.45	0.35	0.38	0.82
Nickel	Ni	0.085	0.071	0.057	0.11	0.13
Nitrate	NO_3^-	ND	ND	ND	ND	ND
Phosphate	PO_4^{-3}	ND	ND	ND	ND	ND
Phosphorus	P	ND	ND	ND	ND	ND
Potassium	K	22	24	17	17	35
Selenium	Se	0.054	0.059	0.077	0.071	0.093
Silicon	Si	31	42	21	36	30
Silver	Ag	ND	ND	ND	ND	ND
Sodium	Na	540	530	540	530	530
Strontium	Sr	0.75	0.58	0.66	1.0	1.6
Sulfate	SO_4^{-2}	380	280	480	290	970
Sulfur	S	130	96	160	98	350
Thallium	Tl	0.028	0.031	0.013	0.041	0.034
Vanadium	V	0.28	0.26	0.37	0.26	0.26
Zinc	Zn	0.31	0.27	0.11	0.36	0.52

Notes: Data for VC-3 shown as mean of duplicate tests (TCLP-A, TCLP-B).
J the result is less than the LLOQ but greater than or equal to the MDL; estimated concentration.
ND the compound was not detected at a concentration above the MDL.
Organic carbon is not reported, as the results are dominated by the organic carbon in the TCLP extraction fluid.

Table 6-9
SPLP (EPA Method 1312) Eluate Concentrations

Analyte	Symbol	VC-1 (mg/L)	VC-2 (mg/L)	VC-3 (mg/L)	VC-4 (mg/L)	Dry (mg/L)
	pH	10.47	10.40	10.38	10.32	10.04
Aluminum	Al	6.8	6.4	4.9	6.7	3.5
Antimony	Sb	0.010	0.014	0.011	0.0093	0.0074
Arsenic	As	0.0066	0.0091	0.0091	0.016	0.0080
Barium	Ba	0.11	0.070	0.12	0.098	0.085
Beryllium	Be	ND	ND	ND	ND	ND
Boron	B	2.5	2.0	1.9	2.1	1.6
Bromide	Br^-	ND	ND	ND	ND	ND
Cadmium	Cd	0.0004 J	0.0015	0.0001 J	0.0006 J	0.0004 J
Calcium	Ca	47	40	47	47	150
Carbon, Inorganic	DIC	3.6	4.7	3.9	3.9	6.0
Carbon, Organic	DOC	2.9	3.0	2.7	2.6	2.5
Chloride	Cl^-	9.0	5.5	5.9	9.8	9.5
Chromium	Cr	0.0026	0.0033	0.0069	0.0022	0.0082
Cobalt	Co	0.0001 J	0.0002 J	0.0001 J	0.0001 J	0.0003 J
Copper	Cu	0.0017	0.0011	0.0018	0.0013	0.0026
Fluoride	F^-	ND	ND	ND	ND	ND
Iron	Fe	0.001 J	0.0077 J	0.0077 J	0.014 J	ND
Lead	Pb	ND	ND	ND	ND	ND
Lithium	Li	0.012 J	0.009 J	0.016 J	0.008 J	0.011 J
Magnesium	Mg	0.0022 J	0.016 J	0.030	0.043	0.16
Manganese	Mn	0.0014	0.0015	0.0014	0.0013	0.0014
Molybdenum	Mo	0.18	0.51	0.10	0.25	0.14
Nickel	Ni	0.0019	0.0017	0.0012	0.0012	0.0054
Nitrate	NO_3^-	250	250	250	220	150
Phosphate	PO_4^{-3}	ND	ND	ND	ND	ND
Phosphorus	P	ND	ND	ND	ND	ND
Potassium	K	7.5	73	5.1	4.9	13
Selenium	Se	0.052	0.041	0.028	0.040	0.028
Silicon	Si	2.0	2.0	3.0	1.8	1.7
Silver	Ag	ND	ND	ND	ND	ND
Sodium	Na	8.6	4.8	5.2	8.2	7.3
Strontium	Sr	0.10	0.059	0.08	0.12	0.42
Sulfate	SO_4^{-2}	76	52	62	63	360
Sulfur	S	27	19	22	22	130
Thallium	Tl	0.0013	0.0015	0.0008 J	0.0017	0.0010
Vanadium	V	0.28	0.24	0.34	0.27	0.24
Zinc	Zn	0.0025	0.0022	0.0013	0.0016	0.0015

Notes: Data for VC-4 shown as mean of duplicate tests (SPLP-A, SPLP-B).
J the result is less than the LLOQ but greater than or equal to the MDL; estimated concentration.
ND the compound was not detected at a concentration above the MDL.

Table 6-10
ASTM (ASTM D3987) Eluate Concentrations

Analyte	Symbol	VC-1 (mg/L)	VC-2 (mg/L)	VC-3 (mg/L)	VC-4 (mg/L)	Dry (mg/L)
	pH	10.48	10.51	10.60	10.51	10.20
Aluminum	Al	6.9	6.6	4.9	7.0	3.2
Antimony	Sb	0.010	0.015	0.012	0.0098	0.0067
Arsenic	As	0.0058	0.0088	0.0085	0.0076	0.0089
Barium	Ba	0.11	0.075	0.12	0.10	0.086
Beryllium	Be	ND	ND	ND	ND	ND
Boron	B	3.9	2.5	1.8	1.9	1.6
Bromide	Br^-	ND	ND	ND	ND	ND
Cadmium	Cd	0.0005 J	0.0012	0.0001 J	0.0006 J	0.0004 J
Calcium	Ca	47	41	46	49	140
Carbon, Inorganic	DIC	29	2.8	4.9	5.5	5.2
Carbon, Organic	DOC	2.2	2.3	2.4	2.2	2.0
Chloride	Cl^-	10	6.8	5.1	12	9.9
Chromium	Cr	0.0084	0.0070	0.011	0.0029	0.0059
Cobalt	Co	0.0003 J	0.0003 J	0.0002 J	0.0002 J	0.0003 J
Copper	Cu	0.001	0.0013	0.0013	0.0025	0.0024
Fluoride	F^-	ND	ND	ND	ND	ND
Iron	Fe	0.012 J	0.0054 J	0.0027 J	0.0053 J	ND
Lead	Pb	ND	0.0004 J	ND	ND	ND
Lithium	Li	0.013	0.0079 J	0.013 J	0.014 J	0.0081 J
Magnesium	Mg	0.039	0.013 J	0.024 J	0.038	0.16
Manganese	Mn	0.0031	0.0053	0.0026	0.0022	0.0020
Molybdenum	Mo	0.18	0.514	0.095	0.25	0.14
Nickel	Ni	0.0018	0.0015	0.0016	0.0018	0.0035
Nitrate	NO_3^-	ND	ND	ND	ND	ND
Phosphate	PO_4^{-3}	ND	ND	ND	ND	ND
Phosphorus	P	ND	ND	ND	ND	ND
Potassium	K	7.5	7.3	5.1	5.1	13
Selenium	Se	0.047	0.038	0.026	0.039	0.037
Silicon	Si	2.1	2.1	3.1	1.9	1.9
Silver	Ag	ND	ND	ND	ND	ND
Sodium	Na	8.0	5.9	3.8	9.1	7.3
Strontium	Sr	0.095	0.06	0.07	0.12	0.41
Sulfate	SO_4^{-2}	77	55	60	67	390
Sulfur	S	27	19	22	24	130
Thallium	Tl	0.0018	0.0022	0.0011	0.0028	0.0013
Vanadium	V	0.26	0.21	0.32	0.25	0.25
Zinc	Zn	0.0071	0.0025	0.0017	0.0028	0.0024

Notes: Data for VC-2 shown as mean of duplicate tests (ASTM-A, ASTM-B).
J the result is less than the LLOQ but greater than or equal to the MDL; estimated concentration.
ND the compound was not detected at a concentration above the MDL.

Comparison of Traditional and LEAF Test Results

When the pH and L/S of leaching tests are recorded, the test results from different leaching tests can be compared based on eluate pH or L/S. An example comparison is shown in Figure 6-8 for Mo leaching from the VC-2 composite. In Figure 6-8, the eluate concentrations (mg/L) are shown in the left column, and mass release values (mg/kg-dry) are shown in the right column. The upper row presents data as a function of pH, with L/S-dependence shown in the bottom row.

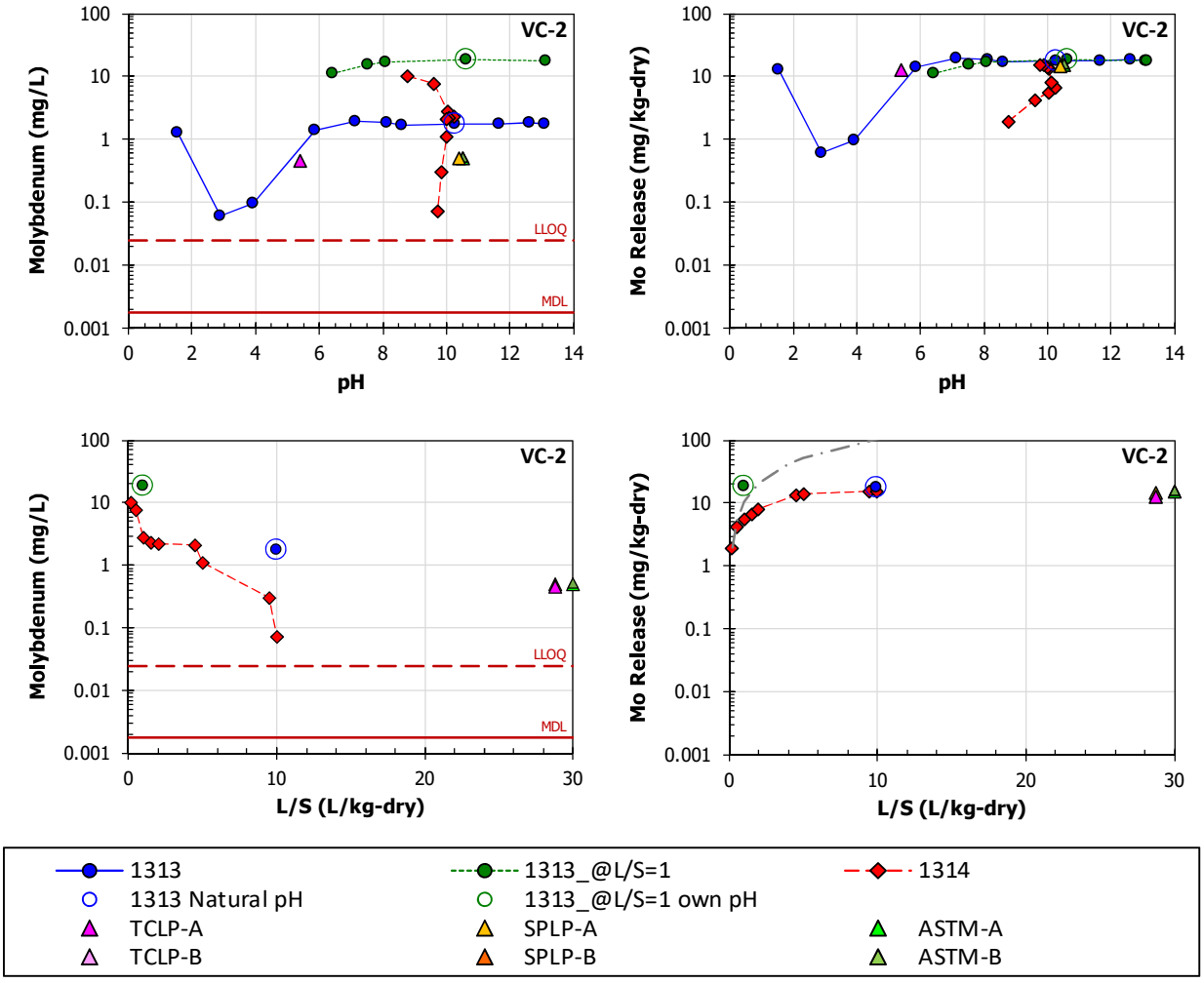

Figure 6-8
Comparison of molybdenum concentration (left) and mass release (right) using traditional (TCLP, SPLP, and ASTM) and LEAF tests (1313, 1313_L/S=1, and 1314); replicates indicated by "-A" and "-B"

For a constituent with available content-limited LSP, for example Mo, the concentrations obtained from the traditional leaching test data are slightly lower than those in EPA Method 1313 and consistent with the higher L/S for the traditional tests. The data for SPLP and ASTM are very close to the leaching response at natural pH measured in EPA Method 1313 due to the little to no acidity added. Conversely, the buffered solution of TCLP leads to a significant lower eluate pH. However, on a mass release basis (Figure 6-8 upper right) all of the results are consistent.

When data for a constituent with available content-limited LSP are compared as a function of L/S, the eluate concentrations of any single extraction at a fixed L/S are unlikely to match the column elution curve. The concentrations in the column test reflect a "progressive" leaching case where material is removed from the column, rather than a batch leaching case represented by single extractions. However, mass release as a function of L/S should be consistent between all tests because the basis of the data is the solid mass. Of course, the L/S of traditional tests are much higher than the L/S of either the LEAF tests or field conditions, so the data are not readily compared or applicable to leaching scenarios with low L/S values.

7
GROUNDWATER, POREWATER, AND SUBSURFACE GAS MONITORING

Measured field parameters for groundwater and porewater sampling as well as graphical presentation of groundwater and porewater concentrations from unfiltered samples are provided in Appendix D-1. These data represented the sampling period from June 2019 through January 2020. Monthly analysis of groundwater wells and PAPs focused on 17 constituents from 40 CFR 257 (As, B, Ba, Be, Ca, Cd, Cl^-, Co, Cr, F^-, Li, Mo, Pb, Sb, Se, SO_4^{-2}, and Tl) and 13 additional constituents (Ag, Br^-, Cu, DIC, DOC, Fe, K, Na, Ni, PO_4^{-3}, Sr, V, and Zn).

Groundwater and Porewater Parameters

Plots of field measurements are shown in Figure 7-1 and Figure 7-2. Within each bar chart, data for the porewater sampled at the four boreholes are presented in solid colors (i.e., blue for VC-1, green for VC-2, gold for VC-3, and purple for VC-4). The downgradient groundwater is presented as stripe-filled bars that are color-coded to their nearest PAP (i.e., the groundwater monitoring well at 209 is associated with VC-2 while the groundwater monitoring well at 931 is more directly opposite VC-4). Due to physical activity at the landfill during sampling (ongoing deposits and grading), not all PAPs were sampled each month.

The data in Figure 7-1 show that the water table elevation, pH, and electrical conductivity remain relatively constant over time at each sample point. The mean water table in the PAPs (386.8 ft AMSL) is approximately 27 feet higher in elevation than the mean water table of the downgradient wells (360.2 ft AMSL). The pH of the porewater in the PAPs is more alkaline ($pH_{ave\text{-}VCs}$=10.5±0.3) than in the downgradient monitoring wells (pH_{ave}=6.7±0.2).

Figure 7-2 presents measured values of water temperature, ORP, and DO, showing seasonal trends for all parameters. The ORP values of the PAP porewater appear to have significant variability, which may be indicative of the nature of the ORP measurement. The mean dissolved oxygen for the two downgradient monitoring wells (DO_{ave}=0.9±0.3 mg/L) is somewhat lower than in the PAPs ($DO_{ave\text{-}VCs}$=1.5±0.3 mg/L). The dissolved oxygen data for all of the porewater and groundwater measurements are notably less than the 9.1 mg/L for saturated surface water at 20 ºC (USGS, 1998) and, therefore, the porewater is considered to be suboxic.

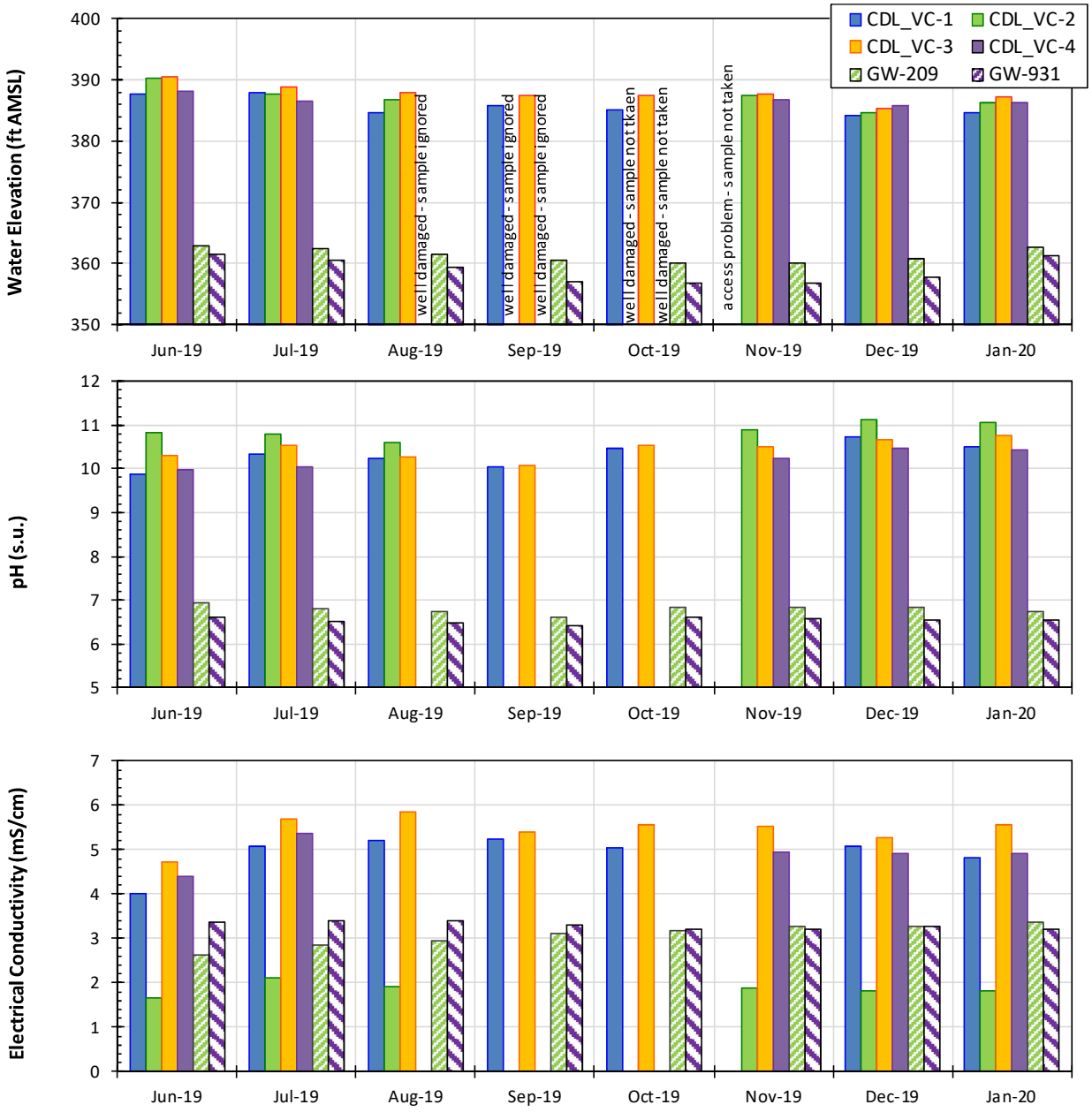

Figure 7-1
Groundwater and porewater field parameters from monthly sampling: water table elevation, pH, and EC

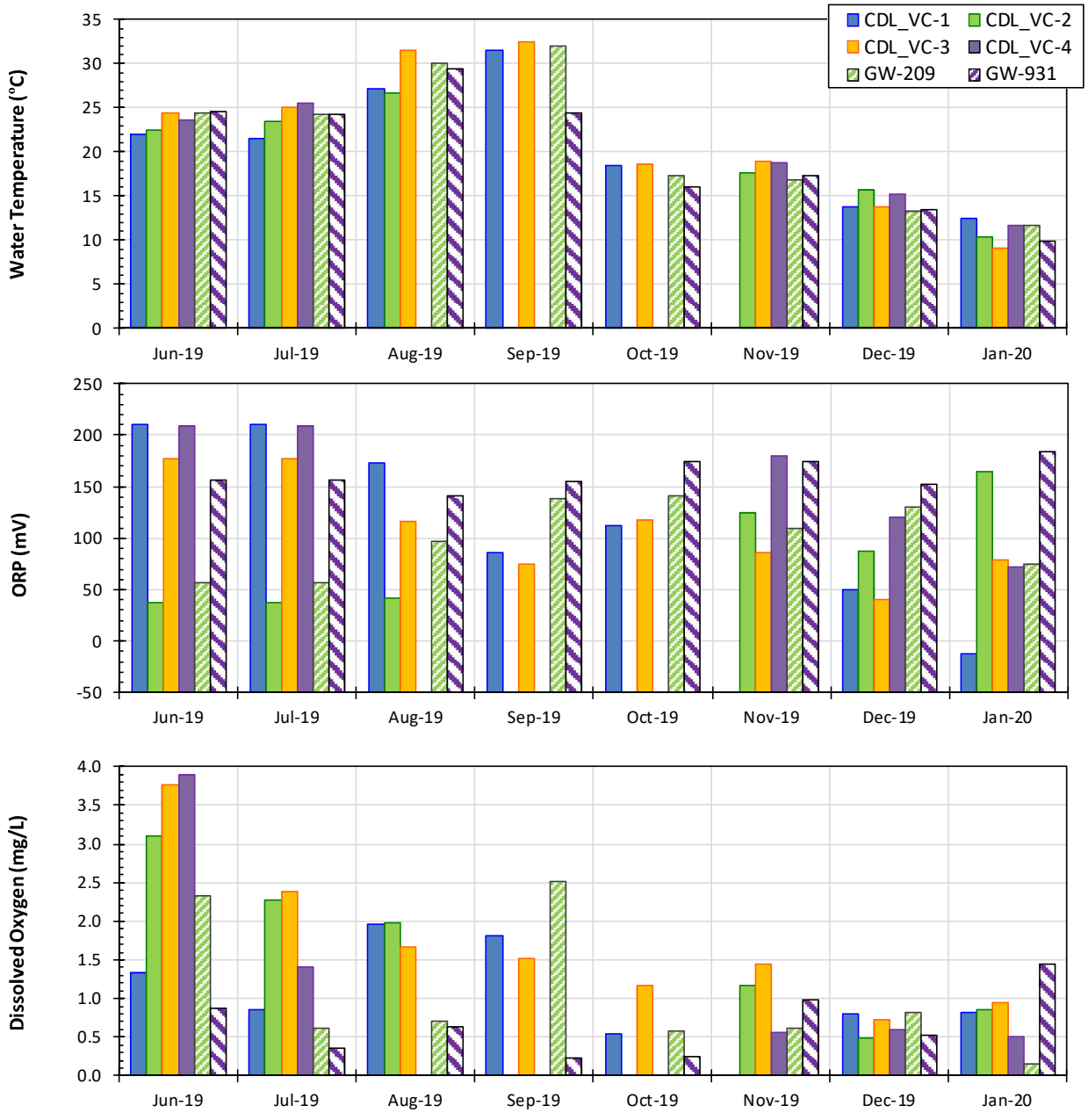

Figure 7-2
Groundwater and porewater field parameters from monthly sampling: water temperature, ORP, and DO

Concentrations in Groundwater and Porewater

Monthly analysis of groundwater wells and PAPs focused on 30 constituents, including 17 from 40 CFR 257 (As, B, Ba, Be, Ca, Cd, Cl^-, Co, Cr, F^-, Li, Mo, Pb, Sb, Se, SO_4^{-2}, and Tl). Thirteen additional constituents that were analyzed were Ag, Br^-, Cu, DIC, DOC, Fe, K, Na, Ni, PO_4^{-3}, Sr, V, and Zn. Examples of the results for selected constituents are presented in Figure 7-3 and Figure 7-4, while the graphical results for all 30 constituents are presented in Appendix D-1.

Given the geography and groundwater flow patterns at this site, there was not an upgradient monitoring well that could be used in a comparison to determine whether or not there were any impacts to groundwater from this CCP unit; therefore this analysis will not attempt to determine whether or not the groundwater quality represents releases from the coal ash. The discussion that follows allows for either possibility as the relationship between porewater and downgradient groundwater is explored.

An analysis of variance (ANOVA) was initially attempted to compare the groundwater and porewater datasets, but in most cases low p-values indicated that groundwater and porewater concentrations were not from the same statistical population. Instead, downgradient concentrations were directly compared to porewater concentrations using means and standard deviations. Table 7-1 summarizes the standard deviation analysis as follows:

- "GW >> PW" and "GW << PW" indicate that the mean groundwater concentration (GW) for a groundwater monitoring well was greater than or less than the mean porewater concentration (PW) at the associated PAP by a difference of three standard deviations or more;
- "GW > PW" and "GW < PW" indicate that the mean groundwater concentration at a groundwater monitoring well was greater than or less than the mean porewater concentration at the associated PAP by a difference of greater than one standard deviation, but less than three standard deviations; and,
- "GW ≈ PW" indicates that the mean groundwater concentration from a groundwater monitoring well was within one standard deviation of the mean porewater concentration of the associated PAP.

In Table 7-1, Ag, Be, Cr, F^-, and Pb are not included because the concentrations of these constituents were below the analytical MDL in both porewater and groundwater. The summary in the table assumes the potential for a connection between specific PAPs and specific groundwater monitoring wells (e.g., VC-2 and Well 209), based solely on geography and a general understanding of groundwater flow direction.

Table 7-1
Relationships between Groundwater and Porewater Based on PAP-Downgradient Groundwater Pairs (Well 209 and PAP at VC-2; Well 931 and PAP at VC-4)

	Monitoring Well 209 (GW) to PAP at VC-2 (PW)	Monitoring Well 931 (GW) to PAP at VC-4 (PW)
GW >> PW	B, Ca, Cl^-, Co, Fe, SO_4^{-2}	Co, Fe
GW > PW	-	Ni, Zn
GW ≈ PW	Ba	Ba, Cl^-,
GW < PW	As, Cu*, V	-
GW << PW	Cd*, Li, Mo, Ni, Sb*, Se, Tl*, Zn*	As, B, Ca, Cd*, Cu, Li, Mo, Sb*, Se, SO_4^{-2}, Tl*, V

Notes * Indicates that groundwater concentrations were all or mostly below the MDL

The following are observations from this summary.

- Co and Fe have higher concentrations in groundwater than in porewater for all comparisons, while Ba and Cl^- concentrations were similar or much higher in groundwater depending on the comparison. Higher groundwater concentrations suggest that porewater from the coal ash is not the primary source of the groundwater concentration and a limited relationship exists between recent porewater concentration and the downgradient groundwater concentrations at this site. Similar concentrations could be indicative of a release, especially if the constituent is environmentally conservative (e.g., B, Cl^-, and SO_4^{-2}); however, it is unlikely that there would be no dilution when leachate would be released to groundwater. The history and variety of residual storage at this site (e.g., underlying large area of sluiced ash, bottom ash collection ponds, gypsum storage stacks) confounds the ability to use boron as an indicator species for release from this landfill.
- Nine constituents (As, Cd, Cu, Li, Mo, Sb, Se, Tl, and V) have higher concentration in porewater than in both downgradient monitoring wells for all comparisons. Higher concentrations in coal ash porewater suggest that porewater has the potential to affect downgradient groundwater quality; however, porewater concentrations for several of these constituents (Cd, Li, Mo, Sb, Tl, and V) are 2 to 3 orders-of-magnitude higher in the coal ash deposit than in the downgradient wells, suggesting limited impact from porewater on downgradient monitoring well concentrations at this site.

Overall, these observations indicate that at this site, high porewater concentrations cannot be assumed to indicate impacts on downgradient groundwater concentrations.

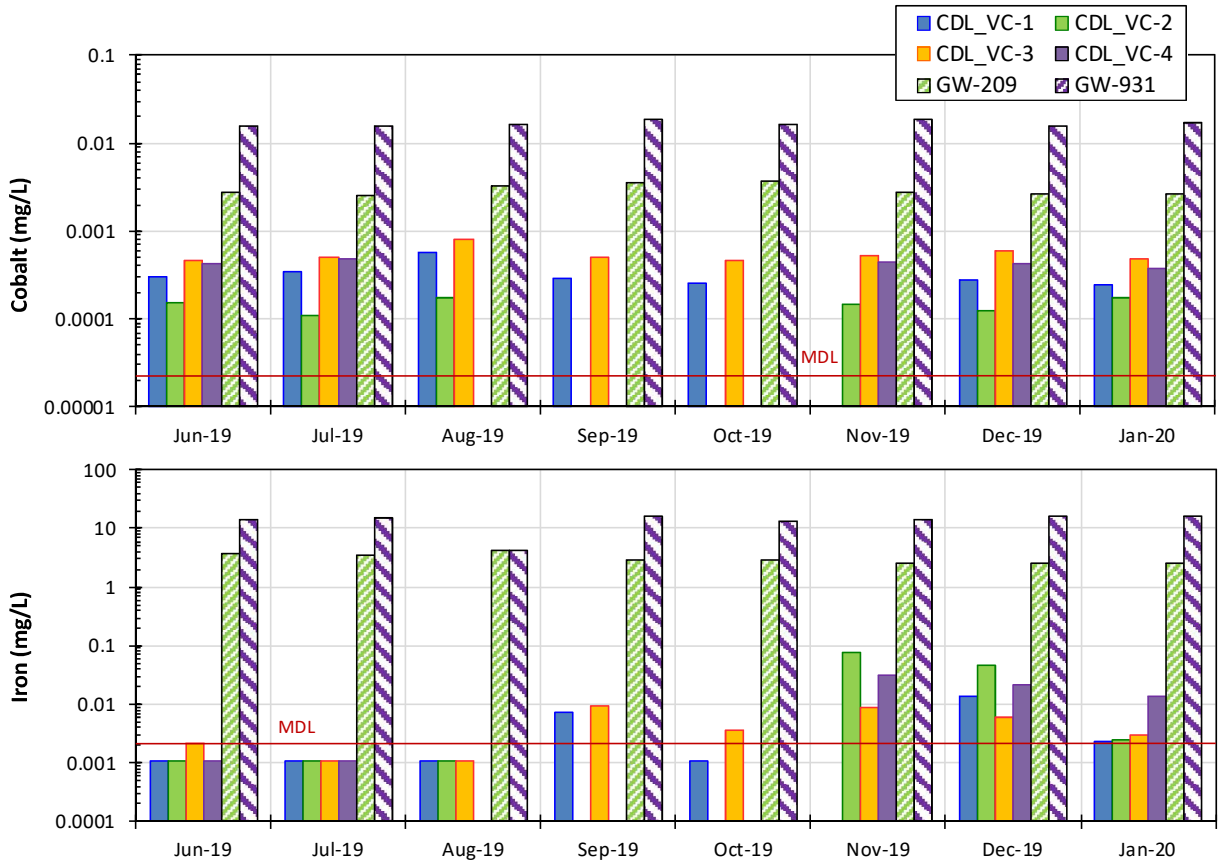

Figure 7-3
Groundwater and porewater monitoring from monthly sampling showing lower concentrations in coal ash porewater (VC-1, VC-2, VC-3, and VC-4) than in downgradient groundwater wells (209 and 931); concentrations plotted on a logarithmic axis

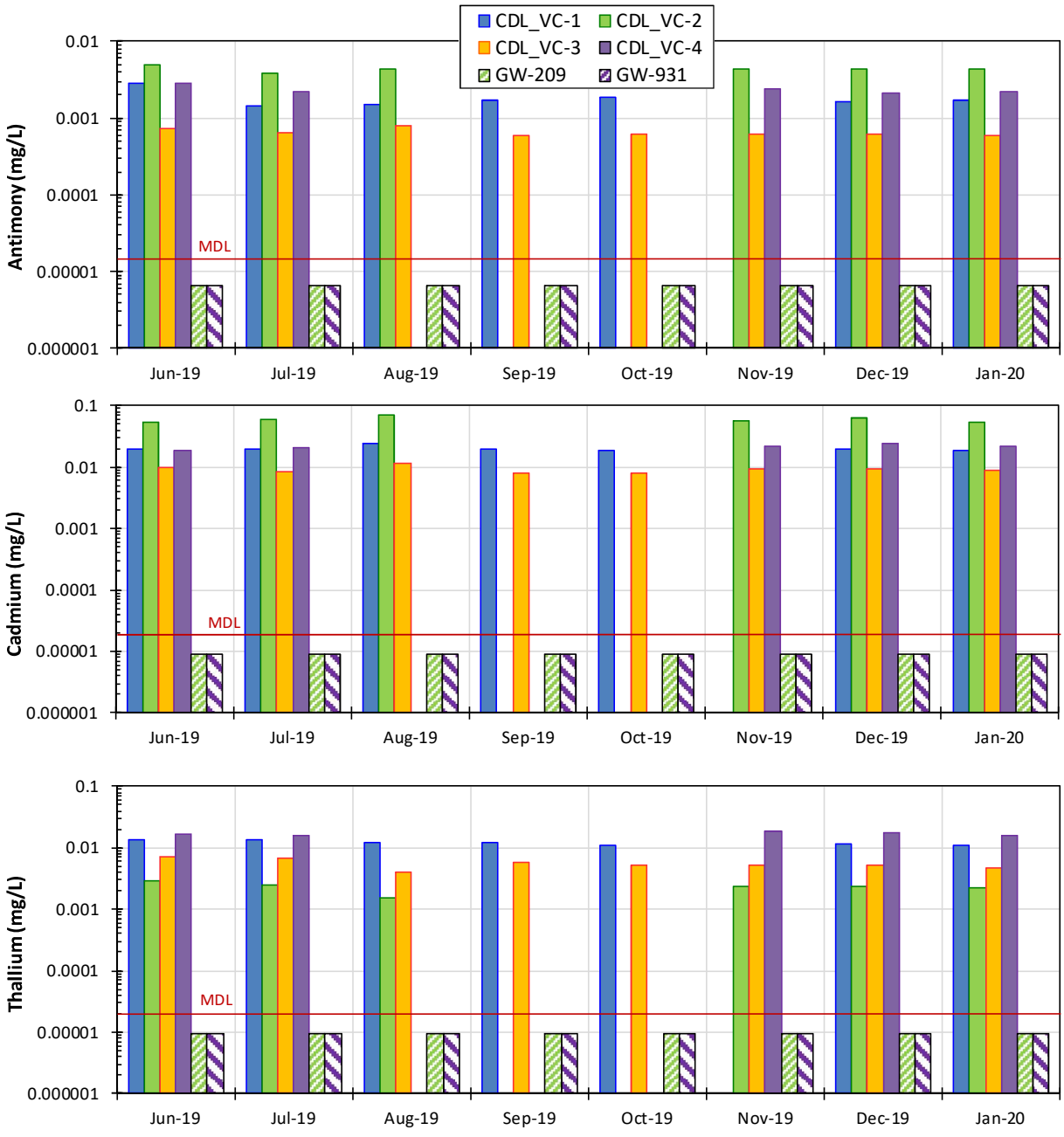

Figure 7-4
Groundwater and porewater monitoring from monthly sampling showing significantly higher concentrations in coal ash porewater (VC-1, VC-2, VB-3, and VC-4) than in groundwater from the downgradient wells (209 and 931); concentrations plotted on a logarithmic axis

Temporal and Spatial Variability in Porewater Parameters

Data reflecting the temporal variability of porewater parameters from monthly monitoring are presented as time-series plots as a function of date. The shapes of the time series distinguish porewater properties that are relatively constant over the sampling period from porewater properties that vary with time. Time-series plots are presented in Appendix D-2. Examples of time series plots for field parameters (Figure 7-5) indicate that variability over the sampling period may be primarily attributed to seasonal changes (e.g., temperature, redox conditions as seen by pH+pE). The trends in porewater constituent concentrations (Figure 7-6) show that many parameters remained relatively constant throughout the monitoring period. The trend lines for VC-2 (green) and VC-4 (pink) were interrupted due to activity on the landfill that caused damage to the PAP. The damage was repaired and the PAPs redeveloped prior to continuation of data collection.

The spatial variability between PAP concentrations was evaluated based on the differences between mean constituent concentrations. Concentrations of a constituent in a PAP were deemed systematically different if the mean concentration in that PAP was more than a factor of five higher or lower than the mean of other PAPs. Based on this analysis, the following observations were made:

- The mean concentrations of Ag, Be, Cr, F^-, and Pb were below the MDL for the analysis and, therefore, no spatial variability could be determined.
- The mean concentrations of Cl^-, Cu, Fe, SO_4^{2-}, Tl, and Zn in VC-2 and Cd and Sb in VC-3 were lower than the mean concentrations in the other PAPs; however, some of this variability may be explained by the damage to wells VC-2 and VC-4.
- The mean concentrations of Cl^- in VC-4, Li in VC-1, and Mo in VC-2 (Figure 7-6) were higher than the mean concentrations in the other PAPs.

Of the 23 constituents evaluated, only Cu and Zn had mean concentrations between PAPs that varied by more than an order-of-magnitude; however, no pattern in spatial variability was observed.

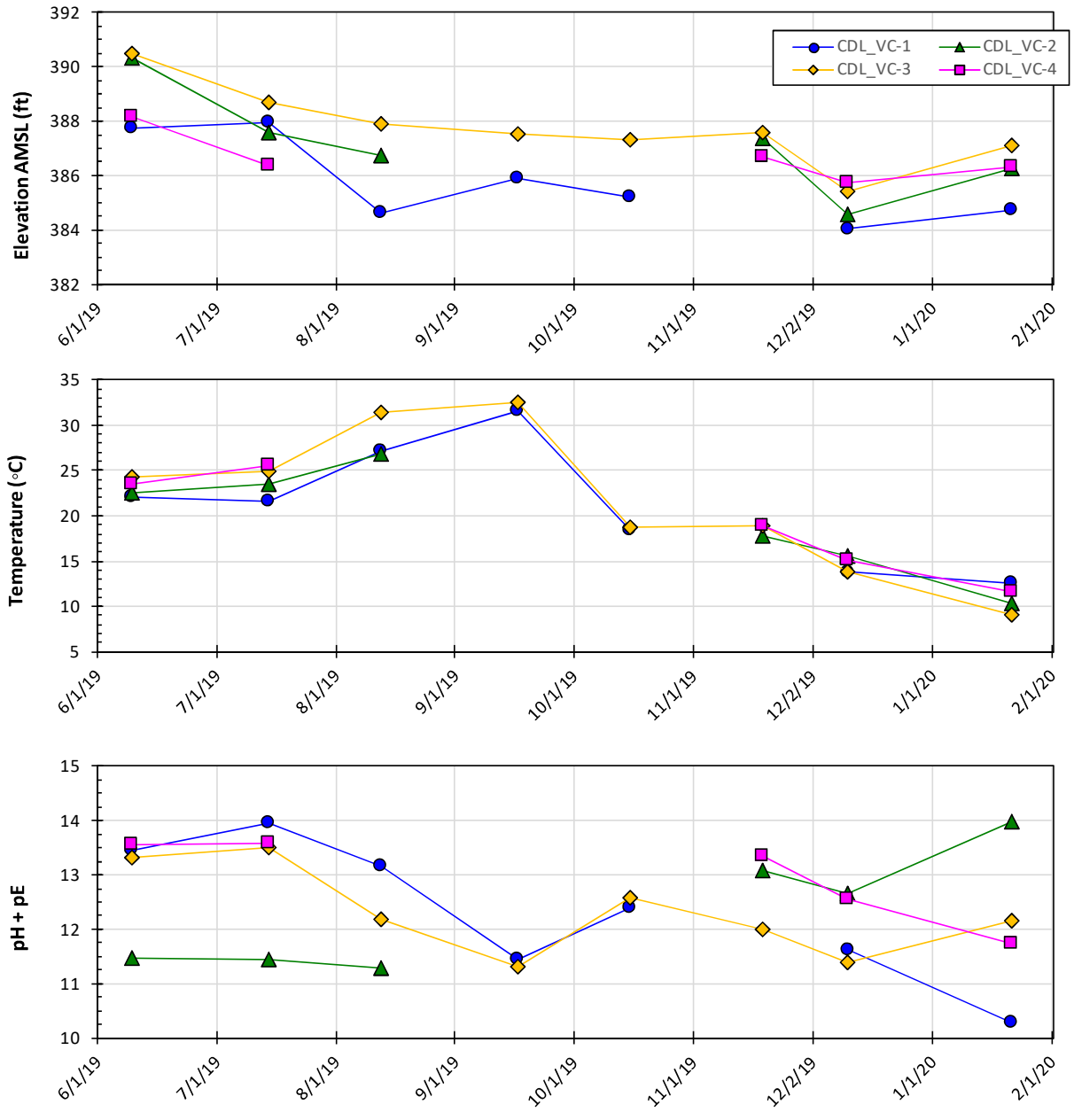

Figure 7-5
Example temporal porewater data showing seasonal or other variability: elevation, temperature, and pH+pE

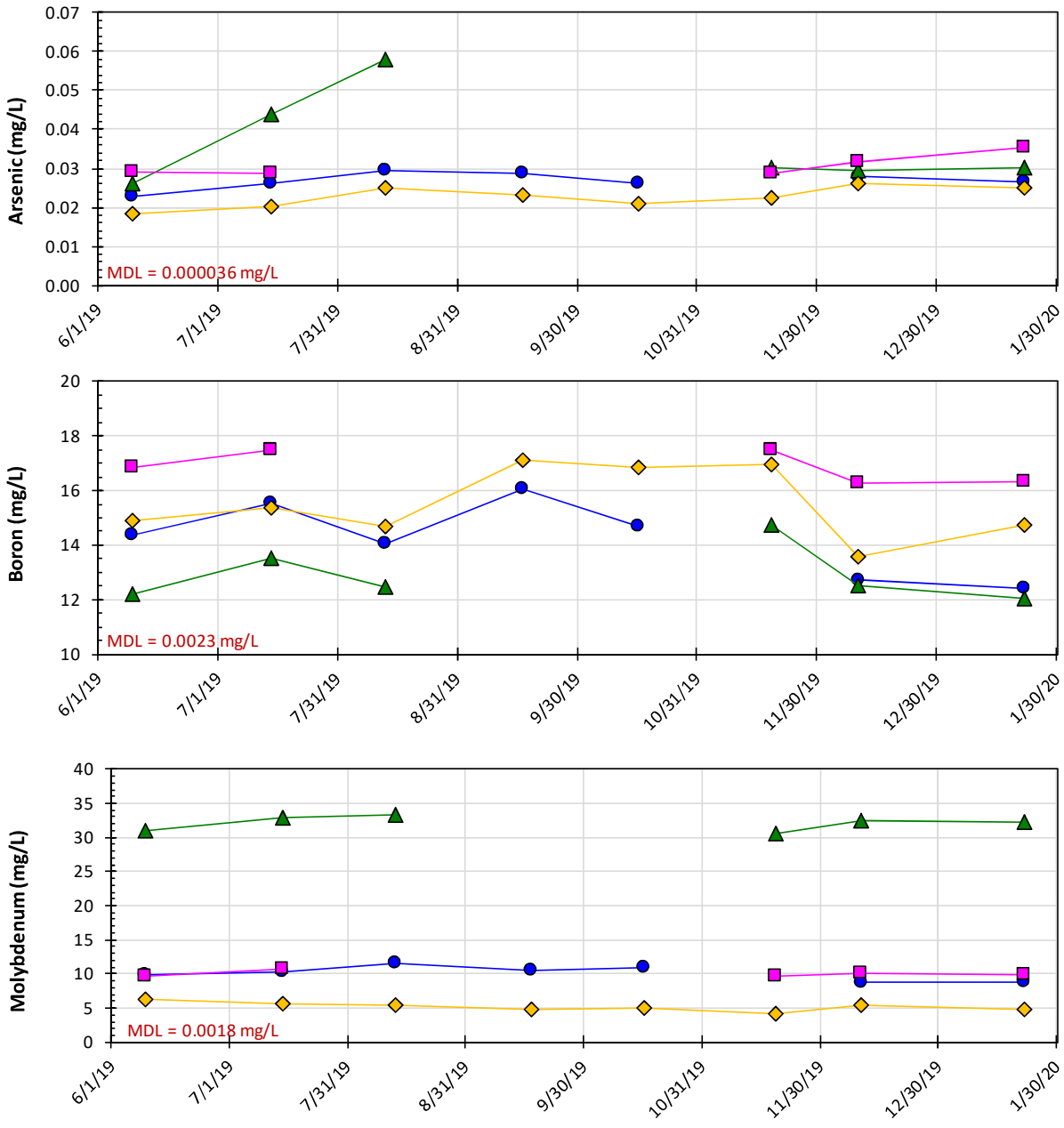

Figure 7-6
Example temporal porewater data showing relatively constant conditions: arsenic, boron, and molybdenum

Subsurface Gas Monitoring

Concentrations of O_2, CO_2, CH_4, NH_4, and H_2S were measured in the four boreholes using gas access points (GAPs). GAPs were installed at VC-1 and VC-3 at three depths (5, 15, and 50 feet BGS), while VC-2 and VC-4 had GAPs installed at 5 and 15 feet BGS. Full tabular data for subsurface monitoring are presented along with graphical comparisons in Appendix D-3.

The results of monthly gas monitoring varied to some degree by borehole:

- VC-1 consistently had higher subsurface O2 concentrations at a depth of 5 feet BGS than at 15 or 50 feet BGS (Figure 7-7). The data at this borehole suggest that oxygen is quickly depleted in the subsurface. At VC-3 and VC-4, there appears to be period of instability as initial O2 concentrations were significantly higher than after the first two months.
- CO2 levels were generally low and variable as a function of depth and time (Figure 7-8).
- CH4 concentration in subsurface gas was detected in VC-1 only at very low concentrations at depth (Figure 7-9). In this scenario, methane detection is likely indicative of localized decay of organic matter rather than a strongly reduced subsurface environment as noted in the closed impoundment discussed in EPRI (2020).
- Subsurface NH4 and H2S concentrations were negligible, detected very sporadically and at very low concentrations (Appendix D-3).

These data are indicative of a heterogeneous redox environment. At depth (> 5 feet BGS), O_2 concentrations, in particular, confirm the suboxic environment indicated by DO measurements in the porewater.

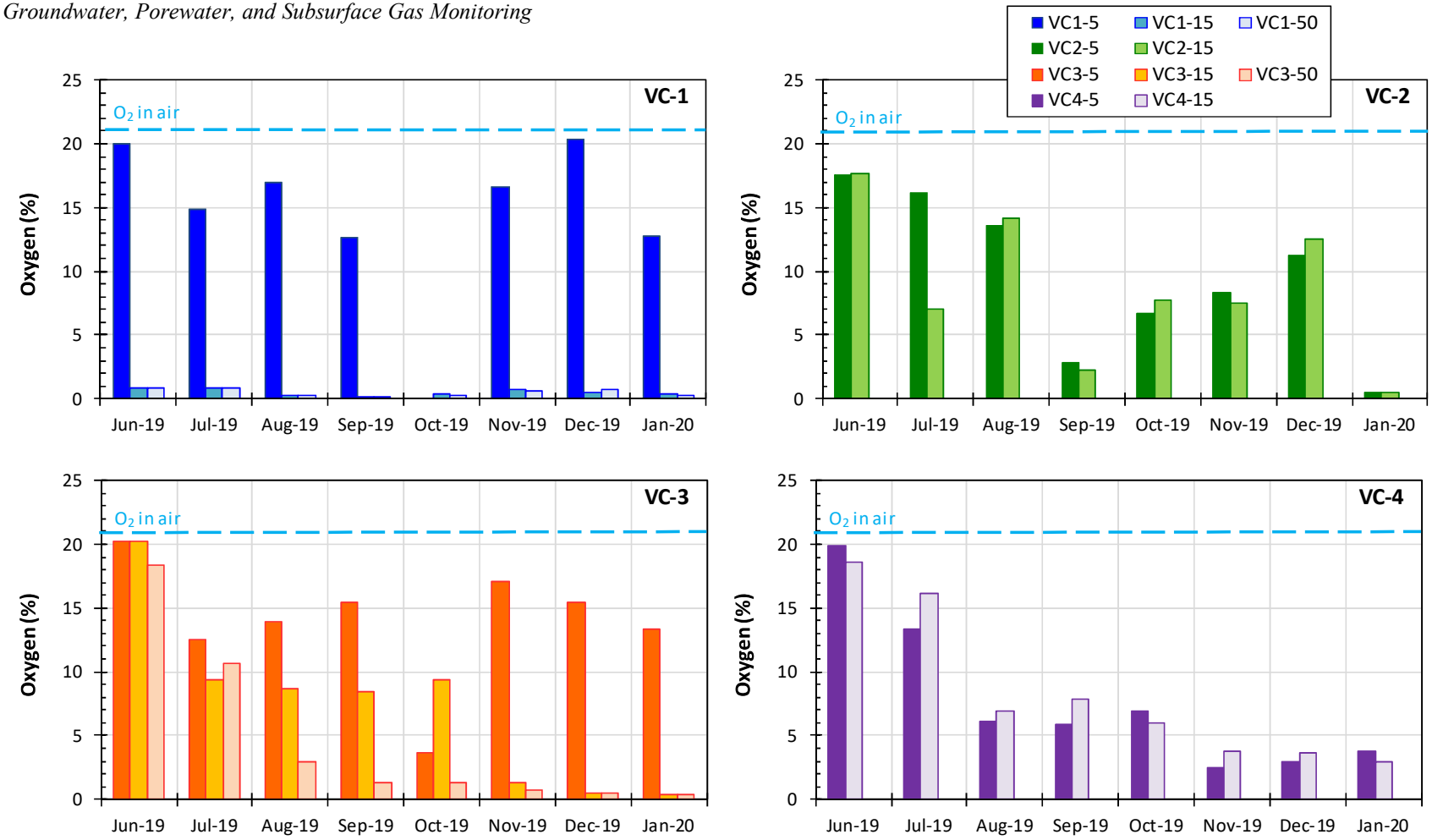

Figure 7-7
Concentration (%) of oxygen (O_2) from GAPs at boreholes VC-1, VC-2, VC-3, and VC-4 in the subsurface of the dry-handled landfill

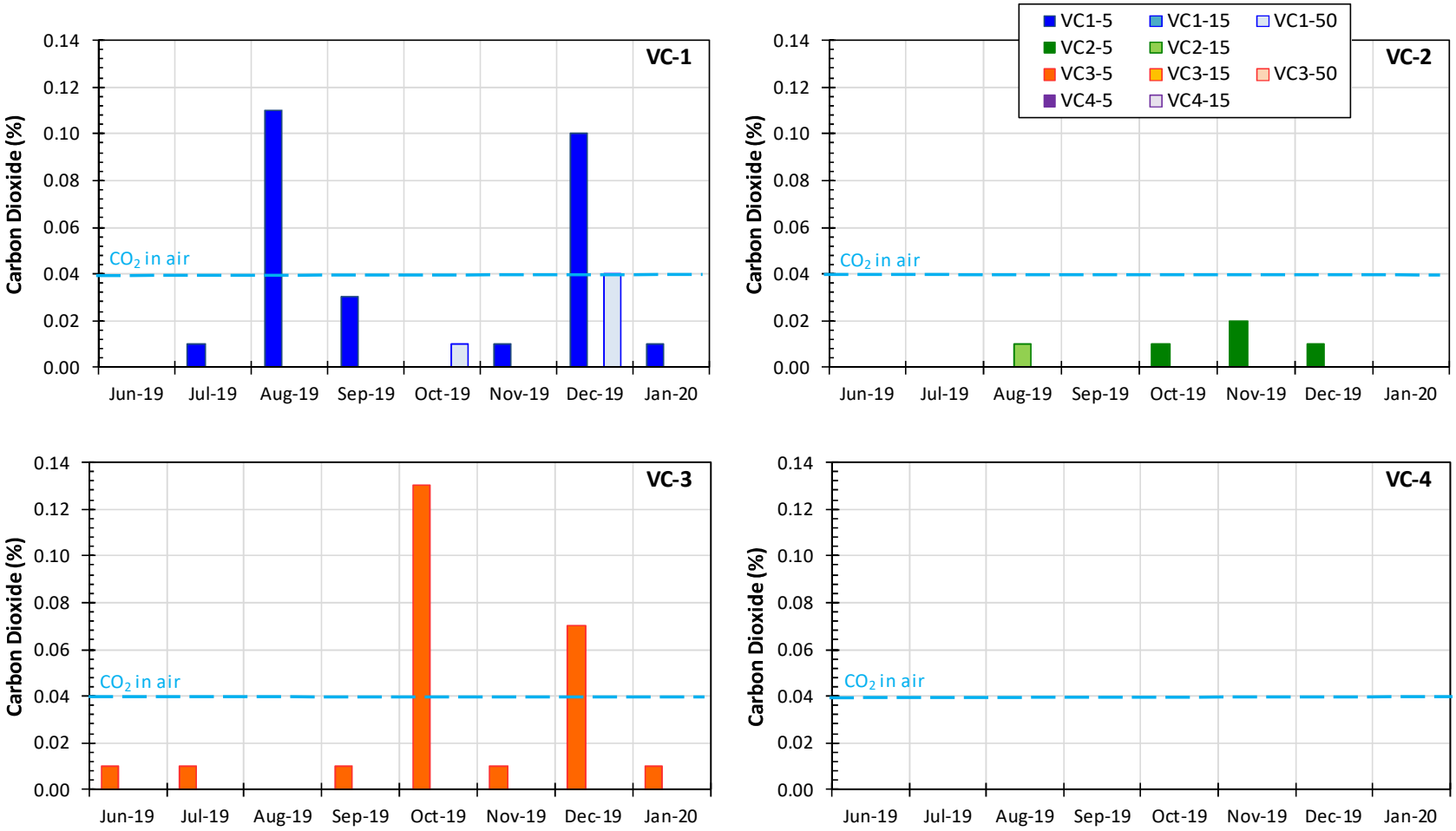

Figure 7-8
Concentration (%) of carbon dioxide (CO_2) from GAPs at boreholes VC-1, VC-2, VC-3, and VC-4 in the subsurface of the dry-handled landfill

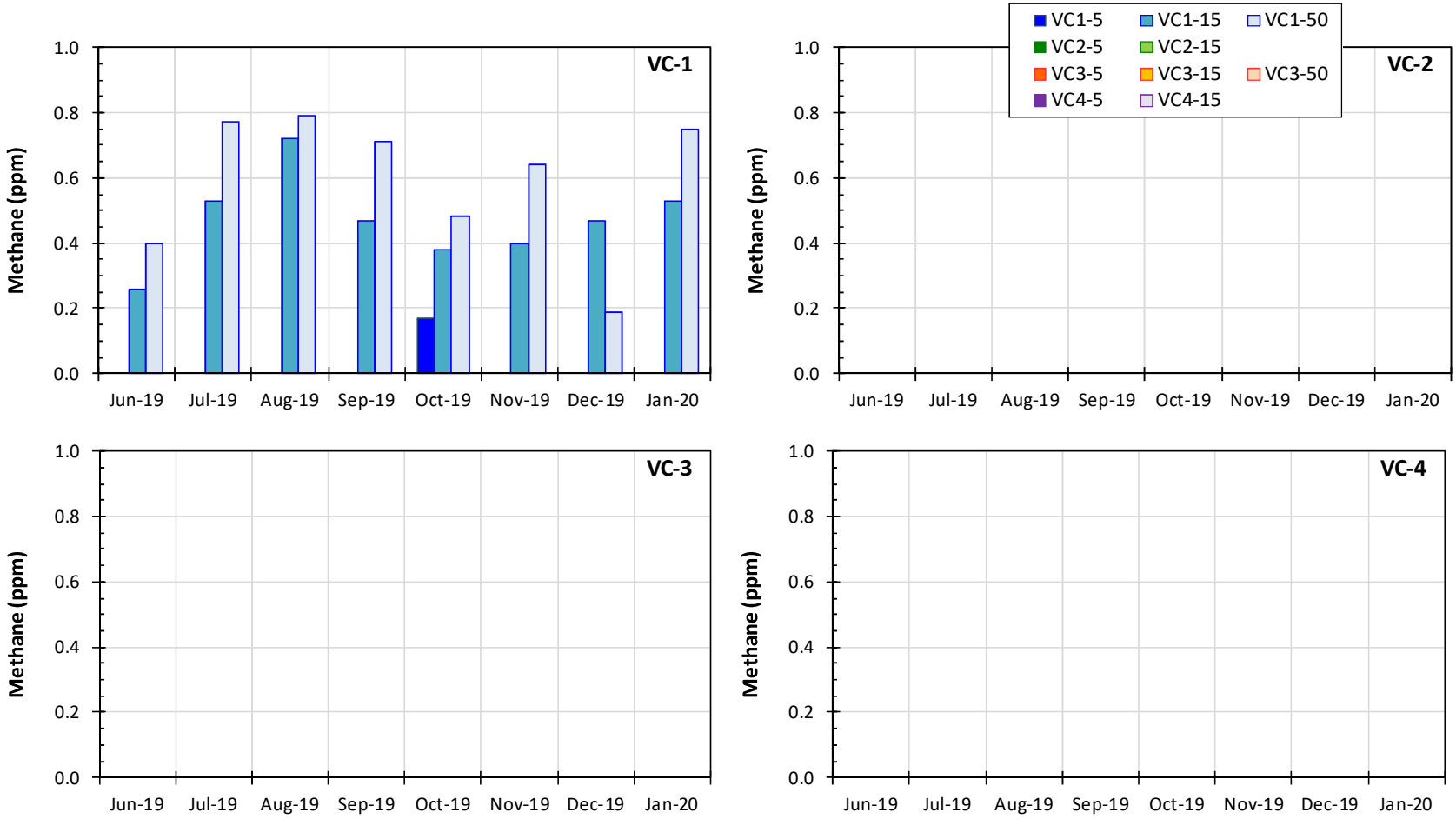

Figure 7-9
Concentration (ppm) of methane (CH_4) from GAPs at borehole VC-1, VC-2, VC-3, and VC-4 in the subsurface of the dry-handled landfill

Comparison of Leaching Tests to Monthly Porewater Samples

The results of LEAF leaching tests and traditional tests (TCLP, SPLP, and ASTM) were plotted as a function of pH along with the porewater concentrations measured at the corresponding borehole (VC-1, VC-2, VC-3, or VC-4). Examples of these comparisons are shown in Figure 7-10 through Figure 7-12, while a full set of results is presented in Appendix E. In the pH-dependence graphs, monitored porewater data are presented both as data points representing monthly measured porewater concentrations and as dashed lines representing the mean pH and mean concentration of all measured values.

To the right of each pH-dependence graph, bar charts show the ratio of the leaching test concentration to the mean porewater concentration. The seven ratios are shown in increasing order of L/S, including:

- the 1st eluate from EPA 1314 at ΣL/S=0.2 mL/g-dry,
- the 2nd eluate from EPA 1314 at cumulative ΣL/S=0.5 mL/g-dry (displayed as L/S=0.3)[4],
- the 1313_L/S=1 concentration at own pH at L/S=1 mL/g-dry,
- the 1313 concentration at natural pH at L/S=10 mL/g-dry,
- TCLP conducted at an average L/S of 23 mL/g-dry,
- SPLP conducted at an average L/S of 22 mL/g-dry, and
- ASTM at an average L/S of 27 mL/g-dry.

The eluate-to-porewater-concentration ratios indicate how closely leaching test concentrations can predict measured field concentrations. For example, Figure 7-10 shows that B porewater concentrations are well predicted by low L/S batch leaching (1313_L/S=1) and, coincidently, by TCLP; however, the test-specific L/S of TCLP and resultant eluate pH are not representative of that in the coal ash porewater. For boron, all leaching test data estimate porewater concentrations within an order-of-magnitude. These observations are consistent with available content-limited LSP where eluate concentration is a strong function of L/S. Since the L/S of ASTM and SPLP is significantly greater than the L/S in the field, these traditional tests tend to underestimate the porewater concentrations for available content-limited LSP constituents by an order-of-magnitude or more.

[4] The first eluate is taken at L/S=0.2, the second is taken 0.3 pore volumes later, so the L/S is 0.3 and ΣL/S=0.5.

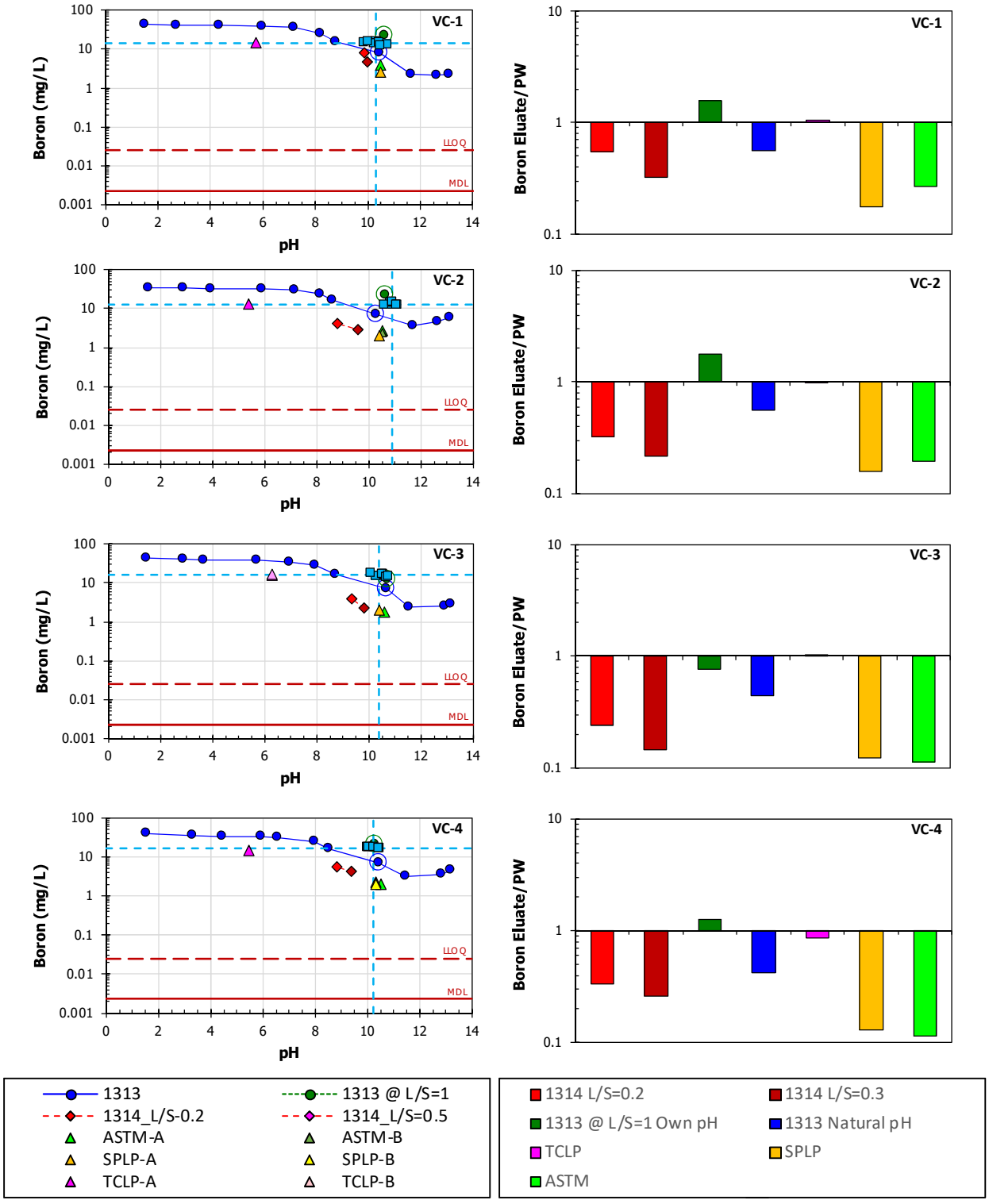

Figure 7-10
Boron concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right)

Of the 30 evaluated constituents, only chromium compared poorly to all of the leaching test concentrations. The porewater concentrations of Cr were less than the analytical MDL of 0.000053 mg/L in all four PAPs, while leaching tests returned concentrations between 0.001 and 0.1 mg/L (Figure 7-11). Subsurface gas measurements indicated a deficit of oxygen (Figure 7-7) without generation of carbon dioxide (Figure 7-8) or significant methane (Figure 7-9), which suggests suboxic conditions. Under these conditions, Cr is reduced to Cr(III), which would be insoluble at the porewater pH conditions. When samples are collected from the field, homogenized in the laboratory, and exposed to laboratory conditions during testing, the material oxidizes enough to convert a portion of Cr(III) to Cr(IV), leading to increased chromium concentrations in leaching test eluates. Conversely, arsenic, also a redox-sensitive constituent, is predicted within an order of magnitude in all leaching test approximations (Figure 7-12). The ability of leaching tests to approximate arsenic concentrations in the porewater is most likely due to the speciation of arsenic and the subsurface conditions. In literature, arsenic retained in fly ash as calcium-arsenate and arsenate hematite was less susceptible to changes due to redox conditions (Deonarine et al., 2016). In addition, the subsurface conditions here, while suboxic, are not sufficiently reducing to be affected by short-term exposures of the solid materials to oxygen in laboratory leaching tests.

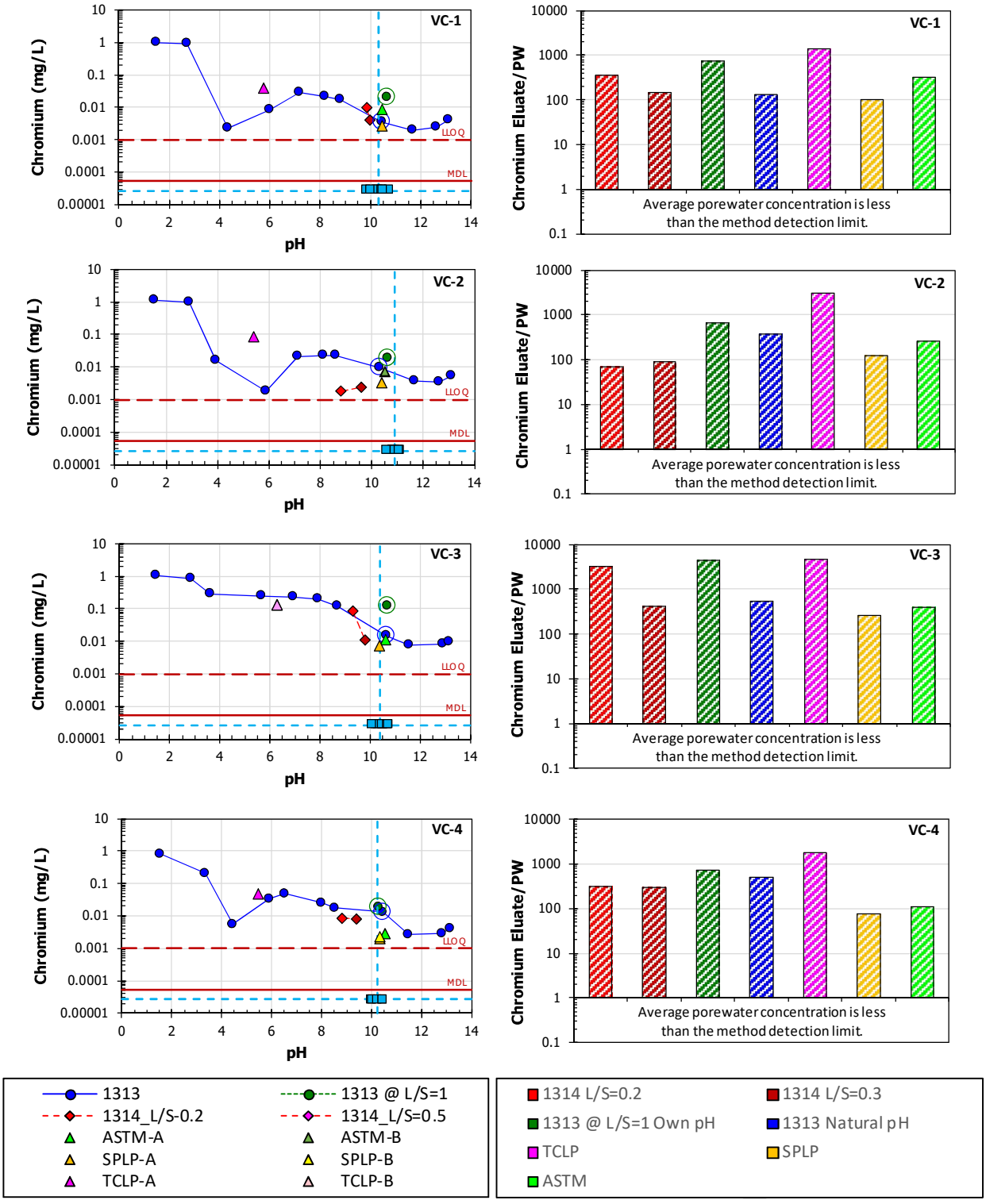

Figure 7-11
Chromium concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right); crosshatched ratio results indicate estimates based on at least one MDL value

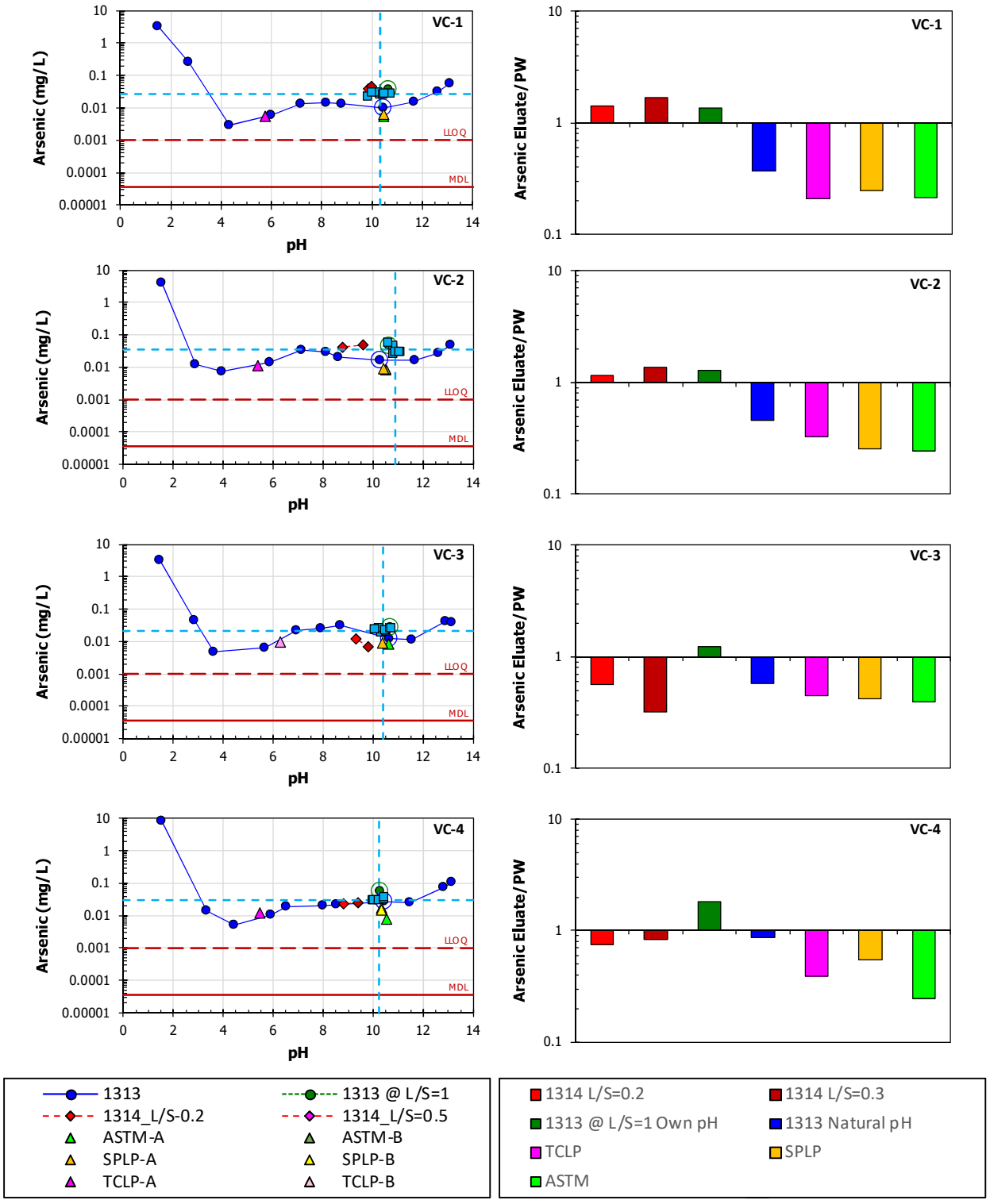

Figure 7-12
Arsenic concentration from leaching tests compared to measured and mean porewater concentrations shown as a function of pH (left) and as a ratio of eluate concentration to porewater concentration (right)

A qualitative summary of the ability of different leaching tests to estimate the measured porewater concentrations at each of the PAPs is shown in Table 7-2 for constituents with solubility-controlled LSP, Table 7-3 for constituents with wash-off followed by solubility control, Table 7-4 for constituents with available content-limited LSP, and Table 7-5 for constituents with non-detected data. In these tables, shading is used to indicate if the leaching test estimate is within 25% of the mean porewater concentration (green), within an order-of-magnitude of the mean porewater concentration (orange), or greater than an order-of-magnitude from the mean porewater concentration (red). These classifications are based on a percentage difference:

$$\%D = \frac{(z - PW)}{PW}$$

where %D is the percentage difference between leaching and porewater concentrations;
z is the leaching tests concentration (mg/L); and
PW is the mean porewater concentration from monthly PAP monitoring (mg/L).

When "GW <MDL" appears in the Notes column, the mean porewater concentration was less than the analytical MDL. Within the field of the table, an asterisk is used to indicate that the leaching test results were less than the MDL.

These tables provide an overview of the ability of leaching tests, conducted on materials collected from a suboxic environment and tests at mildly oxidizing conditions in a laboratory setting, to estimate porewater concentrations. This comparison indicated that the ability of leaching tests, conducted under specific test conditions, to predict porewater concentration varied by constituent and test. While no single leaching test consistently predicted concentrations within 25% of porewater concentrations for all constituents, the following observations were made:

- TCLP tends to over-predict porewater concentrations in alkaline ash (average pH_{nat}~10.4) by more than an order-of-magnitude for many constituents, in part, due to the pH (pH~5) imposed by the acetic acid leaching solution;
- EPA 1313, ASTM, and SPLP were usually within an order-of-magnitude for the solubility-controlled constituents where pH is the critical factor in LSP concentration and the leaching solution (i.e., deionized water for EPA 1313 at natural pH and ASTM, weak acid solution for SPLP) does not significantly alter eluate pH;
- EPA 1313 (L/S=10 L/kg-dry), ASTM (L/S~30 L/kg-dry), and SPLP (L/S~30 L/kg-dry) often under-predicted porewater concentrations by more than an order-of-magnitude for available content-controlled constituents because of the high L/S ratio relative to porewater L/S (0.35 L/kg-dry); and,
- EPA 1313_L/S=1 and low L/S 1314 column fractions usually yielded results within an order-of-magnitude of the porewater concentrations for both solubility-controlled and available content-controlled constituents.

When summarized by constituent, leaching test predictions *typically*:

- Over-predicted porewater concentrations for Sb and Cr;

- Under-predicted porewater concentrations for Ba, B, Cd, Ca, Cl^-, DOC, Li, Mo, Ni, K, Na, Sr, and SO_4^{-2};
- Over-predicted at L/S=0.2 and under-predicted at higher L/S for Co;
- Over-predicted at L/S<1.0 and under-predicted at higher L/S for P;
- Over-predicted at L/S<=1.0 and under-predicted at higher L/S for V; and,
- Did not consistently over- or under-predict porewater concentrations for As, Cu, DIC, Fe, Se, Tl, and Zn.

The above constituent evaluation does not include TCLP tests where leaching concentrations were primarily higher than porewater or those constituents where eluates and porewater concentrations were both usually less than MDL (i.e., Be, Br^-, F^-, Pb, and Ag).

The results of this qualitative summary should not be used without consideration of the redox conditions of the field and should always be shown along with the graphical data (e.g., Figure 7-10 through Figure 7-12) that indicate the pH result for the tests. For example, the table indicates that TCLP would provide a good estimate of porewater concentration for B; however, this is somewhat of a coincidence because the pH of TCLP is more than four pH units less than the natural pH of the ash.

Table 7-2
Summary of Leaching Tests to Porewater Concentrations – Solubility-Controlled LSP

Constituent		1314 L/S=0.2	1314 L/S=0.5	1313 L/S=1 Own pH	1313 L/S-10 Nat pH	TCLP	SPLP	ASTM	Notes
Antimony	VC-1								
	VC-2								
	VC-3								
	VC-4								
Arsenic	VC-1								
	VC-2								
	VC-3								
	VC-4								
Calcium	VC-1								
	VC-2								
	VC-3								
	VC-4								
Dissolved Inorganic Carbon	VC-1								
	VC-2								
	VC-3								
	VC-4								
Thallium	VC-1								
	VC-2								
	VC-3								
	VC-4								

	Estimate within 25% of porewater (±25%)
	Estimate within order of magnitude (±10x)
	Estimate more than order of magnitude (>±10x)
GW <MDL	Mean porewater concentration < MDL
*	Test concentration <MDL

Table 7-3
Summary of Leaching Tests to Porewater Concentrations – Wash-off / Solubility-Controlled LSP

Constituent		1314 L/S=0.2	1314 L/S=0.5	1313 L/S=1 Own pH	1313 L/S-10 Nat pH	TCLP L/S=20 +	SPLP L/S=20 +	ASTM L/S=20 +	Notes
Barium	VC-1								
	VC-2								
	VC-3								
	VC-4								
Boron	VC-1								
	VC-2								
	VC-3								
	VC-4								
Cadmium	VC-1								
	VC-2								
	VC-3								
	VC-4								
Chromium	VC-1								GW
									<MDL
	VC-2								GW
									<MDL
	VC-3								GW
									<MDL
	VC-4								GW
									<MDL
Copper	VC-1								
	VC-2								
	VC-3								
	VC-4								
Dissolved Organic Carbon	VC-1								
	VC-2								
	VC-3								
	VC-4								
Lithium	VC-1								
	VC-2				*				
	VC-3				*				
	VC-4				*				
Nickel	VC-1				*				
	VC-2				*				
	VC-3				*				
	VC-4				*				
Selenium	VC-1								
	VC-2								
	VC-3								
	VC-4								
Strontium	VC-1								
	VC-2								
	VC-3								
	VC-4								

Table 7-3 (continued)
Summary of Leaching Tests to Porewater Concentrations – Wash-off / Solubility-Controlled LSP

Constituent		1314 L/S=0.2	1314 L/S=0.5	1313 L/S=1 Own pH	1313 L/S-10 Nat pH	TCLP L/S=20 +	SPLP L/S=20 +	ASTM L/S=20 +	Notes
Sulfate	VC-1								
	VC-2								
	VC-3								
	VC-4								
Vanadium	VC-1								
	VC-2								
	VC-3								
	VC-4								

	Estimate within 25% of porewater (±25%)
	Estimate within order of magnitude (±10x)
	Estimate more than order of magnitude (>±10x)
GW <MDL	Mean porewater concentration < MDL
*	Test concentration <MDL

Table 7-4
Summary of Leaching Tests to Porewater Concentrations – Available Content-Limited LSP

Constituent		1314 L/S=0.2	1314 L/S=0.5	1313 L/S=1 Own pH	1313 L/S=10 Nat pH	TCLP L/S=20 +	SPLP L/S=20 +	ASTM L/S=20 +	Notes
Chloride	VC-1								
	VC-2								
	VC-3								
	VC-4								
Molybdenum	VC-1								
	VC-2								
	VC-3								
	VC-4								
Potassium	VC-1								
	VC-2								
	VC-3								
	VC-4								
Sodium	VC-1								
	VC-2								
	VC-3								
	VC-4								

	Estimate within 25% of porewater (±25%)
	Estimate within order of magnitude (±10x)
	Estimate more than order of magnitude (>±10x)
GW <MDL	Mean porewater concentration < MDL
*	Test concentration <MDL

Table 7-5
Summary of Leaching Tests to Porewater Concentrations – Non-detected Constituents

Constituent		1314 L/S=0.2	1314 L/S=0.5	1313 L/S=1 Own pH	1313 L/S-10 Nat pH	TCLP L/S=20+	SPLP L/S=20+	ASTM L/S=20+	Notes
Beryllium	VC-1	*	*	*	*		*	*	GW <MDL
	VC-2	*	*	*	*		*	*	GW <MDL
	VC-3	*	*	*	*		*	*	GW <MDL
	VC-4	*	*	*	*		*	*	GW <MDL
Bromide	VC-1	*	*	*	*	*	*	*	GW <MDL
	VC-2	*	*	*	*	*	*	*	GW <MDL
	VC-3	*	*	*	*	*	*	*	GW <MDL
	VC-4	*	*	*	*	*	*	*	GW <MDL
Cobalt	VC-1				*				
	VC-2				*				
	VC-3				*				
	VC-4				*				
Fluoride	VC-1	*	*	*	*	*	*	*	GW <MDL
	VC-2	*	*	*	*	*	*	*	GW <MDL
	VC-3	*	*	*	*	*	*	*	GW <MDL
	VC-4	*	*	*	*	*	*	*	GW <MDL
Iron	VC-1	*	*		*				
	VC-2	*			*				
	VC-3	*			*				
	VC-4		*		*				
Lead	VC-1	*	*	*	*		*	*	GW <MDL
	VC-2	*	*	*	*		*		GW <MDL
	VC-3	*	*	*	*		*	*	GW <MDL
	VC-4	*	*	*	*		*	*	GW <MDL
Phosphorus	VC-1			*	*	*	*	*	
	VC-2				*	*	*	*	
	VC-3				*	*	*	*	
	VC-4				*	*	*	*	
Silver	VC-1	*	*	*	*	*	*	*	GW <MDL
	VC-2	*	*	*	*	*	*	*	GW <MDL
	VC-3	*	*	*	*	*	*	*	GW <MDL
	VC-4	*	*	*	*	*	*	*	GW <MDL

Table 7-5 (continued)
Summary of Leaching Tests to Porewater Concentrations – Non-detected Constituents

Constituent		1314 L/S=0.2	1314 L/S=0.5	1313 L/S=1 Own pH	1313 L/S-10 Nat pH	TCLP L/S=20+	SPLP L/S=20+	ASTM L/S=20+	Notes
Zinc	VC-1				*				
	VC-2			*	*				
	VC-3			*	*				
	VC-4				*				

	Estimate within 25% of porewater (±25%)
	Estimate within order of magnitude (±10x)
	Estimate more than order of magnitude (>±10x)
GW <MDL	Mean porewater concentration < MDL
*	Test concentration <MDL

8
SUMMARY OF OBSERVATIONS

The data presented in this report represent the results of geotechnical, hydrologic, and leaching characterization of samples of coal ash collected from an active CCP management unit at Plant 42197. The hydraulic conductivity of intact cores from the coal ash deposit was measured in context of the distribution of particles in the coal ash samples and the overburden pressure associated with disposal at depth within the coal ash deposit. The leaching test results for LEAF tests (i.e., EPA Methods 1313 and 1314) were compared to the results for traditional tests (i.e., ASTM, TCLP, and SPLP). In addition, porewater estimates derived from leaching tests were compared to measured porewater concentrations, and measured porewater concentrations were compared to groundwater concentrations.

Based on the presented data and analysis, the following general observations can be made:

- Despite differences in coal ash placement (dry-handled ash in the upper portion and wet-handled ash in the lower portion), ***there was little observed variability in vertical concentration profiles***. This observation, in combination with initial concentration from percolation column test results, suggest that infiltration moving through the unsaturated dry-handled ash (e.g., from precipitation, liquid dumps, water spray for dust management) results in migration of readily dissolved constituents from the dry-handled material into the underlying wet-handled coal ash. ***Downward movement of soluble constituents results in the pH and porewater composition within the saturated material similar to the low L/S extraction fractions of composited dry material***.
- The ratio of the available content to the total content shows that ***only a small fraction of total content of most trace constituents is leachable*** over a broad pH range.
- ***Suboxic to anoxic conditions are established at relatively shallow depths (> 5 m) below the ground surface of the dry-handled material***. Oxygen penetration from the surface is limited because of abiotic and biotic reactivity of the freshly deposited fly ash in conjunction with pore filling due to water additions to maintain dust control and compaction of additionally added materials (e.g., bottom ash) for structural workability (truck access).
- ***The high pH within the porewater of deposited material prevents development of significant microbial activity at depths greater than 5 m below the ground surface*** (or potentially even at shallower depths). This is in contrast to observations in some impoundments of only wet-handled material (EPRI, 2020), which showed nearly neutral porewater pH and indicators of robust microbial reduction of iron and sulfate along with methanogenesis.
- ***Hydraulic conductivity of the ashes typically was within the range of 10^{-5} to 10^{-6} cm/s***, with the lower hydraulic conductivities corresponding to higher dry unit weight. Fines content and 2-mm clay content had no consistent influence on hydraulic conductivity, in contrast to

previous experience (EPRI, 2020). Hydraulic conductivity diminished as the effective stress increased, but only modestly.

- ***Some parameters in the PAP porewater (e.g., pH, temp, B, Co, Ni, and Zn) exhibited temporal variability*** due to factors such as seasonal changes or impacts of damage and repair of porewater access points. Other constituents remained relatively constant within each porewater access point throughout the 8-month monitoring period. ***Spatial variability was observed for some constituents between PAPs; however, no consistent pattern was observed***. With the exception of Cu and Zn, concentrations between PAPs were within an order of magnitude.
- There were insufficient data from limited collection points to identify relationships between porewater and downgradient groundwater concentrations. For example, no upgradient groundwater well was identified to provide groundwater conditions in the flow path prior to the landfill. ***The limited data collected from downgradient monitoring wells and PAPs suggest that porewater concentration alone is an unreliable indicator that a constituent has had an impact on elevated groundwater concentrations or for prediction of downgradient concentrations at this site***.
- Traditional leaching tests, such as TCLP, SPLP, and ASTM, are poorer indicators of measured porewater concentrations than LEAF tests. ***Low liquid-to-solid ratio (L/S) eluates from EPA Method 1314 are better indicators than the traditional tests and EPA 1313 for concentrations for available content-limited constituents (e.g., B, Cd, Cl^-, Mo, Se, and SO_4^{-2}) because of the strong L/S-dependence.*** The data presented here showed that the traditional tests, with an L/S greater than 20 L/kg-dry, and EPA 1313 at L/S=10 L/kg-dry often under-predicted field porewater concentrations by an order of magnitude or more. These results indicate that additional information (e.g., available content and porewater L/S) is needed to provide a reasonable approximation of porewater concentrations. ***For constituents with solubility-controlled liquid-solid partitioning (e.g., As, Sb, and Tl), EPA 1313 tests at L/S=1 L/kg-dry provide an estimate of porewater concentrations generally within a factor of 2.*** The combination of pH-dependent leaching data (EPA 1313) with percolation column test results (EPA 1314) provides valuable information for geochemical modeling.
- For field environments that are oxidizing to slightly reducing, leaching test data usually approximated field porewater concentrations of solubility-controlled constituents within an order of magnitude. ***Because of the oxic to suboxic subsurface conditions at this site, sampling, laboratory handing, and testing conditions did not appear to significantly influence the redox condition of the field material.*** This is in contrast to impoundments with highly reducing subsurface conditions, where material handling in the presence of oxygen during sampling and laboratory testing can significantly impact test results. The only constituent not well defined by any of the LEAF tests was chromium, the result for which may have been influenced by oxidization of materials during collection from a suboxic environment and testing in an oxic laboratory. The leaching results for chromium indicate that laboratory testing results for redox-sensitive elements (e.g., As, Cr, Sb, Se, V) may not directly reflect the leaching anticipated in porewater when the field environment is highly reducing, in part due to oxidation incurred during sampling, handling, and testing.

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A
MATERIAL COLLECTION SAMPLE INDEX

Borehole CDL_VC-1, Collected 3/19/19

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
5'-6.5'	CDL_VC-1_5'-6.5'	Dry stack	Tube sample for UVA	-	-	-
6.5'-8'	CDL_VC-1_6.5'-8' (A)	Dry stack	Bulk Material	1-gal. vacuum-seal bag	1,732.0	-
6.5'-8'	CDL_VC-1_6.5'-8' (B)	Dry stack	Bulk Material	1-gal. vacuum-seal bag	552.0	-
8'-9.5'	CDL_VC-1_8'-9.5'	Dry stack	PW Extractor (+ 18.4 mL H2O); L/S=1 Extraction; Moisture Content	No bulk material collected	-	0.16
15'-16.5'	CDL_VC-1_15'-16.5'	Dry stack	PW Extractor (+ 20 mL H2O); L/S=1 Extraction; Moisture Content	No bulk material collected	-	0.23

Borehole CDL_VC-1, Collected 3/19/19 (continued)

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
16.5'-18'	CDL_VC-1_16.5'-18'	Dry stack	Bulk Material	1-gal. vacuum-seal bag	2,131.6	-
18'-19.5'	CDL_VC-1_18'-19.5'	Dry stack	Bulk Material	1-gal. vacuum-seal bag	1,367.0	-
25'-26.5'	CDL_VC-1_25'-26.5'	Dry stack	PW Extractor (+ 20 mL H2O); L/S=1 Extraction; Moisture Content; Bulk Material	1-gal. vacuum-seal bag	571.3	0.21
26.5'-28'	CDL_VC-1_26.5'-28'	Dry stack	Bulk Material	1-gal. vacuum-seal bag	881.0	-
28'-29.5'	CDL_VC-1_28'-29.5'	Dry stack	Tube Sample for UVA	-	-	-

Borehole CDL_VC-1, Collected 3/19/19 (continued)

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
35'-36.5'	CDL_VC-1_35'-36.5'	Dry stack	PW Extractor (+ 20 mL H2O); L/S=1 Extraction; Moisture Content; Bulk Material	1-gal. vacuum-seal bag	360.0	0.18
36.5'-38'	CDL_VC-1_36.5'-38'	Dry stack	Tube sample for UVA	-	-	-
38'-39.5'	CDL_VC-1_38'-39.5'	Dry stack	Bulk Material	1-gal. vacuum-seal bag	849.0	-
45'-46.5'	CDL_VC-1_45'-46.5'	Dry stack	PW Extractor (+ 20 mL H2O); L/S=1 Extraction; Moisture Content; Bulk Material	1-gal. vacuum-seal bag	490.8	0.18
46.5'-48'	CDL_VC-1_46.5'-48'	Dry stack	Bulk Material	1-gal. vacuum-seal bag	656.1	-

Borehole CDL_VC-1, Collected 3/19/19 (continued)

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
48'-49.5'	CDL_VC-1_48'-49.5'	Dry stack/bottom ash layer	Tube sample for UVA	-	-	-
65'-66.5'	CDL_VC-1_65'-66.5'	Impoundment	PW Extractor (+ 10 mL H2O); L/S=1 Extraction; Moisture Content	No bulk material collected	-	0.33
66.5'-68.5'	CDL_VC-1_66.5'-68.5'	Impoundment	Shelby tube for UVA (no recovery)	-	-	-
68.5'-70'	CDL_VC-1_68.5'-70'	Impoundment	Bulk Material	1-gal. vacuum-seal bag	2,485.2	-
70'-72.6'	CDL_VC-1_70'-72.6' (A)	Impoundment	Bulk Material	1-gal. vacuum-seal bag	1,257.1	-

Borehole CDL_VC-1, Collected 3/19/19 (continued)

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
70'-72.6'	CDL_VC-1_70'-72.6' (B)	Impoundment	Tube Sample for UVA	-	1,257.1	-
72.5'-74'	CDL_VC-1_72.5'-74'	Impoundment	Low L/S extractor; L/S=1 digit tube; Moisture content; Bulk	1-gal. vacuum-seal bag	1,323.7	0.23

Borehole CDL_VC-2, Collected 3/14/19

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
5'-6.5'	CDL_VC-2_5'-6.5'	Dry stack	Bulk Material	1-gal. vacuum-seal bag	625.91	-
6.5'-8'	CDL_VC-2_6.5'-8'	Dry stack	Bulk Material	1-gal. vacuum-seal bag	757.99	-
8'-9.5'	CDL_VC-2_8'-9.5'	Dry stack	PW Extractor (+ 20 mL H2O); L/S=1 Extraction; Moisture Content	-	-	0.21
15'-16.5'	CDL_VC-2_15'-16.5'	Dry stack	PW Extractor (+ 20 mL H2O); L/S=1 Extraction; Moisture Content	1-gal. vacuum-seal bag	848.07	0.20
16.5'-18'	CDL_VC-2_16.5'-18'	Dry stack	Bulk Material	1-gal. vacuum-seal bag	1281.9	-

Borehole CDL_VC-2, Collected 3/14/19 (continued)

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
18'-19.5'	CDL_VC-2_18'-19.5'	Dry stack	Bulk Material	1-gal. vacuum-seal bag	1050.75	-
25'-26.5'	CDL_VC-2_25'-26.5'	Dry stack	PW Extractor (+ 20 mL H2O); L/S=1 Extraction; Moisture Content; Bulk Material	1-gal. vacuum-seal bag	1815.3	0.19
26.5'-28'	CDL_VC-2_26.5'-28'	Dry stack	Bulk Material	1-gal. vacuum-seal bag	1,065.3	-
28'-29.5'	CDL_VC-2_28'-29.5'	Dry stack	Tube Sample for UVA	-	-	-
35'-36.5'	CDL_VC-2_35'-36.5'	Dry stack	PW Extractor (+ 20 mL H2O); L/S=1 Extraction; Moisture Content; Bulk Material	1-gal. vacuum-seal bag	1,423.5	0.21

Borehole CDL_VC-2, Collected 3/14/19 (continued)

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
36.5'-38'	CDL_VC-2_36.5'-38'	Dry stack	Bulk Material	1-gal. vacuum-seal bag	1,243.4	-
38'-39.5'	CDL_VC-2_38'-39.5'	Dry stack	Bulk Material	1-gal. vacuum-seal bag	1,863.5	-
45'-46.5'	CDL_VC-2_45'-46.5'	Dry stack	Tube sample for UVA	-	-	-
46.5'-48'	CDL_VC-2_46.5'-48'	Dry stack/bottom ash layer	Bulk Material	1-gal. vacuum-seal bag	1,081.4	-
46.5'-48'	CDL_VC-2_46.5'-48'	Dry stack/bottom ash layer	Bulk Material	1-gal. vacuum-seal bag	1,217.0	-

Borehole CDL_VC-2, Collected 3/14/19 (continued)

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
48'-49.5'	CDL_VC-2_48'-49.5'	Dry stack/bottom ash layer	PW Extractor (+ 20 mL H2O); L/S=1 Extraction; Moisture Content; Bulk Material	1-gal. vacuum-seal bag	1,372.4	0.11
65'-67'	CDL_VC-2_65'-67'	Impoundment	Shelby Tube for UVA	-	-	-
67'-68.5'	CDL_VC-2_67'-68.5'	Impoundment	PW Extractor (+ 10 mL H2O); L/S=1 Extraction; Moisture Content; Bulk Material	1-gal. vacuum-seal bag	1,372.3	0.25
68.5'-70'	CDL_VC-2_68.5'-70'	Impoundment	Bulk Material	1-gal. vacuum-seal bag	2,184.4	-
75'-77'	CDL_VC-2_75'-77'	Impoundment	Shelby Tube for UVA	-	-	-

Borehole CDL_VC-2, Collected 3/14/19 (continued)

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
77'-78.5'	CDL_VC-2_77'-78.5'	Impoundment	PW Extractor (no H2O); L/S=1 Extraction; Moisture Content; Bulk Material	1-gal. vacuum-seal bag	1,529.1	0.35
78.5'-80'	CDL_VC-2_78.5'-80'	Impoundment	Bulk Material	1-gal. vacuum-seal bag	2,553.4	-
80'-81.5'	CDL_VC-2_80'-81.5'	Impoundment	Bulk Material	1-gal. vacuum-seal bag	2,589.9	-
81.5'-83'	CDL_VC-2_81.5'-83'	Impoundment	PW Extractor (no H2O); L/S=1 Extraction; Moisture Content; Bulk Material	1-gal. vacuum-seal bag	2,597.8	0.29

Borehole CDL_VC-3, Collected 3/7-8/19

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
5'-6.5'	CDL_VC-3_5'-6.5'	Dry stack	PW Extractor (+ 10 mL H2O); Moisture Content; Bulk Material	1-gal. vacuum-seal bag	874.3	0.22
6.5'-8'	CDL_VC-3_6.5'-8'	Dry stack	Bulk Material	1-gal. vacuum-seal bag	1,467.7	-
8'-9.5'	CDL_VC-3_8'-9.5'	Dry stack	Bulk Material	1-gal. vacuum-seal bag	1,069.9	-
15'-16.5'	CDL_VC-3_15'-16.5'	Dry stack	Tube Sample for UVA	-	-	-
16.5'-18'	CDL_VC-3_16.5'-18'	Dry stack	PW Extractor (+ 10 mL H2O); Moisture Content; Bulk Material	1-gal. vacuum-seal bag	1,897.2	0.16

Borehole CDL_VC-3, Collected 3/7-8/19 (continued)

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
18-19.5	CDL_VC-3_18-19.5	Dry stack	Bulk Material	1-gal. vacuum-seal bag	2519.2	-

INVENTORY OF FIELD-COLLECTED ASH SAMPLES
CDL_VC-3
Collection Date: **March 8, 2019**

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
25'-26.5'	CDL_VC-3_25'-26.5'	Dry stack	PW Extractor (+ 10 mL H2O); Moisture Content; Bulk Material	1-gal. vacuum-seal bag	652.7	0.16
26.5'-28'	CDL_VC-3_26.5'-28'	Dry stack	Bulk Material	1-gal. vacuum-seal bag	649.8	-
28'-29.5'	CDL_VC-3_28'-29.5'	Dry stack	Bulk Material	1-gal. vacuum-seal bag	1,121.6	-

Borehole CDL_VC-3, Collected 3/7-8/19 (continued)

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
35'-36.5'	CDL_VC-3_35'-36.5'	Dry stack	Tube Sample for UVA	-	-	-
36.5'-38'	CDL_VC-3_36.5'-38'	Dry stack	PW Extractor (+ 10 mL H2O); Moisture Content; Bulk Material	1-gal. vacuum-seal bag	1,844.4	0.15
38'-39.5'	CDL_VC-3_38'-39.5'	Dry stack	Bulk Material	1-gal. vacuum-seal bag	702.8	-
45'-46.5'	CDL_VC-3_45'-46.5'	Dry stack	Tube Sample for UVA	-	-	-
46.5'-48'	CDL_VC-3_46.5'-48'	Dry stack	PW Extractor (+ 10 mL H2O); Moisture Content; Bulk Material	1-gal. vacuum-seal bag	2,147.3	0.21

Borehole CDL_VC-3, Collected 3/7-8/19 (continued)

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
48'-49.5'	CDL_VC-3_48'-49.5'	Dry stack	Moisture Content; Bulk Material	1-gal. vacuum-seal bag	2,351.8	0.20
65'-67'	CDL_VC-3_65'-67'	Impoundment	Shelby Tube for UVA	-	-	-
67'-68.5'	CDL_VC-3_67'-68.5'	Impoundment	PW Extractor (no H2O); Moisture Content; Bulk Material	1-gal. vacuum-seal bag	2,599.1	0.33
75'-77'	CDL_VC-3_75'-77'	Impoundment	Shelby Tube for UVA	-	-	-
77'-78.5'	CDL_VC-3_77'-78.5'	Impoundment	PW Extractor (no H2O); Moisture Content; Bulk Material	1-gal. vacuum-seal bag	2,173.3	0.28

Borehole CDL_VC-3, Collected 3/7-8/19 (continued)

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
78.5'-80'	CDL_VC-3_78.5'-80'	Impoundment	PW Extractor (+ 10 mL H2O); Moisture Content; Bulk Material	1-gal. vacuum-seal bag	2,431.6	0.34
80'-81.5'	CDL_VC-3_80'-81.5'	Impoundment	PW Extractor (+ 10 mL H2O); Moisture Content; Bulk Material	1-gal. vacuum-seal bag	1,727.2	0.32
81.5'-83'	CDL_VC-3_81.5'-83'	Impoundment	Bulk Material	1-gal. vacuum-seal bag	1,352.4	-

Borehole CDL_VC-4, Collected 3/5-6/19

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
5'-6.5'	CDL_VC-4_5'-6.5'	Dry stack	PW Extractor (+ 20 mL H2O); Moisture Content; Bulk Material	1-gal. vacuum-seal bag	1,643.2	0.21
6.5'-8'	CDL_VC-4_6.5'-8'	Dry stack	Bulk Material	1-gal. vacuum-seal bag	1,135.4	-
15'-16.5'	CDL_VC-4_15'-16.5'	Dry stack	Tube Sample for UVA	-	-	-
16.5'-18'	CDL_VC-4_16.5'-18'	Dry stack	PW Extractor (+ 10 mL H2O); Moisture Content; Bulk Material	1-gal. vacuum-seal bag	1,086.8	0.18
25'-26.5'	CDL_VC-4_25'-26.5'	Dry stack	Tube Sample for UVA	-	-	-

Borehole CDL_VC-4, Collected 3/5-6/19 (continued)

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
26.5'-28'	CDL_VC-4_26.5'-28'	Dry stack	PW Extractor (+ 10 mL H2O); Moisture Content; Bulk Material	1-gal. vacuum-seal bag	2,013.7	0.17
35'-36.5'	CDL_VC-4_35'-36.5'	Dry stack	PW Extractor (+ 10 mL H2O); Moisture Content; Bulk Material	1-gal. vacuum-seal bag	1,103.2	0.15
36.5'-38'	CDL_VC-4_36.5'-38'	Dry stack	Sample discarded due to poor recovery	-	-	-
38'-39.5'	CDL_VC-4_38'-39.5'	Dry stack	Sample discarded due to poor recovery	-	-	-
39.5'-41'	CDL_VC-4_39.5'-41'	Dry stack	PW Extractor (+ 10 mL H2O); Moisture Content; Bulk Material	1-gal. vacuum-seal bag	713.7	0.16

Borehole CDL_VC-4, Collected 3/5-6/19 (continued)

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
41'-42.5'	CDL_VC-4_41'-42.5'	Dry stack	Bulk Material	1-gal. vacuum-seal bag	799.5	-
45'-46.5'	CDL_VC-4_45'-46.5'	Dry stack	Bulk Material	1-gal. vacuum-seal bag	715.4	-
47'-48.5'	CDL_VC-4_47'-48.5'	Dry stack	Bulk Material (only bottom part preserved)	1-gal. vacuum-seal bag	601.7	-
48.5'-50'	CDL_VC-4_48.5'-50'	Dry stack	Moisture Content; Bulk Material	1-gal. vacuum-seal bag	795.7	0.19
50'-51.5'	CDL_VC-4_50'-51.5'	Dry stack	Sample discarded due to poor recovery	-	-	-

Borehole CDL_VC-4, Collected 3/5-6/19 (continued)

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
51.5'-53'	CDL_VC-4_51.5'-53'	Dry stack	Tube Sample for UVA	-	-	-
53'-54.5'	CDL_VC-4_53'-54.5'	Dry stack	Sample discarded due to poor recovery	-	-	-
54.5'-56'	CDL_VC-4_54.5'-56'	Dry stack/bottom ash layer	Tube sample for UVA/ Moisture content		-	0.16

INVENTORY OF FIELD-COLLECTED ASH SAMPLES
CDL_VC-4
Collection Date: **March 6, 2019**

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
65'-67'	CDL_VC-4_65'-67'	Impoundment	Shelby Tube for UVA	-	-	-

Borehole CDL_VC-4, Collected 3/5-6/19 (continued)

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
67'-68.5'	CDL_VC-4_67'-68.5'	Impoundment	PW Extractor A (no H2O); PW Extractor B (+ 10 mL H2O); Moisture Content; Bulk Material	1-gal. vacuum-seal bag	2,412.5	0.27
68.5'-70'	CDL_VC-4_68.5'-70'	Impoundment	PW Extractor A (no H2O); PW Extractor B (+ 10 mL H2O); Moisture Content; Bulk Material	1-gal. vacuum-seal bag	1,956.2	0.35
70'-71.5'	CDL_VC-4_70'-71.5'	Impoundment	PW Extractor A (no H2O); PW Extractor B (+ 7 mL H2O); Moisture Content; Bulk Material	1-gal. vacuum-seal bag	2,050.7	0.33
71.5'-73'	CDL_VC-4_71.5'-73'	Impoundment	PW Extractor A (no H2O); PW Extractor B (+ 10 mL H2O); Moisture Content; Bulk Material	1-gal. vacuum-seal bag	2,361.2	0.25
73'-74.5'	CDL_VC-4_73'-74.5'	Impoundment	PW Extractor A (no H2O); PW Extractor B (+ 10 mL H2O); Moisture Content; Bulk Material	1-gal. vacuum-seal bag	2,499.3	0.25

Borehole CDL_VC-4, Collected 3/5-6/19 (continued)

Depth Below Ground Level (ft)	Sample ID	Material Type (Dry Stack or Impoundment)	Target Test	Container & Size	Bulk Weight in bag (g)	Moisture Content (gH2O/g)
74.5'-76.5'	CDL_VC-4_74.5'-76.5'	Impoundment	Shelby Tube for UVA	-	-	-

B
INDIVIDUAL SPLIT SPOON SAMPLE ANALYSIS

Table of Appendices

B-1 Concentration Profiles from In-Field Low L/S Extractions

B-2 Standardized Concentration Profiles of In-field Low L/S Extractions Using the Global Material Mean and Standard Deviation

B-3 Comparison of Standardized Release Profiles for Low L/S and L/S≈1 Extractions

B-1 Concentration Profiles from In-Field Low L/S Extractions

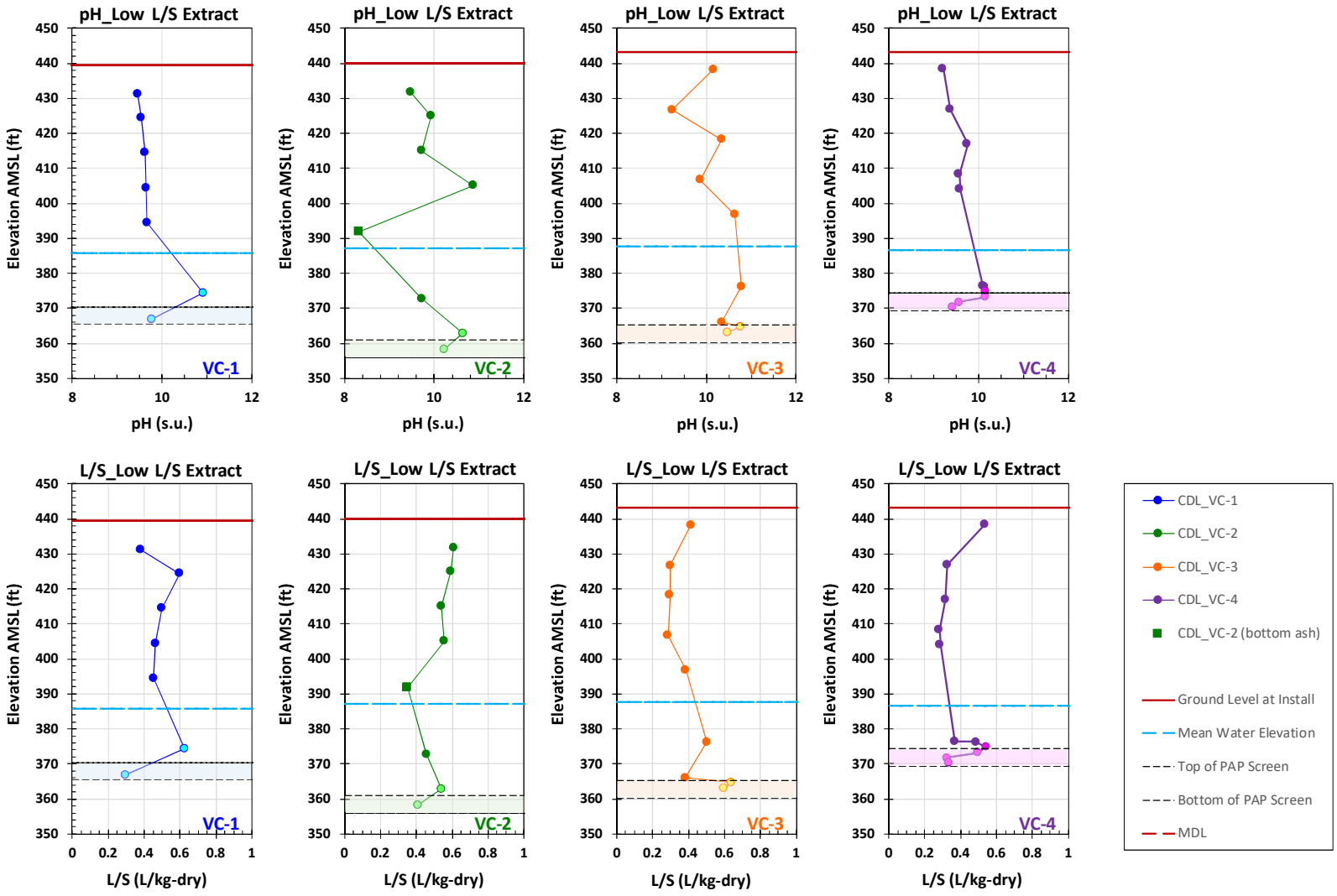

Figure B-1
Concentration profiles from in-field low L/S extractions: pH and liquid-to-solid ratio (L/S)

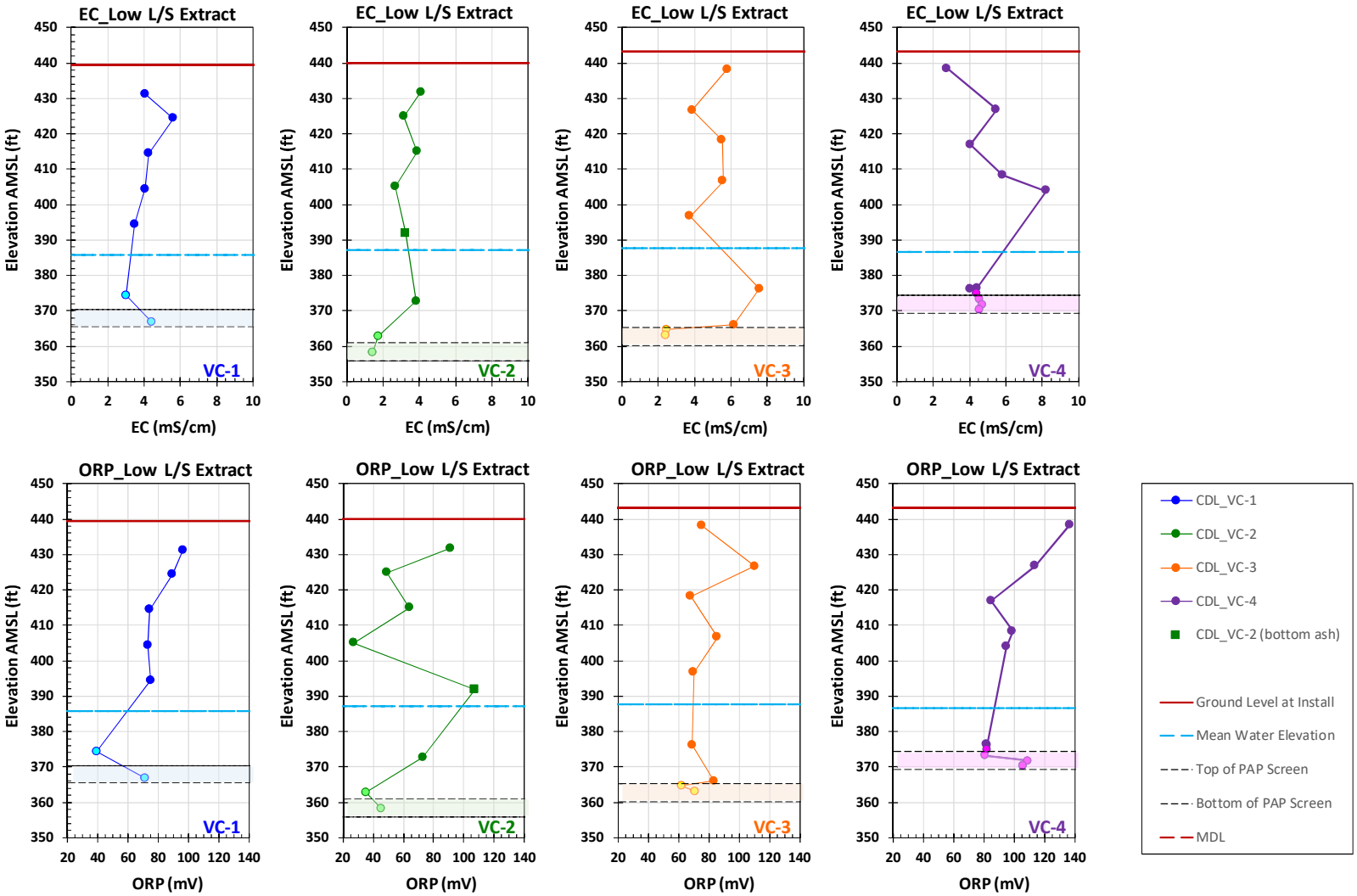

Figure B-2
Concentration profiles from in-field low L/S extractions: electrical conductivity (EC) and oxidation-reduction potential (ORP)

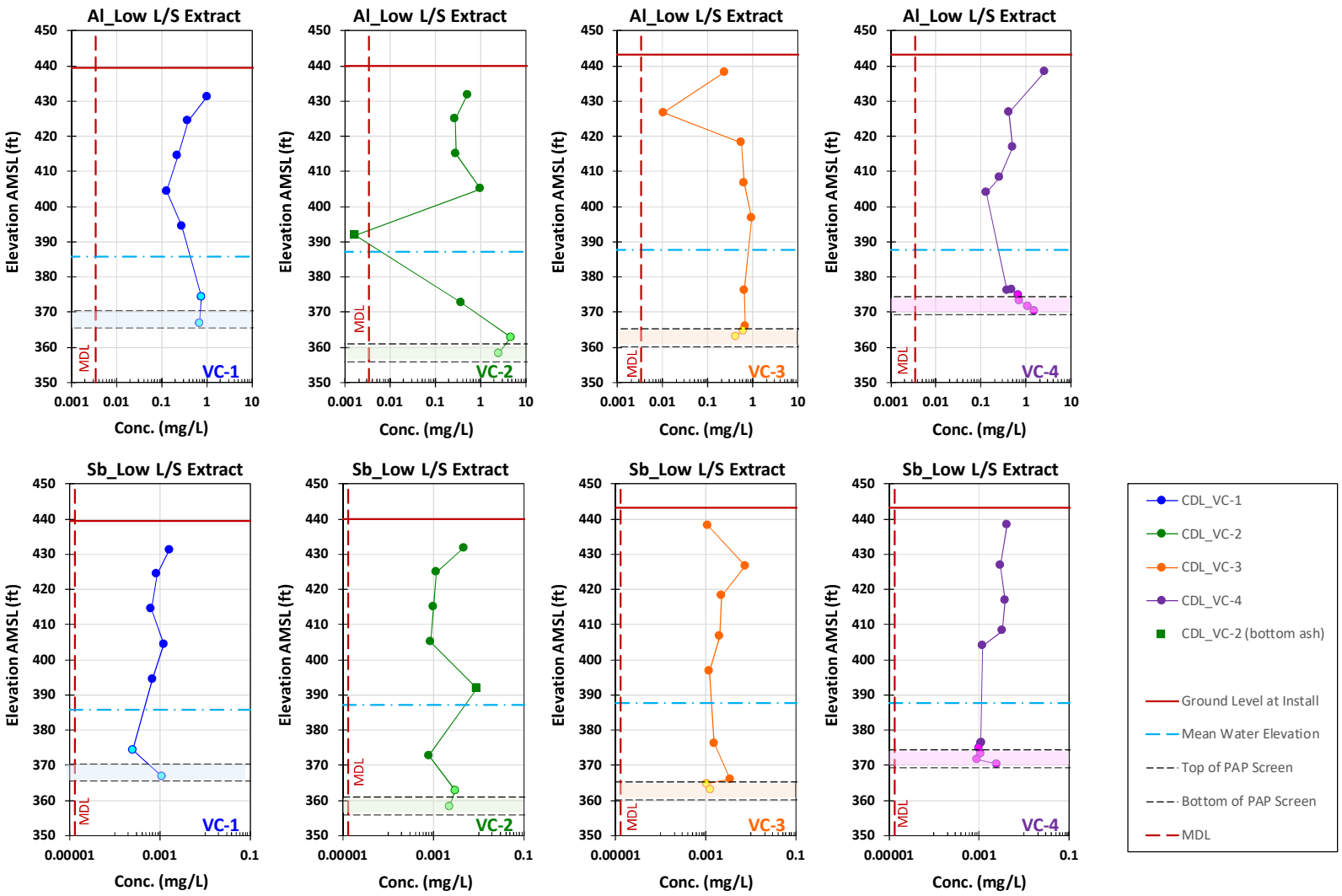

Figure B-3
Concentration profiles from in-field low L/S extractions: aluminum and antimony

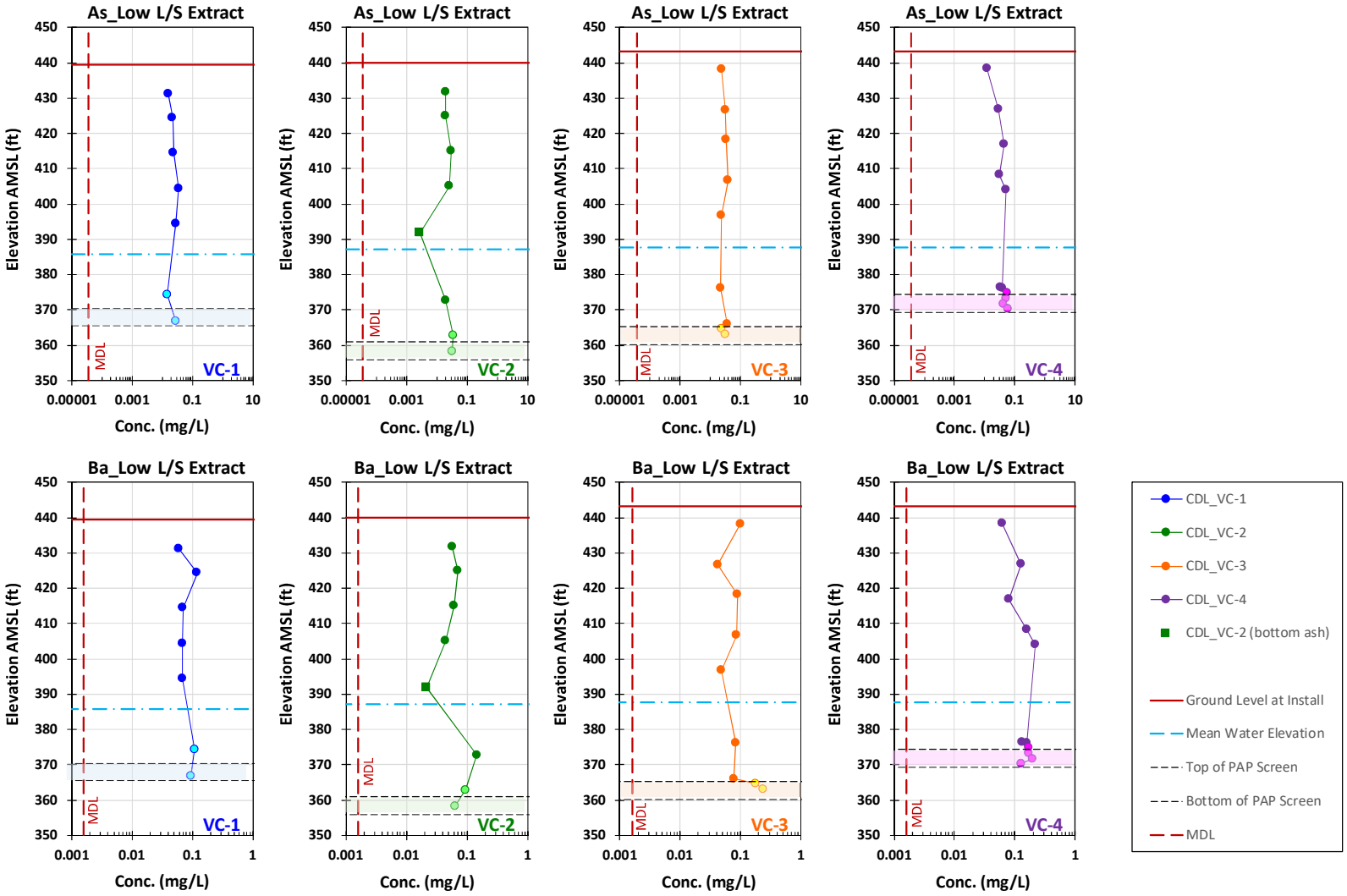

Figure B-4
Concentration profiles from in-field low L/S extractions: arsenic and barium

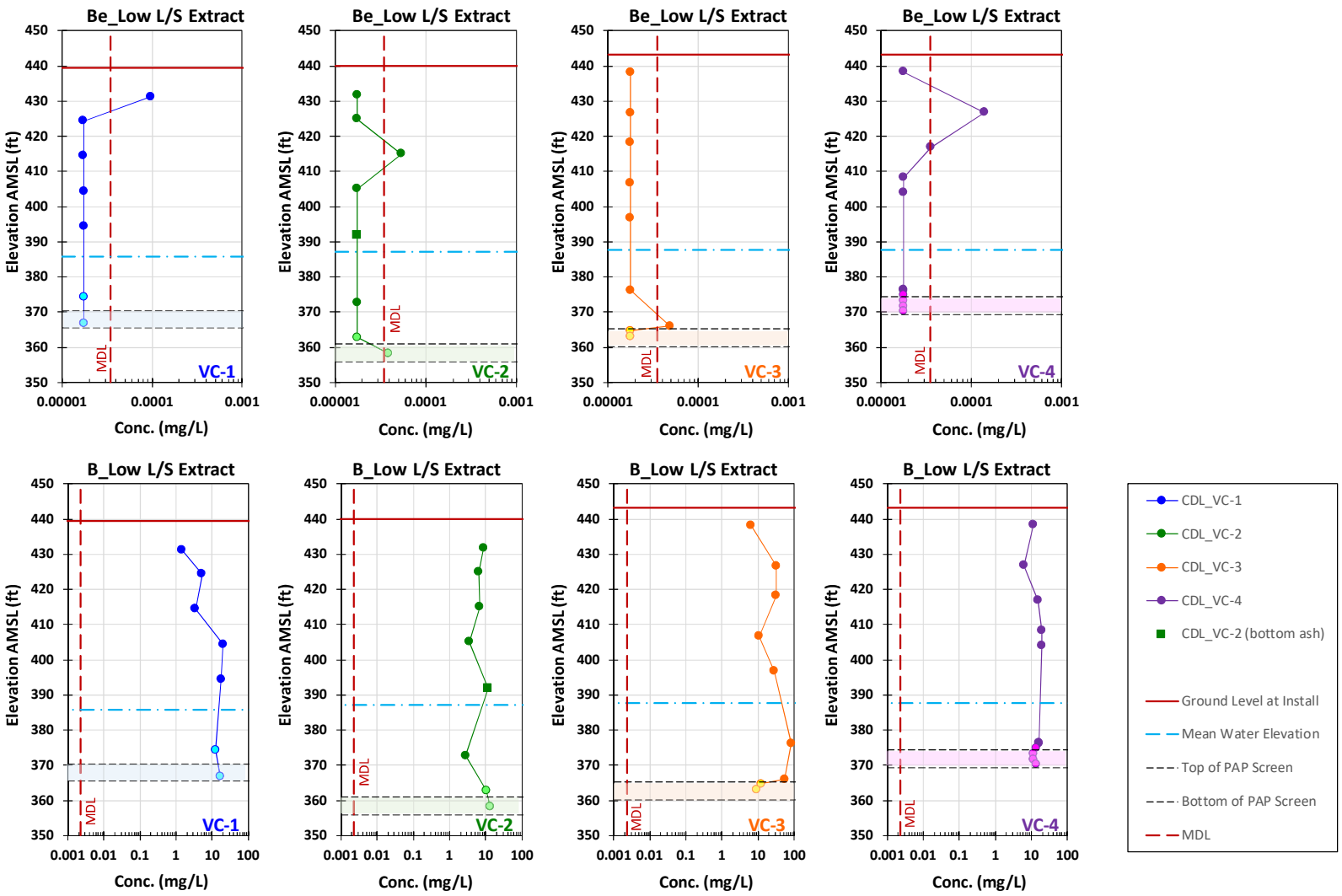

Figure B-5
Concentration profiles from in-field low L/S extractions: beryllium and boron

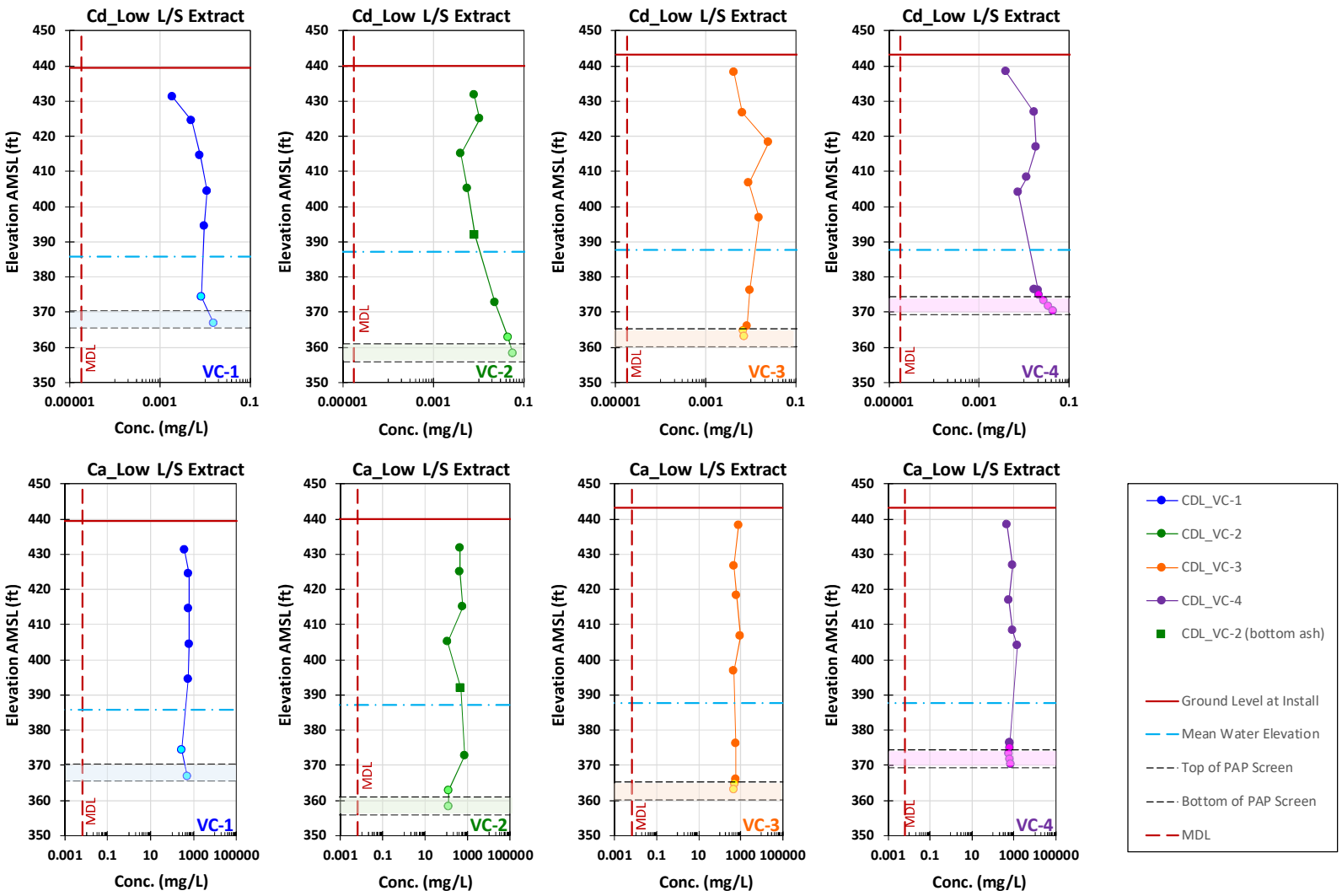

Figure B-6
Concentration profiles from in-field low L/S extractions: cadmium and calcium

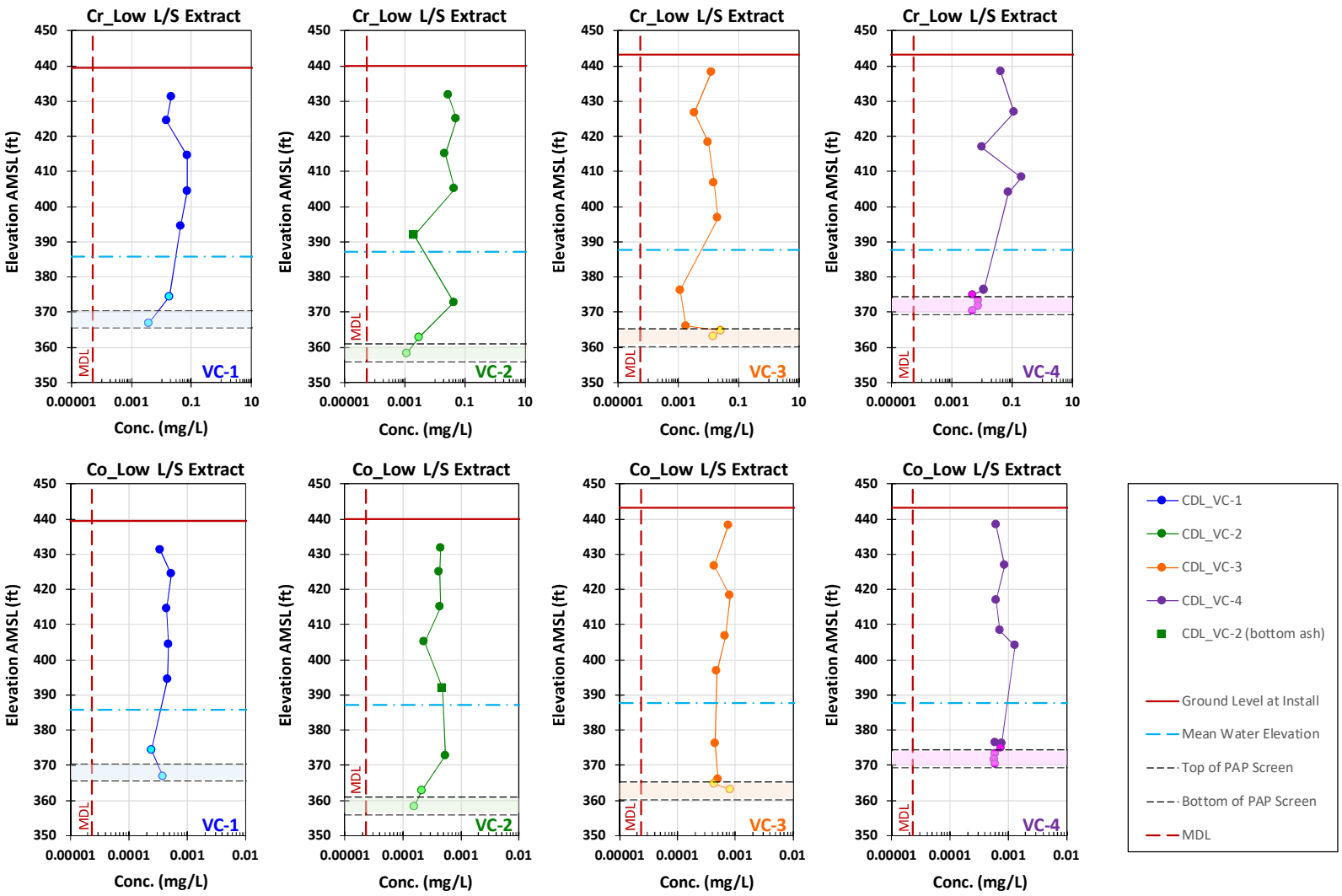

Figure B-7
Concentration profiles from in-field low L/S extractions: chromium and cobalt

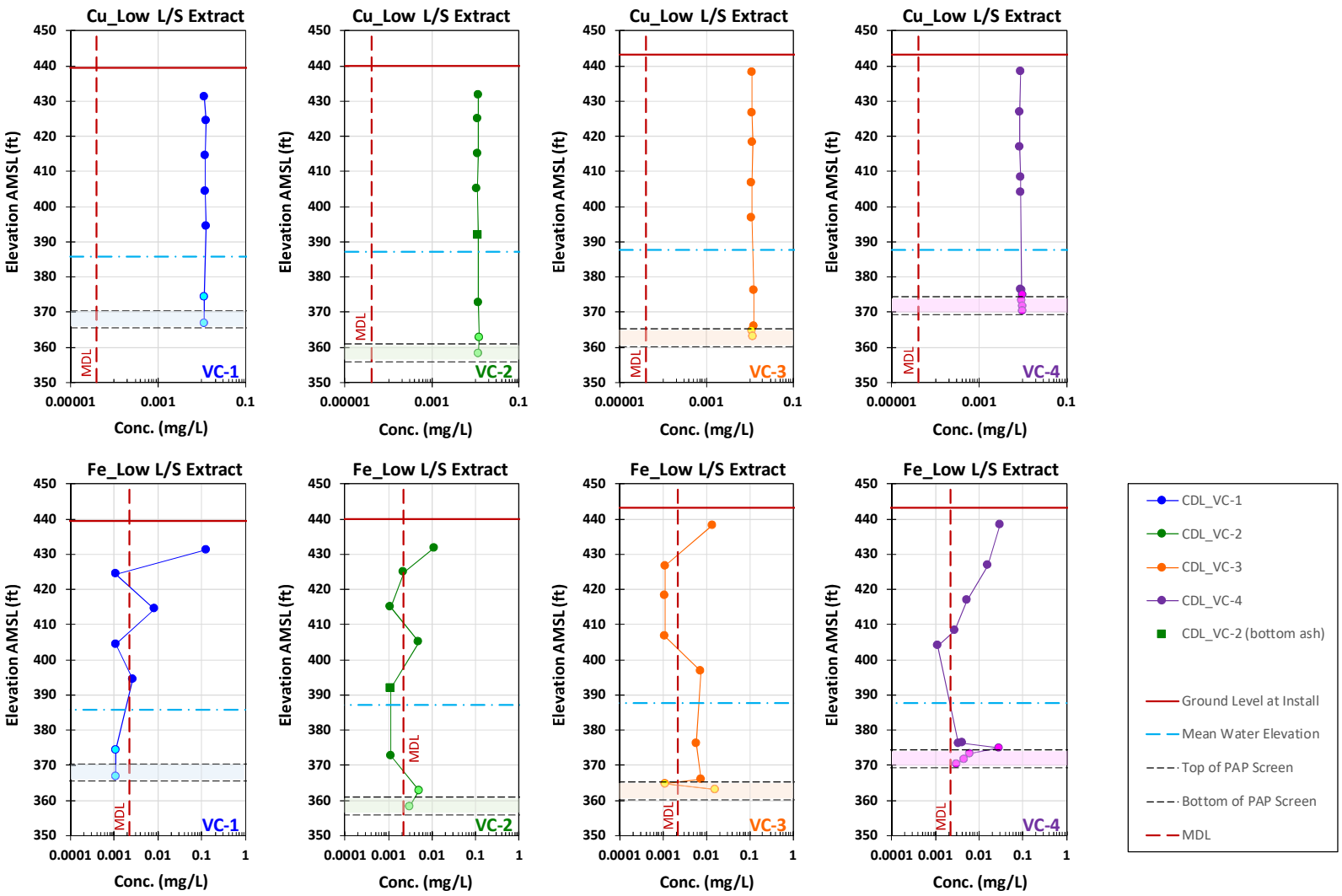

Figure B-8
Concentration profiles from in-field low L/S extractions: copper and iron

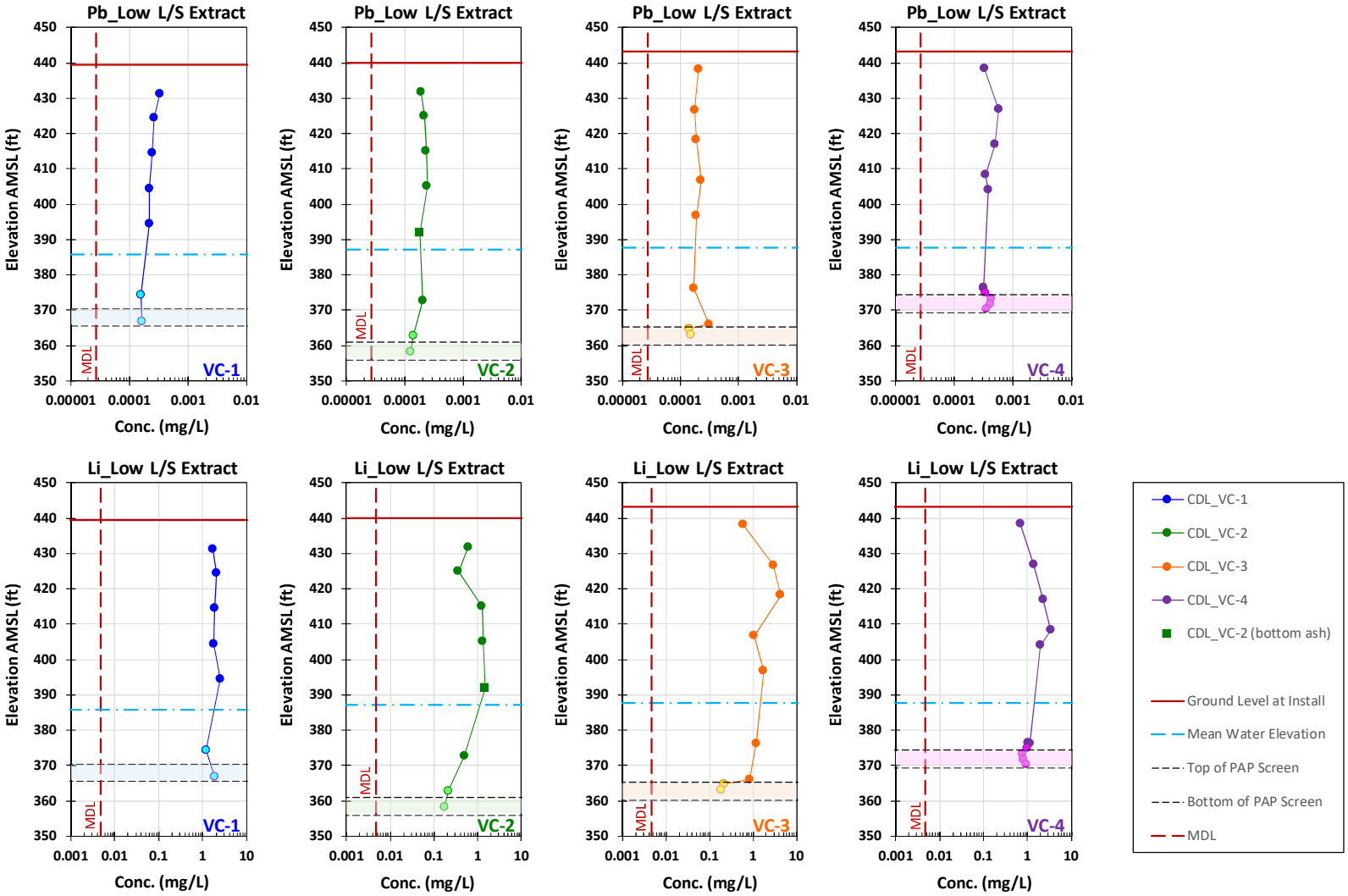

Figure B-9
Concentration profiles from in-field low L/S extractions: lead and lithium

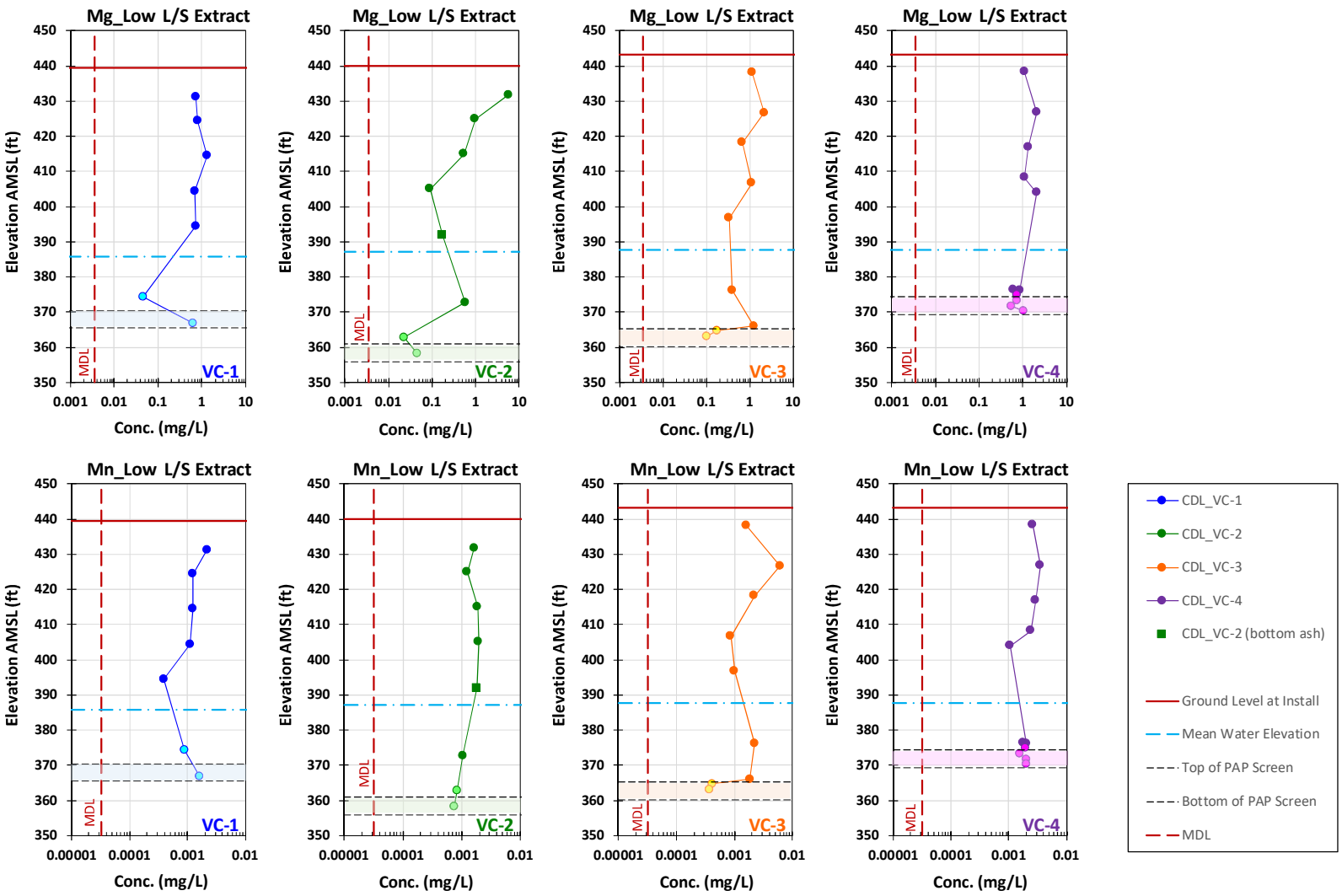

Figure B-10
Concentration profiles from in-field low L/S extractions: magnesium and manganese

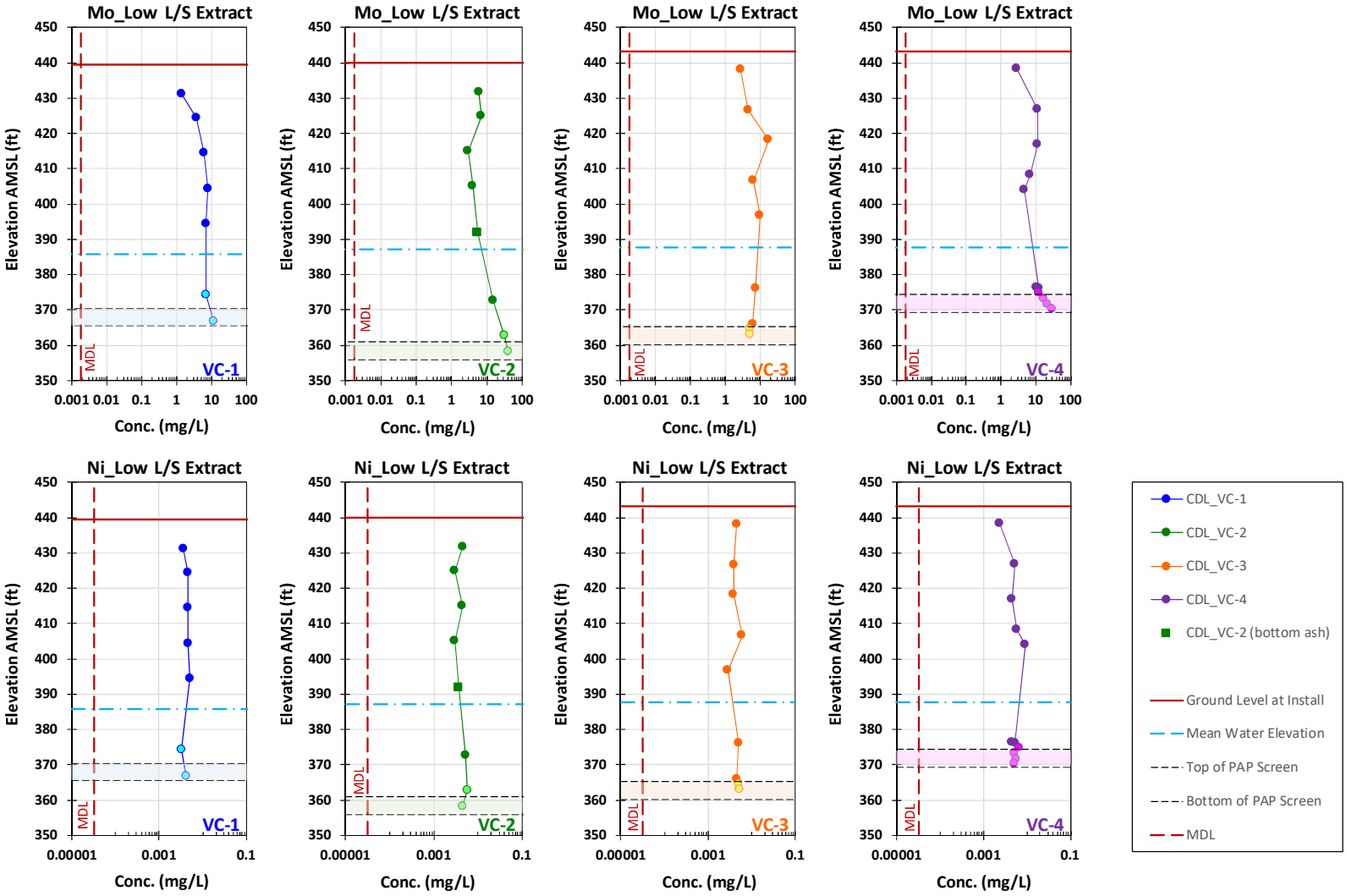

Figure B-11
Concentration profiles from in-field low L/S extractions: molybdenum and nickel

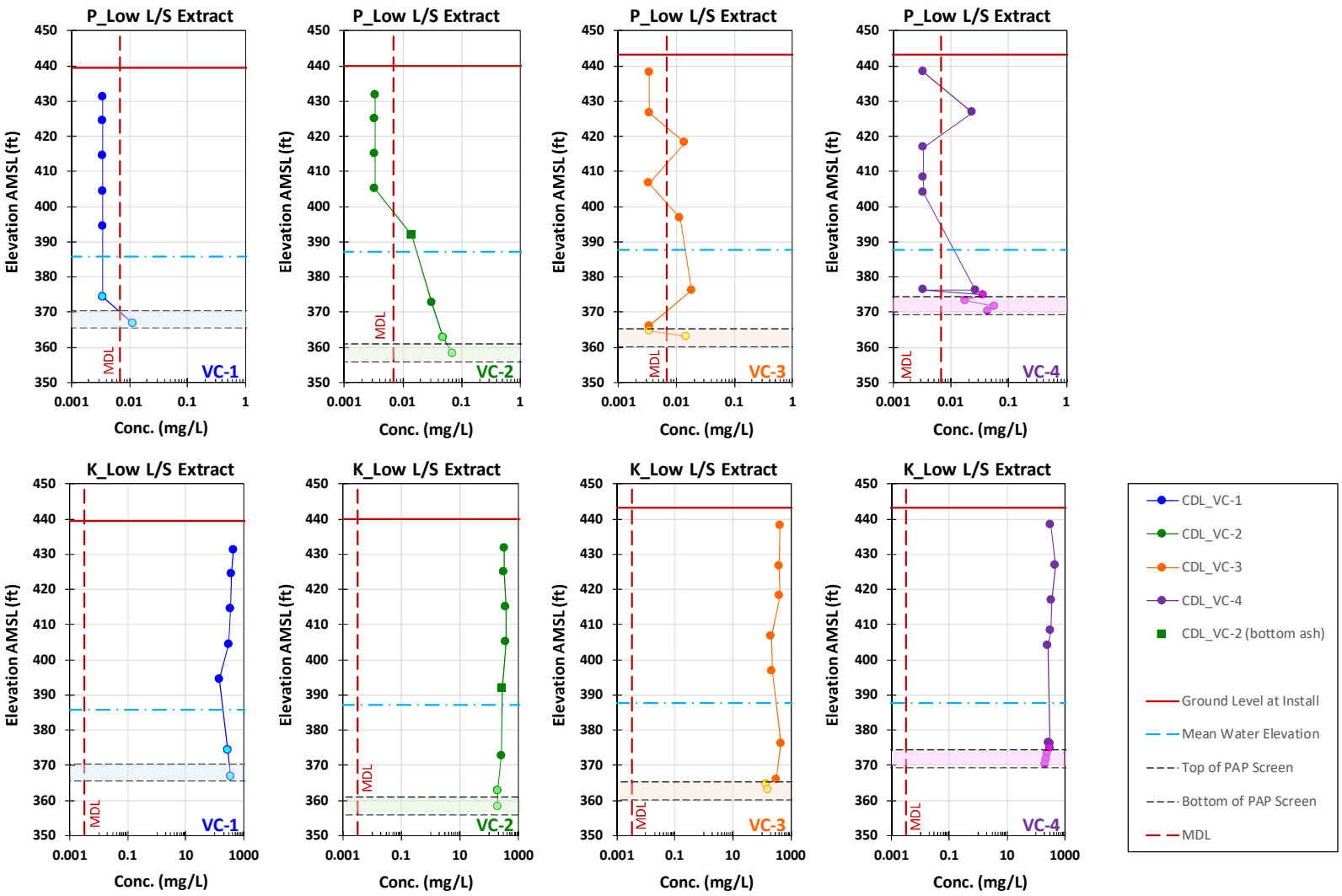

Figure B-12
Concentration profiles from in-field low L/S extractions: phosphorus and potassium

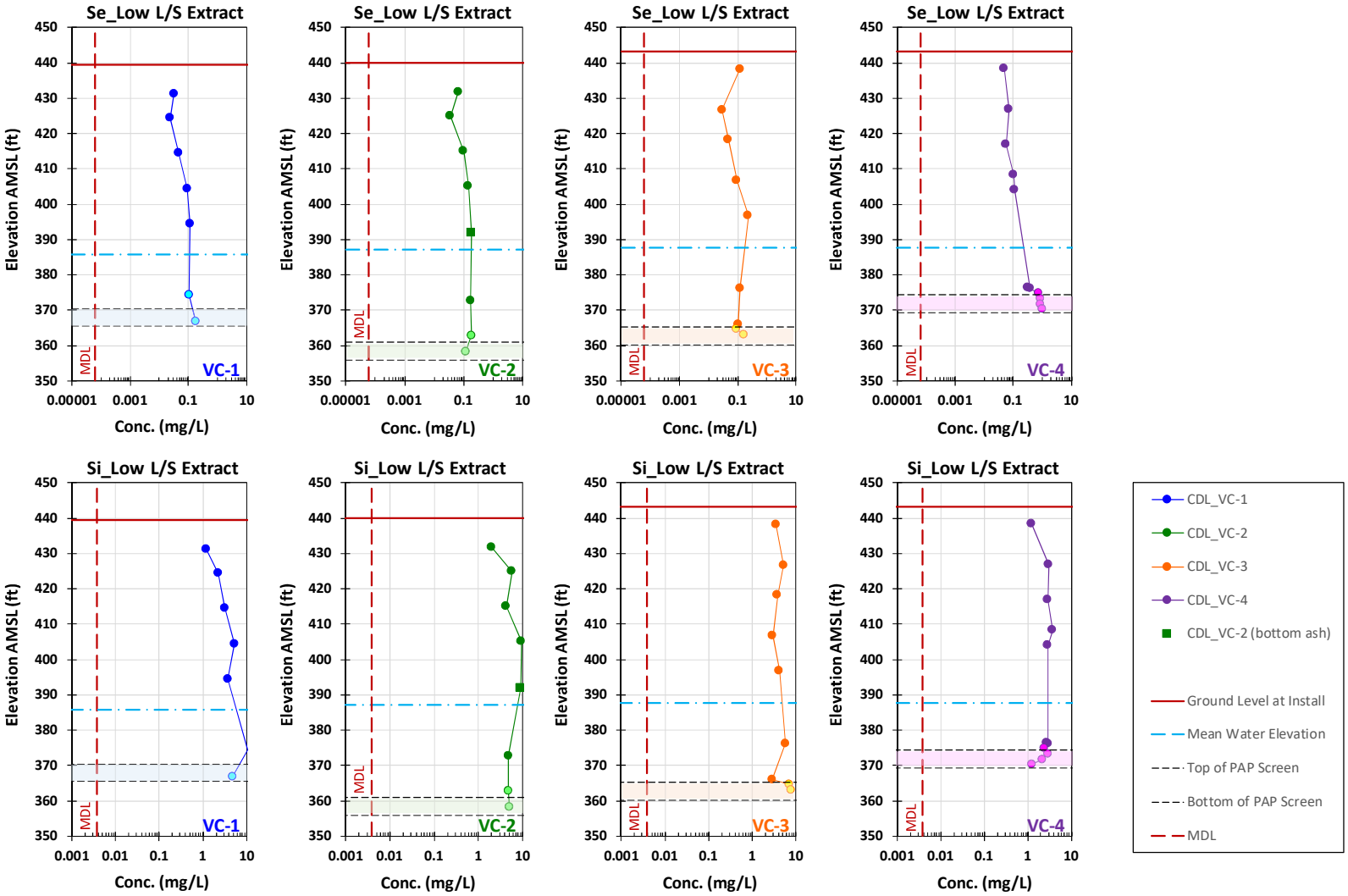

Figure B-13
Concentration profiles from in-field low L/S extractions: selenium and silicon

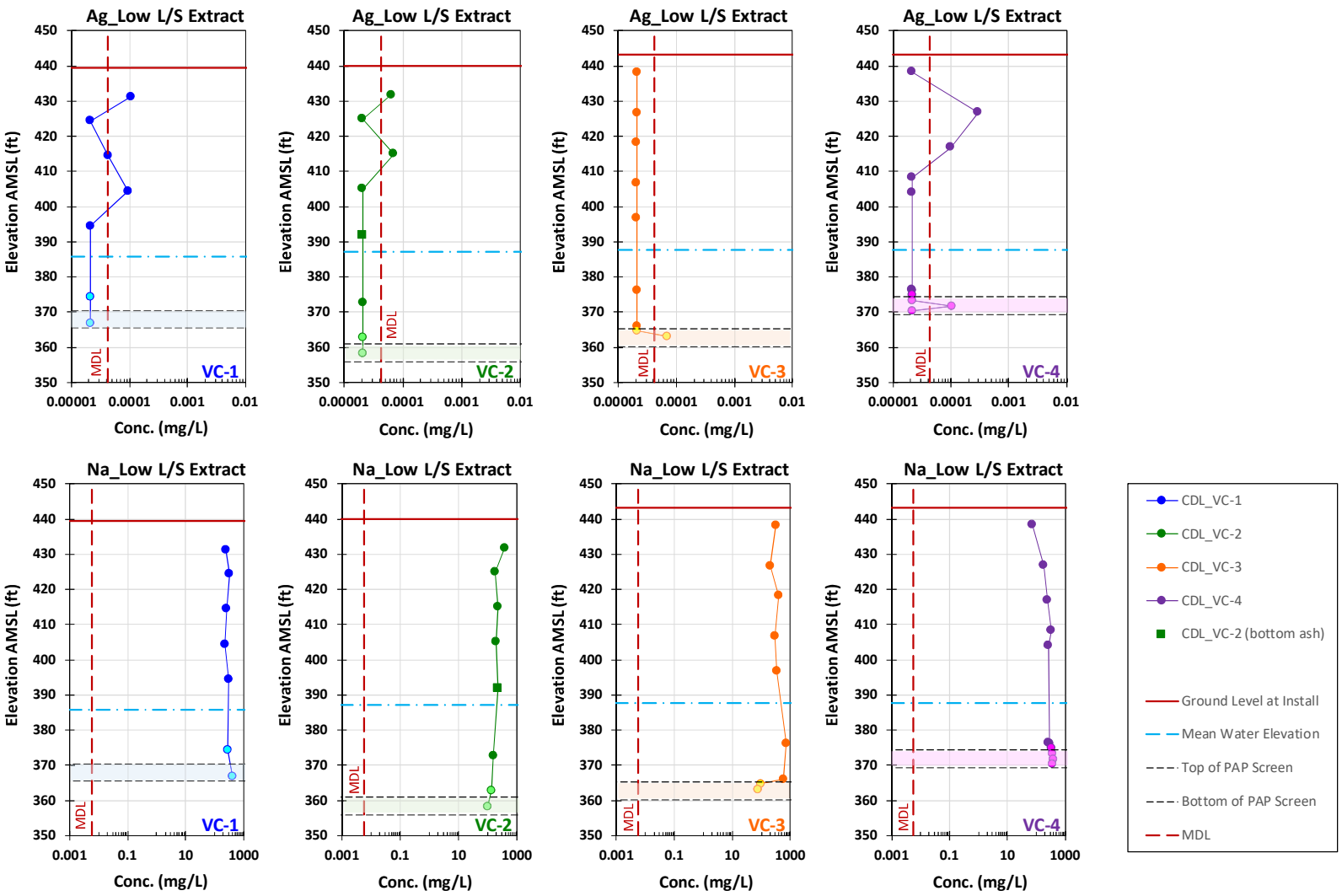

Figure B-14
Concentration profiles from in-field low L/S extractions: silver and sodium

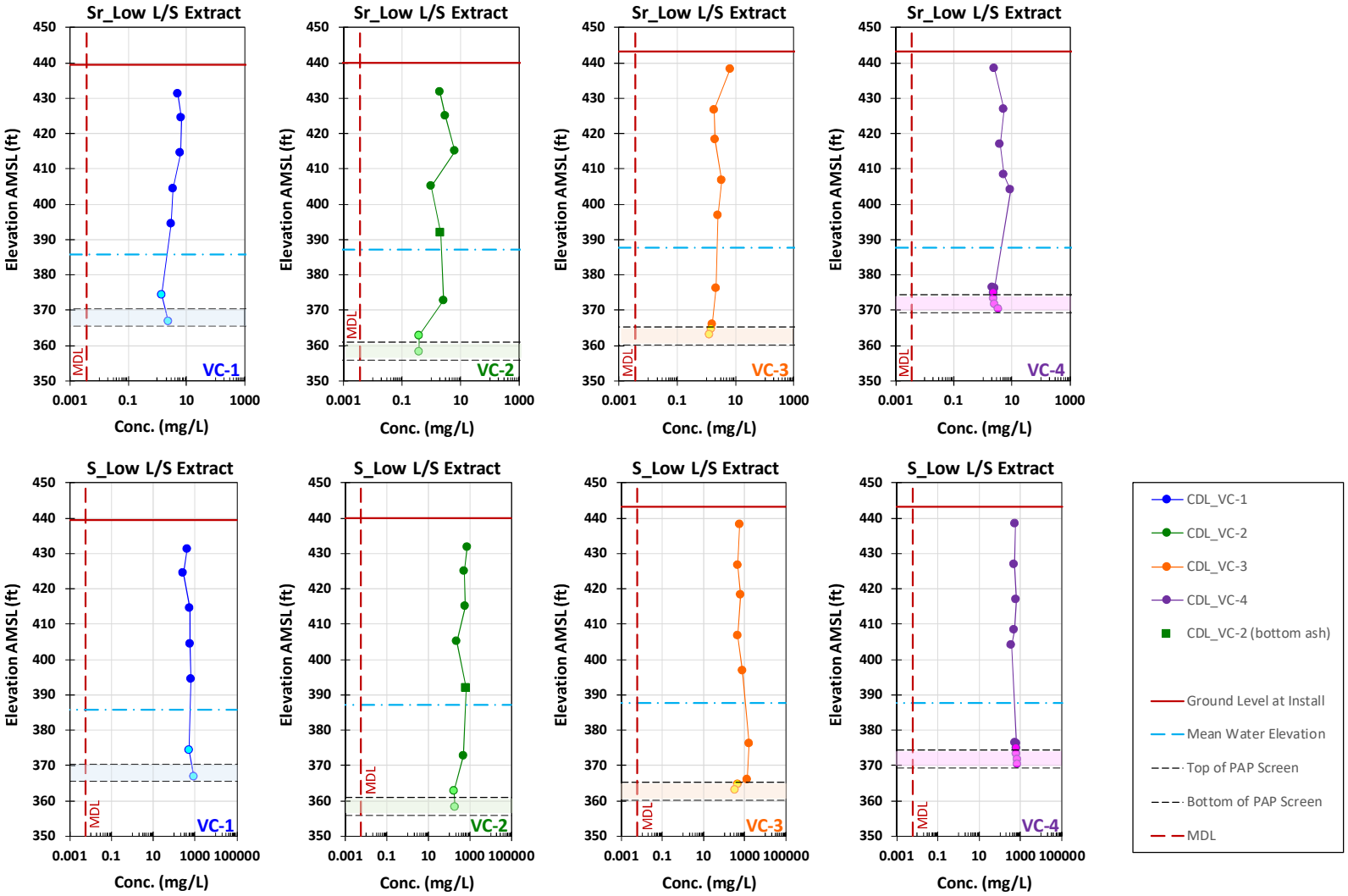

Figure B-15
Concentration profiles from in-field low L/S extractions: strontium and sulfur

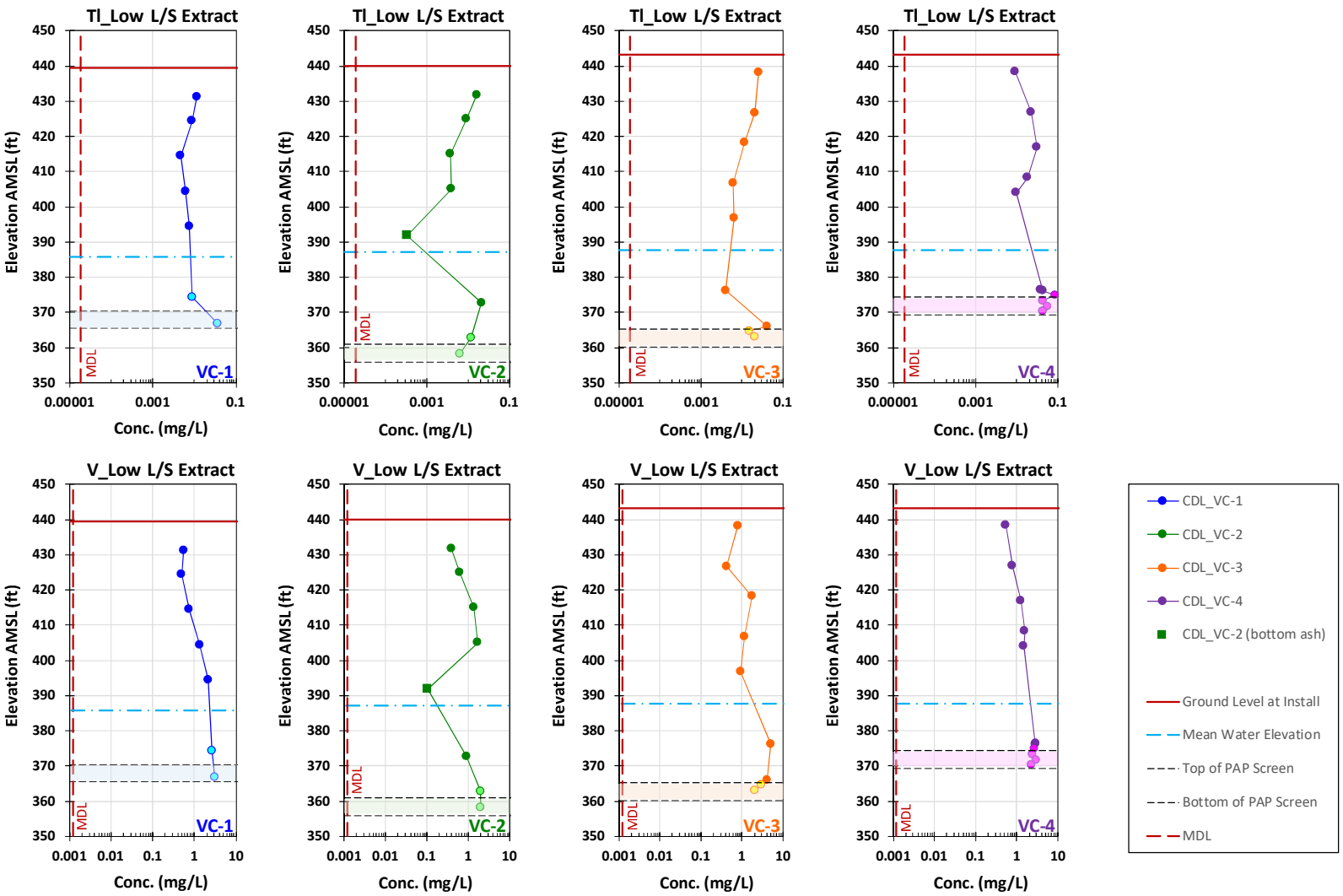

Figure B-16
Concentration profiles from in-field low L/S extractions: thallium and vanadium

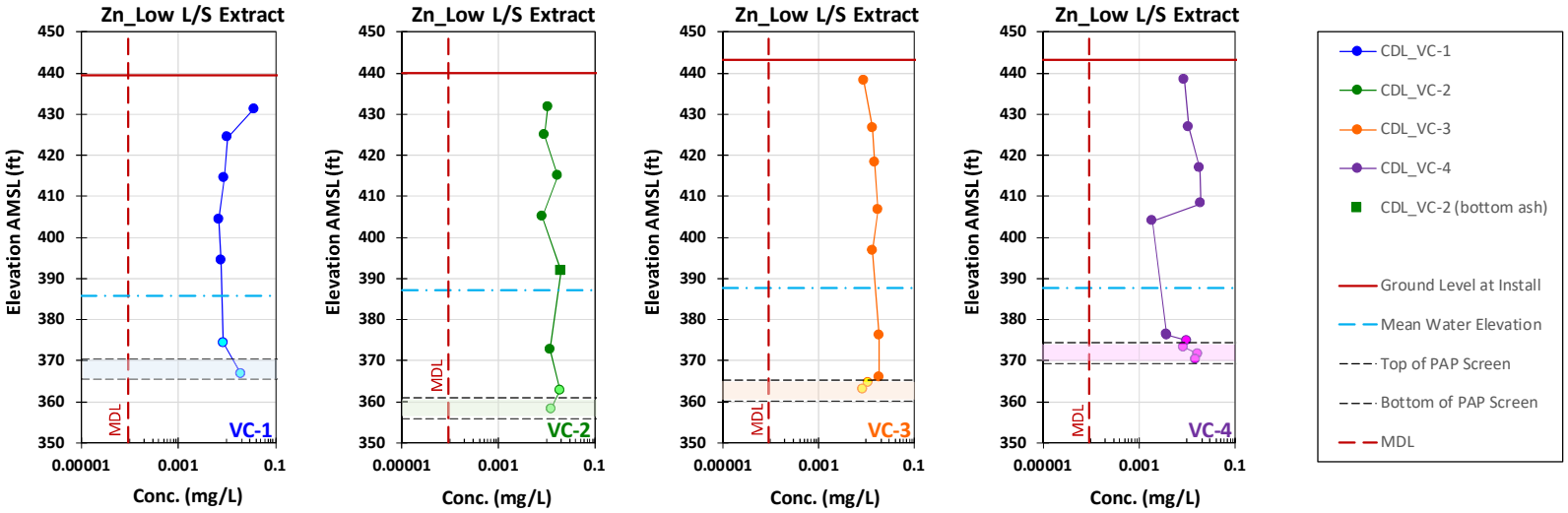

Figure B-17
Concentration profiles from in-field low L/S extractions: zinc

B-2 Standardized Concentration Profiles of In-field Low L/S Extractions Using the Global Material Mean and Standard Deviation

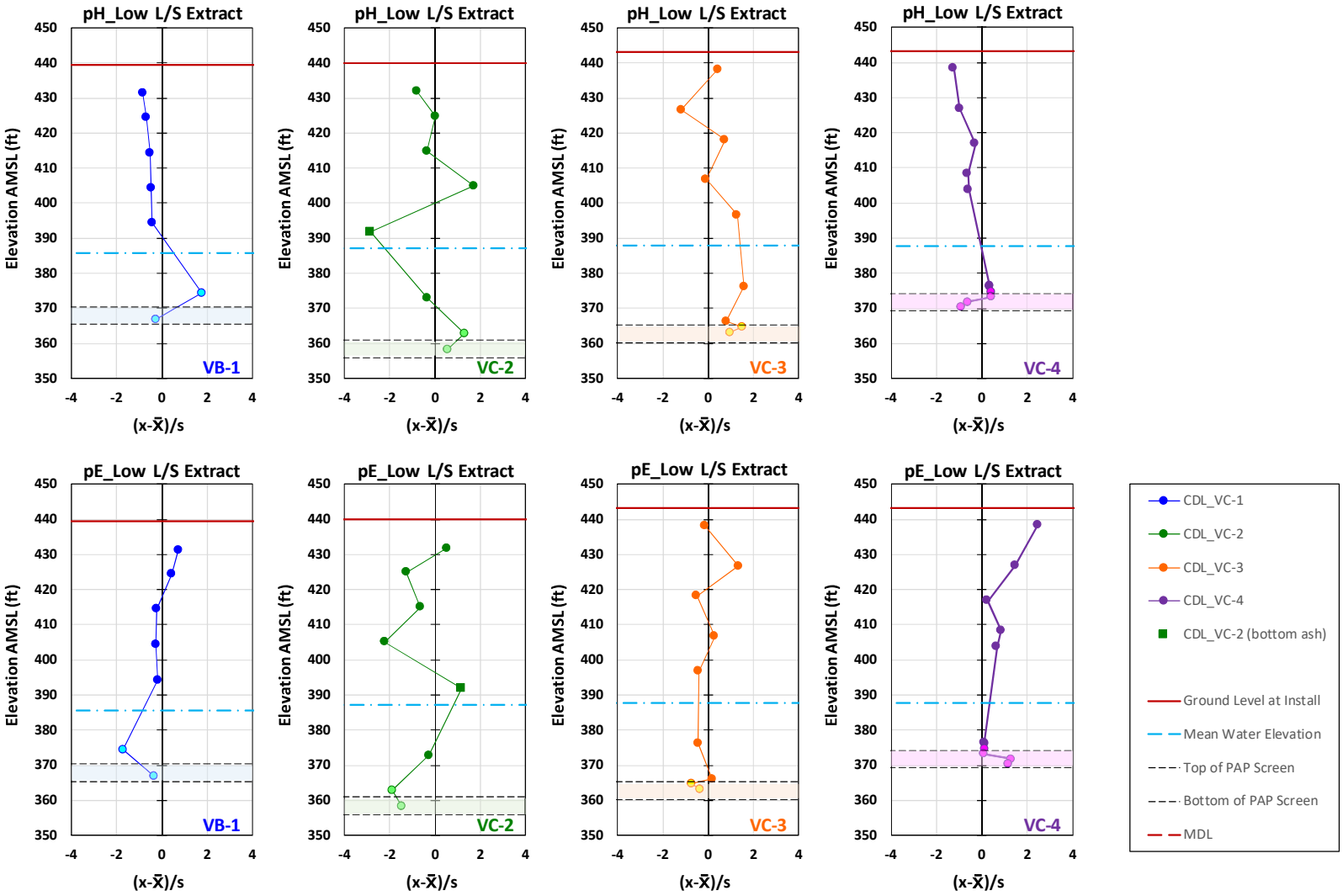

Figure B-18
Profiles from in-field low L/S extractions standardized using the global material mean and standard deviation: pH and pE

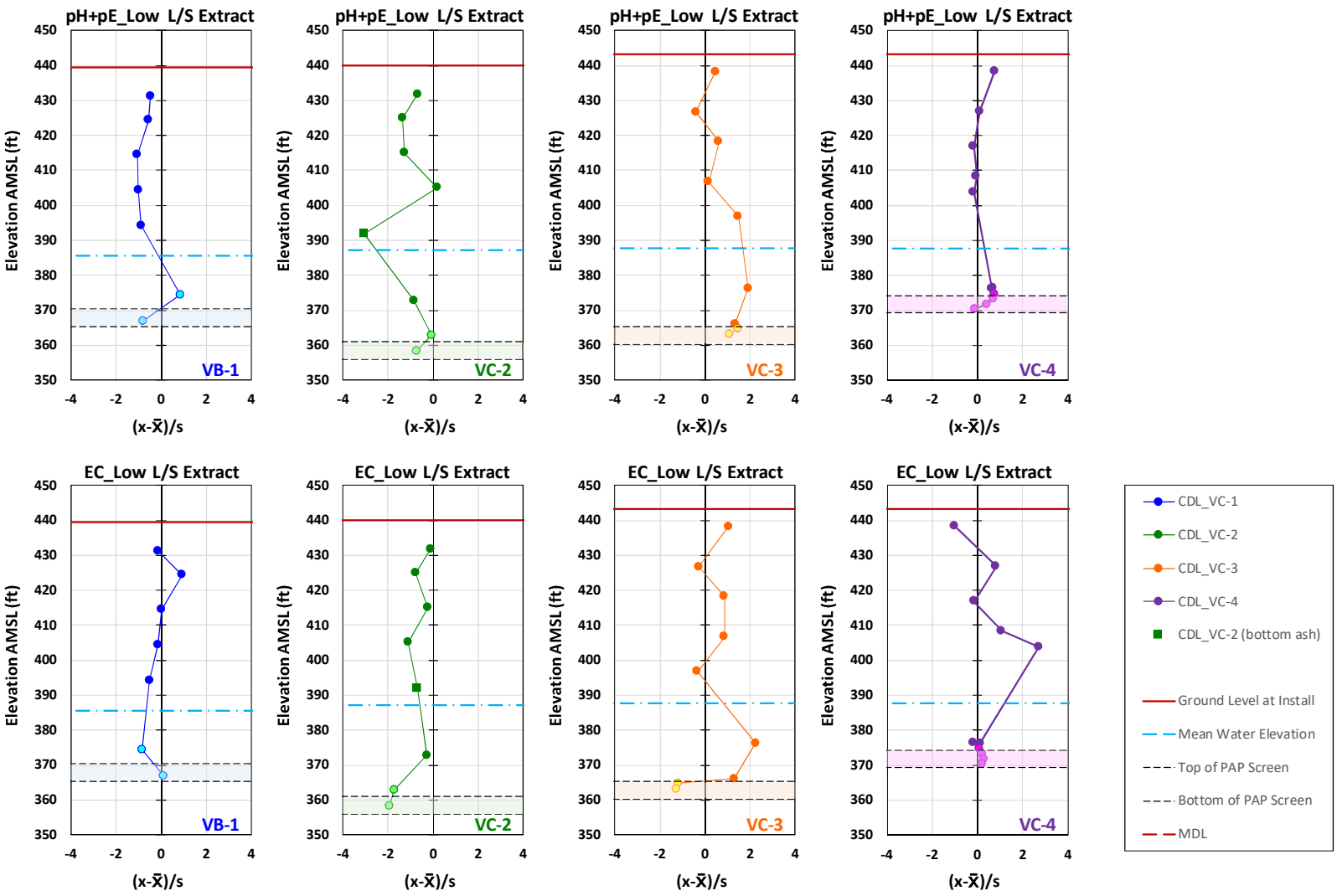

Figure B-19
Profiles from in-field low L/S extractions standardized using the global material mean and standard deviation: pH+pE and electrical conductivity

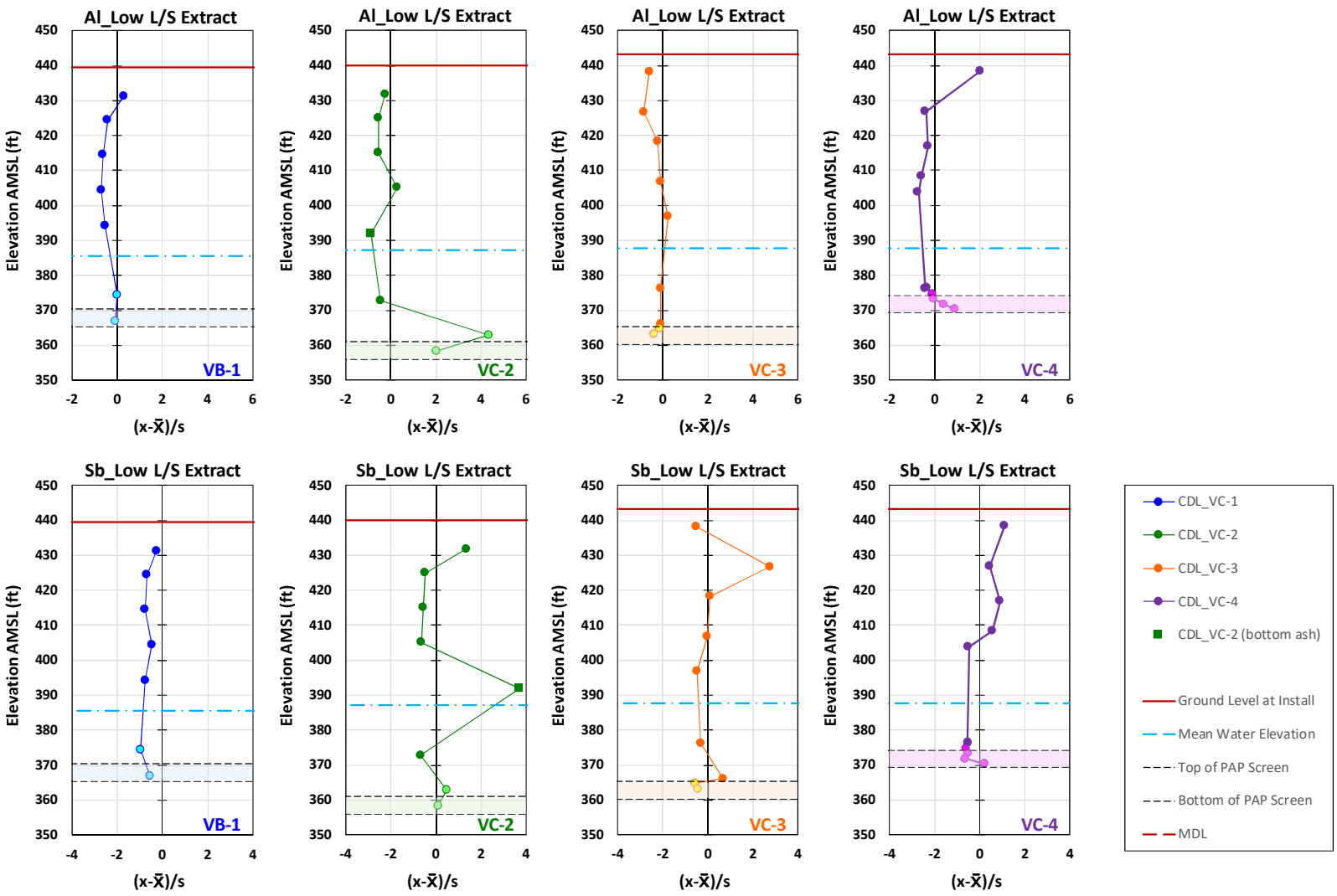

Figure B-20
Profiles from in-field low L/S extractions standardized using the global material mean and standard deviation: aluminum and antimony

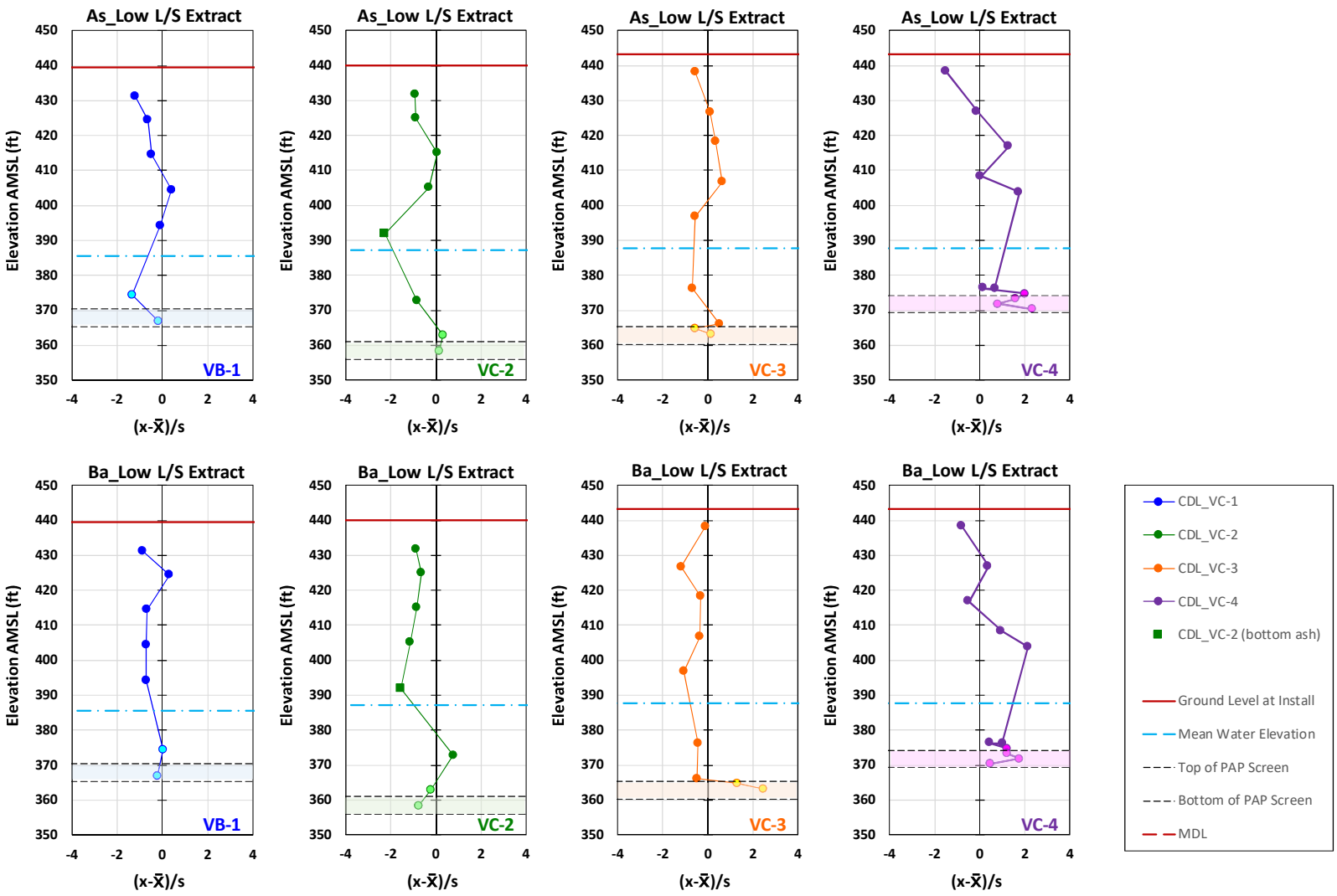

Figure B-21
Profiles from in-field low L/S extractions standardized using the global material mean and standard deviation: arsenic and barium

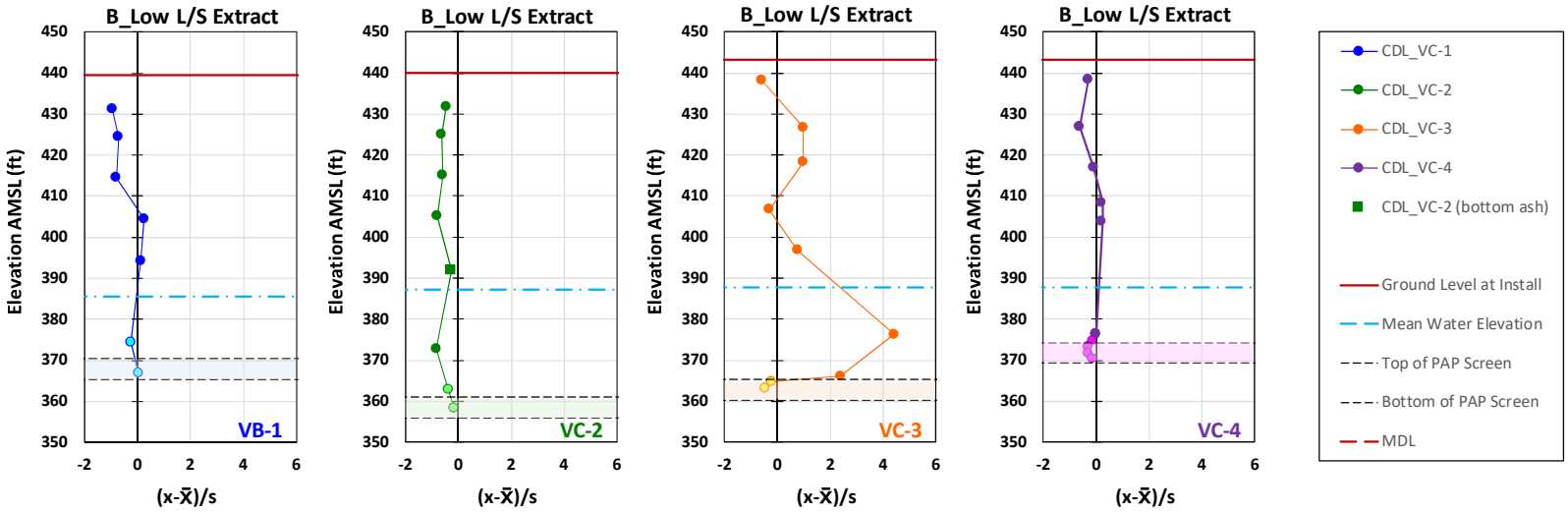

Figure B-22
Profiles from in-field low L/S extractions standardized using the global material mean and standard deviation: beryllium and boron

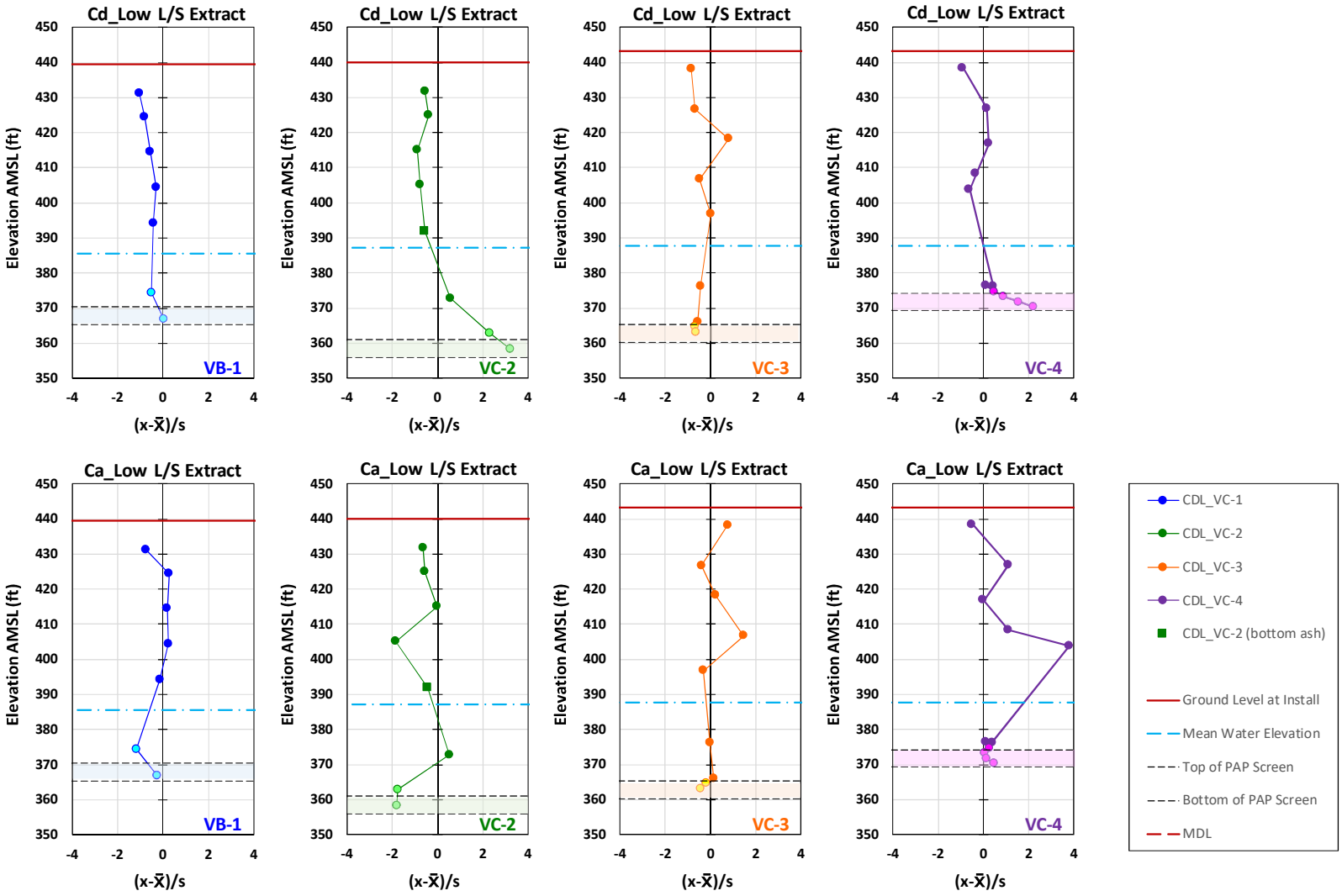

Figure B-23
Profiles from in-field low L/S extractions standardized using the global material mean and standard deviation: cadmium and calcium

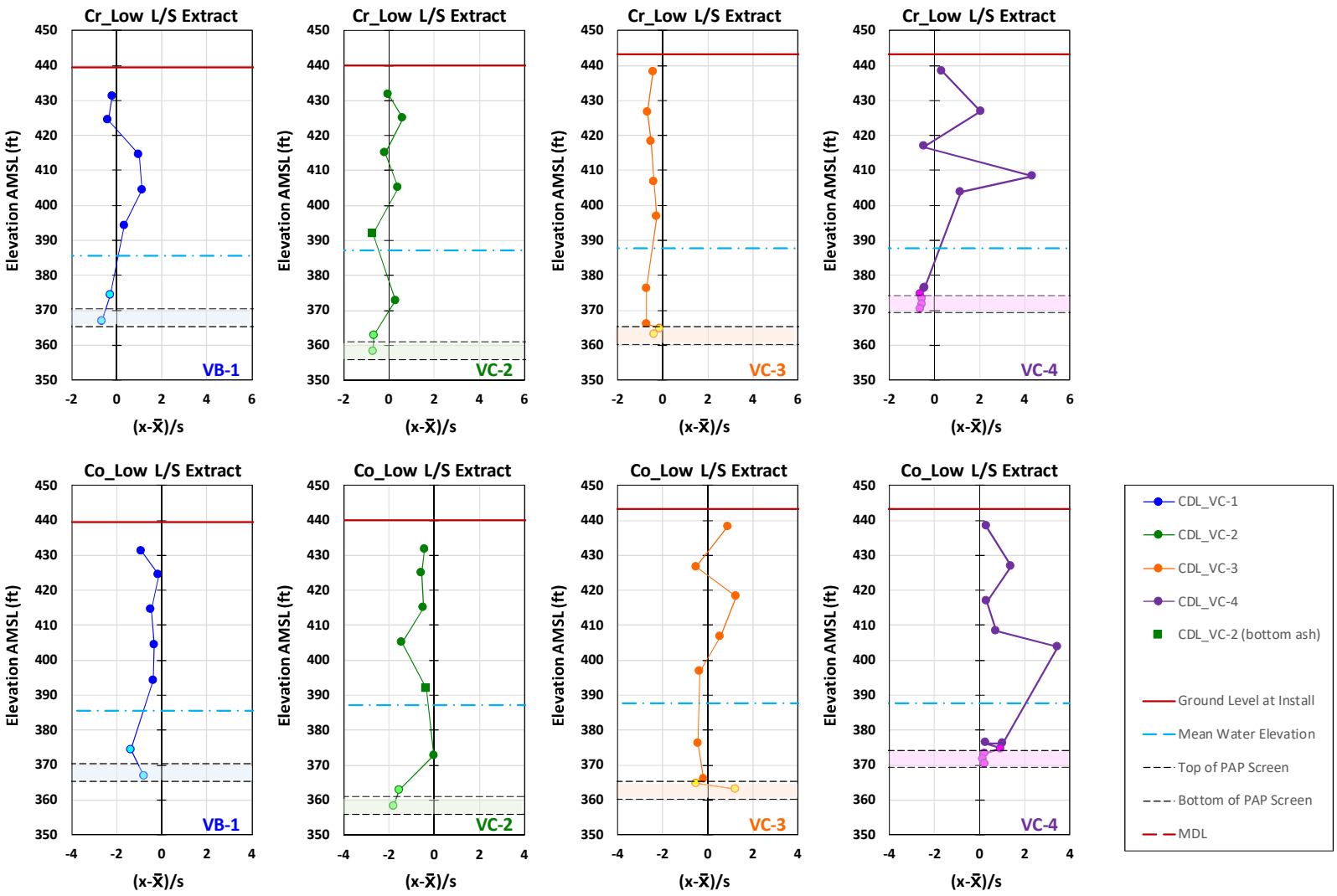

Figure B-24
Profiles from in-field low L/S extractions standardized using the global material mean and standard deviation: chromium and cobalt

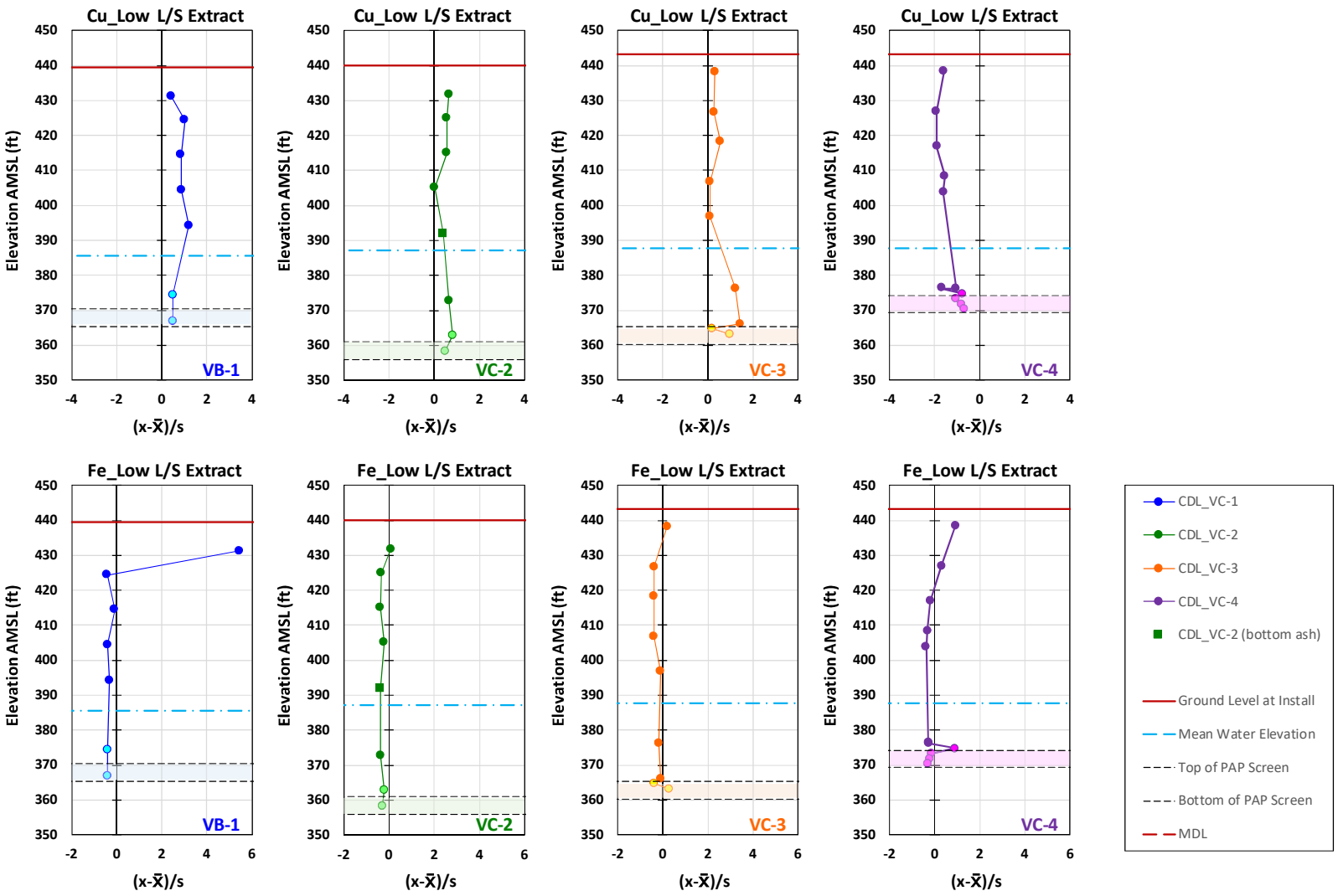

Figure B-25
Profiles from in-field low L/S extractions standardized using the global material mean and standard deviation: copper and iron

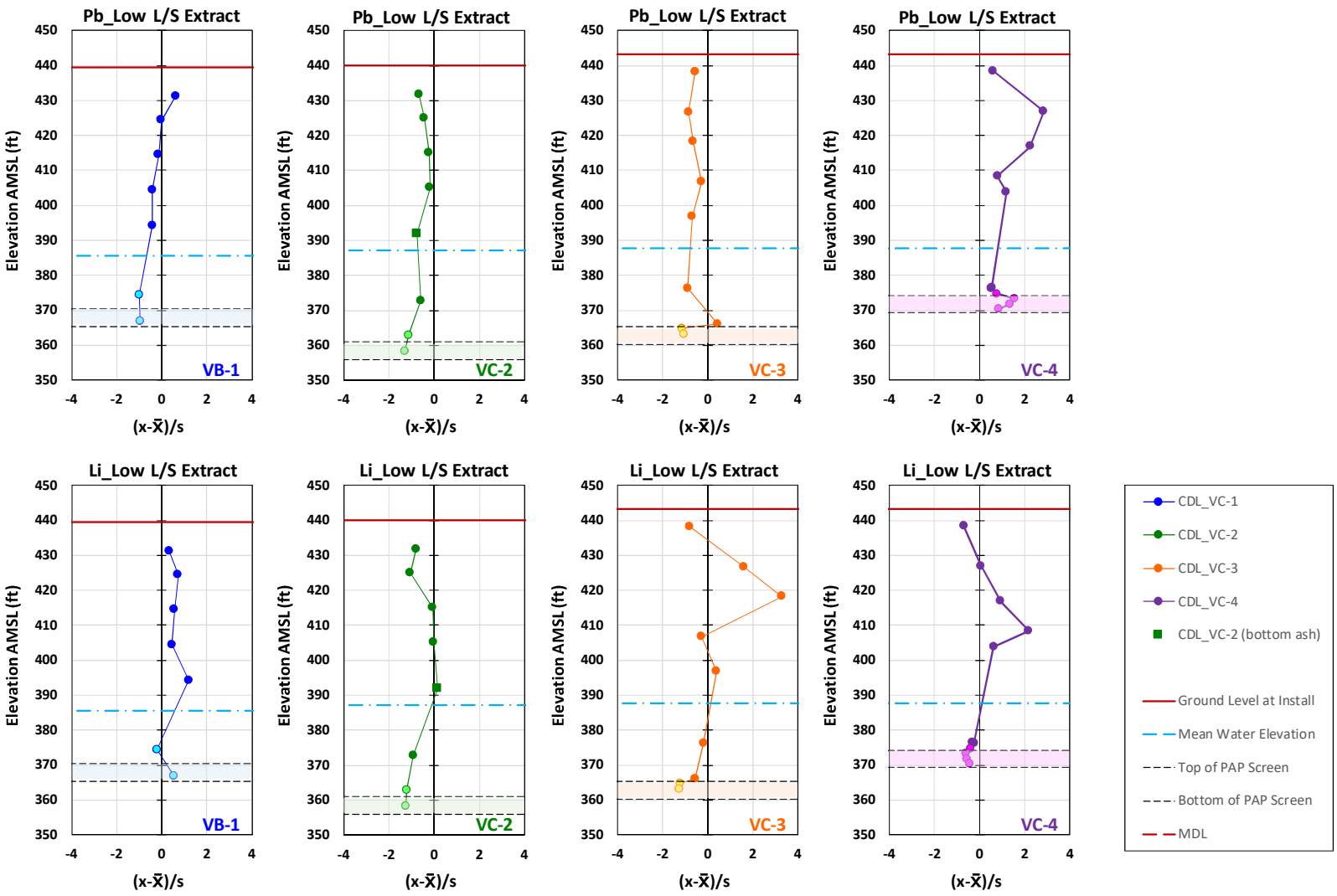

Figure B-26
Profiles from in-field low L/S extractions standardized using the global material mean and standard deviation: lead and lithium

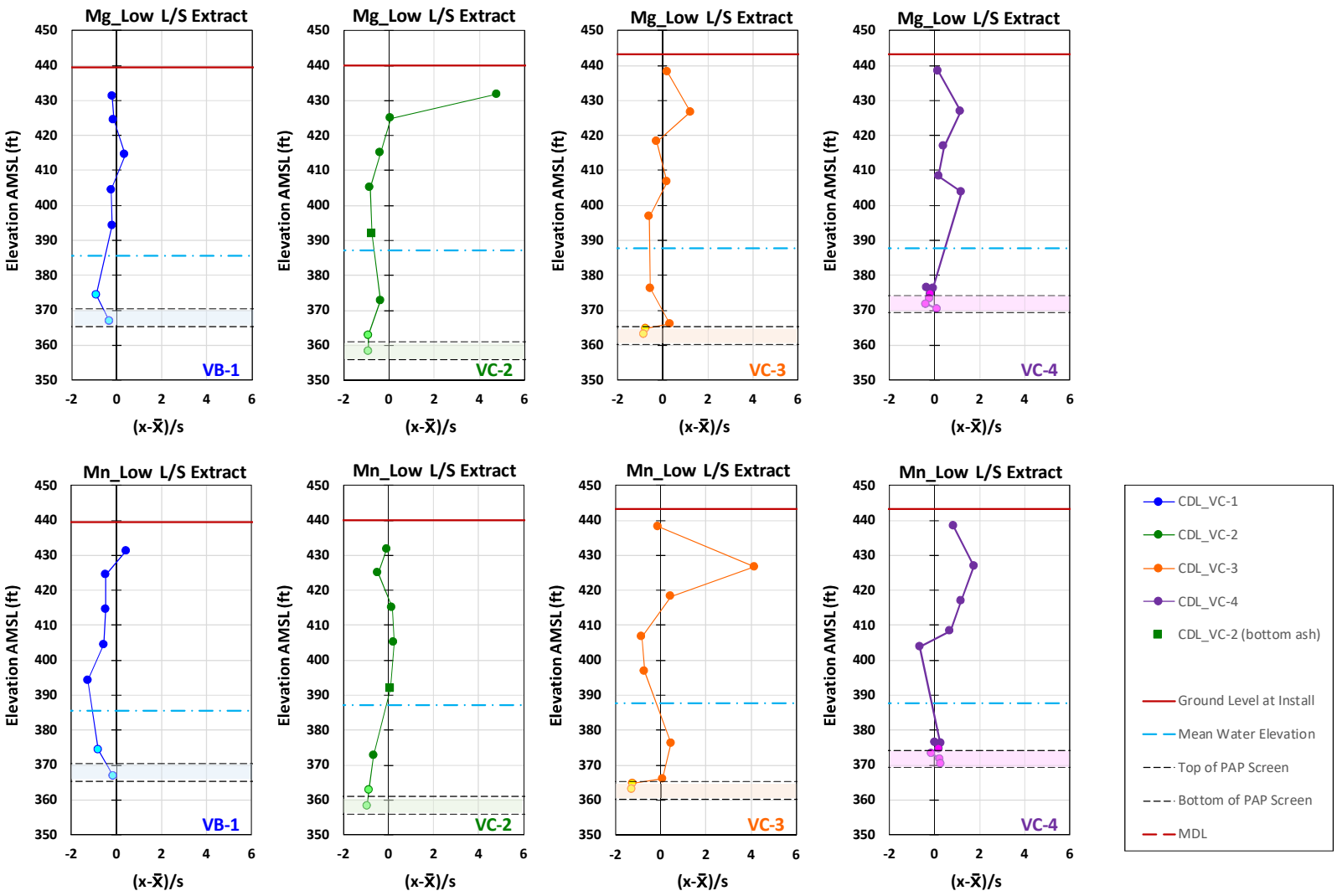

Figure B-27
Profiles from in-field low L/S extractions standardized using the global material mean and standard deviation: magnesium and manganese

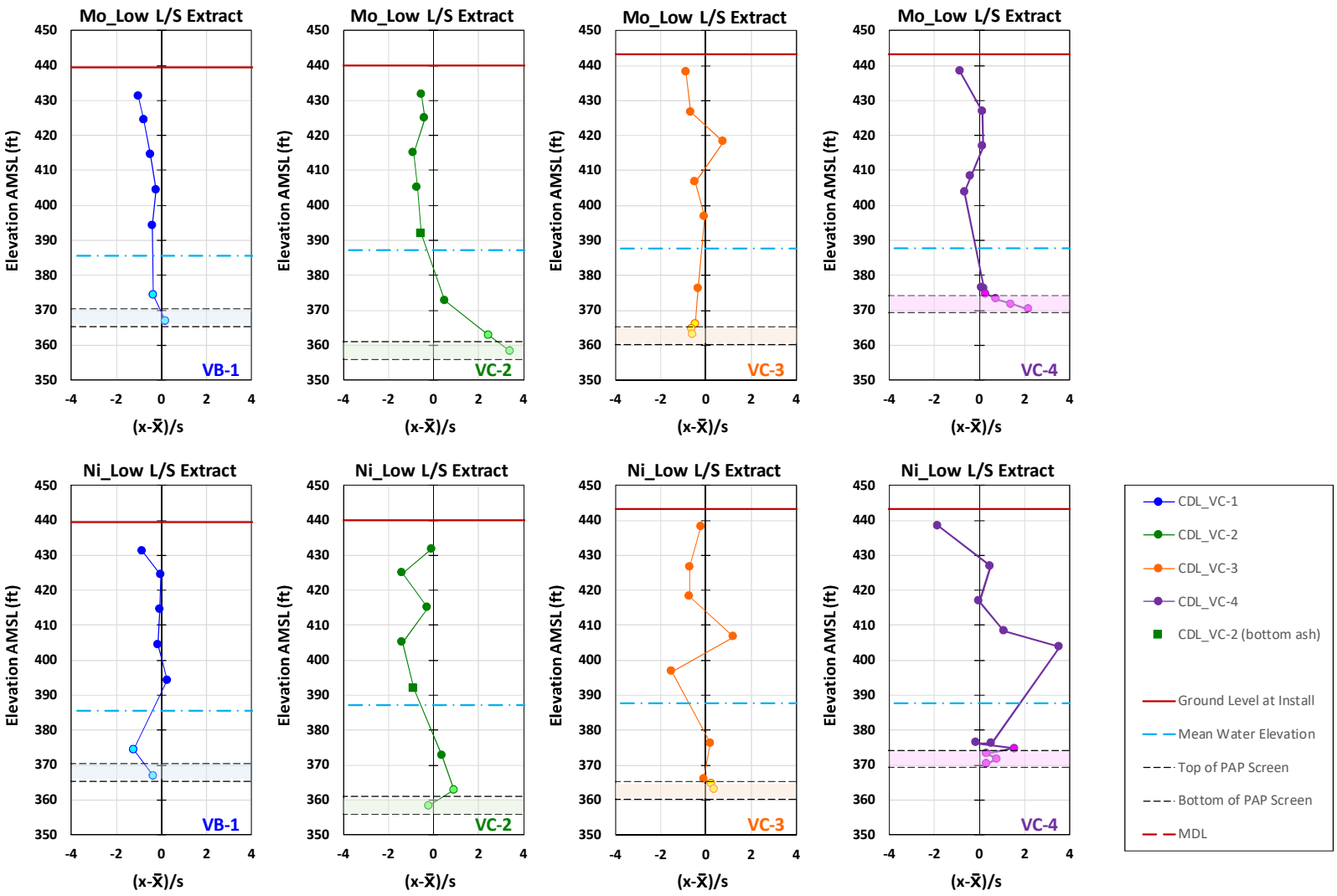

Figure B-28
Profiles from in-field low L/S extractions standardized using the global material mean and standard deviation: molybdenum and nickel

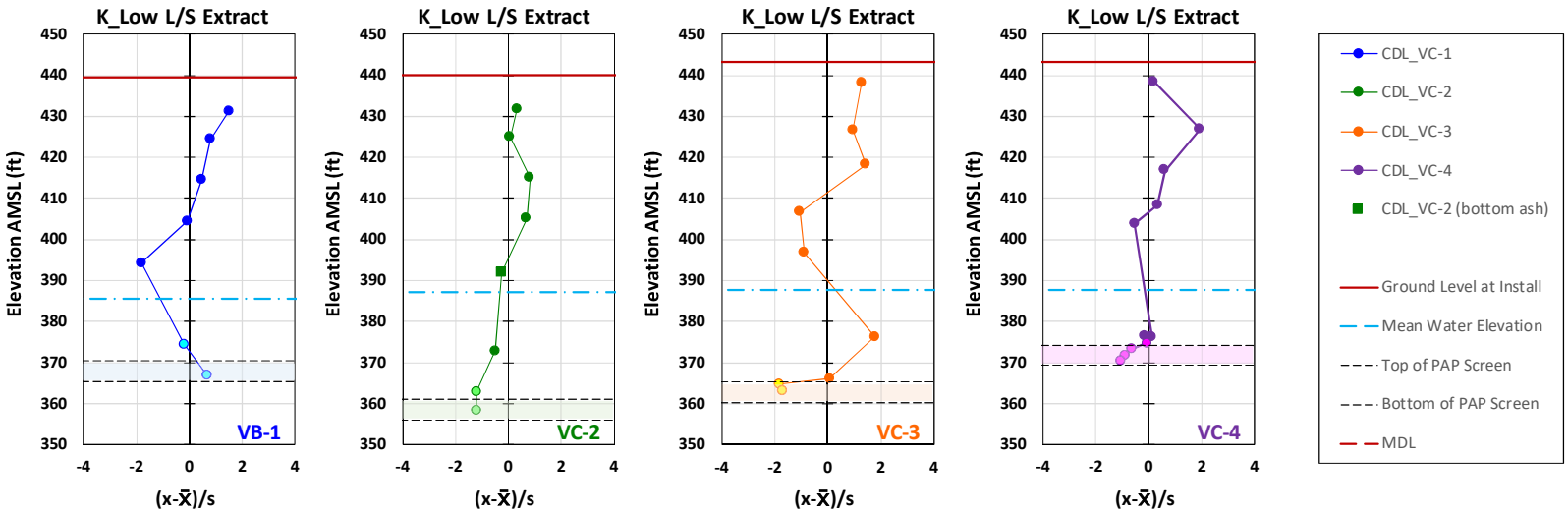

Figure B-29
Profiles from in-field low L/S extractions standardized using the global material mean and standard deviation: potassium

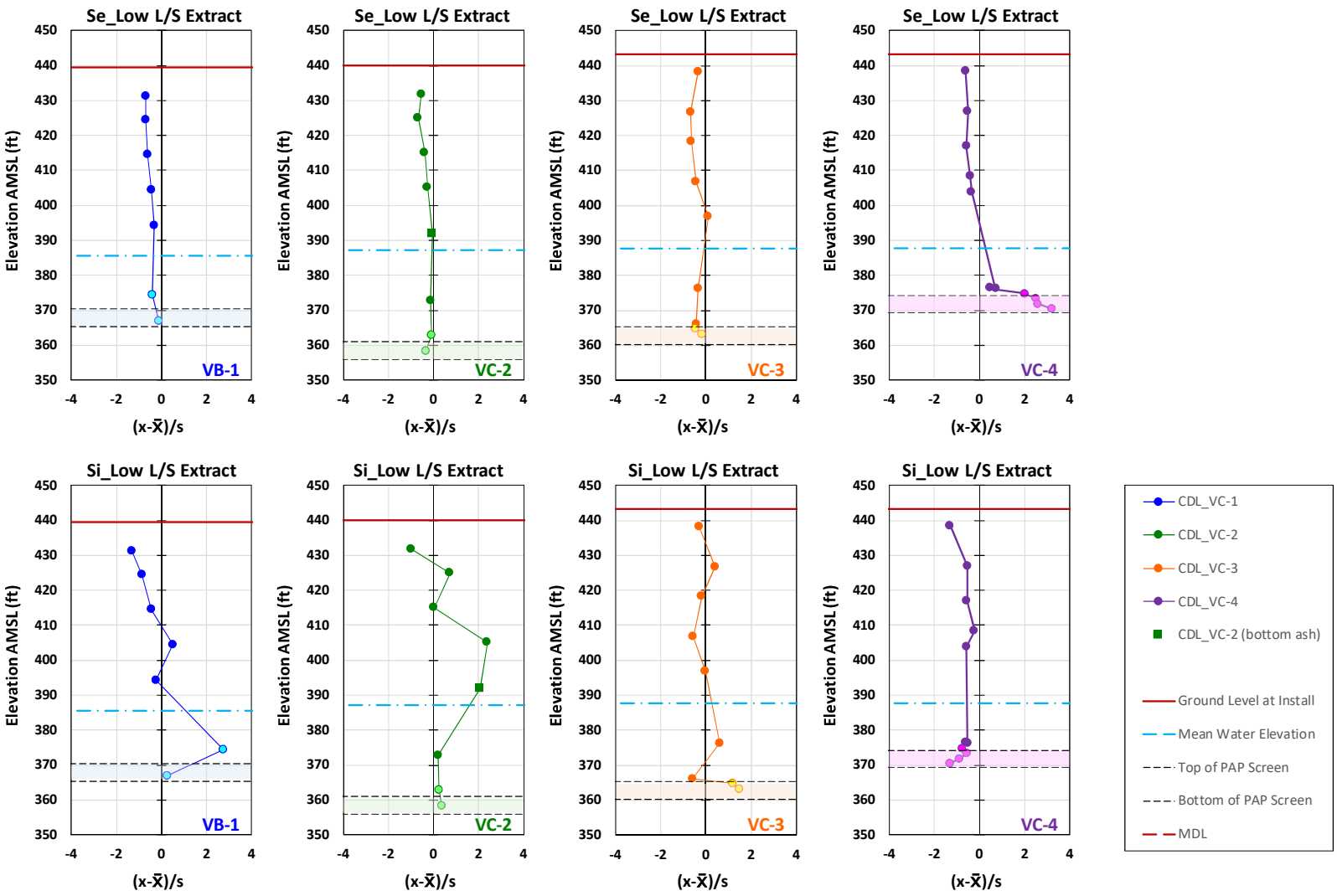

Figure B-30
Profiles from in-field low L/S extractions standardized using the global material mean and standard deviation: selenium and silicon

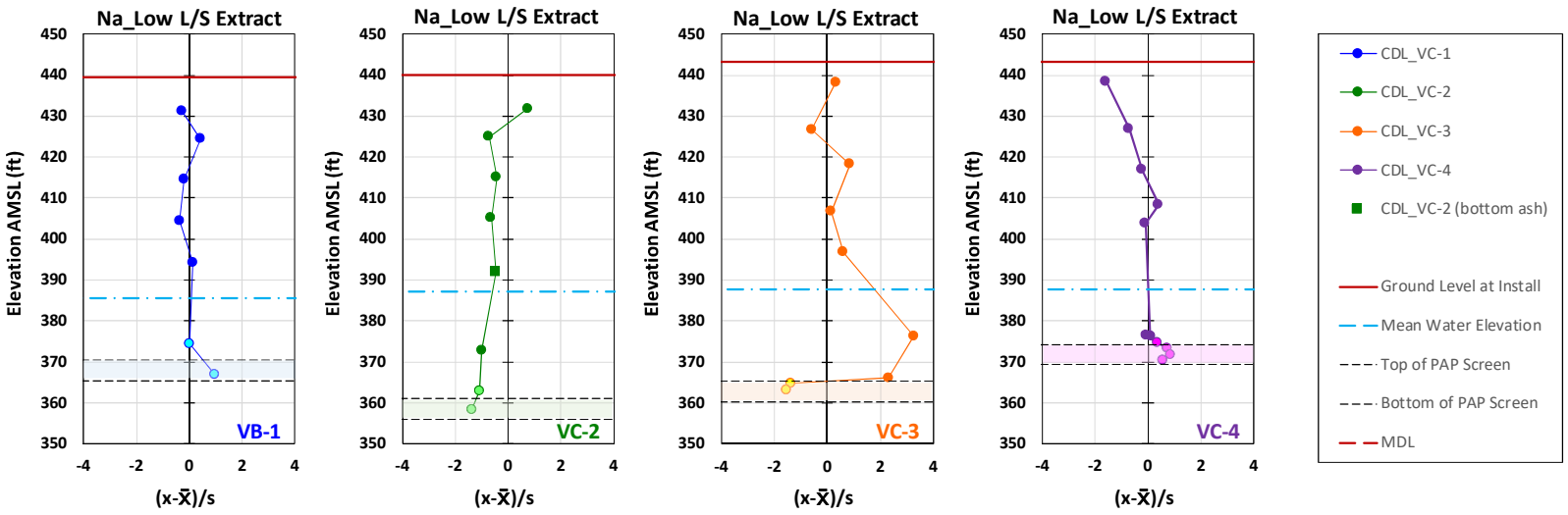

Figure B-31
Profiles from in-field low L/S extractions standardized using the global material mean and standard deviation: sodium

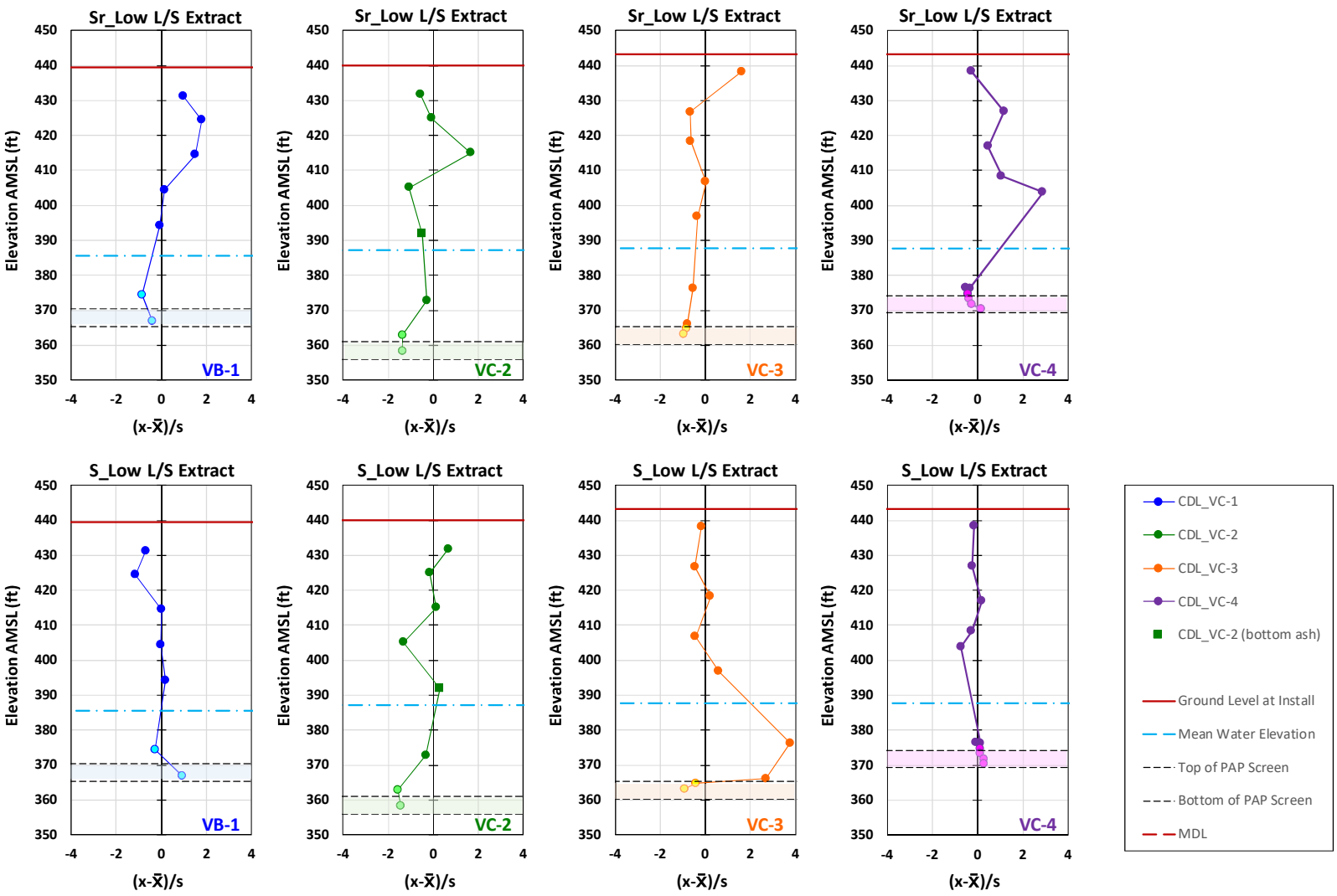

Figure B-32
Profiles from in-field low L/S extractions standardized using the global material mean and standard deviation: strontium and sulfur

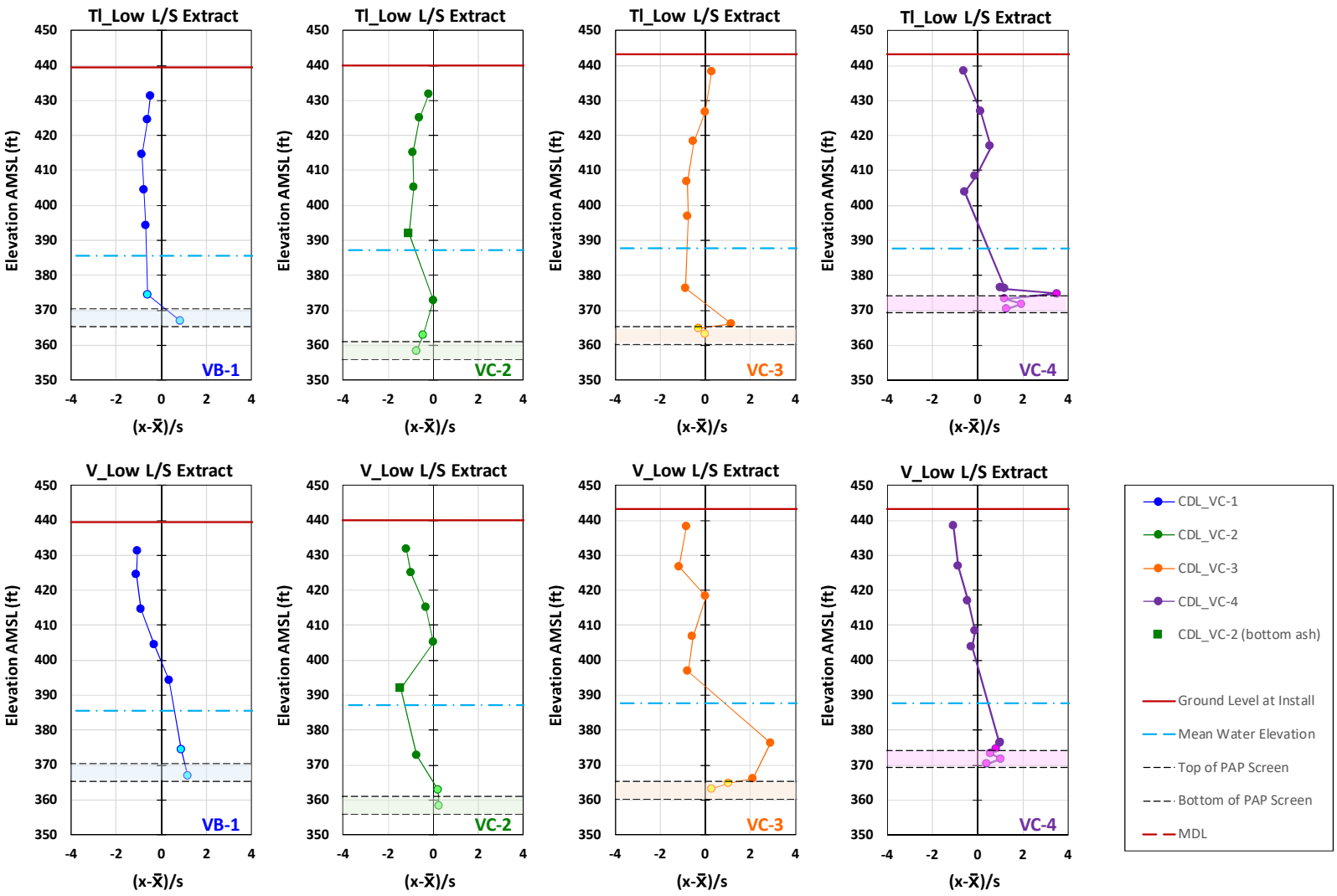

Figure B-33
Profiles from in-field low L/S extractions standardized using the global material mean and standard deviation: thallium and vanadium

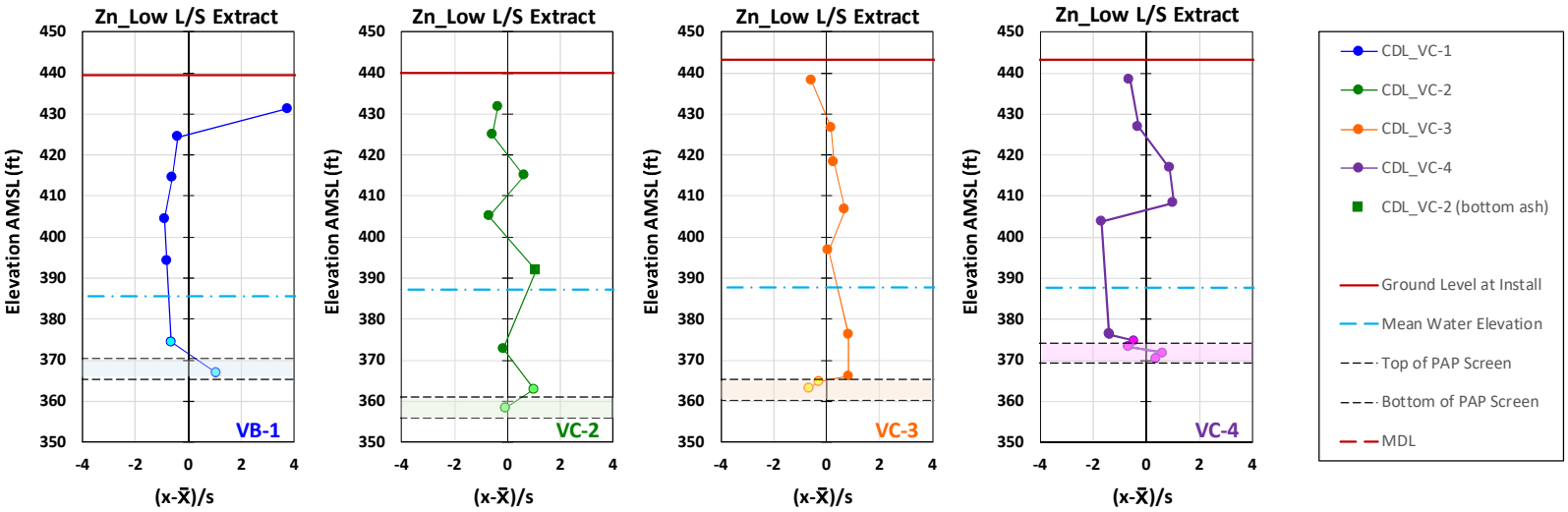

Figure B-34
Profiles from in-field low L/S extractions standardized using the global material mean and standard deviation: zinc

B-3 Comparison of Standardized Release Profiles for Low L/S and L/S≈1 Extractions

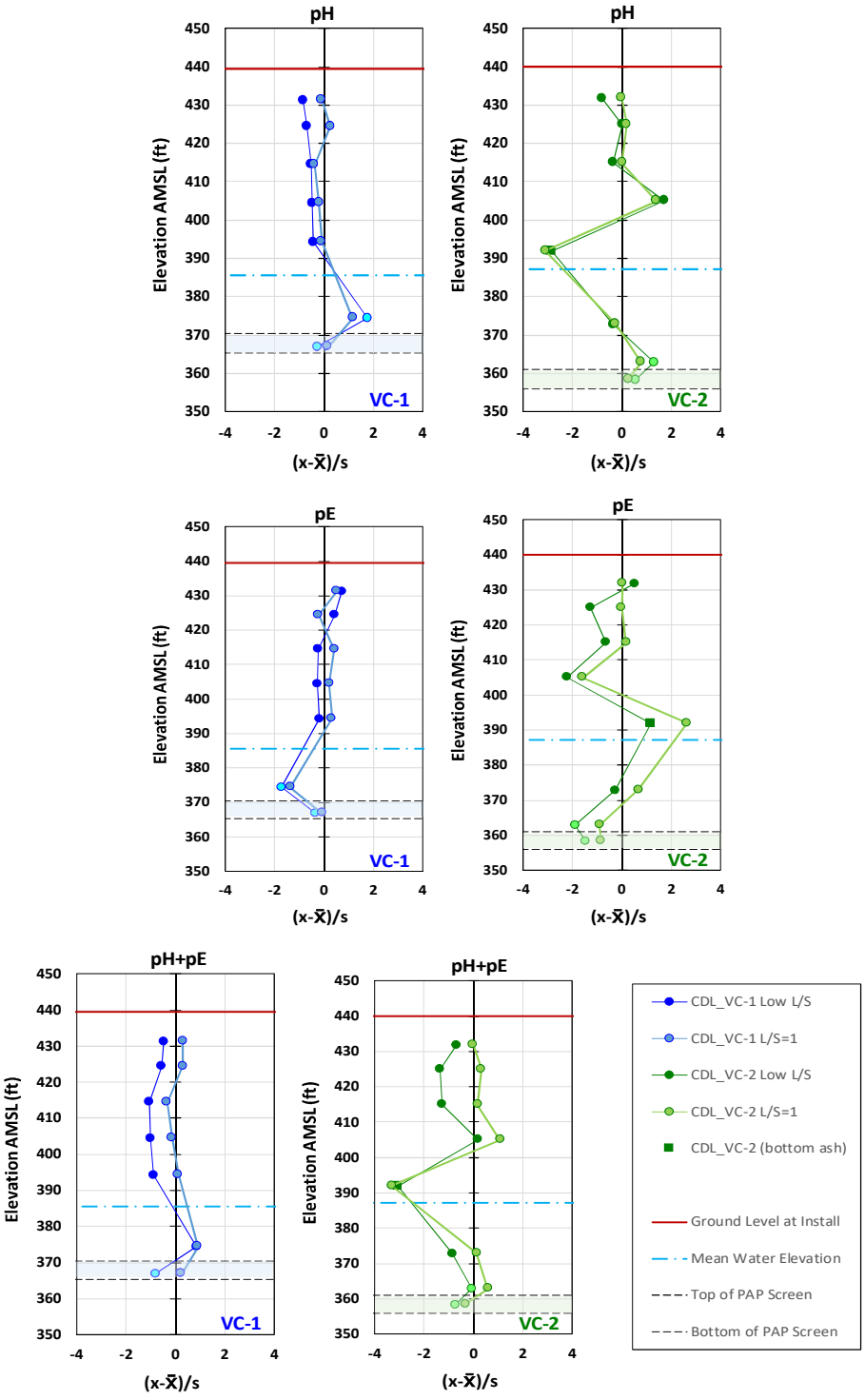

Figure B-35
Comparison of release (mg/kg-dry) from in-field extractions at low L/S and at L/S~1: pH, pE, and pH+pE

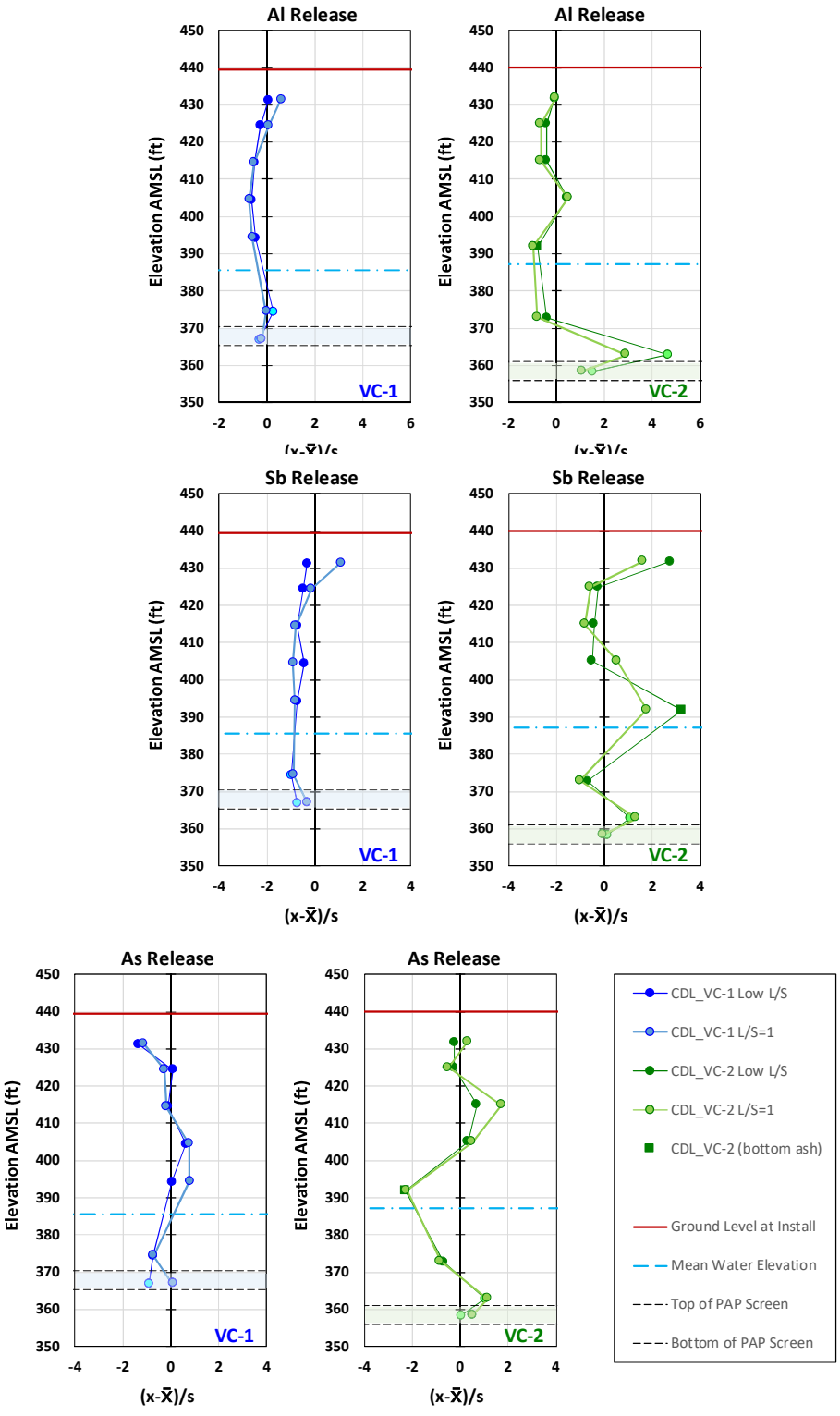

Figure B-36
Comparison of release (mg/kg-dry) from in-field extractions at low L/S and at L/S~1: aluminum, antimony, and arsenic

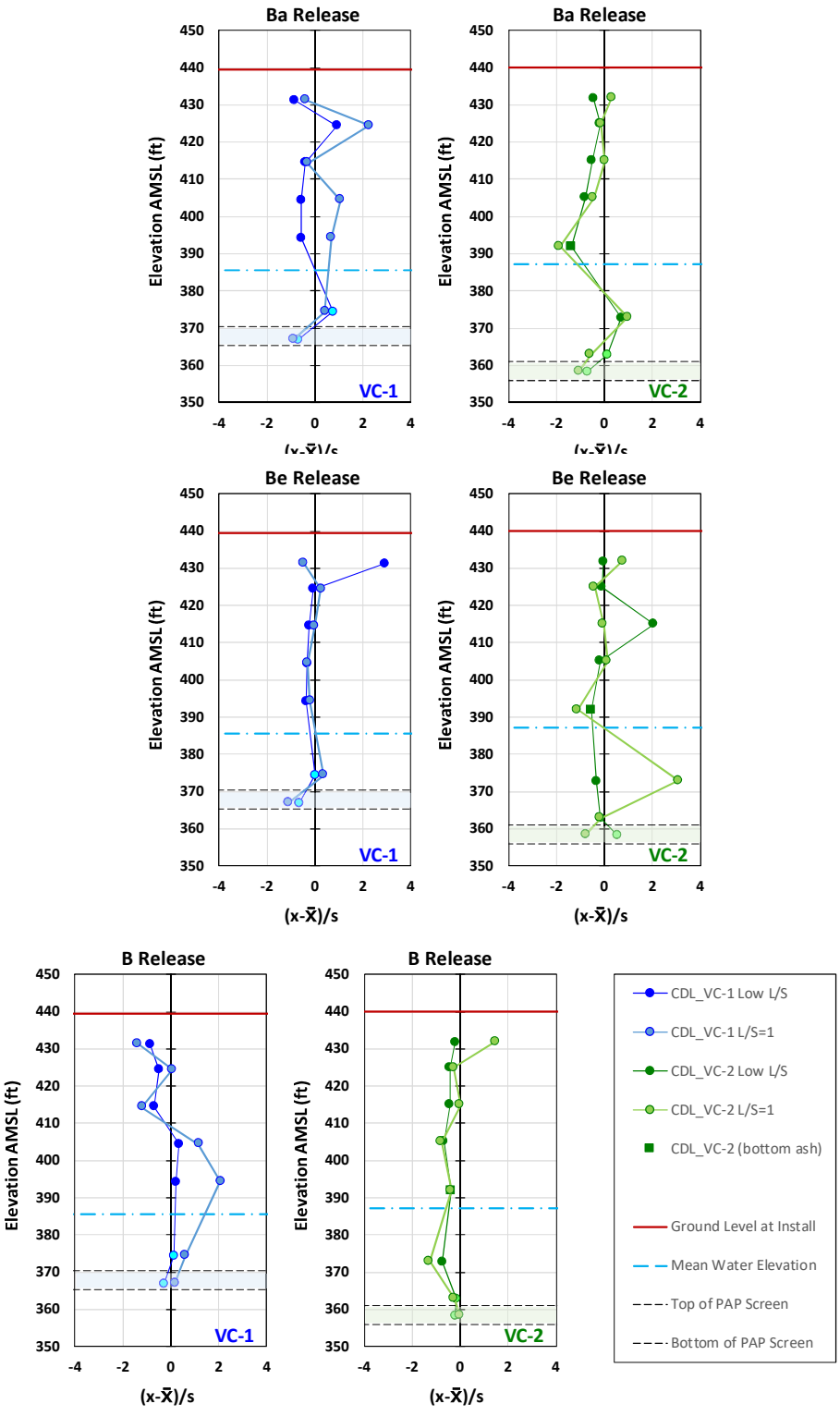

Figure B-37
Comparison of release (mg/kg-dry) from in-field extractions at low L/S and at L/S~1: barium, beryllium, and boron

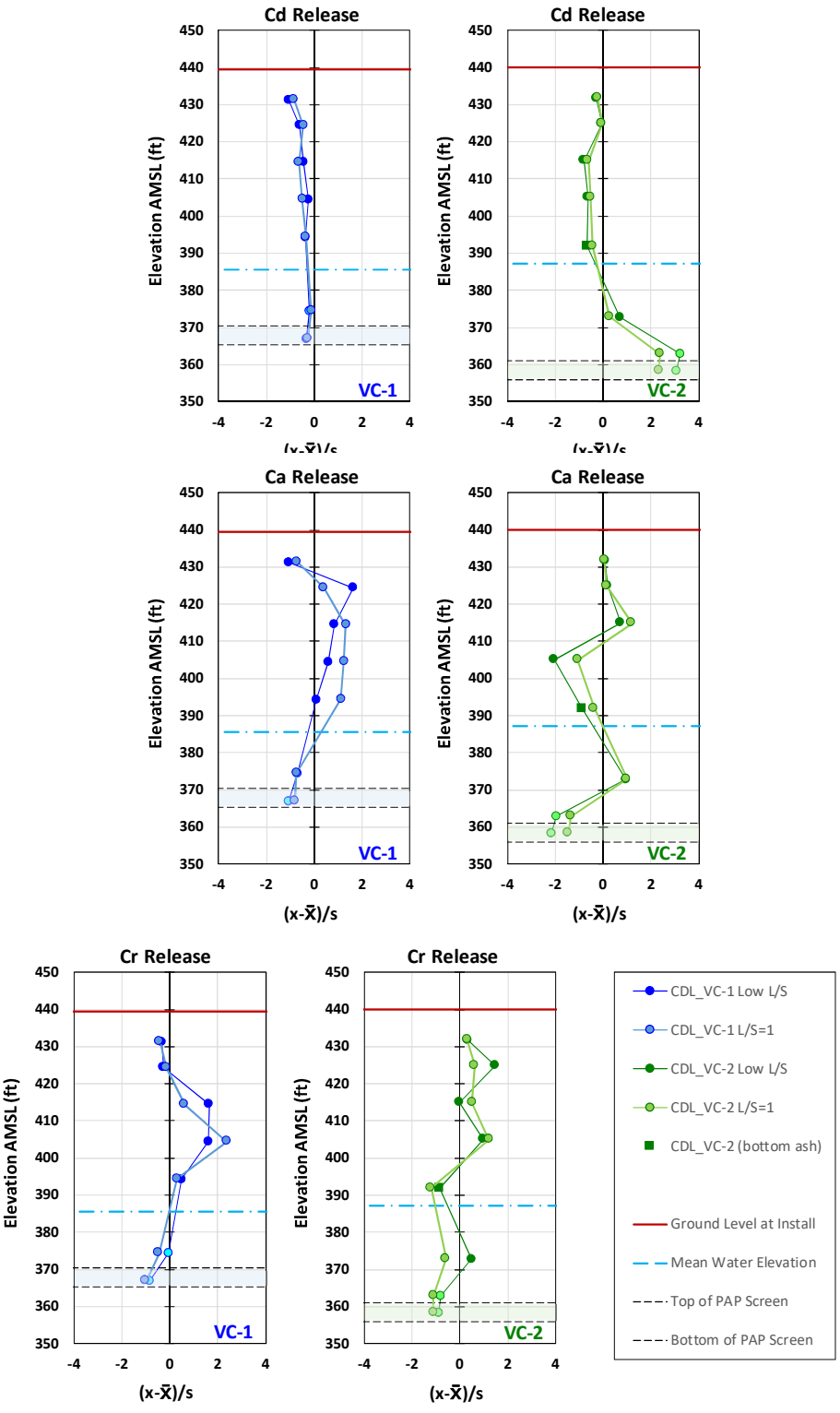

Figure B-38
Comparison of release (mg/kg-dry) from in-field extractions at low L/S and at L/S~1: cadmium, calcium, and chromium

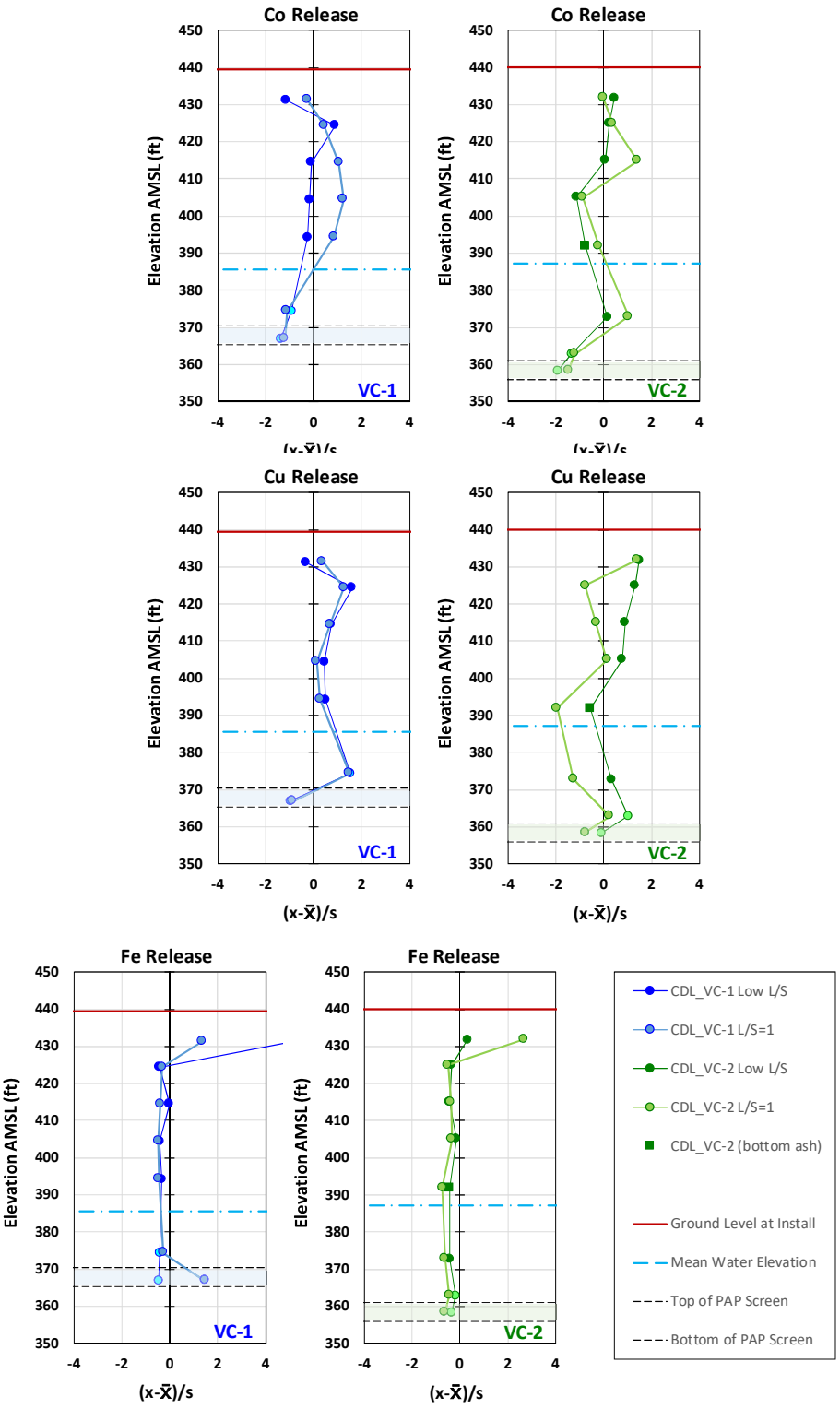

Figure B-39
Comparison of release (mg/kg-dry) from in-field extractions at low L/S and at L/S~1: cobalt, copper, and iron

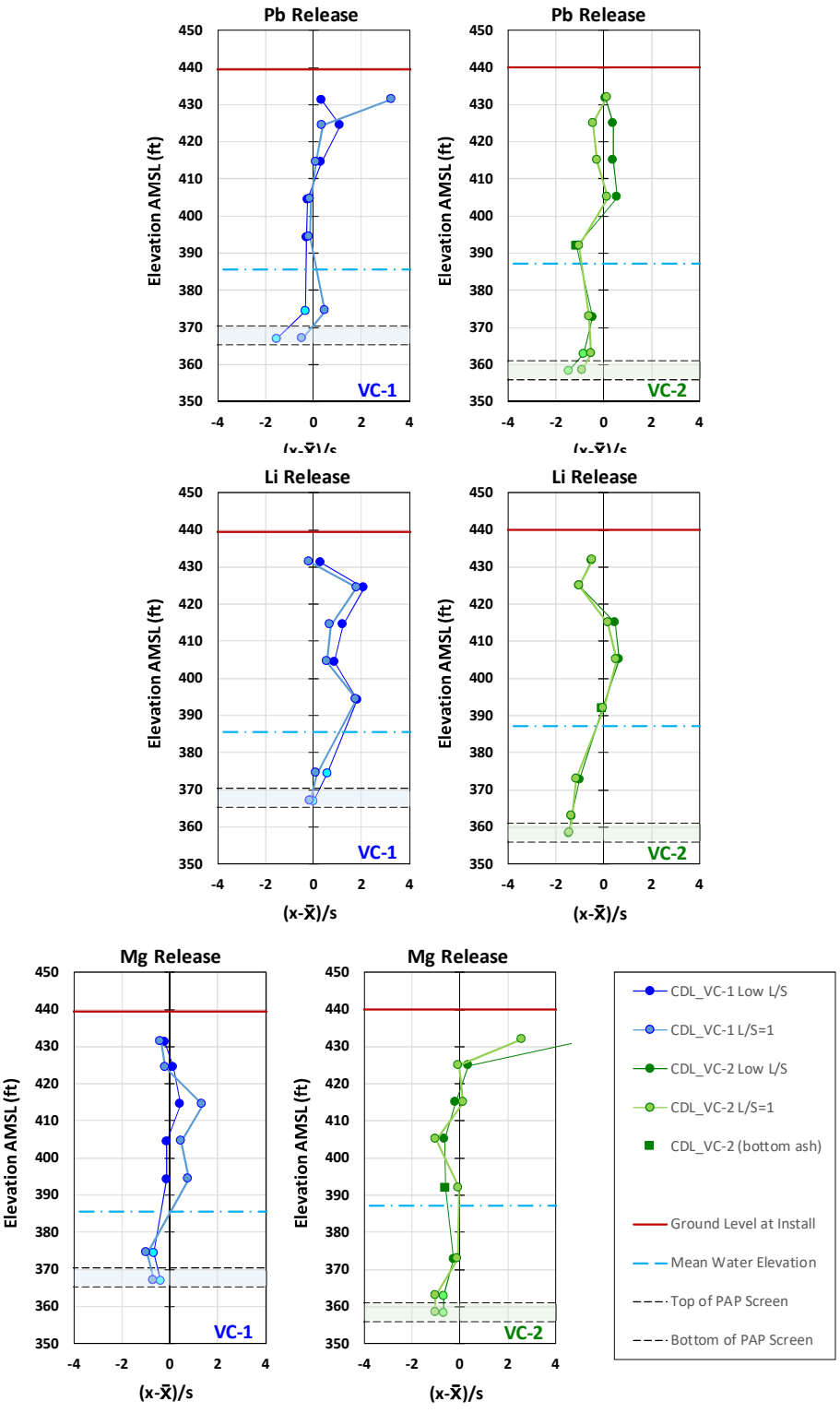

Figure B-40
Comparison of release (mg/kg-dry) from in-field extractions at low L/S and at L/S~1: lead, lithium, and magnesium

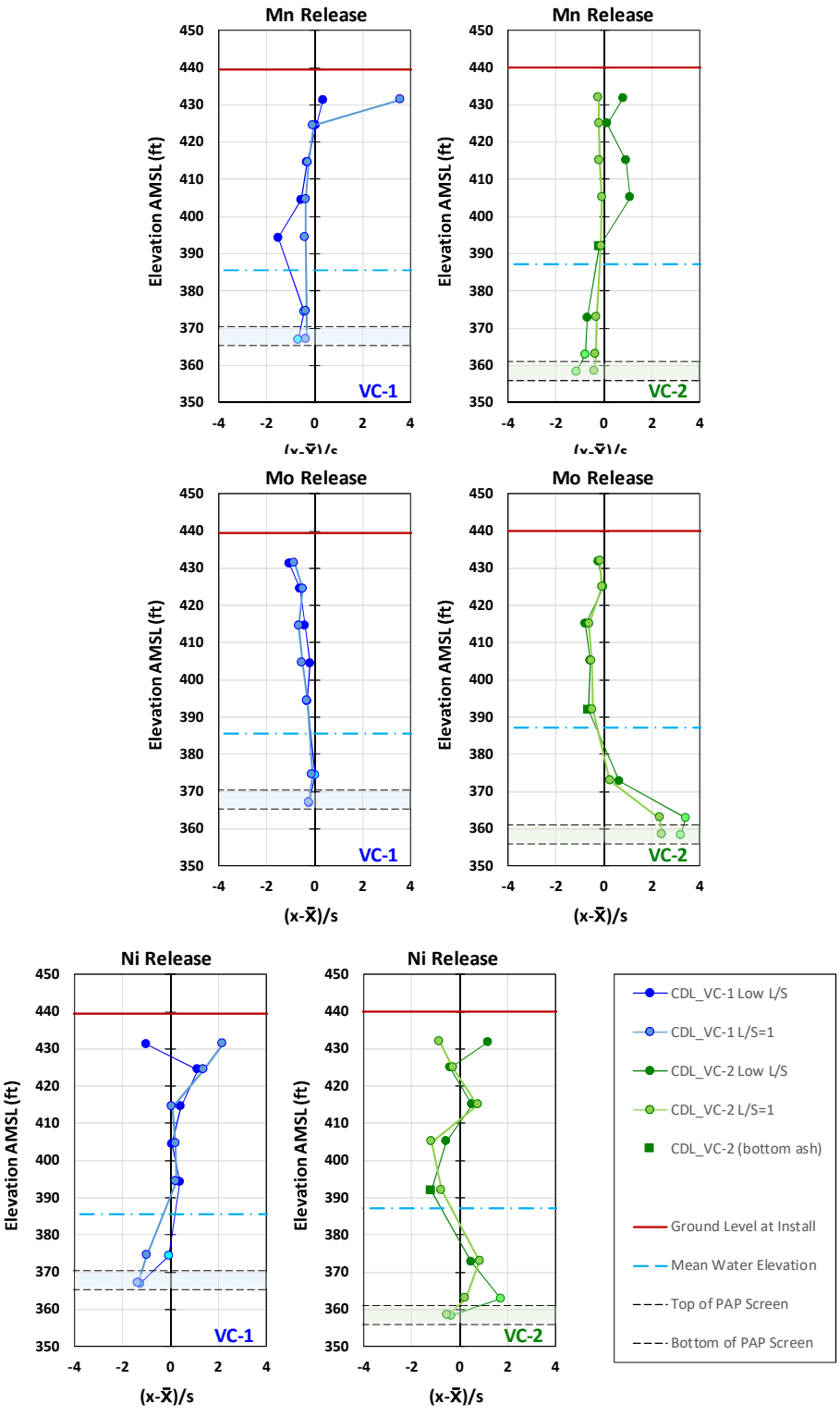

Figure B-41
Comparison of release (mg/kg-dry) from in-field extractions at low L/S and at L/S~1: manganese, molybdenum, and nickel

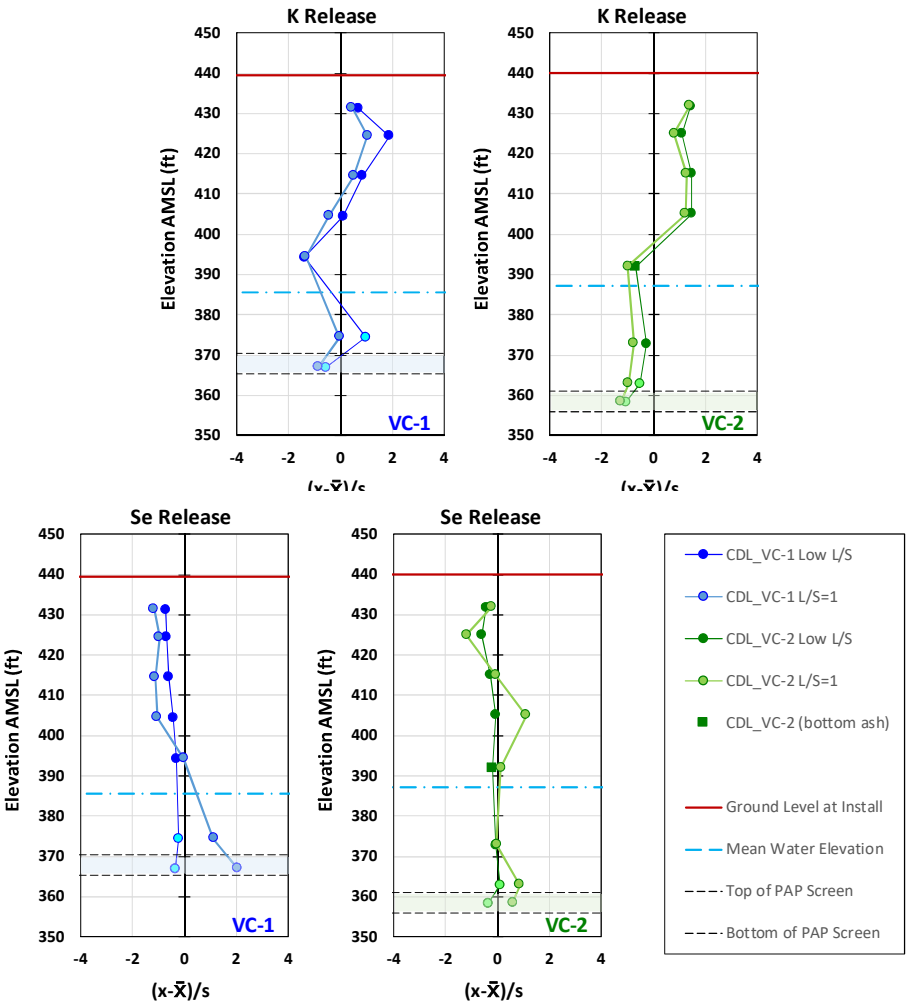

Figure B-42
Comparison of release (mg/kg-dry) from in-field extractions at low L/S and at L/S~1: potassium and selenium

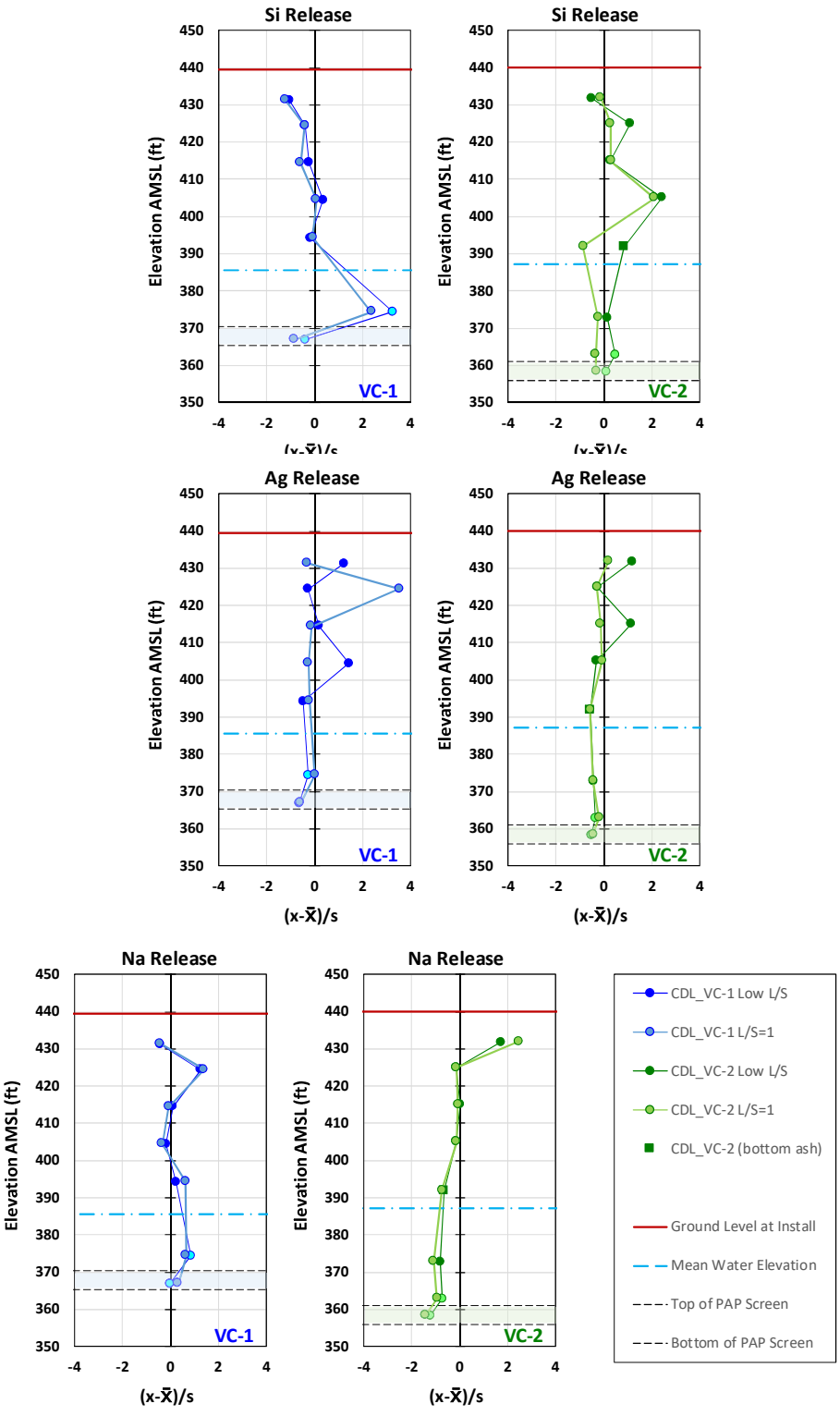

Figure B-43
Comparison of release (mg/kg-dry) from in-field extractions at low L/S and at L/S~1: silicon, silver and, sodium

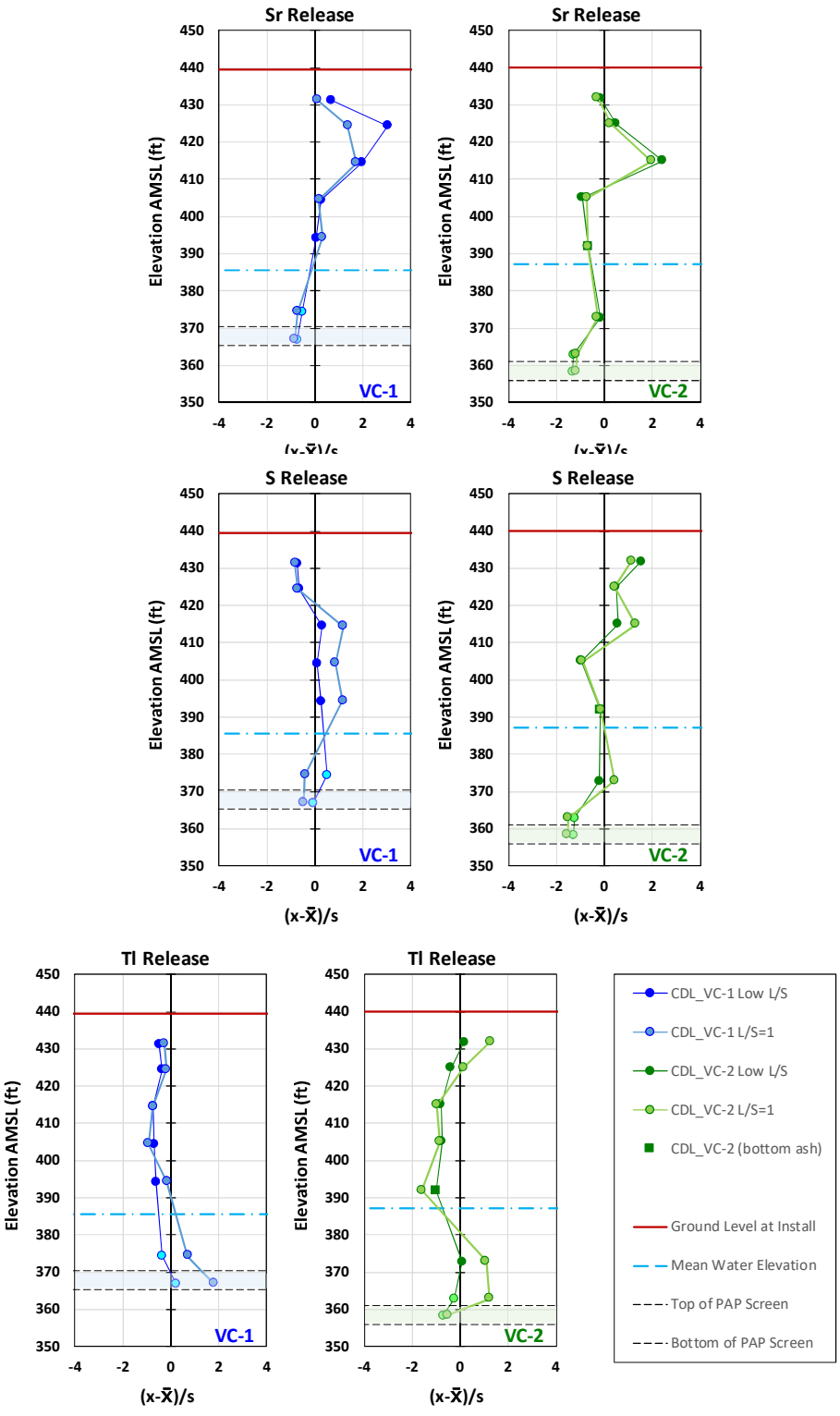

Figure B-44
Comparison of release (mg/kg-dry) from in-field extractions at low L/S and at L/S~1: strontium, sulfur, and thallium

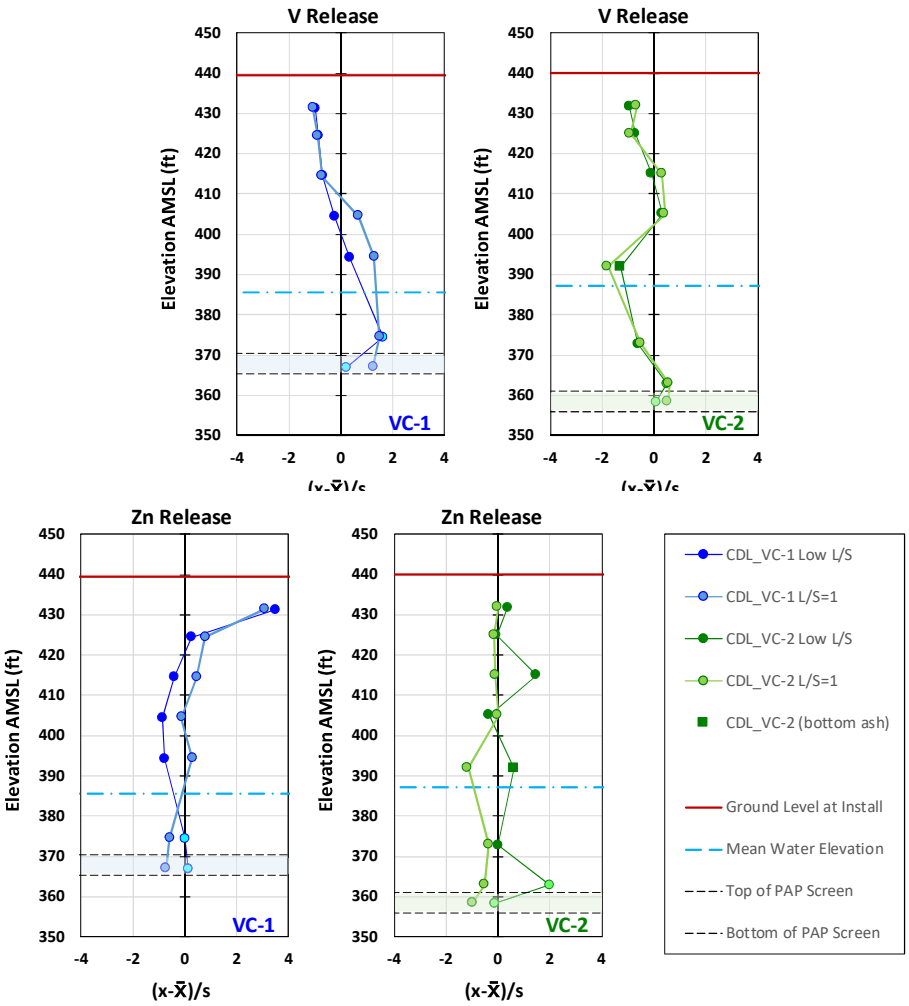

Figure B-45
Comparison of release (mg/kg-dry) from in-field extractions at low L/S and at L/S~1: vanadium and zinc

C
LEACHING TEST METHOD RESULTS

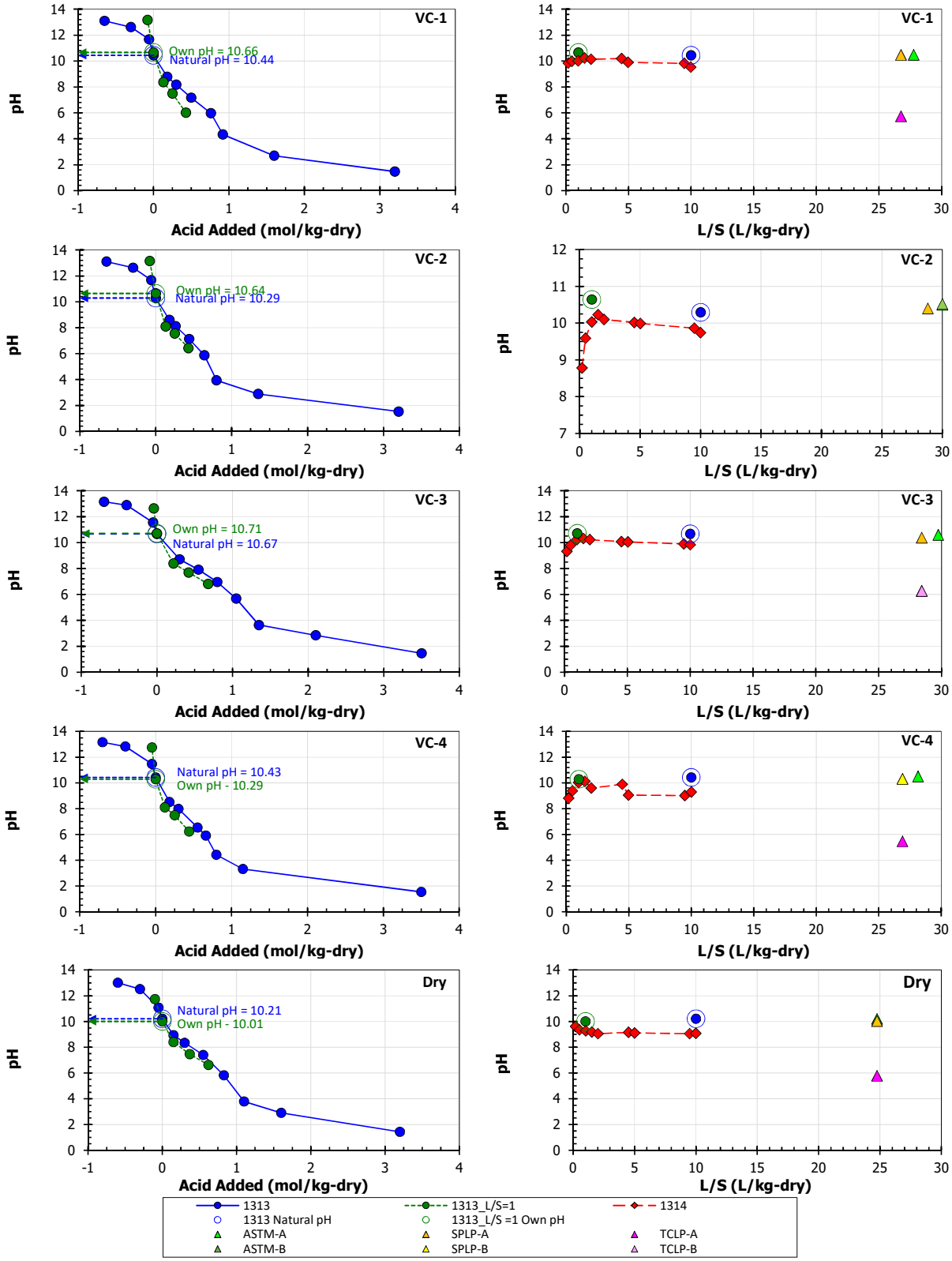

Figure C-1
Titration curve and pH results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

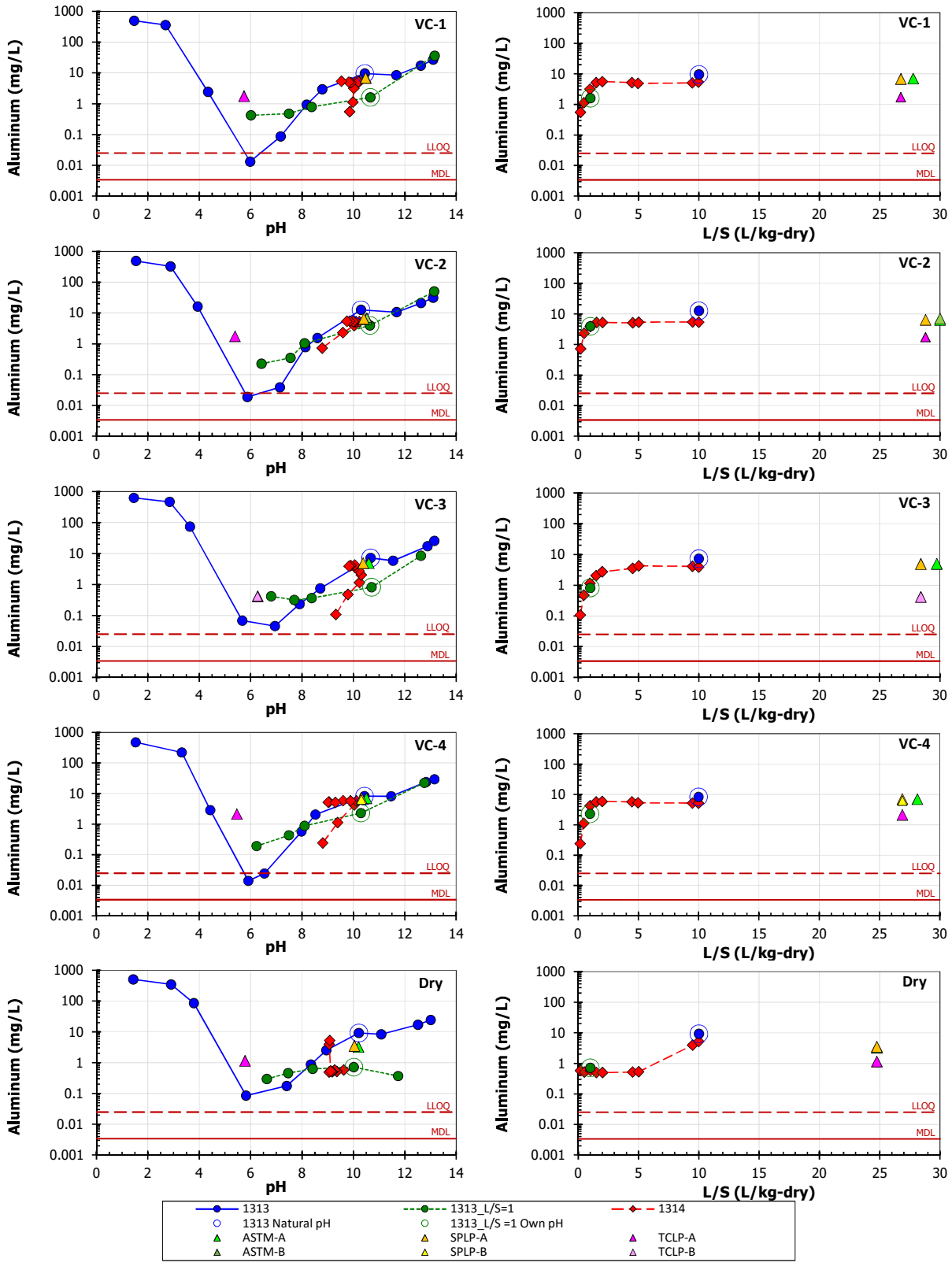

Figure C-2
Aluminum leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

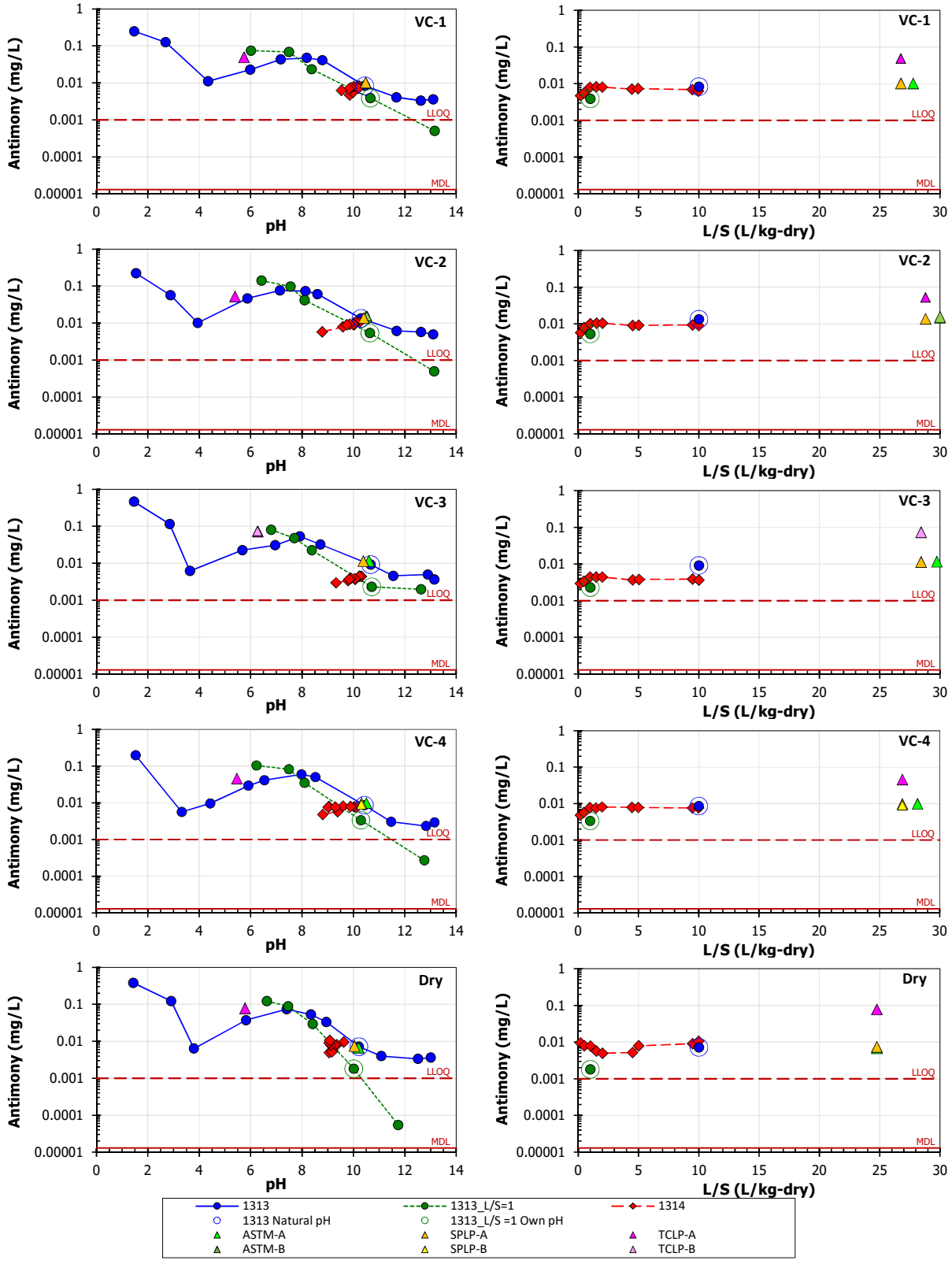

Figure C-3
Antimony leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

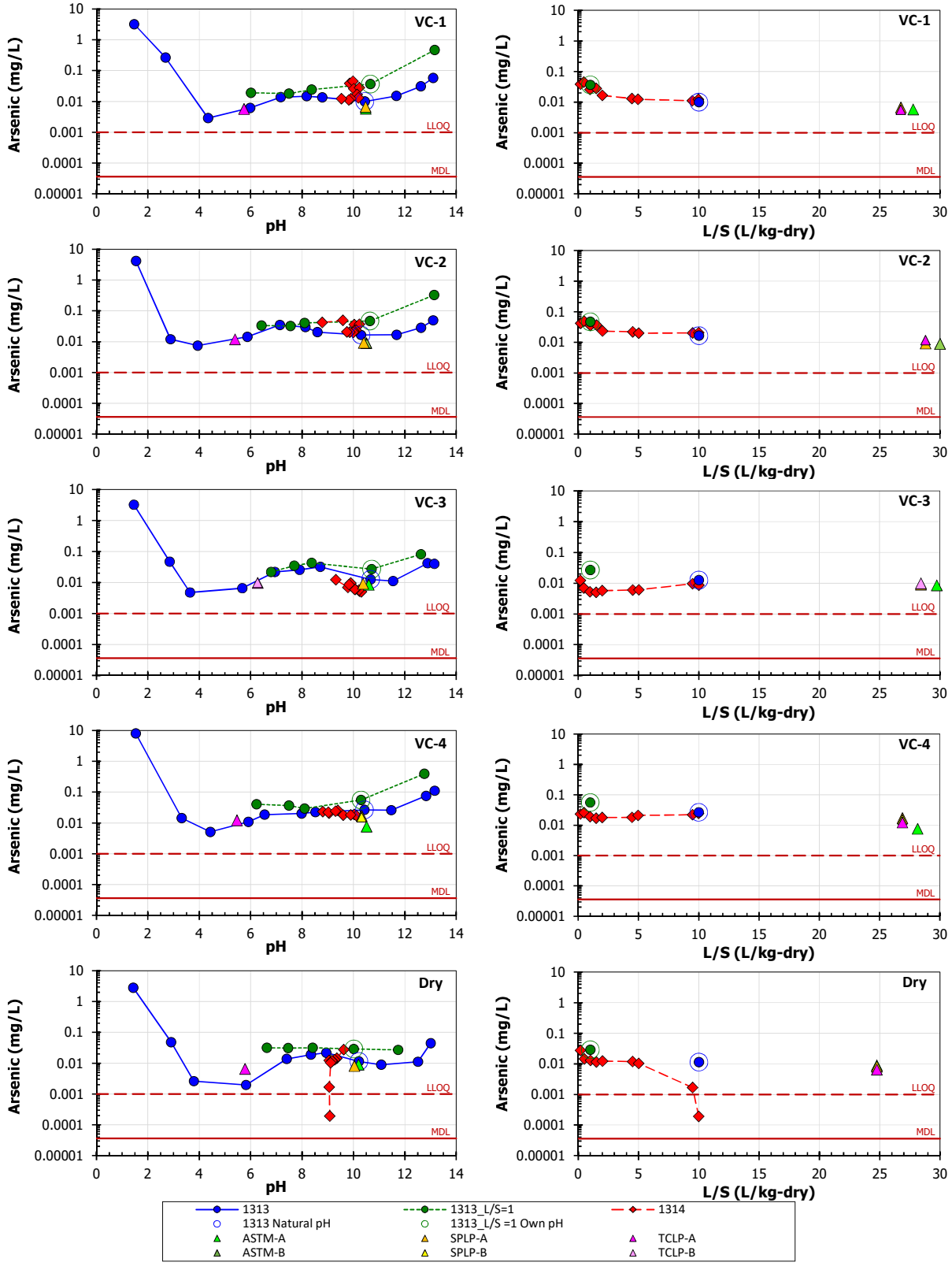

Figure C-4
Arsenic leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

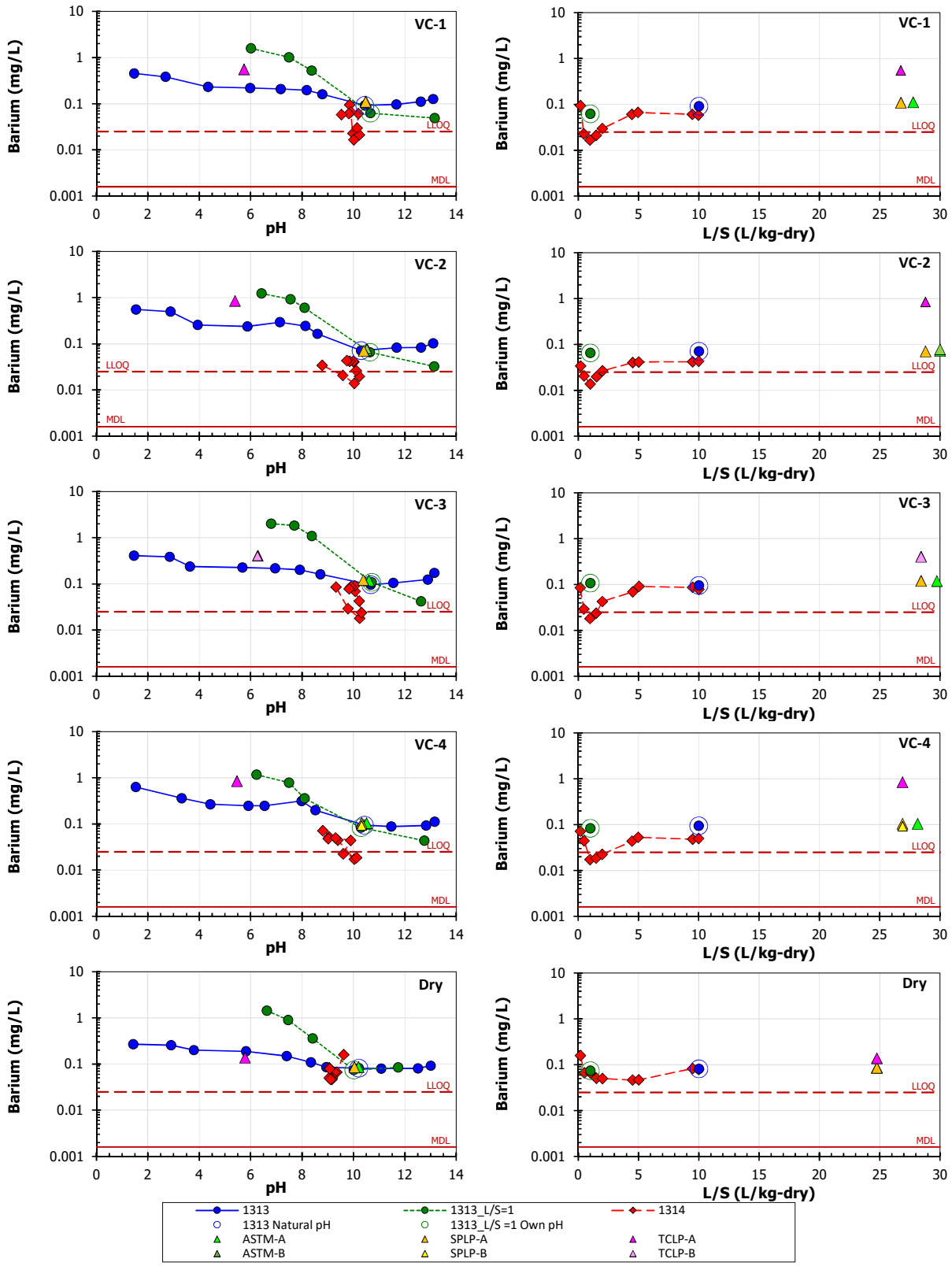

Figure C-5
Barium leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

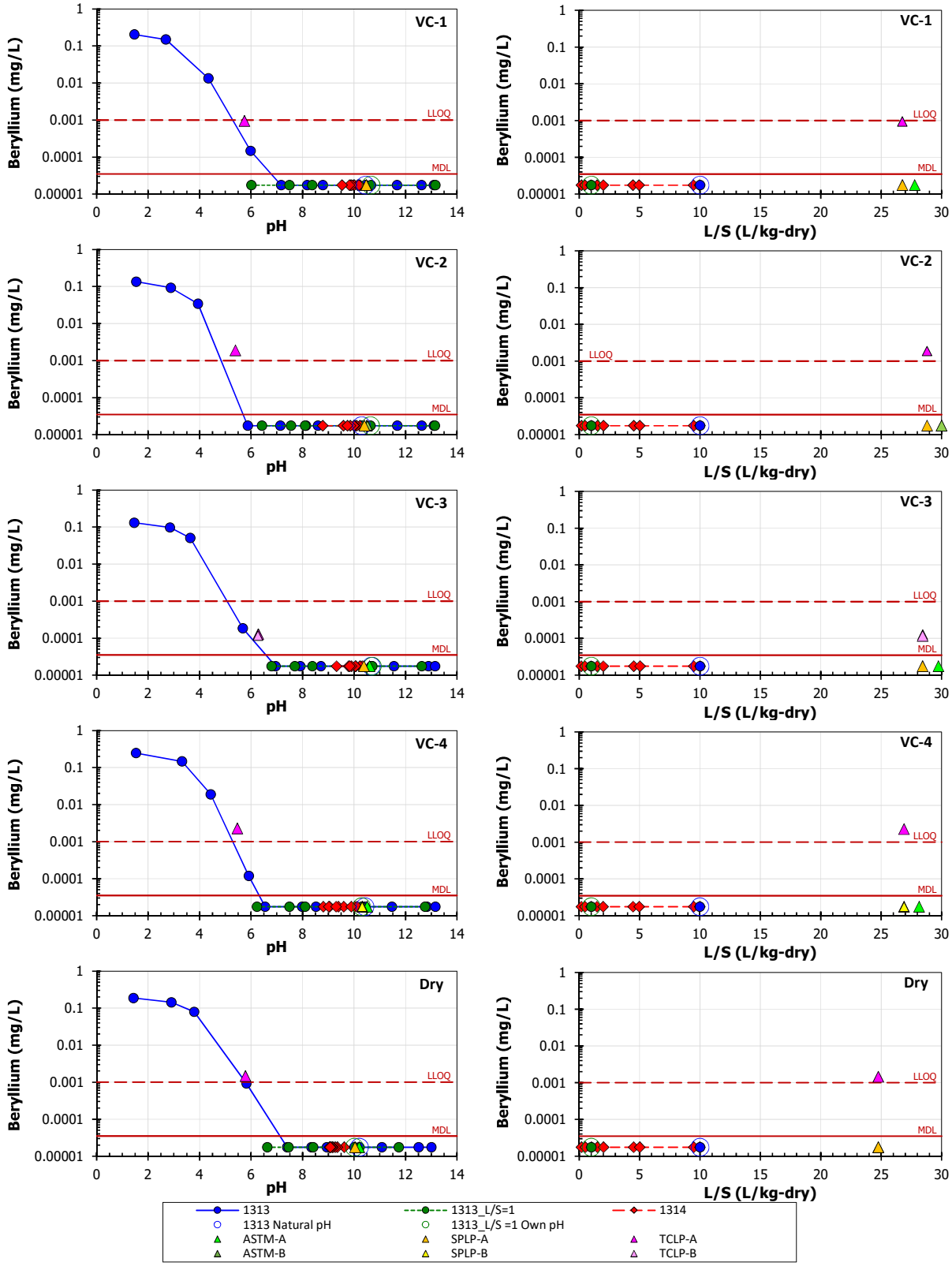

Figure C-6
Beryllium leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

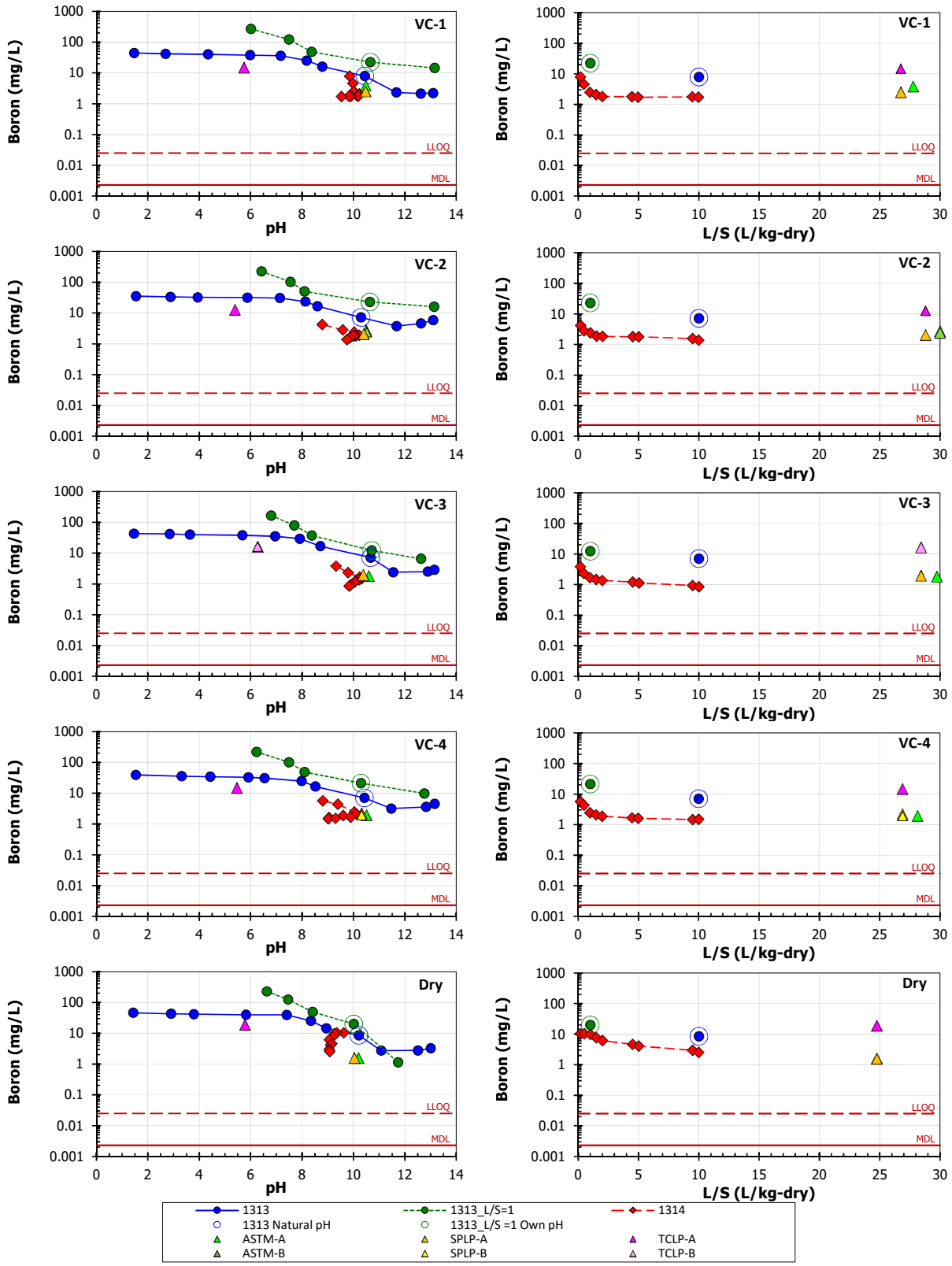

Figure C-7
Boron leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

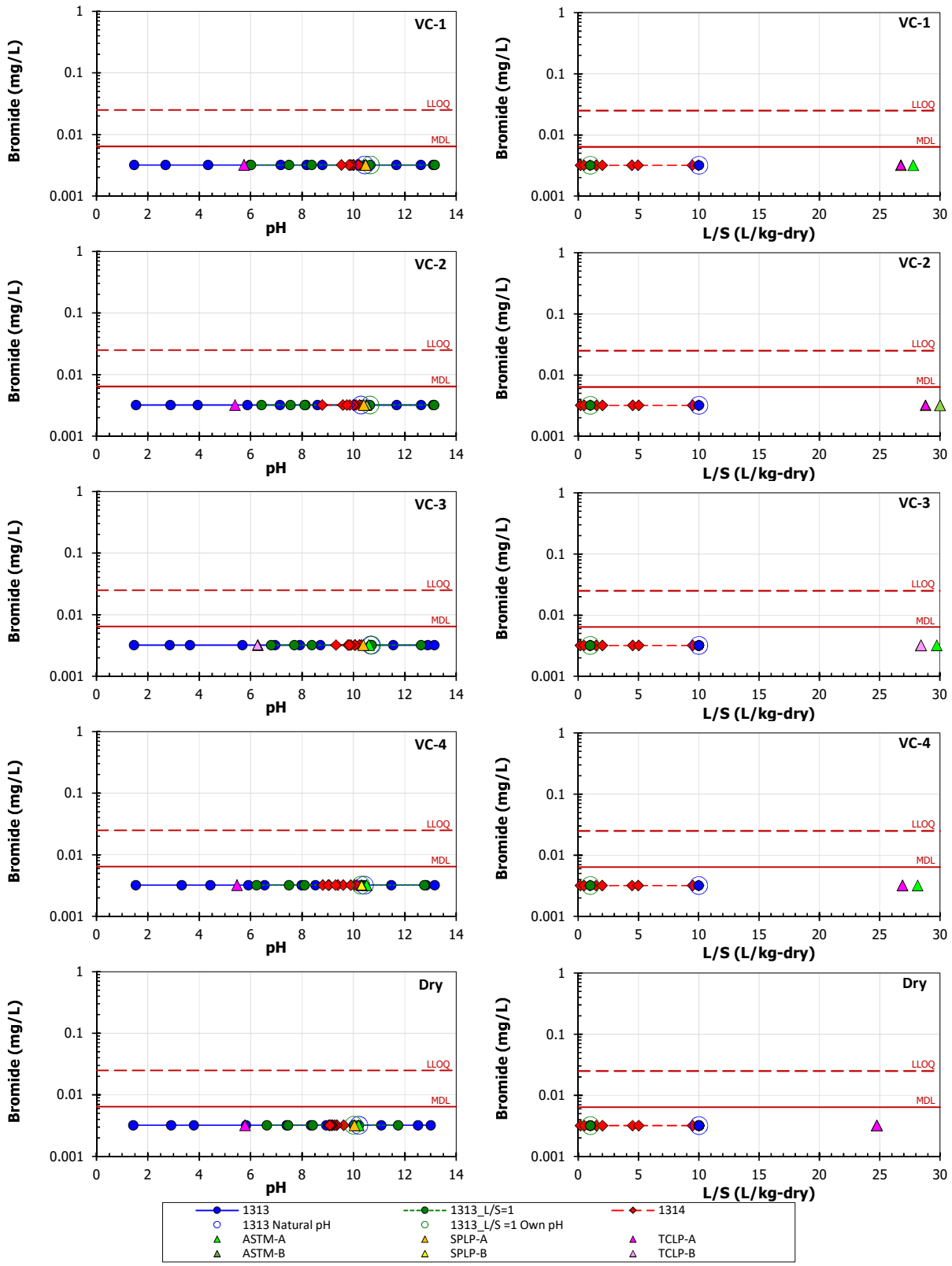

Figure C-8
Bromide leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

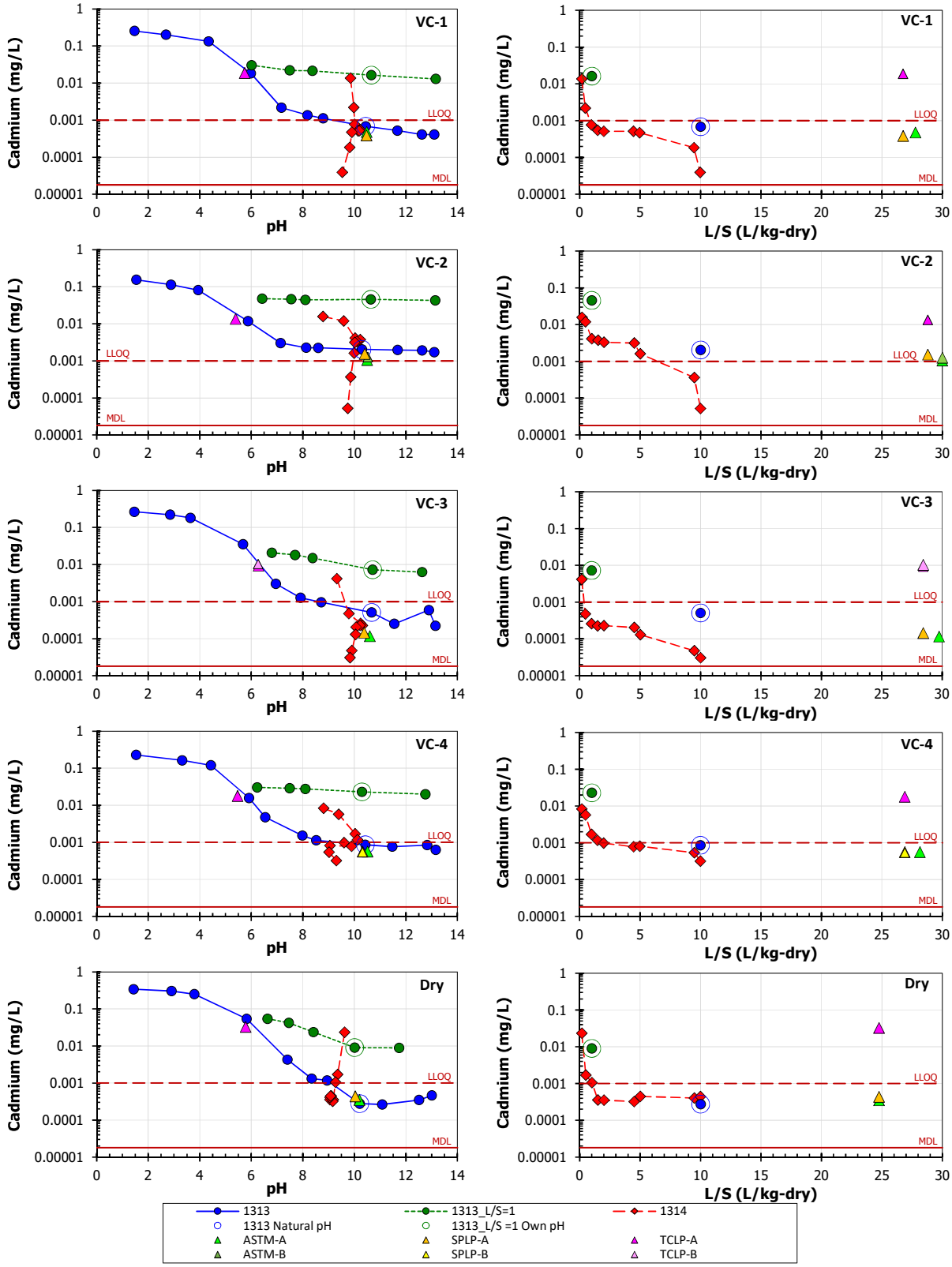

Figure C-9
Cadmium leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

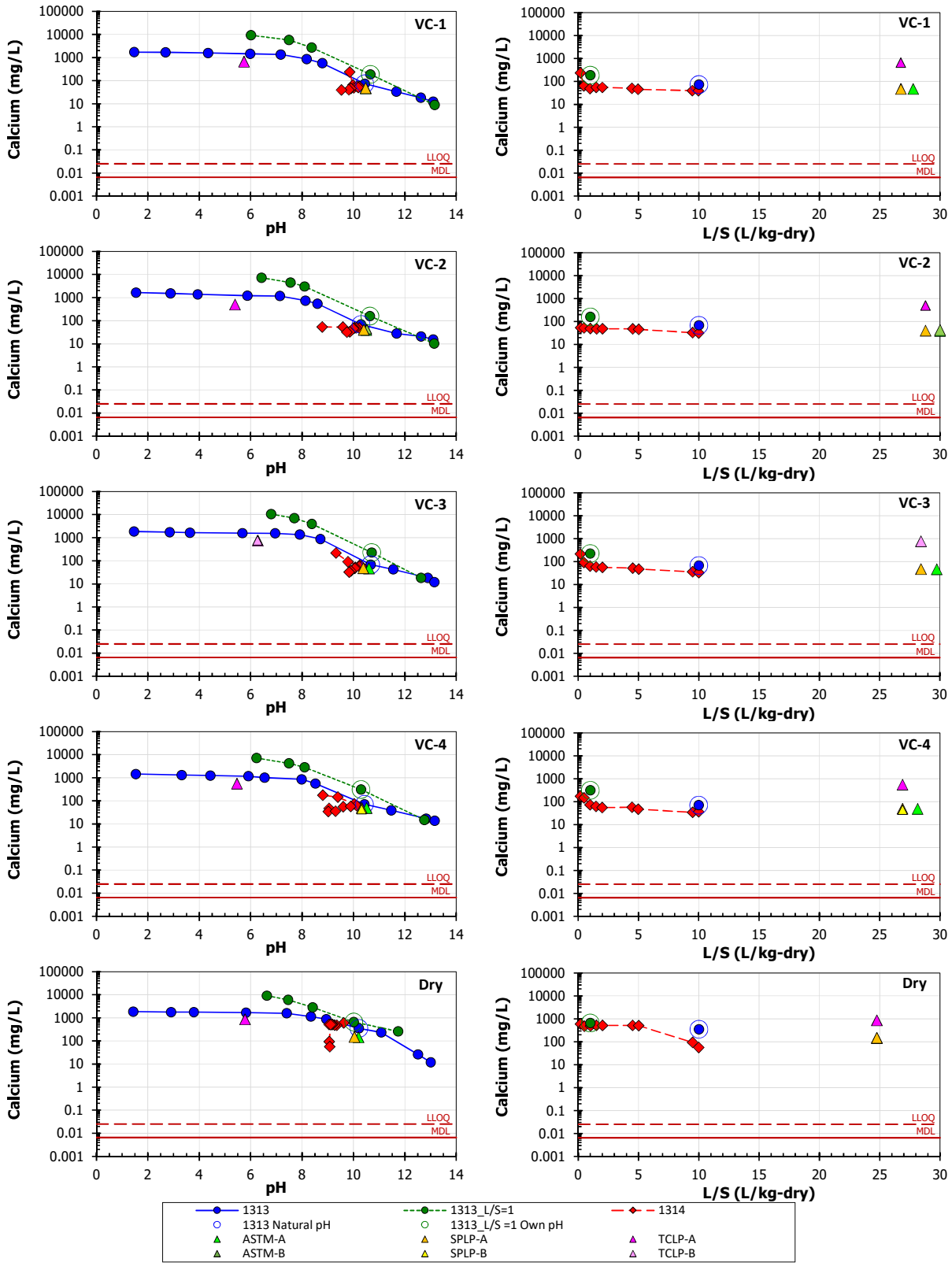

Figure C-10
Calcium leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

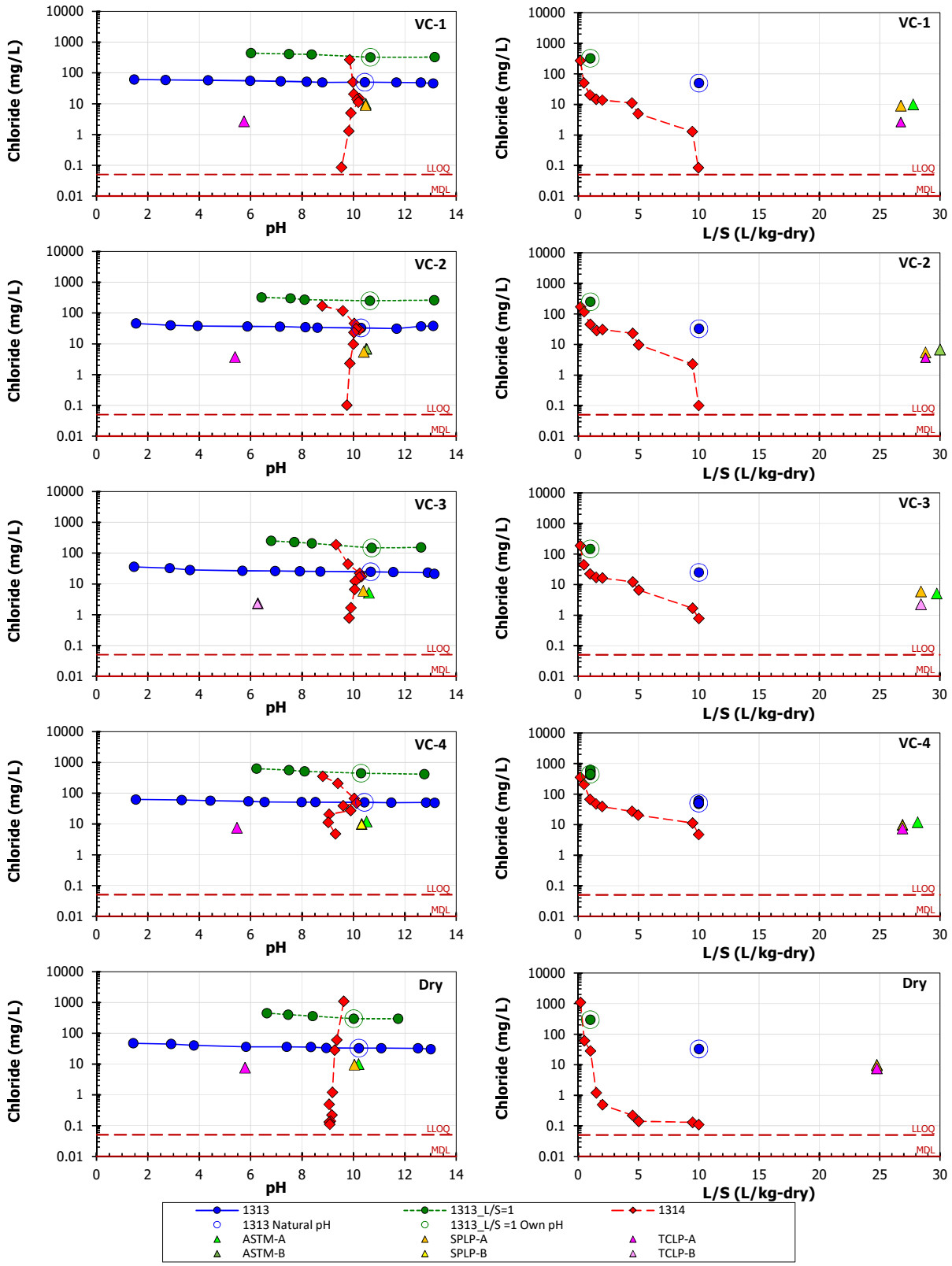

Figure C-11
Chloride leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

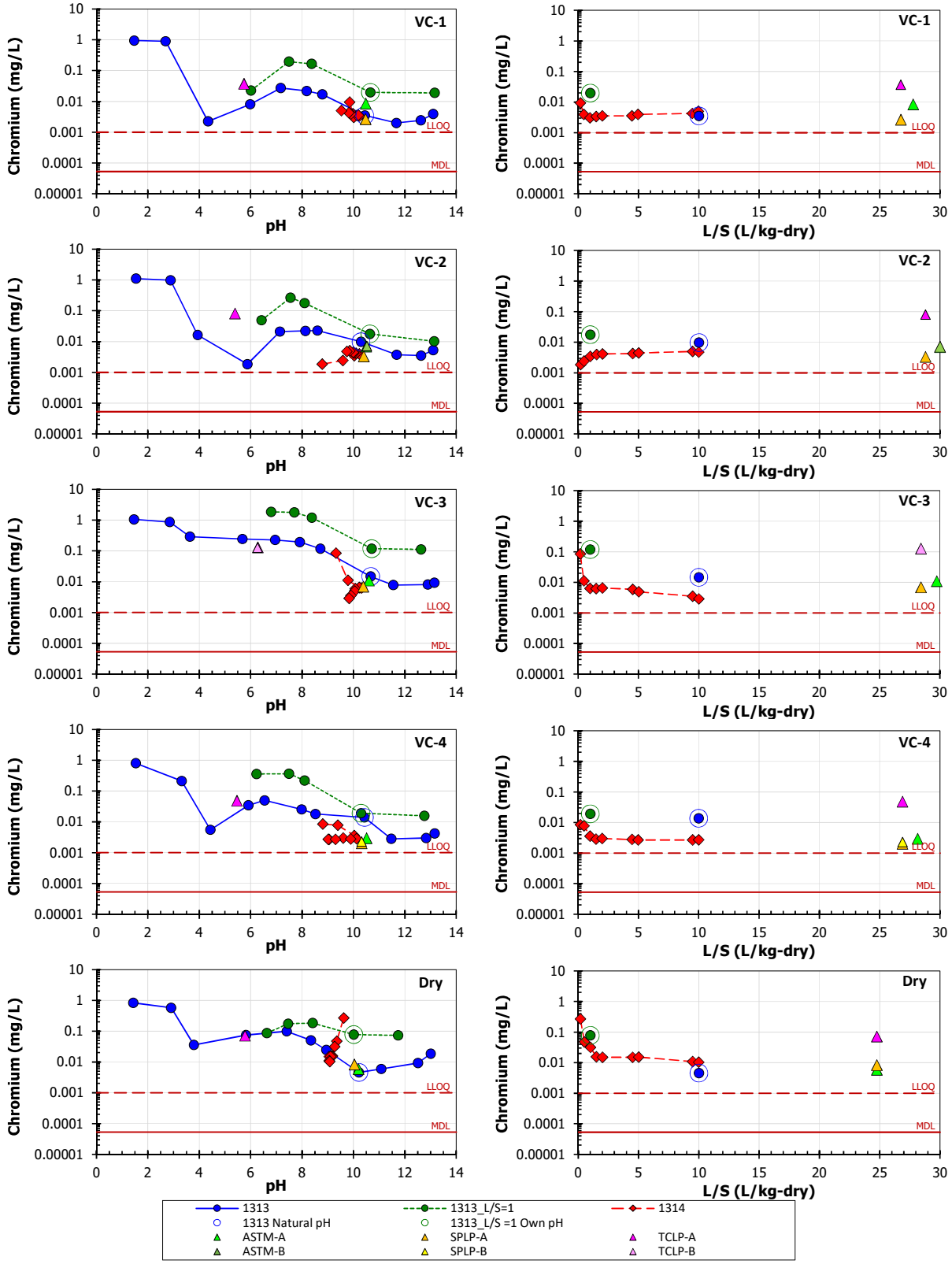

Figure C-12
Chromium leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

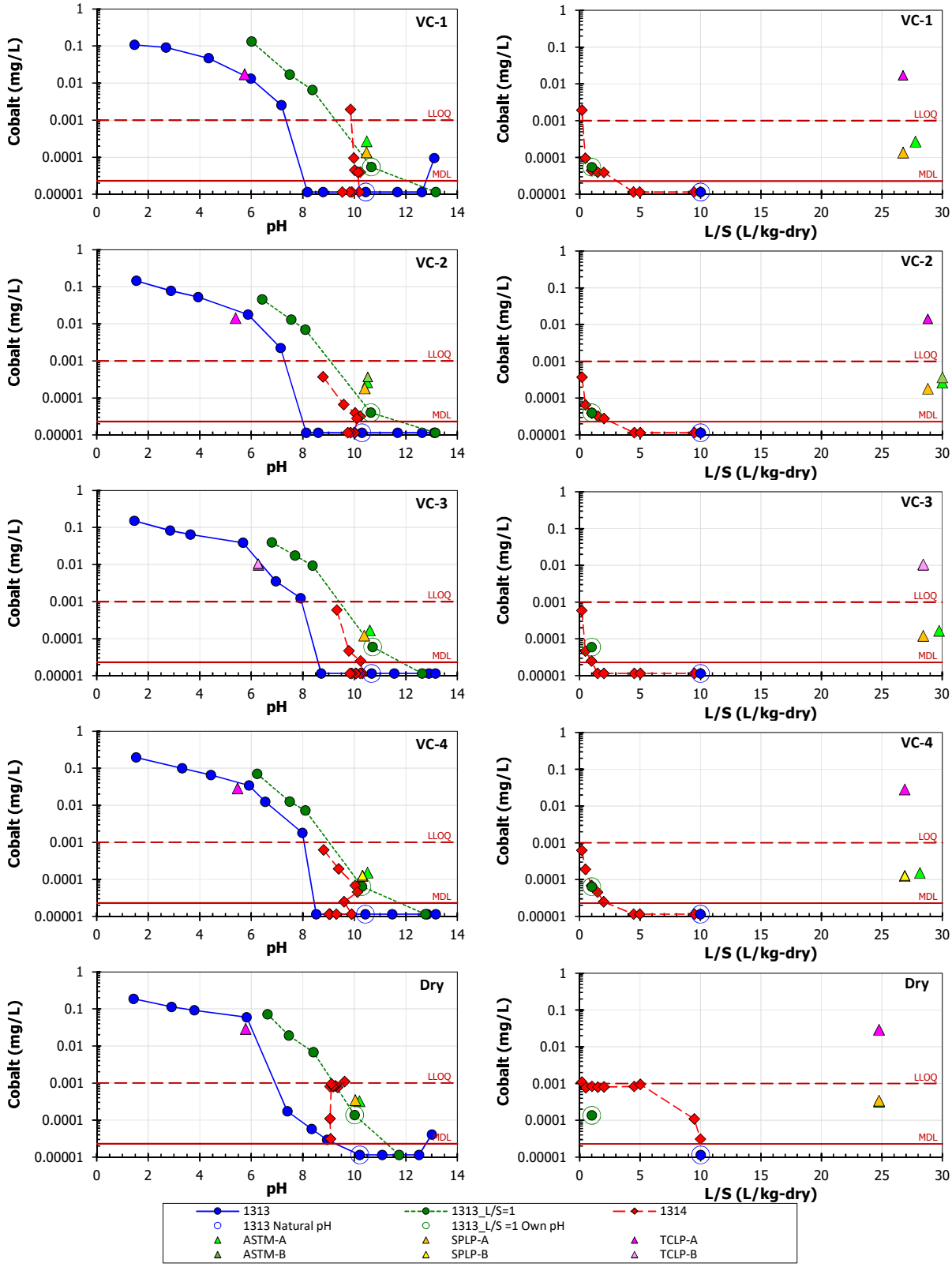

Figure C-13
Cobalt leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

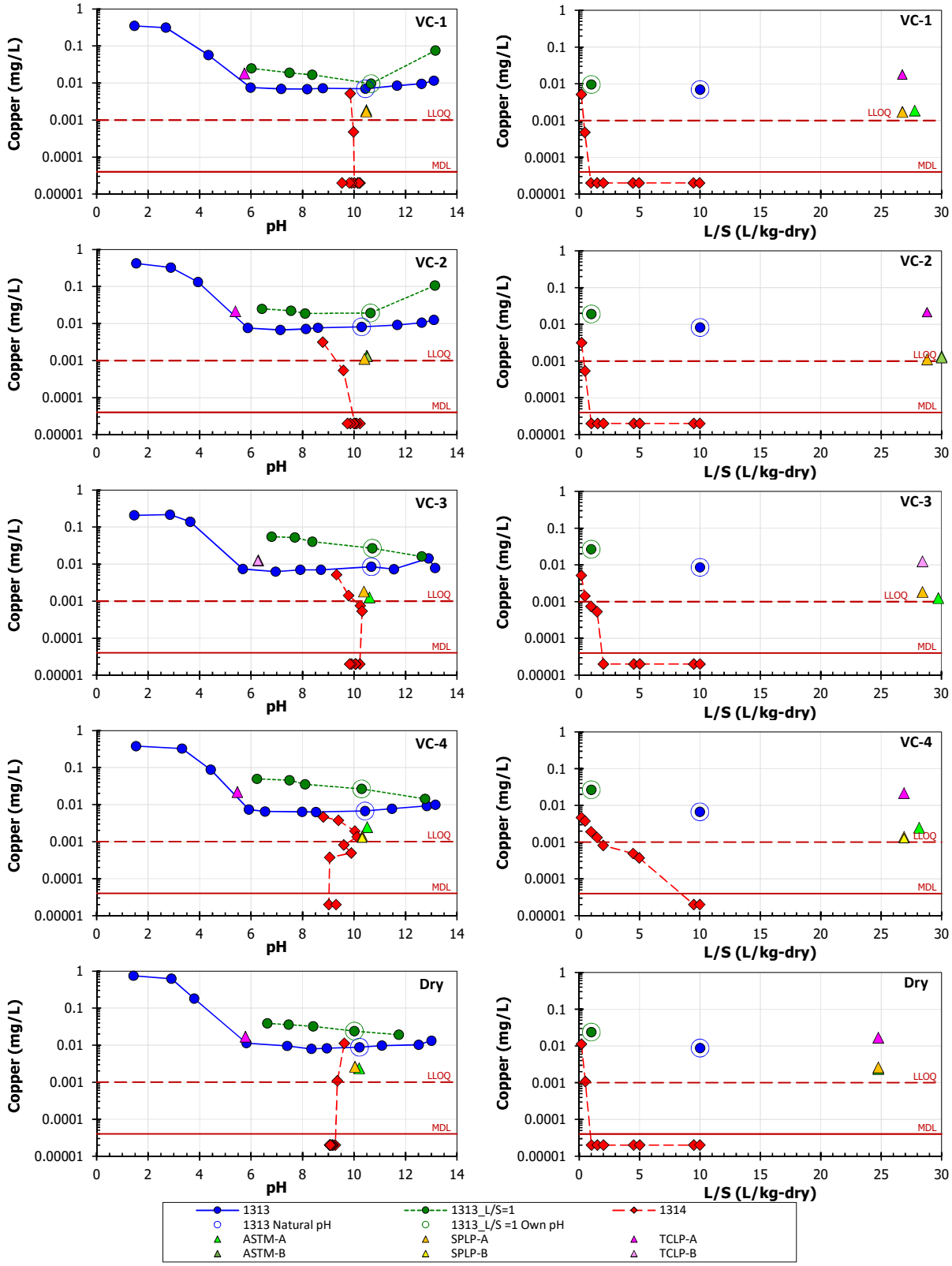

Figure C-14
Copper leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

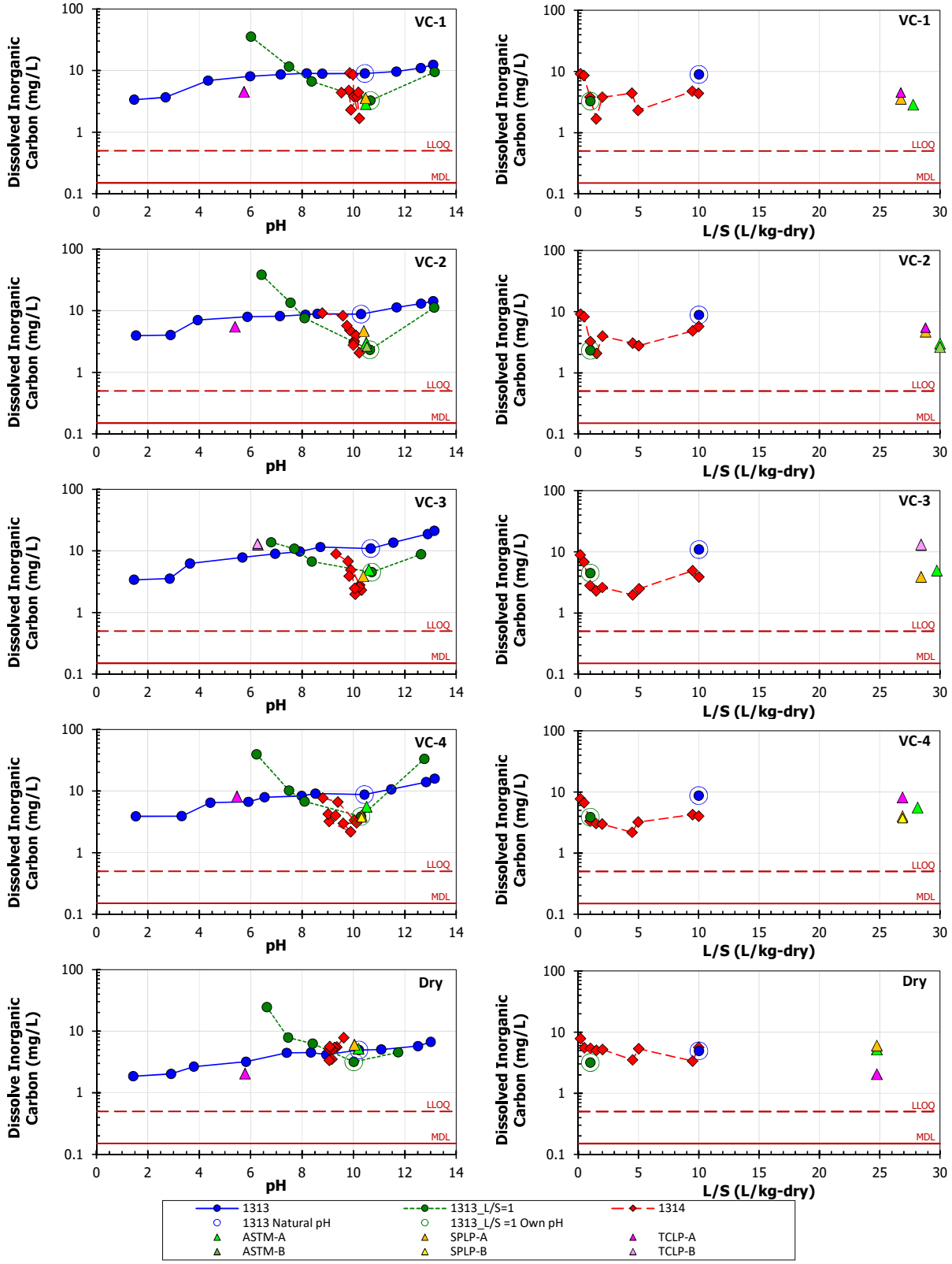

Figure C-15
Dissolved inorganic carbon leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

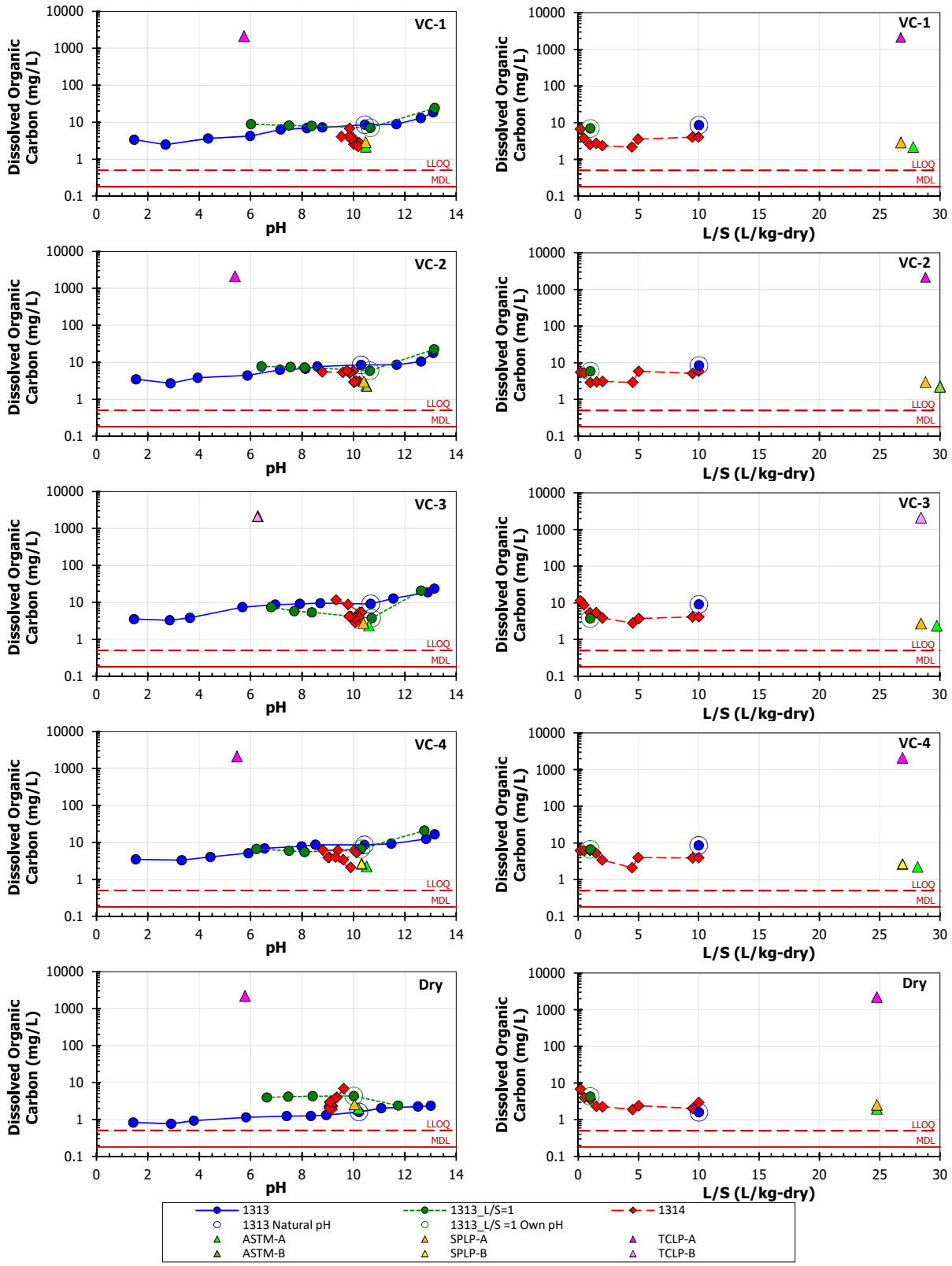

Figure C-16
Dissolved organic carbon leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

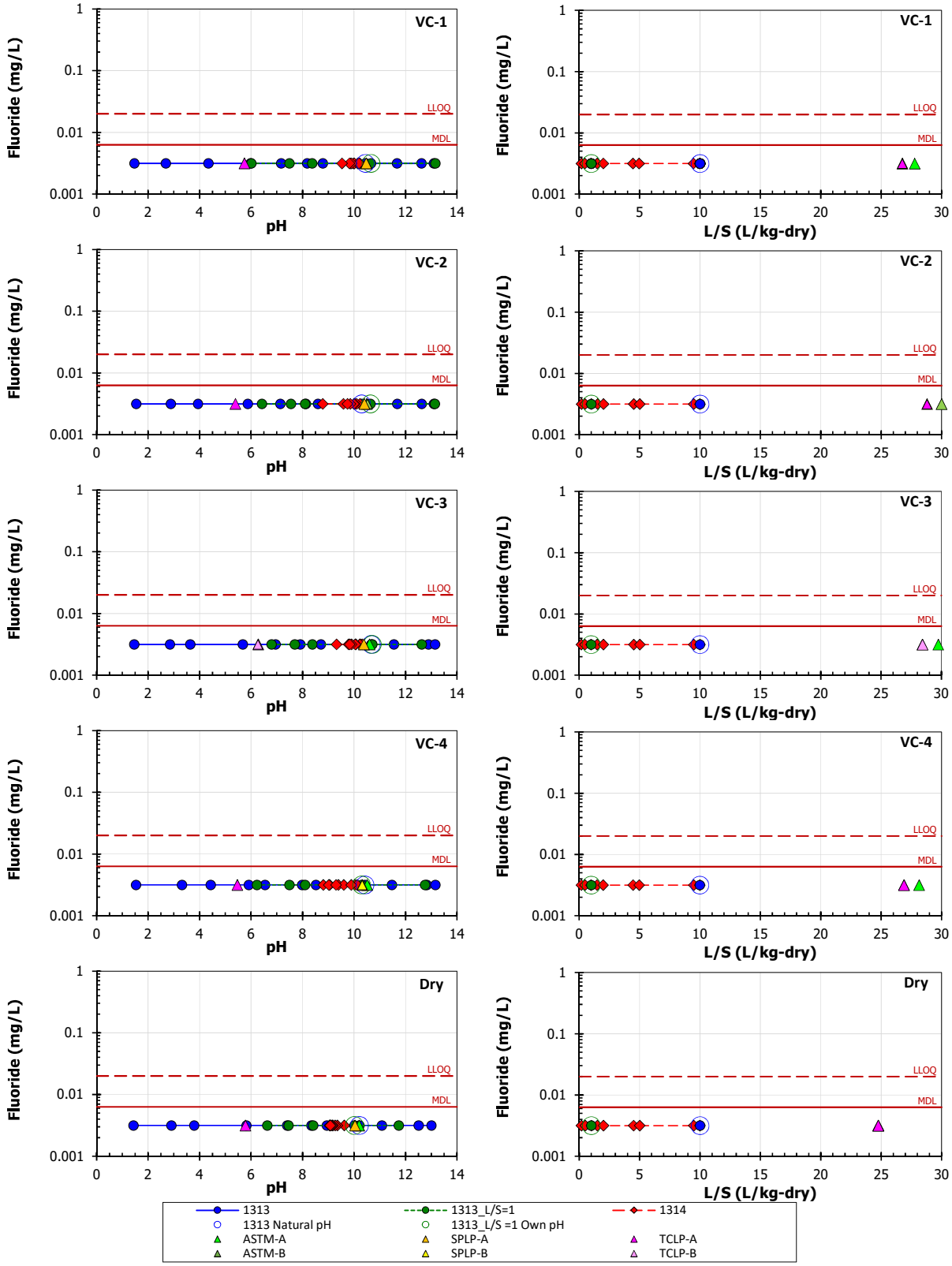

Figure C-17
Fluoride leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

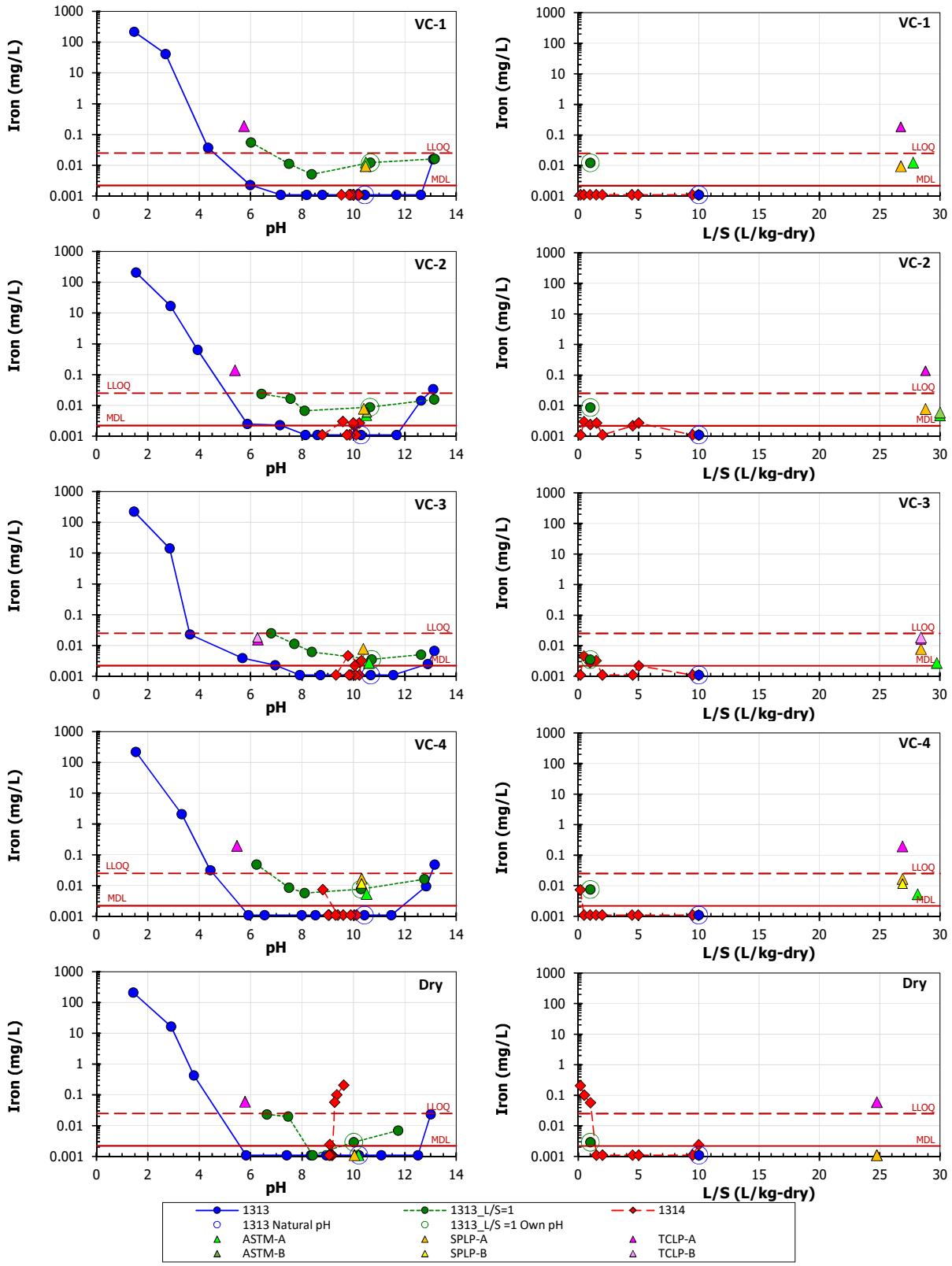

Figure C-18
Iron leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

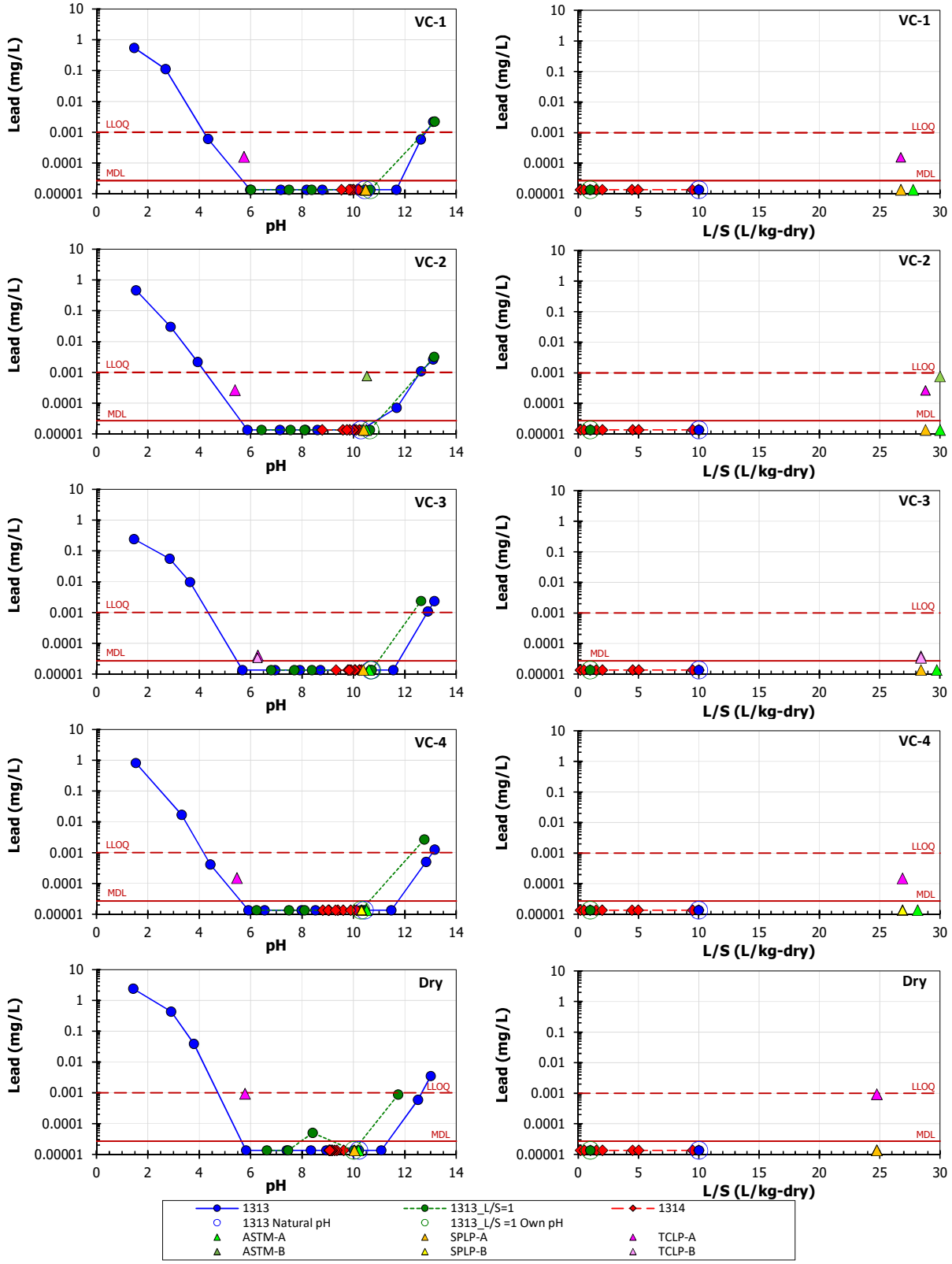

Figure C-19
Lead leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

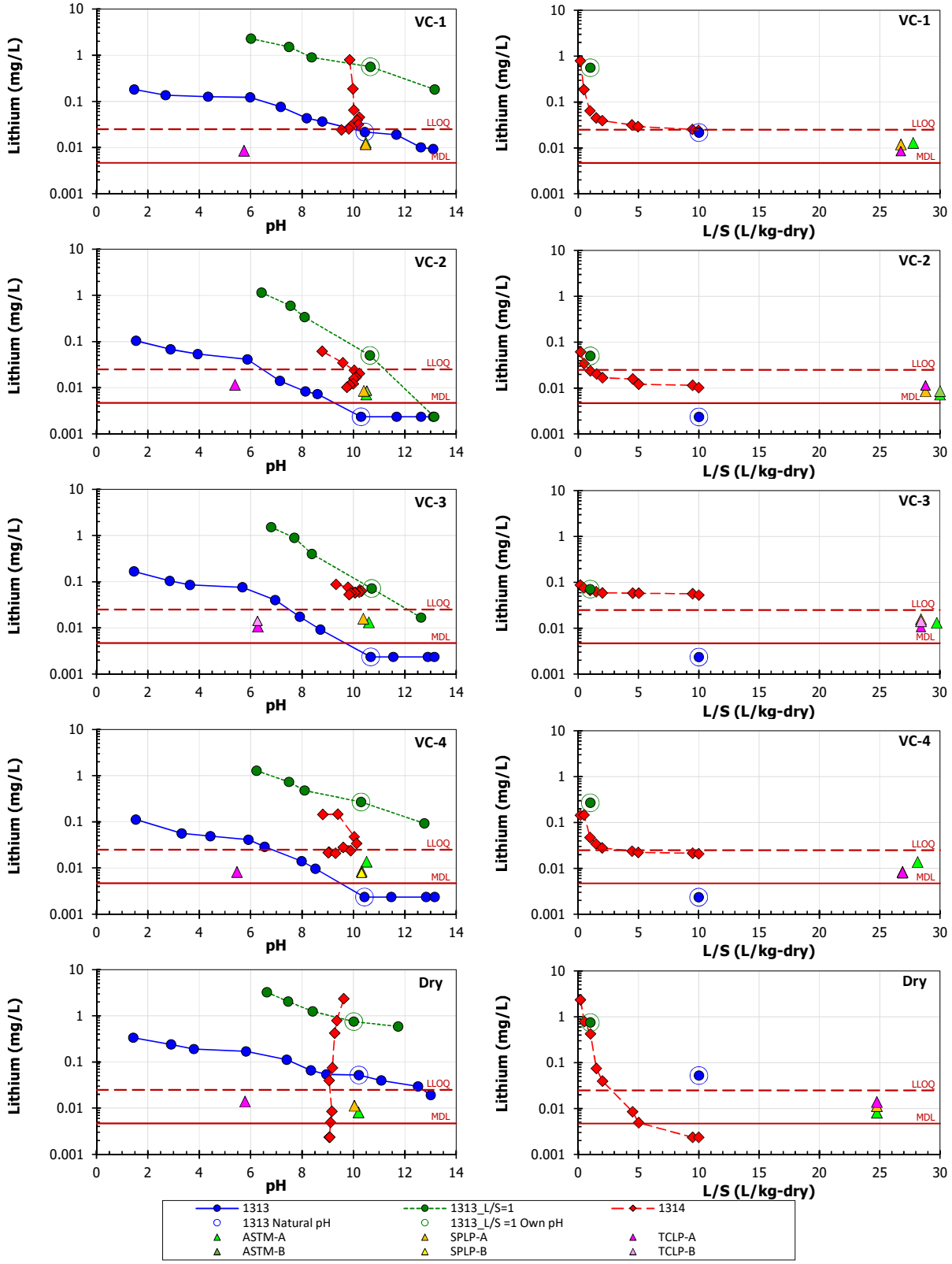

Figure C-20
Lithium leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

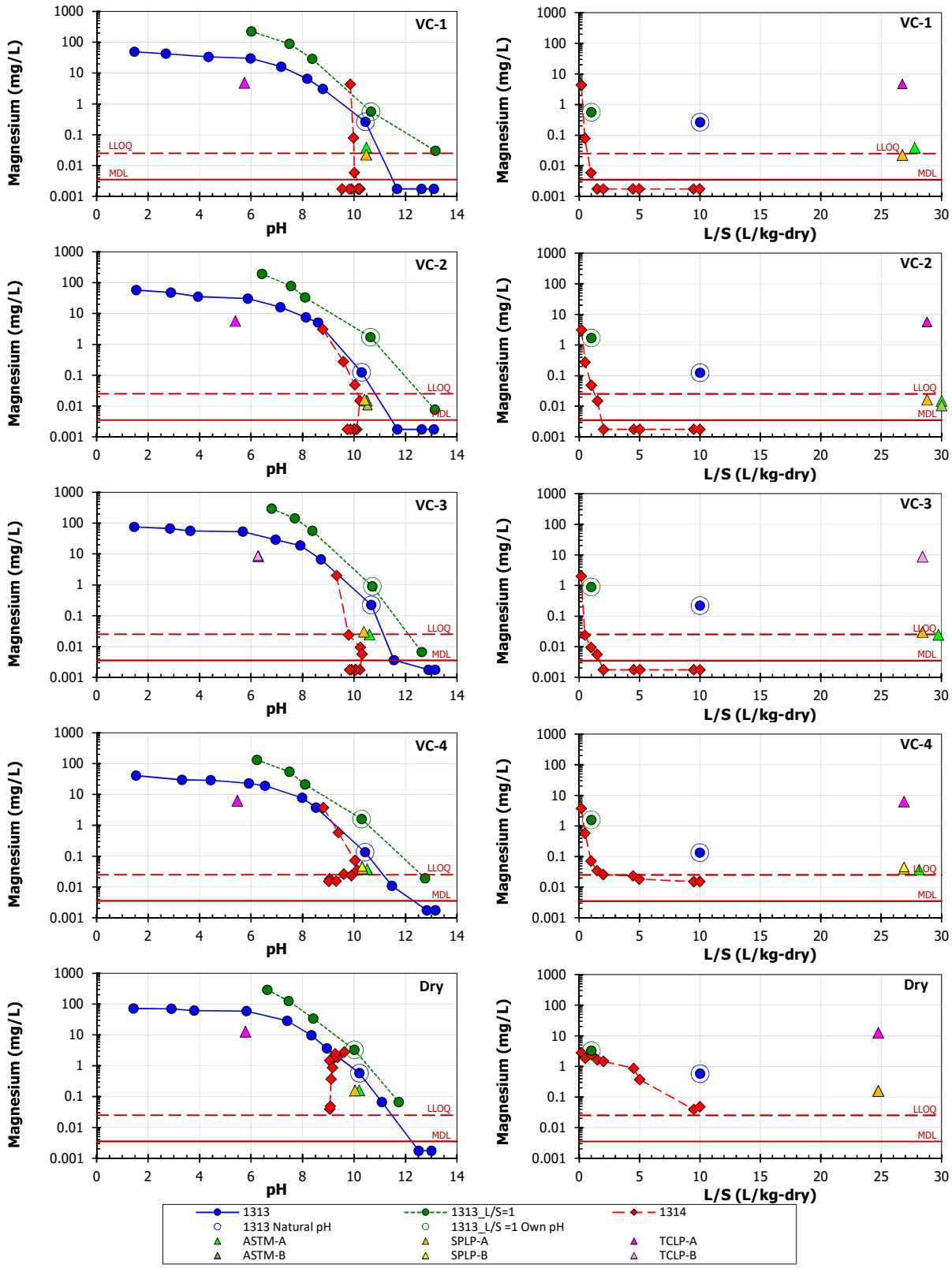

Figure C-21
Magnesium leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

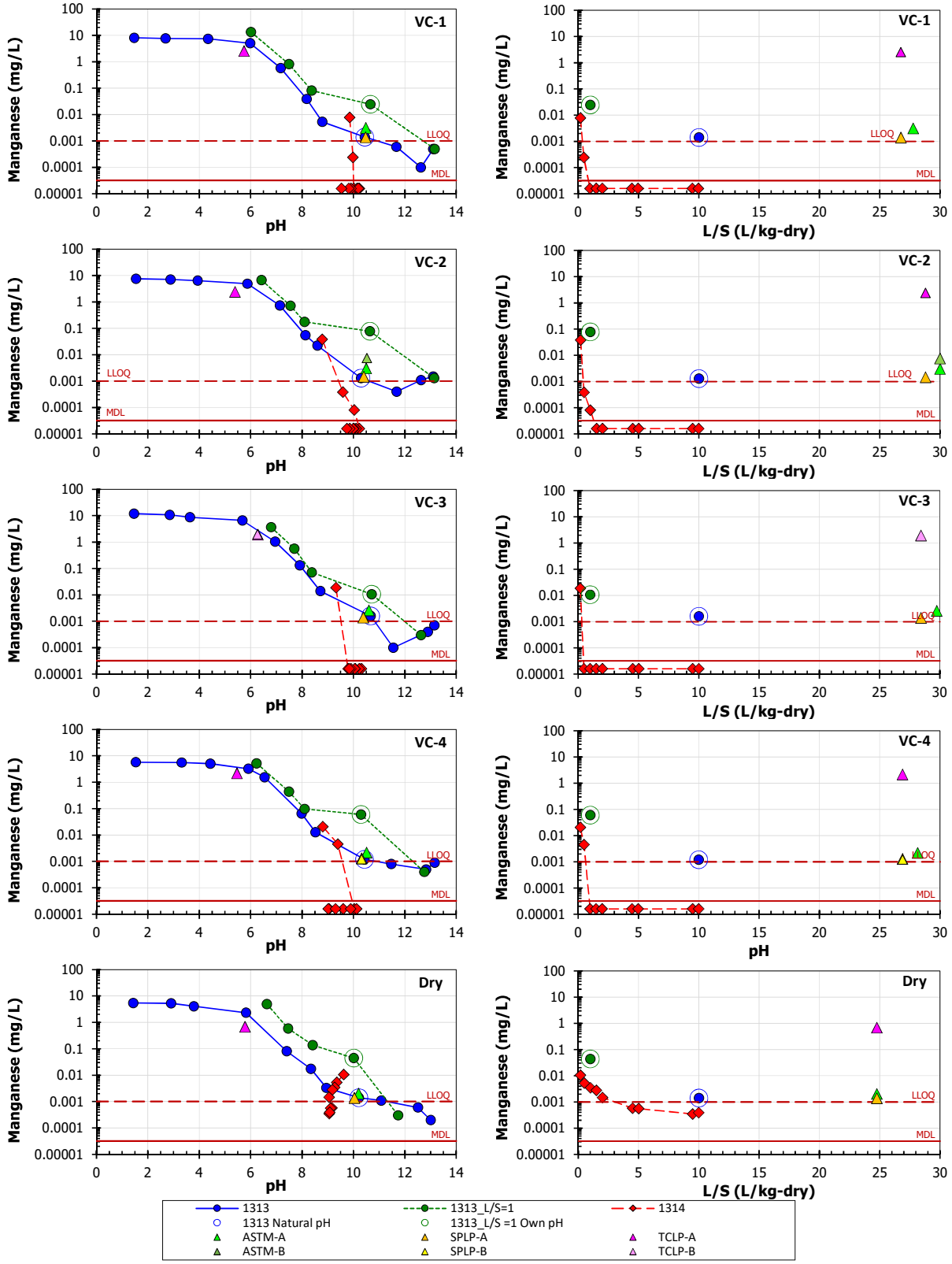

Figure C-22
Manganese leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

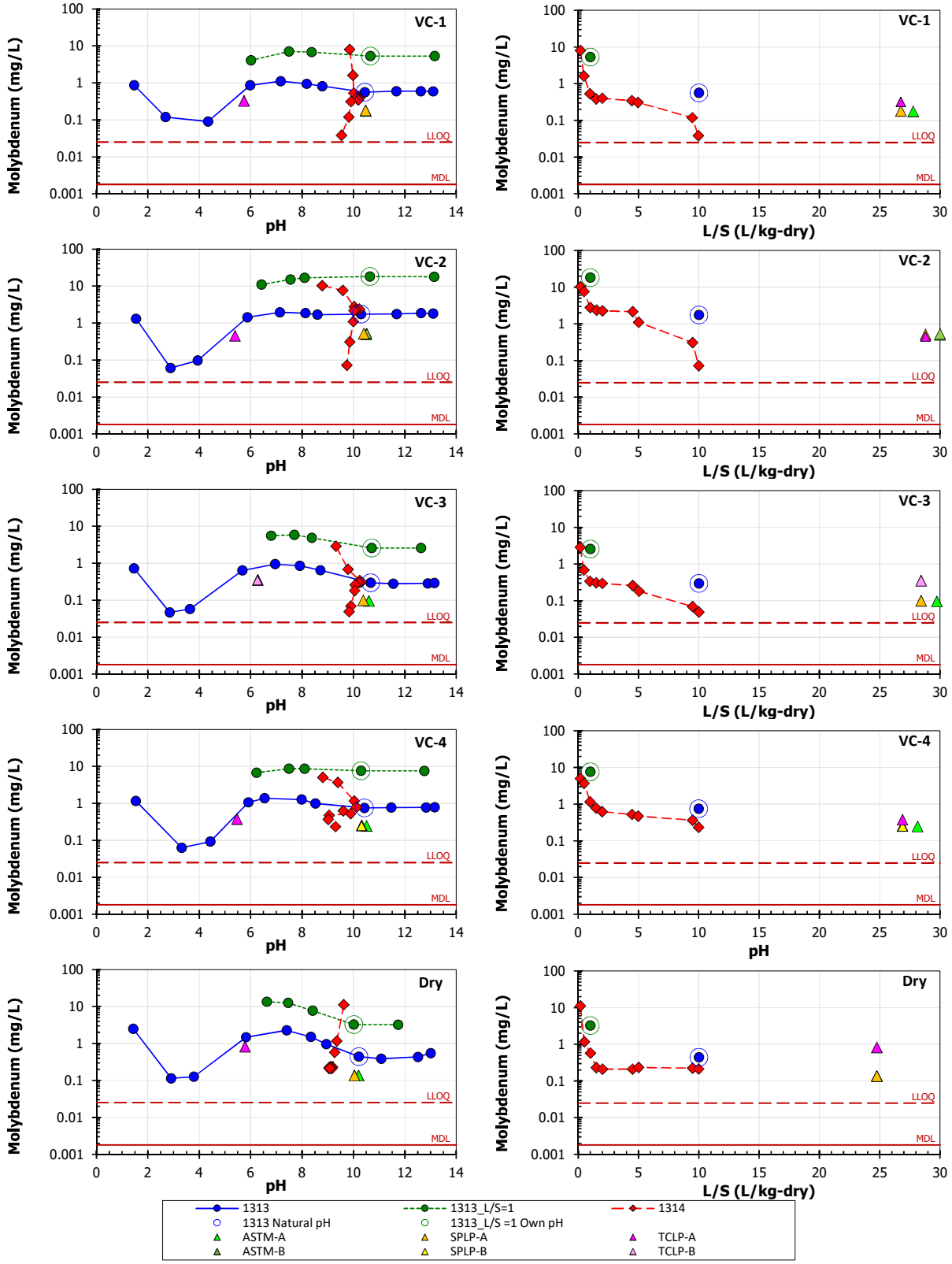

Figure C-23
Molybdenum leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

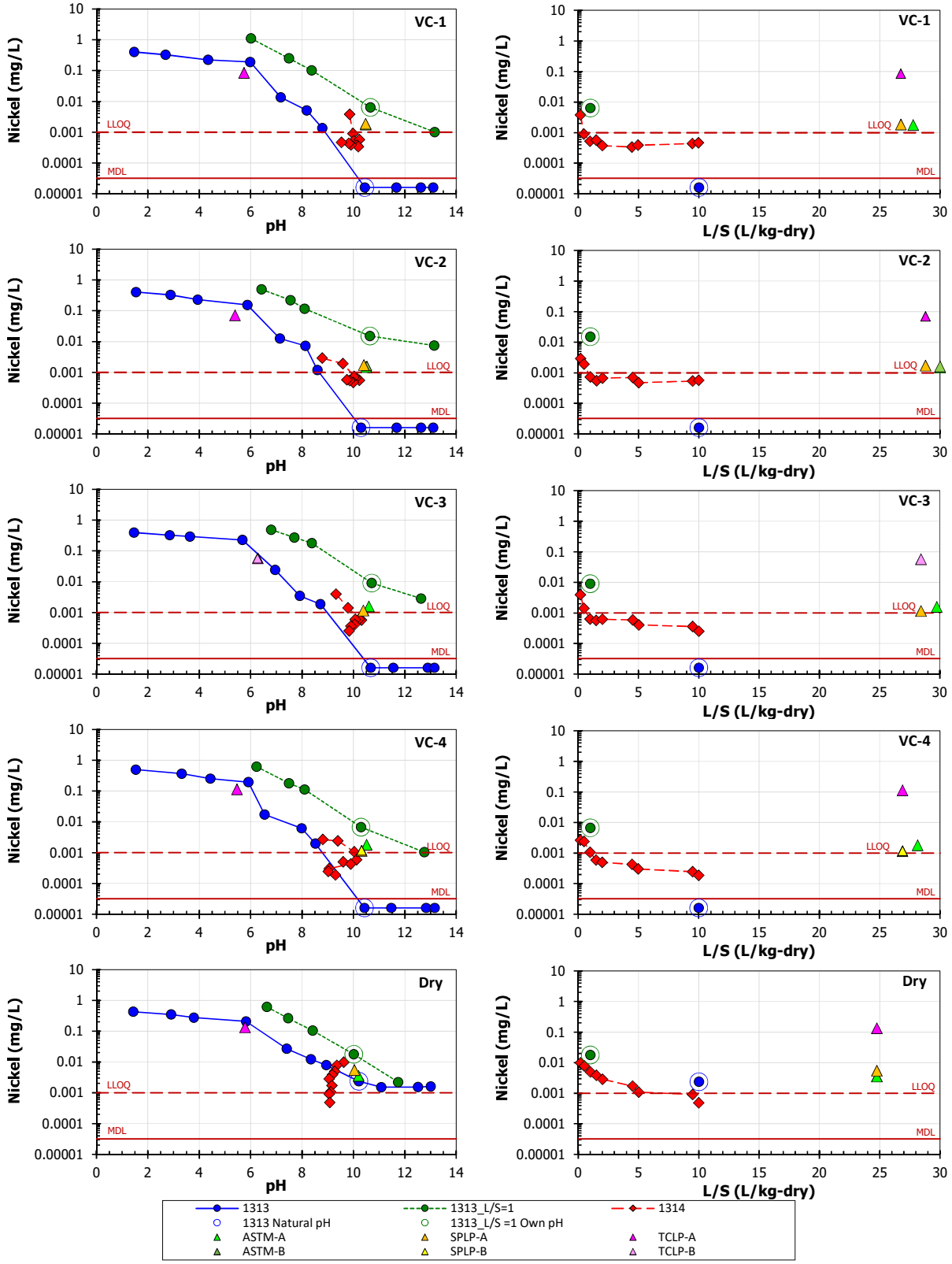

Figure C-24
Nickel leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

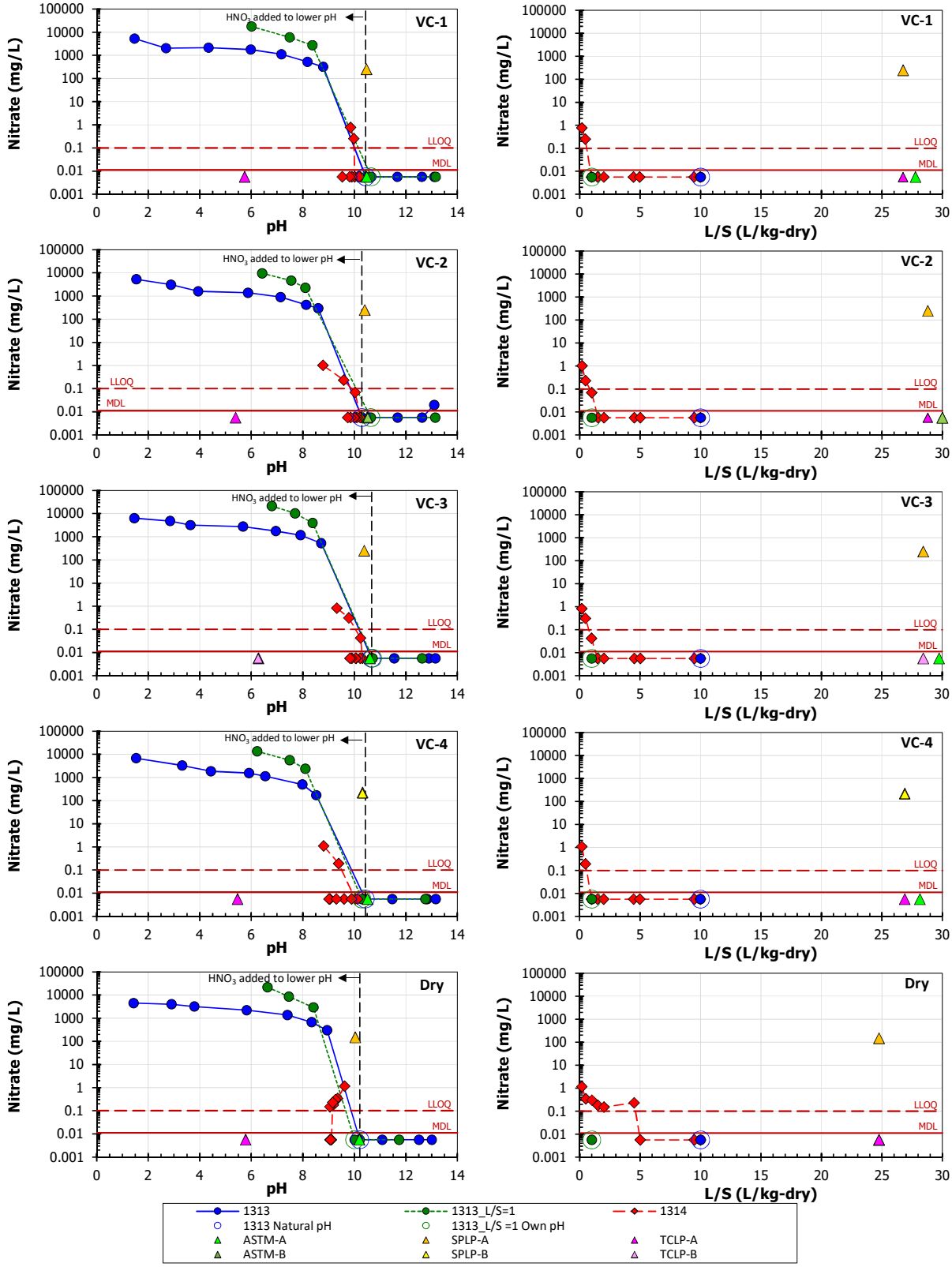

Figure C-25
Nitrate leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

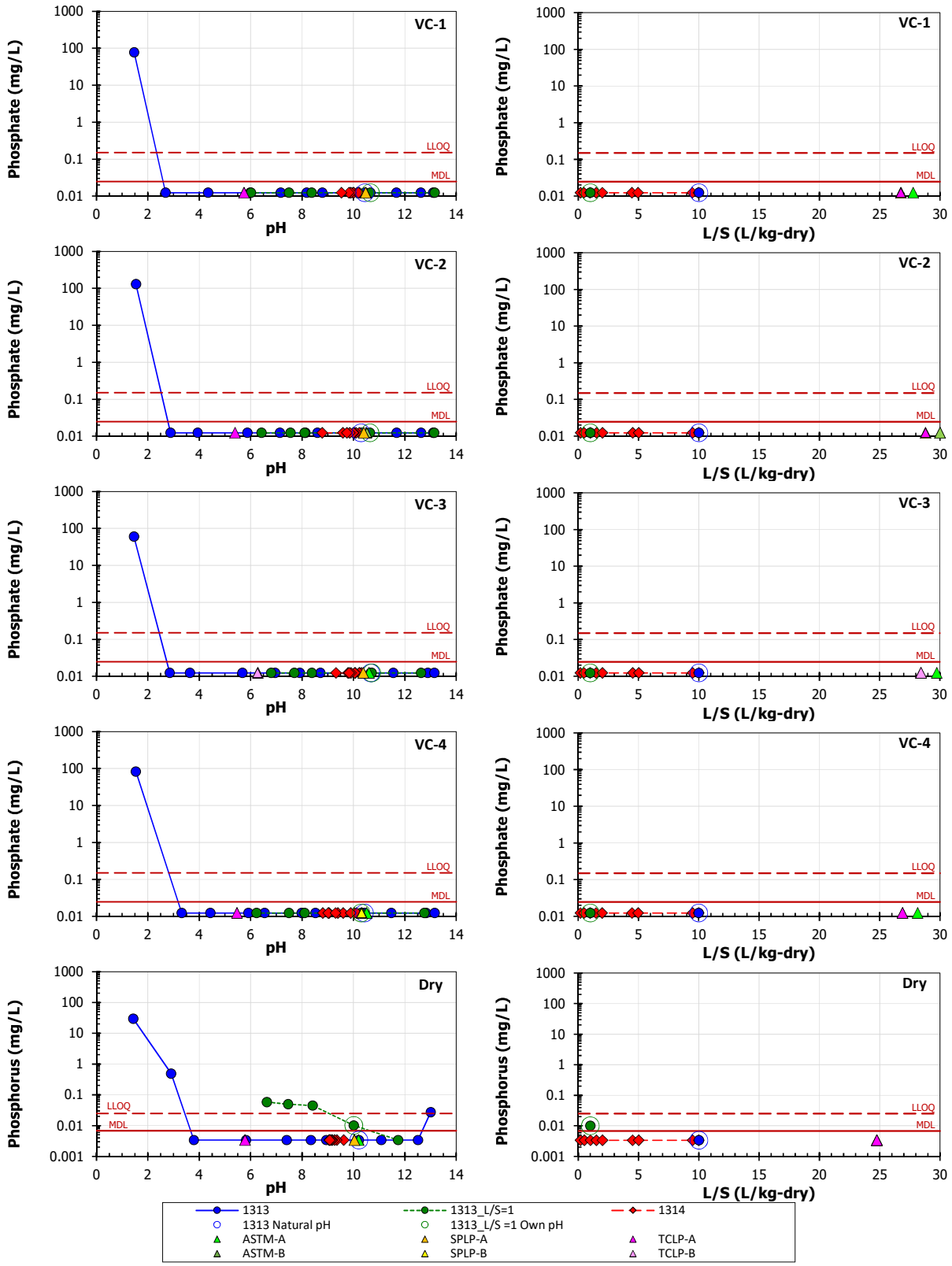

Figure C-26
Phosphate leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

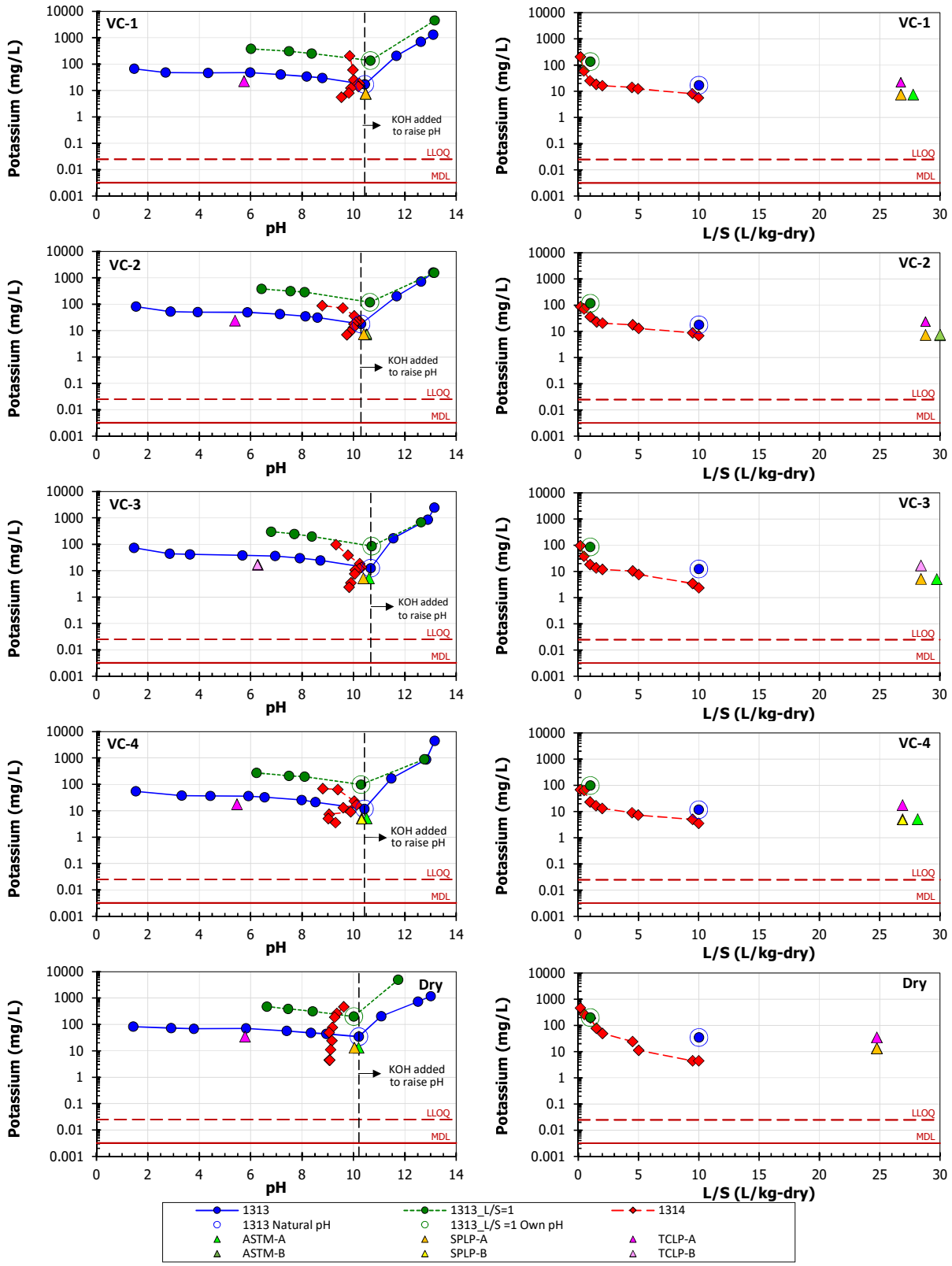

Figure C-27
Potassium leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

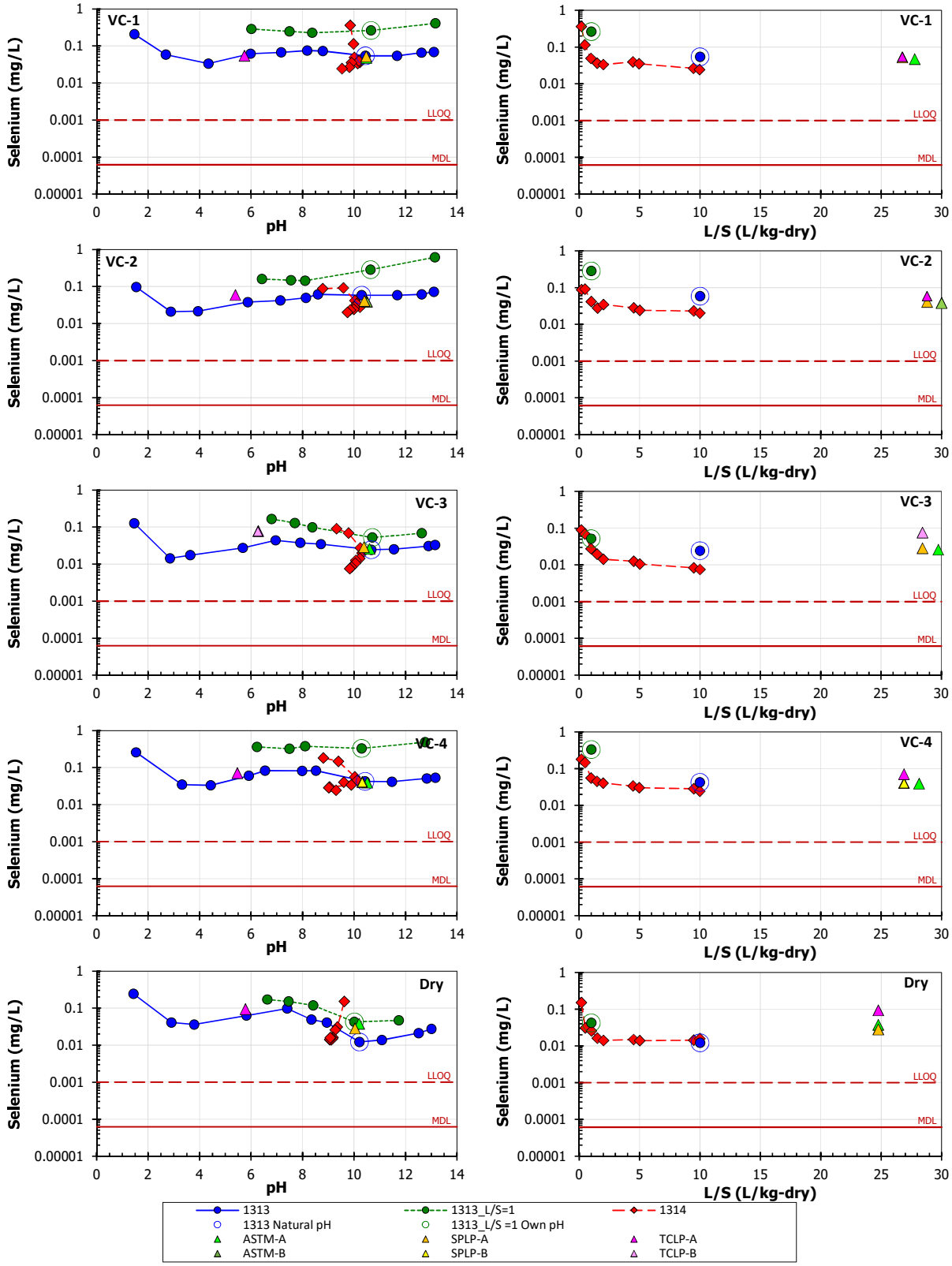

Figure C-28
Selenium leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

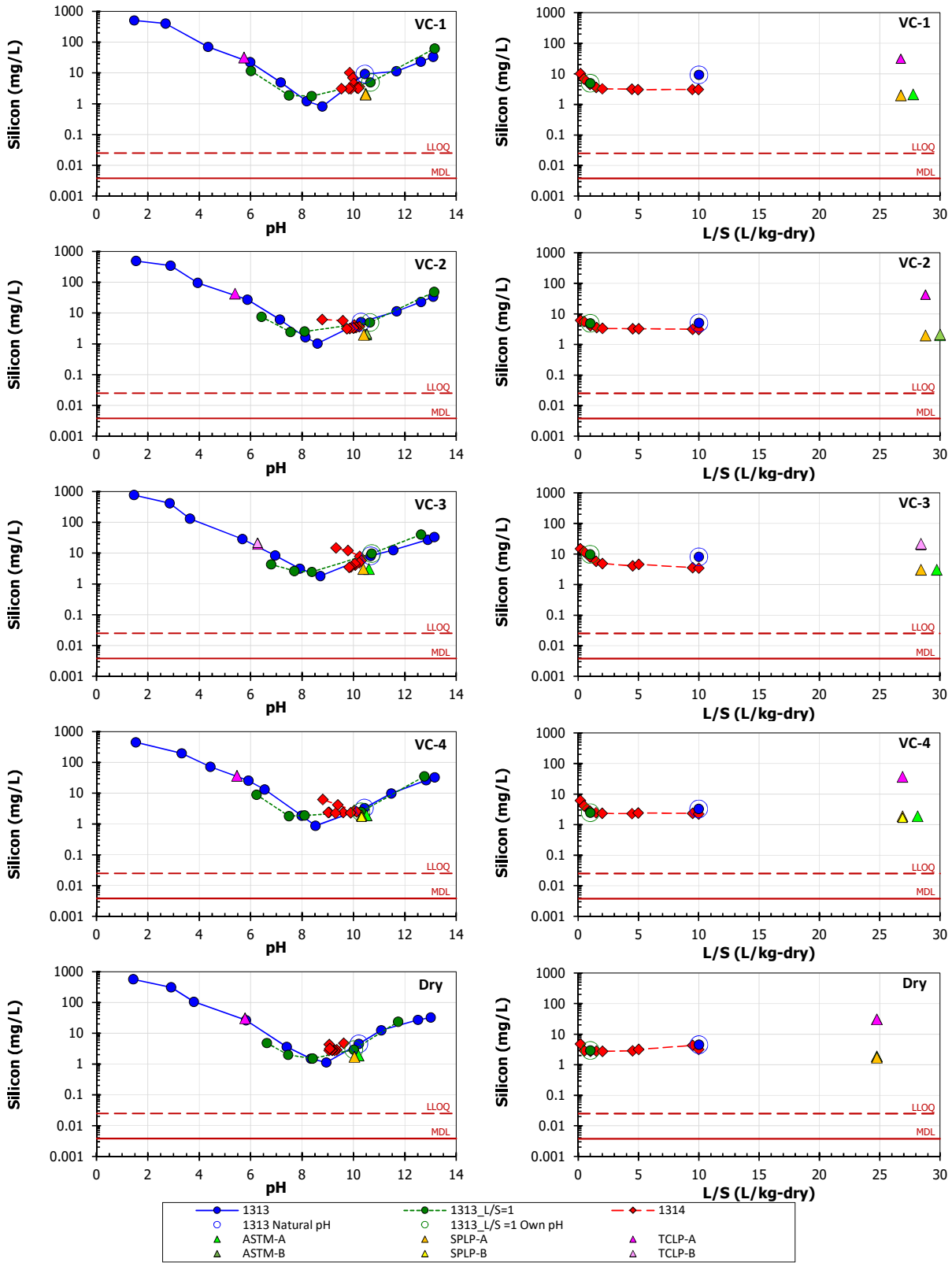

Figure C-29
Silicon leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

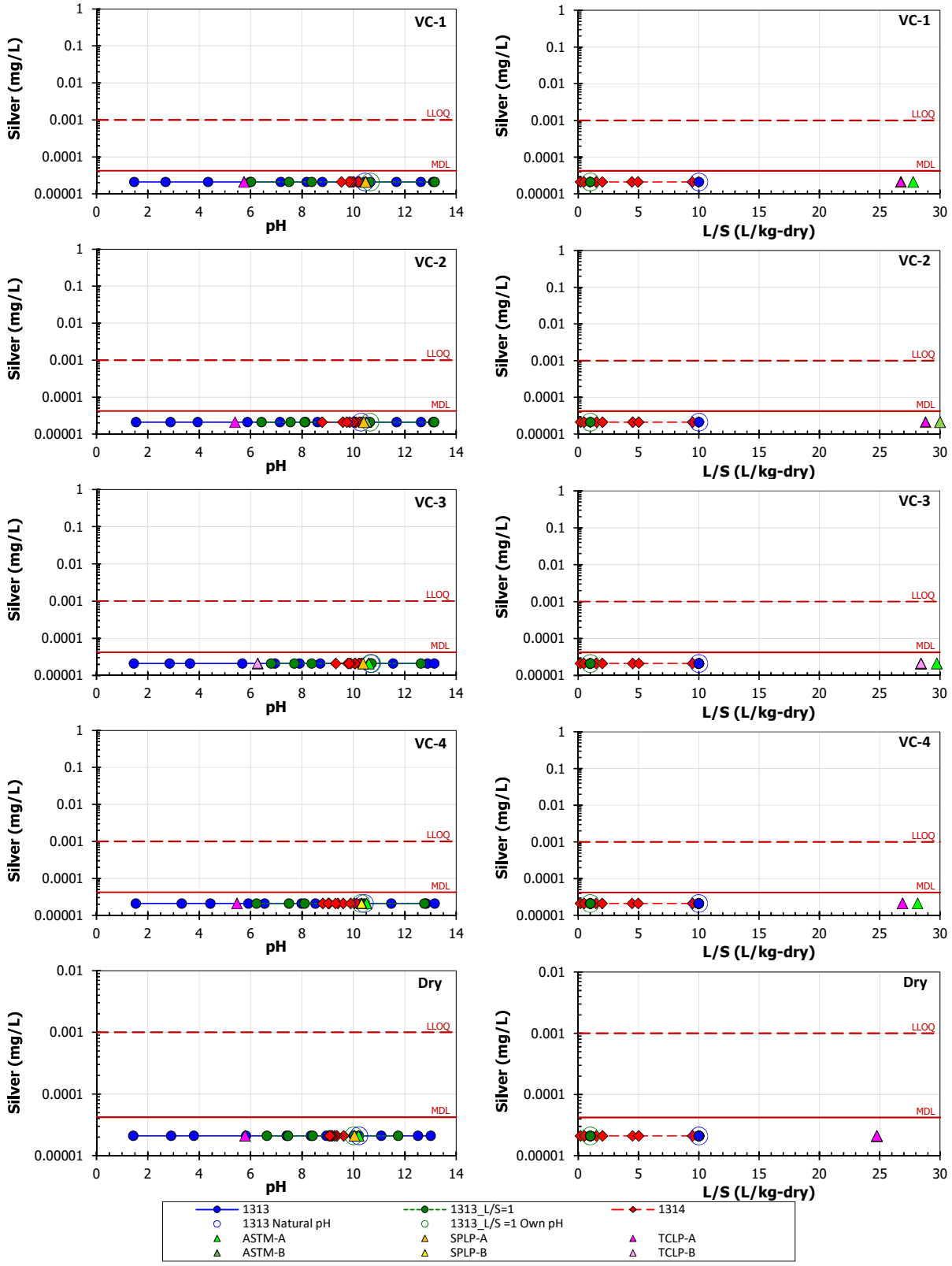

Figure C-30
Silver leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

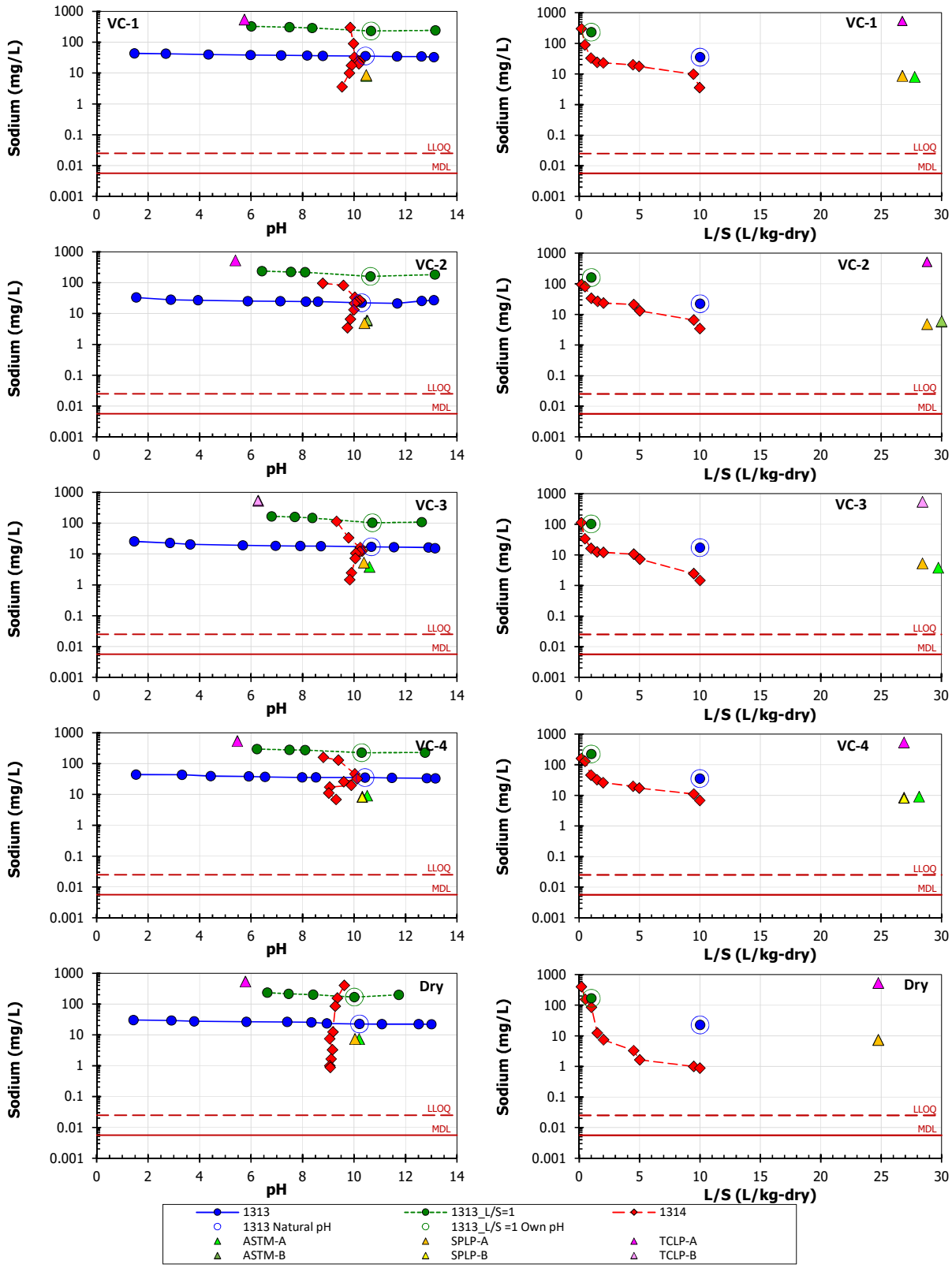

Figure C-31
Sodium leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

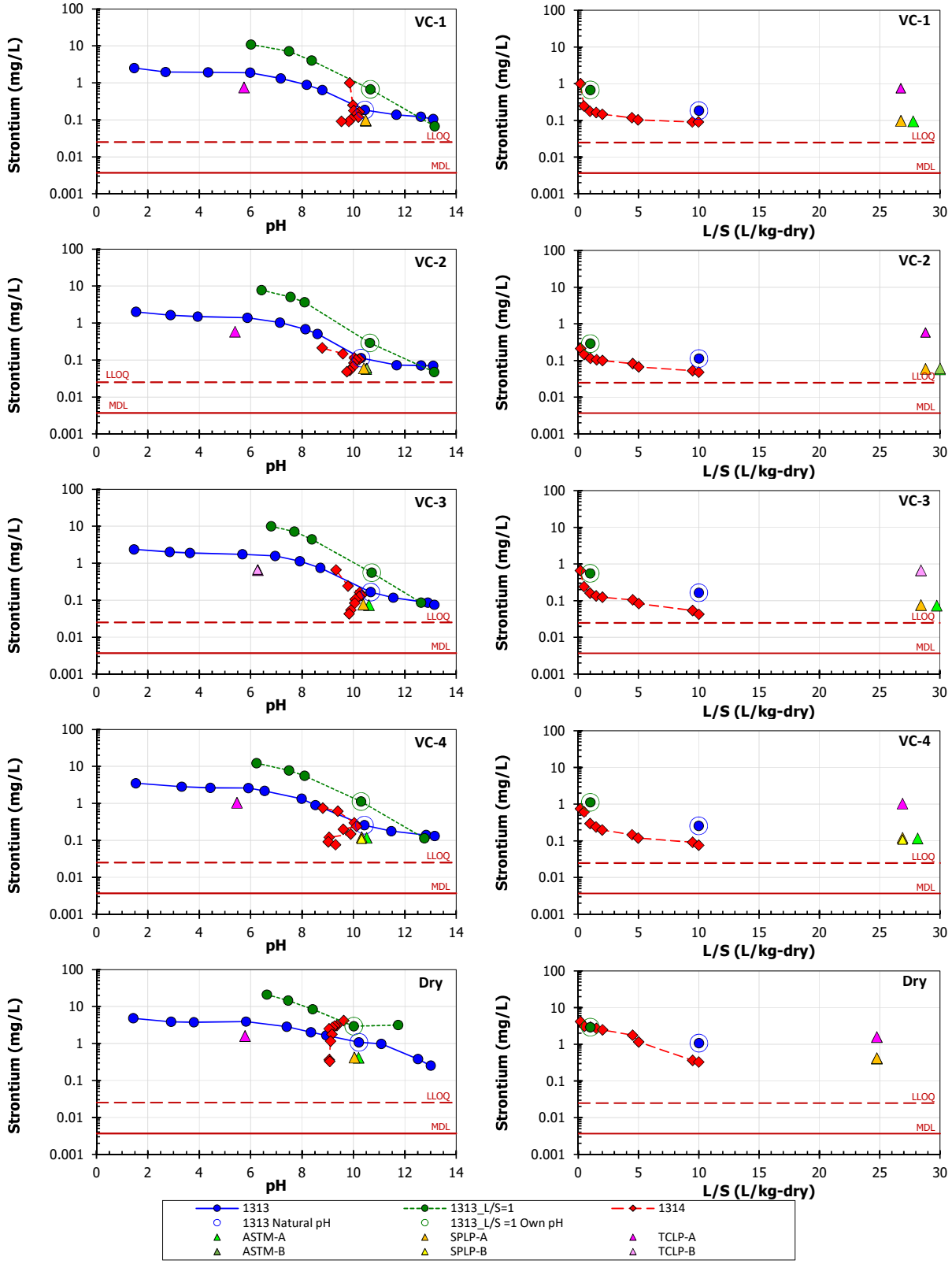

Figure C-32
Strontium leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

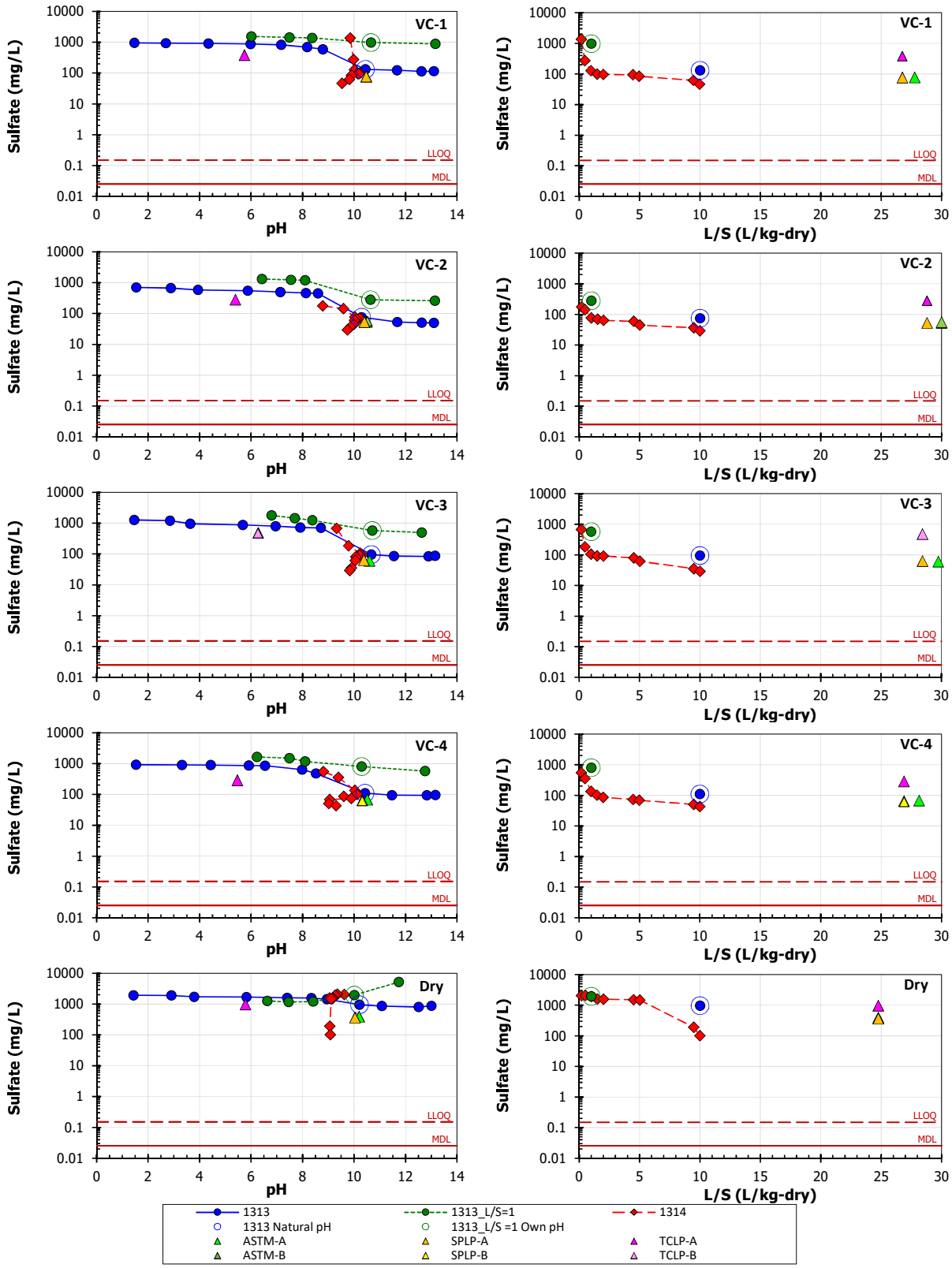

Figure C-33
Sulfate leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

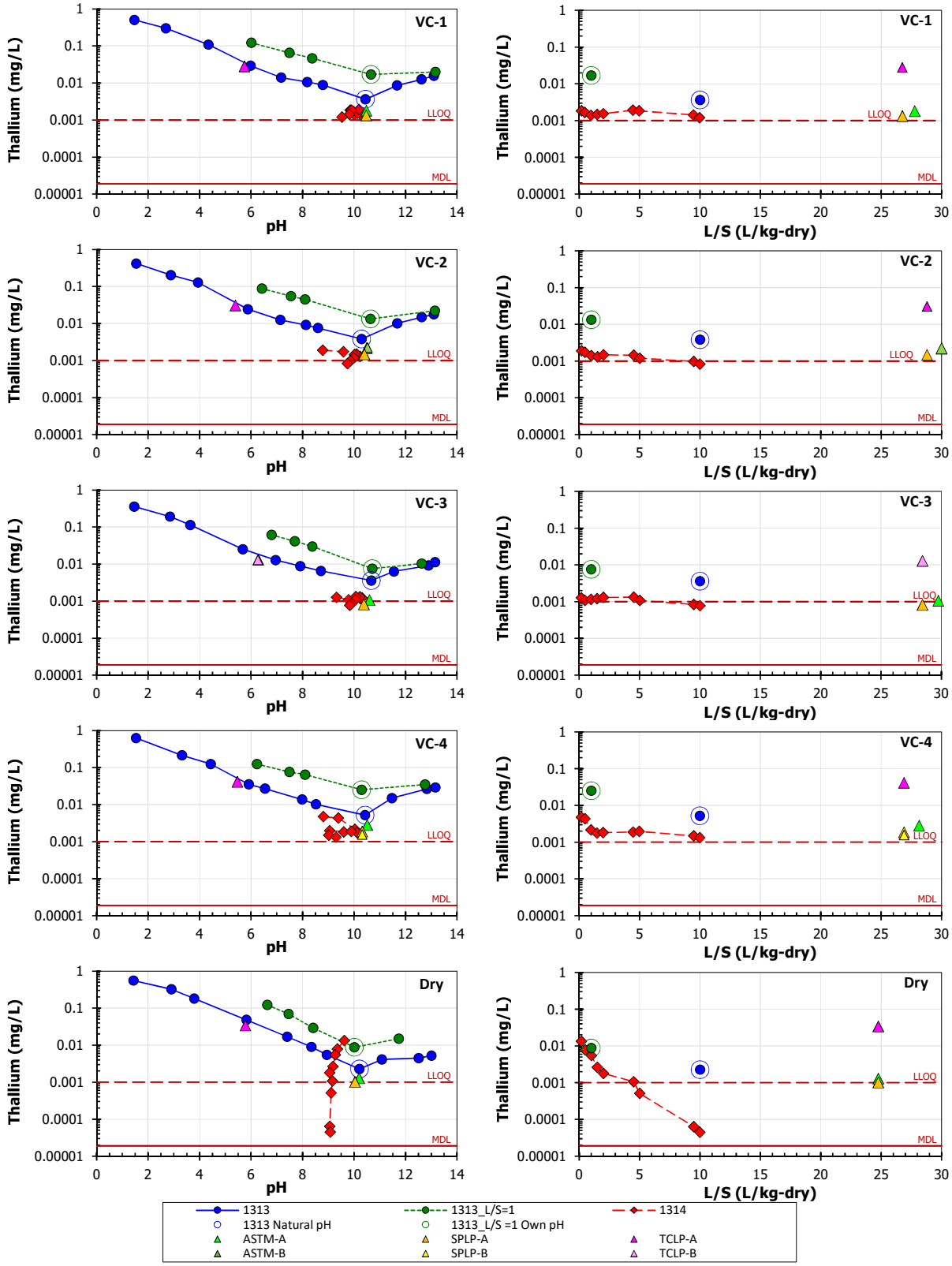

Figure C-34
Thallium leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

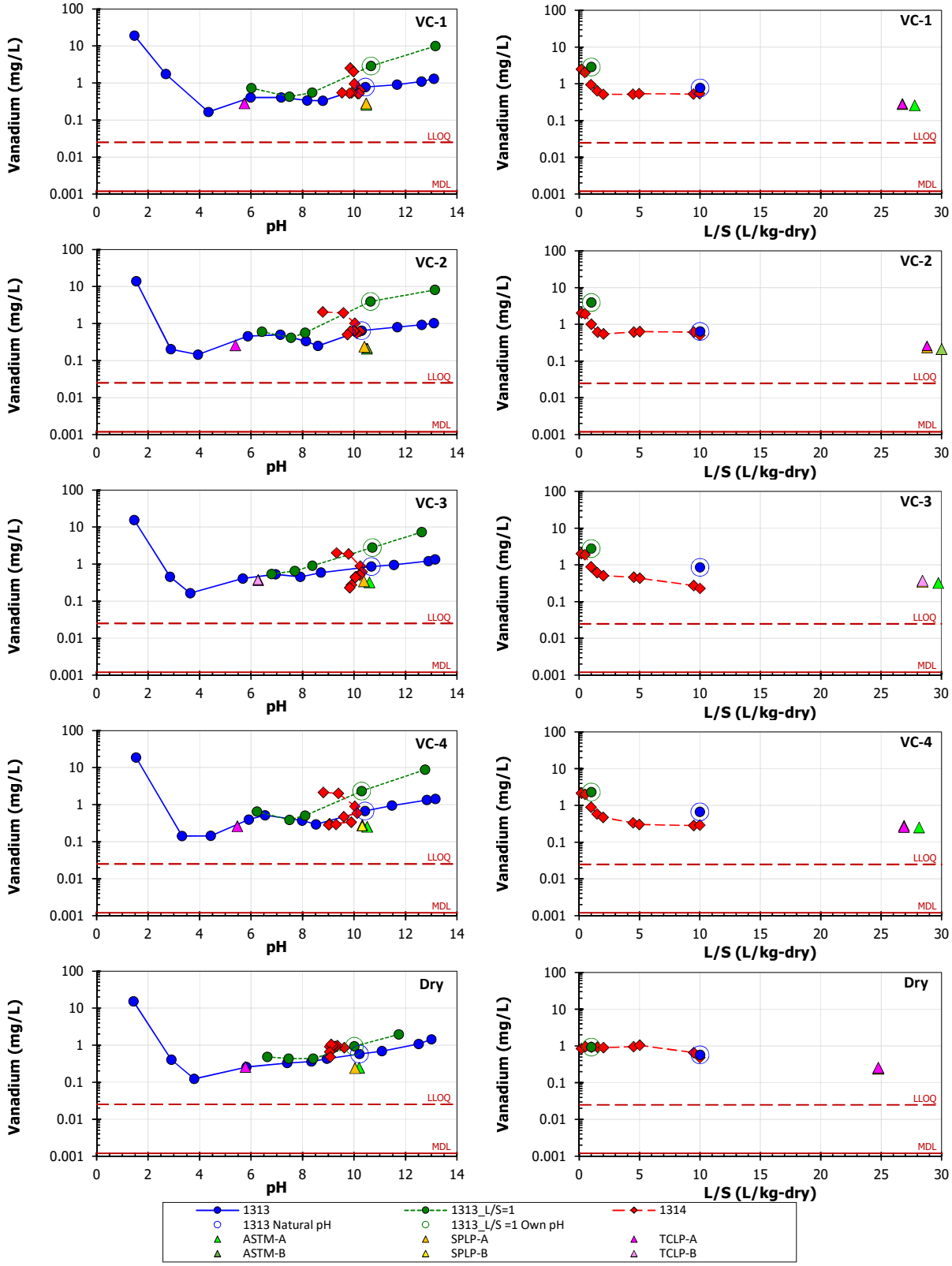

Figure C-35
Vanadium leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

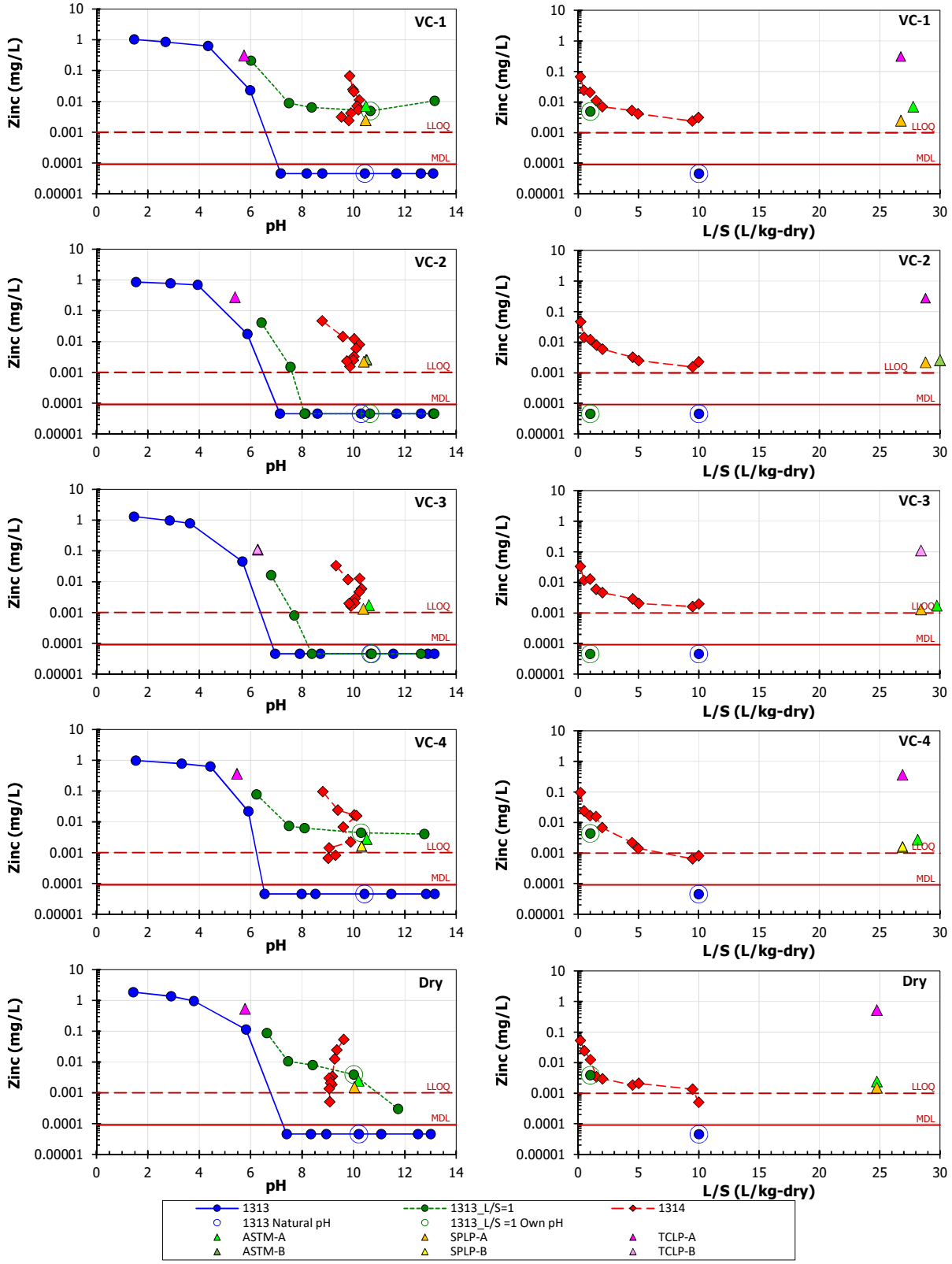

Figure C-36
Zinc leaching results for LEAF tests (1313, 1313@L/S=1, 1314) and traditional tests (TCLP, SPLP, ASTM) for Plant 42197 landfill composites

D
GROUNDWATER AND POREWATER DATA

Table of Appendices

D-1 Groundwater and Porewater Data Tables and Graphs

D-2 Time Series Graphs for Porewater Data

D-3 Subsurface Gas Data Tables and Graphs

D-1 Groundwater and Porewater Data Tables and Graphs

CDL_VC-1 (ash porewater borehole)

	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20
Sampling Date	6/10/19	7/15/19	8/13/19	9/17/19	10/16/19	11/19/19	12/11/19	1/22/20
Time at start	9:28	9:32	9:21	16:00	12:41	Groundwater sampling equipment unable to access borehole due to soft ground. Samples were not collected.	11:17	14:00
Water Table AMSL (ft)	56.71	56.51	59.85	58.58	59.27		60.40	59.73
Temperature (°C)	22.05	21.56	27.15	31.58	18.46		13.85	12.50
pH (s.u.)	9.87	10.35	10.24	10.03	10.47		10.74	10.50
DO (mg/L)	1.33	0.86	1.96	1.81	0.54		0.80	0.81
EC (mS/cm)	4.008	5.063	5.208	5.240	5.039		5.077	4.815
ORP (mV)	211	211	174	86	112		50	-13
Turbidity (NTU)	0.15	0.15	3.70	1.00	0.05		1.20	0.00
Time at end	9:37	9:34	9:27	16:06	12:46		11:24	14:08

CDL_VC-2 (ash porewater borehole)

	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20
Sampling Date	6/10/19	7/15/19	8/13/19	9/17/19	10/16/19	11/19/19	12/11/19	1/22/20
Time at start	10:36	10:37	10:16	PVC borehole casing was damaged by heavy equipment. Collected samples were not analyzed. Casing repaired by CDL contractor during October sampling event.		16:05	13:52	10:55
Water Table AMSL (ft)	54.75	57.50	58.30			57.67	60.51	58.81
Temperature (°C)	22.55	23.42	26.74			17.71	15.63	10.30
pH (s.u.)	10.83	10.81	10.59			10.91	11.11	11.05
DO (mg/L)	3.10	2.27	1.97			1.16	0.50	0.85
EC (mS/cm)	1.648	2.111	1.900			1.878	1.829	1.830
ORP (mV)	38	38	42			125	88	165
Turbidity (NTU)	3.40	3.40	2.30			13.40	4.10	0.05
Time at end	10:42	10:45	10:26			16:10	13:58	11:02

CDL_VC-3 (ash porewater borehole)

	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20
Sampling Date	6/10/19	7/15/19	8/13/19	9/17/19	10/16/19	11/19/19	12/11/19	1/22/20
Time at start	11:31	11:44	11:24	14:27	12:00	13:46	12:10	11:55
Water Table AMSL (ft)	58.46	60.21	61.00	61.40	61.60	61.33	63.50	61.80
Temperature (°C)	24.34	24.98	31.46	32.54	18.66	18.94	13.75	9.10
pH (s.u.)	10.32	10.53	10.26	10.08	10.53	10.51	10.68	10.75
DO (mg/L)	3.77	2.39	1.67	1.52	1.18	1.45	0.72	0.95
EC (mS/cm)	4.730	5.692	5.854	5.388	5.574	5.523	5.279	5.565
ORP (mV)	177	177	117	76	118	87	41	79
Turbidity (NTU)	1.25	1.25	2.10	1.80	0.00	1.50	1.65	0.00
Time at end	11:40	11:55	11:32	14:36	12:06	13:53	12:17	12:05

CDL_VC-4 (ash porewater borehole)

	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20
Sampling Date	6/10/19	7/15/19	8/13/19	9/17/19	10/16/19	11/19/19	12/11/19	1/22/20
Time at start	12:29	12:40				12:48	14:51	1:00
Water Table AMSL (ft)	59.49	61.25				60.97	61.90	61.34
Temperature (°C)	23.53	25.57				18.84	15.14	11.60
pH (s.u.)	9.99	10.04				10.24	10.47	10.45
DO (mg/L)	3.90	1.40				0.56	0.60	0.50
EC (mS/cm)	4.399	5.356				4.960	4.907	4.903
ORP (mV)	210	210				180	120	73
Turbidity (NTU)	0.80	0.80				5.10	1.80	0.00
Time at end	12:34	12:46				12:54	14:58	1:05

PVC borehole casing was damaged by heavy equipment. Collected samples were not analyzed. Casing repaired by CDL contractor during October sampling event.

GW_209 (downgradient groundwater well)

	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20
Sampling Date	6/10/19	7/15/19	8/13/19	9/17/19	10/16/19	11/19/19	12/11/19	1/22/20
Time at start	13:32	13:44	14:50	10:55	10:55	10:19	10:26	15:00
Water Table AMSL (ft)	35.36	35.88	36.68	37.70	38.04	38.01	37.50	35.45
Temperature (°C)	24.46	24.27	30.03	32.00	17.32	16.83	13.28	11.60
pH (s.u.)	6.93	6.80	6.74	6.61	6.85	6.86	6.85	6.75
DO (mg/L)	2.33	0.62	0.71	2.52	0.59	0.62	0.83	0.16
EC (mS/cm)	2.629	2.854	2.954	3.093	3.159	3.279	3.282	3.363
ORP (mV)	57	57	97	138	141	109	131	75
Turbidity (NTU)	0.75	0.75	7.55	1.25	0.00	1.75	0.70	0.00
Time at end	13:37	13:50	14:57	11:03	11:00	10:25	10:31	15:08

GW_931 (downgradient groundwater well)

	Jun-19	**Jul-19**	**Aug-19**	**Sep-19**	**Oct-19**	**Nov-19**	**Dec-19**	**Jan-20**
Sampling Date	6/10/19	7/15/19	8/13/19	9/17/19	10/16/19	11/19/19	12/11/19	1/22/20
Time at start	15:14	15:03	15:59	10:05	9:55	9:32	9:42	9:40
Water Table AMSL (ft)	35.61	36.49	37.75	40.05	40.30	40.25	39.43	35.90
Temperature (°C)	24.53	24.27	29.49	24.46	16.00	17.39	13.52	9.90
pH (s.u.)	6.62	6.50	6.48	6.42	6.60	6.58	6.55	6.54
DO (mg/L)	0.87	0.36	0.63	0.23	0.24	0.98	0.52	1.45
EC (mS/cm)	3.368	3.385	3.410	3.312	3.212	3.205	3.266	3.196
ORP (mV)	157	157	142	155	174	174	153	184
Turbidity (NTU)	9.40	9.40	9.70	9.65	17.45	14.35	7.75	38.40
Time at end	15:25	15:16	16:07	10:10	10:04	9:39	9:49	9:48

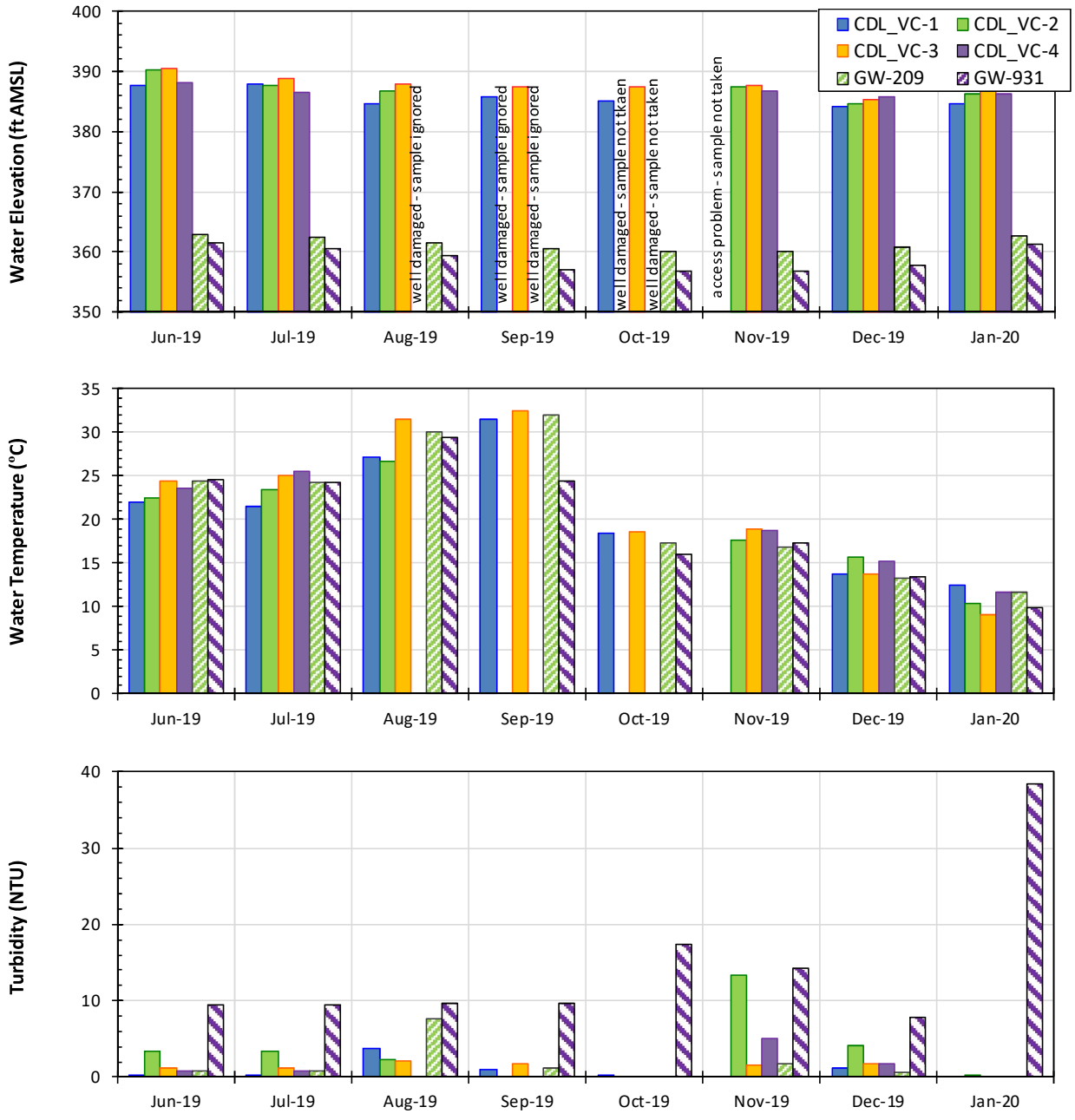

Figure D-1
Groundwater and porewater conditions during monthly sampling: water table elevation ASML, water temperature, and turbidity

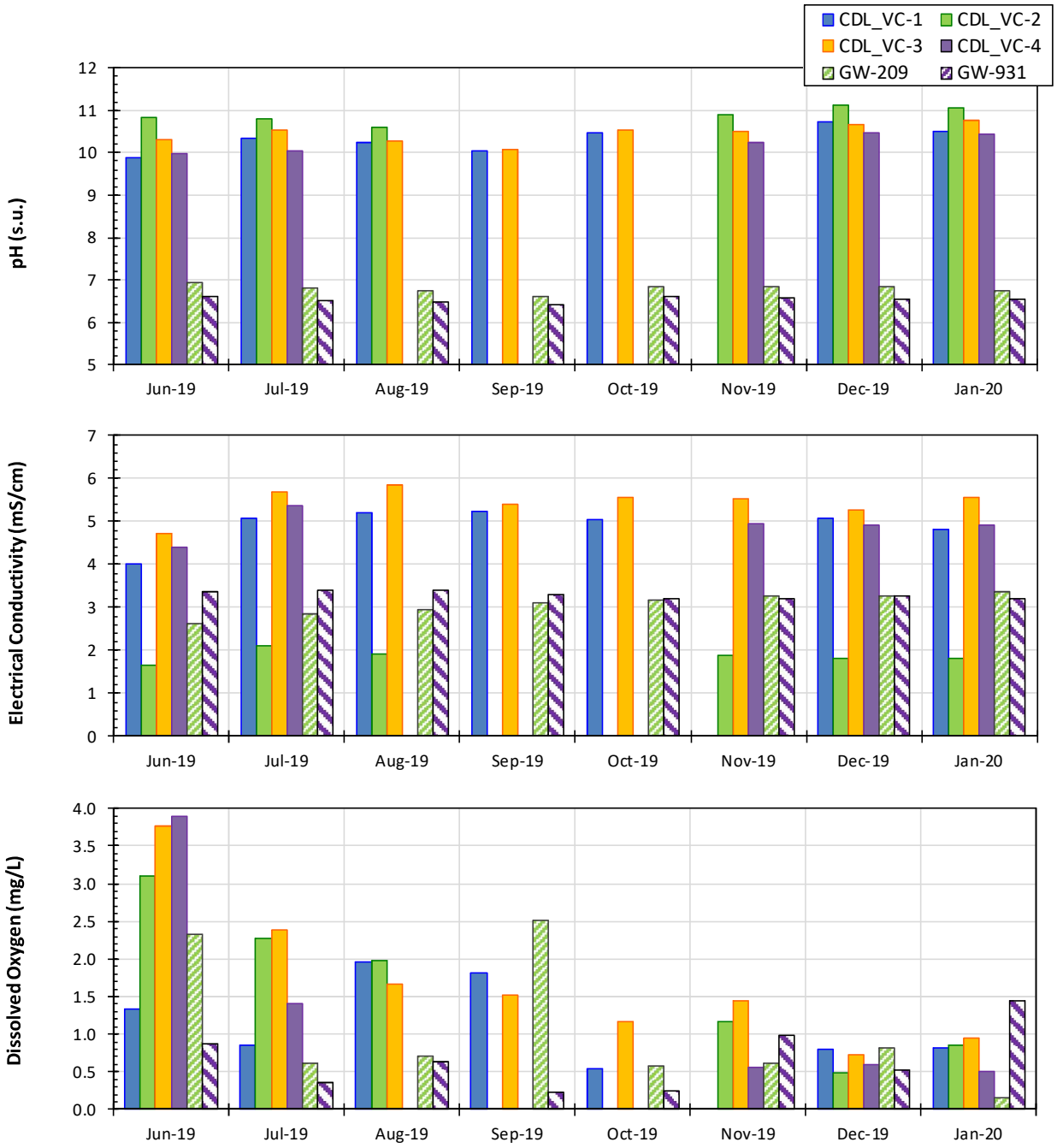

Figure D-2
Groundwater and porewater conditions during monthly sampling: pH, electrical conductivity, and dissolved oxygen

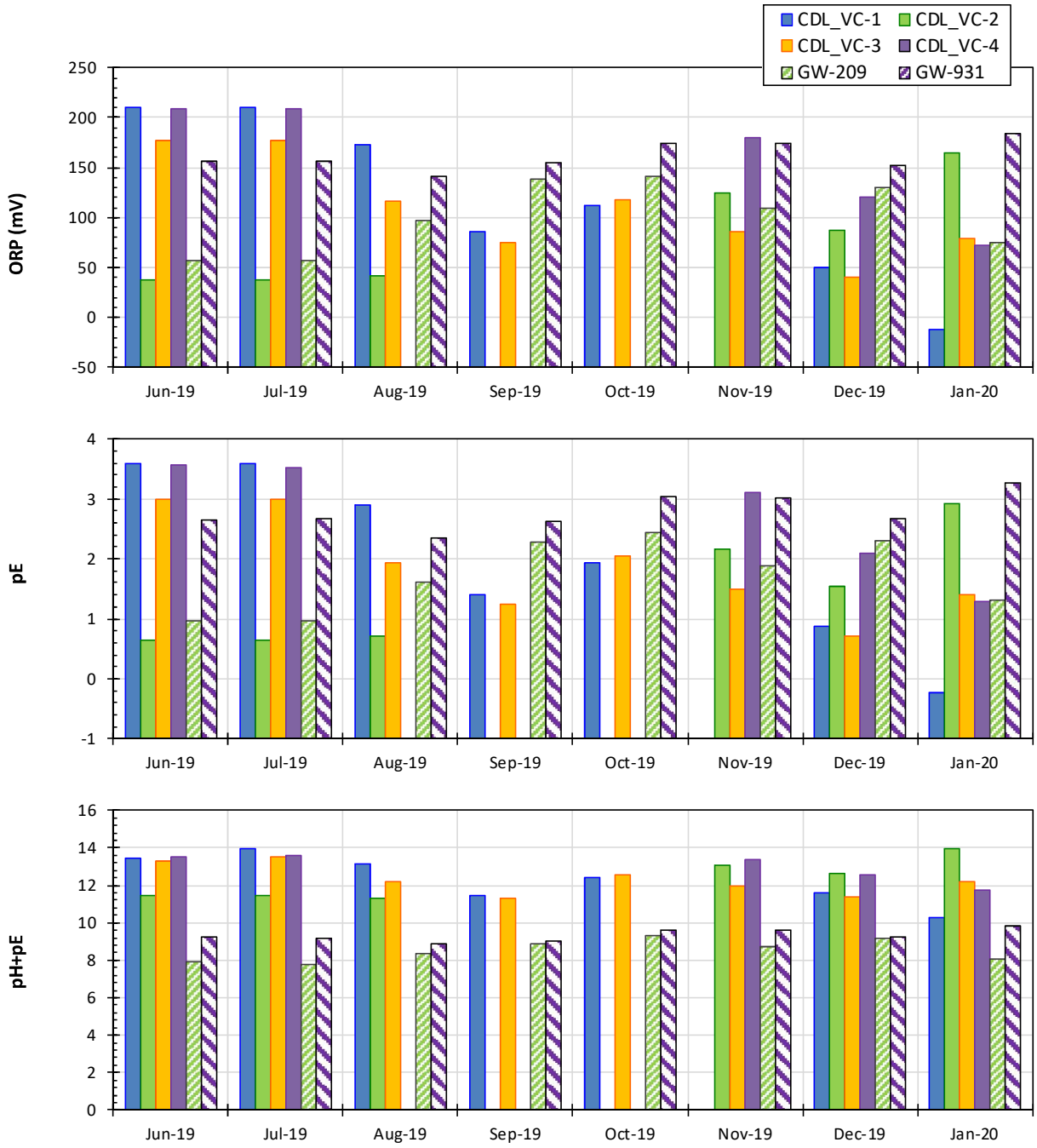

Figure D-3
Groundwater and porewater conditions during monthly sampling: ORP, pE (derived from ORP), and pH+pE (derived from ORP and pH)

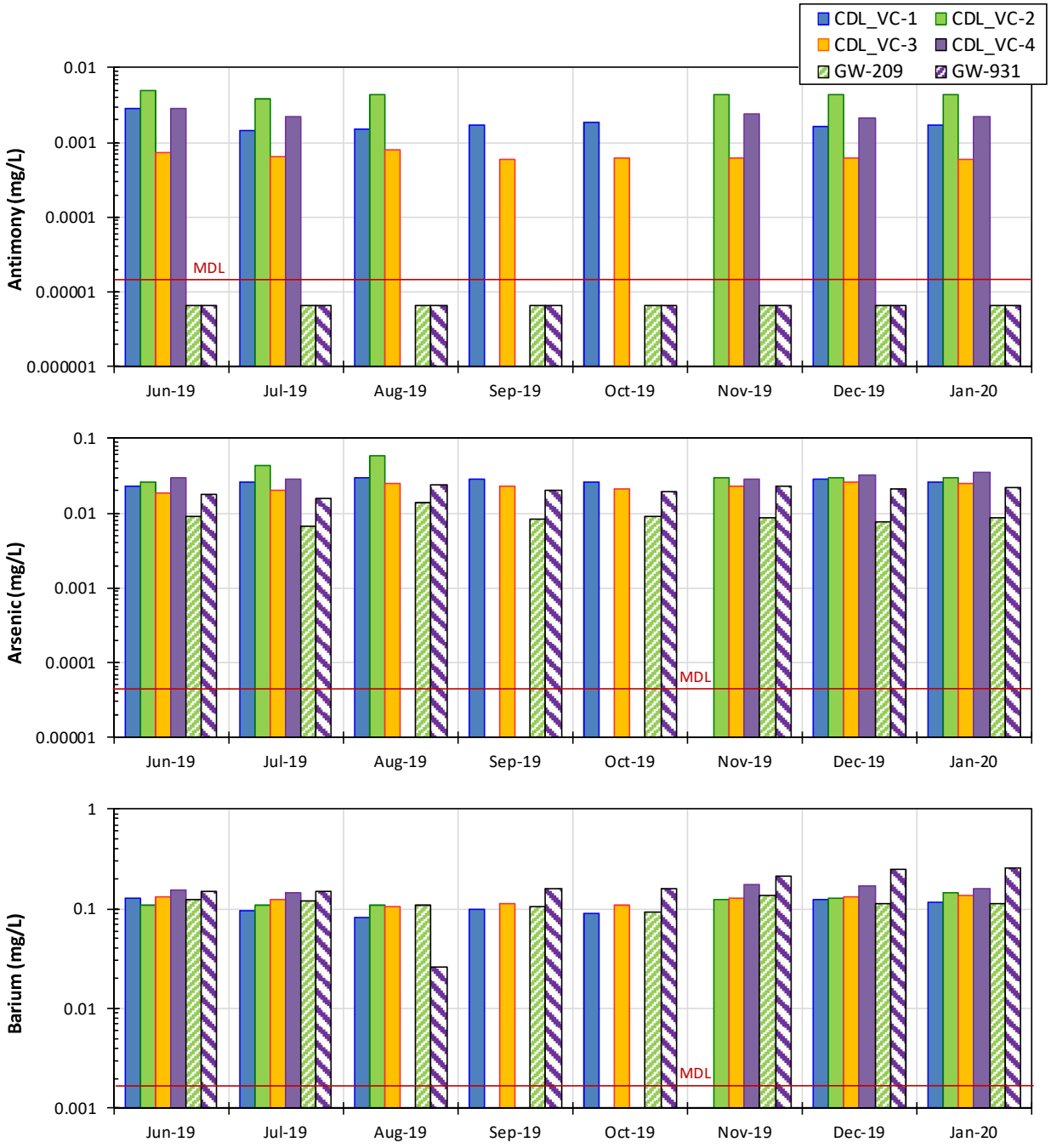

Figure D-4
Measured groundwater and porewater concentrations plotted on a logarithmic axis: antimony, arsenic, and barium

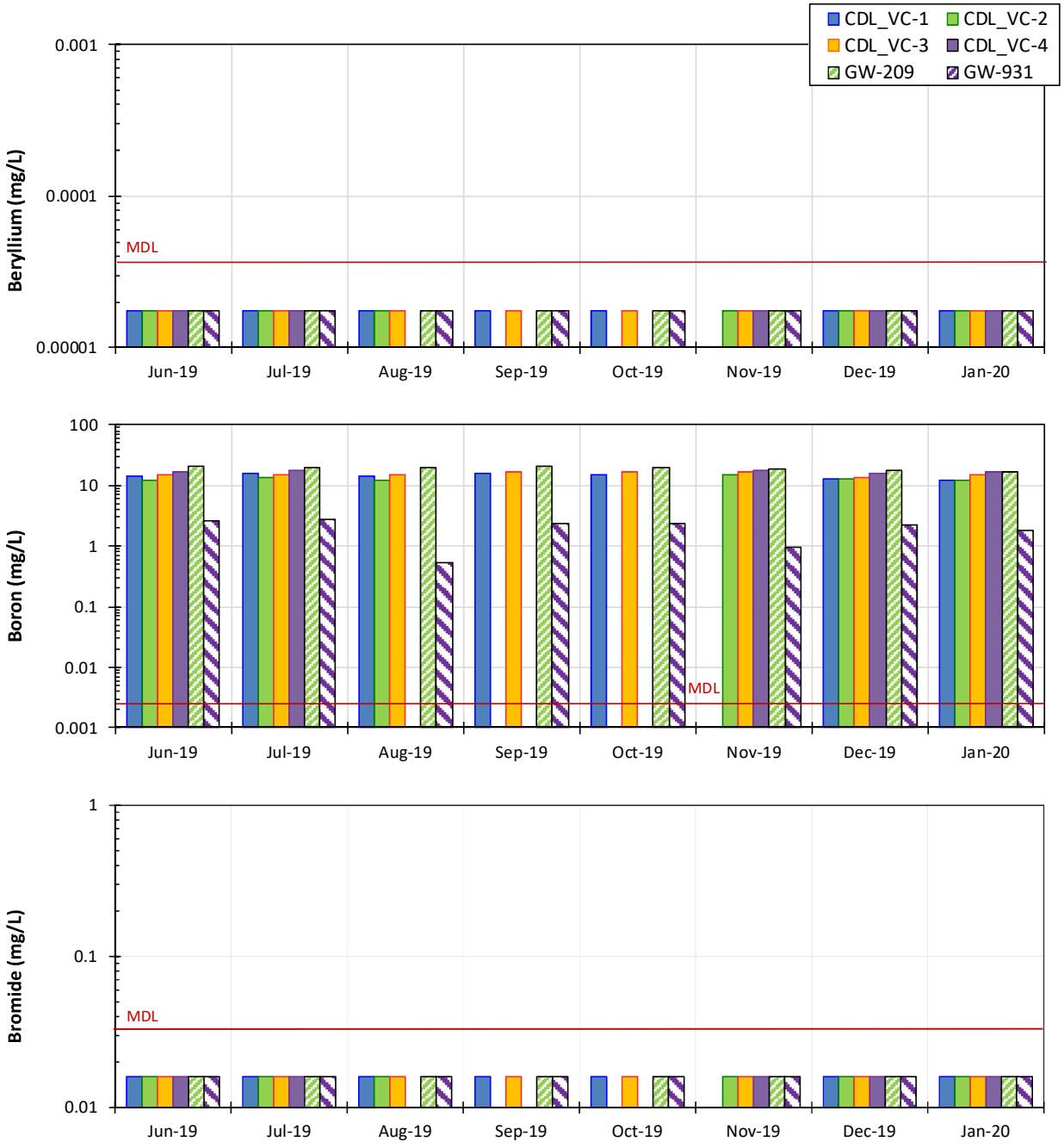

Figure D-5
Measured groundwater and porewater concentrations plotted on a logarithmic axis: beryllium, boron, and bromide

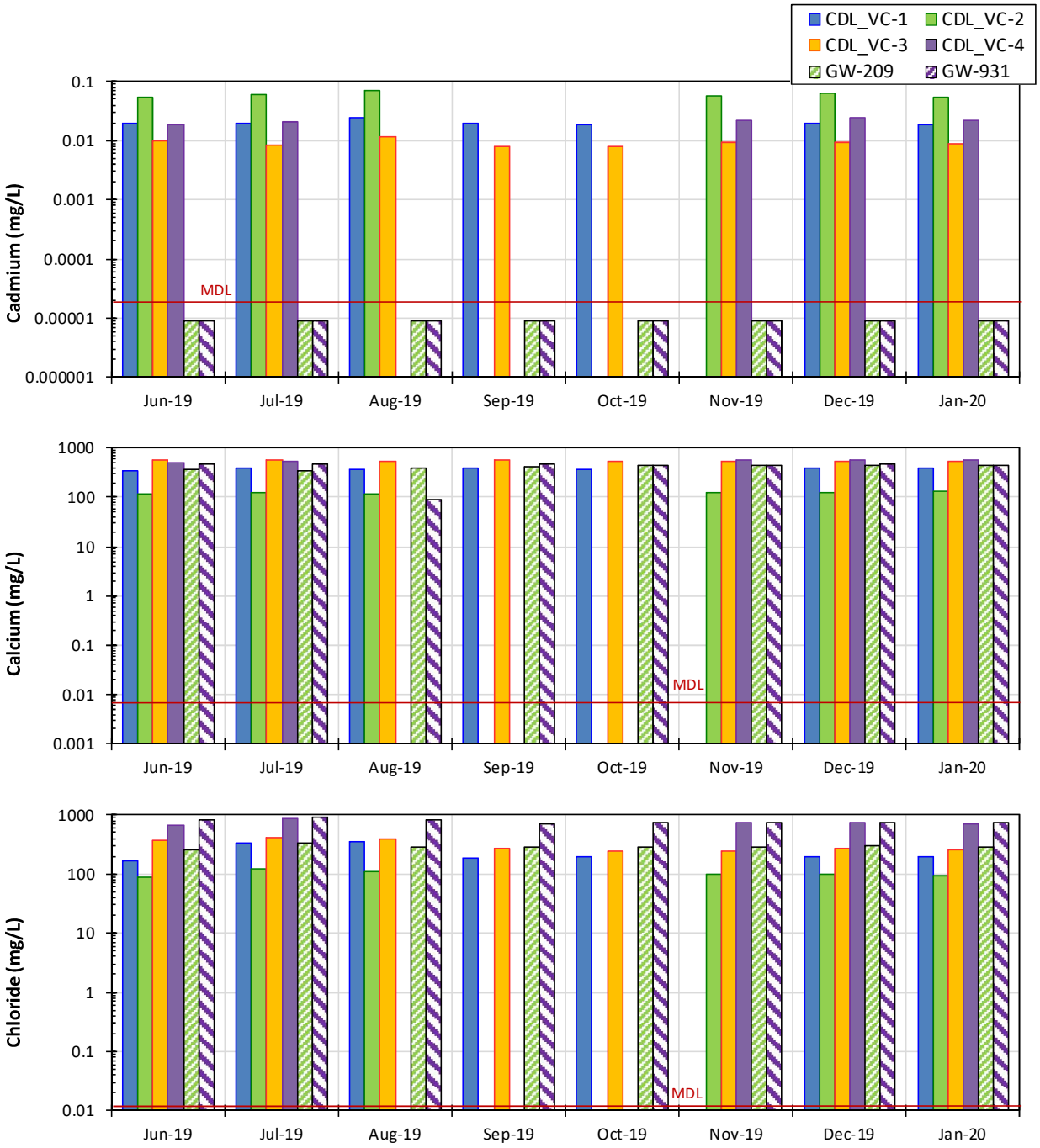

Figure D-6
Measured groundwater and porewater concentrations plotted on a logarithmic axis: cadmium, calcium, and chloride

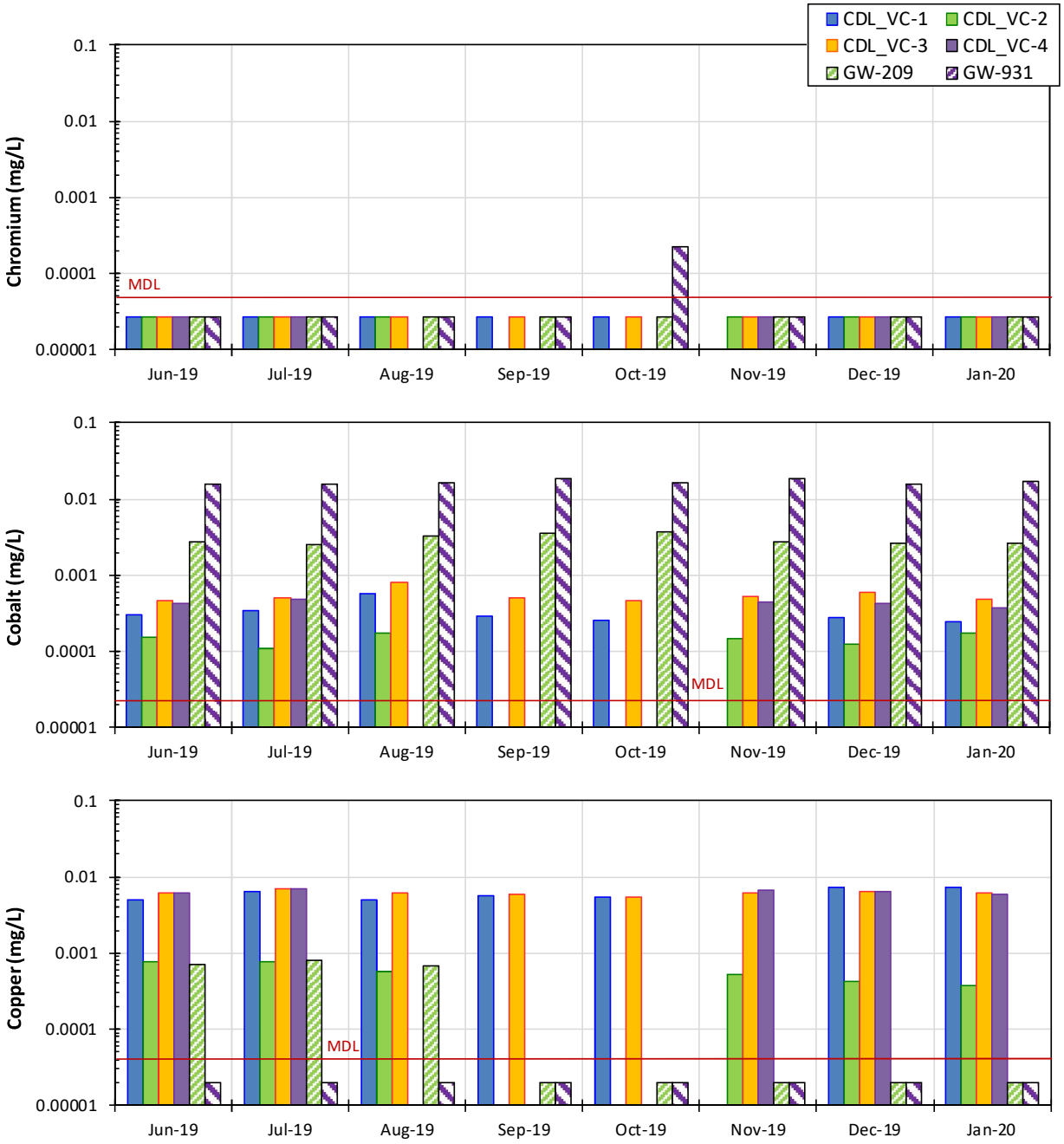

Figure D-7
Measured groundwater and porewater concentrations plotted on a logarithmic axis: chromium, cobalt, and copper

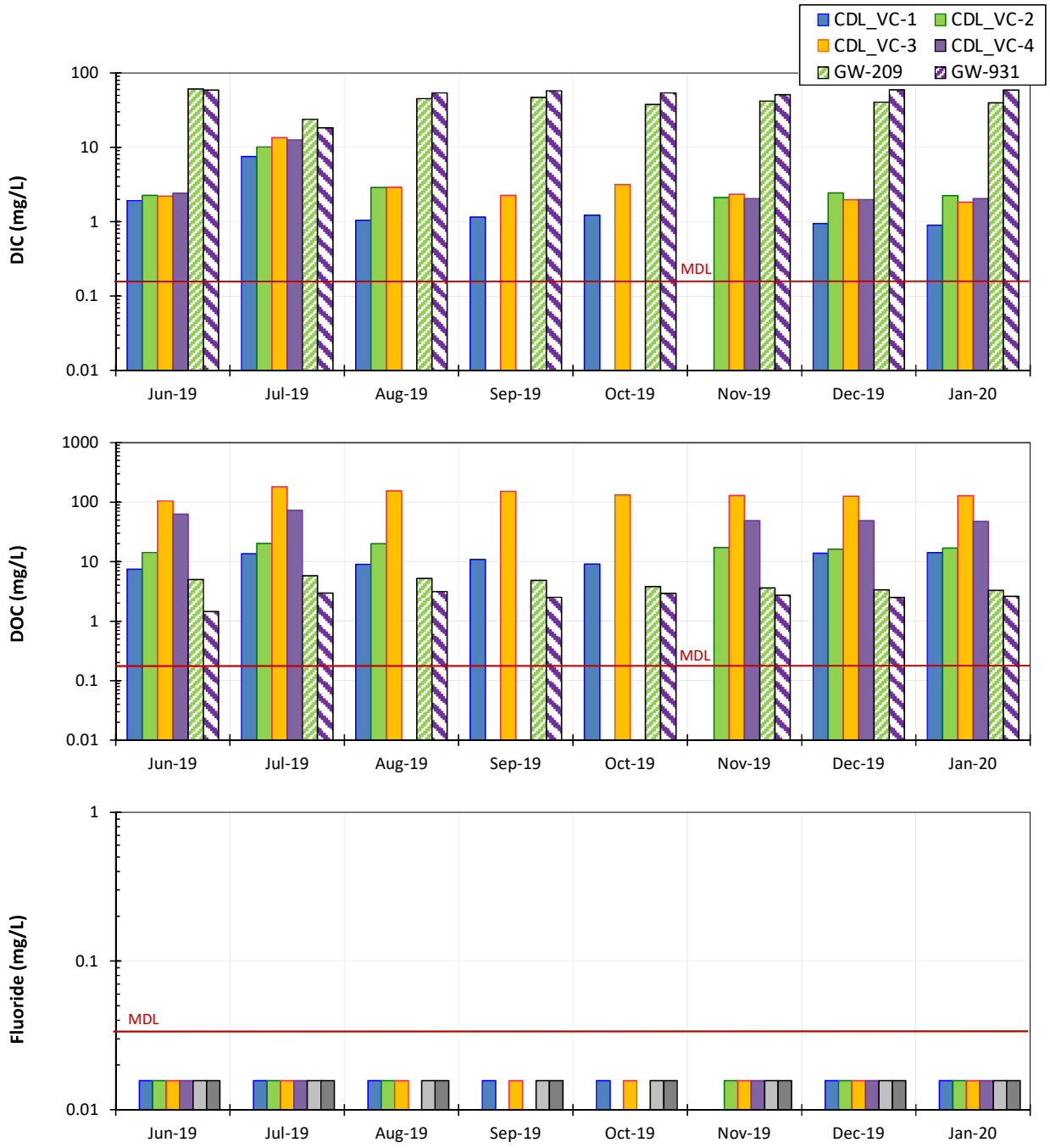

Figure D-8
Measured groundwater and porewater concentrations plotted on a logarithmic axis: dissolved inorganic carbon, dissolved organic carbon, and fluoride

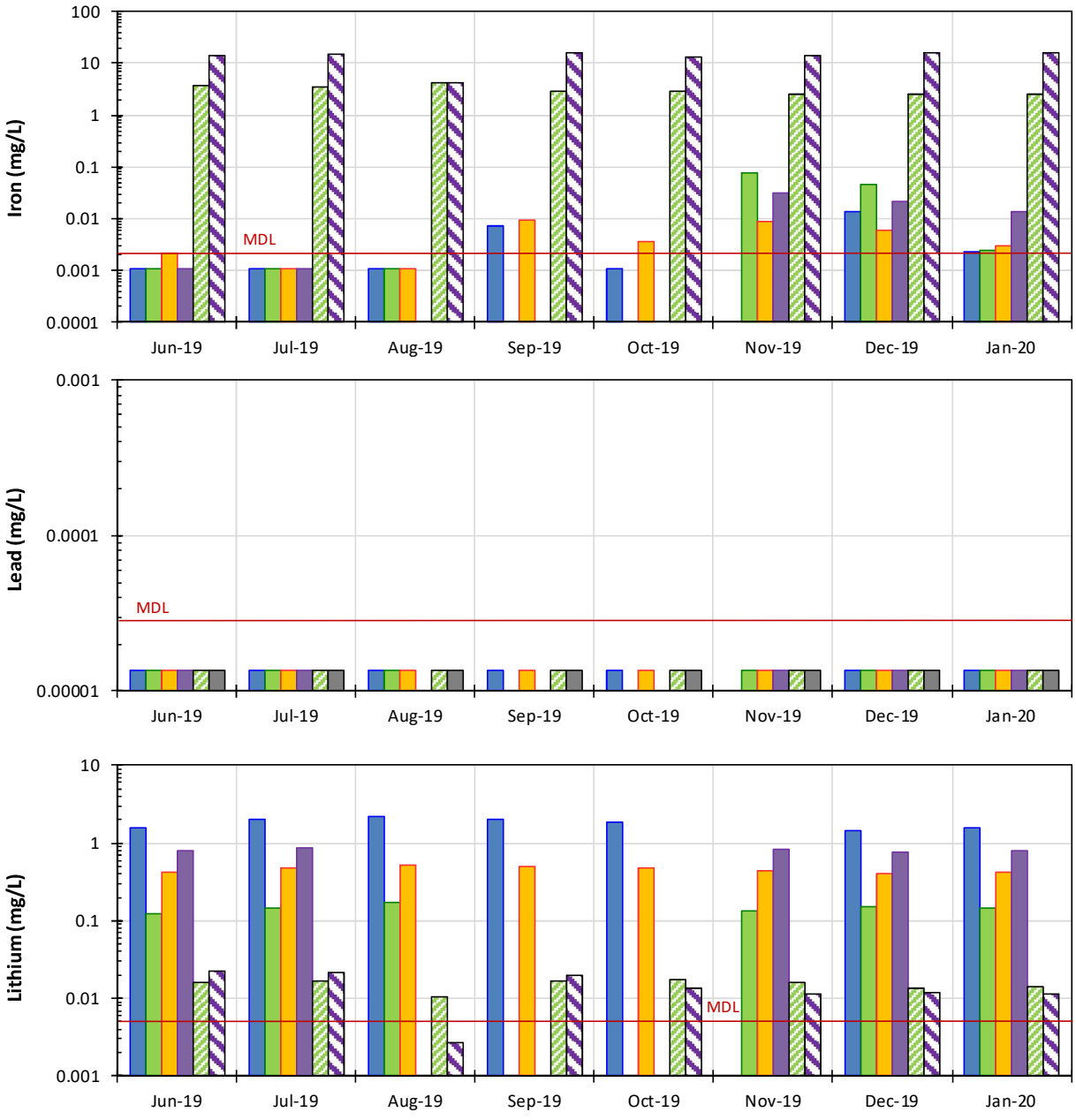

Figure D-9
Measured groundwater and porewater concentrations plotted on a logarithmic axis: iron, lead, and lithium

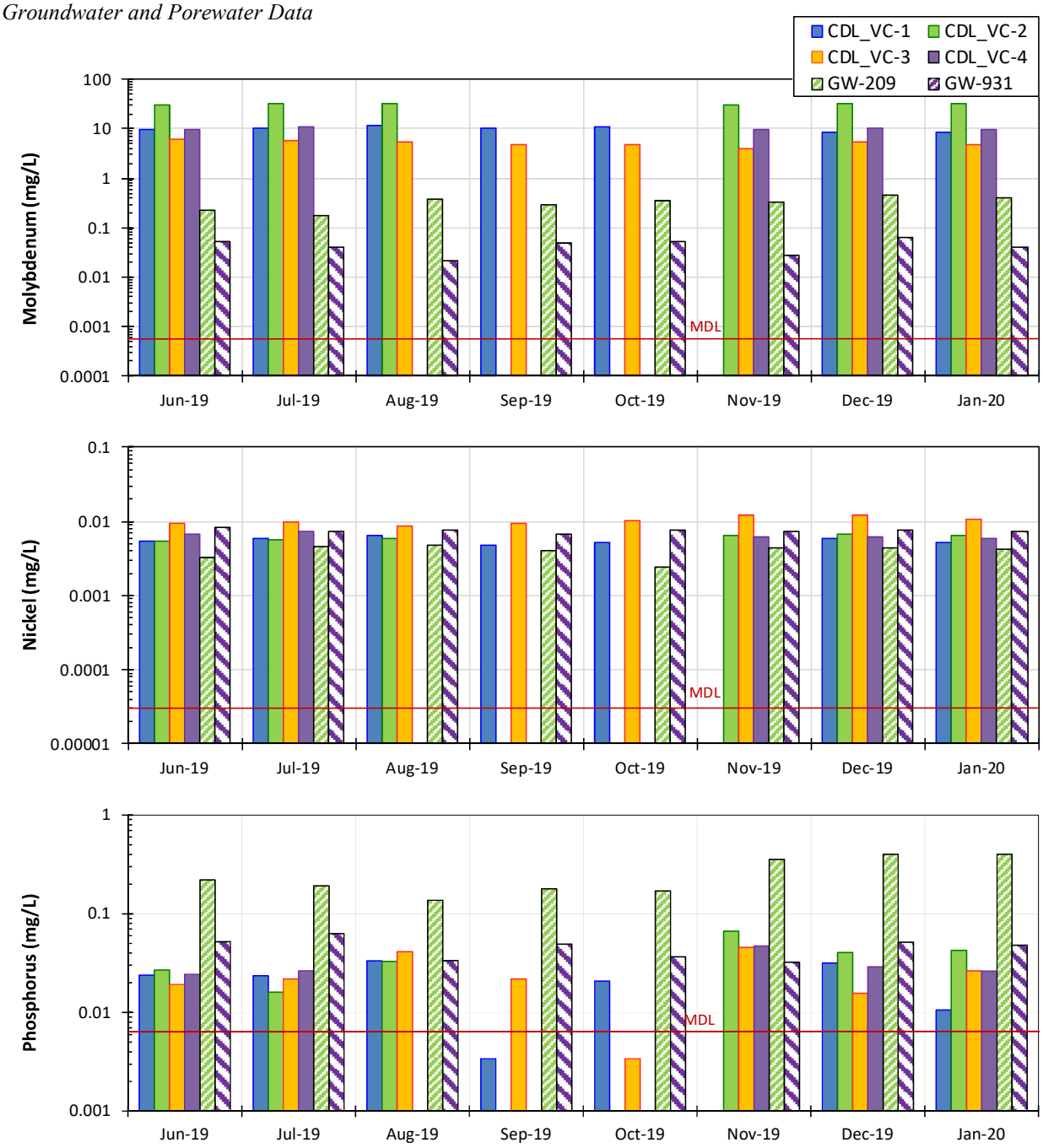

Figure D-10
Measured groundwater and porewater concentrations plotted on a logarithmic axis: molybdenum, nickel, and phosphorus

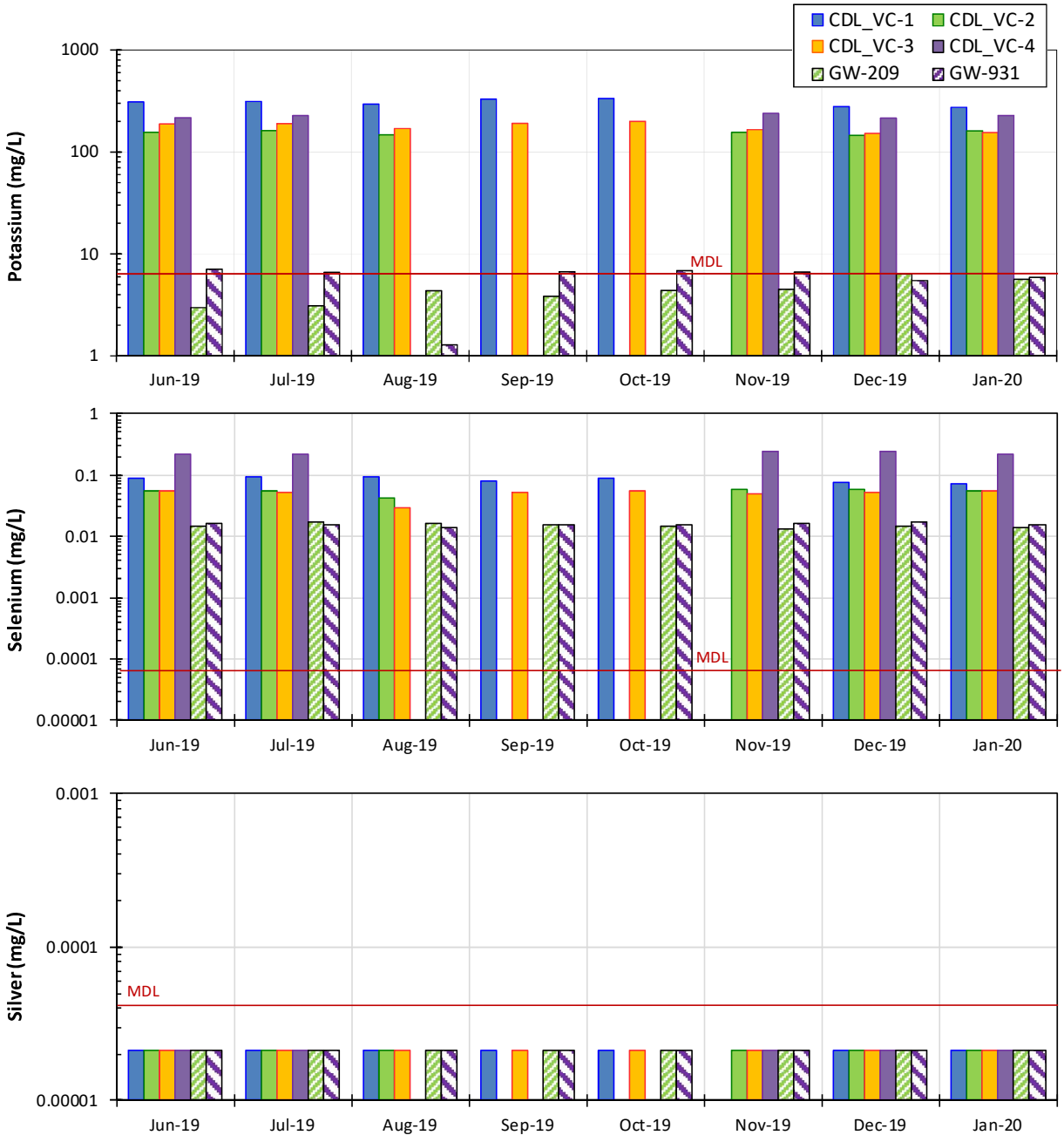

Figure D-11
Measured groundwater and porewater concentrations plotted on a logarithmic axis: potassium, selenium, and silver

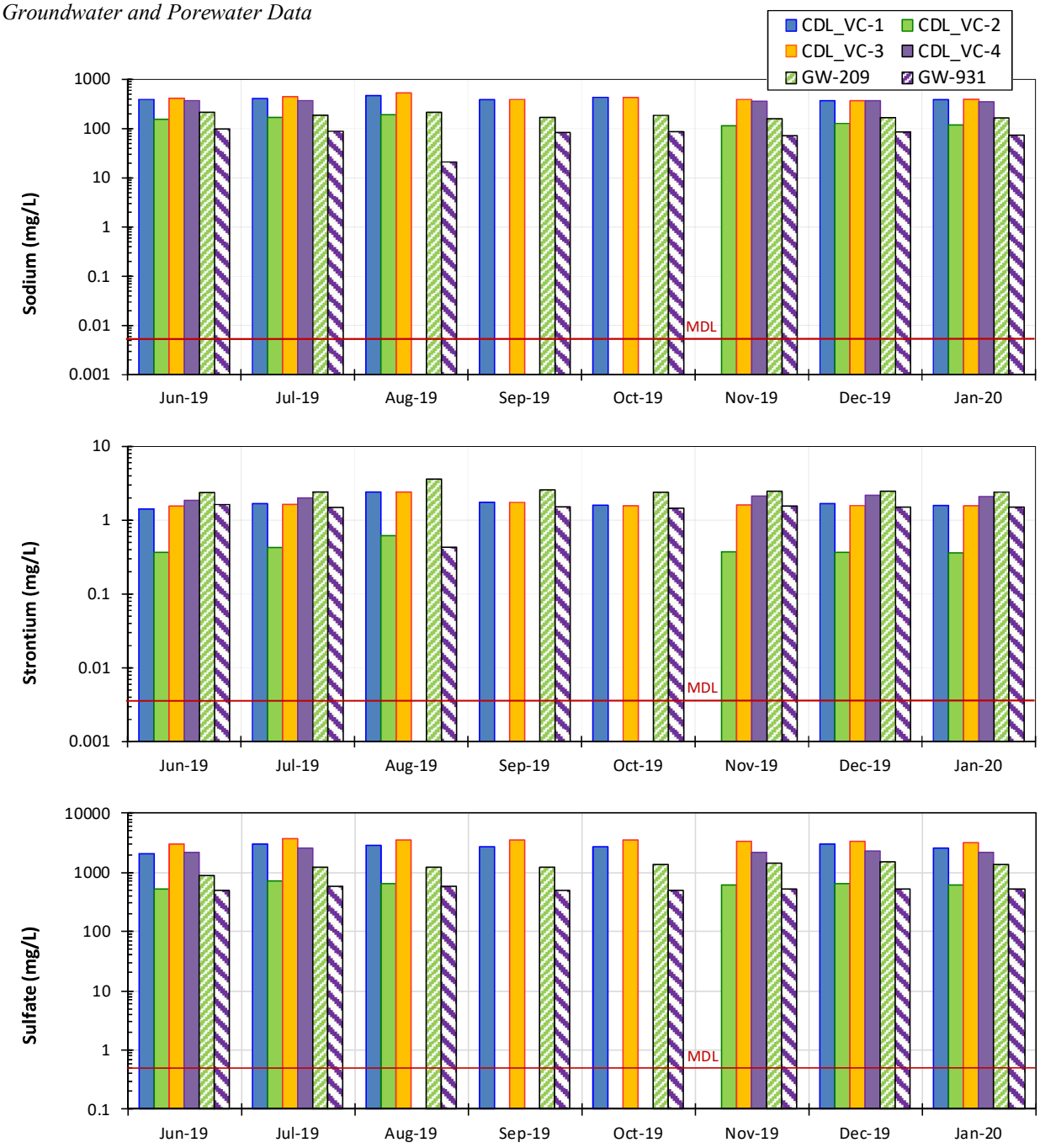

Figure D-12
Measured groundwater and porewater concentrations plotted on a logarithmic axis: sodium, strontium, and sulfate

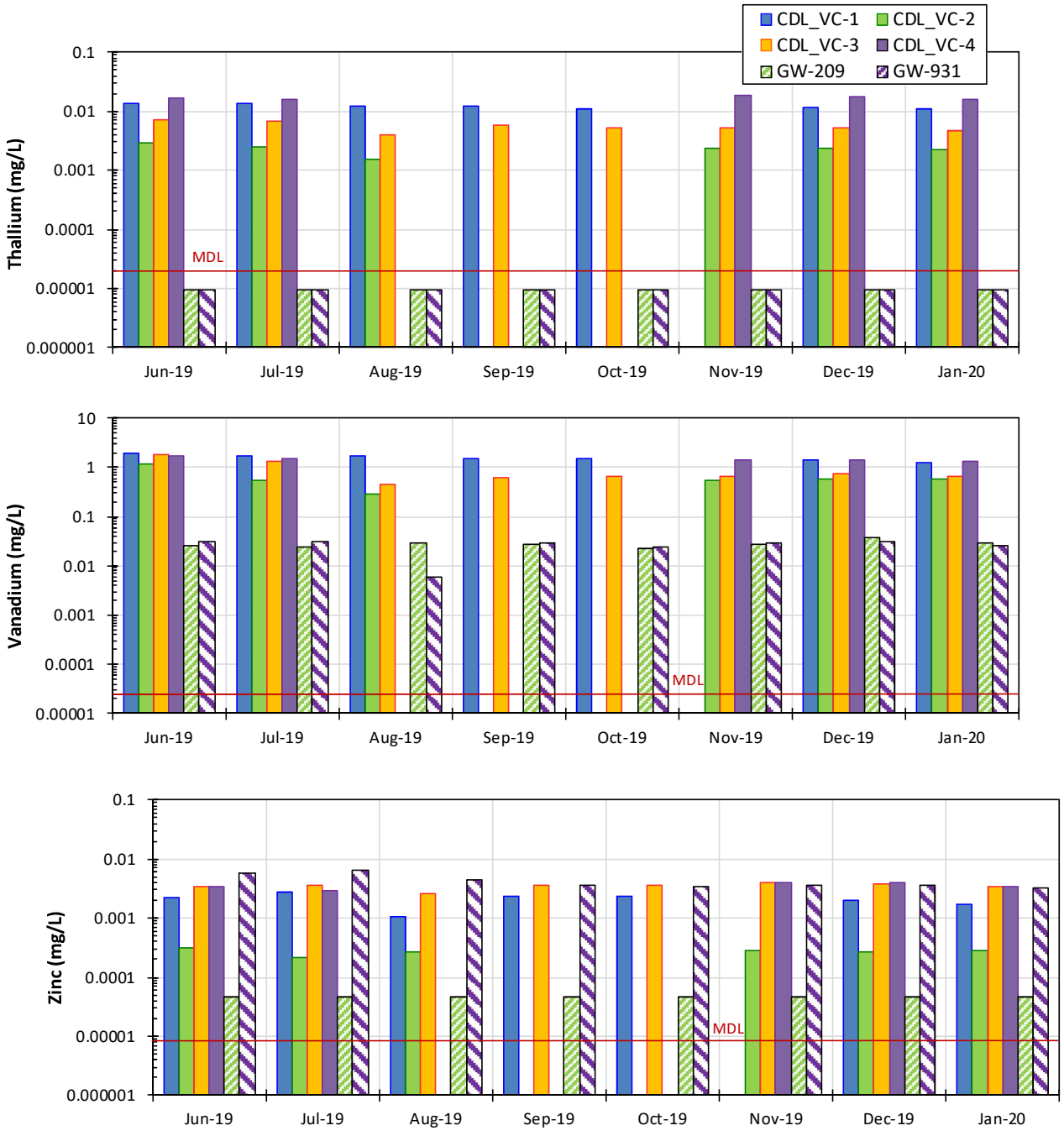

Figure D-13
Measured groundwater and porewater concentrations plotted on a logarithmic axis: thallium, vanadium, and zinc

D-2 Time Series Graphs for Porewater Data

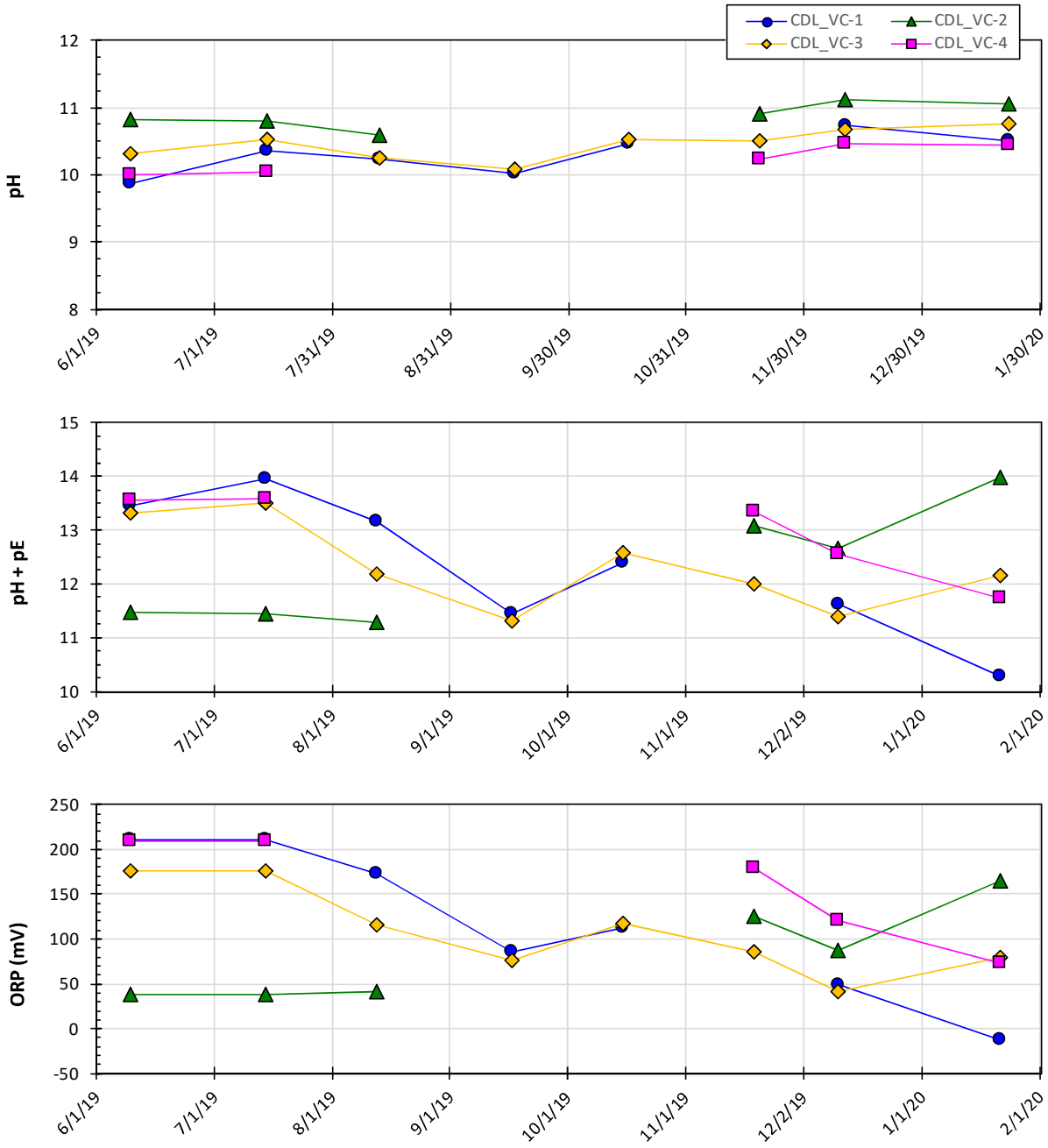

Figure D-14
Time-series plots of porewater conditions: pH, pH+pE, and ORP

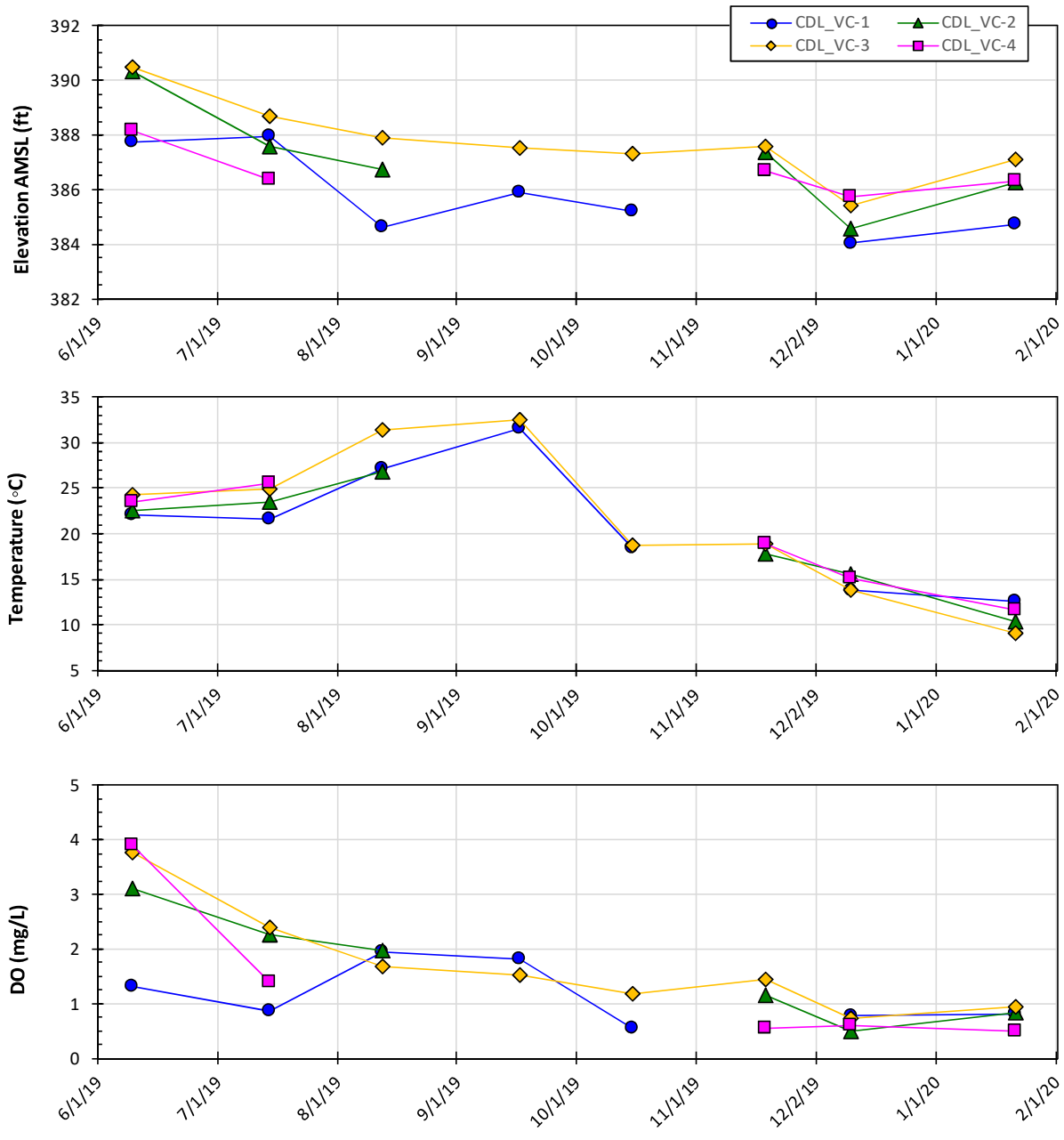

Figure D-15
Time-series plots of porewater conditions: porewater elevation, temperature, and dissolved oxygen

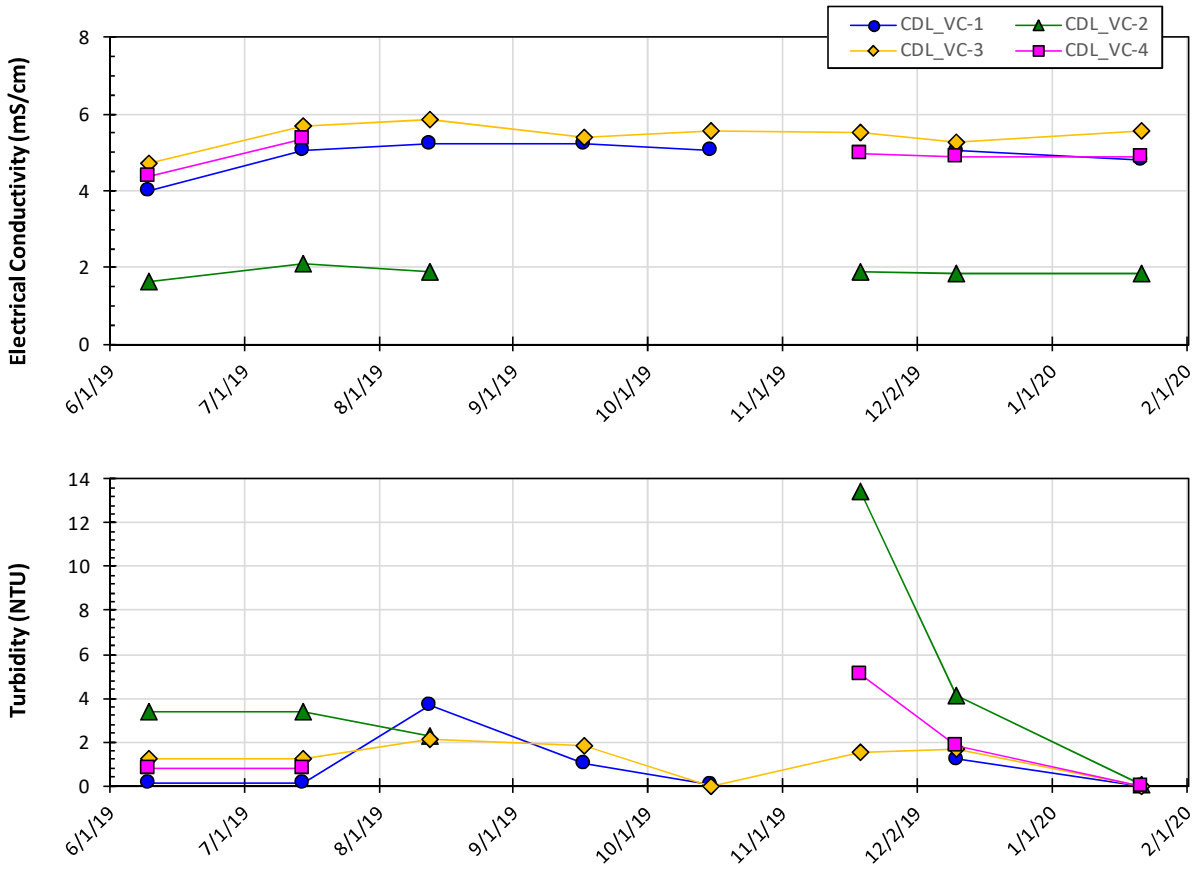

Figure D-16
Time-series plots of porewater conditions: electrical conductivity and turbidity

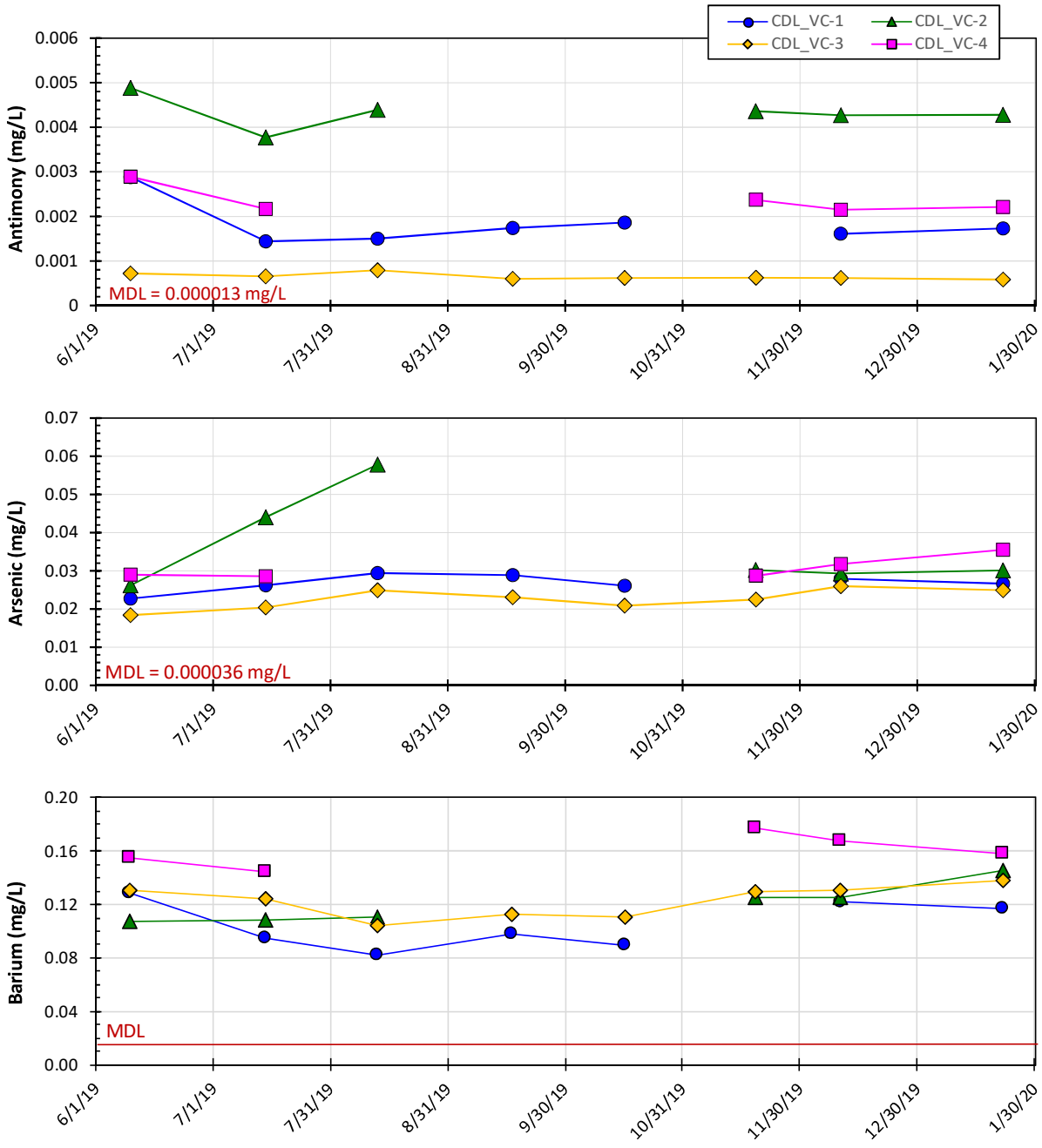

Figure D-17
Time-series plots of porewater conditions: antimony, arsenic, and barium

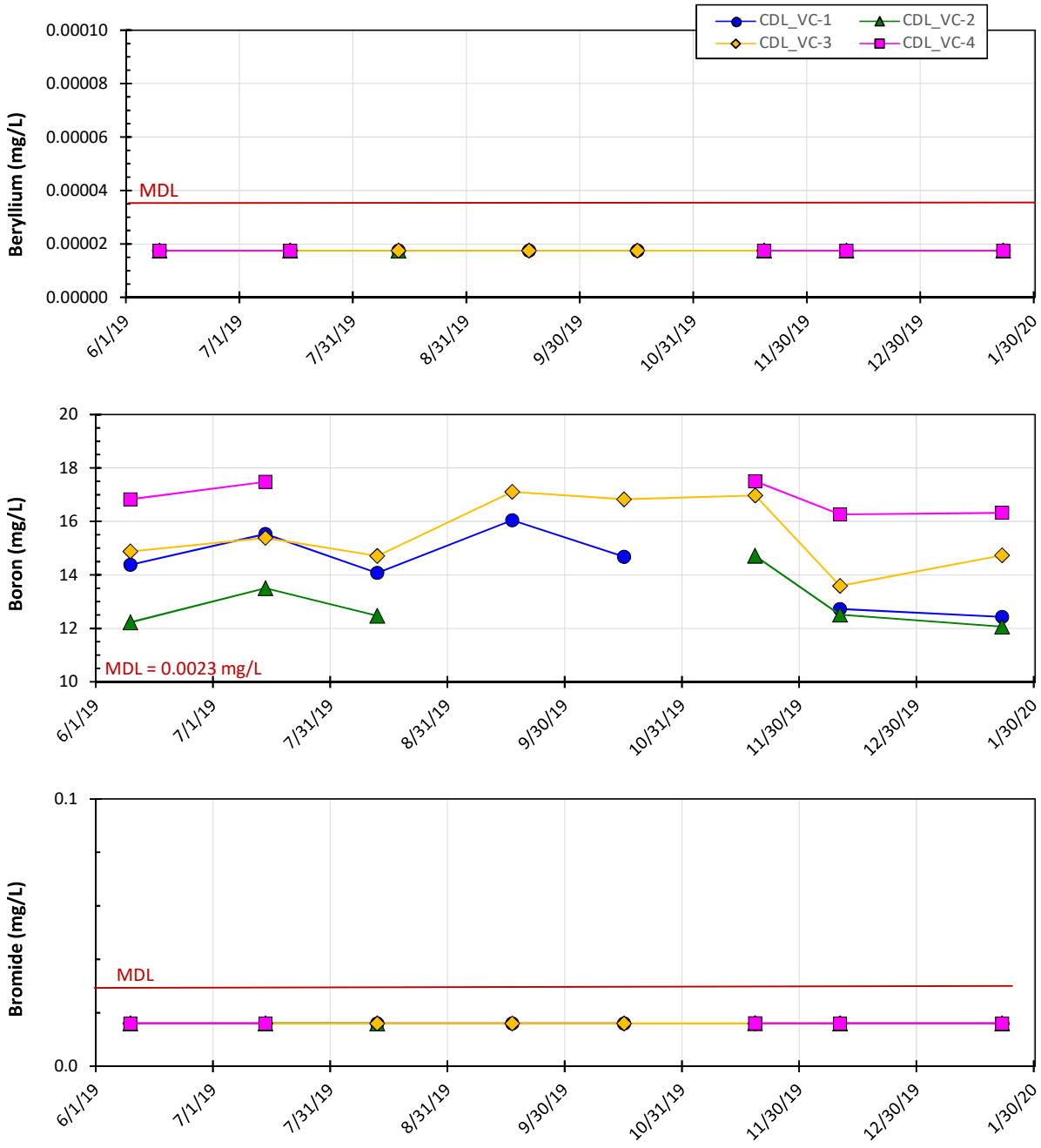

Figure D-18
Time-series plots of porewater conditions: beryllium, boron, and bromide

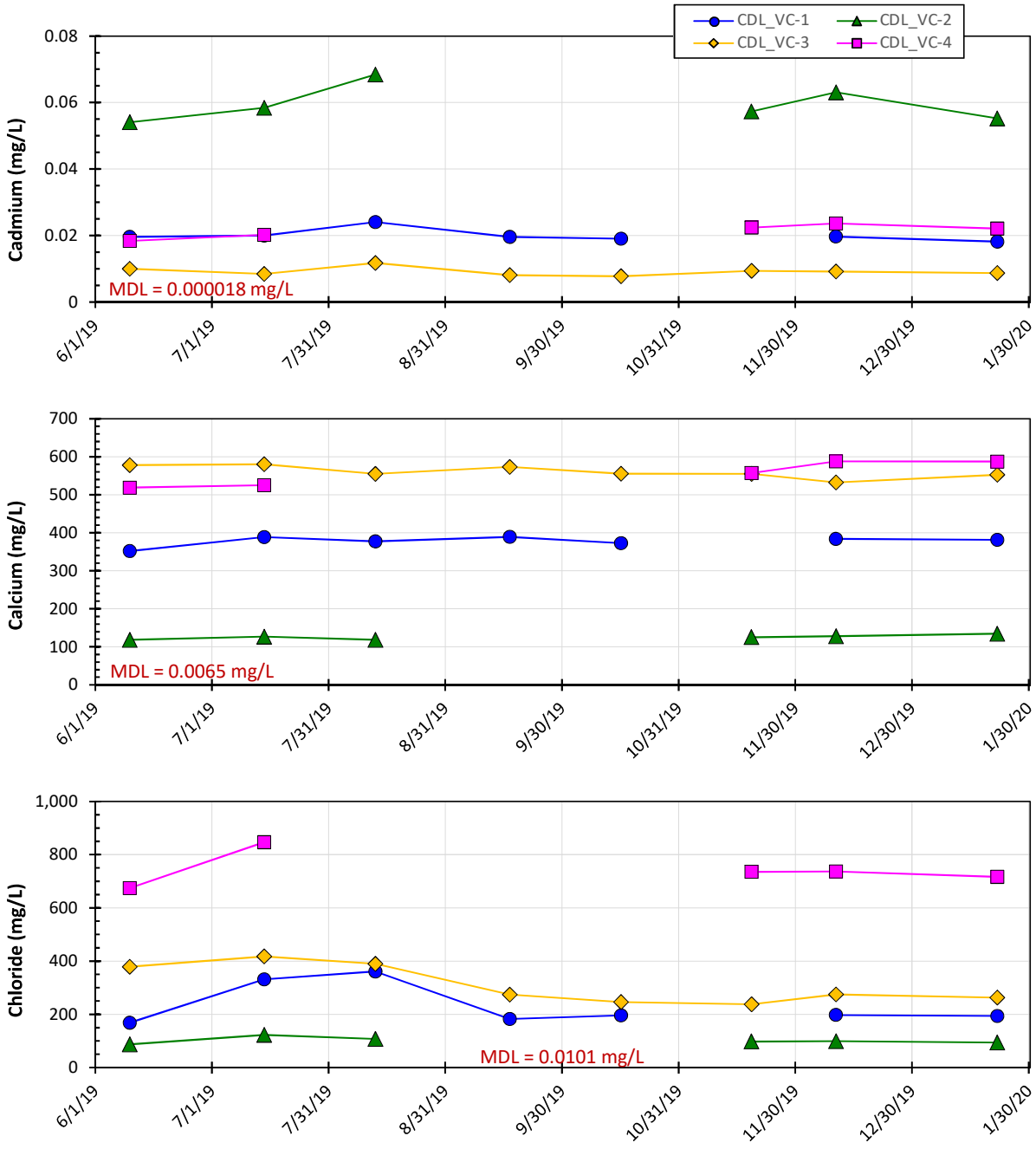

Figure D-19
Time-series plots of porewater conditions: cadmium, calcium, and chloride

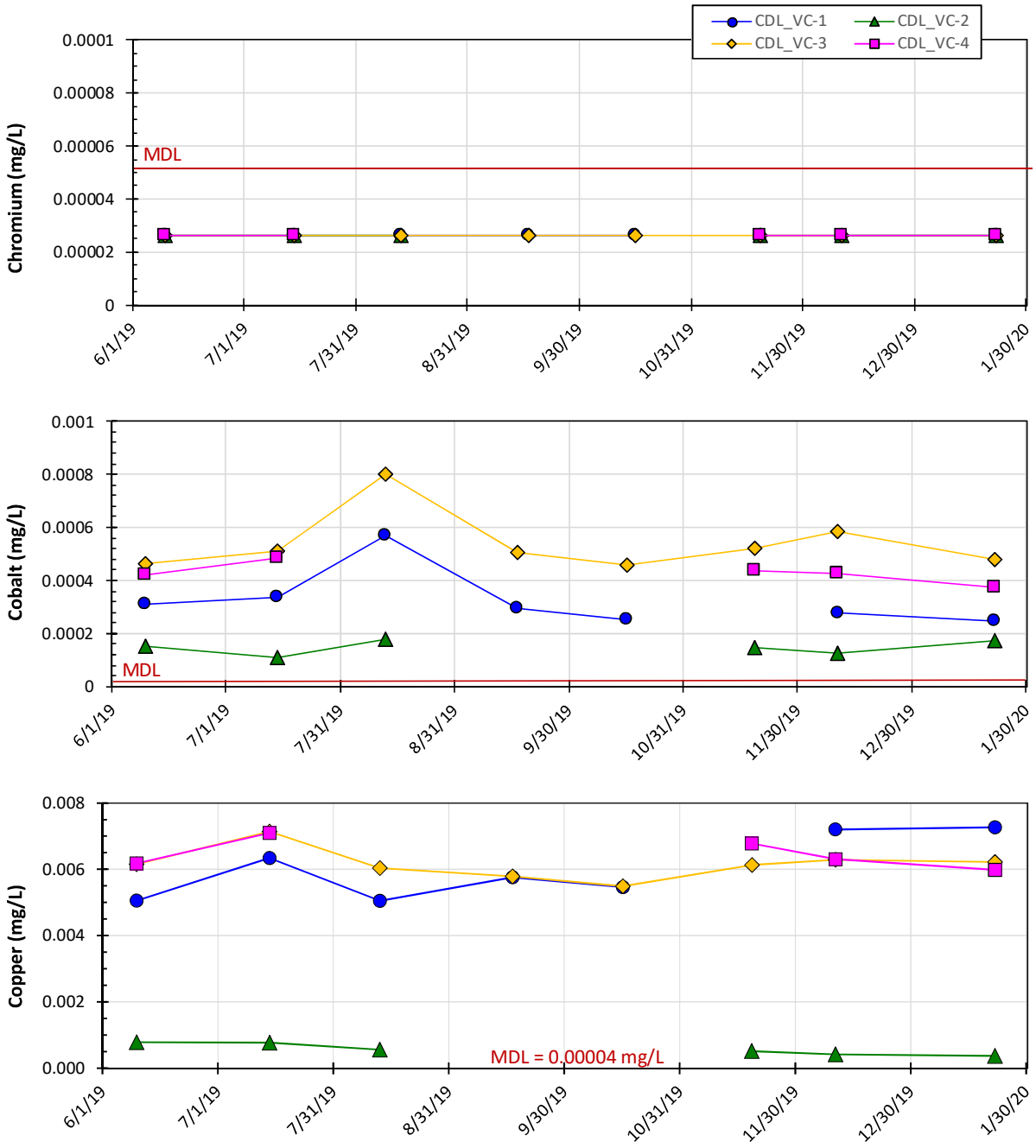

Figure D-20
Time-series plots of porewater conditions: chromium, cobalt, and copper

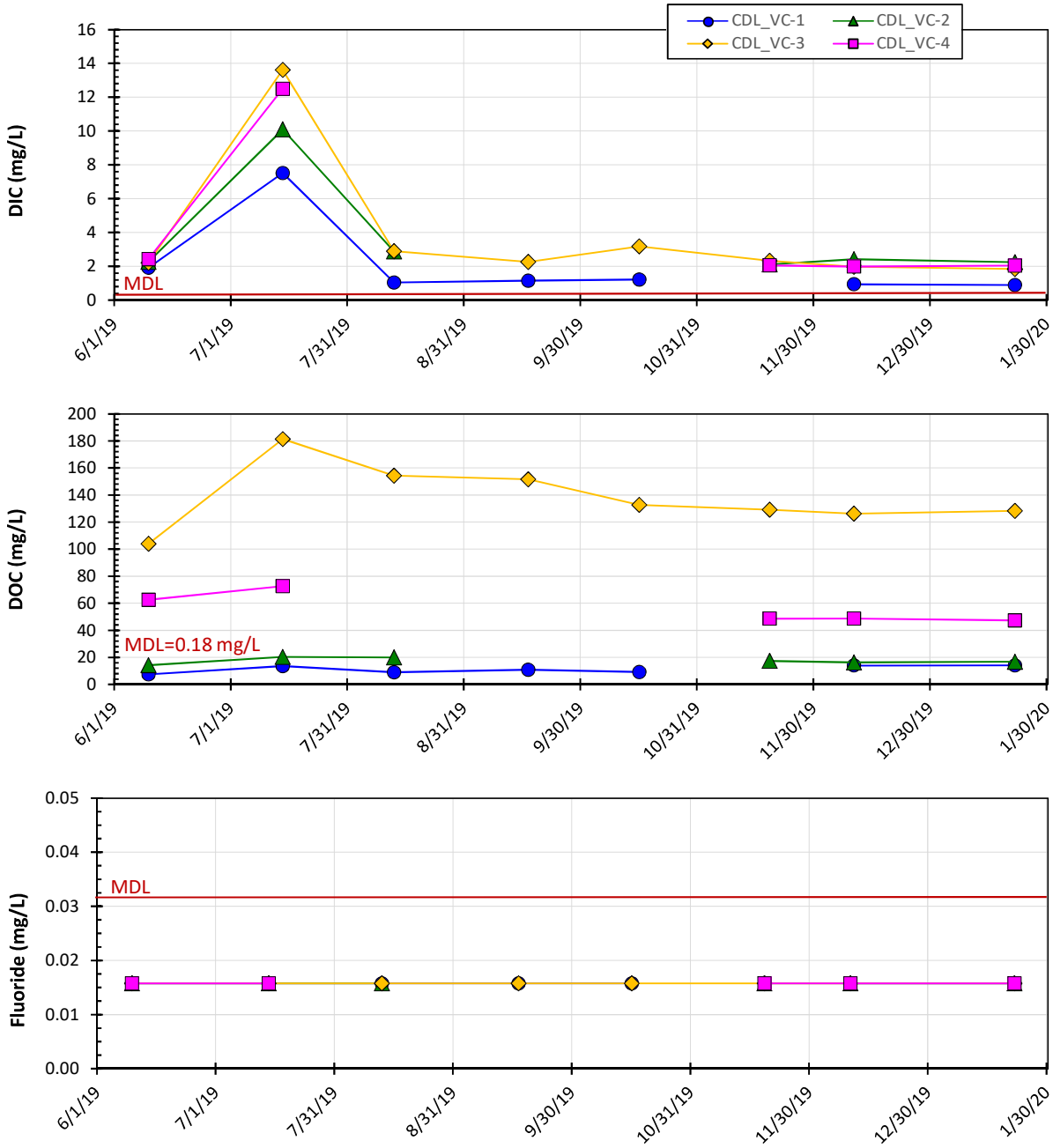

Figure D-21
Time-series plots of porewater conditions: dissolved inorganic carbon, dissolved organic carbon, and fluoride

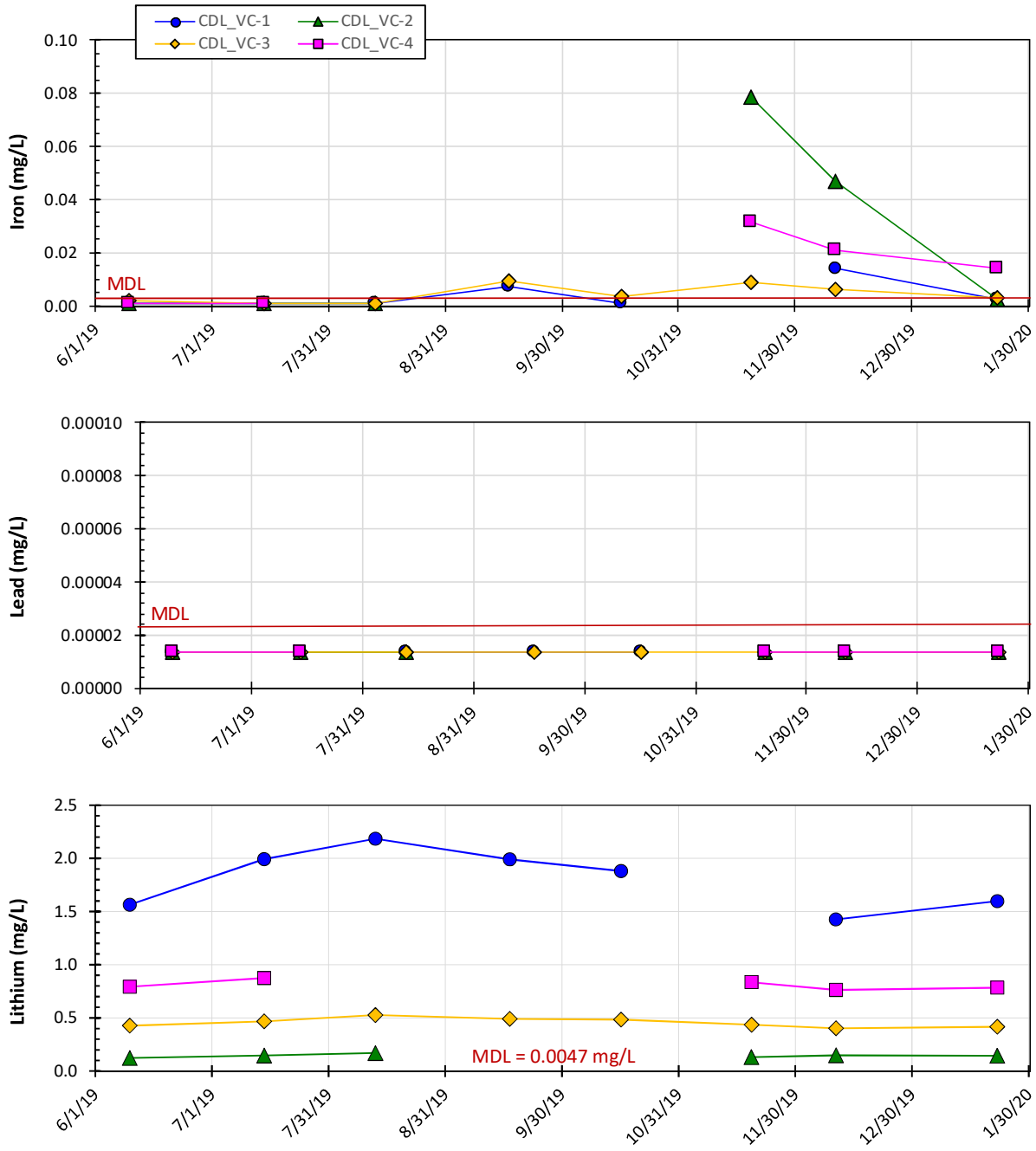

Figure D-22
Time-series plots of porewater conditions: iron, lead, and lithium

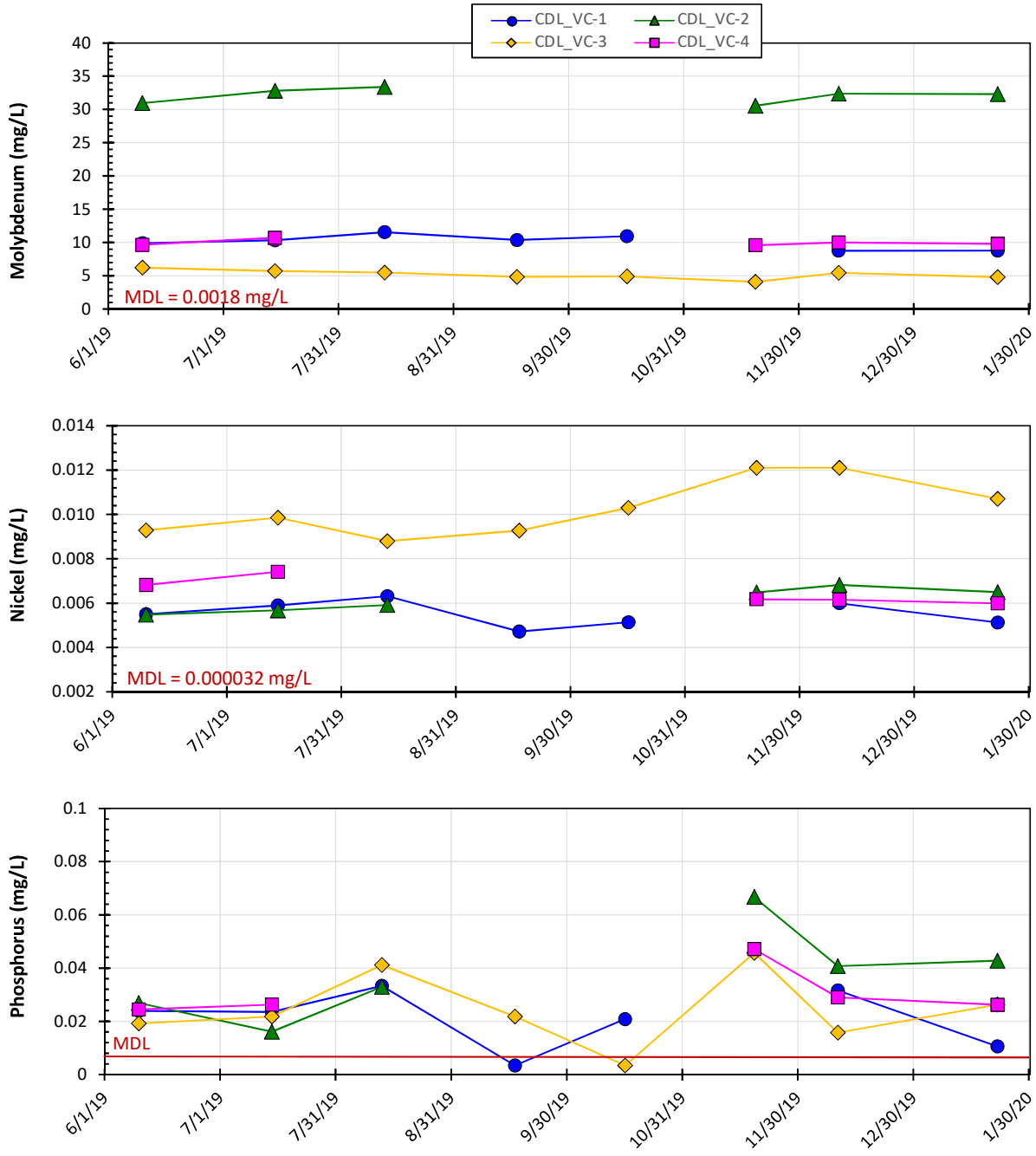

Figure D-23
Time-series plots of porewater conditions: molybdenum, nickel, and phosphorus

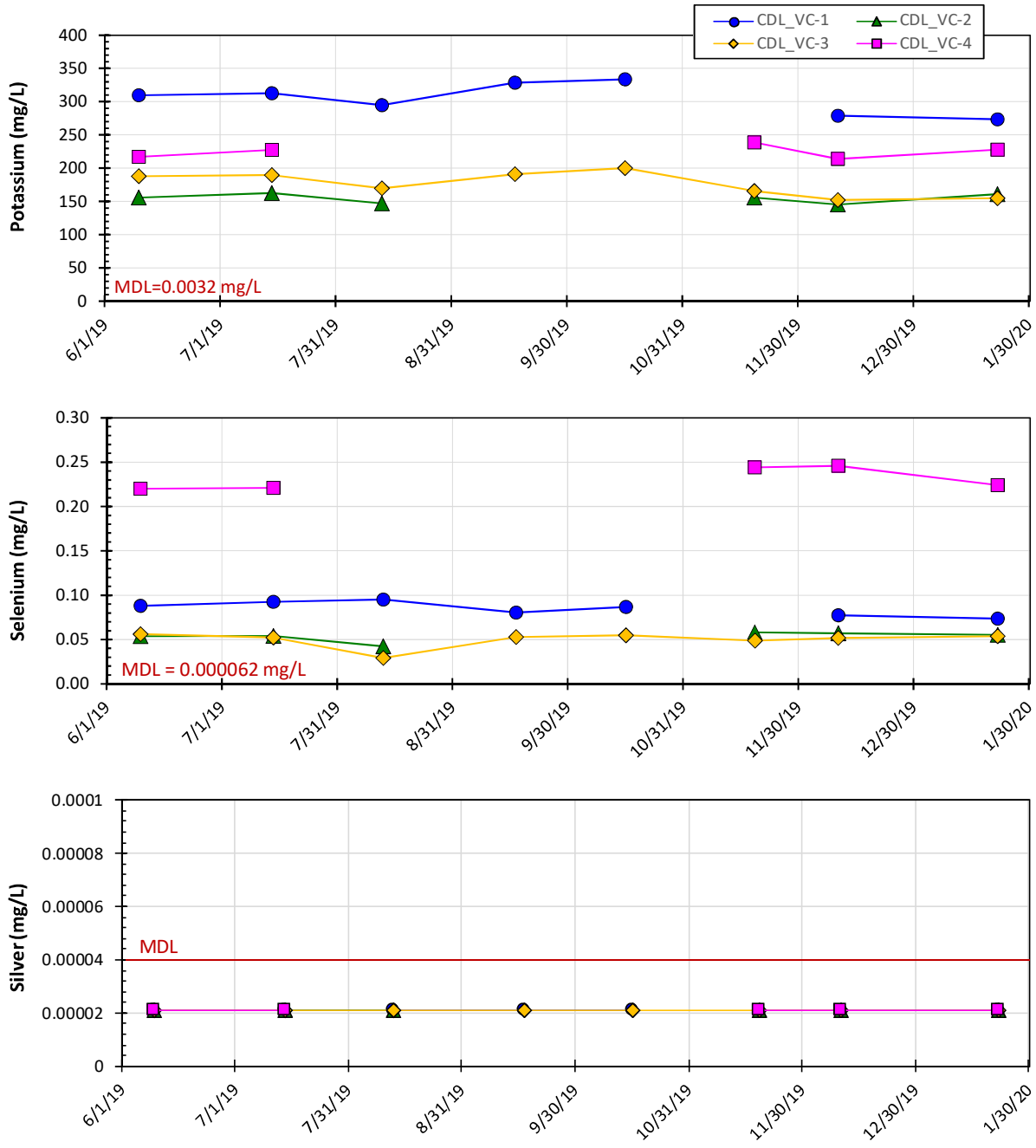

Figure D-24
Time-series plots of porewater conditions: potassium, selenium, and silver

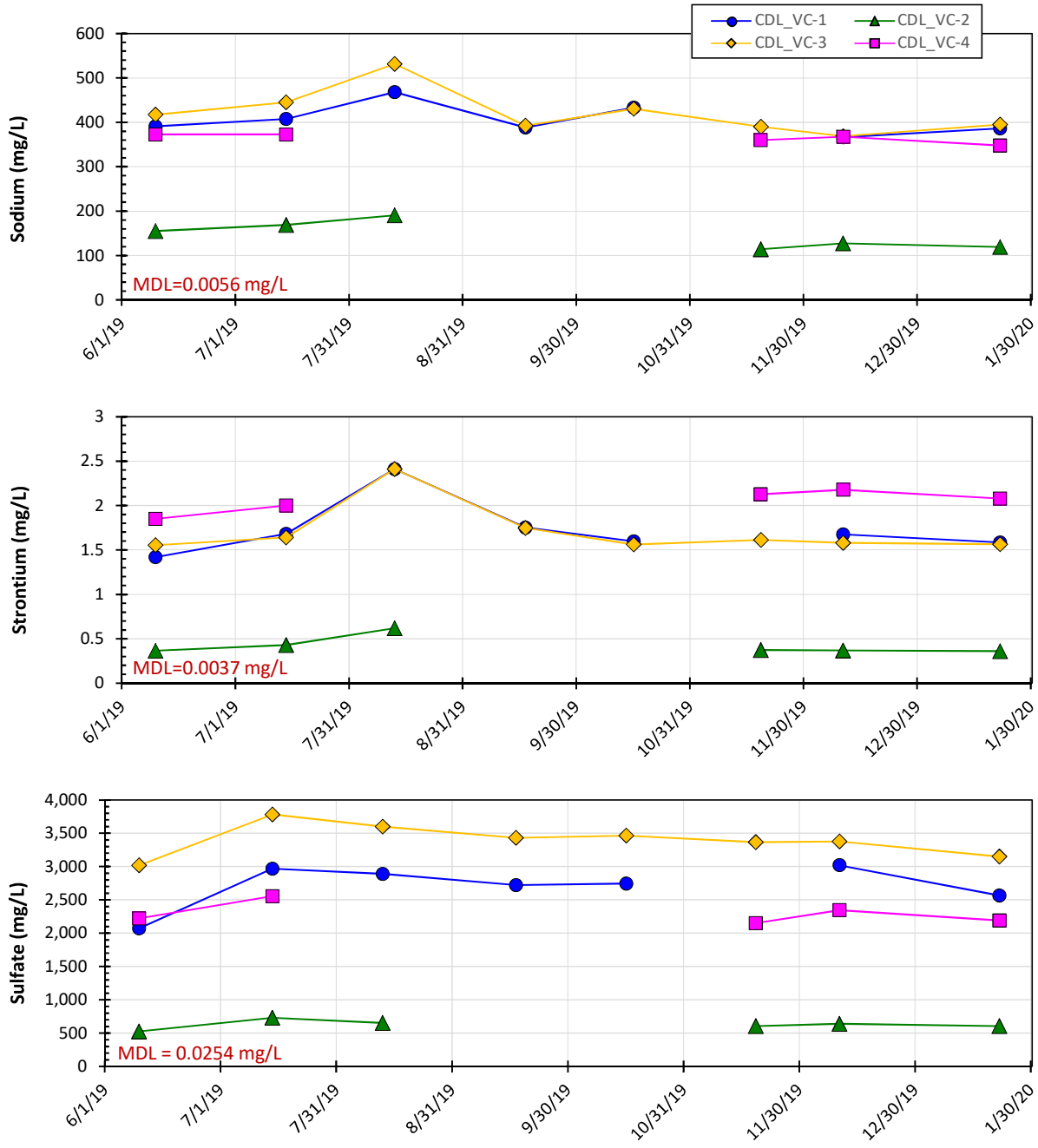

Figure D-25
Time-series plots of porewater conditions: sodium, strontium, and sulfate

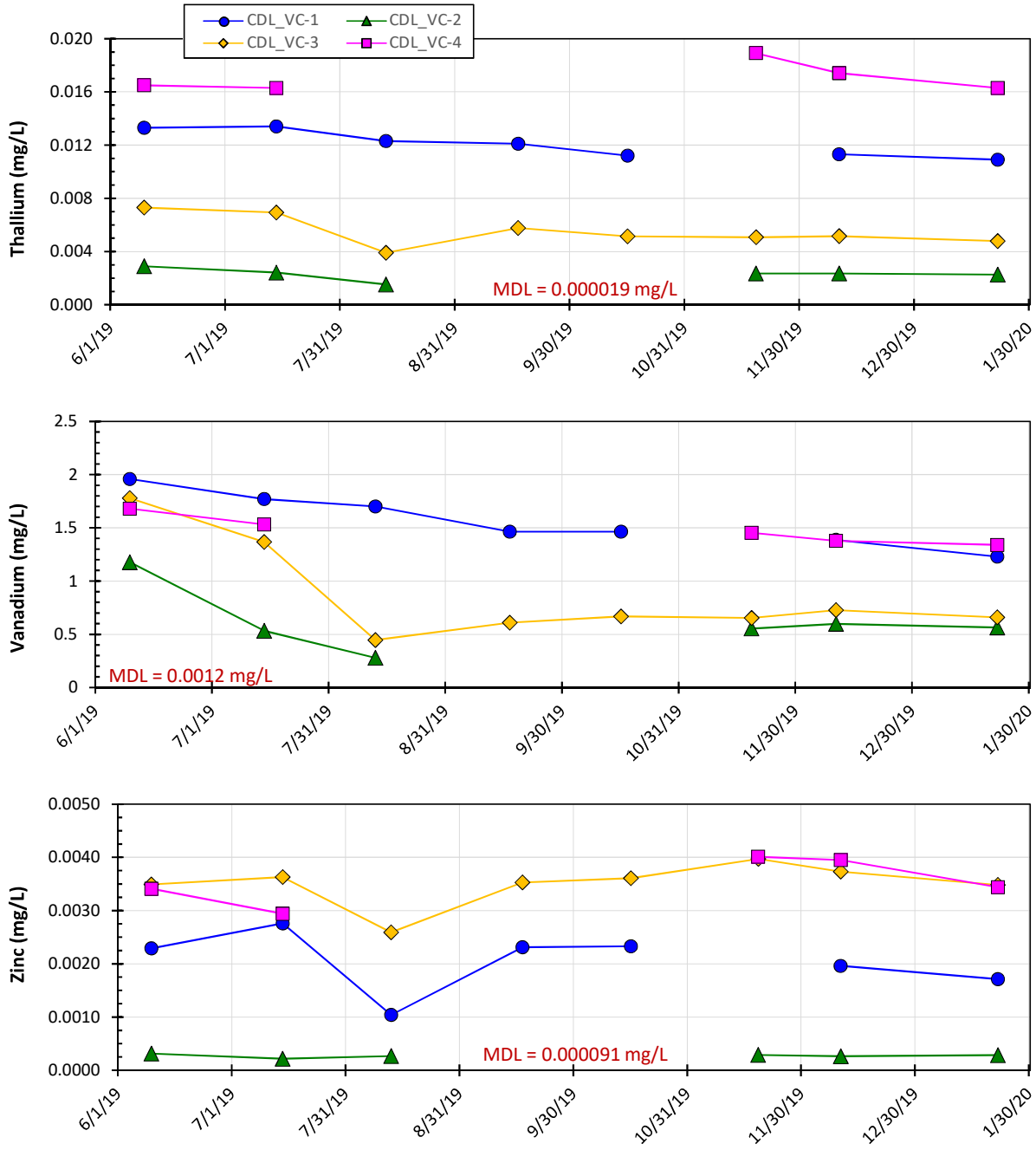

Figure D-26
Time-series plots of porewater concentrations: thallium, vanadium, and zinc

D-3 Subsurface Gas Data Tables and Graphs

VC-1 (gas access points)

5-ft Below Grade	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20
Sampling Date	6/10/19	7/15/19	8/13/19	9/17/19	10/16/19	11/19/19	12/11/19	1/22/20
O_2 (%)	20.0	14.9	17.0	12.6	0	16.6	20.4	12.7
CO_2 (%)	0	0.01	0.11	0.03	0	0.01	0.1	0.01
CH_4 (%)	0	0	0	0	0.17	0	0	0
NH_3 (mg/L)	0	0	0	0	0	0	0	0
H_2S (mg/L)	0	0	0	0	0	0	0	0

15-ft Below Grade	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20
Sampling Date	6/10/19	7/15/19	8/13/19	9/17/19	10/16/19	11/19/19	12/11/19	1/22/20
O_2 (%)	0.9	0.9	0.3	0.2	0.4	0.7	0.5	0.4
CO_2 (%)	0	0	0	0	0	0	0	0
CH_4 (%)	0.26	0.53	0.72	0.47	0.38	0.40	0.47	0.53
NH_3 (mg/L)	0	0	0	0	0	0	0	0
H_2S (mg/L)	0	0	0	0	0	0	0	0

50-ft Below Grade	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20
Sampling Date	6/10/19	7/15/19	8/13/19	9/17/19	10/16/19	11/19/19	12/11/19	1/22/20
O_2 (%)	0.9	0.9	0.3	0.1	0.3	0.6	0.7	0.3
CO_2 (%)	0	0	0	0	0.01	0	0.04	0
CH_4 (%)	0.40	0.77	0.79	0.71	0.48	0.64	0.19	0.75
NH_3 (mg/L)	0	0	0	0	0	0	0	0
H_2S (mg/L)	0	0	0	0	0	0	0	0

VC-2 (gas access points)

5-ft Below Grade	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20
Sampling Date	6/10/19	7/15/19	8/13/19	9/17/19	10/16/19	11/19/19	12/11/19	1/22/20
O_2 (%)	17.5	16.1	13.6	2.8	6.7	8.3	11.2	0.5
CO_2 (%)	0	0	0	0	0.01	0.02	0.01	0
CH_4 (%)	0	0	0	0	0	0	0	0
NH_3 (mg/L)	0	0	0	0	0	0	0	0
H_2S (mg/L)	0	0	0	0	0	0	0	0

15-ft Below Grade	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20
Sampling Date	6/10/19	7/15/19	8/13/19	9/17/19	10/16/19	11/19/19	12/11/19	1/22/20
O_2 (%)	17.7	7.0	14.2	2.2	7.7	7.5	12.5	0.5
CO_2 (%)	0	0	0.01	0	0	0	0	0
CH_4 (%)	0	0	0	0	0	0	0	0
NH_3 (mg/L)	0	0	0	0.3	0	0	0	0
H_2S (mg/L)	0	0	0	0	0	0	0	0

VC-3 (gas access points)

5-ft Below Grade	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20
Sampling Date	6/10/19	7/15/19	8/13/19	9/17/19	10/16/19	11/19/19	12/11/19	1/22/20
O_2 (%)	20.2	12.5	13.9	15.5	3.6	17.1	15.5	13.4
CO_2 (%)	0.01	0.01	0	0.01	0.13	0.01	0.07	0.01
CH_4 (%)	0	0	0	0	0	0	0	0
NH_3 (mg/L)	0	0	0	0	0	0	0	0
H_2S (mg/L)	0	0	0	0	0	0	0	0

15-ft Below Grade	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20
Sampling Date	6/10/19	7/15/19	8/13/19	9/17/19	10/16/19	11/19/19	12/11/19	1/22/20
O_2 (%)	20.2	9.4	8.7	8.4	9.4	1.3	0.5	0.4
CO_2 (%)	0	0	0	0	0	0	0	0
CH_4 (%)	0	0	0	0	0	0	0	0
NH_3 (mg/L)	0	0	0	0	0	0	0	0
H_2S (mg/L)	0	0	0	0	0	0	0	0

50-ft Below Grade	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20
Sampling Date	6/10/19	7/15/19	8/13/19	9/17/19	10/16/19	11/19/19	12/11/19	1/22/20
O_2 (%)	18.4	10.6	2.9	1.3	1.3	0.7	0.5	0.4
CO_2 (%)	0	0	0	0	0	0	0	0
CH_4 (%)	0	0	0	0	0	0	0	0
NH_3 (mg/L)	0	0	0	0	0	0	0	0
H_2S (mg/L)	0	0	0	0	0	0	0	0

VC-4 (gas access points)

5-ft Below Grade	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20
Sampling Date	6/10/19	7/15/19	8/13/19	9/17/19	10/16/19	11/19/19	12/11/19	1/22/20
O_2 (%)	19.9	13.4	6.1	5.9	6.9	2.5	2.9	3.8
CO_2 (%)	0	0	0	0	0	0	0	0
CH_4 (%)	0	0	0	0	0	0	0	0
NH_3 (mg/L)	0	0	0	0	0	0	0	0
H_2S (mg/L)	0	0	0	0	0	0	0	0

15-ft Below Grade	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20
Sampling Date	6/10/19	7/15/19	8/13/19	9/17/19	10/16/19	11/19/19	12/11/19	1/22/20
O_2 (%)	18.6	16.2	6.9	7.8	6.0	3.8	3.6	2.9
CO_2 (%)	0	0	0	0	0	0	0	0
CH_4 (%)	0	0	0	0	0	0	0	0
NH_3 (mg/L)	0	0	0	0	0	0	0	0
H_2S (mg/L)	0	0	0	0	0	0	0	0

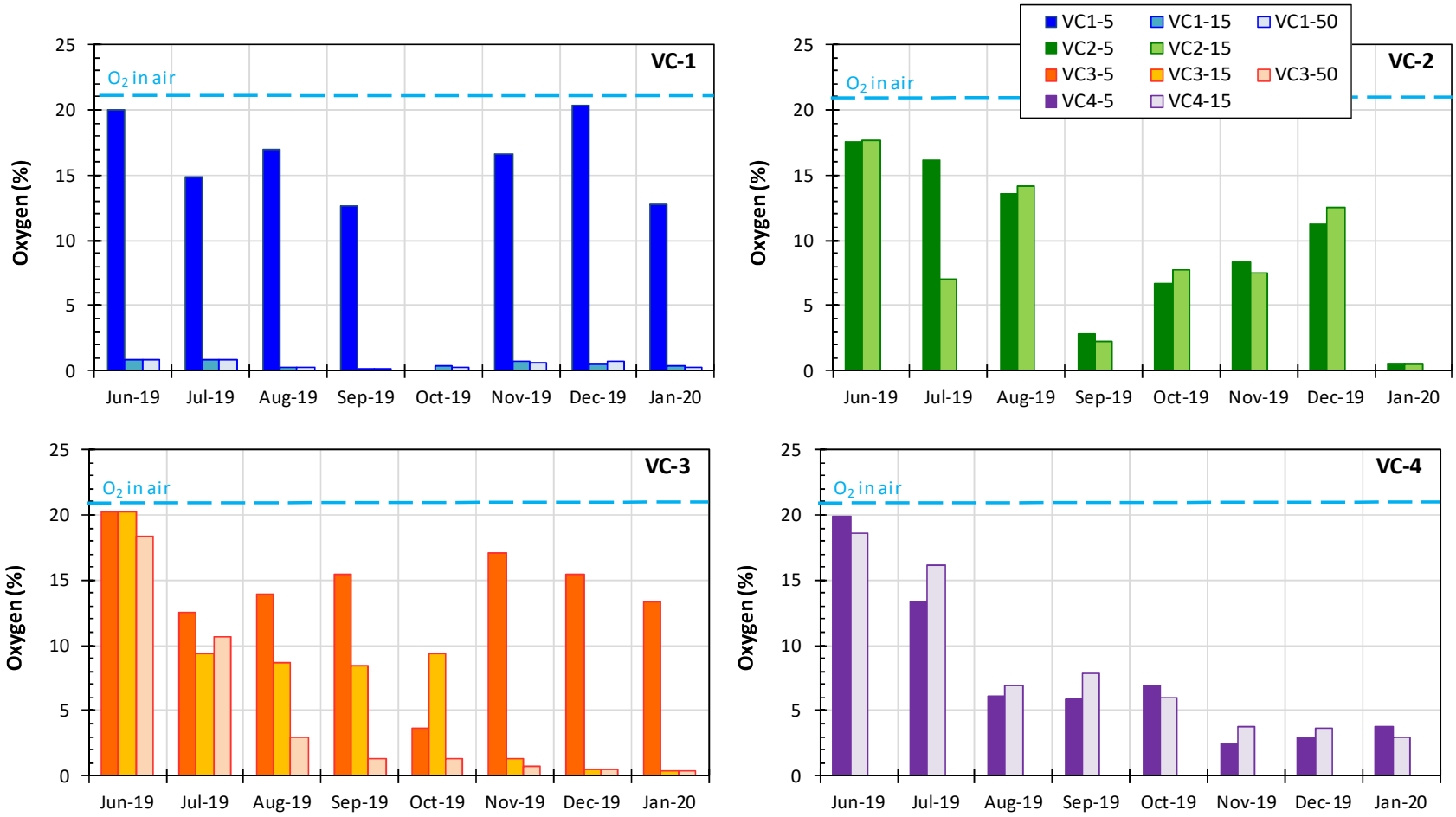

Figure D-27
Measured subsurface oxygen composition by depth below original ground level

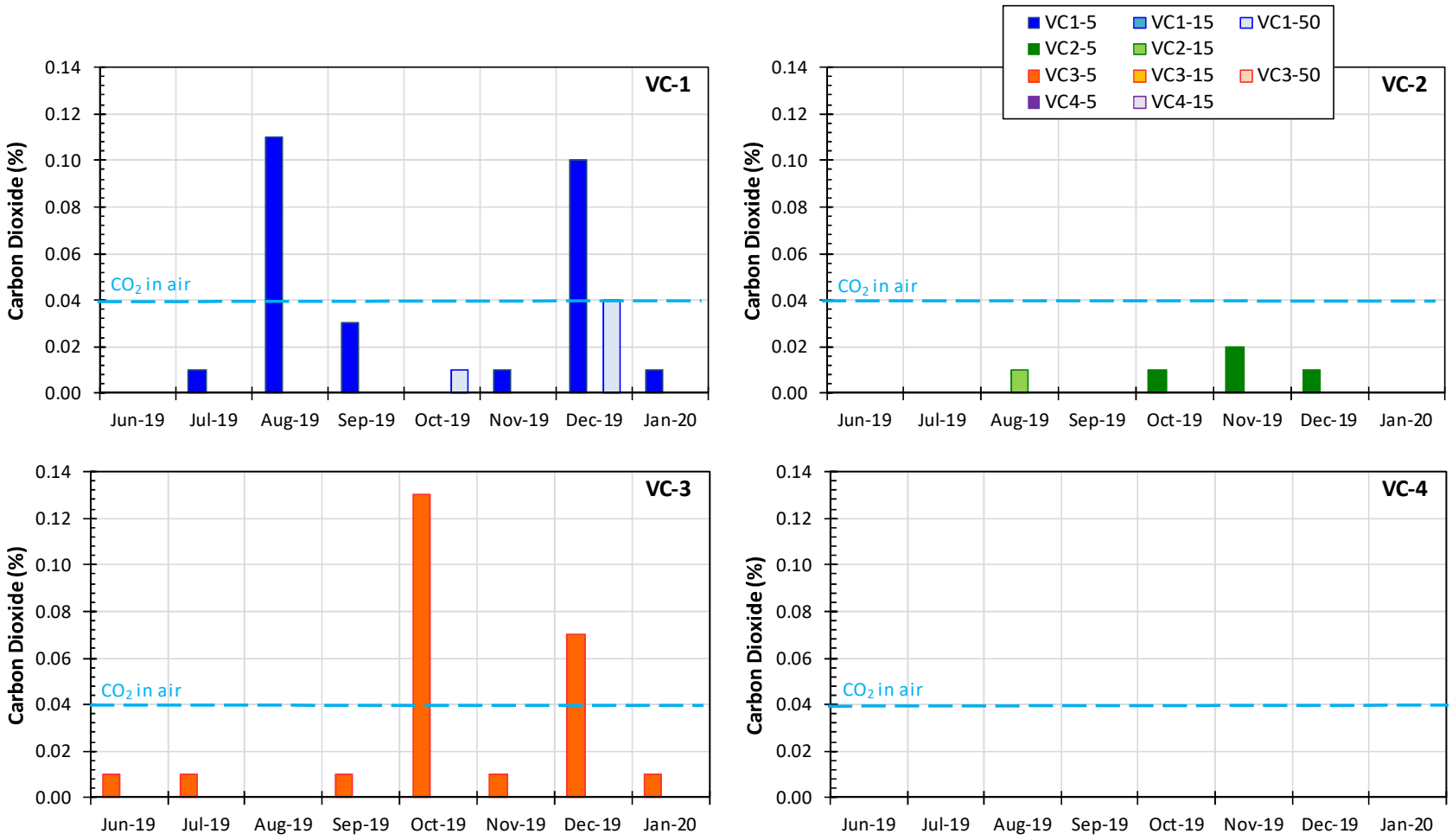

Figure D-28
Measured subsurface carbon dioxide composition by depth below original ground level

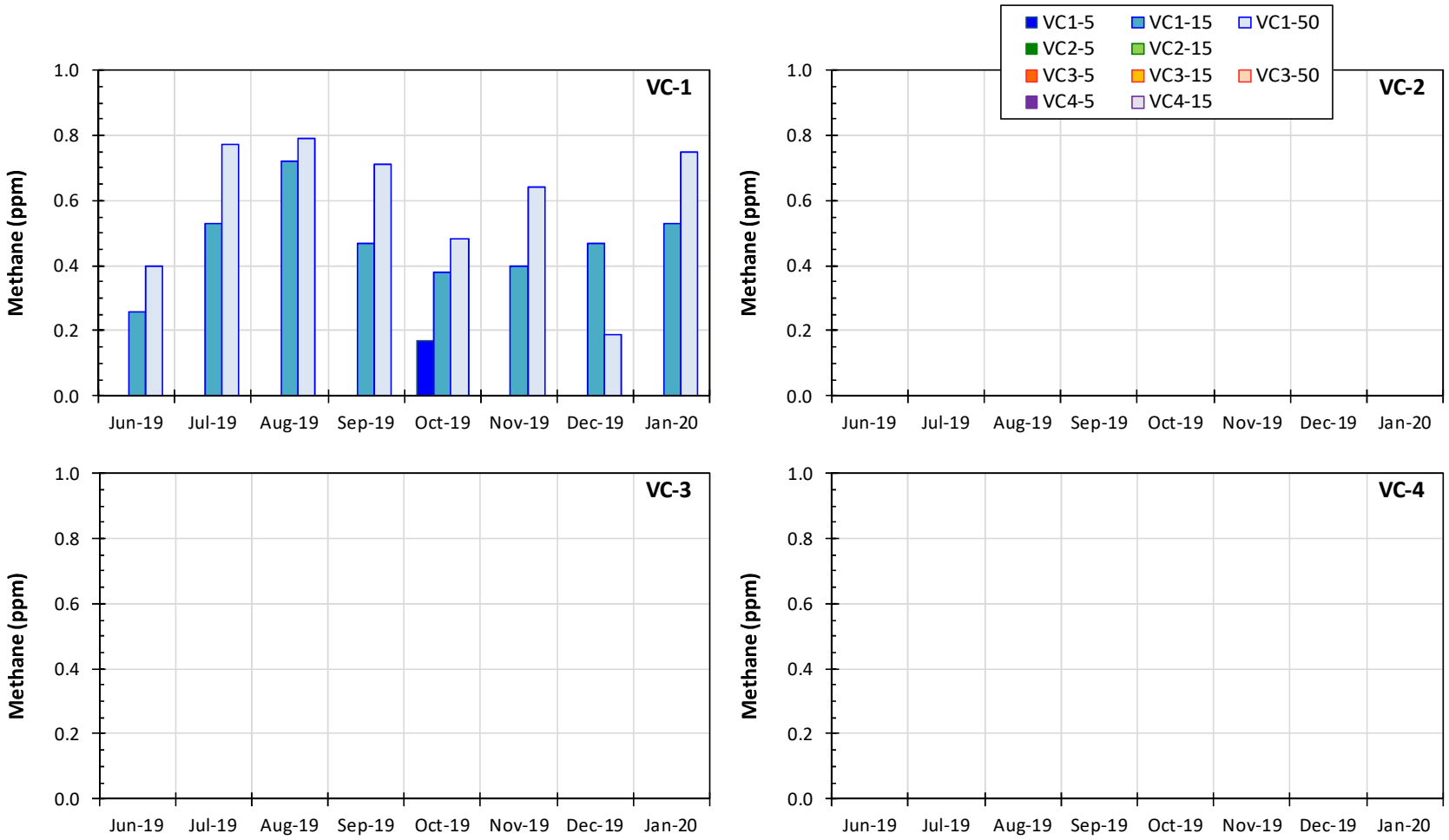

Figure D-29
Measured methane oxygen composition by depth below original ground level

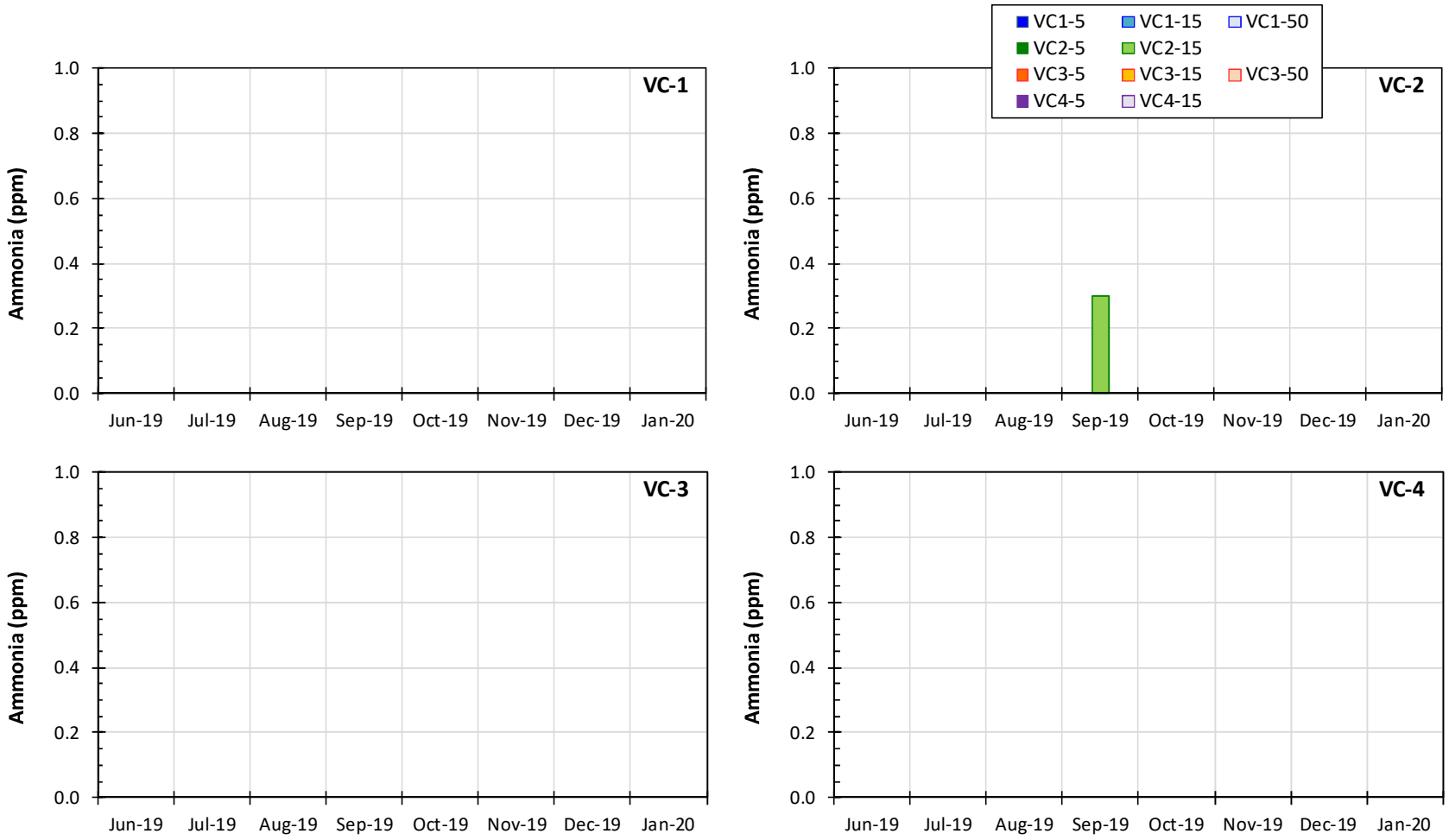

Figure D-30
Measured subsurface ammonia composition by depth below original ground level

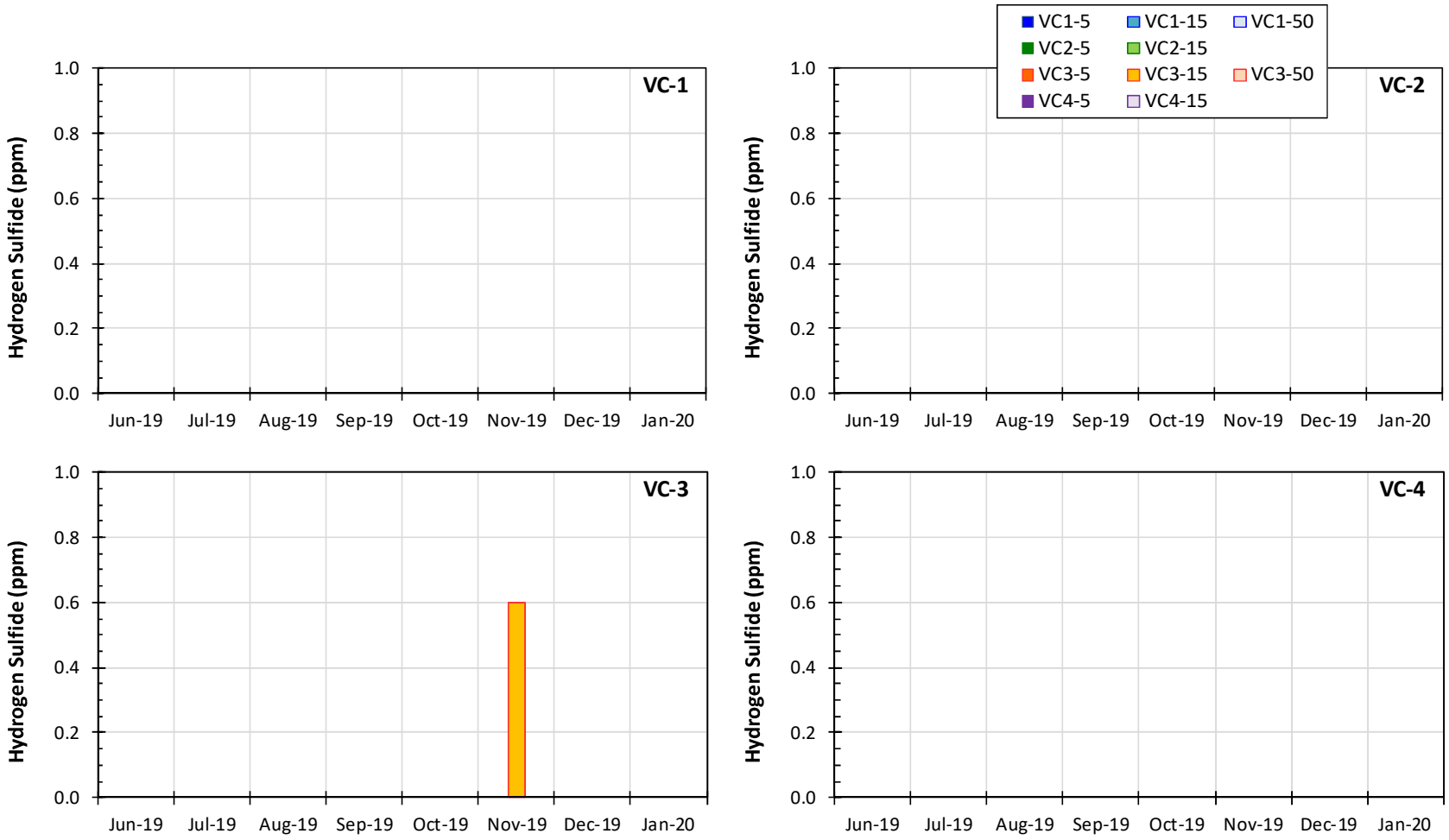

Figure D-31
Measured subsurface hydrogen sulfide composition by depth below original ground level

E
COMPARISON OF POREWATER ESTIMATES FROM LEACHING TESTS WITH MEASURED VALUES

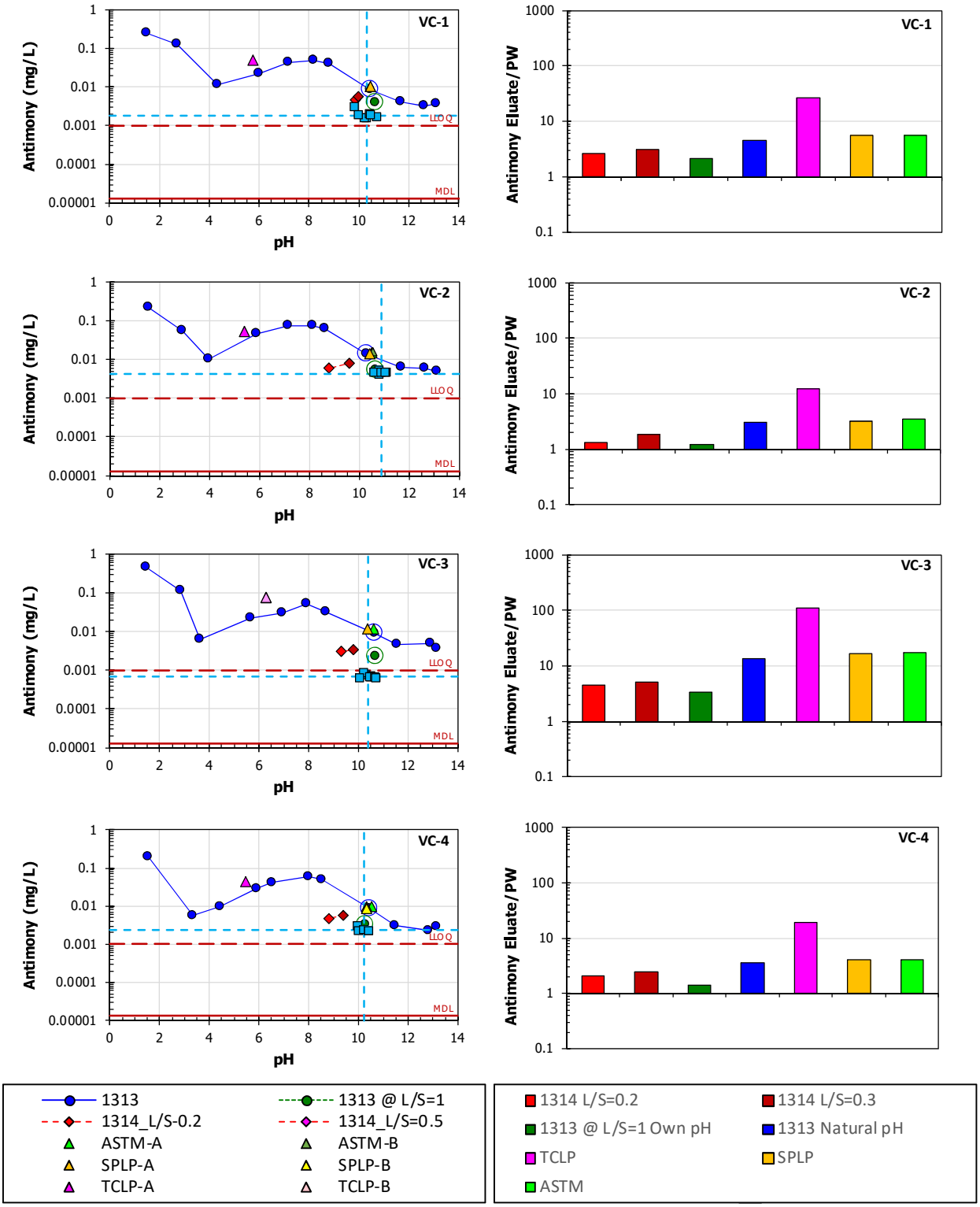

Figure E-1
Antimony concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right)

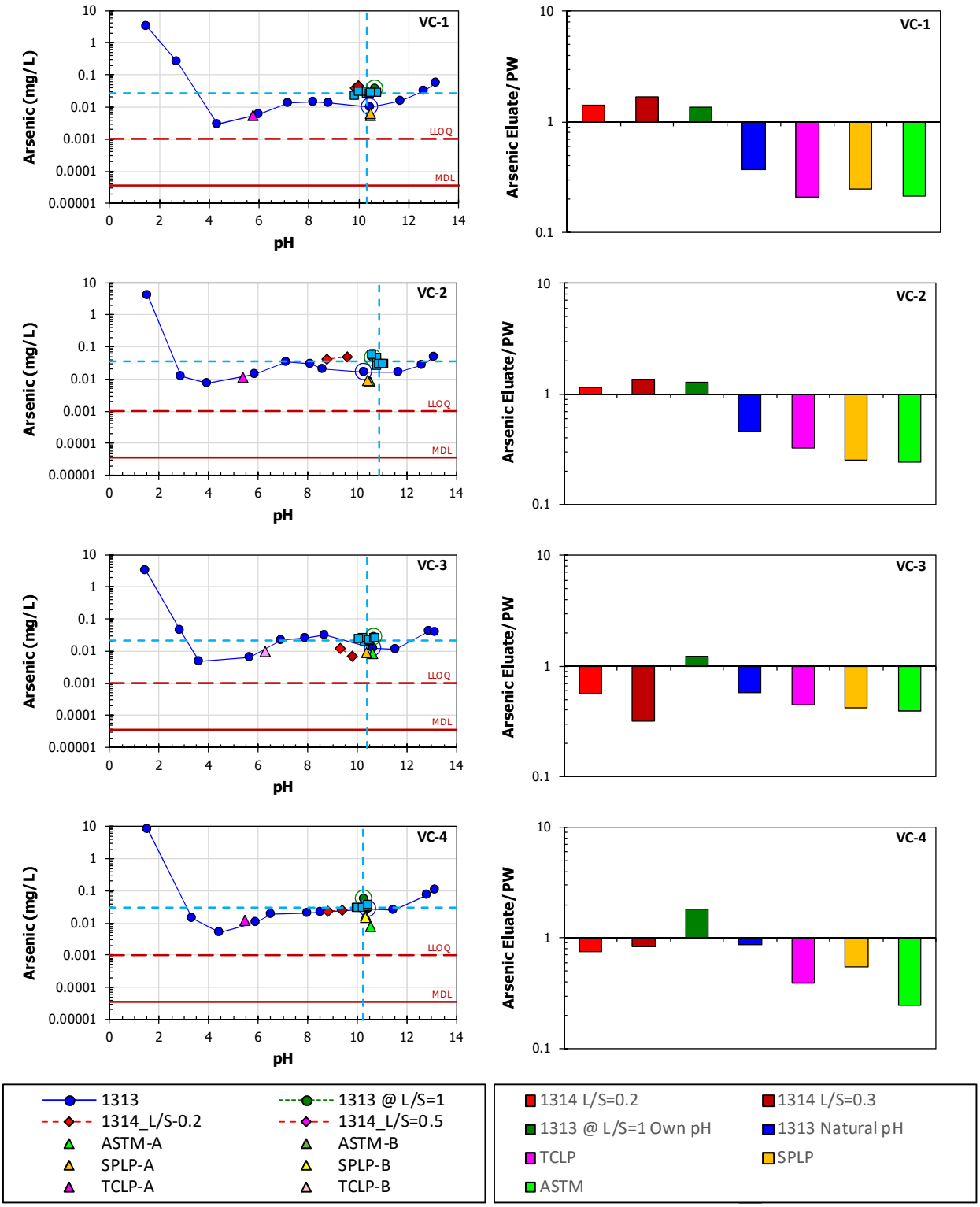

Figure E-2
Arsenic concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right)

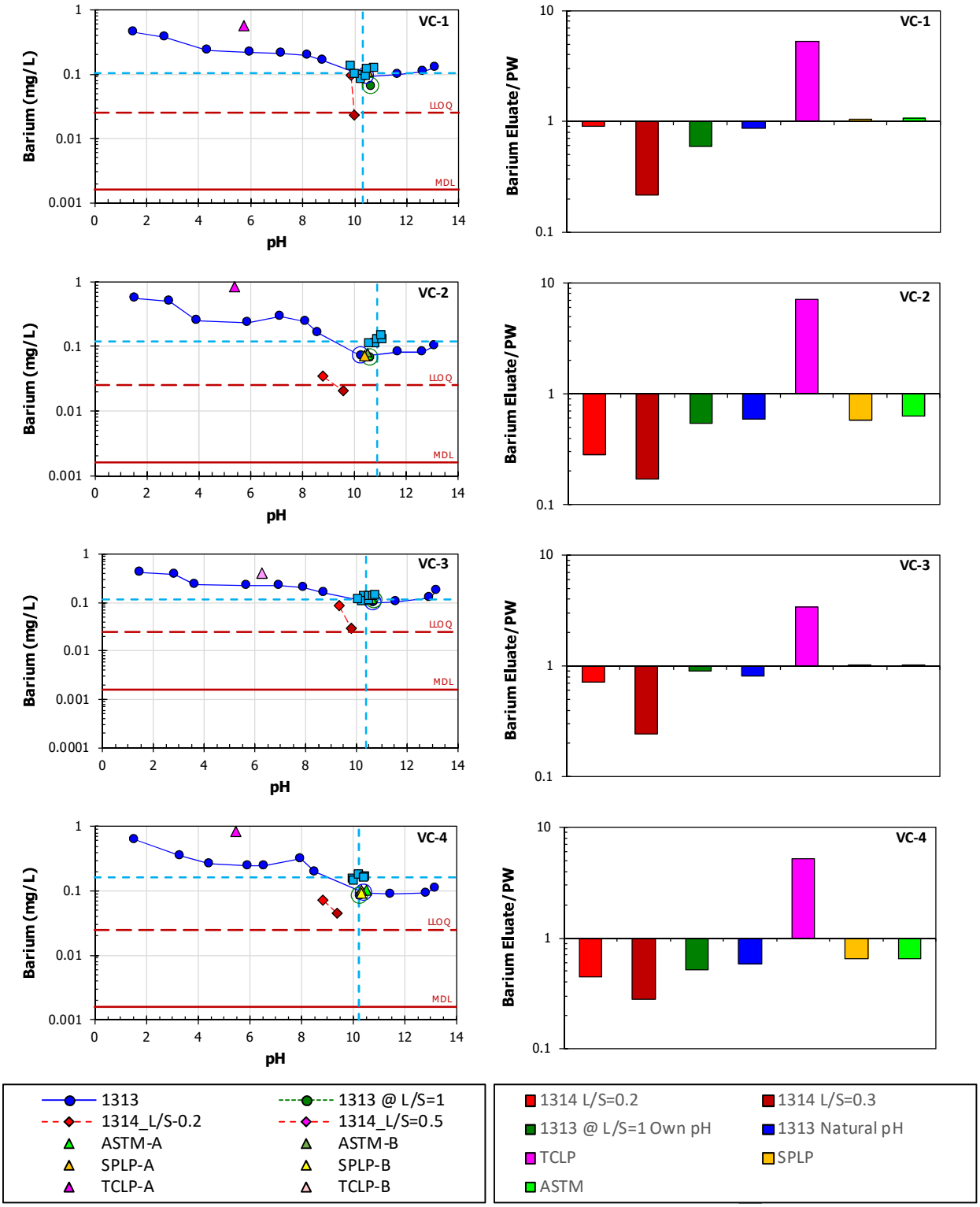

Figure E-3
Barium concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right)

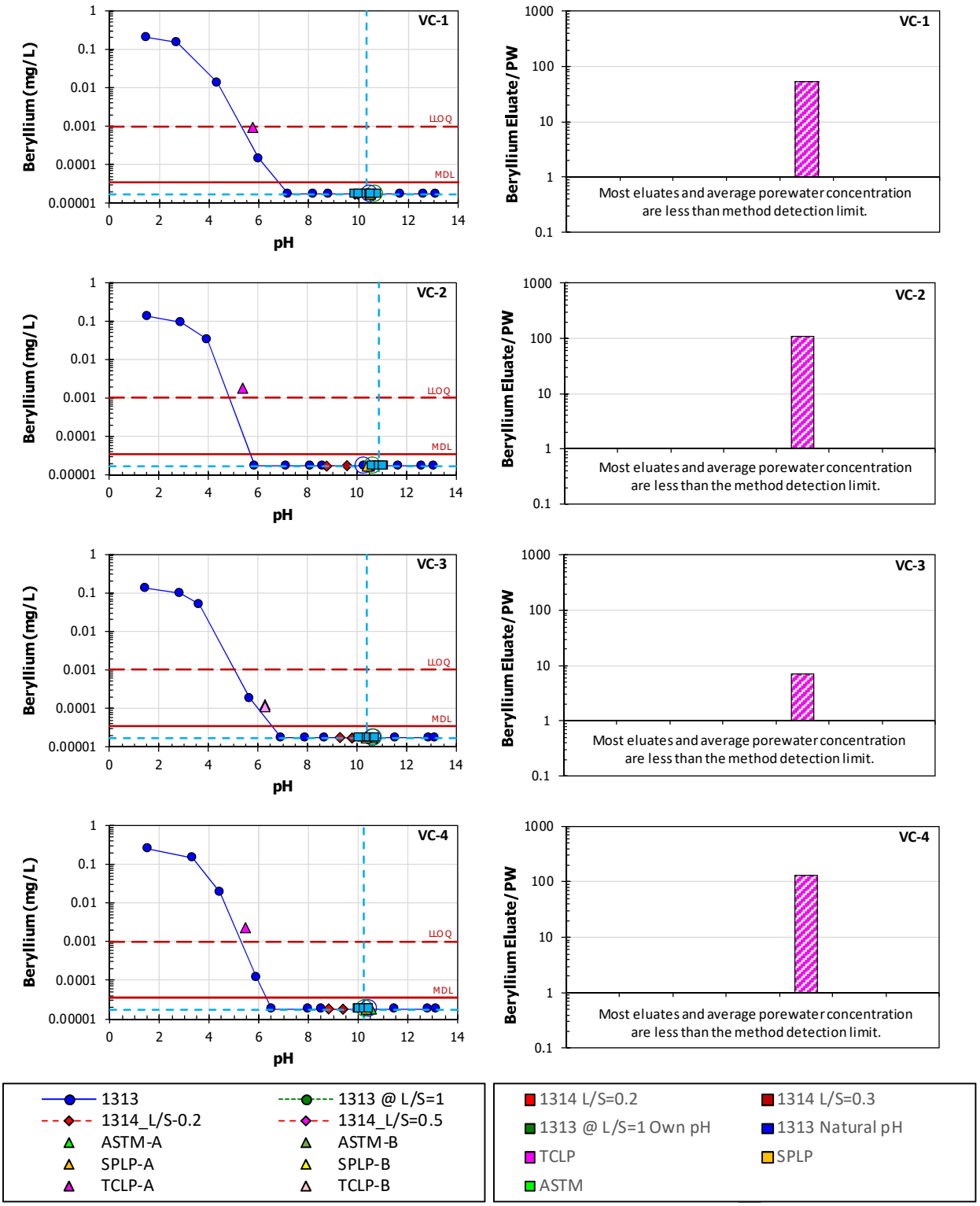

Figure E-4
Beryllium concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right); crosshatched ratio results indicate estimates based on at least one MDL value

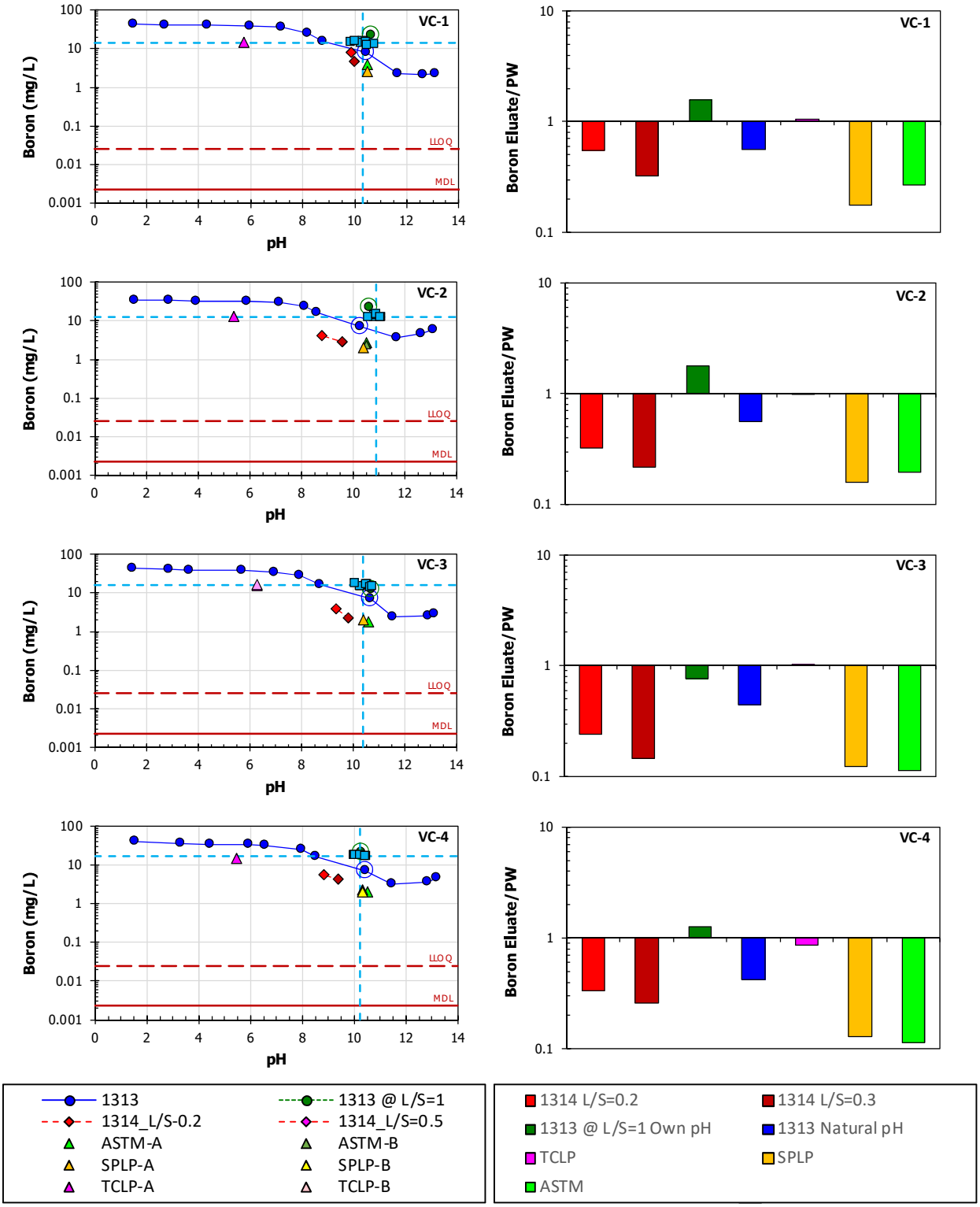

Figure E-5
Boron concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right)

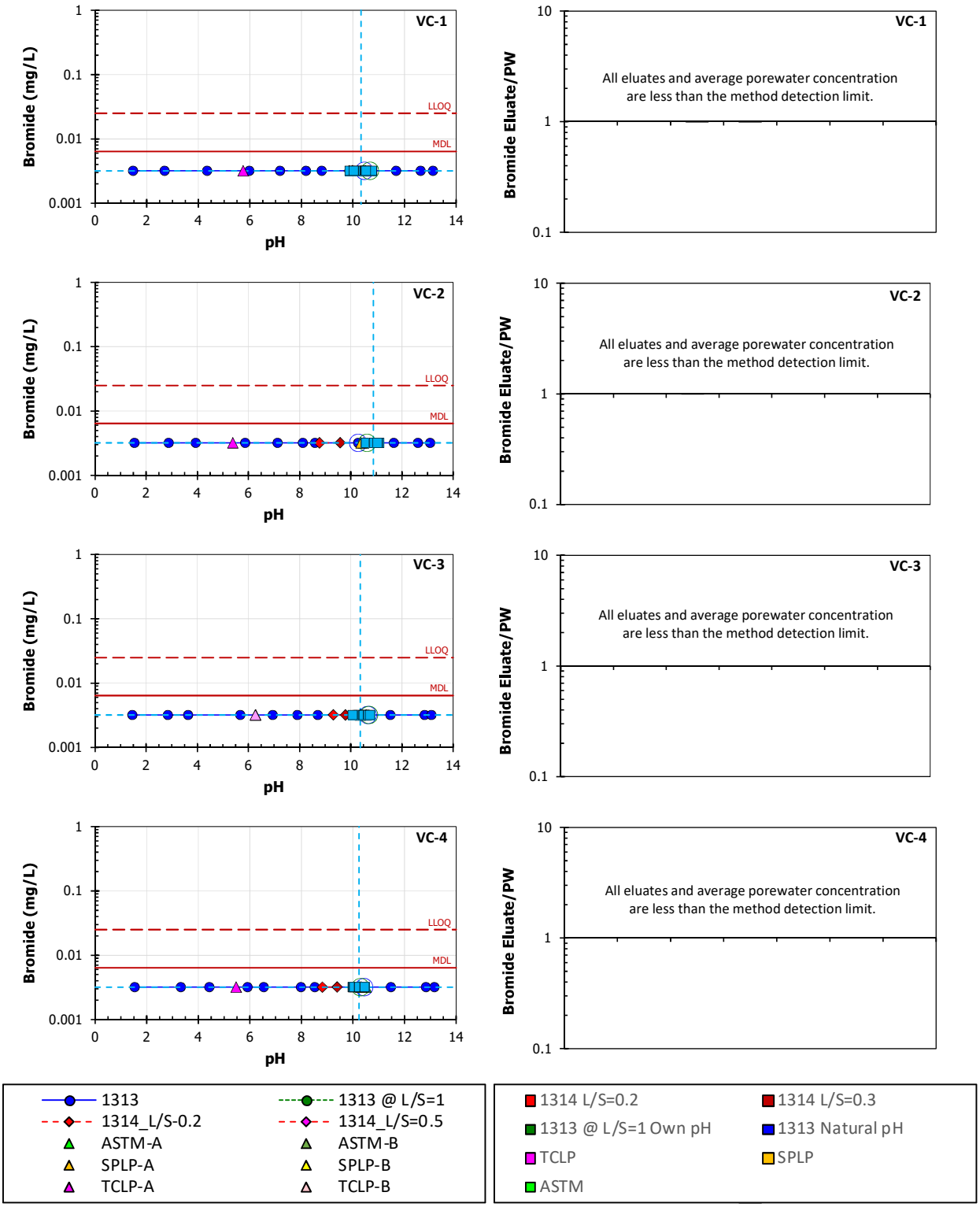

Figure E-6
Bromide concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right)

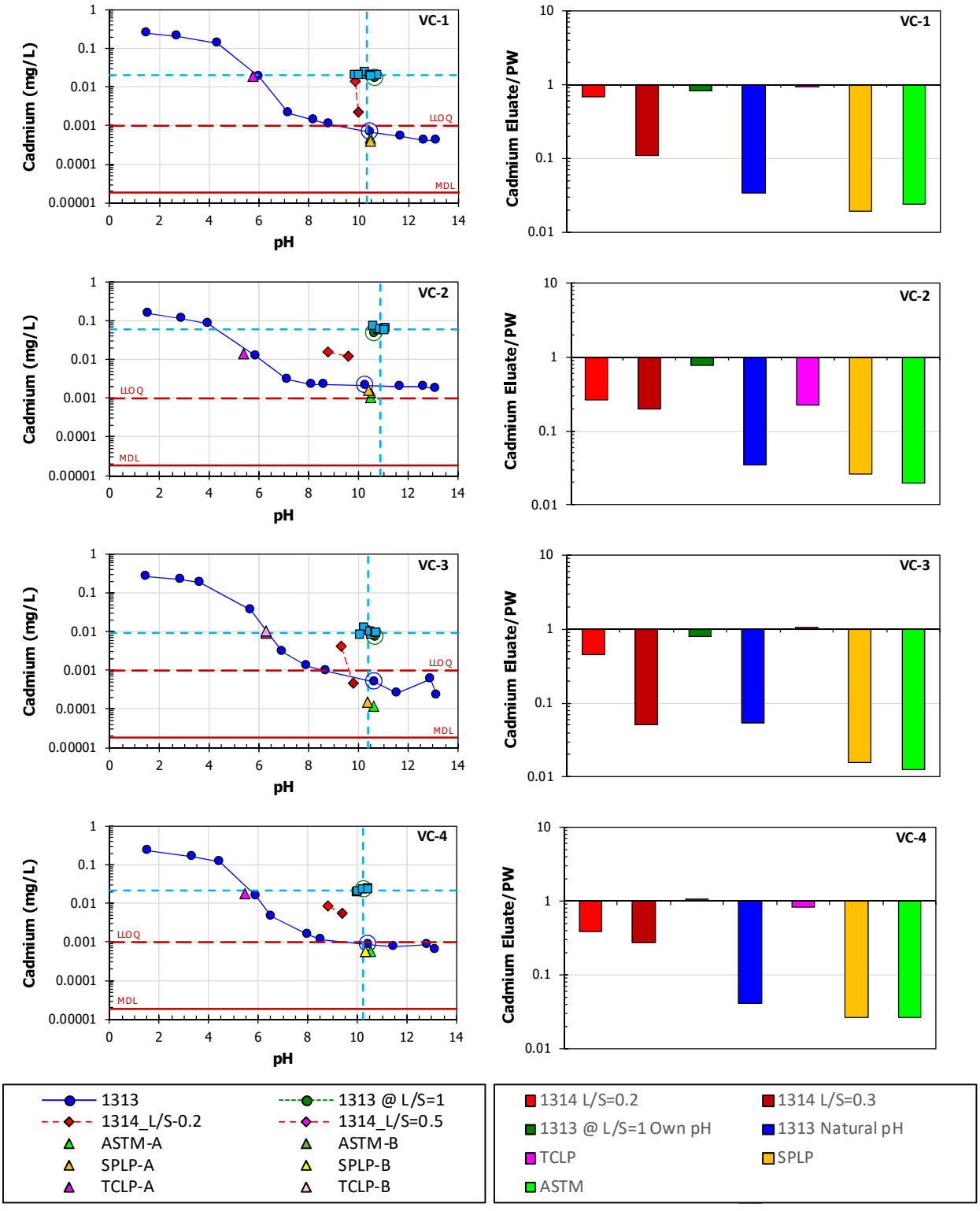

Figure E-7
Cadmium concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right)

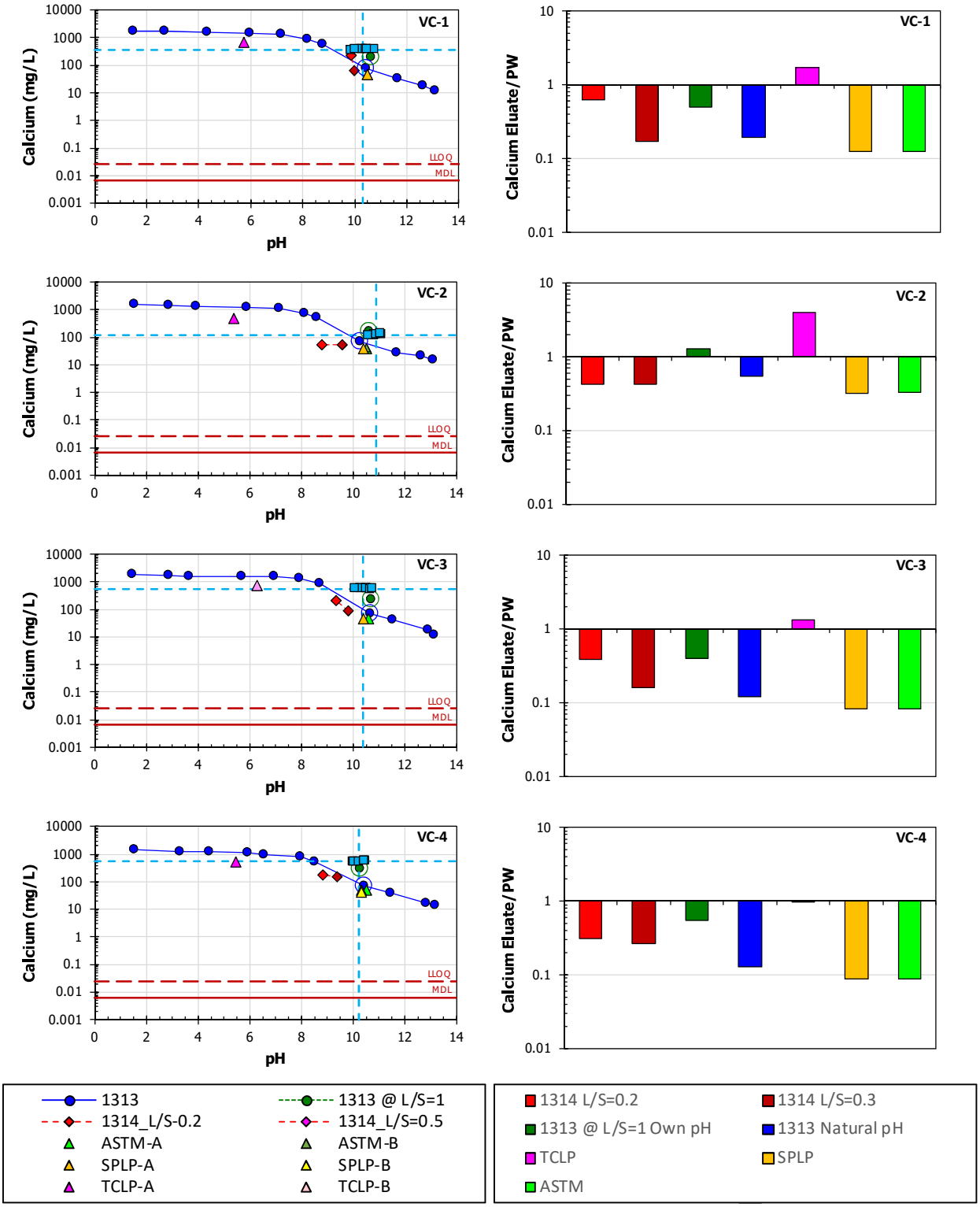

Figure E-8
Calcium concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right)

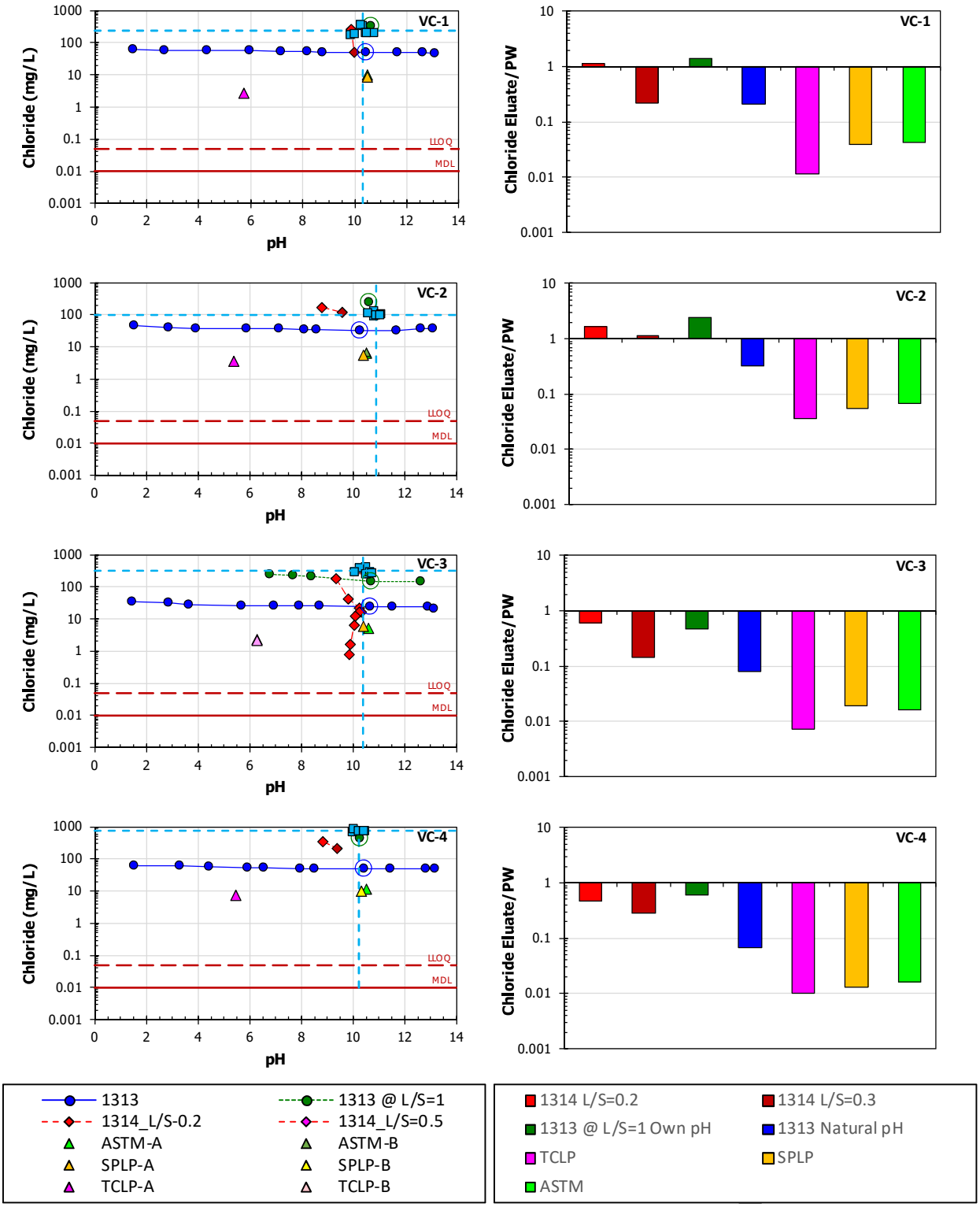

Figure E-9
Chloride concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right)

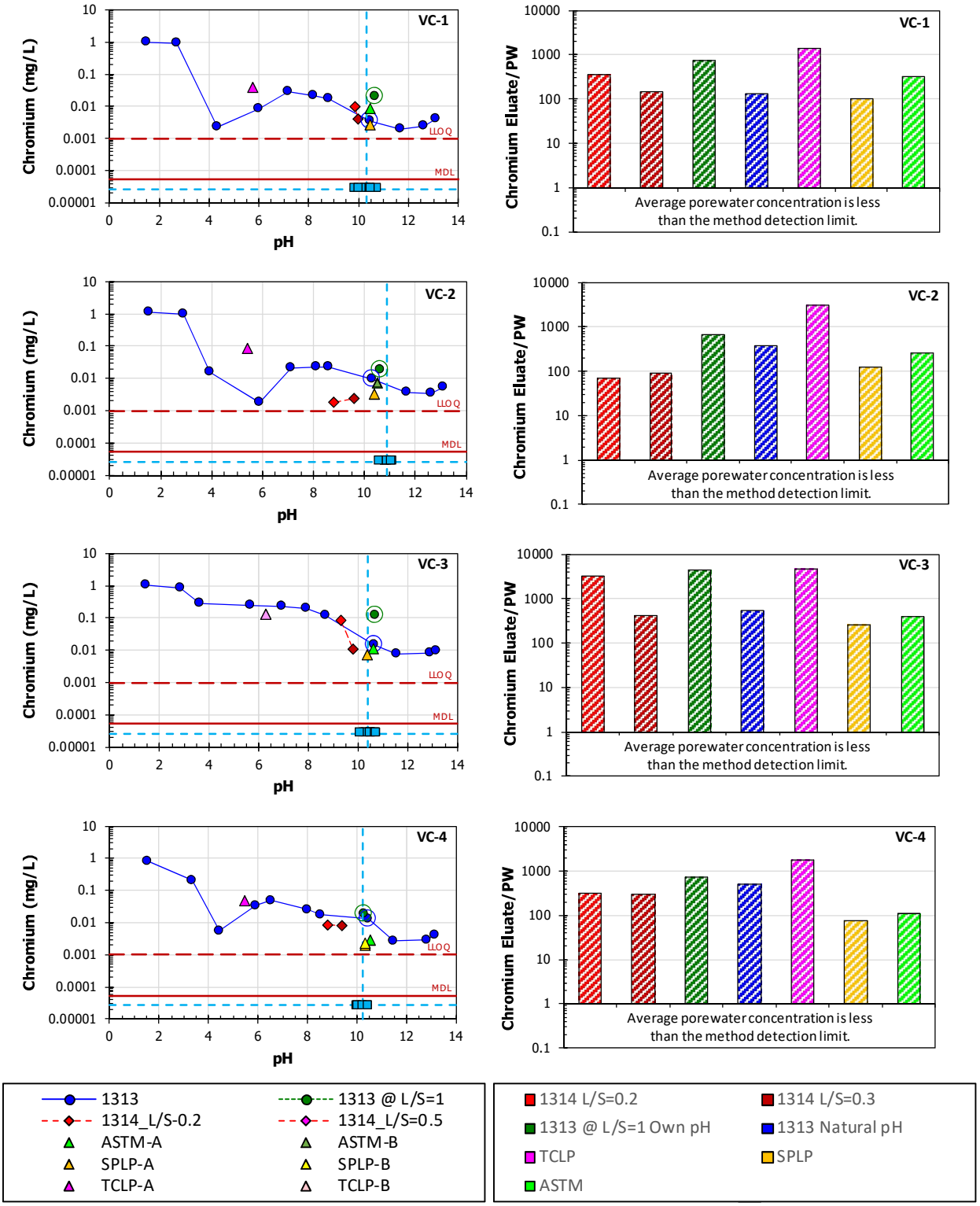

Figure E-10
Chromium concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right); crosshatched ratio results indicate estimates based on at least one MDL value

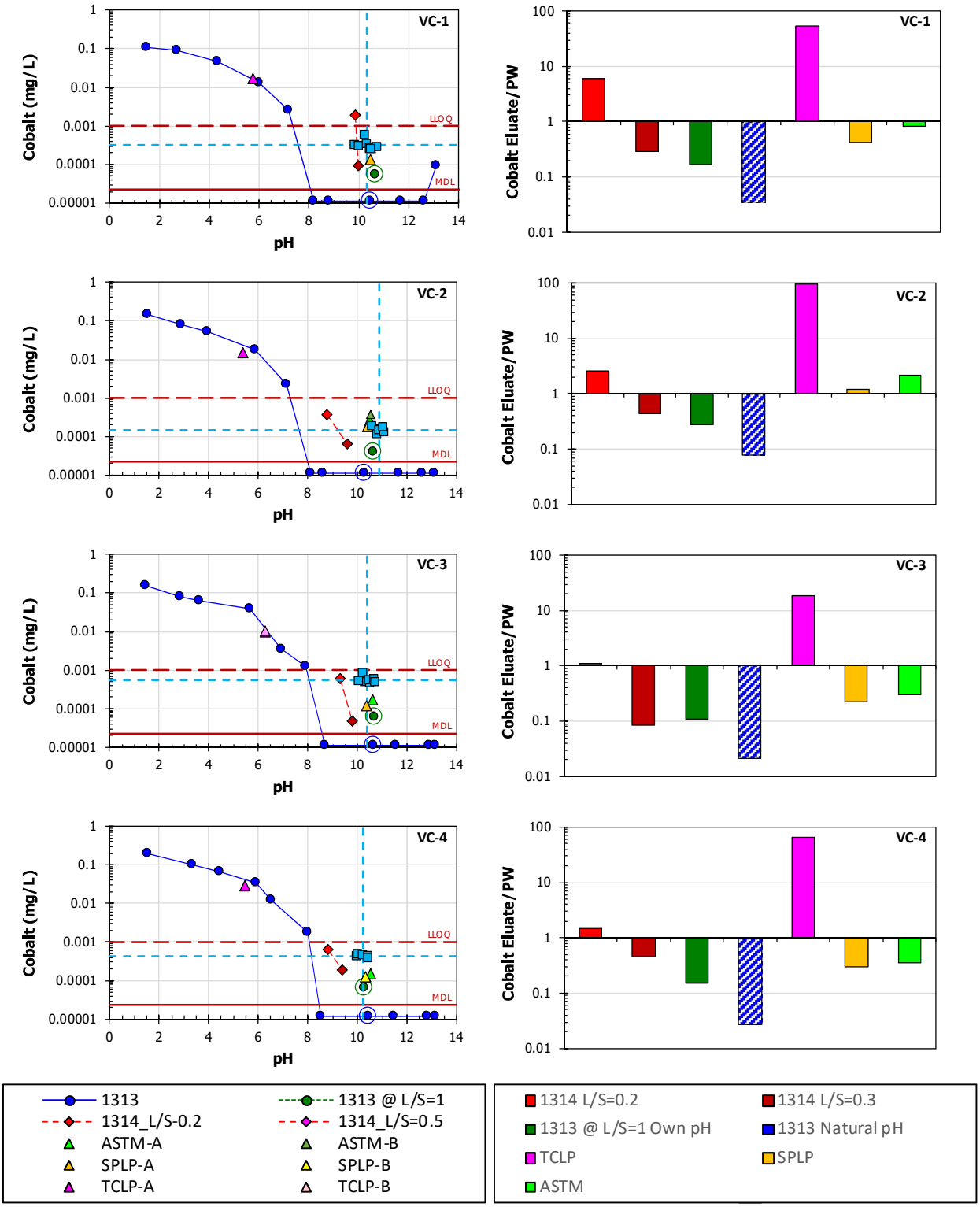

Figure E-11
Cobalt concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right); crosshatched ratio results indicate estimates based on at least one MDL value

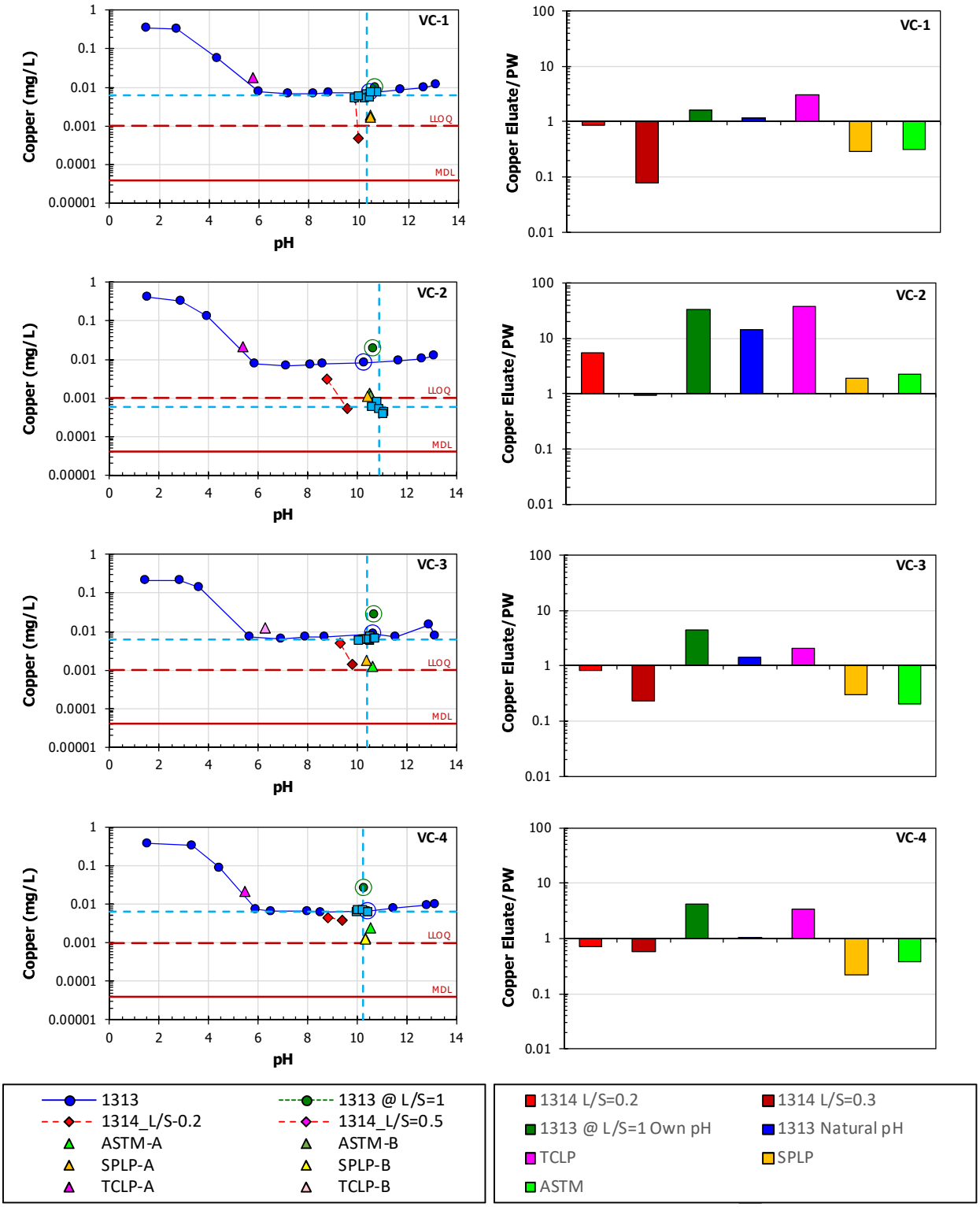

Figure E-12
Copper concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right)

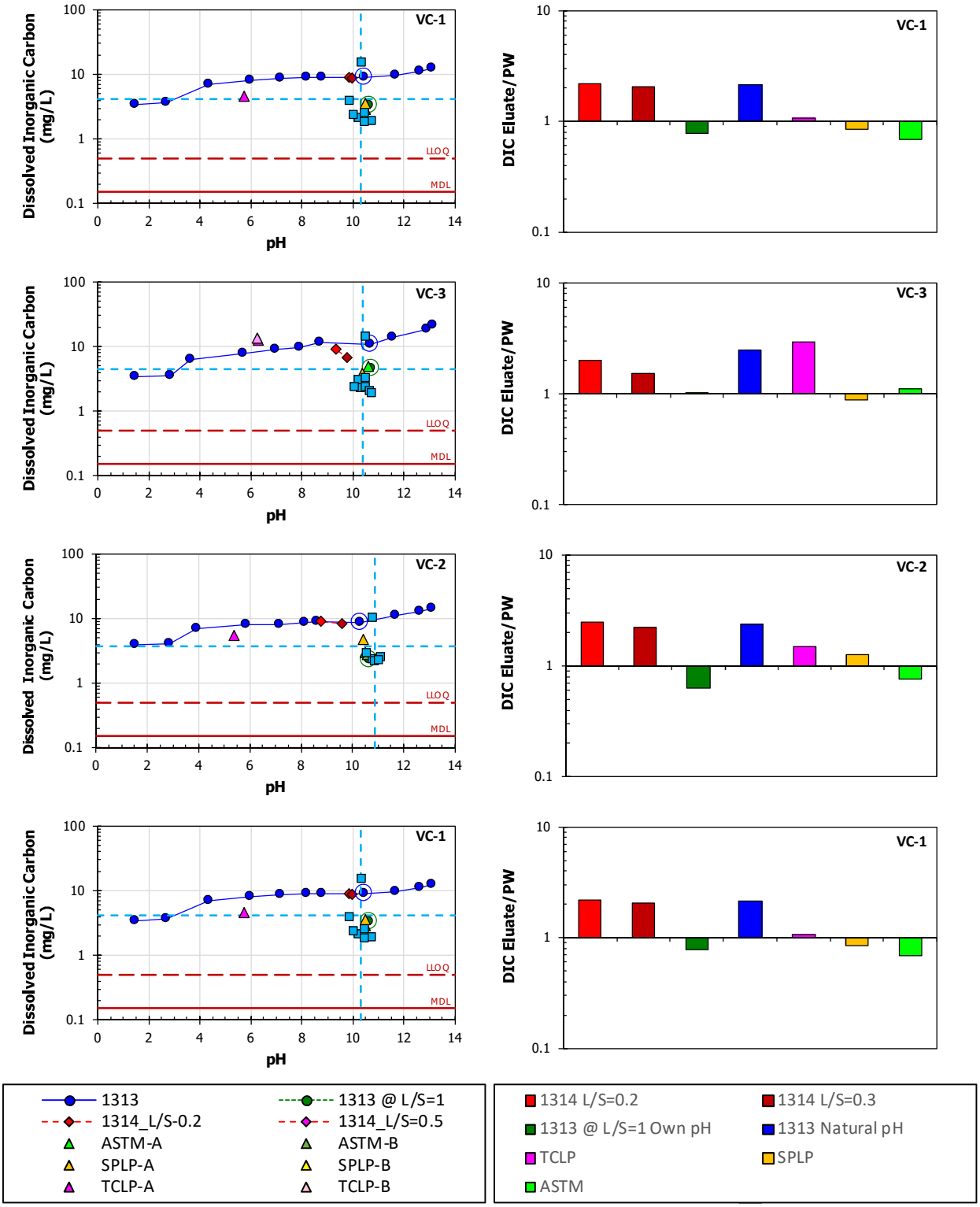

Figure E-13
Dissolved inorganic carbon concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right)

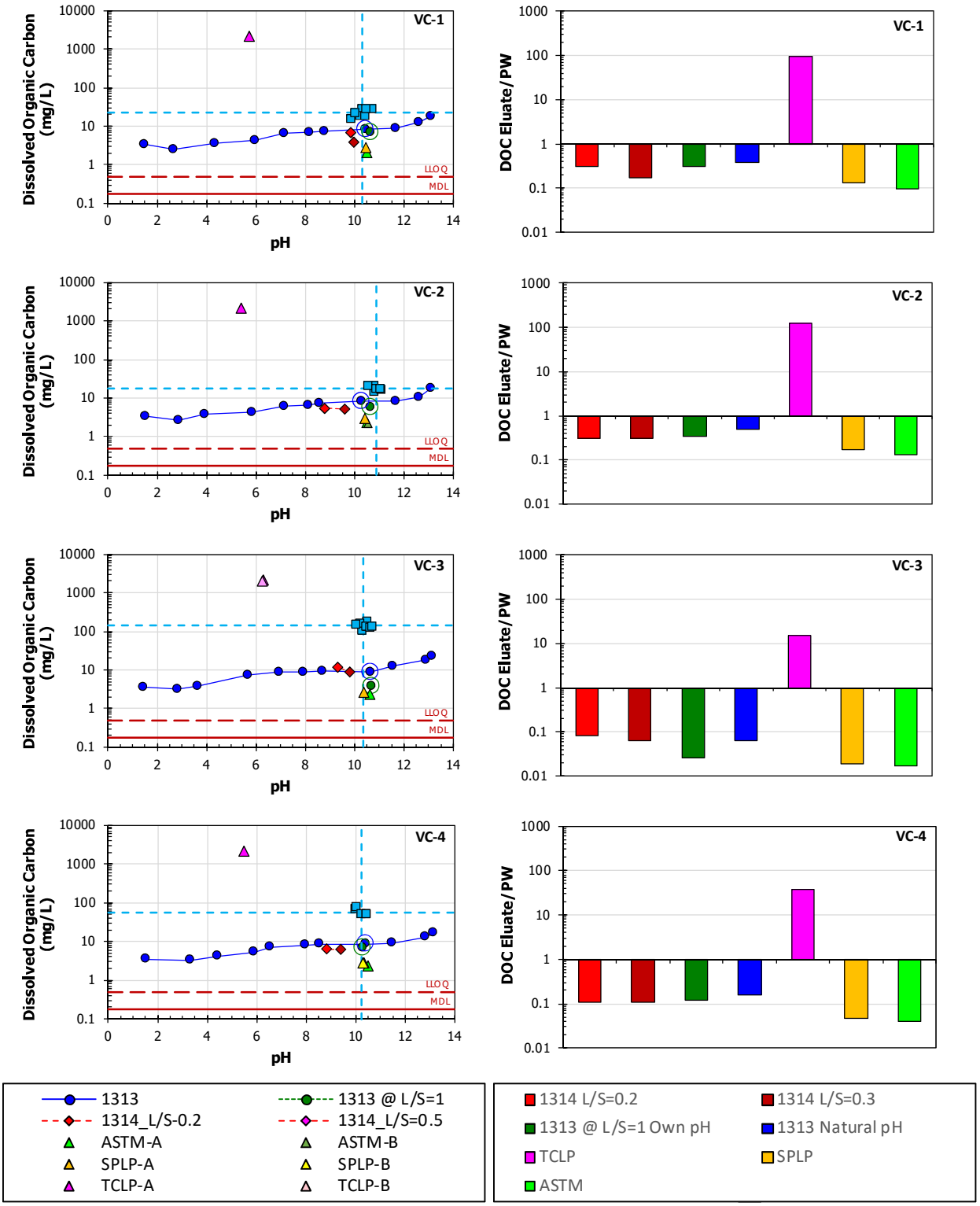

Figure E-14
Dissolve organic carbon concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right)

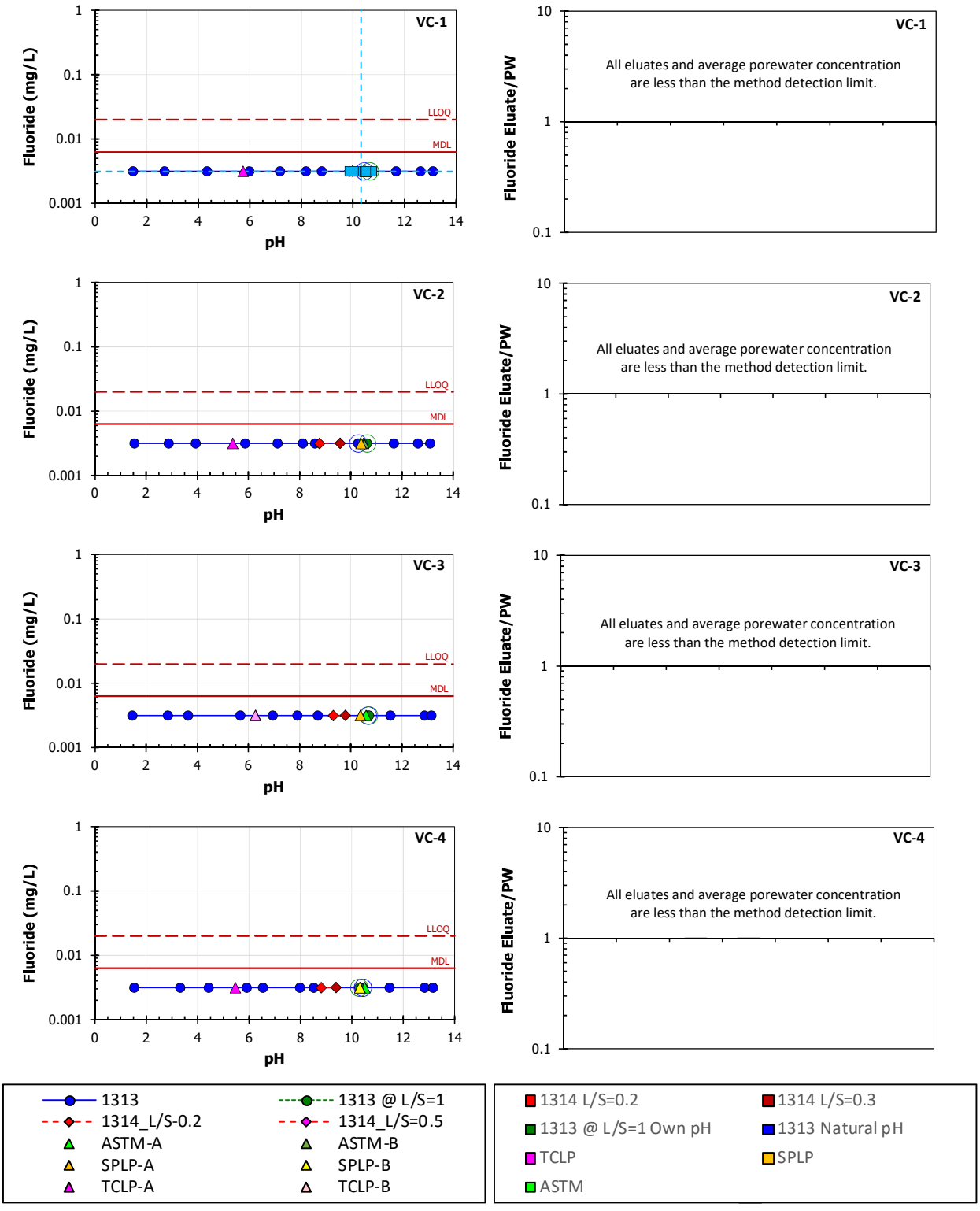

Figure E-15
Fluoride concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right); crosshatched ratio results indicate estimates based on at least one MDL value

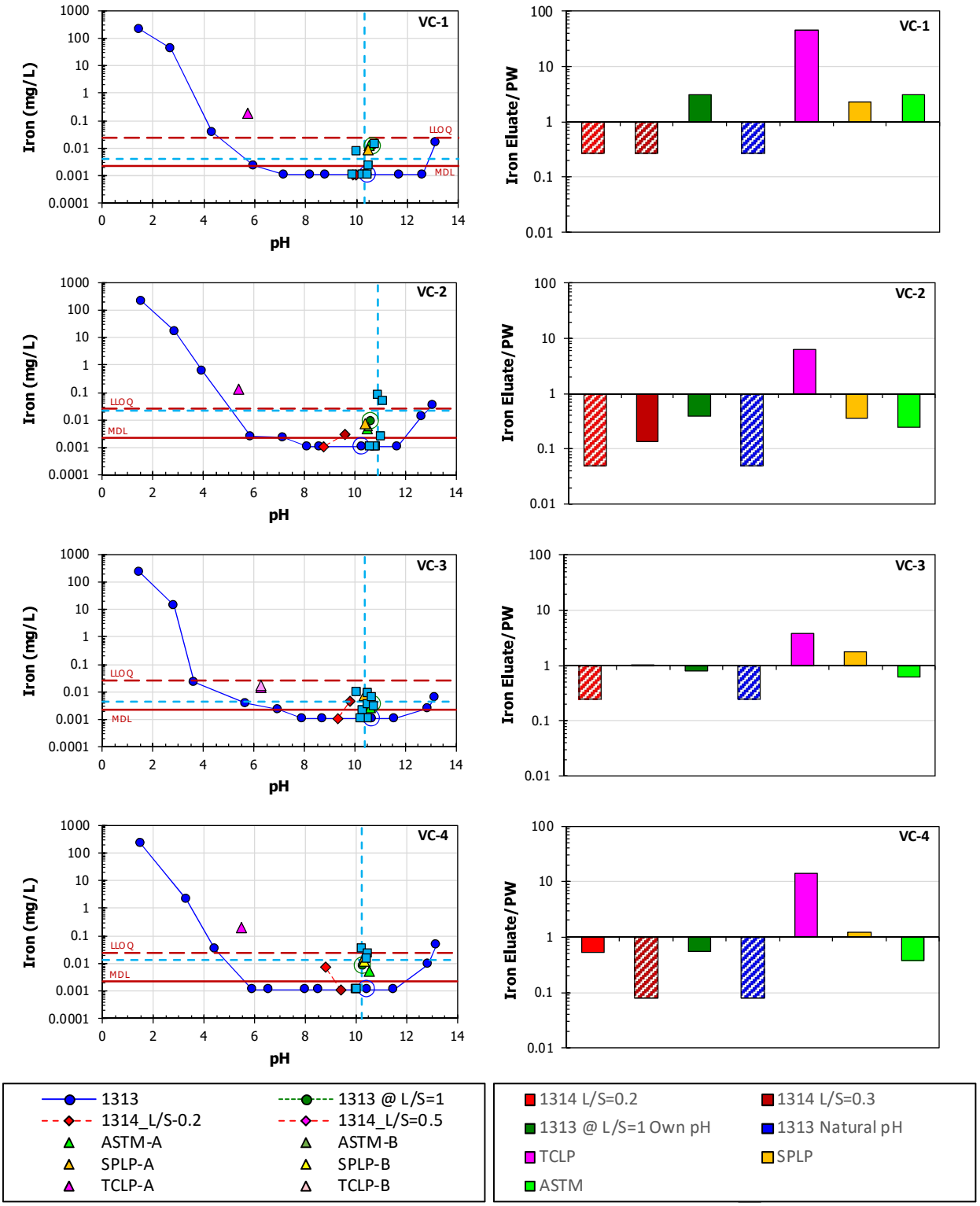

Figure E-16
Iron concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right); crosshatched ratio results indicate estimates based on at least one MDL value

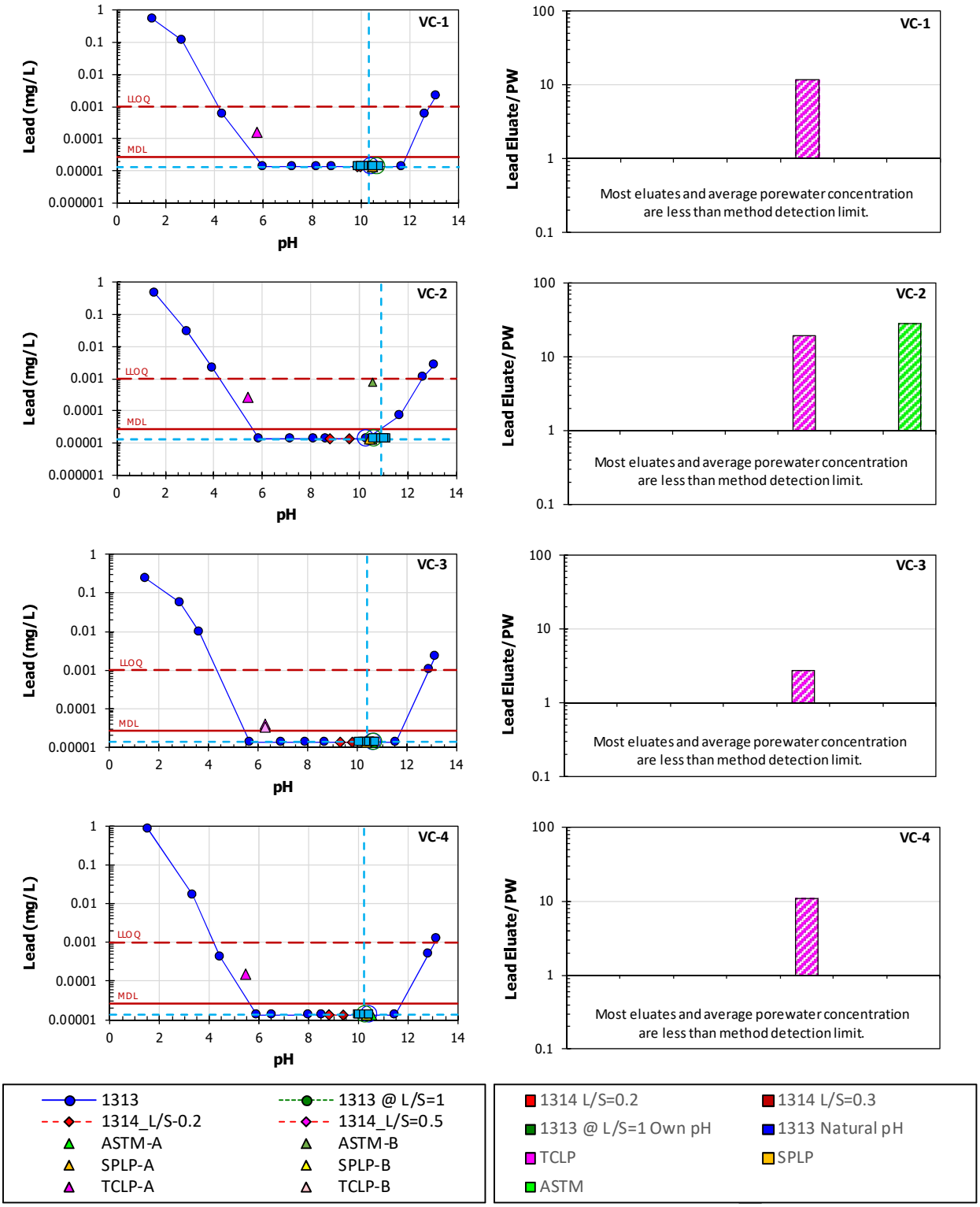

Figure E-17
Lead concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right); crosshatched ratio results indicate estimates based on at least one MDL value

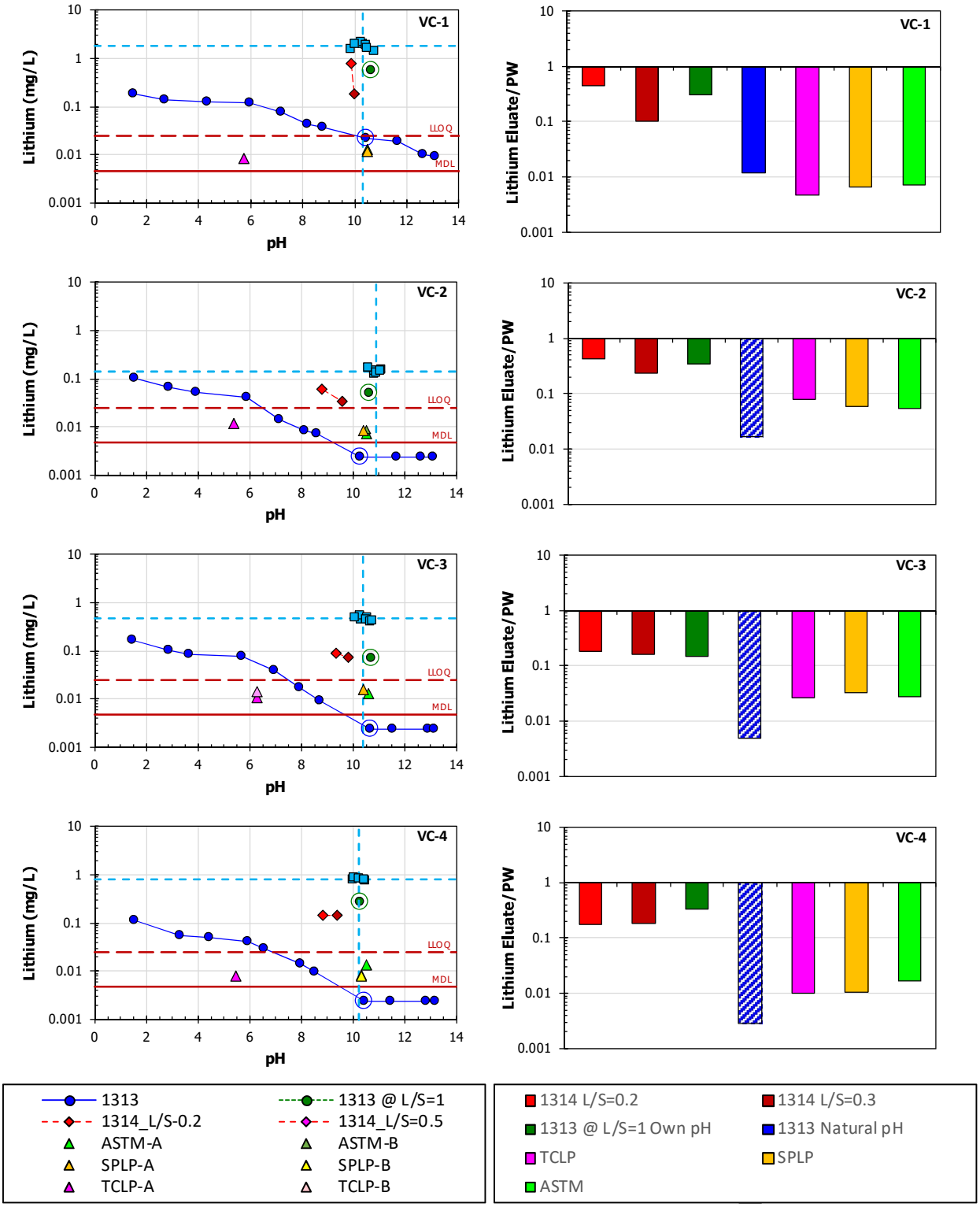

Figure E-18
Lithium concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right); crosshatched ratio results indicate estimates based on at least one MDL value

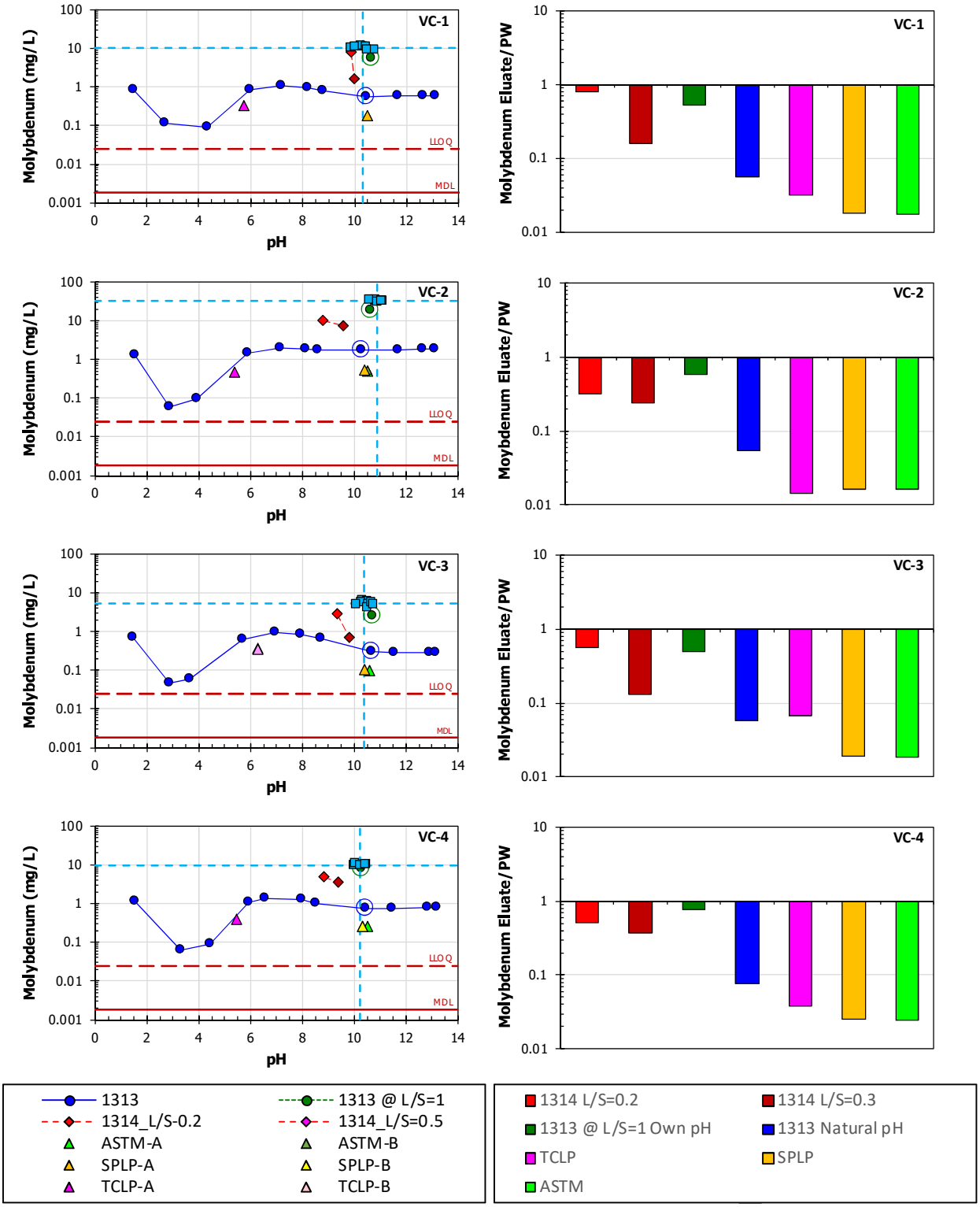

Figure E-19
Molybdenum concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right)

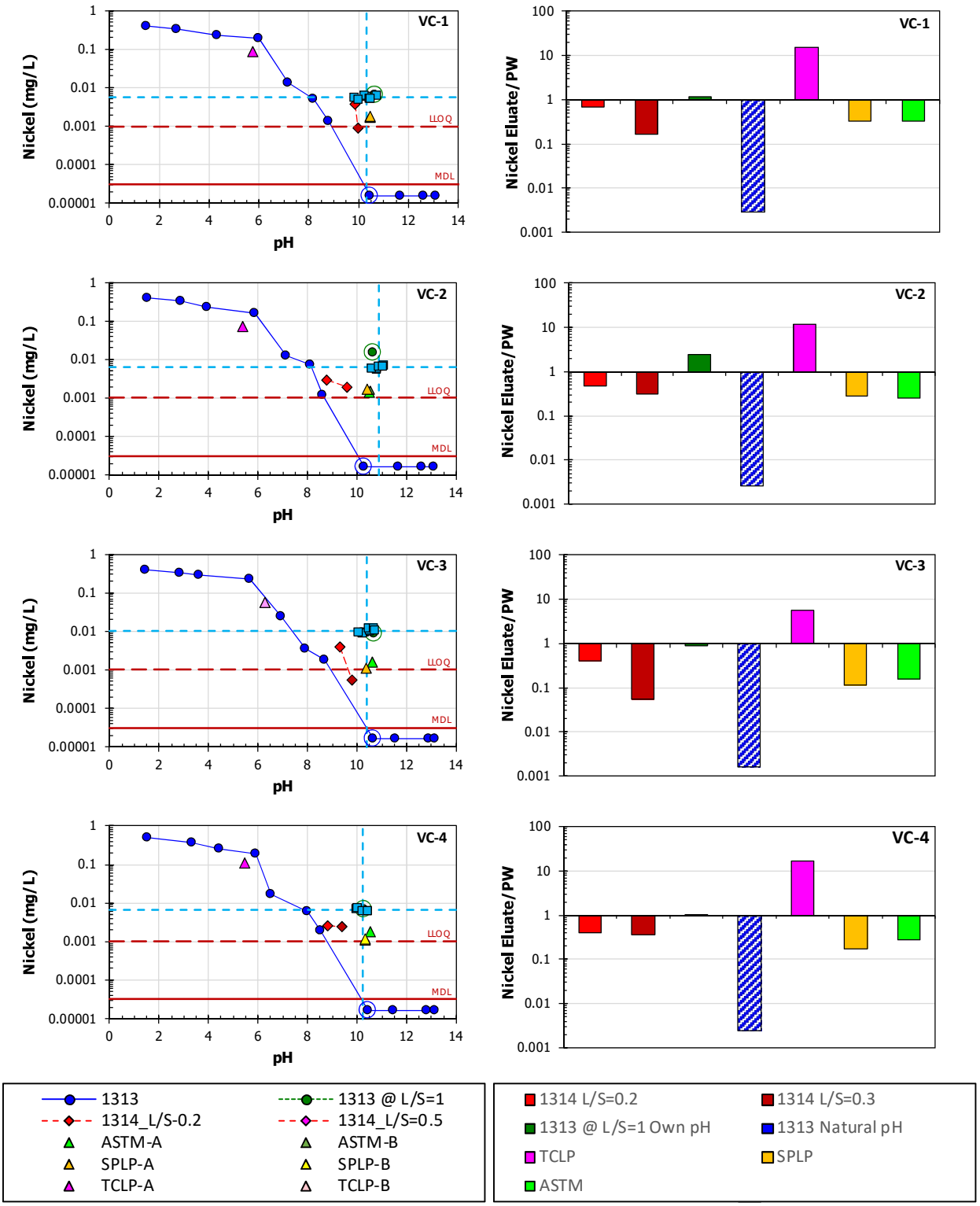

Figure E-20
Nickel concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right); crosshatched ratio results indicate estimates based on at least one MDL value

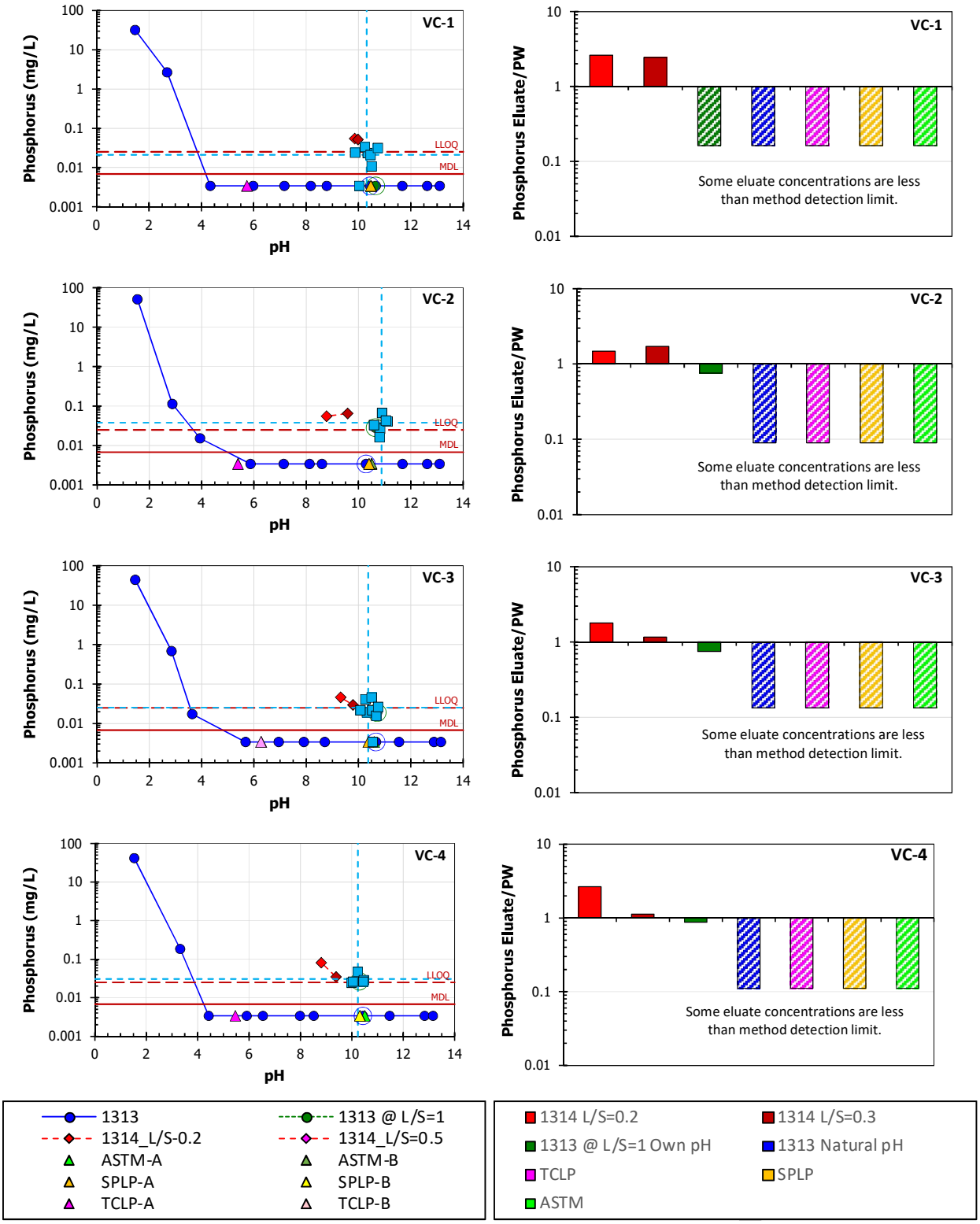

Figure E-21
Phosphorus concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right); crosshatched ratio results indicate estimates based on at least one MDL value

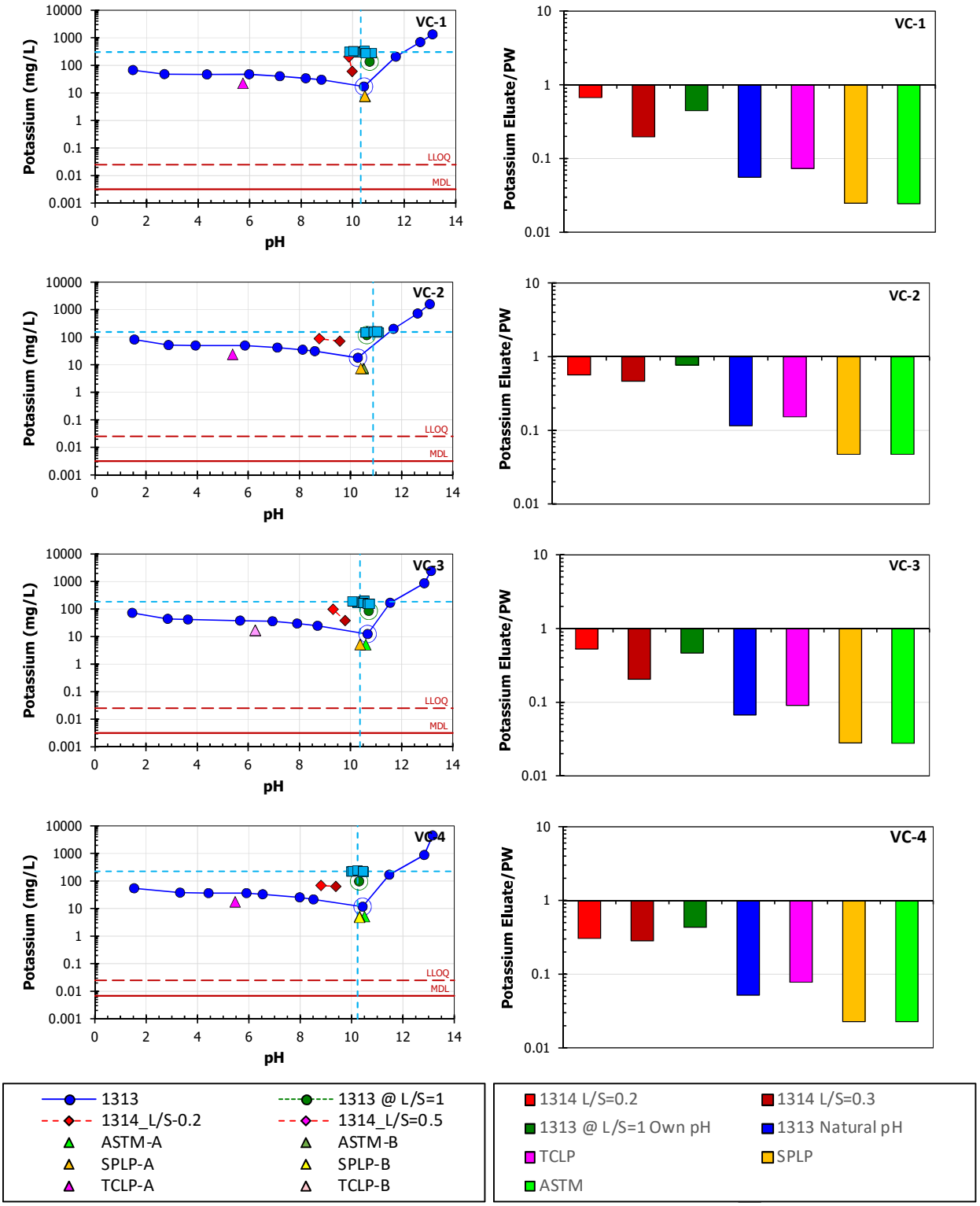

Figure E-22
Potassium concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right)

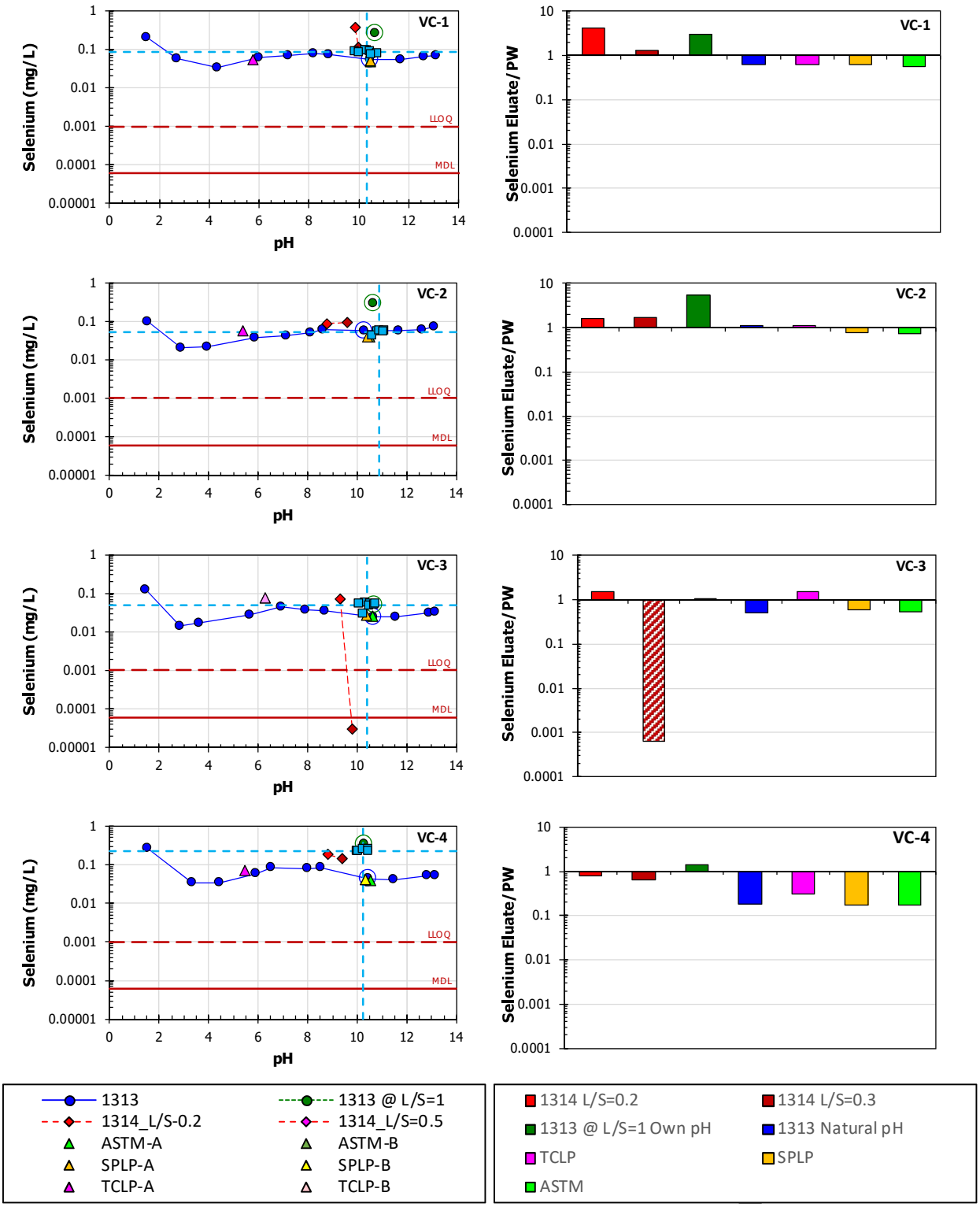

Figure E-23
Selenium concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right); crosshatched ratio results indicate estimates based on at least one MDL value

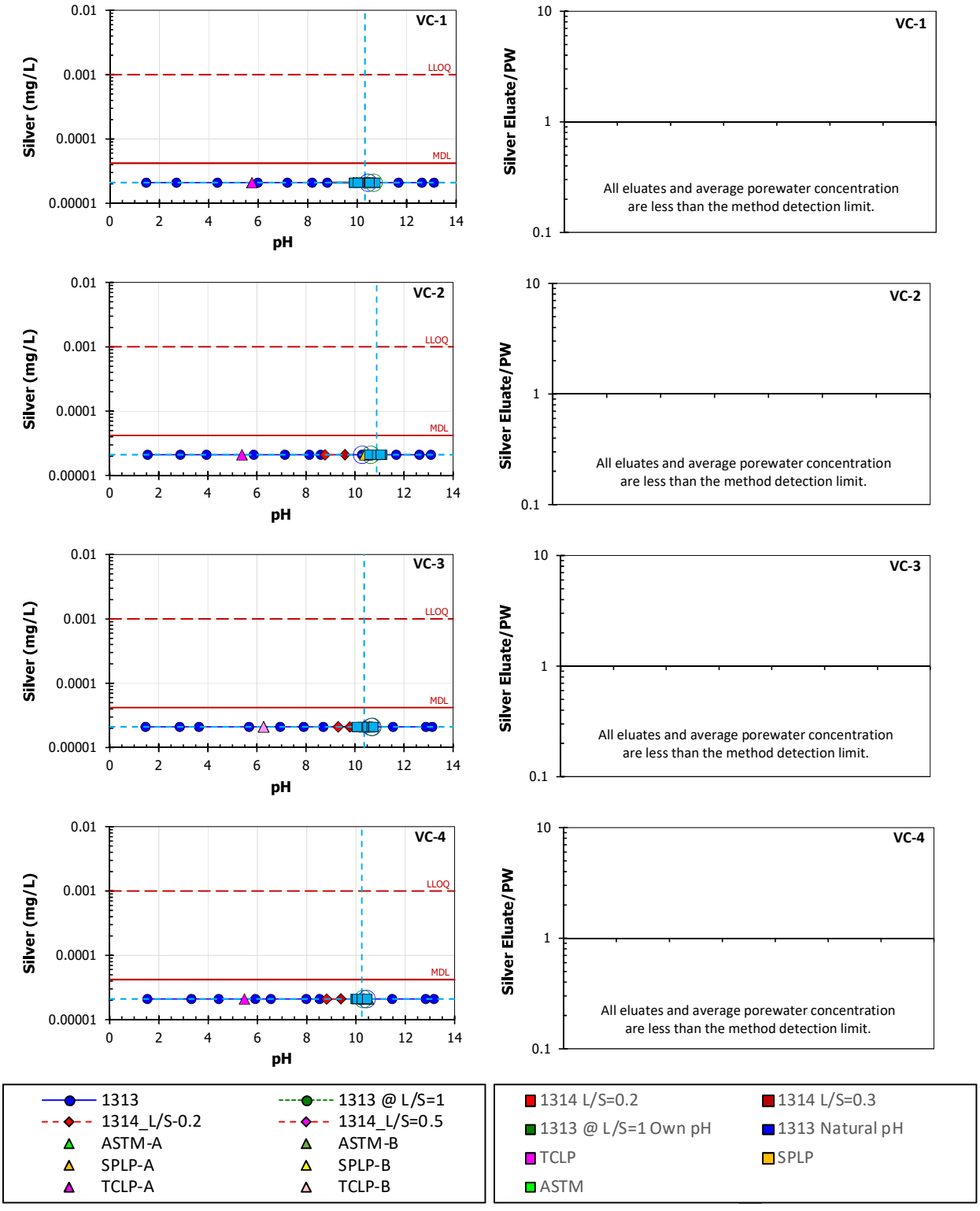

Figure E-24
Silver concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right)

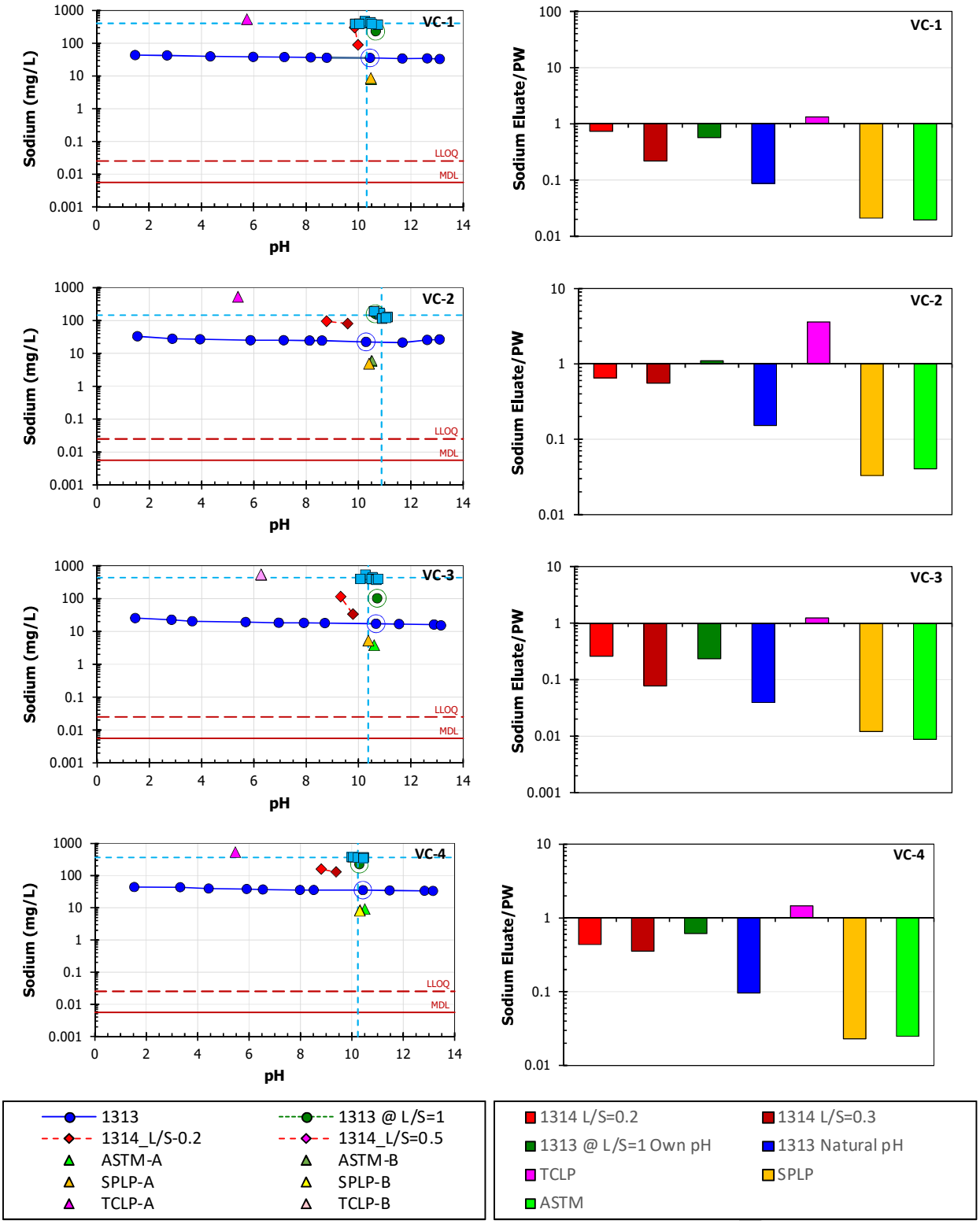

Figure E-25
Sodium concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right)

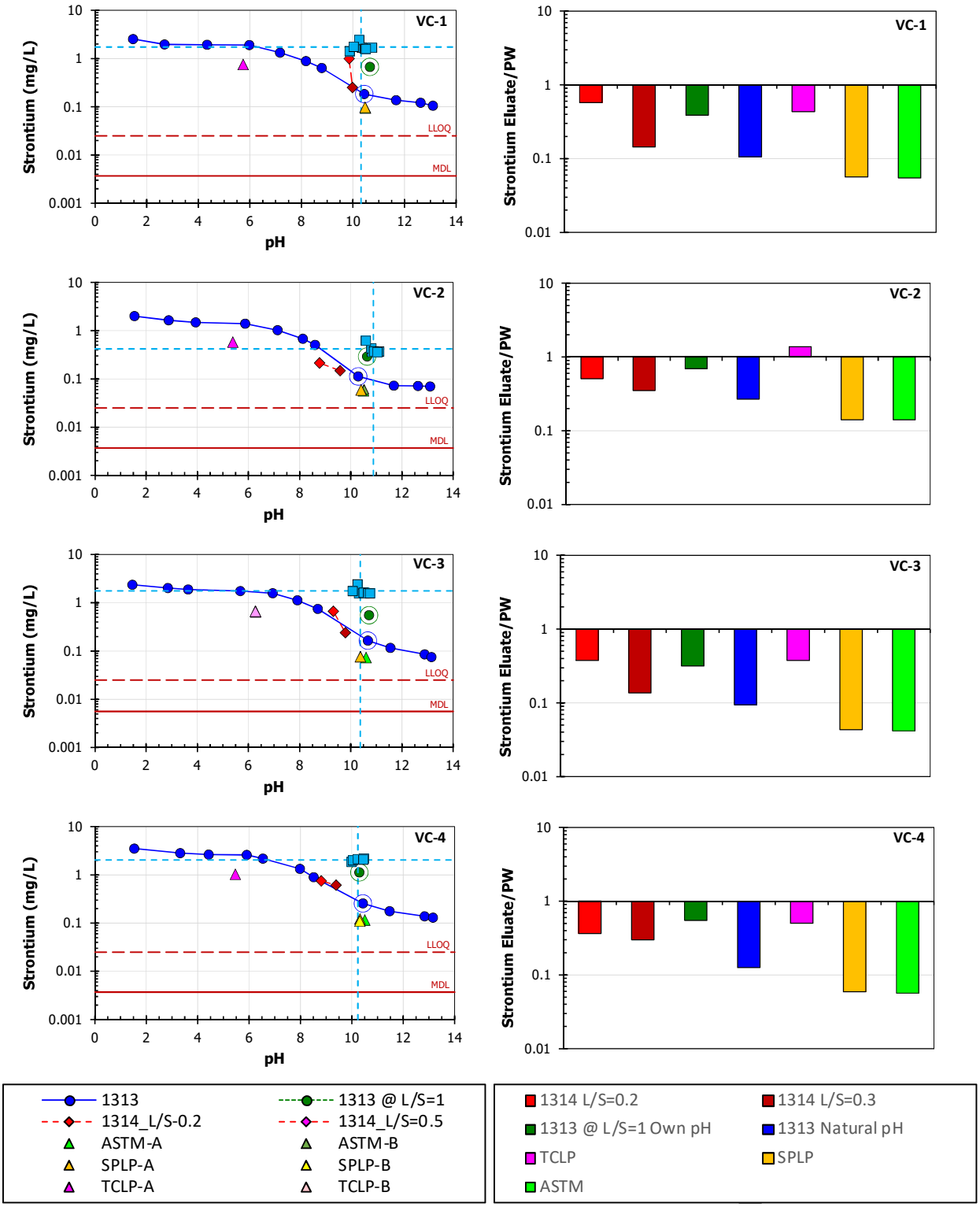

Figure E-26
Strontium concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right)

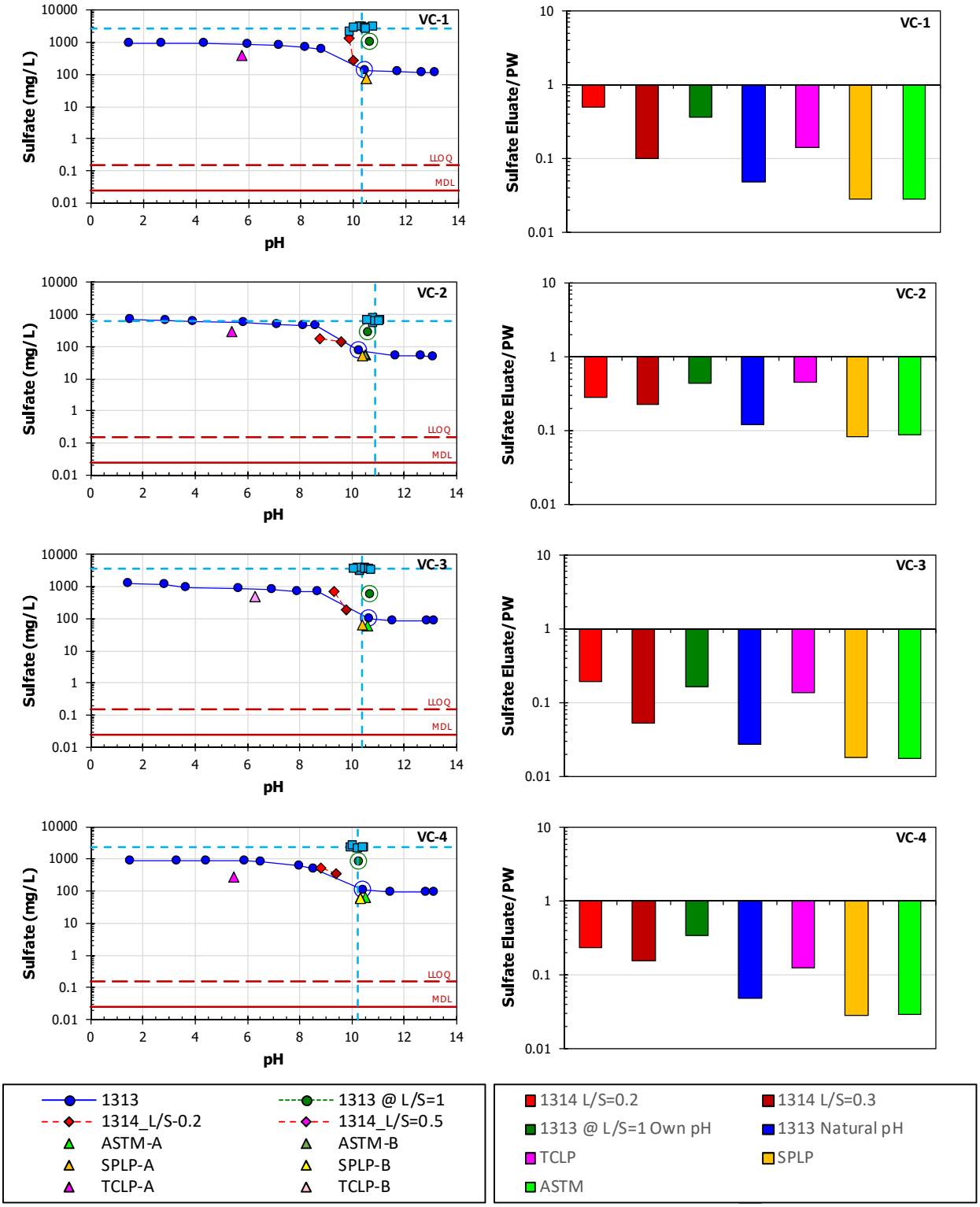

Figure E-27
Sulfate concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right)

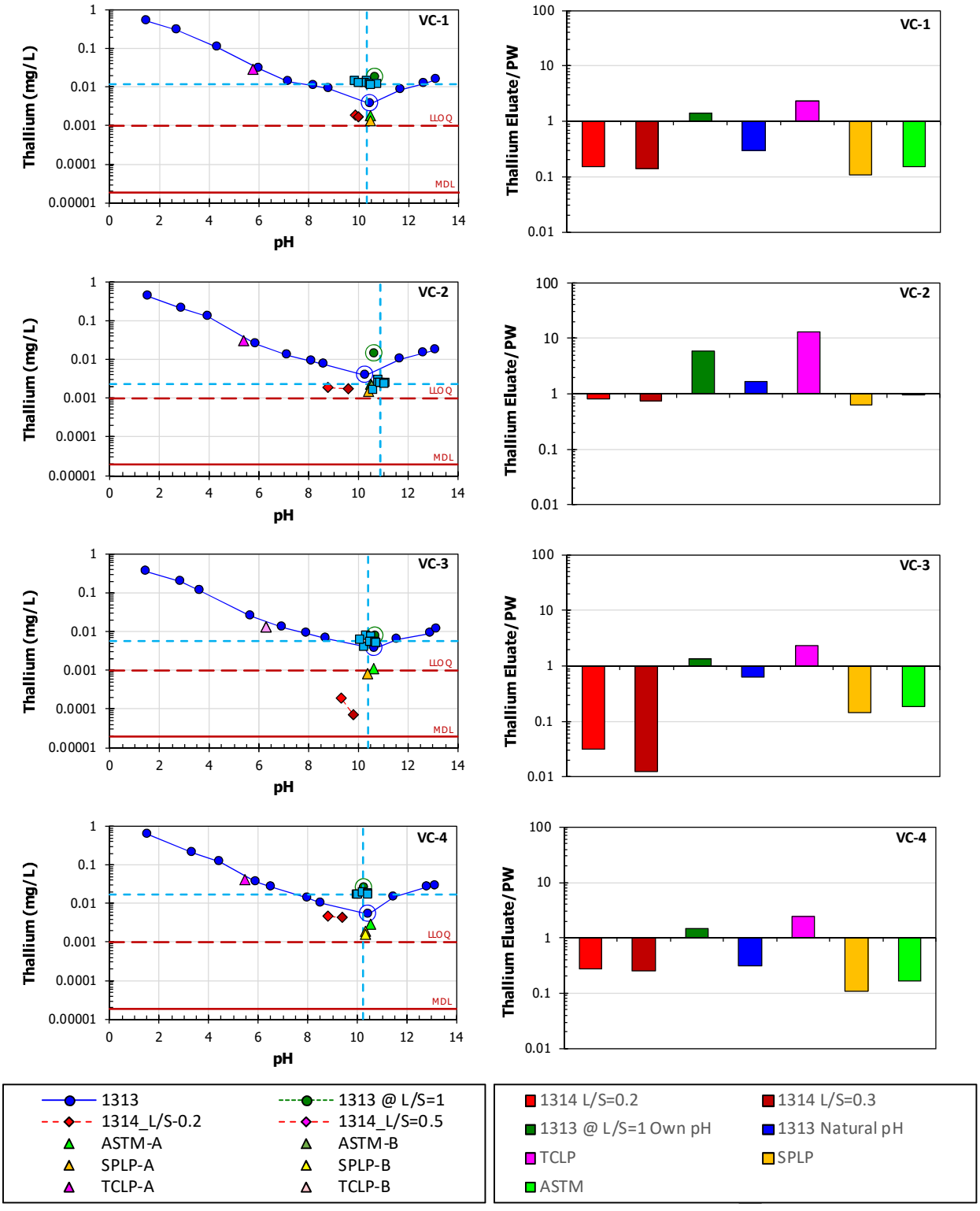

Figure E-28
Thallium concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right)

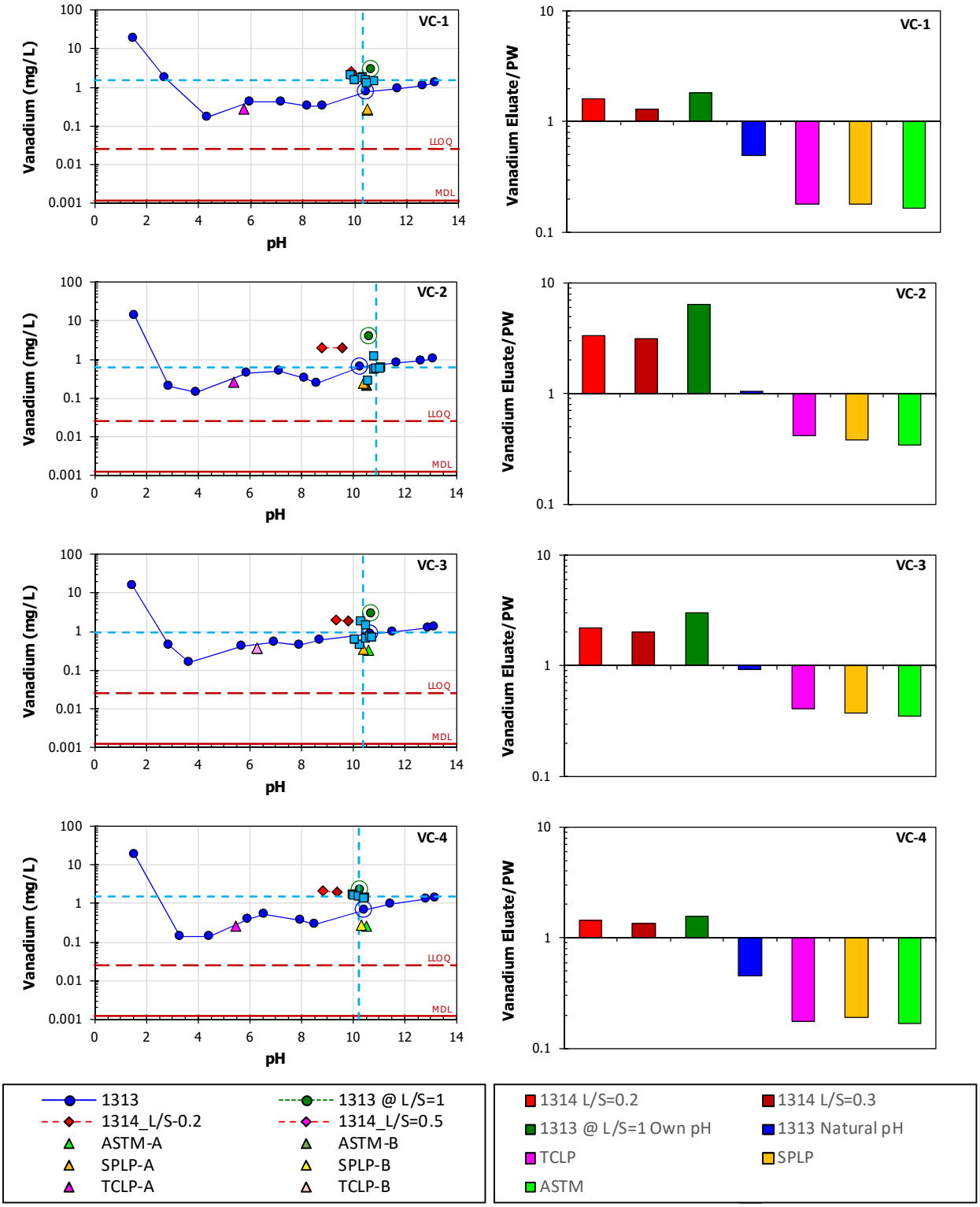

Figure E-29
Vanadium concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right)

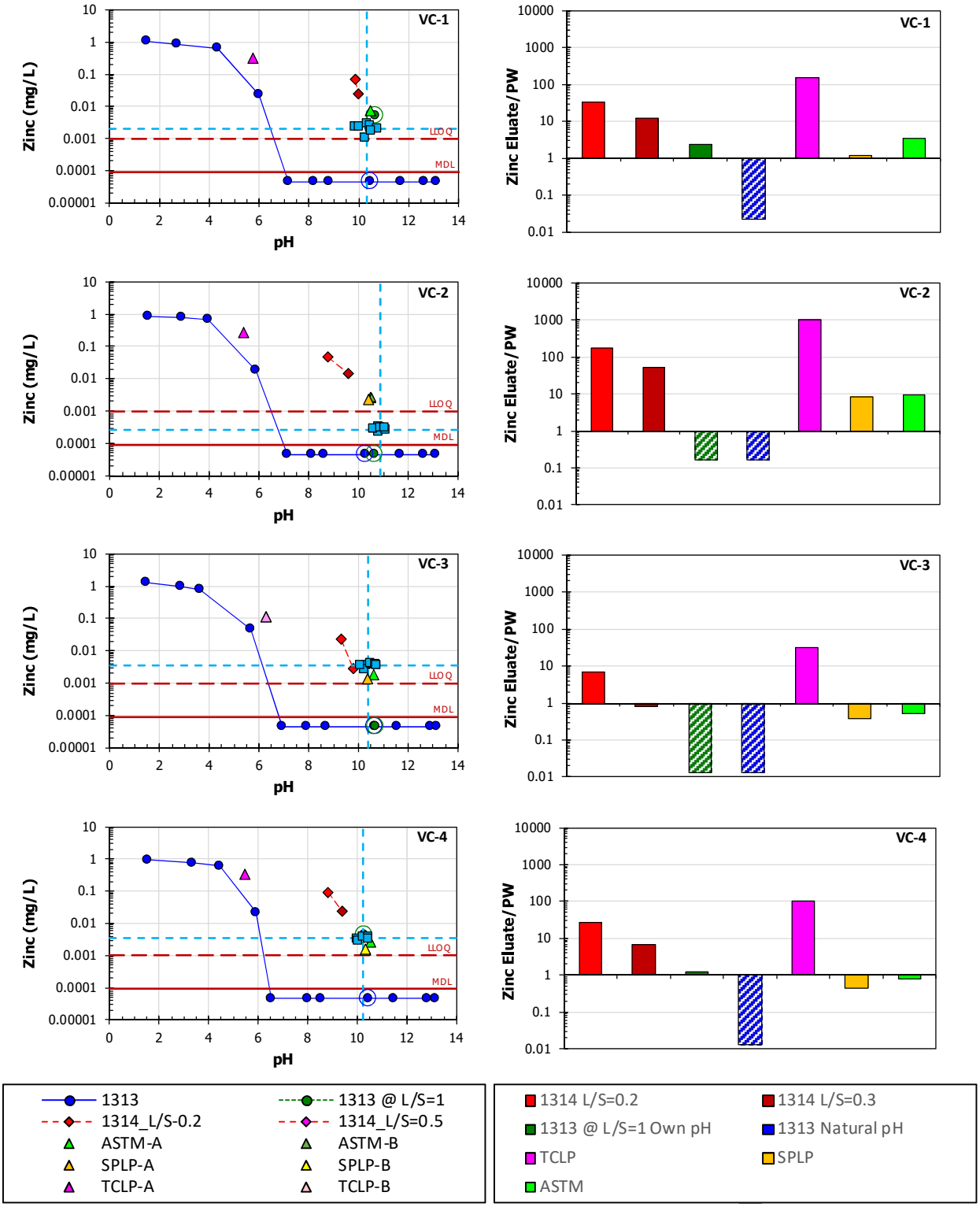

Figure E-30
Zinc concentration from leaching tests compared to measured and mean porewater concentrations as a function of pH (left) and as a ratio of eluate-to-porewater concentrations (right); crosshatched ratio results indicate estimates based on at least one MDL value

F
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Document 8

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Evaluation and Comparison of Leach Test and Porewater Variability for Multiple Coal Combustion Product Management Units

2022 TECHNICAL REPORT

Evaluation and Comparison of Leach Test and Porewater Variability for Multiple Coal Combustion Product Management Units

3002024214

Final Report, November 2022

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ABSTRACT

EPRI is researching coal combustion product (CCP) porewater chemistry to improve predictions of chemical evolution over the long term, particularly post-closure. An EPRI-member company made a large volume of porewater chemistry data available to EPRI, which was used to improve our understanding of porewater chemistry and how it varies between and within CCP units. This data set also provided information on the efficacy of USEPA's SW-846 1313 and 1316 leaching methods (also known as *LEAF 1313* and *LEAF 1316*) for evaluating porewater chemistry.

The objective of this research was to provide information on the chemistry of CCP porewater and how it may vary to help inform decision making on porewater evaluations. The specific objectives of this project were to:

- Evaluate the relationship of total (unfiltered) concentrations versus dissolved (filtered) concentrations in CCP porewater
- Assess the variability of porewater properties within and between CCP units
- Identify whether there are relationships between the laboratory leaching tests and measured porewater concentrations

Keywords

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Coal combustion products (CCPs)
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Product Title: Evaluation and Comparison of Leach Test and Porewater Variability for Multiple Coal Combustion Product Management Units

PRIMARY AUDIENCE: Subject matter experts and project managers responsible for closure or groundwater remediation at coal combustion product (CCP) management units.

SECONDARY AUDIENCE: Groundwater and geochemical modelers responsible for predicting the long-term effects of closure or groundwater remediation at CCP management units.

KEY RESEARCH QUESTION

EPRI is researching CCP porewater chemistry to improve predictions of chemical evolution over the long term, particularly post-closure. The objective of this research was to provide information on the chemistry of CCP porewater and how it may vary to inform decision making when characterizing porewater concentration for groundwater and geochemical models. The specific objectives of this project were to:

- Evaluate the relationship of total (unfiltered) concentrations versus dissolved (filtered) concentrations in CCP porewater
- Assess the variability of porewater properties within and between CCP units
- Identify whether there are relationships between the laboratory leaching tests and measured porewater concentrations

RESEARCH OVERVIEW

CCP porewater data were collected and provided by an EPRI-member company. The porewater data were collected from porewater monitoring points (PMPs) installed at 29 CCP management units between 2015 and 2021. In addition, CCP solids samples from the same location and depth as the PMPs at four units were subjected to leach testing using USEPA SW-846 methods 1313 (LEAF 1313) and 1316 (LEAF 1316). EPRI researchers used graphical and statistical methods to evaluate the data with respect to the project objectives.

KEY FINDINGS

- A comparison of total versus dissolved porewater sample results indicated:
  - Total and dissolved measurements are generally more comparable at concentrations elevated well above the reporting limit where laboratory analytical variability is less significant relative to concentration.
  - Major ions (Ca, Mg, Na, K), certain minor ions (Ba, B, Mn, Mo, Sr, Li), and elements with low detection frequency (Cd, Hg) were least likely to be affected by sample filtration.
  - Elements most likely to be affected by sample filtration were Al, Cr, Cu, Fe, and V.
- A comparison of intra-unit and inter-unit porewater variability results indicated:
  - There does not appear to be an overall pattern to define which parameters exhibit high or low variability. However, parameters of interest—either because they are CCP tracers (B and SO_4) or potential remediation drivers (As, Sb, B, Cr, Co, Li, Mo, and Se)—mostly have medium to high intra-unit variability, which suggests that more extensive porewater evaluation may be helpful to characterize a unit when developing a source term to model these parameters. Lithium was the only remediation driver with low intra-unit variability.

  - As, B, Co, Li, Mo, Se, and SO_4 had high inter-unit variability. Sb and Cr had medium and low inter-unit variability, respectively, which was attributed to their relatively low concentration in the porewater samples.
- Comparing leach test eluates to porewater samples, EPRI researchers observed:
  - LEAF 1313 and 1316 eluate concentrations were usually more than 25% higher or 25% lower than their paired median porewater concentrations. This observation was made for 1313 eluates at natural pH and the broader pH range for all porewaters as well as for 1316 results at low and high L/S.
  - Elements often controlled by available content—such as B, Ca, Cl, Li, Sr, and SO_4—tended to be underpredicted by the LEAF tests.
  - As, Fe, and Mn were also underpredicted, even though they tend to be solubility controlled, because the LEAF testing was performed under oxic conditions when the solubility of these elements is low.
  - Conversely, Se and Cr, which are most soluble under oxic conditions, tended to be overpredicted by the LEAF testing performed under oxic conditions.
  - Sb, Tl, and V tended to be overpredicted by the leach tests while other elements were overpredicted or underpredicted depending on test-specific and site-specific factors.

WHY THIS MATTERS

This research helps stakeholders understand that LEAF tests produce valuable information for comparing CCPs and understanding their geochemistry but are not reliable for predicting in-field porewater quality. This research also helps stakeholders understand CCP porewater variability, which can be used to improve characterization of source terms used in fate and transport or geochemical models and resulting predictions of groundwater quality in response to closure or remediation alternatives evaluated with these models.

HOW TO APPLY RESULTS

The conclusions of this research are stated in this executive summary. Readers interested in more detailed information for specific constituents can reference the body of this report.

LEARNING AND ENGAGEMENT OPPORTUNITIES

Previous research results published by EPRI related to porewater variability and the ability of leach tests to predict porewater chemistry are:

- *Leaching, Geotechnical, and Hydrologic Characterization of Coal Combustion Products from a Closed Coal Ash Impoundment: Capped Unit*. EPRI, Palo Alto, CA: 2020. 3002017363.
- *Leaching, Geotechnical, and Hydrologic Characterization of Coal Combustion Products from an Active Coal Ash Management Unit: Plant 42197*. EPRI, Palo Alto, CA: 2021. 3002018780.

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1
INTRODUCTION

EPRI is researching coal combustion product (CCP) porewater chemistry to improve predictions of chemical evolution over the long term, particularly post-closure. The objective of this research was to provide information on the chemistry of CCP porewater and how it may vary to inform decision making when characterizing porewater concentration for groundwater and geochemical models. The specific objectives of this project were to:

- Evaluate the relationship of total (unfiltered) concentrations versus dissolved (filtered) concentrations in CCP porewater
- Assess the variability of porewater properties within and between CCP units
- Identify whether there are relationships between the laboratory leaching tests and measured porewater concentrations

2
SUMMARY OF DATA

Coal Combustion Product Units

CCP porewater and leach test data were provided for 14 power plants in North Carolina (Synterra, 2021). The 14 power plants and 29 associated CCP management units are summarized in Table 2-1. Porewater data were collected from porewater monitoring points (PMPs) installed at all 29 units between 2015 and 2021. Additional data from laboratory leaching tests were provided for four plants (Allen, BCSS, Cliffside, and Marshall), based on cores collected at the time of PMP installation in 2018. Operational periods are summarized in Table 2-1 and illustrated in Figure 2-1.

All units contain coal ash and are primarily a mix of fly ash and bottom ash. Several units were excavated within the last 15 years (that is, Asheville units 1964 and 1982, Cliffside units 1–4 and ash storage area, Dan River ash basin, Riverbend ash basin and cinder storage area, and Weatherspoon 1979 ash basin).

Leach test data were obtained by LEAF 1313[1] and LEAF 1316.[2] Synthetic precipitation leaching procedure (SPLP) was also performed, but final values for eluate pH were not available, so the SPLP results are not further considered.

Data Preparation and Refinement

Data were provided in two separate files: one containing the porewater data and the other containing LEAF leach test eluate data. Due to differences in how these two files reported data, slightly different data preprocessing and quality assurance steps were taken for the porewater data file and the LEAF eluate data file. For both data files, concentrations reported in units of µg/L were converted to mg/L for consistency across the data set. Radium activities reported as negative values were set to zero for both data files. Quality control replicate sample analyses were removed from the porewater data set to avoid bias because those results are not independent.[3] In the porewater data, non-detect results were identified as those samples flagged with a "U" qualifier, and the method detection limit was used as the result. QA/QC samples were excluded from the LEAF eluate data. In the LEAF eluate data, non-detect results were identified

[1] LEAF 1313 (SW-846, USEPA 2019) is a standardized, parallel batch extraction method used to evaluate the liquid-solid partitioning (LSP) of inorganic constituents as a function of eluate pH.
[2] LEAF 1316 (SW-846, USEPA 2019) is an equilibrium-based leaching test intended to provide eluate solutions over a range of liquid-to-solid ratios (L/S). This method consists of five parallel batch extractions of a particle-size-reduced solid material in reagent water over a range of L/S values from 0.5 to 10 mL/g-dry material.
[3] The data set included four categories of duplicate samples, which combined represented a small fraction of the data set. In the absence of information about the nature of those duplicate sample categories, they were excluded from the data set used in this analysis.

as those samples with analytical results less than method detection limit (MDL), and the MDL was used as the result.

Table 2-1
Summary of sites and CCP units with available porewater and leachate data

Site	Unit(s)	PMPs	Years in Operation	Dry Ash Handling?[1]	Excavation?[2]
Allen	Ash Basin	21	1957–2019	Y	
Asheville	1964 Basin	2	1964–1982		Complete
Asheville	1982 Basin	1	1982–2020		Complete
BCSS	Ash Basin	9	1974–2019	Y	
Buck	Ash Basin, Cell 1	3	1982–2013		In Progress
Buck	Ash Basin, Cell 2	4	1957–2013		
Buck	Ash Basin, Cells 2 and 3	2	1957–2013		
Buck	Ash Basin, Cell 3	1	1957–2013		
Cape Fear	1963 Basin	2	1963–1970		
Cape Fear	1970 Basin	2	1970–1978		
Cape Fear	1985 Basin	2	1985–2012		
Cliffside	Active Ash Basin	6	1975–2018		
Cliffside	Ash Pore Water[3]	2	1975–2018		
Cliffside	Ash Storage Area	1	1970–1978		In Progress
Cliffside	Former Units 1–4 Basin	3	1957–1977		Complete
Cliffside	Inactive Unit 5 Basin	3	1972–1980		In Progress
Dan River	Ash Basin	3	1956– 2012		Complete
Lee	Lay of Land Area	2	<1951		
Lee	Inactive Ash Basin	2	1962–1982		
Marshall	Ash Basin	14	1965–1984	Y	
Marshall	Dry Ash Landfill	1	1984–1999	Y	
Mayo	Ash Basin	3	1983–2016	Y	
Riverbend	Ash Basin	3	1957–2013		Complete
Riverbend	Cinder Storage Area	1	1929–1957		Complete
Roxboro	East Ash Basin	2	1966–1983		
Roxboro	West Ash Basin	2	1973–2018	Y	
Sutton	1971 Basin	1	1971–2013		
Sutton	Former Ash Disposal Area	1	1954–1972		
Weatherspoon	Ash Basin	1	1958–2011		In Progress

Notes:

[1] Dry ash handling may include units constructed on top of the footprint of ash basins.

[2] Excavation of the unit has been performed (complete) or is ongoing (in progress) as of the date the information was provided.

[3] Based on review, these locations are likely within the Active Ash Basin but were kept separate because of their distinction in the database.

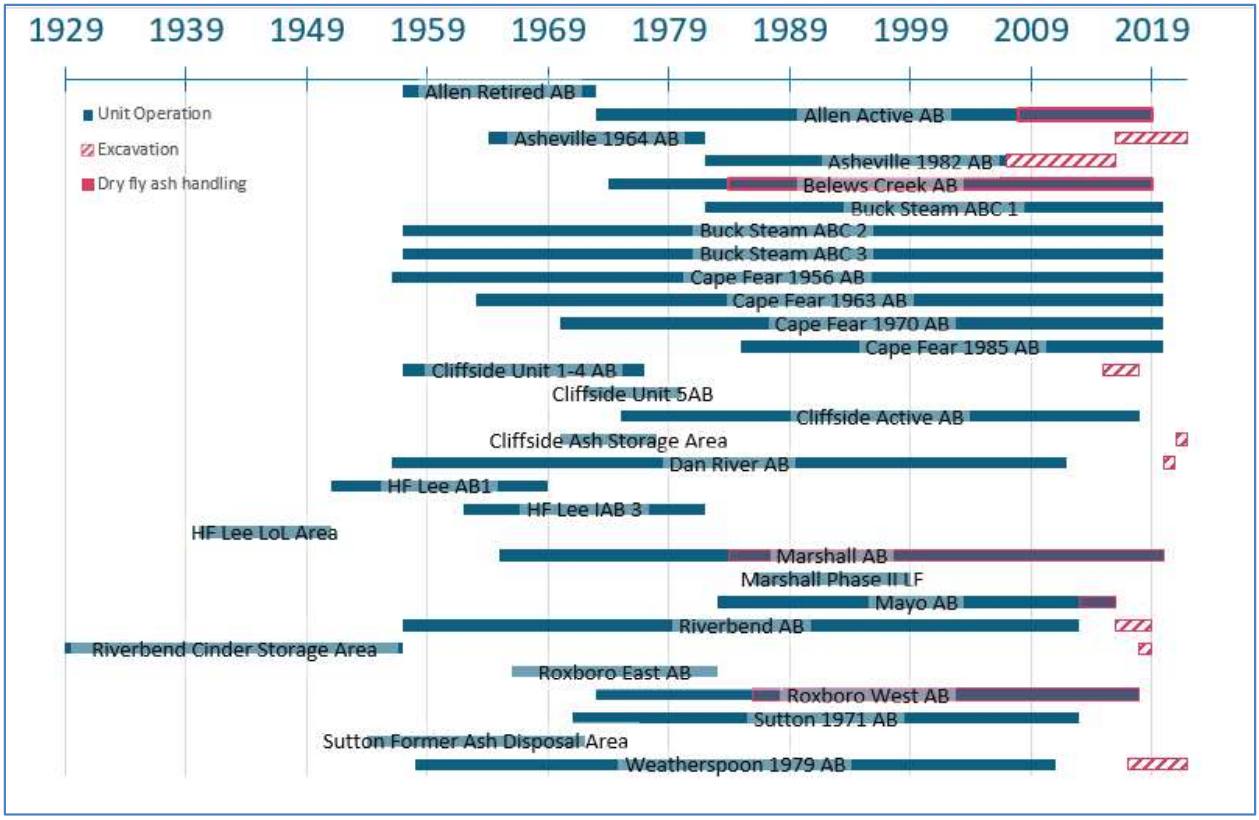

Figure 2-1
Operational history CCP units with available porewater data

Porewater Data

The porewater data set contained 111 parameters (including both total and dissolved fractions for most inorganic parameters) reported at a total of 100 individual PMPs. The porewater data set was refined prior to further analysis based on number of measurements for each parameter and degree of relevance in CCP porewater. Most parameters with fewer than 1,000 measurements were excluded from this analysis. This included redox speciation measurement, dissolved samples filtered at a 0.1 µm level, and some radioactive parameters. Some parameters with fewer than 1,000 total measurements were retained due to their relevance for CCP (fluoride, lithium, and isotopes of radium) or to facilitate comparisons between total and dissolved concentrations. In addition, dissolved oxygen (often unreliable due to contamination during sampling) and oxidation-reduction potential (ORP) (redundant with Eh) measurements were excluded. After refinement, the porewater data set contained 71 parameters measured at 100 PMPs (see Table 2-2 for a list of parameters analyzed in porewater and Appendix A for sample counts and basic statistics).

Table 2-2
Summary of units with observations for each parameter

Parameter	Units	
	Total	Dissolved
Alkalinity (ALK)	29	
Aluminum (Al)	29	29
Antimony (Sb)	29	29
Arsenic (As)	29	29
Barium (Ba)	29	29
Beryllium (Be)	29	29
Bicarbonate Alkalinity (ALK-HCO_3)	29	
Boron (B)	29	29
Cadmium (Cd)	29	29
Calcium (Ca)	29	19
Carbonate Alkalinity (ALK-CO_3)	29	
Chloride (Cl)	29	
Chromium (Cr)	29	29
Hexavalent Chromium (Cr(VI))	26	
Cobalt (Co)	29	29
Copper (Cu)	29	29
Eh	29	
Fluoride (F)	23	
Iron (Fe)	29	29
Lead (Pb)	29	29
Lithium (Li)	23	20
Magnesium (Mg)	29	19
Manganese (Mn)	29	29
Mercury (Hg)	29	29
Molybdenum (Mo)	29	29
Nickel (Ni)	29	29
Nitrate + Nitrite (NO_2+NO_3)	29	
pH	29	
Potassium (K)	29	19
Total Radium (Ra)	8	
Radium-226 (^{226}Ra)	23	
Radium-228 (^{228}Ra)	23	
Selenium (Se)	29	29
Sodium (Na)	29	19

Table 2-2 (continued)
Summary of units with observations for each parameter

Parameter	Units	
	Total	Dissolved
Specific Conductance (EC)	29	
Strontium (Sr)	29	29
Sulfate (SO_4)	29	
Sulfide (S^{2-})	29	
Temperature (TEMP)	29	
Thallium (Tl)	29	29
Total Dissolved Solids (TDS)		29
Total Organic Carbon (TOC)	29	
Total Suspended Solids (TSS)	29	
Turbidity (TURB)	29	
Vanadium (V)	29	29
Zinc (Zn)	29	29

Leach Test Data

The LEAF data set contained 30 parameters and final eluate pH values for tests performed on CCP samples from 18 PMP boreholes. The LEAF and porewater data were paired based on co-location of station and depth of sample (Table 2-3).[4] For cases in which multiple LEAF samples were collected from multiple depths within the borehole spanning the corresponding porewater screen interval, the LEAF results were paired with the same porewater data. Parameters with no corresponding results in the porewater data set (U), three or fewer samples (Hg), and indicator parameters (ORP, specific conductance, and total dissolved solids [TDS]) were not included in the analysis. The combined leach test data set contained 25 parameters and final eluate pH values reported at 18 PMPs. LEAF 1313 testing was performed at pH values of about 4, 6, 8, and 10 and at natural pH. LEAF 1316 testing was performed at L/S ratios of 0.5, 1, 2, 4, 5, 6, 8, and 10.

[4] LEAF test data that did not have porewater data available from the same PMP and at the screened depth interval are not included in the analysis.

Table 2-3
Summary of leach test and porewater pairings for each PMP and depth interval

Site Name	Station ID	LEAF 1313 Sample Depths (ft)	LEAF 1316 Sample Depths (ft)	Porewater Screen Intervals (ft)
Allen[1]	AB-21SL	34–44	34–44	35–45
Allen	AB-25S	7–20	7–20	5–20
Allen	AB-25SL	30–45	30–45	30–45
Allen	AB-29S	9–17	9–17	5–20
Allen	AB-29SL	37–47	37–47	36–46
Allen	AB-35S	42–51	42–51	35–50
BCSS	AB-04S	3–18	3–18	3–18
BCSS	AB-04SL	51–61	51–61	51–61
Cliffside	AB-03S	30–50	30–50	22–37
Cliffside	AB-03SL	54–59	54–59	Unknown[2]
Cliffside	AB-04S	10–21	10–21	5–20
Cliffside	AB-04SL	35–39	35–39	29–39
Cliffside	AS-07S	30–40	30–40	28.5–43.5
Cliffside	U5-02S	47–57	47–57	50–65
Cliffside	U5-02S	57–66.5	57–66.5	50–65
Marshall	AB-12SL	43–45	43–45	43–53
Marshall	AB-15S	3–15	3–15	8–23
Marshall	AB-15S	18–20	18–20	8–23
Marshall	AB-15SL	47–49	47–49	43–53
Marshall	AB-18S	8–13	8–13	6–16

Notes:

[1] Each row represents one set of paired porewater and leach test data.

[2] Assumed to be a relevant comparison in the absence of depth interval information.

Porewater Results

An overview of the refined porewater data set is presented in Table 2-4. Sample sizes for each parameter varied from 70 samples (dissolved measurements for major ions), to between 100 and 1,000 samples (Ra isotopes, F, and Li), to over 1,000 samples (the rest of the parameters). Most of the major ions were detected in more than 90% of samples, except for NO_2+NO_3, (detected in 49% of samples) and ALK-CO_3 (detected in 12% of samples). Many minor and trace elements (total Al, total and dissolved As, Ba, B, Co, Fe, Li, Mn, Mo, Ni, Sr, and V) were detected in more than 75% of samples. Other minor trace elements were detected in between 25% and 75% of samples, including dissolved Al; total Cd and Pb; and both total and dissolved Sb, Be, Cr, Cr(VI), Cu, Se, Tl, and Zn. Total organic carbon (TOC) and total suspended solids (TSS) were also detected in between 25% and 75% of samples. Dissolved Cd, dissolved Pb, and both total and dissolved Hg were detected in 25% or fewer samples. Sulfide (S^{2-}) was also detected in very few samples (8%).

Table 2-5 shows the results of comparing porewater concentrations to a threshold value based on a regulatory standard, specifically the maximum contaminant level (MCL; 40 C.F.R.§141), secondary maximum contaminant level (SMCL; USEPA, 2022a), or regional screening level (RSL; USEPA, 2022b), where a standard was available. Although **these standards are not directly applicable to porewater data,** they provide useful thresholds for evaluating porewater concentrations. For example, if porewater concentrations are consistently below the threshold value for a parameter, the CCP unit would be an unlikely source of downgradient groundwater protection standard (GWPS) exceedances for that parameter. The statistics presented in this table are comparable to a similar tabulation by EPRI (2021a) for a larger, more widely distributed, porewater data set. However, there are differences in the tabulations. The current data set was compiled to determine the percentage of all samples with a concentration higher than a benchmark. The EPRI (2021a) data set is based on the average concentration of all porewater samples collected at a unit (range from as few as 1 to more than 100 samples per unit).

Both data sets show that As and Li have concentrations higher than a GWPS-based threshold in more than 50% of the sample and site average tabulations. In addition, Mn is greater than its SMCL-based threshold in more than 50% of the two tabulations.[5] Conversely, many of the tested constituents (Al, Sb, Ba, Be, Cr, Cu, F, Pb, Hg, Ra, Sr, Tl, and Zn) were unlikely (<15%) to have a concentration higher than their respective thresholds in both tabulations.

[5] The SMCL is based on aesthetic considerations to drinking water quality rather than on health-based considerations.

Table 2-4
Summary of porewater data

Parameter	Unit	Total			Dissolved		
		Sample Count	Detection Frequency (%)	Median	Sample Count	Detection Frequency (%)	Median
Field Parameters							
Eh	mV	1390	100	132	--	--	--
pH	SU	1390	100	7.01	--	--	--
EC	µmhos/cm	1390	100	640	--	--	--
TEMP	Deg C	1390	100	19.695	--	--	--
TURB	NTUs	1388	100	4.8	--	--	--
Major Ions							
ALK	mg/L	1375	94	139	--	--	--
ALK-HCO_3	mg/L	1361	91	137	--	--	--
Ca	mg/L	1383	100	76.5	84	99	75.9
ALK-CO_3	mg/L	1355	12	5	--	--	--
Cl	mg/L	1377	100	10.1	--	--	--
F	mg/L	440	94	0.33	--	--	--
Mg	mg/L	1382	100	15.55	70	99	19.45
NO_2 + NO_3	mg-N/L	1333	49	0.02	--	--	--
K	mg/L	1381	96	10.6	70	91	9.845
Na	mg/L	1383	99	12.5	70	99	10.65
SO_4	mg/L	1376	98	103	--	--	--
Minor and Trace Elements							
Al	mg/L	1357	79	0.128	1199	57	0.1
Sb	mg/L	1343	60	0.00099	1190	54	0.0007385
As	mg/L	1382	99	0.2215	1216	99	0.1965
Ba	mg/L	1288	98	0.172	1173	99	0.158
Be	mg/L	1297	43	0.0001	1178	37	0.0001
B	mg/L	1383	98	1.25	1216	98	1.245
Cd	mg/L	1247	27	0.00008	1159	24	0.00008

Table 2-4 (continued)
Summary of porewater data

Parameter	Unit	Total			Dissolved		
		Sample Count	Detection Frequency (%)	Median	Sample Count	Detection Frequency (%)	Median
Minor and Trace Elements (continued)							
Cr	mg/L	1381	66	0.00076	1211	58	0.0005
Cr(VI)	mg/L	1188	31	0.00003	--	--	--
Co	mg/L	1382	83	0.001095	1213	80	0.001
Cu	mg/L	1117	59	0.00069	1116	50	0.000605
Fe	mg/L	1383	95	2.57	1209	83	2.22
Pb	mg/L	1130	36	0.000105	1115	15	0.0001
Li	mg/L	515	95	0.118	142	96	0.182
Mn	mg/L	1383	95	0.7	1216	93	0.659
Hg	mg/L	1145	6	0.0002	1130	2	0.0002
Mo	mg/L	1287	93	0.0253	1176	93	0.02585
Ni	mg/L	1317	86	0.0023	1185	86	0.00205
Se	mg/L	1353	47	0.00089	1199	46	0.000756
Sr	mg/L	1383	100	1.78	1216	100	1.675
Tl	mg/L	1368	63	0.00018	1208	59	0.00012
V	mg/L	1381	95	0.00312	1214	90	0.0025
Zn	mg/L	1135	51	0.01	1120	41	0.01
Other							
S^{2-}	mg/L	1105	8	0.1	--	--	--
TDS	mg/L	--	--	--	1375	99	411
TOC	mg/L	1281	72	1	--	--	--
TSS	mg/L	1118	62	5.6	--	--	--
Radiologic							
^{226}Ra	pCi/L	393	92	0.333	--	--	--
^{228}Ra	pCi/L	393	88	0.564	--	--	--
Ra	pCi/L	114	100	0.8225	--	--	--

Table 2-5
Comparison of porewater data to reference regulatory standards

Parameter	Unit	Threshold Value	Threshold Basis	Samples Above Threshold (%)	Site Averages Above Threshold (%)[1]
Al	mg/L	20	RSL	3.6	4
Sb	mg/L	0.006	MCL	12	17
As	mg/L	0.01	MCL	84	71
Ba	mg/L	2	MCL	0.16	0
Be	mg/L	0.004	MCL	5.2	6
B	mg/L	4	RSL	24	68
Cd	mg/L	0.005	MCL	1.6	24
Cl	mg/L	250	SMCL	4.1	23
Cr	mg/L	0.1	MCL	0.94	10
Co	mg/L	0.006	RSL	24	27
Cu	mg/L	1.3	MCL	0	0
F	mg/L	4	MCL	5	---
Fe	mg/L	14	RSL	26	4
Pb	mg/L	0.015	MCL	0.62	4
Li	mg/L	0.04	RSL	76	74
Mn	mg/L	0.05	SMCL	83	72
Hg	mg/L	0.002	MCL	0.17	4
Mo	mg/L	0.1	RSL	33	78
Se	mg/L	0.05	MCL	3.1	47
Sr	mg/L	12	RSL	1.8	2
SO_4	mg/L	250	SMCL	24	91
Tl	mg/L	0.002	MCL	8.6	15
Ra	pCi/L	5	MCL	0	---
V	mg/L	0.086	RSL	6.8	31
Zn	mg/L	6	RSL	0.26	0

Note:
[1] The site averages are from EPRI (2021a); --- indicates parameters not listed in EPRI (2021a).

Leach Test Results

An overview of the LEAF test eluates is presented in Tables 2-6 (LEAF 1313) and 2-7 (LEAF 1316). Each individual sample represents the result for one test condition (that is, a specific pH for LEAF 1313 or a specific liquid-to-solid ratio for LEAF 1316) applied to one CCP solid sample. For summary purposes, the LEAF 1313 natural pH values (no acid/base added; sometimes referred to as the *natural pH*) and LEAF 1316 results at liquid-to-solid ratio (L/S) = 1.0 are compiled for table statistics. The proportion of detected results for all parameters in both LEAF tests is higher than those reported in the porewater measurements due to lower detection

limits used for most analytes in the LEAF tests. However, Cd was usually not detected and Hg was not detected in the LEAF 1313 samples, and Be was usually not detected and Pb and Hg were not detected in the LEAF 1316 samples.

Table 2-6
Summary of LEAF 1313 data

Param	Units	All LEAF 1313 Samples		LEAF 1313 @ Natural pH					
		Sample Count	PMP Count	Sample Count	PMP Count	Detection Frequency	Min	Median	Max
Sb	mg/L	93	18	20	18	95%	0.0011	0.0099	0.02
As	mg/L	93	18	20	18	100%	0.0025	0.12	0.25
Ba	mg/L	93	18	20	18	100%	0.025	0.098	0.35
Be	mg/L	93	18	20	18	10%	0.000057	0.000057	0.00016
B	mg/L	93	18	20	18	100%	0.043	0.093	1.2
Cd	mg/L	93	18	20	18	5%	0.00013	0.00013	0.00016
Ca	mg/L	93	18	20	18	100%	1.9	10	32
Cl	mg/L	93	18	20	18	40%	0.71	0.71	48
Cr	mg/L	93	18	20	18	100%	0.001	0.0035	0.022
Cr(VI)	mg/L	83	16	18	16	28%	0.0032	0.0032	0.022
Co	mg/L	93	18	20	18	55%	0.000075	0.00013	0.002
F	mg/L	93	18	20	18	100%	0.1	0.29	0.73
Fe	mg/L	93	18	20	18	80%	0.014	0.048	0.21
Pb	mg/L	93	18	20	18	40%	0.000094	0.000094	0.0032
Li	mg/L	93	18	20	18	95%	0.0026	0.012	0.03
Mn	mg/L	93	18	20	18	75%	0.0014	0.0037	0.28
Hg	mg/L	93	18	20	18	0%	0.000065	0.000065	0.000065
Mo	mg/L	93	18	20	18	100%	0.0031	0.024	0.18
Ni	mg/L	49	10	11	10	82%	0.00031	0.00067	0.011
^{226}Ra	pCi/L	34	7	7	7	100%	0	0.13	0.255
^{228}Ra	pCi/L	34	7	7	7	100%	0.109	0.16	0.344
Se	mg/L	93	18	20	18	100%	0.011	0.040	0.23
Sr	mg/L	93	18	20	18	100%	0.04	0.21	0.53
SO_4	mg/L	93	18	20	18	100%	2.3	12	49
Tl	mg/L	93	18	20	18	75%	0.000063	0.00012	0.00062
V	mg/L	83	16	18	16	100%	0.0023	0.092	0.3

Table 2-7
Summary of LEAF 1316 data

Param	Units	All LEAF 1316 Samples		LEAF 1316 @ L/S = 1					
		Sample Count	PMP Count	Sample Count	PMP Count	Detection Frequency	Min	Median	Max
Sb	mg/L	100	18	20	18	100%	0.004	0.043	0.14
As	mg/L	100	18	20	18	100%	0.004	0.11	0.67
Ba	mg/L	100	18	20	18	100%	0.034	0.11	0.21
Be	mg/L	100	18	20	18	5%	0.000057	0.000057	0.000074
B	mg/L	100	18	20	18	100%	0.15	0.53	11
Cd	mg/L	100	18	20	18	30%	0.00013	0.00013	0.0007
Ca	mg/L	100	18	20	18	100%	7.8	48	210
Cl	mg/L	100	18	20	18	100%	1.3	3.9	520
Cr	mg/L	100	18	20	18	100%	0.00081	0.0038	0.11
Cr(VI)	mg/L	90	16	18	16	50%	0.0032	0.0044	0.12
Co	mg/L	100	18	20	18	90%	0.000075	0.00024	0.0099
F	mg/L	100	18	20	18	100%	0.12	0.61	3.6
Fe	mg/L	100	18	20	18	15%	0.014	0.014	0.08
Pb	mg/L	100	18	20	18	0%	0.000094	0.000094	0.000094
Li	mg/L	100	18	20	18	100%	0.0064	0.044	0.21
Mn	mg/L	100	18	20	18	90%	0.0014	0.020	1.4
Hg	mg/L	100	18	20	18	0%	0.000065	0.000065	0.000065
Mo	mg/L	100	18	20	18	100%	0.0065	0.14	1.5
Ni	mg/L	55	10	11	10	100%	0.00054	0.0023	0.072
^{226}Ra	pCi/L	30	5	6	5	100%	0.0611	0.19	0.533
^{228}Ra	pCi/L	30	5	6	5	100%	0	0.25	0.462
Se	mg/L	100	18	20	18	100%	0.025	0.12	0.85
Sr	mg/L	100	18	20	18	100%	0.21	1.0	2.6
SO_4	mg/L	100	18	20	18	100%	13	100	420
Tl	mg/L	100	18	20	18	100%	0.00013	0.00066	0.0029
V	mg/L	90	16	18	16	100%	0.0038	0.099	0.71

3
POREWATER ANALYSIS

Summary

This section presents an evaluation of the porewater data set that included a comparison of total and dissolved concentrations as well as an evaluation of the variability observed in porewater concentrations.

Total versus dissolved sample results:

- Total and dissolved measurements are generally more comparable at concentrations elevated well above the reporting limit where laboratory analytical variability is less significant relative to concentration.
- Major ions (Ca, Mg, Na, K), certain minor ions (Ba, B, Mn, Mo, Sr, Li), and elements with low detection frequency (Cd, Hg) were least likely to be affected by sample filtration.
- Elements most likely to be affected by sample filtration were Al, Cr, Cu, Fe, and V.

Intra-unit and inter-unit variability results:

- There does not appear to be an overall pattern to define which parameters exhibit high or low variability. However, parameters of interest—either because they are CCP tracers (B and SO_4) or potential remediation drivers (As, Sb, B, Cr, Co, Li, Mo, and Se)—mostly have medium to high intra-unit variability, which suggests that more extensive porewater evaluation may be helpful to characterize a unit when developing a source term to model these parameters. Li was the only remediation driver with low intra-unit variability.
- As, B, Co, Li, Mo, Se, and SO_4 had high inter-unit variability. Sb and Cr had medium and low inter-unit variability, respectively, which, as previously noted, can be attributed to their relatively low concentration (medians lower than 0.001 mg/L; see Appendix A) in the porewater samples reviewed in this analysis.

Analysis of Total Versus Dissolved Concentrations

Background

Porewater samples from CCP may be unfiltered or filtered[6] in the field, resulting in determinations of total or dissolved concentrations, respectively. The presence of suspended solids in porewater samples has the potential to affect total porewater measurements and can cause analytical results to not be representative of actual porewater concentrations. Geochemical modeling studies generally assume that the samples are field-filtered, while samples collected for

[6] Dissolved data represent field filtration using a 0.45-µm filter.

other purposes may not be filtered. Therefore, it is useful to understand the similarity and dissimilarity between total and dissolved measurements in CCP porewater samples.

A dissolved concentration lower than the total concentration suggests desorption of chemical constituents from small particles (>0.45 μm) in the sample when a total sample is acidified. There is no environmental explanation for a dissolved concentration higher than a total concentration. However, additional variability could be a result of heterogeneity in the samples themselves. Although paired total and dissolved samples are collected from the same location in the same sample event, they are often collected sequentially and therefore may represent slightly different fractions of porewater.

Methods

The porewater data set described in Section 2 was refined to include only samples that had both total and dissolved fractions analyzed (that is, samples with paired total and dissolved data). For samples in which either result was a non-detect, the MDL was used to calculate the ratio. The total versus dissolved concentration comparison plots are provided in Appendix B.

Data were evaluated by determining if total and dissolved concentrations were effectively similar for each sample. Total and dissolved concentrations for a sample were considered similar when the difference was within a predefined range of error. A difference of up to 20% was set as the predefined error—a percentage that is typically acceptable to meet quality control standards in a laboratory for a set of duplicate samples (USEPA, 2020). Therefore, a difference of 20% between the total and dissolved measurements was considered similar because it is within the range of accepted typical analytical variability. The overall degree of similarity for a parameter was then quantified by the percent of samples in the entire data set that had a difference of less than 20% between the total and dissolved concentrations.

Results and Discussion

The results of the total versus dissolved concentration comparison are presented in Table 3-1. For each parameter, the percentage of samples for which dissolved results were similar to totals is presented as well as the percent of samples above and below the defined range. The degree to which dissolved and total concentrations were similar ranged from 42% to 97% (Table 3-1). When there was a difference, the dissolved sample usually (63% of sample pairs with a difference) had the lower concentration, but this was not always the case.

Table 3-1
Summary of total versus dissolved concentration comparison

Parameter	Number of Samples Compared	Number Where Total and Dissolved Both Non-Detect	Dissolved Lower Than Total	Dissolved Higher Than Total	Similar Total and Dissolved Concentrations[1]
Al	1199	236	39%	10%	50%
Sb	1185	440	11%	11%	78%
As	1215	6	14%	6%	80%
Ba	1157	8	6%	2%	93%
Be	1164	560	20%	18%	62%
B	1216	19	3%	2%	95%
Cd	1140	794	7%	7%	86%
Ca	84	0	6%	0%	94%
Cr	1209	311	36%	22%	42%
Co	1212	163	21%	9%	71%
Cu	1076	330	28%	28%	44%
Fe	1209	64	35%	6%	59%
Pb	1078	653	19%	9%	72%
Li	136	5	2%	6%	92%
Mg	70	0	4%	0%	96%
Mn	1216	57	6%	3%	90%
Hg	1108	1037	2%	4%	95%
Mo	1162	67	6%	6%	88%
Ni	1176	122	17%	13%	70%
K	70	2	0%	4%	96%
Se	1194	569	14%	11%	75%
Na	70	0	1%	1%	97%
Sr	1216	1	2%	1%	97%
Tl	1204	403	17%	11%	72%
V	1213	41	40%	9%	52%
Zn	1081	448	18%	20%	62%

Note:

[1] Percentages may not add up to 100% due to rounding.

The similarity between total and dissolved results is visualized by plotting the dissolved concentration (y axis) against the total concentration (x axis) (Figure 3-1; Appendix B). Each sample pair is represented by one data point. If total and dissolved concentrations are identical in a sample, that point will fall on the 1:1 line. The 20% range of variability is illustrated by the dashed lines surrounding the 1:1 line. Any points that fall outside of the area between those lines are considered to have different total and dissolved concentrations. Points below the defined range of comparability have lower dissolved than total concentrations, while points above the defined range have higher dissolved than total concentrations (which, as discussed previously, is likely an artifact of sample and/or laboratory variability). The color of each point reflects the turbidity measured for that sample.

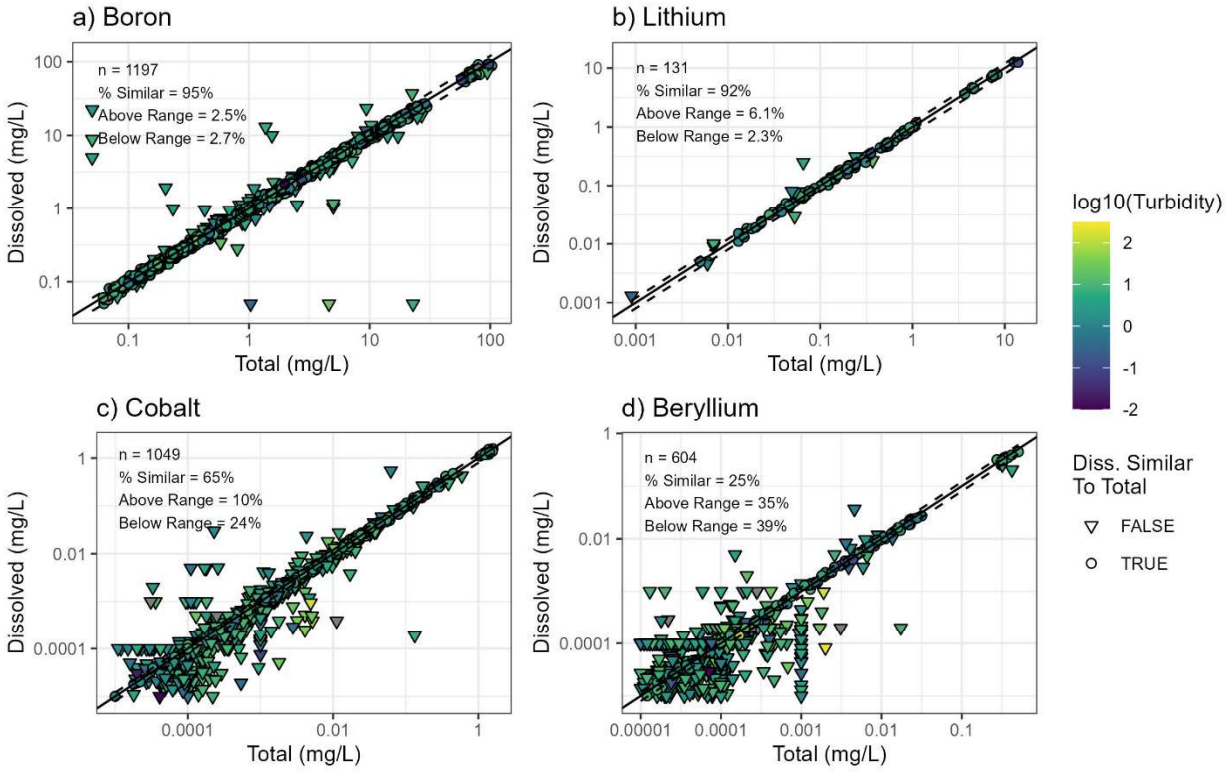

Figure 3-1
Comparison of total versus dissolved measurements for selected parameters when detected in one or both of the paired samples

The statistics on the graphs are for sample pairs where a concentration is detected in one or both samples and differs from Table 3-1 because samples where both results are non-detect were not considered.

Parameters such as Co, which sorb strongly to particulates and therefore have total concentrations more heavily influenced by the presence of turbidity, tend to have a greater proportion of samples below the defined range used for comparison. In contrast, Be does not sorb as strongly to particulates and instead has relatively equivalent proportions of points above and below the defined range. For both Co and Be, fewer samples fall outside the defined range of similarity at higher total concentrations. This suggests that total and dissolved measurements are generally more comparable at concentrations elevated well above the reporting limit (that is, where laboratory analytical variability is less significant relative to concentration).

For both Co and Be, the samples with the highest turbidity typically fall below the defined range. This observation is consistent with turbidity potentially contributing to higher total than dissolved concentrations due to the presence of sorbed ions, although this relationship is qualitative, and turbidity is not the only factor causing differences between dissolved and total concentrations (because not all samples with lower dissolved concentrations compared to totals have elevated turbidity).

Table 3-2 groups the results presented in Table 3-1. This grouping shows that major ions (Ca, Mg, Na, K), certain minor ions (Ba, B, Mn, Mo, Sr, Li), and elements with low detection frequency (Cd, Hg) were least likely to be affected by sample filtration. It is worth noting that Cd and Hg have much lower percentages for similarity (54% and 17%, respectively) when detected in one or both of the total and dissolved samples (see Appendix B). Elements most likely to be affected by sample filtration were Cr, Cu, Al, Fe, and V.

Table 3-2
Grouping of total vs. dissolved sample results

Concentration Tendency for Pairs That Were Not Similar	Percent of Paired Total and Dissolved Samples with Similar Concentration					
	40% to 50%	50% to 60%	60% to 70%	70% to 80%	80% to 90%	>90%
Dissolved more often had lower concentration	Cr	Al, Fe, V	Be, Ni	As, Co, Pb, Se, Tl		Ca, Mg, Ba, B, Mn, Sr
Similar frequency for lower and higher concentration	Cu			Sb	Cd, Mo	Na
Dissolved more often had higher concentration			Zn			K, Li, Hg

Analysis of Variability in Porewater

Background

Porewater composition variability between different CCP units (inter-unit variability) and within the same CCP unit (intra-unit variability) was evaluated in this task. Variability between different units may be due to different operational histories and different CCP source materials. Variability within a single unit may reflect different CCP composition if more than one CCP is managed in the unit (particularly for landfills), differences associated with chemical evolution over time for older vs. newer portions of the unit (particularly for landfills), and, in the case of

sluiced CCPs, the differences in chemistry associated with particle size, because coarse CCP particles will settle near the discharge pipe into the pond, and fine CCP particles will settle near the outfall structure where water exits the pond. This section uses porewater data from 29 CCP units of different sizes and ages (Section 2) to characterize inter-unit and intra-unit variability for a wide range of porewater parameters. The aim of this analysis is not to identify individual causes of variability within and between each of these CCP units; instead, the goal is to describe the variability of different parameters to help inform the characterization of porewater variability within other CCP units.

Methods

Figure 3-2 illustrates how inter-unit and intra-unit variability were evaluated for each parameter. Inter-unit differences were quantified by comparing the highest and lowest medians calculated at the units. Intra-unit differences were quantified using the 25th and 75th percentiles of the data. The 25th and 75th percentiles of the data are visually represented by the lower and upper bounds of the box in a boxplot, and the interquartile range (the difference between the 25th and 75th percentiles) is often used to characterize variability of data.

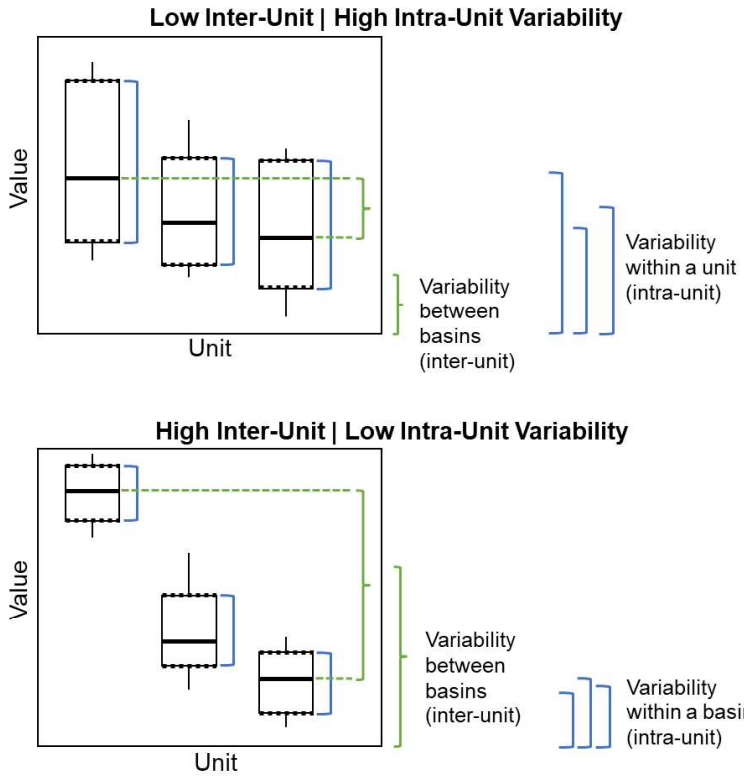

Figure 3-2
Conceptual drawing illustrating how inter- and intra-unit variability were assessed

A median range ratio (MRR) was calculated by taking the ratio between highest and lowest medians to allow for comparison of inter-unit variability across different parameters. For example, an MRR of 10 indicates an order of magnitude difference between the highest and lowest medians regardless of the actual concentrations of a given parameter. One MRR was calculated for each parameter based on the medians for all the units. An MRR could not be meaningfully calculated for Eh because the lowest median was a negative value, resulting in a negative ratio.

Intra-unit variability was quantified by taking the ratio between the 25th and 75th percentile of the data (interquartile ratio [IQR]). By calculating the IQR instead of the interquartile range, differences due to absolute concentration measurements are removed. Because IQRs were calculated by unit, as many as 29 IQRs are calculated for each parameter. The median IQR for each parameter is used in this comparison to represent the overall intra-unit variability.

For parameters with both total and dissolved concentrations available, this analysis uses only total concentrations. Data for most parameters were available for all 29 units, although some parameters were not available for all units (Table 3-3).

Results and Discussion

A summary of inter- and intra-unit variability is presented in Table 3-3. The MRR ranges from 1.6 to 80,000, with half the parameters having an MRR between 14.75 and 150. The IQR ranges from 1.0 to 5.0, with half the parameters falling between 1.4 and 2.6. High, moderate, and low variability were categorized based on approximately the top, middle, and bottom third of results, as shown in Table 3-4.

Table 3-3
Results of inter- and intra-unit variability analysis

Category	Parameter	Number of Units	Sample Count	MRR[1]	Median IQR
Field parameters	Eh	29	1390	NA	2.8
	pH	29	1390	2.0	1.1
	EC	29	1390	15	1.4
	TEMP	29	1390	1.6	1.3
	TURB	29	1388	5.9	2.4
Major ions	F	23	440	82	1.5
	NO_2 + NO_3	29	1333	16	2.0
	ALK	29	1375	130	1.9
	ALK-HCO_3	29	1361	130	1.6
	Ca	29	1383	22	1.5
	ALK-CO_3	29	1355	3.1	1.0
	Cl	29	1377	15	1.5
	Mg	29	1382	210	1.8
	K	29	1381	46	1.2
	Na	29	1383	68	1.4
	SO_4	29	1376	29000	1.9

Table 3-3 (continued)
Results of inter- and intra-unit variability analysis

Category	Parameter	Number of Units	Sample Count	MRR[1]	Median IQR
Minor ions and trace elements	Al	29	1357	400	4.1
	Sb	29	1343	74	2.3
	As	29	1382	1500	2.5
	Ba	29	1288	65	2.3
	Be	29	1297	14	1.8
	B	29	1383	580	1.7
	Cd	29	1247	51	1.1
	Cr	29	1381	7.6	2.6
	Cr(VI)	26	1188	14	4.6
	Co	29	1382	1200	4.5
	Cu	29	1117	12	2.6
	Fe	29	1383	1000	5.0
	Pb	29	1130	44	1.2
	Li	23	515	1800	1.4
	Mn	29	1383	2200	3.6
	Hg	29	1145	4.0	1.0
	Mo	29	1287	80000	2.2
	Ni	29	1317	65	3.1
	Se	29	1353	130	1.9
	Sr	29	1383	17	1.7
	Tl	29	1368	46	2.3
	V	29	1381	360	4.7
	Zn	29	1135	18	1.8
Other	S^{2-}	29	1105	22	1.0
	TOC	29	1281	74	1.3
	TSS	29	1118	54	2.1
Radiologic	^{226}Ra	23	393	26	3.0
	^{228}Ra	23	393	9.8	2.9
	Ra	8	114	3.3	2.4

Note:

[1] The MRR describes the inter-unit variability, and the median IQR describes the intra-unit variability. A higher value indicates greater variability. Dark green indicates low variability, light green indicates moderate variability, and yellow indicates high variability according to the ranges described in Table 3-4.

Table 3-4
Values for variability group cutoff

Value Type	Range[1]	Quantitative Assessment	Parameter Count
Median IQR	[1 to 1.5]	Low intra-unit variability	15
	(1.5 to 2.3]	Medium intra-unit variability	15
	(2.3 to 5]	High intra-unit variability	15
MRR	(1 to 20]	Low inter-unit variability	16
	(20 to 100]	Medium inter-unit variability	14
	(100 to 80,000]	High inter-unit variability	14

Note:

[1] Square brackets are inclusive of the number shown; round brackets are exclusive

Figure 3-3 illustrates examples of low and high values of inter- and intra-unit variability using boxplots for the results from each unit, ordered based on each unit's median value. The units are identified in the x axis by numerical code (the numbers are non-sequential and were derived from the database provided to EPRI). Results for selected parameters are presented and discussed in the text. Similar figures for all parameters that were evaluated are provided in Appendix C.

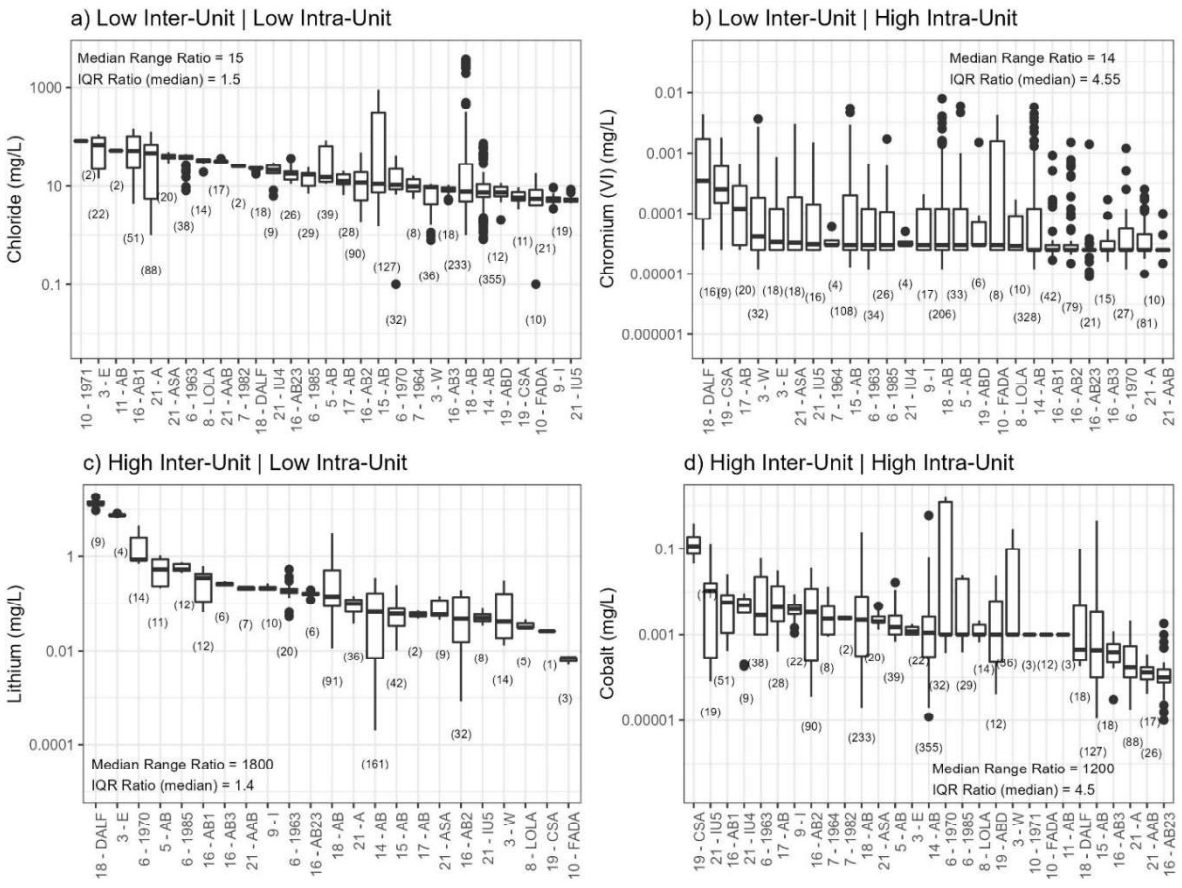

Figure 3-3
Boxplots illustrating both high and low inter- and intra-unit variability for selected parameters

Cl is presented as an example of low inter-unit and low intra-unit variability. An MRR of 15 indicates less than two orders of magnitude variability across all the units. A median interquartile ratio of 1.5 shows that Cl concentrations are relatively consistent within each unit, with units having less than twofold difference in concentration. Few parameters have low inter-unit and intra-unit variability; others with low variability include several field parameters (pH, specific conductance, and temperature) in addition to ALK-CO_3 and Hg, both of which were detected infrequently (Table 3-5).

Cr (Figure 3-3) and Cr(IV) have low inter-unit variability but high intra-unit variability, which may be attributed to the very low concentrations of these parameters. Other parameters with this pattern of variability include Cu, ^{228}Ra, and total Ra (Table 3-5). The maximum and minimum medians are similar because most individual sample results are non-detects, while the occasional detection creates high variability within each unit.

Li is presented as an example of high inter-unit and low intra-unit variability (Figure 3-3). The highest and lowest medians span three orders of magnitude (MRR of 1,800), while concentrations within a unit generally have less than a twofold difference in concentration. This indicates that within a unit there is generally little variability in Li concentration, so a small number of porewater samples may sufficiently characterize Li concentrations. Although no other parameters were observed to have high inter-unit and low intra-unit variability (suggesting that it may be an artifact of a small Li sample size), B and SO_4 (common CCP indicators) along with Mo, alkalinity, and Se had high inter-unit variability and medium intra-unit variability (Table 3-5).

Co is presented in Figure 3-3 as an example of high inter-unit and high intra-unit variability. The medians span three orders of magnitude (MRR of 1,200), and there is over fourfold variation within most units. This suggests that concentrations of Co in porewater may be difficult to predict for a CCP unit and that they may change over time or vary spatially throughout the unit. Other parameters with this distribution include As, Fe, V, Al, and Mn (Table 3-5).

Table 3-5
Inter-unit and intra-unit variability parameter groups

Intra-Unit Variability	Inter-Unit Variability		
	Low (MRR <=20)	**Medium (MRR >20 and <=100)**	**High (MRR >100)**
Low (IQR <=1.5)	pH, EC, TEMP, ALK-CO_3, Cl, Hg	F, Ca, K, Na, Cd, Pb, S^{2-}, TOC	Li
Medium (IQR >1.5 and <=2.3)	NO_2+NO_3, Be, Sr, Zn	Sb, Ba, Tl, TSS	ALK, ALK-HCO_3, Mg, SO_4, B, Mo, Se
High (IQR >2.3)	TURB, Cr, Cr(VI), Cu, ^{228}Ra, Total Ra	Ni, ^{226}Ra	Al, As, Co, Fe, Mn, V

Note: Eh is not shown because MRR was not calculated for this parameter.

There does not appear to be an overall pattern to define which parameters exhibit high or low variability, likely because the porewater concentrations are determined by a combination of the composition of the stored CCP, the operating history of the unit (for example, degree of sluicing), and the *in situ* geochemical conditions as well as the geochemical characteristics of each parameter. Of particular interest are the results for the common CCP tracers (B and SO_4), as well as potential remediation drivers (As, Sb, B, Cr, Co, Li, Mo, and Se; as defined by EPRI, 2021b).

Most of the tracers and remediation drivers have medium to high intra-unit variability, suggesting that more extensive porewater evaluation may be helpful to characterize a unit when developing a source term to model these parameters. Li was the only remediation driver with low intra-unit variability. Except for Sb and Cr, the tracers and potential remediation drivers had high inter-unit variability. Sb and Cr had medium and low inter-unit variability, respectively, which, as previously noted, can be attributed to their relatively low concentration (medians lower than 0.001 mg/L; see Appendix A) in the porewater samples reviewed in this analysis.

4
COMPARISON OF LEAF LEACH TEST ELUATE CONCENTRATIONS TO POREWATER CONCENTRATIONS

Summary

LEAF 1313 (pH-dependent) and 1316 (L/S-dependent) eluate concentrations were compared to median porewater concentrations taken from PMPs screened at the same location and depth as samples used in the LEAF testing for 18 PMPs spread across four CCP management units. This analysis indicated:

- LEAF 1313 and 1316 eluate concentrations were usually more than 25% higher or 25% lower than their paired median porewater concentrations. This observation was made for 1313 eluates at natural pH and the broader pH range for all porewaters and for 1316 results at low and high L/S.
- Elements often controlled by available content—such as B, Ca, Cl, Li, Sr, and SO_4—tended to be underpredicted by the leach tests.
- As, Fe, and Mn were also underpredicted, even though they tend to be solubility controlled, because the LEAF testing was performed under oxic conditions when the solubility of these elements is low.
- Conversely, Se and Cr, which are most soluble under oxic conditions, tended to be overpredicted by the LEAF testing performed under oxic conditions.
- Sb, Tl, and V tended to be overpredicted by the leach tests while other elements were overpredicted or underpredicted depending on test-specific and site-specific factors.
- No bias was detected for Hg because most porewater and all the LEAF test results were non-detect.
- Overall, these observations confirm the observations from EPRI 2020 and 2021c that LEAF tests do not reliably predict porewater concentrations observed in the field.

Background

Laboratory leaching tests can be used to estimate how environmental conditions, the length of exposure to leaching conditions, and material composition affect the release of inorganic constituents from CCP. However, the ability of leaching tests to predict concentrations of inorganic constituents in field porewater depends on the intended purpose of the leaching test, the applied test conditions, individual constituent geochemistry, and the ability of the test to address the principal conditions that control leaching in the field (EPRI, 2020 and 2021c).

Traditional leach tests expose a solid material to a single eluent, which is intended to be representative of *in situ* porewater concentrations. These traditional leach tests include USEPA Method 1311 (Toxicity Characteristic Leaching Procedures; TCLP), USEPA Method 1312 (Synthetic Precipitation Leaching Procedure; SPLP), and ASTM D3987 (Shake Extraction of Solid Waste with Water; ASTM). A more robust approach to leaching tests is the Leaching Environmental Assessment Framework (LEAF) (USEPA, 2019), which uses a gradient of eluent compositions designed to evaluate leaching behavior across a range of environmental conditions. Different LEAF methods alter different controlling variables (for example, pH, liquid-to-solid ratio [L/S]) in their experimental design.

In 2020 and 2021, EPRI published research that compared the results of traditional leaching tests (TCLP, SPLP, and ASTM) to two of the four LEAF leaching methods: USEPA Method 1313 (Liquid-Solid Partitioning as a Function of Eluate pH Using a Parallel Batch Procedure) and USEPA Method 1314 (Liquid-Solid Partitioning as a Function of Liquid-Solid Ratio Using an Up-Flow Percolation Column Procedure) (EPRI, 2020 and 2021c). The 2020 and 2021 research compared porewater to leach test eluates from samples collected from the screened intervals of the PMPs. The results indicated that traditional leaching tests were not reliable predictors of measured porewater concentrations because of the relatively high L/S used in these tests and because they do not necessarily reproduce field pH and redox conditions within a CCP unit.

LEAF testing is designed to span the range of pH and L/S encountered in the field although it can be difficult to determine in advance which pH or L/S will best predict the field concentration—and that point varies by element. In general, EPRI (2020 and 2021c) found that low L/S eluates from USEPA Method 1314 were better indicators for constituents where liquid-solid partitioning (LSP) is limited by the content in the CCP solids (available content LSP). Examples of constituents controlled by available content LSP are B, Cl, Mo, and SO_4. Traditional leaching methods and USEPA Method 1313 use higher L/S ratios and tended to underpredict these constituents. Constituents with porewater concentrations controlled by their solubility (solubility-controlled LSP), such as As and Sb, were better predicted by USEPA Method 1313 although the pH at which the test best predicted field conditions did not always correspond to the field pH, in part because redox also affects leaching of these elements and because it is challenging to duplicate field redox conditions in the laboratory—especially for strongly reducing conditions. EPRI (2020 and 2021c) also found that site-specific conditions influence whether some constituent concentrations are available content–controlled, solubility-controlled, or controlled by wash-off (present in an easily dissolved form that is rapidly removed by initial contact with water).

This research expands on the previous findings by evaluating the effectiveness of two LEAF test methods (1313 and 1316) at predicting porewater concentration across multiple CCP storage units using paired LEAF and porewater data (as described in Section 2). Similar to EPRI (2020 and 2021c), the laboratory leaching tests were performed on solid samples extracted from the location and depth interval within the CCP deposit where the screened interval of the PMP was placed.

Methods

Eluate concentrations from the LEAF tests were normalized by dividing by the median porewater concentration for the paired samples. Due to the high variability in the resulting ratios, the $\log_{10}$ of each ratio was used for analysis and visualization. If a leach method predicted a porewater concentration to complete accuracy, the ratio between the eluate concentration and porewater concentration would be equal to one (for a $\log_{10}$ ratio of zero).

To quantitatively assess how well the LEAF methods predicted porewater concentrations at any pH or L/S, a predefined range of variability between leach test eluate and porewater concentrations was established. Concentrations in leach test eluates and porewater samples were considered "within range" if the $\log_{10}$ of the ratio was within half an order of magnitude of zero (that is, a $\log_{10}$ ratio between -0.5 and 0.5, or approximately a threefold difference in concentrations between the leach test and median porewater results). Note that this criterion was applied to all pH and L/S eluates from Methods 1313 and 1316, respectively, and therefore provides insight on whether the leach test was comparable to field porewater concentrations at any point in the tested pH or L/S range. This criterion provided a broad measure of leach test performance relative to porewater concentrations.

However, being "within range" is not necessarily a reasonable approximation of field conditions. For example, a plus or minus threefold difference (half an order of magnitude) for a porewater constituent with a concentration of 1,000 mg/L would mean that the leach test eluate was either within or outside a range between about 320 mg/L and 3,100 mg/L. Therefore, a follow-up tabulation was performed following the approach of EPRI (2020, 2021c) using the following criteria:

- For LEAF 1313, was the natural pH (no acid or base added) eluate within 25% of the median porewater concentration?
- For LEAF 1316, were eluates at low (<1.0) or high (>1.0) L/S within 25% of the median porewater concentration?

Results and Discussion

Evaluation of LEAF Test Bias

The comparison of LEAF test results to observed porewater concentrations for all pH and L/S is presented in Table 4-1. The proportion of samples with LEAF 1313 test results within half an order of magnitude around the median porewater concentration ranged from 0% (Cr(VI)) to 100% (Hg) although the "within range" result for Hg is a reflection on detection limits because most porewater and all leach test results were lower than detection limits. The proportion of samples with LEAF 1316 test results within half an order of magnitude around the median porewater concentration spanned a range, from 0% (Cr(VI)) to 100% (Be and Hg), although the Be and Hg results were mostly non-detect.

F was the only commonly detected element with more than two-thirds of LEAF results within range for both the 1313 and 1316 tests, while Sb, Cl, Cr(VI), Fe, Mn, Se, and V had fewer than one-third of the results within range for both tests.

Table 4-1
Summary of LEAF 1313 and LEAF 1316 comparison to porewater results

Param	LEAF 1313				LEAF 1316			
	Sample Count	Samples in Range (%)	Samples Above Range (%)	Samples Below Range (%)	Sample Count	Samples in Range (%)	Samples Above Range (%)	Samples Below Range (%)
Sb	88	33	66	1.1	95	8.4	92	0
As	88	34	4.5	61	95	32	4.2	64
Ba	88	44	38	18	95	73	3.2	24
Be	88	76	24	0	95	100	0	0
B	88	19	0	81	95	38	4.2	58
Cd	88	59	31	10	95	79	9.5	12
Ca	88	45	2.3	52	95	47	3.2	49
Cl	88	11	0	89	95	26	8.4	65
Cr	88	23	77	0	95	34	66	0
Cr(VI)	78	0	100	0	85	0	100	0
Co	88	38	33	30	95	43	13	44
F	88	73	4.5	23	95	86	8.4	5.3
Fe	88	18	6.8	75	95	12	1.1	87
Pb	88	59	30	11	95	83	1.1	16
Li	88	30	0	70	95	37	1.1	62
Mn	88	24	15	61	95	13	2.1	85
Hg	88	100	0	0	95	100	0	0
Mo	88	25	8	67	95	46	25	28
Ni	49	49	41	10	55	67	22	11
^{226}Ra	29	59	17	24	30	67	10	23
^{228}Ra	29	59	10	31	30	53	0	47
Se	88	10	90	0	95	4.2	96	0
Sr	88	36	2.3	61	95	39	0	61
SO_4	88	18	0	82	95	43	14	43
Tl	88	59	36	4.5	95	62	35	3.2
V	78	18	81	1.3	85	2.4	98	0

Note: A green highlight indicates that >67% of the tests were within range, a yellow highlight indicates 33% to 66% within range, and no highlight indicates <33% within range.

The leach test to median porewater ratios are graphically illustrated in Figure 4-1. Each bar on the histogram shows the number of sample points within a given range of $\log_{10}$ median porewater ratio. If a particular leach method sample perfectly predicted porewater concentrations, the data point would fall on the x = zero line (equivalent to a ratio of 1). The half an order of magnitude range of defined variability is illustrated by the dashed lines at x = -0.5 and x = 0.5. The distribution of samples outside the area between those lines indicates bias. The color of the boxes represents results from the two LEAF tests (because the total number of samples differed between leach test methods, the absolute height of the bars will be different). Figures for selected parameters are presented in Figure 4-1 to illustrate a range of observed outcomes. Similar figures for all parameters are provided in Appendix D.

Sb provides an example where both LEAF 1313 and LEAF 1316 results are biased high (more of the ratios fall to the right of 0.5 than to the left of -0.5 in Figure 4-1a). Most of the LEAF 1316 results for Sb fall outside the half order of magnitude criterion.

Ba is an example in which LEAF 1313 is biased high and LEAF 1316 is biased low (Figure 4-1b). For both tests, the distribution of data is centered close to zero and most samples have a $\log_{10}$ ratio between -0.5 and 0.5, but there are substantially more ratio results to one side of the range compared to the other side.

The distribution for Mo LEAF 1316 data is centered close to zero (Figure 4-1c), with a similar number of ratios on either side of the range, indicating no bias. LEAF 1313 results are mostly to the left of the range, indicating a bias low in the 1313 testing.

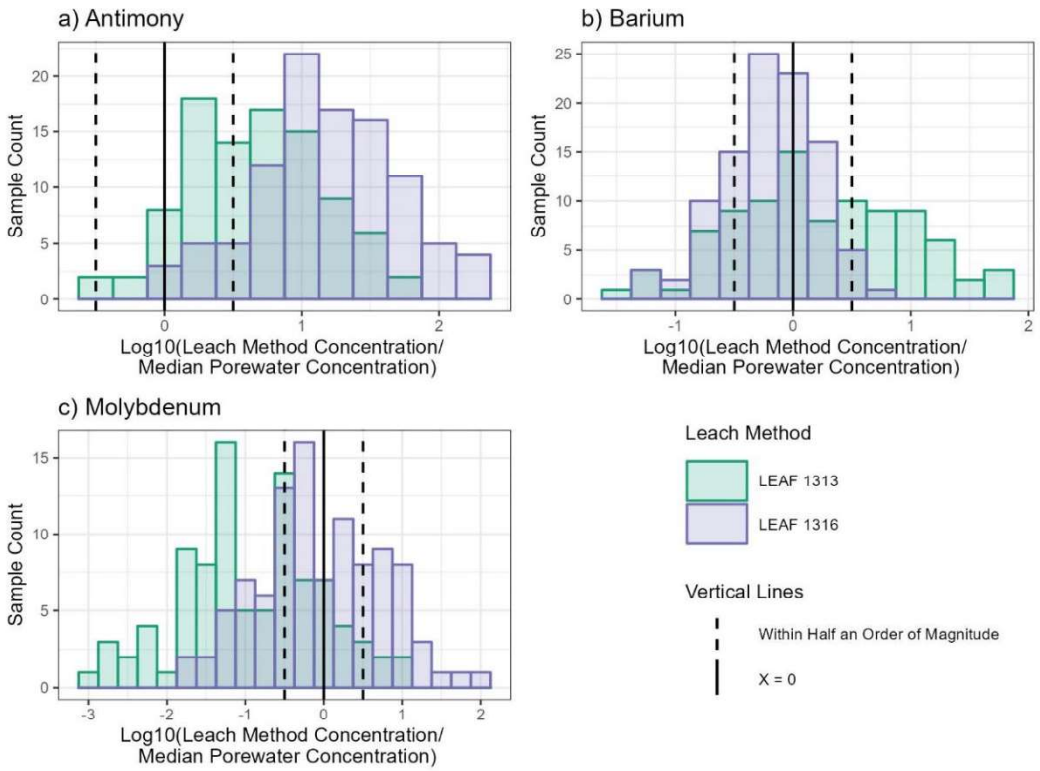

Figure 4-1
Histograms comparing the concentrations predicted by the LEAF 1313 and LEAF 1316 to the median observed porewater concentrations

Sample bias is summarized by element in Table 4-2. A test was considered to impart a bias toward higher concentration (overpredict porewater concentrations) if more than 50% of the samples were above range **or** if at least 20% of the results were above range and there were more than twice as many results above range compared to results below range. Bias low (test underpredicts porewater concentration) was assigned if more than 50% of the samples were below range **or** if at least 20% of the results were below range and there were more than twice as many results below range compared to results above range. The results of this comparison show:

- Elements often controlled by available content—such as B, Ca, Cl, Li, Sr, and SO_4—tend to be underpredicted (bias low) by the leach tests.
- As, Fe, and Mn were also underpredicted, even though they tend to be solubility controlled, because the LEAF testing was performed under oxic conditions when the solubility of these elements is low.
- Conversely, Se and Cr, which are most soluble under oxic conditions, tended to be overpredicted by the LEAF testing performed under oxic conditions.
- Sb, Tl, and V tend to be overpredicted (bias high) by the leach tests while other elements may be overpredicted or underpredicted depending on test-specific and site-specific factors.
- No bias was detected for Hg because most porewater and all the LEAF test results were non-detect.

Table 4-2
Summary of LEAF test bias compared to porewater concentrations

	Bias Low	No Bias	Bias High
LEAF 1313	As, B, Ca, Cl, F, Fe, Li, Mn, Mo, ^{228}Ra, Sr, SO_4	Co, Hg, ^{226}Ra	Sb, Ba, Be, Cd, Cr, Cr(VI), Pb, Ni, Se, Tl, V
LEAF 1316	As, B, Ba, Ca, Cl, Co, Fe, Li, Mn, ^{226}Ra, ^{228}Ra, Sr, SO_4	Be, Cd, F, Pb, Hg, Mo, Ni	Sb, Cr, Cr(VI), Se, Tl, V

Direct Comparison of LEAF Eluate Concentrations to Porewater Concentrations

Figures 4-2 and 4-3 illustrate how leach test concentration varied under the range of pH and L/S conditions imposed by the LEAF 1313 and LEAF 1316 leach tests, respectively. The $\log_{10}$ ratios of leach test sample to median porewater concentrations (y axis) are plotted against the measured sample pH (Figure 4-2) or against the L/S ratio (Figure 4-3). As shown in Figure 4-1, the zero line and predefined range of $\log_{10}$ ratios (-0.5 to 0.5) are shown. In addition, shaded areas represent the order of magnitude and 25% criteria used in EPRI (2020 and 2021c). The same three analytes discussed previously are shown in Figures 4-2 and 4-3 to illustrate a range of potential outcomes. These same figures for all analytes are presented in Appendix E (LEAF 1313, pH dependent) and Appendix F (LEAF 1316, L/S dependent).

Figure 4-1a indicates a tendency for Sb to be overpredicted by LEAF 1313. Figure 4-2a shows this to be the case across the pH range, with some underpredictions at the lowest pH tested. Figure 4-3a shows that porewater Sb tended to be overpredicted at all L/S, especially at low L/S.

Figure 4-1b indicates that Ba was overpredicted by LEAF 1313 and underpredicted by LEAF 1316. Figure 4-2b shows that the 1313 tests for Ba tended to be biased high at low pH and biased

low at high pH. Figure 4-3b shows that Ba can be underpredicted at any L/S and can also be overpredicted at higher L/S.

Figure 4-2c shows that Mo, while biased low across the LEAF 1313 pH range, had more results within range at pH >7.0 SU than at lower pH. Figure 4-3c illustrates that even though the sum of results for Mo testing using Method 1316 showed no bias, the samples at low L/S were biased high, and the samples at high L/S were biased low.

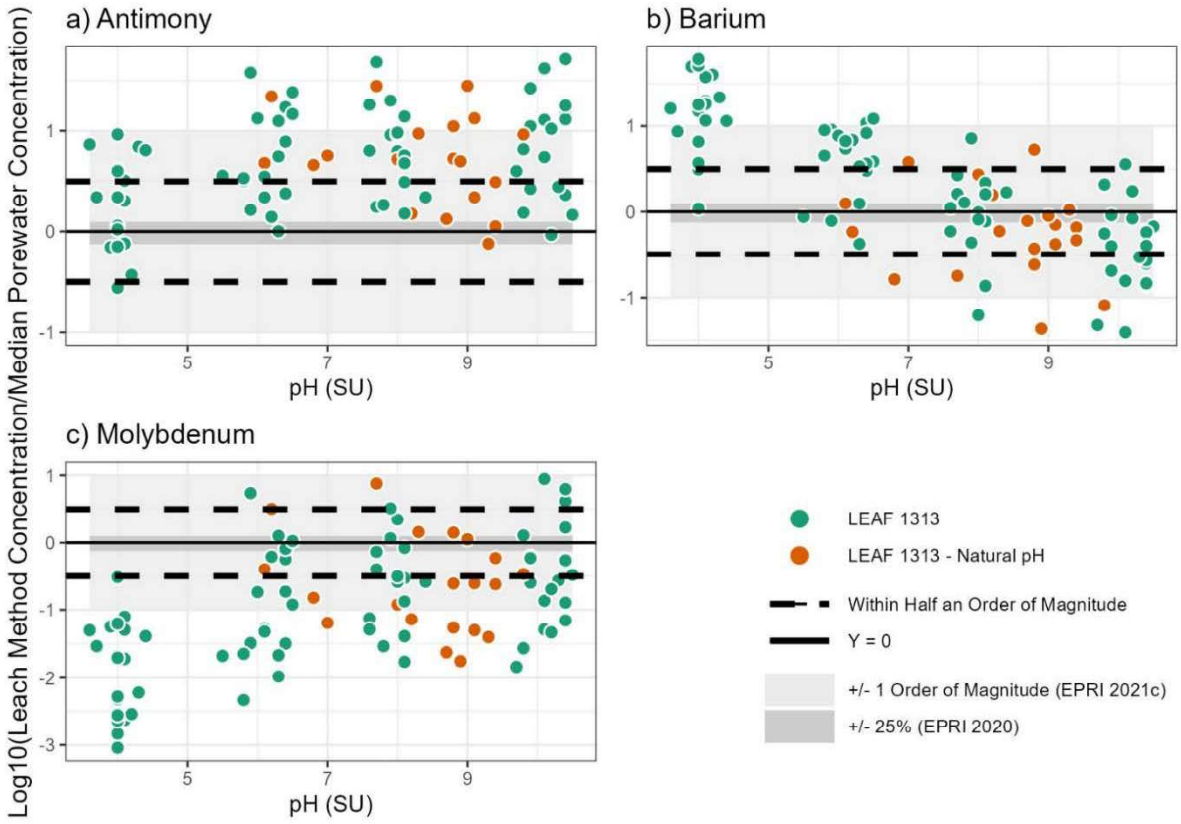

Figure 4-2
Comparison of LEAF 1313 results (normalized to median porewater concentration) across the range of pH levels tested

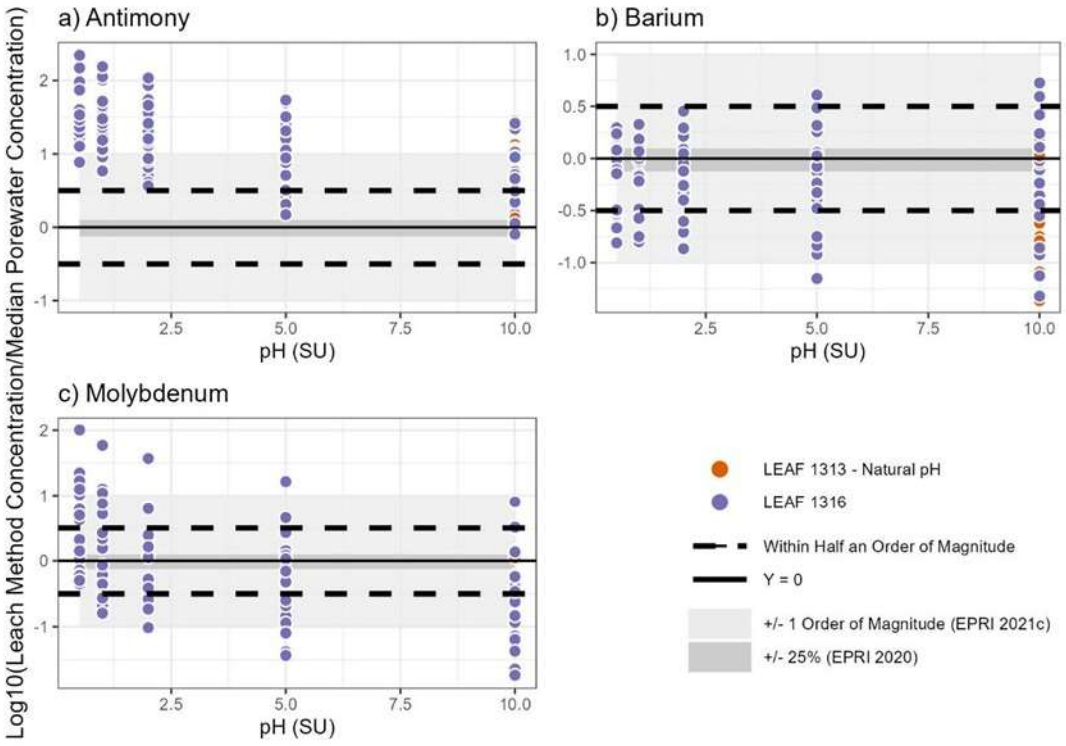

Figure 4-3
Comparison of LEAF 1316 results (normalized to median porewater concentration) across the range of L/S levels tested

Results from the LEAF 1313 test measured at natural porewater pH are included for comparison.

Focusing on natural pH results, the LEAF 1313 tests usually yielded eluate concentrations at natural pH that were higher (>25%) or lower (<25%) than the median porewater concentrations from their paired PMPs (Table 4-3). Taking this comparison a step further, examination of the plots in Appendix E indicates that all LEAF 1313 eluates (natural pH or not) at pH between 6 and 10 were more likely to be outside than inside the ±25% range.[7] The only exception to this observation is for lead, because it was often not detected and the detection limits for the porewater analysis and LEAF 1313 analysis were similar. Similarly, the 1316 eluate concentrations were usually not within ±25% of their paired porewater concentrations. Lead was most likely to yield a concentration within the ±25% criteria but only because the MDLs used for the LEAF 1316 analysis and porewater analyses were similar for this element, which was usually not detected in either porewater or eluates. These results confirm the observations from EPRI 2020 and 2021c that LEAF tests do not reliably predict porewater concentrations observed in the field.

[7] The median porewater concentrations for the ash basins were mostly between 6 and 10 (see pH plot in Appendix C), and the natural pH range for all PMPs was between 6 and 10.

Table 4-3
Tabulation of LEAF 1313 and 1316 eluate concentrations at natural pH and low or high L/S

Parameter	1313 Natural pH Eluates Within ±25%	1313 Natural pH Eluates Outside ±25%	1316 Eluates at L/S <1 Within ±25%	1316 Eluates at L/S >=1 Within ±25%	1316 Eluates Outside ±25%
Sb	10	90	0	3	97
As	5	95	3	9	88
Ba	15	85	5	15	80
Be[1,2,3]	10	90	2	8	90
B	0	100	5	3	92
Cd[1,2,3]	0	100	0	2	98
Ca	0	100	4	7	89
Cl[2]	5	95	5	2	93
Cr	10	90	2	7	91
Cr(VI)[1,2,3]	0	100	0	0	100
Co	10	90	2	11	87
F	10	90	6	19	75
Fe[3]	5	95	0	2	98
Pb[1,2,3]	45	55	15	52	33
Li	0	100	4	2	94
Mn	0	100	1	1	98
Hg[1,2,3]	0	100	0	0	100
Mo	5	95	1	6	93
Ni	0	100	4	9	87
^{226}Ra	29	71	7	23	70
^{228}Ra	14	86	7	17	77
Se[1]	5	95	0	3	97
Sr	0	100	4	6	90
SO_4	5	95	6	6	88
Tl	30	70	2	12	86
V	6	94	0	1	99

Notes:

[1] Low detection frequency (<=50%) in porewater

[2] Low detection frequency (<=50%) in LEAF 1313 eluate at natural pH

[3] Low detection frequency (<=50%) in LEAF 1316 eluate at L/S = 1

5
ADDITIONAL DATA EXPLORATION

This report has discussed porewater composition on a parameter-by-parameter basis. Advanced statistical methods could be used in the future to help characterize entire porewater signatures. Multivariate statistical methods can evaluate the relationships between more than two variables simultaneously, allowing for easier interpretation of entire porewater signatures. Potentially applicable multivariate statistical methods include principal component analysis (PCA), cluster analysis, and linear discriminant analysis (the use of which is discussed in detail in EPRI, 2022).

PCA is a common dimensionality reduction method (Abdi and Williams, 2010; Shlens, 2014). The principal components calculated are essential new "variables," which are linear combinations of the original data that separate the data points and reduce redundancy in the data. In EPRI 2022, PCA was used to distinguish CCP porewater from coal pile runoff water (a potential alternative source of downgradient exceedances). Similar multivariate analyses could be used to assess how parameters co-vary within and between units as well as how successful laboratory leach testing is at determining entire porewater signatures.

6
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A
SUMMARY OF POREWATER DATA

Parameter	Unit	Sample Count	Number of Units	Detection Frequency (%)	Min	Max	Mean	Median
Field Parameters								
Eh	mV	1390	29	100	-244.3	863	166	132
pH	SU	1390	29	100	2.5	11.5	7.17	7.01
EC	µmhos/cm	1390	29	100	0.2	12002	1060	640
TEMP	Deg C	1390	29	100	1.87	35	19.7	19.695
TURB	NTUs	1388	29	100	0	624	6.43	4.8
Major Ions								
ALK	mg/L	1375	29	94	1.4	1690	168	139
ALK-HCO_3	mg/L	1361	29	91	1.2	837	162	137
Ca	mg/L	1383	29	100	0.0628	1830	120	76.5
Ca (Diss)	mg/L	84	19	99	0.1	461	102	75.9
ALK-CO_3	mg/L	1355	29	12	1	1640	9.87	5
Cl	mg/L	1377	29	100	0.1	3650	69.5	10.1
F	mg/L	440	23	94	0.0398	50	0.908	0.33
Mg	mg/L	1382	29	100	0.0654	1030	35.1	15.55
Mg (Diss)	mg/L	70	19	99	0.1	275	28.8	19.45
NO_2 + NO_3	mg-N/L	1333	29	49	0.00002	13.6	0.13	0.02
K	mg/L	1381	29	96	0.893	566	19.8	10.6
K (Diss)	mg/L	70	19	91	0.913	270	20.2	9.845
Na	mg/L	1383	29	99	1.7	445	23.2	12.5
Na (Diss)	mg/L	70	19	99	2.47	246	21.6	10.65
SO_4	mg/L	1376	29	98	0.1	28000	425	103
Other								
S^{2-}	mg/L	1105	29	8	0.0001	10	0.151	0.1
TDS	mg/L	1375	29	99	8.7	15000	849	411
TOC	mg/L	1281	29	72	0.085	56	1.82	1
TSS	mg/L	1118	29	62	0.0025	909	20.7	5.6
Trace Elements								
Al	mg/L	1357	29	79	0.004709	1160	9.26	0.128
Al (Diss)	mg/L	1199	29	57	0.001835	1140	8.81	0.1
Sb	mg/L	1343	29	60	0.000089	0.104	0.00285	0.00099
Sb (Diss)	mg/L	1190	29	54	0.000077	0.0968	0.00271	0.0007385
As	mg/L	1382	29	99	0.000065	6.38	0.422	0.2215
As (Diss)	mg/L	1216	29	99	0.000041	5	0.394	0.1965
Ba	mg/L	1288	29	98	0.000024	3.52	0.238	0.172
Ba (Diss)	mg/L	1173	29	99	0.000023	3.37	0.226	0.158

Parameter	Unit	Sample Count	Number of Units	Detection Frequency (%)	Min	Max	Mean	Median
Trace Elements (continued)								
Be	mg/L	1297	29	43	0.00001	0.507	0.00442	0.0001
Be (Diss)	mg/L	1178	29	37	0.00001	0.449	0.0038	0.0001
B	mg/L	1383	29	98	0.0067	103	5.03	1.25
B (Diss)	mg/L	1216	29	98	0.05	92.8	4.89	1.245
Cd	mg/L	1247	29	27	0.000025	0.0457	0.000672	0.00008
Cd (Diss)	mg/L	1159	29	24	0.000025	0.024	0.000567	0.00008
Cr	mg/L	1381	29	66	0.000091	0.263	0.00387	0.00076
Cr (Diss)	mg/L	1211	29	58	0.000091	0.245	0.00317	0.0005
Cr(VI)	mg/L	1188	26	31	0.000009	0.008	0.00022	0.00003
Co	mg/L	1382	29	83	0.00001	1.58	0.0231	0.001095
Co (Diss)	mg/L	1213	29	80	0.00001	1.57	0.0222	0.001
Cu	mg/L	1117	29	59	0.00011	0.245	0.00341	0.00069
Cu (Diss)	mg/L	1116	29	50	0.00011	0.241	0.00368	0.000605
Fe	mg/L	1383	29	95	0.003841	2480	46.4	2.57
Fe (Diss)	mg/L	1209	29	83	0.003389	2500	42.1	2.22
Pb	mg/L	1130	29	36	0.000028	0.0207	0.000658	0.000105
Pb (Diss)	mg/L	1115	29	15	0.000028	0.016389	0.000477	0.0001
Li	mg/L	515	23	95	0.0002	18.3	0.528	0.118
Li (Diss)	mg/L	142	20	96	0.0011	12.6	0.726	0.182
Mn	mg/L	1383	29	95	0.001852	36.7	2.27	0.7
Mn (Diss)	mg/L	1216	29	93	0.002599	37.4	2.13	0.659
Hg	µg/L	1145	29	6	0.000621	4.6	0.17	0.2
Hg (Diss)	µg/L	1130	29	2	0.02	3.0	0.17	0.2
Mo	mg/L	1287	29	93	0.000085	55.6	0.902	0.0253
Mo (Diss)	mg/L	1176	29	93	0.000095	44	0.759	0.02585
Ni	mg/L	1317	29	86	0.00013	3.22	0.0412	0.0023
Ni (Diss)	mg/L	1185	29	86	0.00011	3.19	0.0388	0.00205
Se	mg/L	1353	29	47	0.000063	1.1	0.00929	0.00089
Se (Diss)	mg/L	1199	29	46	0.000074	0.897	0.0091	0.000756
Sr	mg/L	1383	29	100	0.005	29.5	2.49	1.78
Sr (Diss)	mg/L	1216	29	100	0.005	22	2.3	1.675
Tl	mg/L	1368	29	63	0.000016	0.02	0.000752	0.00018
Tl (Diss)	mg/L	1208	29	59	0.000015	0.0733	0.000684	0.00012
V	mg/L	1381	29	95	0.000073	3.26	0.0461	0.00312
V (Diss)	mg/L	1214	29	90	0.000058	2.22	0.0412	0.0025
Zn	mg/L	1135	29	51	0.001873	7.13	0.0846	0.01
Zn (Diss)	mg/L	1120	29	41	0.001674	6.45	0.0711	0.01
Radiologic								
^{226}Ra	pCi/L	393	23	92	0	2.09	0.41	0.333
^{228}Ra	pCi/L	393	23	88	0	3	0.668	0.564
Total Ra	pCi/L	114	8	100	0	3.84	0.903	0.8225

B
TOTAL VERSUS DISSOLVED CONCENTRATION COMPARISON

The figures in this appendix (Figures B-1 through B-26) compare total vs. dissolved concentrations in filtered and unfiltered sample pairs when a concentration is detected in one or both samples. For clarity, samples where concentrations are below detection limits in both samples are not shown. The statistics on the graphs are for sample pairs where a concentration is detected in one or both samples and will therefore differ from the statistics shown in Table 3-2.

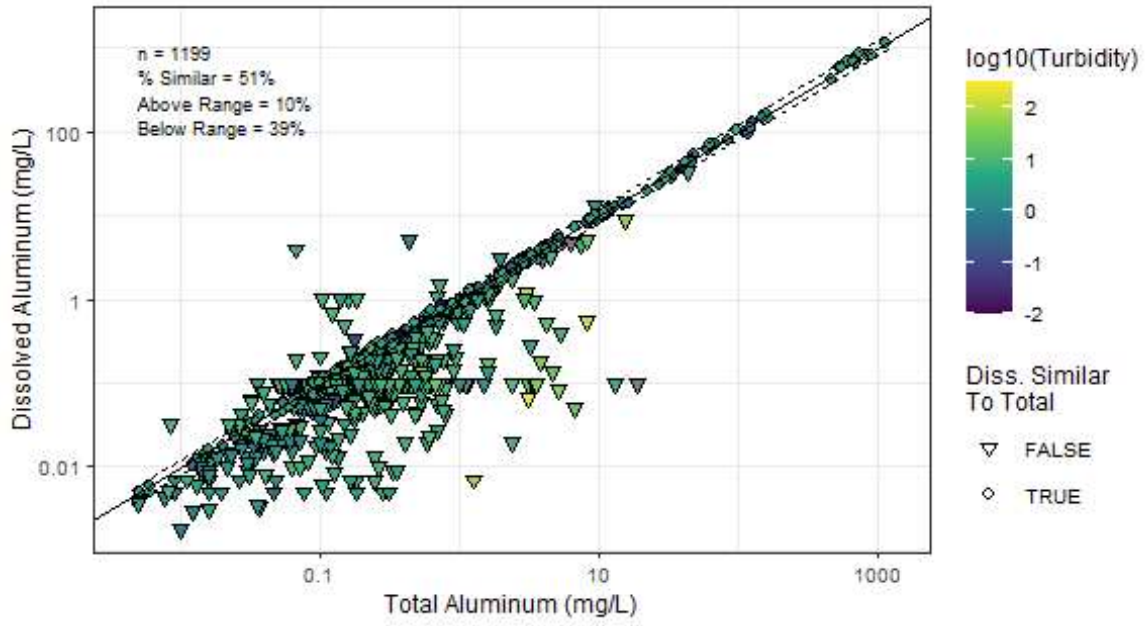


Figure B-1
Aluminum

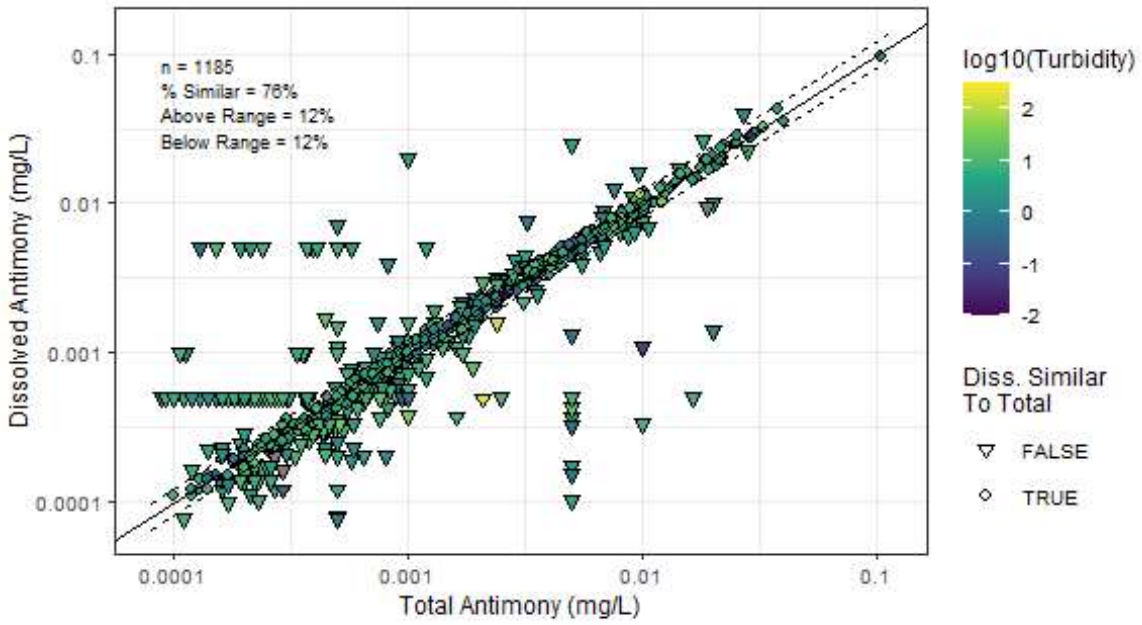


Figure B-2
Antimony

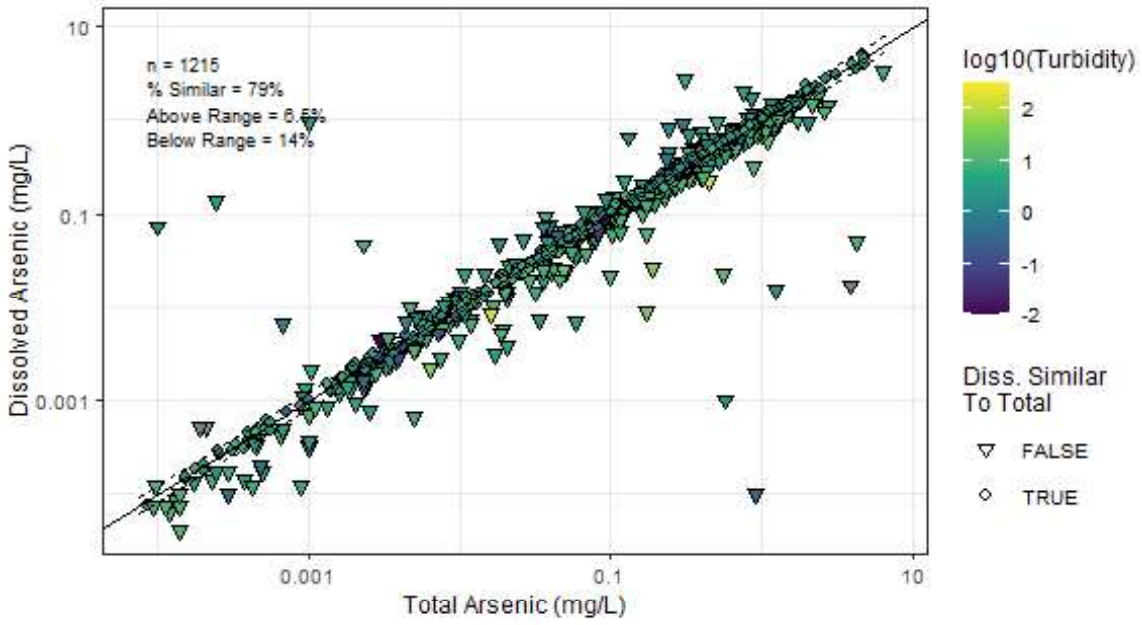


Figure B-3
Arsenic

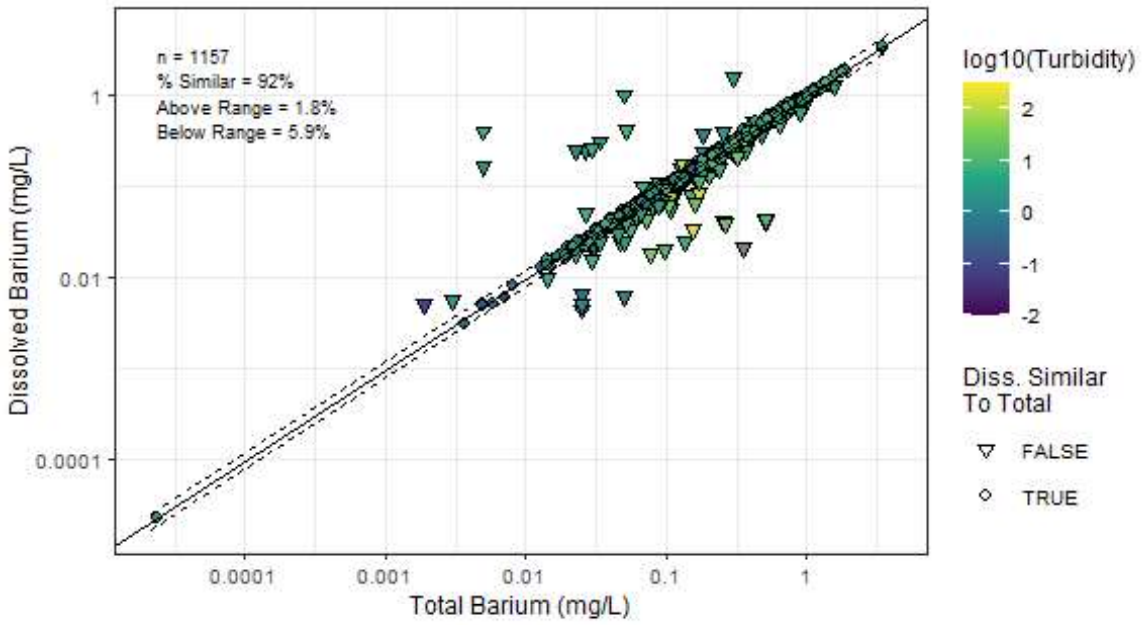


Figure B-4
Barium

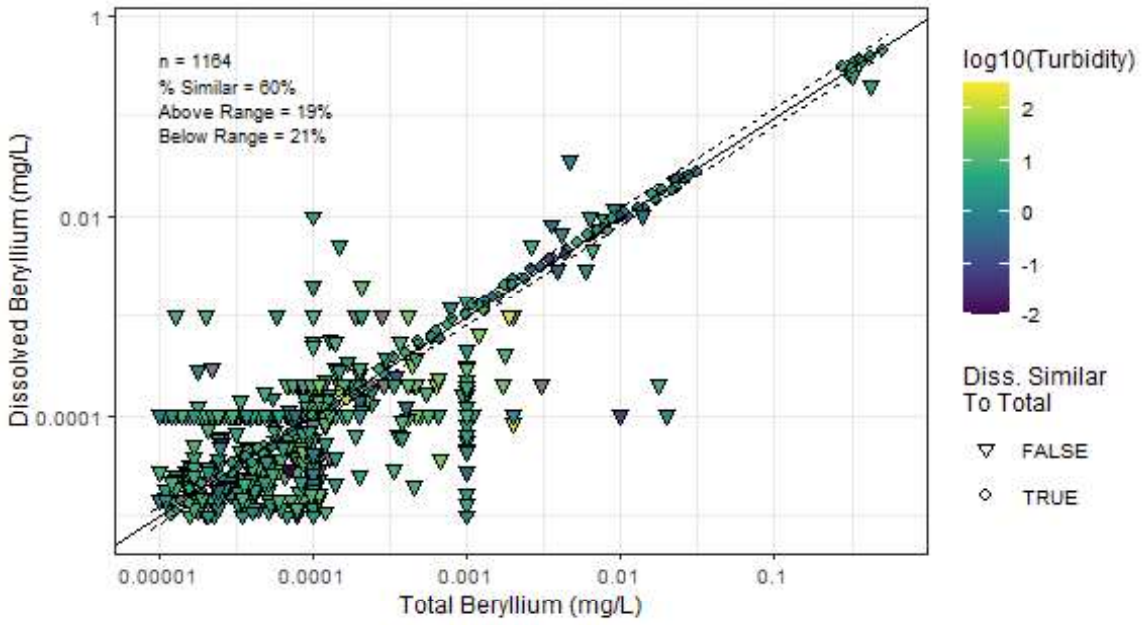


Figure B-5
Beryllium

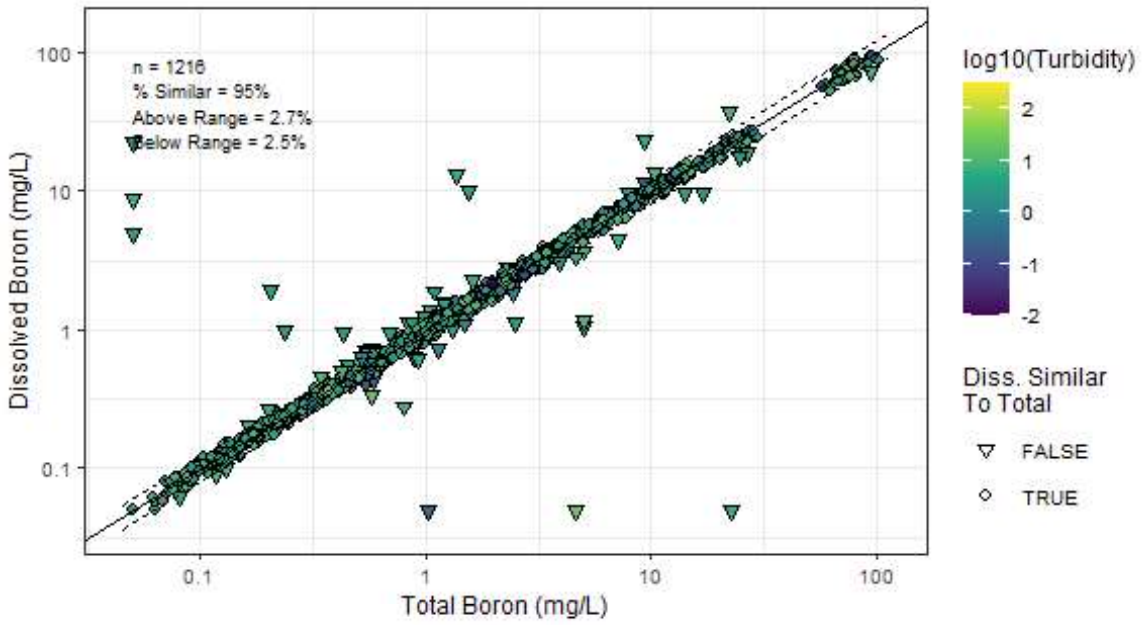


Figure B-6
Boron

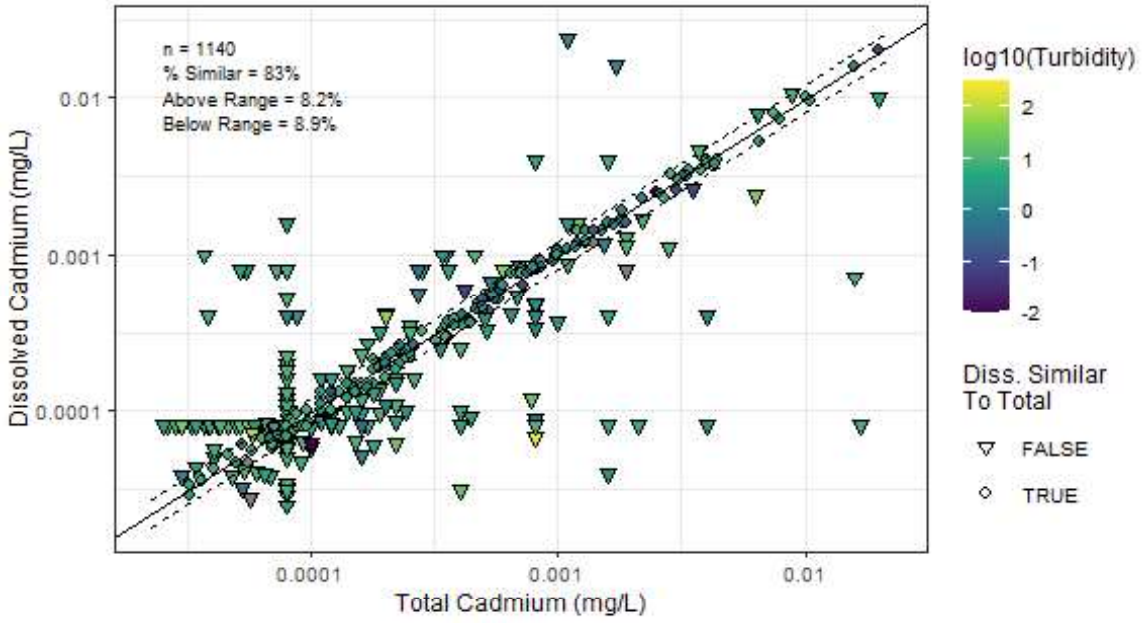


Figure B-7
Cadmium

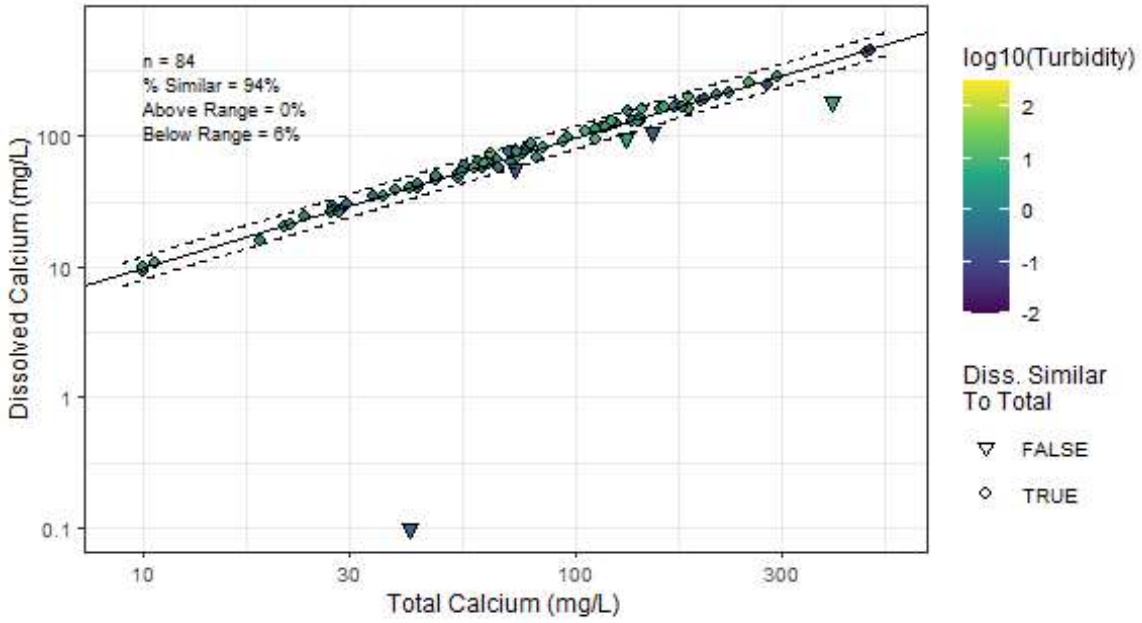


Figure B-8
Calcium

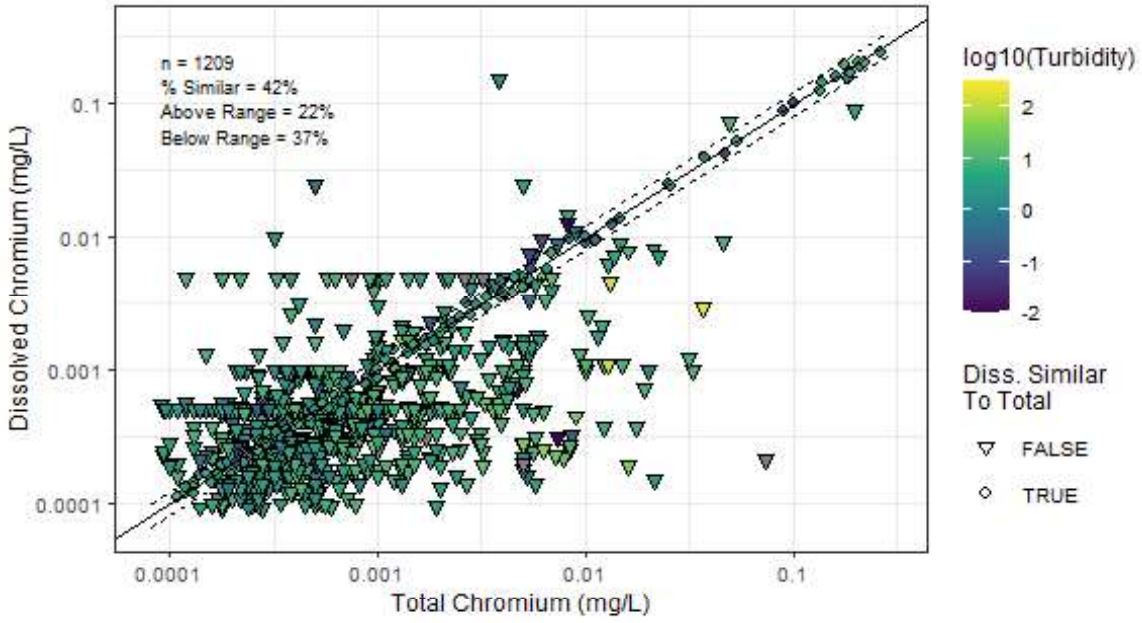


Figure B-9
Chromium

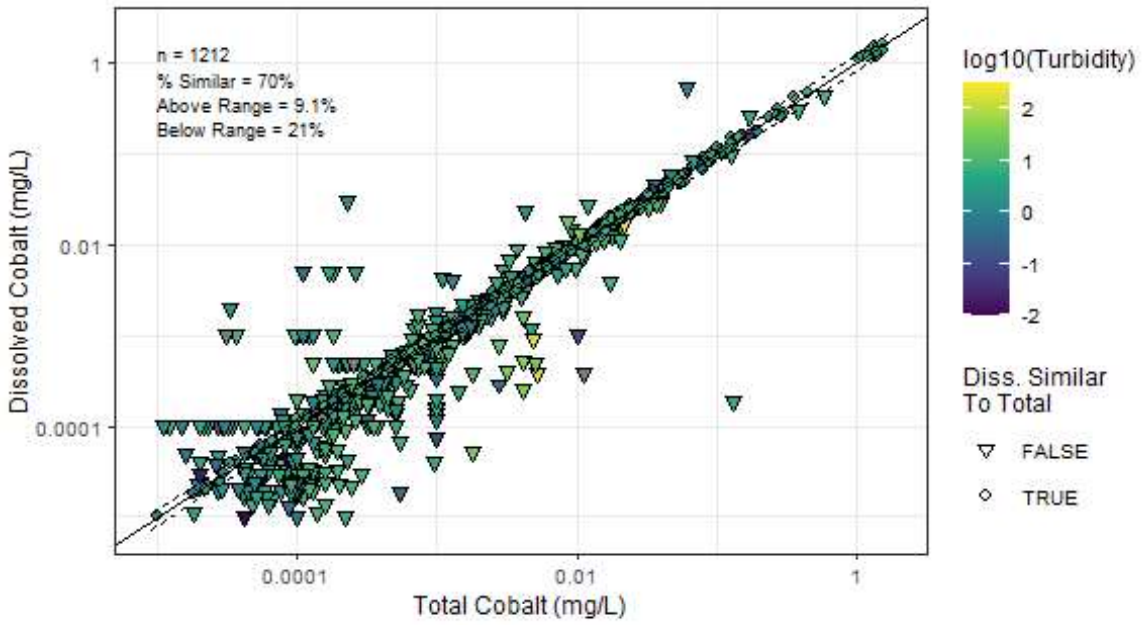


Figure B-10
Cobalt

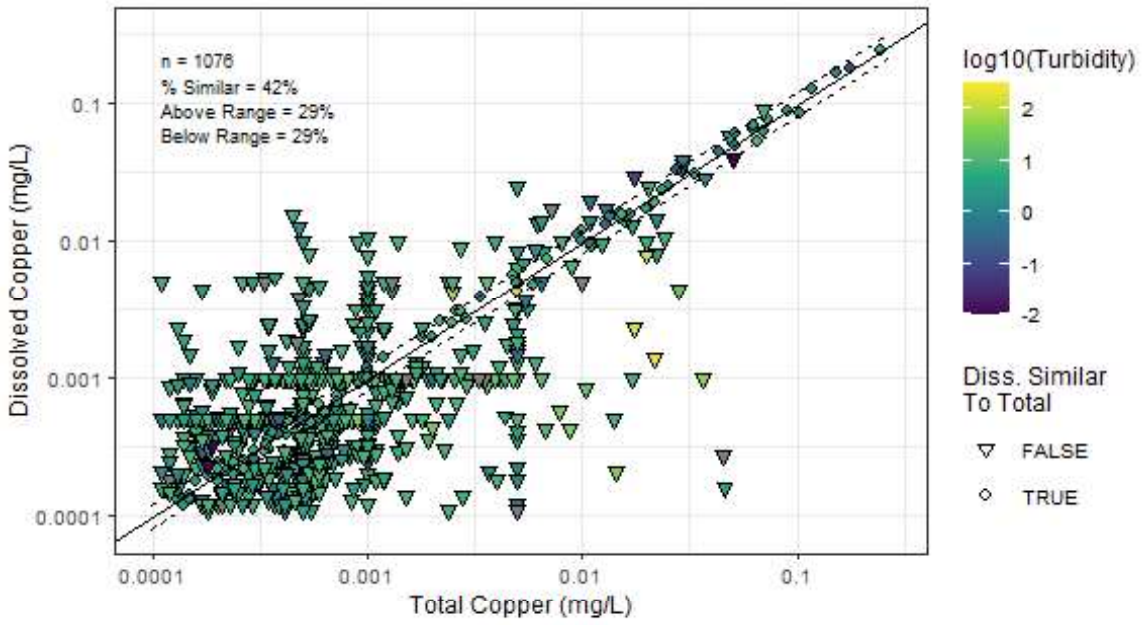


Figure B-11
Copper

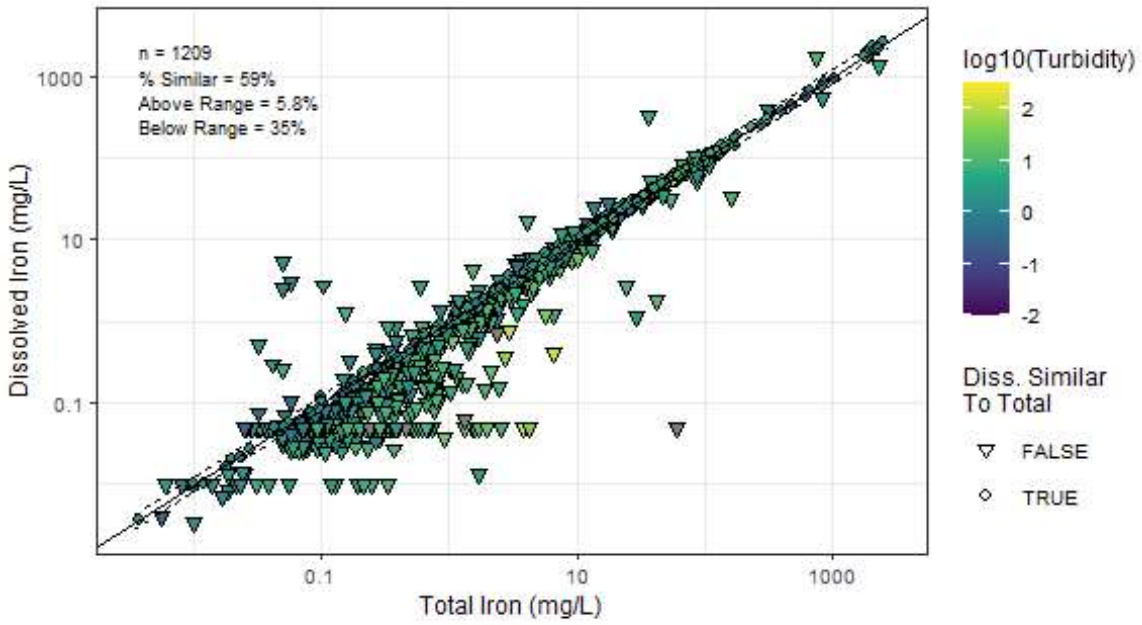


Figure B-12
Iron

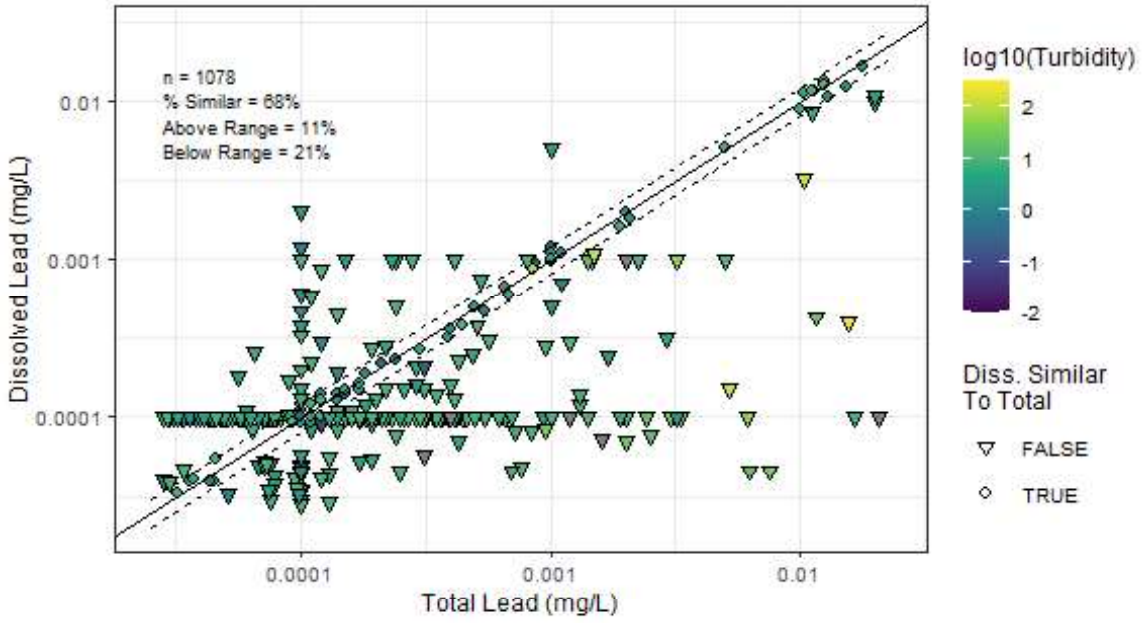


Figure B-13
Lead

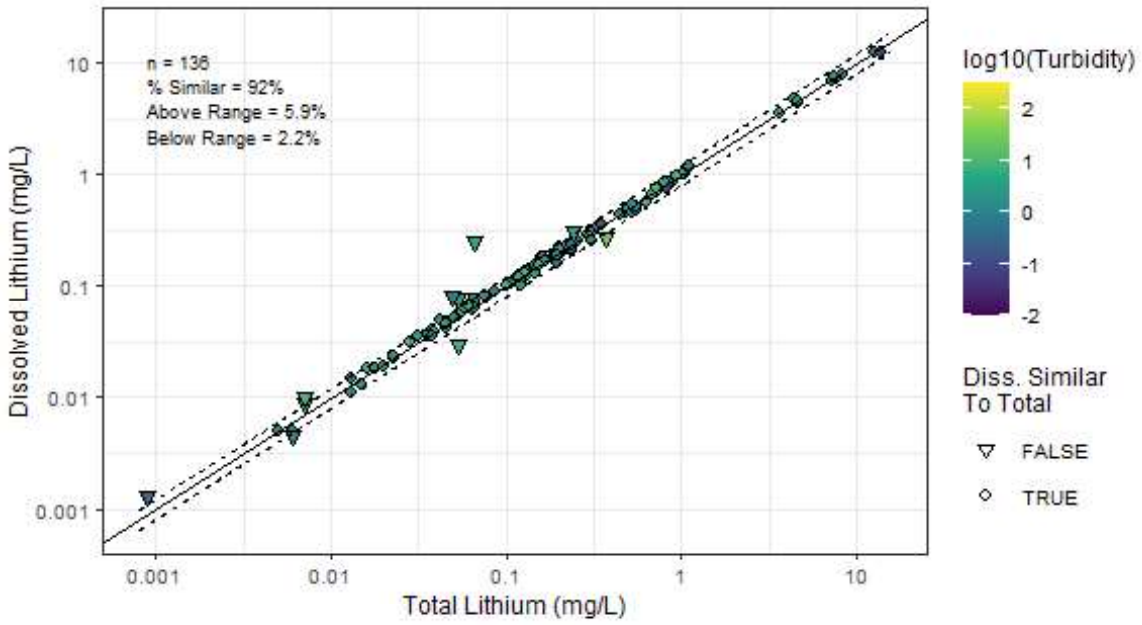


Figure B-14
Lithium

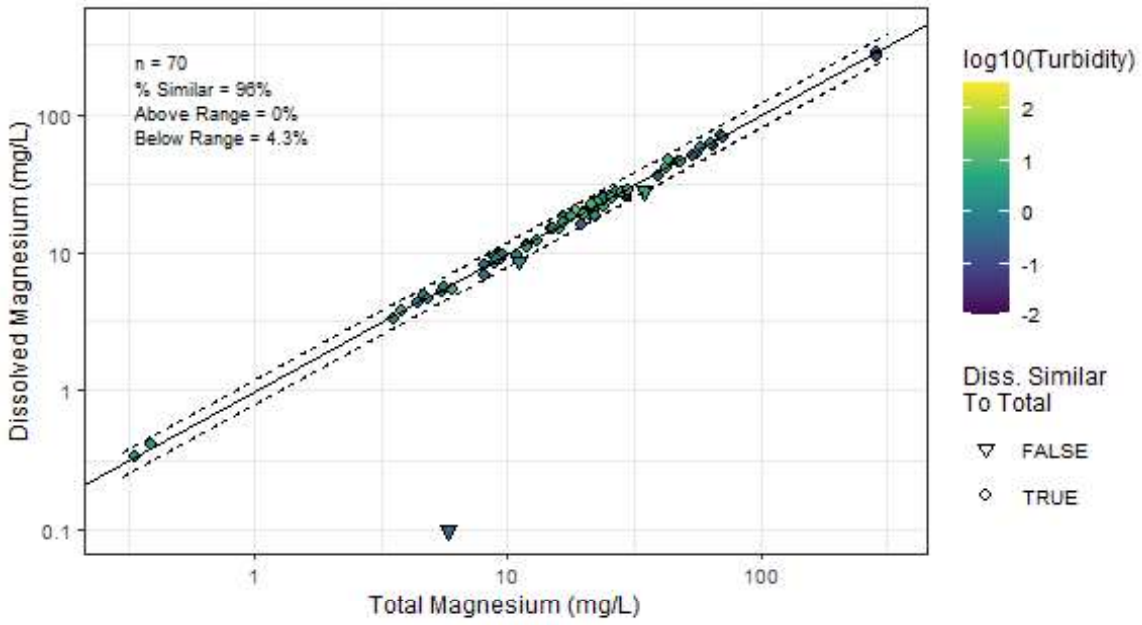


Figure B-15
Magnesium

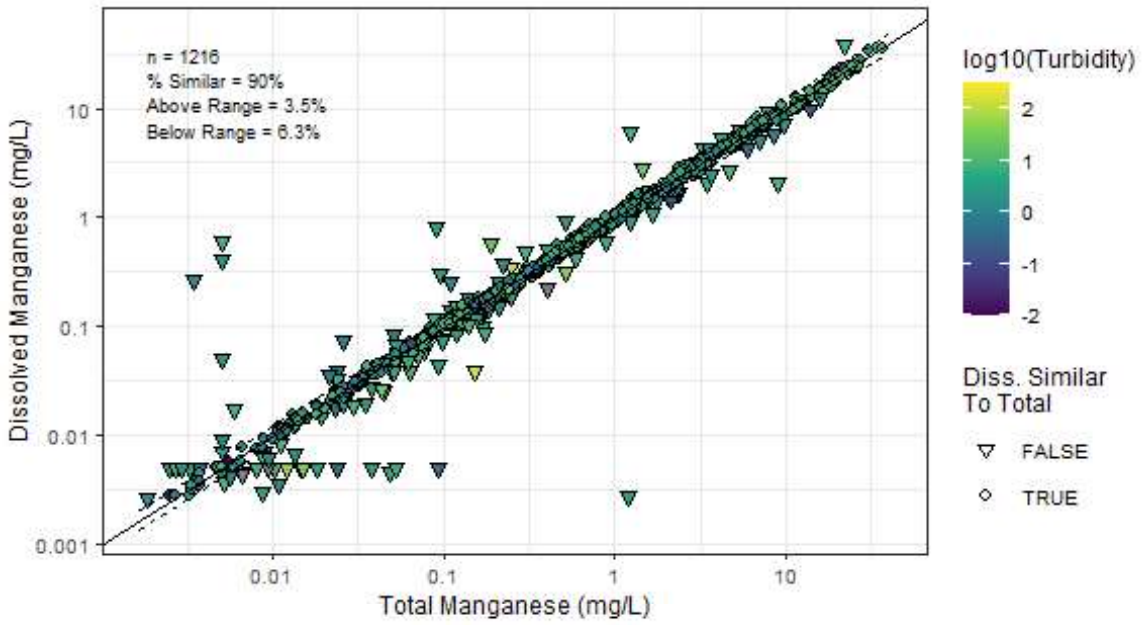


Figure B-16
Manganese

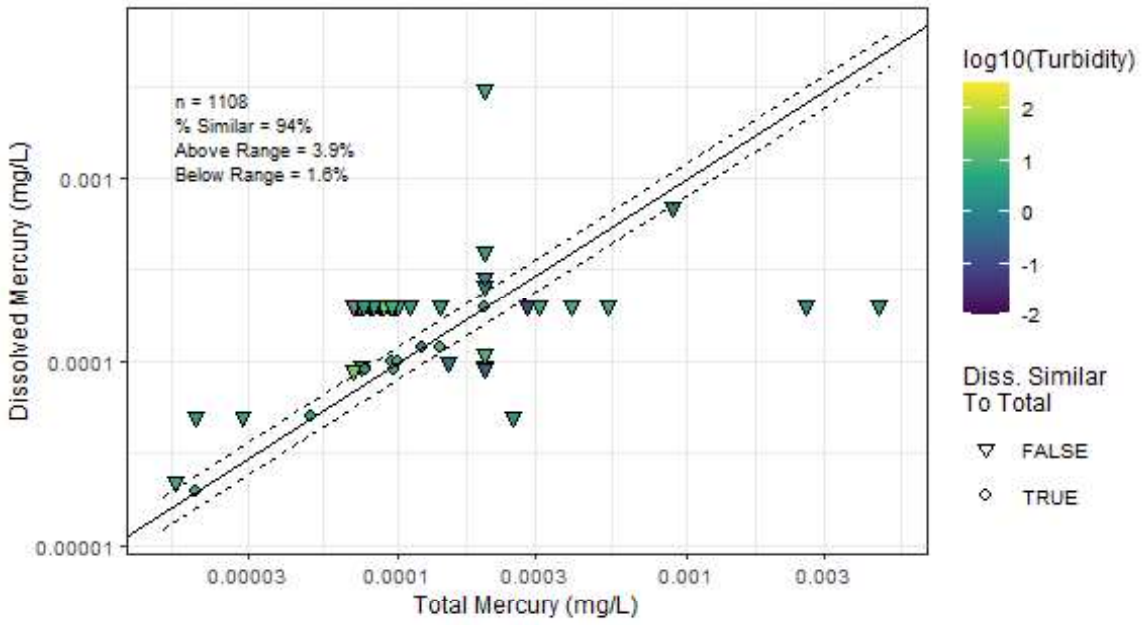


Figure B-17
Mercury

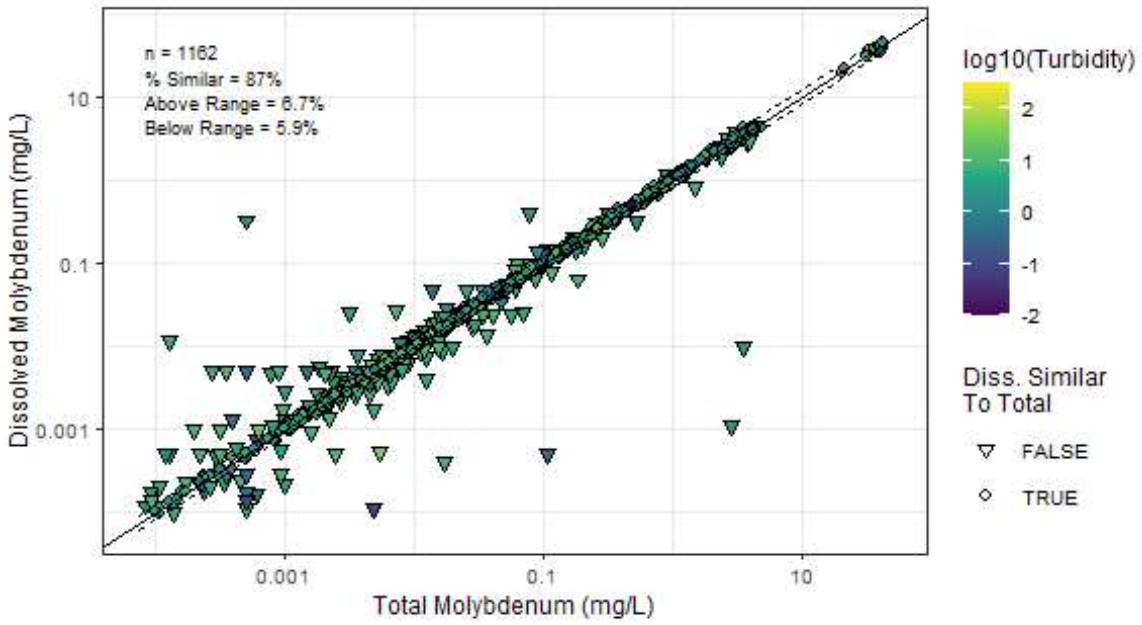


Figure B-18
Molybdenum

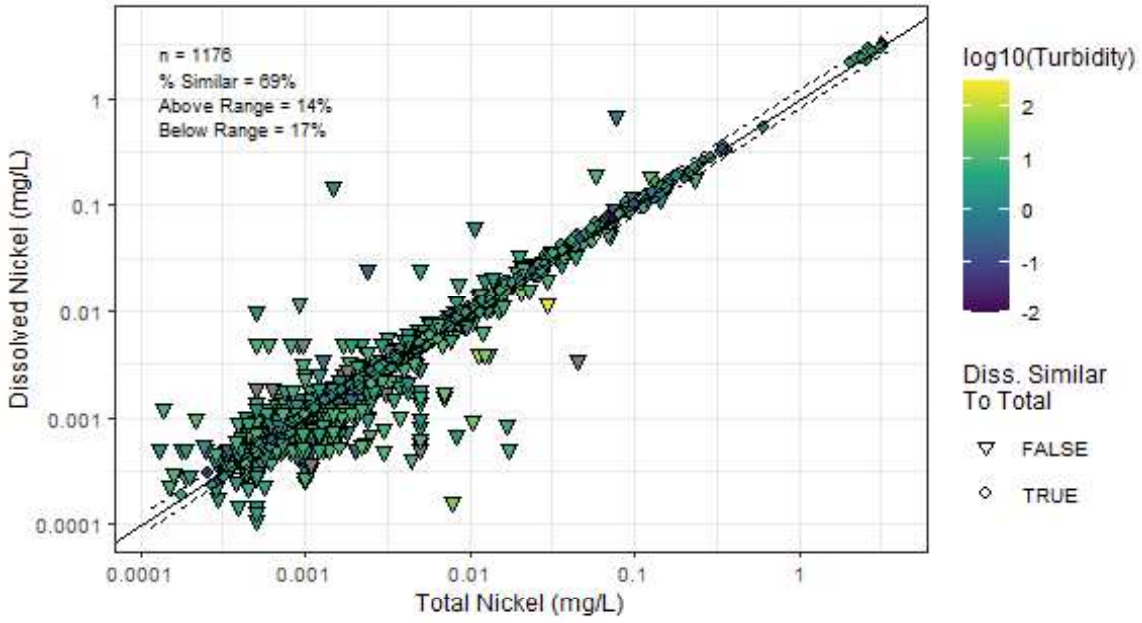


Figure B-19
Nickel

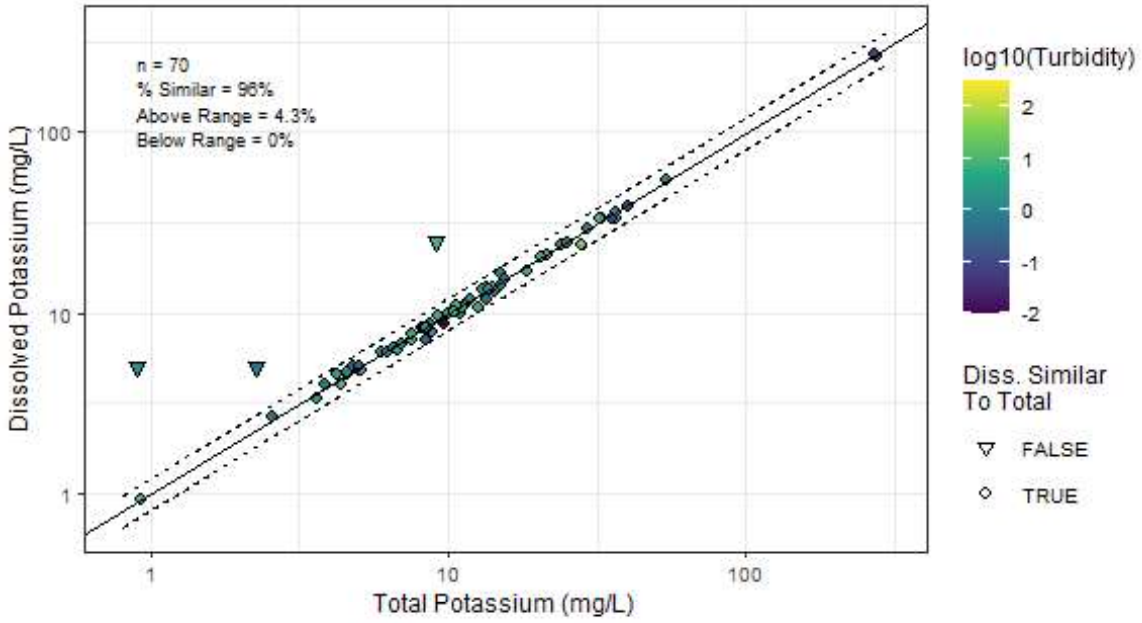


Figure B-20
Potassium

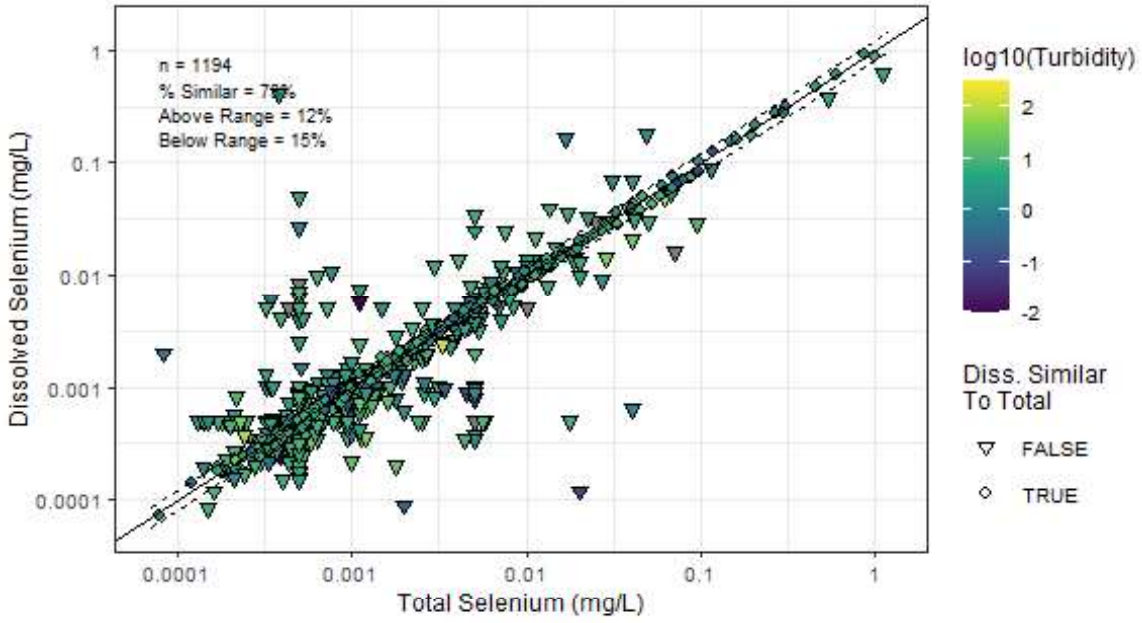


Figure B-21
Selenium

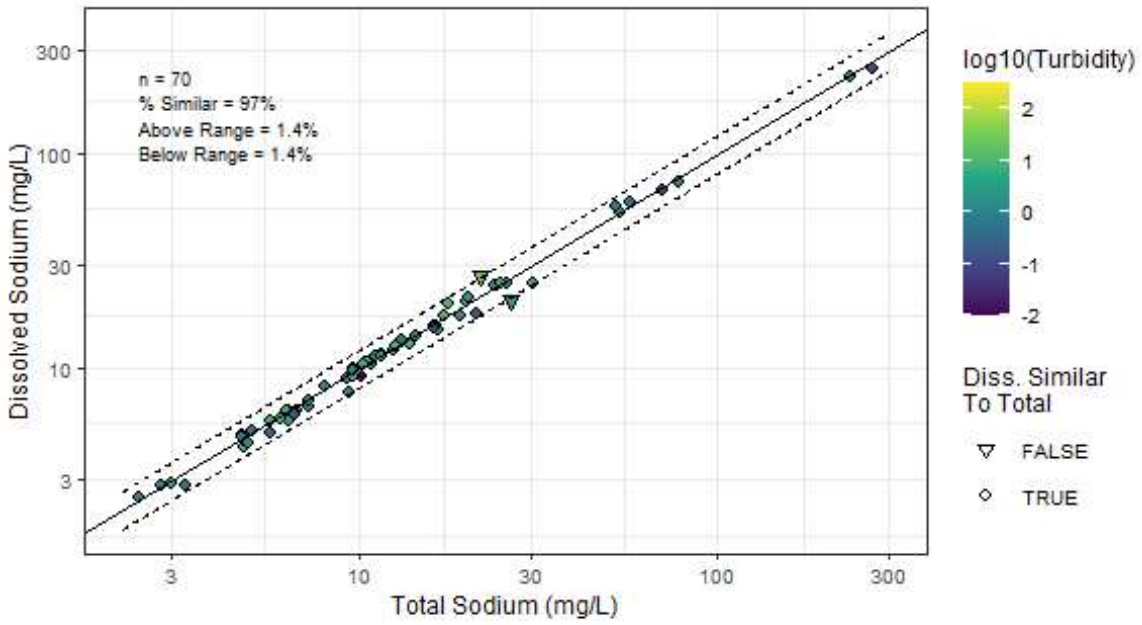


Figure B-22
Sodium

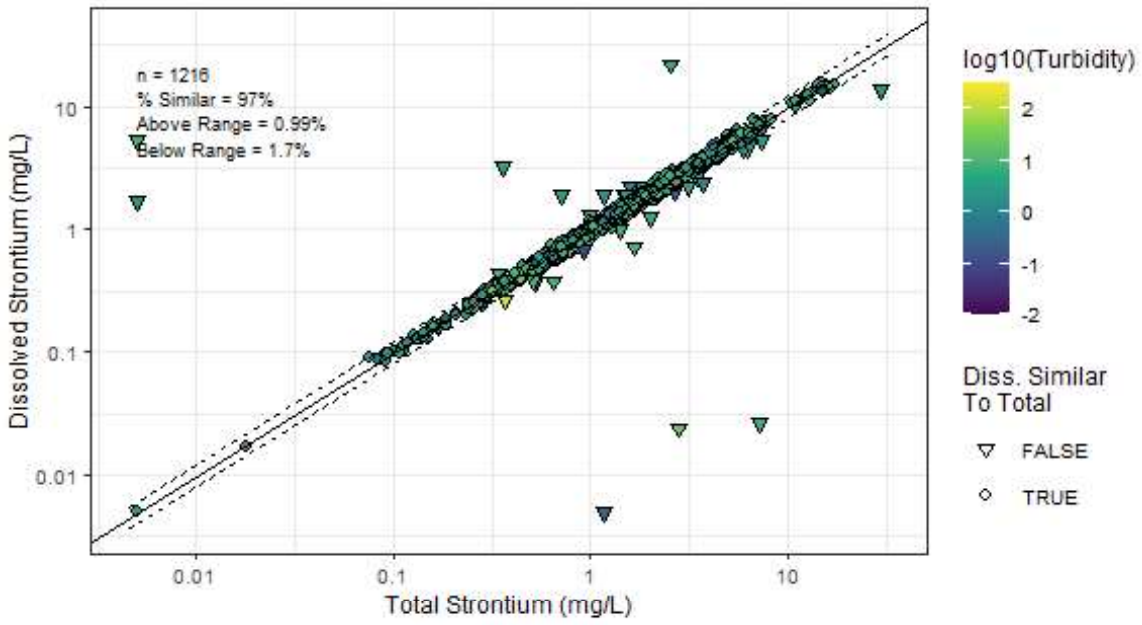


Figure B-23
Strontium

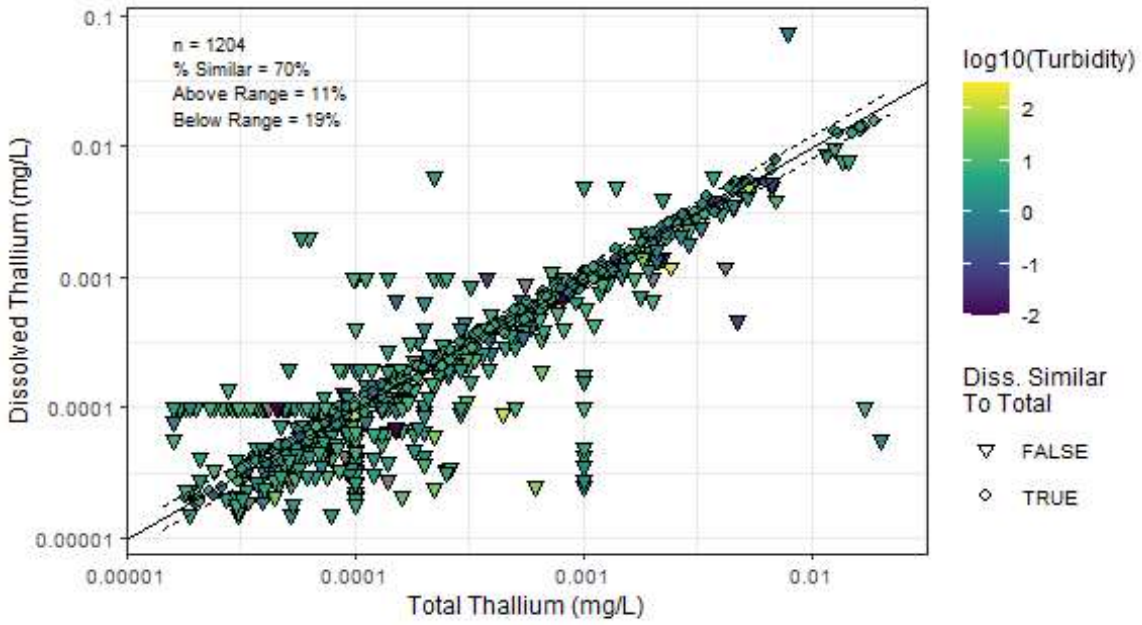


Figure B-24
Thallium

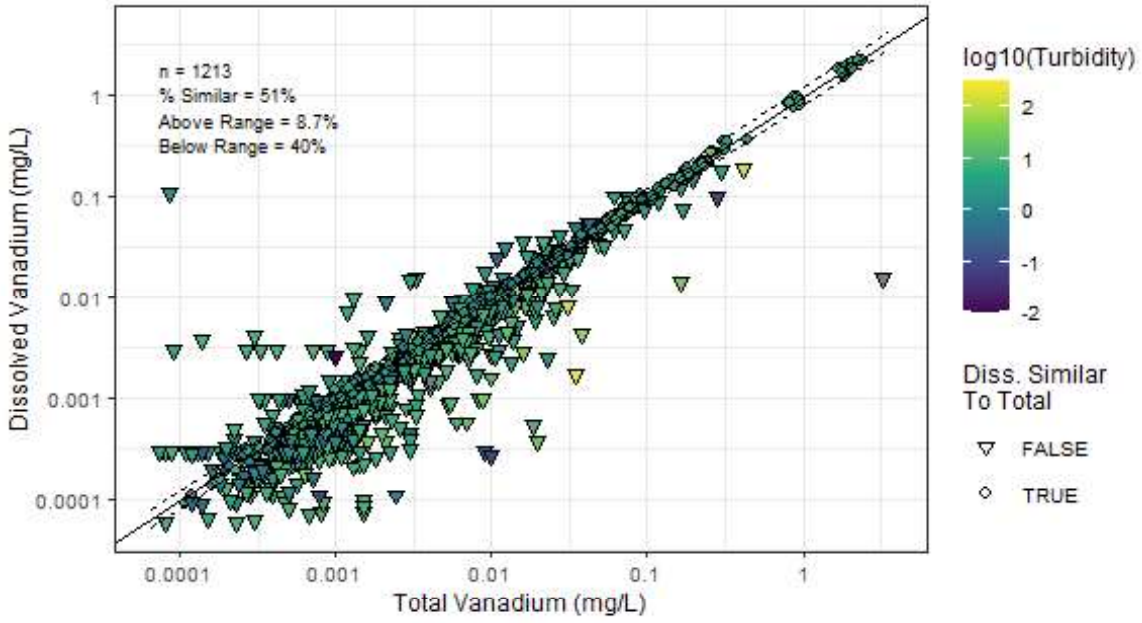


Figure B-25
Vanadium

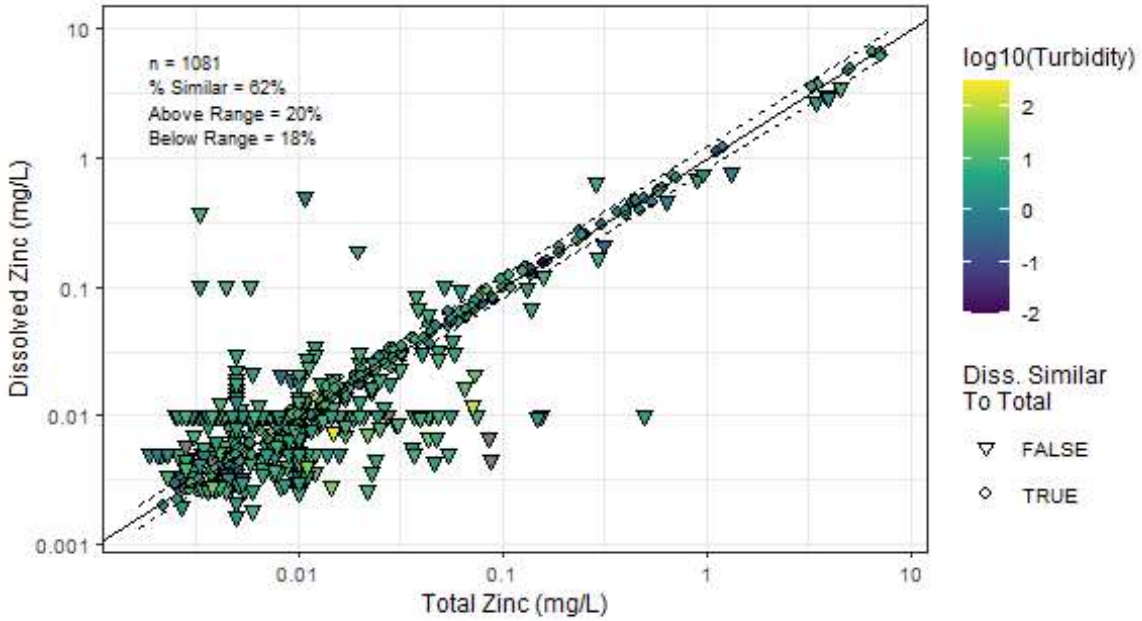


Figure B-26
Zinc

C
POREWATER VARIABILITY

The figures in this appendix illustrate inter- and intra-unit variability using boxplots. Intra-unit variability was based on the ratio of the 75th to 25th percentile (as illustrated by each individual box; a longer box indicates greater intra-unit variability than a shorter box). Inter-unit variability was determined based on the difference between median concentrations (horizontal line within each box) for each parameter across all sites.

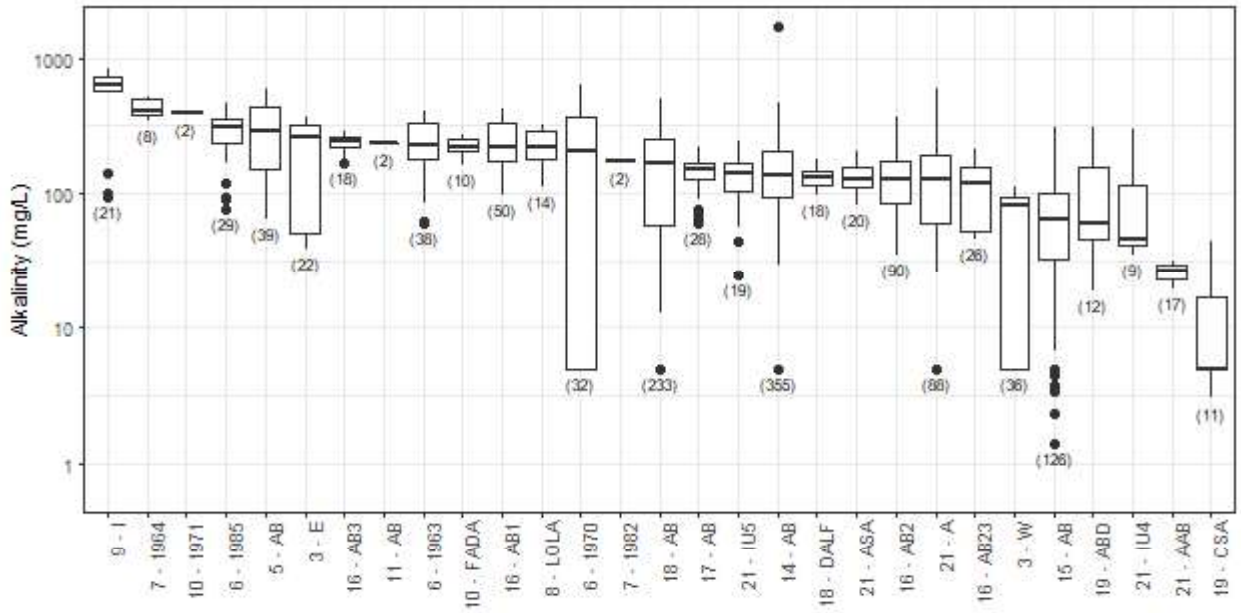


Figure C-1
Alkalinity

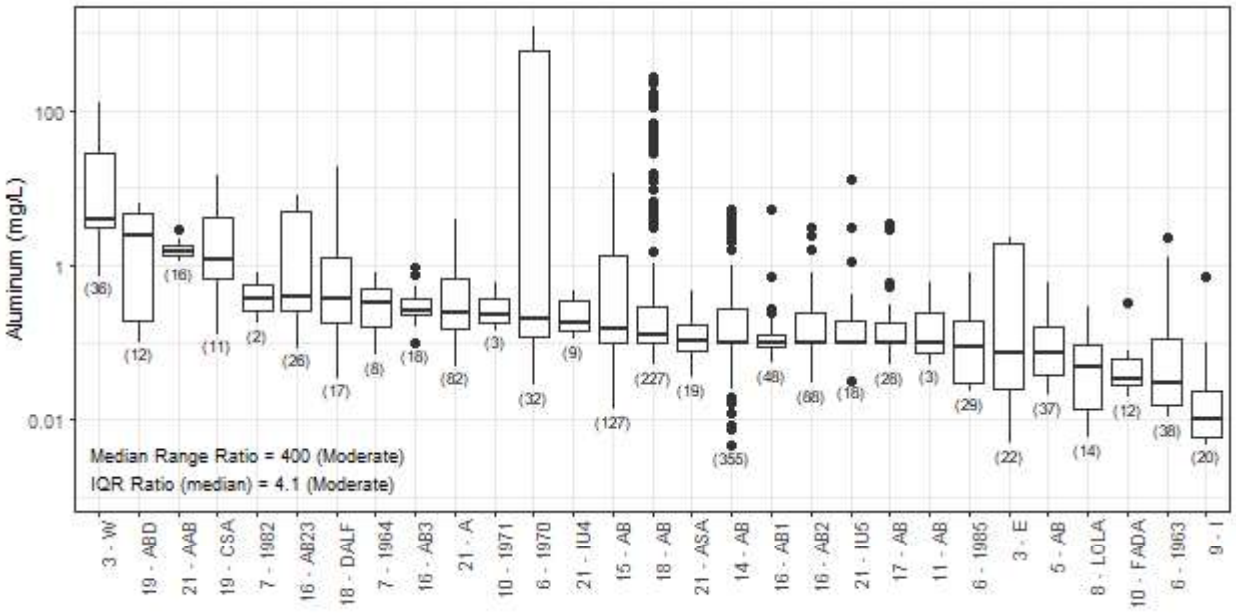


Figure C-2
Aluminum

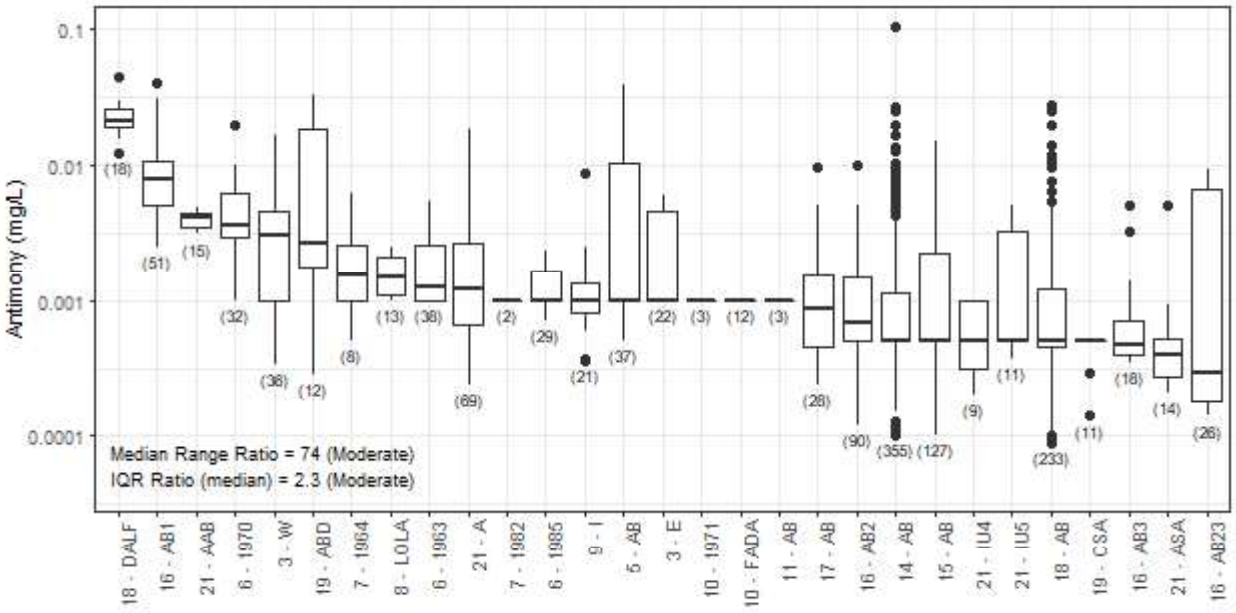


Figure C-3
Antimony

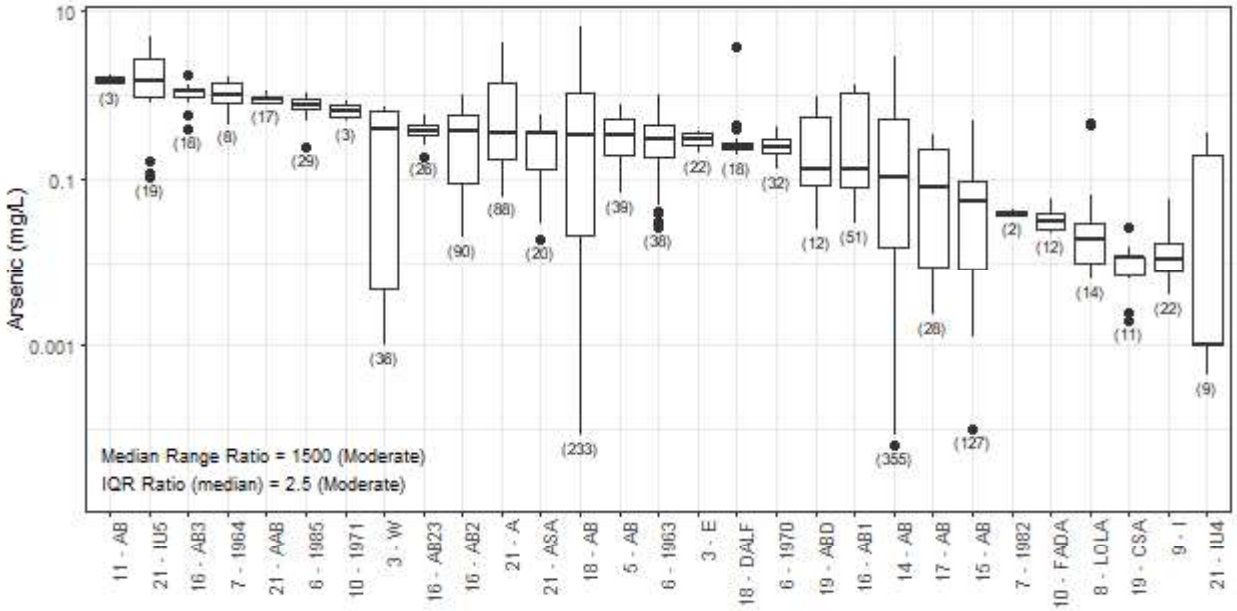


Figure C-4
Arsenic

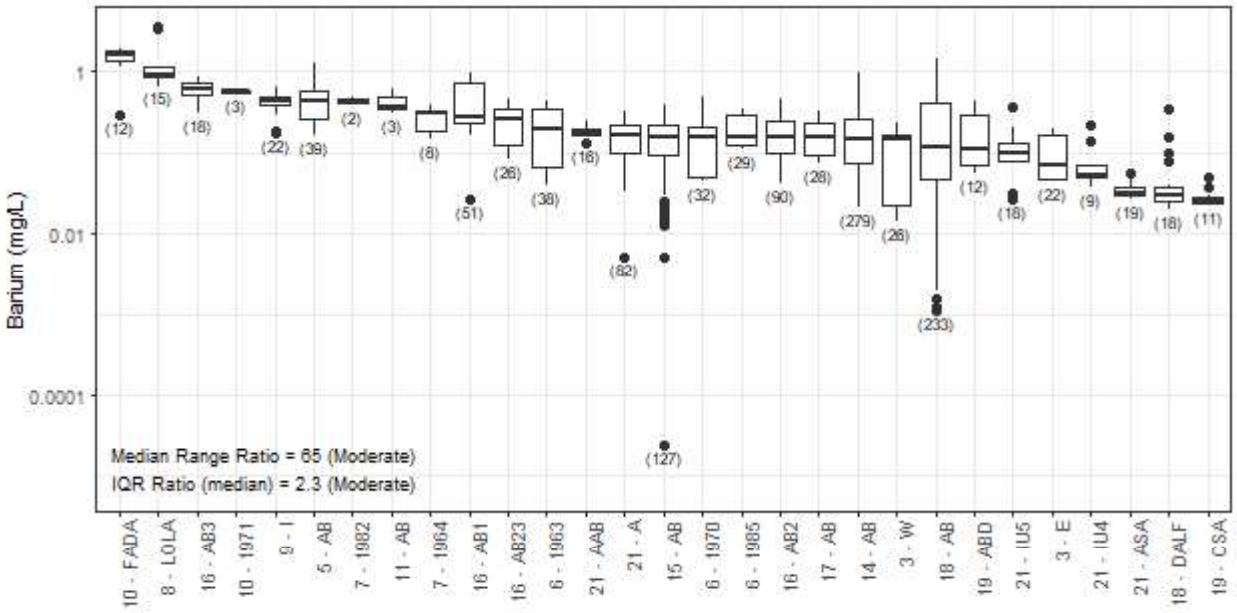


Figure C-5
Barium

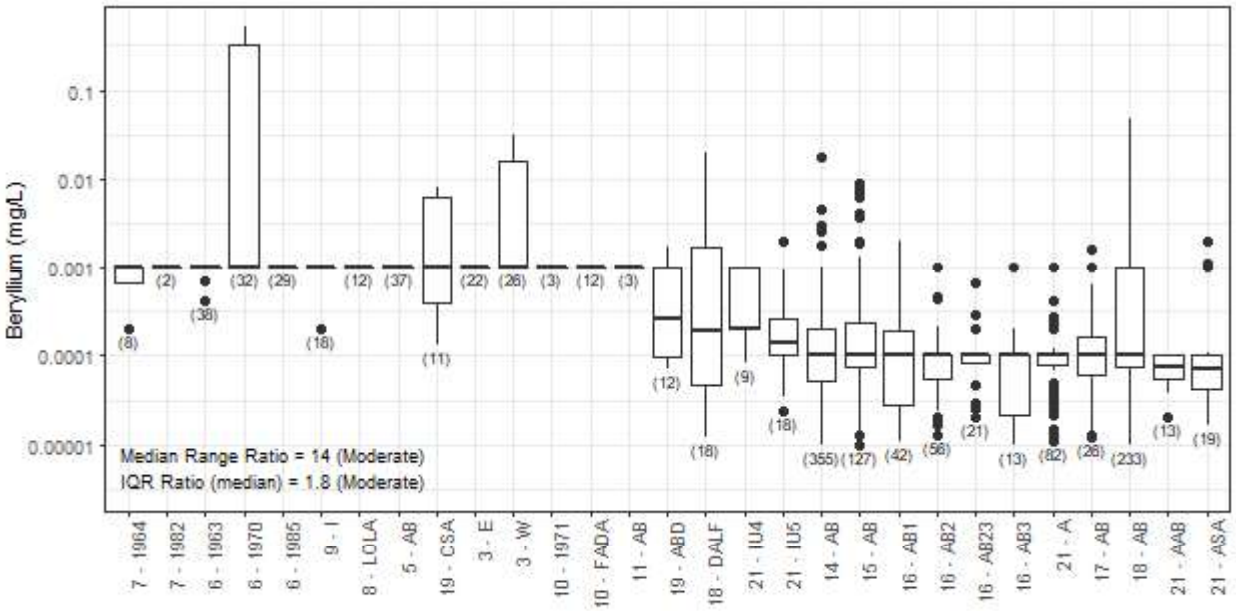


Figure C-6
Beryllium

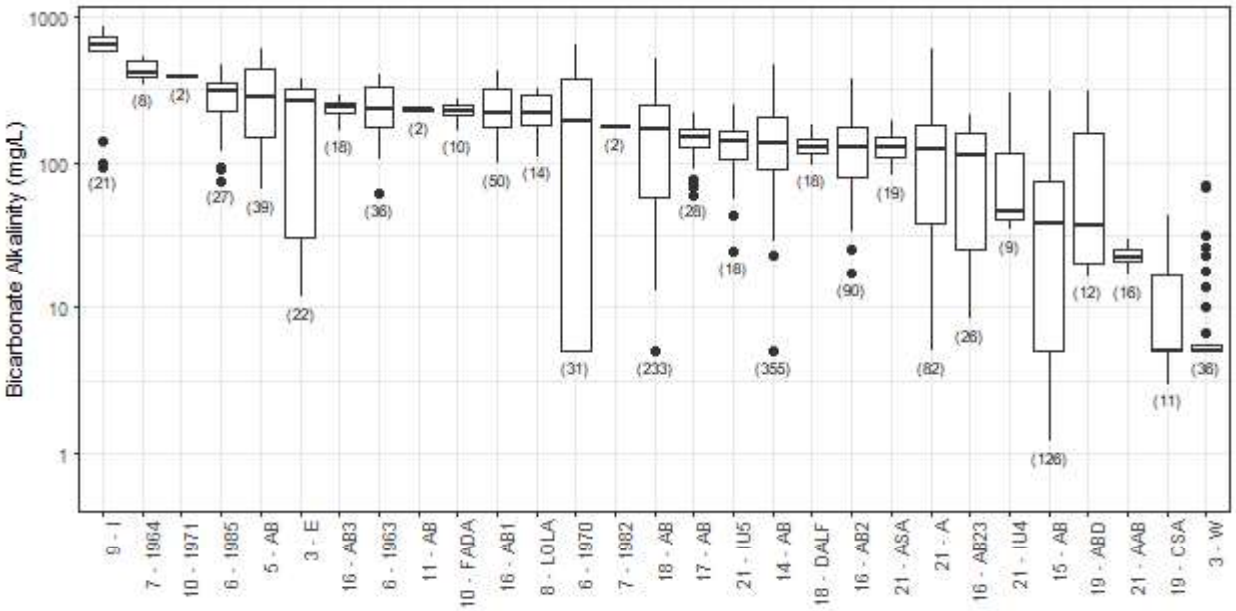


Figure C-7
Bicarbonate alkalinity

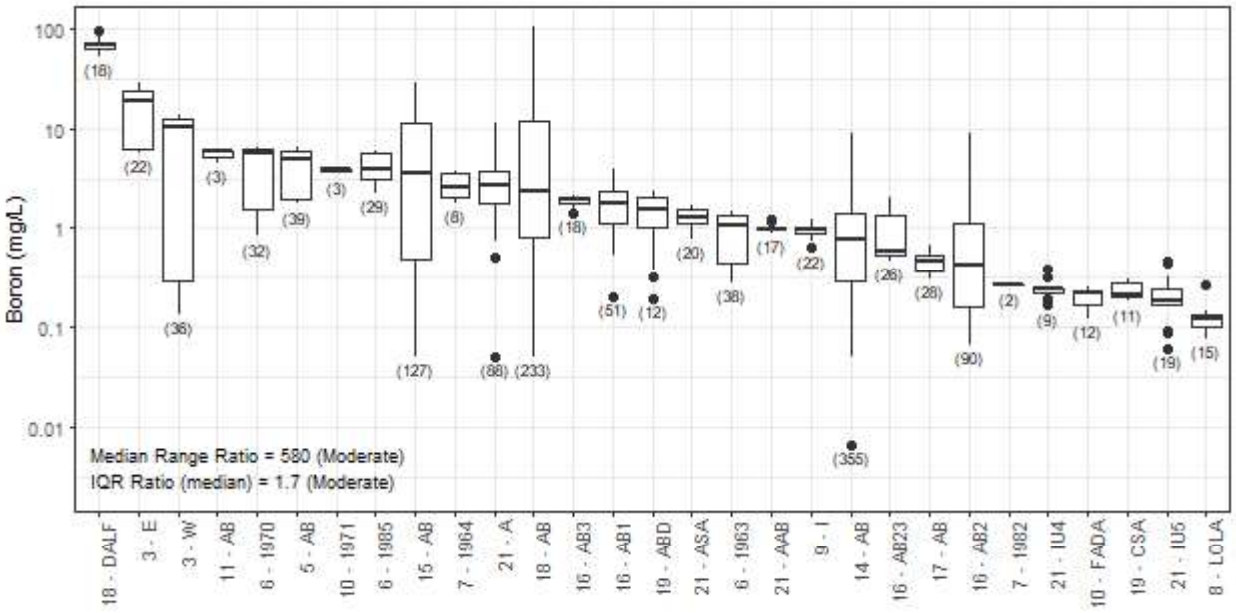


Figure C-8
Boron

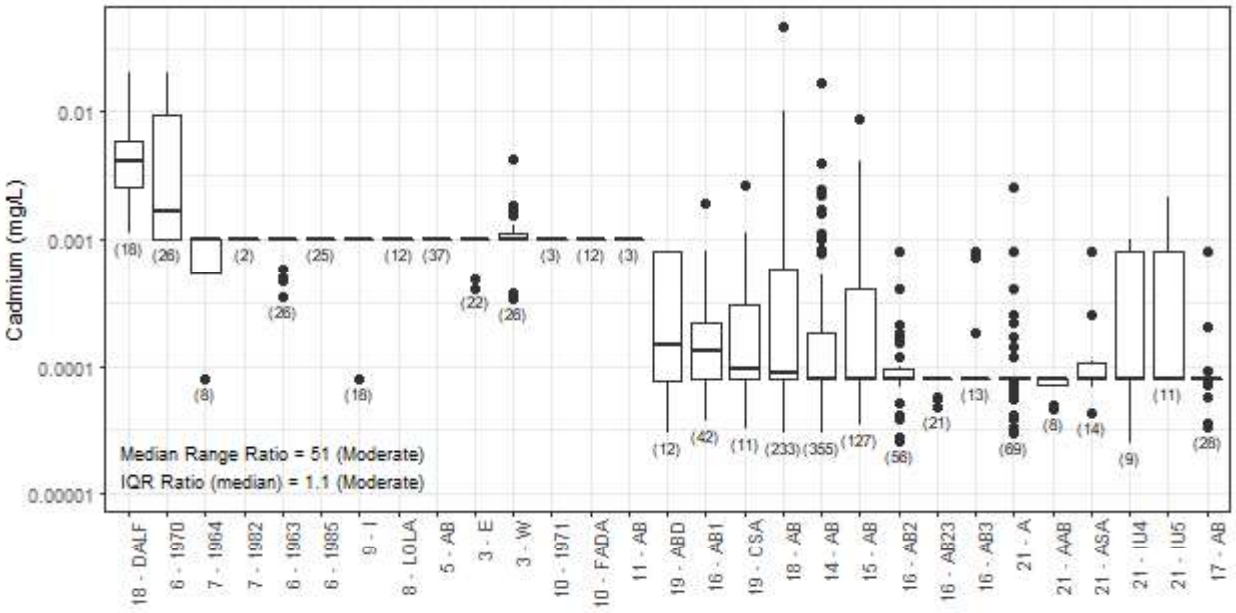


Figure C-9
Cadmium

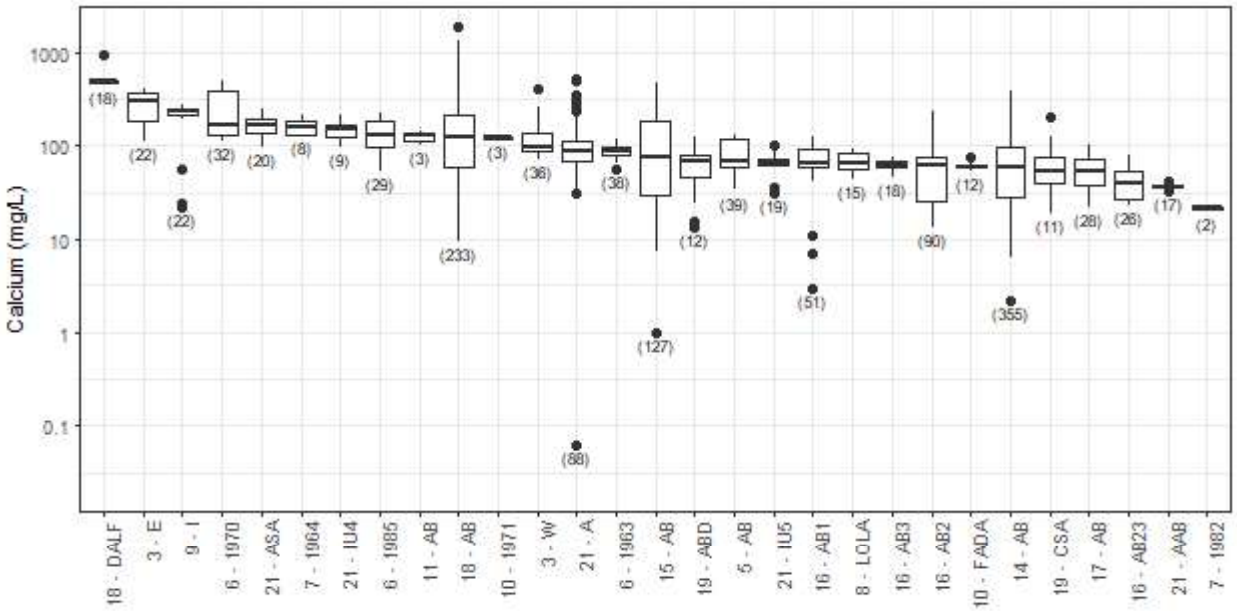


Figure C-10
Calcium

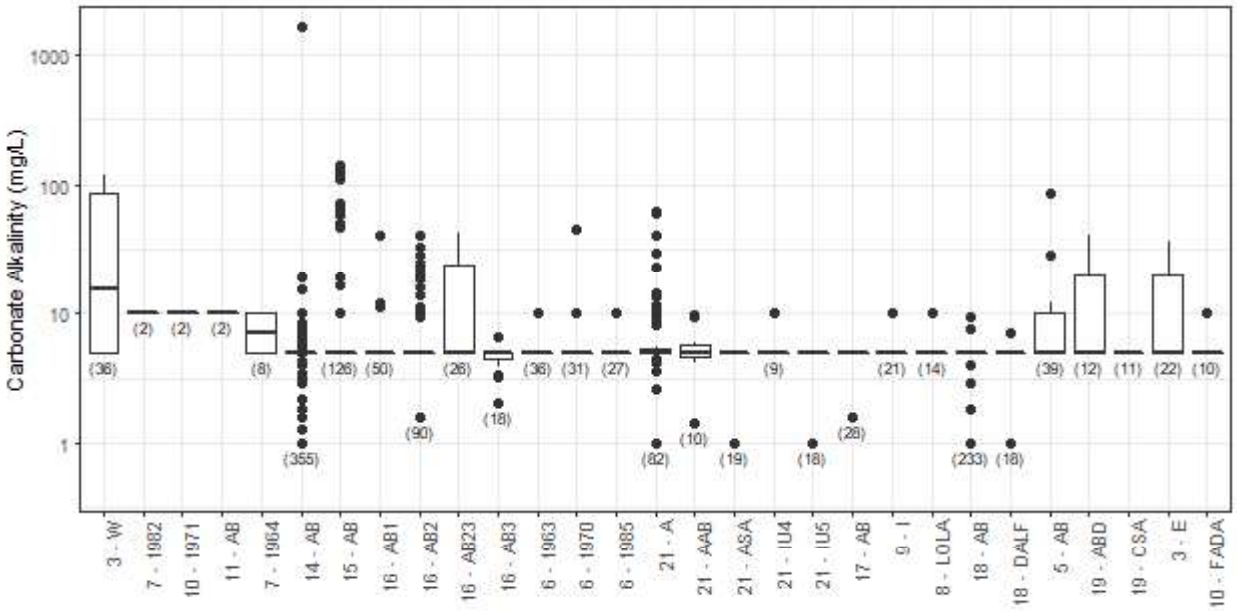


Figure C-11
Carbonate alkalinity

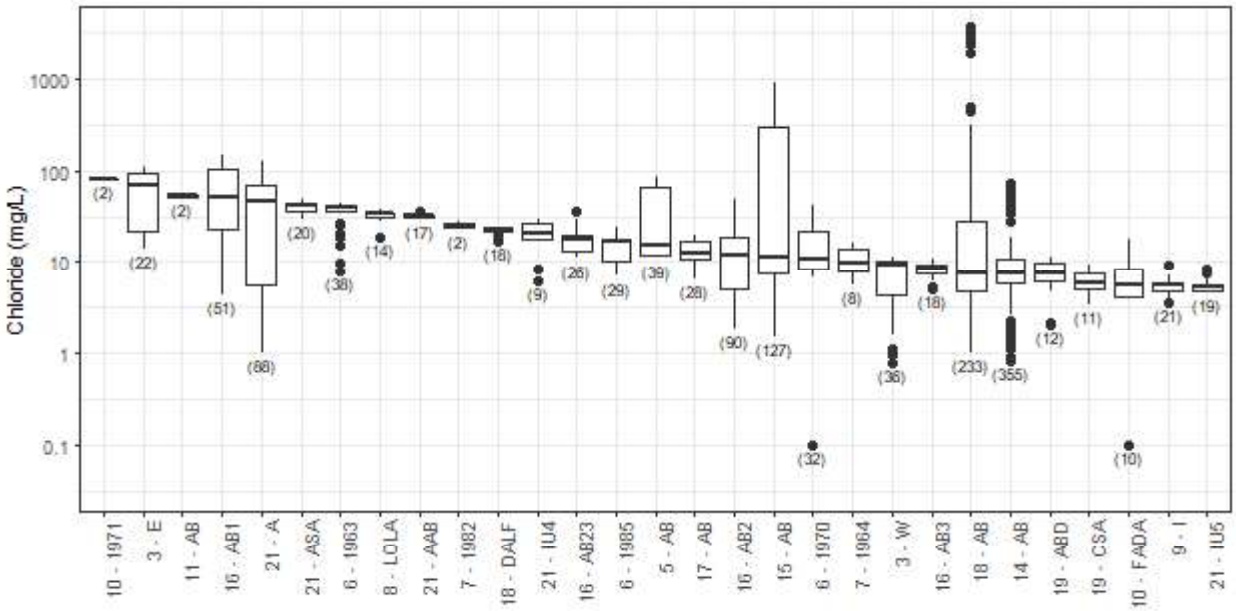


Figure C-12
Chloride

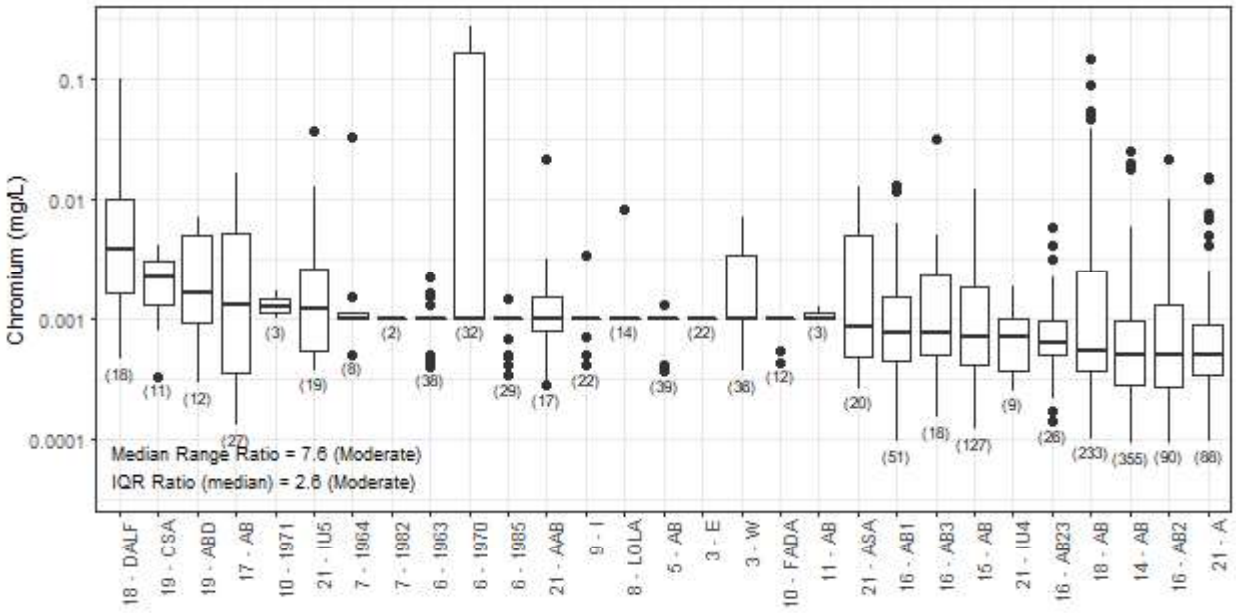


Figure C-13
Chromium

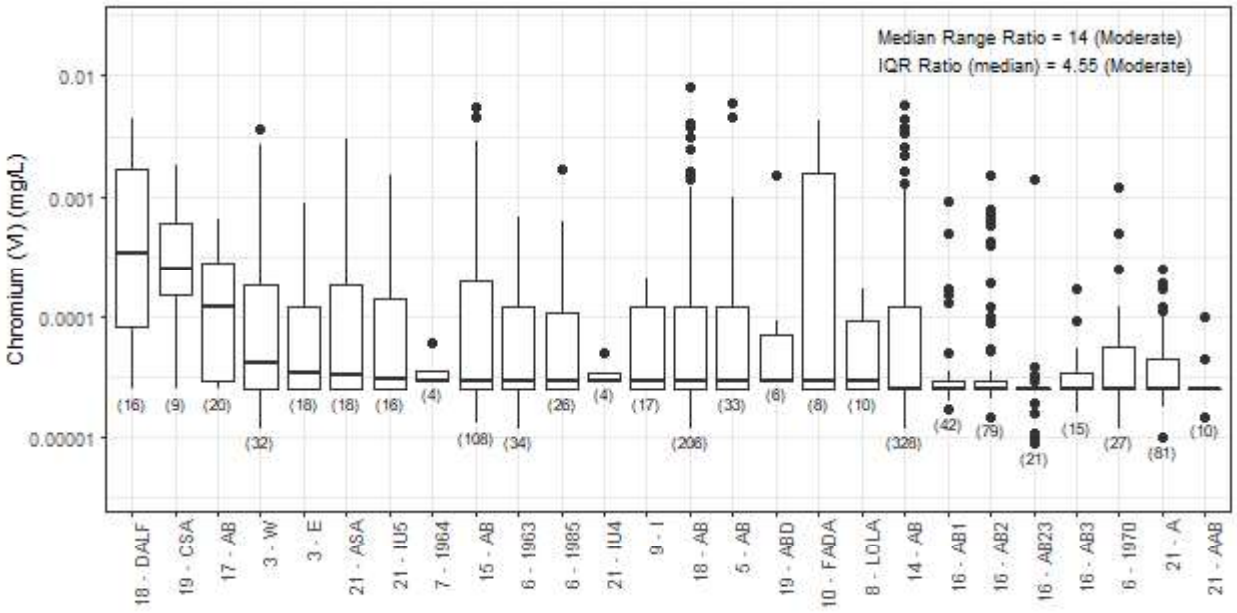


Figure C-14
Chromium (VI)

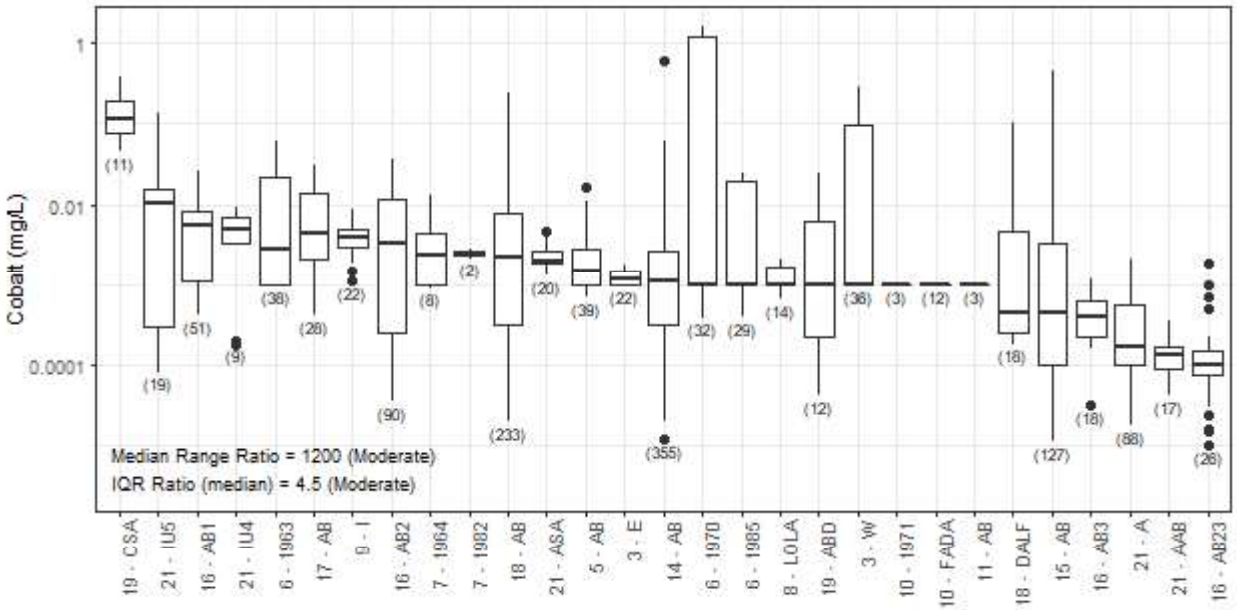


Figure C-15
Cobalt

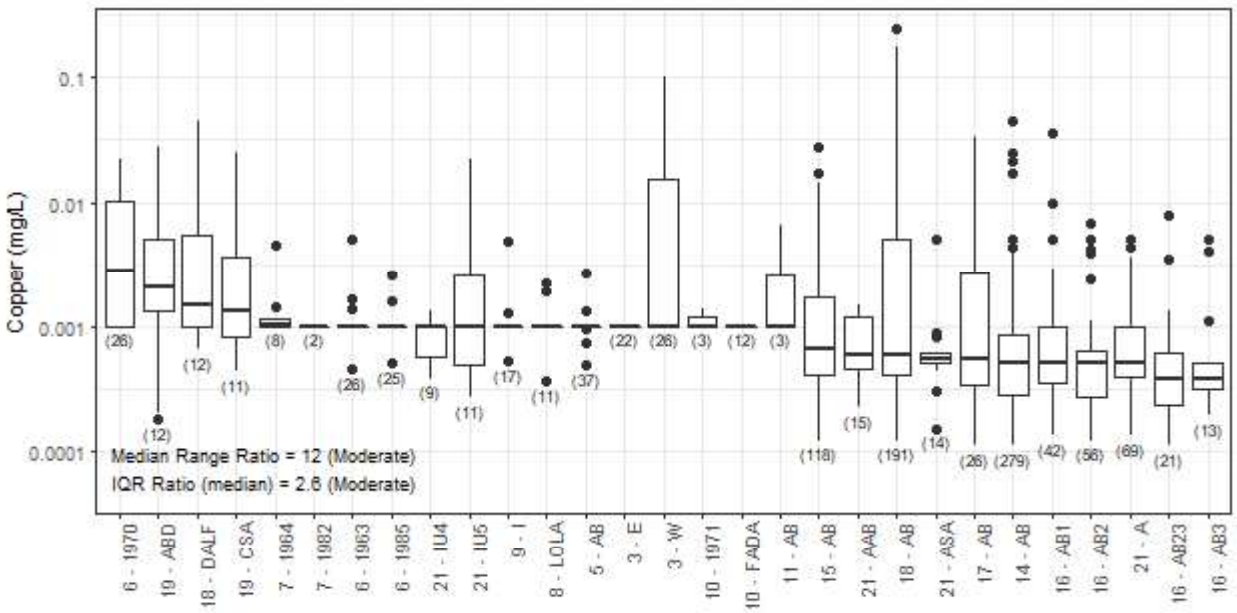


Figure C-16
Copper

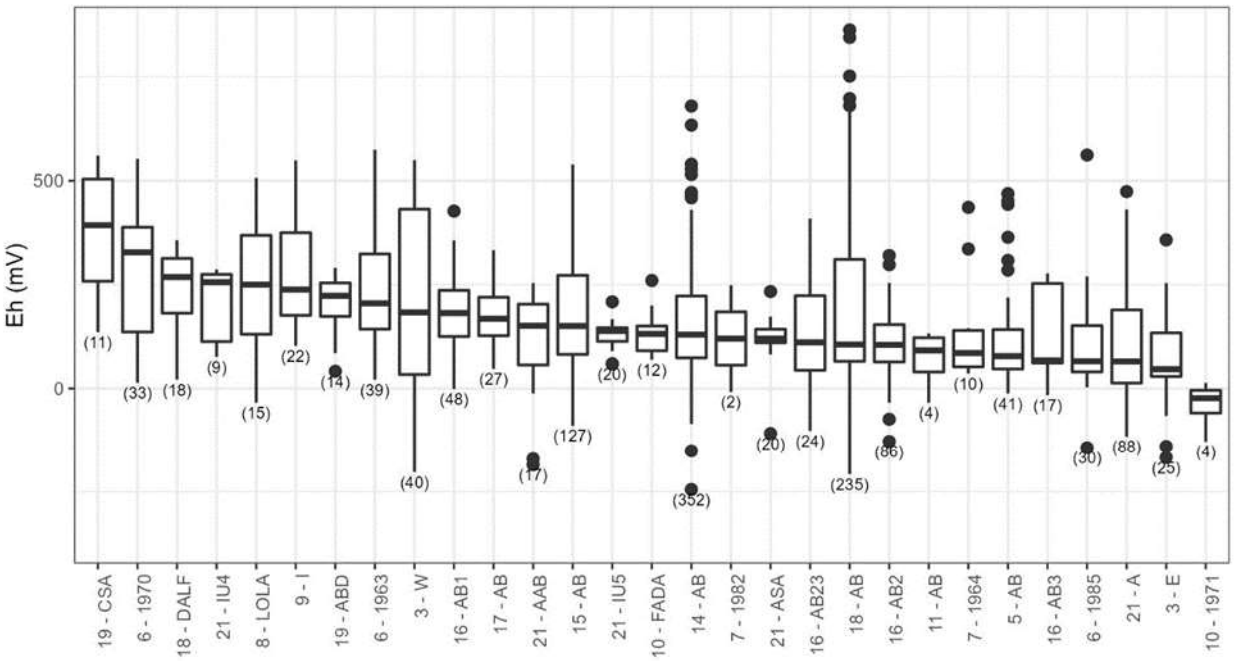


Figure C-17
Eh

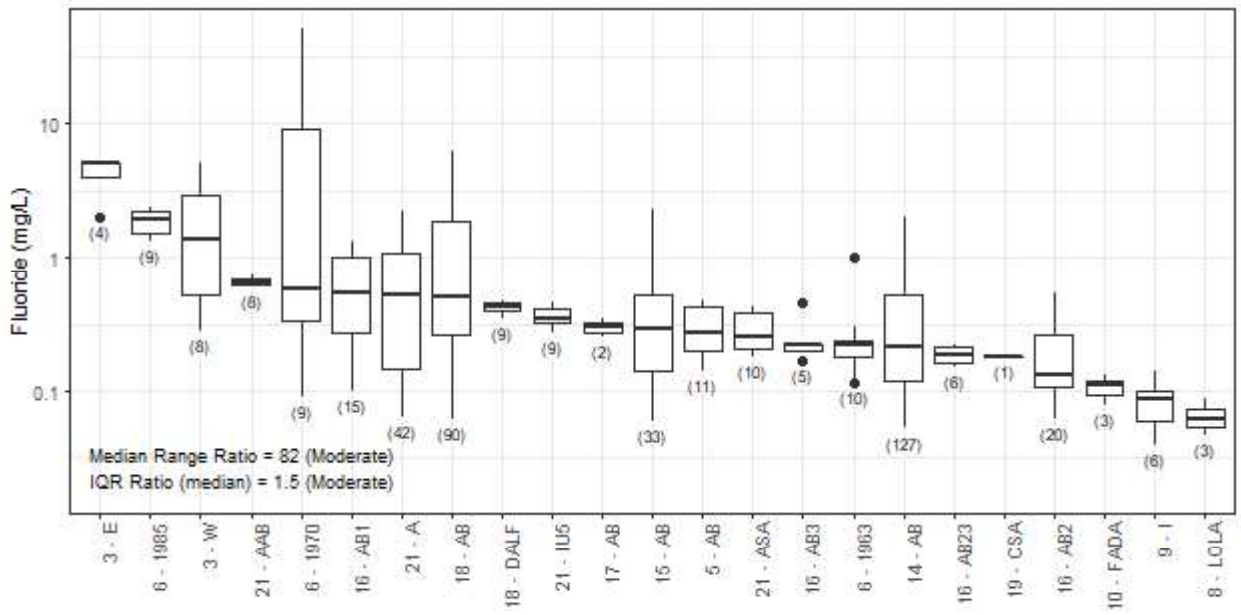


Figure C-18
Fluoride

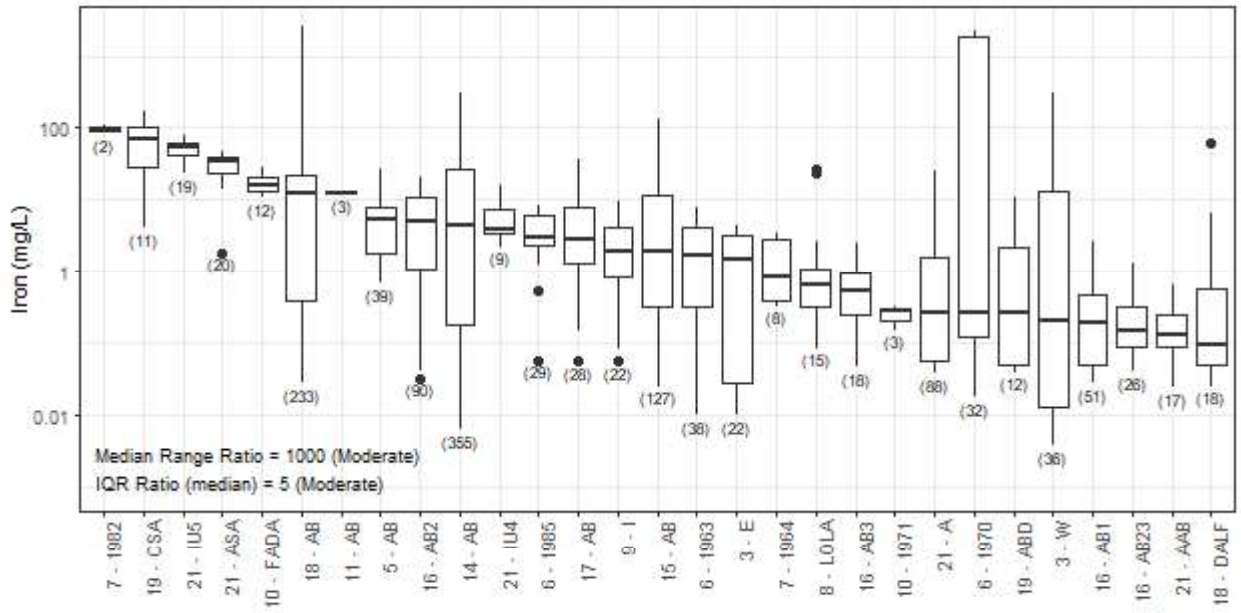


Figure C-19
Iron

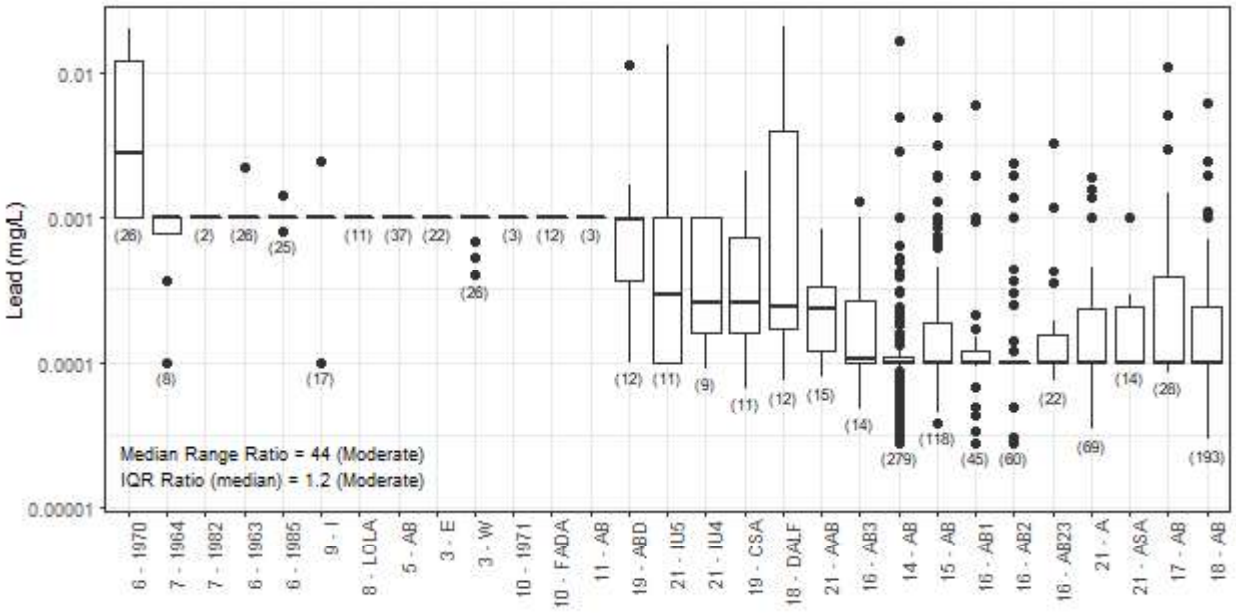


Figure C-20
Lead

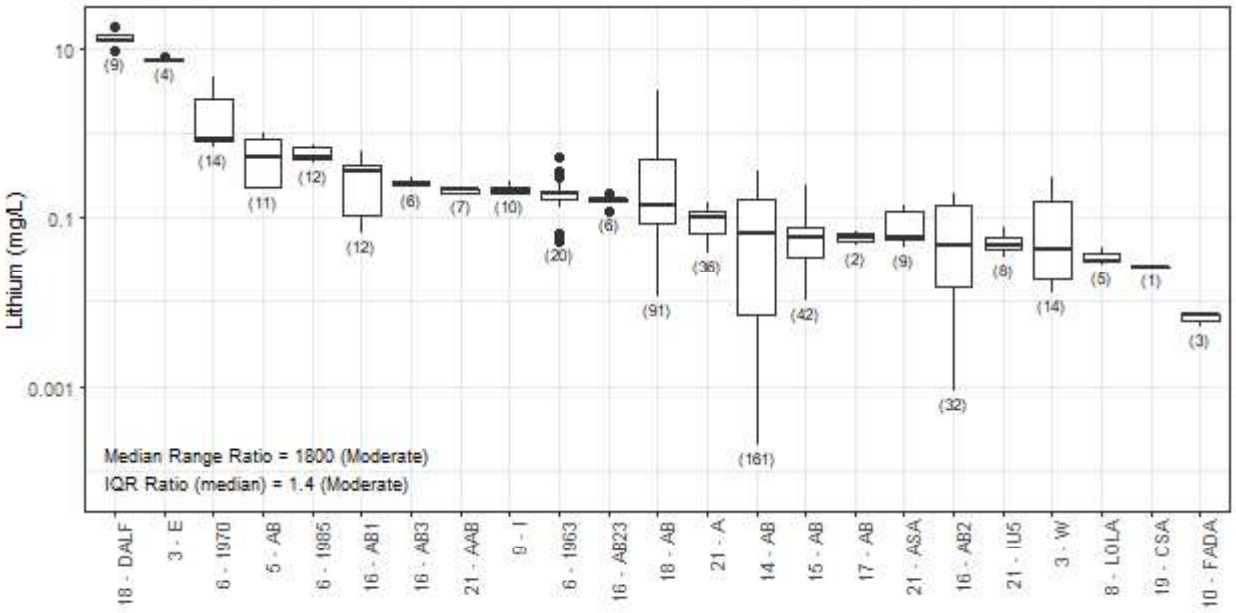


Figure C-21
Lithium

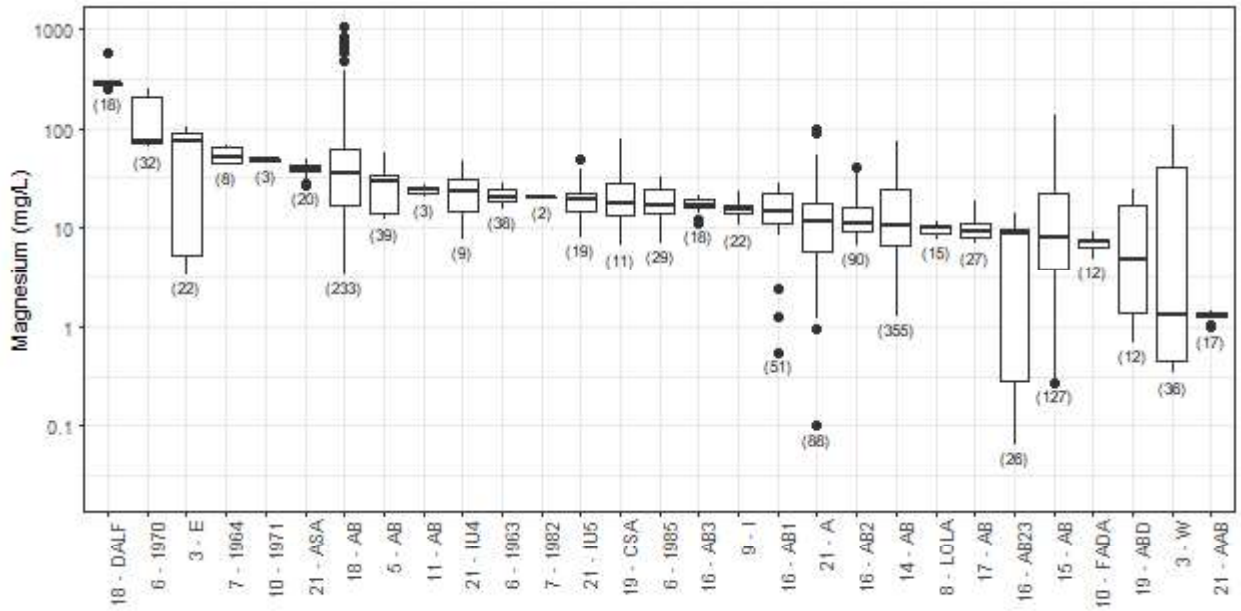


Figure C-22
Magnesium

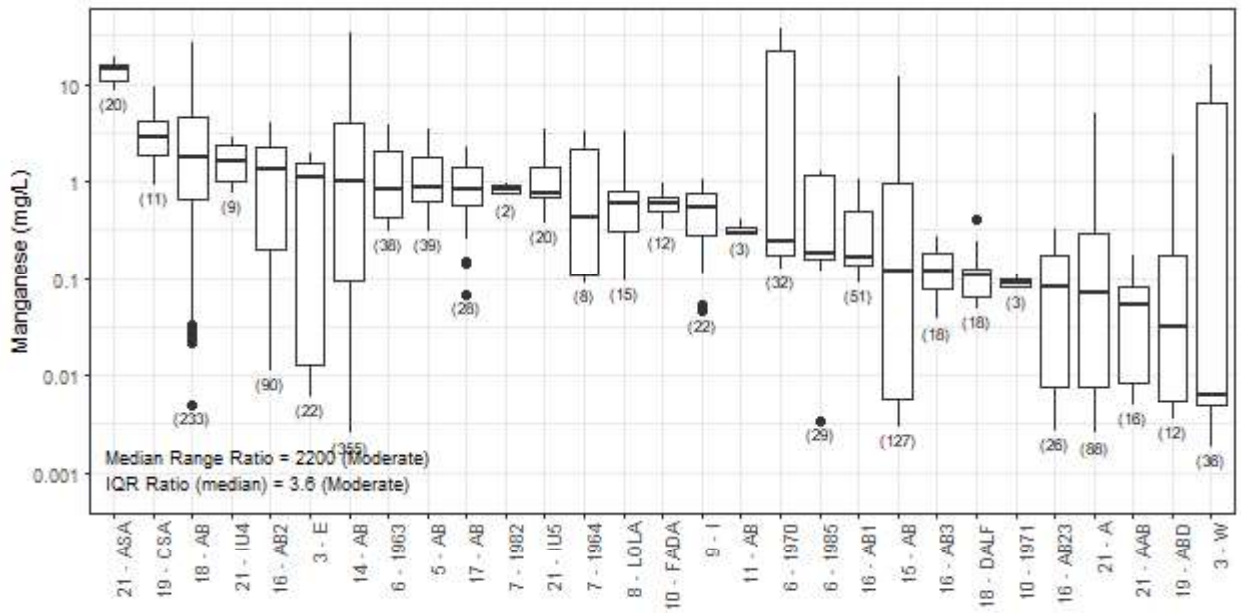


Figure C-23
Manganese

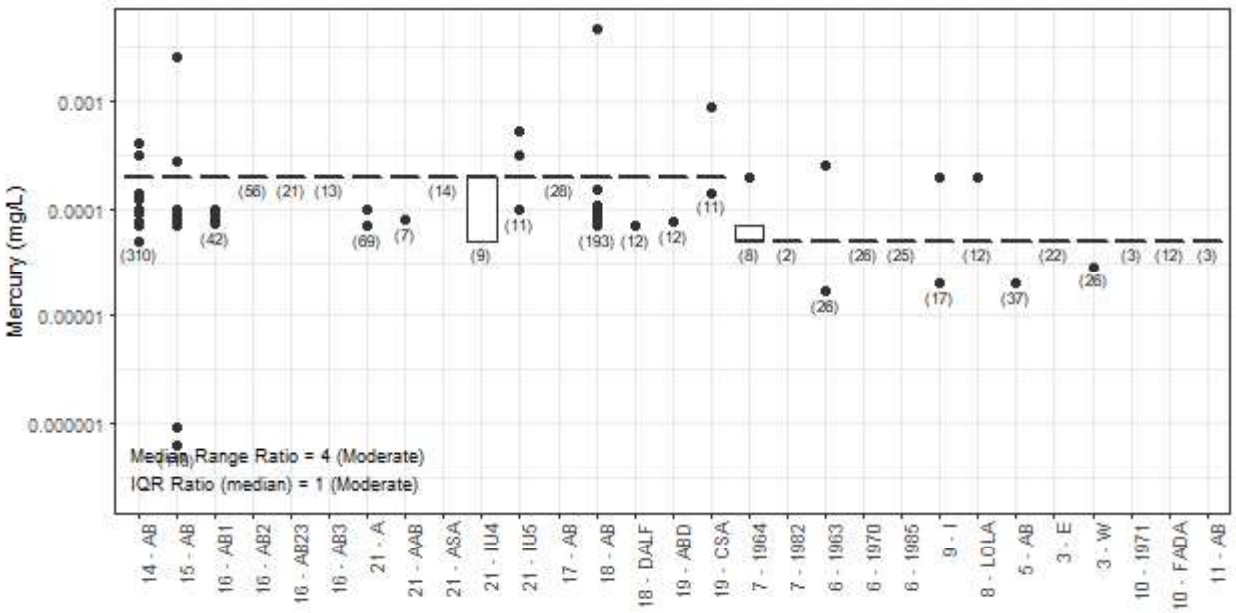


Figure C-24
Mercury

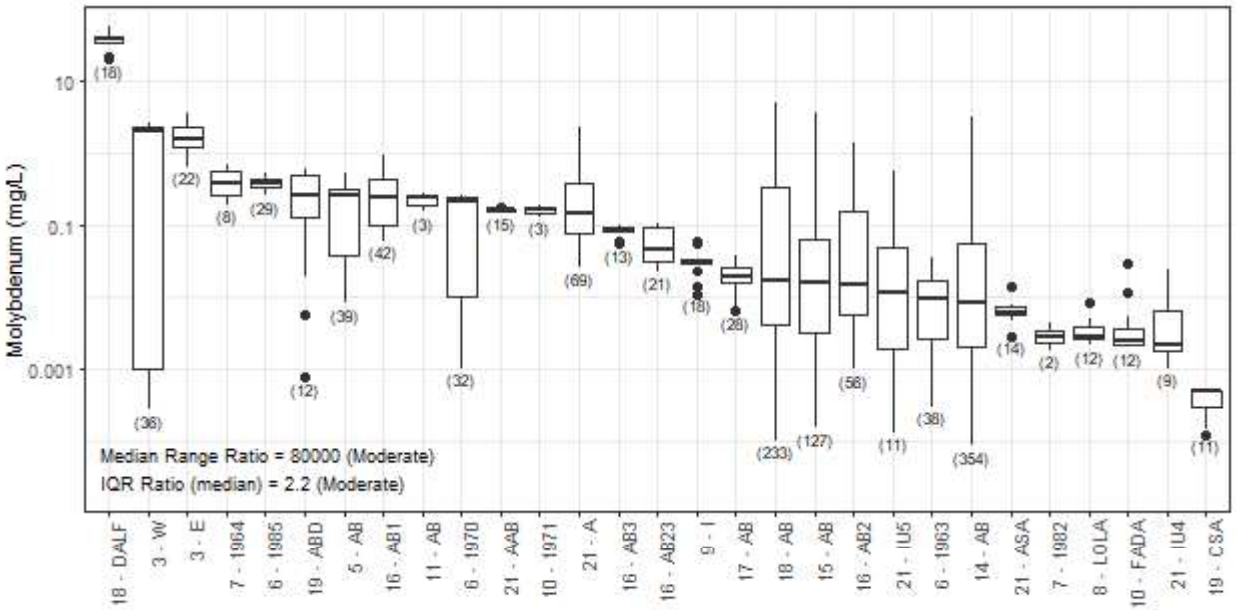


Figure C-25
Molybdenum

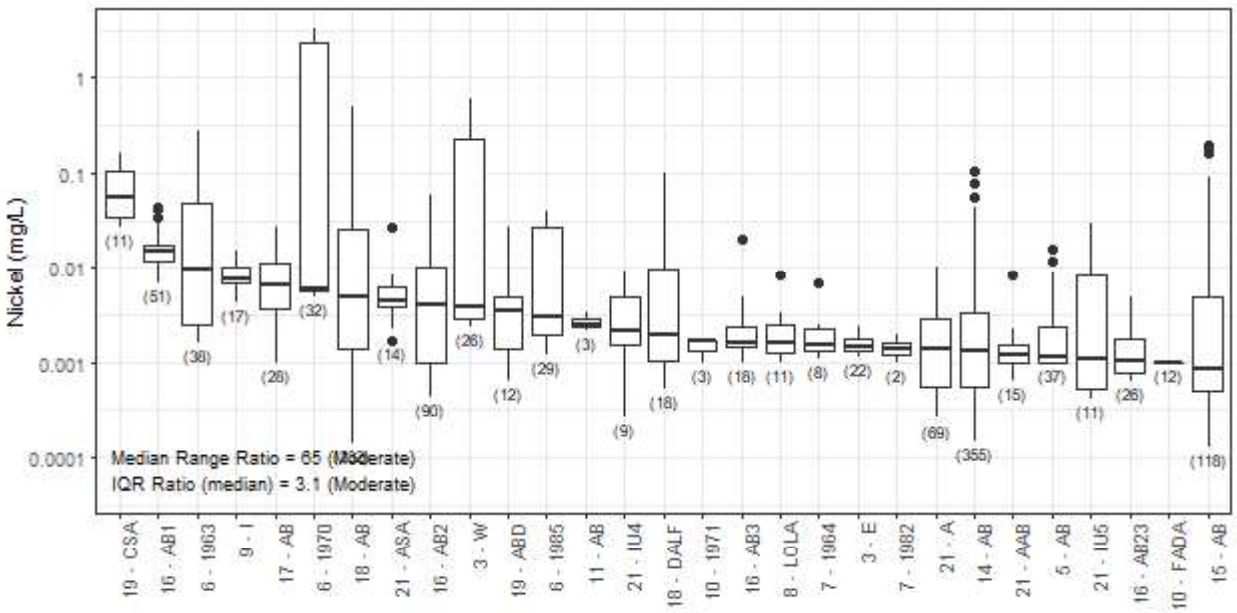


Figure C-26
Nickel

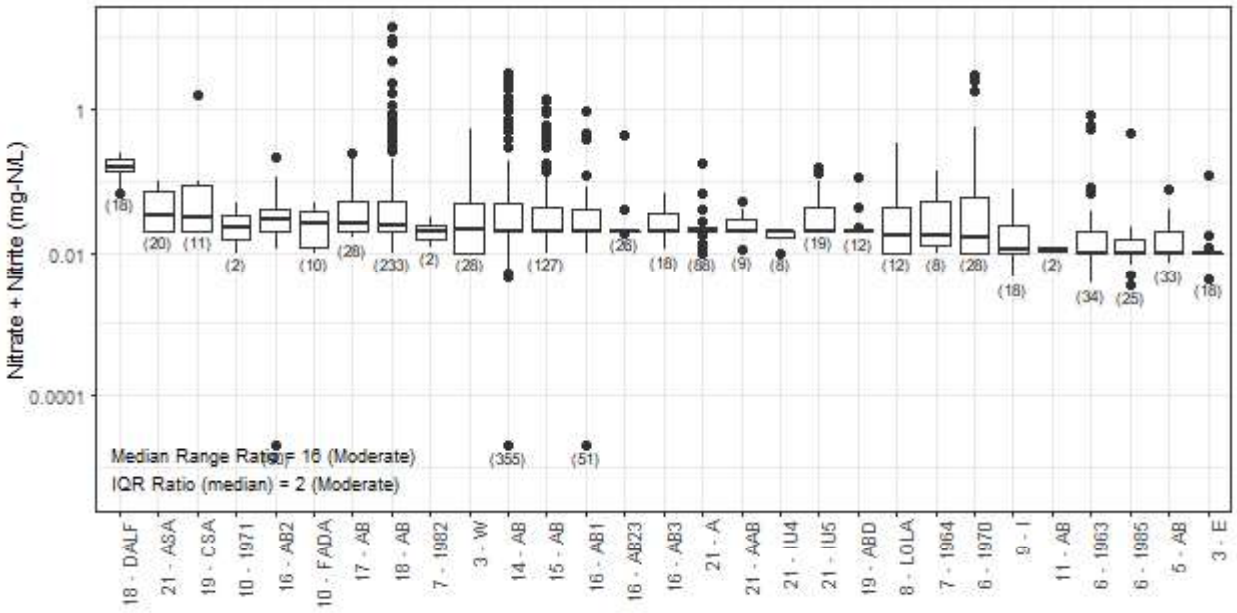


Figure C-27
Nitrate + Nitrite

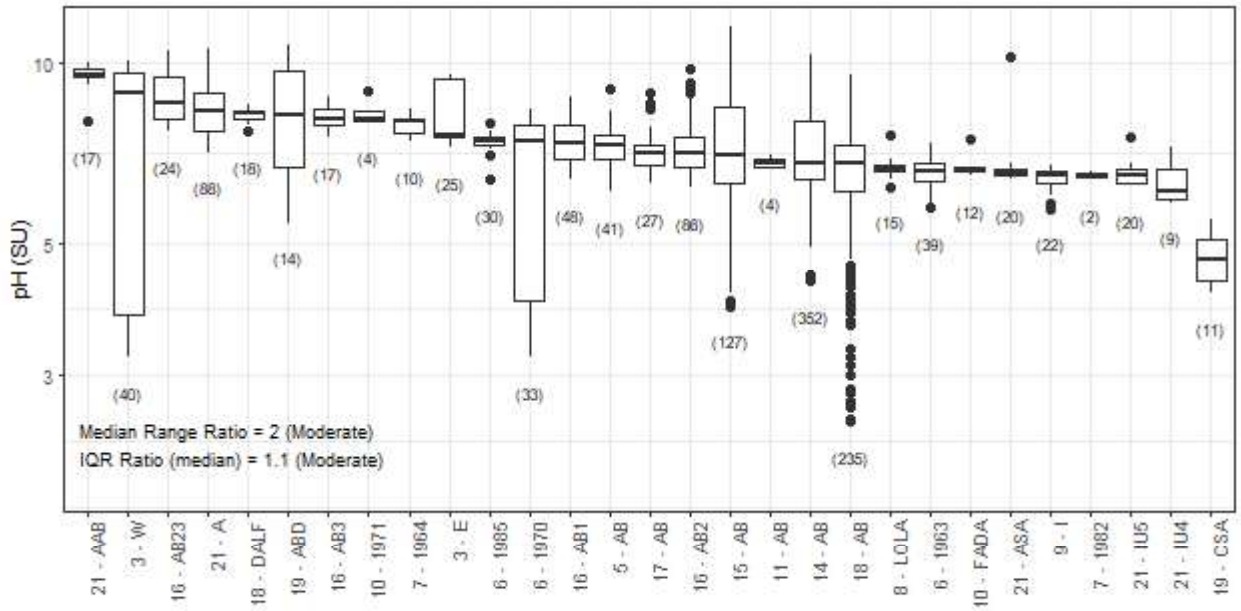


Figure C-28
pH

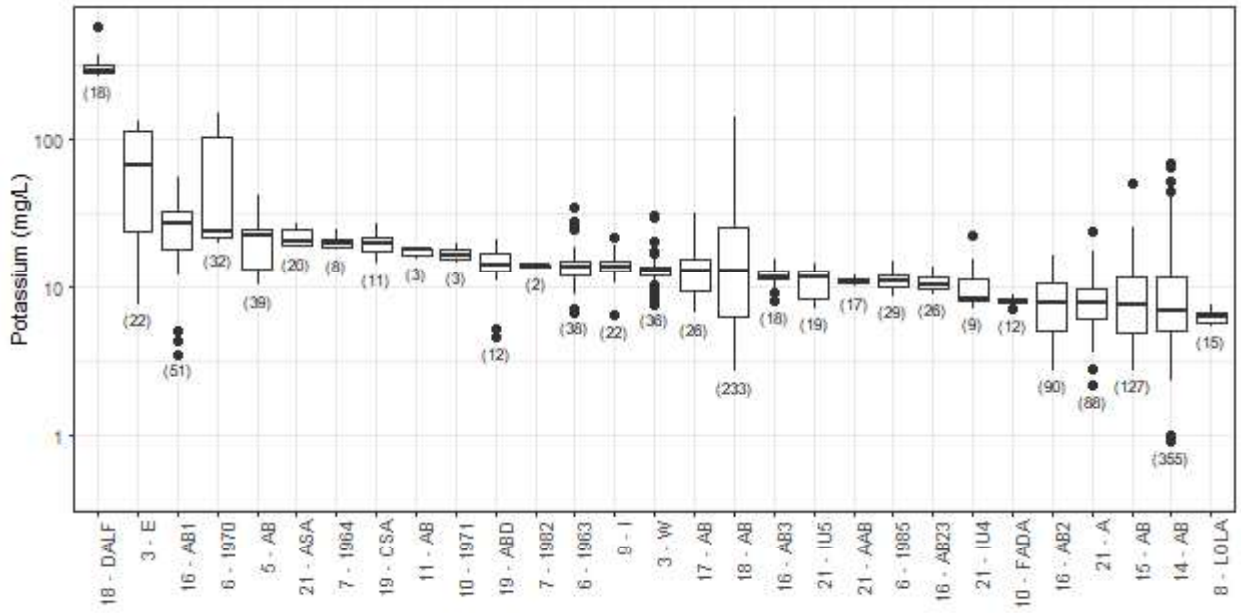


Figure C-29
Potassium

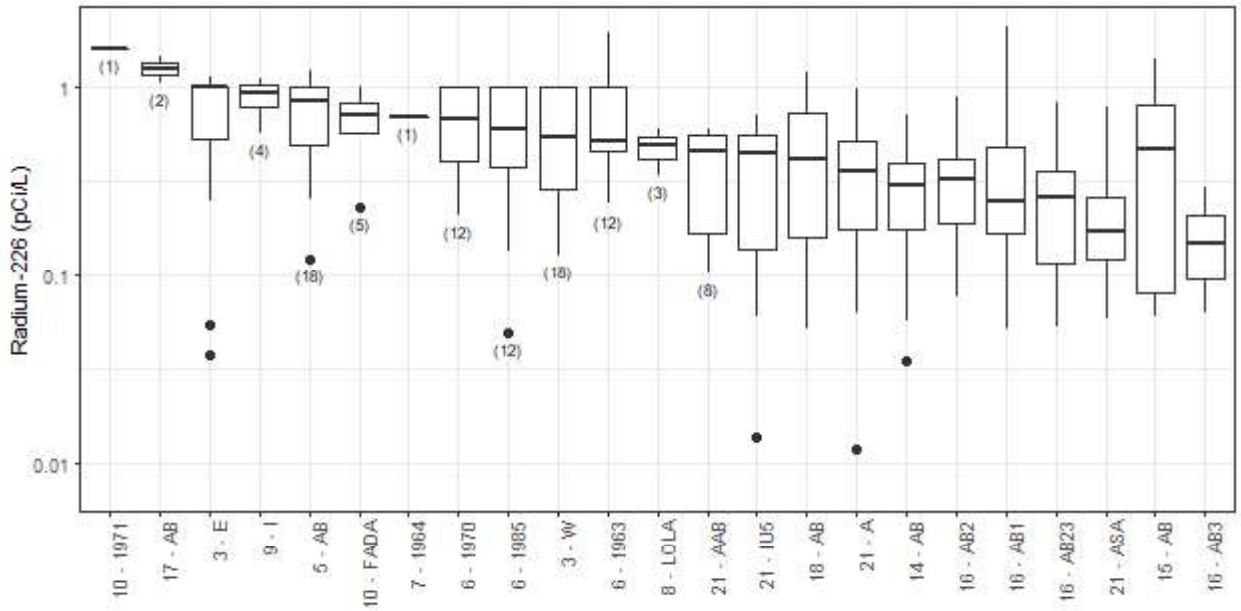


Figure C-30
Radium-226

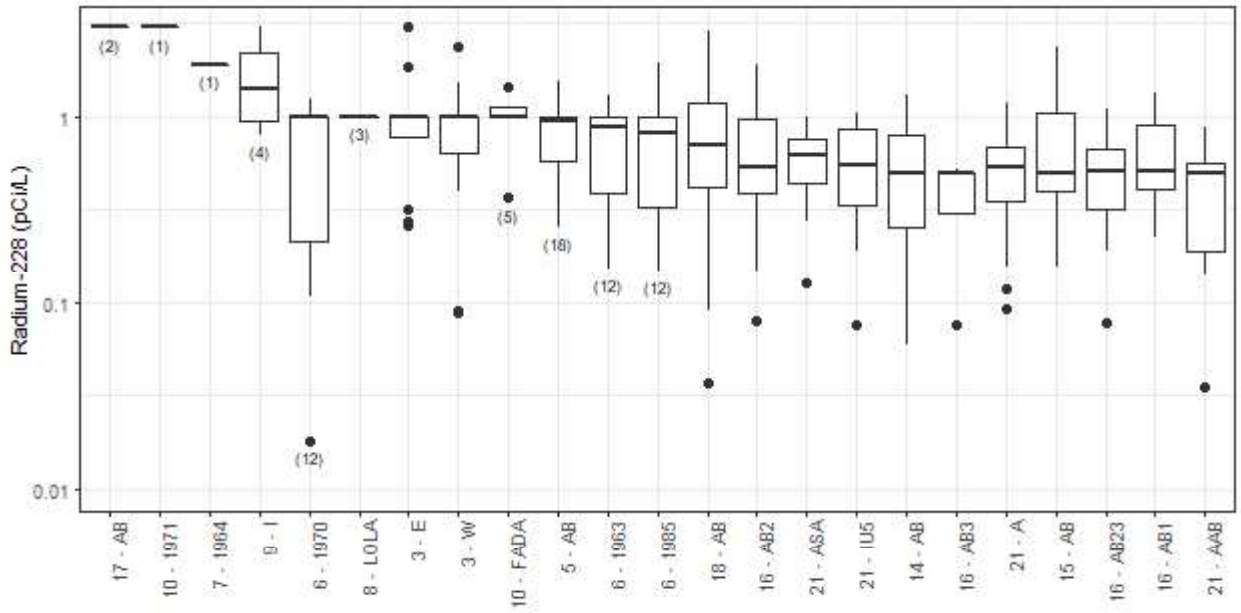


Figure C-31
Radium-228

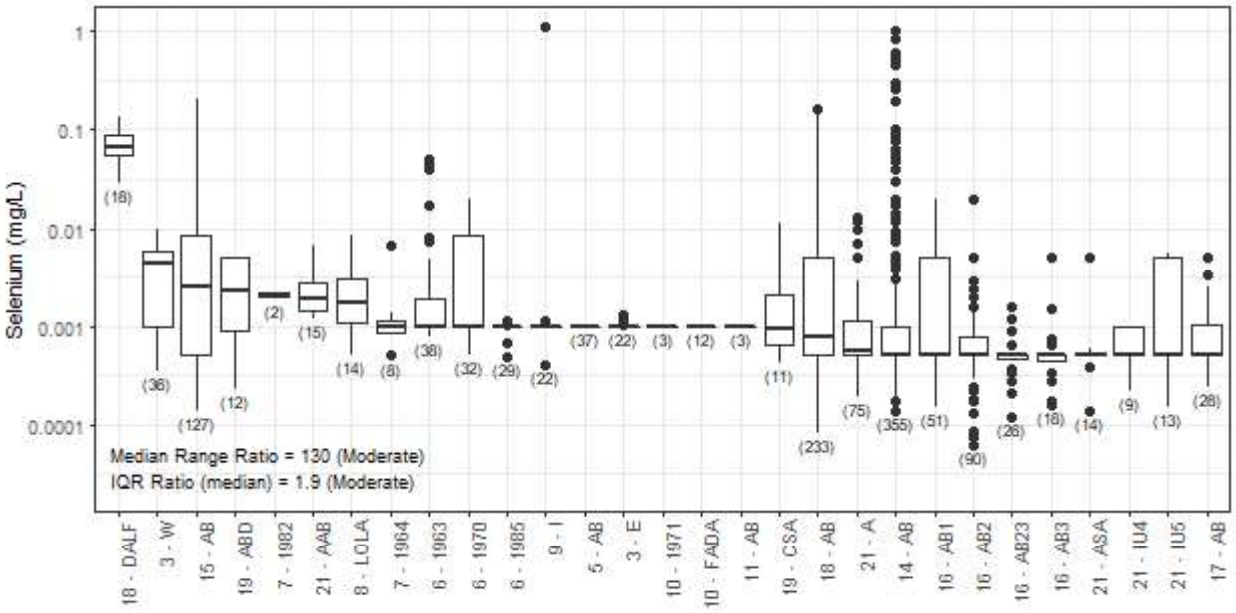


Figure C-32
Selenium

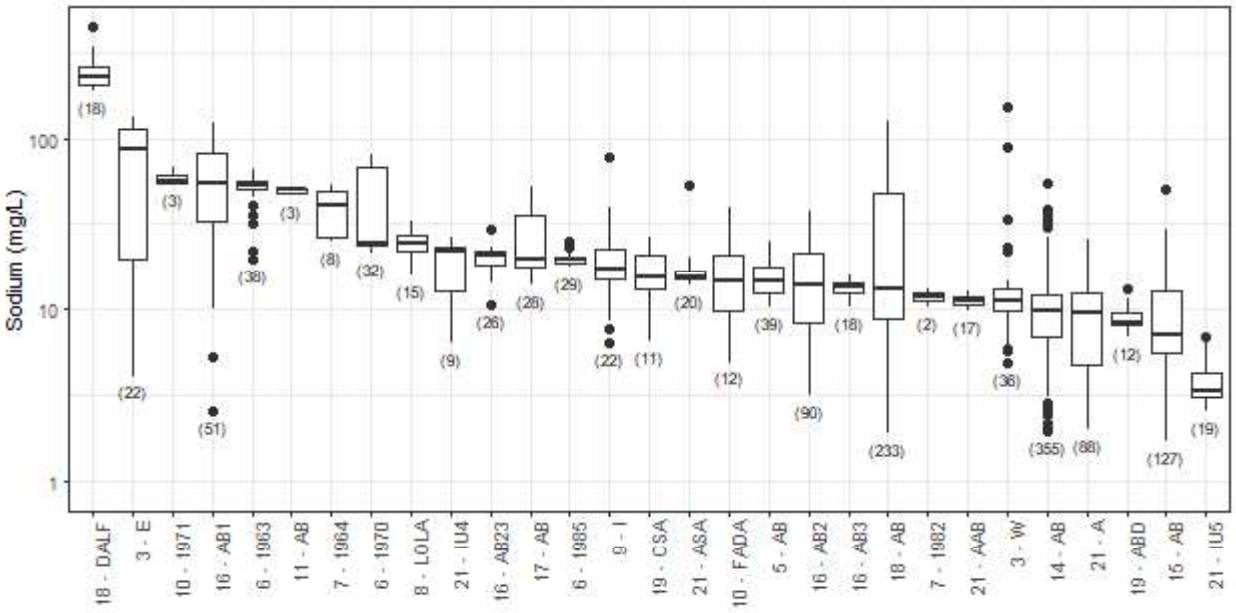


Figure C-33
Sodium

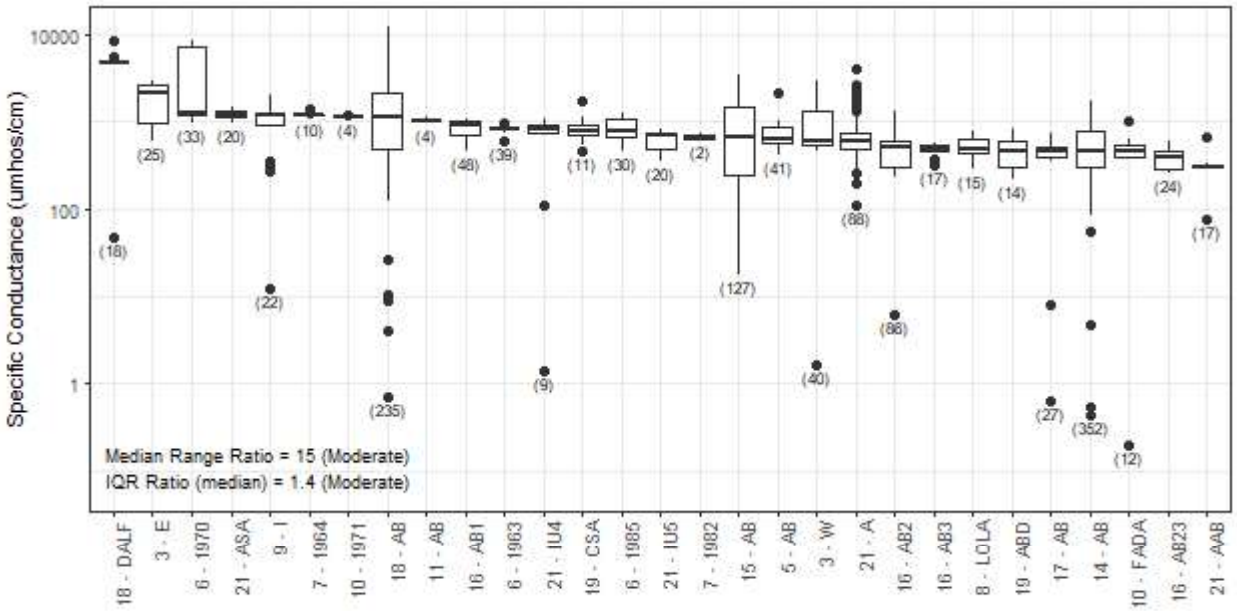


Figure C-34
Specific conductance

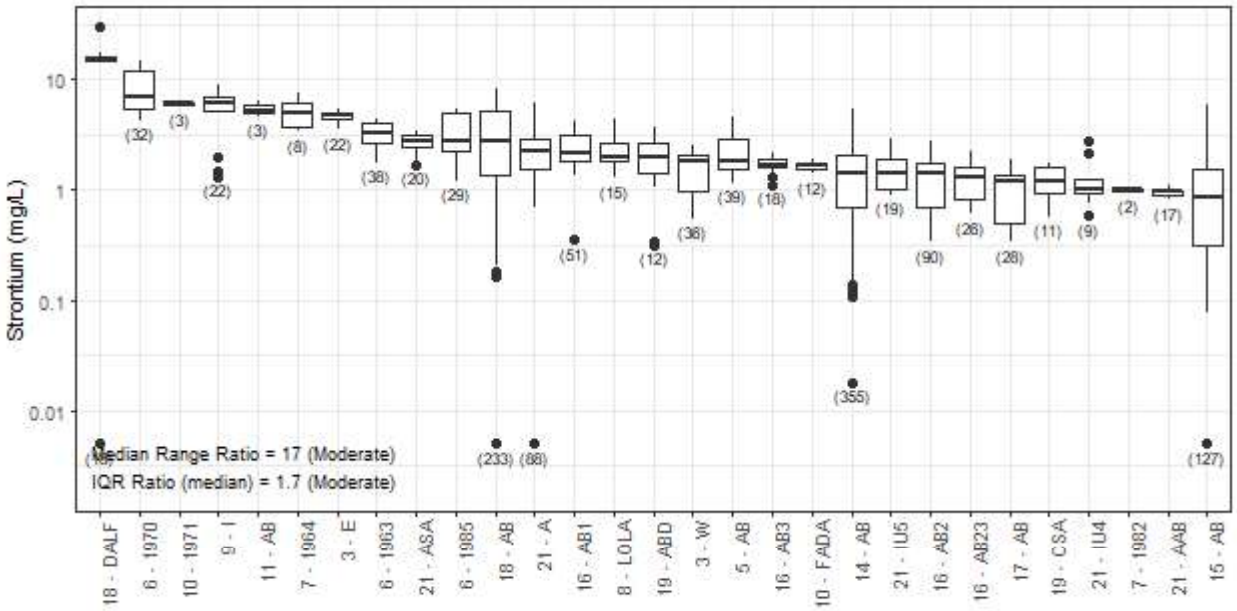


Figure C-35
Strontium

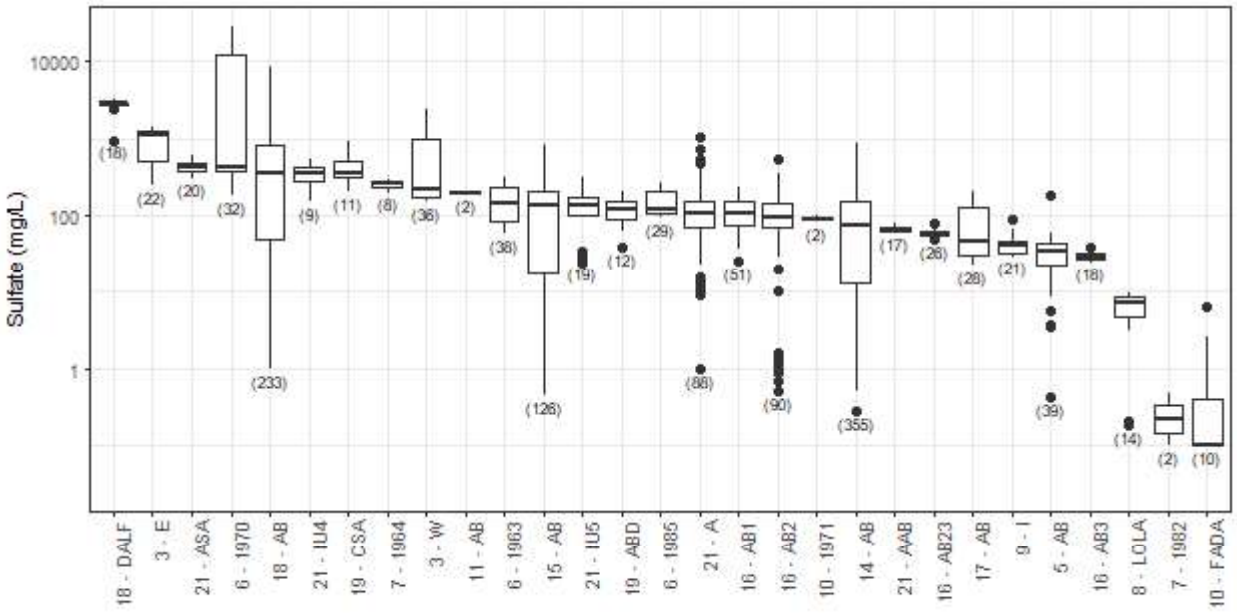


Figure C-36
Sulfate

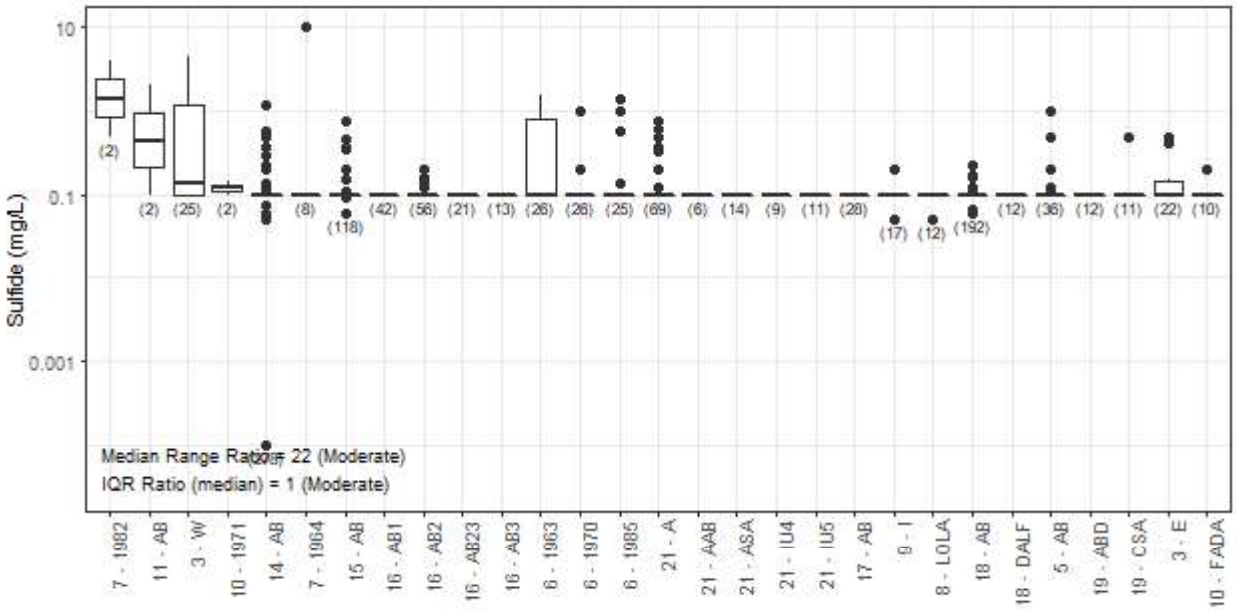


Figure C-37
Sulfide

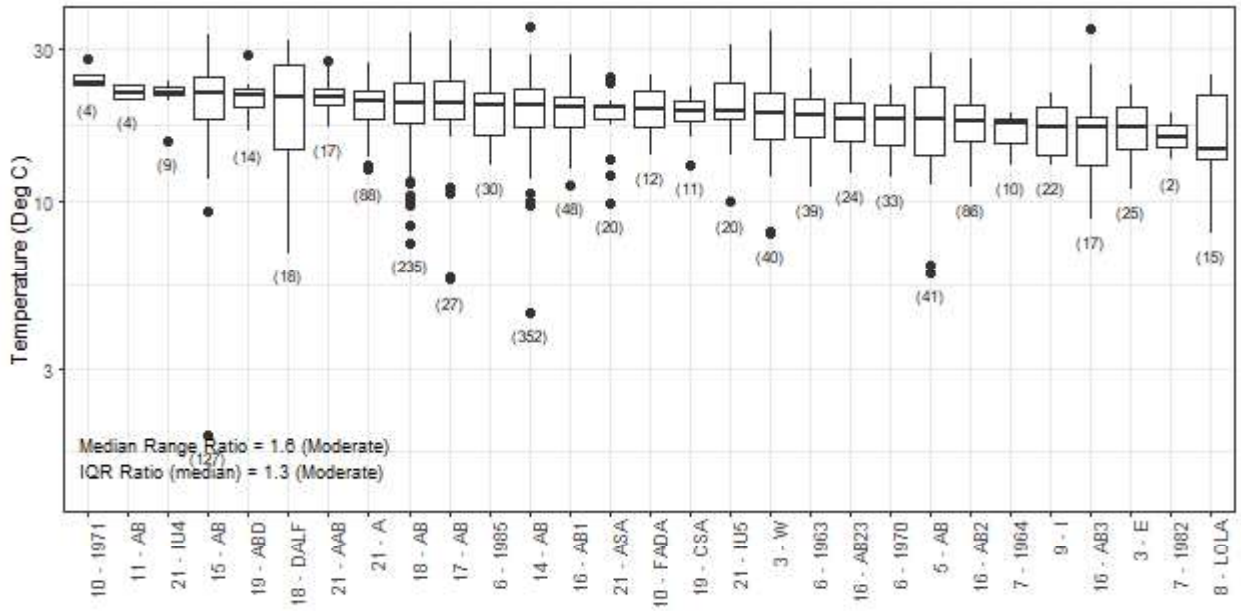


Figure C-38
Temperature

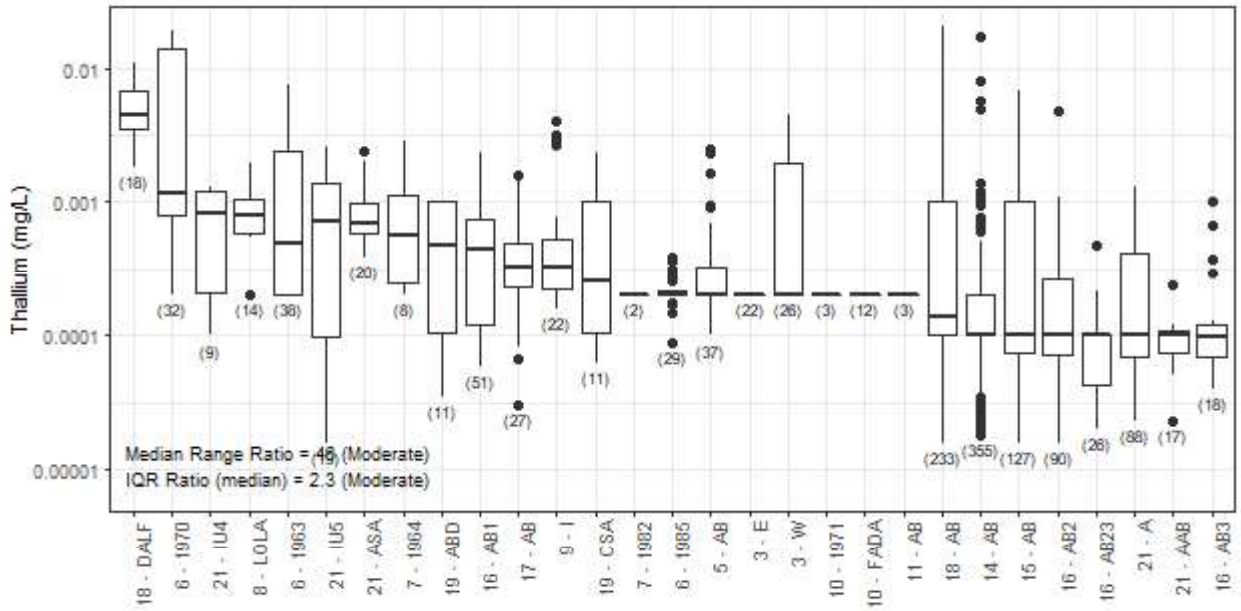


Figure C-39
Thallium

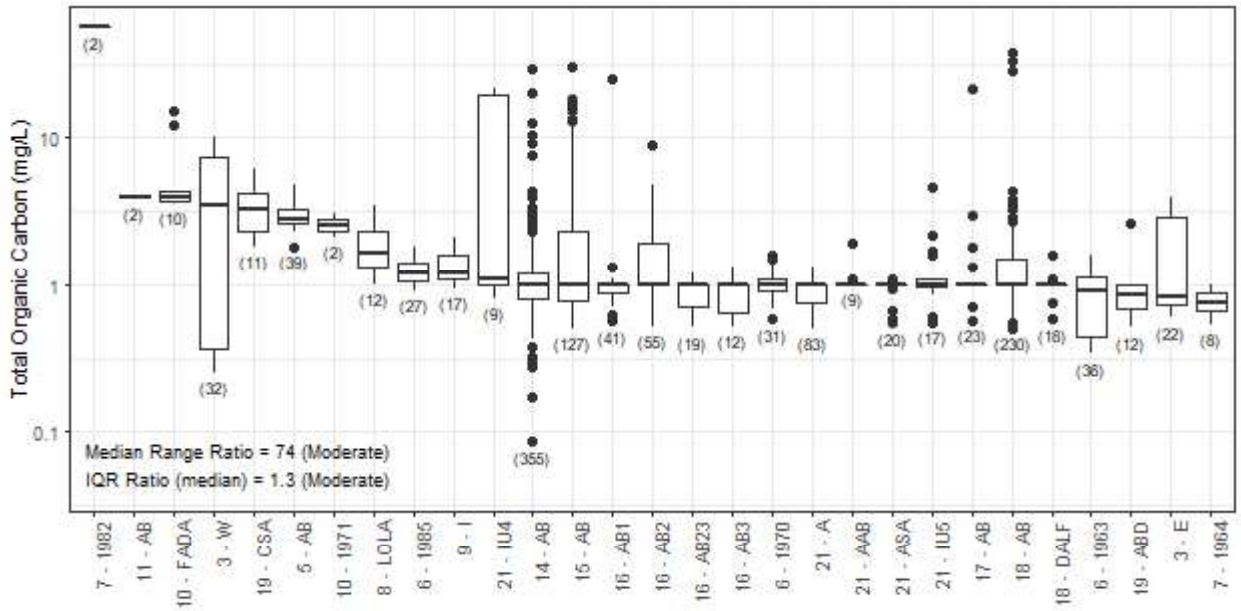


Figure C-40
Total organic carbon

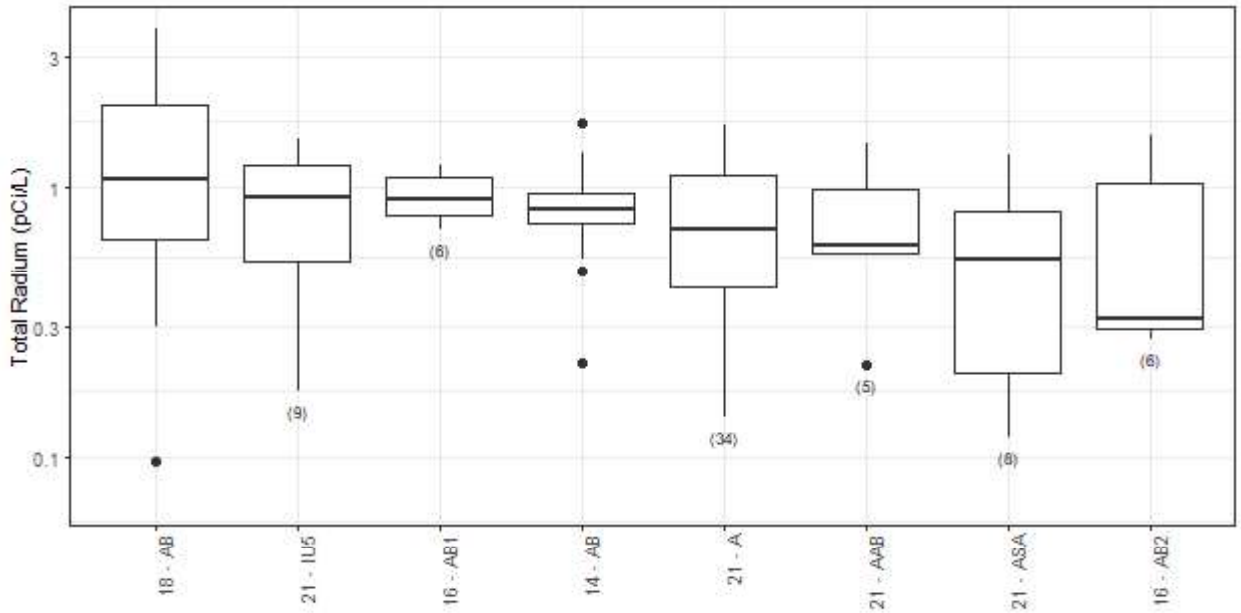


Figure C-41
Total radium

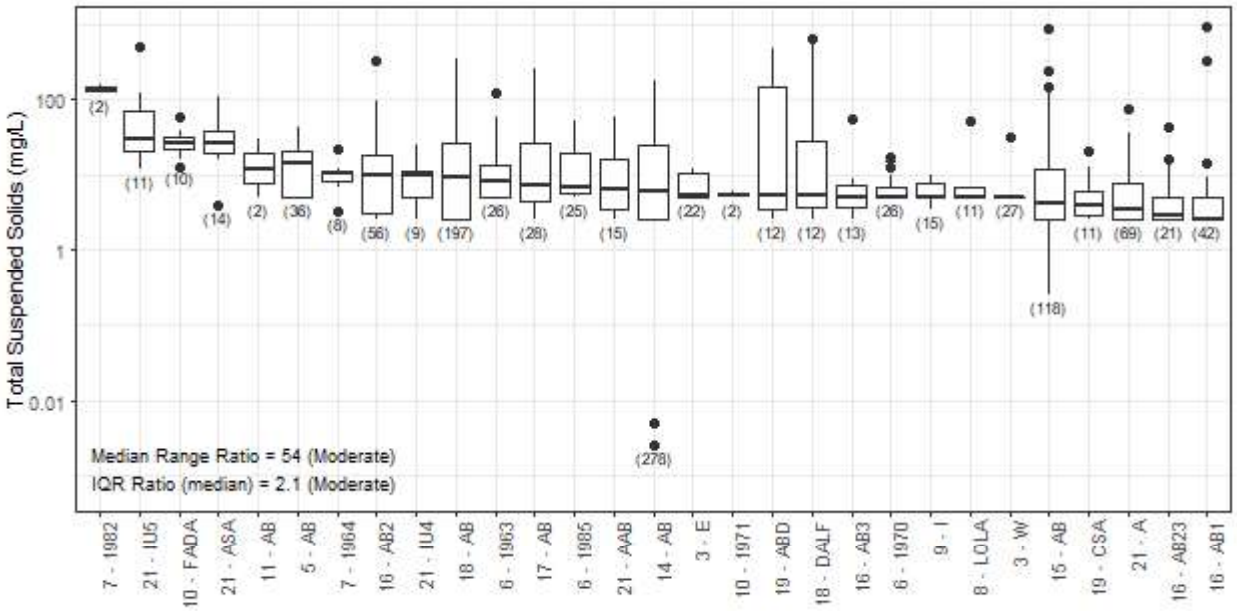


Figure C-42
Total suspended solids

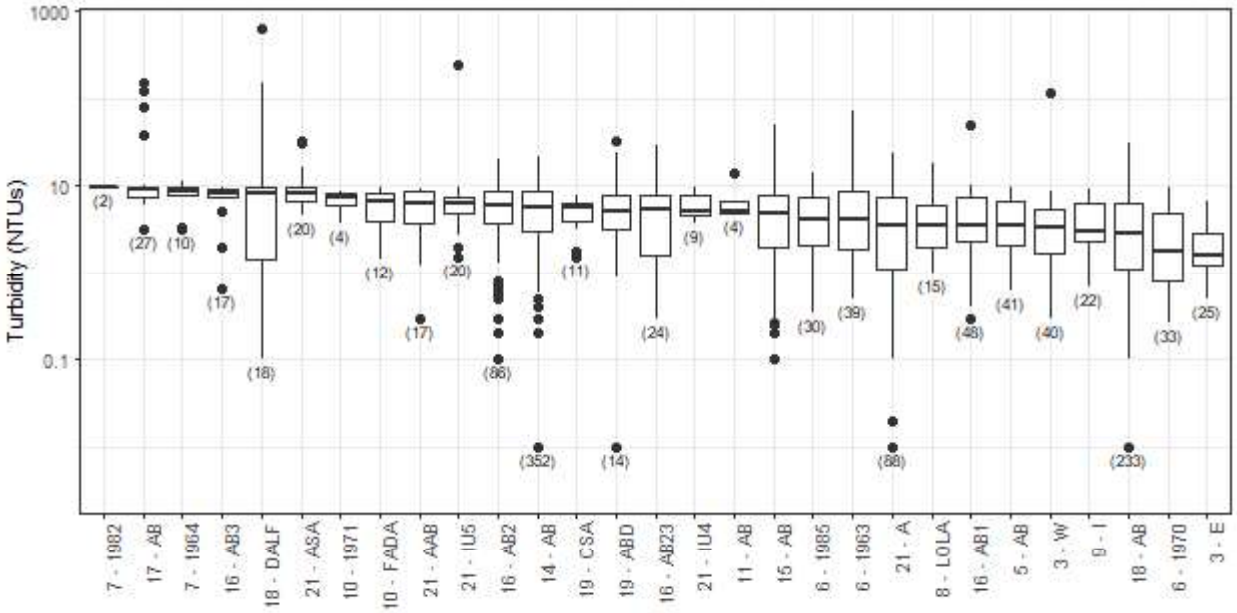


Figure C-43
Turbidity

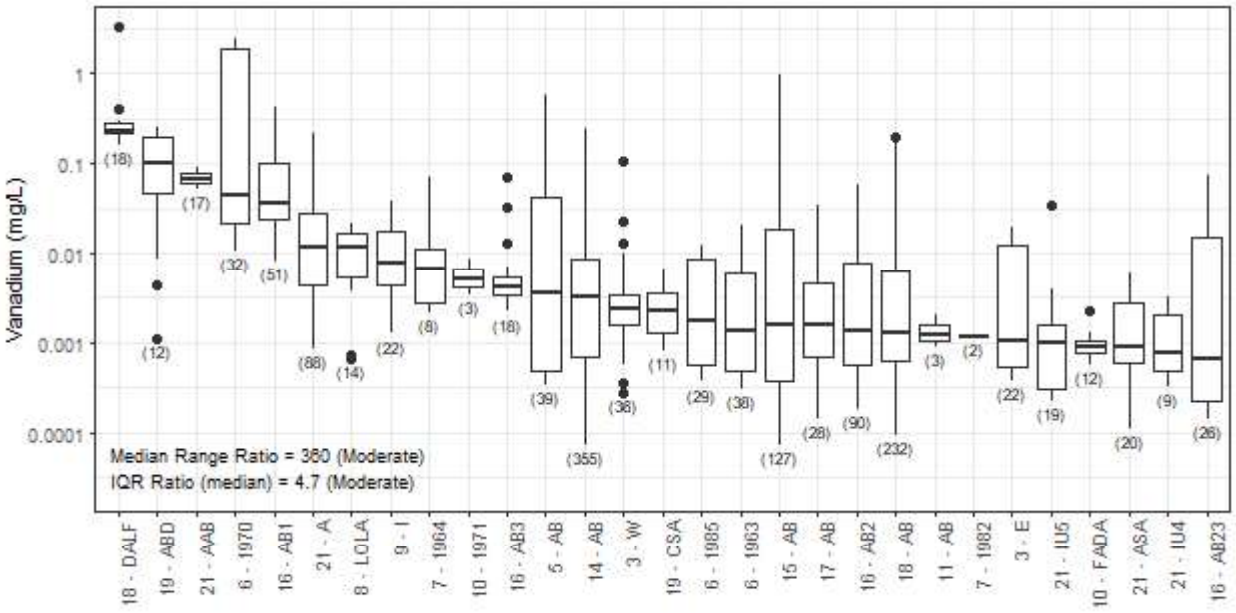


Figure C-44
Vanadium

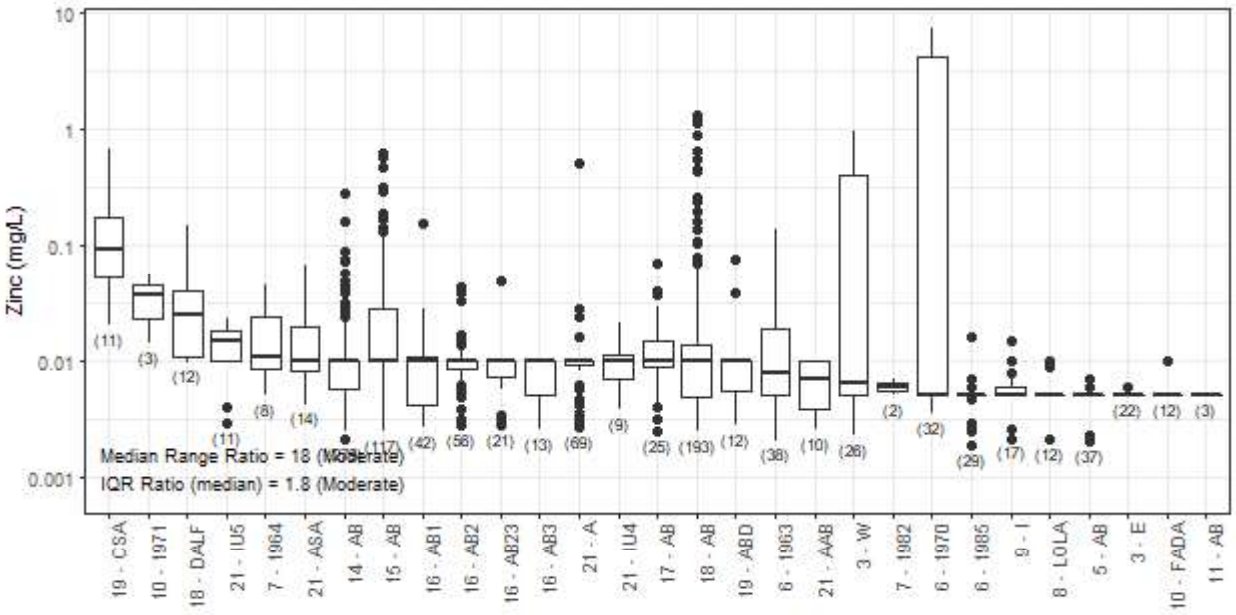


Figure C-45
Zinc

D
HISTOGRAM COMPARISON OF LEAF 1313 AND LEAF 1316 LEACH TEST METHODS

Figures D-1 through D-26 use histograms to compare results of the LEAF 1313 and LEAF 1316 leach test methods. The position of the distribution indicates LEAF test bias. A distribution centered within the vertical dashed lines with a similar sample count to either side indicates little bias, while a distribution that extends more to the left or more to the right of the dashed lines indicates that the leach test results were biased low or biased high, respectively.

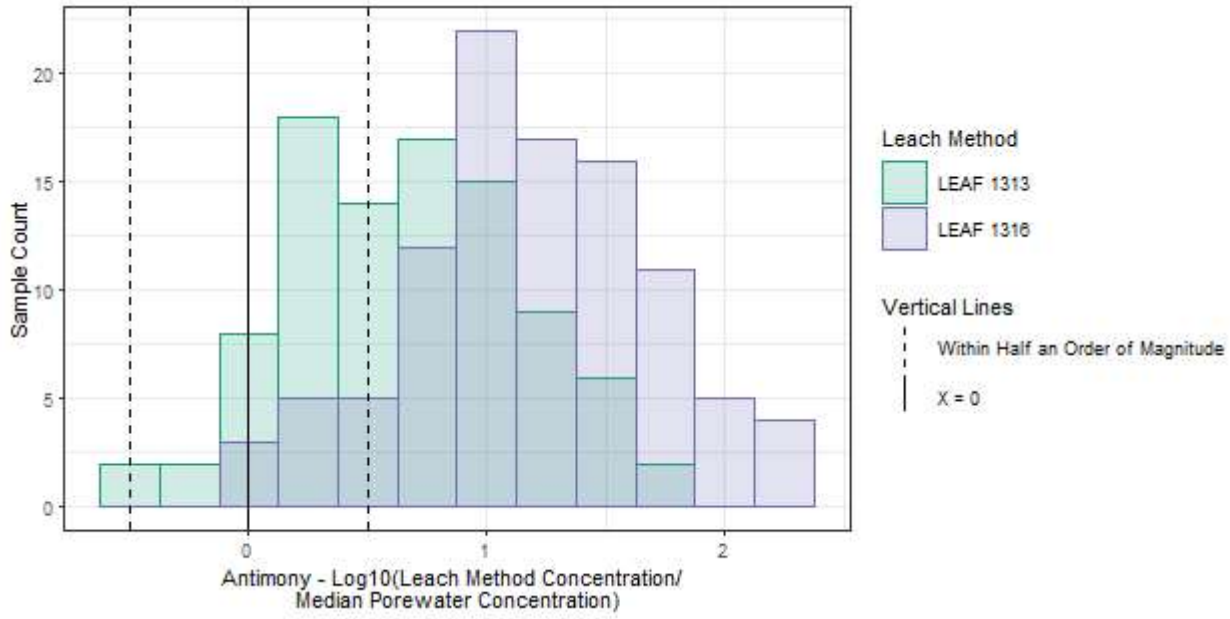


Figure D-1
Antimony

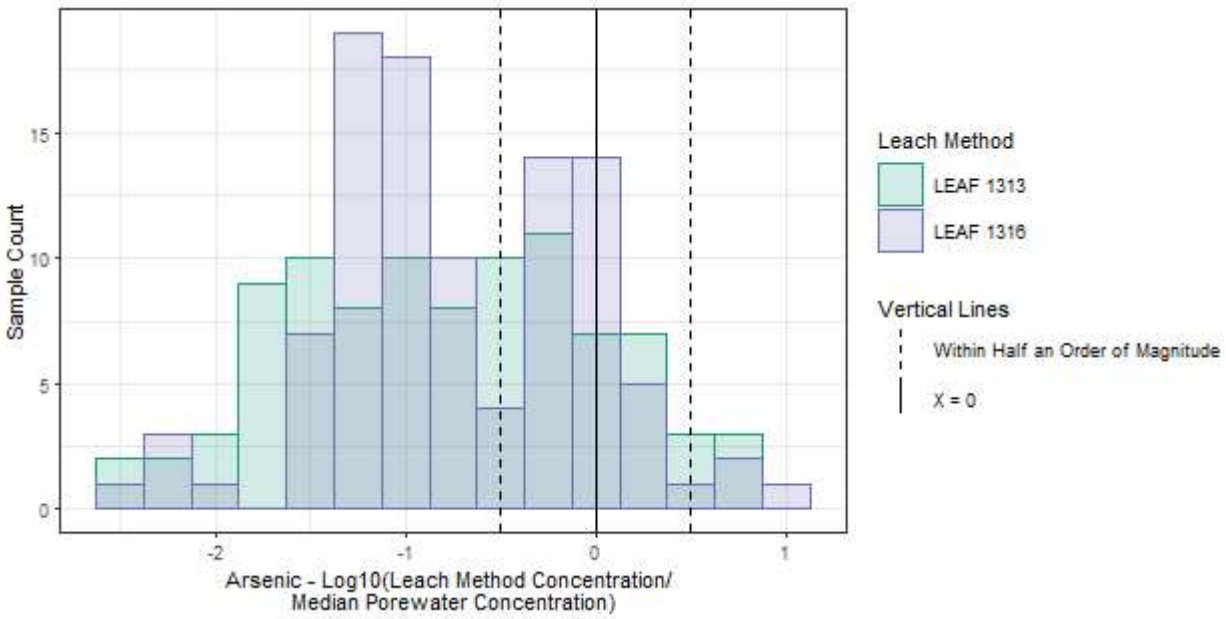


Figure D-2
Arsenic

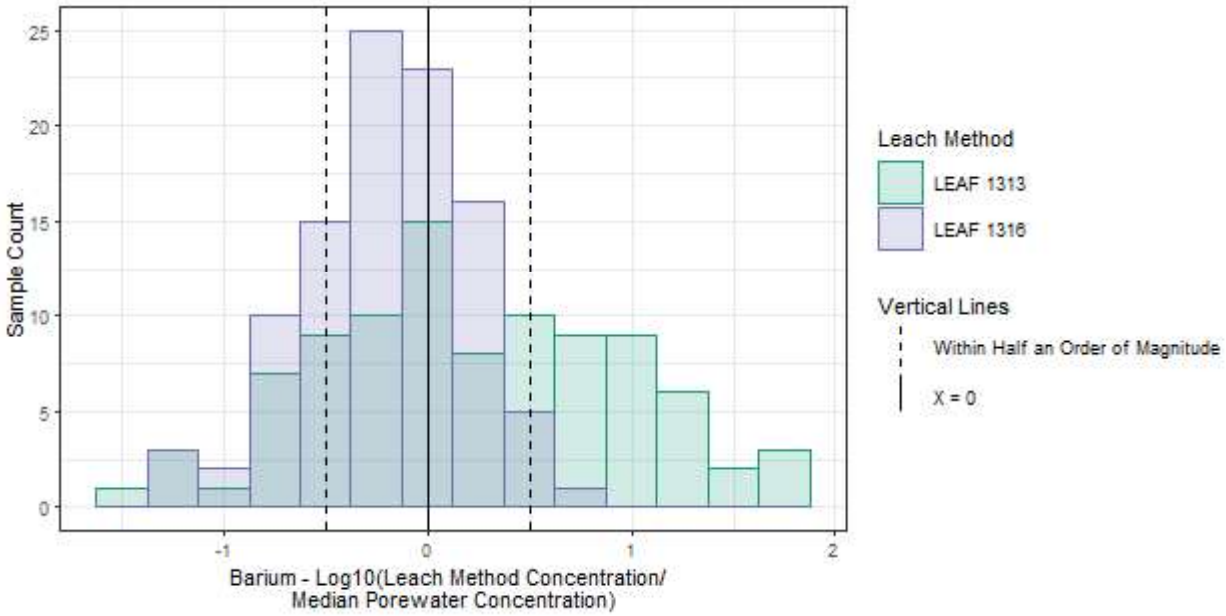


Figure D-3
Barium

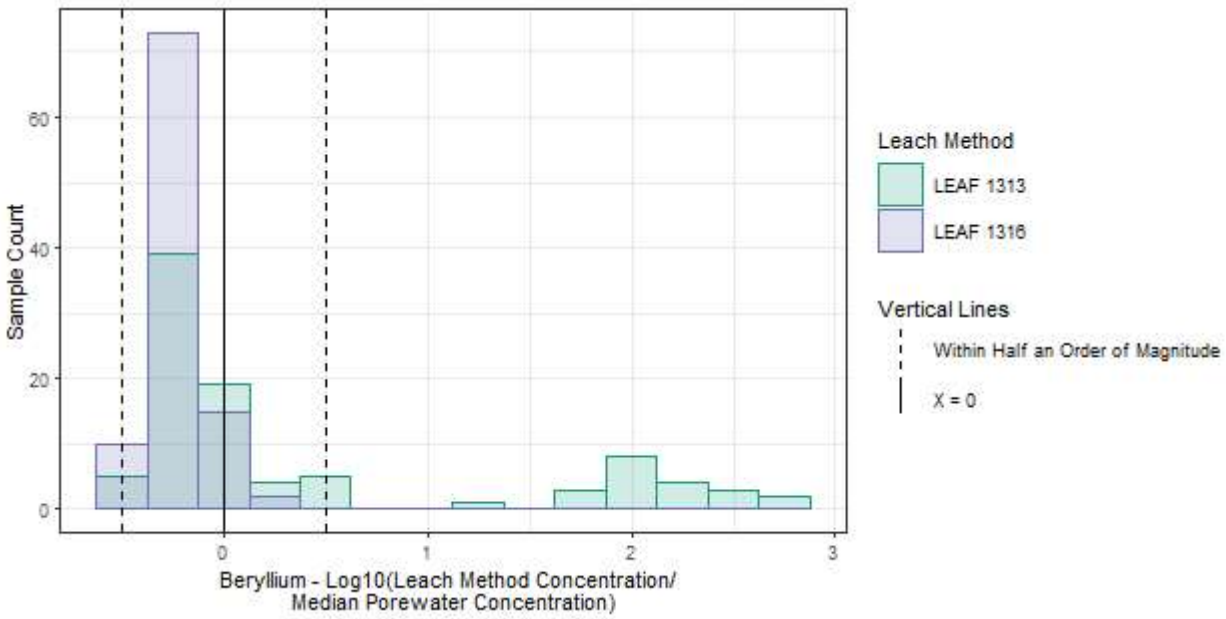


Figure D-4
Beryllium

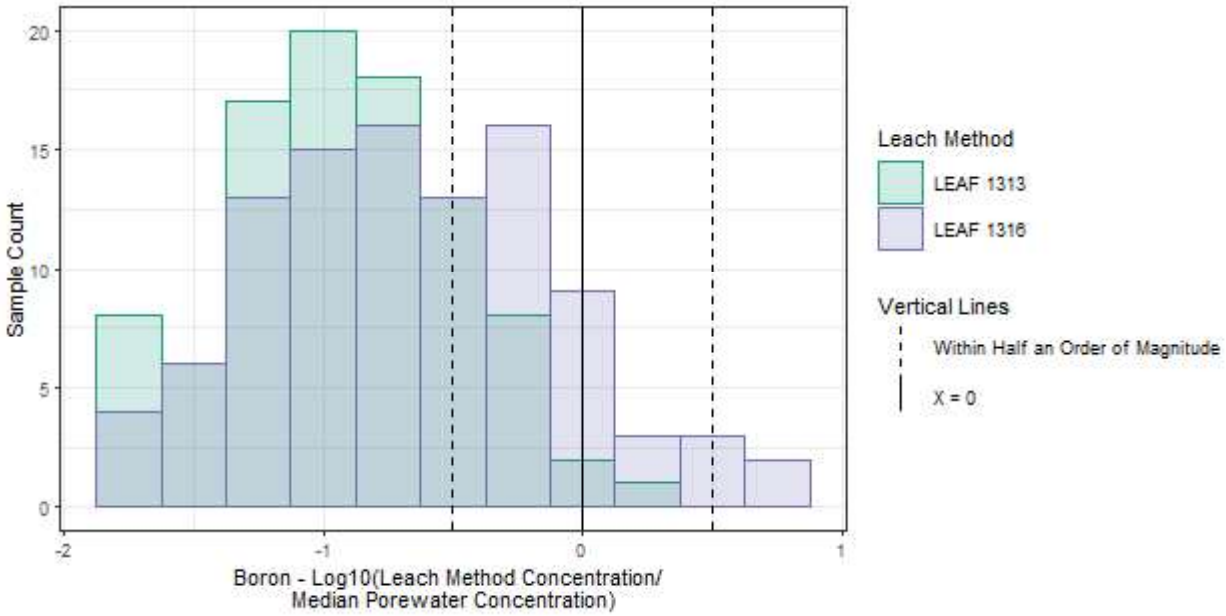


Figure D-5
Boron

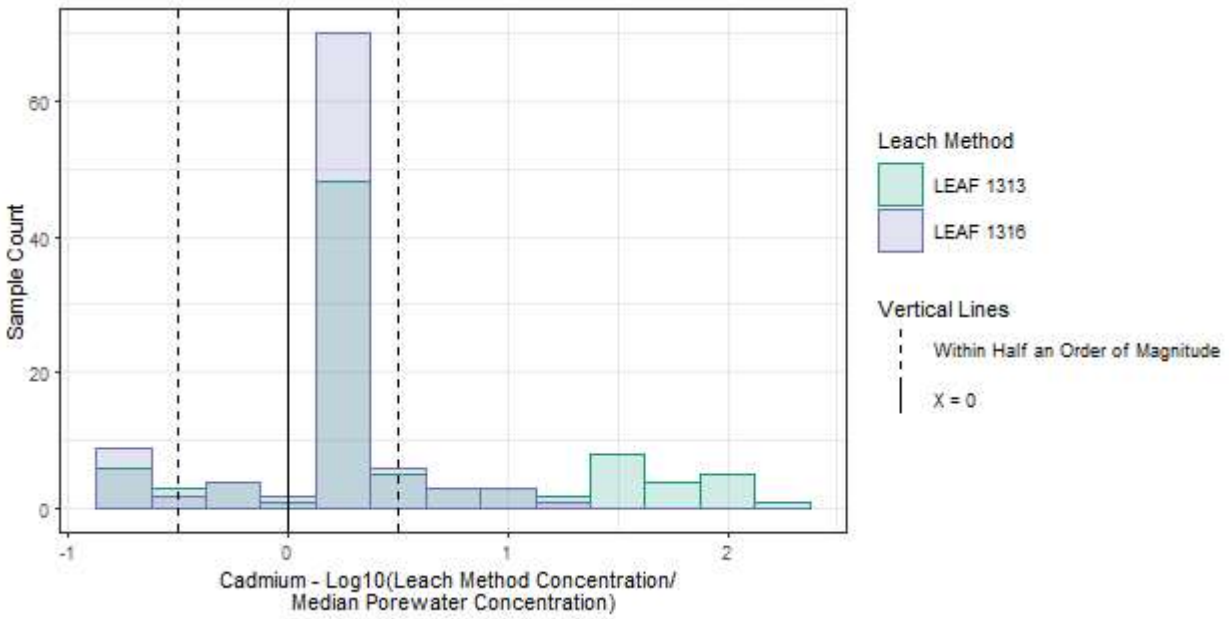


Figure D-6
Cadmium

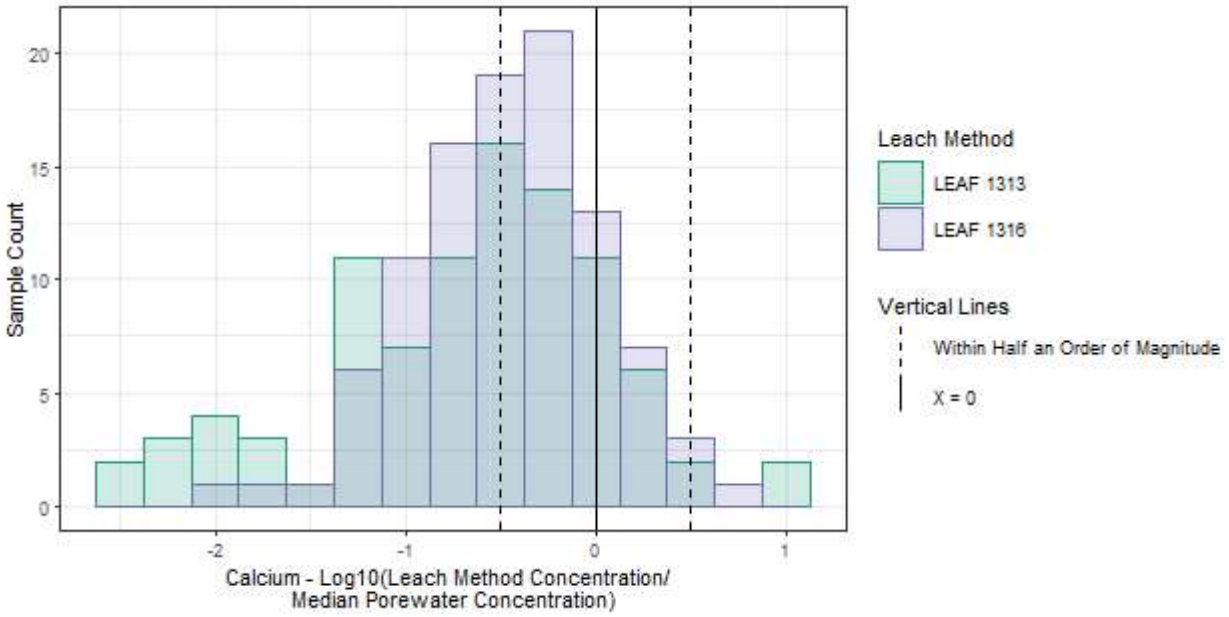


Figure D-7
Calcium

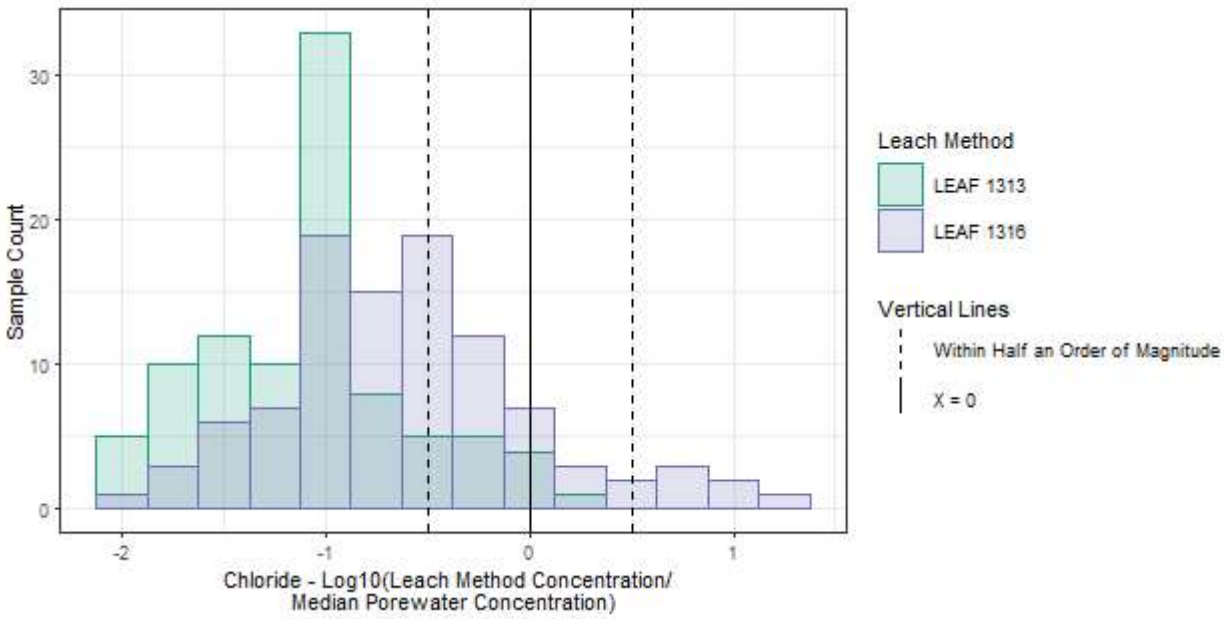


Figure D-8
Chloride

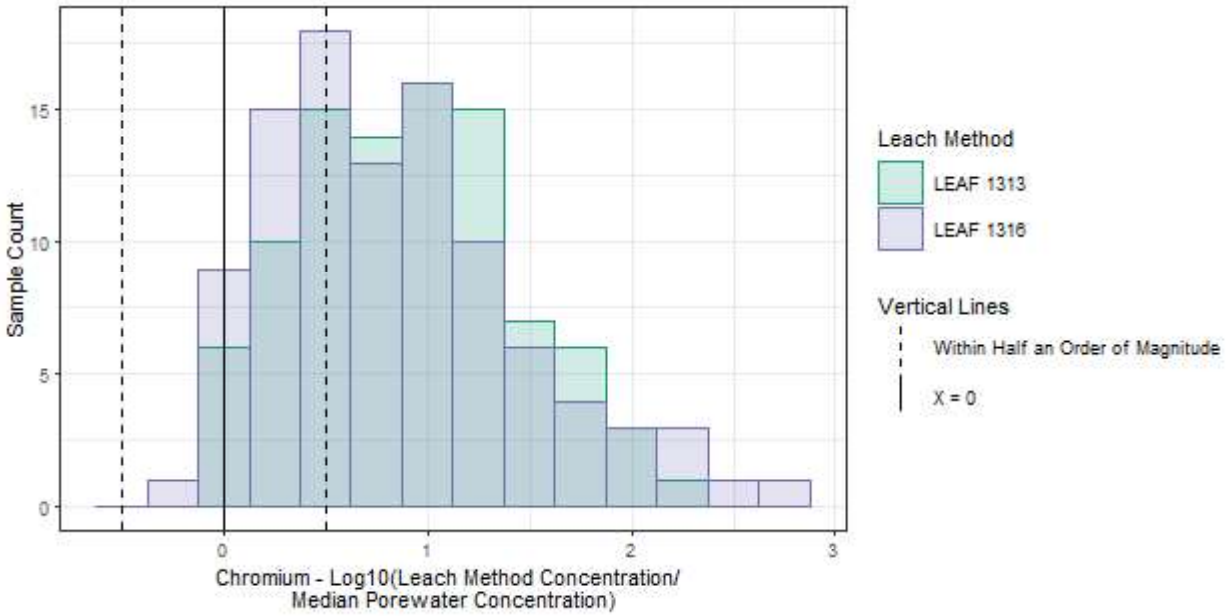


Figure D-9
Chromium

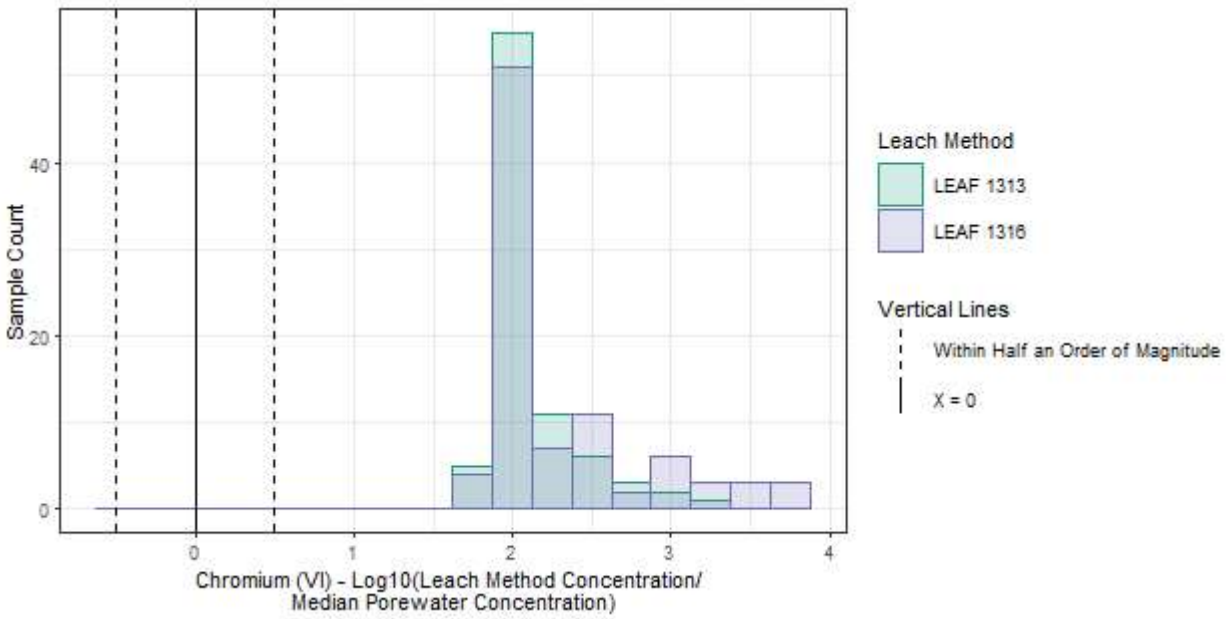


Figure D-10
Chromium (VI)

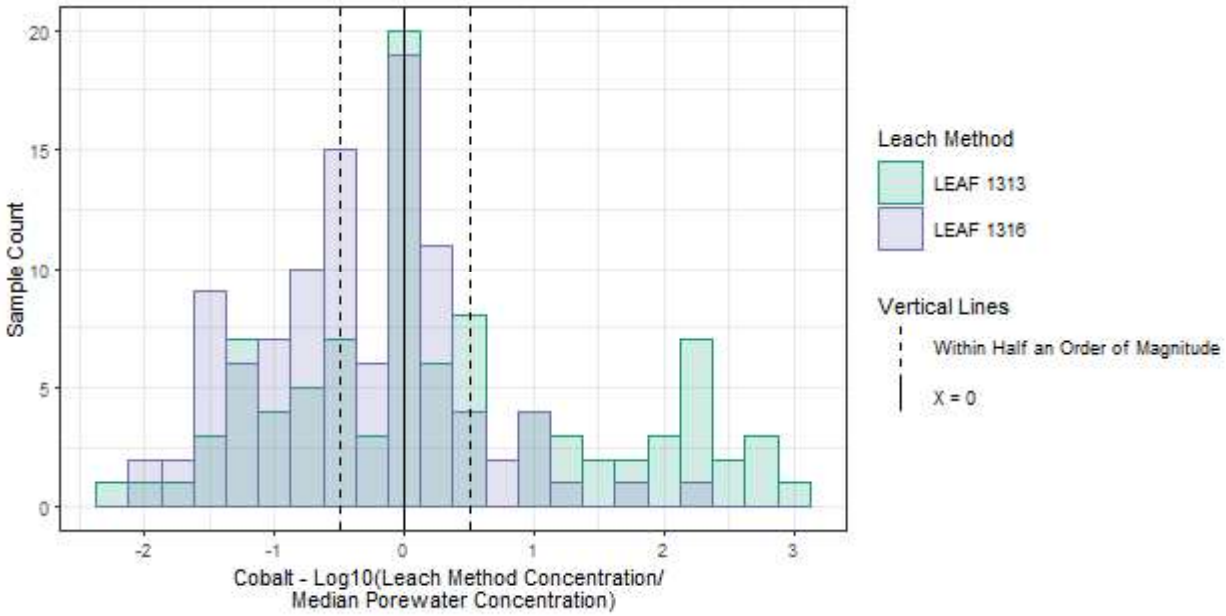


Figure D-11
Cobalt

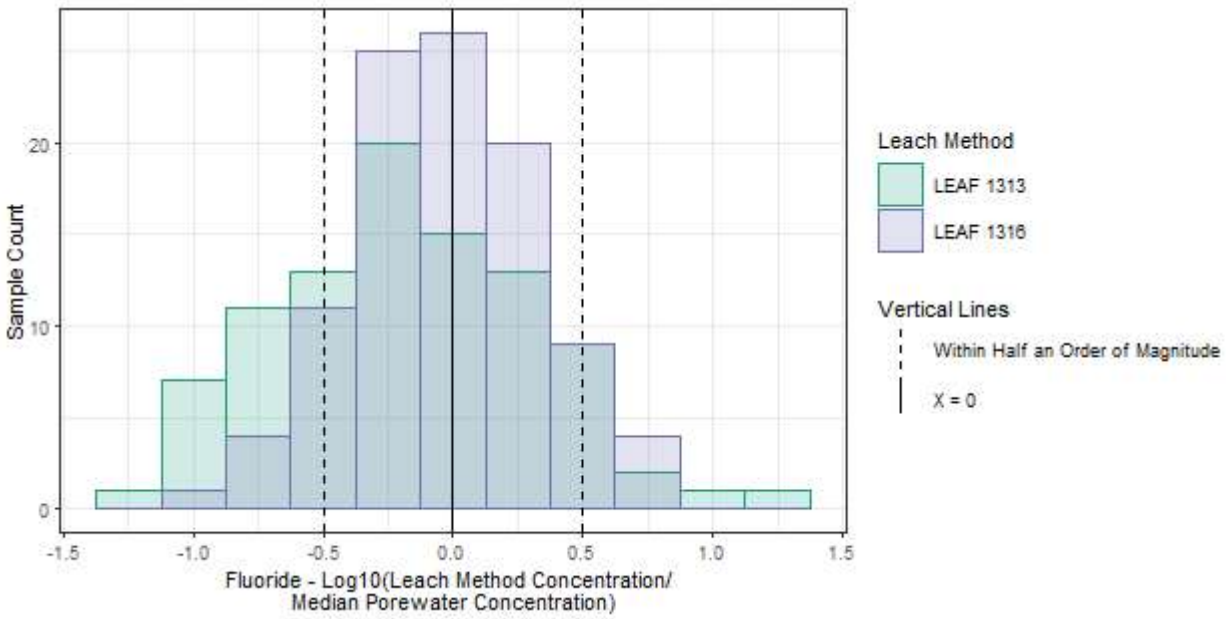


Figure D-12
Fluoride

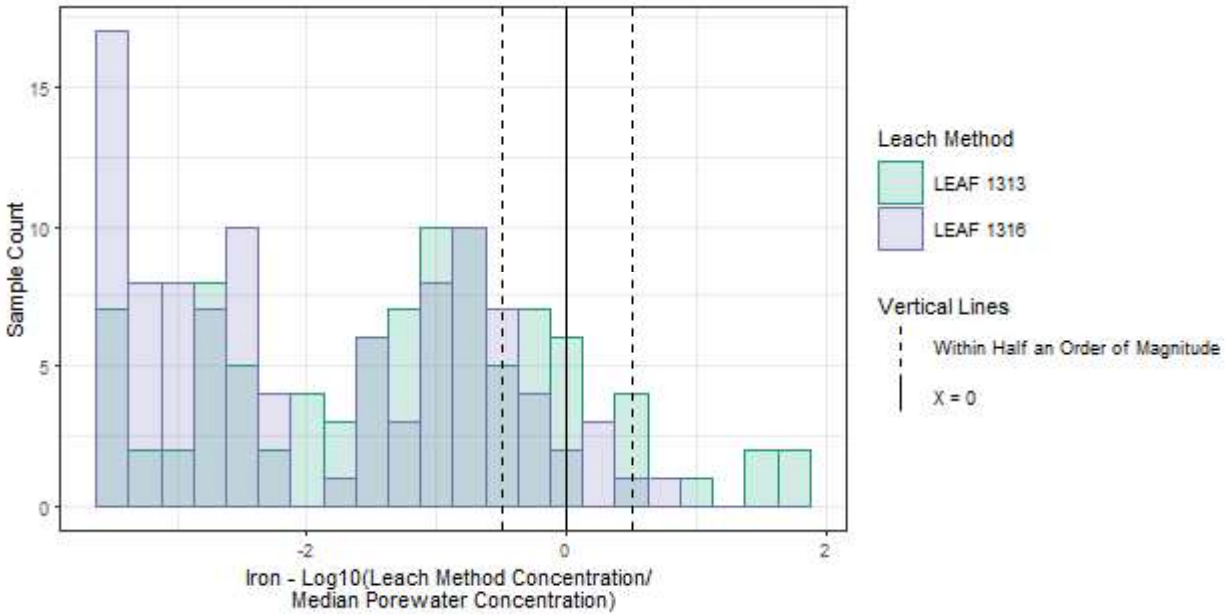


Figure D-13
Iron

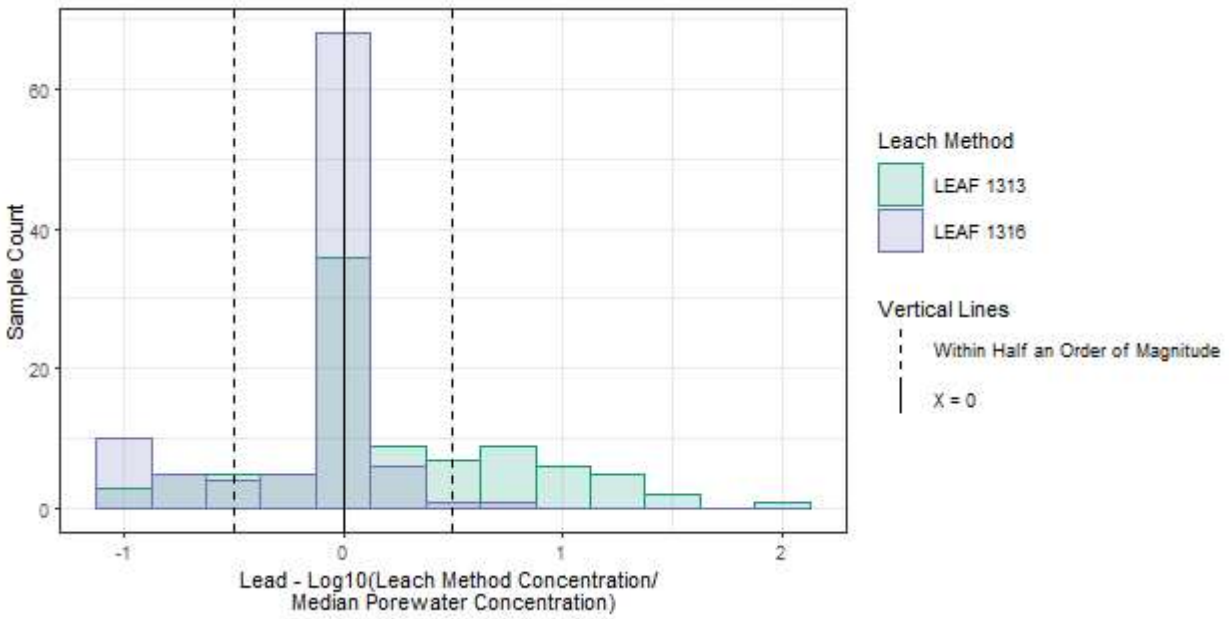


Figure D-14
Lead

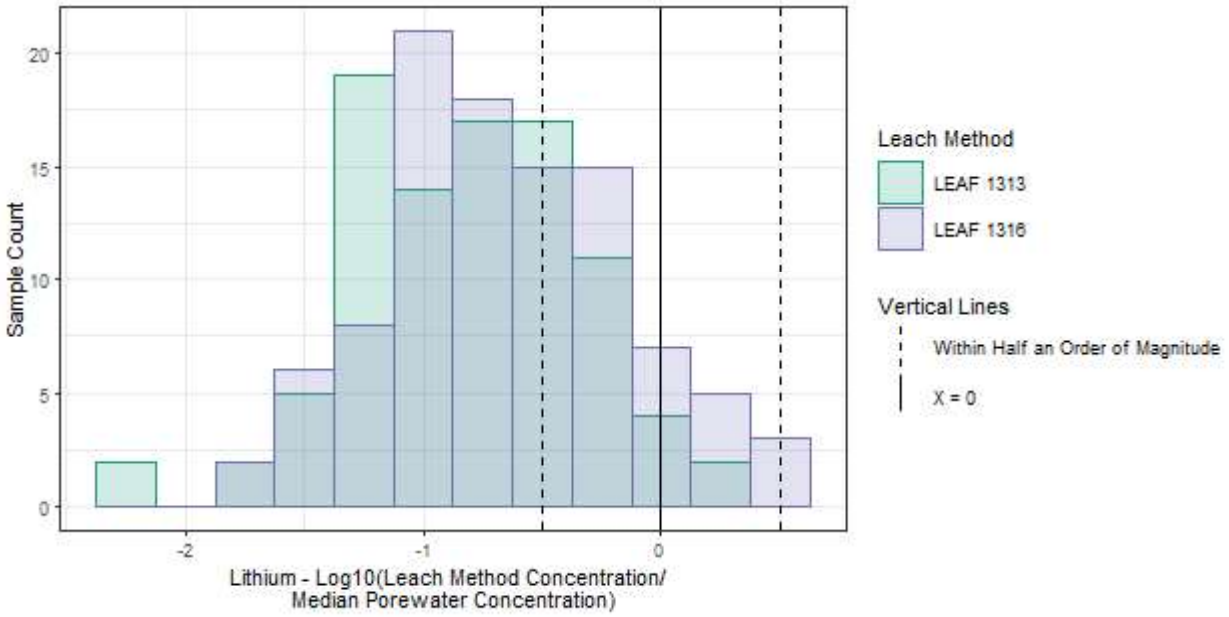


Figure D-15
Lithium

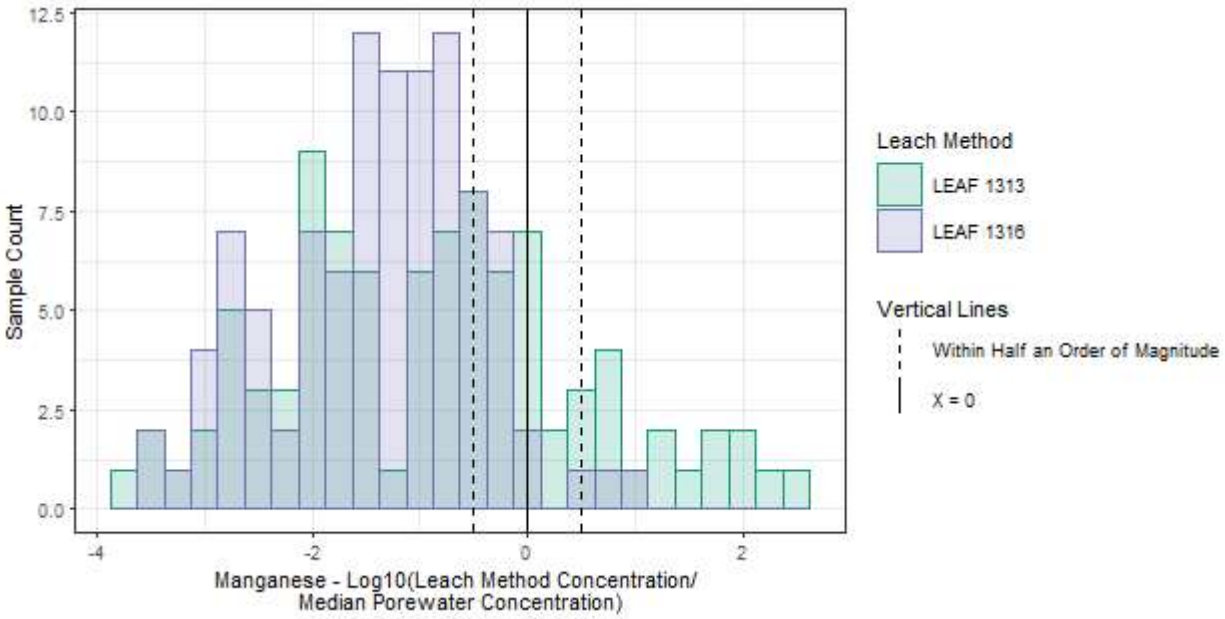


Figure D-16
Manganese

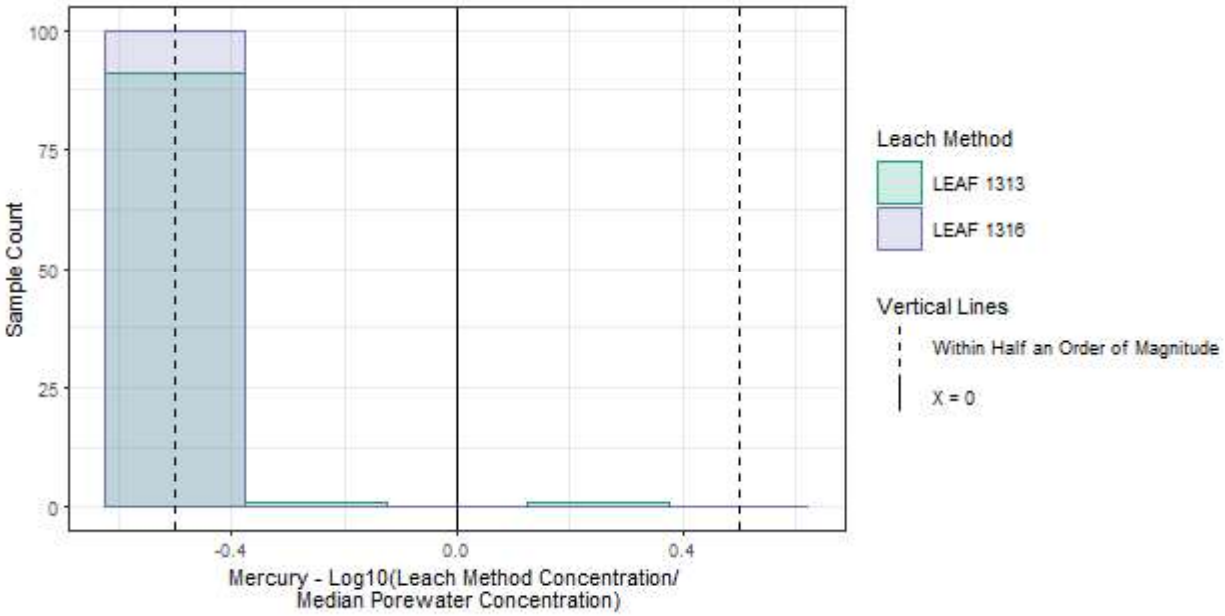


Figure D-17
Mercury

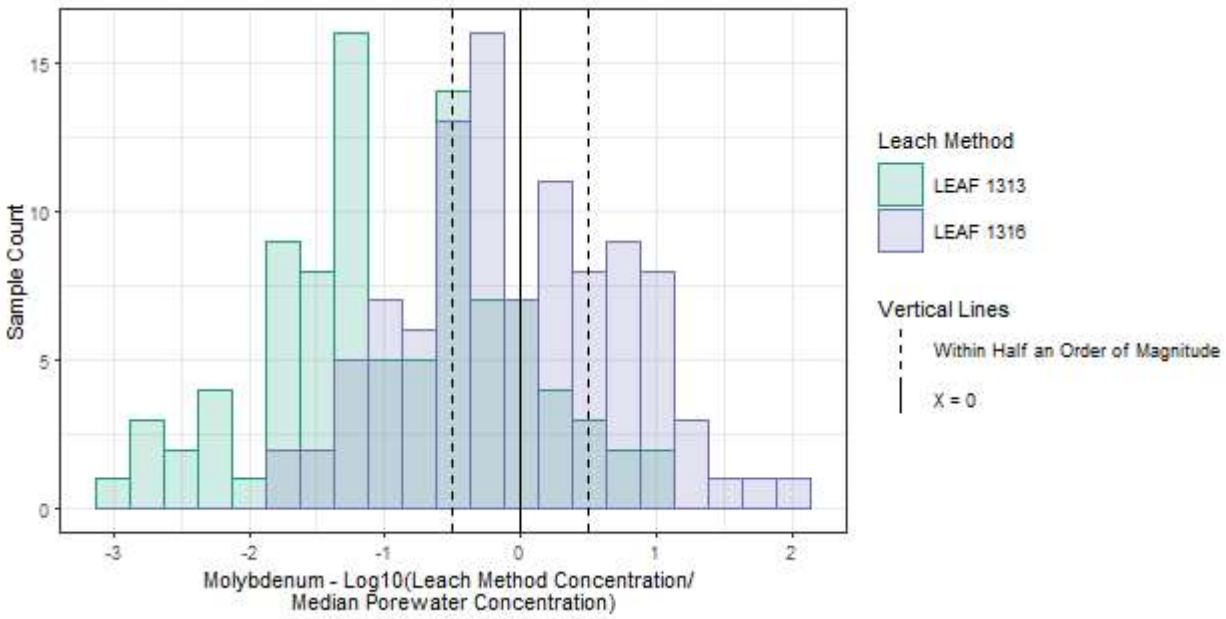


Figure D-18
Molybdenum

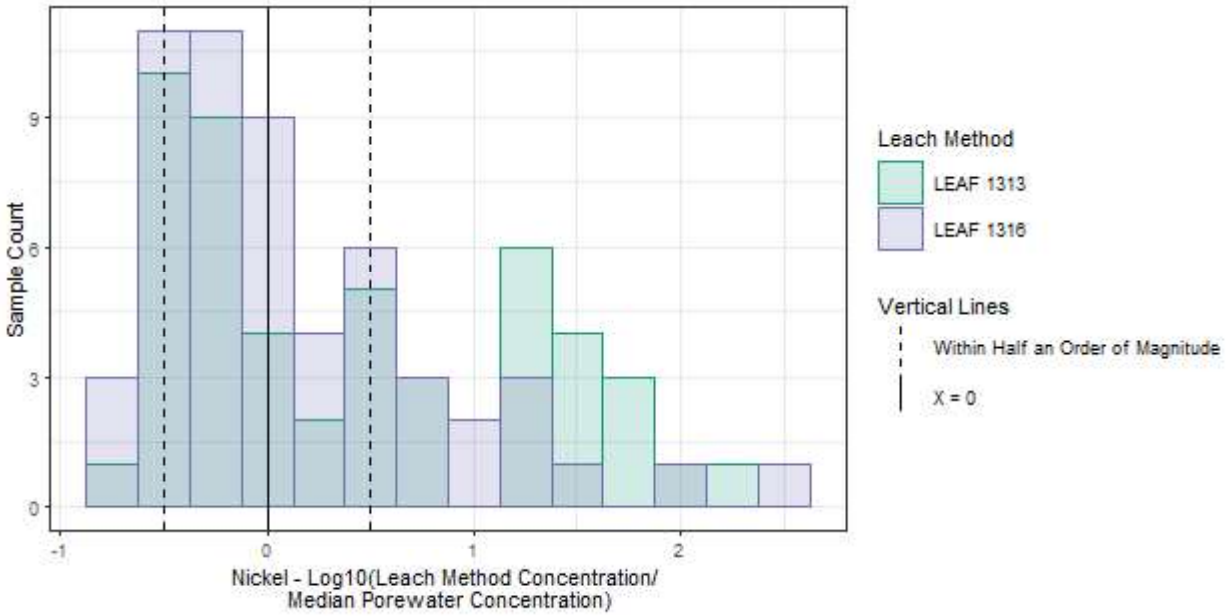


Figure D-19
Nickel

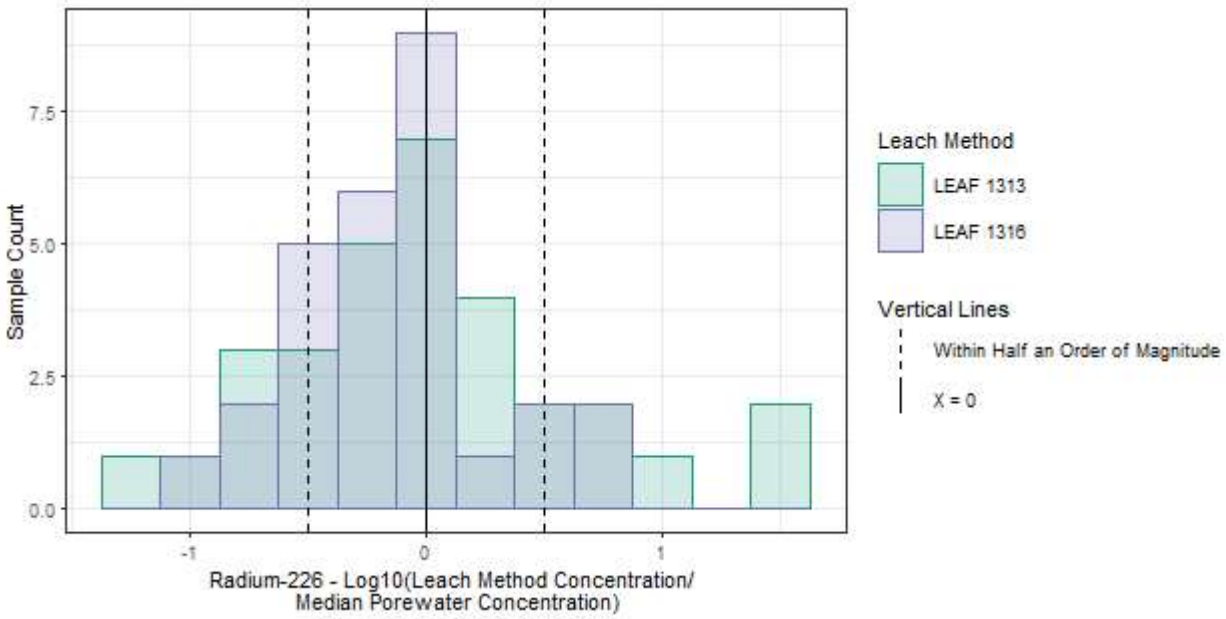


Figure D-20
Radium-226

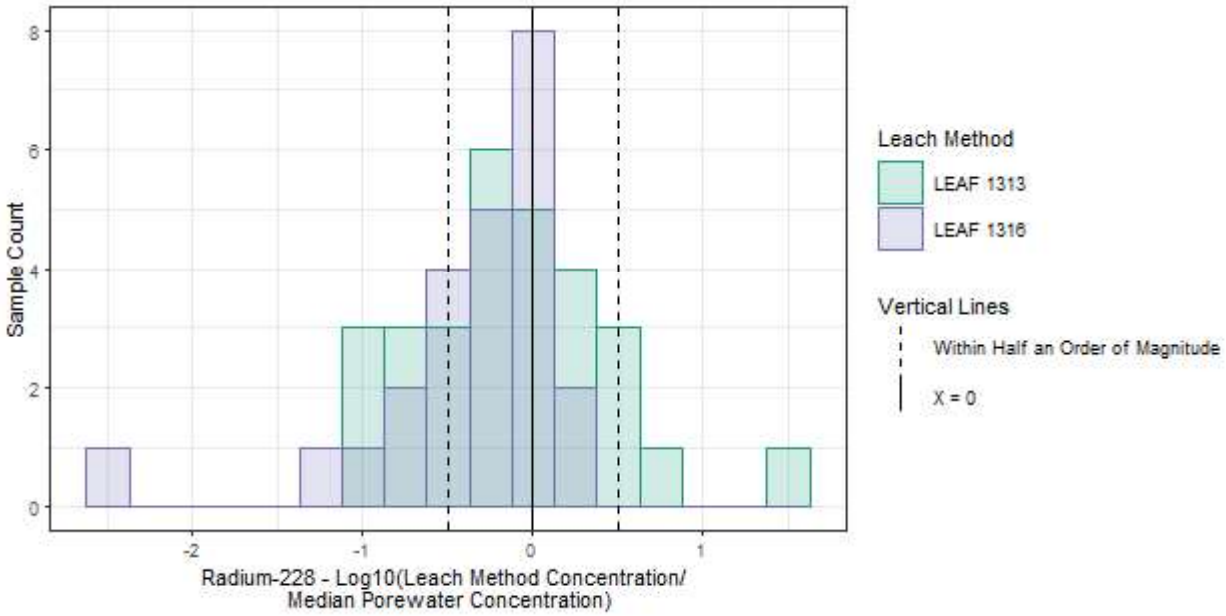


Figure D-21
Radium-228

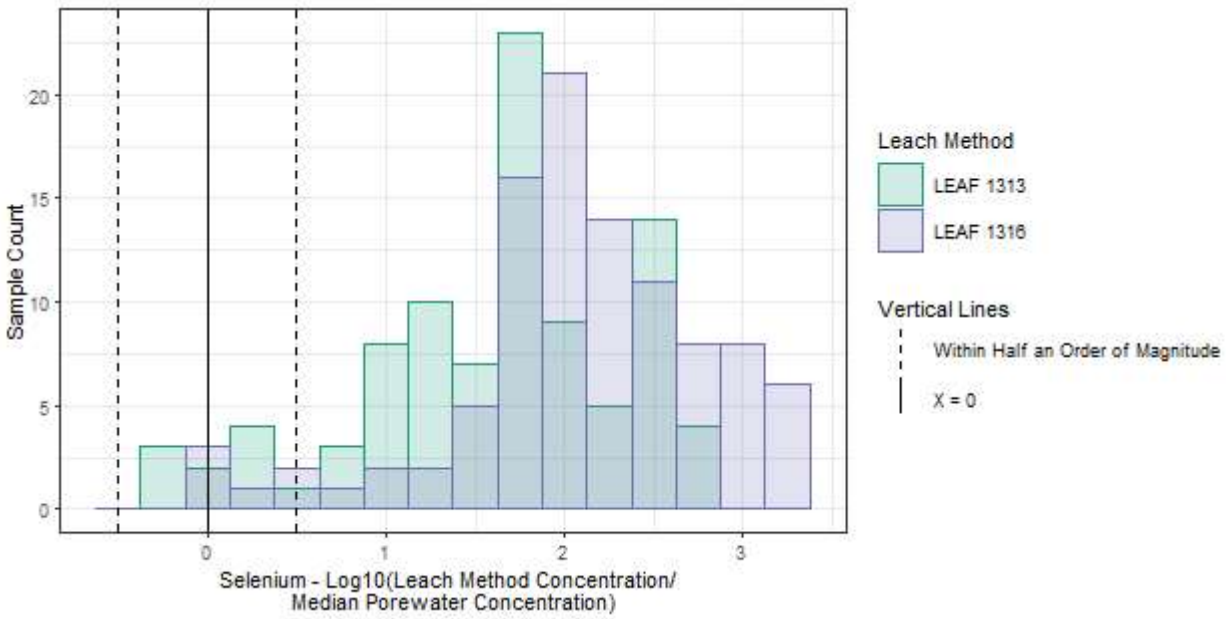


Figure D-22
Selenium

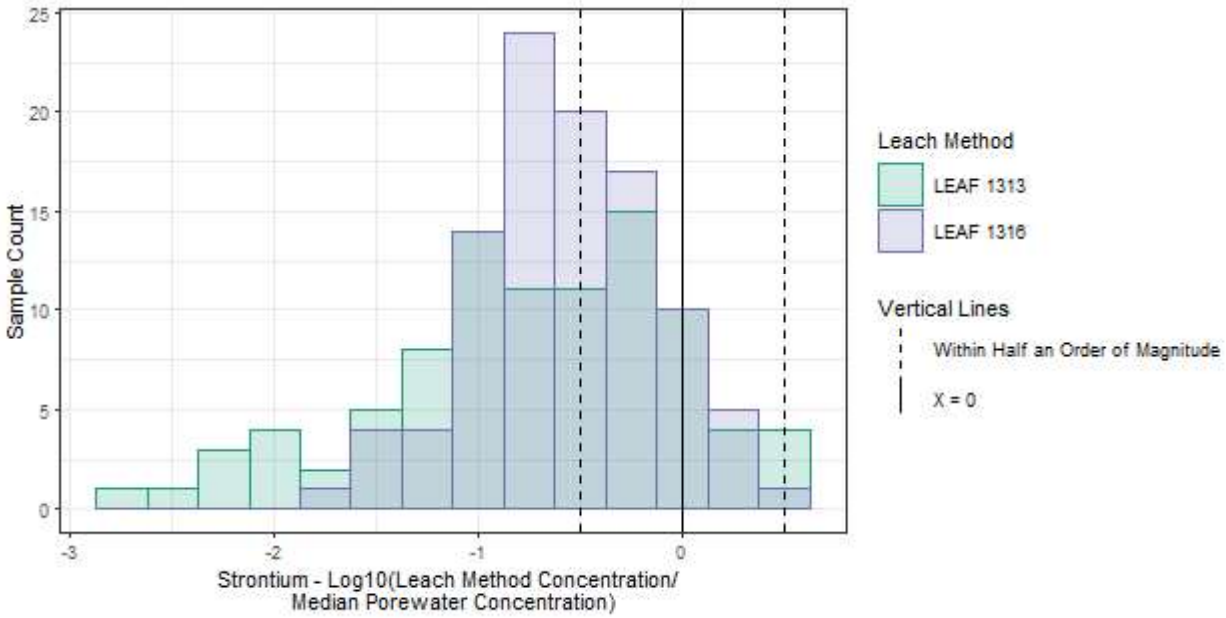


Figure D-23
Strontium

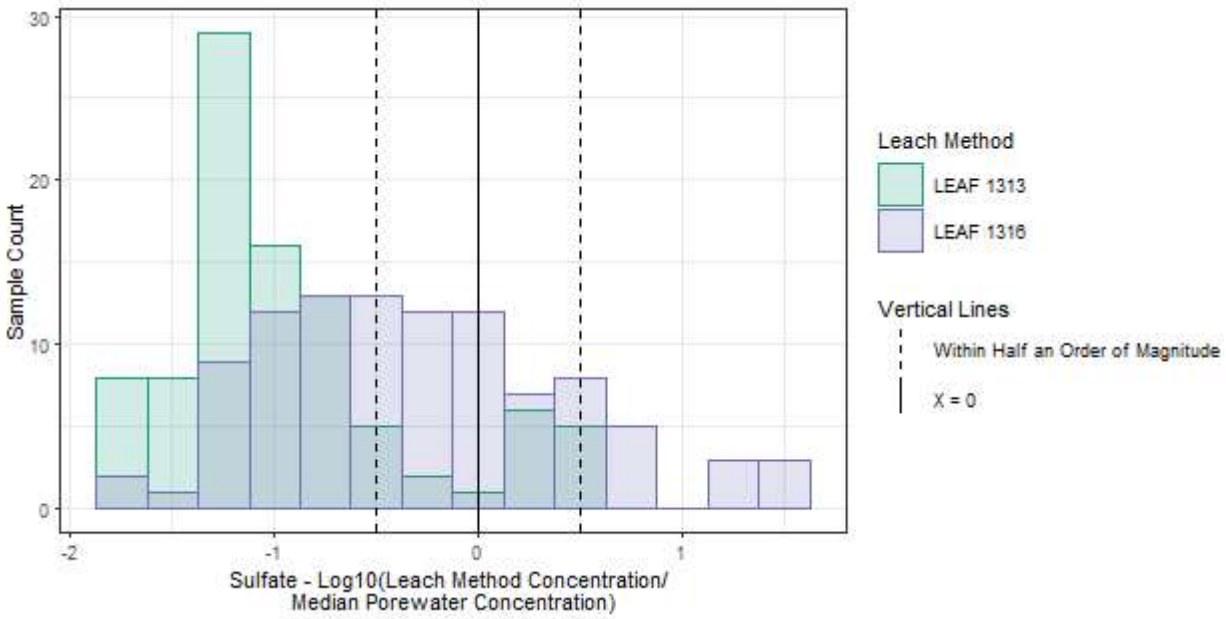


Figure D-24
Sulfate

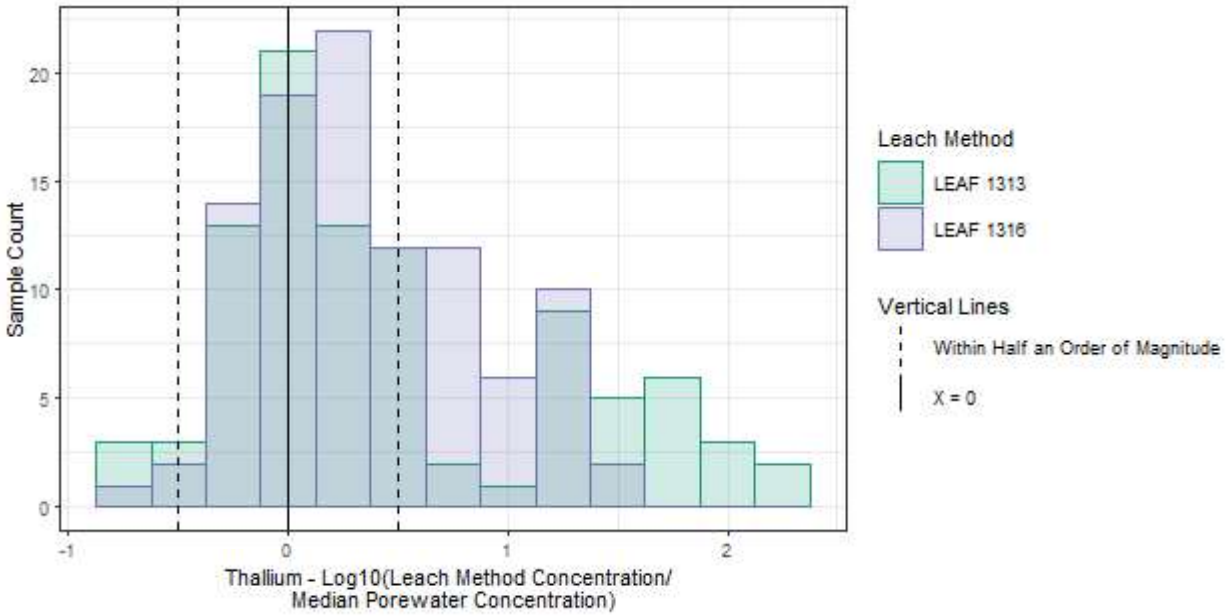


Figure D-25
Thallium

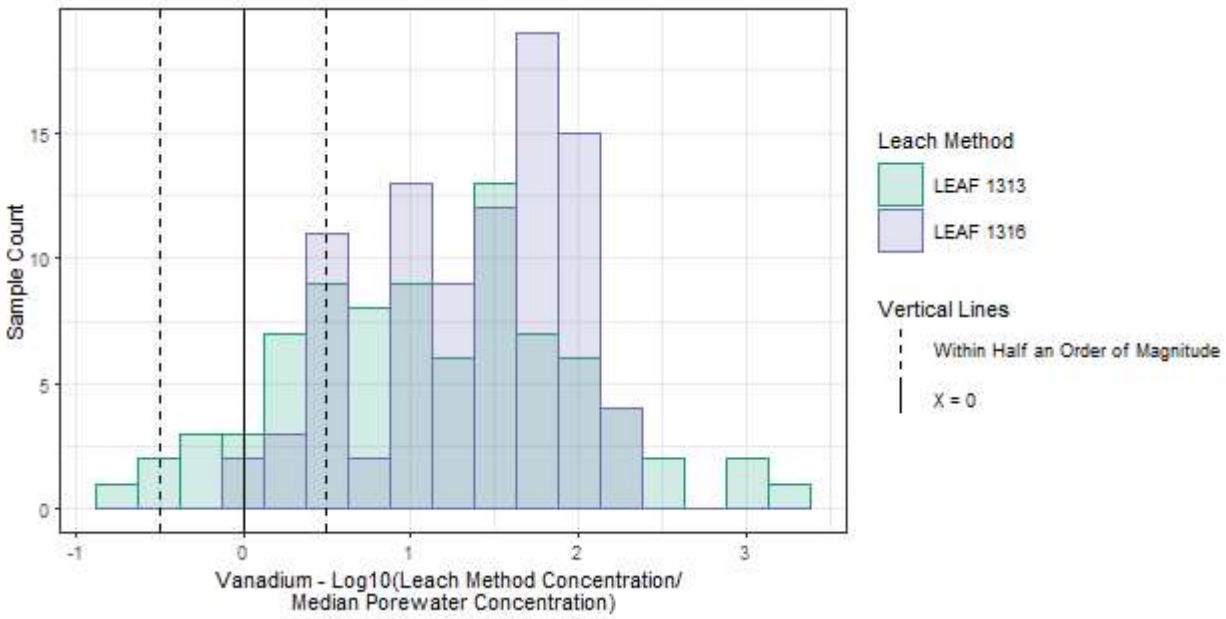


Figure D-26
Vanadium

E
PLOTS SHOWING NORMALIZED LEAF 1313 TO POREWATER RESULTS ACROSS THE RANGE OF pH LEVELS TESTED

Figures E-1 through E-26 show normalized LEAF 1313 test results, where the results were normalized by dividing by the median porewater concentration (because results are displayed as $\log_{10}$, a value of zero indicates exact agreement). The ability of the 1313 test to reproduce porewater concentrations was evaluated based on how many results at natural pH plotted within the dark-shaded ±25% range.

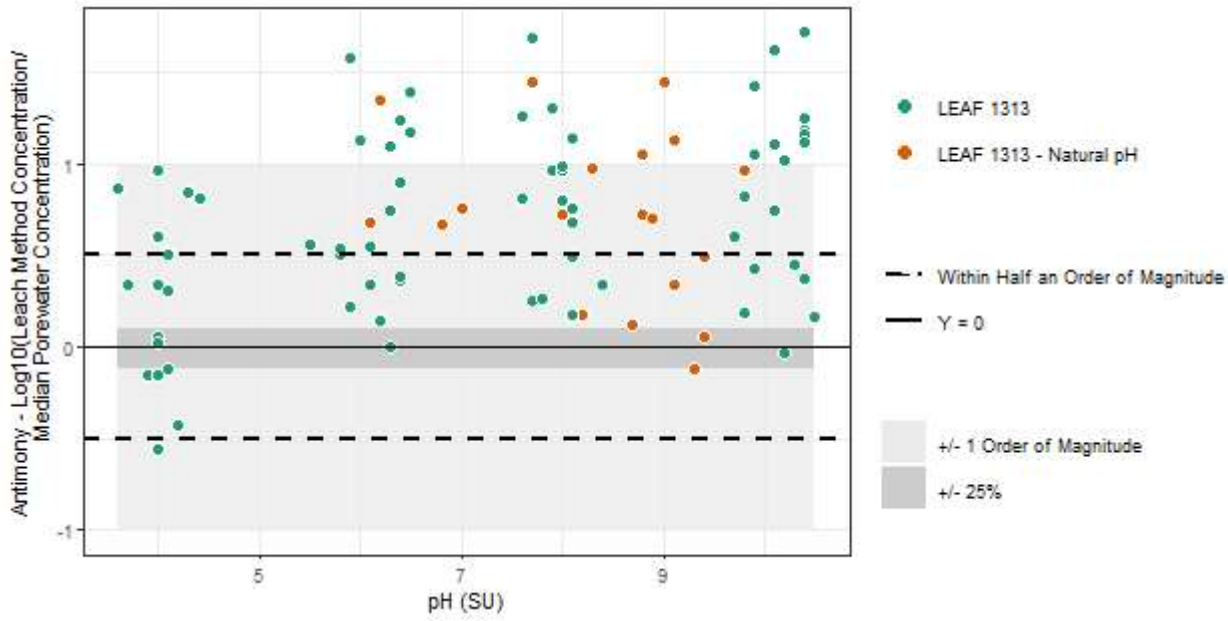


Figure E-1
Antimony

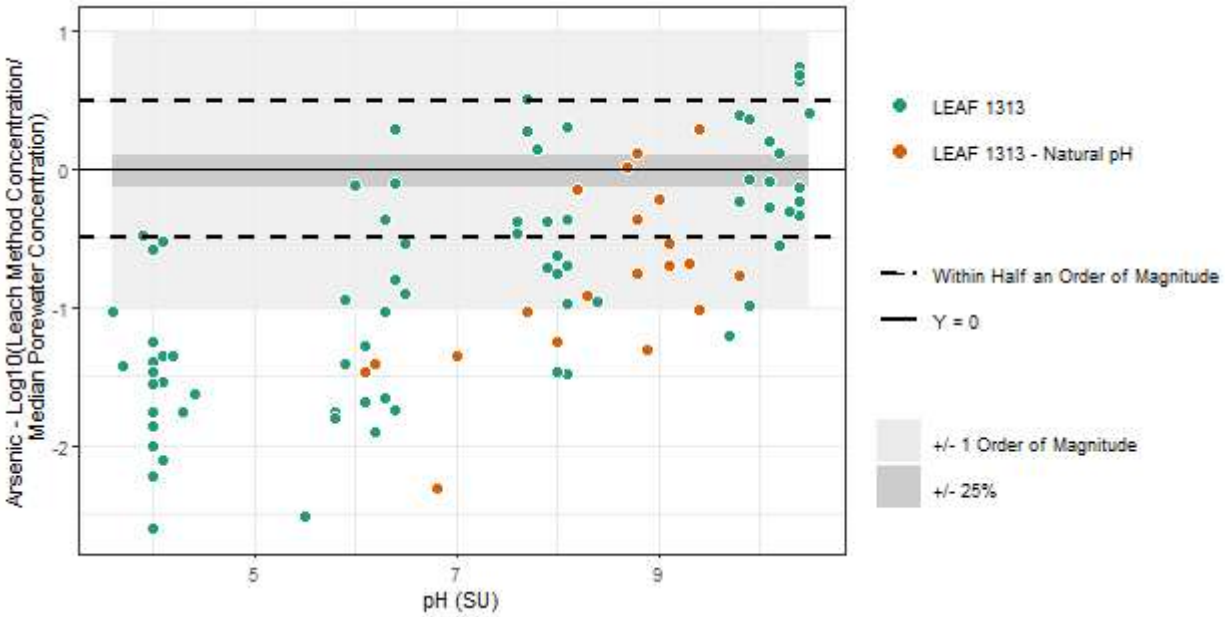


Figure E-2
Arsenic

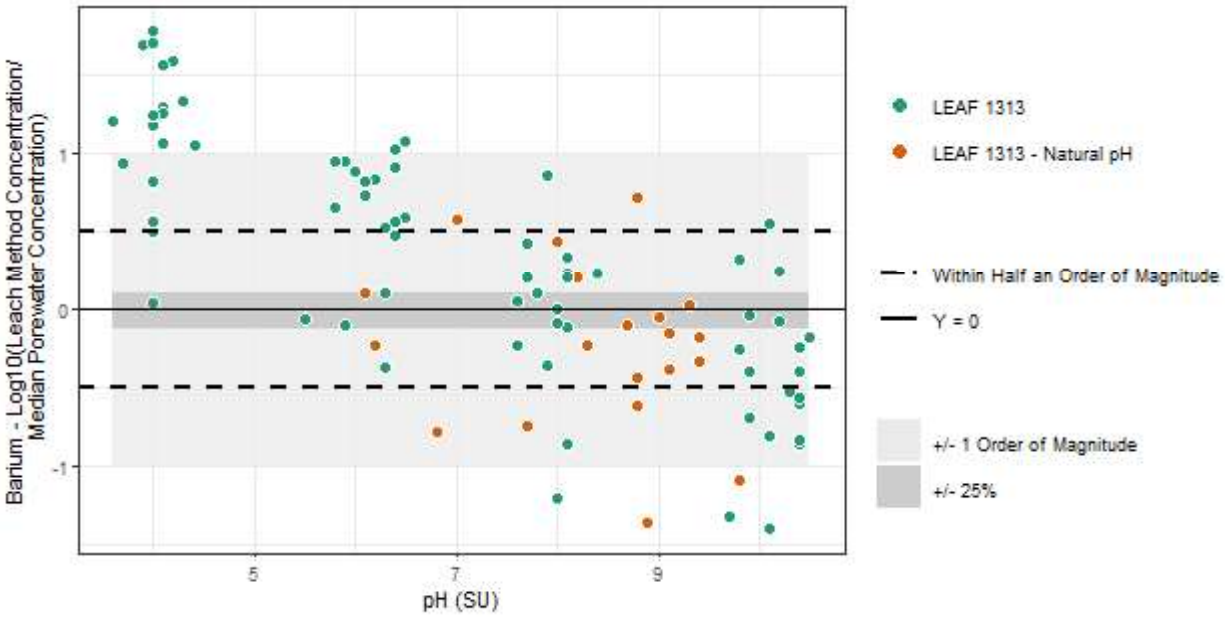


Figure E-3
Barium

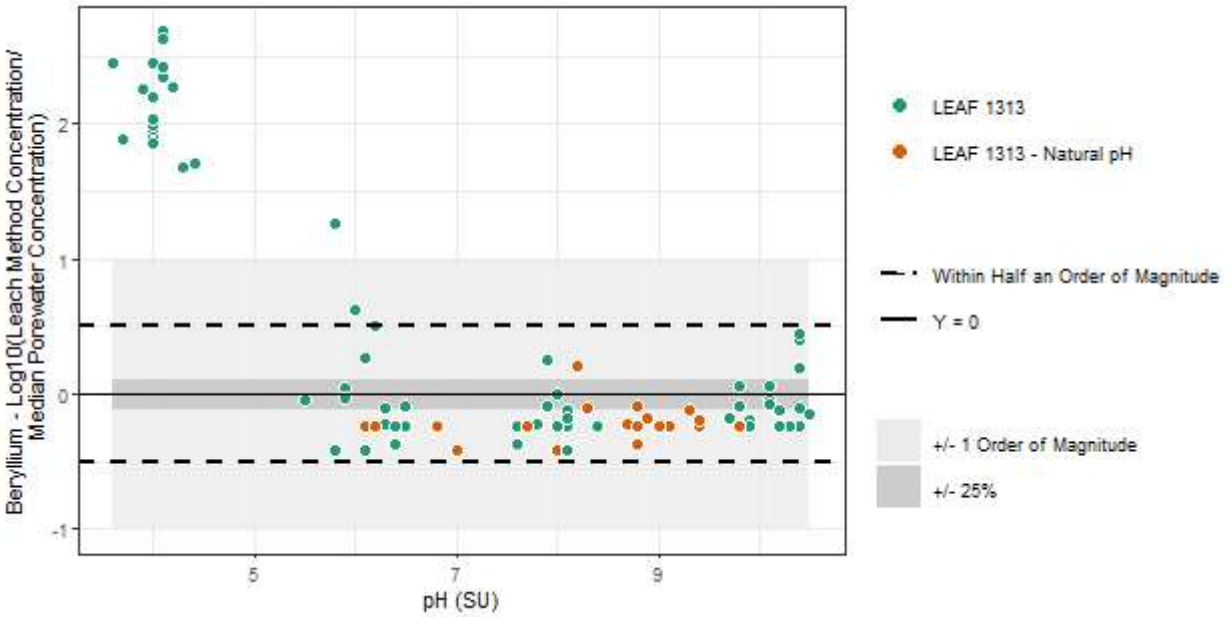


Figure E-4
Beryllium

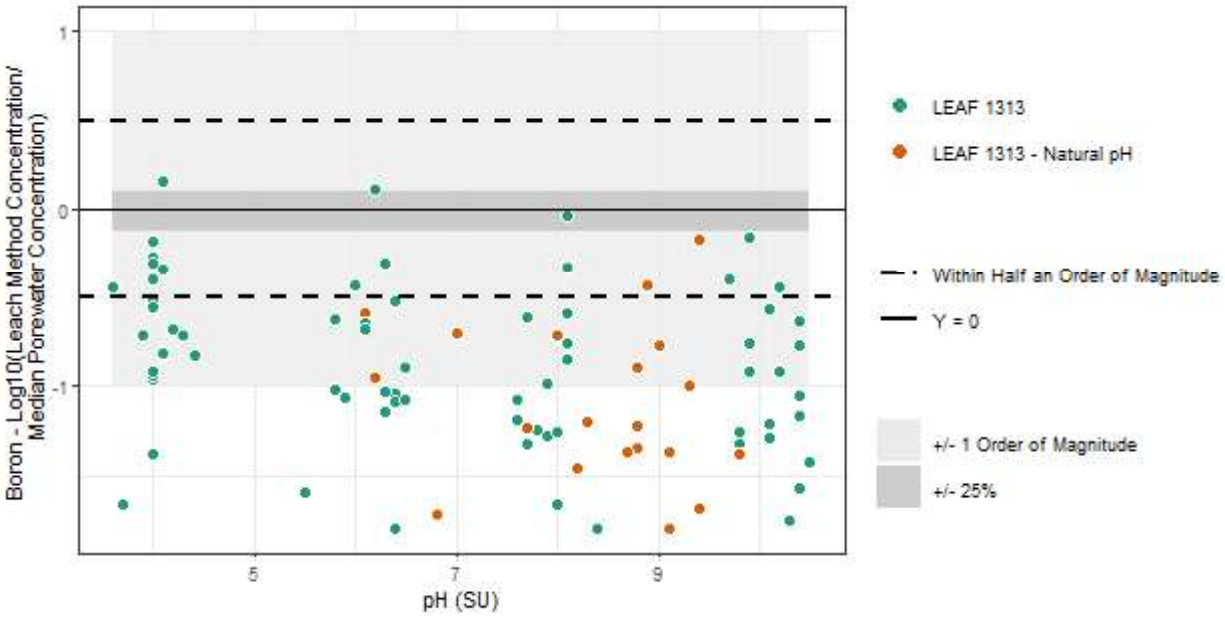


Figure E-5
Boron

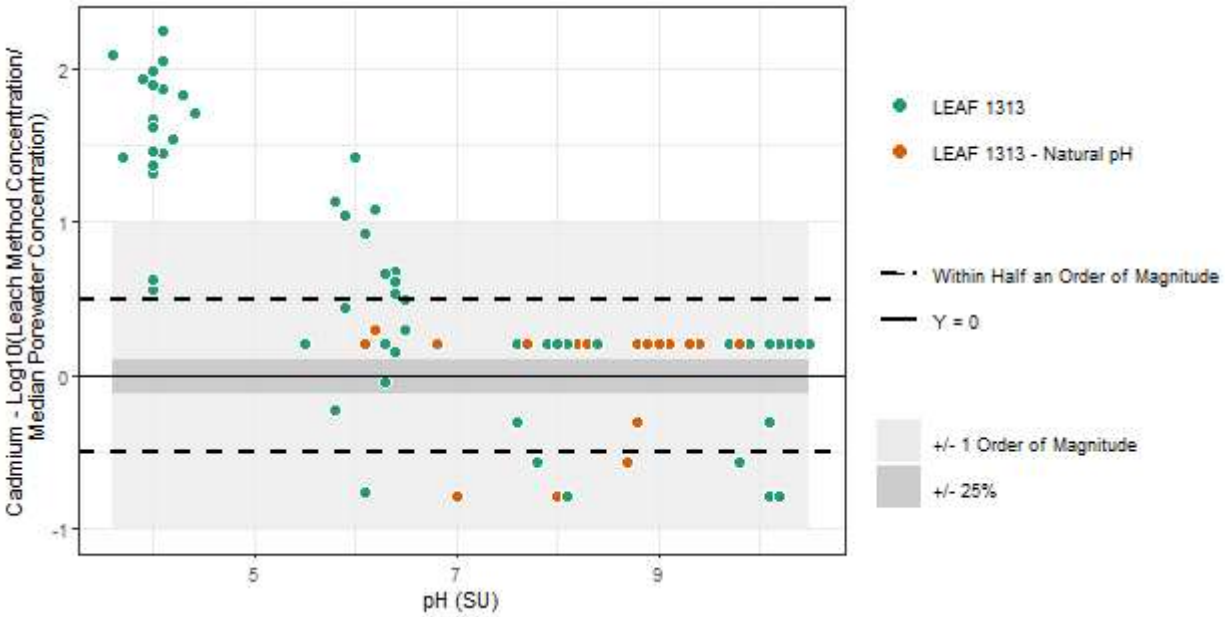


Figure E-6
Cadmium

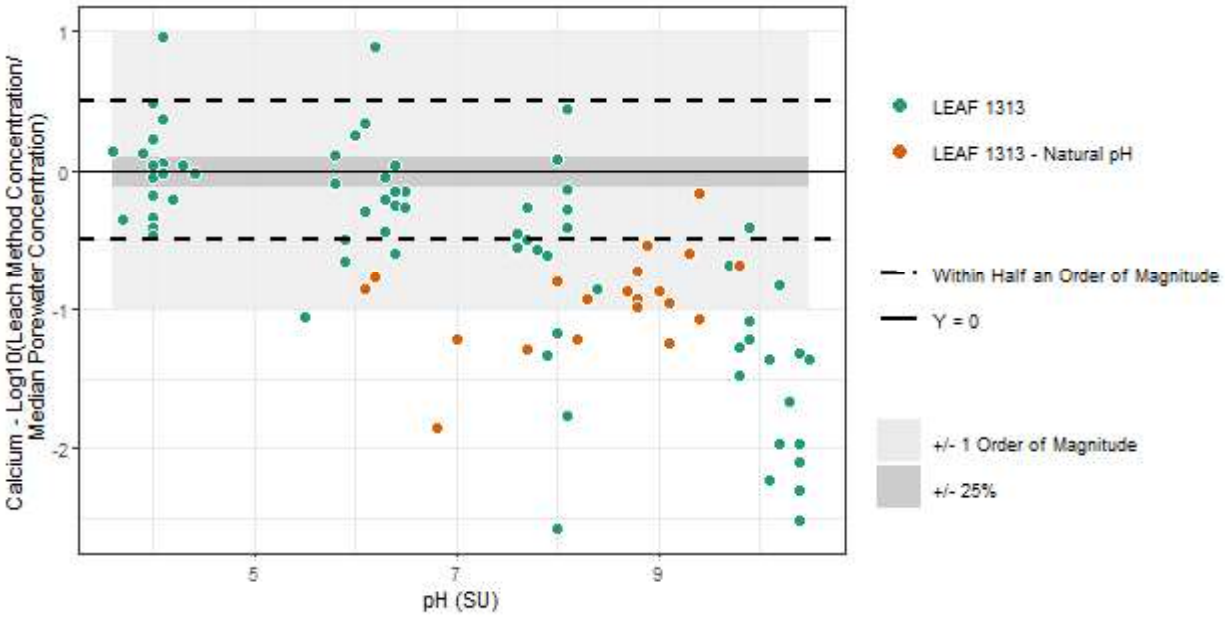


Figure E-7
Calcium

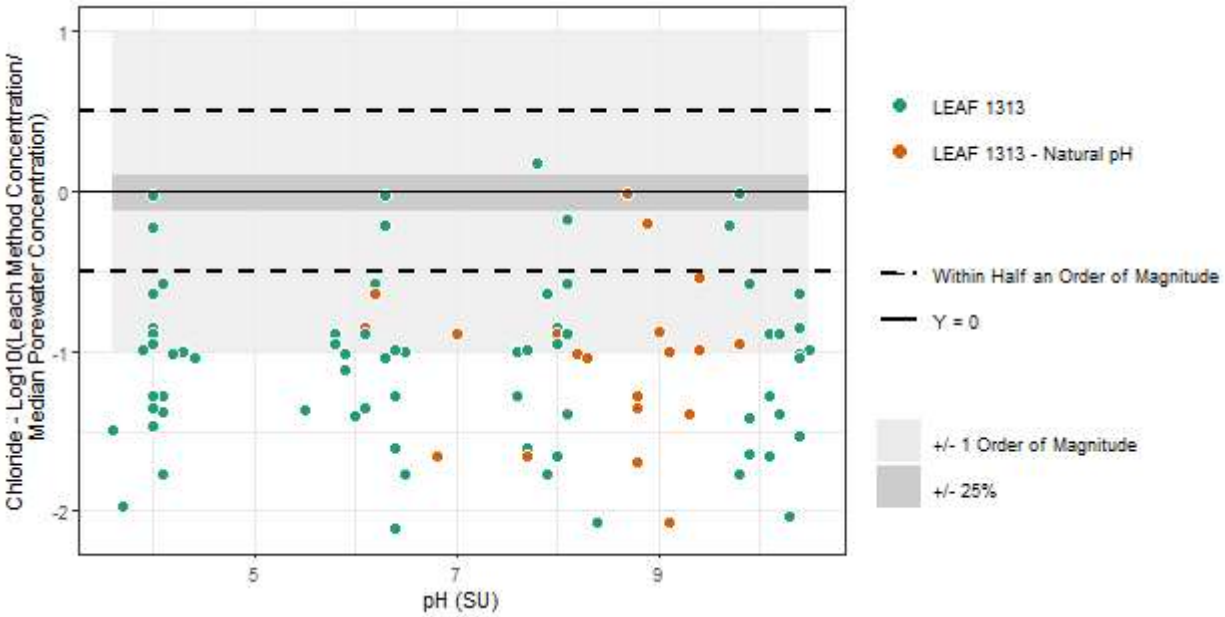


Figure E-8
Chloride

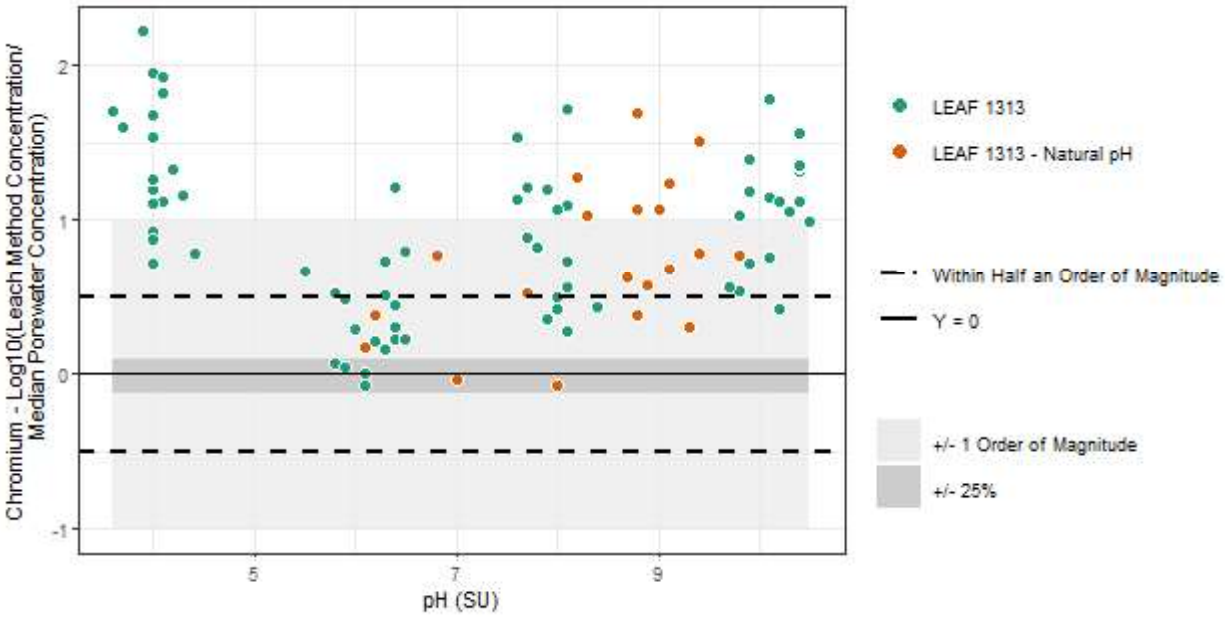


Figure E-9
Chromium

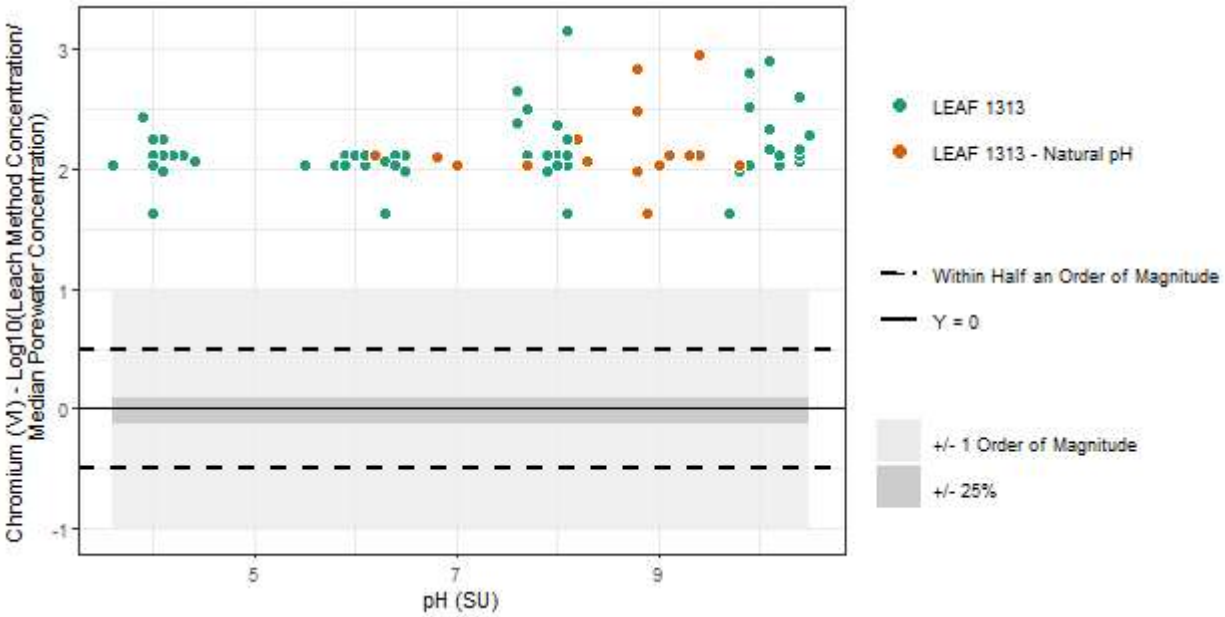


Figure E-10
Chromium (VI)

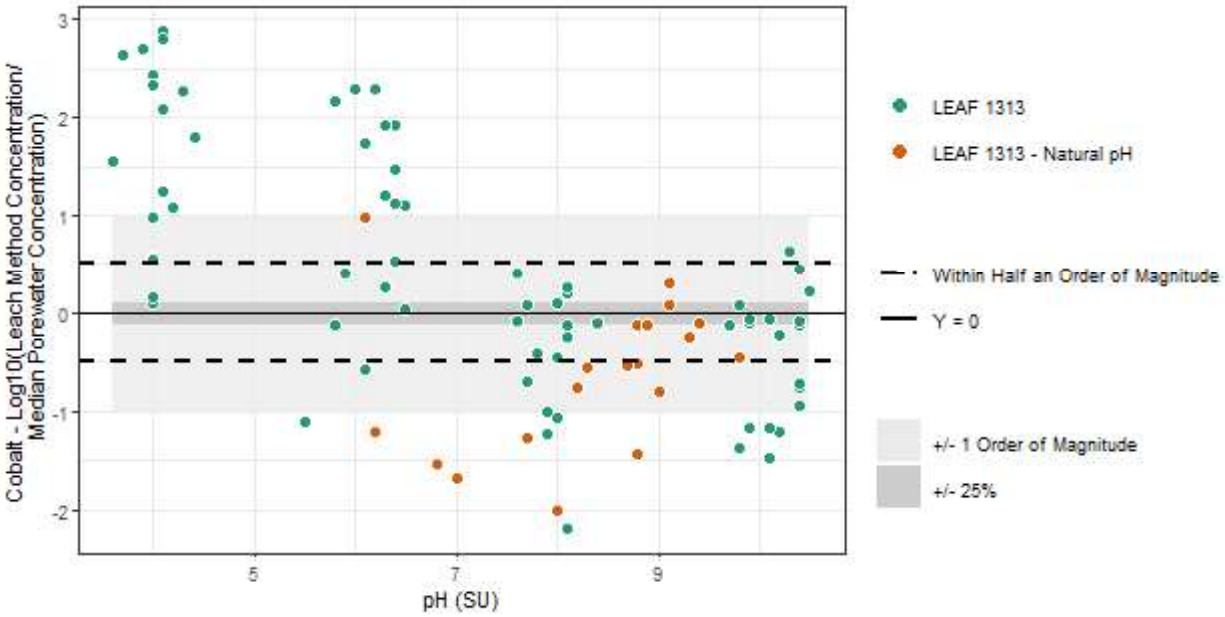


Figure E-11
Cobalt

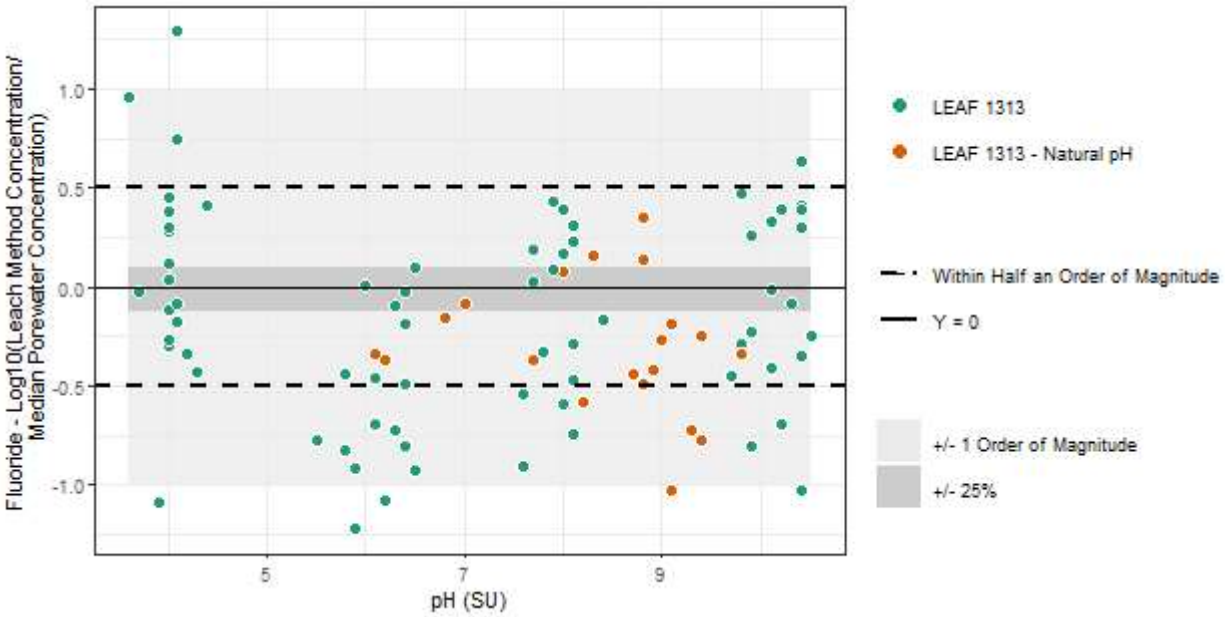


Figure E-12
Fluoride

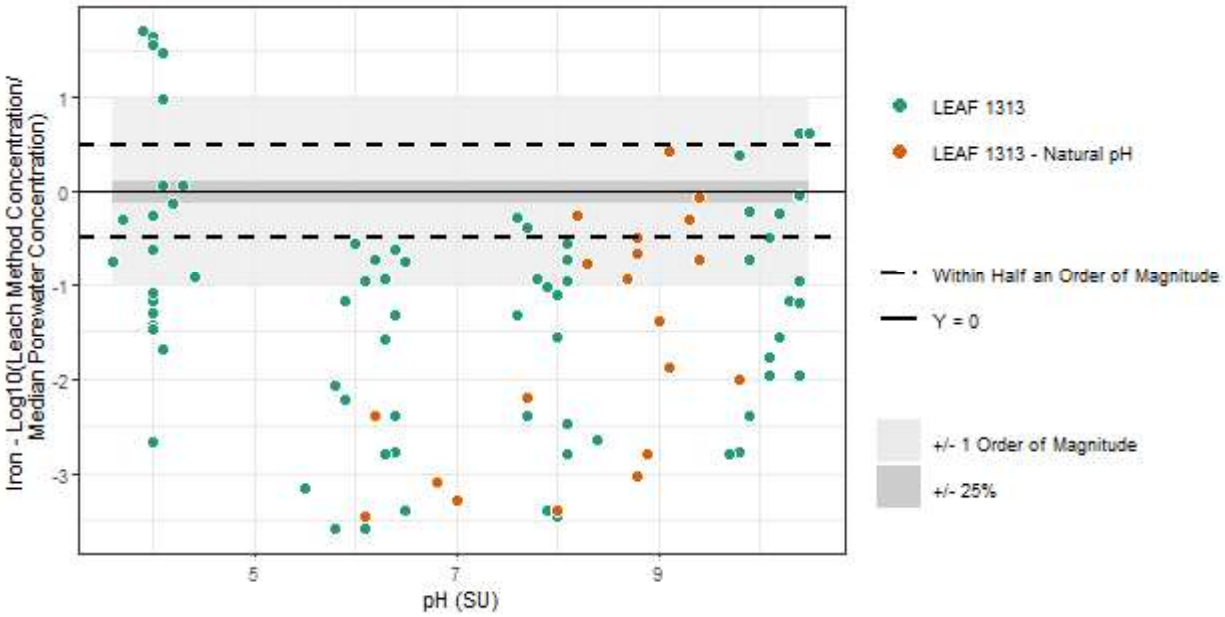


Figure E-13
Iron

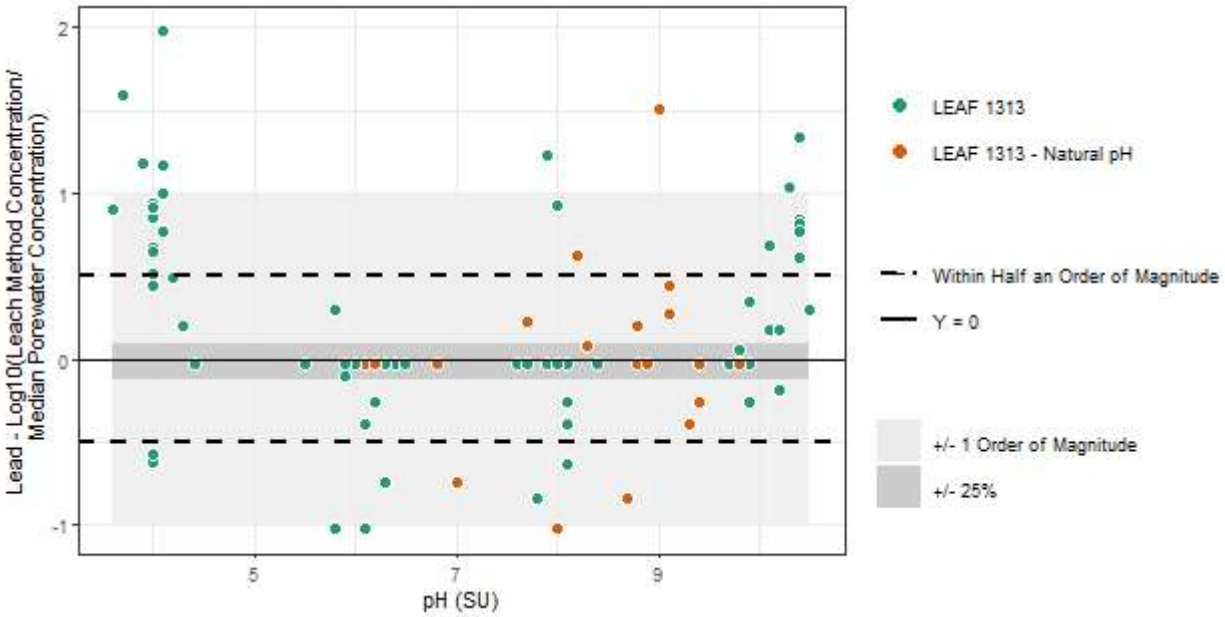


Figure E-14
Lead

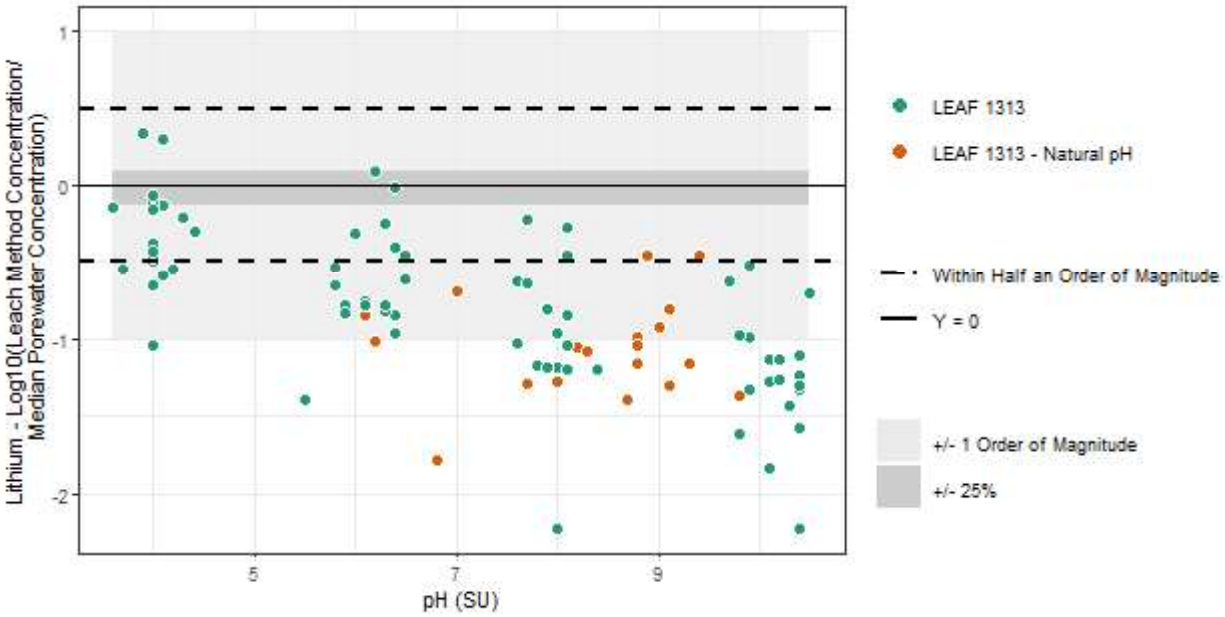


Figure E-15
Lithium

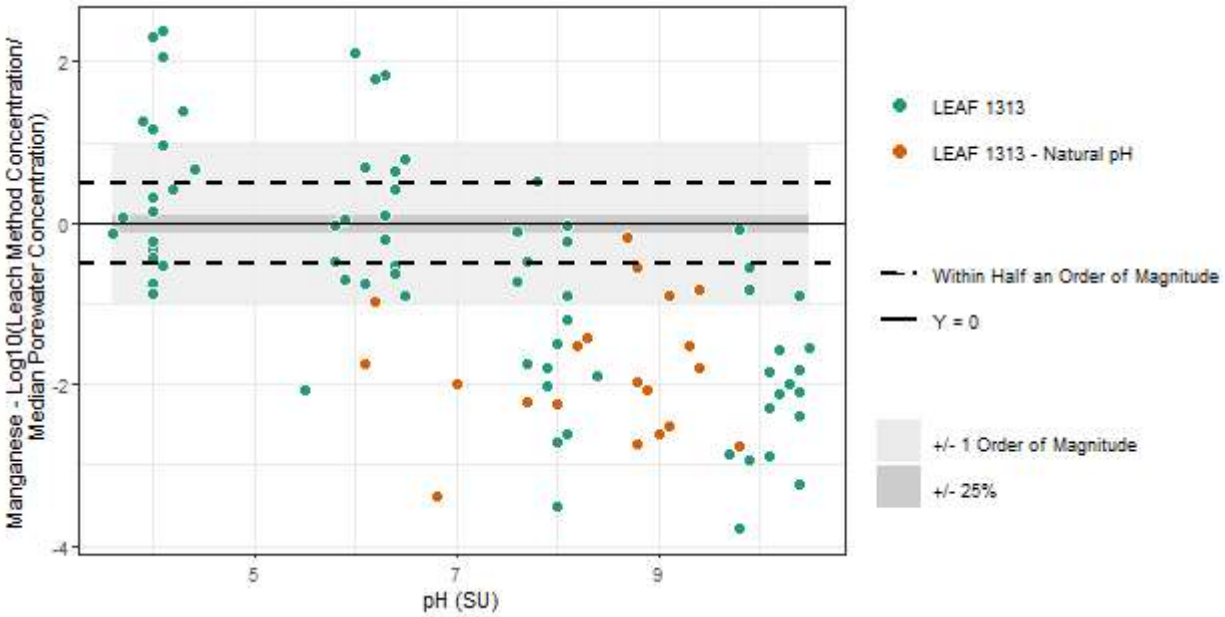


Figure E-16
Manganese

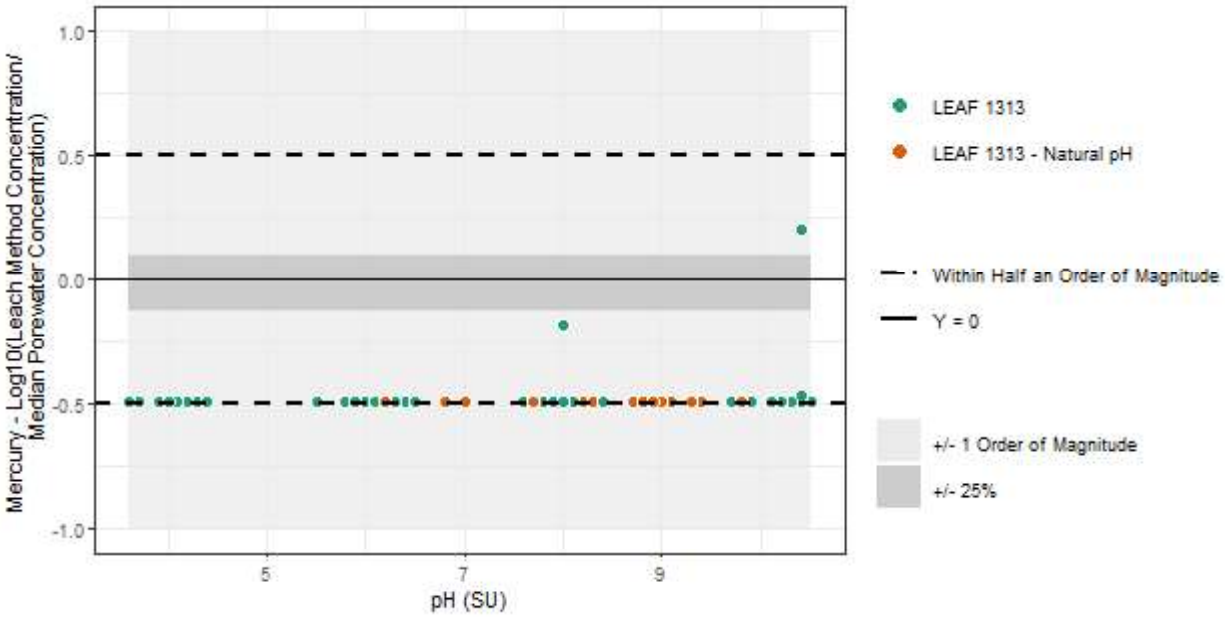


Figure E-17
Mercury

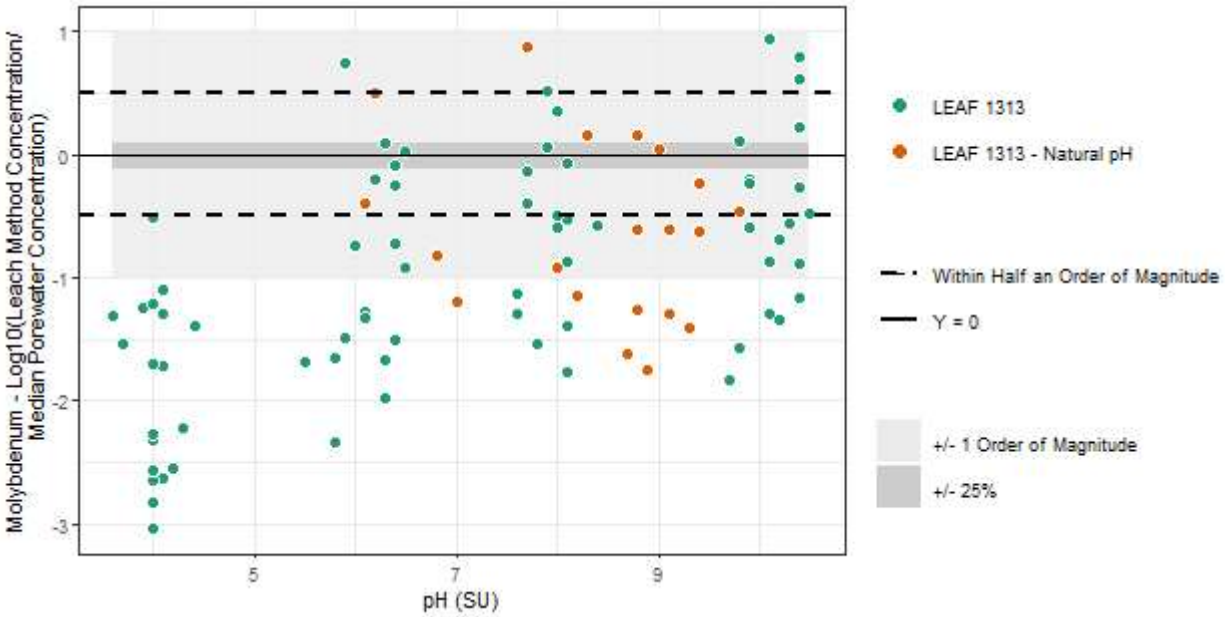


Figure E-18
Molybdenum

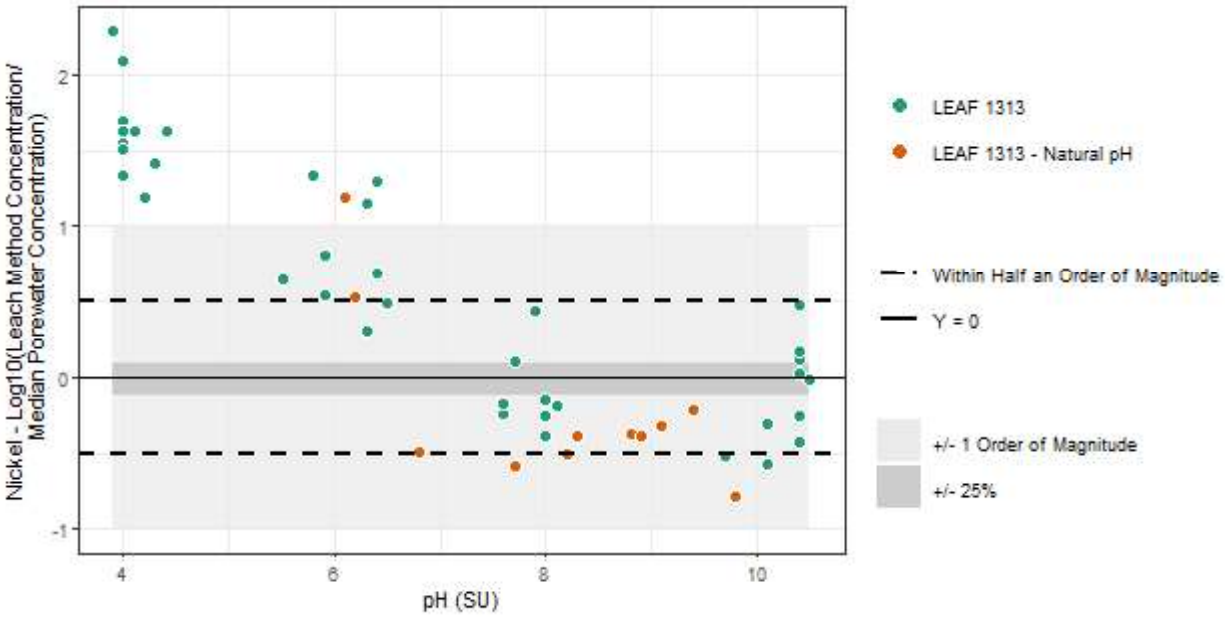


Figure E-19
Nickel

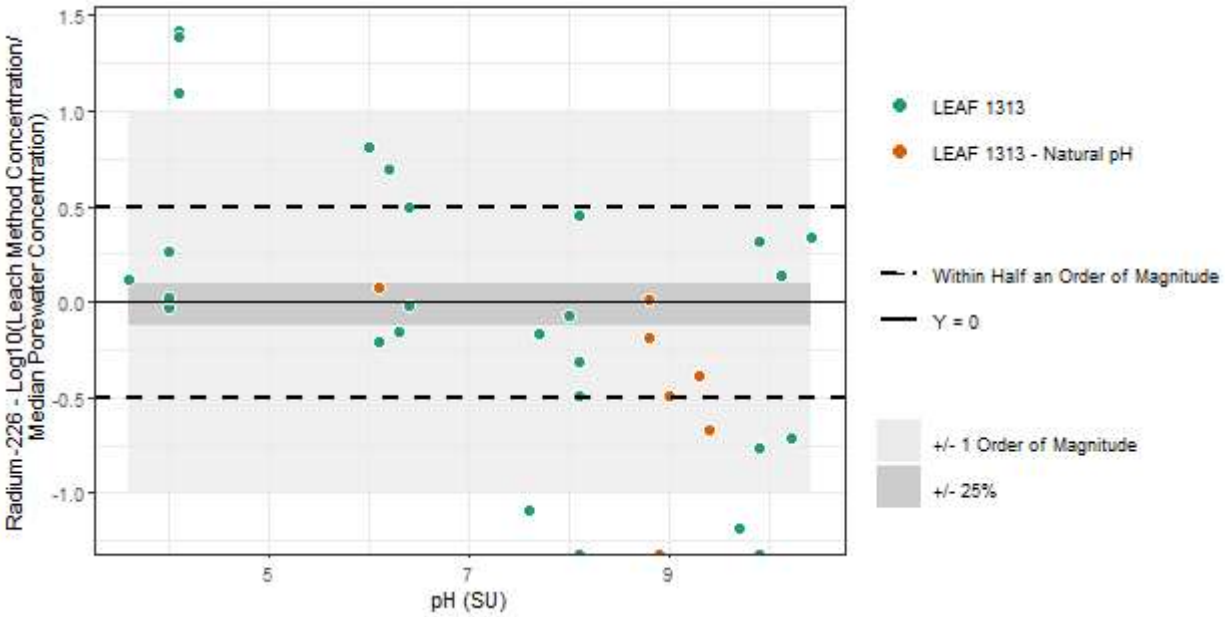


Figure E-20
Radium-226

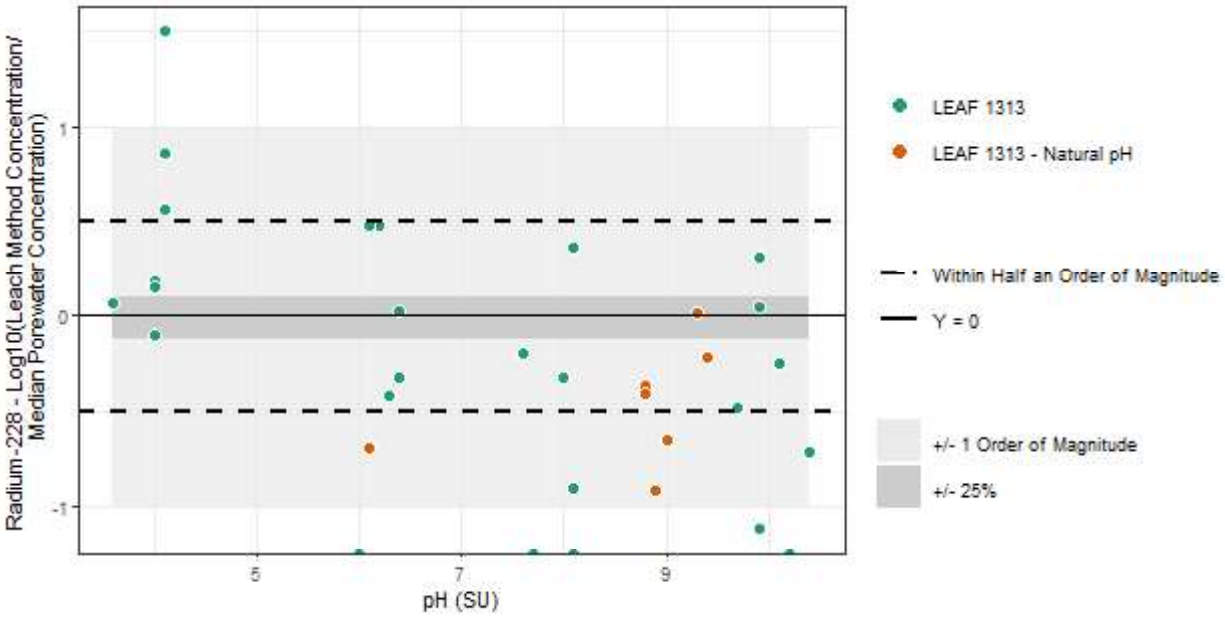


Figure E-21
Radium-228

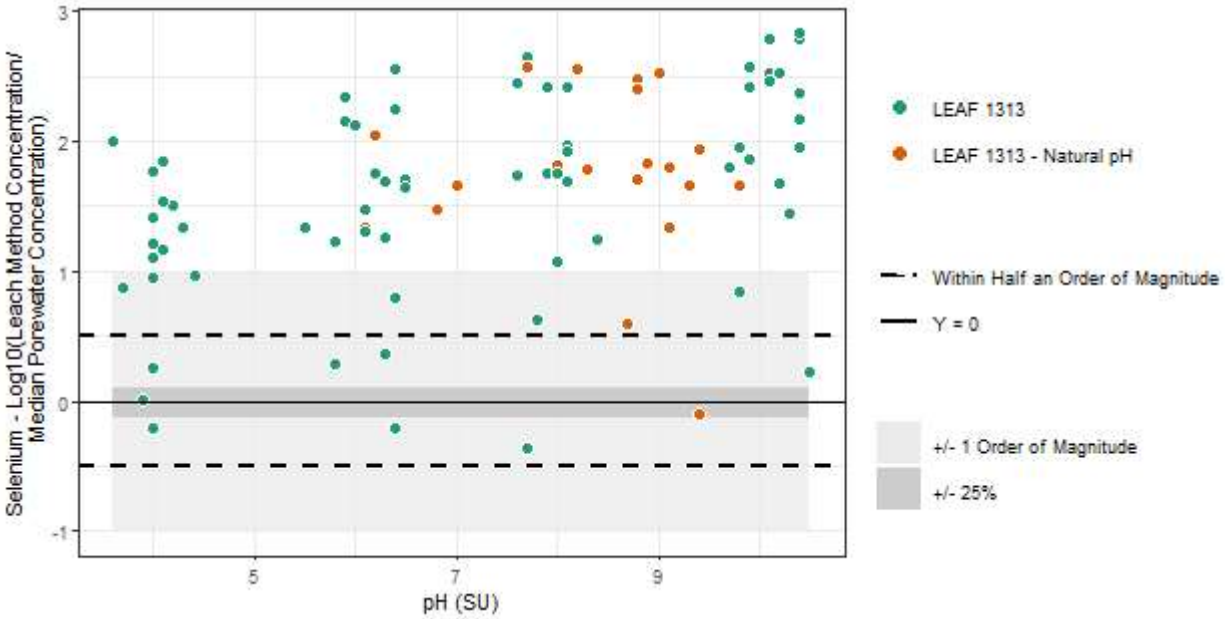


Figure E-22
Selenium

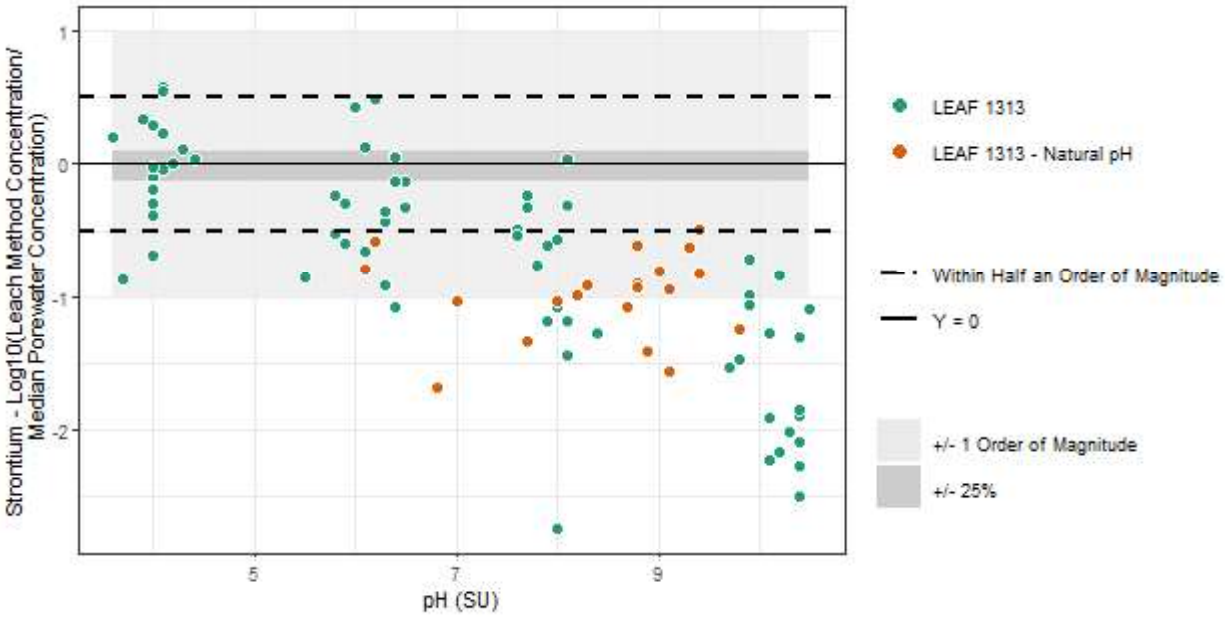


Figure E-23
Strontium

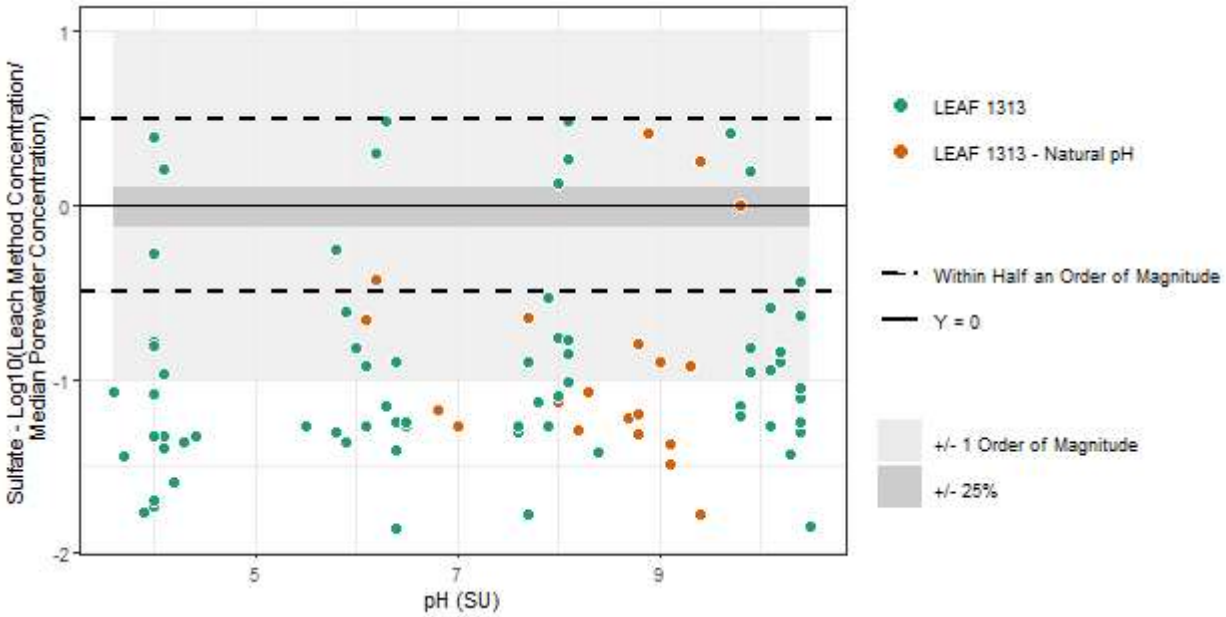


Figure E-24
Sulfate

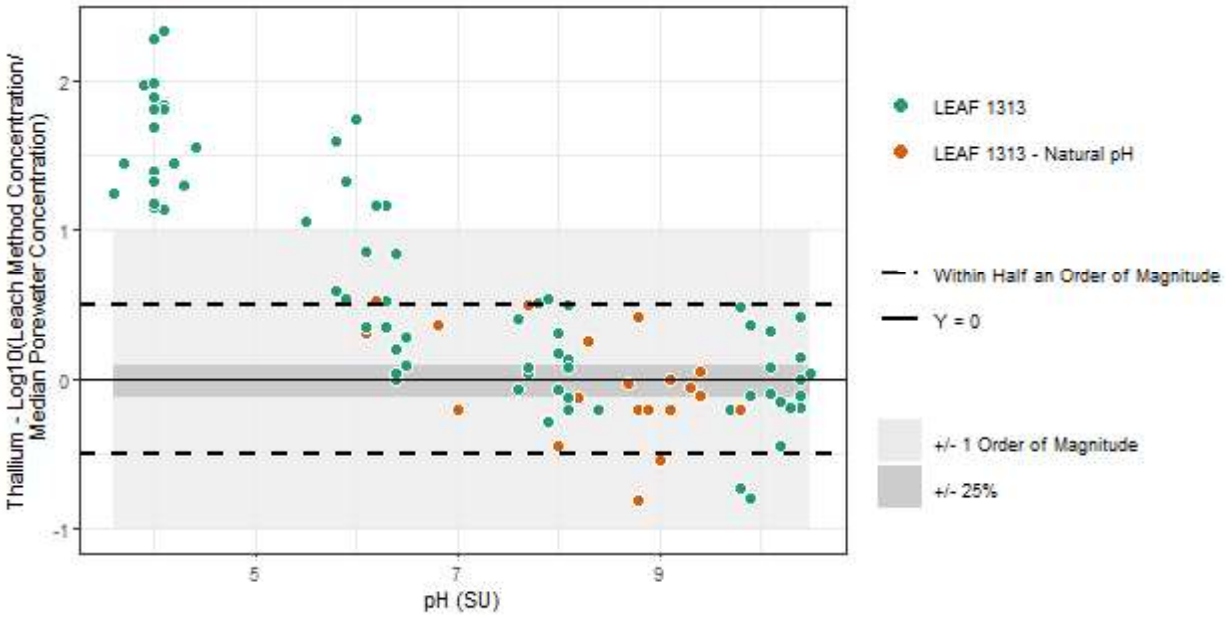


Figure E-25
Thallium

Plots Showing Normalized LEAF 1313 to Porewater Results across the Range of pH Levels Tested

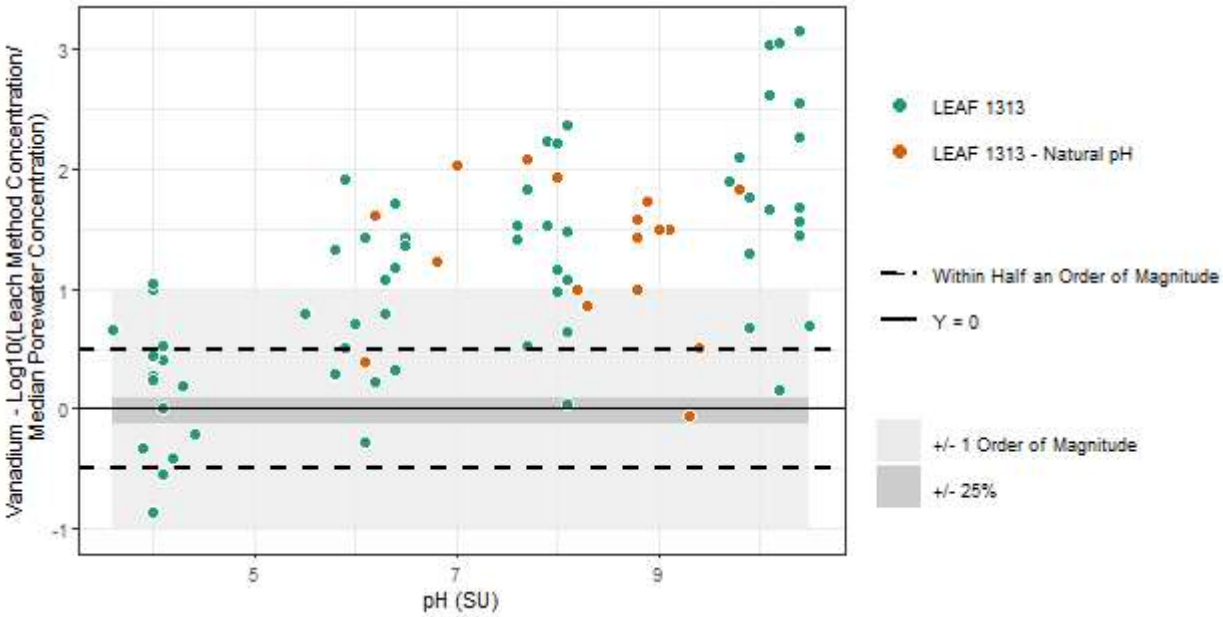


Figure E-26
Vanadium

F

PLOTS SHOWING NORMALIZED LEAF 1316 TO POREWATER RESULTS ACROSS THE RANGE OF L/S VALUES TESTED

Figures F-1 through F-26 show normalized LEAF 1316 test results (and 1313 at natural pH) as a function of L/S ratio. The results were normalized by dividing by the median porewater concentration (because results are displayed as $\log_{10}$, a value of zero indicates exact agreement). The ability of the 1316 test to reproduce porewater concentrations at any given L/S was evaluated based on how many results plotted within the dark-shaded ±25% range.

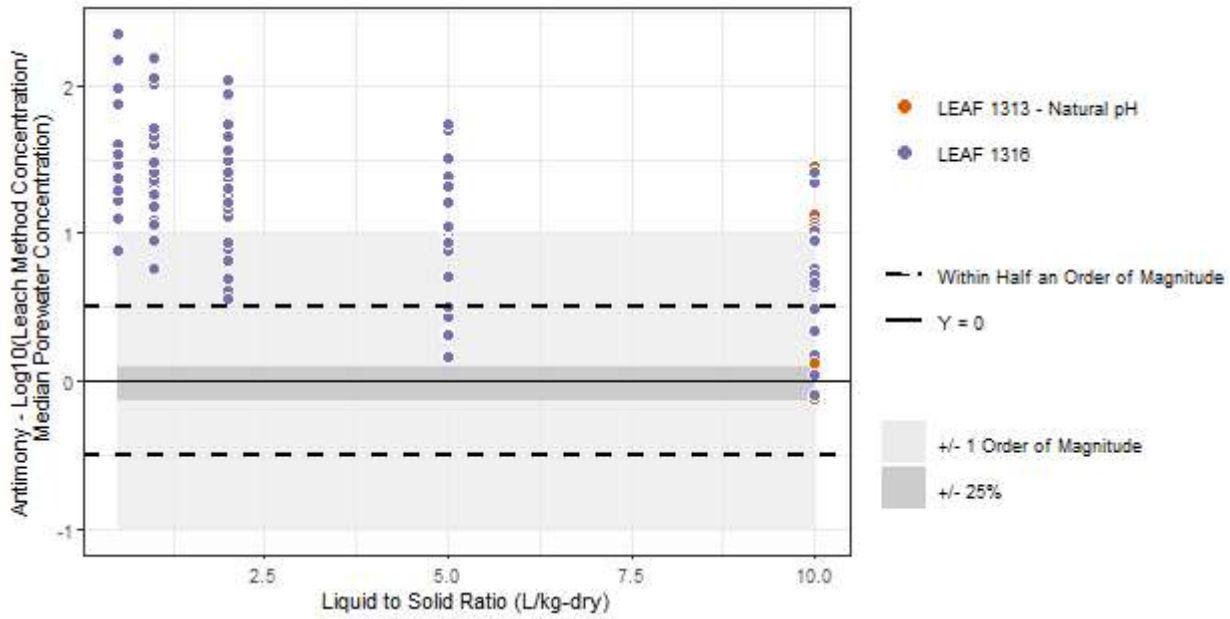


Figure F-1
Antimony

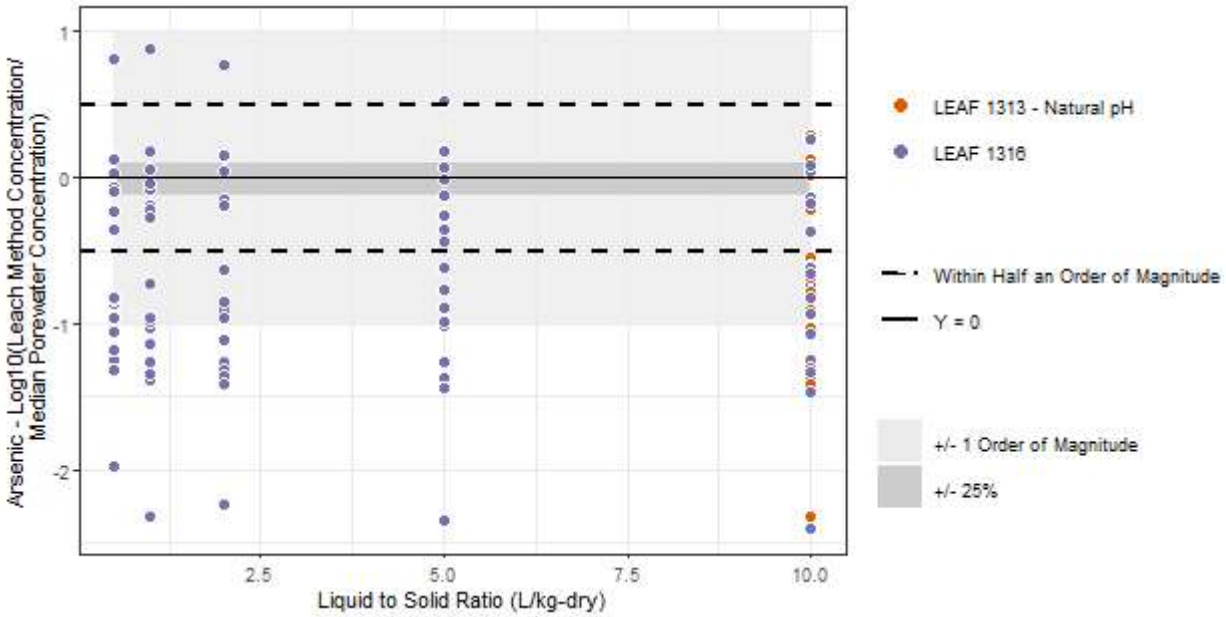


Figure F-2
Arsenic

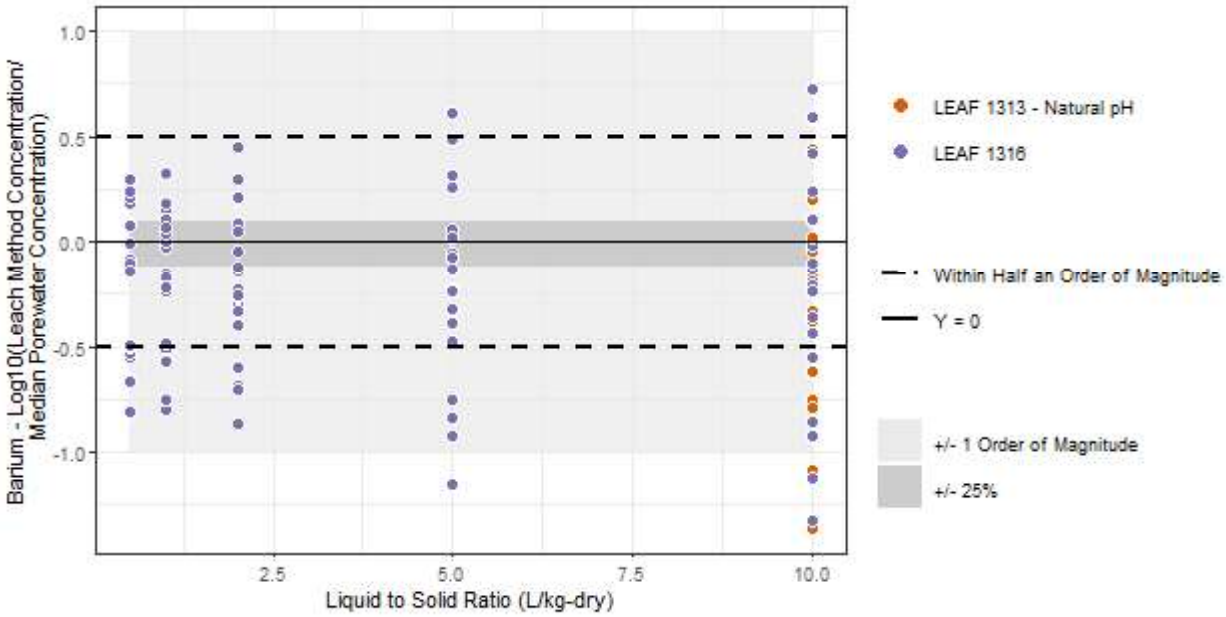


Figure F-3
Barium

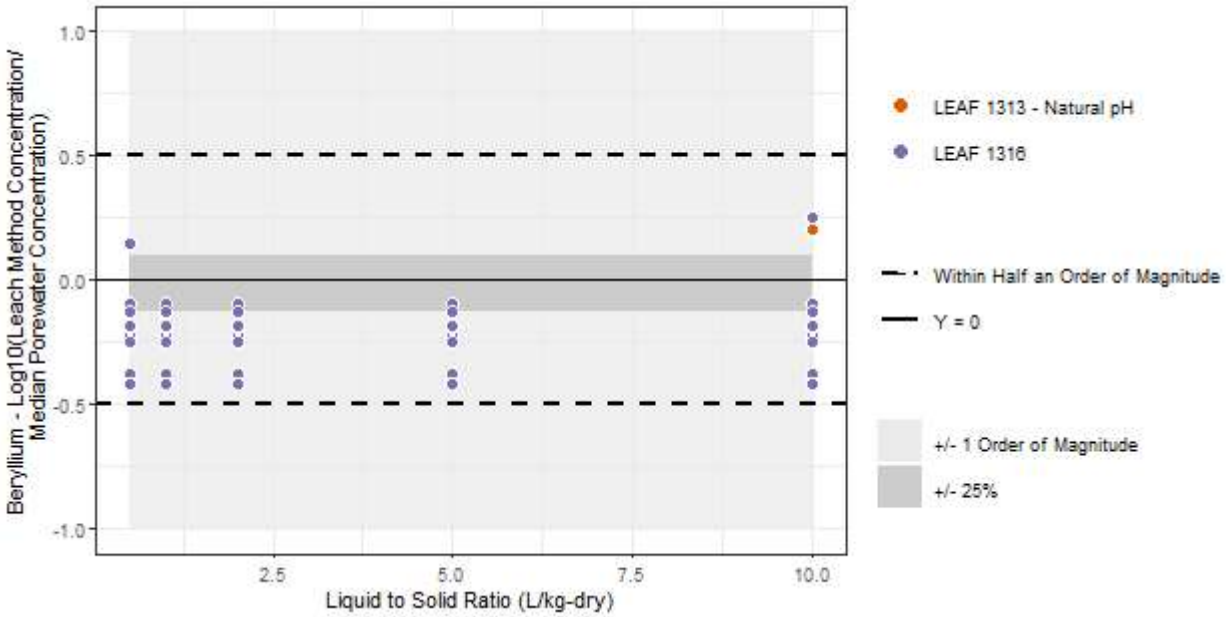


Figure F-4
Beryllium

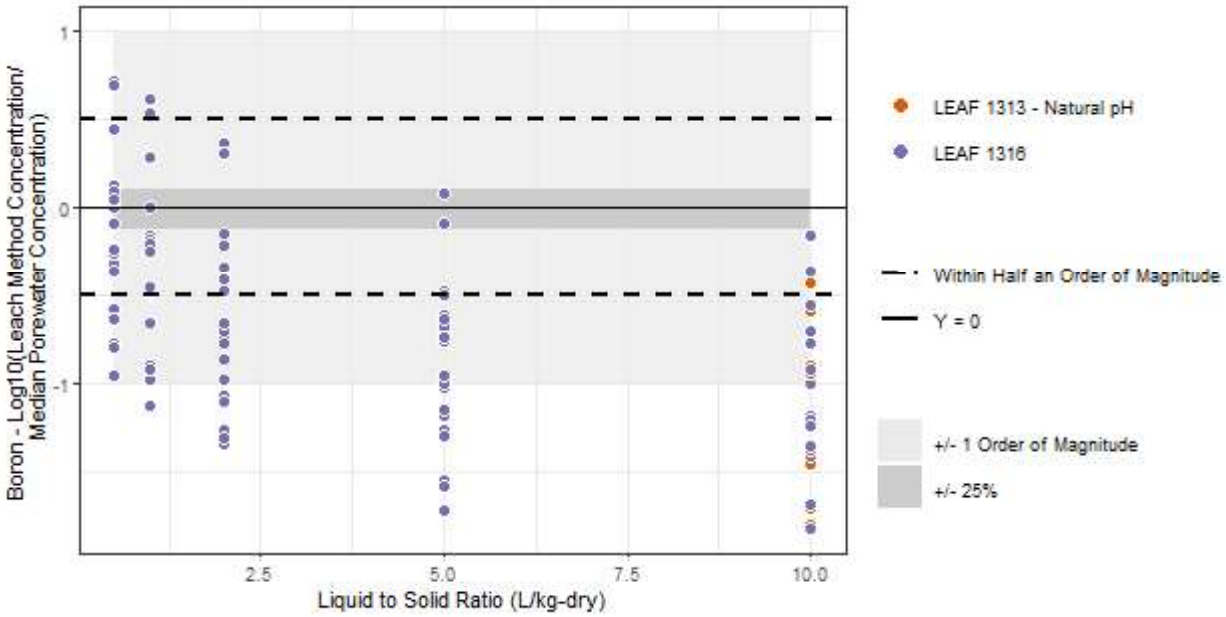


Figure F-5
Boron

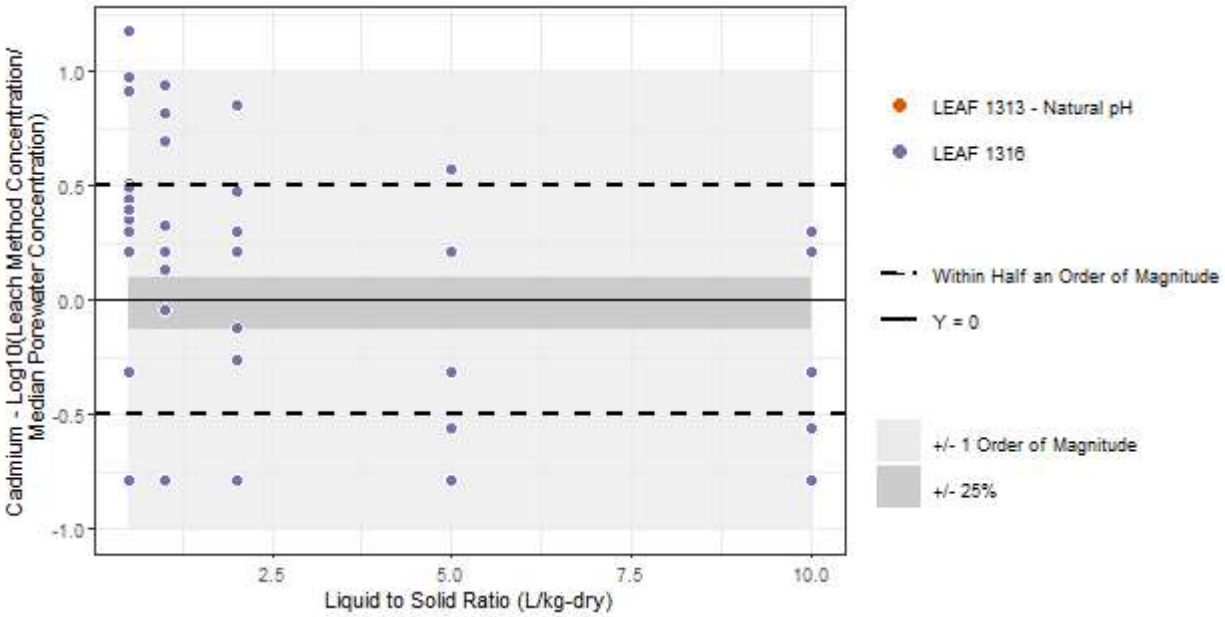
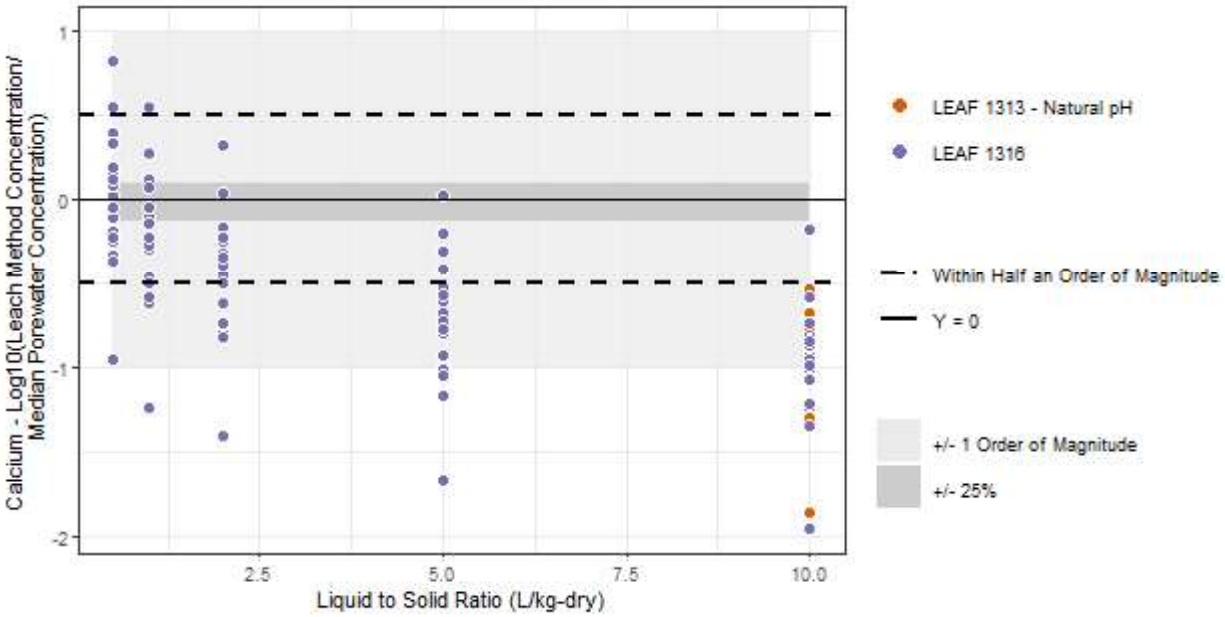


Figure F-6
Cadmium



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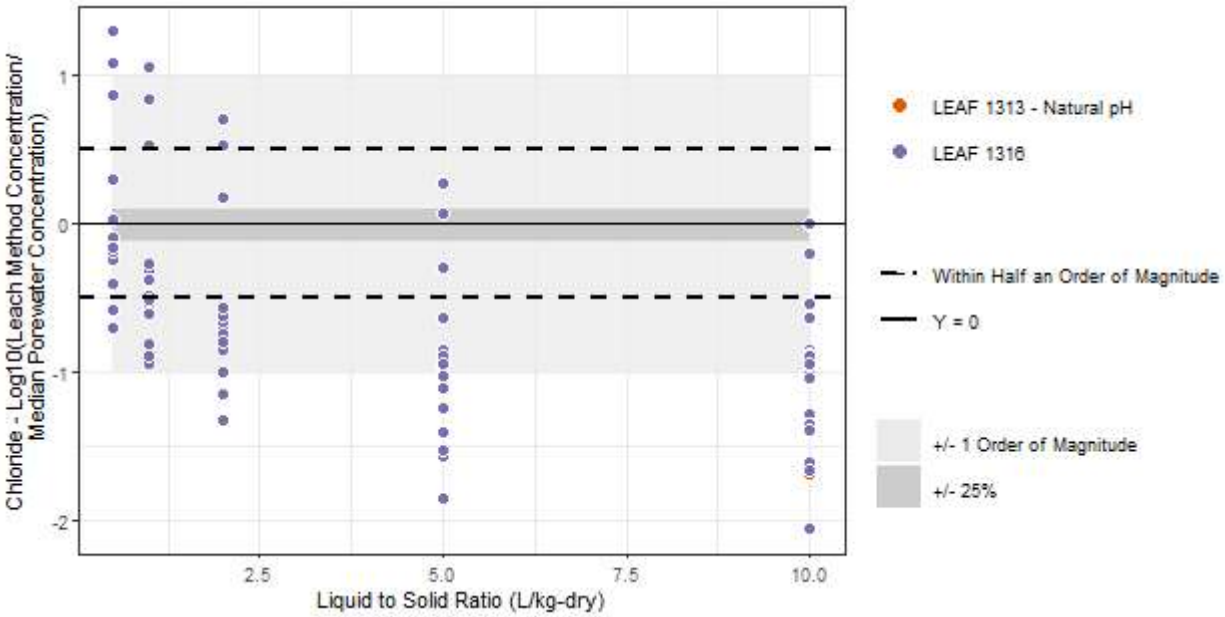

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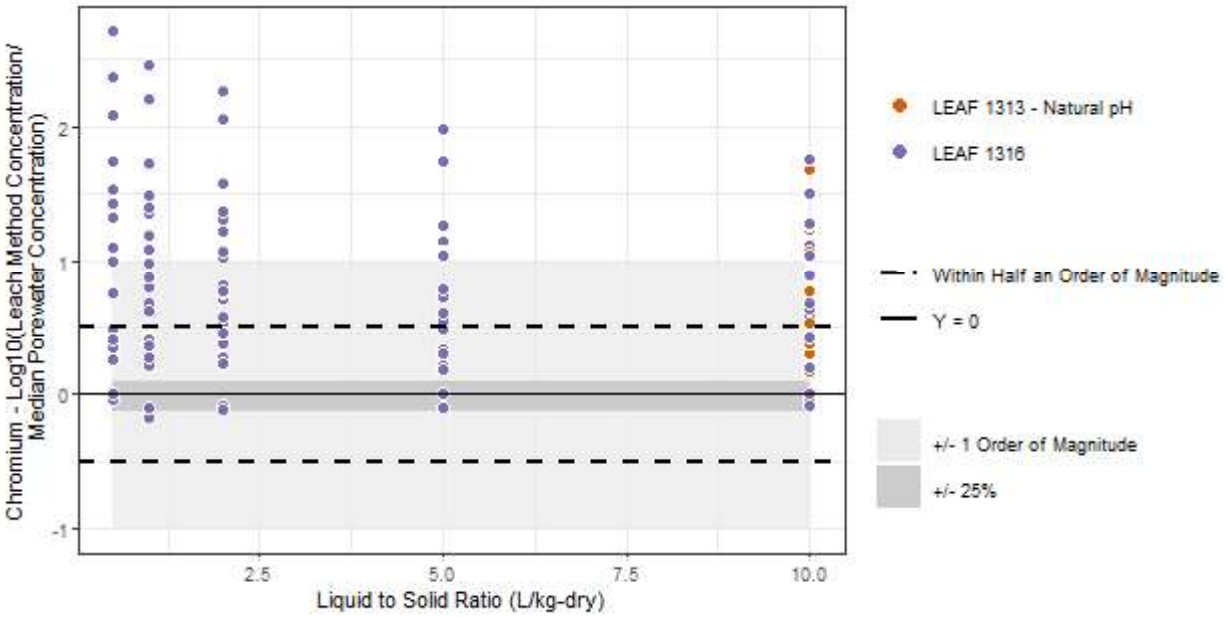

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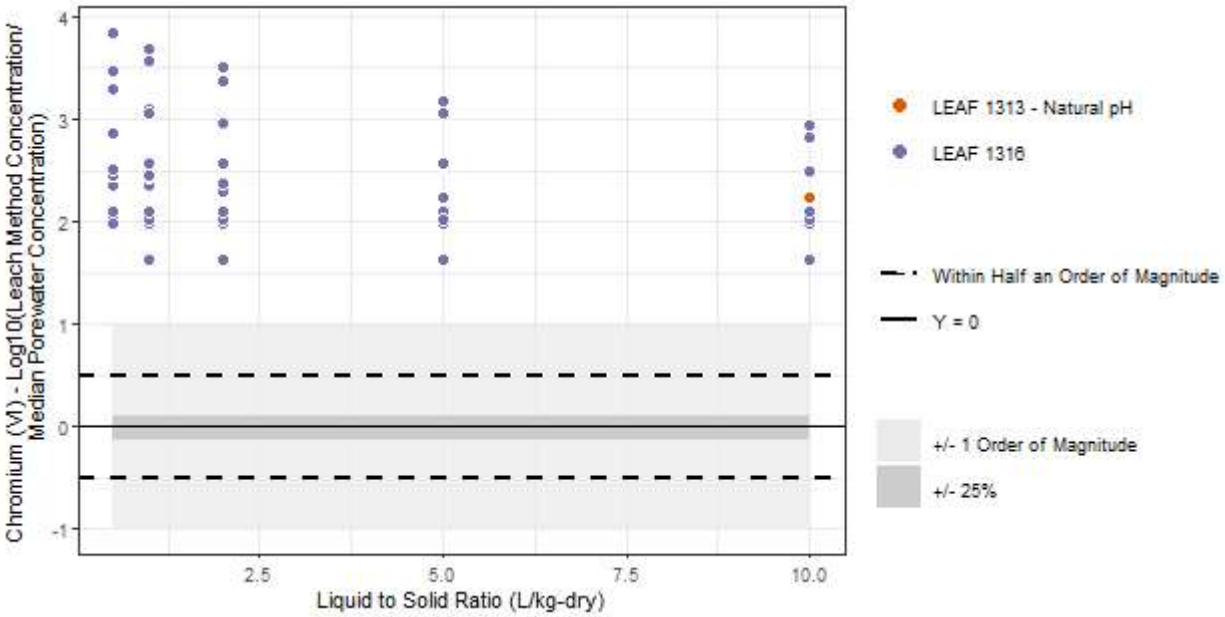

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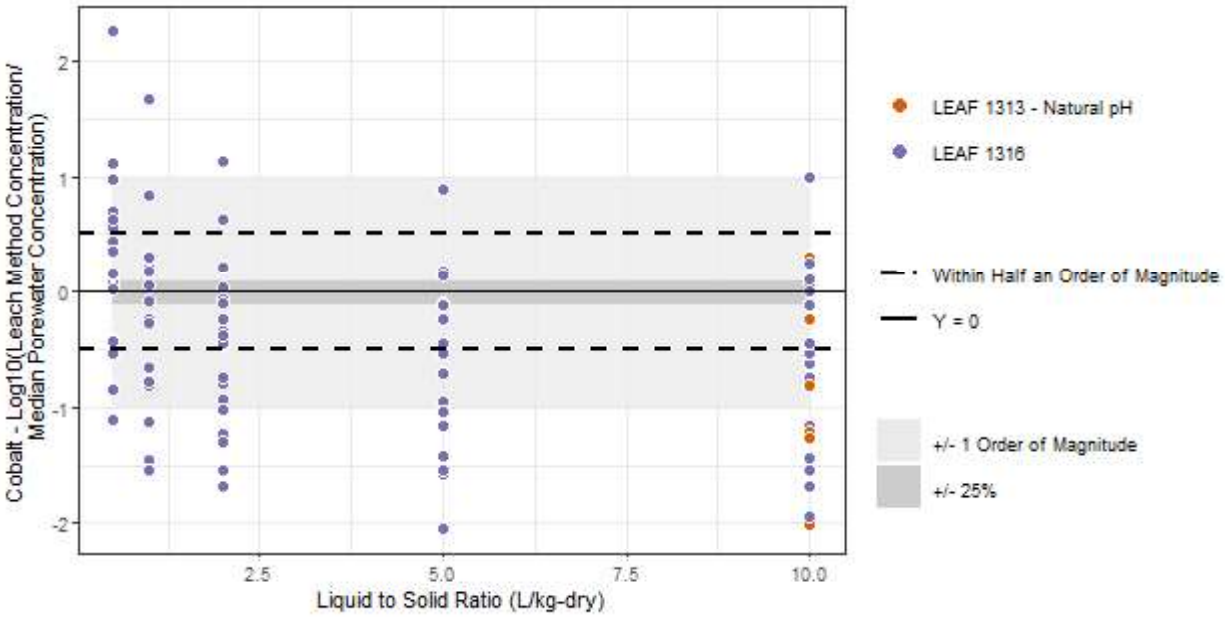

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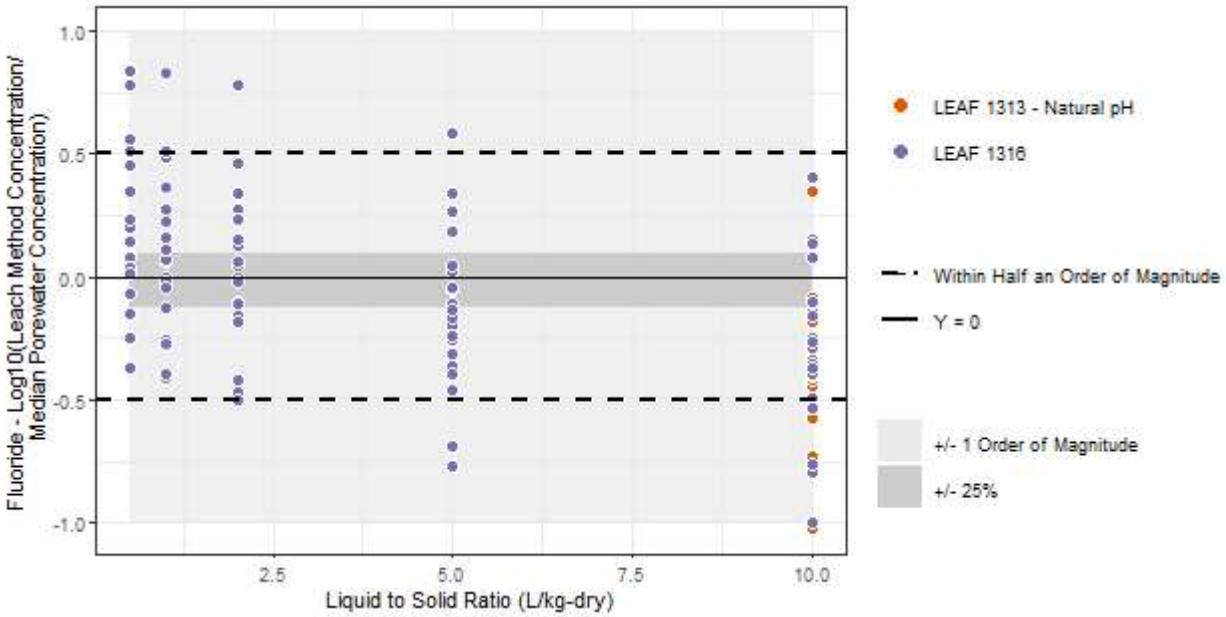

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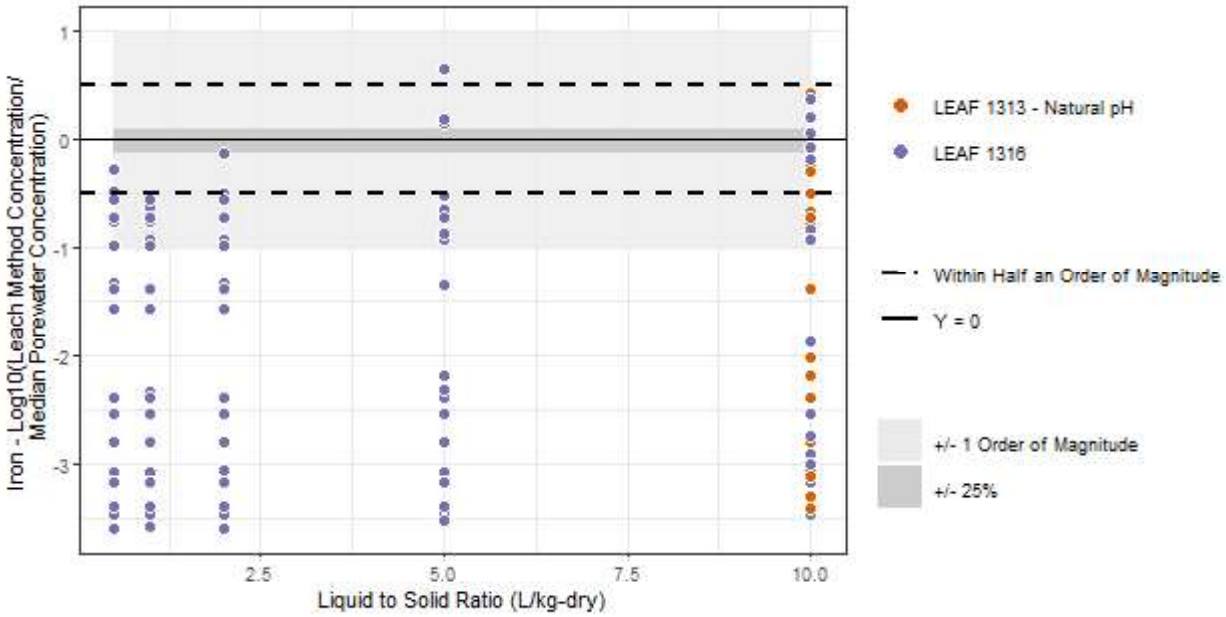

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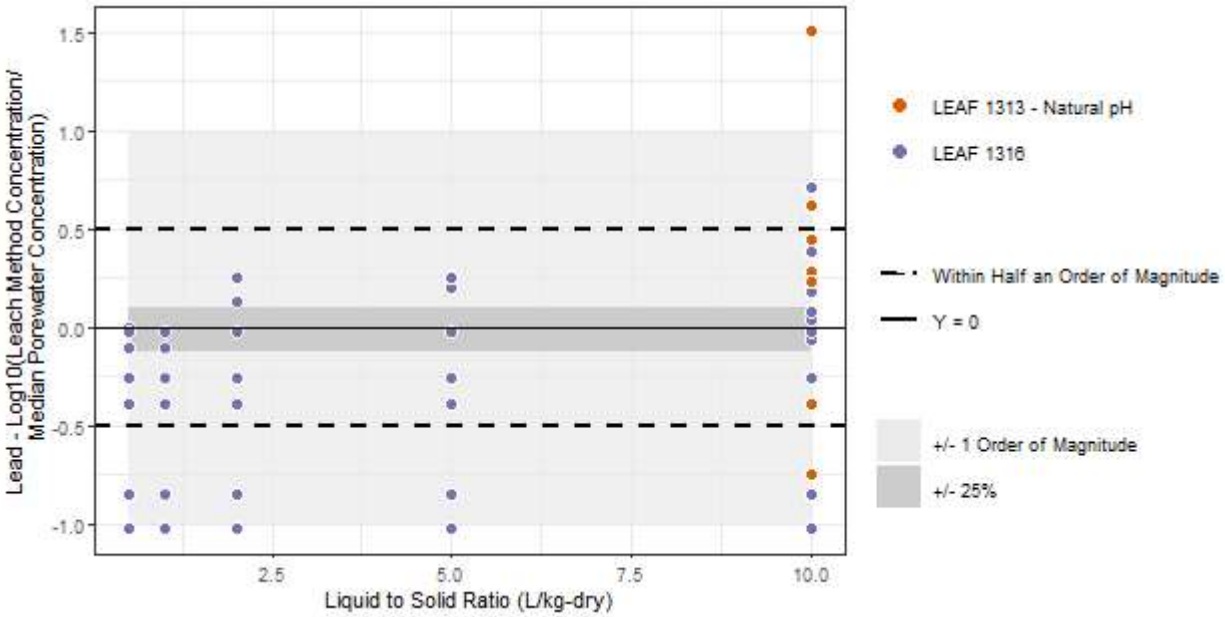

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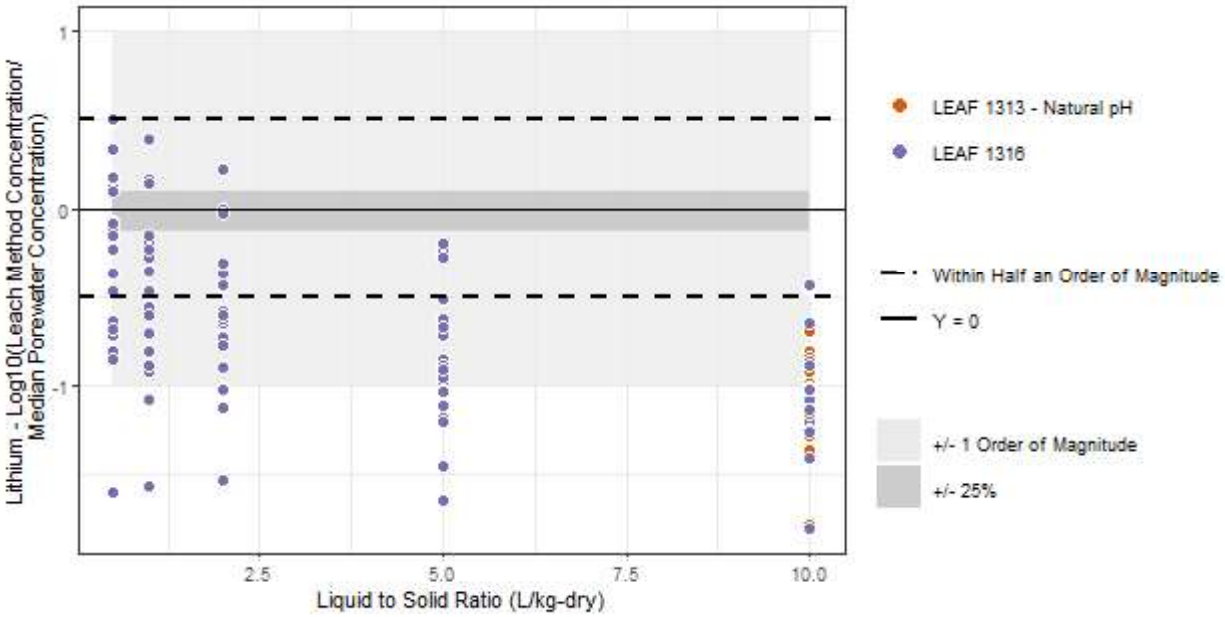

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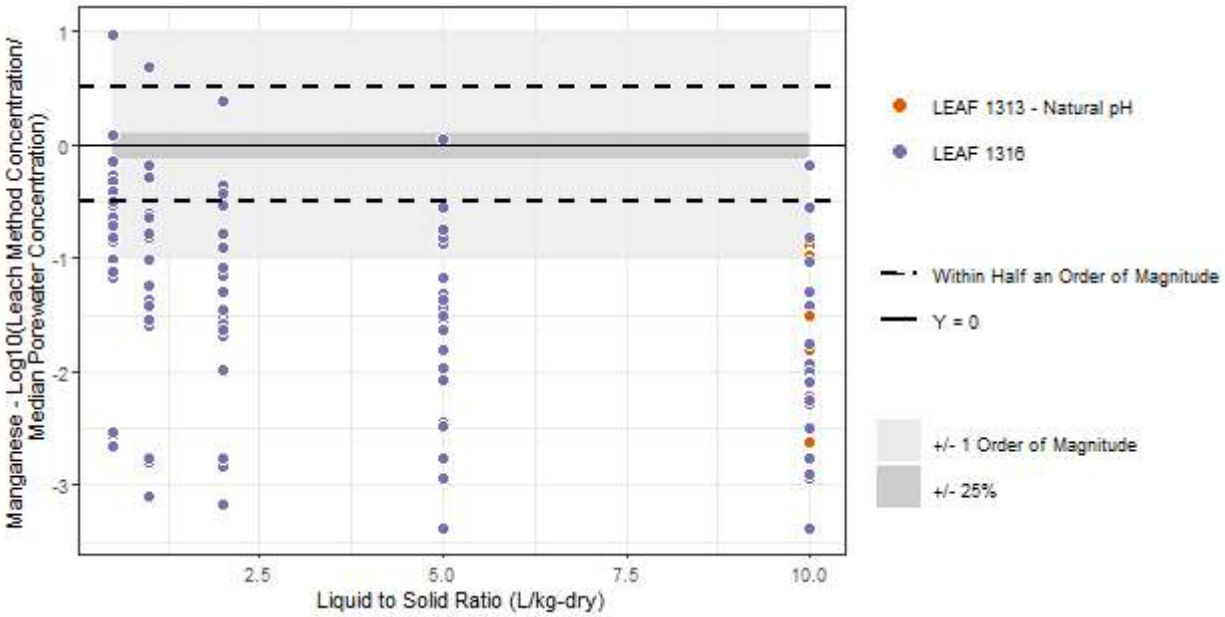

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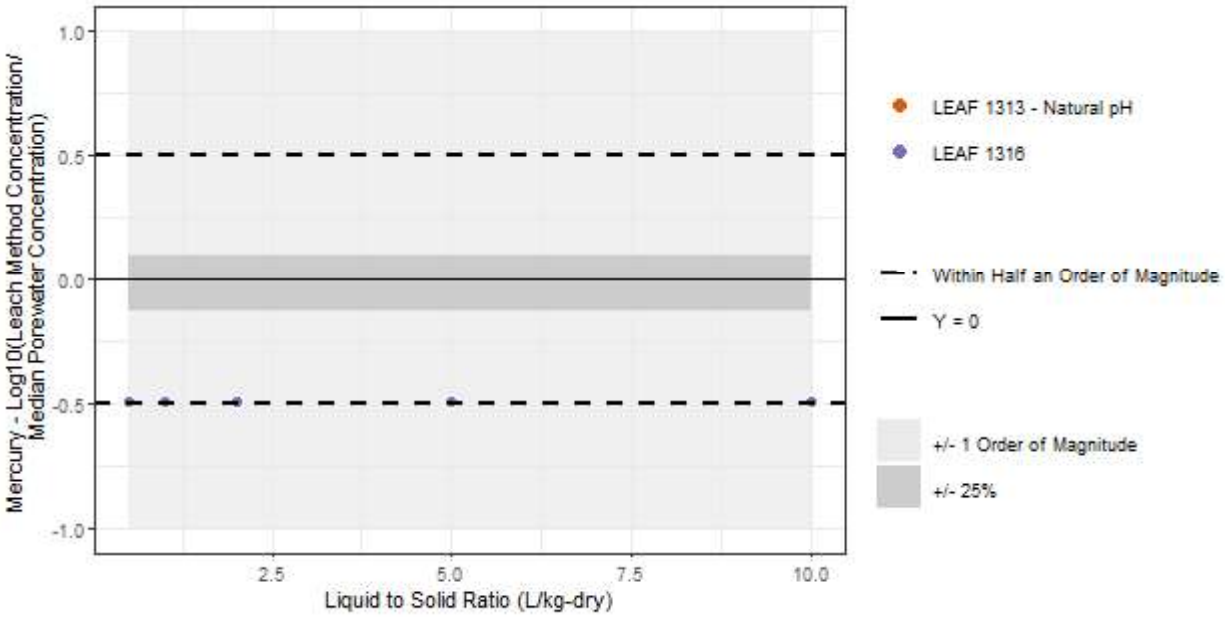

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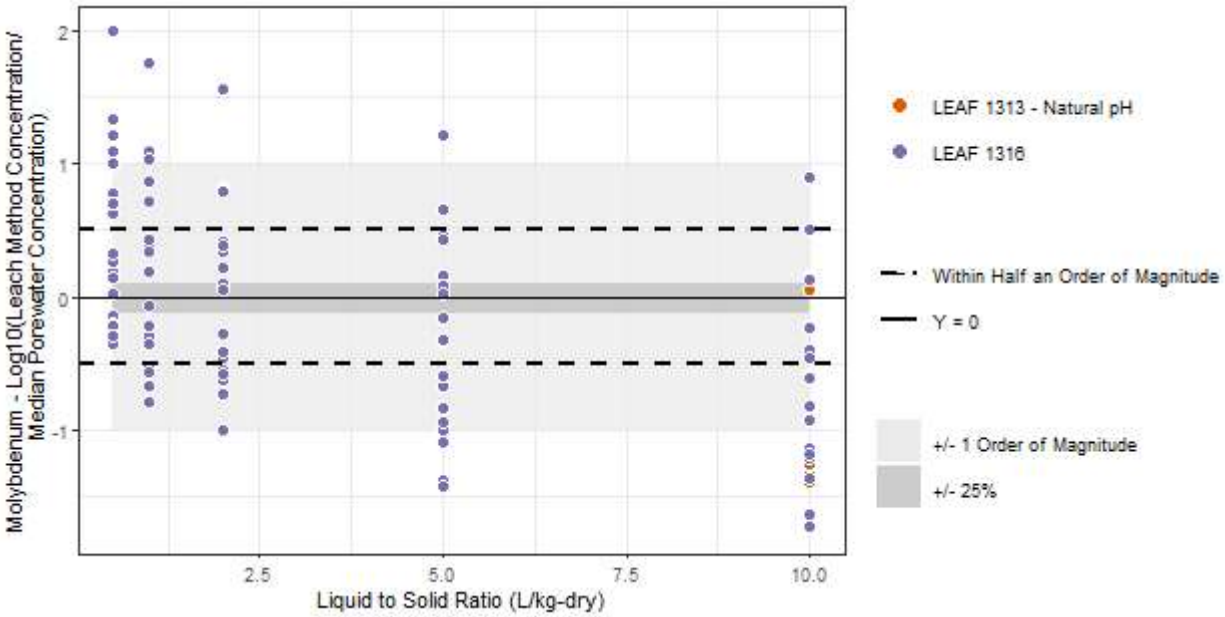

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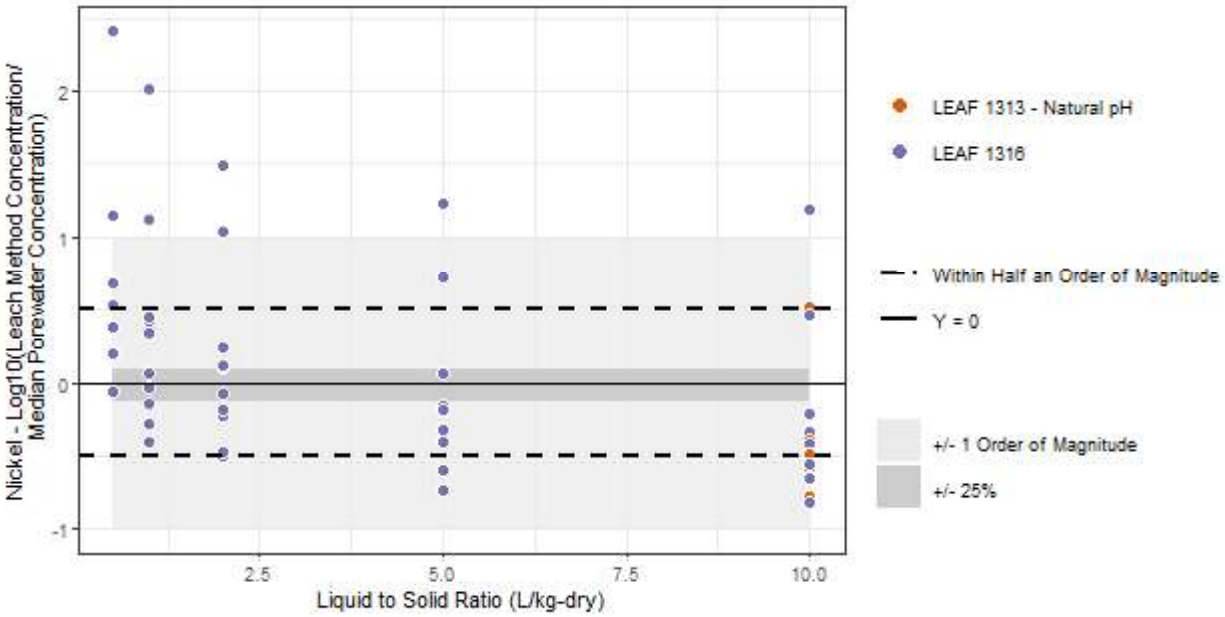

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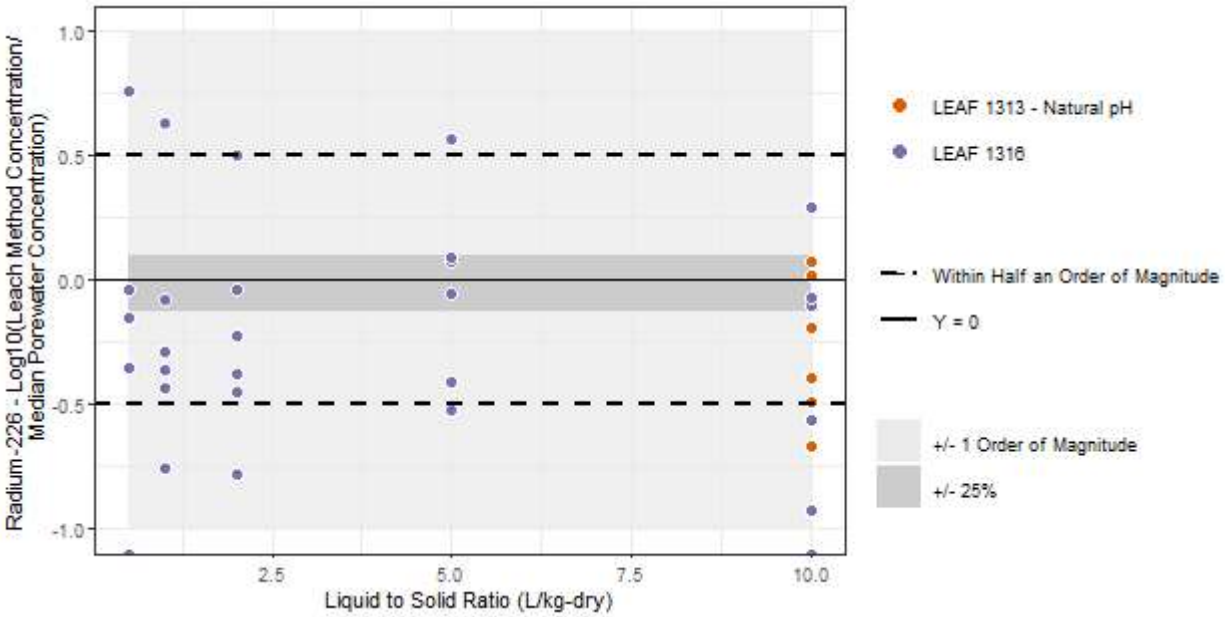

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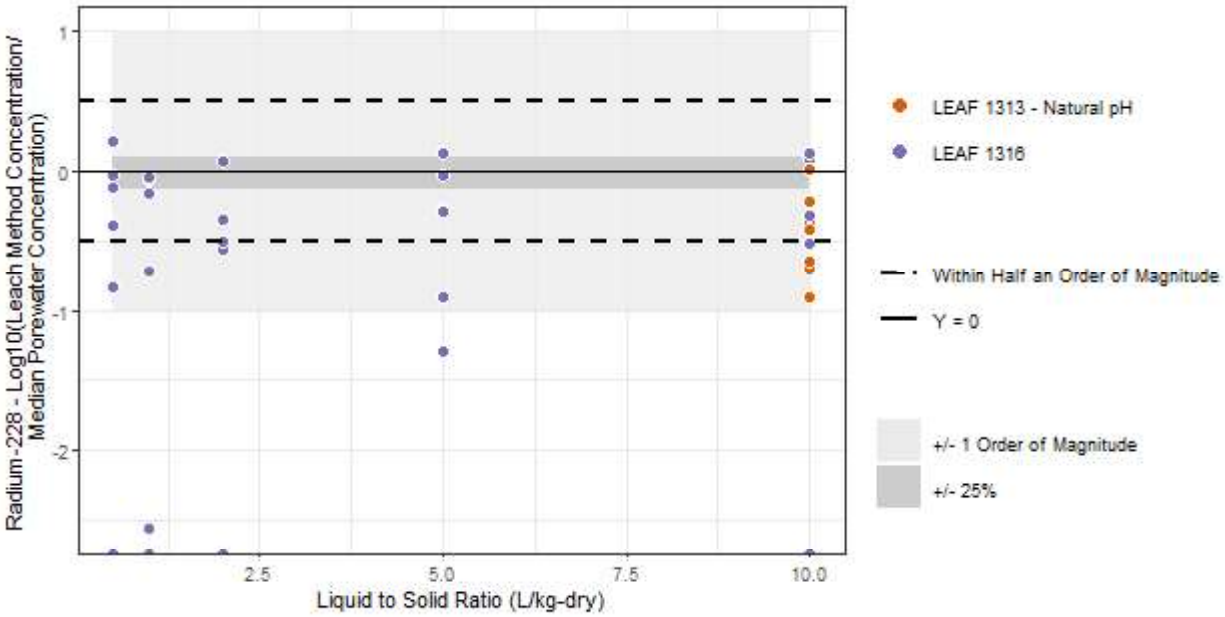

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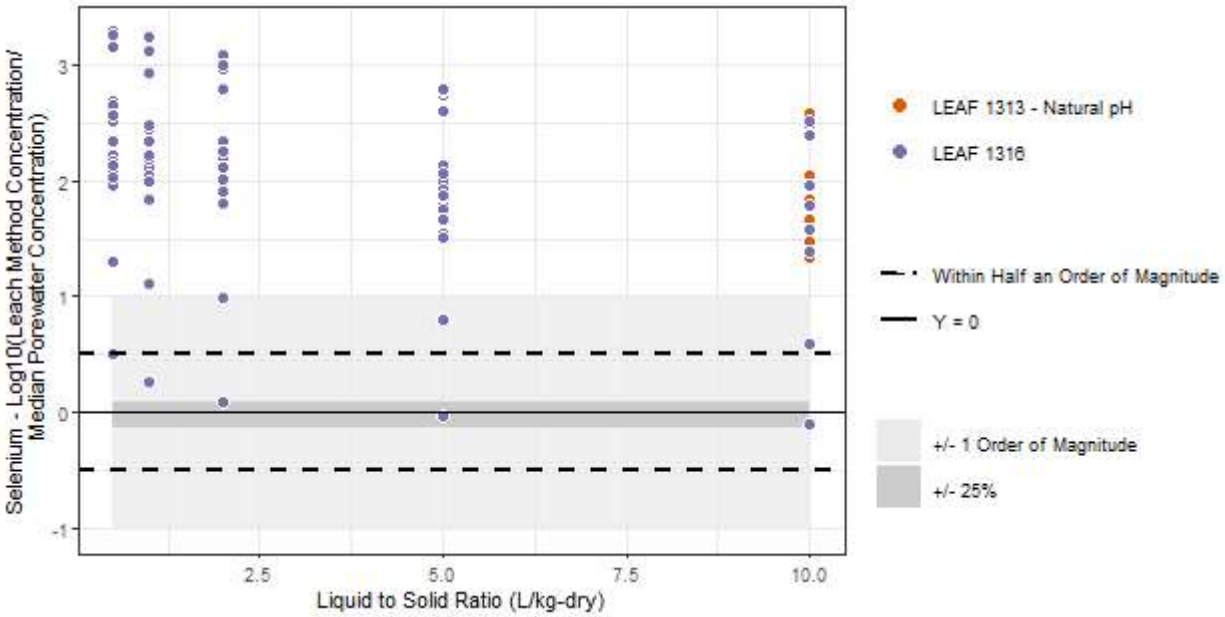

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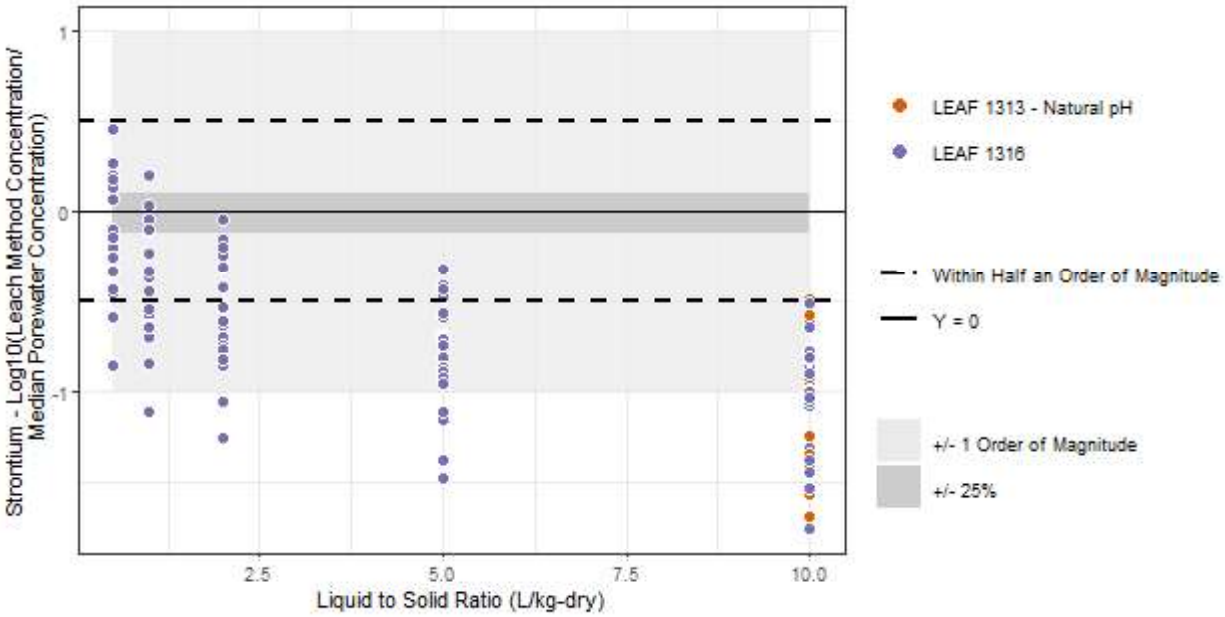

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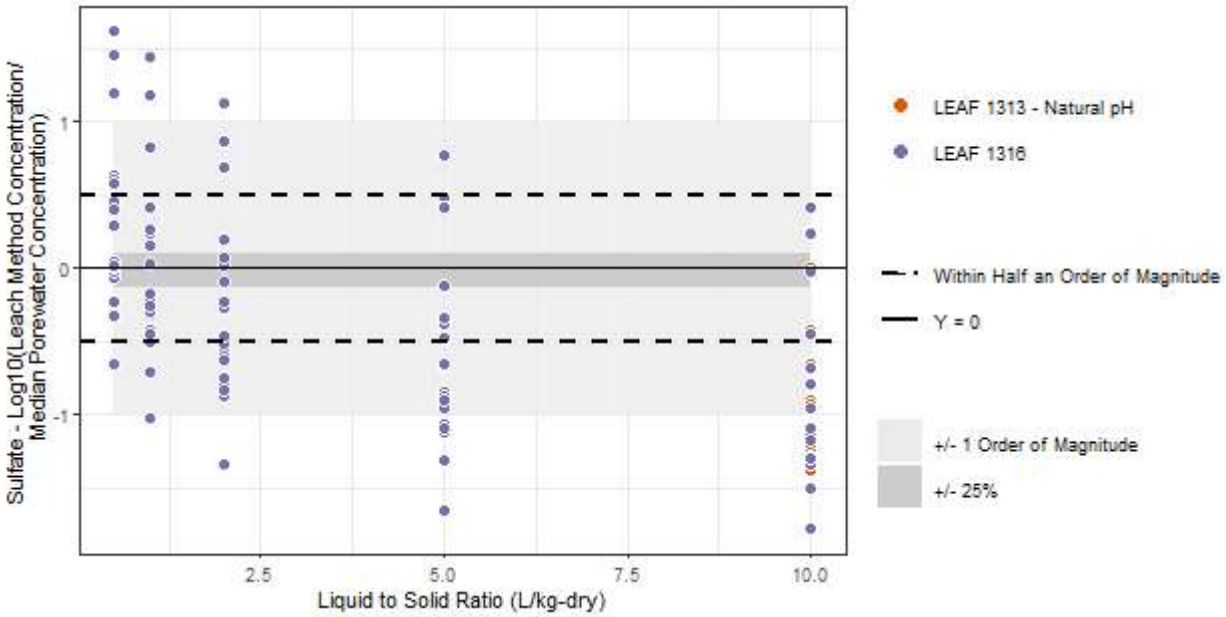

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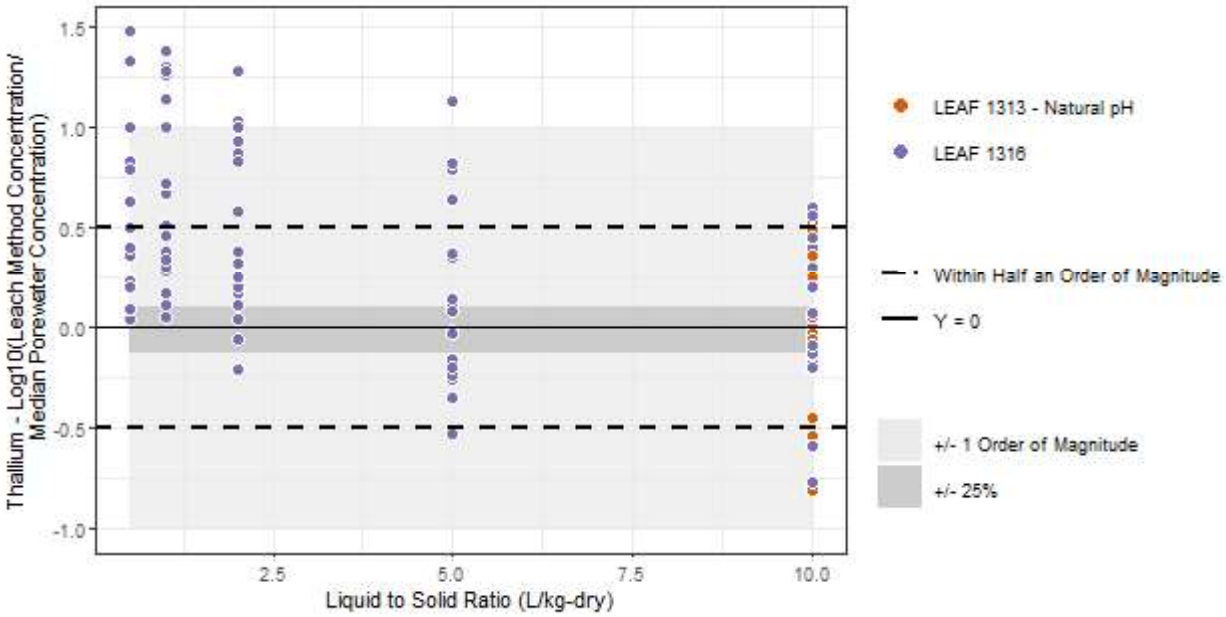

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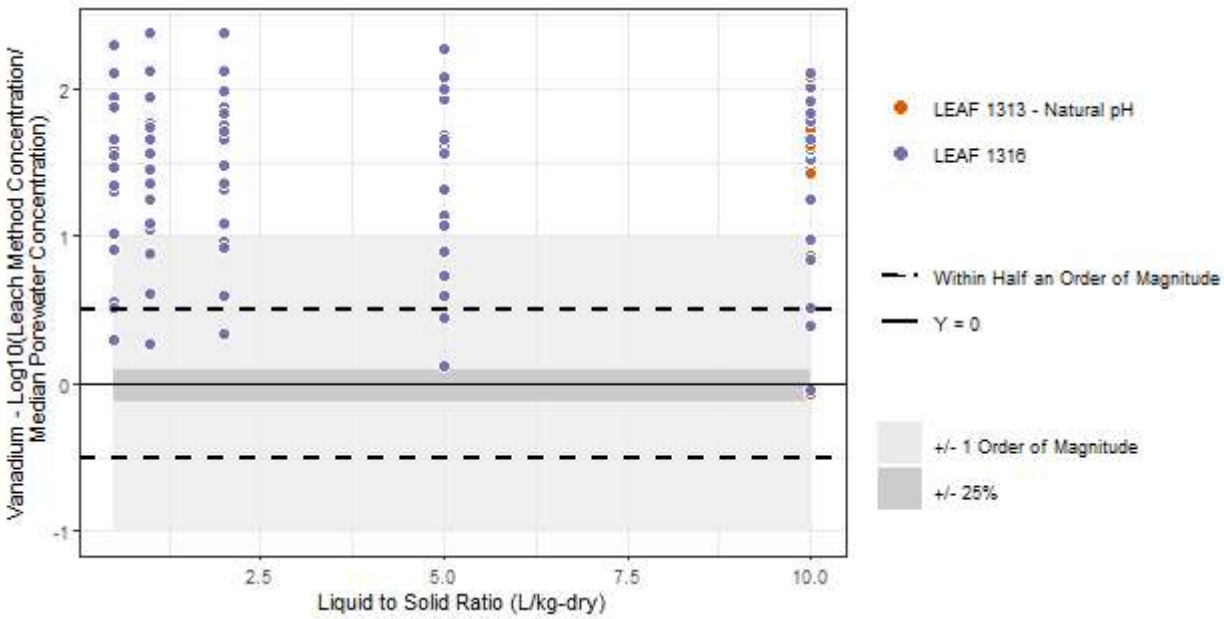

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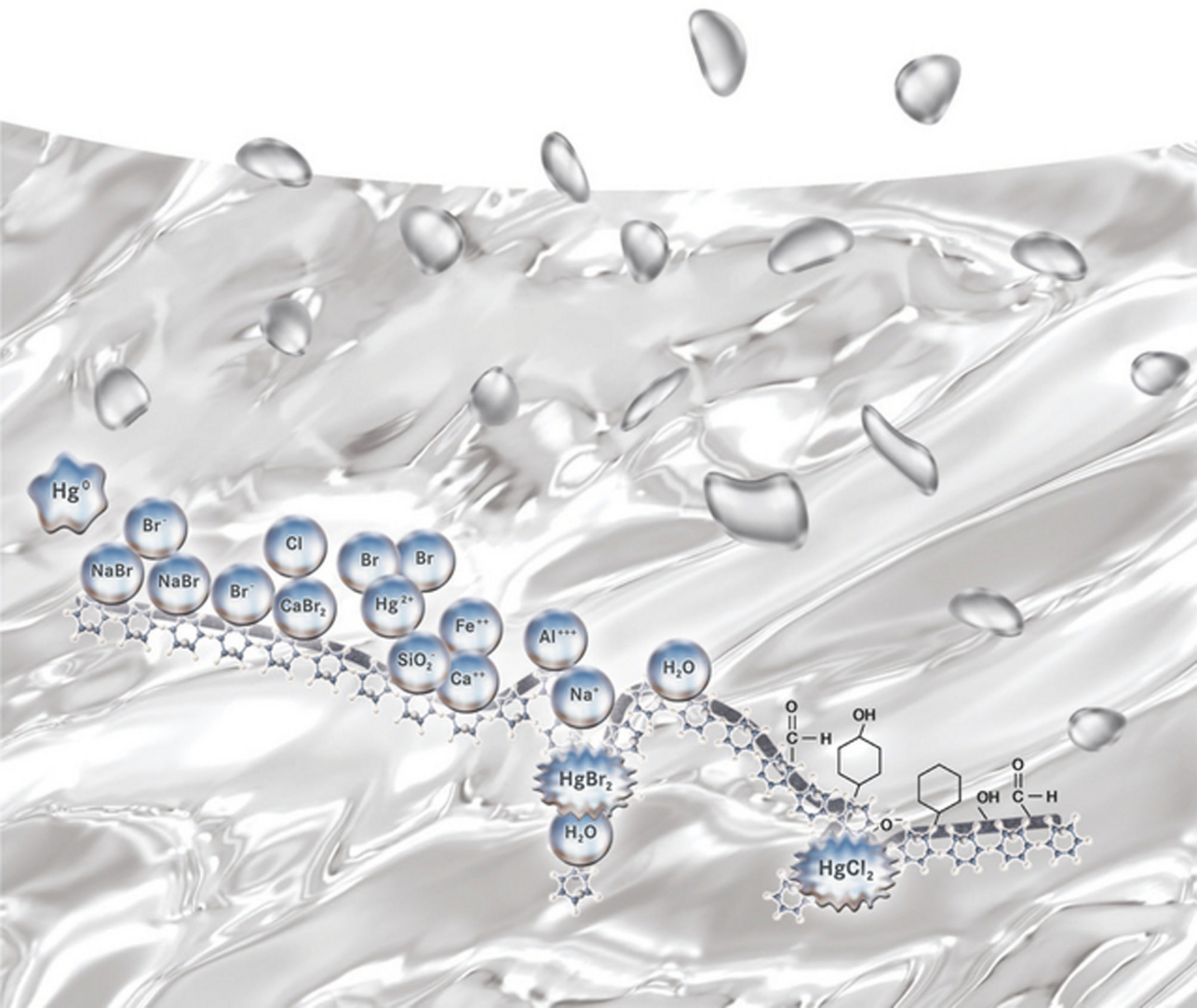

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Mercury R&D Book Foreword

This book is very timely and important, because as I write this foreword, the U.S. Environmental Protection Agency (EPA) is finalizing the first mercury emission limitations on coal-fired power plants, known as the *Mercury and Air Toxics Standards* (*MATS*) rule. This regulation will require significant reductions of the amount of mercury (and other chemicals) contained in the coal fuel before the flue gas is released into the atmosphere.

The information in this volume has mostly been developed over the past decade, where I was engaged as a front line research manager for one of the largest power companies in the United States, Southern Company, which has many coal-fired power plants in its fleet. I have testified before the U.S. Senate on mercury chemistry and behavior in coal-fired boilers (*http://epw.senate.gov/108th/Monroe_060503.htm*), and have been in a leadership position for the utility industry in several organizations, namely, the Electric Power Research Institute (EPRI), the Coal Utilization Research Council (CURC), and the Utility Air Regulatory Group (UARG). I was the project manager for one of the first full-scale power plant tests of dedicated mercury control, at Alabama Power's Plant Gaston – which won an *R&D Magazine* "R&D 100" award in 2003. The Gaston project involved many of the authors included in this volume, especially Tom Feeley, Ramsay Chang, and Sharon Sjostrom. This is a subject that I know well.

In addition, several authors and I have collaborated on other related mercury studies. One of the most intriguing was the innovative research of the fate of mercury in coal power plant plumes, using first a fixed wing airplane and then an airship for plume sampling. This effort was led by Leonard Levin of EPRI, and included Dennis Laudal (University of North Dakota) and Jeff Ryan (U.S. EPA). Another cooperative effort through EPRI has been the computer modeling of mercury in power plants in two different efforts, led by Constance Senior and Steve Niksa.

The utility industry was taken by surprise with the announcement by the outgoing Clinton administration that it would be subject to a Maximum Achievable Control Technology (MACT) rule for mercury on 14 December 2000. That action kicked the industry into a frantic search for any data or information that could help us develop reliable control technology choices. Notably, EPRI, through the efforts of Ramsay Chang, and the U.S. Department of Energy (DOE)'s National

Energy Technology Laboratory (NETL), had already started working on mercury chemistry and control for coal-fired power plants. The subsequent efforts have largely been successful as an example of a public – private R&D partnership; where the utility industry and the suppliers of technology and materials to the industry worked with the DOE NETL to quickly advance the state of knowledge.

As the R&D progressed, an informal steering group of utility researchers, vendors of hardware and materials, and the U.S. DOE NETL was able to leverage the NETL funding to explore different options for controlling mercury from almost all power plant and coal-type combinations. In the early years of R&D, we found that we knew less and less about mercury chemistry with every new test and discovery, as contradictory results were more the rule.

The editors have assembled an experienced group of authors to make this volume, a "Who's Who's" of mercury research from the United States over the past decade. I feel lucky to have worked with virtually every one of the assembled group, and call most of them close friends. There is no better group of technical professionals to guide you in understanding the issues of mercury in coal-derived gas streams.

The volume is arranged in a logical sequence, beginning with the fate of mercury in the environment, written by Leonard Levin of EPRI. The applicable regulations, both for the United States and the international context, follow along with descriptions of trace elements in coal and the means to measure mercury in gas streams. The heart of the work is presented in the following sections on mercury chemistry, research programs, and the different technology systems that can be used and adapted for mercury control. The important topic of the stability of mercury in the solid coal combustion residues is also addressed next. Finally, the state-of-the-art in mercury modeling, both at the fundamental and process levels, is presented.

This is the manuscript that I – and the whole industry – needed back in 2000, as we contemplated what we would have do to reduce mercury emissions to meet upcoming regulations. It will serve as both a reference for those already engaged in the research and control efforts, and as an invaluable introduction for those just now becoming interested in the subject. I highly recommend it to the technical reader.

October 2014

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Preface

This book has its genesis in a Department of Energy (DOE) Topical Report on "Sorbents for Mercury Removal from Flue Gas" that Henry Pennline asked me to write in 1996. As a new post-doc hired to study sorbents for the capture of mercury, Henry suggested that a thorough literature review and survey would be an excellent way to start. As the topical report progressed and was nearly complete in 1997, I suggested to Henry that we write a book about mercury in flue gas. Henry shot this idea down at the time, correctly stating that we had much more to learn. Henry Pennline has turned out to be the best supervisor, researcher, colleague, and friend I could ever have. He was a little skeptical of my abilities at first, having observed my unusual photographic memory for foods; my suit and tie attire in the laboratory (unusual at DOE); and my dropping a large $25 quartz tube for the micro-balance on my first day on the job. I hope I end up doing something good in my research career to justify Henry's faith in me.

Mercury is a semi-noble metal, with both a fascinating chemistry and numerous applications throughout human history. Coal-derived flue gas and coal-derived syngas are both complex stews containing numerous species and exist over a wide temperature range at pulverized combustion and integrated gasification combined cycle (IGCC) plants, respectively. Having completed a MS thesis on coal gasification, I already knew going into the DOE that one could happily study coal flue gas and syngas for many lifetimes. Being introduced to mercury at DOE, I quickly found a terrific subject, with many wonderful colleagues.

In 1998 I met Dr Constance Senior at DOE in Pittsburgh. Constance was leading a large DOE-funded study on the behavior of the trace elements in coal-fired power plants. She impressed me immediately as a tenacious leader and terrific researcher. Constance exhibited extraordinary leadership – her efforts in corralling a large and diverse group of researchers from industry, academia, and the government resulted in a nearly 800-page report for DOE; a special issue of Fuel Processing Technology on the trace elements in coal-fired power plants in 2000; and a great expansion of our understanding of mercury in flue gas. I had the pleasure of meeting Constance again at the Workshop on Source Emission and Ambient Air Monitoring in Minneapolis in 1999. Despite the fact that I was an unknown post-doc at DOE, she introduced me to many of the researchers at dinner (a large pot of minestrone soup and a gigantic pizza that covered the

entire table) in the Mall of America. I learned a lesson that day from Constance; always be nice to your colleagues. Hopefully I have done this. Dr Senior made Herculean efforts to help this book get completed; she is one-in-a-million.

Our work at DOE has allowed us to meet many wonderful colleagues at venues such as the Annual Mercury Control Technology Meetings that were held in Pittsburgh; the AIChE and ACS National Meetings; the Air Quality Conferences, and the Mega Symposiums. At the joint ACS-AIChE National Meeting held in the spring of 2008 in New Orleans, I recruited Tom Feeley, Ramsay Chang, and Constance Senior to be my keynote speakers on mercury. They did an outstanding job, highlighting a program that had 29 speakers on the various aspects of mercury in coal-derived gases. The idea for the book on mercury, having never left my mind, was revived. In 2009 I came up with a draft outline for this book, and happily in 2010, Dr Julia Stuthe from John Wiley recruited me to organize a book on mercury in coal-derived gases. Having already planned a book, I bent her ears with a 40-page PowerPoint presentation, abstract, and outline over a burrito and spicy chicken tortilla soup dinner in San Antonio during the 2010 AIChE National Meeting. Julia – forgive me. Dr Stuthe has recently left John Wiley, and I wish her great success. Lesley Belfit from John Wiley has done an outstanding job in helping us complete this book.

Coal contains a trace level of mercury of approximately 0.1 ppm. Mercury is a neurotoxin, and can travel long distances once emitted through the stacks of coal-burning power plants. Approximately 30–40% of the electricity in the United States is generated through the combustion of coal. Coal is an abundant resource in the United States – the country has a supply for at least 200 years. The challenge is to utilize the abundant domestic coal for energy independence in environmentally friendly ways.

With the US EPA issuing a national regulation on 21 December, 2011, requiring 91% removal of mercury, and many states already with their own regulations, the need exists for low-cost mercury removal techniques that can be applied to coal-burning power plants. The injection of powdered activated carbon into the ductwork upstream of the particulate control device is the most developed technology for mercury capture. Alternative techniques for mercury capture will also play a role in the near future because of the numerous configurations of air pollution control devices present within the power plants, as well as the many different coals being burned. These methods employ sorbents, catalysts, scrubber liquors, flue gas or coal additives, combustion modification, flue gas cooling, barrier discharges, and ultraviolet radiation for the removal of mercury from flue gas streams. The DOE Mercury Program has been a huge success, spurring development, demonstration, and commercialization of many technologies for the capture of mercury.

The future research needs for mercury control include improved sorbent-flue gas contact, development of poison-resistant sorbents and catalysts, new scrubber additives for retention of mercury within wet flue gas desulfurization

(WFGD) systems, concrete-friendly activated carbons, new continuous measurement methods, by-products research, and development of an ASTM standard laboratory test for sorbent activity for mercury capture.

This book aims to cover the technologies for mercury capture and measurement from coal-derived flue gas. The fate of mercury in the environment, a great motivation for the regulations, research, development, and commercialization of capture and measurement methods, is covered in Chapter 1. The trace elements in coal are detailed in Chapter 2. In addition, the regulatory issues, both in the United States and internationally, are discussed in Chapters 3 and 4. Methods for the detection of mercury in flue gas are covered in Chapters 5 and 6. Later chapters discuss the many methods for mercury control, the various research programs, activated carbon technologies, the cement industry, gasification, mercury carbon surface chemistry, and modeling.

I thank Constance and Henry for their outstanding efforts in making this book become a reality. Constance and Henry took my crude initial outline for the book and greatly improved it. Tom Feeley deserves many thanks for the great success of the DOE Mercury Program, and for supporting our in-house research on flue gas. Gary Stiegel and Jenny Tennant from DOE have been terrific in supporting our efforts in understanding the trace elements in gasification systems. Our authors and colleagues Constance Senior, Henry Pennline, Larry Monroe, Leonard Levin, Allan Kolker, Jeff Quick, Leslie Sloss, Nick Hutson, Denny Laudal, Carrie Yonley, Tom Feeley, Ramsay Chang, Tom Gale, Brian Higgins, April Sibley, Gary Blythe, Joe Wong, Nick Lentz, Sharon Sjostrom, Rob Nebergall, Behrooz Ghorshi, Ed Olson, Karen Uffalussy, Jennifer Wilcox, and Steve Niksa did an outstanding job. They are the leading figures in the mercury capture research, development, demonstration-commercialization communities; and are also terrific colleagues and friends. Some of our authors have been working on the mercury issue for over 20 years.

Finally, I thank Phil and Rita Granite, for interest in mercury, suggestions over the years for techniques for mercury control, and for being terrific parents. The same thanks also go to my brother Larry Granite at Environmental Protection Agency (EPA). Linda Granite has humored me, feigning interest in mercury while we were dating (I bent her ears with papers on sorbents and photochemical removal of mercury on our first date – a steak dinner; despite this she went out with me again!), and has been an angel through the years as my mind is sometimes elsewhere on the topic of mercury. Linda and our daughters Ana and Marissa Granite always provide inspiration.

October 2014

Evan Granite
Pittsburgh, PA

List of Abbreviations

ACI	Activated carbon injection
APCD	Air pollution control device
APH	Air preheater
BAT	Best available technique or technology
BEP	Best environmental practice
CAMR	Clean air mercury rule
CEMS	Continuous emission monitoring system
CFBC	Circulating fluidized bed combustor
CSAPR	Cross-states air pollution rule
CS-ESP	Cold-side ESP
DOE	Department of Energy
DSI	Dry sorbent injection
EC	European Commission
ECN	Economizer
EGU	Electricity generating unit
ELV	Emission limit value
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ESP	Electrostatic precipitator
ESPc	Cold-side electrostatic precipitator
ESPh	Hot-side electrostatic precipitator
EU	European Union
FBC	Fluidized bed combustor
FF	Fabric (or baghouse) filter
FGD	Flue gas desulfurization
GHSV	Gas hourly space velocity
HAP	Hazardous air pollutant
HELCOM	Helsinki Commission
ICI	Industrial, commercial, and institutional
ICR	Information collection request
IED	Industrial Emissions Directive
IPPC	Integrated pollution prevention and control
L/G	Ratio of volumetric flowrates of liquid to gas in WFGD

LCPD	Large Combustion Plant Directive
LNB	Low NOx burner
LOI	Loss on ignition
LRTAP	Long-range transboundary air pollution
MATS	Mercury and air toxics standards
MEPOP	Mercury and persistent organic pollutants
MW	Megawatt
NARAP	North American regional action plan
NEPM	National Environmental Protection Measures (Australia)
NERP	National Emission Reduction Plan
NETL	National Energy Technology Laboratory
NHMRC	National Health and Medical Research Council (Australia)
NPI	National Pollutants Inventory
OFA	Overfire air
OSPAR	Oslo and Paris Commission
PAC	Powdered activated carbon
PCD	Particulate control device
PM	Particulate matter
SCEM	Semi-continuous emissions monitor
SCR	Selective catalytic reduction
SDA	Spray dry absorber for flue gas desulfurization
SED	Solvent Emissions Directive
SNCR	Selective non-catalytic reduction
SO_2	Sulfur dioxide
TOXECON	Advanced sorbent injection configuration licensed by EPRI
UBC	Unburned carbon
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
WFGD	Wet flue gas desulfurization
WID	Waste Incineration Directive
XAFS	X-ray absorption fine structure
XPS	X-ray photoemission spectroscopy

Part I
Mercury in the Environment: Origin, Fate, and Regulation

Mercury Control: for Coal-Derived Gas Streams, First Edition.
Edited by Evan J. Granite, Henry W. Pennline and Constance Senior.
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1
Mercury in the Environment

Leonard Levin

1.1
Introduction

Mercury is a naturally occurring chemical element found ubiquitously throughout both the natural and human environments. Mercury occurs throughout the earth's crust and is most commonly found in its geological occurrence as the mineral cinnabar (mercuric sulfide, HgS_2). Elemental mercury, the uncombined form, occurs at room temperature and sea level pressure as a liquid, the only chemical element so occurring. Due to its relatively high vapor pressure, liquid mercury will evaporate readily into the atmosphere.

Elemental mercury can be oxidized to the mercurous (Hg^{1+}) or mercuric (Hg^{2+}) inorganic form in the presence of hydroxyl radicals, ozone, or a number of other oxidizing agents. The more commonly occurring mercuric form readily recombines into either water-soluble forms, such as with halogens (e.g., $HgCl_2$), or insoluble salts (HgS_2).

Surface exposure of geological mercury minerals or elemental mercury concentrations led to the presence of both elemental and inorganic mercury in the global atmosphere, even prior to its enhanced release due to human activity after the onset of the Industrial Revolution (mid-eighteenth century). Indeed, this ubiquity of mercury, and its uptake by fauna via leaf stomata and root systems, leads to its association with fossil fuels such as oil and coal. These fuels derive from burial and metamorphosis of plant matter under anoxic conditions via stages starting with peat formation. Core sampling of peat formations in Arctic Canada by Givelet *et al.* [1] has shown transitory excursions of mercury deposition dating from before 1700 CE attributed to wildfires set by First Nations for land clearing.

One feature of interest to investigators is the relative increase in abundance of mercury in the environment from the pre-Columbian era to the present day, due to human mobilization of the substance. This mobilization has occurred in several ways, but primarily through either direct use of mercury in products or via combustion-related emissions of fuel-associated mercury. The use of elemental mercury in medical and consumer products has occurred over hundreds of years, in such instances as the forming of pelts and felts into chapeaux and

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its use in electric switches. Fuel-associated mercury continues to be released globally in the production of power, space and process heat, process steam, and other uses.

This relative increase in global mercury cycling in the modern era can be determined by comparing mercury concentrations at both deep and shallow depths in cores of glacial ice or lake sediments, or by comparing global source inventories of mercury. In the case of inventory comparisons, the modern: preindustrial ratios are derived from separately calculating emission rates from undisturbed natural background sources (exposed mercuriferous deposits, surface, and undersea volcanism) with the total of those sources and human sources (atmospheric evasion from inactive mining sites, mineral recovery sites, point and area fuel combustion sources, and waste sites).

Each such method has both advantages and disadvantages. Core samples can represent localized conditions (e.g., lensing of lake sediments), while global inventories are subject to large uncertainties due to spatial scaling of local measurements, inaccurate extrapolation to unmeasured sources, and so on. Generally, results indicate that, globally, there is roughly three to four times as much mercury cycling through the biogeochemical and human environment currently as there was in pre-Columbian times (see Figure 1.1) [2]. This modern: preindustrial ratio, however, is a global average. There are many individual experimental samples in ice cores, peat bogs, lake-bottom sediments, and other environments globally exhibiting much higher ratios. For example, Schuster *et al.* [3] found a 20-fold enhancement ratio in ice core data from the Lower Fremont Glacier, Wind River Mountains, Wyoming, USA.

The atmospheric lifetime of vapor-phase elemental mercury is believed to be roughly 7–12 months, in bulk, although the mean lifetime of reactive oxidized mercury is more likely measured in days to weeks. Atmospheric oxidized mercury may undergo chemical reduction to the insoluble gaseous elemental form, or may be removed from the atmosphere by solution in precipitation or by dry deposition to the earth's surface.

Mercury concentrations in the planetary boundary layer appear to react to changes in global input within months to years (see, for example, [5]). There is a much longer period for aquatic systems to fully react to changes in mercury input via deposition and runoff, but this is somewhat dependent on the trophic depth of the ecosystem involved. Large piscivorous fish represent multiyear mercury reservoirs whose body burden of mercury (primarily as methylmercury) acts as multiyear transfers of an integrated record of mercury exposure from their feeding patterns.

1.2
Mercury as a Chemical Element

Mercury is a chemical element (atomic number 80, isotope-weighted atomic mass 200.59 amu) known as a *distinct substance* since the earliest days of civilization.

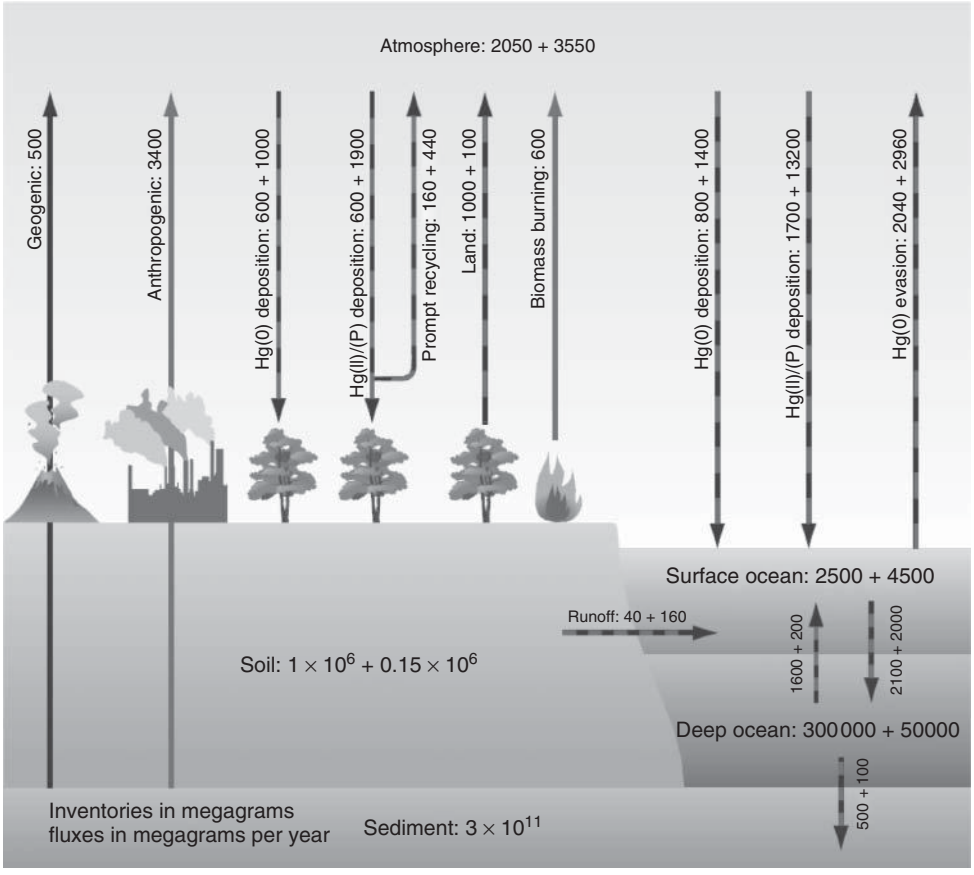

Figure 1.1 Global biogeochemical cycle for mercury. Natural (preindustrial) fluxes (megagrams (Mg) per year) and inventories, in megagrams, are noted in black. Anthropogenic contributions are in gray. Natural fluxes augmented by anthropogenic activities are noted by gray-and-black dashed lines. (Modified from Selin *et al.* [4].) A mean enrichment factor of 3 between the preindustrial and present-day mercury deposition, based on remote sediment cores, is used as a constraint. (Figure from Selin [2] © 2009 by Annual Review.)

The Greek word for mercury, Υδραργυρος, means "water + silver." This was adapted into the Latin hydrargyros, for "water – silver." Both terms refer to the morphology of pure elemental mercury at room temperature, a silvery liquid, and the only chemical element occurring in pure form as a liquid at ambient temperatures.

The abundance of naturally occurring stable isotopes of mercury is shown in Table 1.1 [6]. In addition, several unstable isotopes of mercury are known. One of these, 203Hg, is commonly used as a spiked tracer in, for example, experiments on mercury methylation in aquatic systems [7].

Table 1.1 Background natural abundance of stable mercury isotopes.

Isotope	^{198}Hg	^{199}Hg	^{200}Hg	^{201}Hg	^{202}Hg	^{204}Hg
Abundance (%)	10	17	23	13	30	7

1.2.1 Physical and Chemical Properties of the Forms of Mercury

A key variable of mercury and its chemically combined forms is its vapor pressure. The vapor pressure is of interest because one form of transference of mercury from the earth's surface to the overlying atmosphere is evasion, or net positive flux into the atmosphere [8].

1.2.2 Associations with Minerals and Fuels

Mercury is typically found in association with fossil fuels: coal, petroleum, and natural gas. Mercury associated with coal deposits ranges globally from 0.02 to 1.0 ppmw [9]. This range is similar to that found for the occurrence of mercury in background topsoil samples (<0.01 – 4.6 ppmw, [10]). Mercury association with coal is thought to be via diagenesis in coalbeds [11, 12]: during metamorphic processes, inclusions of pyritic minerals into coalbed fracture zones have brought with them mercury inclusions. This is in opposition to the obvious association of naturally occurring atmospheric mercury in surface vegetation later incorporated into sedimentary precursors to coalbed seams. The pyritic association of mercury in coal is primarily evident in bituminous and anthracite seams, while subbituminous and lignite coals tend to have mercury associated with organic constituents, perhaps the remnant of mercury ligands in surface vegetal deposits. The pyrite association is borne out by concentration enrichments of ~×100 in analyses of pyrites from coal versus the concentrations in whole coal samples.

1.3 Direct Uses of Mercury

Mercury in medical treatment: Mercury in various chemical forms has long served as an artisanal medical treatment. Although liquid mercury is still used in scattered applications in the United States, it was more widely used in the early twentieth century for treatment of venereal disease; one documented example is the syphilis treatment of Karen Blixen ("Isaac Dinesen," *Out of Africa*) in Kenya by prescription of mercury pills [13]. Chinese herbal balls, with recommended doses of two balls swallowed per day, have been found to have mercuric sulfide added to

Table 1.2 Total mercury sold in pumps in the United States (pounds).

2001 Total mercury	2004 Total mercury	2007 Total mercury
12 745 (6.4 ton)	13 911 (7.0 ton)	10 383 (5.2 ton)[a)]

a) *http://www.newmoa.org/prevention/mercury/imerc/factsheets/pumps.cfm#4*
Source: NEWMOA [19].

their composition [14]. The daily dose of mercury can amount to 1200 mg. For a 70 kg consumer, this dose is equivalent to nearly 200 000 times the Environmental Protection Agency (EPA) mercury Reference Dose of 0.1 $\mu g\,kg^{-1}\,day^{-1}$. More common uses of mercury have been in medical devices such as thermometers and sphygmomanometers; in the latter case, replacement of these devices where mercury is employed by aneroid or digital versions has produced problematic intercomparisons of readings [15].

Mercury in products: Mercury, particularly elemental mercury in liquid form, has often been directly used in consumer and industrial products and processes. In the United States, this was particularly the case for its use in batteries and switches [16]. Another common use was as a conductor in quiet mercury switches, which were commonly used in natural gas and petroleum distribution lines [17]. These uses have dropped significantly in recent years (Table 1.2). One of the last remaining large consumer uses for mercury is in fluorescent lamps, including compact fluorescent lamps (CFLs), each of which typically contains several milligrams of mercury [18].

1.4 Atmospheric Transport and Deposition

The concentration of mercury in ambient air is on the order of 1 – 5 ppt. Most of this occurs as gaseous elemental mercury (GEM), especially above the atmospheric boundary layer, although trace levels of the divalent form and even methylmercury have been measured [20]. A recurring public fallacy is that, as mercury is classified as a "heavy metal," [21, 22], the substance "falls out of the sky" quickly upon being emitted to the atmosphere. Because the mercury from heated elevated sources disperses in the atmosphere, gravitational settling at the atomic or molecular level does not play a role in mercury dynamics – except for particulate-bound mercury (Hgp, primarily HgII bound to crustal and combustion particles), where particle deposition velocities do play a role. The high vapor pressure of elemental mercury serves to disperse it widely so that atmospheric turbulence keeps GEM in the atmosphere for a lifetime of 7 – 16 months (e-folding time). This long lifetime in the free troposphere classifies mercury, particularly elemental mercury, as a global pollutant [23].

1.5 Atmospheric Reactions and Lifetime

Mercury released to the atmosphere from natural sources, such as volcanoes or mercuriferous crustal deposits, is generally in the form of elemental mercury (Hg^0), commonly termed *gaseous elemental mercury* in its atmospheric occurrence. Anthropogenic emissions are, in general, a mix of GEM and divalent mercury (Hg^{II}), referred to as *reactive gaseous mercury* or *RGM* in its atmospheric occurrence. The lifetime of mercury species in the atmosphere is bounded by the reaction and removal rates of the two primary species, GEM and RGM. The oxidation of GEM to RGM by ozone, O_3, has been studied by many investigators. An important removal mechanism for RGM is due to its relatively high solubility in precipitable water. Calvert and Lindberg [24] concluded that the single-stage reaction $Hg + O_3 \rightarrow HgO + O_2$ was less likely to occur than an intermediary unstable molecule HgO_3, decaying to OHgOO, and then decomposing into $HgO + O_2$. Further removal reactions have been investigated; one such process, the oxidation of Hg^0 by hydroxyl radical, OH, was found by Goodsite *et al.* [25] to be a relatively unimportant step.

The atmospheric lifetime (average residence time) of GEM is normally assumed to be 7–15 months. Work by Selin *et al.* [4] tried to refine these numbers into the contributing factors: removal by dry deposition; oxidation to RGM by homogeneous- and heterogeneous-phase reactions in the atmosphere; additions by reduction reactions of RGM in the upper troposphere/lower stratosphere (UTLS); and evasion of GEM from surface reservoirs. Each of these processes is still poorly understood, particularly the subsidence and transport of UTLS mercury forms. The reservoir of RGM just above the tropopause plays an important role in nighttime subsidence peaks of RGM in the lower troposphere [26] and in Arctic mercury depletion events (AMDEs) [27].

1.6 Mercury Biogeochemical Cycling

Once deposited to the earth's surface, mercury may undergo a complex series of reactions that may result in one or more steps in its biogeochemical cycling: being re-evaded to the atmosphere, bound to organic compounds in the terrestrial understory; dissolved in seawater and removed by binding to marine "snow" [28].

One important study of mercury dynamics in an aquatic watershed was the Mercury Experiment to Assess Atmospheric Loading in Canada and the United States (METAALICUS) experiment [29]. During the METAALICUS experiment, solutions of mercuric chloride, each "tagged" with elevated concentrations of a different naturally occurring stable isotope of mercury, were deposited in segments of a test watershed in Ontario, Canada. This isotope spiking allowed tracing of the rate and partitioning of mercury introduced into each watershed compartment to be traced over both time and space. The isotope spikes were introduced into the

upland and wetland compartments as simulated precipitation: using fixed-wing aircraft, solutions of isotope-spiked $HgNO_3$ were distributed over each compartment just prior to or during periods of rainfall in the area. The wetland and upland spikes were added yearly for 3 years. The waterbody spike was applied by a small boat cruising a crisscross pattern on the lake itself; the water surface applications occurred every 2 weeks during the open-water seasons.

METAALICUS results from the first 3 years of the study showed that mercury movement from the application compartments (surfaces of wetlands, uplands, and waterbody) to sequestration in soils and sediments, respectively, was still underway at the end of the application period. Upland spike mercury was, by that time, preferentially found (areal mass distribution) in the underlying soil, but still progressing from the surface vegetation exposed to the original spike application. Wetland spike mercury exhibited the opposite distribution: that addition was still predominantly in the lowlands vegetation than in the underlying peat. Overall, there was a 2–5% increase in peat, soil, and sediment mercury concentrations from the 3 years' additions.

Lake water column mercury showed an overall 53% increase in concentration due to the introduction of the lake spike itself, while the upper layer of lake-bottom sediments revealed a 5% concentration increase. Since Lake 658 communicates with an adjacent shield lake via a narrow weird outflow, a 5% portion of the spike was itself lost through the outflow. The researchers estimated that 25–30% of the wetland and upland spikes, and 45% of the lake spike, were lost to the atmosphere via evasion over the 3-year period.

The METAALICUS findings are significant in several regards. As the only whole-ecosystem mercury study to date, the experiment demonstrates once more the relatively slow response of lake bodies to changes in atmospheric deposition. The authors conclude that lakes receiving all of their new mercury via deposition, such as perched seepage lakes, might respond to step changes in deposition (such as were simulated by the spike additions) over about a decade; that is, a proportional change in water column mercury to the deposition step would require that period of time to be reached. For drainage lakes, a longer adjustment period can be expected.

Additionally, the findings concerning evasion losses are a critical experimental check on assumptions used in mercury modeling. Generally, regional and global models of mercury assume a prompt re-emission of 50% of deposited mercury (see, e.g., [30]). This re-emitted or evaded mercury is the primary contributor to what is generally termed the *grasshopper effect* [31]: successive deposition and re-emission of mercury from lower to higher latitudes (down-gradient transport), leading to a successive and relatively high build-up rate of mercury (and other pollutants) in high temperate and boreal regions. The experiment at Lake 658 reveals that this effect is probably dominated by evasion from oceans and water bodies rather than terrestrial environments, and so is limited by the sum of deposition to and native mercury emissions from those marine and aquatic environments.

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2
Mercury and Halogens in Coal

Allan Kolker and Jeffrey C. Quick

2.1
Introduction

2.1.1
Mode of Occurrence of Mercury (Hg) in Coal

In bituminous coals, the iron disulfide, pyrite and its FeS_2 polymorph, marcasite, typically host the greatest fraction of Hg present [1–8], with lesser fractions of Hg associated with organic matter and with non-FeS_2 mineral hosts. Evidence for the occurrence of Hg and other trace metals in Fe disulfides in coal is reviewed by Kolker [9], including crystal chemistry and controls on element substitution in Fe disulfides and available data on Hg concentrations from direct determinations by microanalysis. In cases where individual Fe disulfide grains in coal have been analyzed, Hg contents are in the tens to hundreds of times those in the whole coal. But assuming that pyrite-rich coals are necessarily Hg-rich coals is an oversimplification. A good example to the contrary is the U.S. bituminous Illinois #6 coal. This commercially important coal has relatively high contents of total and pyritic sulfur widely attributed to marine influence, but low to moderate Hg (and As) contents [10–12], as the extent of substitution in Illinois #6 pyrite by impurities is relatively small [7, 12–14].

In low-rank coals, including lignite and subbituminous coals, Hg and S contents are generally lower overall than in bituminous coals, and the proportion of Hg occurring in association with organic material is greater [2, 15]. From the standpoint of Hg capture, compared to bituminous coals, the lower overall Hg content of low-rank coals is offset by the tendency of these coals to also have lower halogen contents, and, because of their lower calorific value, the requirement that greater amounts of low-rank coal are needed to achieve an equivalent energy output.

As shown elsewhere in this volume, the form of Hg in feed coal does not impact Hg speciation at boiler temperatures. In the furnace, Hg is present in the elemental form but it can combine to form compounds as the flue gas cools. Knowledge of the mode of occurrence of Hg in coal has important implications for the extent to

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which pre-combustion Hg control might be possible (following section), whereas the halogen species present influence post-combustion Hg capture.

2.1.2 Effectiveness of Pre-Combustion Mercury Removal

Three approaches, coal preparation, selective mining, and upgrading low-rank coals by drying, offer the potential to reduce Hg input to the boiler. A detailed review of each is beyond the scope this chapter, but some of the major factors influencing the effectiveness of pre-combustion removal are highlighted in this section.

For coal preparation, the major factors influencing its effectiveness in Hg reduction are the mode of occurrence of Hg in coal, its particle size, and the approach taken in preparation. For bituminous coals having pyrite as the primary mineralogic host of Hg, preparation by density separation, such as in a heavy media cyclone, is more likely to be effective than methods that depend on differences in surface characteristics, such as froth flotation, because coal and pyrite have similar surface characteristics [16, 17]. Grain size is especially important in multistage preparation circuits because gravity concentration is the dominant cleaning method for coarse and intermediate size fractions of coal, whereas flotation is the dominant method for cleaning fine size fractions [18]. Where pyrite occurs primarily as framboids, their fine grain size (typically 10 μm) and presence of interstitial voids filled with non-pyrite material may make them especially difficult to remove by coal preparation. Low-rank coals having a greater fraction of organically bound Hg than bituminous coals are also less likely to be responsive to coal preparation for Hg reduction. Recent studies by Wang *et al.* [19, 20] show significant degrees of removal of Hg and/or associated elements in large-scale preparation plants processing Chinese coals. Huggins *et al.* [14] determined element concentrations, and modes of occurrence by spectroscopic methods, for a range of major and trace elements in fractions of an Illinois #6 coal produced by physical separation at a preparation plant. For Hg, results show a 25% reduction on a weight concentration basis for the cleaned product relative to the feed coal, with corresponding enrichment in the reject fractions. These investigations follow from previous work showing the effectiveness of coal preparation in reducing air toxics as a co-benefit to reducing ash and increased calorific value (e.g., [21–24]).

Effective reduction of Hg by selective mining requires characterization and analysis of the coal beds being mined. This approach has been used to better define the spatial distribution of Hg variation in bituminous coals of the Illinois Basin in Indiana, USA [25, 26], in the Appalachian Basin of eastern Kentucky, USA [27, 28], and in subbituminous coals of western Canada [29]. Where Hg is concentrated by geologic processes, such as along fault-controlled zones of mineralization, or controlled stratigraphically, such as by incursion of marine waters, detailed characterization can be effective in delineating Hg-rich zones to avoid in mining operations.

Various thermal pretreatment processes have been proposed or are in place for low-rank coals, for the purpose of enhancing power plant performance [30–32]. Thermal pretreatment can have the co-benefit of Hg reduction, as reported by Merriam [33] for a Powder River Basin subbituminous coal and subsequently, by Guffey and Bland [34], for a Powder River Basin coal, and a North Dakota lignite. These studies show Hg removals in the 70–80% range with heating of both coals to temperatures ranging from 150 to 290 °C. Mercury driven from these coals primarily enters the gas stream of the process.

2.1.3 Methods for Mercury Determination

Sub-parts per million levels of Hg in coal require methods with adequate sensitivity, but generally do not require the most sensitive methods used for low-level determinations of Hg in the environment ([35], this volume). The two methods most widely employed for analysis of Hg in coal are cold vapor atomic absorption spectrometry (CVAA; [36, 37]), and thermal decomposition, amalgamation, and atomic absorption spectrophotometry, otherwise known as direct mercury analysis (DMA; [38]). Mercury concentrations normally encountered in coal are well within the working range of either method. DMA has gained acceptance in recent years because sample digestion, required in CVAA analysis, is not necessary. In U.S. Geological Survey (USGS) databases discussed in this chapter, Hg data obtained before about 2005, including coal quality (COALQUAL) [11] were obtained by CVAA. Results for international coals in the World Coal Quality Inventory (WoCQI, [39]) include data obtained by both methods, depending on the date of sample acquisition.

Other methods that have been used to determine Hg in coal include instrumental neutron activation analysis (INAA; [10, 40]) and cold vapor atomic fluorescence spectrometry (CVAFS; [41]). INAA can be used directly on small samples, but requires sample irradiation by neutrons at a reactor facility and subsequent counting of gamma rays emitted at the energies of radionuclides present [40]. CVAFS offers better detection limits than either CVAA or DMA, with the potential to obtain higher precision total Hg results than by the other two methods. However, CVAFS has not been widely employed because low-level determinations in the parts per billion range are generally not required for coal. Furthermore, because total mercury contents are controlled to a large degree by Fe disulfide minerals, sample heterogeneity, especially in pyrite content, can result in total Hg variations for different sample splits that are larger than analytical uncertainties by CVAFS. Other methods for Hg analysis of coal have been used in specific applications. For example, multicollector inductively coupled plasma mass spectrometry (ICP-MS) methods with cold vapor Hg generation have been used in recent studies to determine variations in the natural Hg isotopic composition of coal [42, 12]. Synchrotron-based determinations of element speciation by X-ray absorption fine structure (XAFS), which have been very useful for As in coal, have limited applicability for Hg as only the most unusually Hg-rich coals

have sufficient Hg to apply this method (F.E. Huggins, personal communication, 2012) [43].

2.2 Mercury in U.S. Coals

2.2.1 U.S. Coal Databases

Three large databases, described here, and several smaller ones, provide detailed information on the Hg contents of U.S. coals. These are (i) the 1999 U.S. Environmental Protection Agency (EPA) Information Collection Request (ICR) database [44], (ii) the 2010 EPA Utility MACT ICR (MACT, maximum achievable control technology) [45, 46], and (iii) an extensive USGS database known as COALQUAL [11]. Each database provides coverage for a wide range of U.S. commercial coals, but with somewhat different emphases. The two EPA databases emphasize Hg contents of coals delivered to U.S. utility power stations, whereas the COALQUAL database reflects the composition of coal in the ground. As noted by Quick *et al.* [47], in a comparison of the COALQUAL and 1999 ICR data, sample frequency in these databases is not production weighted and therefore, mean values for each database are not accurate indicators of the Hg content of either in-ground or delivered U.S. coal. The databases nonetheless provide useful comparisons with international coal sample databases in which large numbers of samples are compiled and averaged.

2.2.1.1 USGS COALQUAL Database

The USGS COALQUAL database consists almost entirely of results for coal samples collected or calculated to represent the entire thickness of a coal bed in the ground [48, 11]. The COALQUAL data include analytical results for 7432 coal samples collected from 399 counties in 33 U.S. states. Up to 136 data fields listing the sample type, location, and assay results are included for each sample record. Nearly all records have complete proximate and ultimate assays as well as major, minor, and trace-element values. Excluding weathered coal and samples from non-producing counties, COALQUAL contains records for 4566 samples originating from 170 of the 198 counties that produced coal during 2009 (see comparison of databases). Most of the samples were collected as whole-bed or bench samples from working mines. These samples give an arithmetic mean of 0.17 ppm Hg ([48]; Table 2.1), almost twice the mean Hg content in the 1999 EPA ICR for coals delivered to utilities (following section). The difference in mean Hg contents between the USGS and EPA databases is a consequence of (i) COALQUAL data include the portion of Hg that is removed by coal preparation and (ii) compared to current U.S. coal production, in which the Power River Basin is the largest single producer, COALQUAL is weighted heavily toward eastern U.S. bituminous coals, with nearly 60% of its samples from the Appalachian Basin.

Table 2.1 Comparison of mercury, halogen, and trace-metal content of coal samples in the COALQUAL, 1999 ICR, and 2010 ICR data.

	Parts per million, ppm (dry)												
	Cl	F	Hg	Sb	As	Be	Cd	Cr	Pb	Mn	Ni	Se	Co
COALQUAL *4 566 in-ground samples*													
Maximum	8 200	4 900	2.90	35.0	2200.0	18.0	150.0	190	1 900	1 100	190.0	150.0	180.0
Average	**633**	**102**	**0.17**	**1.3**	**28.6**	**2.2**	**0.19**	**15**	**9.2**	**31**	**14.6**	**3.0**	**6.1**
Median	360	60	0.11	0.8	9.4	1.9	0.07	13	5.9	17	12.0	2.4	4.8
Apparent detection limit	140	14	0.02	0.2	0.3	0.2	0.05	1	1.7	2	1.2	0.6	0.7
Number of records	3 161	4 557	4 564	4 555	4 546	4 469	4 559	4 548	4 564	4 561	4 561	4 543	4 545
% below detection limit	29	7	7	5	1	2	29	1	9	1	1	6	2
1999 ICR *37 916 shipment samples*													
Maximum	11 000	—	1.30	—	—	—	—	—	—	—	—	—	—
Average	**820**	—	**0.11**	—	—	—	—	—	—	—	—	—	—
Median	628	—	0.09	—	—	—	—	—	—	—	—	—	—
Apparent detection limit	50	—	0.02	—	—	—	—	—	—	—	—	—	—
Number of records	37 916	—	37 916	—	—	—	—	—	—	—	—	—	—
% below detection limit	13	—	1	—	—	—	—	—	—	—	—	—	—

(*continued overleaf*)

Table 2.1 (*Continued*)

	Parts per million, ppm (dry)												
	Cl	F	Hg	Sb	As	Be	Cd	Cr	Pb	Mn	Ni	Se	Co
2010 ICR part 2 *13 968 shipment samples*													
Maximum	4 900	300	0.95	5.4	96.7	6.8	14.2	99	77.2	484	161.0	9.9	26.8
Average	**980**	**90**	**0.12**	**1.0**	**9.5**	**1.5**	**0.32**	**16**	**7.6**	**29**	**14.1**	**2.5**	**5.5**
Median	965	88	0.11	1.0	5.7	1.3	0.14	17	7.1	20	13.7	2.2	5.0
Apparent detection limit	—	—	0.04	1.0	1.0	2.0	0.20	—	2	—	—	1.0	—
Number of records	3 507	994	13 130	901	1 265	845	978	1 031	1 120	914	1 030	1 045	749
% below detection limit	—	—	1	26	5	3	22	0	6	0	0	11	0
2010 ICR part 3 *1 590 feedstock samples*													
Maximum	3 600	320	0.97	50.9	167.0	2.9	10.2	85	77.3	326	155.7	36.9	42.5
Average	**576**	**74**	**0.12**	**1.1**	**6.7**	**0.8**	**0.35**	**14**	**7.8**	**31**	**11.7**	**2.4**	**5.1**
Median	355	66	0.08	0.8	3.0	0.5	0.13	10	5.5	16	9.0	1.1	3.4
Apparent detection limit	10	45	0.02	2.0	1.0	1.0	0.40	5	2.0	0.1	10.0	1.0	1.0
Number of records	1 253	1 001	889	684	868	883	877	903	903	912	892	844	798
% below detection limit	7	7	4	48	17	18	44	3	6	3	3	32	11

Bold values — Averages of multiple analyses

COALQUAL: Compiled data exclude weathered coal as well as samples from counties that did not produce coal during 2009. Non-detects are reported in COALQUAL as 0.7 times a detection limit, but the actual detection limit and affected records are not identified. Instead, the percent of affected records for each element (called *qualified* data within COALQUAL) is noted in text that accompanies the data. We used this percent value to identify the apparent detection limit from the corresponding percentile distributions.

1999 ICR: Compiled data exclude non-coal fuels but include waste coal. We estimated the apparent detection limit as the median value of all values reported with a < symbol.

2010 ICR: Compiled data exclude duplicate records and non-coal fuels, but include waste coal. Values annotated with a < symbol were multiplied by 0.5 and included in the compilation. We estimated the apparent detection limit as the median value of results reported with a < symbol. The 2010 ICR part 2 data collection did not identify the Cl and F values that were below detection limits.

Whereas the EPA ICR databases are more representative of current U.S. steam coal production, COALQUAL is nonetheless useful as a reference in comparing U.S. and international coal samples, especially for the in-ground state.

2.2.1.2 1999 EPA ICR

The 1999 ICR coal quality data [44] Originated from an ICR issued by the EPA to inform its Section 112 rulemaking to regulate Hg emissions from electric utility steam generating units. The EPA required units of 25 MW or more to report coal origin, as well as dry-basis tonnages, ash, S, and heating value for every solid fuel shipment received during 1999, and to periodically report fuel Hg and Cl content. This systematic data collection effort produced analyses for 152 476 samples, which are available in four quarterly EXCEL files on an EPA website [44]. Excluding non-coal fuels and records without Hg or Cl values, the 1999 ICR includes results for 37 916 coal samples. Limitations of these data include erroneously low Hg values for most Gulf Coast coal, coal shipments of unknown origin (14% of records), inconsistent reporting bases (8%), and duplicate or nominal data (4%; [49]). Nonetheless, the 1999 ICR data were systematically collected and include coal from most coal-producing counties. Estimates based on the 1999 ICR coal analyses and corresponding emissions testing showed that coal burned in U.S. utility boilers during 1999 contained 75 ton of Hg, of which 48 ton (64%) was emitted to the atmosphere [50].

2.2.1.3 2010 EPA ICR

The 2010 ICR coal quality data originate from an ICR issued by the EPA in 2009 to inform its Mercury and Air Toxics Standards (MATS) rulemaking effort. The data were made available in two ACCESS databases, designated Part II [45] and Part III [46]. Limitations of these data include inconsistent reporting units for trace and minor elements and numerous duplicate records.

The Part II data include analyses reported by U.S. electric utilities for more than 14 000 coal samples. Most of the samples were collected from coal shipments delivered to power plants during 2009 and the corresponding data records include dry-basis ash, S, Hg, and heating values. About 25% of the records also include coal Cl content, and 10% include trace-metal content. Comparison of the Part II data with 2009 EIA-923 data [51] showed that about one-third of the ash, S, and heating values are actually on a moist basis, rather than the dry basis indicated in the Part II database [52]. State origins are listed for most samples and county origins are listed for about half of the samples.

The Part III data include analyses for over 1600 coal samples reported by electric utilities that were selected for mandatory emission testing to inform the MATS rulemaking. These were feedstock samples intended to represent the coal that was burned during the emission testing. Sample collection methods were not noted, but probably included automated or manual sampling from feed belts, as well as grab samples from stockpiles. Most of the data records include analytical results for Hg, Cl, F, and trace metals, and many also include complete proximate and ultimate analyses (moisture, ash, volatile matter, fixed carbon, heating value, C,

H, N, O, and S). The Part III data include numerous coal blends with multiple or uncertain origins. Nonetheless, state origins are listed for about half of the samples and county origins are listed for about a third.

In December 2011, results from the 2010 ICR were used in developing a final rule for MATS that limits emissions of Hg, other non-Hg metal air toxics, including As, Ni, Cr, and Se, as well as acid gasses (HCl, HF; [53]). The health-based rationale for MATS, the events leading to its approval, and the process of its implementation are covered in greater detail by Hutson [54], this volume.

2.2.2 Comparison of U.S. Coal Databases

Table 2.1 compares the halogen and trace-metal content of coal samples in the COALQUAL, 1999 ICR, and 2010 ICR data. Note that the Hg content of coal shipped to utilities (ICR data sets) is lower than the Hg content of the in-ground coal resource (COALQUAL data). This difference is a result of impurities removed from commercial coal during coal washing and selective mining of higher quality coal [47], as well as the greater proportion of Appalachian Basin coals in COALQUAL [11]. Similarly, Table 2.1 shows that delivered commercial coals contain less Sb, As, Be, Pb, and Se than indicated for in-ground coal by COALQUAL.

The lower apparent detection limit for Cl in the 2010 ICR Part III data compared to the 1999 ICR is noteworthy. Because Cl promotes Hg capture, the lower apparent detection limit for Cl should improve prediction of Hg capture for units burning low-Cl coal. Also notable is the relatively large number of Hg analyses in the 2010 Part II data (13 130 records) compared to other trace metals (~1000 records). The abundance of available Hg analyses for coal shipments is likely due to mandatory reporting of coal Hg content on the U.S. Energy Information Administration Form 923 [51]. Although the Hg content of U.S. coal shipments to electric utilities has been reported to the EIA since 2008, these data have not yet been published.

Publication of Hg assays collected with the EIA-923 data should eventually provide an accurate estimate of the Hg content of coal burned at U.S. electric utilities. In the meantime, the Hg content of coal burned at U.S. power plants can be reasonably estimated. This is done by assigning a Hg content to each coal shipment in the EIA-923 data according to the shipment origin using county-average Hg contents from the 1999 ICR [49]. The same estimation can be applied to Cl in coal. The resulting estimates of the Hg and Cl contents of coal shipped to electric utilities during 2009 are compared in Figure 2.1 with Hg contents of samples listed in the COALQUAL, 1999 ICR, and 2010 ICR databases. Heating values, ash yields, and sulfur contents of these databases are also compared. Note the lower ash, S, Cl, and Hg values for the 2009 EIA-923 data, which are weighted by delivered tons, compared to the other data sets. Comparison of the ash and S distributions helps to explain this difference. Figure 2.1 shows that the 2010 ICR coal samples have more S and more ash than coal delivered to U.S. power plants during 2009. This

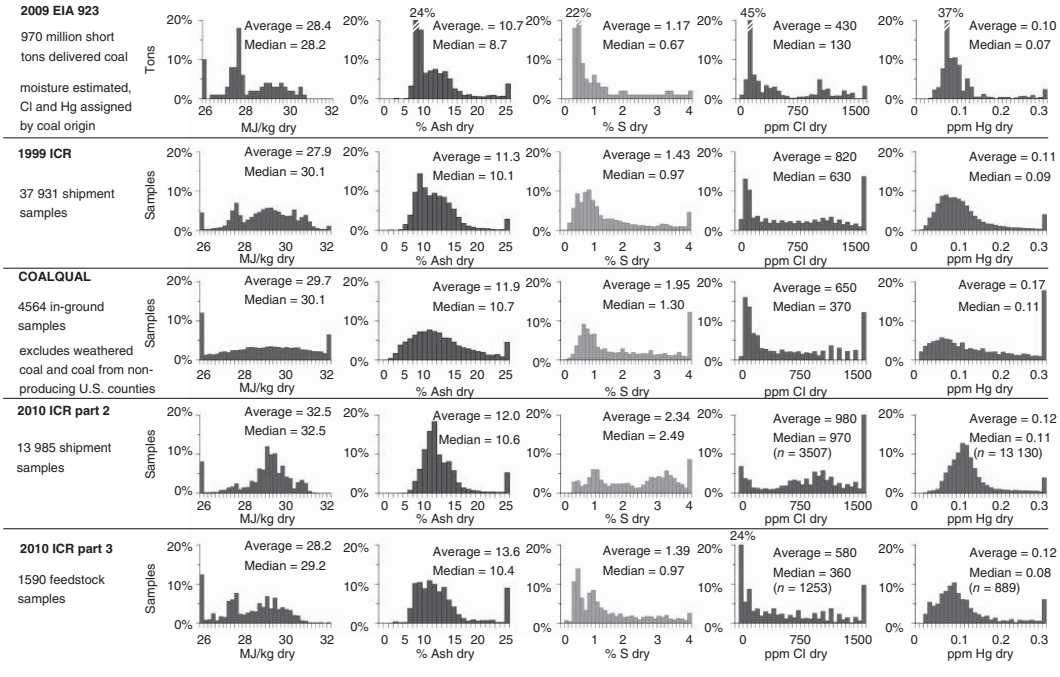

Figure 2.1 Comparison of megajoules per kilogram, ash, S, Cl, Hg distributions for shipped coal tons (EIA 923, 2009) with sample frequency distributions for in-ground (COALQUAL), shipped (1999 ICR; 2010 ICR part 2), and feedstock (2010 ICR part 3) samples. Notably, sample frequency distributions indicate higher ash, S, Cl, and Hg values than the shipped coal tons distributions shown at the top of the figure. Heat and ash values for the 2009 EIA 923 data [51] were adjusted to a dry basis using estimated moisture values, whereas Cl and Hg values were assigned to coal shipment tons by county origin based on compiled 1999 ICR data [49]. The data sets are described in the text. (Modified from Reference [47] Copyright © 2003, Springer.)

is consistent with the higher Hg content for the 2010 ICR coals, given that Hg is associated with pyritic S and is abundant in high-ash waste coal. More importantly, this comparison suggests that like COALQUAL, the 2010 ICR data are not representative of commercial U.S. coal. Consequently, the non-Hg trace-metal content of commercial U.S. coal will likely differ from the values listed in Table 2.1 and remains uncertain. Nonetheless, the 2010 ICR data are unique in that they are publicly available and include trace-element values for a wide range of commercial U.S. coals. Consequently, these data should assist efforts to understand the abundance, behavior, and fate of Hg and other trace metals in coal-derived gas streams.

2.3 Mercury in International Coals

2.3.1 Review of Mercury in Coal in the Largest Coal Producers

China, the United States, and India, listed in order of hard coal production rank, accounted for ~75% of 2010 world coal production [55]. If Australia, South Africa, the Russian Federation, and Indonesia are added, these countries accounted for more than 90% of 2010 hard coal production (Table 2.2). Of the major coal-producing countries, detailed nationwide surveys of Hg distribution are available only for the United States and China, as described below. For countries lacking comprehensive surveys of Hg distribution, brief summaries of available information are given below, together with the possible implications of these results for Hg output from coal combustion. Where applicable, results from the USGS WoCQI [39] are compared to other published results. WoCQI is a publicly available database that contains analyses of 1580 samples from 57 countries, including Hg, Cl, and other relevant coal quality determinations on a dry, whole-coal basis. For China, WoCQI contains 328 samples from 25 provinces

Table 2.2 Production data by country, listed in order of hard coal production (in megatons).[a)]

	China	United States	India	Australia	South Africa	Russian Federation	Indonesia	Kazakhstan	Poland	Columbia	Others	World total
Hard coal	**3162**	**932**	**538**	**353**	**255**	**248**	**173**	105	77	74	269	**6186**
Brown coal	[b)]	**65**	**33**	**67**	**0**	**76**	**163**	6	57	0	576	**1043**

a) 2010 data.
b) Brown coal included in hard coal data. Countries shown in bold are discussed in the text.
Source: IEA [55] Copyright © 2011, OECD/IEA.

and autonomous regions, representing an estimated 80% of production at the time of sampling. For major coal producers India, Australia, South Africa, the Russian Federation, and Indonesia, WoCQI sampling is much less complete than for China. For India, Australia, and the Russian Federation, USGS sampling is limited to specific study areas.

2.3.1.1 China

China is both the world's largest producer and user of coal. Recent compilations confirm that Hg concentrations of coals used commercially in China are similar to those used elsewhere [56–59], with nationwide means from studies over the last 10+ years ranging from 0.10 to 0.22 ppm [59]. The most recent compilations show less variability and an overall value for Chinese commercial coal between 0.15 and 0.19 ppm is likely (Table 2.3). For example, Dai *et al.* [58] report a mean of 0.16 ppm Hg for 1666 samples, which is identical to that determined by the USGS (0.16 ppm) for 305 WoCQI samples, excluding 23 samples of prepared coal [60]. Streets *et al.* [56] used a merged dataset of USGS results and available data from the literature to determine a mean for China of 0.18–0.19 ppm. Ren *et al.* [61], as reported by Dai *et al.* [58] give a mean of 0.19 ppm for 1413 samples. A subset of 619 of the Ren *et al.* samples reported by United Nations Environment Programme (UNEP) [62], give a mean of 0.33 ppm where a large proportion (21%) of samples is from Guizhou Province. Zheng *et al.* [57] determined an arithmetic mean of 0.19 ppm for 1699 samples, but with 16% (276) of these from Guizhou Province, compared to only 5% (16 of 305) in the USGS dataset (see next section). Taken together,

Table 2.3 Compilation of results for Hg in Chinese coal (in microgram per gram).

Arithmetic mean (±s.d.)	Number of samples	Samples from Guizhou Province	References
0.22[a)]	234	NA	[63]
0.1	1458	NA	[64]
0.19	NA	NA	[56][b)]
0.19	1413	NA	[61][c)]
0.33	619	133 (21%)	[61][d)]
0.16 ± 0.14	305	16 (5%)	[60]
0.19 ± 1.22	1699	276 (16%)	[57]
0.154	1123	NA	[65]
0.18[e)]	~900	NA	[66]
0.163	1666	NA	[58]
0.17 (U.S. mean)	7430	—	[11]

NA, not available.
a) Value calculated from 14 provinces sampled and other published results.
b) Data include USGS data and other published results merged.
c) As reported by Dai *et al.* [58] Copyright © 2012, Elsevier.
d) As reported in Ref. [62] Copyright © 2011, United Nations Environment Programme.
e) Mean value noted in oral presentation.
Source: After Refs [58, 59, 62] Copyright © 2012, Elsevier; Copyright © 2006, DEStech Publications, Inc.

the result of various compilations of Hg in Chinese coal are comparable to the in-ground mean for U.S. coals (0.17 ppm; [11]) both in concentration value and numbers of samples, but unlike COALQUAL, are probably more representative of current production.

It is apparent in coal Hg compilations for China that some provinces, especially Guizhou, and to a lesser extent Shanxi, and Inner Mongolia, have greater variability in Hg contents than others [56, 59, 62, 67]. Furthermore, province-wide means for Guizhou are strongly influenced by the proportion of Hg-enriched samples included in the data. In an analysis of USGS data for Chinese coals, Wu *et al.* [67] showed that the distribution of Hg contents in Guizhou Province coals contains a tail of values in excess of 1 ppm Hg, giving an overall mean of 0.51 ppm for 46 samples. A similar trend in Hg distribution was shown for coals in Shanxi Province. The highest Hg values in Guizhou Province are associated with mineralized coals produced in small-scale mines and used primarily for domestic purposes [68, 69]. While various studies [69, 70–73] have drawn attention to health risks associated with the latter, inclusion of mineralized coal samples from small-scale workings in database compilations to assess Hg input to the utility sector is inappropriate and has resulted in over-estimates in the past. If mineralized coals are excluded from those produced on a commercial scale, the province-wide mean for Guizhou is comparable to current estimates of the nationwide mean (Figure 2.2). Consideration of Hg in Chinese coals on a production-weighted basis could help refine the estimate for China and keep pace with rapidly evolving utilization patterns.

2.3.1.2 India

India is the world's third largest coal producer after China and the United States, and coal accounted for 69% of India's electric power generating capacity in 2010 [55, 74]. Coals in the Indian subcontinent originated in the Gondwana supercontinent encompassing all or part of peninsular India, Australia, southern Africa, South America, and Antarctica. These coals are dominantly of Permian age, in contrast to Carboniferous coals of Europe and North America. Compared to Carboniferous coals in the northern hemisphere, Gondwana coals tend to be relatively high in ash and low in sulfur, with a greater proportion as organic sulfur, except where coal beds are overlain by marine sediments [75].

Unlike China and the United States, detailed studies of elemental concentrations, especially Hg, in Indian coals are lacking. For example, a recent report by Mukherjee *et al.* [76] on Hg emissions from industrial sources assumed a mean value of 0.376 ppm Hg for Indian coal, based on the average of coals sampled at eight (of about 80) operating power stations in India, whose range in Hg contents was from 0.18 to 0.61 ppm. In a study of global Hg flow from coal utilization, Mukherjee *et al.* [77] give a range from 0.11 to 0.80 ppm for Hg in coal from India, but note a much smaller variation (0.11–0.14 ppm) in results provided by the National Thermal Power Corporation of India. Rajagopalan [78] gives a range for Hg in Indian coal from 0.26 to 0.49 ppm that was reported by Mukherjee and Zevenhoven [79]. The number of samples on which these ranges are based, and the analytical methods employed, are not clearly stated.

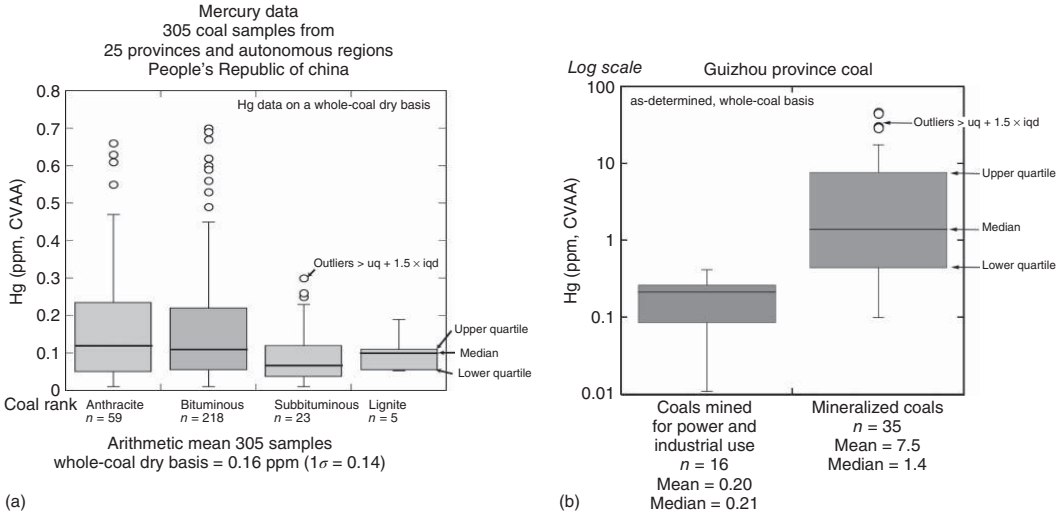

Figure 2.2 (a) Comparison of mercury content of Chinese coals by rank. (Results from Belkin *et al*. [60].) (b) Comparison of Guizhou Province, China, coals produced for power generation and industrial uses with mineralized coals. (Results from Ref. [60, 80].)

USGS sampling in India (102 samples; [39]) is limited to the Sohagpur Basin, an important Permian coal basin, together with reconnaissance sampling of younger, Tertiary coals having more limited commercial use. Together, these samples give a mean Hg value of 0.09 ppm. Additional sampling is required to determine an overall Hg content of Indian coals similar to values obtained by more comprehensive sampling in China and the United States. Coal washing is widely employed in India to reduce high-ash contents, a characteristic of some Gondwana coals. Additional characterization is needed to determine the effect of coal washing on Hg contents and to expand the information available on Hg in Indian coals.

2.3.1.3 **Australia**

Australia is the largest hard coal exporter (298 Mton in 2010) and the fourth largest producer [55]. Australia relied on coal for 77% of its 2010 power generation needs [55]. Mercury contents in Australian coals are low by international standards. In estimating Australia's atmospheric Hg emissions, Nelson [81] assumed a mean value of 0.05 ppm Hg for Australian hard coal, based on work by Dale [82] and Riley *et al.* [83], giving mean values of 0.045 and 0.040 ppm, respectively, on an as-received basis, for a suite of 100 Australian hard coals. A mean value of 0.08 ppm, on a dry basis, was assumed for Australian brown coals, as noted by Brockway *et al.* [84]. Most Australian hard coals are Permian in age, whereas brown coals are Tertiary. Mercury contents in Australian export coals are especially low, ranging from 0.01 to 0.08 ppm, with a mean of 0.02 ppm according to CSIRO [85]. Only 10 samples are included in WoCQI for Australia. Four export bituminous coals from the Bowen Basin, Queensland, have Hg contents ranging from 0.011 to 0.026 ppm on a dry, whole-coal basis [39]. One low-rank coal has a much higher Hg concentration (0.16 ppm), consistent with higher Hg values for low-rank coals suggested by Brockway *et al.* [84]. Of four bituminous coals investigated in detail in an international round robin study of methods for determining element affinities in coal [86], the Wyee (Australia) coal had the lowest pyritic S content (0.05 wt%) and the lowest Hg content (0.01 ppm; [87, 4]). As part of a more recent study of element modes of occurrence, Riley *et al.* [88] determined Hg contents by cold vapor atomic fluorescence for six Permian and Triassic Australian coals, including several blended coals. These six samples give a mean of 0.050 ppm Hg and a median of 0.022 ppm, reflecting one sample (GG) of high sulfur coal, formed under marine influence, having a Hg content of 0.16 ppm. Selective leaching studies of these six coals are consistent with pyrite as the predominant mineral association for Hg [88].

2.3.1.4 **South Africa**

South Africa is of particular interest from the standpoint of Hg emissions because it has the highest proportion of its electricity produced by coal combustion (93%; [74]), and is a major user of coal for liquid fuels. South Africa is also the world's fifth largest hard coal producer and a significant (68 Mton) coal exporter [55]. There is considerable range in coal products produced, both by natural variation in quality and by coal beneficiation, with the best quality (lowest ash, highest calorific

values) coals produced for export and higher ash coals retained for domestic use or rejected (C. van Alphen, personal communication, 2011) [89]. This variation likely contributes to a considerable range in Hg content, even for a single coal by a single producer, with export coals expected to be lowest by virtue of removal of mineral matter, including pyrite. A large portion of coal production and generation capacity has traditionally come from central coalfields within the main part of the Permian Karoo Supergroup in Mpumalanga Province, including the Witbank, Highveld, and Ermelo coals. The Witbank and Highveld coals are approaching exhaustion. The largest remaining coal reserves are in the Waterburg coalfield in Limpopo Province to the northwest; together these three coal fields constitute more than 70% of total reserves in South Africa [90].

Wagner and Hlatshwayo [91] determined a series of potentially hazardous trace elements in five Highveld coals, giving a range of 0.04–0.27 ppm Hg and a mean of 0.15 ± 0.05 ppm. These authors recognized that many of the element concentrations determined were either less than or comparable to global values for coal with the exception of Cr, which is noticeably higher. Bergh *et al.* [17] investigated the potential for trace-element reduction by beneficiation of the Witbank no. 4 coal. The no. 4 coal has a higher ash yield than the no. 2 coal, historically the most important producer in the Witbank coalfield, but whose reserves are declining. Bergh *et al.* [17] give a mean of 0.3 ppm Hg for an unspecified number of run-of-mine samples of the Witbank no. 4 coal. Extents of trace-element reduction by dense media and by froth flotation were investigated, with dense media beneficiation showing a greater reduction of pyrite-associated elements such as Hg.

Reconnaissance USGS sampling of South African coals (40 WoCQI samples, major coalfields represented; [39]), gives a mean of 0.20 ppm Hg for 11 samples of Highveld coal, comparable to findings of Wagner and Hlatshwayo [91]. But for 10 samples of Witbank coal, the mean is only 0.045 ppm, excluding one Witbank sample with 0.83 ppm Hg. The ash yield of the 10 USGS Witbank samples ranges from only 7.2% to 16.4%, suggesting these are export coals, whereas the outlier with 0.83 ppm Hg has an ash yield of 32.5% (Figure 2.3). USGS results confirm that Highveld coals are especially Cr-enriched, in agreement with Wagner and Hlatshwayo [91] and consistent with possible exposure of chromite-($Fe^{2+}Cr_2O_4$) bearing source rocks during Karoo sedimentation.

Wagner and Tlotleng [92] prepared and analyzed density fractionated mineral concentrates from four Waterburg coal samples. Results show a strong association of As with the most pyritic fractions for all four samples and a more variable mode of occurrence for Hg, which includes a pyritic association for three samples from the Grootegeluk formation. These results suggest that Waterburg coals may be amenable to reduction of As and Hg by coal preparation.

2.3.1.5 **Russian Federation**

Russia has the world's second largest coal reserves, after the United States, and currently (2010) is the sixth largest hard coal producer (248 Mton) immediately following South Africa [55]. Thermal power stations account for nearly 70% of the power generation sector in the Russian Federation, but the majority of these

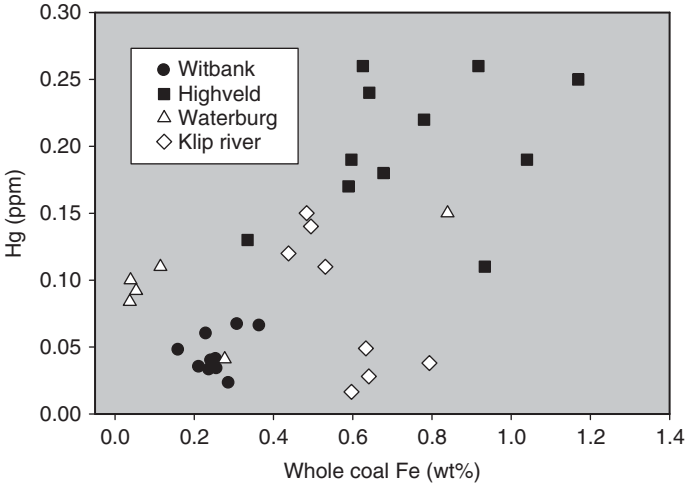

Figure 2.3 Plot showing variation in Hg content as a function of Fe content (a proxy for pyrite) for reconnaissance USGS sampling of South African coals from four coalfields. Both parameters are expressed on a dry, whole-coal basis. One Witbank sample with 1.24% Fe and 0.83 ppm Hg is omitted as well as four other WoCQI samples – two with unidentified locations and two from other coalfields (Hg in these four samples ranges from detection limit to 0.62 ppm). Low-Hg Witbank samples (lower left) are probably export coals (see text).

plants are gas-fired. Coal accounts for nearly 30% of this capacity, comprising about 20% of overall electric power generation [93, 94]. Although coal is produced in several parts of the Russian Federation and adjacent areas of Ukraine and Kazakhstan, three coal basins, the Ekibastuzsk Basin in northeastern Kazakhstan bordering Siberia, the Kuznetsk Basin in southwestern Siberia, and the Kansk-Achinsk Basin, also in Siberia, accounted for about 60% of the coal used for power generation in 2007 [95, 94]. Of these, the Kuznetsk Basin is the primary source of coal produced for export, whereas in the Kansk-Achinsk Basin, brown coals are produced, with use outside of Siberia limited to small amounts that are shipped to European Russia [94].

Mercury contents of Russian coals show some variability within and between major coal basins, but available data for areas with the greatest production are well within international standards. Mercury contents of Kuznetsk coals tend to be on the low side, with an average of 0.06 ppm given by ACAP [96] for coal produced in 40 mines, similar to that reported by Meij and te Winkel [97] about 0.05 ppm for Kuznetsk coal exported to the Netherlands. Higher Hg contents have been reported for some basins. The Donets Basin (Donbas region) of eastern Ukraine and adjacent parts of the Russian Federation has historically been an important coal-producing region, especially for metallurgical coals. These coals are known to have relatively high Hg concentrations with Hg enrichment that is controlled geologically by faulting and other structures. Kolker *et al.* [98] report a mean content of 0.68 ppm Hg for 29 samples of commercial coal collected from active mines in

the vicinity of Donetsk, Ukraine, but this is reduced to 0.43 ppm for 17 samples if 11 samples from the mining district closest to the geologic Hg source, and one outlier with 3.5 ppm Hg, are excluded. On a nationwide basis, the proportion of Hg-enriched coals used for power generation in the Russian Federation is likely to be small, as commercial coal production is dominated by three main sources, each having low to moderate Hg contents.

2.3.1.6 **Indonesia**

Indonesia is the world's largest producer of brown coal (163 Mton), the second largest hard coal exporter (162 Mton) after Australia, and the seventh largest hard coal producer (173 Mton; [55]). Indonesia's production is likely to increase as new coal fields are developed. Coal in Indonesia is present in a series of shallow, geologically young basins that are distributed across the archipelago. As a result, 85% of coal produced in Indonesia is lignite or subbituminous in rank. In a study of trace elements in coal imported to the Netherlands, Indonesian coal is at the lower end of the range of Hg concentrations in coal from 14 countries, with a mean value <0.10 ppm [97]. In an effort to better define the environment of deposition of coals in Kutai Basin, East Kalimantan, Widodo *et al.* [99] examined the distribution of pyrite in these coals and found excellent correlations between the occurrence of pyrite and total iron content, which likely extends to Hg.

Detailed geochemistry for eight samples of in-ground Indonesian coal is given by Belkin and Tewalt [100]. These are the only Indonesian samples in the USGS WoCQI database, but give a range in rank (lignite B to semi-anthracite) and geographic distribution. Most of these samples are low in S, as is typical of Indonesian coals. These eight samples give a mean Hg content of 0.10 ppm with a range of 0.02–0.19 ppm, and Cl contents ranging from <150–300 ppm, with a mean of 260 ppm.

2.4
Halogens in Coal

2.4.1
Introduction

Information on the controls and natural variation of halogens in coal is provided here as background to their impact on mercury capture in combustion systems. In general, halogen contents of coals used for power generation increase with rank, which, in the absence of localized thermal sources, corresponds to depth of burial or paleo-depth in coal-forming sedimentary basins. This is because the salinity of formation waters and the concentration of dissolved constituents such as halogens increase with depth in sedimentary basins, and halogen concentrations are influenced by exchange between formation waters and coal.

2.4.1.1 Chlorine (Cl)

Elemental Hg is a semi-noble metal, exceedingly water insoluble, and difficult to capture by adsorption on unpromoted activated carbons, or by absorption in wet scrubbers. Compounds of mercury, such as mercuric chloride, have some water solubility, and are more amenable to capture by sorbents or scrubbers. Halogens such as Cl can also facilitate the oxidation of mercury by selective catalytic reduction (SCR) catalysts located upstream of wet scrubbers. At flue gas temperatures, the Cl content of coal strongly influences Hg speciation, converting Hg^0 present at boiler temperatures to oxidized forms that can react with Cl species in the flue gas to form Hg – Cl complexes or compounds. These Hg – Cl complexes or compounds can be captured by air pollution control devices or taken up by halogen-doped sorbents ("[100], [101,102], this volume" or equivalent.). The proportion of oxidized Hg formed in combustion systems increases with increasing Cl, for coals having Cl contents between about 100 and 1000 ppm Cl [7, 104].

The range in coal Cl values shown to be effective in enhancing Hg capture is rank-dependent and corresponds to values typically found in bituminous coals [105, 106]. Yudovich and Ketris [105] compiled Cl data for coals throughout the world and their ashes. This compilation gives a median Cl concentration in hard coals (340 ± 40 ppm) that is roughly three times that for lignites (brown coals; 120 ± 20 ppm). The world value for hard coal and the mean for Chinese coal (255 ppm; [58]) are comparable. Both values are lower than the U.S. mean (614 ppm; [11, 107]) that is elevated by the predominance of eastern U.S. bituminous coals in COALQUAL.

U.S. coals show rank dependence of Cl concentration (Figure 2.4a) and considerable variation within and between U.S. coal basins [106]. In the Appalachian Basin, Bragg *et al.* [106] have shown that chlorine contents have a pronounced stratigraphic dependence with the highest mean concentrations found in the lowermost coals sampled (Table 2.4). A similar variation in Cl contents with depth has been observed in the Illinois Basin (USA), with concentrations ranging from below detection at outcrop to 0.8 wt% in the deepest part of the basin [108, 109]. Some of the highest Cl values shown in Figure 2.4a for the U.S. Interior Province correspond to deep-basin samples from the Illinois Basin. Variation in Cl contents with depth in the Illinois Basin is attributed to equilibration with groundwater whose salinity increases with depth. For 13 mines in which Cl was determined for both coal and ground water, a correlation coefficient of 0.93 was obtained for these two parameters [108]. Elsewhere, proximity to geologic structures that have acted as pathways for influx of Cl-bearing fluids can result in localized Cl enrichment. This is thought to be the case in the Southwestern reserve district of eastern Kentucky, USA, where the major coal beds present have higher mean Cl contents than their equivalents elsewhere in eastern Kentucky [28]. Whereas Cl is desirable for its capacity to enhance Hg capture, at high concentrations it can be deleterious. Chlorine contents greater than about 0.3 wt% are known to cause significant fouling and corrosion of boilers [109]. Moreover, HCl emissions from Cl in coal are regulated under the new MATS rule.

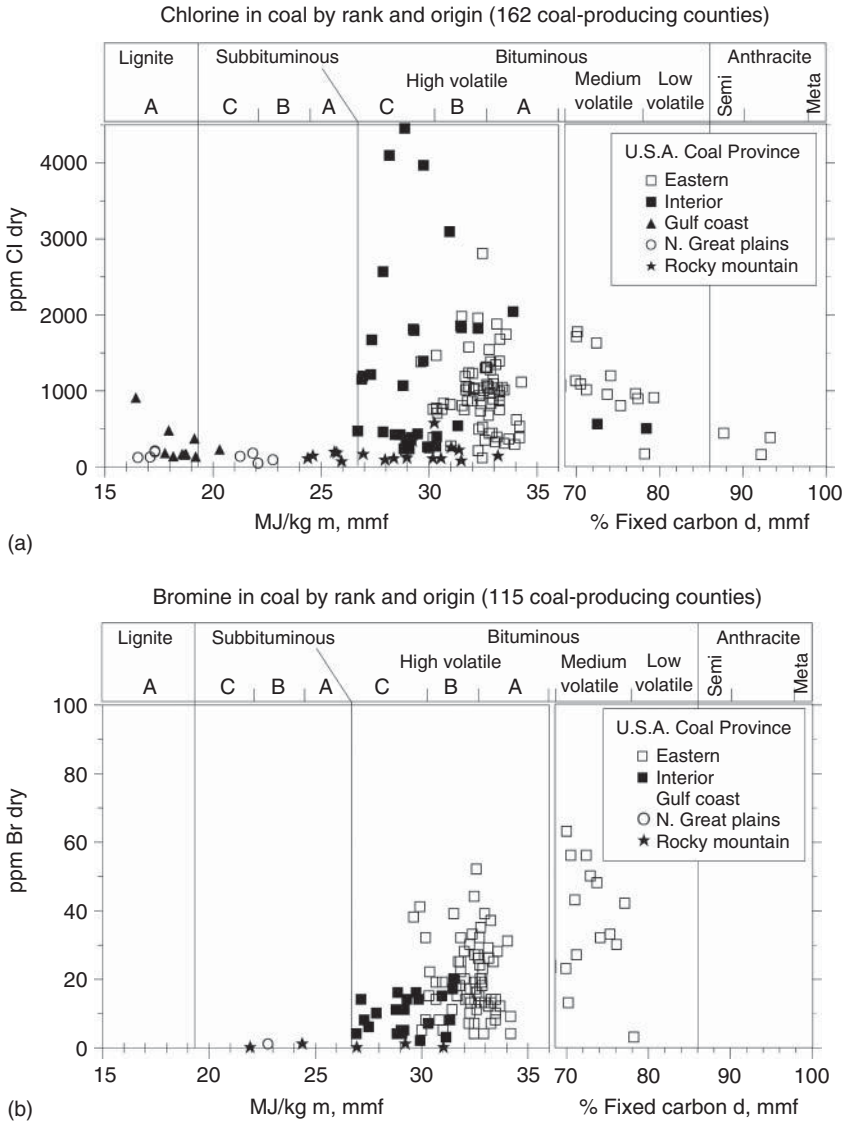

Figure 2.4 (a,b) Plots showing variation of county-average Cl and Br contents of U.S. coal with ASTM [110] coal rank and geographic origin. County-average values were calculated from at least five samples. With a few exceptions, Cl values are from the 1999 ICR, Br values are from COALQUAL, megajoules per kilogram values are mostly from year 2005 EIA-423 coal shipment assays with a few from the 1999 EIA-423 data, and fixed carbon values are mostly from COALQUAL with a few from Keystone. Additional data from the Illinois Geological Survey, which include Br and Cl values for coal from 12 counties in Illinois, were also used. The data sets have been described elsewhere [111]. Compared to Cl, relatively few data are available for Br in lower rank U.S. coal. (Modified from Reference [7] Copyright © 2006, Elsevier.)

Table 2.4 Mean chlorine content of coal by formation in the central Appalachian Basin, Pennsylvania, and West Virginia, USA.

Age	Formation	Number of samples	Mean (ppm)[a)]
Permo-Pennsylvanian	Dunkard Group	44	162
Upper Pennsylvanian	Monongahela	73	477
Upper Pennsylvanian	Conemaugh	41	828
Middle Pennsylvanian	Allegheny	709	1097
Middle Pennsylvanian	Kanawha[b)]	36	1408
Lower Pennsylvanian	New River[b)]	56	1503

Formations are listed in order of increasing age.

a) Detection limit is 100 ppm. In calculating mean, non-detects are assumed to contain 70% of the detection limit.

b) Samples from southern West Virginia; other samples are from Pennsylvania.

Source: Ref. [106].

The mode of occurrence of Cl in coal has drawn considerable attention in part because of boiler corrosion problems caused by coals with excessive Cl contents and in part because multiple forms of Cl have been suggested, which has led to considerable disagreement. Major forms recognized or suggested include inorganic Cl in mineral chlorides or other mineral matter in coal, organically bound Cl, and chloride anions present within moisture in coal [105, 112, 113]. Huggins and Huffman [112] used Cl K-edge XAFS spectroscopy to investigate the mode of occurrence of Cl in bituminous and low-rank coals and compare Cl in raw coals with that in cleaned coals, and before and after aqueous leaching treatments. These authors found that hydrated chloride species provided a much better fit to the Cl K-edge X-ray absorption near edge structure (XANES) spectra obtained for a range of U.S. and U.K. coal samples than either a series of organochlorine compounds or crystalline NaCl. They concluded that in coals with typical Cl contents, Cl is present as chloride anions associated with coal moisture and weakly bound to the surfaces of micropores in coal macerals by organic–ionic complexes [112]. A similar model was advanced for Br (following section).

2.4.1.2 **Bromine (Br)**

Compared to Cl, on a molar equivalent basis, Br is a much more effective oxidizer of Hg in power plant flue gas ([102], this volume). As a result, the native Br content in coals may be even more important than Cl in determining the extent of spontaneous Hg oxidation and self-capture in combustion systems [104, 114–117]. For coals that are low in halogens, including many low-rank coals, this has led to the suggestion that limited addition of Br would effectively enhance Hg oxidation and capture [117]. As a result, a range of Br-based commercial sorbents has been developed, particularly for use with subbituminous coal ([103], this volume).

Like Cl, the absolute concentration of Br in coal is rank-dependent (Figure 2.4b). However, the proportions of Br and Cl are relatively constant. Vosteen *et al.* [117] reviewed the native halogen content of coals in the United States, China, and several other countries, and determined that Br/Cl mass ratios of 0.01–0.04 were

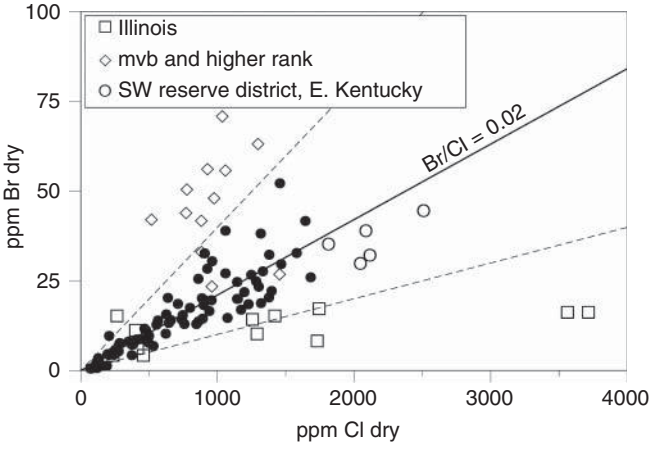

Figure 2.5 Average Cl and Br contents for coal produced in 110 U.S. counties showing that most have Br/Cl mass ratios near 0.02. Points show county-average values calculated from selected COALQUAL records where there were at least five Cl and Br analyses. Dashed lines show Br/Cl ratios of 0.04 (top) and 0.01 (bottom). Data for nonproducing counties are included in the figure but weathered coal and samples collected from outcrop have been ignored. Additional data from the Illinois Geological Survey were also used. The data sets have been described elsewhere [80, 111].

typical, even in coals having low overall halogen contents (i.e., regardless of rank). For U.S. coals, most scatter about a Br/Cl ratio of 0.02 (Figure 2.5). Exceptions include high-rank coals (above high volatile bituminous rank) and coals influenced by saline formation waters, including coal from the Southwestern reserve district in eastern Kentucky, and some Illinois coals (Figure 2.5). Using a Br/Cl ratio of 0.02 as a guide, Br concentrations near 2 ppm might be expected for a subbituminous coal with 100 ppm Cl, and 8 ppm Br for a bituminous coal having 400 ppm Cl. In some cases, for example, in selected coals from Bulgaria and parts of the Ukraine Donbas, exceptionally high Br concentrations are present, with Br contents in excess of those for Cl for some samples ([113, 117]; Figure 2.6). Inclusion of these highly Br-enriched coals in results for 34 world coal deposits [113] gives a mean Br value in excess of 100 ppm that is probably not representative. Excluding seven deposits with Br contents >50 ppm gives a mean Br/Cl ratio of 0.05 for the 27 remaining deposits, which is more in line with typical Br/Cl proportions. In a review of Cl and Br in U.K. coals, Spears [118] found that means for both elements were enriched proportionally in a representative suite of 24 samples.

Bromine/chlorine ratios are potentially of use in distinguishing the processes controlling halogen distribution in coal. In the simplest cases, this ratio is controlled by pore waters present during coal formation or by formation waters presently in equilibrium with coal. At the peat stage, halogens are enriched in peat and its pore water relative to atmospheric deposition [119, 120] and the proportion of Br to Cl is higher than that of modern seawater, which has a consistent Br/Cl ratio of 0.0035 on a weight concentration basis [121]. Typical Br/Cl ratios

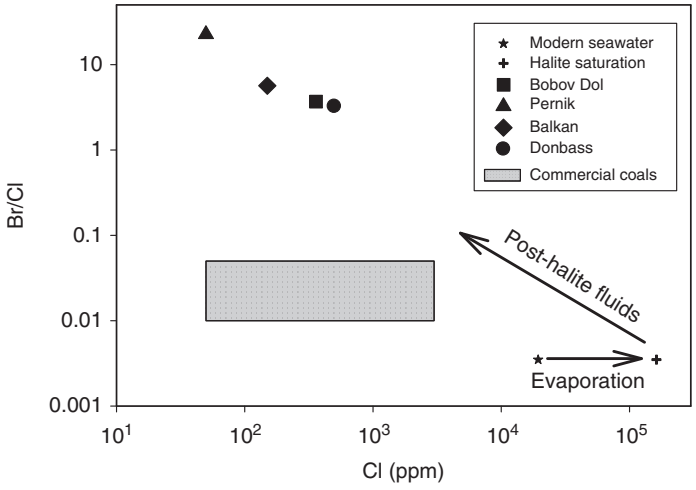

Figure 2.6 Generalized Br–Cl systematics for coals and brines, showing compositions typical of commercial coals (gray swath) and results from Vassilev *et al.* [113] for four coal deposits with extreme Br enrichment including Bobov Dol, Pernik, and Balkan, in Bulgaria, and Donbass in Ukraine. Halite precipitation enriches residual fluids in Br, thereby increasing Br/Cl. Actual trajectory is dependent on conditions present in a particular basin. Range for commercial coals assumes a Br/Cl from 0.01 to 0.05, 50 ppm Cl as a minimum and 3000 ppm as a maximum, based on boiler corrosion problems using more Cl-rich coals.

in coal are approximately 5–10 times that of seawater (Figure 2.6), reflecting either inheritance from the peat stage, exchange with formation waters, or both. As seawater evaporates and salinity increases, Br/Cl remains relatively constant until halite (NaCl) precipitates, which excludes Br. As a result, halite precipitation in saline formation waters enriches the residual fluids in Br, increasing the Br/Cl ratio ([122], expressed as lowering Cl/Br; Figure 2.6). Halite-bearing "salt coals" in a number of countries have unusually high Cl concentrations and atypical Br/Cl ratios [113, 120], which may be inherited in part from the peat stage or a consequence of halite precipitation. Conversely, halite dissolution by less saline formation waters serves to decrease Br/Cl ratios ([122], expressed as raising Cl/Br).

Like Cl, the mode of occurrence of Br in coal has been difficult to ascertain with certainty. In Cl-enriched coals containing discrete mineral chlorides such as halite (NaCl), sylvite (KCl), or other Cl-bearing minerals such as chlorapatite ($Ca(PO_4)_3$(Cl, F, OH), limited inclusion of Br may be expected. But as suggested by Huggins and Huffman [112], mineral occurrence of halogens in coal may be the exception rather than the rule. Based on more limited XAFS spectroscopy at the Br K-edge showing many features in common with the Cl data, Huggins and Huffman concluded that the dominant mode of occurrence for Br is in association with coal moisture, similar to that for Cl. Based on the similarity of Cl and Br, Spears [118] concluded that moisture-hosted Cl and Br were consistent with results for U.K.

coals showing (i) correlation between Cl in coal with that in adjacent groundwater; (ii) correlation between coal Cl content and moisture content; and (iii) brine-like water extracted from coal moisture by centrifugation.

2.4.1.3 Iodine (I)

Various studies have found I and its compounds such as potassium iodide to be effective oxidants and sorbent promoters for capture of Hg^0 in flue gas from coal combustion [104, 123–125]. On a volume-equivalent basis, Chi *et al.* [125] determined I to be even more effective than Br in promoting Hg^0 oxidation, whereas Cao *et al.* [104] found Br (as HBr) to be more effective, and both HBr and HI more effective on a per volume basis than either HCl or HF. These results follow a general trend that the heavier halogens (Br, I) are more effective oxidants than the lighter halogens (Cl, F), a surprising result given that oxidizing ability decreases in the group with increasing atomic weight.

Information on the naturally occurring I content of coals is limited. However, several recent studies have introduced methods to quantify I content, particularly in Chinese coals [126–128]. Wu *et al.* found a range in I content from 0.04 to 39.5 ppm for 305 samples of coal from throughout China, with an arithmetic mean of 2.6 ppm and a geometric mean of 1.27 ppm. Iodine content was found to be positively correlated with coal rank and with depositional environment, with anthracite having the highest values. Chinese coals deposited under the influence of marine or brackish conditions have a higher mean I content than those deposited in non-marine settings and this is likely to be applicable elsewhere, analogous to other marine-associated elements such as B [129]. Bettinelli *et al.* [130] give a range of 0.15–12.8 ppm I by ICP-MS for 158 commercial coal samples imported to Italy from China, Columbia, Poland, South Africa, the United States, and Venezuela. This study confirms that median I concentrations in the 1–3 ppm range are typical from various sources. Wang *et al.* [126] report I contents (by INAA) ranging from 2.2 to 15.7 ppm for a series of coals from Guizhou Province, China. There, the most I-enriched coals reflect post-coalification interaction with hydrothermal fluids and are not representative of values for coals used commercially. Wang *et al*. [126] (their Figure 1) and Zheng *et al.* [73] argue that domestic use of I-enriched coal in Guizhou Province limited the incidence of iodine deficiency disorders in the Province to wood-burning areas, prior to its virtual elimination by introduction of iodized salt throughout China.

2.4.1.4 Fluorine (F)

Comparison of the impact of F addition on oxidation of Hg^0 with addition of Br, I, and Cl indicates that the effect of F is similar to or less than that of Cl [104]. As a result, there has been less interest in addition of F, the lightest halogen, as a means to promote Hg capture from combustion systems. However, because its behavior is comparable to that of Cl, in coals with naturally high F contents, the sum of F and Cl may be a more important indicator of the potential for Hg self-capture than Cl itself.

Like other halogens, F concentrations in coal show considerable variation. Values in the 50–100 ppm range are typical, with similar means estimated for world coal (88 ppm; [131]), U.S. coal (98 ppm; [11, 107]), and coal in China (82 ppm; [71, 132]), although Dai *et al.* [58] later give a higher mean value for China (130 ppm). Unusually F-enriched coals (mean of 286 ppm for 29 samples) in Inner Mongolia, described by Wang *et al.* [133], are thought to be the result of introduction of Al- and F-bearing solutions to the mire during coal formation. These solutions are likely derived from an adjacent geologically ancient, deeply weathered, bauxite-bearing terrane. This history is reflected by the presence of boehmite (AlO(OH)) in these coals and a strong correlation between F concentration and the volume percentage of boehmite [133]. Elsewhere in China, high F contents are known in some stone coals (carbonaceous mudstone), and in manufactured coal briquettes that use F-rich clay as a binder. Domestic use of these materials is thought to contribute to endemic fluorosis in China [71, 73, 133], but based on the moderate F contents typical of Chinese coals, the contribution of coal itself to the fluorosis problem is considered to be secondary [71].

2.5 Summary

As discussed elsewhere in this volume, interaction of coal-derived Hg and halogens in the flue gas of combustion systems provides a fundamental mechanism for mercury capture. Variation in the concentrations of these parameters in coal is a consequence of geologic processes, and as a result, to some extent, every coal is unique. In general, low-rank coals have lower contents of both Hg and halogens than bituminous coals, and when combined with their lower energy output and higher moisture content, may offset some of the advantage of being low in Hg. At the other end of the spectrum, bituminous coals generally have higher Hg content but also have halogen concentrations in a range that promotes a greater degree of Hg self-capture. Compared to low-rank coals, bituminous coals have a greater fraction of Hg occurring within Fe disulfides, which potentially allows for pre-combustion removal of Hg to some extent. Concentrations of halogens in coal are influenced by the interaction of coal with associated fluids that may include pore water present during various stages of coal formation, formation waters present in a coal basin, or thermally or structurally driven brines. Where coals are in equilibrium with deep-basin brines, halogen contents may be especially high, and this may limit their commercial usefulness due to corrosion of boilers and emission of acid gasses. The content of Br in coal is typically only a small percentage of the Cl content, but even so, this proportion is enriched relative to that of seawater. As shown elsewhere in this volume, the capacity of Br to promote Hg oxidation is substantially greater and disproportionate to that of Cl.

Of the major coal-producing countries, database compilations sufficient to estimate Hg input to the boiler on a nationwide basis are available only for the United States and China. More detailed sampling and analysis of Hg in coal are

needed, especially for the next largest coal-producing countries such as India, South Africa, the Russian Federation, and Indonesia. In the absence of available detailed compilations, extrapolation of limited datasets to estimate Hg input to the utility sector on a nationwide basis is unlikely to be representative.

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3
Regulations

Nick Hutson

3.1
U.S. Regulations

3.1.1
Background

The enactment of the Clean Air Act of 1970 (1970 CAA) resulted in a major shift in the federal government's role in air pollution control. This legislation authorized the development of comprehensive federal and state regulations to limit emissions from both stationary (industrial) and mobile sources. At this time, the National Emission Standards for Hazardous Air Pollutants (NESHAP) program was initiated to limit emissions of toxic or hazardous air pollutants (HAPs) from stationary sources. CAA Section 112 addresses emissions of HAPs, which are those pollutants which are hazardous to human health or the environment but are not specifically covered under another portion of the CAA. These pollutants are typically carcinogens, mutagens, or reproductive toxins. In 1990, the U.S. Congress, believing that the 1970 CAA and subsequent amendments had failed to provide substantial reductions of air toxic pollutants, passed the Clean Air Act Amendments of 1990 (1990 CAAA). The 1990 CAAA authorized, among other things, the incorporation of the NESHAP into a greatly expanded program for controlling toxic air pollutants.

The new law included a list of 189 toxic air pollutants (including mercury and its compounds) for which emissions must be reduced. Congress then mandated that the Environmental Protection Agency (US EPA) publish a list of source categories that emit certain levels of these pollutants within 1 year of the law's passage. For major sources (those emitting more than 10 ton of any single HAP or more than 25 ton cumulatively of all the listed HAPs), Section 112 mandates that the EPA establish emission standards that require the maximum degree of reduction in emissions of HAPs. These emission standards are commonly referred to as *maximum achievable control technology* or *MACT* standards. These standards are to be based on the best demonstrated control technology or practices within the regulated industry.

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Eight years after issuance of the technology-based standards, the EPA is required to review those standards to determine whether any residual risk exists for that source category and must, if necessary, revise the standards to address such risk.

3.1.2 Electric Generating Units (EGUs)

Congress established a specific structure for determining whether to regulate electric generating units (EGUs) under CAA Section 112. Specifically, Congress required the EPA to conduct a study to evaluate the remaining public health hazards that are reasonably anticipated to occur as a result of EGUs' HAP emissions after imposition of other CAA requirements. The EPA was required to report the results of that study – referred to as *the Utility Study* [1] – to Congress, and to regulate EGUs "if the Administrator finds such regulation is appropriate and necessary," after considering the results of that study.

The Utility Study included numerous analyses. The EPA first collected HAP emissions test data from 52 EGUs, including a range of coal-, oil-, and natural gas-fired units, and the test data along with facility-specific information were used to estimate HAP emissions from all 684 utility facilities. The EPA determined that 67 HAP were potentially emitted from EGUs. EPA conducted a screening level assessment of all 67 HAP to prioritize the HAP for further analysis. Six HAPs (mercury, radionuclides, arsenic, cadmium, lead, and dioxins) were considered a priority for multi-pathway assessment of exposure and risk. Based on these analyses, EPA determined that Hg from coal-fired EGUs was the HAP of greatest potential concern.

Congress also directed the EPA to conduct a study specifically on mercury emissions from EGUs, municipal waste combustion units, and other sources. This is referred to as *the Mercury Study*. In this study, the EPA was directed to consider the rate and mass of mercury emissions, the health, and environmental effects of such emissions, available control technologies, and the costs of those technologies. Congress also directed the National Institute of Environmental Health Sciences (NIEHS) to conduct a study to determine the threshold for mercury concentrations in the tissue of fish which may be consumed (including consumption by sensitive populations) without adverse effects to public health. In addition, Congress directed the EPA to fund the National Academy of Sciences (NAS) to perform an independent evaluation of the available data related to the health impacts of methylmercury (MeHg). Specifically, Congress required the NAS to advise the EPA as to the appropriate reference dose (RfD) for MeHg. The RfD is the amount of a chemical which, when ingested daily over a lifetime, is anticipated to be without adverse health effects to humans, including sensitive subpopulations.

As directed by Congress through different vehicles, the NAS Study and the NIEHS Study evaluated the same issues. The NIEHS completed their study in 1995 and the NAS study was completed in 2000.

On 20 December 2000, the EPA issued a finding that it was "appropriate and necessary" to regulate coal- and oil-fired EGUs under CAA Section 112 and added such units to the list of source categories subject to regulation. Once the source category was listed, the EPA was then required to establish technology-based emission standards. More specifically, the EPA was required to establish emission standards that reflect the "MACT" level of control. By statute, the MACT standards for existing sources must be at least as stringent as the average emission limitation achieved by the best performing 12% of existing sources in the category (for which the Administrator has emissions information). This level of minimum stringency is referred to as the *MACT floor*, and the EPA cannot consider cost in setting the floor. For new sources, MACT standards must be at least as stringent as the control level achieved in practice by the best controlled similar source. The EPA must also consider more stringent "beyond-the-floor" control options, but must take into account costs, energy, and nonair quality health and environmental impacts when doing so.

The EPA did issue standards for Hg emissions from coal- and oil-fired power plants. However, instead of issuing emission standards under CAA Section 112 (covering HAPs), the Agency, on 29 March 2005, issued the Section 112(n) Revision Rule that removed EGUs from the list of sources subject to regulation under CAA Section 112. This Revision Rule essentially reversed the Agency's previous finding and determined that it was neither appropriate nor necessary to regulate such units under CAA Section 112.

Subsequently, on 18 May 2005, the EPA issued the Clean Air Mercury Rule (CAMR). That rule established standards of performance for emissions of Hg from new and existing coal-fired EGUs under CAA Section 111 (New Source Performance Standards, NSPS).

A collection of environmental groups, states, and tribes challenged the Section 112 delisting action and the legality of the CAMR. On 8 February 2008, the D.C. Circuit Court vacated both the 2005 delisting action and the CAMR. The D.C. Circuit held that the EPA had failed to comply with the requirements for delisting source categories from Section 112. Thus, CAMR and the 2005 delisting action became null and void and the rule was never implemented.

On 18 December 2008, several environmental and public health organizations filed a complaint in the U.S. District Court for the District of Columbia. They alleged that the EPA had failed to perform a nondiscretionary duty by failing to promulgate final CAA Section 112(d) standards for HAP from coal- and oil-fired EGUs by the statutorily-mandated deadline. The EPA settled the litigation and agreed to issue final MACT emission standards for coal- and oil-fired EGUs by 16 December 2011.

3.1.3 Mercury and Air Toxics Standards ("MATS") – Existing Sources

On 16 December 2011, the EPA Administrator signed the Mercury and Air Toxics Standards (or "MATS") which requires that coal- and oil-fired EGUs meet HAP

Table 3.1 Final mercury emission limits in the U.S. EPA "Mercury and Air Toxics Standards (MATS)" for existing fossil fuel power plants.

Sources	lb $TBtu^{-1}$ (input)	lb GWh^{-1} (output)	~µg m^{-3}
Existing plants			
Coal > 8300 Btu lb^{-1}	1.2	0.013	1.40
Coal < 8300 Btu lb^{-1}	4.0	0.04	4.70
Solid oil-derived fuel	0.2	0.002	0.23
IGCC units	2.5	0.03	2.90

The emission limits for existing units are provided in pounds of mercury per trillion British thermal unit of heat input or alternatively in units of pounds of mercury per gigawatt-hour of power output, both based on a 30 day rolling average. The measured emission in micrograms per cubic meter is an approximate value only; the affected units must show compliance with the input or output based standard. The EPA did not set emission limits for natural gas-fired power plants. Solid oil-derived fuel is commonly known as *petroleum coke* or *pet coke*.

standards reflecting the performance of the MACT. The rule [2] established uniform emissions-control standards that affected sources can meet with proven and available technologies and operational processes. The rule set emission limits for mercury and other toxic metals (such as arsenic, cadmium, lead, and nickel), for hazardous acidic gases (such as hydrochloric and hydrofluoric acids) and set work practice standards to limit the emissions of toxic organic pollutants, including benzene and dioxins.

The specific limits for subcategories of existing EGUs are given in Table 3.1. The emission limits are provided for mine-mouth units designed for and burning low rank, virgin coal with a calorific value <8300 Btu lb^{-1} (this will represent primarily units utilizing lignite coal), all other coals, solid oil-derived fuel (petroleum coke), and integrated gasification combined cycle (IGCC) units (regardless of fuel source). If an EGU burns coal (either as a primary fuel or as a supplementary fuel) or any combination of coal with another fuel (except for solid waste) where the coal accounts for more than 10.0% of the average annual heat input during any three consecutive calendar years or for more than 15.0% of the annual heat input during any one calendar year after the applicable compliance date, the unit is considered to be coal-fired.

For coal-fired, IGCC, and solid oil-derived fuel-fired units, operators must use a Hg continuous emissions monitoring system (CEMS) or a sorbent trap monitoring system for both initial and continuous compliance.

CAA Section 112 specifies the dates by which affected sources must comply with this rule. New or reconstructed units must be in compliance immediately upon startup or the effective date of this rule, whichever is later. Existing sources may be provided up to 3 years after the effective date to comply with the final rule; if an existing source is unable to comply within 3 years, a permitting authority (usually the state) has the ability to grant such a source up to a 1 year extension, on a case-by-case basis, if such additional time is necessary for the installation

of controls. The EPA's Office of Enforcement and Compliance Assurance (OECA) also issued a memorandum describing the Agency's "intended approach regarding the use of administrative orders ("AOs") for sources that must operate in noncompliance with MATS for up to 1 year to address a specific and documented reliability concern."

3.1.4 Mercury and Air Toxics Standards ("MATS") – New Sources

On 16 December 2011, the final "MATS" also contained standards for new fossil fuel-fired EGUs (i.e., those that commence construction after 3 May 2011). The rule set emission limits for mercury and other toxic metals (such as arsenic, cadmium, lead, and nickel), for hazardous acidic gases (such as hydrochloric and hydrofluoric acids) and set work practice standards to limit the emissions of toxic organic pollutants, including benzene and dioxins. The CAA specifies that, for new sources, the emission limitation "shall not be less stringent than the emission control achieved in practice by the best controlled similar source."

Following promulgation of the final MATS rule, the EPA received several petitions for reconsideration of numerous provisions of both the MATS rules, including the achievability of the final new source standards. The EPA Administrator agreed to reconsider certain aspects of the final MATS rule and the reconsideration proposal was published on 30 November 2012 [3]. The reconsidered emission limits for new sources were finalized in March 2013.

The mercury emission limits for subcategories of new EGUs are given in Table 3.2. The original final emission limits are given along with final reconsideration emission limits. As with existing sources, the emission limits are provided for mine-mouth units designed for and burning low rank, virgin coal with a calorific value <8300 Btu lb^{-1} (this will represent primarily units utilizing lignite

Table 3.2 Final mercury emission limits in the U.S. EPA "Mercury and Air Toxics Standards (MATS)" for new fossil fuel power plants.

Sources	MATS original (lb GWh^{-1}) (output)	MATS revised (lb GWh^{-1}) (output)	Revised (~µg m^{-3})
New plants			
Coal > 8300 Btu lb^{-1}	0.0002	0.003	0.35
Coal < 8300 Btu lb^{-1}	0.04	0.04	4.70
Solid oil-derived fuel	0.002	0.002	0.23
IGCC units	0.003	0.003	0.35

The emission limits for new coal-fired or IGCC power plants are provided only in units of pounds of mercury per gigawatt-hour of power output, based on a 30 day rolling average. The measured emission in micrograms per cubic meter is an approximate value only; the affected units must show compliance with the output based standard. The EPA did not set emission limits for natural gas-fired power plants. Solid oil-derived fuel is commonly known as *petroleum coke* or *pet coke*.

coal), all other coals, solid oil-derived fuel (petroleum coke), and IGCC units (regardless of fuel source). New sources may only meet an output based emission limitation.

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4
International Legislation and Trends

Lesley L. Sloss

4.1
Introduction

Some regions and countries in Europe, Australia, and Asia are actively monitoring and controlling mercury emissions. However, they are currently doing so without the apparent urgency incurred by national and regional binding legislation and specific mercury reduction targets that are being applied in Canada and introduced in the United States at the moment. That is not to say that mercury is not being controlled outside North America. Rather that this control of mercury is largely being achieved as a result of co-benefit effects.

There were a number of international treaties, set by the United Nations Environment Programme (UNEP), which included mercury. These were not challenging with respect to mercury limits and therefore did not require any action to be taken at coal-fired utilities. The UNEP Governing Council made a decision in February 2009 to further strengthen international action on mercury and initiated negotiations toward producing a "Global legally binding instrument on mercury." This instrument, is known as the *Minamata Convention*, was completed in February 2013. The convention promotes BAT at all new coal-fired power plants and requires a national action plan, with options for BAT, emission limits, reduction targets and so on, to be taken at all existing plants. There is enough flexibility in the wording to allow signatory countries to determine their own best approach to reducing mercury emissions from this sector.

Concern has been expressed that the rapid increase in coal use in countries such as those in Asia may override reductions in emissions achieved elsewhere. It is therefore essential that any international mercury legislation is made both technically and economically viable in developing countries to ensure that the current upward trend in global mercury emissions is controlled effectively. These are the kind of issues which have been addressed within the flexibility of the UNEP convention.

This chapter will summarize both international and national legislation (excluding the United States). Mercury legislation is currently in a state of extreme flux and, as a result, the information included in this chapter can only be regarded as a

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snapshot of the issue as this document goes to print. However, it is clear that many countries, not just those in North America, are moving toward stringent control of all toxic emissions and so legislation for mercury control can be regarded as somewhat inevitable. It remains only to be seen what form this legislation may take in different regions and how soon it will be initiated.

4.2 International Legislation

There are a number of international agreements and action plans to co-ordinate activities to reduce mercury emissions. These include [1]

UNECE	The United Nations Economic Commission for Europe (UNECE) has a convention on long-range trans-boundary air pollution (LRTAP). This convention was published in 1998 and covers heavy metals including mercury. The protocol has been signed by Canada, Europe, Russia, and the United States. Although the protocol calls for the installation of BAT at new stationary sources, it does not go so far as to define BAT for coal-fired plants or to specify any reduction strategies.
OSPAR	Oslo and Paris Commission's program on reduction of land-based pollutants transported to the North Sea.
HELCOM	The Helsinki Commission program covering the North Sea.
Barcelona Convention	A program similar to OSPAR and HELCOM covering the Mediterranean Sea.
MEPOP	European political initiative studying the atmospheric cycling of mercury and persistent organic pollutants.
Nordic	Co-ordination of projects between Denmark, Finland, Norway, and Sweden to reduce mercury emissions.
Arctic	The Arctic Council's Environmental Protection Strategy includes mercury.
NARAP	North American Regional Action Plan between Canada, the United Mexican States, and the United States to reduce mercury fluxes.
Binational Toxics	Canada and the United States have a project for cleaning up substances, including mercury, in the Great Lakes Basin Area.

None of these agreements or programs includes guidelines on how the proposed reductions in emissions or concentrations should be achieved other than by recommending "best practices." The agreements rely on the individual governments of each signatory country to produce a successful strategy to reduce mercury emissions. They therefore do not necessarily guarantee results. Action is rarely, if ever, taken against countries that are not as successful as others in

reducing emissions. For the moment, there is no international treaty that requires specific mercury control at coal-fired utilities. However, this may change with the introduction of the UNEP "Minamata Convention."

4.2.1 UNEP International Legally Binding Instrument on Mercury ("Minamata Convention")

In February 2009, the Governing Council of the UNEP agreed on Decision 23/9 defining the need to develop a global legally binding instrument on mercury. The convention was completed in February 2014. The final text requires that signatory parties take measures to control and, where feasible, reduce emissions. New plants will have to apply BAT/BEP and BAT/BEP is an option, alongside emission limit values, reduction targets, multi-pollutant strategies or "alternative measures", for existing sources. The definition of BAT within the convention is to be determined by the conference of the parties but must take geographical, technical and economic considerations into account. And so, at this stage, it is up to each signatory country to determine how the convention will be applied to sources within their jurisdiction.

4.2.2 European Union (EU)

There are three established directives which are currently relevant to coal-fired utilities in the European Union (EU) member states:

- the Integrated Pollution Prevention and Control (IPPC) Directive;
- the Large Combustion Plant Directive (LCPD); and
- the Waste Incineration Directive (WID, applicable to plants co-firing waste with coal).

All these directives will continue to apply until they are replaced by

- the Industrial Emissions Directive (IED), which comes into force for coal-fired power plants in 2016.

It is therefore necessary to discuss each of these directives in turn to appreciate the ramifications for utilities in Europe. Although none of these Directives specifies emission limits or control requirements for mercury, the technologies that plants must install to meet SO_2 and NO_x limits will have a significant effect on mercury emissions.

EU-Directive on IPPC (2008/1/EC) (EC, European Commission) applies an integrated environmental approach to the regulation of around 45 000 industrial facilities, including large combustion plants, in the EU. The directive is based on a plant-specific permit which details the requirements relevant to each individual facility and can therefore take into account not only any international and national requirements (such as reduction targets for UNECE protocols and EU emission limits) but also regional and local considerations such as preservation of sensitive

watershed areas. For particulates, the BAT options are electrostatic precipitator (ESP) (99.5% efficiency) in combination with wet flue gas desulfurization (FGD); or bag houses (fabric filters) (99.95% efficiency) in combination with wet FGD. For SO_2, the BAT options are either low-sulfur fuel, wet FGD, spray dry FGD, seawater FGD, or combined SO_2 and NO_x systems. For NO_x, the BAT options are primary measures (air/fuel staging, low NO_x burners, re-burn) in combination with SCR (selective catalytic reduction) or SNCR (selective non-catalytic reduction) in some cases; or combined SO_2 and NO_x systems. However, the choice of which control combination is suitable as BAT for each individual plant has to be defined on a case-by-case basis under each permit and is based on extensive BAT reference documents (BREFs) provided by the EC.

The revised LCPD (2001/80/EC) applies to combustion plants with a thermal output of >50 MW. According to the directive, by 1 January 2008, all large combustion plants in Europe had to opt for one of the following three compliance options:

1) meet emission limit values (ELVs) for particulates, SO_2 and NO_x;
   a. 200 mg m^{-3} SO_2 for new plant and 400–2000 mg m^{-3} for existing plant (based on size);
   b. 200–400 mg m^{-3} NO_x for new plant and 500–600 mg m^{-3} for existing plant (based on plant size)
2) sign up to lower SO_2 and NO_x "bubbles" that are equivalent to the ELV reductions and which are part of a National Emission Reduction Plan (NERP); or
3) "opt-out" of ELVs and NERP and commit to close by 2015, operating for no more than 20 000 h over that period.

Therefore, to meet both the IPPC BAT requirements and the LCPD ELV with fuel switching alone, plants would need to be firing very low-sulfur coal to avoid having to install FGD [2]. In simple terms, the IPPC and LCPD together mean that all plants must install wet FGD (or a technology with similar or greater SO_2 control) and make at least combustion modifications to reduce NO_x (some plants will require SCR in addition to combustion modifications). Plants which could not comply with either option 1 or 2 above were to close by 2016 and run limited operating hours until that date.

Many plants within Europe regarded the ELVs defined by the LCPD as too challenging. Before the LCPD was replaced by the IED, almost 25 GW of coal units and 10 GW of lignite units decided not to install FGD, particularly in Spain, France, and the United Kingdom in Western Europe. These plants chose to opt-out of the LCPD and close by 2016 [3].

If co-combustion of other waste is to be applied at an existing coal-fired plant, the emission limits must be revised according to the EU WID (2000/76/EC). Table 4.1 includes a summary of the EU emission limits under the WID alongside the emission limits in Germany (*see* below) [4].

The WID limits are more stringent than those in the LCPD. Under the "mixing rule," plants firing waste materials defined under the WID must calculate a specific emission limit based on the amount of waste material being co-fired. However, this

Table 4.1 German emission limits for waste incineration plant and power plant [4].

Compound	Thirteenth BImSchv[a)]	Seventeenth BImSchv[a)]		EU-Directive			
	Power plants	Waste incineration		Waste incineration		Co-combustion	
						Power plants >300 MWth	Cement kilns
	Daily average (6% O_2)	Daily average (11% O_2)	Half-hour average (11% O_2)	Daily average (11% O_2)	Half-hour average (11% O_2)	Daily average (6% O_2)	Daily average (10% O_2)
CO (mg m^{-3})	250	50	100	50	100	Mixing rule	—
Organic compounds as total C (mg m^{-3})	—	10	20	10	20	Mixing rule	10
Particulate matter (mg m^{-3})	50	10	30	10	30	30	30
SO_2/SO_3 as SO_2 (mg m^{-3})	400	50	200	50	200	200	50
Sulfur emission factor (%)	15	—	—	—	—	5	—
NO_x (mg m^{-3})	500	200	400	200	400	200	800
HCl (mg m^{-3})	100	10	60	10	60	Mixing rule	10
HF (mg m^{-3})	15	1	4	1	4	Mixing rule	1
Σ TI + Cd (mg m^{-3})	—	0.05	—	0.05	—	0.05	0.05
Hg (μg m^{-3})	—	0.03	0.05	0.05	—	0.05	0.05
Σ Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V, Sn (mg m^{-3})	—	0.5	—	0.5	—	0.5	0.5
PCDD/PCDF (ng m^{-3})	—	0.1	—	0.1	—	0.1	0.1

a) Bundesimmissionsschutz-Verordnung or BImSchv limits.

does not apply to mercury and its compounds, for which the limit is 0.050 mg m^{-3} for all co-incineration plants. The WID is far more challenging with respect to compliance than the LCPD and so existing coal-fired plants are generally reluctant to co-fire waste material that falls under the remit of the WID. In addition to the more stringent emission limits, the WID also has more demanding monitoring requirements.

In 2007, in recognition that the EU legislation at that time was somewhat piecemeal and confusing, the EC launched a review of the existing legislation with the aim of merging seven different directives into one. The directives which were merged were

- the Large Combustion Plant directive (LCPD);
- the Integrated Pollution Prevention and Control Directive (IPPC);
- the Waste Incineration Directive (WID);
- the Solvent Emissions Directive (SED); and
- the three existing directives on Titanium dioxide on (i) disposal (78/176/EEC), (ii) monitoring and surveillance (82/883/EEC), and (iii) programs for the reduction of pollution (92/112/EEC).

These directives were all merged into the new IED which was published by the EC in December 2010. The IED was to be drafted into national legislation within each of the Member States by 6 January 2013.

For coal-fired plants, the IED is effectively a combination of the IPPC and LCPD discussed above, containing aspects of both permitting and plant-specific requirements along with ELVs or equivalent reduction strategies. Each plant must have its own plant-specific permit with performance, based on a combination of BAT and ELVs.

The new IED allows some flexibility in the definition of BAT, according to the decisions of the local competent authority, and requires continued work at the EC level on BREFs. The IED also includes potential derogations where BAT is considered to be of a disproportionately high cost, as long as the ELV are still met. There is also still the option of a minimum desulfurization rate for plants which cannot comply with ELVs due to specific fuel characteristics.

As with the original LCPD, the IED allows the same three options for compliance: the ELV, the NERP (now referred to as the *National Action Plan*), or opt-out (eventual closure).

The new ELVs for SO_2 for combustion plants granted permits before 7 January 2013 are as follows:

Emission limit for SO_2 for plants permitted pre-2013 (mg m^{-3})

Plant size (MWt)	Coal, lignite, and other solid fuels	Biomass	Peat	Liquid
50–100	400	200	300	350
100–300	250	200	300	250
>300	200	200	200	200

The remaining plants must then meet more stringent SO_2 limits after 2016.

Emission limit for SO_2 for plants permitted post-2013 (mg m^{-3})

Plant size (MWt)	Coal, lignite, and other solid fuels	Biomass	Peat	Liquid
50–100	400	200	300	350
100–300	200	200	300	200
>300	150	150	150	150

For those plants, originally permitted prior to 2013, which cannot meet the prescribed ELV due to specific fuel characteristics, there is still the option of meeting a minimum rate of desulfurization, shown below.

Desulfurization rate for SO_2 for plants with challenging fuel, permitted pre-2013

Plant size (MWt)	Plants permitted before 27 November 2002 (%)	Other plants (%)
50–100	80	92
100–300	90	92
>300	96	96

All other plants must meet tighter reduction requirements.

Desulfurization rate for SO_2 for plants with challenging fuel, permitted post-2013

Plant size (MWt)	(%)
50–100	93
100–300	93
>300	97

Both these reduction requirements and the ELVs listed above would require, in most if not all instances, the use of FGD technologies.

For those plants firing low-sulfur fuel, there is a potential derogation period of 6 months, which will be permitted during instances of interruption in the supply of low-sulfur fuel (such as that resulting from a serious shortage).

The new NO_x limits (milligrams per cubic meter) for combustion plants granted permits before 7 January 2013 are as follows:

Emission limit for NO_x for plants permitted pre-2013 (mg m^{-3})

Plant size (MWt)	Coal	Lignite	Biomass and peat	Liquid
50–100	300	450	300	450
100–300	200	200	250	200
>300	200	200	200	150

Plants not permitted before 7 January 2013 must meet the following limits after 2016:

Emission limit for NO_x for plants permitted post-2013 ($mg\,m^{-3}$)

Plant size (MWt)	Coal	Lignite	Biomass and peat	Liquid
50–100	300	400	250	300
100–300	200	200	200	150
>300	150	200	150	100

For most plants, low NO_x burning systems may not be able to reach these limits and additional SCR or SNCR technologies will be required.

As with the original LCPD, under the new IED, plants may be exempt from the ELV if they agree to the following:

- to operate no more than 17 500 h between 1 January 2016 and 31 December 2023 (a more forgiving timescale than the LCPD);
- to report hours of operation on an annual basis; and
- ELVs prescribed in the plant permit on 31 January 2015 shall be maintained for the remaining operation period of the plant.

The IED carries with it requirements for continuous emission monitoring (CEM) of particulates/dust, SO_2, and NO_x on all plants. Although the IED does not set an ELV for mercury from coal-fired utilities, it does introduce a requirement for annual monitoring of mercury emissions.

Although this monitoring requirement for mercury is the only mention of mercury in the new IED, this does not mean that mercury is not under control. Studies carried out in the EU and elsewhere have consistently shown that the installation of control technologies for particulates, SO_2 and NO_x on coal-fired power plants can effectively reduce mercury emissions. For most plants and coals, the combination of particulate controls and wet FGD systems will mean at least 70% mercury reduction [5, 6]. If SCR is also included, as will be the case at many EU plants, mercury capture can be up to and over 90%. While this significant reduction rate is certainly not guaranteed, especially for some challenging coals, most plants will still achieve some co-benefit mercury control. By introducing the requirement for mercury monitoring at all plants, the EC will gather data on just how effective the control systems required under the IED are for mercury control and, based on this, may or may not set mercury specific legislation in the future. Although, for the moment, mercury emissions are regarded as largely under control, the new IED BREFs (currently being updated to include mercury) may well define BAT levels for mercury based on available information and reductions achieved so far and this could mean requirements for mercury on some plants in the future.

4.3
Regional and National Legislation

The following sections summarize the situation in several example countries and regions (excluding North America) that either have legislation for mercury control or have monitoring and compliance regimes that are potentially moving toward mercury specific legislation.

4.3.1
Europe

As discussed earlier, the existing IPPC and LCPD and their replacement, the IED, will not target mercury directly but are still likely to result in significant mercury reductions as a result of co-benefit effects.

Individual member states within the EU must adopt EU legislation as national legislation within a set time period. Over and above this, each country may set its own legislation or reduction targets based on more local environmental challenges or concerns. Countries such as Germany and the Netherlands often go above and beyond what is required by EU legislation.

4.3.1.1 Germany

The Thirteenth Ordinance of the Federal Immission Control Act (13 BImSchV) set an emission limit of 30 $\mu g\, m^{-3}$ for mercury at all coal-fired utility plants, and continuous emission monitors for mercury are also required at all plants. Daily average and half-hour average values are required. As all plants have FGD and SCR fitted, mercury is also captured efficiently and, as yet, no mercury specific control technologies have been required at any plants firing coal alone (H. Thorwarth, Personal Communication, 2008). Germany has around 20 plants co-firing sewage sludge with coal, as summarized by Fernando [7]; these plants face a significant challenge with respect to mercury emissions and control.

Under the IPPC/IED permitting scheme, individual plants may be granted a permit that sets emission limits or control requirements which are more challenging than those for other national plants. Unpublished information suggests that a new coal-fired plant (Staudinger) in Germany will be facing a mercury emission limit in the order of 15 $\mu g\, m^{-3}$. No more details are available at this time.

4.3.1.2 Netherlands

Similar to Germany, the Dutch Government takes a pro-active approach to emission control and often sets national and regional legislation, which is significantly more stringent than that set by the EU. Although the current IED for the EU specifies BAT requirements only for particulates, SO_2 and NO_x, permits for Dutch coal-fired plants must also consider BAT for mercury. This is based on an estimated mercury input (fuel content) and the yearly average removal efficiency of the air pollution control devices (APCDs), as measured during monitoring campaigns.

KEMA in the Netherlands have developed the KEMA TRACE MODEL® (KTM), an empirical and statistical model developed from mass balance studies

at all the coal-fired plants in the Netherlands over 25 years. The model can cope with co-firing secondary fuels such as biomass up to 30% on a mass base. The model covers 46 elements, including mercury. The calculated emissions, based on the fuel data, are compared to relevant emission regulations such as the LCPD or IED and any national regulations. The KTM is well trusted and is used in the impact statements and permit applications of coal-fired plants in the Netherlands (H. Te Winkel, Personal Communication, 2011).

Although there has been nothing published as yet, it would appear that three new coal-fired plants in the Netherlands, including units at Maasvlakte and Datteln, could face plant-specific mercury regulations that would limit mercury emissions to around 3 $\mu g\, m^{-3}$ on an annual basis.

4.3.2 Asia

Asia contains some of the cleanest and some of the dirtiest coal-fired plants in the world. Several areas of Asia, such as Japan and South Korea, have already retrofitted most if not all of their plants with state-of-the-art emission control systems. Other areas, such as China and India, have such rapidly growing populations and economies that bringing all plants up to satisfactory emission limit standards is a challenge. The majority of environmental work being undertaken in India under a national government program is to improve the efficiency of existing coal-fired plants. Significant improvements in efficiency can be achieved, resulting in extended plant lifetime, reduced fuel consumption, increased energy output, and reduced emissions. For most of the plants studied, this rehabilitation makes more economic sense than the construction of new plants.

China has a range of plans and programs to reduce emissions of SO_2 based on limits and emission fees. The Chinese Government has recently introduced a new policy based on the phasing out of smaller, less-efficient coal-fired units. Other Asian nations face their own local challenges. To date, the environmental performance of each plant in many developing Asian nations depends on the location (for example, whether it is causing noticeable local effects) or on the operator/utility (depending on the level of pro-activeness). Emission monitoring is not common in most of Asia and therefore it is hard to determine compliance with any applicable emission standards. It is also difficult to determine which plants should receive priority when it comes to investment for rehabilitation or retrofitting without emission information. A move toward increased measurement and monitoring in these areas would help evaluate areas of concern to produce the most effective national policies.

The following sections summarize the situation in selected countries in Asia.

4.3.2.1 China

Chinese emission legislation is defined within 5- and 10-year plans. These plans are not law, but are rather targets that are achieved through agreements, performance, incentives, or existing laws [8]. Recently, the Chinese government's

efforts have concentrated on sulfur emissions. Despite some missed reductions in the past, the reduction target for SO_2 under the Eleventh 5 year plan (2006–2010; 10% reduction below 2005 levels) was met early and exceeded (a 14% reduction was achieved). This reduction was achieved largely due to the installation of FGD. The success of this Eleventh plan may be due to the strengthening of the approach with binding agreements with provinces and key emitters, economic and administrative incentives, performance audits, and stronger enforcement of existing laws. There has also been an unprecedented installation rate of FGD in China. In 2005, only 14% of the installed coal-fired generating capacity had been fitted with FGD but this had increased to 86% by the end of 2010 [9]. This would no doubt have resulted in significant co-benefit mercury reduction.

The *Emission Standard of air pollutants for thermal power plants* (GB 13223-2011) was adopted by the Chinese Ministry for Environmental Protection (MEP) on 18 July 2011 and should be effective starting 1 January 2012 [10]. The standard applies to particulate, SO_2, NO_x, and mercury emissions from coal-fired plants but does not apply to plants co-firing waste or biomass. Emissions of mercury will be controlled from 1 January 2015. The limit for mercury is set at 0.03 mg m^{-3}. However, because of known co-benefit effects, the limits for SO_2 and NO_x are also relevant. The full emission limits are listed in the table below.

Emission limits for coal-fired boilers in China, from 2011 (for particulates, SO_2 and NO_x) to 2015 (for mercury)

Pollutant	Conditions	Limit (mg m^{-3})
Soot	All units	30
	Plants in "key regions"[a)]	20
SO_2	New boiler	100
		200[b)]
	Existing boiler	200
		400[b)]
	Plants in "key regions"[a)]	50
NO_x (as NO_2)	All	100
		400[c)]
	Plants in "key regions"[a)]	100
Hg and compounds	All	0.03

[a)] Plants in "key regions" are defined as those situated where development is concentrated and environmental capacity is low (such as existing weak environmental capacity, vulnerable ecological environment, and major air pollution problems, as defined by the MEP).
[b)] Applies in Guangxi Zhuang Autonomous Region, Chongqing Municipality, Sichuan Province, and Guizhou Province.
[c)] W-type thermal power generation boilers, furnace chamber flame boilers, circulating fluidized bed boilers, and boilers in operation before 31 December 2003.

The limit set for mercury, 30 μg m^{-3}, is equivalent to the general emission limit for coal-fired units in Germany (see below) and applies to both existing and new

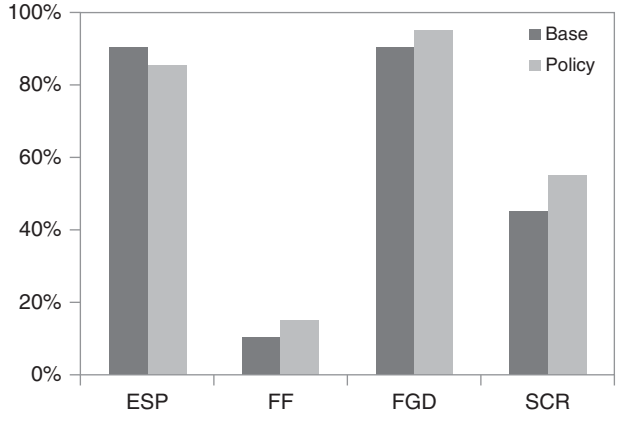

Figure 4.1 Chinese projections: application rate of emission controls in 2020.

plants. It is therefore significantly less stringent than the limits set in the United States and would be achieved by most modern plants fitted with ESP or baghouse systems firing standard coals. However, the limits set for SO_2 and NO_x will be challenging and are likely to result in FGD on all plants and upgrades on many existing FGD systems, SCR on almost all plants, and upgrading of ESPs with potential retrofitting of fabric filters in some cases. This will mean that, although the mercury limit will not itself result in mercury control, the co-benefit effects of the new SO_2, NO_x, and particulate limits are likely to result in significant mercury reduction.

A report produced by Tsinghua University for MEP under a UNEP Coal Partnership project included emission estimates for mercury from coal-fired utilities in China for 2005 and 2008 along with predictions for mercury reduction under future energy scenarios in 2020 [11]. The scenarios are summarized in Figure 4.1 and the predicted reductions as a result of each of these are summarized in Figure 4.2. It is important to note that these scenarios were produced prior to the new 2011 standards and so the predicted mercury reduction may be even more significant.

The new Chinese limits are challenging and are predicted to cost the Chinese economy at least 260 billion yuan ($40.74 billion) [12]. It is not clear whether this cost will include potential new monitoring requirements including CEM systems to ensure compliance. It therefore remains to be seen whether the Chinese coal sector can afford to comply with the new limits, bearing in mind the current increase in coal prices.

4.3.2.2 Japan

Environmental legislation in Japan is set on an individual company/plant basis and it is not simple to summarize the requirements that apply. There is a very high priority based on social responsibility and most companies wish to enhance their public credibility by not exceeding any requirements set. Most, if not all, coal-fired

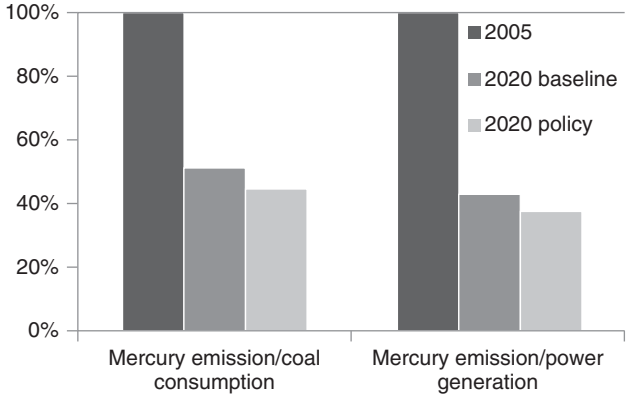

Figure 4.2 Chinese projections: mercury emission intensities in 2020.

units in Japan already have FGD and deNO_x systems in place and many plants pride themselves in fitting the most up-to-date systems [1]. By 2000, over 90% of plants had wet scrubber systems installed and <3% had no flue gas treatment for sulfur. Over 75% of plants have both low NO_x burners and SCR systems installed and the remainder had one or the other [13].

4.3.2.3 **Other Asian Countries**

The Philippines have a mercury emission limit from any source of 5 mg m^{-3}. At the moment, there are 12 coal-fired plants in the country, four of which are FBC systems (fluidized bed combustion) systems. New plants are required to install FGD systems and low NO_x burners. There is also a fee levied, which is proportional to emissions. However, some plants obtained a "grace period" from these fees to help fund the installation of control technologies, for which tax credits are also available [14].

Prior to 2010, there was no limit for mercury from coal-fired plants in *Korea* other than the general limit for mercury emissions for all industrial emissions set at 5 mg m^{-3}. However, the new standards, promulgated in 2010, set an emission limit for mercury and its compounds for all coal-fired facilities at 0.1 mg m^{-3}. As can be seen in Figure 4.3, this limit can easily be met by almost any plant fitted with an ESP system. New legislated emission limits for SO_2 are set at 100 ppm for existing plants >100 MW (in operation before 1996) and 80 ppm for new plants. The limit for NO_x is 150 ppm for existing plants and 80 ppm for new plants. This is equivalent to around 300 mg m^{-3}. This may require SCR systems on some plants, which will improve mercury capture due to co-benefit effects. However, it has been proposed that mercury CEMs be introduced at plants in Korea to monitor the effectiveness of the potential co-benefit effects of the SO_2 and NO_x control systems, which would provide information for a future review of the legislation by policy makers to potentially tighten mercury emission limits [15].

NB – the limit cited for Germany in this figure may be lower in practice as the standards are currently 50 μg m^{-3} for 30 min averages and 30 μg m^{-3} for 24 h

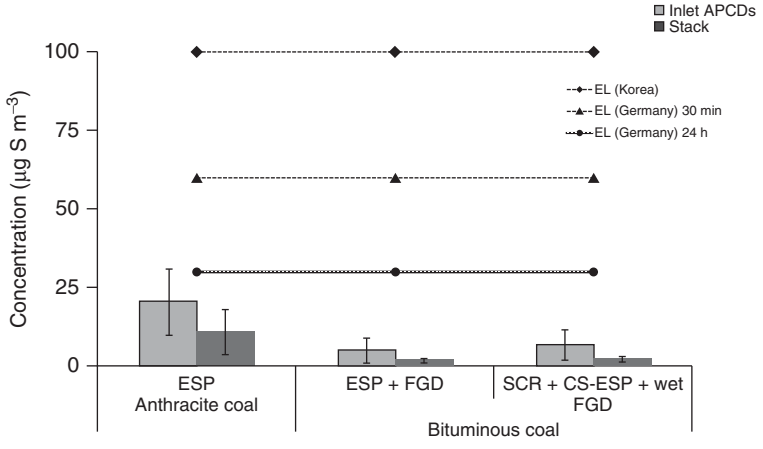

Figure 4.3 Measured mercury emission concentration and the permissible emission limit in current Korean and German regulations [15].

averages. However, the standards are still well above that which can be achieved in most plants fitted with APCD.

4.3.3 Other Countries

The following short sections summarize the situation on mercury emissions and control in selected countries.

4.3.3.1 Australia

Individual states in Australia have the jurisdiction to set their own emission legislation, including targets for greenhouse gas reduction. Over and above this, National Environmental Protection Measures (NEPM) can be set, based on goals, standards, protocols and/or guidelines. At the moment, although there is a National Pollutants Inventory (NPI) for the quantification of emissions, there are no binding national emission standards for SO_2 or NO_x. Emission guidelines for SO_2 and NO_x have been issued by the National Health and Medical Research Council (NHMRC). However, the limits are very general and were set at levels which could be met relatively easily. Australian coals are generally low in sulfur and therefore SO_2 emissions are not regarded as a high priority for control and there are, to date, no FGD or similar controls on any Australian coal-fired plants. Although NO_x limits have been specified in some states, it is thought that these are relatively lenient and have not required the installation of any NO_x control technologies [1].

The focus of Australian emission legislation is very much on the development of new clean coal technologies and low carbon options. So, for the moment at least, existing coal-fired power plants are not facing any retrofit requirements. Morrison and Nelson [16] have looked at future strategies for energy in Australia toward 2050. Most of the strategies considered relate to the reduction of mercury

and CO_2 emissions through the use of brown coal in IGCC (integrated gasification combined cycle) with and without CCS (carbon capture and storage). Australia's future energy strategies appear more concerned with greenhouse gas reductions and energy efficiency while SO_2 and NO_x emissions have much lower priority. It can therefore be assumed that there will be limited co-benefit reductions in mercury emissions, based on current legislation.

4.3.3.2 **Canada**

When the United States first introduced its Clean Air Mercury Rule (CAMR), Canada was quick to follow suit. However, the format the Canadian standard took differs from the CAMR and therefore, although the CAMR has now been abandoned, the Canada-Wide Standard (CWS) still applies. The CWS sets stringent emission reduction targets. There are provincial caps for each province, which apply to existing plants that require a total reduction of 60–70%. BAT is required on new plants. Individual provinces must decide the most appropriate means of meeting the required reduction targets and the approaches vary from enhanced co-benefit controls to activated carbon injection, and even complete plant closure [1].

4.3.3.3 **Russia**

In 1991, a national emissions charge system was introduced in Russia, which applied to over 300 air and water pollutants from a large number of stationary sources. However, monitoring and administrative capabilities are limited and the final charge is often open to negotiation between the source and the local authority. It is not uncommon for fees to be waived for sources experiencing financial problems. There does not appear to be any imminent move toward requirements for SO_2, NO_x, or mercury control [1].

4.3.3.4 **South Africa**

In March 2010, the South African Government established updated requirements for sulfur emission control. The limits are 3500 mg m^{-3} for SO_2 from existing coal-fired power plants and 500 mg m^{-3} for new plants (>50 MW). The emission limits for NO_x are 1100 and 750 mg m^{-3} for existing and new plants respectively [17]. There is also a move toward requiring the installation of FGD on all large coal-fired units in the country. However, the financial constraints and, perhaps more importantly, the limited availability of water in the country, will make the installation of FGD within the required time period a significant challenge. However, once FGD or equivalent sulfur control is required, some level of co-benefit mercury control can be expected.

4.4 Summary

At the moment, the majority of mercury control requirements apply in North America. Although there are international and national mercury emission limits

outside North America, the majority of these are not currently set at levels that require any significant action to be taken. This does not, however, mean that mercury is not being controlled. In fact, mercury reduction rates of over 50% and even over 95% are being achieved in countries which require state-of-the-art technologies for particulate, SO_2 and NO_x control as a result of co-benefit effects. Significant reduction in mercury emissions from the coal combustion sector have been achieved and are continuing in the EU and in countries such as Japan, Korea and, more recently, in China. And so, as a result, there is currently no real urgency to take specific action to control mercury. This may well change in the future if international and national bodies decide that current rates of mercury reduction in these regions are not sufficient.

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Part II
Mercury Measurement in Coal Gas

Mercury Control: for Coal-Derived Gas Streams, First Edition.
Edited by Evan J. Granite, Henry W. Pennline and Constance Senior.
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5
Continuous Mercury Monitors for Fossil Fuel-Fired Utilities

Dennis L. Laudal

5.1
Introduction

Instrumentation to measure mercury has been available for many years. However, until recently, these monitors were designed to measure ambient mercury and mercury in liquids. It has only been since about 1990 that the concept of using mercury instrumentation to measure mercury in flue gas generated by burning fossils fuels, such as coal, has been considered. Until that time, mercury measurements were made using wet-chemistry methods such as U.S. Environmental Protection Agency (EPA) Method 29, EPA Method 101A and, later, the Ontario Hydro method. Although these methods could be highly accurate, they were expensive and difficult to apply. As a result, a serious effort was made to further develop and optimize continuous mercury monitors (CMMs). CMMs have the following advantages over traditional wet-chemistry methods:

- Yield real- or near-real-time results
- Able to assess process variability
- May be used for system optimization
- Provide feedback for Hg control strategies
- Have the potential to be less costly and are less labor-intensive
- Give direct measure of pollutants
- May promote better public relations.

Before these monitors could be reliably used in utility applications, many challenges had to be overcome:

- Reliability
- Ability to accurately measure low mercury concentrations
- Measurement environment
- Dynamic range
- National Institute of Standards and Technology (NIST) traceability for calibration.

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To resolve some of these issues, as well as others, CMMs have become complex, with multiple parts, and new definitions were needed. For the purposes of this chapter, the entire mercury measurement system is called a *CMM*. The section of the CMM that actually analyzes the mercury in the gas steam is referred to as a *mercury analyzer*. Even this is a bit of a misnomer in that these instruments are not actually continuous. With the exception of a few *in situ* systems, all mercury monitors draw flue gas into an analyzer utilizing a pump and there is a time lag between instrument readings, which can be minutes or seconds depending on the instrument. The exact number of CMMs installed is unknown because many of the CMMs that were installed were not verified and/or removed following the vacature of the Clean Air Mercury Rule (CAMR). However, it is known that about 600 CMMs have been sold to the utility industry with about two-thirds

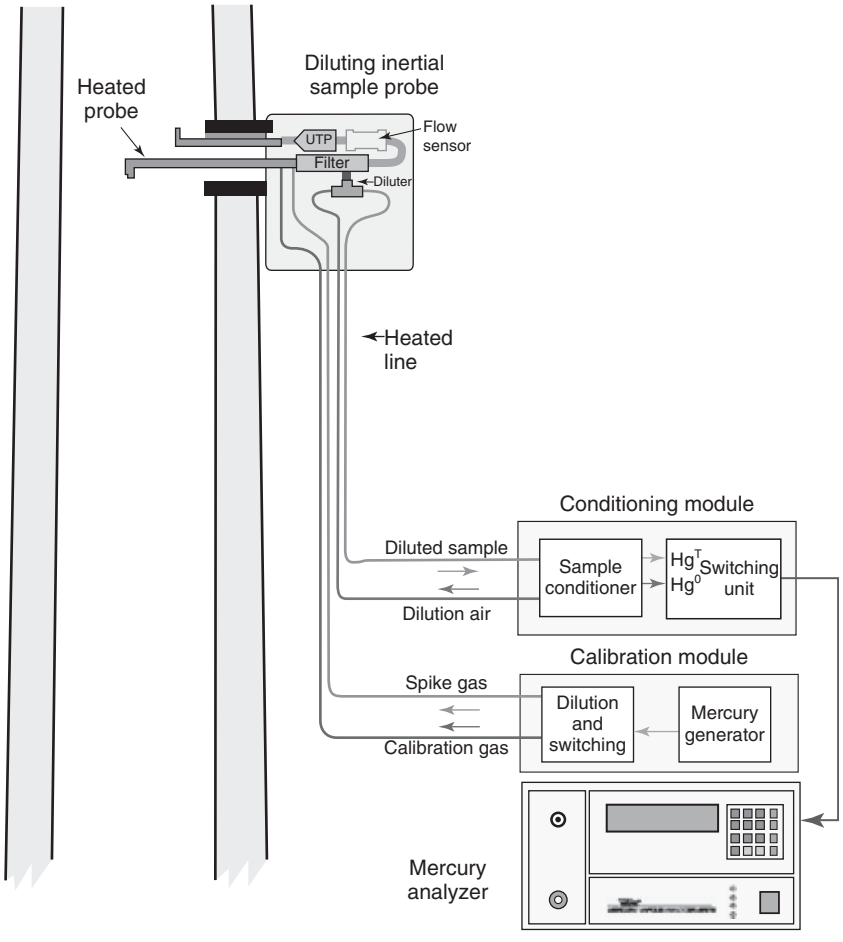

Figure 5.1 Diagram of a CMM.

manufactured by Thermo Scientific and about one-third by Tekran, with a small number supplied by other CMM vendors [1].

5.2 Components of a CMM

In general, a CMM designed for combustion flue gas has four main sections: the probe, the pretreatment and conversion system, the mercury analyzer, and the calibration system. How each of these sections is configured is highly dependent on the vendor. A diagram illustrating this is shown in Figure 5.1.

5.2.1 Mercury Analyzer

With several exceptions, all mercury analyzers measure mercury using either cold-vapor atomic absorption spectroscopy (CVAAS) or cold-vapor atomic fluorescence spectroscopy (CVAFS).

5.2.1.1 Cold-Vapor Atomic Absorption Spectrometry

The most popular method for determining mercury in almost any type of sample in the past has been based on CVAAS and the technique is still widely used today. Mercury is unique among metals in that it has a very high vapor pressure at relatively low temperatures and can be introduced quantitatively to the spectrometer as a vapor without difficulty. Absorption at 253.65 nm in the ultraviolet (UV) region has been measured with the use of mercury vapor lamps as well as hollow cathode lamps as the light source. Such methods are quite old; mercury vapor meters were first developed in the 1930s [2]. A typical CVAAS scheme is shown in Figure 5.2. CVAAS systems typically are considered to have detection limits somewhere in the $0.05-1.0\,\mu g\,m^{-3}$ range, depending on the design of the system.

When mercury concentration in a mixed gas stream is measured, a number of gases such as SO_2 can interfere with a CVAAS detector. A number of approaches have been taken to either remove these interference gases or greatly reduce their impact [3]. These include the use of a dual path with two detectors, gold amalgamation of the mercury, and the Zeeman effect.

In the dual-path method, the gas stream is split, with one of the streams having the mercury removed using a gold or activated carbon cartridge. The absorbance of the two streams is then subtracted, resulting in the absorbance due to the mercury. The second technique, gold amalgamation, is based on the selective adsorption of mercury on a gold surface at room temperature. Mercury is released from the gold trap by heating and then introduced into the spectrometer using an inert gas. As a result, the only gas analyzed is the mercury. The method has the advantage of not only removing interferences but also allowing for the mercury to be concentrated, making it possible to achieve increased sensitivity without actually

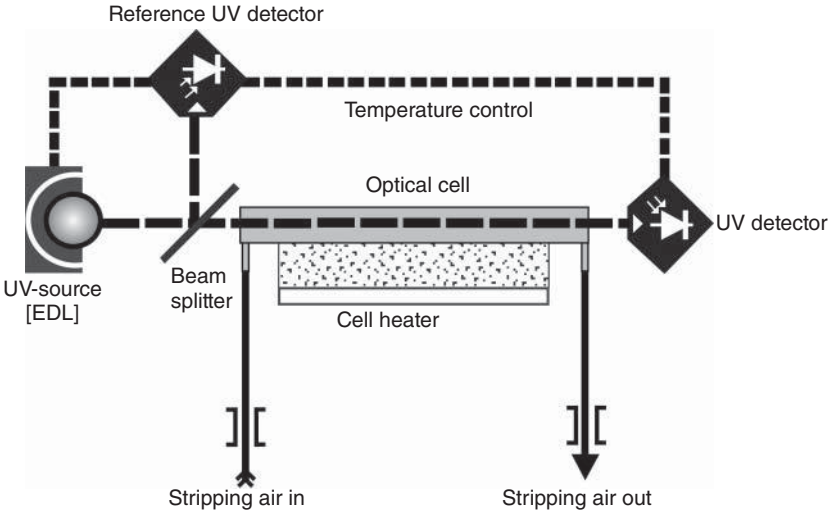

Figure 5.2 Simplified diagram of a CVAAS analyzer with dual beam (EDLs, electrodeless discharge lamps).

changing the detection limit. Because of this concentration effect, it is possible to use dilution to help minimize gases that could poison the gold trap, which is a concern when this technique is used.

As stated previously, one of the flue gas constituents that greatly reduces the sensitivity of CVAAS for mercury is SO_2, particularly in concentrations >100 ppm. Unfortunately, the UV absorption peak for SO_2 is a broad band that partially overlaps the mercury absorption peak of 253.65 nm. As a result, several mercury analyzers use the Zeeman effect to offset this. The Zeeman effect was first used as a background correction in the mid-1960s. The radiation source (mercury lamp) is placed in a permanent magnetic field, resulting in a frequency splitting. The total absorbance of the sample gas is measured at the center frequency. The absorbance of everything except mercury is measured on the slightly shifted frequency. The results are then subtracted, providing the absorbance due to the mercury present in the gas stream. Although this has proved effective, there is still a dependence on the concentration of the interfering gases [4].

5.2.1.2 Cold-Vapor Atomic Fluorescence Spectrometry

CVAFS makes use of the unique characteristic of mercury that allows measurement at room temperature. Free mercury atoms in a carrier gas are excited by a collimated UV source at a wavelength of 253.65 μm [5]. The excited atoms reradiate their absorbed energy (fluoresce) at this same wavelength. The fluorescence is omnidirectional and can be detected with a photomultiplier tube. The excitation path and viewing path are perpendicular to each other to allow separation. The CVAFS technique differs from the CVAAS technique in that it is more sensitive, more selective, and linear over a wide range of concentrations. However, any

molecular species, particularly diatomic molecules such as O_2 and N_2 present in the carrier gas, will quench the fluorescence signal. One method of circumventing this is to use gold-coated traps to collect mercury from the flue gas stream. The traps are then heated, releasing the mercury from the gold and using an inert carrier gas such as argon to carry the mercury to the detector. The method is highly sensitive, with a detection limit of $<0.1\ pg\ m^{-3}$, and inherently linear (greater than five orders of magnitude) [6].

However, several CMM vendors have taken the approach of simplifying the process by not using gold traps but directly analyzing the flue gas after diluting with N_2 to reduce the interfering gases. In this approach, the resulting quenching of the fluorescence is not considered significant when measuring mercury in combustion flue gases. The detection limit is still generally considered to be $<0.03\ \mu g\ m^{-3}$ [7].

5.2.1.3 Other Analytical Methods

Although almost all of the CMMs that have been developed for measuring mercury in fossil fuel-fired flue gases use either CVAAS or CVAFS, other techniques have been developed. One such method is plasma emission spectroscopy (PES). This method is the basis for the Envimetrics Argus-Hg CMM. In this process, a plasma source is generated using microwave technology. Because the plasma emits light that is characteristic of the induced molecule, a low-resolution spectrometer can then identify that molecule based on the UV spectrum [8].

At one point, Opsis introduced a true *in situ* analyzer based on differential optical atomic spectroscopy. However, this analyzer could only measure elemental mercury, with no possibility of measuring total mercury. Therefore, this analyzer had very limited application for measuring mercury in fossil fuel combustion streams [9].

Cooper Environmental has developed a CMM based on X-ray fluorescence (XRF). When materials are exposed to short-wavelength X-rays or gamma rays, ionization of their component atoms takes place. Ionization consists of the ejection of one or more electrons from the atom. The removal of an electron in this way renders the electronic structure of the atom unstable and electrons in higher orbitals "fall" into the lower orbital to fill the hole left behind. In falling, energy is released in the form of a photon, the energy of which is equal to the energy difference of the two orbitals involved. Thus the material emits radiation, which has an energy output that is characteristic of the atoms present. With a solid-state detector, the concentration of the atoms present in the gas can be determined, based on the emitted radiation [10]. This type of detector has the advantage of not only measuring the mercury concentrations but also other metals.

5.2.2 Pretreatment/Conversion Systems and Probe

For all CMMs, essential parts of the system are the pretreatment/conversion system and the probe. These have four major functions, which are as follows:

1) To provide a stinger and probe that is inserted into the flue gas to sample the flue gas.
2) To convert all mercury forms into elemental mercury.
3) To remove or greatly reduce gases that may interfere with the mercury analyzer.
4) To provide mercury speciation for some CMMs.

5.2.2.1 Sampling Probe

During the early development stage of CMMs, the probe consisted only of the stinger, the filter, and the filter holder. Some type of filter was necessary to prevent the fly ash from ruining the optics of the analyzer. However, depending on the flue gas and fly ash, it was discovered in the early 1990s that the fly ash captured on the filter could adsorb mercury and/or change the speciation [11]. As a result, methods were developed to remove the fly ash but minimize the contact between the collected fly ash and the mercury-containing flue gas. The most successful method was a concept called an *inertial separation probe* (*ISP*) [12]. A diagram of an ISP developed by ADA-ES is shown in Figure 5.3. As shown in Figure 5.3, a large amount of flue gas (>20 l min^{-1}) is pulled through the annulus of the ISP using an eductor. Typically, only about 0.5 l min^{-1} (may vary depending on the CMM) is needed for the CMM. The analyzer pump pulls the small amount of needed gas through the sintered-metal filter portion of the ISP, removing the particulate matter. The high velocity of flue gas passing through the annulus of the ISP continually removes the particulate matter, resulting in minimal contact between the particulate matter and flue gas passing into the mercury analyzer. A detailed diagram of the sintered-metal portion of the ISP is shown in Figure 5.4.

Although most of the CMMs currently available use some type of ISP, there have been several design changes over the past several years. One of the major changes occurred as a result of wet stacks [13]. The ISPs were being corroded by the acidic flue gas (see Figure 5.5) and also had severe plugging problems. As a result, more exotic alloys such as Hastelloy® are being used. Also, the flue gas flow rates through the ISP have been changed to help prevent plugging.

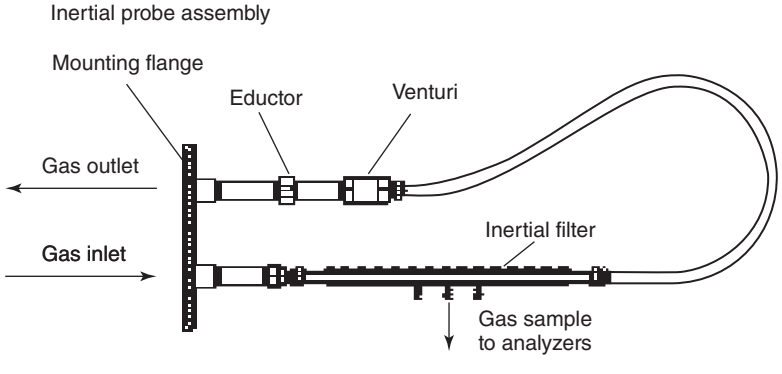

Figure 5.3 Diagram of an ISP. (Courtesy of ADA-ES, Littleton, CO.)

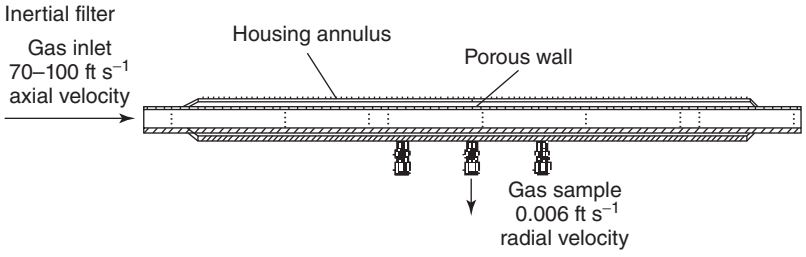

Figure 5.4 Detailed diagram of the inertial filter portion of the ISP. (Courtesy of ADA-ES, Littleton, CO.)

Figure 5.5 Photograph of a sampling probe after 1 month in a wet stack.

5.2.2.2 **Pretreatment and Mercury Conversion**

Pretreatment/conversion systems are essentially classified into two main types. The first are those based on wet chemistry and the second are those based on thermal decomposition. Almost all of the mercury research done in the 1990s and early 2000s used wet-chemistry systems. These systems can be utilized with either CVAAS- or CVAFS-based CMMs. A diagram of a typical wet-chemistry pretreatment conversion unit is shown in Figure 5.6 [14].

Because of the research nature of most of the work being done prior to the introduction of CAMR, it was also necessary that a CMM provide mercury speciation data. Therefore, the wet-chemistry pretreatment/conversion systems were designed such that the CMM would provide speciated data. As shown in Figure 5.6, the speciation was done by splitting the gas flow and passing each gas stream through a separate solution. To measure total mercury, the flue gas passed through a solution of $SnCl_2$/NaOH, which removed the acid gases and reduced all mercury forms to elemental mercury. To measure only elemental mercury, the flue gas passed through a solution of KCl or other Hg^{2+} solution, which removed oxidized forms of mercury. The difference between the two measurements is the concentration of oxidized mercury. For CVAAS mercury analyzers, it has been

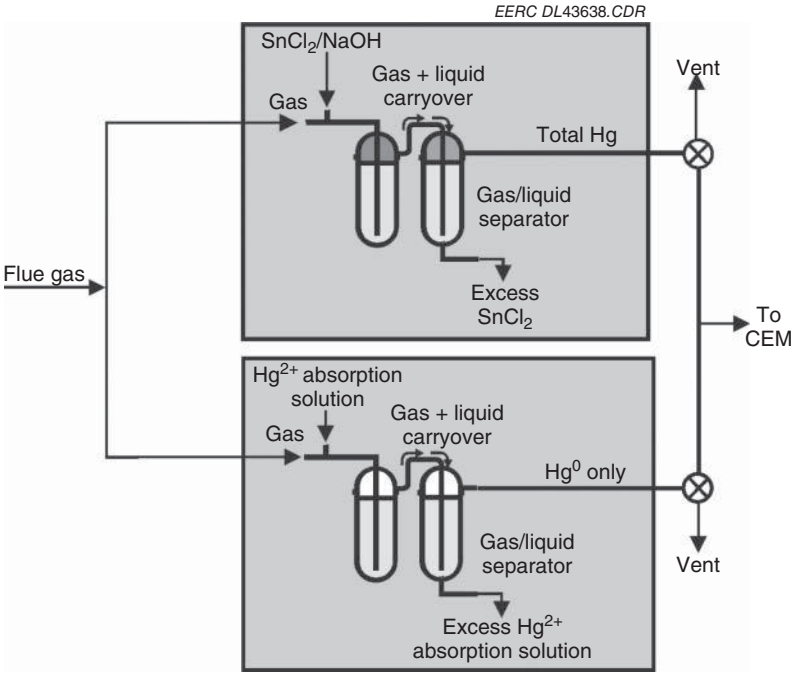

Figure 5.6 Diagram of a wet-chemistry pretreatment/conversion system for a CMM.

reported [15] that the efficiency of mercury conversion is greatly decreased by high levels (>500 ppm) of SO_2 in the gas stream. For a CVAFS mercury analyzer using gold traps, the acid gases must also be removed but for a different reason. If HCl and NO_2 are present in the flue gas, the gold trap is permanently poisoned [16]. To prevent this, it is necessary that the HCl (much easier to remove than NO_2) be removed prior to the flue gas passing through the gold trap.

Although the wet-chemistry pretreatment/conversion systems have worked well for research, they are not suited for long-term compliance monitoring for the following reasons:

- Extensive engineering or technician support is required.
- The NaOH solution will remove CO_2 from the sample gas, requiring that the CO_2 flue gas concentration be known.
- Tin plating and crystallization of solutions can cause problems.
- It is difficult to ensure that no cold spots accumulate mercury, which will show up as mercury spikes in the data.

For these reasons, the mercury CMM vendors developed other pretreatment/conversion systems that did not rely on wet chemistry.

Currently, almost all CMM pretreatment/conversion systems are based on thermal reduction of the Hg^{2+} forms of mercury to Hg^0. Because very high temperatures (near 900 °C) are needed to ensure complete reduction, it is

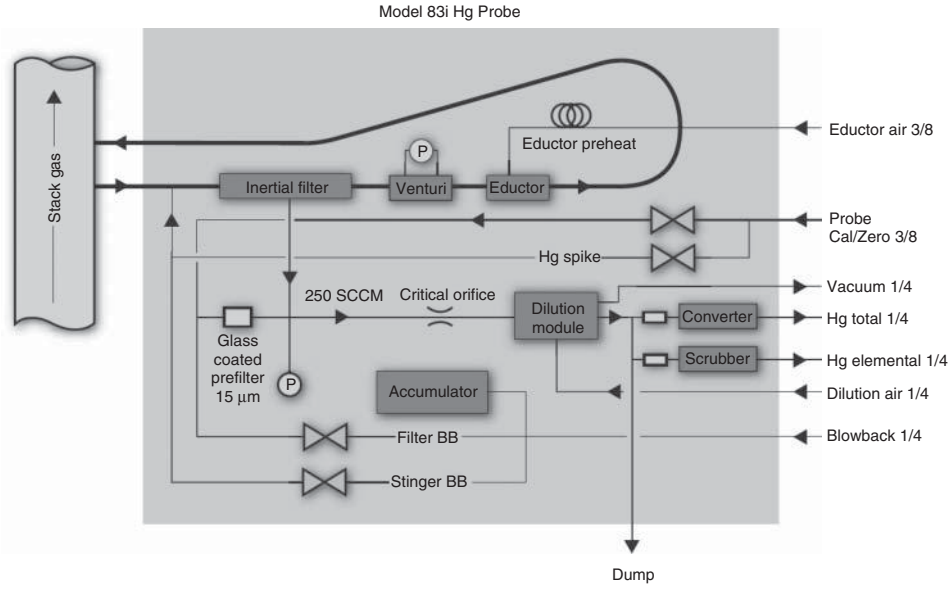

Figure 5.7 Diagram of the Thermo Scientific probe.

not practical to maintain these temperatures. If the temperature is allowed to decrease, the mercury will recombine, resulting in a low bias in the measurement [17]. Therefore, most CMM vendors use some form of catalytic dilution to reduce the temperature and, at the same time, prevent recombination. The actual catalyst used is considered propriety to the vendor. In addition, by diluting the gas stream, the potential of interference from other flue gas constituents is greatly reduced. Depending on the vendor, the pretreatment/conversion system is part of the probe (Thermo Scientific) or is a separate unit generally located near the analyzer section of the CMM (Tekran). A diagram of a pretreatment/conversion system is shown in Figure 5.7.

Typically, dilution systems are mostly associated with CVAFS mercury analyzers because of their inherent lower detection limits. However, some of the CVAAS systems that use gold traps to preconcentrate the mercury also use dilution. Although CVAAS systems have inherently higher detection limits than CVAFS systems, if the mercury is concentrated on the gold trap, low mercury concentrations can still be accurately measured by sampling and allowing more collection time.

5.2.3 CMM Calibration System

A critical component of any CMM is the ability to calibrate the monitor to ensure accurate results. In most continuous emission monitors (CEMs) such as those for

SO_2 or NO_x that are routinely used in power plants, calibration is done using certified calibration gas cylinders. However, because of the low mercury concentrations and the stability required, the development of these calibration gases has been difficult. NIST has been working with Spectra Gases in an attempt to certify calibration gases [18]. Because of the cost and volume of gas needed to conduct a CMM calibration prescribed by Performance Specification (PS)-12A, most likely these calibration gases will have limited uses. As a result, all CMM systems sold today provide an elemental mercury calibrator. These calibrators are either internal to the mercury analyzer or a separate unit. The elemental mercury calibration gas is generated either by heating a pool of elemental mercury so that a carrier gas is saturated and then the concentration is determined, based on the mercury vapor pressure curves or by using permeation devices. In either case, it is critical that the temperature and flow rates of the calibration devices be maintained very precisely. In most CMMs, the generated elemental mercury calibration gas can be sent to a variety of points within the system, from the probe tip to directly into the mercury analyzer. This allows not only for instrument calibration but also for troubleshooting the instrument and providing quality control checks. A diagram of a typical elemental mercury calibration system is shown in Figure 5.8.

When the CAMR was promulgated, the calibration requirements for CMMs stated that the calibrators were to be NIST-traceable. The same NIST traceability is also part of the new National Emission Standards for Hazardous Air Pollutants (NESHAPs) for coal-fired power plants as NIST traceability is required under PS-12A. In 2005, with funding from EPA, NIST began developing protocols for producing vendor prime calibration systems. To date, NIST has certified and recertified its NIST Prime elemental Hg generator and has certified the first round of the vendor prime generators. Vendor prime generator recertification is

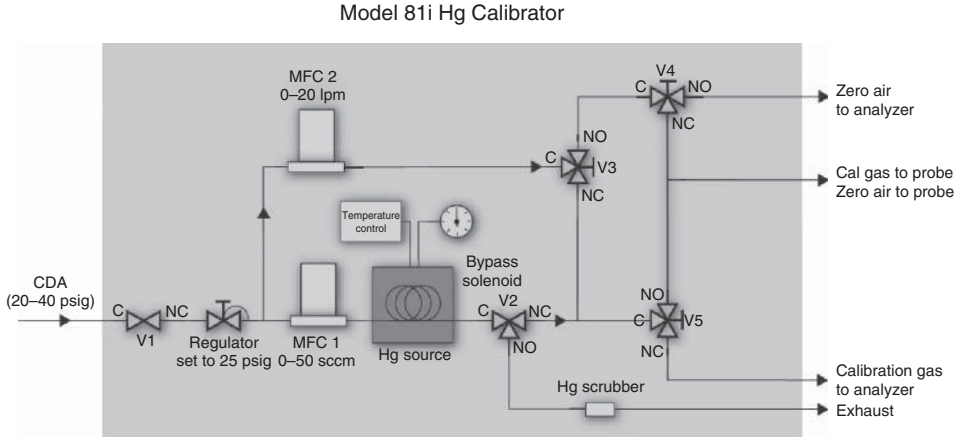

Figure 5.8 Diagram of the Thermo Scientific elemental calibrator.

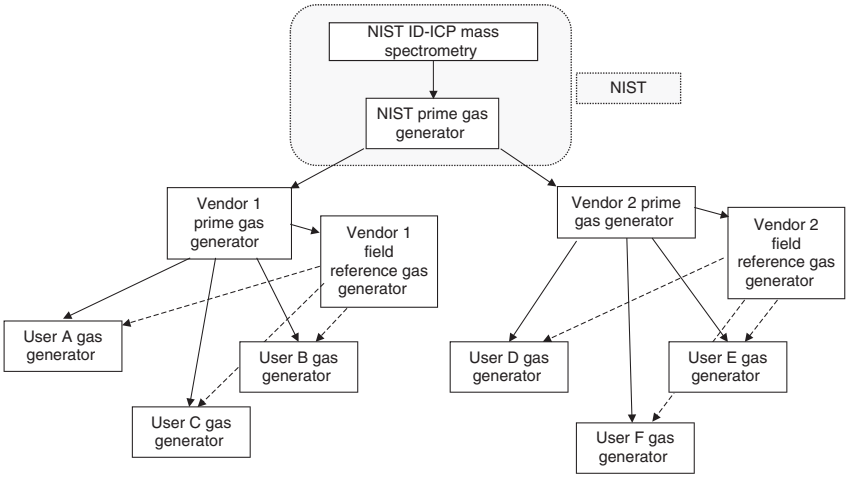

Figure 5.9 NIST traceability scheme for CMM calibration.

expected to begin in the near future [18]. The overall NIST traceability scheme for CMMs is shown in Figure 5.9.

PS-12A requires that compliance CMMs be calibrated using both NIST-traceable elemental mercury calibrators and oxidized mercury calibrators. The primary purpose of the oxidized mercury calibrator is to ensure that the conversion system is converting all mercury to Hg^0 and not creating a low bias. Rather than actually providing vendor prime NIST-traceable oxidized mercury calibrators, it was determined by EPA that NIST-traceability would be accomplished by certifying that all parts of the system be NIST-traceable. For example, the source of mercury, mass flow controllers, and temperature controllers would need to be NIST-traceable. As a result, NIST-traceable protocols for oxidized mercury calibrators were not needed.

There have been essentially two approaches to the manufacture of oxidized mercury calibrators. The first approach is to use the HovaCal® gravimetric approach. A NIST-traceable $HgCl_2$ solution is made or bought and weighed precisely on a continuous basis. A small amount of the $HgCl_2$ solution is continuously pumped in an evaporator, resulting in gaseous $HgCl_2$. Using mass flow controllers, a mercury-free carrier gas is then mixed with the $HgCl_2$ vapor, which is introduced into the CMM. This is the procedure used by Tekran and also by Cemtrex. A diagram of the technique is shown in Figure 5.10.

The second approach is to convert the mercury generated by a NIST-traceable elemental mercury calibrator to $HgCl_2$. This is done by passing the output of the elemental mercury calibrator over a heated catalyst and introducing Cl_2. This the procedure used by Thermo Scientific for its oxidized mercury calibrator. Spectra Gases also has patented a version of this calibrator called *MerCal*™ [19].

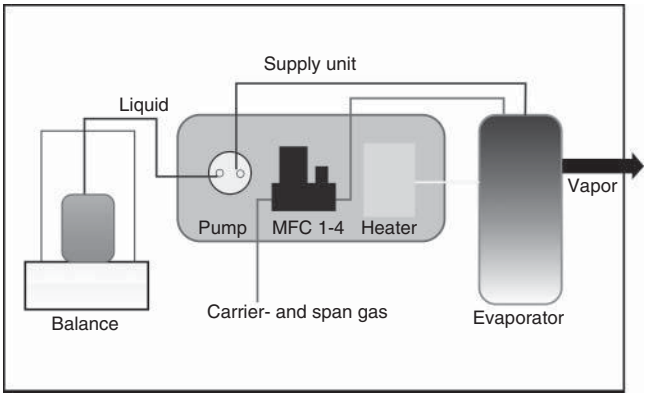

Figure 5.10 Basic diagram of a gravimetric oxidized mercury generator.

5.3 Installation and Verification Requirements

Installation and verification of CMMs for power plants are detailed in PS-12A. The following is a brief summary of PS-12A, which assumes that the vendor recommendations for installation are also being followed.

5.3.1 Installation

Obviously, for compliance purposes, the CMM must be installed following the last air pollution control device. This most often will be at stack location. However, it is important that the CMM probe be installed in a location that is readily accessible, as some maintenance will be required. Therefore, a duct location may also be considered. Because a CMM is a single-point monitor, it is required that the location be chosen such that the flue gas is representative with little or no stratification. As such, the chosen location must follow the requirements of EPA Method 1 and be at least two equivalent diameters downstream of the nearest control device or any other point at which a change in gas flow or mercury concentration could occur. This may require mercury stratification testing using EPA Method 30B or, alternatively, SO_2 stratification testing.

Once the sampling location has been chosen, the stinger is inserted such that it is no <1.0 m from the stack wall or duct. Also, it must be within the centroidal velocity traverse area of the stack or duct cross section.

5.3.2 CMM Verification

Three tests must be performed to certify a CMM installation:

1) Measurement error (ME)

2) Seven-day calibration drift (CD)
3) Relative accuracy test audit (RATA).

5.3.2.1 Measurement Error

This test requires that three levels (zero, midlevel, and high) of a mercury reference gas be sequentially injected into the CMM such that all sections of the CMM are challenged. This test is done in triplicate. Using the average CMM value, the ME for each of the three reference gas concentrations is calculated using the following equation:

$$\mathrm{ME} = \frac{|R - A|}{\mathrm{Span}} \times 100\% \tag{5.1}$$

where R is the reference gas concentration and A is the average of the CMM reading for the three injections at that reference gas level. The span gas is defined in PS-12A as gas concentration no greater than twice the emission limit. To pass the ME test, each of the values calculated using Equation 5.1 must be ≤5%.

5.3.2.2 Seven-Day Calibration Drift

The purpose of the CD test is to verify the ability of the CMM to conform to the established response used for determining emission concentrations. The test is conducted with a zero gas and either the mid-level or high-level gas used for the ME test. The gases are added to the probe sequentially. The CD is calculated using Equation 5.2. This test is done for seven consecutive operation days.

$$\mathrm{CD} = \frac{|R - A|}{\mathrm{Span}} \times 100\% \tag{5.2}$$

To pass the CD test, each of the values calculated using Equation 5.2 must be ≤5% for each of the 7 days.

5.3.2.3 Relative Accuracy Test Audit

The third CMM verification test that must be performed is a RATA. This test involves comparison of the mercury concentration measured using a reference method (RM) to the average CMM concentration measured over the same time period. Although an instrumental RM (EPA Method 30A) can be used in almost all cases, the procedures outlined in EPA Method 30B (sorbent traps) are used.

A RATA using EPA Method 30B requires that nine paired sorbent samples (C_a and C_b) be taken at a representative location in the same duct or stack as the CMM. Depending on the potential for the flue gas to be stratified, this may or may not involve traversing. To be a valid pair, the relative difference between the two paired samples (Equation 5.3) must be ≤10% at Hg concentrations ≥1.0 μg m^{-3}. If the average Hg concentration is ≤1.0 μg m^{-3}, then the relative difference between the paired samples must be ≤20% or have an absolute difference of ≤0.2 μg m^{-3}.

$$\mathrm{RD} = \frac{|(C_a - C_b)|}{(C_a + C_b)} \times 100\% \tag{5.3}$$

The relative accuracy (RA) is calculated using Equation 5.4. Note that the mercury concentrations for the CMM and RM must be on the same basis, either wet or dry.

$$\mathrm{RA} = \frac{|\overline{d}| + |\mathrm{cc}|}{\overline{\mathrm{RM}}} \times 100\% \tag{5.4}$$

where $\overline{d}$ is the sum of the difference between the RM concentrations and the corresponding CMM concentration, cc is the value of the confidence coefficient (Equation 5.5), and $\overline{\mathrm{RM}}$ is the mean of the RM values.

$$\mathrm{cc} = t_{0.025} \frac{S_\mathrm{d}}{\sqrt{n}} \tag{5.5}$$

where $t_{0.025}$ is the Student t value based on n (from statistical tables), S_d is the standard deviation (Equation 5.6), and n is the number of paired RM tests.

$$S_\mathrm{d} = \sqrt{\frac{\sum_{i=1}^{n} d_i^2 - \frac{\left(\sum_{i=1}^{n} d_i\right)^2}{n}}{n-1}} \tag{5.6}$$

To pass the RATA, the calculated value RA in Equation 5.4 must not exceed 20%. Alternatively, if an average RM concentration is $<5.0\ \mu g\ m^{-3}$, the results are acceptable if the absolute value of the difference between the mean RM values and CMM does not exceed $1.0\ \mu g\ m^{-3}$.

5.4 Major CMM Tests

Over the last 15 years, a number of tests have evaluated the ability of CMMs to measure mercury at fossil fuel-fired boilers. These tests have been conducted by the vendors themselves and/or the utilities as well as by independent agencies such as the U.S. Department of Energy (DOE), EPA, and the Electric Power Research Institute (EPRI). Below is a summary of some of these tests.

One of the first systematic tests was funded by EPA and DOE at a cement plant in Holly Hills [20]. Three different CMMs were tested at the Holly Hills cement plant in 1995. The installed CMMs were compared to the RM, EPA Method 29. In general, these tests were not very successful for a number of reasons. The cement plant burned a wide variety of fuel, including hazardous wastes and, as such, the flue gas constituents changed widely during the testing. Because the effects of these flue gas constituents were not very well known at the time, the CMM mercury measurements were not very accurate. Also, there were several mechanical and engineering problems because these instruments were still in the development stage.

EPA's Environmental Technology Verification Program's Advanced Monitoring Systems Center, operated by Battelle under a cooperative agreement with EPA, between 2001 and 2007, evaluated 10 different instrumental CMMs and a sorbent trap CMM. The verification testing was conducted in three phases. It should be noted that not all CMMs were tested in all three phases. In the first phase, four CMMs were tested under conditions simulating (i) coal-fired flue gas and (ii) municipal incinerator flue gas. The tests took place at a pilot-scale incinerator in Research Triangle Park, North Carolina, over a 3-week period. In the second phase, five CMMs (including two of the technologies tested in the first phase) were evaluated at a full-scale hazardous waste incinerator in Oak Ridge, Tennessee. The third phase was conducted at a coal-fired power plant. The reports for each of these systems are available on EPA's Web site at *www.epa.gov/etv/vt-ams.html#mcem*. As would be expected, the results were mixed. Some of the systems compared very well to the RM, while others had more difficulties.

One of the more extensive field tests was completed at Tennessee Valley Authority's Trimble County Power plant, Unit 1 [21]. This plant burns an eastern bituminous coal, utilizes selective catalytic reduction for NO_x removal (operates during the ozone season), an electrostatic precipitator, and a wet scrubber. As a result, the mercury concentration at the outlet of Unit 1 was low, typically $<2.0\,\mu g\,Nm^{-3}$. Testing began in November 2004 and continued through September 2005. The purpose of this field test program was to collect data to assess the ability of commercially available CMMs to provide reliable and accurate data over an extended time period while meeting certification, durability, data availability, and setup/maintenance requirements. In particular, data were collected to assess the ability of the CMMs to satisfy the requirements of PS-12A. The testing was divided into two phases (Phases 1 and 2). Phase 1 consisted of the setup and verification of four different CMMs at the power plant. In addition, some data were gathered as to the maintenance requirements. In Phase 2, two additional CMMs (plus the original four) were added and verified. Phase 2 saw 7 months of testing.

The results of this test program demonstrated that the source characteristics can have a significant effect on CMM performance. Regardless of the vendor supplying the CMMs, it is clear that CMMs should be appropriately modified for the source. For instance, the source sampled for this demonstration project had a wet stack and thus required a CMM with efficient sample transfer and conditioning capabilities in order to function properly. Detailed results of this test program can be found at *www.epa.gov/ttn/emc/cem/hgcemsdemo.pdf*.

With the promulgation of the Utility NESHAPs Mercury and Air Toxics (MATs), mercury limits are based on maximum achievable control technology (MACT). Obtaining this level of control will often require measuring mercury at concentrations $<1.0\,\mu g\,m^{-3}$. There is little data in the literature as to the validity of using CMMs to consistently and accurately measure mercury concentrations $<1.0\,\mu g\,m^{-3}$. As a result, the Energy & Environmental Research

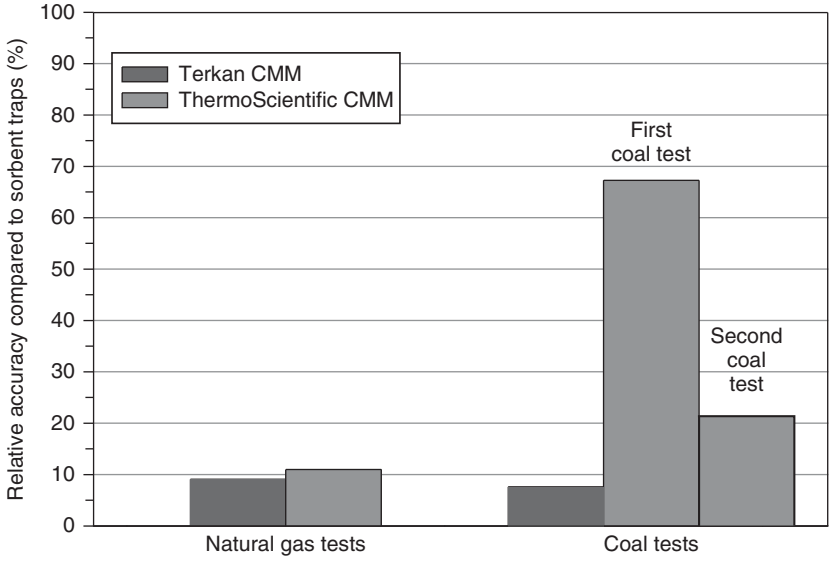

Figure 5.11 Summary of the low-level mercury testing at the EERC.

Center (EERC), with funding from the Illinois Clean Coal Institute (ICCI), DOE, EPRI, and the EERC Center for Air Toxic Metals®, conducted a pilot-scale test program to systematically determine the precision and accuracy of the two most widely used CMMs by the utility industry – Tekran and Thermo Scientific CMMs – when measuring mercury at these levels [22]. The first portion of the test was conducted firing natural gas with 0.5–1.0 $\mu g\,Nm^{-3}$ of elemental and oxidized mercury spiked into the flue gas. The second portion of the test involved firing an Illinois bituminous coal with a baghouse and wet scrubber in operation. Again, the outlet mercury concentration was $<1.0\,\mu g\,Nm^{-3}$. A summary of the results are shown in Figure 5.11. As can be seen in Figure 5.11, the results for the Thermo Scientific CMM were problematic. This was believed to be a result of a software error; therefore, a second week firing coal was conducted using only the Thermo Scientific CMM. The results were considerably better the second week. In general, it was concluded that both instruments provided quite good agreement with the RM even at these low mercury concentrations. Detailed results of this test program can be found at the ICCI Web site at *www.icci.org/reports/10Laudal6A-1.pdf*.

Under the MATs rule, the reliability of CMMs will be a critical issue as utilities will be penalized for incomplete or missing data. Although the experiences of the utilities with CMMs have been varied, in general, once these instruments have been installed, are operating correctly, and properly maintained, they are highly reliable. Figure 5.12 shows the percent availability for 10 different Tekran monitors over the year 2009 [23]. As can be seen, the average reliability was >91%, with the lowest being about 87%. This is typical of many of the CMM installations.

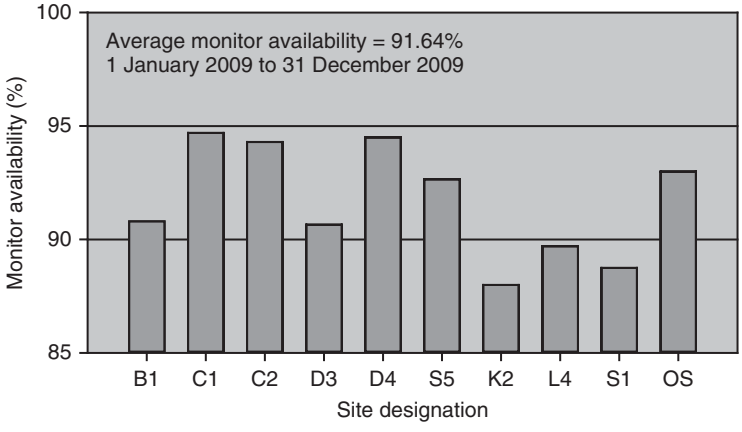

Figure 5.12 Availability of Tekran CMM during the 2009 calendar year.

5.5 CMM Vendors

As stated earlier, most of the CMM sales to the utility industry have been either Tekran or Thermo Scientific. However, a number of other vendors are also offering complete systems. Table 5.1 provides a listing of vendors that have the potential to provide complete mercury measurement systems to the utility industry as of 2011. Currently, these other instruments have primarily been used to measure mercury for non-utility industries such as incineration, natural gas refining, mining, or the manufacture of cement. For a detailed description of the CMMs, Web sites are provided in Table 5.1.

Table 5.1 List of vendors offering CMM systems to the utility industry.

Vendor	Instrument	Analysis method	Web site
Thermo Scientific	Mercury Freedom System	CVAF	*www.thermoscientific.com/*
Tekran Instrument Corp.	Series 3300	CVAF	*www.tekran.com/*
Envimetrics	Argus-Hg	PES	*www.envimetrics.com/*
PS Analytical	PSA 10.665 System	CVAF	*www.psanalytical.com/*
Gasmet	Gasmet CMM	CVAF	*www.gasmet.fi/*
Cemtrex	SM-4	CVAA	*www.cemtrex.com/*
Sick Maihak GmbH	MERCEM300Z	CVAA	*www.sick.com/*
Durag Group	HM 1400 TR	CVAA	*www.durag.com/*
Pall Corporation	Xact 645	XRF	*http://pall.com/*

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6
Batch Methods for Mercury Monitoring

Constance Senior

6.1
Introduction

The previous chapter discussed continuous emissions monitoring systems (CEMS) for quantifying mercury concentrations in combustion flue gas. In this chapter, several batch methods for quantifying mercury concentration are discussed. A number of batch, wet-chemistry based methods are available for measuring mercury in flue gas. Recently, dry batch methods, also known as *sorbent trap methods*, have been preferred for many applications. In the United States, sorbent trap methods have been specified by the U.S. Environmental Protection Agency (EPA) as being acceptable for compliance with federal mercury emissions standards for a number of industrial combustion sources.

6.2
Wet Chemistry Batch Methods

6.2.1
Early EPA Total Hg Methods

EPA developed several wet chemistry methods for measuring mercury in industrial stack gases in order to quantify emissions. Descriptions of these methods can be found at the EPA website [1]. EPA Method 101A was developed for determination of gaseous and particulate mercury emissions from sewage sludge incinerators, but is often applied to coal-fired boilers to measure total mercury emissions. EPA Method 29 was developed to measure mercury and other metals in stack emissions.

Figure 6.1 gives a schematic of Method 101A. A probe is inserted into the flue gas with a nozzle designed for isokinetic sampling of the flue gas. A pitot tube probe and a thermocouple are also inserted into the duct. The size of the nozzle is matched to the gas velocity in the flue gas. The probe is traversed in the flue gas during the test in order to collect a representative sample. The sample is

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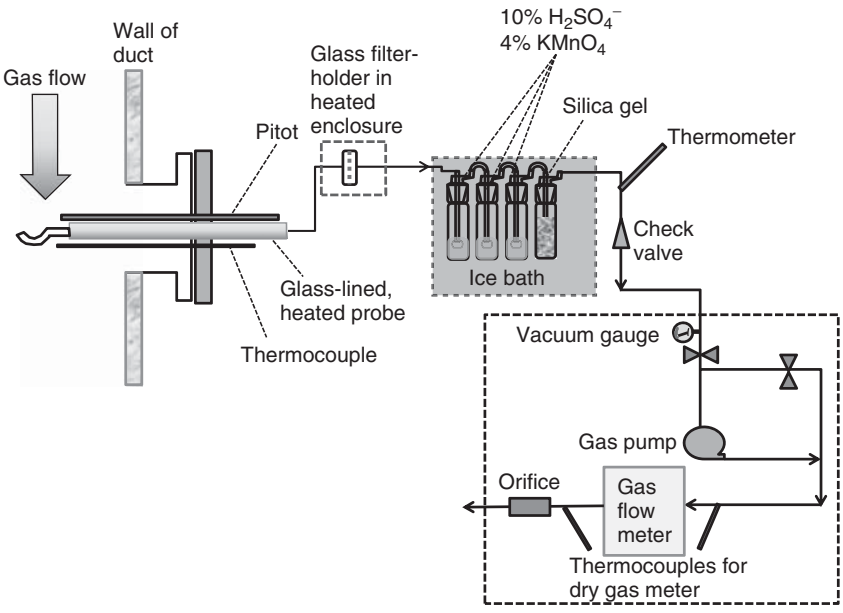

Figure 6.1 Schematic of EPA Method 101A.

withdrawn through the probe and into a heated filter. The filter collects the particulate matter (PM). After the filter, the sample gas is pulled through a series of four glass impingers in an ice bath. The first three impingers contain a solution of 4% $KMnO_4$ – 10% H_2SO_4 (wt% basis). The fourth impinger contains silica gel to dry the gas. Following the impingers, there is a pump and dry gas meter.

EPA Method 29 is designed to measure the solid particulate and gaseous emissions of mercury and 16 other trace elements (antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, lead, manganese, nickel, phosphorus, selenium, silver, thallium, and zinc). The equipment and sampling train are similar to that for Method 101A, with the exception of the impingers. In Method 29, gaseous metals and mercury are collected in two impingers in series containing an acidic peroxide solution (5% HNO_3/10% H_2O_2). An empty impinger follows the first two impingers in the train. Elemental mercury that passes through the first three impingers is collected in the two following impingers in series containing acidified permanganate (10% H_2SO_4/4% $KMnO_4$). A final impinger containing silica gel is used to dry the sample gas. After the measurement, the contents of the peroxide impingers are saved separately from the contents of the permanganate impingers in an attempt to quantify mercury speciation.

A minimum sampling time of 2 h is recommended for Method 101A. Similar sampling time is usually used for Method 29. The limits of detection of the methods may be improved by increasing the sample time. In Method 101A, if there is an excess of oxidizable organic matter in the gas stream, it may be impossible to

sample for the minimum time. This problem will be indicated by the loss of the purple color of the $KMnO_4$ solution.

Both methods require leak-checking before and after the test. Post-test, the glassware, including the glass-lined probe, must be rinsed, and the rinsate saved for analysis. The method also requires the use of blanks for the impinger solutions and the filter in the field. After the test, the filter, collected solutions, and blanks are analyzed in a commercial laboratory using cold-vapor atomic absorption (CVAA) spectroscopy.

Three replicate measurements are usually conducted for these methods. These can be done in 1 day, but are often completed over 2 days. The methods require considerable time to set up and recover samples from each measurement. A high level of quality assurance/quality control (QA/QC) and well-trained personnel are needed for these wet chemistry methods.

6.2.2 Development of Wet Chemistry Methods to Speciate Hg

EPA Method 29 was not originally designed for mercury speciation analysis. In the 1980s, various research groups evaluated the method for mercury speciation, because it was thought that the gaseous oxidized (Hg^{2+}) and elemental (Hg^0) species would be selectively absorbed in the separate acidified hydrogen peroxide and acidified permanganate solutions, respectively. However, experience from data validation experiments showed that the two different impinger solutions were not effective for reliably separating the Hg^{2+} and Hg^0 species in a coal-combustion flue gas containing high levels of SO_2. As a consequence, several groups proposed modifications to the impinger solutions used in EPA Method 29. These included the Ontario Hydro, Tris buffer, and Research Triangle Institute (RTI) methods. All three methods used the framework of Method 29, but substituted different impinger solutions for the speciation of mercury [2].

The Ontario Hydro method was developed by Dr. Keith Curtis and colleagues at Ontario Hydro Technologies in late 1994. In this method, three aqueous 1 N potassium chloride (KCl) impinger solutions were substituted for one of the HNO_3–H_2O_2 solutions. Originally, no acidified peroxide impingers were included in the sampling train. However, it was discovered that when SO_2 concentration in the flue gas was >~750 ppm, the SO_2 reacted with the $KMnO_4$ neutralized, which meant that sampling time had to be very short. To avoid this problem, an impinger of acidified peroxide solution was used directly after the KCl impingers in order to absorb the SO_2. It is assumed that any mercury collected in the acidified peroxide solution was Hg^0, as the KCl solutions would collect all of the Hg^{2+}. Early testing also showed a substantial portion of the mercury was lost from the solutions [3]. To prevent this, acidified permanganate, dichromate, or acidified peroxide solution was added to the KCl solution immediately following sampling.

Formal evaluation of the Ontario Hydro method was completed with dynamic spiking of Hg^0 and $HgCl_2$ into a flue gas stream [3]. The Ontario Hydro method

Table 6.1 Comparison of wet chemistry methods.

Method	Sampling train configuration		Impinger configuration (number of impingers – impinger set solution)			Analytical method
	Front-half collection (PM and Hg_p)	Back-half collection (gaseous Hg)	First set	Second set	Third set	
EPA Method 101A	Glass fiber filter	Impinger solutions	$3H_2SO_4$ – $KMnO_4$	None used	None used	CVAA
EPA Method 29	Glass fiber filter	Impinger solutions	$2HNO_3$ – H_2O_2	1 dry	$2H_2SO_4$ – $KMnO_4$	CVAA
Ontario-Hydro Method	Glass fiber filter	Impinger solutions	3KCl	$1HNO_3$ – H_2O_2	$3H_2SO_4$ – $KMnO_4$	CVAA

is now ASTM Method D6784-02 [4]. The method outlines QA/QC procedures, including leak-checking, calibration, and the use of blanks. The three wet chemistry methods discussed are compared in Table 6.1.

6.2.3 Method Application and Data Quality Considerations

The precision of measurement of particulate, oxidized, and elemental mercury is influenced by many factors: flue gas concentration, source, procedural, and equipment variables. To ensure that precise results are achieved, the sampling system must be leak-free, system components must be accurately calibrated, the proper sampling locations must be selected, glassware must be thoroughly cleaned, and prescribed sample recovery, preparation, and analysis procedures must be followed.

In the ASTM method description [4], 0.5 $\mu g\,m^{-3}$ is estimated as the lower limit for most applications. Ryan and Keeney [5] stated that, assuming a 50–50 split between oxidized and elemental mercury in a flue gas, the lower limit of quantitation for total mercury in the Ontario Hydro Method ranges from 0.31 to 0.62 $\mu g\,m^{-3}$. The lower limit of quantitation can be reduced by using low mercury calibration standards. However, at such low concentrations, achieving adequate blank samples may be difficult.

The impinger-based methods were designed to be used downstream of the plant's particulate control device. In many cases (for research or survey purposes), these wet methods are used before the particulate control device, when there is a lot of particulate matter present in the flue gas. In these situations, reactive particulate matter can bias the speciation. This bias can be manifest as either artificially high oxidized mercury (in the case of the Ontario Hydro Method) or high particulate mercury. All the sample gas must pass through the filter. Gaseous mercury species in flue gases can interact with fly ash particles collected

on the filter and can produce a positive particulate mercury bias. In some cases, particulate-bound mercury collected on the filter can volatilize because of flue gas exposure, and be collected in the impingers. Such vaporization losses of mercury result in a negative particle-bound mercury bias.

There are practical limitations to the impinger-based methods arising from the complex sample trains, which are composed of relatively large amounts of glassware and tubing. Furthermore, the glass impingers contain strongly oxidizing and acidic reagents requiring labor-intensive sample recovery and analytical procedures. Usually, these solutions must be shipped to a laboratory quickly. In some cases, testing contractors have brought complete analytical laboratories on-site for analysis. This reduces the turnaround time for obtaining results, but can substantially increase the cost of the measurements.

6.3
Dry Batch Methods

6.3.1
Sorbent Trap Method History

In this section, the general concept of sorbent trap methods will be discussed, in addition to specific methods such as Performance Specification 12B (PS-12B) and Method 30B. In addition, speciation sorbent traps, which are used for research and demonstrations, will also be discussed.

Sorbent trap methods for measuring mercury in combustion gas were developed in the early 1990s in the United States and have been used, in one form or another, for the last 20 years. The first method was developed by Frontier Geosciences and was called the *mercury speciation adsorption* (*MESA*) method [6]. The MESA method was used in a number of pilot and field demonstrations of mercury control technology on coal-combustion systems in the mid- to late-1990s [7]. Improvements were made to the method, under sponsorship of the Electric Power Research Institute (EPRI), and the resulting method was known as *QuickSEM*. In 2004, U.S. EPA adopted the method as part of the draft Utility Mercury Reduction Rule and called it *Method 324*. In 2005, EPA proposed a different utility regulation on mercury emissions called the *Clean Air Mercury Rule* (*CAMR*); CAMR utilized a sorbent trap method known as the *Appendix K method*. CAMR was ultimately not promulgated by EPA. In 2010, EPA included PS-12B in the compliance monitoring procedures promulgated as part of the Portland Cement Maximum Achievable Control Technology (MACT) rulemaking [8]. In February 2012, EPA finalized the Mercury and Air Toxics Standard (MATS) rule for utility boilers, and this rule included PS-12B as an acceptable method for mercury measurement for compliance with the rule.

Total mercury measurement is needed for compliance with regulations. However, scientists and engineers need to measure speciated mercury in flue

gas in order to evaluate control technology options. As discussed above, the wet method, the Ontario Hydro Method, provides speciated mercury information, but this method is complicated and time-consuming to implement. Therefore, speciation sorbent trap methods have been developed.

The MESA sorbent trap method uses a trap containing KCl/soda lime to collect oxidized mercury. It has been used for measurement of both total Hg and speciated Hg in flue gas as for the EPRI PISCES program [9, 10] and performance-tested for total mercury using EPA Method 301 [11, 12]. It was evaluated for speciated Hg in coal flue gas [13, 14]. Total Hg results were within acceptable limits for sensitivity, accuracy, and precision [13, 15].

Frontier Geosciences developed the flue gas mercury sorbent speciation (FMSS) method in which a semi-isokinetic sample was pulled from the flue gas through a mini-particulate filter and a heated solid sorbent sample train, consisting of parallel sorbent traps. Analysis of the filter was carried out for particulate mercury and the sorbents were analyzed for gaseous Hg species. In the sorbent trap section, the first trap contained dry KCl-coated quartz chips and was used to capture the oxidized mercury. The second trap contained iodine-impregnated activated carbon to capture the elemental mercury. The FMSS method was validated according to the modified EPA Method 301 [16]. EPA Method 301 [17] specifies procedures for determining the precision and bias of measured emissions using a specific method at the concentrations typical of the specific standard for the source.

Currently, the most widely used speciated Hg sorbent trap method is the flue gas adsorption for mercury speciation (FAMS) method [18], which uses the KCl/quartz trap to remove oxidized mercury and an activated carbon trap to remove elemental mercury. The FAMS method was also developed by Frontier Geosciences.

As both CEMS and sorbent trap methods for compliance with mercury emissions regulations were being developed, there was a need for a reference method (RM) to verify the performance of the measurement system once installed at a specific plant. This performance verification was initially conducted using wet chemical methods, such as the Ontario Hydro Method (ASTM D6784) as the RM. However, such methods proved to be complex, slow, and cumbersome. In 2007, the EPA issued a direct final rule to add two reference measurement methods for coal-fired power plants. The two methods, Method 30A and Method 30B, were intended for use in relative accuracy audits (RATAs) of mercury emissions monitoring systems installed in combustion systems. Method 30A was based on a continuous monitoring instrument, while Method 30B was a sorbent trap method [19].

Monitoring of mercury emissions from coal-combustion systems for compliance purposes in the United States can be carried out using either a continuous emission monitoring system (CEMS) (as specified in EPA's PS-12A) or a sorbent trap (PS-12B). A part of the certification process for either emissions monitoring system is a RATA, which can be performed using the Ontario Hydro Method, Method 30A (instrumental RM) or Method 30B (sorbent trap RM).

6.3.2 Method Overview

In a sorbent trap method, a known volume of flue gas is pulled through paired, pre-spiked traps located in the stack or duct. The exposed traps can be analyzed by any method that meets the specified QA/QC criteria. The collection of paired samples is needed to determine the method precision.

Figure 6.2 shows a general schematic of the sampling set-up for sorbent trap methods. Two sorbent traps are located in the flue gas duct (detail not shown in figure). Gas is drawn through the traps in parallel. The sample is not isokinetic. Sorbent trap methods are intended for use only under conditions of relatively low particulate loading (i.e., sampling after particulate control devices); in cases where significant amounts of particle-bound Hg may be present, an isokinetic sampling method for Hg should be used.

The rest of the sampling system consists of a system to remove moisture, a pump, and dry gas meter. The measurement of the temperature and pressure at the dry gas meter (sampling console) is critical for calculating an accurate sample volume. The actual temperature and pressure of the sampled (flue) gas is not required. For a continuous mercury monitor, the flow rate is adjusted to maintain sample flow rate in proportion with total flue gas flow rate in the duct.

6.3.3 Total Hg Measurements

6.3.3.1 PS-12B

The purpose of this method is continuous monitoring of mercury from combustion stacks. Each trap must have the sorbent configured into three sections

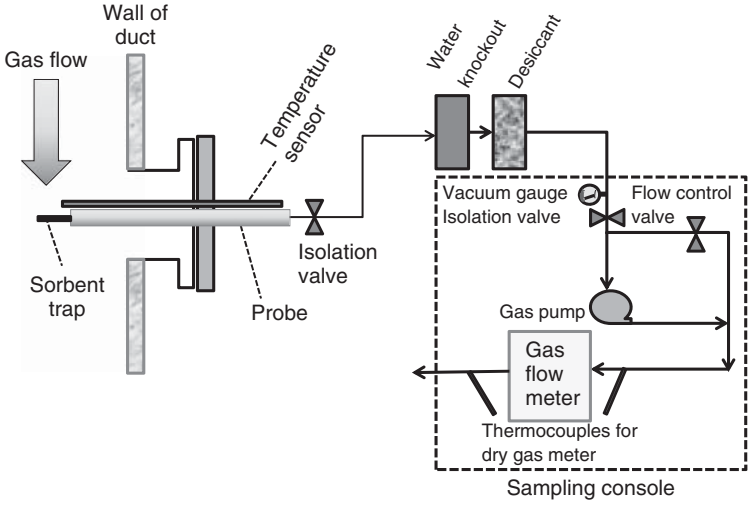

Figure 6.2 Schematic diagram of sorbent trap sampling system.

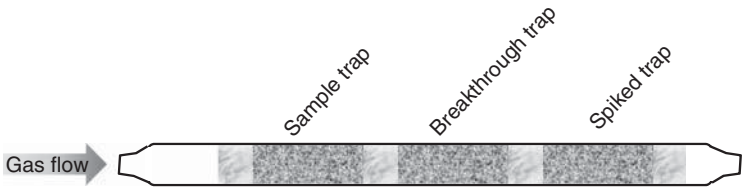

Figure 6.3 Three-section trap for PS-12B.

that can be tested independently (Figure 6.3). Plugs of quartz wool separate the sections. There is also a quartz wool plug before the first section and after the last section. A common trap sorbent material is activated carbon impregnated with a halogen such as iodine or bromine. The first section is for primary mercury collection. The second section is to provide an indication of mercury breakthrough. If there is too much breakthrough (i.e., too much mercury in the second trap), the sample could be invalidated. The third section is for spike recovery testing.

The spiked section is prepared in advance, using a mercury sample gas, which is flowed through the section. The method allows the use of any method for generating a known mass of gaseous elemental mercury as long as National Institute of Standards and Technology (NIST)-traceable standards are used. For example, an elemental mercury gas generator or cylinder of mercury calibration gas can be used to generate the mercury for the spike.

6.3.3.2 **Method 30B**

For RATA testing, Method 30B is used. The Method 30B trap has two sections, as shown in Figure 6.4. Quartz wool plugs separate the sections and an initial quartz wool plug removes any particles in the sample gas. There is no separate section for spiking but the first section of one of the paired traps is spiked with elemental mercury to assess the measurement bias and to verify data acceptability in the field.

6.3.4 Speciation Measurements

Speciation traps have been developed as an alternative to the Ontario Hydro Method for speciation of mercury in flue gas. As noted above, the most widely

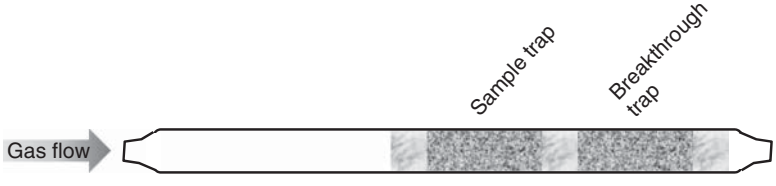

Figure 6.4 Two-section trap for Method 30B.

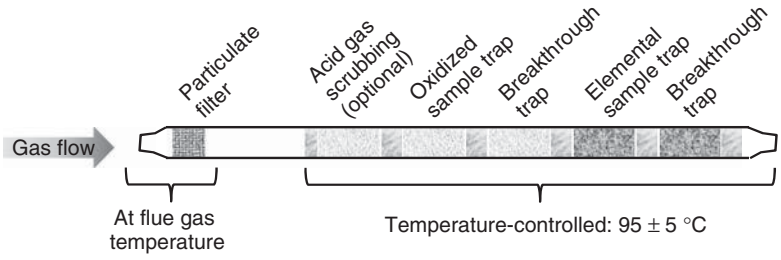

Figure 6.5 Sorbent trap configuration for speciated Hg measurement.

used speciation sorbent trap method is based on Method 30B [18]. Figure 6.5 shows a schematic of the sections in each trap.

In this method, there is a particulate collection section, followed by two sections to collect oxidized mercury (primary and breakthrough), which contain KCl on quartz chips, and two sections to collect elemental mercury (primary and breakthrough), which contain iodated or brominated carbon. An acid-gas scrubbing trap may also be used to remove acid gases like SO_2. In some implementations of speciation traps, the particulate collection section of the trap is at the temperature of the flue gas being sampled, and in other implementations, a quartz wool plug is used upstream of the first trap. In any case, the other sections of the traps are controlled to $95 \pm 5\,°C$ to prevent breakthrough of mercury on the KCl sections. One manufacturer of speciation traps also recommends that the trap should be kept 20–30 °C above the dew point of the sample gas in the duct [20].

Speciation sorbent traps use the same sampling apparatus as that for the total mercury methods, with the exception of a special probe to control the temperature of the sections intended to collect gaseous mercury.

6.3.5 Sampling Protocol

6.3.5.1 Procedure and Apparatus

The assembled system is leak-checked before the sampling begins and after the sampling ends. After a period of sampling, the traps are removed and the individual sections are analyzed to measure the total amount of mercury in the traps. The mass of mercury collected in the traps divided by the total gas volume over the period of the sampling indicates mercury concentration in the gas.

As noted above, the speciation trap method requires a temperature-controlled probe, which the total mercury trap methods do not.

During the sampling period, it is important to measure the characteristics of the flue gas, for example, the oxygen content, flue gas velocity, and the moisture content. These will be used to determine the sample rate (for proportional sampling) and to convert the results to the units of emissions (pound per trillion British thermal unit or pound per gigawatt hour). To compare the sorbent trap result to that

of a mercury CEMS, the results might have to be converted to concentration on a wet volume basis, because this is how some CEMS measure mercury in flue gas.

The sampling period is not specified in the methods. There are several factors that influence the sampling period. The total amount of mercury collected on an individual trap depends on the concentration in the flue gas, the sampling time, and the sample flow rate. The amount of mercury collected on a trap must fall within the range of the calibration curve for the analytical method. Furthermore, the spikes of mercury added to section 3 (PS-12B) or section 1 (Method 30B) must have a mass of mercury that is in the expected range of mercury to be collected in the sample (section 1). For Method 30B, the spiked amount of mercury must be within ±15% of the expected mass of mercury on section 1. Method 30B is not intended for long sample times, as is PS-12B. If the sample period for PS-12B is too long (days to weeks), there may be breakthrough of mercury from section 1 to section 2, which will invalidate the run. Finally, if the sampling time is too short (<30 min), then small errors in the start and end times might result in substantial errors in the measured concentration.

6.3.6 Trap Analysis

The two most widely used approaches to analyzing the traps for mercury are (i) a wet digestion method using cold vapor atomic fluorescence (CVAF) spectroscopy and (ii) direct pyrolysis into a CVAA analyzer. The latter approach can be done on site with the proper equipment, adherence to standards of cleanliness, and proper calibration. Analysis of the traps is destructive; if there is a problem with the analysis, it cannot be repeated. Elemental mercury will absorb 253.7 nm UV light, and a CVAA detector will have exquisite low detection limits for mercury. However, contaminants such as sulfur dioxide, water, oxygen, halogens, and organic species can interfere with the determination of elemental mercury by CVAA.

6.3.7 Relative Accuracy and Quality Assurance/Quality Control

The sorbent trap methods are performance-based, which means that while some specifics of the method are not dictated (e.g., sample time, trap composition), the method must meet rigorous QA/QC criteria. The QA/QC criteria for PS-12B [8] and Method 30B [19] are similar, as seen in Tables 6.2 and 6.3.

For PS-12B, initial certification of the system requires a RATA using an RM. Acceptable RMs are the Ontario Hydro Method, Method 30A, or Method 30B. Twelve RM samples must be taken and the best nine samples compared to corresponding sorbent traps. The average relative difference between the sorbent trap measurements and the RM can be no >20%. If the RM concentration is $\leq 5\ \mu g\ m^{-3}$, then the relative accuracy (RA) criterion is satisfied, if the difference between the average values of the continuous measurement and the RM is not $>1\ \mu g\ m^{-3}$.

Table 6.2 QA/QC criteria for PS-12B.

QA/QC test or specification	Acceptance criteria	Frequency	If criteria not met
Pre-monitoring leak check	≤4% of target sampling rate	Prior to monitoring	Cannot start sampling
Post-monitoring leak check	≤4% of target sampling rate	After monitoring	Data from pair traps invalidated, or if certain conditions met, report adjusted data from a single trap
Ratio of stack gas flow rate to sample flow rate	Hourly ratio may not deviate from the reference ratio by more than ±25%	Every hour throughout the monitoring period	Data from pair traps invalidated, or if certain conditions met, report adjusted data from a single trap
Sorbent trap section 2 breakthrough	≤5% of section 1 Hg mass	Every sample	Data from pair traps invalidated, or if certain conditions met, report adjusted data from a single trap
Paired sorbent trap agreement	≤10% relative deviation (RD) if the average concentration is $>1.0\,\mu g\,m^{-3}$ ≤20% relative deviation (RD) if the average concentration is $\leq 1.0\,\mu g\,m^{-3}$ Results also acceptable if absolute difference between concentration from parallel traps is $\leq 0.03\,\mu g\,m^{-3}$	Every sample	Either invalidate the data from the paired traps or report the results from the trap with the highest Hg concentration
Spike recovery	Average recovery between 85% and 115% for each of the three spikes' concentration levels	Prior to analyzing field samples and prior to the use of new sorbent media	Field samples must not be analyzed until the percent recovery criteria are met
Multipoint analyzer calibration	Each analyzer reading within ±10% of true value and $r^2 \geq 0.99$	On the day of analysis, before analyzing any sample	Recalibrate until successful

(*continued overleaf*)

Table 6.2 (*Continued*)

QA/QC test or specification	Acceptance criteria	Frequency	If criteria not met
Analysis of independent calibration standard	Within ±10% of true value	Following daily calibration, prior to analyzing field samples	Recalibrate and repeat independent standard analysis until successful
Spike recovery from section 3 of both sorbent traps	75–125% of spike amount	Every sample	Data from pair traps invalidated, or if certain conditions met, report adjusted data from a single trap
Relative accuracy (RA)	RA ≤20.0% of reference method (RM) value; or if RM value ≤5.0 μg m^{-3}, absolute difference between RM and sorbent trap monitoring system mean values ≤1.0 μg m^{-3}	RA specification must be met for initial certification	Data from the system are invalid until an RA test is passed
Gas flow meter calibration	An initial calibration factor (Y) has been determined at three settings; for mass flow meters, initial calibration with stack gas has been performed. For subsequent calibrations, Y within ±5% of average value from the most recent three-point calibration	At three settings prior to initial use and at least quarterly at one setting thereafter	Recalibrate meter at three settings to determine a new value of Y
Temperature sensor calibration	Absolute temperature measured by sensor within ±1.5% of a reference sensor	Prior to initial use and at least quarterly thereafter	Recalibrate; sensor may not be used until specification is met
Barometer calibration	Absolute pressure measured by instrument within ±10 mm Hg of reading with a NIST-traceable barometer	Prior to initial use and at least quarterly thereafter	Recalibrate; sensor may not be used until specification is met

Table 6.3 QA/QC criteria for Method 30B.

QA/QC test or specification	Acceptance criteria	Frequency	If criteria not met
Pre-monitoring leak check	≤4% of target sampling rate	Prior to monitoring	Cannot start sampling
Post-monitoring leak check	≤4% of target sampling rate	After monitoring	Data from pair traps invalidated, or if certain conditions met, report adjusted data from a single trap
Sorbent trap section 2 breakthrough	≤10% of section 1 Hg mass for Hg concentration is >1.0 μg m^{-3} ≤20% of section 1 Hg mass for Hg concentration is ≤1.0 μg m^{-3}	Every sample	Sample invalidated
Paired sorbent trap agreement	≤10% relative deviation (RD) if the average concentration is >1.0 μg m^{-3} ≤20% relative deviation (RD) or ≤0.2 μg m^{-3} if the average concentration is ≤1.0 μg m^{-3}	Every sample	Run invalidated
Multipoint analyzer calibration	Each analyzer reading within ±10% of true value and $r^2 \geq 0.99$	On the day of analysis, before analyzing any sample	Recalibrate until successful
Analysis of independent calibration standard	Within ±10% of true value	Following daily calibration, prior to analyzing field samples	Recalibrate and repeat independent standard analysis until successful
Temperature sensor calibration	Absolute temperature measured by sensor within ±1.5% of a reference sensor	Prior to initial use and at least quarterly thereafter	Recalibrate; sensor may not be used until specification is met
Barometer calibration	Absolute pressure measured by instrument within ±10 mm Hg of reading with a NIST-traceable barometer	Prior to initial use and at least quarterly thereafter	Recalibrate; sensor may not be used until specification is met

(*continued overleaf*)

Table 6.3 (*Continued*)

QA/QC test or specification	Acceptance criteria	Frequency	If criteria not met
Sample analysis	Within valid calibration range (within calibration curve)	All section 1 samples where stack Hg concentration is $\geq 0.5\,\mu g\,m^{-3}$	Reanalyze at more concentrated levels if possible, samples invalidated if not within calibrated range
Sample analysis	Within bounds of Hg^0 and $HgCl_2$ analytical bias test	All section 1 samples where stack Hg concentration is $\geq 0.5\,\mu g\,m^{-3}$	Expand bounds of Hg^0 and $HgCl_2$ analytical bias test; if not successful, samples invalidated
Field recovery test (spiked trap)	Average recovery between 85% and 115%	Once per field test	Field sample runs not validated without successful field recovery test
Gas flow meter calibration (at three settings)	Calibration factor Y within ±2% of average value of Y	Prior to initial use and when post-test check is not within ±5% of Y	Recalibrate at three points until acceptance criteria met
Gas flow meter calibration, post-test (single-point)	Calibration factor Y within ±5% of average value from the most recent three-point calibration	After each field test. For mass flow controllers must be done on-site using stack gas	Recalibrate at three points to determine new Y. For mass flow meters, must be done on-site using stack gas. Apply new Y values to field test data
Analytical matrix interference test (wet chemical analysis only)	Establish minimum dilution (if any) needed to eliminate sorbent matrix interferences	Prior to analyzing any field samples; repeat for each type of sorbent used	Field sample results not validated
Analytical bias test	Average recovery between 90% and 110% for Hg^0 and $HgCl_2$ at each of the two spike levels	Prior to analyzing field samples and prior to use of new sorbent media	Field samples shall not be analyzed until the percent recovery criteria has been met
Analysis of continuing calibration verification standard	Within ±10% of true value	Following daily calibration, after analyzing ≤10 field samples, and at end of each set of samples	Recalibrate and repeat independent standard analysis, reanalyze samples until successful, if possible; for destructive techniques, samples invalidated
Test run sample volume	Within ±20% of total volume sampled during field recovery test	Each individual sample	Sample invalidated

6.4 Recommendations

For long-term monitoring of mercury emissions or for short-term testing of mercury control technologies, CEMS or batch methods can be used. The two types of methods have advantages and disadvantages. Consideration should be given to some of the following factors when choosing a mercury measurement method.

6.4.1 Particulate Matter

If there is a need to sample a gas that has a high dust loading and there is an expectation that there will be a significant component of mercury in the particulate matter, the best option is one of the wet chemistry methods, which collect an isokinetic sample on a filter (bearing in mind the potential for bias because of the particulate matter on the filter). When sampling after the particulate control device, the mercury in the flue gas will be almost entirely gaseous mercury and a CEMS or sorbent trap will give representative results.

6.4.2 Total Versus Speciated Mercury

For evaluating emissions from a combustion source for compliance purposes, only total mercury is required. This can be measured with a CEMS or with one of the batch methods that measure total mercury (Method 101A, Method 29, PS-12B). For research or testing reasons, it is sometimes necessary to measure gaseous speciation; for example, if there is a need to quantify re-emission of elemental mercury across a wet scrubber, speciated mercury measurements (CEMS, Ontario Hydro Method, FAMS) should be made at the inlet and outlet of the scrubber.

6.4.3 Expected Mercury Concentration in the Flue Gas

The Ontario Hydro Method is generally accurate above a total mercury concentration in the flue gas of $0.5\,\mu g\,m^{-3}$, although the lower limit of detection can be higher, depending on the care taken by the test personnel. At present, NIST-traceable calibration gases for Hg CEMS provide concentrations from ~0.2 to $>40\,\mu g\,m^{-3}$. Most commercial CEMS can accurately measure mercury in flue gas down to the lower concentration of $0.2\,\mu g\,m^{-3}$. Sorbent traps can measure even lower concentrations of mercury in flue gas, because the sampling time can be increased to ensure that an adequate mass of mercury is collected in the traps. When very low levels of mercury are expected in the flue gas, sorbent traps are preferred.

6.4.4
Need for Real-Time Data

In some instances, a concentration of mercury averaged over 30 min to several hours (or even days) will suffice. In this case, batch sampling methods can be used. However, in some cases (for example, process control or short-term technology demonstrations), a continuous mercury measurement is required, and a CEMS must be used. Furthermore, batch methods use destructive analysis; if a measurement is lost or invalidated, there are no data for a specific period. CEMS provide data every 1–2 min typically.

6.4.5
Complexity of Installation and Operation

Sorbent trap methods are less expensive and complicated to install than CEMS or wet chemistry methods. Sorbent trap systems are less complex than CEMS and do not require as much training of technical personnel over long-term operation. Wet chemistry methods are not used for continuous monitoring of a source. These methods require specifically trained personnel and great care in preparation, set-up, and post-test sample collection and stabilization.

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Part III
Mercury Chemistry in Coal Utilization Systems and Air Pollution Control Devices

Mercury Control: for Coal-Derived Gas Streams, First Edition.
Edited by Evan J. Granite, Henry W. Pennline and Constance Senior.
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7
Mercury Behavior in Coal Combustion Systems

Constance Senior

7.1
Introduction

Control of mercury emissions from coal combustion systems relies on an understanding of the chemistry of mercury and its interactions with various elements in the combustion system. In coal utilization systems, mercury can take on different chemical forms in flue gas: gaseous elemental (Hg^0), gaseous oxidized (Hg^{2+}), and particulate-bound (Hg_p). As discussed in Chapter 1, the form in which mercury is emitted to the atmosphere determines its fate and transport in the environment. In this chapter, the factors influencing the forms of mercury found in coal combustion flue gas are elucidated.

Coal combustion systems that are used in electricity generating unit (EGU) boilers or industrial, commercial, and institutional (ICI) boilers have a variety of designs. The compositions of coals, which are burned to generate electricity and/or steam in these boilers, vary considerably. Finally, there are different types of air pollution control devices (APCDs) in use on coal-fired boilers to control emissions of NO_x, SO_x, and particulate matter (PM). These three factors – combustion system, coal type, and existing APCD configuration – affect the form and speciation of mercury that is emitted to the atmosphere and the degree of difficulty in controlling the emission of mercury to the atmosphere.

Later chapters in this book will discuss control technologies that are specific to mercury capture from coal-fired boilers. In this section, the groundwork will be laid for understanding mercury control technologies applied to coal combustion systems. The characteristics of coal combustion boilers and APCDs will be described. Then, the chemistry of mercury in coal combustion systems will be discussed. Finally, the behavior of mercury in the existing APCDs on coal-fired boilers will be explored.

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7.2
Coal Combustion Boilers

The purpose of EGU or ICI boilers is to generate steam, which is used to generate electricity in EGU boilers and certain ICI boilers or to generate steam for chemical processes or heating in ICI boilers. Generating steam from coal combustion is accomplished by creating a high temperature gas and then transferring energy from the gas to water or steam, first in a radiant zone and then in a convective zone [1]. After this heat has been transferred, the flue gas has a temperature of 340–370 °C (650–700 °F). The combustion air is preheated in a gas–gas heat exchanger, called an *air preheater* (*APH*). The flue gas that exits the convective heat exchangers then passes through the APH, and its temperature drops to 135–175 °C (275–350 °F) as illustrated in Figure 7.1. The temperature of the flue gas drops rapidly from the combustion temperatures in the range of 900–1500 °C (1650–2750 °F) to post-APH temperatures in a few seconds [2]. The peak combustion temperature depends on the type of combustion system. This rapid quench of the flue gas has consequences for the chemistry of mercury in the gas, as discussed below.

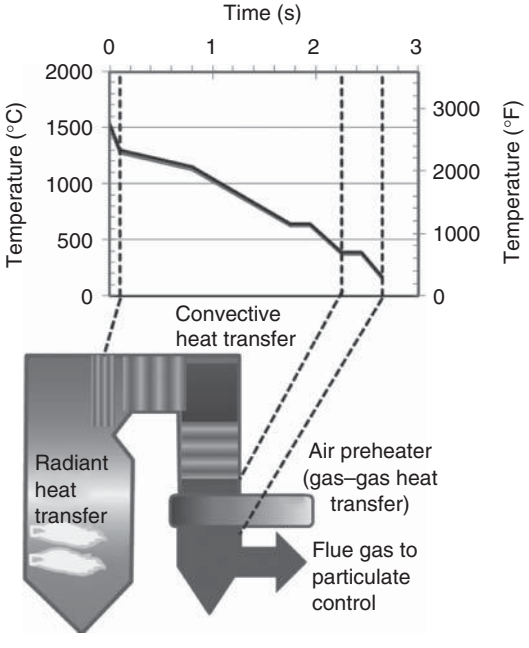

Figure 7.1 Time–temperature history in a coal-fired boiler from radiant section to air preheater.

7.3
Mercury Chemistry in Combustion Systems

Mercury is present in coal in low concentrations, on the order of 0.1 $\mu g\, g^{-1}$, as discussed in Chapter 2. In the combustion zone of a coal-fired boiler, all the mercury in coal is vaporized as elemental mercury, yielding vapor concentrations of mercury in the range of 5–40 $\mu g\, m^{-3}$. At furnace exit temperatures, all of the mercury is expected to remain as the thermodynamically favored elemental form in the gas. As the gas cools in the convective heat transfer zone, oxidation reactions can occur, significantly reducing the concentration of elemental mercury by the time the post-combustion gases reach the stack. Measurements of the concentration of mercury species taken in the stacks of pilot and full-scale coal combustion systems show that the range of the values of the fraction of oxidized mercury is broad: studies have reported anywhere from almost no Hg^{2+} to 95% Hg^{2+} upstream of the particulate control device (PCD) [3]. Laboratory experiments [4] have shown that mercury is not oxidized in the gas phase by O_2 at temperatures up to 700 °C (1290 °F). Combustion experiments in laboratory combustion systems have shown an increase in oxidized mercury post-combustion with increasing chlorine or bromine content [5–8]. Quench rate has been shown to affect the degree of homogeneous oxidation [6, 7].

Comparison of mercury speciation data from full-scale coal-fired boilers with those from particle-free laboratory combustion studies [9] shows higher amounts of oxidized Hg in the former, for similar amounts of chlorine in the fuel. Two conclusions arise from such comparisons:

- Oxidation of mercury by chlorine in practical coal combustion systems must be kinetically limited [10, 11].
- Heterogeneous oxidation of mercury on fly ash particles in coal-fired boilers is as important, or more important, than homogeneous oxidation of mercury [12, 13].

Gas-phase oxidation relies on the reaction between elemental mercury and halogen radicals. The inherent concentrations of these halogens in coal as well as the specific halogen species formed in the combustion system affect homogeneous mercury oxidation.

The range of concentrations of chlorine and bromine species in coal combustion flue gas depends on the concentrations in the coal. In U.S. coal-fired power plants, the concentration of HCl in the flue gas is on the order of 1–10 ppmv when low-rank coals (subbituminous and lignite) are burned, but HCl concentrations can be as high as 150 ppmv when bituminous coals are burned. These estimates assume coal chlorine concentrations of up to 100 $\mu g\, g^{-1}$ in subbituminous and lignite coals and up to 2000 $\mu g\, g^{-1}$ in bituminous coals. Bromine concentrations in coals are significantly less than chlorine concentrations, as discussed in Chapter 2. The concentrations of bromine (expressed as HBr) in the flue gas of coal-fired combustion systems is estimated to be <0.5 ppmv in boilers firing subbituminous or lignite coals and up to 3.5 ppmv in bituminous-fired boilers.

The differences between the speciation of chlorine and bromine in combustion flue gas have implications for the oxidation of mercury by halogens. As flue gases cool in a practical combustion system, most of the chlorine is predicted to be HCl, with a very minor amount as the free radical Cl, the species thought to be responsible for the homogeneous oxidation of elemental mercury [2]. Recent kinetic modeling [12] results suggest that bromine speciation is different from chlorine speciation in coal combustion flue gases. In contrast, the concentrations of HBr and Br are comparable at flame temperatures and, as the flue gases cool, the concentration of Br is on the same order as that of HBr.

Experiments on the gas-phase oxidation of mercury by halogens were conducted in a bench-scale, laminar, methane-fired (300 W), quartz-lined reactor in which gas composition (HCl, HBr, NO_x, SO_2) was varied [7]. In the experiments, the post-combustion gases were quenched from flame temperature to about 350 °C, and then speciated mercury was measured using a wet conditioning system and continuous emissions monitor system (CEMS). Bromine was shown to be much more effective than chlorine in the post flame, homogeneous oxidation of mercury, on an equivalent molar basis, as illustrated in Figure 7.2.

In these experiments, the addition of NO to the flame (up to 400 ppmv) had no impact on mercury oxidation by chlorine or bromine. Addition of SO_2 had no effect on mercury oxidation by chlorine at SO_2 concentrations below about 400 ppmv; some increase in mercury oxidation was observed at SO_2 concentrations of 400 ppmv and higher. The addition of chlorine caused minor increases in the extent of oxidation by bromine.

Smith *et al.* [8] obtained similar results in a different methane-fired laboratory furnace: homogeneous oxidation of mercury was <30% when the concentration of HCl was as much as 500 ppmv. The researchers observed inhibition or enhancement of mercury oxidation by chlorine when SO_2 was added, and

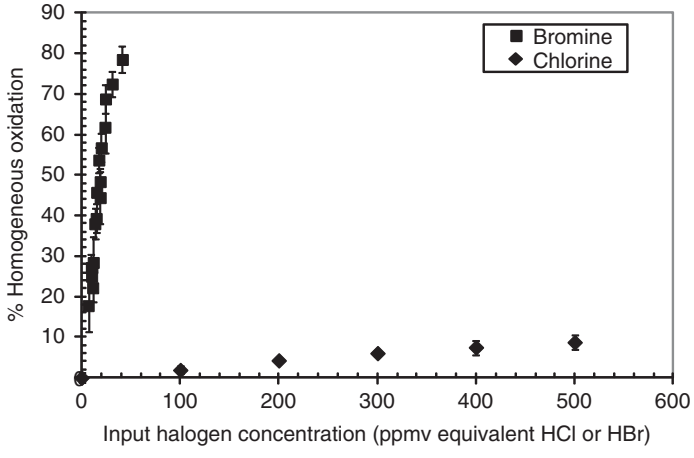

Figure 7.2 Homogeneous oxidation of mercury by halogens in a laboratory combustor as a function of initial halogen concentration [7].

the effect depended on the concentrations of SO_2 and HCl. There was little effect when the concentration of SO_2 was 400 ppmv with up to 550 ppmv HCl. However, at an HCl concentration of 200 ppmv and lower concentrations of SO_2 (100–200 ppmv), SO_2 did affect the level of mercury oxidation observed.

A detailed chemical kinetic mechanism for mercury oxidation by chlorine species in flue gas was applied to pilot-scale coal combustion results by Niksa and Fujiwara [13], but was unable to predict the extent of mercury oxidation. The authors concluded, based on gas-phase kinetic modeling, that the quench rate in the pilot-scale system was not high enough to produce sufficient chlorine radicals to oxidize elemental mercury. A heterogeneous pathway, utilizing the interaction of mercury and HCl on carbon surfaces, was suggested to explain the results.

In coal-fired boilers, concentrations of HCl are expected to be <150 ppmv, which means that the contribution from homogeneous oxidation of mercury by chlorine in practical combustion systems should be 10% or less. The concentration of bromine native to coal is too low to promote significant gas-phase oxidation, although the addition of bromine to the coal or the flue gas does yield increased oxidation, as discussed in Chapter 14.

Gas-phase oxidation of mercury by chlorine has been shown to be inadequate for explaining the observed mercury oxidation in coal-fired furnaces (see Part VI for details of gas-phase mercury models). Heterogeneous oxidation (that is, catalyzed by surfaces) must be responsible for much of the mercury oxidation observed in coal combustion systems.

Transition metal oxides have been shown to oxidize mercury in coal flue gas. Studies have shown that vanadium oxide can oxidize mercury in simulated coal combustion flue gas, and that mercury oxidation increases with increasing concentration of HCl in the gas [14–16]. Studies on V_2O_5 have been carried out at temperatures on the order of 350 °C, which is the temperature of selective catalytic reduction (SCR) reactors in power plants. (This is discussed in more detail in Chapter 15.) At these temperatures, other oxides also catalyze mercury oxidation in the presence of HCl. Kamata *et al.* [17] reported that the activity for mercury oxidation was as follows: $MoO_3 \sim V_2O_5 > Cr_2O_3 > Mn_2O_3 > Fe_2O_3 > CuO > NiO$.

Metal oxides have been demonstrated to oxidize mercury in simulated flue gas at post-APH temperatures (120–180 °C) in many different published works. For example, in fixed-bed experiments with simulated ash (mixtures of oxides), Ghorishi *et al.* [18] showed that the transition metal oxides, CuO and Fe_2O_3, acted as catalysts for the oxidation of Hg^0 in the presence of HCl. Galbreath *et al.* [19] flowed coal combustion flue gas from a pilot-scale combustor through a fixed bed of γ-Fe_2O_3 at 150 °C and observed the conversion of Hg^0 to Hg^{2+} and/or Hg_p. Smith *et al.* [8] injected either α-Fe_2O_3 or montmorillonite clay particles into combustion flue gas from a methane flame doped with mercury and HCl. Mercury oxidation increased in the flue gas with respect to pure homogeneous oxidation when iron oxide particles were injected, but not when the clay particles were injected.

Efforts to find such a relationship between oxidation and metal oxides have produced ambiguous results when using actual coal fly ash (containing mixed inorganic oxides and unburned carbon).

In fixed-bed studies using simulated flue gas and fly ash from two different coal combustion boilers, Norton *et al.* [20] concluded that HCl and NO_2 were of primary importance to mercury oxidation, with NO and SO_2 being of secondary importance. Tests were performed at 120 and 180 °C (248 and 356 °F). The extent of mercury oxidation generally correlated well with the surface areas of the different ash samples. One iron-rich ash sample did not show significantly more oxidation than a low-iron ash sample.

Ash samples from a variety of sources and coal types were tested by Dunham *et al.* [21] in a fixed-bed reactor using elemental mercury in simulated flue gas mixtures at 121 and 177 °C (250 and 350 °F). Oxidation of elemental mercury increased with increasing amounts of magnetite in the fly ash. However, one high-carbon subbituminous ash with no magnetite showed considerable mercury oxidation that may have been due to the carbon surface area. Galbreath *et al.* [22] also noted that the presence of maghemite (γ-Fe_2O_3) in fly ash and HCl in flue gas promoted oxidation of elemental Hg. These works suggest that an iron oxide with a spinel-type structure is active in fly ash with respect to mercury oxidation. The importance of surface area suggests that unburned carbon and/or soot (which have much higher surface areas than inorganic ash particles) dominate the oxidation of mercury at these temperatures.

Fly ash can adsorb elemental and oxidized mercury, in addition to catalyzing the oxidation of elemental mercury. Early experimental work by Hall and coworkers [4] on the adsorption of mercury by activated carbon or fly ash in the presence of O_2 suggested that physisorption of mercury dominated at temperatures below 100 °C (212 °F), but that chemisorption dominated between 100 and 300 °C (212 and 572 °F). The rate of mercury adsorption peaked at a temperature of 200 °C (392 °F) in their experiments, and there was no mercury adsorption observed above 350 °C (662 °F).

A large body of work (much of it summarized by Hower *et al*. [23]) suggests that the unburned carbon in fly ash from coal combustion systems can adsorb mercury in flue gas. For example, in the fixed-bed study of Dunham *et al.* [21], all the fly ash samples that acted as oxidation catalysts for elemental mercury also adsorbed elemental mercury in simulated flue gas mixtures. The adsorption capacity of the ash for elemental mercury was similar to that for $HgCl_2$. There was a correlation between fly ash surface area and adsorption of elemental Hg and $HgCl_2$, although the correlation was better for $HgCl_2$. The adsorption capacity had an inverse dependence on temperature, over the range studied (121–177 °C). Most of the fly ash surface area is due to the presence of unburned carbon and/or soot, which seems to dominate the adsorption process.

Fly ash, and in particular the unburned carbon in fly ash, has been observed to both oxidize mercury and adsorb mercury. Most of the theoretical and experimental work carried out to date on the fundamental mechanisms of mercury–carbon reactions in combustion systems has focused on activated

carbon, instead of unburned carbon in fly ash. Part VI of this book discusses mechanisms and models for the interaction of mercury and carbon surfaces in detail, and these will be discussed only briefly here.

The review by Hower *et al.* [23] provides detailed information on the properties of unburned carbon as related to mercury adsorption in flue gas. Acid gases in flue gas – for example, HCl, Cl_2, H_2SO_4 – promote the oxidation of mercury in the presence of carbon surfaces at post-APH temperatures. However, some of these species are not oxidants; therefore, other species in the flue gas must be responsible for oxidation of mercury on carbon surfaces. As discussed in Chapter 25, a mechanism has been hypothesized and validated in which acid gas species such as HCl bind to the carbon surface, forming a site at which elemental mercury can bind and subsequently be oxidized, principally by NO_2. Furthermore, there is a competition for these active carbon sites between mercury species and H_2SO_4, which has profound implications for capture of mercury by carbon in practical combustion systems. Sulfuric acid can occupy surface sites either by adsorption of gaseous SO_3 or H_2SO_4 or by adsorption of SO_2 and subsequent oxidation by NO_2 on the surface. As H_2SO_4 accumulates on the surface, the bound, oxidized mercury species are displaced and desorbed, probably as $HgCl_2$. The rate of mercury adsorption decreases as temperature increases, but the rate of oxidation of elemental mercury increases as temperature increases [24].

Alkaline species in fly ash, particularly calcium oxide, if present, have been shown to adsorb oxidized mercury in flue gas. As discussed above, mercury–halogen compounds are the most likely gas-phase oxidized mercury species present in combustion flue gas. Chapter 13 provides a detailed discussion of the interaction between mercury and calcium species in combustion flue gas.

The coal combustion boiler represents a series of chemical reactors, which change the elemental mercury produced in the flame to gaseous oxidized mercury and particulate-bound mercury. The transformations of mercury in coal combustion flue gases are influenced by gas-phase species (halogens, NO_x, SO_x) and the PM (unburned carbon, inorganic ash) suspended in the gas as well as the quench rate and gas temperatures. The most significant of these transformations take place in the APCDs downstream of the boiler. Therefore, an understanding of the APCDs used on coal-fired boilers is essential for understanding the mercury emissions and the potential for control of mercury on a wide variety of combustion systems.

7.4
Air Pollution Control Devices on Utility and Industrial Boilers

Before discussing the chemistry of mercury in APCDs, a brief overview will be presented of the major pollution control equipment in use on coal-fired boilers. These APCDs have been installed to control the major pollutants NO_x, SO_2, and

Table 7.1 Air pollution control devices for PM, NO_x, and SO_2.

Particulate control	
C-ESP	Cold-side electrostatic precipitator
H-ESP	Hot-side electrostatic precipitator
FF	Fabric filter (baghouse)
WPS	Wet particulate scrubber (venturi scrubber)
Cyclone	Sometimes known as *mechanical collector*
NO_x control	
LNB	Low-NO_x burner
OFA	Overfire air
SNCR	Selective non-catalytic reduction
SCR	Selective catalytic reduction
SO_2 control	
DSI	Dry sorbent injection
dFGD	Dry flue gas desulfurization
wFGD	Wet flue gas desulfurization

PM. In this section, the major types of APCDs for coal-fired boilers are introduced. Table 7.1 contains a glossary of the processes.

7.4.1 PM Control

Combustion processes emit both primary and secondary PM. Primary PM emissions are called *fly ash* (e.g., non-combustible inorganic matter and unburned solid carbon). Secondary PM emissions are the result of substances that condense in the stack, such as sulfuric acid, to produce PM in the atmosphere. PM control technologies include fabric filters (FFs) or "baghouses," wet and dry electrostatic precipitators (ESPs), venturi scrubbers, and mechanical collectors (cyclones). ESPs are the most widely used PM control device on coal-fired boilers. Most ESPs are located after the APH (see Figure 7.1) and operate at temperatures of 120–190 °C (250–370 °F); these are called *cold-side electrostatic precipitators* (*C-ESPs*). A small fraction of ESPs are located upstream of the APH at temperatures in the range of 350–400 °C (650–750 °F); these are called *hot-side electrostatic precipitators* (*H-ESPs*). ESPs charge fly ash particles and then collect the charged particles in an electric field. Particles are collected on electrically charged plates and periodically removed by mechanical means. The particles drop from the plate into a hopper. FFs, in contrast, collect particles on a filter or bag, such that the flue gas must pass through the "cake" of collected particles. Periodically, the dust cake is removed by agitating the bag so that the cake falls off into a hopper. FFs operate in the same temperature range as C-ESPs. FFs and ESPs represent about 97% of the PM control devices on EGU boilers. Other PM control devices, like wet particulate scrubbers and cyclones, are more commonly found on ICI boilers.

7.4.2 NO_x Control

Emission control strategies for NO_x fall into two categories: combustion controls and post-combustion technologies. Combustion control technologies minimize the formation of NO_x in the furnace and include combustion tuning, low-NO_x burners (LNBs), and overfire air (OFA). LNBs (or staged combustion conditions) may introduce higher carbon monoxide and unburned carbon in fly ash, which reflect lower plant efficiency. In an OFA system, the primary combustion zone is operated at less than a stoichiometric air/fuel ratio, and additional air is added in the upper furnace. Unburned carbon in ash can still increase in boilers using OFA, depending on the type of fuel and design of the system.

Post-combustion technologies reduce the amount of NO_x that has been formed during combustion. In selective non-catalytic reduction (SNCR), a nitrogen-containing reagent is injected into the furnace in the temperature range of 900–1100 °C (1600–2000 °F). NO_x reduction with SNCR is in the range of 30–50%, depending on the residence time and degree of mixing achieved. Higher NO_x reduction (80–90%) is achieved using SCR. In this process, ammonia is injected over a vanadia-based catalyst at temperatures in the range of 350–400 °C (650–750 °F) in order to chemically reduce NO_x to nitrogen and water.

7.4.3 SO_2 Control

SO_2 emission control technologies are post-combustion devices that remove SO_2 by reacting it with an alkaline reagent. The two most commonly used SO_2 controls are dry flue gas desulfurization (FGD) units and wet FGD units. In the former, an aqueous slurry (usually lime) is sprayed into a contacting vessel in order to contact the alkaline reagent with SO_2. The reagent dries and is collected in a PCD (usually a FF). A lower-cost version of a dry process is dry sorbent injection (DSI) in which there is no dedicated contacting vessel; instead, the dry reagent (sodium carbonate or sodium sesquicarbonate) is injected into the flue gas duct and then collected in the PCD. Dry FGDs can achieve 90–95% reductions, although they are used when the coal sulfur content is less than about 2 wt%. DSI results in more modest SO_2 reductions, but the low capital cost of this technology makes it attractive for some boilers.

In a wet FGD, a solution of water and limestone or lime contacts the flue gas. The scrubbing solution is sprayed into the gas and collected as a liquid in the bottom of the scrubber; in some designs, the flue gas is bubbled through a liquid solution. Wet FGDs turn SO_2 into either calcium sulfite or calcium sulfate. The end product is either a sludge or gypsum, depending on the oxidation potential in the solution. Wet FGDs are the most efficient for removal of SO_2 and are typically used when the coal sulfur content is higher than 1–2 wt%; removals of >95% can be achieved.

7.4.4 Boiler Populations in the United States

There are ~1100 coal-fired EGU boilers in the United States with capacities >25 MW at more than 500 facilities [25]. The generating capacities of EGU boilers are generally in the range of 150–1300 MW. According to a survey of industrial and commercial boilers in the United States in 2005 [26], there were about 2600 coal-fired industrial and commercial boilers. The fuel firing rate of these coal-fired boilers averaged 37 MJ s^{-1} (125 million Btu h^{-1}), which is much smaller than the firing rate of EGU boilers; for comparison, the firing rate of a 500 MW EGU boiler is about 1700 MJ s^{-1}.

The distribution of APCDs on EGU boilers is summarized in Table 7.2 [27]. The table indicates the number of APCDs in individual categories. Some boilers have only a PCD, while other boilers have scrubbers and SCRs in addition to PCDs. Those boilers with both an SCR and a scrubber are called out separately in Figure 7.3, because, as discussed below, this combination of APCDs can remove a significant fraction of mercury from the flue gas.

Bituminous coals have higher sulfur contents than low-rank coals (i.e., subbituminous and lignite), which results in a different distribution of APCD equipment on bituminous plants as compared to low-rank plants. Many bituminous-fired plants are located in the Eastern half of the United States, where NO_x emissions are regulated in order to reduce the formation of ground-level ozone. Thus, bituminous-fired boilers are more likely to have a combination of SCR for

Table 7.2 Air pollution control devices on EGU boilers in the United States [27] in terms of number of boilers.

APCD	Coal rank				
	Bituminous	Subbituminous	Lignite	Other[a)]	Total
Particulate control					
Cold-side ESP[b)]	454	257	17	1	729
Fabric filter[c)]	120	112	12	31	275
Hot-side ESP	78	23	0	0	101
Other	16	14	1	0	31
Post-combustion NO_x					
SNCR	146	22	2	15	185
SCR	208	84	2	1	295
SO_2 control					
Fluidized bed[d)]	20	4	7	29	60
Dry sorbent injection	29	7	1	0	37
Dry FGD	54	31	3	0	88
Wet FGD	255	89	16	1	361

a) Includes waste coal and petcoke.
b) Includes combinations of cold-side and hot-side.
c) Includes combinations of ESP and FF.
d) Includes in-bed capture in fluidized bed.

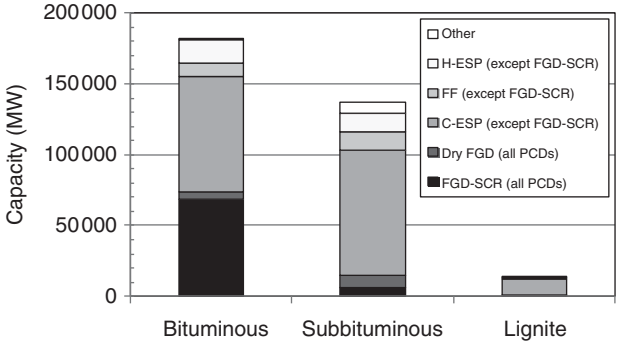

Figure 7.3 Distribution of APCDs on EGU boilers in the United States by boiler capacity [27].

NO_x control and wet FGD for SO_2 control. Subbituminous-fired plants have a larger share of dry FGDs, because the fuels have <1% sulfur. For all types of fuel, the largest category of APCDs is a C-ESP alone, with no scrubber and no post-combustion NO_x control. (Most boilers have some form of combustion control of NO_x, whether or not they have post-combustion NO_x controls.)

New APCD equipment will be installed by 2015 on EGU boilers in the United States as a result of the new Mercury and Air Toxics Standards (MATSs) regulation and the Cross-State Air Pollution Rule (CSAPR). US EPA's analysis of EGU boilers [25] projects an additional 20 GW of dry FGD, 44 GW of DSI, 102 GW of additional FFs, 63 GW of scrubber upgrades, and 34 GW of ESP upgrades by 2015.

ICI boilers tend to have less pollution control equipment than EGU boilers. For example, a survey of ICI boilers firing wood or coal in four states in Northeastern USA [28] showed that about half the boilers had no air pollution controls, 40% of the boilers had only PM control, and 8% of the boilers had a combination of NO_x control and PM control. There were no boilers with SO_2 controls in this population.

7.5
Mercury Behavior in Coal-Fired Boilers

7.5.1
Data Sources

Understanding the behavior of mercury in full-scale coal-fired boilers requires a large body of data from the field. Laboratory and pilot-scale data can provide useful information but the complexity of coal combustion boilers necessitates full-scale data. Over the past 15 years, a large body of data has been generated in the United States and it is largely from these data that the mechanisms and pathways presented here have been drawn.

Table 7.3 Types of coal-fired boilers sampled in 1999 ICR by coal type and APCD, compared with total boiler population [29].

APCD equipment	Coal type	% units tested	% existing units
Cold-side ESP	Bituminous	7.2	48.3
Cold-side ESP	Low rank	7.1	11.7
Hot-side ESP	Bituminous	7.2	6.6
Hot-side ESP	Low rank	3.6	2.4
Cold-side ESP + wet FGD	Bituminous	6	8.8
Cold-side ESP + wet FGD	Low rank	9.2	2.5
Hot-side ESP + wet FGD	Bituminous	4.8	0.7
Hot-side ESP + wet FGD	Low rank	3.6	1
FF	Bituminous	3.6	2.9
FF	Low rank	7.2	2.7
FF + wet FGD	Bituminous	7.2	1.6
FF + wet FGD	Low rank	3.6	1.6
Dry FGD + FF	Bituminous	3.6	2.9
Dry FGD + FF	Low rank	7.2	1.3
Dry FGD + ESP	Bituminous	2.4	0.2
Dry FGD + ESP	Low rank	3.6	0.3
FF + FBC	Bituminous	3.6	2.9
Other	Other	9.3	1.6

US EPA has carried out two Information Collection Requests (ICRs) as part of rulemaking for the electric utility industry. These ICRs have provided much data on the speciation and removal of mercury in various APCD configurations.

The first ICR was carried out in 1999. Part 3 of the ICR consisted of measurements of mercury speciation from 83 coal-fired power plants. Plants were selected based on the configurations of air pollution control equipment and fuel type. For each plant, the mercury content of the coal was measured (along with other coal composition data). Mercury measurements were made at the stack and at the inlet to the last APCD using the Ontario Hydro method (see Part II for a description of the method); the result was a set of gaseous elemental, gaseous oxidized, and particulate-bound mercury at the inlet and outlet of APCDs. Table 7.3 summarizes the configurations for the ICR data sets, comparing the distribution of units tested with the distribution of the boiler population in the United States. As the table shows, a wide range of APCD configurations were tested, which proved valuable for understanding mercury behavior.

The 1999 ICR was used to support the creation of the Clean Air Mercury Rule (CAMR), which was proposed in 2005. The CAMR was ultimately vacated by the courts. EPA decided to issue another ICR in order to support development of a new rule for EGU boilers, because there had been considerable changes in the APCD configurations since the original ICR. At the end of 2009, EPA issued another ICR to the electric utility industry, requesting information on emissions of mercury and other hazardous air pollutants (HAPs) from EGUs firing coal or

oil. In 2010, a subset of coal-fired EGUs was required to conduct measurements of mercury and non-mercury HAP metals (antimony, arsenic, beryllium, cadmium, chromium, cobalt, lead, manganese, nickel, and selenium) in the boiler stack. Mercury was measured using CEMS or sorbent traps (see Part II for descriptions of methods) at the stack, as well as measured in a coal sample taken concurrently with each stack test. This ICR data set represents a range of fuel types and APCD types, as shown in Table 7.4.

There were many changes in APCD configurations in the industry in the 11 years between the two ICRs. The 1999 ICR dataset contained very few boilers that had post-combustion NO_x control (SCR and SNCR) and no boilers that had activated carbon injection (ACI) for mercury control or DSI for acid gas control. Furthermore, the 2010 ICR dataset contains more data from fluidized bed combustors (FBCs) as compared to the 1999 dataset.

Part IV of this book discusses the substantial research and development efforts undertaken by US DOE, EPA, and EPRI in the mercury control area. Sampling campaigns and technology demonstrations at coal-fired power plants sponsored by these organizations have also provided much valuable information on mercury behavior in coal-fired power plants.

7.5.2 Mercury Behavior in APCDs

In this section, the reader will follow the path of mercury through a coal-fired boiler, using full-scale data from DOE- and EPRI-sponsored mercury measurement campaigns at coal-fired utility boilers [30], unless otherwise noted.

As discussed above, mercury is released from the coal in the flame as gaseous Hg^0 and halogens present in the gas are the primary pathway for gas-phase oxidation. In an evaluation of homogeneous models and data for mercury oxidation by chlorine in combustion systems, Krishnakumar and Helble [11] concluded that oxidation of Hg^0 occurs at temperatures below 625 °C (1160 °F) and the chlorine radical is the most important reactive species for mercury oxidation in the gas phase. Halogens are also involved in the heterogeneous oxidation of mercury, catalyzed either by SCR catalysts or by fly ash.

Oxidation of mercury by SCR catalysts is discussed in detail in Chapter 15. The primary variables that affect the oxidation of mercury across SCR catalysts are halogen content of flue gas, temperature, space velocity (residence time), and catalyst design. Without the injection of additional halogens (Chapter 14), the halogen content of the flue gas is primarily related to the chlorine content of the coal. As Figure 7.4 shows, mercury oxidation across SCR reactors is strongly correlated with the chlorine content of the coal.

All coal-fired utility boilers and most coal-fired industrial boilers have a gas–gas heater exchanger to preheat the combustion air by contacting it with the flue gas. This APH decreases the flue gas temperature from typically 350 to 150 °C, while heating the combustion air to ~300 °C. There are two types of APHs: regenerative and tubular. The majority of APHs are drum-type regenerative heat exchangers,

Table 7.4 Number of coal-fired boilers sampled in 2010 ICR by coal type and APCD.

	Bituminous	Subbituminous	Lignite	Waste coal
Units with cold-side ESPs				
C-ESP only	42	51	1	—
SNCR, C-ESP	5	1	—	—
SCR, C-ESP	—	9	—	—
C-ESP, wet FGD	14	5	2	—
SNCR, C-ESP, wet FGD	8	1	—	—
SCR, C-ESP, wet FGD	25	2	—	—
Dry FGD, C-ESP	—	1	—	—
DSI, C-ESP	—	1	—	—
SNCR, DSI, C-ESP	—	1	—	—
Units with fabric filters				
FF only	8	14	3	—
SNCR, FF	—	1	1	—
FF, wet FGD	7	6	—	—
SNCR, FF, wet FGD	1	—	—	—
SCR, FF, wet FGD	4	2	—	—
Dry FGD, FF	14	7	1	—
SNCR, dry FGD, FF	2		2	—
SCR, dry FGD, FF	7	2	—	—
SNCR, DSI, FF	1	—	—	—
Units with hot-side ESPs				
H-ESP only	5	5	—	—
SNCR, H-ESP	1	—	—	—
SCR, H-ESP	1	—	—	—
H-ESP, wet FGD	2	2	—	—
SNCR, H-ESP, wet FGD	2	—	—	—
H-ESP, SCR, wet FGD	1	—	—	—
Units with venturi scrubbers				
Venturi, wet FGD		1	—	—
Units with activated carbon injection (*ACI*)				
ACI, C-ESP	1	15	—	—
SNCR, ACI, C-ESP, wet FGD	1	—	—	—
ACI, FF	3	6	—	—
ACI, FF, wet FGD	—	4	—	—
SCR, ACI, FF, wet FGD	1	—	1	—
ACI, dry FGD, FF	—	2	—	—
SCR, ACI, dry FGD, FF	1	6	—	—
ACI, venturi, wet FGD	—	1	—	—
Fluidized bed combustors (*FBCs*)				
FBC, FF	1	—	—	2
FBC, SNCR, FF	5	—	—	6
FBC, DSI, FF		—	—	1
FBC, SNCR, dry FGD, C-ESP	1	—	—	—
FBC, SNCR, dry FGD, FF	5	—	—	3
	169	146	11	12

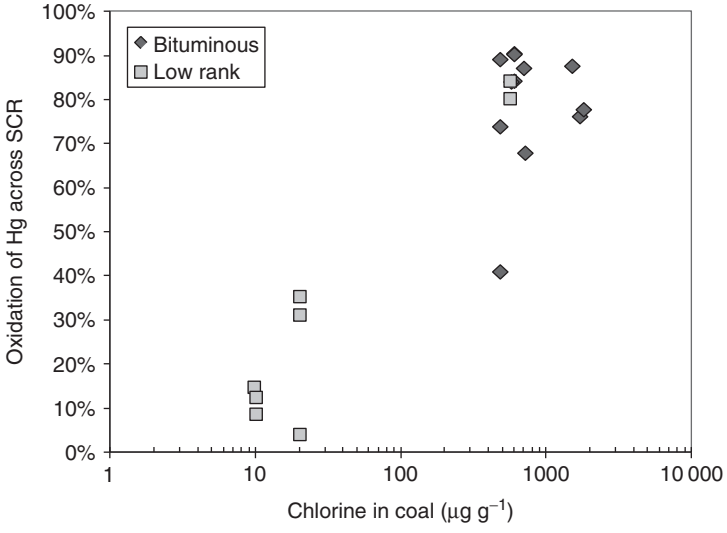

Figure 7.4 Oxidation of mercury across full-scale SCRs as a function of coal chlorine content.

in which a large wheel containing metal surfaces rotates through the flue gas path, alternating contact with the hot flue gas and the cold combustion air. Tubular APHs are shell-and-tube heat exchangers in which the flue gas passes through tubes and the combustion air flows outside the tubes. In either case, there is a lot of cold metal surface area, which can become coated with ash particles. The large surface area in APHs can promote oxidation of elemental mercury. Figure 7.5 shows full-scale data on the oxidation of elemental mercury across APHs as a function of coal chlorine content. Chlorine is not the only important parameter for mercury oxidation across APHs; the unburned carbon in the fly ash (which can act as a catalyst), the temperature, and the quench rate (determined by the design of the APH) are also important for mercury oxidation. The variation in unburned carbon in fly ash can be large, because the amount of unburned carbon depends on the coal rank and on the combustion system [23]. Unless the chlorine content of the coal is very low, a significant amount of mercury oxidation can be expected across an APH.

In almost all coal-fired boilers, a PCD follows the APH. The exceptions to this are a boiler with a H-ESP in which the ESP is located upstream of the APH or a boiler with a spray dryer (dry FGD) for SO_2 control in which the spray dryer is located between the APH and the PCD. Only about 9% of coal-fired utility boilers employ a H-ESP as the only PCD and about 8% of coal-fired utility boilers have a dry FGD (Table 7.2). C-ESPs are the most common PCD on coal-fired utility boilers. These devices remove mercury that has been converted to a particulate form upstream of the ESP by reaction with unburned carbon in fly ash. There is little contact between the flue gas and the ash collected in the ESP; therefore, mercury does not oxidize or adsorb on fly ash within the ESP.

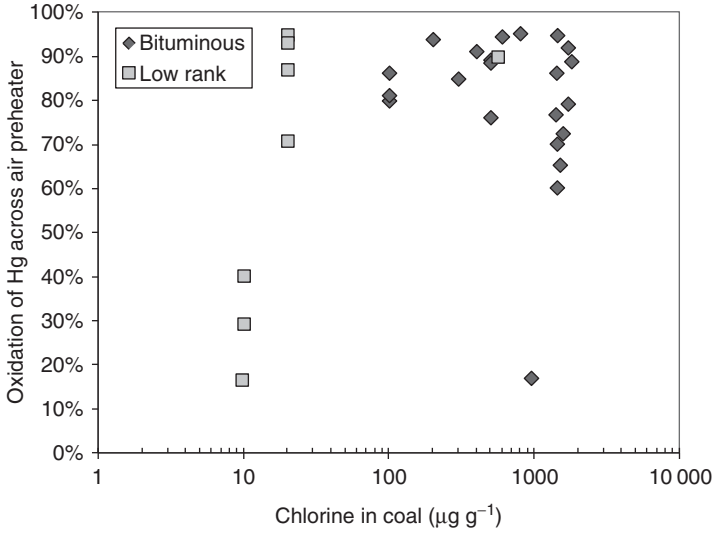

Figure 7.5 Oxidation of mercury across air preheaters on full-scale, coal-fired boilers as a function of coal chlorine content.

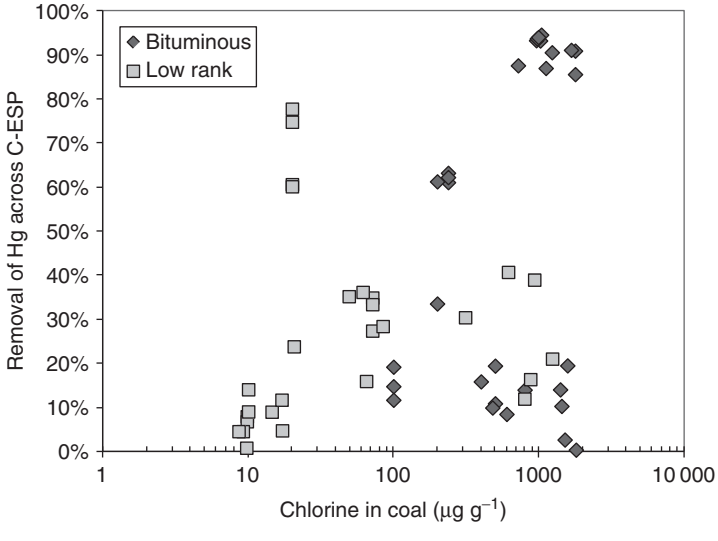

Figure 7.6 Removal of Hg across cold-side ESP as a function of coal chlorine content.

The chlorine content of the coal has an influence on how much of the mercury is converted to a particulate form via reaction with the fly ash upstream of the ESP. However, as Figure 7.6 illustrates, chlorine is not the only factor that determines how much mercury is removed across C-ESPs. There are other factors that influence how much mercury adsorbs on the fly ash [18–24] as was noted previously in the discussion of fixed-bed experiments on mercury interactions with fly

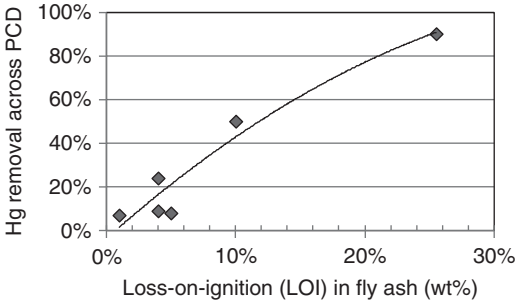

Figure 7.7 Mercury removal across cold-side ESPs as a function of LOI, for bituminous pulverized-fired boilers [31].

ash. The amount of unburned carbon in the fly ash is also important. Figure 7.7 shows mercury removal at full-scale bituminous coal-fired boilers as a function of loss-on-ignition (LOI), that is, unburned carbon, in the fly ash [31]. For pulverized coal-fired boilers with C-ESPs, there is a good correlation between LOI and mercury removal.

In FFs, there is more contact between the flue gas and the fly ash, because the fly ash builds up on the filter over a period of several hours before being removed. Thus, in addition to removing particulate-bound mercury, which is formed upstream of the PCD, FFs also remove oxidized elemental mercury and gaseous mercury. The fixed-bed experiments using fly ash and simulated flue gas discussed previously [18–21] are similar to a FF in that the gas must pass through a layer of ash. The temperature, composition of the flue gas, unburned carbon in the fly ash, and baghouse cleaning frequency all affect the removal of mercury across FFs.

Figure 7.8 illustrates the removal of both gaseous mercury and total (gas plus particulate-bound) mercury across the FF on a 170 MW tangential boiler burning a low-sulfur bituminous coal [32]. The unburned carbon in ash was varied by changing combustion conditions and the FF temperature was 130 °C (265 °F).

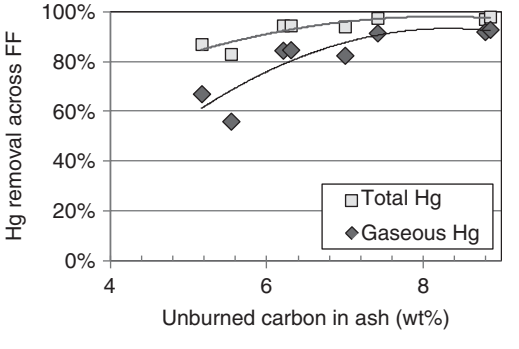

Figure 7.8 Mercury removal across fabric filter as a function of unburned carbon in fly ash [32].

The FF removed both gaseous and particulate mercury, and the mercury removal increased with increasing unburned carbon in ash. In certain situations (temperature, gas composition), unburned carbon in fly ash can be effective at capturing mercury. However, reliance on unburned carbon alone as a mercury control strategy is not without risk of non-compliance, because changes in combustion conditions affect the amount of unburned carbon, and such changes are not always predictable or controllable. Furthermore, increasing the amount of unburned carbon in ash means decreasing the efficiency of the combustion process, which is not desirable.

Thus, both C-ESPs and FFs can remove mercury from the flue gas. H-ESPs operate at too high a temperature to remove significant amounts of mercury. Particulate-bound mercury that has formed upstream of the PCD is removed by a C-ESP; in contrast, FFs remove both particulate-bound mercury and gaseous mercury. The degree to which mercury is removed in PCDs depends on the amount of unburned carbon in the fly ash, the halogens present in the flue gas, and the temperature of the PCD. The design and operation of a FF can also have an effect on its ability to remove mercury.

Both wet and dry FGD scrubbers remove mercury, if it is in the oxidized form. Mercuric halides (such as $HgCl_2$) are soluble in water but elemental mercury is not. Thus, the removal of mercury across FGD scrubbers depends on how much oxidized mercury enters the scrubber, as illustrated in Figure 7.9. The removal of mercury across wet FGD scrubbers is complicated by the aqueous reactions that take place in the scrubbing solution [33], as discussed in Chapter 16. The complex aqueous chemistry can result in some of the absorbed Hg^{2+} being reduced back to

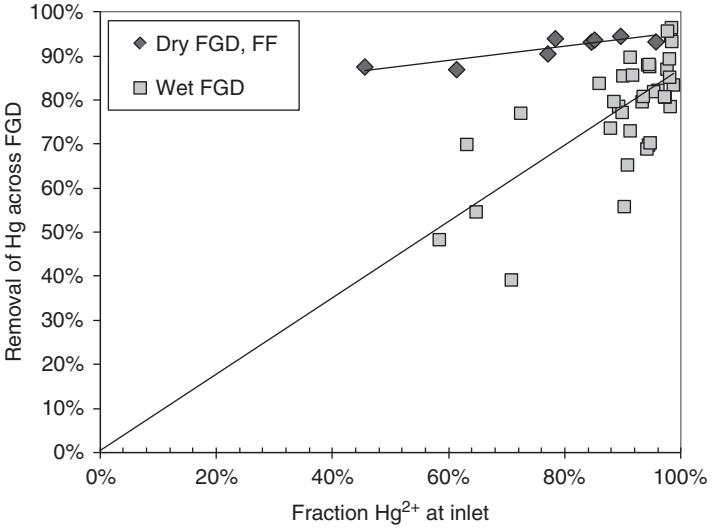

Figure 7.9 Mercury removal across dry and wet FGD scrubbers on bituminous-fired boilers as a function of the fraction of oxidized mercury at the inlet.

Hg^0. This re-emission of Hg^0 can reduce the efficiency of mercury capture across wet FGD scrubbers.

7.6 Summary

The transformations of mercury in coal-fired boilers and APCDs are summarized in Figure 7.10. Although Hg leaves the combustion zone as gaseous elemental mercury, varying amounts can be transformed to gaseous oxidized mercury and particulate-bound mercury as the flue gas passes through the economizer and air heater. The efficiency of Hg capture by APCDs depends on the gas-phase speciation as well as on the partitioning between gaseous and particulate forms. In turn, the coal composition (Cl and S content, ash composition) and boiler operation (unburned carbon content, gas cooling rate, and residence time) affect the Hg speciation and partitioning in the flue gas. Existing APCDs provide a range of "native" Hg removals; FFs and scrubbers have the highest Hg removals, as much as

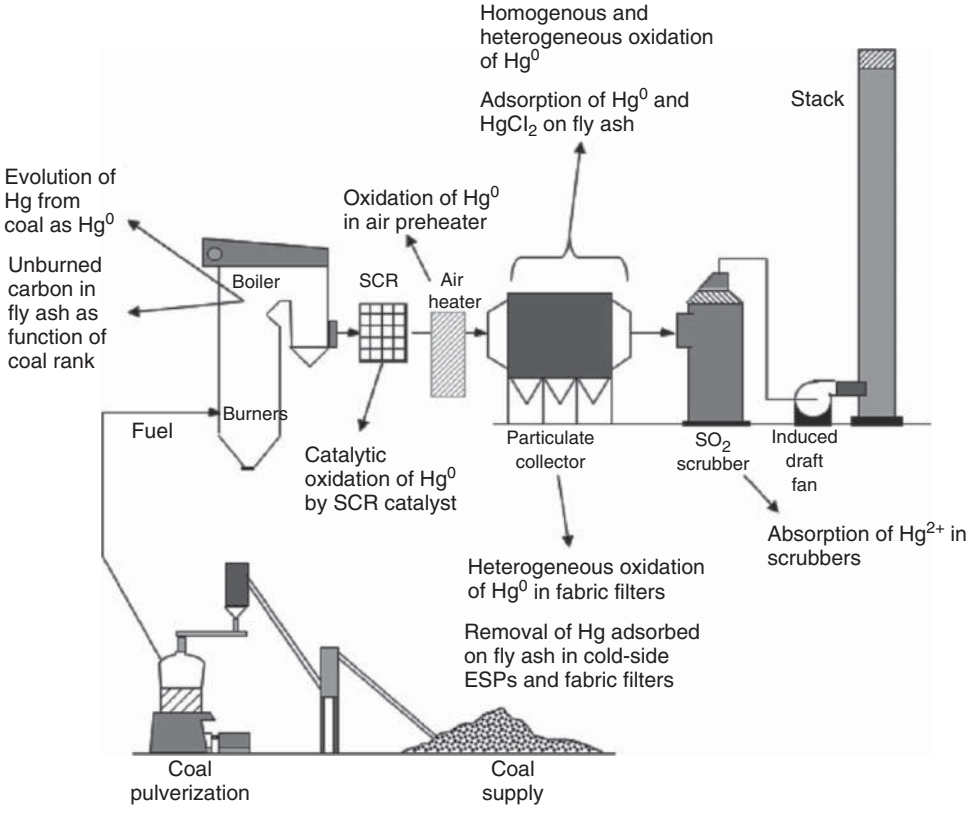

Figure 7.10 Summary of mercury behavior in coal-fired boilers.

90%, for units burning bituminous coal. Moderate to low levels of natural capture are typically found in units that burn either subbituminous coals or lignites.

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8
Gasification Systems

Nicholas Lentz

8.1
Principles of Coal Gasification

Coal gasification processes employ fixed-bed, fluidized-bed, or entrained-flow reactor systems to react coal with air or oxygen and steam over a range of temperatures from 650 °C (1202 °F) for fixed- and fluidized-bed gasification to about 1500 °C (2732 °F) for entrained flow gasifiers. The ash byproducts are dry, agglomerated, or slagging ash, depending on the gasifier type, operating pressure, and operating temperature. Process pressures range from near atmospheric to up to 82 bar (1200 psig). Gasification reactions can be classified into the following groups: pyrolysis, combustion, steam gasification, and secondary reactions among gaseous products and with carbon. Each reaction group produces a significantly different gas composition. The common coal gasification reactions and enthalpy energies are presented below:

Pyrolysis and tar cracking	
Coal → char + tar, light oil, H_2O, H_2, CO, CO_2, and hydrocarbon gases	
Tar, light oil → CH_4 and other HC gases + CO + H_2 + CO_2	
Combustion	ΔH ($Btu\,lbmol^{-1}$)
$C + O_2 \rightarrow CO_2$	−169 300
$C + (1/2)O_2 \rightarrow CO$	−47 600
$CO + (1/2)O_2 \rightarrow CO_2$	−121 700
Steam gasification	
$C + H_2O \rightarrow CO + H_2$	+56 490
Secondary reactions	
$C + CO_2 \rightarrow 2CO$	+74 200
$H_2 + (1/2)O_2 \rightarrow H_2O_{(g)}$	−104 000
$C + 2H_2O_{(g)} \rightarrow CO_2 + 2H_2$	+38 780
Water–gas shift reaction	
$CO + H_2O_{(g)} \rightarrow CO_2 + H_2$	−17 700

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Methanation reactions	
$C + 2H_2 \rightarrow CH_4$	−32 200
$CO + 3H_2 \rightarrow CH_4 + H_2O$	−88 700
$CO + H_2 \rightarrow (1/2)CH_4 + (1/2)CO_2$	−53 200

(−) indicates exothermic and (+) indicates endothermic.

The primary products of gasification are CO, H_2, and CH_4, along with some carbon dioxide and nitrogen when air is used as the oxidant. If water–gas shift catalysts are being used, the shift catalysts will convert the majority of the CO into CO_2 so that the main syngas products are H_2 and CO_2. This is desirable when carbon capture is required. Other byproducts produced during gasification can include tars, oil, phenols, chars, hydrogen sulfide, carbonyl sulfide, ammonia, and hydrogen cyanide. The primary reactions involving pyrolysis and steam gasification are endothermic and heat must be provided either externally or by the combustion of carbon. Smaller bench and pilot-scale systems typically require external heat sources to maintain consistent gasification conditions due to their small size and increased thermal effects related to scaling of the equipment. Heat from combustion can also be supplied indirectly by recycling bed material to provide either sensible heat or chemical energy (e.g., the CO_2 acceptor process). The water–gas shift and methanation reactions are exothermic and contribute to the energy balance at lower temperatures and high pressures where CH_4 is a principal product. The particular gas composition obtained from various types of gasifiers depends on the effects of temperature, pressure, flow patterns (e.g., cocurrent vs countercurrent), fluid dynamic intensity, solid and gas residence times, and catalysis on chemical kinetics and equilibrium.

8.2 Gasification Technologies Overview and Gasifier Descriptions

Different gasifiers are utilized for different applications and fuel sources. A comprehensive review of the different gasifier types is provided by Sondreal and Benson [1]. Table 8.1 summarizes the different gasifier types and characteristics. Gasifiers are typically categorized into three main classes: entrained-flow, fixed-bed, or fluidized-bed systems followed by describing the system as either a slurry or dry coal feed. Another classification can be if the system has a dry ash, or a slab byproduct discharge. Designs and classifications are typically based on the type of coal to be gasified and the desired syngas exit conditions for subsequent downstream processes and desired syngas conditions.

Figure 8.1 shows the diagrams and temperature profiles for the fixed bed (moving bed), fluidized bed, and entrained flow gasifiers. Each gasifier has a very unique temperature profile which affects the fuel types and ranks that provide optimal performance as well as the syngas composition. Entrained flow gasifiers exhibit the highest temperature profile and also have the hottest syngas exiting the gasifier.

Table 8.1 Gasifier types and characteristics [2].

Gasifier type	Fixed bed	Fluidized bed	Entrained flow
Coal feed size	6–50 mm	6–10 mm	<100 μm
Acceptability of fines	Limited	Good	Unlimited
Oxidant demand	Low	Moderate	High
Outlet temperature	Low (425–600 °C)	Moderate (900–1050 °C)	High (1250–1600 °C)
Ash conditions	Dry ash or slagging	Dry ash or agglomerating	Slagging
Other characteristics	Methane, tars, and oils are present in the syngas	Low carbon conversion	Pure syngas and a high carbon conversion

8.3 Gasification Applications and Downstream Gas Cleanup and Processing

Syngas produced as a result of coal gasification can be a very flexible feedstock for a wide range of applications and manufacturing processes. Electrical power output is oftentimes not the primary function of a gasification plant. In addition to chemical production, syngas can also be directly used to produce power and/or steam for municipal purposes. Syngas is commonly comprised mainly of H_2 and CO and the ratio between H_2 and CO can be adjusted via water gas shift catalyst reactions in order to provide a specific syngas composition to a downstream process such as a Fischer Tropsch reactor. Gasification plants often are equipped with multiple product production streams and can sometimes modify the syngas composition to shift product stream yields in order to maximize profit as commodity prices and/or outlooks change. A list of potential products from syngas includes

- Gaseous fuels
- Synthetic natural gas
- Liquid fuels
- Chemicals
- Fertilizers
- CO_2 for use in enhanced oil recovery (EOR) applications
- Hydrogen as a fuel and/or for power generation.

8.4 Mercury Transformations and Fate

Mercury has been measured for over 20 years from stationary sources to assess emissions, develop control technologies, and set appropriate mercury regulations. Mercury is present in three different forms, particulate bound, oxidized, and

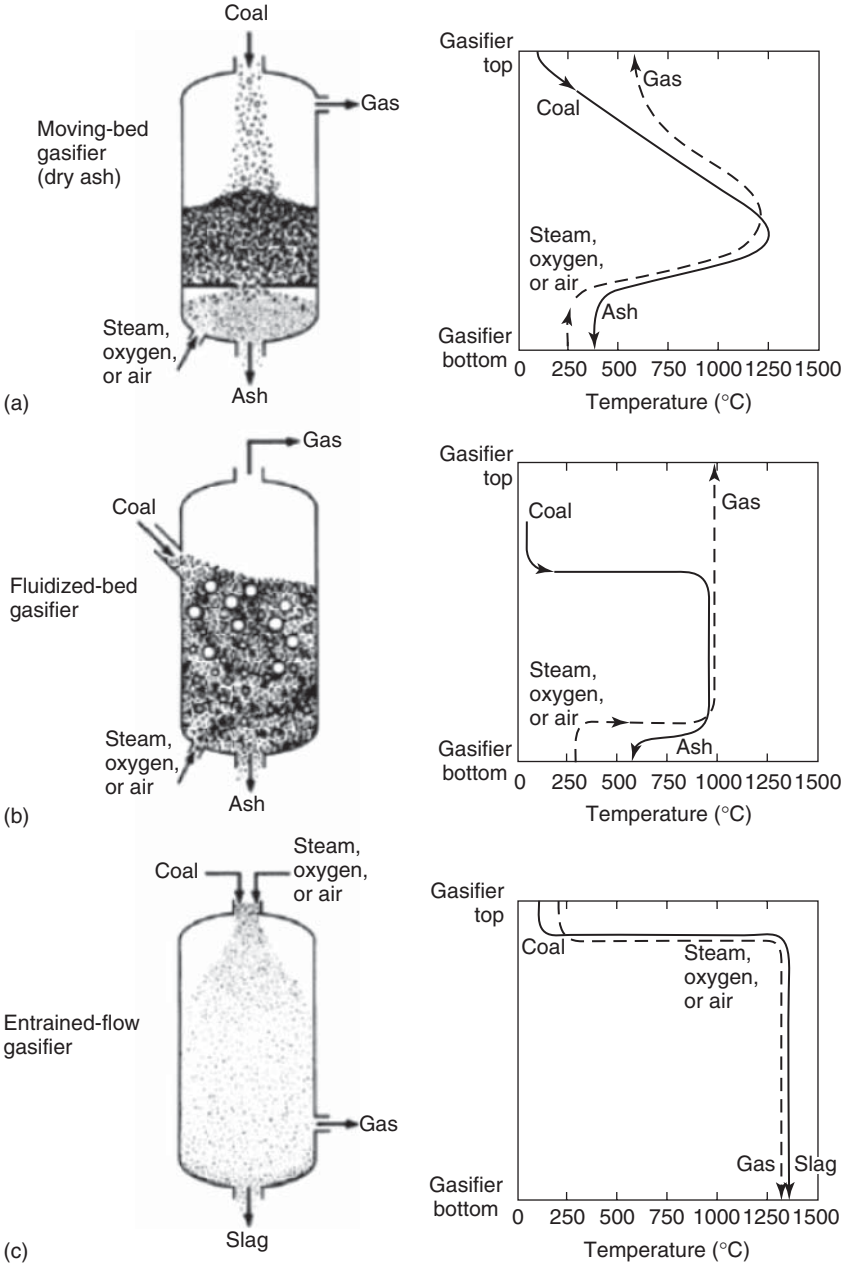

Figure 8.1 (a–c) The three major types of gasifiers [3].

elemental (Hg[p], Hg^{2+}, and Hg^0), which greatly complicates the measurement process. The low mercury concentrations (low-parts per billion by volume range) also make measuring mercury difficult.

Five measurement methods are used to measure mercury from combustion sources: continuous mercury monitors (CMMs), the Ontario Hydro (OH) method, EPA M30B, EPA M29, and EPA M101A (EPA, U.S. Environmental Protection Agency) (see Chapters 5 and 6). Of these methods, the OH method is the only method validated to obtain speciated mercury measurements. Each method is able to provide accurate and reliable data, provided that the mercury concentrations are within the range of the method. All of the methods require samplers who are extremely familiar with the methods and their corresponding biases and/or interferences. Most mercury measurement methods were developed for combustion applications and later tested on gasification systems. Further discussion will show their applicability in gasification systems.

Under gasification conditions, mercury typically only exists in the elemental form due to the reducing conditions in the gasifier. Research conducted at the Energy and Environmental Research Center (EERC) confirmed the presence of elemental Hg during simulated gasification conditions and speculated that CH_3Hg may also be possible [4, 5]. In combustion systems, mercury can exist in both the elemental and oxidized forms with a wide range depending on the fuel type, boiler type, and place in the pollution control system. Elemental Hg is usually found in the higher temperature regions of combustion systems and is also likely why elemental Hg is the predominant form in gasification systems. The high gasification temperatures and reducing environment make it challenging for any oxidized forms to remain stable and favor the formation of Hg^0. Erickson *et al.* [6] investigated the volatility of elements under gasification conditions. They found that the majority of elements behaved similar to combustion systems but arsenic, lead, and cadmium were found to volatilize in the finer sized particle fractions.

8.5 Hg Measurement in a Reducing Environment

In previous chapters, Laudal and Senior have provided extensive reviews of mercury measurement technologies. Mercury measurements in a reducing (gasification) environment present a significant challenge, especially for any method that utilizes liquid impingers or scrubbing systems such as a CMM wet conversion system. Syngas constituents such as H_2, H_2S, CO, and CO_2 often react with the chemical solutions and render them ineffective at either capturing the Hg or performing their specific function [7]. The result is that there can be very fast mercury breakthroughs that invalidate the test. Traditional 2 h EPA impinger tests exhibit breakthrough and render the tests invalid. Shorter sampling times often to not capture enough mercury for a good data point with the tests that utilize

impingers. Measurement methods such as M29, OH, and CMMs with wet conversion systems all have exhibited challenges in obtaining consistent mercury data in reducing environments [8].

The most favorable mercury measurement methods are the methods that do not utilize liquid solutions and impinger trains. Dry conversion CMM systems and sorbent traps are the most widely used systems that do not use liquids as a part of their sampling process and are the most widely used methods on gasification systems. Sorbent traps are not able to provide continuous data, but suffer the least interferences in a gasification environment and have provided the most accurate values [9].

8.6 Hg Control Technologies for Gasification

Mercury control technologies for gasification are commonly a part of the cold, warm, or hot gas cleanup system that is designed to remove an array of pollutants including Hg, H_2S, halogens, and other trace metals such as As and Se. Currently, hot gas cleanup technologies are not mature and most of the focus through Department of Energy (DOE) and National Energy Technology Laboratory (NETL) has subsequently concentrated on warm gas cleanup systems. Warm gas cleanup systems are also favorable because they operate at temperatures that are suitable for phase shift catalysts, such as Fischer Tropsch catalysts, which allow the syngas stream to be converted into numerous useful byproducts. A hot gas filter vessel is commonly utilized for gasification particulate removal upstream of the gas cleanup system. The filter vessel is able to remove most of the particulates as well as the particulate bound Hg. The mercury control technologies are typically fixed beds and can be grouped into two main categories: carbon-based sorbents and metal-based sorbents. Chapter 22 discusses these in more detail; a brief description is provided here.

Carbon-based sorbents are commonly utilized in cold or warm gas cleanup systems and have a very high capacity with respect to mercury. Carbon-based sorbents have been extensively used at municipal waste-to-energy facilities for many years and have demonstrated the ability to cost effectively remove high levels of mercury. The carbons are typically either iodine or sulfur impregnated in order to facilitate Hg capture. Select tests under integrated gasification combined cycle (IGCC) conditions have utilized sulfur impregnated sorbents to successfully remove mercury and other contaminants [10]. A Parsons-GTI group conducted a study that demonstrated a carbon bed mercury capacity as high as 20 wt%, which correlates to a bed lifetime of ~2 years [11]. Often, pressure drop across the bed, water buildup, and other operating factors determine when a bed is replaced, rather than the Hg capacity of the sorbent bed [12].

Metal-based sorbents are another mercury control technology that has been tested. Metal-based sorbents are designed to target warm gas and hot gas cleanup systems. Most of the developed sorbents are precious metal based, with Pd, Pt, Au, Ir, and Rh being the most widely used metals. Of these, Pd has been identified as the best absorber of mercury [13, 14]. Even though metal-based sorbents have shown some promise, the technology is currently not a cost effective option for mercury capture, largely due to the cost of the precious metals required for the sorbents. Further research is required to identify cheaper surrogate metals that will also maintain sufficient activity and capture rates in warm and hot gas cleanup systems.

8.7 Hg and the MATS Rule for Gasifiers

The Mercury and Air Toxics Standards commonly called the *MATS rule* was recently finalized with the latest version published in the Federal Register on 16 February 2012. The MATS rule regulates filterable particulate matter (PM) (as a trace metal surrogate), mercury, and HCl (as an acid gas surrogate) emissions from coal-fired electricity generating units (EGUs), including IGCC units. The gasifier emission limits (PM, HCl, and Hg) for new and existing sources are presented in Table 8.2.

The data for existing units is based on a limited dataset because there are very few operating IGCC gasifiers in the United States. The only two IGCC plants in operation are the Polk Power Station operated by TECO Energy, and the Wabash River Generating Station operated by Duke Energy. These gasifiers have shown high native mercury captures of around 60%, with most of the mercury emitted in the elemental form [15]. The emission limits for the new IGCC units were based on permit data for some of the units that are either in the planning phase or the construction phase. An example is the Kemper County IGCC plant that is currently in the construction phase.

Table 8.2 Emission limits for coal-fired IGCC EGUs.

Subcategory	Filterable PM	HCl	Mercury
Existing IGCC	4.0E−2 lb $MMBtu^{-1}$ (4.0E−1 lb MWh^{-1})	5.0E−4 lb $MMBtu^{-1}$ (5.0E−3 lb MWh^{-1})	2.5E0 lb $TBtu^{-1}$ (3.0E−2 lb GWh^{-1})
New IGCC	7.0E−2 lb MWh^{-1} a) 9.0E−2 lb MWh^{-1} b)	2.0E−3 lb MWh^{-1} c)	3.0E−3 lb GWh^{-1} d)

a) Duct burners on syngas; based on permit levels in comments received.
b) Duct burners on natural gas; based on permit levels in comments received.
c) Based on best-performing source.
d) Based on permit levels in comments received.

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9
Mercury Emissions Control for the Cement Manufacturing Industry

Robert Schreiber Jr., Shameem Hasan, Carrie Yonley, and Charles D. Kellett

9.1
Introduction

The manufacturing of portland cement is performed in a large industrial process that is raw material and fuel intensive. The industry is considered as one of the anthropogenic contributors of mercury to the environment. During the pyroprocessing step that occurs in the cement kiln system, the mercury compounds are vaporized from the fuels and raw materials due to the very high temperatures achieved inside the kiln. There are different types of pyroprocessing systems used in the cement industry, and the specifics of each system have been shown to have an effect on reactions and emissions/emissions control of mercury. However, the state of knowledge on the fate of mercury, speciation of emissions from the kiln system, and potential for control is still in the early stages of development and testing, although knowledge is being amassed more rapidly over recent years. This chapter describes the specifics of the cement manufacturing process and the corresponding effects of the process chemistry and temperatures within the kiln system on mercury speciation. The discussion includes the current state of the study of mercury in the industry and knowledge on mercury control.

9.2
Cement Manufacturing Process Description

Portland cement (hereinafter, cement) is the gray powder that is the active chemical binder used to produce concrete by mixing it with sand, gravel, and water. Cement manufacturing is performed in a large-scale industrial production process using large volumes of raw materials and fuels. The basic steps of cement production are generally as follows:

- Raw material procurement
- Raw material feed preparation

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- Pyroprocessing of raw material in the kiln system (formation of cement "clinker")
- Clinker cooling
- Clinker grinding and cement packaging.

The basic raw materials used to manufacture cement include sources of calcium carbonate, silica, alumina, and iron, with trace amounts of other compounds such as alkalis (sodium, potassium), sulfur, chlorine, and metals naturally occurring in the raw materials. Typical raw feed to a kiln contains about 80–85% calcium carbonate, 10–15% silica, and small amounts of alumina and iron. Maintaining the quality of raw feed is an important step in manufacturing quality cement. Traditional mineralogical sources of the cement ingredients include the calcareous component such as limestone, marl, or chalk; the argillaceous components such as clay, shale, slate, or sand which provide the silica and alumina; and iron components, in some cases provided by mill scale or a similar material. Cement plants are generally located in areas that have an abundant supply of readily available raw materials. With about 80–85% of the raw materials being limestone, plants are usually located at or near abundant limestone quarries for economics related to raw material transportation costs.

Raw material feed preparation involves sizing through crushers and mixing and grinding raw materials in a raw mill(s) to obtain correct size and chemical composition for kiln feed, also termed as *raw mix* or *raw meal* (Figure 9.1). The process used to prepare raw meal is dependent on the type of pyroprocessing system being used.

The main types of systems used in the cement industry include the wet process and the dry process. The dry process is further subdivided into the

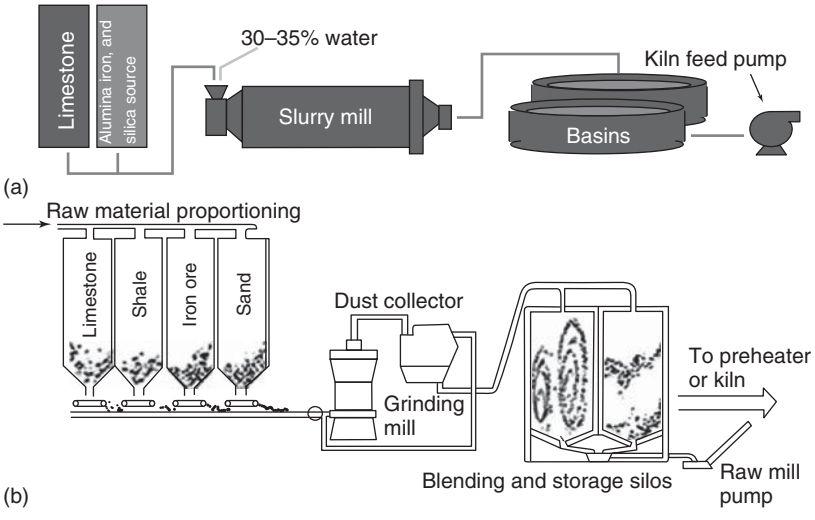

Figure 9.1 Schematic of raw meal preparation for (a) wet kiln and (b) dry kiln.

long dry process, the preheater process, and the most recent technology – a preheater/precalciner system. Each type of system is further described below.

For use in the wet process, the raw materials are mixed and ground with water (~30–35 wt%) to produce slurry, which simplifies the blending of the kiln feed to produce a uniform chemical composition. The dry process involves mixing a calculated proportion of raw materials, drying, and grinding the mixture to a powdered form, blending the materials together in silos, and feeding the raw meal to the kiln in a dry state. For the preheater and preheater/precalciner processes, heat to dry the raw material may be recovered from the kiln system and utilized in an in-line raw mill system. For a continuous operation, the raw mill must grind more raw materials than can be used in the kiln system in a given time frame; otherwise, sufficient kiln feed would not be available on a consistent basis as the raw mills require more down time for maintenance and repair than the kiln. Normally, raw mill systems are designed to grind enough material such that they can be taken off-line once a week for repair and maintenance. Under most circumstances, raw mills are designed to operate about 85–90% of the kiln operational time. For the in-line raw mill design, this phenomenon is known as *raw mill on* and *raw mill off* operating conditions.

The kiln system is where the key process step occurs, where a specific combination of minerals is heated to a temperature of about 1500° C in a large, cylindrical, rotating, refractory-lined kiln, and associated equipment, depending on the type of kiln system. The raw materials are fed counter-current to the gases from burning fuel in the combustion zone of the kiln and undergo the chemical and physical reactions required to produce quality cement. Inside the kiln, the minerals are partially fused at high temperatures, resulting in the formation of clinker nodules, which is the intermediate product of cement. Cement kiln dust (CKD) is generated during raw materials processing inside the kiln system. CKD includes thermally changed and unchanged raw feed that becomes entrained in the counter-current gas flow through the kiln system. Gases that exit the cement kiln system are vented to an air pollution control device (APCD) where the CKD is removed, followed by the exhaust stack. Traditionally, an electrostatic precipitator (ESP) or baghouse is used as the APCD in the cement industry. New APCD technologies are beginning to be studied and tested as regulations are becoming increasingly stringent for additional pollutants.

Large amounts of fuel are necessary to drive the pyroprocessing that occurs in the kiln system. Typical fuels used in cement kilns are coal, petroleum coke, natural gas, oil, and/or alternative materials used for energy recovery, such as used tires, plastics, and oil. The most significant quantity of traditional fuel continues to be solid fuel, including coal and coke. In a typical kiln, ~2–6 million British thermal units of heat value are required to produce a ton of clinker [1]. Fuels fired in the hot end generally need to have a relatively high heat value as fired to maintain the high flame temperature required at the front of the kiln. Fuel fired at the hot end of the kiln also must be finely atomized to promote rapid combustion, which is important to clinker quality. The most important factor for fuel is the consistency. If each load has a different consistency, maintaining stable kiln

operations, maximum kiln production, and product quality is challenging. Also, an accurate control of energy input is required for the critical clinkering step. Insufficient energy input in the kiln will not allow necessary chemical reactions to occur during the clinkering process, which may result in unreacted lime in the clinker, thereby producing poor quality cement. Too much energy input will shorten the life of the kiln refractory lining, which may damage the kiln shell. It can also cause molten clinker to drop into the clinker cooler, causing significant damage and shutting down the system.

The clinker exits the hot end of the kiln, and is cooled from ~1500 to 90° C in the clinker cooler where ambient air is forced through a slowly moving bed of clinker for rapid cooling to stabilize its molecular structure. Typically, the air used to cool the clinker is recovered and used as preheated combustion air in the kiln. The cooled clinker is conveyed to a finishing mill (e.g., ball mill) for grinding. In the finishing mill system, the clinker is interground with a small amount of gypsum ($CaSO_4 \cdot 2H_2O$), an agent that controls the setting time of the concrete, and grinding aid, a material used to make the grinding process more efficient (too varied to describe within the context of this chapter) into the powder known as *portland cement*. At this point, the product is ready for commercial distribution.

Typical portland cement clinker comprises 67% CaO, 22% SiO_2, 5% Al_2O_3, 3% Fe_2O_3, and other minor components such as MgO, K_2O, TiO_2, and Mn_2O_3. Four major phases, including $3CaO \cdot SiO_2$ (50–70%), $2CaO \cdot SiO_2$ (15–30%), $3CaO \cdot Al_2O_3$ (5–10%), $4CaO, Al_2O_3 \cdot Fe_2O_3$ (5–15%), also termed *alite*, *belite*, *aluminate*, and *ferrite*, respectively, are present in clinker [2]. The phases in portland cement clinker are important as they function as a strength development agent in cement when mixed with water. The American Society for Testing and Materials (ASTM) specifies different types of portland cement based on the mineralogical properties of the clinker [3]. Among them, normal portland cement (Type I), modified portland cement (Type II), high-early-strength portland cement (Type III), low-heat portland cement (Type IV), and sulfate-resisting portland cement (Type V) are most common.

9.2.1 Wet Process Kiln

In the wet process, the blended raw feed is introduced to the "cold end" of the rotary kiln and tumbles down the length of the kiln toward the flame in the lower "hot end" of the kiln. In general, a rotary kiln is 400–700 ft in length, and has a 3–4% slope with the horizontal and rotates at 1–2 rev min^{-1} during operation. Figure 9.2 shows the temperature profile of a typical wet kiln [4]. There are essentially four stages to the pyroprocessing – evaporation and preheating, calcining, clinkering (sintering), and cooling. Fuel normally is fired at the hot end of the kiln, although some kilns are equipped with a secondary mid-kiln firing location. Evaporation and preheating remove moisture from the raw feed and raise the feed temperature to about 870° C. At 760° C, calcination of the material takes

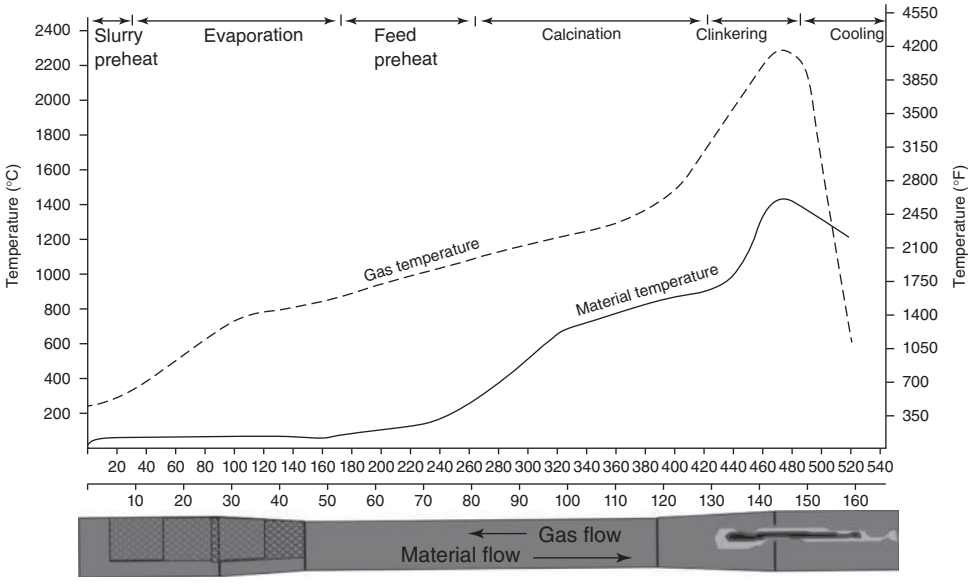

Figure 9.2 Typical temperature profile of wet kiln system in cement industry [4]. (Reproduced from Ref [4] © (1986) with permission from Chemical Publishing Co. Inc.)

place, breaking the calcium carbonate down into calcium oxide and carbon dioxide. At 1500° C, ~20–30% of the load melts and the formation of calcium silicate occurs. At this stage, the material forms the clinker nodules due to gravitational flow and the rotating effect of the kiln. The clinkering process occurs in the hottest zone of the kiln, called the *burning zone*, where the material temperature reaches about 1500° C and in which the material spends ~10–15 min.

Due to the nature of raw feed preparation, the wet process offers more uniform feed blending and generates less dust particles. Wet kilns require more combustion energy per ton of clinker produced than the dry process kiln systems as the water must be evaporated from the slurry feed.

9.2.2
Dry Process Kiln

More than 80% of the U.S. cement industry uses dry process kilns in which raw meal is prepared without adding any water. Dry process kilns are further divided into three types – long dry, preheater, and preheater/precalciner systems, with those built over the last two to three decades typically being the modern preheater/precalciner design. A long dry kiln is similar to a wet kiln with the exception that the raw materials are fed to the kiln as a dry powder, therefore requiring less combustion energy to produce clinker than a wet kiln but more electrical energy to blend the dry raw materials. The preheater kiln system uses dry raw meal that passes through a tower containing one or more cyclone-type vessels that simulate

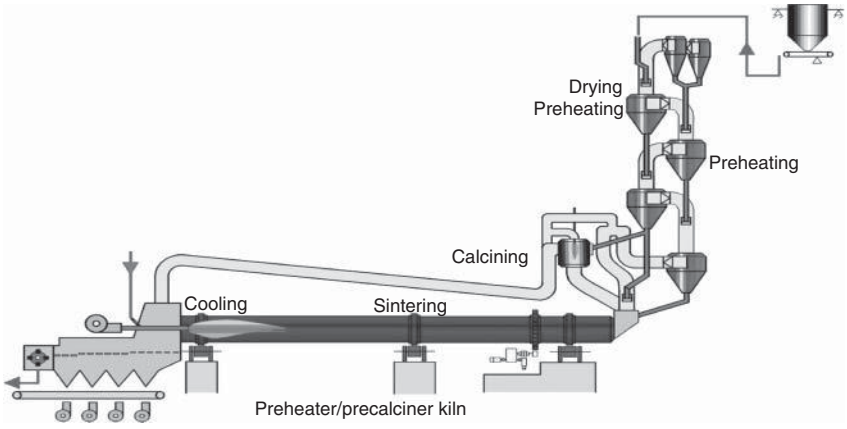

Figure 9.3 Schematic of a typical preheater/precalciner dry kiln in cement industry.

a fluidized bed heat transfer mechanism before entering the rotary kiln. The raw feed is suspended by the hot counter-current kiln gases prior to entering the kiln, and the preheating phase of the process is accomplished in the tower in a few seconds. This allows a rapid and more efficient energy transfer between the hot kiln (flue) gases and raw meal than a typical long dry or wet process kiln.

A preheater/precalciner kiln system has a tower with preheater vessels but also contains a secondary combustion vessel, called a *calciner*, near the lower stages of the preheater tower. (Figure 9.3 shows a typical preheater/precalciner kiln system, and Figure 9.4 documents the temperature profile of a preheater/precalciner kiln.) Fuel is introduced into the calciner and about 90% of the kiln feed is calcined within a few seconds in the hottest zone of that vessel. In this type of process, drying, preheating, and most of the calcining take place before the feed enters the rotary kiln. Preheater and preheater/precalciner systems require shorter rotary kilns, and the process is the most energy-efficient from a fuel standpoint. Approximately 60% of the overall fuel requirements for a precalciner system is at the calciner versus the main burner in the rotary kiln [5]. Therefore, the addition of a precalciner also extends the refractory service life of the kiln by reducing the heat load inside the rotary kiln. A variety of fuels with larger particle sizes and lower heat values can be accommodated in the calciner as the temperature required for calcination is much lower than sintering (clinkering) the raw meal into clinker. Most of the preheater/precalciner kiln systems are equipped with in-line raw mills usually located between the preheater tower and the APCD, allowing the exhaust gas from the preheater to be further used to dry the raw material in the raw mill. The gases exit the raw mill and pass through the APCD before being released from the stack to the atmosphere. APCDs employed for these types of systems are primarily fabric filters, or baghouses; however, some kilns do use ESPs.

Modern large kilns produce 4000–5000 tons of clinker per day or ~1.5 million tons of clinker per year. This requires processing between 6000 and 8000 tons of raw materials daily. Due to the large amounts of fuel and raw materials required to

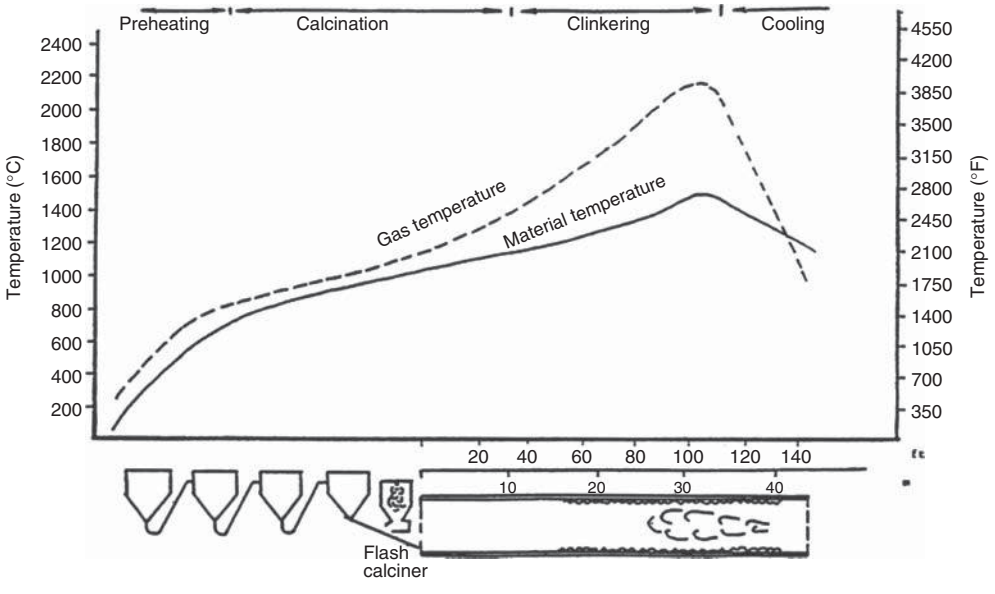

Figure 9.4 Temperature profile of a typical preheater/precalciner dry kiln system [4]. (Reproduced from Ref [4] © (1986) with permission from Chemical Publishing Co. Inc.)

produce cement clinker, there is a production incentive in the cement industry to find alternate fuels and raw materials compatible with the manufacturing process, where cost-effectiveness of the operations can be improved and quarrying of naturally occurring materials can be reduced.

9.3
State of Knowledge on the Source and Behavior of Mercury in the Cement Kiln System

Mercury can enter the kiln system from two sources – the raw material and the fuel – both of which inherently contain trace amounts of mercury as naturally occurring substances and are used in large quantities in manufacturing cement. The mass and chemical composition of the raw material and fuel and the type of pollution abatement technology ultimately determine the quantity of the mercury emissions from a cement kiln system. Studies have been conducted to determine the mercury content of cement manufacturing raw materials and fuels. The studies have revealed mercury concentrations ranging from 0.01 to >1.0 ppm in raw materials [6]. The amount of mercury in the raw feed is highly dependent on the quarry characteristics. The mercury input from fuel can also be significant. The concentration and distribution of mercury content in coal has been documented through U.S. Geological Survey research over the last 20 years. The study results show concentrations ranging from 0.058 to 0.362 ppm [6]. It is also important to note there are several constituents in raw materials that can have an effect on the kiln operations/chemistry and resulting air emissions.

These include sulfur content, alkali content, chlorine content, and other minor constituents (e.g., fluorine). The understanding of the chemistry can also play an important part in the understanding of potential mercury reactions in the cement kiln system and the form of the mercury in the exhaust gas from the kiln.

All mercury and mercury compounds in the fuel or raw material are volatilized and converted completely to the elemental form (Hg^0) at temperatures above 500 °C in the kiln system. The volatilized mercury is subsequently carried through the kiln system toward the raw feed end of the kiln along with combustion gases, where it is subject to cooling from ~1900 °C down to ~200 °C. Generally, once mercury enters a cement kiln system, it has five potential fates [7]:

- It may remain unchanged and exit the kiln as part of the clinker (very small amount).
- It may react with raw materials and exit the kiln as part of the clinker (very small amount).
- It may vaporize in the high temperature zone of the kiln and/or preheater.
- It may condense or react with the CKD and be removed by the APCD.
- It may exit the kiln system in vapor form or be adsorbed to a dust particle as emitted from the stack.

If the primary source of mercury is the raw feed, studies have shown that it is likely to be in the form of mercury sulfate ($HgSO_4$) or mercury sulfide (HgS) in the raw material [7]. If the mercury is primarily from the fuel, then it is most likely in the mercuric chloride ($HgCl_2$) or HgS form, or already existing as mercuric oxide (HgO). Also, during combustion, oxidizing agents that may be present in the fuel, such as chlorine and sulfur, are released. These oxidizing agents play an important role in the speciation of mercury emitted from cement kiln systems.

Mercury is reported to be present in the combustion gas (or flue gas) comprising varying percentages of Hg^0, oxidized (Hg^{2+}), or particle-bound (Hg_p) form [8]. Hg^0 is considered as less reactive, highly volatile, and also insoluble in water. It passes through the entire kiln system and exits the stack in the vapor phase. Hg^0 and a minor proportion of HgO can be present in the flue gas at high temperatures; however, only Hg^0 is stable at the high temperatures. As the flue gas cools, mercury is oxidized through the reaction with compounds from the raw materials and fuel (e.g., chlorinated compounds, oxygen, bromine, etc.). Hg^0 and Hg^{2+} comprise the vapor-phase mercury. Organomercury compounds would be minuscule in comparison to inorganic mercury or not likely to be found in the emissions of a cement kiln as these compounds would be destroyed in the presence of the high temperatures in the kiln system. In the cooler zones of the kiln system, the Hg^{2+} may adsorb or condense onto CKD particles in flue gas to form Hg_p. Much of the dust containing mercury would then be captured by the APCD and, for most kiln systems, returned to the kiln. A portion of the CKD is often removed from the system in order to lower the alkali content of the clinker to meet product specifications. The removal of CKD is a mechanism to bleed the kiln system of alkali salts that build up as they circulate through the system. Mercury adsorbed onto the dust would also be removed in the same way.

A number of complex thermo-chemical gas-phase reactions control the speciation of mercury associated with cement kilns. The presence of hydrogen chloride (HCl) in the exhaust (flue gas with a range of HCl from 1 to 120 ppm or greater), which may accelerate the mercury oxidation reaction in the kiln through the Decon reaction, can result in the formation of $HgCl_2$ [9–12]. The oxidation of mercury occurs when the elemental mercury reacts with chlorine to form $HgCl_2$ below the gas temperature range of 480–590 °C due to a thermo-chemical process [6, 13]. The possible mercury oxidation in the kiln system is reported to be a homogeneous- or heterogeneous-phase reaction [14]. The homogeneous oxidation may occur in the gas phase whereas the heterogeneous oxidation occurs on the interface of solid particles inside the kiln system or APCD. As the flue gas passes through the APCD, temperatures continue to drop below 200 °C, allowing some of the Hg^0 to be adsorbed onto the CKD. Some of the Hg^{2+} compounds also adsorb and condense onto the CKD. The remaining mercury compounds pass through the stack and are emitted. Mercury oxidation reactions in the cement kiln system are as follows:

$$Hg^0 + Cl_2 \rightarrow HgCl_2 \tag{9.1}$$

$$Hg^0 + HCl \rightarrow HgCl_2 \tag{9.2}$$

There has been a limited, but recently increasing amount of sampling and analysis of mercury speciation in U.S. cement kiln stack emissions. Figure 9.5 shows the averages for Hg^0, Hg^{2+}, and Hg_p emissions for wet kilns, long dry kilns, and preheater/precalciner kilns with both raw mill on and off conditions [15]. Due to the limited data, the results shown in Figure 9.5 may not be representative. However, this limited data indicates that wet kilns predominantly emit higher concentrations of Hg^0 compared to long dry and preheater/precalciner kiln systems. This may be explained by kiln system heat profile differences between wet kilns and long dry or preheater/precalciner kilns. More data are needed to be more definitive on mercury speciation from different kiln systems.

In a long wet or dry kiln, the raw materials are introduced through the kiln feed end where they encounter gas temperatures of ~200–300 °C. In the long kiln, the evaporation of water from the slurry (wet kiln) or kiln feed (dry kiln) must first occur, with the raw meal being maintained in the 50–100° C range, with gas temperatures being as high as 300 °C (Figure 9.2). Hg^0 that may form during drying and subsequent calcination of raw meal will reach the APCD with a very limited interaction with CKD. For long dry kilns, as there is little water to evaporate, the temperature profile may be sufficiently different compared to the long wet kiln that oxidation may be more pronounced. In consideration of the limited data and knowledge of other influencing factors that may be present, additional long-term data are necessary to confirm the assumed mechanisms of formation.

In contrast, in a preheater/precalciner kiln system, the raw meal passes through the preheater cyclones and calciner before entering the rotary kiln. The heat profile of this system, as shown in Figure 9.4, allows sufficient time and temperature for the oxidation of mercury to occur in the presence of an oxidizing agent (e.g., chlorine, sulfur, and oxygen). In the preheater/precalciner system, the formation of

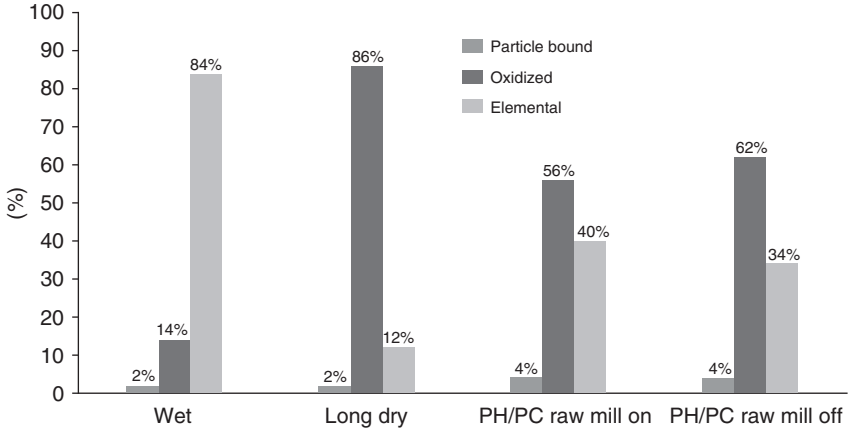

Figure 9.5 Mercury speciation percentages – averages for all kiln types [15]. (Reproduced from Ref [15] © (2009) with permission from Portland Cement Association.)

Hg^0 occurs when the temperature of the raw meal reaches in excess of 500 °C as it descends through the preheater tower.

Figures 9.5 and 9.6 show mercury speciation data for all kiln types and for preheater/precalciner systems with the raw mill on-line and off-line conditions. The data for preheater/precalciner systems is derived from tests on seven different kiln systems. The studies have shown that, during the raw mill off-condition, the gas stream delivered directly to the system's APCD is found to have a higher concentration of mercury as compared to the raw mill on-condition [16]. When the mill is on-line, exhaust gas exits the top of the preheater tower and is introduced into the raw mill to dry the raw meal. The temperature of the mercury-laden hot flue gas exiting the preheater tower prior to entering the in-line raw mill ranges from 315 to 398 °C. The preheater tower exit gas typically contains ~100–150 g nm^{-3} of fine

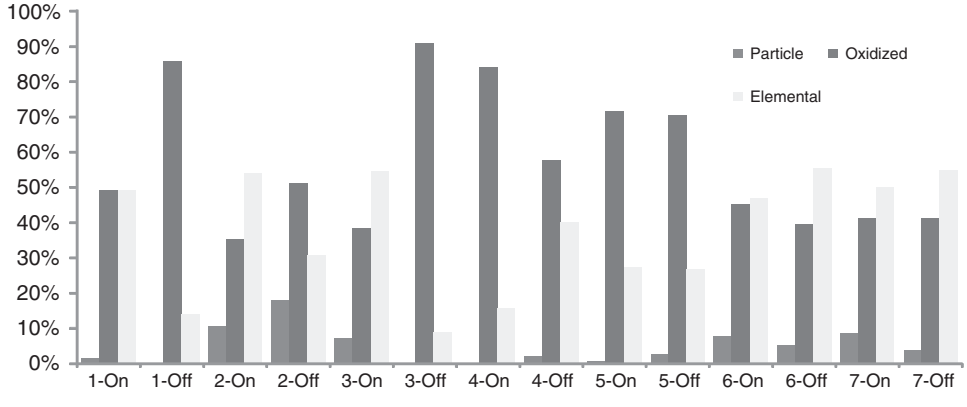

Figure 9.6 Mercury speciation percentages – raw mill on and raw mill off [15]. (Reproduced from Ref [15] © (2009) with permission from Portland Cement Association.)

dust particles [15] containing volatilized Hg^0. In this scenario, the operating raw mill acts as both a dry scrubber and condenser. The gas temperature is reduced through heat exchange in the raw mill to the exit temperature of 90–120 °C. The larger surface area of the finer dust particles in the gases allows adsorption of condensed material containing mercury to occur at the lower temperatures.

The gas stream exiting the raw mill with mercury-laden fine particles is ducted to cyclones in most system designs prior to the APCD, thus removing 85–90% of the coarser particles (10–50 μm range) from the gas stream. The finer particulate (0–5 μm) is carried to the APCD where further gas/particulate separation occurs. In essence, with the raw mill operating, mercury-laden particulate is captured by both the raw mill system and the APCD and is transported to the blend silos where it is re-blended into the raw meal and used as kiln feed, creating the opportunity for a significant mercury recycle loop. The cleaned gas stream is exhausted out the stack. When the re-blended raw meal reaches temperatures in the preheater cyclones of ~400 °C, the captured mercury is again volatilized and returned in the gas stream to the raw mill, only to be recaptured in the particulate. The repeated volatilization and adsorption of mercury in the preheater tower, raw mill, and APCD create an enriching mercury loop in the kiln system during the raw mill on operating condition.

For illustrative purposes, Figure 9.7 shows a mercury loop in a cement kiln for the raw mill off and on conditions. When the mill is off, the kiln flue gas stream continues to be cleaned by the APCD. This stream has particulates, in the form of CKD, with elevated levels of mercury. In general, the mercury-laden CKD

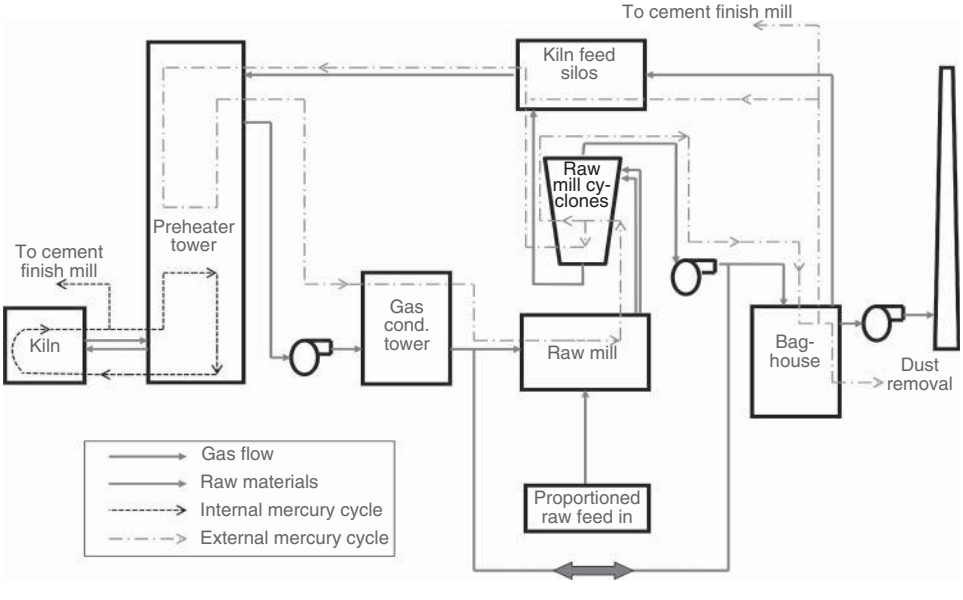

Figure 9.7 Possible internal mercury pathways in cement kiln system and external cycle during raw mill off and on condition.

captured by the APCD would be returned to the kiln. As the CKD is returned to the system, a circulation of mercury will be created through the preheater, raw mill, and APCD. Depending on the APCD inlet temperature, some of the mercury may be in the gaseous state due to higher operating temperatures in the mill off condition, will not be attached to the CKD, and will be released to the environment. The net effect of raw mill on and off is simply accumulation of mercury in the kiln system. Eventually, the mercury will be released to the environment over time [17].

The release and form of mercury in cement kiln systems is not completely understood. In general, the form of mercury in the system will be dependent on the cooling rate, temperature, and opportunities for the oxidation/chemical reaction to occur. These conditions correspond to the gas-phase chemistry relevant to the specific kiln characteristics, which are driven by the raw materials, gas conditions, and operating conditions. For example, the concentration of chlorine in the flue gas depends on a complex series of gas-phase reactions involving oxygen, water vapor, hydrocarbons, chlorine, and sulfur compounds present in the flue gas in the kiln system [18, 19].

Without significant data on mercury speciation in cement kilns, it is difficult to make definitive statements about the types of mercury compounds. However, the gas-phase equilibrium studies for coal-based flue gas suggest that $HgCl_2$ is the dominant oxidized species in flue gas at temperatures below 480–590 °C [19, 20]. The equilibrium of the oxidation reaction also depends on the concentration of chlorine and the degree of flue gas cooling [19]. It is generally assumed that the oxidation of mercury may have a similar pattern in the cement kiln system. Therefore, the degree of oxidation of mercury in the cement kiln system would be expected to decrease with increased flue gas cooling rates. As the flue gas temperatures continue to cool to the mercury boiling point (~357 °C), some of the mercury reacts to form HgO, which may further react with chlorine to form $HgCl_2$. However, the gas-phase homogeneous oxidation of Hg^0 is kinetically limited because of the short residence time [10], on the order of ~2 s. At gas temperatures below ~325 °C, some of the mercury may react with sulfur dioxide (SO_2) to form $HgSO_4$ and its subsequent reaction with gaseous HCl produces volatile dichloride which remains within the flue gas [21]. Therefore, the presence of SO_2 compounds in the flue gas may limit the concentration of chlorine and subsequent conversion of Hg^0 to $HgCl_2$.

The formation of complex silicates in a kiln system is also possible due to the high silica content in typical raw feed (13–15% by weight) and sufficient residence time for reactions to take place as vaporized mercury cycles through a kiln system. Owens *et al.* [22] stated that the formation of mercury silicates is possible based on the estimated thermodynamic data at temperatures ranging between 225 and 325 °C. However, the formation of mercury silicate may be inhibited by the presence of chlorine and sulfur. Additional research and alternative laboratory methods for clinker analysis will be required to confirm that mercury silicates are stable above temperatures of 325° C. As the flue gas passes through the APCD, the temperature continues to drop below 200° C, allowing some of the Hg^0 to adsorb

Table 9.1 Potential mercury transformation within cement kiln systems [15]. (Reproduced from Ref [15] © (2009) with permission from Portland Cement Association.)

System temperature (°C)	Chemical species influencing reactions	Resulting mercury compounds
2200	—	Hg (elemental, vapor)
<480–590	Chlorine	$HgCl_2$
<350	Oxygen, chlorine	HgO, $HgCl_2$
<325	Sulfur	$HgSO_4$
225–325	Silica	$HgSiO_3$

onto CKD particles. Also, some of the Hg^{2+} compounds (i.e., $HgCl_2$, HgO, $HgSO_4$) adsorb onto the CKD particles as mentioned already. It is evident that a lower flue gas temperature would produce more Hg_p, which would be efficiently removed by the APCD [23] with the remaining mercury compounds exiting the stack. The mercury reactions that can take place at different temperatures in a cement kiln system are summarized in Table 9.1.

It is postulated that nearly all forms of mercury exiting the kiln system will be gaseous or condensed on the fine particulate that exits with the gas stream. However, there is some very limited data that shows the presence of low but detectable levels of mercury in cement clinker. As cement manufacturing is a large industrial process that involves complicating factors such as raw mill on versus raw mill off and accumulation of mercury in the feed silo or accumulation at different parts of the system, it is important to note that a short-term stack emission test is not necessarily representative of actual annual emissions.

9.4
Mercury Emissions Control Solutions in the Cement Industry

U.S. Environmental Protection Agency (EPA) recently set a new limit for maximum mercury emissions from U.S. cement kiln stacks at 55 lb MM ton^{-1} clinker for an existing kiln, and 21 lb MM ton^{-1} clinker for a new kiln [24]. Therefore, reductions of mercury from cement kiln stacks will need to be further accomplished in the near future, in addition to those reductions already being implemented.

As described earlier, the source of mercury emissions from cement kiln systems are trace amounts of mercury in the raw materials and fuel that are inherently introduced into the kiln system as a part of the cement manufacturing process. The behavior of mercury in cement kiln systems is very complex as mercury can exist in various forms depending on the type of system and the chemical reactions that occur in that specific system. The following possible approaches can be considered for mercury control, which are based on the current state of mercury

control knowledge as applied to the cement process. Further study is ongoing and may provide additional approaches or variations to the following.

Option 1: The mass of mercury entering the kiln system can be reduced by using different raw materials or different fuels containing smaller trace amounts of mercury, although this option is limited.

Option 2: Some of the CKD captured in the APCD that contains elevated mercury concentrations can be removed from the system and wasted, treated, or mixed with clinker.

Option 3: The gas stream can be treated to remove the mercury before it is exhausted out the kiln stack.

Each of these options is further described in the following paragraphs.

Option 1: Although this option may sound the most practical, reducing mercury emissions by reducing mercury concentrations in the raw materials may be difficult to accomplish without profound economic consequences. Cement plants are located in areas where raw materials are readily available. Therefore, changing sources of raw materials, if possible, could impose a huge economic burden on a cement plant. In a situation where the fuel is found to contain relatively high trace levels of mercury, the economics, and practicality of reducing mercury inputs may also be difficult. Transportation costs for fuel can be very significant and the location of a potential alternate source of fuel with lower mercury content may significantly increase costs of fuel acquisition.

Option 2: In cement kiln operations, a portion of the CKD is often removed from the system in order to lower the alkali content of the clinker to meet U.S. product specifications. This mode of operation is also known in the cement industry as wasting CKD. This practice is minimized as much as possible to keep from wasting material that has already been partially calcined, thus continuing to have economic value as a partially processed raw material. As a matter of fact, the U.S. cement industry has made significant reductions in dust wastage rates over the last few decades. The removal of CKD is a mechanism to bleed the kiln system of alkali salts that build up as they circulate through the system in a pattern similar to mercury. If a portion of the dust from the APCD is not wasted, the mercury remains in the system and is recirculated, with the concentration of mercury in the external loop of a preheater/precalciner system (shown in Figure 9.7) increasing over a period of time. If the raw mill exhaust is equipped with cyclones to separate coarse dust particles that are transported to the blending silo, then the mercury concentration in the APCD may not be significantly different between raw mill off versus raw mill on operating modes. If the raw mill exhaust is not equipped with cyclones, then diverting APCD dust with the raw mill on will not be as efficient for removing mercury from the system because of the dilution effect of the large mass of dust captured by the APCD. The amount of CKD generated in a typical kiln system when the raw mill is off can be

significant at 8–15 ton h^{-1}. Wasting all the CKD would not be economically viable due to its value as a raw material to the process.

A patent-pending, mercury-laden, kiln CKD roasting technology has been identified as a possible mercury removal mechanism for the cement industry [25]. In the roasting system, the mercury-laden CKD is heated above the boiling point of mercury. While mercury is in the gas phase, an ESP is used to separate the dust from the gas-phase mercury, which can then be removed by various techniques such as activated carbon injection (ACI). The cleaned dust is taken back to the blending silo to be used as kiln feed.

Another practice possible for cement plants is called *dust shuttling*. This practice is utilized currently at some facilities, and is being considered by others as a potentially viable option to remove mercury from the kiln system by shuttling dust from the APCD. For this practice, the facility maintains a specific mix chemistry to allow incorporating a small quantity (3–5% of product) of CKD in the finish mill, intermixing the CKD with cement [25–27].

For those cement kilns that do not waste or shuttle CKD, it is reasonable to assume that essentially all the mercury in the raw material and fuel will end up as stack emissions over the course of a year. However, if a portion of the dust is shuttled, this will lower mercury stack emissions, as some of the mercury becomes bound up in the cement product matrix. This is a viable mercury reduction option to the extent the CKD can be interground with the clinker while still maintaining a quality product. Since only a portion of the collected CKD from the APCD can be diverted, the mercury reduction capability is limited. It is reported that the efficiency of mercury removal of APCD dust is dependent on site-specific conditions, including the flue gas composition, operating temperature at the inlet of APCD, and dust loading in the systems [25]. Thus, dust shuttling is expected to have a limited impact on mercury emission reductions. However, in the event, as the shuttled CKD has a high mercury content, dust shuttling may present an effective method of removing mercury from the system, subsequently being a significant mercury control option.

Option 3: When considering cement industry options for treating the gas stream for mercury removal before exhausting the gas through the kiln stack, the majority of the controls require tailpipe treatment after the existing APCD. In fact, as described below, control technologies being currently considered would require an additional APCD between the existing APCD and the stack.

Mercury control technologies currently being considered as options for cement kiln system emissions include

- Activated carbon injection (ACI)
- Wet scrubbing
- Selective catalytic reduction (SCR) and wet scrubbing.

9.4.1 Activated Carbon Injection (ACI)

Activated carbon is a widely used adsorbent in several industries due to its unique physical and chemical properties. The large surface area, pore volume, and pore size distribution of activated carbon make it a potential adsorbent to accomplish mercury removal from the cement kiln flue gas. ACI applications have been used historically for mercury control in municipal waste incinerators, hazardous waste incinerators, and power plant applications. However, there are some factors that make direct transfer of this technology to the cement industry less effective. For example, the variable SO_2 and HCl concentrations along with a high dust loading of calcium and alkali materials may interfere with the absorption sites on the activated carbon. The percent mercury removal using ACI in the cement industry will be dependent on the temperature and composition of kiln flue gas and the amount and type of activated carbon used. Cement kiln APCD operating temperatures are usually at the high end of absorption temperatures of activated carbon, being effective up to 204 °C. It has been found that typical mercury reduction ranges from 20% to 90% using ACI rates of 2 – 10 lb $MMacf^{-1}$. It is reported that the mercury adsorbed onto activated carbon is stable. It does not readily desorb, nor is it leachable (based on toxicity characteristic leaching procedure (TCLP) results) [28, 29]. This becomes an important factor as the carbon and CKD captured in the APCD must be appropriately managed for final disposal.

There are at least two cement kilns in the United States currently using ACI technology for mercury control. However, there are additional issues to study and resolve as described in the following paragraphs.

The new EPA MACT (maximum achievable control technology) standard for HCl in an existing cement kiln is 3 ppm [24]. When facilities comply with the HCl standard concurrently with the Hg standard, there may be an impact on the effectiveness of mercury control technologies. This correlation needs to be taken into account for determining the final control mechanism for a particular kiln. Moreover, chlorine in the cement kiln may combine with the alkalis (sodium and potassium) prevalent in the raw materials, resulting in insufficient chlorine to convert Hg^0 to Hg^{2+}. In addition, the presence of SO_2 in the flue gas may interfere with the carbon absorption efficiency [30].

In employing ACI technology to a cement kiln system, an additional APCD may be required to be constructed between the existing APCD and the kiln stack for further polishing. Activated carbon would be injected into the gas stream between the first and second APCDs. By capturing the remaining mercury from the flue gas in the second APCD before it is exhausted through the stack, mercury can be effectively removed from the system, as the mercury-laden activated carbon is separated from the kiln flue gas stream prior to the gases being released to the environment through the stack. This activated carbon can be wasted typically to a sanitary landfill as non-hazardous solid waste, which would effectively remove mercury from the kiln system.

Another approach to collecting and removing mercury from a cement kiln would be to use the absorption capacity of the kiln system, which could also be enhanced by using activated carbon. In a current kiln system configuration, the CKD is typically recycled to the maximum extent possible back to the kiln as part of the kiln feed, with most of the Hg_p being absorbed by the dust recycled back to the kiln. However, in some kiln systems, activated carbon could be injected into the main baghouse, depending upon the mercury carbon absorption properties of the collected dust. Some of this collected dust could be shuttled to the finished mill, with the remainder sent to the blend silos. This would work where the dust shuttled material would be small enough not to impact product quality. The material from the blend silos would re-enter the kiln system, destroying the carbon, and releasing the mercury to be once again collected on new carbon that is injected into the baghouse. This would have the effect of increasing the mercury concentration of the baghouse dust, which would make the removal of that dust a more efficient mechanism for mercury removal from the kiln system.

For an in-line raw mill system, ACI might be a mercury control option when the raw mill is off-line. However, the adsorption of mercury onto activated carbon is temperature-dependent. It is reported that ACI can work effectively only at temperatures below 160 °C [31]. This may be a problematic temperature for some existing systems as the flue gas temperature is comparatively high when the raw mill is not operating. Some halogenated powdered activated carbon (PAC) is reported to reduce mercury emission by more than 70% at APCD inlet temperatures up to 343 °C, but further investigation is needed to test the PAC performance for a longer period of time at various cement plants. As an example of potential issues, the brominated PACs could cause operational issues in a kiln system if they are reintroduced, causing an imbalance in the alkali–halogen ratio in the kiln.

As described above, both temperature and mercury concentrations in the flue gas may be issues that render the use of ACI technology less effective in the cement kiln system environment. Moreover, the baghouse dust with activated carbon may be problematic when used in clinker grinding or dust shuttling, but this issue will be site-specific. Activated carbon negatively impacts the air entrainment capabilities of the final cement product [25, 32]. Although ACI has the potential for mercury control in a cement kiln system, the industry still faces the significant economic issues of an additional large capital cost to construct a second APCD and to deal with disposal of the mercury-laden carbon material.

9.4.2 Wet Scrubbing

Wet scrubbing has been used in several industrial processes such as the electric power generation industry to reduce the SO_2 content of flue gases. In this process, a slurry of limestone or lime is sprayed into the gas stream, usually after the APCD, and the acidic SO_2 content of the gas reacts with the basic lime content to form gypsum. Therefore, the soluble components within the gas stream are removed in the scrubber, and a clean gas stream results. The solid residue that is

formed is removed and discarded. Wet scrubbers have not been used extensively in the cement industry historically due to lime inherently being in the kiln system. This creates a natural dry scrubbing process that removes much of the SO_2 content from gaseous effluents, nullifying the need for additional SO_2 control. It is reported that wet scrubbers have the capability of capturing soluble forms of mercury [33]. The oxidized mercuric compounds such as $HgCl_2$ are generally soluble in water, whereas Hg^0 is not soluble in water. EPA has reported that the electric power generation industry has had some success in mercury removal in wet scrubbers, especially in plants burning medium to high sulfur bituminous coals that tend to produce a larger amount of the Hg^{2+} species.

A limited number of cement kiln systems in the United States (five known installations to date) have installed wet scrubbers primarily for SO_2 and acid gas control. It is reported that the wet scrubber can capture more than 80% of SO_2 and $HgCl_2$ from the cement kiln flue gases [25]. However, there are several problems in transferring the process from electric power generation to the cement industry for mercury control. The effectiveness of wet scrubbing is highly dependent on the temperature of the gas stream, and the scrubber is normally located after the APCD. In many cases, the cement kiln gas stream exiting the APCD is >204 °C when the raw mill is off-line. Wet scrubbers have been shown to be effective in capturing up to 90% of the Hg^{2+} in the kiln flue gases. Hg_p not captured in the APCD will likely be captured in the wet scrubbers. However, Hg^0 is not removed from the flue gases due to its non-solubility.

As described, the effectiveness of wet scrubbers for mercury removal mainly depends on the mercury species present in the flue gas. In addition, the reemission of mercury may occur with wet scrubbers. Reemission is a result of mercury reduction chemistry in wet scrubbers, where Hg^{2+} is reduced to insoluble Hg^0. Thus, the overall effectiveness of wet scrubbing for cement kiln emissions is unclear [34]. Studies based on the coal-fired power plant flue gases have shown that the amount of mercury retained in the scrubber solids may range from 40% to 85% [35]. The primary reported factor affecting mercury retention by a wet scrubber is the liquid to gas ratio, which may limit the mass transfer of pollutants. In addition, the scrubber solids must be properly managed and the water chemistry must be controlled to prevent reemission of the captured mercury.

9.4.3 Selective Catalytic Reduction (SCR) and Wet Scrubbing

SCR has been developed to remove NO_x emissions from flue gas. In an SCR system, the reducing agent of ammonia or urea is injected into the flue gas at the upstream side of the catalyst bed. The flue gas is passed through the catalyst bed containing oxides of vanadium or titanium where NO_x is reduced to form elemental nitrogen and water vapor. The SCR system is generally installed before the primary APCD in a cement plant for NO_x control as temperatures in the

range of 288–460 °C are required for the catalyst to be effective. A wet scrubber is installed after the APCD to control SO_2 emissions. A co-benefit of the SCR process is reported to be its ability to convert Hg^0 to Hg^{2+}, primarily $HgCl_2$ [36]. As described earlier, $HgCl_2$ is water soluble and can be captured in a wet scrubber along with SO_2. EPA has reported data from its Mercury Information Collection Request (ICR) showing that some electric power generation facilities use a combination of SCR and wet scrubber technologies to control the oxides of nitrogen and sulfur, which is also very effective in removing mercury from flue gases. The oxidation of mercury by the SCR process appears to be dependent on the type of coal combusted, furnace conditions, and physical and chemical properties of the catalyst [37, 38].

The catalyst used in an SCR system has the potential to catalyze the formation of sulfur trioxide (SO_3) from SO_2 and gas-phase chlorine (Cl_2) from HCl that are present in the flue gas [37]. Cl_2 in the flue gas will affect the overall conversion of Hg^0 to $HgCl_2$. Bituminous coal typically contains higher Cl_2 and sulfur than the low-ranking sub-bituminous and lignite coals that are abundant with high calcium [37–40]. Higher quantities of Cl_2 result in greater conversion of Hg^0 to Hg^{2+} in an SCR system and subsequently increase the removal of mercury in the wet scrubber. Conversely, the flue gas from the combustion of sub-bituminous and lignite coal appears to reduce the effectiveness of the SCR in converting mercury. This is due to the Cl_2 in the power plant flue gas from coal combustion tending to react with the alkaline materials in ash resulting in little, if any, Cl_2 being available for the oxidation of mercury. In a power plant SCR application, ~80–90% Hg^0 in the flue gases from bituminous coal use is reported to be oxidized to $HgCl_2$. When the gas stream passes through the wet scrubber, the soluble $HgCl_2$ is dissolved in the solution sprayed into the wet scrubber. Therefore, the wet scrubber would then be expected to remove ~90% of the soluble mercury. The reduction of mercury from the flue gases of a power plant utilizing sub-bituminous and lignite coals is found to be only 20% with or without SCR [40]. However, the use of an SCR system at a cement plant will be dependent on site-specific conditions. The SCR catalyst bed must be located in an area where the flue gas temperature is in the appropriate range. There may be catalyst poisons such as alkali metals and calcium oxide in the cement kiln flue gas that will deactivate the catalyst by reacting with active sites. The catalyst may also become plugged in the high dust installations associated with preheater/precalciner kiln systems.

9.5 Conclusions

The cement manufacturing industry is a raw material-driven industry with demanding combustion conditions a part of the pyroprocessing portion of the process. As such, the study of mercury sources, forms, and emissions are unique in this industry. With the wide range of temperatures existing within a kiln system, mercury can be present in several chemical forms at different locations within the system. It can pass through the system as Hg^0 or a volatile mercury

compound. It can condense or adsorb onto CKD in cooler parts of the system, such as in the APCD or raw mill (for preheater/precalciner kilns), when the temperature falls below 200° C. It has been shown that there are mercury recycle loops within the kiln system. CKD generated during processing of raw meal is recycled back to the kiln as kiln feed, with some systems being designed to continuously bleed some portion of the CKD from the APCD to maintain cement quality. This process inherently helps break the mercury accumulation cycle in the kiln, subsequently reducing the mercury load in the system and therefore reducing annual emissions.

As increased regulatory controls have just been put in place, and corresponding control of mercury emissions is currently being evaluated for future installations, the status of proven mercury control technologies used in cement kiln systems to treat the kiln exit gas stream is not yet clearly established. There are several technologies, including the use of ACI, a wet scrubber, and SCR; all of which are currently used to control mercury from flue gases in the electric power generation industry and for municipal and hazardous waste incinerators. These technologies may potentially be transferable to a cement kiln system, although the gas streams that exit the kiln are different than those industries currently using these technologies for mercury control. Current mercury control technologies used in other industries and transferred to cement kilns would require the installation of an additional APCD for an ACI installation or wet scrubber for particulate control downstream of the existing APCD. Another mercury control solution may be through wasting or shuttling some of the mercury-enriched CKD collected in the APCD when the raw mill of a preheater/precalciner kiln is off-line.

Regardless of the control system(s) used for mercury in a cement plant, additional data collection on the variation of mercury emissions over time needs to be conducted. This is especially true of emissions under the raw mill on/off scenarios of a preheater/precalciner kiln. Additional data collection is also needed to determine the speciation of mercury emissions from cement kiln stacks and within the kiln process. As described in this chapter, and throughout this book, many of the control technologies are dependent on the exact form of mercury. There are limited definitive studies on the speciation of mercury in a cement kiln system, and there is yet much to learn on mercury control for this industry. It is anticipated that much knowledge will be gained over the next few years and that additional control technologies currently being developed and tested will become additional solutions for the industry.

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Part IV
Mercury Research Programs in the United States

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10
DOE's Mercury Control Technology Research, Development, and Demonstration Program

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10.1
Introduction

The U.S. Department of Energy's (DOE's) National Energy Technology Laboratory (NETL) managed a comprehensive, collaborative program from the mid-1990s to 2008 that focused on the research, development, and demonstration (RD&D) of cost-effective mercury (Hg) control technologies, including investigating the potential impact of Hg control on the use and disposal of coal combustion byproducts. The overall goal of the program was to significantly lower the cost and increase the capture efficiency of advanced systems to remove Hg from coal combustion flue gas, should coal-fired power plants be regulated. NETL achieved this ambitious goal and ultimately was successful in bringing Hg control technology from what was only a concept in the early 1990s to a commercial product. As of 2010, pollution control equipment vendors have sold nearly 150 full-scale activated carbon injection (ACI) systems, a signature technology of the NETL program, to U.S. coal-fired power generators. These sales represent more than 56 GW of coal-fired electric generating capacity. The U.S. Environmental Protection Agency (EPA) projects that 146 GW of ACI will be installed on U.S. power plants by 2015 in order to comply with proposed Federal Hg emission control regulations [1]. The Hg control systems developed under the NETL program that are currently being deployed by the electric-utility industry have the potential to achieve 80–90% or more Hg reduction at a cost that can dip below $10 000 per pound of Hg removed, compared to baseline costs of $50 000–70 000 per pound of Hg.

10.2
Background

Coal is one of the United States' most abundant and secure energy resources and coal-based power systems generated ~45% of the nation's electricity in 2009 [2]. Coal is projected to continue to be an important component of the U.S. energy

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portfolio well into the twenty-first century. While coal-based power plants have made significant strides since the early 1970s in substantially reducing emissions of particulate matter (PM), sulfur dioxide (SO_2), and nitrogen oxide (NO_x), environmental challenges still exist. One of those challenges is Hg. Mercury is found in trace amounts in coal, and much of it escapes capture by technologies designed to remove PM, SO_2, and NO_x. Today, coal-fired utility boilers represent the largest source of anthropogenic Hg emissions in the United States, accounting for about 50% of all man-made emissions [1].

Mercury is present in dilute concentrations in power plant flue gases. Liquid at room temperature and pressure, Hg, when heated, is volatile and easily vaporized. Depending on the type or mix of coal being burned and the downstream emissions control systems being employed by a power plant, Hg is released to the atmosphere in varying percentages in two primary gaseous forms – elemental Hg and oxidized Hg. It can also be emitted as particulate-bound Hg.

As part of the 1990 Clean Air Act Amendments (CAAAs), Congress mandated that EPA assess the potential health impacts of Hg and other hazardous air pollutants and, if necessary, set standards that would reduce these impacts. In 2000, EPA determined that there was sufficient evidence of a link between Hg emitted from stationary sources and certain adverse health effects and began crafting regulations. In March 2011, EPA proposed new Federal Hg standards (known as *Maximum Achievable Control Technology* (*MACT*)) that would reduce Hg emissions from coal- and oil-fired power plants by more than 90%. The new proposed rule will replace the vacated Clean Air Mercury Rule (CAMR) that was issued by EPA in March 2005. The proposed MACT standards would establish plant-specific numerical emission limits for Hg, PM (a surrogate for toxic, non-Hg metals), and hydrochloric acid (a toxic acid gas). The final MACT rule was promulgated in November 2011. Due in part to EPA's delay in setting Federal Hg emission standards, state regulatory agencies began implementing Hg standards. As of February 2011, at least 14 states had laws or regulations requiring Hg emission reductions at coal-fired power plants [3].

10.2.1 NETL's Hg Control Technology R&D

Paralleling EPA's assessment of the health effects of Hg, NETL initiated an ambitious Hg control technology research and development (R&D) program in the mid-1990s [4]. The program was driven by concerns that cost-effective Hg capture technology did not exist should EPA conclude that Hg emissions from coal-fired power plants and other stationary sources needed to be regulated. Under DOE's Office of Fossil Energy's (FEs) Innovations for Existing Plants (IEP) Program, NETL worked collaboratively with EPA, the Electric Power Research Institute (EPRI), the University of North Dakota Energy and Environmental Research Center (UNDEERC), power plant operators, and state and local agencies, as well as a host of research organizations, technology developers, and academic institutions, to bring to commercial readiness both reliable techniques for measuring the

different chemical forms of Hg in coal-based flue gas and cost-effective technologies and approaches for reducing Hg emissions from power plants.

More than $120 million in Federally funded extramural and in-house research was conducted under the IEP Hg Program – including more than $30 million in private-sector cost sharing – directed at five interrelated research areas:

- Emissions characterization.
- Development and testing of measurement devices.
- Speciation research.
- Development and field testing of control technologies.
- Coal utilization byproducts (CUBs) characterization.

The overall short-term goal of the NETL Hg R&D Program was to develop Hg control technologies that would be ready for commercial demonstration by 2007 and that could achieve 50–70% Hg capture at 50–75% of the cost of state-of-the-art ACI estimated to be between $50 000 and $70 000 per pound of Hg removed. The NETL Hg R&D Program had a longer-term goal of developing advanced Hg control technologies that could achieve 90% or greater capture at 50–75% of the cost of state-of-the-art ACI technology for commercial demonstration by 2010. However, in 2008, it was determined that DOE had successfully achieved its goal of bringing efficient, cost-effective Hg control technologies to commercial readiness and that further development and refinement of Hg control systems should be carried out by the private sector.

10.2.2 Mercury Speciation

Analysis of flue gas samples conducted early in the NETL program revealed that the trace amount of Hg present in coal is volatilized during combustion and converted to gaseous elemental mercury (Hg^0). Subsequent cooling of the coal combustion flue gas and interaction of the gaseous Hg^0 with other flue gas constituents, such as chlorine (Cl) and unburned carbon (UBC), result in a portion of the Hg^0 being converted to gaseous oxidized forms of mercury (Hg^{2+}) and particulate-bound mercury (Hg_P) [5].

The initial research conducted by NETL and other organizations, such as EPRI and UNDEERC, further showed that the varying percentages of Hg_P, Hg^{2+}, and Hg^0 had a profound effect on the Hg capture efficiency of existing air pollution control devices (APCDs) designed to control PM, SO_2, and NO_x emissions, ranging from 0% to more than 90% removal [6]. The Hg_P fraction typically was captured by a power plant's particulate control system, such as an electrostatic precipitator (ESP) or fabric filter (FF). The Hg^{2+} portion is water-soluble, and therefore a relatively high percentage was shown to be removed in a plant's wet flue gas desulfurization (FGD) unit designed to remove SO_2. The Hg^0 fraction is generally not captured by any existing APCD. In addition, operation of a selective catalytic reduction (SCR) system for control of NO_x emissions was shown to promote Hg^0 oxidation and enhance Hg capture across a downstream FGD [7].

In summary, NETL's Hg speciation research revealed that (i) several key factors influence Hg speciation in coal combustion flue gas; (ii) Hg speciation impacts the level of Hg control achieved by existing APCD configurations; and (iii) Hg capture across existing APCD configurations could be enhanced.

10.2.3 Mercury Control Technologies

The Hg speciation research set the stage for the development of a suite of Hg control technologies that would be needed for the diverse fleet of U.S. coal-fired power plants. The research was directed at two general approaches for controlling Hg: (i) Hg^0 oxidation concepts that maximize co-benefit removal of Hg^{2+} in wet FGD systems and (ii) Hg-specific control technology, such as ACI. In a typical ACI configuration, powdered activated carbon (PAC) is injected downstream of the power plant's air heater and upstream of the particulate control device – either an ESP or FF (Figure 10.1). The PAC adsorbs the Hg from the combustion flue gas and is subsequently captured along with the fly ash in the ESP or FF.

In 2000, following laboratory-through pilot-scale development of these approaches, NETL launched a three-phase field testing program. The program called for full-scale and slip-stream testing of Hg control technologies over a limited test period at operating coal-fired power plants. The initial field testing (Phase I) focused on both slip-stream and larger-scale testing of conventional (untreated) PAC and on improving the capture of Hg across wet FGD systems. Phase II, which began in 2003, included longer duration, full-scale field testing of chemically treated ACI, sorbent enhancement additives (SEAs), and sorbent-based technologies designed to preserve fly ash quality. Phase II also included evaluations of chemical additives and Hg^0 oxidation catalysts to enhance FGD Hg capture. The goal of Phase I and Phase II was to develop Hg control technologies that could achieve 50–70% Hg capture at costs 25–50% less than

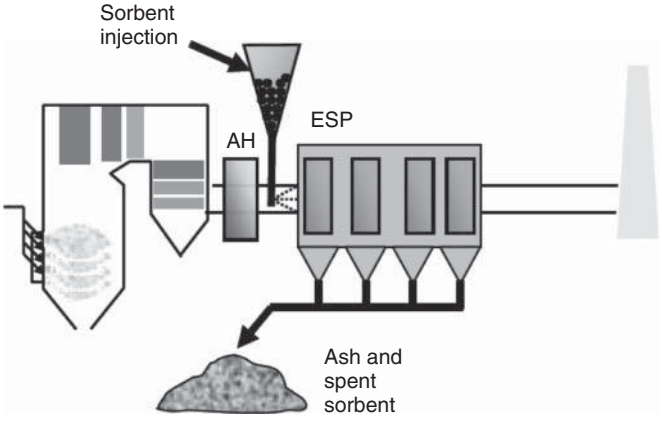


Figure 10.1 Activated carbon injection technology schematic.

the baseline (1999) estimate of about $60 000 per pound of Hg removed ($/lb Hg removed).

While the 30-day-long tests conducted in Phase II yielded significant information on the performance of the advanced Hg control technologies, the testing period was not always sufficient to answer all of the questions about the impact these systems might have on power plant operations. To better understand potential balance-of-plant impacts and to further push the capture effectiveness of the Hg control technologies, NETL initiated nine new projects in 2006 to conduct longer duration field tests. The Phase III projects supported the NETL Hg R&D Program's longer-term goal of developing advanced Hg control technologies that could achieve at least 90% Hg capture and be available for commercial demonstration by 2010.

10.2.4
Results from Field Testing Program

Between 2000 and 2008, the NETL Hg R&D Program managed full-scale field tests of Hg control technologies at nearly 50 U.S. coal-fired power generation facilities. The flexibility of the Hg R&D Program allowed NETL to quickly incorporate insights and lessons learned into the development of advanced Hg control technologies tailored to specific areas of need. For instance, a determination that Cl released during coal combustion promotes Hg oxidation in flue gas led to field testing of technologies designed to provide a halogen "boost" for coals such as subbituminous and lignite. NETL had observed a step-change improvement in both the cost and performance of Hg control during full-scale field tests of coal treatment with an aqueous calcium bromide ($CaBr_2$) solution at plants equipped with a wet FGD system, and during tests using chemically treated (or brominated) ACI upstream of a particulate control device.

10.2.5
Oxidation Enhancements

Oxidation of flue gas Hg^0 followed by absorption of Hg^{2+} across a wet FGD system has the potential to be a reliable and cost-effective Hg control strategy for some coal-fired power plants. To optimize Hg capture across FGD systems, NETL funded field tests of technologies, such as chemical additives and Hg^0 oxidation catalysts that promote Hg^0 oxidation in coal combustion flue gas. The impacts of combustion modification, such as coal reburn, on flue gas Hg^0 oxidation were also examined under the NETL Hg R&D Program [8]. In addition, NETL evaluated FGD additives designed to suppress Hg^0 reemissions across an FGD system. Originally thought to be a sampling artifact, Hg^0 reemissions were observed at several coal-fired units to occur when Hg^{2+} captured by a wet FGD is chemically reduced within the vessel and reemitted as Hg^0.

10.2.6 Chemical Additives

The ability of chemical additives, sprayed onto the coal as an aqueous salt solution, to promote flue gas Hg^0 oxidation and enhance FGD Hg capture was evaluated during a full-scale field test at Luminant Power's Monticello Station Unit 3 [9]. During a 2-week trial conducted at Monticello Station, which burns a 50 : 50 blend of Powder River Basin (PRB) subbituminous and Texas lignite (TxL) coals, total Hg capture across the ESP/FGD configuration averaged 86% with a $CaBr_2$ injection rate equivalent to 113 ppm Br in the dry coal. Greater than 90% total Hg capture was observed during a short-term test with a $CaBr_2$ injection rate equivalent to 330 ppm Br in the coal.

NETL also conducted pilot- and full-scale field tests of wet FGD additives designed to limit Hg^0 reemissions through the formation of insoluble salts with Hg^{2+} [10]. The effectiveness of Degussa Corporation's TMT-15 additive in suppressing Hg^0 reemissions was also evaluated at the Monticello Station and at Southern Company's bituminous-fired Plant Yates. The results were inconclusive due to (i) the absence of reemissions, even without chemical addition, at Monticello Station and (ii) Hg measurement issues at Plant Yates. However, TMT-15 had the anticipated impact on FGD byproducts as the FGD liquor Hg concentrations were significantly reduced during both tests. During a full-scale field test at Indianapolis Power and Light's Petersburg Station, which burns high-sulfur bituminous coal, a modest decline in Hg^0 reemissions was observed during an 8-day TMT-15 injection test, but the additive did not impact the partitioning of Hg in FGD byproducts at this site. Meanwhile, full-scale results obtained during a 30-day evaluation of Nalco Company's 8034 additive at Plant Yates were confounded by low baseline Hg^0 reemission levels. A third wet FGD additive to reduce Hg reemission, Babcock and Wilcox's Absorption Plus (Hg)™, was evaluated at E.ON America's high-sulfur bituminous-fired Mill Creek Station after parametric trials revealed that untreated ACI had little, if any, impact on Hg removal [11]. During long-term testing, total Hg removal averaged about 92% with the addition of Absorption Plus (Hg). Note that more than 80% of total Hg removal was observed under baseline conditions.

10.2.7 Catalysts

The ability of fixed-bed catalysts to promote flue gas Hg^0 oxidation was evaluated at pilot-scale, and a full-scale field test of a gold-based catalyst was conducted in 2008/2009 at Lower Colorado River Authority's Fayette Unit 3 [12]. The catalysts were designed for installation downstream of an ESP or FF to (i) minimize fly ash deposition on the catalysts; (ii) prevent or minimize catalyst erosion; and (iii) ensure a low flue gas temperature and flow rate, which reduces the catalyst space velocity and minimizes the length of catalyst required. The full-scale catalyst test was planned for 24 months to provide catalyst life data. However, the test

was terminated after 17 months because of continual increases in pressure drop across the catalyst. The adverse effects of the fly ash buildup on oxidation catalyst performance, along with variable Hg reemissions across the Unit 3 wet FGD absorbers, led to an increase in Hg removal averaging only 27–30% during the demonstration.

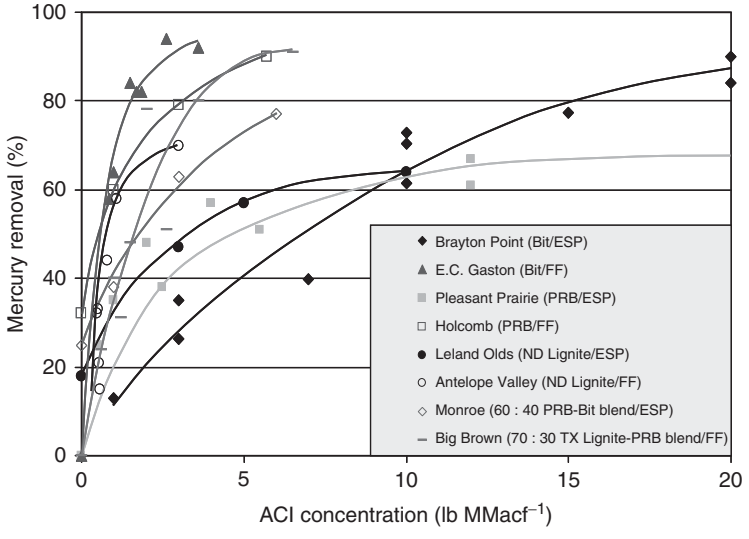
During pilot-scale testing at Great River Energy's (GREs) North Dakota lignite-fired Coal Creek Station, about 67% Hg^0 oxidation was measured across a palladium-based (Pd#1) catalyst after 20 months of operation. Following thermal regeneration, Hg^0 oxidation across the Pd#1 catalyst increased from 67% to 88% (near the 95% activity of the fresh catalyst). Meanwhile, nearly 80% total Hg capture was observed across the pilot-scale wet FGD, with 84% Hg^{2+} at the FGD inlet. At Luminant Power's Monticello Station, severe fly ash buildup was observed on the catalyst surfaces, likely caused by frequent pilot unit outages during the test campaign. Following catalyst cleaning, Hg^0 oxidation was ~72% across the regenerated Pd#1 catalyst (transferred from Coal Creek) and 66% across a gold-based catalyst after about 20 months of pilot-scale operation. Total Hg capture across a pilot-scale wet FGD ranged from 76% to 87%, compared with only 36% removal under baseline conditions. This equates to about 70% incremental Hg capture due to the catalysts.

10.2.8 Activated Carbon Injection

DOE/NETL's portfolio of full-scale field testing projects encompassed several variations of sorbent injection technology: untreated PAC, untreated PAC with chemical additives, chemically treated PAC, EPRI's toxic emissions control (TOXECON™) configuration, TOXECON II™, and non-carbon and "concrete-friendly" PAC sorbents. The development, and subsequent field testing, of ACI with chemically treated PAC and chemical additives, in conjunction with untreated PAC, represented a concerted effort to enhance Hg capture at units firing low-rank coal after Phase I results at the PRB-fired Pleasant Prairie Unit 2 showed total Hg removal via untreated PAC was limited to about 65%. These advanced, Hg-specific control technologies were designed to introduce excess halogens into the Cl-deficient flue gas emitted from low-rank coals to promote Hg^0 oxidation and adsorption. Meanwhile, minimizing the impact of ACI on fly ash utilization was the driving force behind field testing of the TOXECON configurations and non-carbon/"concrete-friendly" sorbent injection.

10.2.8.1 Untreated PAC

NETL's initial field testing using ACI with untreated PAC was conducted by ADA-ES at four coal-fired power plants (E.C. Gaston, Pleasant Prairie, Brayton Point, and Salem Harbor) in 2001–2002 [13]. Testing included parametric tests using several commercially available PAC products at various feed rates and operating



* All data generated using NORIT Americas' DARCO® Hg.

Figure 10.2 Test results for untreated activated carbon injection.

conditions, followed by a 1–2 week short-term test with a PAC selected from the parametric testing. Test results for E.C. Gaston, Pleasant Prairie, and Brayton Point are shown in Figure 10.2. The ACI test results at Salem Harbor were inconclusive because average Hg capture was already at 90% during baseline testing without PAC injection. The high baseline Hg removal was attributed to high levels of UBC and low flue gas temperature.

Untreated PAC was also evaluated during two 30-day long-term tests at Plant Yates Unit 1 during subsequent field testing during Phase II of NETL's R&D Program. URS selected RWE Rhinebraun's Super HOK sorbent and total Hg capture varied from 50–86%, with injection rates ranging from 4.5 to 9.5 lb MMacf^{-1} [14]. Plant Yates was selected for long-term testing, in part, to gain a better understanding of the effect of ACI on small specific collection area (SCA) ESP (173 SCA) and wet FGD operation. URS observed an increase in the ESP arcing rate during continuous ACI, particularly at high load. While the 30-day long-term injection test caused no visible physical damage to the ESP, it was unclear what effect the increased arcing rate would have on ESP performance over longer time periods.

ADA-ES chose DARCO® Hg PAC for the 30-day long-term test conducted at DTE Energy's Monroe Station Unit 4, which burns a 60% PRB and 40% bituminous coal blend and is equipped with an SCR and cold-side-electrostatic precipitator (CS-ESP) [15]. Total Hg removal averaged 78% with DARCO Hg injection at 4.9 lb MMacf^{-1}. The performance of untreated DARCO Hg during select full-scale field tests is presented in Figure 10.2.

10.2.8.2 Chemically Treated PAC

The limited Hg removal achieved by untreated ACI at Pleasant Prairie spurred the development and full-scale field testing of alternatives, such as PAC chemically treated with Br. Two brominated PACs – NORIT Americas' DARCO Hg-LH and Sorbent Technologies' B-PAC™ – were consistently top performers at field testing units burning lower-rank coals. In fact, the outstanding performance (see Figure 10.3) of these brominated sorbents accelerated the commercialization of Hg-specific control technologies and drastically reduced the estimated cost of Hg control due to a reduction in the ACI rate required to achieve a given level of control, which offsets the higher cost of these sorbents.

ADA-ES selected brominated DARCO Hg-LH for 30-day long-term field tests at two PRB-fired units: Sunflower Electric's Holcomb Station Unit 1 and AmerenUE's Meramec Station Unit 2. At Meramec, 93% average total Hg removal was achieved across the CS-ESP with DARCO Hg-LH injection at 3.3 lb $MMacf^{-1}$ [16]. Total Hg capture averaged 93% across the spray dryer absorber (SDA)/FF configuration at Holcomb with DARCO Hg-LH injection at 1.2 lb $MMacf^{-1}$ [17]. UNDEERC also conducted a 30-day evaluation of DARCO Hg-LH at GRE's North Dakota lignite-fired Stanton Station Unit 10. With DARCO Hg-LH injection at 0.7 lb $MMacf^{-1}$, total Hg capture across the SDA/FF configuration averaged 59% [18]. However, >90% Hg capture was achieved at this unit during parametric trials with both DARCO Hg-LH and B-PAC injection at 1.5 lb $MMacf^{-1}$.

The brominated B-PAC sorbent was also selected for 30-day long-term trials at three of NETL's field testing sites. At GRE's PRB-fired Stanton Station Unit 1, URS observed 85% average total Hg removal across the CS-ESP with B-PAC injection at 1.7 lb $MMacf^{-1}$ [19]. Sorbent Technologies conducted long-term field tests with B-PAC at DTE Energy's St. Clair Station Unit 1 that burned an 85% PRB and 15% bituminous coal blend, and at Progress Energy's bituminous-fired Lee Station

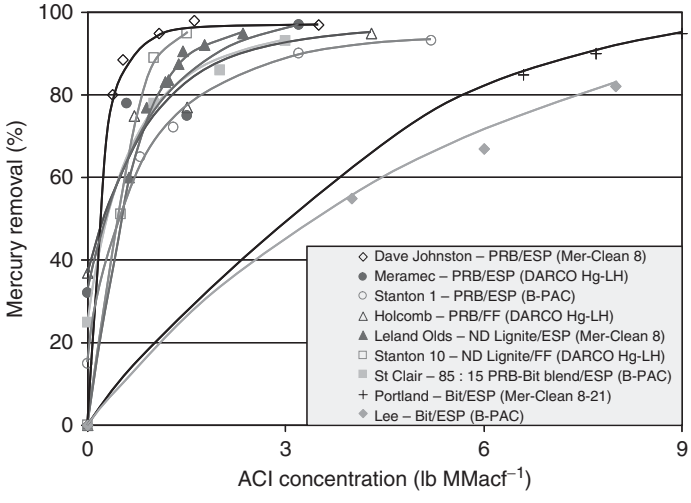


Figure 10.3 Test results for treated activated carbon injection.

Unit 1. At St. Clair, 94% average total Hg removal was achieved across the CS-ESP with B-PAC injection at 3 lb MMacf^{-1} [20]. Total Hg capture averaged 85% across the CS-ESP at Lee with B-PAC injection at 8 lb MMacf^{-1} [19]. Note that the 30-day long-term test at Lee was conducted with the sulfur trioxide (SO_3) flue gas conditioning (FGC) system idled and opacity levels remained acceptable.

ADA-ES conducted field testing at Rocky Mountain Power's PRB-fired Hardin Generating Station to evaluate the Hg removal performance, long-term emissions variability, and associated operating and maintenance costs of PAC injection for >90% Hg control during a year-long, full-scale demonstration. Baseline Hg capture at Hardin ranged from 20–30% across the SCR and SDA/FF configuration [21]. During parametric testing, an injection rate of about 1 lb MMacf^{-1} was required to attain slightly more than 90% total Hg removal with DARCO Hg-LH and Calgon Carbon's brominated FLUEPAC™-MC Plus. In addition, injection of a DARCO Hg and FLUEPAC-MC Plus mixture achieved 90% total Hg at 0.14 lb MMacf^{-1}, with a low KNX™ additive rate.

URS conducted field testing at NRG Texas Power LLC's Limestone Electric Generating Station Unit 1 that fired a 70 : 30 blend of TxL and PRB coals and was equipped with a CS-ESP and wet FGD. Baseline Hg removal was highly variable, ranging from about 5–50%. Since this unit markets its fly ash for reuse, two Hg control technologies designed to preserve ash quality were evaluated during parametric tests: low-ash impact sorbent injection and TOXECON II [22]. During injection upstream of the ESP, the brominated B-PAC and DARCO Hg-LH sorbents performed similarly, with about 90% ACI Hg removal at 2–3 lb MMacf^{-1}. Untreated DARCO Hg also achieved 90% ACI Hg removal with injection at slightly <6 lb MMacf^{-1}. Injection of the "concrete-friendly" C-PAC™ sorbent at about 1.5 lb MMacf^{-1} resulted in ~73% ACI Hg removal. During parametric trials with the TOXECON II configuration, ACI Hg removal was limited to about 60% with DARCO Hg and DARCO Hg-LH injection at about 5–6 lb MMacf^{-1}. Note that DARCO Hg-LH injection into the TOXECON II configuration took place with the unit firing 100% PRB coal. A 2-month continuous injection test was completed with DARCO Hg-LH injection at 2 lb MMacf^{-1}, and results indicated that the project goal of 50–70% ACI Hg removal across the ESP was achieved. In addition, URS was confident that the low DARCO Hg-LH injection rate would not prohibit fly ash reuse.

Another chemically treated ACI technology tested under the NETL Hg Program, ALSTOM Power, Inc.–U.S. Power Plant Laboratories' (ALSTOM–PPLs) Mer-Cure™ process, is unique in that injection takes place in the high-temperature region upstream of the air preheater (APH) and the process employs a proprietary "processor" to prevent chemically treated Mer-Clean™ sorbent agglomeration and to ensure uniform sorbent dispersion [23]. Three 30-day long-term field tests of Mer-Cure were completed at sites equipped with a CS-ESP: (i) PacifiCorp's PRB-fired Dave Johnston Unit 3; (ii) Leland Olds Unit 1; and (iii) Reliant Energy's medium-sulfur (2%) bituminous-fired Portland Station Unit 1. Chemically treated Mer-Clean eight injection rates of 0.63 and 1.4 lb MMacf^{-1} achieved average total Hg removals of 92% and 90% at Dave

Johnston and Leland Olds, respectively. At Portland, about 95% average total Hg capture was observed with chemically treated Mer-Clean 8–21 injection at 8.5 lb $MMacf^{-1}$. The reduced efficiency of the Mer-Clean sorbents at Portland might have been caused by elevated levels of flue gas SO_3, resulting from the combustion of medium-sulfur bituminous coal.

An evaluation of Mer-Cure was completed at LCRA's Fayette Unit 3 in April 2007 [24]. Baseline Hg capture was ~50% across the CS-ESP and wet FGD. ALSTOM–PPL evaluated three sorbents (eSorb™ 11, eSorb™ 13, and eSorb™ 18) designed to preserve fly ash quality, along with Mer-Clean 8, during parametric testing. Excluding eSorb 18, 80% ACI Hg capture was achieved with injection at 0.4–0.5 lb $MMacf^{-1}$. At an injection at about 0.8 lb $MMacf^{-1}$, eSorb 11, and Mer-Clean 8 attained 90% ACI Hg capture. Test results indicate that fly ash remains marketable with eSorb 13 at about 0.5 lb $MMacf^{-1}$ (85% ACI Hg capture).

10.2.8.3 Conventional PAC with Chemical Additives

As an alternative to using chemically treated PAC, NETL also sponsored field tests using conventional PAC supplemented with chemical additives – known as *sorbent enhancement additives* (*SEA*) – applied to the coal and/or flue gas to overcome the poor performance of conventional PAC in low-rank coal applications. Through funding provided by NETL, UNDEERC conducted two 30-day long-term field tests at full-scale units firing North Dakota lignite coal to determine whether SEA coal treatment enhances the performance of untreated ACI at units burning lower-rank coals [18]. Indeed, SEA coal treatment improved the Hg capture efficiency of untreated ACI at both of these field testing sites. During the 30-day trial at Basin Electric's Leland Olds Station Unit 1, 58% average total Hg capture was observed across the CS-ESP with DARCO Hg injection at 2.7 lb $MMacf^{-1}$, coupled with the addition of an aqueous $CaCl_2$ solution to the North Dakota lignite coal at a rate of 2.9 lb $MMacf^{-1}$. UNDEERC also evaluated this advanced, Hg-specific control technology at Basin Electric's Antelope Valley Station Unit 1. Total Hg removal averaged 92% across the SDA/FF configuration with the addition of SEA2 to the North Dakota lignite coal at a rate of 0.033 lb $MMacf^{-1}$ and DARCO Hg injection at 0.81 lb $MMacf^{-1}$.

UNDEERC conducted additional field testing at Montana-Dakota Utilities Company's Montana lignite-fired Lewis and Clark Station that was equipped with a mechanical collector and wet venturi scrubber. Parametric tests evaluated the Hg capture efficiency of SEA1 and SEA2 addition to the coal with and without ACI upstream of the wet venturi scrubber [25]. With SEA1 injection at 600 ppm coal equivalent, about 90% Hg removal was achieved with untreated DARCO Hg injection at 3 lb $MMacf^{-1}$. Slight improvements in performance were observed with higher SEA1 and DARCO Hg injection rates. Ninety percent Hg removal was also observed with SEA2 injection at 100 ppm coal equivalent and DARCO Hg injection at 1 lb $MMacf^{-1}$. Note that in the absence of PAC injection, Hg removal was limited to about 55% with SEA2 injection at 100 ppm coal equivalent.

UNDEERC evaluated PAC and SEA injection, as well as the SEA2 technique 2 (SEA2 T2) technology that involves co-injection of the proprietary SEA2 additive and PAC upstream of the particulate control device. Full-scale field testing was conducted at Kansas City Power & Light's Hawthorn Unit 5 that burns PRB coal and was equipped with an SCR and SDA/FF configuration. During parametric testing at Hawthorne, >90% total Hg capture was achieved with SEA1 added to the coal at 1200 ppm and DARCO Hg-LH injection at 3 lb $MMacf^{-1}$ [26]. With the SEA2 T2 technology, the co-injection of DARCO Hg at 2.8 lb $MMacf^{-1}$ and SEA2 at 0.14 lb/lb of PAC resulted in about 85% total Hg removal.

10.2.8.4 ACI Upstream of a Hot-Side ESP

NETL also evaluated Hg control technologies designed specifically for hot-side electrostatic precipitator (HS-ESP) applications where the elevated flue gas temperature limits the Hg capture efficiency of ACI. A 4-day trial conducted at Duke Energy's low-sulfur bituminous coal-fired Buck Plant achieved ~70% total Hg removal with the injection of Sorbent Technologies' chemically treated H-PAC™ at 10 lb $MMacf^{-1}$ [20]. Sorbent Technologies conducted additional field testing at Midwestern Generation's PRB-fired Will County Unit 3. A high-temperature version of the brominated, "concrete-friendly" C-PAC sorbent was evaluated as fly ash from this unit is marketed for reuse. Using a newly developed X-a-Lance distributing lance design, 73% Hg removal was achieved during a parametric trial with C-PAC injection at 5 lb $MMacf^{-1}$ [27]. During a 6-day continuous test, Hg removal ranged from about 60–73% with C-PAC injection at 5 lb $MMacf^{-1}$.

Under a separate project, ADA-ES evaluated the impact of adding high-temperature liquid sorbents to the pre-combusted coal and/or upstream of the HS-ESP on Hg control at MidAmerican's PRB-fired Louisa Station Unit 1 [28]. While Alstom's brominated KNX coal additive promoted Hg^0 oxidation, the lack of a downstream FGD at this unit led to no increase in Hg removal.

10.2.9 Remaining Technical Issues

Although the development of chemically treated ACI, oxidation additives, and catalysts under NETL's R&D Program has significantly improved the cost and performance of Hg control for coal-based power plants, two primary technical issues remain – impacts on fly ash and sulfur trioxide interference.

10.2.9.1 Impacts on Fly Ash

The typical ACI system is located upstream of a particulate control device to enable simultaneous capture of the spent sorbent and fly ash. This Hg control strategy leads to commingling of the sorbent and fly ash that can prohibit certain fly ash recycling efforts. In 2009, U.S. power plants generated 63 million tons of fly ash, with nearly 25 million tons put to beneficial use. One of the highest-value reuse applications for fly ash is as a substitute for Portland cement in concrete

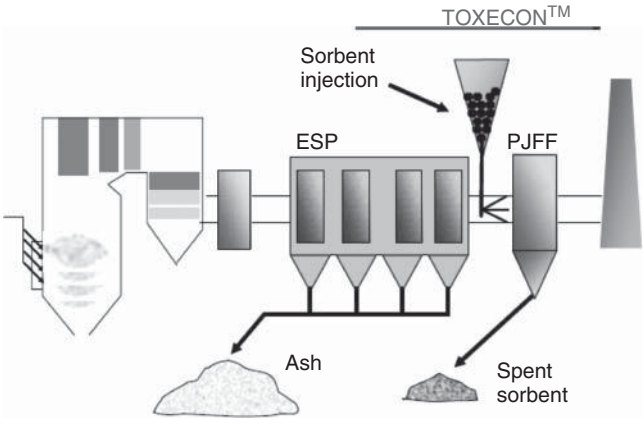


Figure 10.4 EPRI's TOXECON™ process configuration.

production [29]. The utilization of fly ash in concrete production is particularly sensitive to carbon content as well as the surface area of the carbon present in the fly ash.

NETL's Hg control technology portfolio included alternative sorbent injection technologies designed to minimize fly ash carbon contamination caused by ACI upstream of a particulate control device. The TOXECON configuration, developed by EPRI, is designed not to impact fly ash utilization because the ash is removed by an ESP upstream of the sorbent injection location, whereas the spent sorbent is captured by a downstream FF (Figure 10.4). EPRI's TOXECON II technology injects sorbents directly into the downstream collecting field(s) of an ESP. Because the majority of fly ash (~90%) is collected in the upstream ESP fields, only a small portion of the total collected ash contains spent sorbent. During full-scale TOXECON II testing at Entergy's PRB-fired Independence Station Unit 1, DARCO Hg-LH injection at 5.5 lb $MMacf^{-1}$ achieved 90% total Hg removal [30]. A remaining concern with any Hg control strategy involving sorbent injection, particularly the TOXECON II configuration that limits ESP residence time, is the potential for inefficiencies in the existing particulate control system that could trigger New Source Review.

Activated carbon passivated during production can potentially allow coal-fired power generators to continue marketing fly ash commingled with the spent sorbent as a suitable replacement for Portland cement in concrete. Sorbent Technologies conducted a 30-day evaluation of their brominated, "concrete-friendly" C-PAC sorbent at Midwest Generation's PRB-fired Crawford Station Unit 7 [31]. Total Hg removal averaged 81% with C-PAC injection upstream of the ESP at about 4.6 lb $MMacf^{-1}$. A high-temperature version of C-PAC was tested at Midwest Generation's PRB-fired Will County Unit 3 that is equipped with an HS-ESP [32]. During a 6-day continuous test, Hg removal ranged from about 60–73% with C-PAC injection at 5 lb $MMacf^{-1}$. Most importantly, test results indicated that fly

ash collected during C-PAC injection at these sites remained suitable for reuse in concrete production.

During testing at Lower Colorado River Authority's PRB-fired Fayette Unit 3, Alstom evaluated three sorbents (eSorb 11, eSorb 13, and eSorb 18) designed by Envergex to preserve fly ash quality [33]. Results indicated that fly ash remains marketable with eSorb 13 at about 0.5 lb MMacf^{-1} (~85% ACI Hg capture).

10.2.9.2 Sulfur Trioxide Interference

Field testing showed that SO_3 in the flue gas, even at low concentrations, can impede the performance of ACI. It appears that SO_3 competes with Hg for adsorption sites on the sorbent surface, thereby limiting its performance [34]. During field testing at American Electric Power's (AEP's) high-sulfur (3–4%) bituminous-fired Conesville Station Unit 6, total Hg removal was limited to ~30% with chemically treated ACI at 12 lb MMacf^{-1} [35]. Consequently, a long-term field test was not conducted at this unit; instead, NETL evaluated the impact of SO_3 FGC on ACI performance at AmerenUE's PRB-fired Labadie Station Unit 2 [36]. As shown in Figure 10.5, turning the SO_3 FGC system off at Labadie increased total Hg removal from about 50–80% with DARCO Hg-LH injection at 8 lb MMacf^{-1}. Greater than 90% Hg removal was observed with no SO_3 injection and DARCO Hg-LH injection upstream of the APH at about 5 lb MMacf^{-1}. The performance of brominated B-PAC was also impacted by SO_3 FGC at Progress Energy's Lee Station Unit 1 [37]. With B-PAC injection at 8 lb MMacf^{-1}, Hg capture increased from 32% to 82% when SO_3 FGC was idled.

One possible solution to the SO_3 issue that was considered was dual injection of Hg sorbents and alkaline materials. This approach was explored during a field test

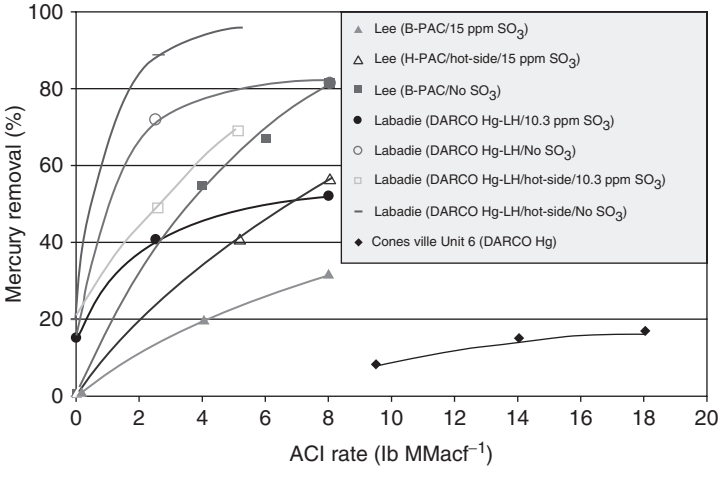


Figure 10.5 Impact of flue gas SO_3 on ACI performance.

at Public Service of New Hampshire Company's Merrimack Station Unit 2 that utilized a cyclone-fired boiler to burn a blend of bituminous coals (~1% sulfur) and is equipped with an SCR system followed by two ESPs in series [38]. During parametric testing, several Hg sorbents were evaluated both with and without the injection of two potential SO_3 mitigation additives – magnesium oxide (MgO) and sodium sesquicarbonate (trona). Results indicated that trona injection enhanced ACI performance to a greater degree than MgO; however, the sodium content of trona could limit fly ash recycling opportunities. Without SO_3 mitigation, Hg removal was limited to about 22% with brominated DARCO Hg-LH injection between the two ESPs at 8 lb $MMacf^{-1}$. During a continuous injection test completed in March 2008, 50% Hg removal was achieved with trona injection upstream of the APH at 500 lb h^{-1} and DARCO Hg-LH injection between the two ESPs at about 4 lb $MMacf^{-1}$.

10.2.10 NETL In-House Development of Novel Control Technologies

In addition to the technologies developed in partnership with private sector companies, researchers from NETL's Office of Research and Development (ORD) also developed and patented technologies for capturing and detecting mercury from coal-based power systems. In one case, ultraviolet light near the wavelength of 254 nm was found to oxidize elemental mercury [39]. The oxidized form of mercury is much more readily removed by the more traditional capture techniques than elemental mercury. This method was unique not only because the photochemical technique enhances the capture of mercury, but also because, as a spinoff, it can be used as the basis for mercury detection. Another patented technique that had been developed uses a lance or "thief" to extract a partially combusted coal from the combustion section of a pulverized coal-fired combustor [40]. This material acts very similarly to that of activated carbon and will remove mercury when injected into the flue gas ductwork. Not only can the thief process be used to capture mercury, the carbon-based material itself, and a few other materials were also found able to catalytically convert elemental mercury to the oxidized form.

Recognizing the need for a low-cost technique to remove Hg from coal-based integrated gasification combined cycle (IGCC) power plants, ORD researchers invented a new palladium (Pd)-based sorbent that works on fuel gas at elevated temperatures [41]. IGCC plants will be affected by the new mercury regulation. Although electricity in the United States is primarily a product of combusting coal, IGCC may be the power generation method in the future if mitigation of the greenhouse gas carbon dioxide is imposed on the power industry. Unlike conventional sorbents such as activated carbon, which operate at a lower temperature, high-temperature Pd sorbents remove Hg and arsenic at temperatures above 500 °F, resulting in a major improvement in overall thermal energy efficiency of the IGCC power process.

10.2.11 Hg Control Technology Commercial Demonstrations

A key component of the overall success of NETL's Hg Program was the full-scale commercial demonstration of Hg control technology under DOE's Clean Coal Power Initiative (CCPI). CCPI was part of DOE's Major Demonstration Program directed at accelerating advanced coal technology adoption, thus rapidly moving promising new concepts to a point where private-sector decisions on deployment could be made.

In the first project, EPRI's TOXECON was selected for demonstration on a 270-MW slipstream at We Energies' Presque Isle Power Plant in Marquette, Michigan. During initial operation in 2006, the TOXECON configuration maintained >90% total Hg removal for 48 consecutive days. Sorbent injection rates of about 1.7 and 1.2 lb $MMacf^{-1}$ were required to achieve at least 90% total Hg removal with untreated DARCO Hg and brominated DARCO Hg-LH, respectively [42]. Over a 3-year demonstration period (2006–2009), We Energies consistently demonstrated more than 90% Hg removal based on monthly averages while maintaining acceptable baghouse pressure drops of 5–6 in. of water and providing significant opacity improvements. The TOXECON installation at Presque Isle cost $128 per kilowatt (kW) and increased the cost of electricity by about 0.3–0.5 cents kWh^{-1} [43].

In the second project, NeuCo, Inc., a developer of power plant control and optimization technologies, demonstrated the capability to optimize Hg speciation and control Hg emissions from an existing power plant. This demonstration took place at an 890 MW utility boiler in Jewett, Texas, that was completed in 2010 and is owned by NRG Energy. NeuCo utilized state-of-the-art sensors and neural, network-based optimization and control technologies to maximize the proportion of Hg^{2+} species in order to increase the rate of co-benefit Hg capture. Artificial intelligence and simulation technologies were used to control and optimize appropriate operational parameters. Critical sensing devices were added to the unit to monitor inputs and emissions from the plant. Data from these sensors was analyzed by the neural network to optimize plant operations, while simultaneously minimizing Hg emissions [44].

10.2.12 Mercury Control Cost Estimates

NETL has conducted in-depth economic analyses for both ACI and wet FGD enhancement technologies for Hg control, based on the results of its field testing program. The increase in cost resulting from Hg control via ACI is primarily determined by annual PAC consumption costs that are dependent on the required ACI rate, delivered PAC price, and the volume of flue gas being treated. Chemical composition also affects PAC price since manufacturers charge a higher price for chemically treated PAC to offset the additional production costs required to alter the sorbent's molecular structure. The ACI rate required to achieve a given level

of Hg control can be impacted by a host of plant-specific dynamics, including, but not limited to, Cl and sulfur contents of the coal being burned, APCD configuration, flue gas temperature, boiler efficiency, UBC content of the fly ash, and ductwork geometry in proximity to the ACI location.

10.2.12.1 Economic Analyses for ACI

In 2003, NETL prepared an economic assessment of ACI with untreated PAC based on the results of its Phase I field testing program [45]. The report developed "study-level" costs for Hg control using ACI at representative 500 MW bituminous- and subbituminous-fired power plant units equipped with an existing CS-ESP. Costs were estimated for ACI into an existing CS-ESP, as well as a TOXECON configuration. The cost estimates were developed for equipment designed to achieve Hg control at low (50%), mid-range (60–70%), and high (90%) levels. It is important to note that the costs developed here were based on the current state of knowledge and understanding of ACI technology at three of the Phase I field test sites. The incremental cost of Hg control for this analysis, excluding impact to fly ash sales and disposal practices, was estimated to range from $33 000/lb Hg removed to $131 000/lb Hg removed for the bituminous-fired unit, and from ~$18 000/lb Hg removed to $55 000/lb Hg removed for the subbituminous-fired unit.

A follow-up NETL economic analysis released in May 2007 indicated that the high Hg capture efficiency of chemically treated sorbents drastically reduced the estimated cost of Hg control due to the lower injection rate required to achieve a given level of control that offsets the higher cost of these treated sorbents [46]. As shown in Figure 10.6, the 20-year levelized incremental cost of 90% ACI Hg control ranged from about $30 000 to <10 000/lb Hg removed (without considering impacts on CUBs) for seven of NETL's field testing sites where chemically treated ACI was evaluated. The May 2007 report provides "study-level," plant-specific cost estimates and gives NETL a gage to measure its success in achieving the target of reducing the baseline Hg control cost estimate of $60 000/lb Hg removed by 25–50%.

10.2.12.2 Economic Analyses for Wet FGD Enhancement

In May 2008, NETL released a report that provided cost estimates for technologies developed to enhance co-benefit Hg capture for wet FGD systems [47]. The report provides "study-level" cost estimates for two such technologies: fixed-bed Hg^0 oxidation catalysts, and coal treatment with a $CaBr_2$ solution. The economics were developed for an average Hg control level of 73% at "representative" 500 MW units burning three types of low-rank coal: North Dakota lignite, PRB subbituminous, and a blend of 50% TxL and 50% PRB subbituminous coals. The report estimated an incremental cost of control <$17 000 per pound of Hg removed ($/lb Hg removed) using the Hg^0 oxidation catalysts. Addition of $CaBr_2$ solution at an injection rate of about 5.90 lb h^{-1} was required to achieve 73% total Hg removal at the "representative" PRB-fired unit equipped with an SCR, resulting in a cost of $2200/lb Hg removed. Without an SCR in-service, a $CaBr_2$ injection rate of

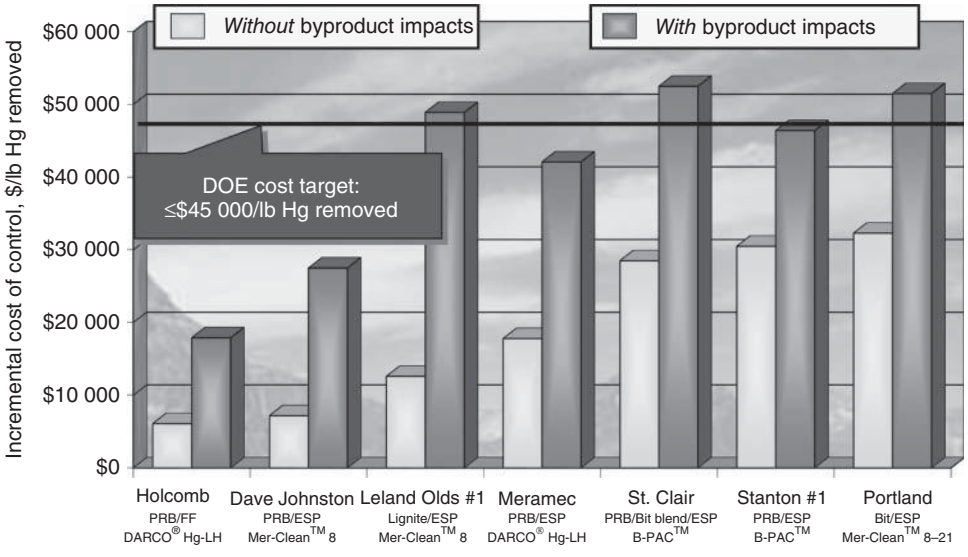


Figure 10.6 Six-year levelized incremental cost of 90% Hg control with chemically treated ACI.

322 lb h^{-1} was required to achieve the same level of control and the levelized costs rise to $21 200/lb Hg removed.

10.2.13 Coal Utilization Byproducts (CUB) R&D Program

In addition to developing cost-effective control technologies for coal-fired power plants, NETL's program also investigated the potential implication of Hg control on the use and disposal of CUB [48, 49]. CUB are the solid materials resulting from the combustion of coal and the removal of air pollutants from coal-based flue gas that include bottom ash, fly ash, boiler slag, and FGD gypsum. U.S. power plants produced 134.7 million tons of CUB in 2009, with nearly 42% put to beneficial use in applications such as concrete, flowable fill, road base, snow and ice control, blasting grit, fertilizer, and wallboard [29]. Put another way, this was 56 million tons of material that did not have to be landfilled or placed in an impoundment.

The CUB research was directed at better understanding the transfer and ultimate fate of Hg and other trace metals from the flue gas to the power plant's solid and liquid effluent streams as a result of implementing Hg control systems. Although the NETL CUB program was ended in 2008, it was determined that DOE had successfully achieved its goal of bringing efficient, cost-effective Hg control technologies to commercial readiness and that further research into the fate of Hg and other trace metals in fly ash, scrubber solids, and other byproducts should be carried out by the private sector.

ACI Hg control leads to commingling of the PAC and fly ash that can prohibit certain fly ash recycling efforts. As part of the economic analyses noted above

[42, 43], NETL evaluated the 20-year levelized costs of Hg control both with and without the inclusion of byproduct impacts. The analyses assumed that for units equipped with a CS-ESP, the utility was able to sell all fly ash collected in the ESP hoppers for $18/ton prior to ACI. Following installation of an ACI system, it was assumed that the fly ash could no longer be sold; instead, the utility must pay $17/ton for non-hazardous fly ash disposal. For an SDA/FF system, it was assumed that solids that were given away prior to ACI would have to be disposed of at a price of $17/ton (non-hazardous). Using these assumptions, NETL estimated that the cost for Hg control, with chemically treated ACI and accounting for the cost of byproduct disposal, ranged from $52 500/lb Hg removed to $17 900/lb Hg removed for seven of NETL's field testing sites, as shown in Figure 10.6.

While CUB were, and still are, regulated as non-hazardous under the Resource Conservation and Recovery Act, EPA is considering alternative regulatory approaches for CUB, including a hazardous designation due in part to concerns over the partitioning of Hg to these materials. Such a designation would significantly increase the cost of Hg control because the cost of hazardous waste disposal can be more than five times more expensive than non-hazardous disposal. Therefore, it was extremely important to evaluate the potential for leaching and volatilization of Hg and other trace metals from CUB to the environment as part of the NETL Hg Program.

10.2.14 Determining the Fate of Hg in FGD Byproducts

NETL's ORD conducted research directed at determining the fate of Hg in FGD materials [50]. This activity focused on Hg stability during FGD gypsum drying, Hg stability during wallboard production using FGD gypsum, Hg leachability from FGD gypsum, and the Hg-binding phase in FGD gypsum. The stability of Hg during FGD gypsum drying was studied by collecting samples before and after natural gas-fired heating that reduces the moisture content of the FGD solids for ease of handling during the wallboard manufacturing process. Results indicated that within analytical precision, no Hg desorbed during the drying process.

The stability of Hg in FGD gypsum during wallboard production was also analyzed by collecting samples of FGD gypsum feedstock and the corresponding wallboard products from five wallboard manufacturing plants. The Hg present in the unprocessed FGD gypsum and the finished wallboard product ranged from 0.04 to 1.5 ppm on a dry basis. The quantity of Hg retained in the finished wallboard product varied, with three samples showing nearly complete Hg retention during the wallboard manufacturing process. For the other two samples, Hg losses were 12% and 58%, suggesting that the quantity and thermal stability of Hg in FGD gypsum and wallboard depends on the origin of the gypsum and/or the nature of processing.

Research was also performed using FGD slurry samples in an attempt to isolate the Hg-binding phase from bulk gypsum. During settling, Hg partitioned almost exclusively to the top, slower-settling layer of the FGD slurry. Analysis of this

residue revealed that both Hg and iron (Fe) were enriched in the top layer by factors of about 20 and 10, respectively. Meanwhile, Hg was not mobilized during FGD slurry leaching experiments using a continuous, stirred-tank extractor. This is indicative of a strong chemisorption rather than physical adsorption of Hg. As a result, it is believed that Hg sequestered in FGD gypsum is primarily bound to an iron-rich phase, such as iron-coated clay materials or iron oxide/hydroxide particles, probably introduced with the limestone used as the FGD reagent. Additional research [51] also showed that some Hg retained in FGD gypsum requires hydrogen peroxide oxidation for release, such as a phase containing sulfides or carbonaceous materials.

Leach testing was also used to evaluate the impacts of pH and oxidation–reduction potential (ORP) on Hg mobility in FGD byproducts. Leaching of six FGD materials to pH > 2 under aerobic conditions failed to mobilize appreciable amounts of Hg. While no Hg was released to the leachate during experiments with pH > 4 and ORP > 100 mV, dissolution of the major immobilized form of Hg was complete with pH < 1 and an ORP of ~350 mV. Consequently, ORD researchers concluded that the Hg-retaining phase will immobilize Hg in many reuse applications, with one possible exception being placement in mine-land reclamation areas where the FGD byproducts could be exposed to acidic, anaerobic conditions.

As part of NETL's CUB research, the Tennessee Valley Authority (TVA) evaluated Hg retention in FGD gypsum from three sources: an Hg-amended commercial calcium sulfate, a laboratory-scale wet FGD system, and a full-scale wet FGD system [52]. TVA researchers concluded that no Hg would evolve from disposed FGD byproducts up to a maximum temperature of 140 °F, although thermal desorption of Hg from FGD gypsum did occur at ~400 °F.

USG Corporation provided data on the extent and location of Hg loss during the wallboard production process, and also provided information on the potential for Hg leaching at the end of the wallboard life cycle, when it is disposed in municipal landfills [53]. FGD gypsum evaluation tests from six different power plant/FGD feedstock variations were completed to investigate the impact of different configurations on the stability of Hg during wallboard production. Testing included the use of FGD gypsum produced during TMT-15 injection into a power plant scrubber. Test results indicated that use of fines blowdown in wet FGD systems significantly reduced Hg content in the FGD gypsum. For FGD gypsum generated without fines blowdown, Hg loss amounted to <8%, while tests using FGD gypsum from power plants employing fines blowdown indicated Hg loss of 46–55%.

10.2.15 Determining the Fate of Hg in Fly Ash

NETL awarded a contract to Frontier Geosciences, Inc. (Frontier) to conduct independent laboratory analysis of CUB generated during NETL's Phase II full-scale Hg control technology field testing program [54]. The purpose of the independent

laboratory analysis was to ensure accurate and consistent laboratory procedures were used to determine the environmental fate of Hg in CUB. NETL's ORD also conducted in-house leaching experiments with fly ash collected from ACI field testing sites.

The Frontier work included leaching studies using the Synthetic Precipitation Leaching Procedure (SPLP, EPA Method 1312); low-temperature (40 °C for 30 days), medium-temperature (190 °C for 1 h), and high-temperature (900–1200 °C for 5 min) Hg volatility tests; microbial methylation experiments; and halide analysis. The SPLP results indicated that little to no Hg would be released under normal disposal conditions. In addition, Hg bound to PAC sorbents, particularly those that were chemically treated, appeared to be more stable than the UBC-bound Hg. During the low-temperature volatility tests, essentially no Hg was emitted from the fly ash samples. Thermal desorption of Hg was observed during the medium- and high-temperature volatility tests conducted by Frontier.

A pure culture of sulfate-reducing bacteria known to methylate Hg or produce methyl-mercury, was monitored over a 30-day period to assess the methylation potential of Hg present in CUB. Results from this "worst-case-scenario" microbial mobilization study indicated an increase in methyl-mercury production. However, microbial activity also stabilized a number of target metals.

NETL's ORD researchers also conducted leaching experiments on the Phase II byproducts using the modified SPLP, the NETL Serial Batch Leaching Procedure (SBLP), and NETL Column Leaching on a select number of sample pairs. During a 5-month continuous column experiment using four leachants, water (pH = 5.7), dilute sulfuric acid (pH = 1.2), dilute acetic acid (pH = 2.9), and sodium carbonate (pH = 11.1) [55], the PAC/ash mixtures were generally found to effectively immobilize the captured Hg over a range of laboratory conditions. Overall, very little of the Hg (always below 0.5% and often under 0.1%) contained in the ash samples was solubilized during leaching. Neither the pH nor the nature of the anion had a noticeable effect on the leachate Hg.

Not only have the Hg control technologies demonstrated capture of Hg that would otherwise be released into the environment, but the Hg has generally been shown to be retained in the control technology byproducts under conditions of laboratory leaching tests. For some of these materials, the tests performed show these control technology byproducts, in spite of their higher Hg content, to be environmentally more stable with respect to Hg release than the corresponding baseline ashes of lower Hg content [56].

10.3 Summary

Working closely with key stakeholders, NETL's Hg RD&D program successfully brought Hg control technology from what was a concept in the early 1990s to a commercial product by 2008. As of June 2010, nearly 150 full-scale ACI systems,

a signature technology of the NETL Hg R&D Program, have been ordered by U.S. coal-fired power generators [57]. These contracts represent more than 56 GW of coal-fired electric generating capacity. This includes ~43 GW of existing capacity (almost 15% of total U.S. coal-fired capacity) that will be retrofit with ACI systems to control Hg emissions. EPA projects that 146 GW of ACI will be installed on U.S. power plants by 2015 in order to comply with proposed Federal Hg regulations [1].

The ACI systems have the potential to remove up to 90% or more of the Hg in many, but not all, applications based on results from NETL's field testing program, at a cost estimated to be as low as $10 000/lb Hg removed in some situations. However, although the results achieved during NETL's field tests met or exceeded the program goals, only through experience gained during long-term continuous operation of these advanced technologies in a range of full-scale commercial applications will their actual costs and performance be determined.

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11
U.S. EPA Research Program

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11.1
Introduction

The U.S. Environmental Protection Agency (EPA) has maintained a broad research program examining the emissions and control of hazardous air pollutants (HAPs), including mercury, from stationary sources. The EPA has also maintained research programs studying the fate and transport of mercury and the resulting impacts, including health impacts, on the environment. There is considerable documentation of the studies of the fate and transport and the resulting effects of mercury on the environment. This section focuses exclusively on the EPA research program dealing with emissions of mercury from coal combustion. This work includes studies that were mandated by Congress to evaluate the emissions and hazards of mercury emissions from fossil-fuel-fired electricity generating units. It also includes fundamental work focused on development and evaluation of control technologies for mercury control. The EPA has also conducted considerable and significant work on the fate of mercury and other toxic metals in coal combustion residuals (CCRs) and other process effluents. That work is summarized in full in another section. The EPA has also played a leading role in the development and testing of technologies and techniques for continuous measurement and monitoring of mercury emissions in the very low concentrations (parts per trillion) and in the harsh environments that are seen in typical coal combustion flue gas streams. That work is also summarized in another section and is thus not covered here.

11.2
Congressionally Mandated Studies

In the 1990 Clean Air Act (CAA) amendments, Congress established a specific structure for determining whether to regulate HAP emissions from electric generating units (EGUs). Congress required that various reports concerning HAP emissions from EGUs be completed.

Mercury Control: for Coal-Derived Gas Streams, First Edition.
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The first report, the Utility Study, required the EPA to evaluate the hazards to public health reasonably anticipated to occur as the result of HAP emissions from EGUs after imposition of the requirements of the CAA. The EPA issued the Utility Study, which included numerous analyses, in February 1998. The EPA first collected HAP emissions test data from 52 EGUs, including a range of coal-, oil-, and natural-gas-fired units. The test data along with facility specific information were used to estimate HAP emissions from all 684 utility facilities. The EPA determined that 67 HAPs were potentially emitted from fossil-fuel-fired EGUs.

The EPA evaluated exposures, hazards, and risks due to HAP emissions from coal-, oil-, and natural-gas-fired EGUs. The EPA conducted a screening-level assessment of all 67 of the potentially emitted HAPs to prioritize the pollutants for further analysis. A total of 14 were identified as priority HAPs that would be further assessed. Twelve HAPs (arsenic (As), beryllium (Be), cadmium (Cd), chromium (Cr), manganese (Mn), nickel (Ni), hydrochloric acid (HCl), hydrofluoric acid (HF), acrolein, dioxins, formaldehyde, and radionuclides) were identified as priority pollutants for further assessment based on inhalation exposure and risk. Six HAPs (Hg, radionuclides, As, Cd, Pb, and dioxins) were considered a priority for multipathway assessment of exposure and risk. On the basis of the multipathway assessments, the EPA determined that Hg from coal-fired EGUs was the HAP of greatest potential concern.

The second report directed the EPA to "conduct a study of mercury emissions from EGUs, municipal waste combustion units, and other sources, including area sources." This is referred to as the *Mercury Study*. In conducting the Mercury Study, Congress directed the EPA to "consider the rate and mass of emissions, the health and environmental effects of such emissions, technologies which are available to control such emissions, and the costs of such technologies." The EPA issued the Mercury Study in December 1997. The Mercury Study assessed the magnitude of U.S. Hg emissions by source, the health and environmental implications of those emissions, and the availability and cost of control technologies.

The last required report was to be completed by the National Institute of Environmental Health Sciences (NIEHS). Congress directed NIEHS to conduct "a study to determine the threshold level of Hg exposure below which adverse human health effects are not expected to occur." In conducting this study, NIEHS was to determine "a threshold for mercury concentrations in the tissue of fish which may be consumed (including consumption by sensitive populations) without adverse effects to public health." In addition, Congress, in the conference report language associated with EPA's fiscal year 1999 appropriations, directed the EPA to fund the National Academy of Sciences (NAS) to perform an independent evaluation of the available data related to the health impacts of methyl mercury (MeHg). Specifically, NAS was tasked with advising the EPA as to the appropriate reference dose (RfD) for MeHg, which is the amount of a chemical which, when ingested daily over a lifetime, is anticipated to be without adverse health effects to humans, including sensitive subpopulations.

The EPA completed the Mercury Study and the Utility Study by 1998. The NIEHS study was completed in 1995, and the NAS study was completed in 2000.

In December 2000, after considering public input, the results of the required studies described and other relevant information, including Hg emission data from EGUs, EPA determined that it was appropriate and necessary to regulate EGUs under CAA Section 11.2.

11.3 Control Technology from Work on Municipal Waste Combustors (MWCs)

There has been significant public and scientific concern over the risks of air pollution emissions from municipal waste combustors (MWCs). Historically, the primary pollutants of concern have been dioxins/furans (e.g., polychlorinated dibenzo-*p*-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs)), and mercury (Hg). The potential emissions of each of these toxic pollutants can vary considerably depending on the composition of the waste and the control technologies used. The EPA conducted work in the mid-1990s to examine the effectiveness of typical air pollution control (APC) technologies for mitigation of emissions of PCDDs/PCDFs and Hg from MWC [1]. Much of this knowledge was later applied to the initial development and testing of similar controls for mercury emissions from coal-fired electricity generating units. EPA researchers noted that powdered activated carbon (PAC) can be injected into MWC flue gas to reduce Hg emissions from SD/FF (spray dryer/fabric filter) and SD/ESP (electrostatic precipitator) systems and that it can also be used to improve PCDD/PCDF capture in these systems. The researchers also identified fundamental Hg properties that affect capture in flue gas cleaning equipment.

EPA researchers also conducted bench-scale experiments under conditions simulating MWCs and coal-fired units to study Hg capture by dry sorbents, including PAC [2]. The focus of the work was specifically to evaluate the effects of reaction temperature on the capture of different Hg species (Hg^0 and Hg^{2+}) by various types of dry sorbents.

Ghorishi *et al.* [3] followed with tests designed to better understand the transformation of mercury species (elemental and oxidized forms) in stationary waste combustion sources. Elemental mercury (Hg^0) poses a challenging flue gas control issue, and oxidized forms of mercury (Hg^{2+}) are of concern because of the potential for local deposition. Gas-phase studies indicated that homogeneous oxidation of Hg^0 in the presence of hydrogen chloride (HCl) is slow, proceeding at measurable rates only at temperatures >700 °C and with HCl concentrations of 100 ppm or more. The effect of fly ash composition on heterogeneous Hg^0 oxidation was investigated using a fixed-bed reactor containing different synthetic model fly ash components such as alumina (Al_2O_3), silica (SiO_2), ferric oxide (Fe_2O_3), copper oxide (CuO), and calcium oxide (CaO). The transition metal oxides, CuO and Fe_2O_3, exhibited significant catalytic activity in the surface-mediated oxidation of Hg^0 in the presence of HCl. This was suggested to be possibly caused by the Deacon process in which chlorine gas (Cl_2) is produced via catalytic oxidation of HCl over these two oxides. The researchers also studied the effect of the sulfur dioxide

to HCl ratio (SO_2 : HCl) on Hg^0 oxidation. The addition of SO_2 to the moist flue gas at high SO_2 : HCl ratios (from 10 : 1 to 4 : 1) caused a notable decrease in oxidation of Hg^0. This was attributed to a scavenging effect of SO_2 and H_2O on Cl_2. Addition of CaO to the synthetic fly ashes also caused a drop in Hg^0 oxidation – likely due to the neutralization of HCl by reaction with CaO.

11.4 Mercury Chemistry, Adsorption, and Sorbent Development

Most of the larger scale mercury control demonstration projects have been sponsored or cosponsored by the Department of Energy (DOE), by the Electric Power Research Institute (EPRI), and by the electric utilities. By contrast, the EPA focused its research efforts on smaller scale experimental work with the goal of better understanding the fundamental aspects of mercury control.

Much of the early work originated from results obtained from studies aimed at controlling organic emissions and mercury from MWCs (as just described). Other work looked at sorbent injection technology to reduce emissions of trace air toxic metals (including Hg) from coal combustion facilities. Gullett and Raghunathan [4] conducted pilot-scale tests of high-temperature furnace injection using hydrated lime, limestone, kaolinite, and bauxite sorbents. They found that the impact of sorbent injection on trace metal emissions is a function of metal type, sorbent type, and injection mode. Reductions in submicron concentrations of antimony, arsenic, mercury, and selenium were observed when hydrated lime and limestone were injected.

Krishnan *et al.* [5] studied the mechanisms and rate of elemental mercury (Hg^0) capture by activated carbons using a bench-scale apparatus. Three types of activated carbons were chosen to study the effects of surface area, sorption temperature (from room temperature to 140 °C), and varying Hg^0 concentration. The results suggested the sorption mechanism to be a combination of physisorption and chemisorption at lower temperature and primarily via chemisorption at 140 °C.

Additional bench-scale experiments were conducted in a flow reactor to simulate entrained-flow capture of elemental mercury (Hg^0) by activated carbon [6, 7]. Mercury adsorption by several commercial activated carbons was examined at different carbon-to-Hg mass ratios, particle sizes, Hg^0 concentrations, and temperatures (from room temperature to 250 °C). Increasing the carbon-to-Hg mass ratio increased mercury removal in some cases and capture increased with a decrease in the particle size of the sorbent.

Efforts were made to use detailed chemical models to better understand and explain mercury reaction and control mechanisms in a coal combustion flue gas environment. Mercury speciation in combustion-generated flue gas was modeled using a detailed chemical mechanism consisting of 60 reactions and 21 species [8]. The model confirmed a strong sensitivity to reaction temperature. Starting

with pure HCl, at higher reactor temperatures (more than 630 °C), model predictions were in good agreement with experimental data. But, at lower reactor temperatures, the model tended to underpredict Hg chlorination compared with experimental data, indicating that Hg oxidation at lower temperatures is dominated by heterogeneous mechanisms.

EPA researchers also conducted considerable bench-scale work to understand binding mechanisms of mercury on activated carbon sorbents. Li *et al.* [9] conducted experiments to examine the effect of surface moisture on low-temperature Hg adsorption on activated carbons. A bituminous coal-based activated carbon and an activated carbon fiber were tested for Hg^0 adsorption capacity. Tests showed that Hg^0 adsorption decreased considerably when the sorbent moisture was removed by heating at 110 °C before the adsorption experiments. These observations suggested that moisture contained in activated carbons may play an important role in retaining Hg^0 under these conditions. This effect of moisture on Hg adsorption was observed for both carbon sorbents, despite extreme differences in their ash contents. Temperature programmed desorption (TPD) experiments performed on the two mercury-containing carbons indicated that chemisorption of Hg is the predominant process over physisorption for the moisture-containing samples. The nature of the mercury binding on the carbon surface was examined by X-ray absorption fine structure (XAFS) spectroscopy. XAFS results provided evidence that mercury binding on the carbon surface was associated with oxygen. The results of the study suggested that surface oxygen complexes provide the active sites for mercury binding. The adsorbed H_2O is closely associated with surface oxygen complexes and the removal of the H_2O from the carbon surface by low-temperature heat treatment reduces the number of active sites that can chemically bind Hg^0 or eliminates the reactive surface conditions that favor Hg^0 adsorption.

Li *et al.* [10] studied the effect of varying physical and chemical properties of activated carbons on adsorption of elemental mercury (Hg^0) by treating two activated carbons to modify their surface functional groups and pore structures. Heat treatment (to 927 °C) in nitrogen (N_2), air oxidation (at 420 °C), and nitric acid treatment (6 N HNO_3) of two activated carbons were conducted to vary their surface oxygen functional groups. Adsorption experiments of Hg^0 by the activated carbons were conducted using a fixed-bed reactor at a temperature of 125 °C and under a N_2 atmosphere. The pore structures of the samples were characterized by N_2 and carbon dioxide (CO_2) adsorption. TPD and acid–base titration experiments were conducted to determine the chemical characteristics of the carbon samples. Characterization of the physical and chemical properties of activated carbons in relation to their Hg^0 adsorption capacity can provide important mechanistic information on Hg^0 adsorption. The results suggested that oxygen surface complexes, possibly lactone and carbonyl groups, are the active sites for Hg^0 capture. The carbons having a lower carbon monoxide (CO)/CO_2 ratio and a low phenol group concentration tended to have a higher Hg^0 adsorption capacity, suggesting that phenol groups may inhibit Hg^0 adsorption. The high Hg^0 adsorption capacity of one carbon sample was also found to be associated with a low ratio of

the phenol/carbonyl groups. The EPA concluded that a possible Hg^0 adsorption mechanism may involve an electron-transfer process in which the carbon surfaces act as an electrode for Hg^0 oxidation.

11.4.1 Halogenated Activated Carbon Sorbents

Ghorishi *et al.* [11] conducted studies in an effort to discern the role of an activated carbon's surface functional groups on the adsorption of Hg^0 vapor and gaseous mercuric chloride ($HgCl_2$). The results demonstrated that chlorine (Cl) impregnation of a virgin activated carbon using dilute solutions of HCl leads to increased (by a factor of 2–3) fixed-bed capture of these mercury species. A commercially available activated carbon was Cl impregnated and tested for entrained flow, short-time-scale capture of Hg^0. In the entrained-flow reactor, the chlorine-impregnated powdered activated carbon (Cl-PAC) was introduced in Hg^0-laden synthetic flue gases (containing 86 ppb of Hg^0) of varying compositions with gas/solid contact times of about 3–4 s. The results indicated significant Hg^0 removal (80–90%), compared to virgin activated carbon (10–15% Hg removal). These levels of Hg^0 removal were observed across a wide range of very low carbon-to-Hg weight ratios. Variation of the natural gas combustion flue gas composition, by doping with nitrogen oxides and sulfur dioxide, and the flow reactor temperature (ranging from 100 to 200 °C) had minimal effect on Hg^0 removal by the Cl-PAC in the studied carbon-to-Hg weight ratios. The results demonstrated significant enhancement of activated carbon reactivity with minimal halogen treatment.

Brominated powdered activated carbon (Br-PAC) sorbents have been shown to be quite effective for Hg capture when injected into the flue gas duct at coal-fired power plants and are especially useful when burning western subbituminous and other low-chlorine coals. Hutson *et al.* [12] used X-ray absorption spectroscopy (XAS) and X-ray photoelectron spectroscopy (XPS) to determine information about the speciation and binding of Hg on two commercially available brominated activated carbons. The results were compared with similar analysis of a conventional (nonhalogenated) and chlorinated activated carbon. Both the XAS and XPS results indicated that the Hg, although introduced as elemental vapor, was consistently bound on the carbon in an oxidized form. The conventional and chlorinated activated carbons appeared to contain mercury bound to chlorinated sites and possibly to sulfate species that have been incorporated onto the carbon from adsorbed SO_2. The Hg-containing brominated sorbents appeared to contain Hg bound primarily at bromination sites. The researchers concluded that the mechanism of capture for the sorbents likely consists of surface-enhanced oxidation of the Hg^0 vapor via interaction with surface-bound halide species with subsequent binding by surface halide or sulfate species.

With the use of halogenated PACs, concerns were raised about the potential for these PACs to assist in the formation and emission of brominated and/or chlorinated dioxins and furans. To evaluate this, Hutson *et al.* [13] conducted

sampling campaigns at two U.S. DOE demonstration sites where Br-PAC was being injected for control of mercury emissions. The results of the studies showed that injection of the Br-PAC upstream of the ESP did not increase the emissions of total and Toxic EQuivalent (TEQ) chlorinated and brominated dioxin compounds. Rather, the data suggested that the sorbent may capture these compounds and reduce their concentration in the flue gas stream. This effect, when seen, was small, and independent of the type of plant emission controls, temperature at the point of injection, or fuel-chlorine content. The addition of the brominated-PAC sorbent resulted in slight increases in the total content of chlorinated dioxins and furan in the particulate matter (ash) collected in the ESP, but did not increase its overall toxicity.

11.4.2 Non-Carbonaceous Sorbents

Efforts to develop multipollutant control strategies have demonstrated that adding certain oxidants to different classes of Ca-based sorbents leads to a significant improvement in elemental Hg vapor (Hg^0), SO_2, and NO_x removal from simulated flue gases. Ghorishi *et al.* [14] studied the multipollutant capacity of two classes of Ca-based sorbents (hydrated limes and silicate compounds). A number of oxidizing additives at different concentrations were used in the Ca-based sorbent production process. The Hg^0, SO_2, and NO_x capture capacities of the oxidant-enriched sorbents were evaluated and compared to those of a commercially available activated carbon in bench-scale fixed- and fluidized-bed experimental systems. Calcium-based sorbents prepared with two unspecified oxidants exhibited Hg^0 sorption capacities ($-100\,\mu g\,g^{-1}$) comparable to that of the activated carbon; and they showed far superior SO_2 and NO_x sorption capacities.

Meyer *et al.* [15] studied the use of copper-doped Fe nanoaggregates silanized with organic sulfur as bis-(triethoxy silyl propyl)tetrasulfide for the capture of Hg^0 vapor for potential power plant applications. Silanization procedures resulted in 70% deposition of the targeted sulfur level, with particles containing ~4 wt% S. The addition of copper was found to increase the fixed-bed (total) capacity of the sorbent from $170 \pm 20\,\mu g$ Hg/g-sorbent with no copper doping to $2730 \pm 80\,\mu g$ Hg/g-sorbent at 1.2 wt% Cu loading. When no S was deposited, the capacity of Fe/Cu nanoaggregates was only 180 μg Hg/g-sorbent. The findings suggested that a combined Cu–S mechanism is responsible for Hg capture using these sorbents. Moving-bed (injection) testing of the Fe-based sorbents in a simulated flue gas stream showed that the 1.2 wt% Cu sample was able to achieve significant removal of Hg.

Meyer *et al.* [16] conducted additional work to examine the use of Cu–S sites for Hg capture from the gas phase for a silica-based platform using an S4 organic polysulfane and copper sulfate. The maximum fixed-bed equilibrium capacity achieved when using these materials was for a sorbent material with 2.5 wt% Cu and 6 wt% S. When compared to two other platforms, commercially available brominated-PAC and the previously tested Fe–Cu–S4 nanoaggregates, the Si-1

material performed the best in fixed-bed testing. During entrained-flow testing, the performance of Si-1 was only diminished 10% when exposed to 20 ppm SO_3, an encouraging result for flue gas applications where SO_3 levels range from 1 to 40 ppm.

Hutson and Attwood [17] studied Hg capture using adsorbent material derived from the bauxite residue (red mud) from two North American aluminum refineries. The red mud, a seawater-neutralized red mud, and an acid-treated red mud were evaluated for their mercury adsorption capacity and compared with other, more conventional sorbent materials. Two different seawater-neutralized red mud samples were treated with HCl and HBr in an effort to increase the mercury sorption capacity. In all cases, the acid treatment resulted in a significant increase in the total surface area and an increase in the total pore volume. The fixed-bed mercury capture experimental results showed that the HBr activation treatment was effective in increasing the mercury capture performance of both sorbent samples. The HCl treatment, however, had no effect on the mercury capture performance; and entrained-flow experiments revealed that the bromine-containing red mud sorbent was much less effective for in-flight mercury capture.

11.4.3 Mercury Control in a Wet-FGD Scrubber

Experimental data from a laboratory-scale wet scrubber simulator confirmed that oxidized mercury, Hg^{2+}, can be reduced by aqueous S(IV) (sulfite and/or bisulfite) species and result in elemental mercury (Hg^0) emissions under typical wet flue gas desulfurization (FGD) scrubber conditions [18]. The S(IV)-induced Hg^{2+} reduction and Hg^0 emission mechanism was described by a model which assumed that only a fraction of the Hg^{2+} can be reduced, and that the rate-controlling step of the overall process is a first-order reaction involving the Hg–S(IV) complexes. Experimental data and model simulations predicted that Hg^{2+} in the flue gas can cause a rapid increase of Hg^0 concentration in the flue gas across a wet-FGD scrubber. The researchers also noted that forced oxidation enhanced Hg^{2+} reduction and Hg^0 emission by decreasing the S(IV) concentration in the scrubbing liquor. The model predictions also indicated that flue gas Hg^0 increases across a wet-FGD scrubber can be reduced by decreasing the pH, increasing the S(IV) concentration in the scrubber liquor, and lowering the temperature.

Chang and Zhao [19] discussed additional observations of elemental mercury (Hg^0) reemissions from a pilot-scale limestone wet scrubber. In those studies, simulated flue gas was generated by burning natural gas in a down-fired furnace and doped with 2000 ppm of SO_2. A solution of mercuric chloride ($HgCl_2$) was delivered to the scrubber at a controlled rate to simulate the absorption of ionized mercury (Hg^{2+}). The testing results indicated that, after Hg^{2+} was injected, elevated Hg concentrations were soon detected both in the flue gas exiting the scrubber and in the hold tank air, indicating the occurrence of Hg^0 reemissions in both places. When the $HgCl_2$ feed was stopped, the Hg^0 reemission continued

for more than 2 h. In addition, a significant Hg^0 reemission was also detected outside the scrubber loop. In an attempt to understand the Hg^0 reemission increase across the wet scrubber system under transient and steady-state conditions and to understand the underlying relationship with the mercury complexes retained in the wet scrubber system, a mercury reemission model was developed. With this model, the researchers determined that the Hg^0 reemission rate under the current testing conditions could be simulated by a first-order reaction, and only a portion of Hg – S(IV) complexes retained in the slurry were participating in the reemission reaction.

Hutson *et al.* [20] and Krzyzynska *et al.* [21, 22] conducted a series of bench- and pilot-scale studies to examine the simultaneous control of SO_2, NO_x, and mercury (both Hg^0 and Hg^{2+}) from a coal combustion flue gas in a multipollutant wet scrubber. The multipollutant capacity of a calcium-carbonate-based wet scrubber was enhanced with the addition of the oxidizing salt, sodium chlorite. The initial bench-scale results showed a maximum scrubbing of 100% for SO_2 and Hg species and near complete NO oxidation with about 60% scrubbing of the resulting NO_x species. The chlorite additive was less effective as an oxidant in the absence of SO_2 and NO in the flue gas. Oxidation of NO and mercury were only about 50% and 80%, respectively, when no SO_2 was present in the simulated flue gas. The mercury oxidation was similarly affected by the absence of NO in the flue gas.

Parametric studies investigating the effects of flue gas components, temperature, and oxidant addition rate were completed with the bench- and pilot-scale experimental facilities. Various process configurations were examined to optimize the addition of sodium chlorite. Additional studies by Krzyzynska and Hutson [23] showed that the location of the sodium chlorite application (before, in, or after the wet scrubber) greatly influences which pollutants are removed and the amount removed. This effect is related to the chemical conditions (pH, absence/presence of particular gases) that are present at different positions throughout the flue gas cleaning system profile. The results indicated that there is a potential to achieve very high SO_2, NO_x, and Hg removals from the flue gas when sodium chlorite was applied before the wet limestone scrubber. However, applying the oxidizer after the wet limestone scrubber was the most effective configuration for Hg and NO_x control for extremely low chlorite concentrations (below 0.002 M) and therefore appears to be the best configuration for Hg control or as an additional step for NO_x polishing (after other NO_x control technologies).

Krzyzynska and Hutson [24] further examined the role of slurry pH on the multipollutant capacity of the oxidant-enhanced wet scrubber. The results showed that the slurry strongly influenced the chemical mechanism in the scrubber and, therefore, affected pollutant removal. Different NO_x removal efficiencies and mechanisms were found in acidic and alkaline slurry in the multipollutant scrubber. The acidic solution was favorable for NO and Hg^0 oxidation, while increasing the slurry pH above 7.0 was disadvantageous for NO and Hg oxidation/removal.

11.4.4 Effect of SCR on Mercury Oxidation/Capture

Selective catalytic reduction (SCR) technology is increasingly being applied for controlling emissions of nitrogen oxides (NO_x) from coal-fired boilers. Field and pilot studies suggested that the operation of SCR could affect the chemical form of mercury in coal combustion flue gases. The speciation of Hg is an important factor influencing the control and environmental fate of Hg emissions from coal combustion. The vanadium and titanium oxides, used commonly in the vanadia–titania SCR catalyst for catalytic NO_x reduction, promote the formation of oxidized mercury (Hg^{2+}).

Lee *et al.* [25] conducted bench-scale experiments to investigate Hg^0 oxidation in the presence of simulated coal combustion flue gases and under SCR reaction conditions. Flue gas mixtures with different concentrations of hydrogen chloride (HCl) and sulfur dioxide (SO_2) for simulating the combustion of bituminous coals and subbituminous coals were tested. The tests showed that HCl is the most critical flue gas component contributing to conversion of Hg^0 to Hg^{2+} under SCR reaction conditions.

Lee *et al.* [26] followed the bench-scale work with pilot-scale studies to investigate the effect of SCR catalyst on mercury (Hg) speciation in bituminous and subbituminous coal combustion flue gases. Three different Illinois Basin bituminous coals (from high to low sulfur and chlorine) and one Powder River Basin (PRB) subbituminous coal with very low sulfur and very low Cl were tested in a pilot-scale combustor equipped with an SCR reactor for controlling nitrogen oxide (NO_x) emissions. The SCR catalyst induced high oxidation of Hg^0, decreasing the percentage of Hg^0 at the outlet of the SCR to values <12% for the three Illinois coal tests. The PRB coal test indicated a low oxidation of Hg^0 by the SCR catalyst, with the percentage of Hg^0 decreasing from similar to 96% at the inlet of the reactor to similar to 80% at the outlet. The low Cl content of the PRB coal and corresponding low level of available flue gas Cl species were believed to be responsible for low SCR Hg oxidation for this coal type. The test results indicated a strong effect of coal type on the extent of Hg oxidation.

Additional studies were conducted in a bench-scale reactor consisting of a natural gas burner and an electrically heated reactor housing an SCR catalyst that was constructed for studying elemental mercury (Hg^0) oxidation under SCR conditions [27]. A subbituminous coal combustion fly ash was injected into the entrained-flow reactor along with SO_2, nitrogen oxides, HCl, and trace Hg^0. Concentrations of Hg^0 and total mercury upstream and downstream of the SCR catalyst were measured using an online Hg monitor. The effects of HCl concentration, SCR operating temperature, catalyst space velocity, and feed rate of PRB fly ash on Hg^0 oxidation were evaluated. It was observed that HCl provides the source of chlorine for Hg^0 oxidation under simulated PRB coal-firing conditions. The decrease in Hg mass balance closure across the catalyst with decreasing HCl concentration suggests that transient Hg capture on the SCR catalyst occurred during the short test exposure periods and that the outlet

speciation observed may not be representative of steady-state operation at longer exposure times. Increasing the space velocity and operating temperature of the SCR led to less oxidized mercury. Introduction of PRB coal fly ash resulted in slightly decreased outlet oxidized mercury as a percentage of total inlet Hg and correspondingly resulted in an incremental increase in Hg capture. The injection of ammonia (NH_3) for NO_x reduction was found to have a strong effect to decrease Hg oxidation. The observations suggest that Hg^0 oxidation may occur near the exit region of commercial SCR reactors. Passage of flue gas through SCR systems without NH_3 injection, such as during the low-ozone season, may also impact Hg speciation and capture in the flue gas.

11.5
Coal Combustion Residues and By-Products

Flue gas from coal combustion contains significant amounts of volatile toxic trace elements such as arsenic (As), selenium (Se), and mercury (Hg). The capture of these elements in the FGD scrubber unit has resulted in generation of a metal-laden residue. With increasing reuse of the FGD residues in beneficial applications, it is important to determine metal speciation and mobility to understand the environmental impact of its reuse. Al-Abed *et al.* [28] reported the solid-phase speciation of As, Se, and Hg in FGD residues using XAS, X-ray fluorescence spectroscopy (XRF), and sequential chemical extraction (SCE) techniques. The SCE results combined with XRF data indicated a strong possibility of As association with iron oxides, whereas Se was distributed among all geochemical phases. The Hg appeared to be mainly distributed in the strong-complexed phase. XRF images also suggested a strong association of Hg with Fe oxide materials within FGD residues. XAS analysis indicated that As existed in its oxidized state (As(V)), whereas Se and Hg were observed in primarily reduced states as selenite (Se(IV)) and Hg(I), respectively. The results from the SCE and variable pH leaching tests indicated that the labile fractions of As, Se, and Hg were fairly low and thus suggestive of their stability in the FGD residues. However, the presence of a fine fraction enriched in metal content in the FGD residue suggested that size fractionation is important in assessing the environmental risks associated with their reuse.

Changes in emissions control at U.S. coal-fired power plants will shift metal content from the flue gas to the APC residues. To determine the potential fate of metals that are captured through use of enhanced APC practices, the leaching behavior of 73 APC residues was characterized following the approach of the Leaching Environmental Assessment Framework [29]. Materials were tested over pH conditions and liquid solid ratios expected during management via land disposal or beneficial use. Leachate concentrations for most metals were highly variable over a range of coal rank, facility configurations, and APC residue types. Liquid–solid partitioning (equilibrium) as a function of pH showed significantly different leaching behavior for similar residue types and facility configurations. Within a facility, the leaching behavior of blended residues was shown to follow

one of four characteristic patterns. Variability in metal leaching was greater than the variability in total concentrations by several orders of magnitude, inferring that total content is not predictive of leaching behavior. The complex leaching behavior and lack of correlation to total contents indicates that release evaluation under likely field conditions is a better descriptor of environmental performance than total content or linear partitioning approaches.

11.6 EPA SBIR Program

With support from EPA's Small Business Innovation Research (SBIR) Program and the U.S. DOE, Albemarle Mercury Control Division (formerly Sorbent Technologies Corporation) developed gas-phase bromination, a proprietary treatment, for PACs that can increase cost effectiveness for mercury control significantly when compared to non-brominated PAC.

With support from EPA's SBIR Program and the EPRI, Apogee Scientific, Inc. developed an advanced dry-catalytic gas sample conditioning system for use in the determination of in-duct mercury concentrations in coal-fired utility boilers. The Apogee Dry Sample Conditioning System (DSCS) represents a breakthrough in real-time mercury measurement technology.

EPA's SBIR Program also supported Advanced Fuel Research, Inc. (AFR) in the development of a technology to address both (i) removal and recovery of mercury from combustion/incineration flue gas and (ii) reprocessing of waste tires into value-added products. AFR's approach is based on mercury adsorption on low-cost, sulfur-rich activated carbons derived from scrap tires. The sulfur added to tire rubber in the process of vulcanization makes the tire-derived sorbents particularly effective in mercury removal. The first step in the waste-tire-processing scheme is pyrolysis, which involves thermal decomposition of tire rubber in an oxygen-free atmosphere. The solid product of pyrolysis (tire char) is subsequently converted into activated carbon. The sulfur content increases during tire processing, which is believed to facilitate mercury-capture efficiency. The cost-performance characteristics of tire-derived carbons are excellent and more favorable than those of the benchmark commercial carbon, Norit FGD.

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12
The Electric Power Research Institute's Program to Control Mercury Emissions from Coal-Fired Power Plants

Ramsay Chang

12.1
Introduction

The Electric Power Research Institute (EPRI) draws on decades of research to help member companies operate electric power plants in an efficient and cost-effective manner, in compliance with state and federal environmental regulations. This chapter describes EPRI's research and development program to control mercury (Hg) emissions from power plants firing different coals under various configurations and operating conditions. EPRI gratefully acknowledges the participation of stakeholders who have made this research possible, and the work of others who have contributed specific information on the many aspects of mercury control.

12.2
Co-Benefits of Installed Controls

At coal-fired electric generating units, mercury control co-benefits occur when installed control equipment, combustion conditions, and mercury pathways offer a baseline level of flue gas mercury removal that does not depend on adding new controls. Using the co-benefits of installed controls for nitrogen oxides (NO_x) and sulfur oxides (SO_x) is the first key, near-term technology for controlling mercury emissions. Co-benefits assume new importance as power plant owners seek all avenues of compliance with the Mercury and Air Toxics Standards (MATS) rule.

12.2.1
Selective Catalytic Reduction/Flue Gas Desulfurization

When flue gas passes through a selective catalytic reduction (SCR) system, the SCR converts elemental mercury to oxidized mercury, the form most easily captured in a downstream wet or dry flue gas desulfurization (FGD) system. The resulting baseline mercury removal is a co-benefit of SCR operation to control NO_x and FGD operation to control SO_x.

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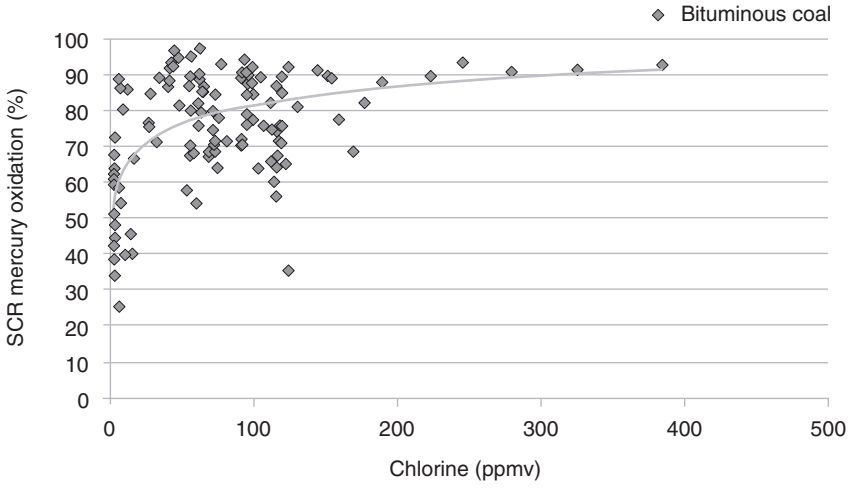

Figure 12.1 SCR mercury oxidation for bituminous coal-fired units.

Some eastern bituminous (EB)-fired units with combined SCR/FGD operation experience baseline mercury removals exceeding 90% [1]. However, many such units fail to achieve 90% control, especially over extended periods of time. For consistent, long-term regulatory compliance, these co-benefit units may require operational adjustments to counter excursions above the 1.2 lb $TBtu^{-1}$ MATS mercury emission limit, and a significant number may require supplemental mercury controls, such as activated carbon injection (ACI) and boiler halogen addition, to meet the limit.

A recent analysis of 240 datasets collected by EPRI at EB-fired co-benefit units shows highly variable mercury oxidation, with an average oxidation of 75% across the SCR; only about one-third of the datasets describe 90% or greater mercury oxidation (Figure 12.1) [2]. In research that will contribute to stable, high mercury removal at these co-benefit units, EPRI is working to enhance mercury oxidation across the SCR by evaluating high-mercury-oxidation SCR catalysts, improving catalyst management, and optimizing flue gas conditions such as halogen (chloride, bromide) content and temperature. EPRI is also pursuing a full characterization and understanding of wet flue gas desulfurization (wFGD) chemistry with the goal of enhancing reliable, continuous mercury removal by managing wFGD processes.

12.2.2 Unburned Carbon

When coal combustion is incomplete, unburned carbon (UBC) particles in fly ash remain available to adsorb flue gas mercury. Capture of the UBC-laden ash in particulate control devices provides a modest level of baseline mercury removal.

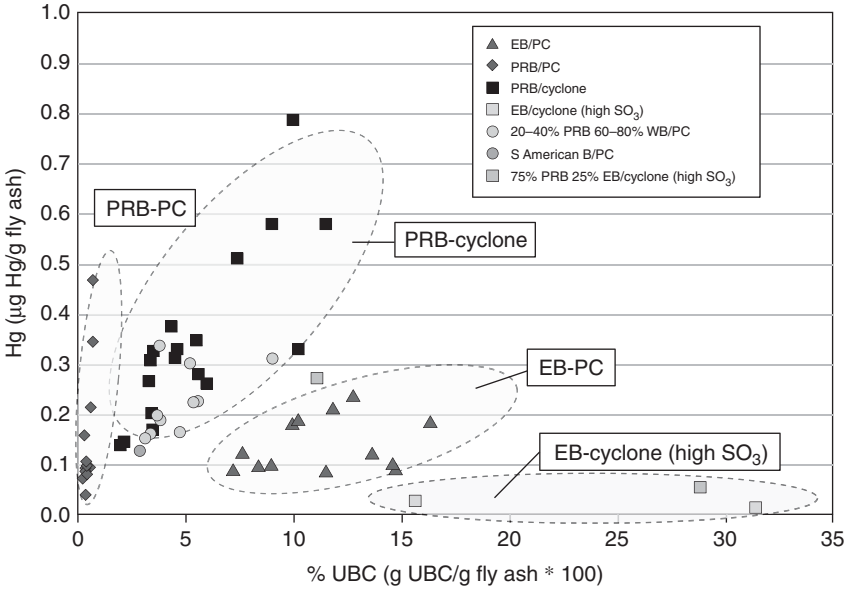

Figure 12.2 Influence of coal type, UBC concentration, and boiler type on fly ash mercury adsorption. (EB, eastern bituminous coal; WB, western bituminous coal; PRB, Powder River Basin coal; and PC, pulverized coal.)

The amount of mercury adsorbed on fly ash depends on coal type, the concentration of UBC in the ash, and boiler type. As shown in Figure 12.2, UBC in fly ash derived from western Powder River Basin (PRB) coal adsorbs much more mercury than does UBC in fly ash derived from high-sulfur eastern bituminous (HSEB) coal [1]. For a given coal, increasing UBC in fly ash enhances mercury capture. Increasing halogen levels in flue gas can enhance UBC affinity for elemental mercury.

12.3 Sorbent Injection

Sorbent injection – in particular, the use of ACI and BACI (brominated activated carbon injection) – is the second key, near-term technology for controlling mercury emissions.

In 2011, EPRI reported that ACI was installed at more than 60 U.S. power plants (more than 100 units) on coal-fired boilers rated from 73 to 1375 MWe [3]. Most of these ACI installations have operated since 2009, in compliance with state regulations and consent decrees. During site visits in 2010–2011, EPRI conducted detailed surveys of 11 ACI installations representing a broad cross section of the industry. EPRI member companies have hosted numerous ACI field studies.

12.3.1 Units Equipped with Electrostatic Precipitators

12.3.1.1 Western Coals

At electrostatic precipitator (ESP)-equipped units firing western coals, ACI removes about 75% of flue gas mercury at an injection rate of 5 lb MMacf^{-1} (Figure 12.3) [1]. This poor performance results from the low halogen content of the flue gas environment created by western coal combustion. Fundamental studies to date show that elemental mercury adsorption is enhanced by halogens that oxidize mercury and form halogen–mercury–carbon bonds. Use of BACI at injection rates similar to those for ACI removes more than 90% of flue gas mercury (Figure 12.3). BACI does not perform significantly better than ACI for EB coals, where a significant fraction of vapor-phase mercury is in the oxidized form [1].

12.3.1.2 Eastern Bituminous Coals and High-Sulfur Flue Gases

At ESP-equipped units firing EB coals, ACI mercury removals vary widely (Figure 12.4) [1]. Although the flue gas environment created by EB coal combustion contains more halogen (chloride) than western coal flue gas, it also contains more sulfur – especially if the coal fired is HSEB (S > 3%). Under these conditions, researchers postulate that sulfur trioxide (SO_3) in the flue gas competes with mercury for active adsorption sites on injected carbon or forms sulfuric acid (H_2SO_4) that blocks carbon pores. High concentrations of SO_3 in flue gas can form during combustion of high-sulfur coal, SCR conversion of sulfur dioxide (SO_2) to SO_3, or the use of SO_3 flue gas conditioning to improve ESP performance.

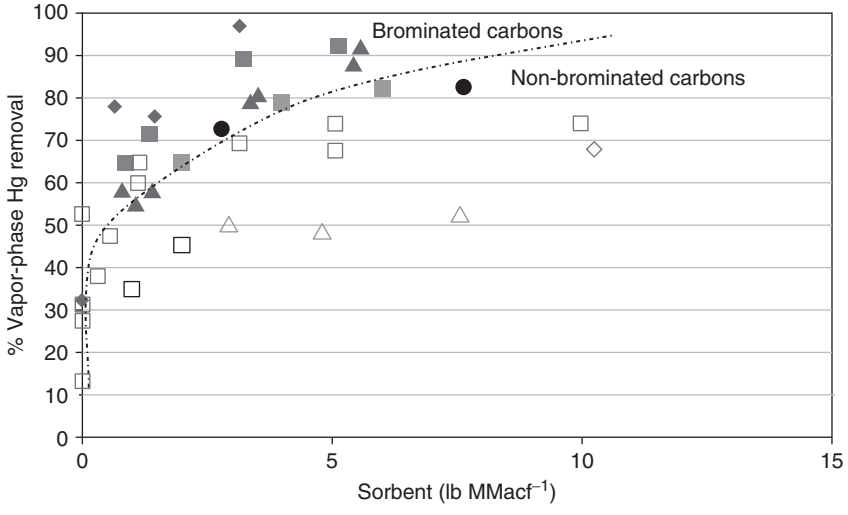

Figure 12.3 ACI mercury removal across ESPs for western coals. (Symbol shapes denote different sorbents, with solids representing BACs and outlines representing ACs.)

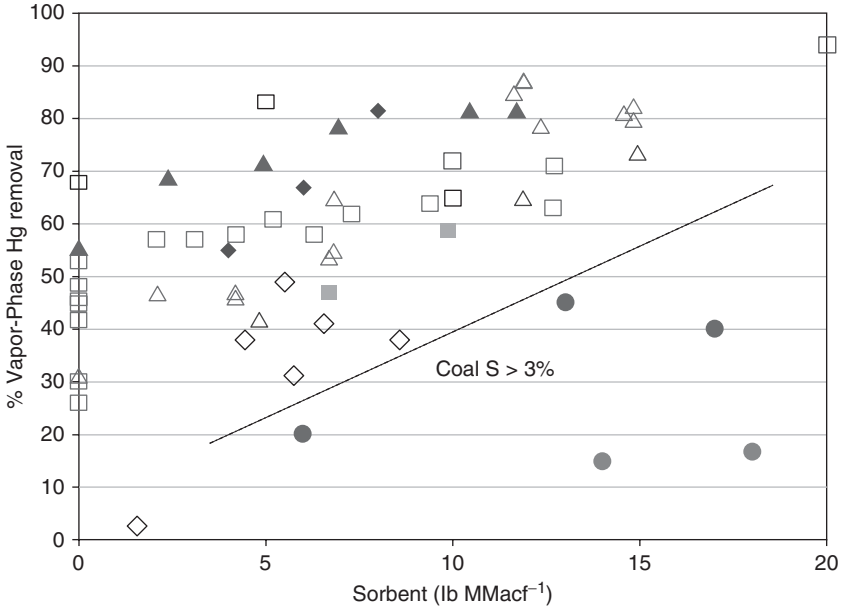

Figure 12.4 ACI mercury removal across ESPs for EB coals. (For LSEB coal (S < 3%), symbol shapes denote different sorbents, with solids representing BACs and outlines representing ACs.

Figures 12.4 and 12.5 illustrate the impact of flue gas SO_3 concentration on mercury removal across an ESP when using ACI for mercury control [1]. EPRI is evaluating various options to mitigate SO_3 impacts, including the use of SO_3-tolerant sorbents, alkali injection to reduce flue gas SO_3 concentrations, and alternate ESP flue gas conditioning agents.

12.3.2 Units Equipped with Fabric Filters or TOXECON®

To date, results show that using ACI or BACI with fabric filters (FFs) – including TOXECON® [4] (an ESP followed by a polishing FF) – can effectively remove mercury from western and low-sulfur eastern bituminous (LSEB) coal flue gases (Figure 12.6) [1]. Few ACI or BACI results are available for HSEB coal flue gas, as very few FFs are installed on HSEB-fired units; most of these units are equipped with an ESP and wFGD. EPRI is investigating whether ACI before an FF can effectively remove mercury from HSEB coal flue gas and whether mercury removals can be enhanced with alkali injection to reduce SO_3 levels.

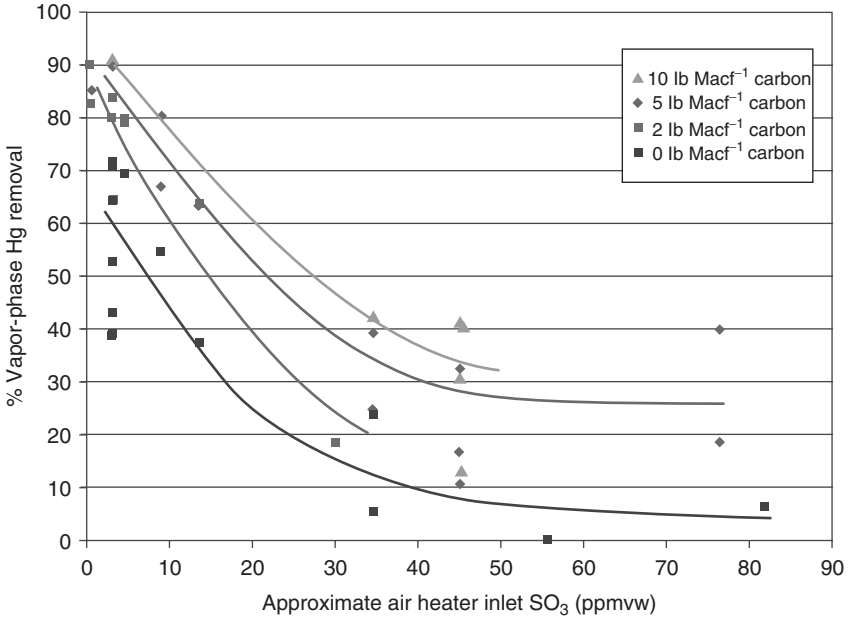

Figure 12.5 Influence of flue gas SO_3 concentration on ACI mercury removal across an ESP.

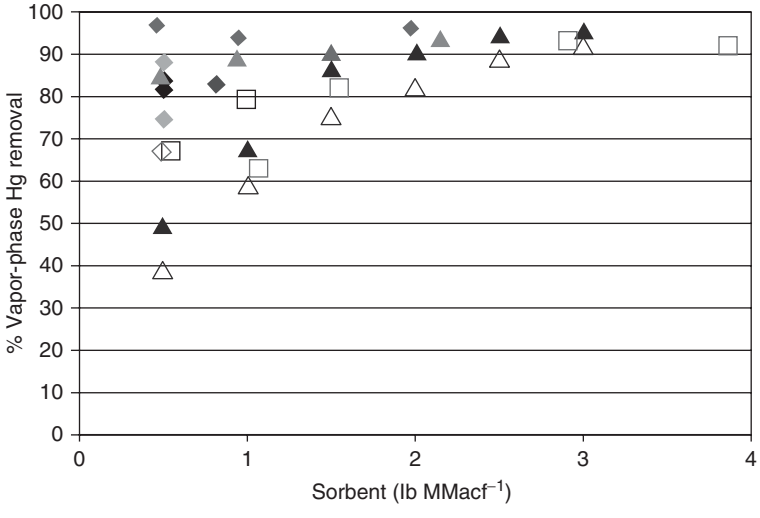

Figure 12.6 ACI mercury removal across FFs for western and LSEB coals. (Symbol shapes denote different carbons, with solids representing brominated and outlines representing non-brominated carbons.)

12.3.3 Challenges and Responses

Potential balance-of-plant impacts associated with ACI and BACI present challenges that must be addressed to contain the cost of regulatory compliance and, hence, the cost of electricity.

12.3.3.1 Preserving Fly Ash Sales

Preserving fly ash sales and avoiding ash disposal costs are important economic goals for many power plants. But these goals are thwarted if ACI or BACI increases the carbon content of fly ash, making it unsuitable for sale as a replacement for Portland cement in concrete.

Even small amounts of activated carbon (AC) in fly ash can adsorb the organic, air-entraining agents (AEAs) that fabricators add to improve concrete expansion and contraction over freeze/thaw cycles. To avoid this problem while continuing to use ACI for mercury control, power plant owners have evaluated mitigation measures such as minimizing the amount of injected AC, treating carbon-laden fly ash with chemicals to block AEA adsorption, injecting specially treated ash compatible carbons or non-carbon sorbents, or installing TOXECON. In EPRI's TOXECON configuration, an initial ESP captures 99% of the fly ash before carbon injection occurs between the ESP and an FF, or secondary particulate collector. Because fly ash collects in the ESP hoppers before it is exposed to AC, the ash remains uncontaminated and suitable for sale.

Some wholesalers purchase fly ash with relatively consistent concentrations of carbon, allowing them to predict the amount of AEA needed for concrete fabrication. Thus, another option to preserve ash sales is to maintain a relatively stable and predictable ratio of AC to fly ash [1].

12.3.3.2 Optimizing Electrostatic Precipitator Performance

- *Particulate matter emissions and opacity*: Although ACI increases the carbon burden in flue gas, EPRI found no significant ACI-related changes in particulate matter (PM) mass emissions or opacity monitored at the stacks of 12 ESP units surveyed in 2010 [5]. With or without ACI, historical data indicate that PM mass emissions from large ESPs and TOXECON units fall below the 0.03 lb $MMBtu^{-1}$ new source performance standard for power plant emissions, which is identical to the MATS limit for filterable PM. However, some small ESPs (specific collection area ~300 ft^2 $kacfm^{-1}$ or lower) do have PM mass emissions above this limit [5]. The electric power industry is evaluating low-cost performance upgrades for these small ESPs.
- *Mercury removal in the presence of flue gas conditioning*: Units firing either EB or western coals may employ both ACI and SO_3 flue gas conditioning to reduce ash resistivity and improve ESP collection efficiency. However, because SO_3 adversely impacts mercury adsorption on AC in flue gas, EPRI has tested the performance of alternative flue gas conditioners.

At a PRB-fired unit equipped with an ESP, researchers replaced SO_3 with an alternative liquid flue gas conditioner (LFGC) in tests of ACI mercury control. The LFGC proved to be as effective as SO_3 conditioning in controlling particulate emissions across the ESP. Furthermore, it did not interfere with mercury removal [3].

12.3.3.3 Optimizing Fabric Filter and TOXECON Performance

- *Optimal ash-to-carbon ratio*: In the TOXECON configuration, if the ESP is too efficient in removing fly ash from flue gas during ACI, PM entering the FF is largely carbon. As observed at one unit, fine carbon particles can clog filter bags – increasing pressure drop and cleaning pulse frequency while decreasing actual mercury removal. To solve this problem, plant operators at the unit detuned the ESP to allow more fly ash to enter the FF [5]. Thus, there may be an optimal ash-to-carbon ratio that must be determined empirically for some TOXECON installations to optimize mercury capture in the FF while maintaining reasonable pressure drop and cleaning frequency.
- *Hopper fires*: The high carbon content of ash in TOXECON FF hoppers also creates the possibility of hopper fires. At one TOXECON installation where fires were reported, researchers modeled combustion of the carbon-rich ash and suggested mitigation measures. These measures included installing temperature sensors and ash level detectors in the hoppers, as well as implementing an aggressive hopper cleaning schedule [6].
- *Influence of flue gas temperature*: AC adsorbs mercury more readily at lower flue gas temperatures. Figure 12.7 illustrates the response of ACI mercury removal to temperature variations from 330 to 360 °F at a PRB-fired unit equipped with an FF. To maintain stable mercury removal at this unit, plant operators must adjust the ACI rate for seasonal variations in temperature from winter to summer months [1].

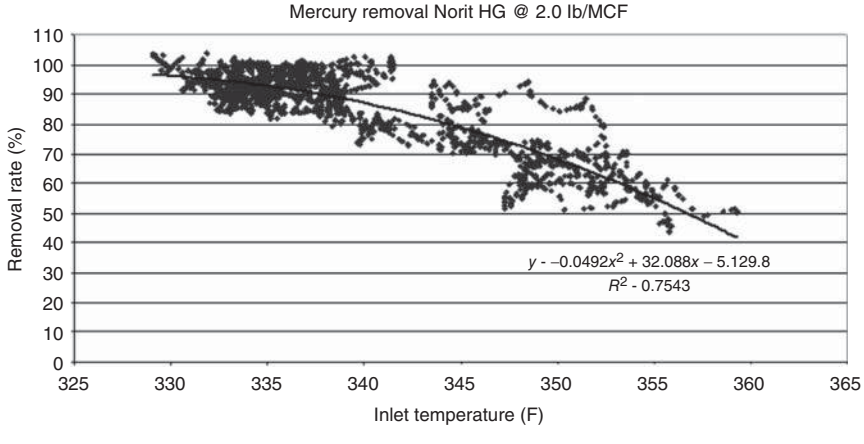

Figure 12.7 Influence of temperature on ACI mercury removal across an FF for PRB coal.

12.4
Boiler Chemical Addition

Boiler chemical addition (BCA) is the third key, near-term technology for controlling mercury emissions. BCA introduces halogens – usually bromide salts, such as calcium bromide (CaBr) – in solid or liquid form to the coal feed [7, 8]. Plant operators may also inject hydrogen bromide (HBr) into flue gas upstream of the air heater. Figure 12.8 shows the locations of these treatments, along with potential bromine balance-of-plant impacts on fly ash, the SO_2 scrubber, and stack emissions.

Since 2004, EPRI has conducted several full-scale demonstrations of boiler bromide addition (BBA) at units firing western coals (PRB and Texas lignite). In these demonstrations, more than 90% of flue gas mercury was oxidized at BBAs equivalent to 25–300 ppm by weight in coal [1]. This oxidizing effect is enhanced at units with SCR. For example, BBA (25 ppm Br) removed 90% of flue gas mercury in a 2-month test at a PRB-fired unit equipped with an SCR, ESP, and a downstream wFGD to capture the bromine-oxidized mercury (Figure 12.9) [9].

In a continuous 12-day test at an EB-fired unit equipped with an ESP and wFGD, BBA failed to achieve more than 90% mercury oxidation and did not improve total mercury removal [3]. At another EB-fired unit, researchers determined that BBA took several weeks to equilibrate in the wFGD; this reduced mercury reemissions and improved total mercury removal (Unpublished EPRI field test data). EPRI continues to study BBA at EB-fired units.

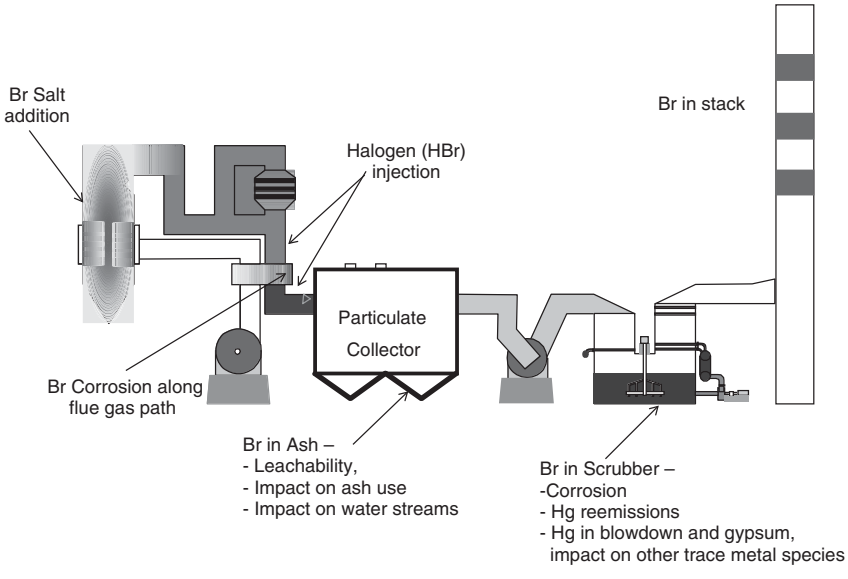

Figure 12.8 BCA options and potential balance-of-plant impacts.

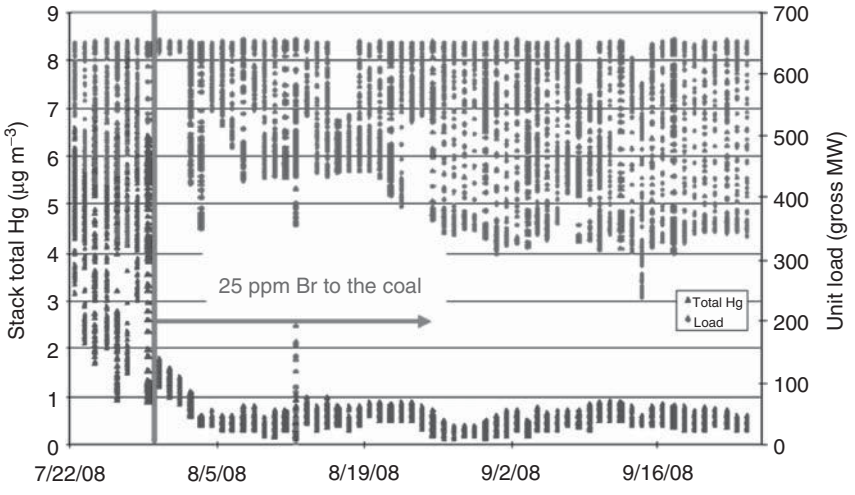

Figure 12.9 BBA promotes SCR mercury oxidation and removal across a wFGD for PRB coal.

12.4.1 Combined Technologies

Recently, several power plants have combined BBA with ACI. Combined technologies may offer an advantage over BACI at western coal-fired units because they reduce the amount of AC needed to achieve a given level of mercury control. At a North Dakota lignite-fired unit equipped with an ESP and wFGD, researchers tested the relative effectiveness of ACI (Norit Darco Hg) and BACI (Norit Darco Hg-LH) used as sole technologies or in combination with varying concentrations of BBA (CaBr). BACI was not as effective as BBA plus ACI in controlling mercury emissions, requiring an injection rate of 2 lb MMacf^{-1} or more to meet the 4.0 lb TBtu^{-1} MATS mercury emission limit for lignite coal-fired units (Figure 12.10). BBA (75 ppm Br) paired with ACI was the most effective treatment, meeting the emission limit at even the lowest sorbent injection rate (Unpublished EPRI field test data). This reduced use of AC can be an important consideration in preserving fly ash sales.

BBA can enhance the mercury removal effectiveness of ACI at units with FFs or TOXECONs, as well as ESPs. In one field test at a TOXECON unit firing PRB coal, the use of BBA (CaBr) alone supported 70–85% mercury removal across the TOXECON FF without ACI. Combining BBA with ACI delivered an average of 90% removal at an ACI rate of about 0.75 lb MMacf^{-1}. On the other hand, several days of continuous BACI offered 90% mercury removal at a rate of 1.26 lb MMacf^{-1} [5]. The decision to use BBA plus ACI versus BACI will depend on cost, including any potential balance-of-plant impacts.

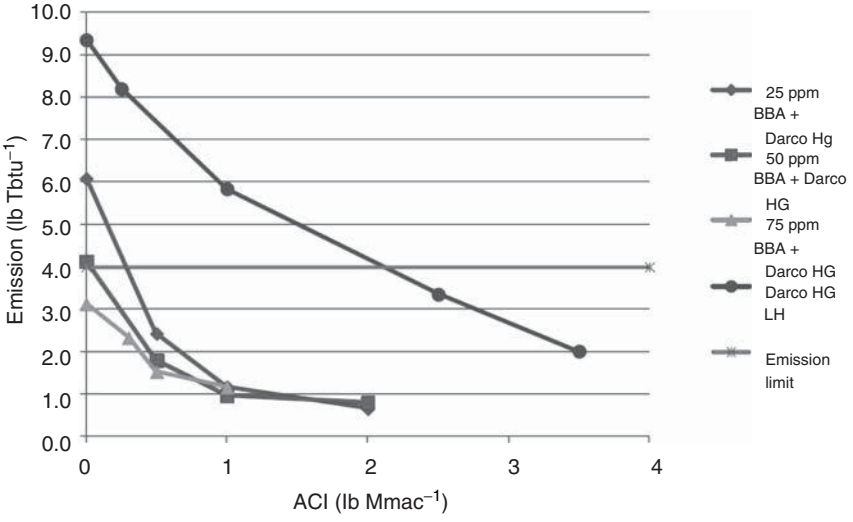

Figure 12.10 Combined BBA and ACI for mercury control.

12.4.2
Challenges and Responses

EPRI pursues a comprehensive research program to clarify potential balance-of-plant impacts associated with BBA to control mercury emissions at coal-fired units (Figure 12.11). This section describes challenges encountered during power plant operation and responses offered by EPRI research.

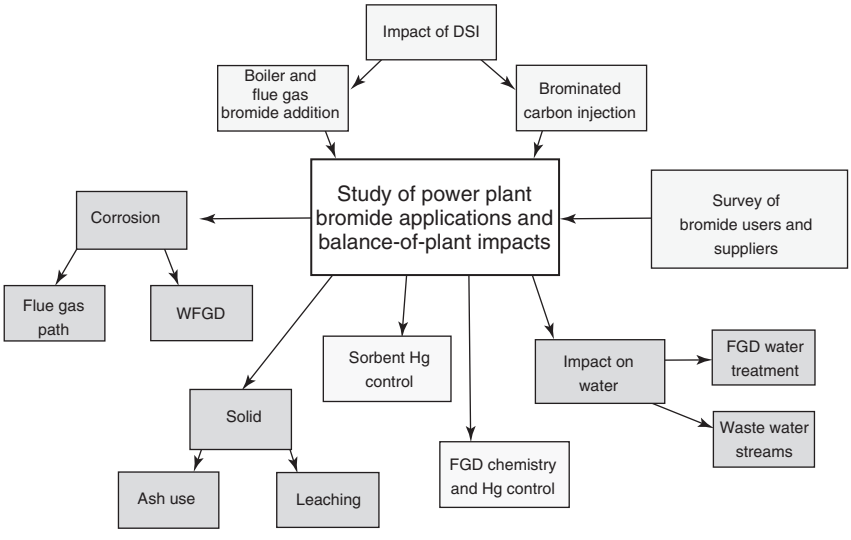

Figure 12.11 EPRI research program to clarify potential balance-of-plant impacts associated with BBA.

12.4.2.1 Wet Flue Gas Desulfurization Chemistry and Mercury Partitioning

Clarity about wFGD chemistry may allow researchers to partition mercury (and other trace metals such as selenium) to the most advantageous liquid or solid waste stream for a given unit. EPRI is conducting fundamental studies of chemical reactions within the scrubber that influence mercury and selenium (Se) partitioning, including mercury reemissions. These reactions involve constituents that concentrate in the FGD, such as limestone ($CaCO_3$) used in forced oxidation scrubbers and the inert materials the limestone contains, ferric chloride ($FeCl_3$) added for water treatment, and trace metals.

In one study at a PRB-fired unit equipped with an SCR, ESP, and wFGD, researchers observed no impact of BBA (CaBr) on mercury reemissions from the FGD. At this unit, most of the scrubbed mercury reported to the FGD solids under baseline conditions and BBA [1].

In contrast, most of the mercury reported to the FGD liquor during BBA at an EB-fired unit equipped with an ESP and wFGD. Under baseline conditions, about 67% of the wFGD mercury partitioned to the liquor. With BBA, these results remained basically unchanged (74%). However, adding AC to the sump liquor decreased wFGD mercury in the liquor to about 5%. This dramatic decrease demonstrated that added carbon was adsorbing mercury from the wFGD liquor. No other trace metals, including selenium, were significantly adsorbed by the added carbon [3].

12.4.2.2 Corrosion along Flue Gas Path and in the wFGD

Bromides formed with BBA are scrubbed and can reach high concentrations (500 to >30 000 ppm) in the wFGD over time, depending on scrubber design and the amount of recirculation that occurs [3]. There is concern that such high bromide concentrations may corrode FGD metal surfaces, especially in conjunction with high chloride levels.

In EPRI-sponsored laboratory studies, researchers exposed various metal alloys to simulated FGD liquors, creating corrosive environments reflecting the operation of a PRB-fired unit equipped with an SCR, ESP, and wFGD. The halogen content of the simulated liquors was based on chlorine already present and BBA rates needed for 90% mercury removal with SCR operation (25 ppm Br) or without SCR operation (100 ppm Br). Under these test conditions, alloys 2205, 317LM, and 316L experienced corrosion at 100 ppm BBA, as shown by the pitting potential in Figure 12.12, where lower voltages indicate greater susceptibility to corrosion [1]. These results suggest that careful selection of FGD construction materials may mitigate corrosion at units employing BBA for mercury control.

In addition to potential corrosion in wFGD scrubbers, corrosion along the flue gas path – for example, in air heater baskets – appears to occur at some full-scale units using BBA [10]. EPRI is conducting field and laboratory studies to determine whether bromide in flue gas causes the observed corrosion, or whether other factors and flue gas constituents are involved.

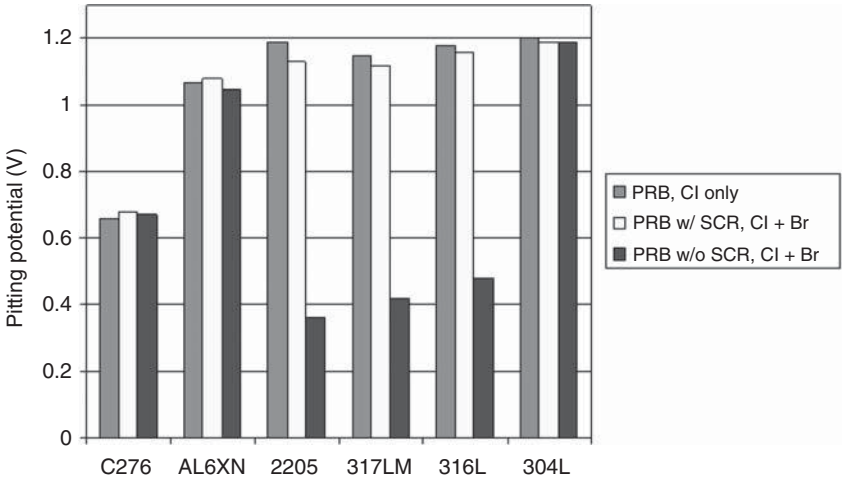

Figure 12.12 Corrosion of alloys in simulated FGD liquor for PRB coals, with and without SCR operation. (Lower pitting potential voltages indicate greater susceptibility to corrosion.)

12.4.2.3 Preserving Fly Ash Sales

At a PRB-fired unit equipped with an SCR, ESP, and FGD, 95% of bromide added to the boiler was scrubbed in the FGD unit. Fly ash adsorbed only 1–2% of the added bromide after 2 weeks of continuous treatment. This bromide concentration in fly ash did not affect physical properties of prepared concrete mixes, such as air content, compressive strength, set time, slump, or unit weight [1].

12.4.2.4 Selenium Partitioning in Wet Flue Gas Desulfurization Systems

Tracking selenium through a unit may alert operators to possible waste disposal issues. EPRI investigated selenium partitioning with BBA at an EB-fired unit equipped with an ESP and wFGD. Under baseline conditions, about 70% of the selenium appeared in the fly ash. BBA displaced this selenium from the fly ash to the FGD liquor, whose selenium concentration increased fourfold – from 151 µg/100 g of liquor at baseline to 590 µg/100 g of liquor at test [3]. This displacement may occur because selenium and bromide react to form selenium bromide (SeBr), a highly volatile compound that is not easily adsorbed on fly ash.

Selenium in the FGD liquor was largely selenate (SeO_4^{2-}), the form most difficult to remove with traditional wastewater treatments. Selenate displacement to the FGD liquor is an undesirable outcome, given the more stringent effluent guidelines proposed by the U.S. Environmental Protection Agency for fluid waste streams from coal-fired power plants.

12.4.2.5 Bromide Leaching from Fly Ash

As reported, 1–2% of bromide added to the boiler was adsorbed by fly ash at a PRB-fired unit equipped with an SCR, ESP, and FGD. In Synthetic Precipitation

Leaching Procedure tests on fly ash samples from the unit, 60–100% of total bromide content leached from the fly ash, confirming bromide's high water solubility [1]. Companies disposing of fly ash in landfills should consult state and local regulations to determine whether specific limits apply to bromide concentrations in landfill leachate.

12.5 Novel Concepts for Mercury Control

Novel concepts address the need to contain capital and operating costs while offering the most effective and efficient controls for mercury and other air pollutants.

12.5.1 TOXECON II®

This adaptation offers many of the advantages of TOXECON, without the expense of installing a compact FF. In the TOXECON II® configuration, sorbent is injected between the fields of an ESP [11]. Most of the fly ash collects in the inlet fields, before carbon injection, and can be sold. About 10% of the remaining fly ash collected in the final fields is contaminated and requires disposal. TOXECON II flue gas mercury removals of about 80% are possible for western coal-fired units without SO_2 scrubbers [1].

12.5.2 Gore® Carbon Polymer Composite Modules

W. L. Gore & Associates, Inc. has developed a carbon polymer composite (CPC) material made of AC granules embedded in a Teflon™ polymer matrix and formed into sheets [12]. When a CPC sheet is placed in the flue gas path, its carbon granules adsorb mercury and oxidize SO_2 to SO_3. Both elemental and oxidized mercury remain bound to the embedded carbon granules, while the SO_3 reacts with flue gas moisture to form sulfuric acid droplets that drain from the surface of the hydrophobic sheet. CPC modules can be placed above the mist eliminator at the top of a wFGD (Figure 12.13) [13]. The goal is to capture residual mercury and SO_2 downstream of the wFGD, where flue gas temperature is low (ensuring maximal mercury adsorption) and moisture is high. Depending on SO_x levels, a CPC reactor could be an alternative to an upgraded or new FGD system.

In 2010, EPRI demonstrated the feasibility of the Gore® CPC concept at an EB-fired unit equipped with an ESP and wFGD. In these tests on slipstream flue gas sampled after a limestone wet scrubber, mercury removal efficiency remained high (80–95%) over the entire 180 days of testing (Figure 12.14), resulting in outlet emissions of <1 lb $TBtu^{-1}$ mercury. About 60% of SO_2 was removed from slipstream flue gas during the same test period [14]. EPRI is conducting further

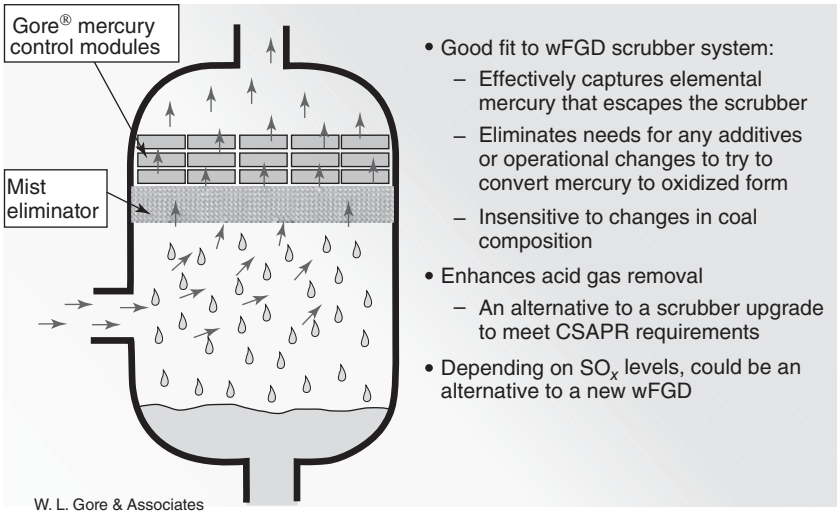

Figure 12.13 CPC modules placed above the mist eliminator in a wFGD.

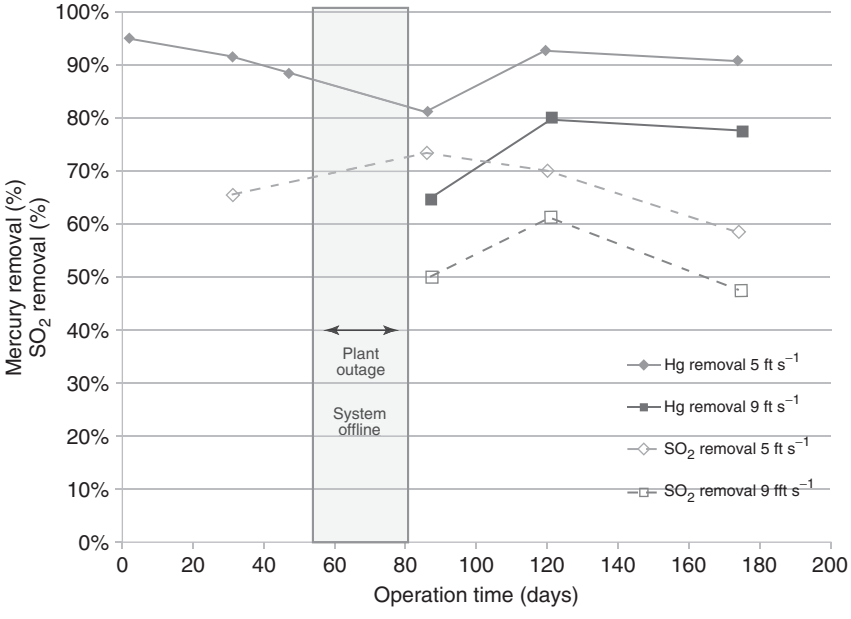

Figure 12.14 Mercury and SO_2 removal by CPC during 180 test days for EB coal.

pilot- and full-scale evaluations at other power plant sites to assess the potential for full-scale applications of CPC technology. Gore has recently renamed the CPC as Gore Mercury Control System (GMCS).

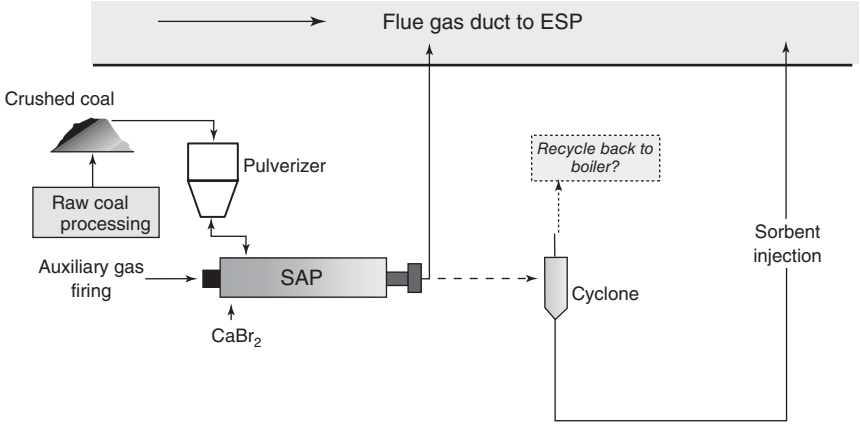

Figure 12.15 SAP process schematic.

12.5.3 Sorbent Activation Process

The Sorbent Activation Process (SAP®) [15, 16] reduces AC cost by more than 50% using on-site feedstocks to produce AC for mercury removal via a much simplified production process. Patented by EPRI and the University of Illinois at Urbana-Champaign, SAP uses a high-temperature reaction chamber to convert pulverized coal feedstock to AC in a matter of seconds (Figure 12.15) [17]. The AC is then injected directly into flue gas before an ESP or other particulate control device. Alternately, SAP flue gas and product AC are separated by a cyclone. The gas is recirculated to the boiler and the AC is injected into the flue gas. SAP uses the coal burned at the power plant site, together with activating agents and other chemicals, to create sorbents with unique surface areas, pore structures, and surface chemistries.

Field tests at a PRB-fired unit and an EB-fired unit confirmed that SAP ACs made from these coals are comparable to commercially available ACs used for mercury control. For example, both a commercial brominated activated carbon (BAC) and an SAP BAC removed about 80% to more than 90% of the mercury from flue gas across an FF (TOXECON configuration) at the PRB-fired unit (Figure 12.16) [17].

Further field tests at the EB-fired unit equipped with an ESP and wFGD offered proof of concept that SAP also can produce lime from limestone co-injected with pulverized coal for acid gas removal [17]. EPRI is demonstrating the cost-effectiveness of SAP at a Texas lignite-fired unit equipped with an ESP and wFGD.

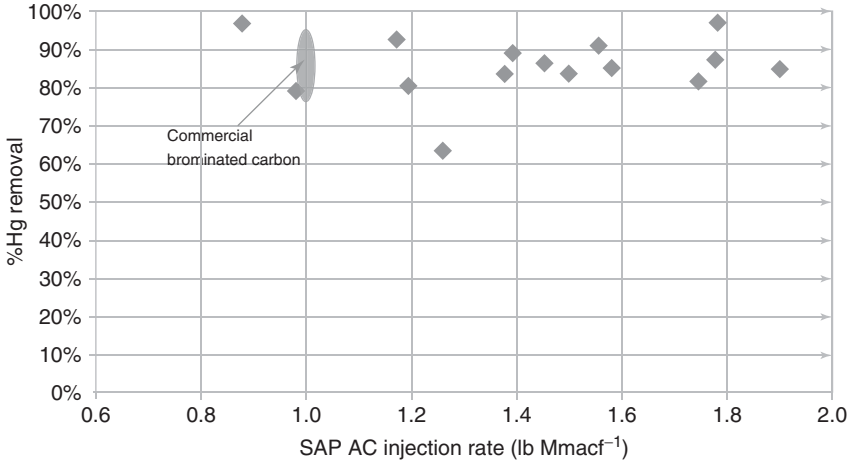

Figure 12.16 Mercury removal for PRB coal using SAP-produced BAC compared to commercial BAC.

12.6
Integration of Controls for Mercury with Controls for Other Air Pollutants

In the era of compliance with strict MATS limits and other pollution control regulations, such as the Cross-State Air Pollution Rule (CSAPR), mercury control technologies must work effectively with other pollution control technologies, such

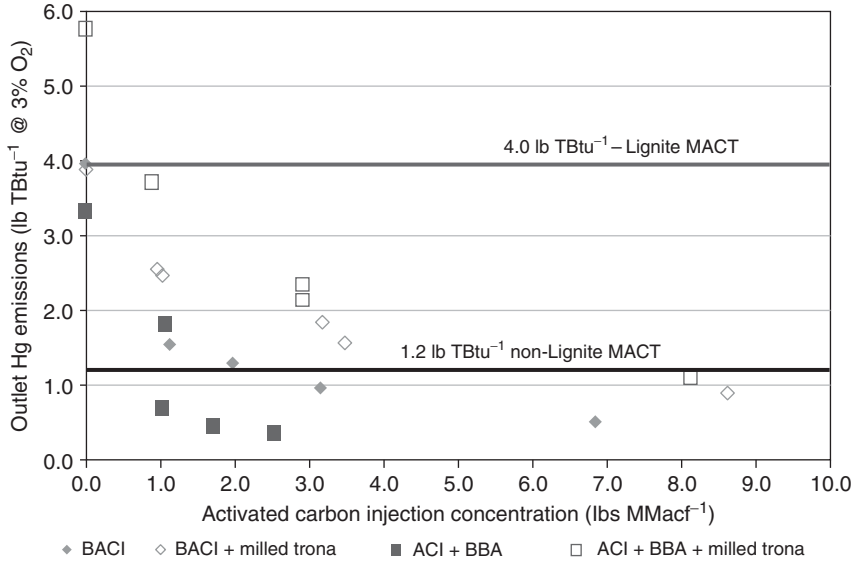

Figure 12.17 DSI (Trona) impact on ACI plus BBA mercury removal across an ESP for PRB coal.

as dry sorbent injection (DSI) for FGD. Many power plants are investigating DSI as a low capital cost, interim solution to meet acid gas control requirements. Tests are being conducted with Trona, sodium bicarbonate, or hydrated lime.

However, evidence suggests that alkali sorbents may reduce the effectiveness of ACI for mercury control. They may interact with BBA for mercury control by removing bromide and other halogens from flue gas. Injection of sodium-based alkali also produces nitrogen dioxide (NO_2), a compound that can reduce ACI mercury removal effectiveness. An example of these interactions is shown in Figure 12.17, where DSI and ACI were tested at a PRB-fired unit equipped with an ESP (Unpublished EPRI field test data). In these tests, milled Trona was simultaneously injected upstream of the air heater with either BAC or AC (paired with BBA in some runs). Co-injecting Trona had a significant, negative impact on mercury control effectiveness with ACI plus BBA.

12.7 Summary

This chapter presents results of EPRI's research and development program to support technologies that offer the most effective flue gas mercury removal at the lowest capital and operating cost. It reviews the achievements, balance-of-plant challenges, and research responses associated with near-term mercury control technologies, and describes novel, longer term concepts.

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Part V
Mercury Control Processes

Mercury Control: for Coal-Derived Gas Streams, First Edition.
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13
Mercury Control Using Combustion Modification

Thomas K. Gale

13.1
Mercury Speciation in Coal-Fired Power Plants without Added Catalysts

13.1.1
Mercury is all Liberated and Isolated in the Furnace

The predominant forms of mercury in coal-fired flue gas are elemental (Hg^0) and oxidized ($HgCl_2$) [1–3]. The percentage of oxidized mercury in the stack effluent of a particular power plant depends on the coal type, combustion efficiency, and the pollution control equipment used. Essentially, all of the mercury entering the furnace with the coal is vaporized and exists in the elemental form until the flue gases cool below ~600 °C (~1000 °F) [1–3]. The oxidation of mercury in coal-fired boiler systems is kinetically limited [1–3]. Because the concentration of mercury is exceedingly small at around 1 ppb in flue gas, any favorable mercury-oxidation reaction does not have the ability to promulgate itself. In virtually every conceivable competitive reaction, the competing gas component, much in excess of mercury, dominates. Where the formation of mercuric compounds is thermodynamically favored, the kinetically controlled oxidation requires the oxidant to be in vast abundance compared with mercury.

13.1.2
Chlorine Speciation in Coal-Fired Power Plants

Chlorine (Cl_2) is more reactive for the oxidation of mercury compared to hydrogen chloride (HCl). Chlorine gas (Cl_2) is not thermodynamically promoted at high temperatures. However, below 370 °C (644 K or 700 °F), a significant driving force toward the formation of Cl_2 develops. This driving force begins to dominate over the formation of HCl below 260 °C (533 K or 500 °F). Chlorine speciation is governed by equilibrium in furnace sections of coal-fired boilers and limited by kinetics and residence time downstream. Therefore, several statements can be made relative to chlorine speciation in coal-fired power stations. Chlorine gas

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injection through the burner or entering with the coal will be entirely converted to HCl and Cl^- in the furnace. Any form of chlorine injected through the primary-air line will be converted in the furnace to HCl and a smaller amount of Cl^-, as long as it vaporizes in the flame. The result downstream (~600 °F) will be to increase the total amount of chlorine in the flue gas by the amount injected through the burner. The form of chlorine will be primarily HCl. However, as more total chlorine is injected through the burner, a small but higher concentration of Cl^- may persist a short distance downstream of the furnace. Although a driving force toward the formation of Cl_2 begins to form below 370 °C (644 K or 700 °F), the formation of Cl_2 is expected to be limited by kinetics at this point. Thus, the majority of the HCl is expected to remain in that form for the residence times that exist in full-scale power plants. Furthermore, if Cl_2 gas was injected at a lower temperature location downstream, where the thermodynamic driving force was more favorable to its formation (i.e., after the economizer), then it would remain in the form in which it was injected.

13.1.3 Mechanisms Governing Mercury Speciation

The following mechanism [4] was proposed whereby carbon, in the form of unburned carbon (UBC), activated injected carbon, or other carbon types could oxidize mercury by effectively removing the activation barrier, preventing HCl from directly reacting with elemental mercury atoms in the flue gas:

$$\mathrm{UBC + HCl \Leftrightarrow UBC \cdot Cl + H} \quad \text{and} \quad \mathrm{UBC \cdot Cl + Hg^0 \Leftrightarrow HgCl + UBC} \tag{13.1}$$

Equations 13.2–13.6 describe how UBC can effectively catalyze mercury oxidation by reacting with HCl to form chlorinated carbon sites, which then react with mercury on the surface of the carbon to form adsorbed HgCl, which finally desorbs as oxidized mercury. The oxidized mercury may in turn readsorb onto open UBC sites.

Equation 13.2 describes the formation of chlorinated carbon sites.

$$\mathrm{HCl + C \Leftrightarrow Cl \cdot C + H} \tag{13.2}$$

Equation 13.3 allows for desorption of chlorine, thus providing some moderation of chlorine accumulation on the carbon surface.

$$\mathrm{2Cl \cdot C \Leftrightarrow Cl_2 + C} \tag{13.3}$$

Equation 13.4 describes the capture of elemental mercury by reaction with chlorinated carbon sites located on the surface of ash particles.

$$\mathrm{Cl \cdot C + Hg^0 \Leftrightarrow HgCl \cdot C} \tag{13.4}$$

Equation 13.5 allows for the desorption of oxidized mercury.

$$\mathrm{HgCl \cdot C \Leftrightarrow HgCl + C} \tag{13.5}$$

Various homogeneous pathways can convert HgCl to $HgCl_2$, such as reaction of HgCl with Cl^- or Cl_2. The conversion is assumed to be very fast, and thermochemical equilibrium calculations predict nearly all mercury to be in the $HgCl_2$ form in flue gas downstream of the airheater [1, 5].

Equation 13.6 allows for the readsorption of oxidized mercury onto open carbon sites (as in the dissociative adsorption of mercuric chloride shown here).

$$HgCl_2 + C \Leftrightarrow HgCl \cdot C + Cl^- \tag{13.6}$$

13.2 Role of Unburned Carbon in Mercury Oxidation and Adsorption

13.2.1 UBC is the Only Catalyst with Enough Activity in Coal-Fired Power Plants

Extensive parametric investigations of mercury speciation in coal-fired flue gas and coal-fired power plants *without selective catalytic reductions* (*SCRs*) *installed* (or other catalysts or reagents introduced for the purpose of enhancing mercury oxidation or capture) have shown [1, 5, 6] that variable parameters such as exposed iron-oxide surfaces in the convection pass, flue-gas concentrations of O_2, N_2, H_2O, NO, NO_2, SO_2, CO, and CO_2, or the concentrations of Fe, Al, Si, Na, or derivatives of iron in the flyash have little impact on mercury oxidation or removal under conditions that exist within actual coal-fired power plants. What has been shown to have an impact on mercury oxidation and capture within the flue gas of coal-fired power plants (without SCR or other catalysts or reagents) is the type and extent of carbon in the flyash.

As mentioned earlier, the HCl concentration of the flue gas will have little impact on mercury oxidation if the UBC is low. Figure 13.1, previously published elsewhere [6], compares the relationship between Hg oxidation across a baghouse, HCl concentration in the flue gas, and UBC in the flyash, during a pilot-scale [7] mercury-speciation study. The HCl and UBC concentrations were varied by injecting chlorine gas through the burner while firing Powder River Basin (PRB) coal (a low-chlorine, high-calcium ash, sub-bituminous coal) and by blending PRB with higher chlorine bituminous coals.

A mass balance on coal-mercury suggested that the majority of mercury at the baghouse inlet was in the gas phase for all blend conditions. As shown, chlorine injection alone (i.e., resulting in HCl addition in the back pass) had some impact on mercury oxidation. However, much more mercury oxidation was realized as a result of coal blending, even though there was less chlorine. Adding bituminous coal also yielded more UBC in the ash, which catalytically enhanced mercury oxidation. The chlorine and UBC levels shown in Figure 13.1 are low relative to the levels produced from most eastern bituminous coals. Nevertheless, UBC clearly plays a significant role in catalyzing the oxidation of elemental mercury with hydrochloric acid vapor in the flue gas, and the concentration of UBC in flue

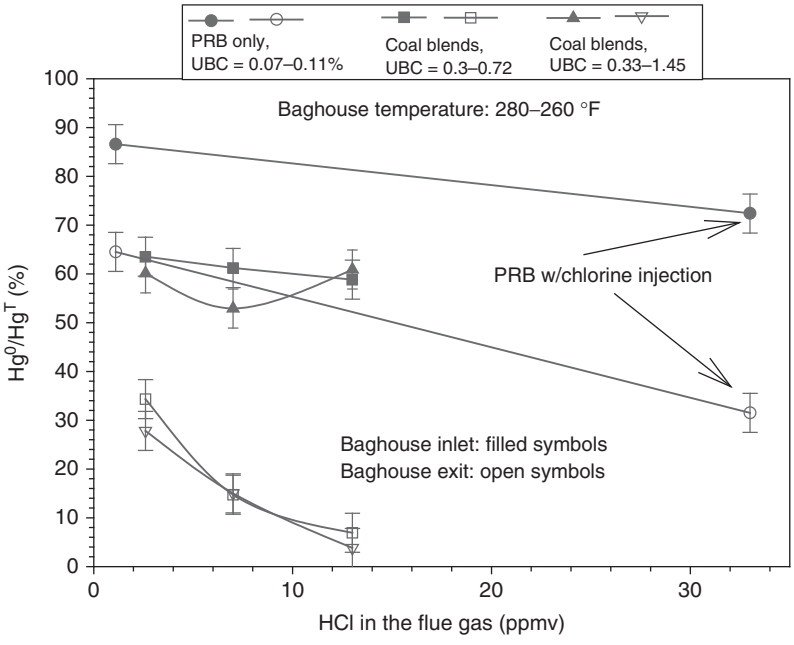

Figure 13.1 Effect of flue-gas– chlorine on mercury oxidation ahead of and across a baghouse [6] (shown as a decrease in the elemental mercury (Hg^0) concentration at the measurement location relative to total mercury (Hg^T) at the baghouse inlet). (Reproduced with permission from Ref [6]. Copyright © 2009, Elsevier Limited.)

gas will be as important, or more important, than the concentration of HCl in the flue gas for many plants relative to mercury oxidation.

13.2.2
UBC can Remove Hg or Oxidize Hg, Depending on the UBC Concentration

It is known [8] that the desorption rate of HgCl from carbon at a given temperature decreases with increasing available carbon sites, as the desorption rate depends primarily on the HgCl concentration deposited on the carbon surface and the concentration of vacant carbon sites per unit mass of carbon. Furthermore, for a given temperature, the adsorption rates of Hg^0 and $HgCl_2$ increase with an increase in the number of sites available for sorption – that is, the UBC sites for activation by HCl and adsorption of $HgCl_2$ (i.e., through the mechanisms described in Equations 13.2 and 13.6, respectively) and the Cl·C sites (see Equation 13.4) for adsorption of Hg^0. Hence, the speciation and removal of mercury by particulate, produced by a given coal and firing condition, depend on the amount (and surface activity) of the carbon (in the flue gas) available to adsorb mercury, keep it adsorbed, and to readsorb oxidized mercury.

With sufficient carbon (i.e., high enough C/Hg ratio), the overall adsorption rate of mercury may be overwhelmingly greater than the overall desorption rate, in

which case significant mercury removal will be observed. On the other hand, if sufficient carbon (activated carbon or UBC) is present to yield significant mercury adsorption on chlorinated carbon sites, but not enough carbon is available to slow the desorption of HgCl and to allow significant readsorption of $HgCl_2$, then extensive mercury oxidation may be observed without significant mercury removal.

13.2.3 Nature of Carbon Type Depends on Parent Coal and Combustion Efficiency

Activated carbon used for mercury control is often made from coal, typically a low-rank coal or lignite, and less often from coconut or walnut shell or other biomass feedstock such as wood. The feedstock, be it biomass or coal based, is subjected to thermal decomposition with strategic oxidation (often with steam) in order to produce an active sorbent for mercury adsorption with a high internal surface area. The carbon–steam reaction, shown here, is typically used to generate internal porosity and high-surface-area carbons.

$$C + H_2O \rightarrow CO + H_2 \tag{13.7}$$

If the temperature is too hot, the heating rate too slow, or if too much oxygen is present and not enough steam, then the resulting activated carbon will be less active than that produced under optimized conditions. Similarly, UBC in flyash has gone through a thermal decomposition process and been subject to reactions with steam, carbon dioxide, and oxygen. Although coal-fired boilers are clearly not optimized to produce UBC with a high activity for mercury adsorption, the activity of the carbon for mercury adsorption may differ significantly from one plant to another, depending on the coal type fired, the efficiency of the boiler, the furnace exit oxygen of the furnace, and moisture content of the coal and humidity of the secondary air.

The impact of the coal type on the resulting carbon activity can be determined from the coalification curve. Peat, although not coal, is the first material that plant matter was converted into as it began the coalification process. Peat consists of high moisture content, high volatile content, and will produce a highly active carbon type when thermally decomposed. Graphite, although not coal, sits on the other end of the coalification curve and is the end product of material passing through the coalification curve. Graphite has little moisture and no volatiles, and consists of an unreactive carbon type before and after heat treatment. In between these two endpoints are the different types of coal we burn in power plants at present, with the more reactive carbon types produced from the younger coals (i.e., lignites and sub-bituminous coals) and the less reactive carbon types being produced from the older coals (low-volatile bituminous and anthracite coals).

The order of coals from youngest to oldest from the coalification curve is maintained in the heating value and proximate analysis charts produced by Hendrickson in 1975 [9], reproduced in Perry's Chemical Engineers' Handbook [10]. As shown in those charts, the younger the coal, the more moisture content, the more

volatiles, the less fixed carbon, and the lower the heating value. It is also true that the char produced from the initial stages of combustion known as *devolatilization* (which takes place in <25 ms in pulverized coal (PC) boilers) is more reactive for younger coals and less reactive for older coals. The char produced from younger coals is more reactive for essentially two reasons. First, the solid organic network comprising the char structures contain more aliphatic material (i.e., attachments to organic rings, such as methane and toluene and components that can easily be released as light gases), and the aromatic structures are less ordered and graphitic in nature (i.e., the rings contain fewer inclusions and the ring structures tend to be more planar with respect to each other) [11, 12]. Second, in large part due to the first reason (i.e., the nature of the solid carbon structure), the char produced from the younger coals tends to have a higher porosity and internal surface area than char produced from the older coals.

The higher moisture content of the younger coals also tends to yield higher medium-sized pores or mesopores, through which increase the reaction rate of chars with oxygen would, if the chars survived, yield more active carbon structures for mercury capture.

Firing a coal that yields char with a high reactivity results in two trends that tend to cancel each other out in terms of yielding highly active UBC, outlined as follows: The higher reactivity does indeed relate to a higher activity for mercury capture. However, the higher reactivity also means that more of the carbon will be burned out in the furnace by oxygen and will not survive to serve as an actor for mercury adsorption or oxidation. A good example of this is PRB coal. PRB coal yields a highly reactive char type that is very effective for oxidizing and adsorbing mercury. However, most power plants that burn PRB coal have very low UBC in their flyash, because most of the carbon burns out in the boiler, before reaching the backpass.

It has been shown that high oxygen contents tend to decrease the reactivity of coal chars by consuming the outer surface of the char (eating the char particles from the outside in), while high-steam concentrations tend to increase the char reactivity by increasing the char mesoporosity and Brunauer–Emmett–Teller (BET) surface area [13]. The water molecules, with orders of magnitude lower reaction rate than oxygen with carbon, are able to penetrate the micropores of the coal char and react with their inner walls, thus widening the micropores and creating mesopores, without reducing the particle diameter. Hence, higher moisture contents in the furnace may increase the carbon activity for mercury if the active carbon produced is not all consumed by oxygen in the furnace.

13.2.4 Concentration of UBC Needed to Oxidize or Remove Mercury from Flue Gas

The mechanism of carbon enhancement of mercury oxidation is consistent with bench-, pilot-, and full-scale Hg-adsorption and speciation data, which have shown a direct relationship between mercury adsorption and carbon concentration [1, 5, 14]. At low carbon concentrations, the rate of Hg adsorption

is of the same magnitude as the rate of mercury desorption. As the carbon concentration increases, assuming at least some chlorine in the flue gas, mercury adsorption begins to dominate over mercury desorption, until most of the mercury is observed to be removed from the flue gas. The mechanism is observed even more clearly for mercury speciation. At very low concentrations of carbon in the flue gas (i.e., PRB-fired power plants with high carbon burnout), the mercury will neither be oxidized nor adsorbed. For slightly higher concentrations of UBC (i.e., up to about 4.0% in the ash) in the absence of much calcium, extensive mercury oxidation will be observed, and for still higher concentrations of UBC, mercury removal will dominate even without much calcium present (as observed at power plants with high levels of UBC in the ash, that is, 20–50% UBC).

If firing conditions can be changed to increase the UBC in the flyash from PRB coal by just 0.2%, a significant increase in mercury oxidation will likely be observed, while an increase in UBC to several percent may result in high removals of mercury in the flyash (calcium content of the ash will also have an impact on removal for PRB coals). On the other hand, UBC concentrations as much as 10% in the flyash from bituminous coal may not produce high mercury removals or complete mercury oxidation.

In the same pilot-scale system [7] from which the data shown in Figure 13.1 were obtained, the concentration of UBC in the flyash needed to oxidize mercury across a baghouse was also measured (see Figure 13.2 published previously [6]). Combustion modifications were used to increase the concentration of UBC from the PRB coal, which is a highly reactive carbon type. As shown in Figure 13.2, the resulting increase in UBC was highly effective at oxidizing mercury. The coal blends were primarily of PRB and bituminous coals, where the average UBC type produced was also effective for oxidizing mercury.

13.3
Synergistic Relationship between UBC and Calcium in Flyash

13.3.1
Calcium Enhances the Retention of Mercury on Carbon

A fundamental investigation by Gale *et al.* [6] on the impact of calcium on mercury removal in power plants found that the presence of calcium, in the form of PRB flyash, injected hydrated lime, calcium carbonate, or calcium, enhanced mercury removal from the flue gas under certain conditions. Among other things, it was demonstrated that adding different forms of calcium to the baghouse collecting bituminous coal flyash changed the measured form of mercury at the baghouse outlet from about 90% oxidized with about 25% removed across the baghouse, to over 80% of the mercury removed across the baghouse. It was further shown [6] that calcium powders would only increase mercury removal across the baghouse if they were mixed with the UBC in the flyash. Without UBC from flyash, the

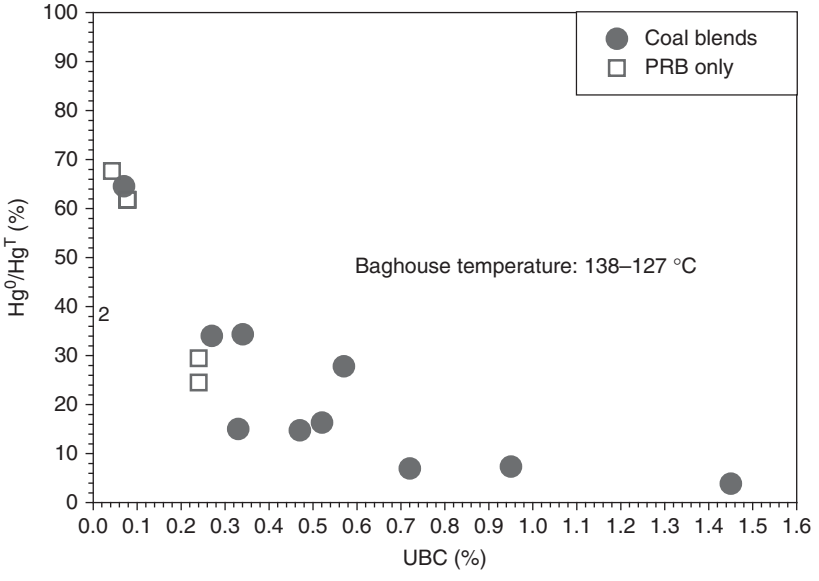

Figure 13.2 Mercury oxidation versus UBC [6]. (Reproduced with permission from Ref [6]. Copyright © 2009, Elsevier Limited.)

calcium powders had no effect, even for flue gas containing a high percentage of oxidized mercury.

The synergistic relationship of calcium and UBC for the removal of mercury also extends to mercury removal across an electrostatic precipitator (ESP) [6]. Contour lines showing the concentration of calcium and UBC necessary to achieve different mercury removal percentages derived in this work are reproduced here in Figures 13.3–13.5. All of this work was performed on low-sulfur coals, with SO_3 concentrations <2 ppmv, so the impact of calcium on protecting the carbon from deactivation by SO_3 was not significant.

As shown in Figures 13.3–13.5, different combinations of calcium and carbon concentrations can be used to obtain the same mercury removal percentages at the inlet and outlet of an ESP. The contour lines shown in these figures were created from data interpolation. No extrapolations were made. Therefore, all of the points on each of the contour lines are achievable.

13.3.2 Calcium/Carbon Synergism is Limited to a Range of Conditions

Synergism between calcium and UBC in flyash or injected activated carbon was found to be effective only for UBC concentrations in the flyash that would otherwise yield significant mercury oxidation with moderate mercury capture. If a large concentration of UBC was present, such that mercury removal was already high, the impact of adding calcium would be far less effective or not effective at all.

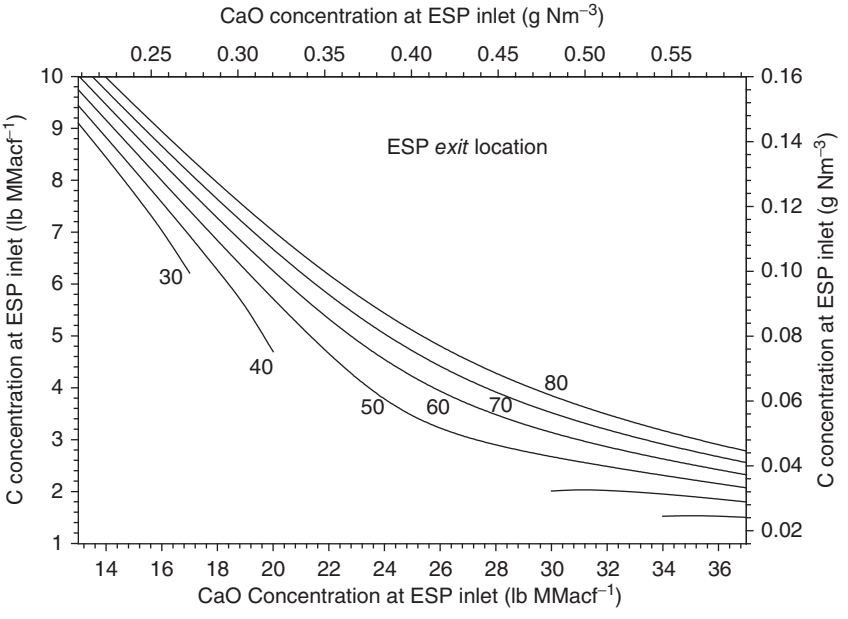

Figure 13.3 Predicted Hg removal contours for PRB/eastern bituminous blend tests (ESP exit) [6]. (Reproduced with permission from Ref [6]. Copyright © 2009, Elsevier Limited.)

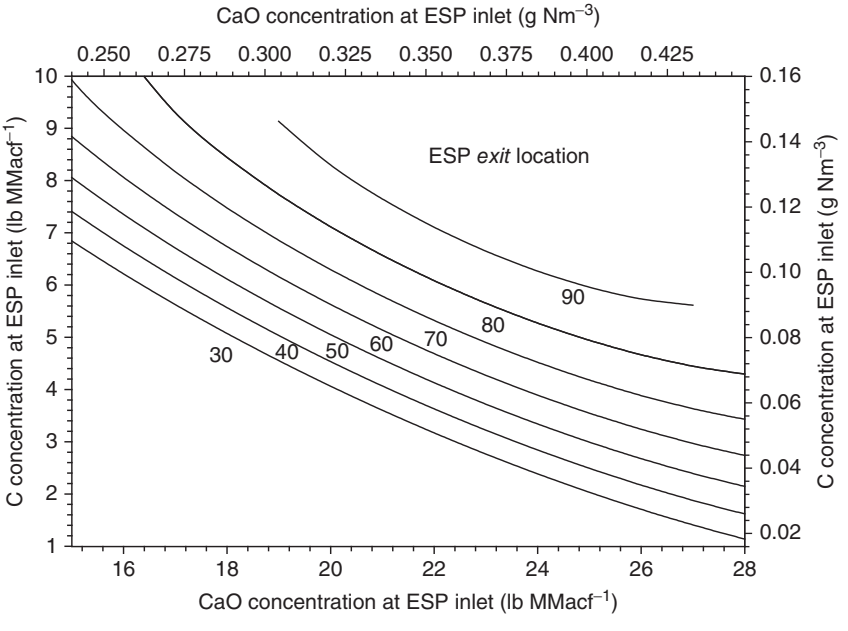

Figure 13.4 Predicted Hg removal contours for PRB/West Elk blend tests (ESP exit) [6]. (Reproduced with permission from Ref [6]. Copyright © 2009, Elsevier Limited.)

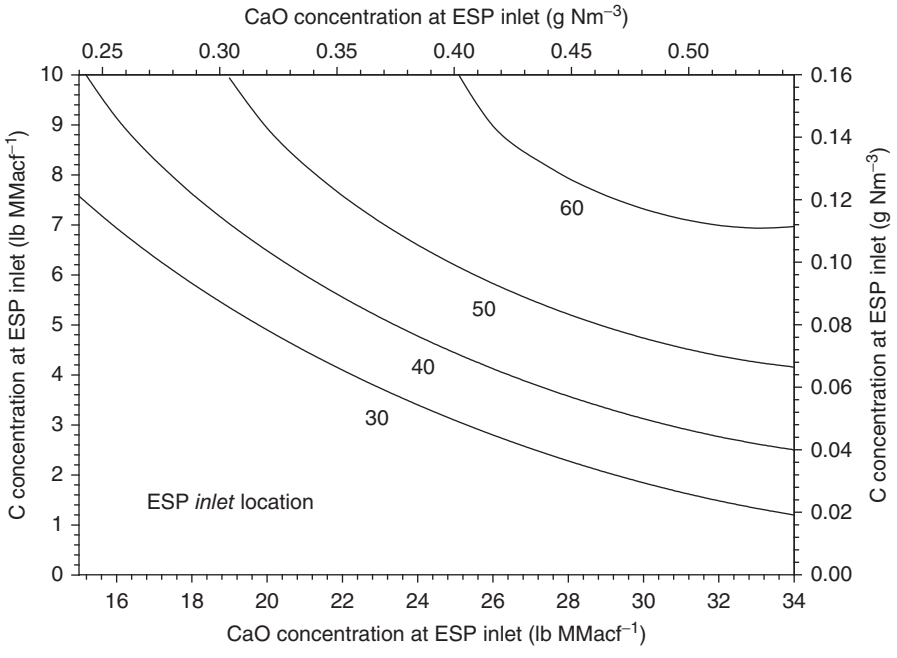

Figure 13.5 Predicted Hg removal contours for PRB/West Elk blend tests (ESP inlet) [6]. (Reproduced with permission from Ref [6]. Copyright © 2009, Elsevier Limited.)

Furthermore, the calcium/carbon synergism work by Gale *et al.* [1, 5, 6], was confined to relatively low-chlorine coals, that is, with flue-gas concentrations below 50 ppmv.

13.4 Potential Combustion Modification Strategies to Mitigate Mercury Emissions

Coal blending, although technically not a combustion modification, is a way to change the nature of the combustion by burning a different fuel type with a more or less active carbon type, more or less moisture, and more or less calcium than normally fired, all of which have the potential to impact the overall mercury removal strategy. The specific application of this method will vary significantly from plant to plant, depending on the plant configuration, coal type currently being burned, efficiency of the boiler, and availability and cost of different coal types.

Several specific examples are provided for clarification.

In a power plant that currently fired PRB coal, did not have an SCR or wet scrubber, and had a fairly high furnace efficiency, such that the UBC in the flyash was 0.1% or less, co-firing with a higher rank coal, well up on the coalification curve would likely increase the mercury capture to perhaps 80% or 90% across the ESP or even more across a baghouse.

A similar but much less efficient power plant that burned bituminous coal, resulting in >10% UBC in the flyash, may be able to significantly reduce mercury emissions by blending with or switching completely to PRB coal. If so, the power plant would have the added benefit of a much lower UBC concentration in their flyash.

Although these examples are realistic, it is not likely that the anticipated regulatory standards can be met through coal blending alone, as most standards are anticipated to require >95% removal of the mercury from the flue gas, which is unlikely to be achievable by coal blending for most power plants.

Reduced combustion efficiency is another way to increase the UBC concentration in the flyash and thereby increase the mercury removal in the particulate collection device (PCD). This would be most effective while burning PRB coal or lignite and would provide the least problem with high UBC concentrations in the ash. However, increasing the UBC in the flyash while firing PRB or lignite is quite difficult, because of the highly active carbon type.

It should be understood that if this approach is taken to increase the UBC in the flyash, it must be done in a way so as to only increase the UBC from the char. If radical measures are taken to produce a highly unstable flame or channeling of gases that are not completely burned, there is a possibility that some of the UBC produced will be from unburned volatile matter. Carbon produced in the ash from unburned volatile matter, or soot, will not produce the desired results. Soot once formed through incomplete combustion of volatiles is unreactive and will not provide an active carbon concentration in the flyash for the promotion of either mercury oxidation or capture.

Reburning is a technology where fuel is fired in the furnace downstream of the main burners to reduce NO_x that were formed in the primary combustion zone, by creating a reducing zone at the location of the reburning. As the objective of reburning is to create a reducing zone, there will be less oxygen needed to burn all of the solid fuels and so provides a great opportunity to combine this technology with production of activated carbon types for mercury adsorption in the flyash. Reburning can be done with natural gas, but it can be done with a variety of different solid fuels, including the same coal that is fired through the main burners. If the reburning system is designed for both the reduction of NO_x and for limited burnout and activation by steam, the cost should be reasonable to solve both the NO_x and Hg emissions problems. This may be a possible approach for smaller plants that are trying to extend their life and cannot afford to add an SCR unit for deNO_x.

Furnace intrusion modifications is the final area of combustion modification possibilities for existing coal-fired power plants. This broad area of modification requires intrusion into the furnace itself to either add equipment or redirect part of flame flow downstream of the furnace. An example of such a modification would be a highly isolated jet of inert gas that was directed through part of a flame or the whole furnace, sweeping unburned char out of the flame zone, and transporting it downstream unreacted and quenched so that it would not continue to burn. Another example would be a mechanical device or high-temperature vanes in a

boiler that would extract some of the char from the flame zone downstream before it was completely burned out.

The Thief Process is an example of a commercial Furnace Intrusion Modification [15]. The Thief Process extracts coal out of the flame zone through a pipe outside the furnace and then reinjects the UBC downstream where it can be used as a sorbent to capture mercury.

13.5
Effects of Combustion Modifications on Mercury Oxidation across SCR Catalysts

13.5.1
Inhibition of Mercury Oxidation can Occur in Low-Chlorine Flue Gas

Although it is unlikely that combustion modifications would be used as a mercury mitigation strategy at a power plant where an SCR was installed for deNO_x, combustion modifications, or tuning for other reasons can have a significant effect on mercury oxidation across the SCR catalyst. Walsh *et al.* [16] showed that as little as 10 ppmv of CO can significantly inhibit the oxidation of mercury across an SCR catalyst in flue gas with an HCl concentration of 2.0 ppmv, which is typical of the HCl concentration at some plants firing PRB coal. Hence, care should be taken when considering combustion modification that might increase the CO concentration when firing a low-chlorine coal and using an SCR to oxidize mercury.

At chlorine concentrations as high as 50 ppmv, there was no effect of the CO concentration on mercury oxidation.

Although ammonia slip can inhibit mercury oxidation across SCR catalysts in low-chlorine flue gas, the concentration of NO treated has little impact [17]. Nevertheless, efforts to change UBC or lower NO through combustion modifications could have negative impacts on mercury oxidation across an SCR by increasing the concentration of carbon monoxide.

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14
Fuel and Flue-Gas Additives

John Meier, Bruce Keiser, and Brian S. Higgins

14.1
Background

The primary mercury oxidation pathway during coal combustion occurs as a function of coal halogen content and subsequent release during the combustion process. Native oxidation occurs [1] through the reaction of mercury with HCl (or Cl^- or Cl_2 produced by the Deacon reaction [2]), utilizing the inherent chlorine in the coal.

The easiest and most readily available method to increase mercury oxidation is through the introduction of halogen-containing material to the fuel before combustion. Typical methods include treating the coal with a liquid solution containing halogen salts, such as $CaBr_2$ or $CaCl_2$. These salt compounds vaporize and dissociate, or react during combustion, to form molecular halogen compounds or precursors in the flue gas, primarily forming HBr, Br_2, HCl, and Cl_2. These halogen species then oxidize elemental mercury to its oxidized form, which is readily capturable across downstream air quality control devices.

Additives to promote enhanced mercury capture were first implemented to augment mercury capture by activated carbon. Initial generic-powdered activated carbon injection (ACI) studies noted that with low chlorine fuels (e.g., $<200\,\mu g\,g^{-1}$) there was poor mercury removal relative to units burning higher chlorine coal (e.g., $>500\,\mu g\,g^{-1}$) [3]. Because of this result, manufacturers began impregnating the activated carbon with various halogen additives (i.e., iodine, chlorine, or bromine). While all of these halogens are effective in oxidizing mercury and facilitating activated carbon mercury capture [4], bromine-based additives have often exhibited the best cost performance.

An additional factor affecting mercury capture by activated carbon is the flue-gas temperature. At elevated flue-gas temperatures, approaching 200 °C, activated carbon efficiency is reduced, specifically for elemental mercury [5]. By increasing the portion of oxidized mercury in the gas stream, high-temperature mercury capture is improved with activated carbon.

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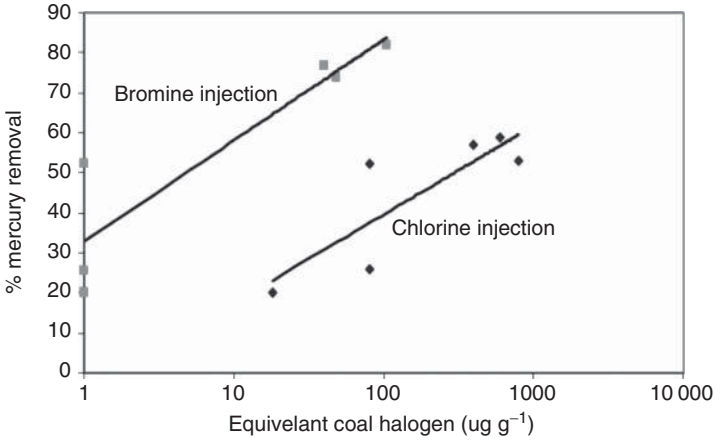

Figure 14.1 Mercury oxidation in coal-fired boilers with bromine and chlorine addition .

The effect of the concentration of several halogen-based oxidants have been considered by Senior *et al.* [6] Figure 14.1 illustrates the difference in native capture as a function of halogen concentration in the coal, where the halogen concentration is artificially augmented. Increased mercury removal is directly attributed to higher halogen concentration before coal combustion. In this study, bromine addition reaches 80% mercury removal (Br ~ 100 μg g^{-1}), while the peak mercury removal with chlorine (Cl ~ 1000 μg g^{-1}) does not exceed 60%, even with a concentration 10-fold larger.

14.1.1
Bromine-Salt Mercury Oxidation

The case studies presented here show results from injecting a bromine salt solution into a boiler to produce a molecular halogen or molecular halogen precursor, which promotes mercury oxidation. The proprietary bromine salt solution injected by Nalco is branded as MerControl® 7895 technology. In the results that follow, the data is presented as micrograms per gram, representing the number of micrograms of *MerControl 7895 solution* per gram of coal. This is equivalently referred to as milligrams per kilogram or parts per million weight.

14.1.2
Fuel Additive Injection Equipment

The application of halogen salt solutions is typically to the coal before injection into the furnace. The point of application is usually at the coal feeders just before the pulverizers. Permanent injection systems include a bulk storage tank, metering pumps, and injection assemblies. The pumps are controlled relative to plant operational data; for example, coal flow, gross mega watts, and/or

outlet mercury speciation (when a plant continuous mercury monitor (CMM) is available). The injection point is a simple lance comprising an open-ended stainless steel tube, without a nozzle, or a constriction, which may plug. An even distribution of the product across the coal flow is not required at the application point as the additive will be well mixed with coal during the pulverization process.

Different precombustion application locations have been investigated, at various points from the coal yard to the burners. The application equipment is less expensive the further upstream the chemistry is added. Alternatively, the control response to a downstream feedback control parameter (e.g., a stack mercury measurement) is faster the further downstream the chemistry is added. However, these differences are slight and neither approach appears to have a strong advantage over the other.

Alternative injection strategies include injecting the oxidizer additives directly into the boiler or in the back-pass through a grid injection system.

Injection into the boiler can be performed by using compressed or fan-boosted air to facilitate mixing. Often, this is performed by combining the oxidizer injection with other air or chemical injection systems such as over-fired air or a selective noncatalytic reduction (SNCR) system. The key point is to confirm that there is good mixing with all of the flue gas. One reason to pursue this approach is to remove the bromine from the coal handling and milling systems; however, an operational performance advantage to doing this has not been established.

Halogen-containing solutions can also be injected into the flue gas downstream of the economizer using a grid injection system. The decreased flue-gas temperature at this injection point may require the use of a larger quantity and/or a more hazardous reagent, such as hydrobromic acid. Either may raise the costs and safety concerns with handling and storage. Again, good mixing needs to be confirmed. It has not been demonstrated that injection downstream of the economizer is more effective or more economical than precombustion addition of halogen salts.

14.1.3 Case Study Results

The following two sections present results from different case studies. The first section summarizes conditions where an halogen based fuel additive will likely lead to advantageous performance and the second summarizes conditions where there is likely not an advantageous performance.

Note that every boiler application must be individually analyzed, as results are heavily dependent on flue-gas temperatures, coal constituents, post combustion temperatures, mixing, residence time, metal surface characteristics, and, most importantly, the operation of downstream air pollution control devices. Nalco commonly demonstrate the effectiveness of fuel additives, with and without activated carbon, through field trials to help our clients fully understand the cost–benefit of various operational scenarios.

14.1.3.1 Case Studies where Halogen-containing Fuel Additives are Advantageous

Nalco has performed a number of demonstrations with fuel additives with the specific goal of reducing mercury compliance costs. In this section, the results from three case studies are reviewed:

Case Study One: Optimized carbon and halogen-containing additive for preservation of fly ash quality in concrete reuse
Case Study Two: Bituminous coal with performance shortfalls and SCR (selective catalytic reduction)/wFGD (wet flue-gas desulfurization)
Case Study Three: Subbituminous coal with high fly ash unburned carbon.

Case Study One: Optimized Carbon and Halogen Oxidizer for Concrete Applications

The demonstration site for this case study was a 615-MW boiler, burning low-sulfur subbituminous coal. The boiler was equipped with low-NO*x* burners and a cold-side electrostatic precipitator (CS-ESP) for particulate control. No desulfurization equipment was installed [7]. The coal chlorine content averaged 100 $\mu g\, g^{-1}$ during the demonstration, resulting in only 30–35% native mercury oxidation during baseline measurements.

The goal of this demonstration was to achieve 90% mercury capture, with <2 $lb\, MMacf^{-1}$ activated carbon addition rates. Through previous testing, the client had determined that at <2 $lb\, MMacf^{-1}$ activated carbon addition, the fly ash integrity was sufficient to permit economic reuse as a concrete feedstock.

A temporary MerControl 7895 technology injection system was installed, with injection occurring at the coal feeders before the pulverizer. ACI was injected both before and after the air heater. However, the injection before the air heater produced much better results and therefore only these data are presented.

Case Study One: Results Two temporary CMMs were installed at the exit of the economizer and at the stack. The inclusion of the inlet CMM was to provide information regarding changing coal conditions and was considered representative of the coal mercury concentration.

In Figure 14.2, injection of over 2.5 $lb\, MMacf^{-1}$ of a standard halogenated activated carbon, introduced before the air heater, resulted in about 91% mercury capture. Also, in Figure 14.2, two nonhalogenated activated carbons were injected with the application of a fuel additive, MerControl 7895 technology. ACI-I is a higher reactivity carbon designed to be used in conjunction with fuel additives. ACI-II is a standard nonhalogenated activated carbon. The significant difference in performance between the two activated carbons emphasizes that all activated carbons are not equal in terms of performance when used in conjunction with fuel additives.

ACI-I required 50% less carbon than ACI-II to reach 91% mercury capture, using the same fuel additive injection rate (168 $\mu g\, g^{-1}$). ACI-I, with a fuel additive concentration of 168 $\mu g\, g^{-1}$ in coal, required 80% less carbon to reach 91% mercury capture, when compared to results obtained with a standard halogenated activated carbon alone.

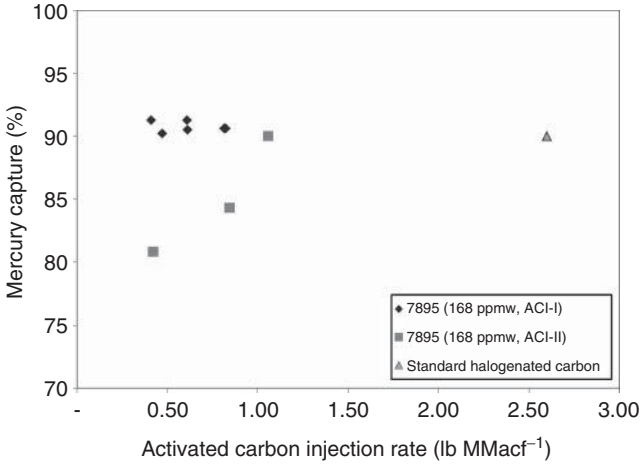

Figure 14.2 Mercury capture as a function of the activated carbon injection rate, with and without MerControl 7895 technology injection.

The 2.5 lb $MMacf^{-1}$ injection rate with the halogenated activated carbon did not meet the initial requirements of 90% mercury capture at <2 lb $MMacf^{-1}$ injection rates to preserve fly ash quality. The application of halogen-containing fuel additive and a greatly reduced activated carbon flow rate met both of the client's goals and resulted in the lowest annual compliance cost.

Case Study Two: Bituminous Coal with Performance Shortfalls and SCR/wFGD Typically, halogen-containing fuel additives are discussed with respect to application on low-chlorine, subbituminous, fuels [8]. The reason is that bituminous coals usually have sufficiently high levels of chlorine to oxidize most of the mercury. This is particularly true when there is also an SCR present. However, as shown earlier, even with high levels of chlorine, mercury oxidation is limited, and cannot reach as high a level of mercury oxidation as a bromine-based fuel additives.

Oxidized mercury is readably soluble in water, specifically in wFGD systems. Elemental mercury is not readably soluble in wFGD water. Units with a wFGD system are limited in mercury capture by their mercury oxidation rate. If 80% of the mercury entering the wFGD is oxidized and reemission is controlled, 80% mercury capture across the wFGD is expected. Because bromine-based fuel additives increase the oxidation of mercury, it also increases the unit overall mercury capture in a wFGD.

Case Study Two: Results The case study outlines the application of a bromine-based fuel additive on a 195-MWe high-chlorine bituminous-coal-fired boiler, equipped with an SCR for NO*x* control, a wFGD for SO_2 control, and a CS-ESP for particulate control. The typical coal chlorine level was around 1600 $\mu g\, g^{-1}$ of fuel, which in combination with the SCR should have resulted in excess of 90% mercury oxidation and subsequent capture in the wFGD. SCR catalysts typically increase the oxidation rate of mercury in the presence of high concentrations of chlorine.

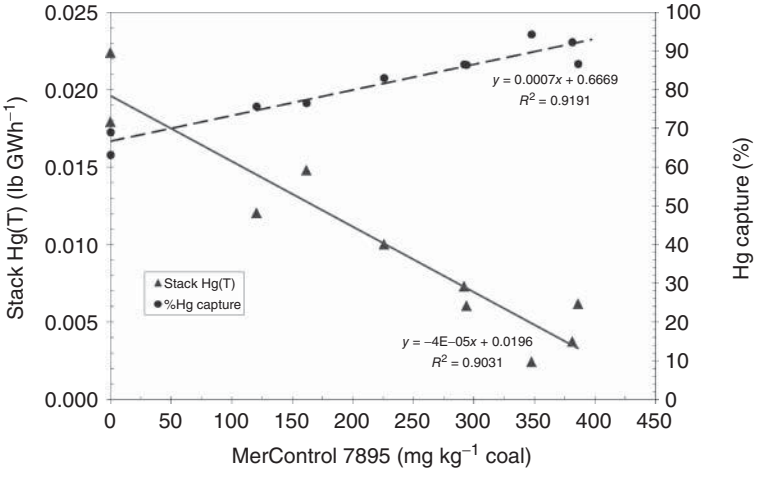

Figure 14.3 Decreasing stack emissions (left) and increasing mercury capture (right) shown for increasing MerControl 7895 technology concentration.

However, owing to the catalyst type and age, mercury oxidation was limited to 70% as observed in previous testing and validated with Ontario Hydro (OH) measurements [9] performed during the baseline observation.

In order to increase the mercury oxidation, a MerControl 7895 solution was applied using a temporary injection system. OH measurements were performed daily, and were validated against Environmental Protection Agency (EPA) Method 30B [10] carbon traps. As with CMMs, halogens can result in fouling of the OH impinger trains, so it is important to validate measurements with an alternative reference method to ensure data accuracy.

The results of the addition of MerControl 7895 technology are shown in Figure 14.3. The mercury oxidation rate during baseline measurements was suggested to be about 80% and the overall mercury capture rate was about 70%. The wFGD was estimated to be nearly 100% efficient in removing oxidized mercury and showed no evidence of reemission. The reason the mercury capture rate is less than the mercury oxidation rate is due to an estimated 5–10% of the flue gas bypassing the wFGD through a leaking flue gas bypass damper.

With increasing dosage rates of MerControl 7895 technology, there is a linear decrease in stack emissions, as shown in Figure 14.3. With the addition of at least 265 mg MerControl 7895 technology per kg coal, the client was able to maintain their required emission rate of 0.008 lb GWh^{-1}, equal to a net 85% mercury capture rate, which includes the bypass damper leakage.

Using the wFGD as the primary mercury removal mechanism was highly desired by the client relative to the injection of activated carbon. High-sulfur bituminous coal burning units with SCRs result in formation of high levels of SO_3 in the flue gas. The deleterious effect of SO_3 on activated carbon performance is well known, resulting in greatly increased ACI rates required to maintain high levels of mercury removal. We estimate that 5–7 lb $MMacf^{-1}$ of ACI would

be required to reach the same removal rate as 265 $\mu g\,g^{-1}$ of MerControl 7895 technology because of the CS-ESP as the primary particulate control device and the high levels of SO_3. Because of this, the MerControl 7895 technology application resulted in substantial savings compared to an option with ACI alone.

Case Study Three: Subbituminous Coal with High Fly Ash Unburned Carbon[†] For units that are not equipped with a wFGD, the primary mercury removal mechanism is formation of particulate mercury. Mercury absorbs on the surface of a carbonaceous material, such as injected activated carbon or unburned carbon from the combustion process. Units with high unburned carbon in the fly ash, typically >2% loss on ignition (LOI), do not require much, if any, activated carbon to be injected because the carbon in the fly ash is adequate to achieve high levels of mercury capture when in the presence of high levels of oxidized mercury. For units that produce a high fraction of elemental mercury (e.g., >20%), the addition of an halogen-containing fuel additive can increase total mercury capture through oxidation and adsorption onto the unburned carbon in the fly ash.

Not all unburned carbon is created equal in terms of oxidized mercury capture efficiency. Owing to high volatility and moisture content, subbituminous coals typically produce higher quality unburned carbon in terms of capturing mercury, relative to bituminous coals. Subbituminous fly ash has better performing pore size, better carbon distribution throughout the ash, more favorable alkali content, and higher surface area resulting from the thermal activation processes that occur during combustion.

If no activated carbon is required, the total capital cost for a halogen-containing fuel additive mercury can be 20% that of an ACI system. Typically, annual operating and maintenance (O&M) costs are substantially lower as well.

Case Study Three: Results The injection of a halogen salt solution was demonstrated on a tangentially fired, 400-MW boiler burning subbituminous coal. The boiler was equipped with low NO*x* burners and a CS-ESP, for particulate control. Before the demonstration, the unit was in compliance with their mercury regulation (0.008 lb GWh^{-1}) by injecting approximately 1.7 lb $MMacf^{-1}$ (~61 kg h^{-1} at full load) of a relatively concrete-friendly halogenated activated carbon. The injection location during normal operation occurred after the air heater through eight injection lances. The goals of the fuel additive demonstration were as follows:

- Reduce ACI flow rates to permit high-value fly ash resale for concrete manufacture. High amounts of activated carbon present in the fly ash causes discoloration when used for concrete manufacture, and also increases the amount of air entrainment chemicals required.
- Decrease overall compliance costs, while maintaining their regulated mercury emission limit.

Selling fly ash for concrete manufacturing can be a significant revenue stream for coal-fired utilities. If the fly ash is unsuitable for concrete, the utility will be

[†] These results have not yet been independently published.

forced to landfill their ash off site at considerable cost. Therefore, poor fly ash quality impacts the utility's profitability by both the loss of sale and the price to landfill. Two main concerns with the quality of fly ash are air entrainment and structural integrity. Activated carbon, while not the only factor, will negatively affect the quality of fly ash by preventing proper air entrainment of the concrete. By reducing the amount of activated carbon used during normal operations, halogen-containing fuel additives can help produce fly ash suitable for concrete manufacturing.

Given the client's goals, we implemented an approach to (i) determine the effect of MerControl 7895 technology on reducing activated carbon consumption rates and (ii) determine the effect of changing the injection location of the activated carbon to upstream of the air heater to further reduce the activated carbon flow with and without MerControl 7895 technology. Gas-phase measurements were provided by an independent third party using two CMMs, one placed at the inlet of the ESP and the other at the stack. CMMs can become fouled during the addition of halogen-containing fuel additives. In order to verify the CMM accuracy, EPA Method 30B carbon trap sampling should always be performed to validate the CMM.

We have found that inlet CMM measurements provide essential information related to process variation and changes in coal mercury concentration. By monitoring the inlet mercury concentration, we can account for process variables that otherwise could systematically affect the results and lead to incorrect conclusions. When coal analyses are solely used to determine inlet mercury concentration, we have found that this does not work as well and does not illuminate process variable effects.

We applied a liquid-based bromine salt solution (MerControl 7895) to all five of the coal feeders. The MerControl 7895 product was delivered to site in 240-gal Schutz totes. A pump-and-control skid provided product pressure, flow control, and flow rate measurements. Temporary injection lines were provided from the pump skid to the injection nozzles, installed on the coal mill feeders. As part of this project, we also provided movable ACI lances to be able to inject carbon before the air heater. The demonstration was completed in under 2 weeks.

Fly ash samples acquired during the demonstration showed LOI values over 2.0%. This level of LOI provided adequate sites for mercury adsorption during application of MerControl 7895 technology. As shown in Figure 14.4, the addition of $10\,\mu g\,g^{-1}$ of MerControl 7895 technology produced mercury emissions $<0.005\,lb\,GWh^{-1}$, below the required emission rate of $0.008\,lb\,GWh^{-1}$. The application of MerControl 7895 technology reduced overall compliance cost by over 90% compared to the application of activated carbon.

14.1.4 Case Studies where Conditions Are Disadvantageous to Fuel Additive

There are several conditions in which the utilization of fuel additives is unlikely to provide economic justification. These need to be considered on a case-by-case basis.

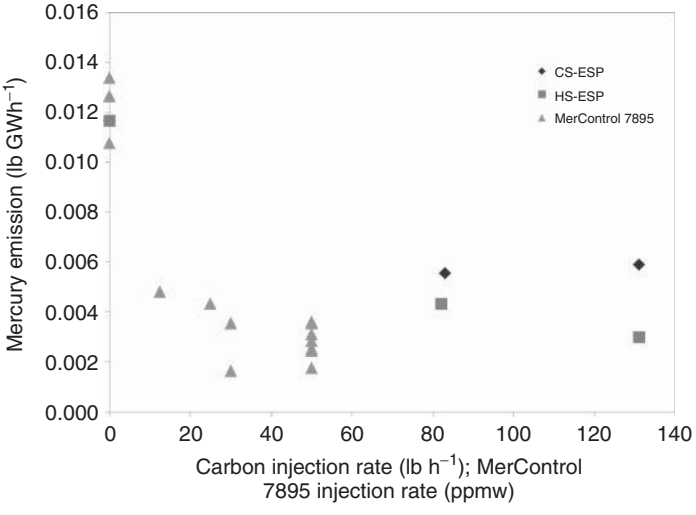

Figure 14.4 Decrease in mercury emissions for increasing carbon and MerControl 7895 technology injection rate.

14.1.4.1 Units Burning High Chlorine Fuel with an SCR

SCR systems have a synergistic effect with available chlorine in the combustion gas in oxidizing mercury. Units burning fuels containing chlorine over 800 μg g^{-1} and employing an SCR will typically result in over 90% mercury oxidation. Addition of halogen-containing fuel additives is unlikely to show benefit for these conditions because of the high inherent mercury oxidation rates. Some catalysts contained in the SCRs are less effective than others in oxidizing mercury, and application of fuel additives may still be beneficial.

Generally, the combination of high chlorine and an SCR should not require fuel additives. However, additives can be used to augment deficiencies in fuel chlorine content or SCR function.

14.1.4.2 Subbituminous Fired Units with Flue Gas Conditioning (SO_3 Injection)

A significant fraction of subbituminous fired units inject SO_3 into the ductwork to modify ash resistivity. This, in turn, increases the collection efficiency of the ESP. The injection of SO_3 reduces the performance of activated carbon, requiring relatively high levels of ACI compared to similar configurations without SO_3 injection. These high levels of ACI virtually always spoil the ash for resale.

We have found for these cases that the benefits from applying a bromine oxidizer are rarely economical. This is primarily due to specialty activated carbons that are better suited for high SO_3 applications without the co-benefit of using halogen-containing fuel additives.

For boilers that have high SO_3 concentrations, injected to improve ESP function, and also have a wFGD, the use of halogen-containing fuel additives would be economically justified. These configurations are infrequent because of low sulfur content traditionally found in subbituminous coals.

14.1.4.3 Units without Acid Gas Scrubbing and a Fabric Filter (FF)

Units employing a FF for particulate control, but without a spray dry absorber (SDA) or wFGD, will see little benefit from the application of a bromine-containing fuel additive. Compliance costs are generally low for this condition, typically requiring <1 lb $MMacf^{-1}$ halogenated ACI to reach around 90% mercury capture. Compliance costs are so low for this configuration that there is typically not enough economic opportunity to reduce the ACI rates to justify the use of a halogen-containing fuel additive.

There are other considerations that can make the addition of halogen-containing fuel additives attractive for these configurations, such as increased fly ash quality because of reduced ACI rates with addition of halogen-containing fuel additives or the inclusion of an SCR, reducing the typically required dosage rates of halogen-containing fuel additives.

14.2 Summary

Elemental mercury can be difficult to remove using existing air pollution control equipment. The addition of halogen-containing fuel or flue-gas additives to promote mercury oxidation can increase overall mercury capture, decrease compliance costs, and/or reduce activated carbon requirements. The efficacy of halogen-based oxidizers is subject to a number of operational parameters (e.g., flue-gas temperature, unburned carbon, and ash alkalinity), and as such, low-cost trial demonstrations are often used to show results.

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15
Catalysts for the Oxidation of Mercury

April Freeman Sibley

15.1
Introduction

In December of 2011, the United States Environmental Protection Agency (EPA) issued an emissions standard aimed primarily at mercury but an extensive list of other hazardous air pollutants as well. The regulation was finalized in February of 2012. Targeted toward coal and oil-fired electric generating units, this rule requires applied and potentially newly installed emission control technologies to meet these standards using a maximum achievable control technology application as stemming from the Clean Air Act. In response to this regulation, it has been noted that an approach of utilizing existing emissions control systems retrofitted in the current fleet and capitalizing on a co-benefit strategy as a likely option.

This section discusses the applicability of selective catalytic reduction (SCR) catalysts in the oxidation of mercury contained within the flue gas from coal combustion as it pertains to mercury control using existing technology. Through various operating conditions, multiple responses to varying levels of mercury oxidation can be observed. Factors that affect mercury oxidation include temperature, halogen concentration in the flue gas (from the coal type burned), flow rate, and rate of deNO*x* (or ammonia concentration in the flue gas). By optimizing the rate of mercury oxidation, co-benefit capture can be observed downstream in the wet FGD (flue gas desulfurization) vessel and this could make it easier to comply with potential future mercury emissions regulations. Contained within this section are various tables, figures, and data to substantiate this application.

15.1.1
Process Overview

Mercury emissions from coal-fired boilers can be characterized into three main forms: elemental mercury (Hg^0), oxidized mercury (Hg^{2+}), and particle-bound mercury (Hg^p). The concentration of Hg^0, Hg^{2+}, and Hg^p primarily depends on coal composition and combustion conditions. During combustion, Hg^0 is liberated from coal. In the high-temperature regions of coal-fired boilers, mercury

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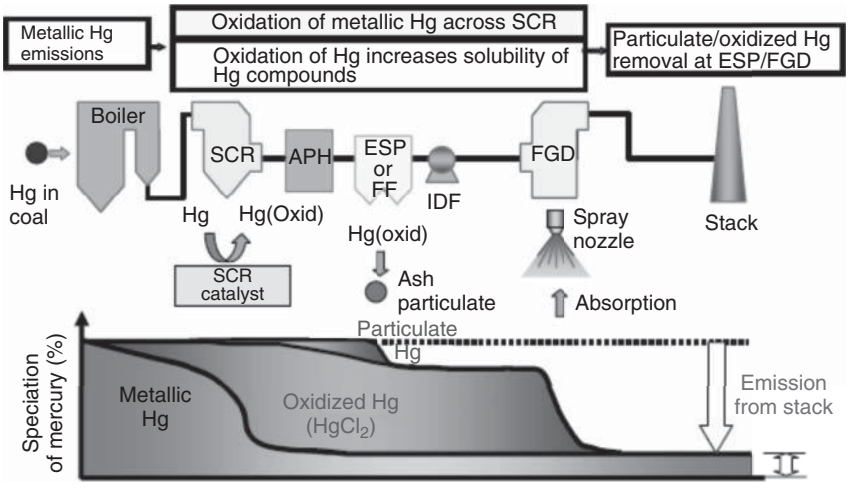

Figure 15.1 Typical behavior of mercury.

in coal is volatized and converted into the elemental form. However, depending on the coal type, a significant fraction of the mercury can be oxidized, as well as become associated with the fly ash particles in the post-combustion environment of a coal-fired boiler. Relative to Hg^0, Hg^{2+}, and Hg^p are more effectively captured in conventional pollution control systems, such as FGD systems, fabric filters, and electrostatic precipitators (ESPs). The identification of a process for converting Hg^0 to Hg^{2+} and/or Hg^p forms would improve the mercury removal efficiencies of existing pollution control systems. Mercuric chloride compounds are soluble and can be captured in FGD systems used for SO_2 removal. It is known that the catalysts used for SCR of NO*x* compounds can exhibit the co-benefit of promoting mercury oxidation. In addition to catalyzing the decomposition of NO*x* compounds to form nitrogen and water, the metal contents of the SCR catalysts have been shown to aid in the oxidation of elemental mercury into a water-soluble compound form. Figure 15.1 depicts the behavior of Hg through a typical eastern bituminous SCR-ESP-wFGD (wet flue gas desulfurization) system [1].

15.2
Hg Oxidation and Affecting Parameters

Upon focusing on the operations of the SCR and its affect on the oxidation of mercury, it is important to note some key areas. The potential contributing factors that can affect mercury oxidation across the SCR reactor include reaction with the catalyst, increased residence time, change in flue gas chemistry (including, but not limited to, the reduction in NO*x* concentration), and reaction with NH_3. Some tests conducted within various electric generating fleets show clearly that for low-halogen flue gases, increases in flue gas chlorine and/or bromine levels will have beneficial effects on SCR mercury oxidation. To capitalize on this effect, facilities

may consider the artificial adjustment of halogens, through direct injection or fuel additives. In addition, tests have shown that direct injection of hydrogen chloride before an SCR can enhance mercury oxidation across the SCR and this will likely enhance the overall mercury removal at sites equipped with an SCR-ESP-wFGD. The data show that lower temperature operation of the SCR will help maximize SCR mercury oxidation. Thus, in designing both retrofit and green-field facilities, lower SCR operating temperatures aid in mercury oxidation and capture. For green-field installations, boiler/SCR designs that provide for generally lower SCR temperatures will help maximize the achievable mercury oxidation through the SCR, at least with conventional catalysts. Lower operating temperatures also have potential benefits in terms of minimizing SO_2 oxidation to SO_3, but the benefits of lowering the SCR temperature must be weighed against the possible loss of catalytic activity for NO*x* decomposition (removal).

15.2.1
Hg^0 Oxidation Reaction Mechanism

On the basis of experimental data available, theories suggest that elemental mercury conversion can occur either through a homogeneous or heterogeneous oxidation. In terms of rate order, it appears that the heterogeneous reaction occurs at a faster rate than the homogeneous reaction. Both reactions, however, have a commonality of kinetics limitation. Factors affecting oxidation reaction kinetics include any of the following: fuel type, halogen content of coal, SCR catalyst age and/or type, SCR reactor temperature, and space velocity.

15.2.2
Homogeneous Oxidation of Mercury

During the homogeneous oxidation reaction, elemental gas-phase mercury reacts with other gas-phase constituents, primarily halogens, to achieve oxidation. There is a very specific temperature window of 400–700 °C in which this occurs. This temperature range is key to the abundance of halogen radicals, namely, chlorine, allowing for sufficient oxidation to occur. It is then that the mercury undergoes two steps to reach a more favorable oxidized state, in the form of water-soluble $HgCl_2$. The following equations represent what chemically occurs during the homogeneous oxidation of mercury.

$$Hg(g) + Cl(g) \rightarrow HgCl(g) \tag{15.1}$$

$$HgCl(g) + HCl(g) \rightarrow HgCl_2(g) \tag{15.2}$$

15.2.3
Heterogeneous Oxidation of Mercury over SCR Catalysts

We can propose numerous reaction mechanisms to describe heterogeneous catalytic reactions. The mechanism described as a catalytic reaction will

often fall into one of these three categories: (i) Langmuir–Hinshelwood; (ii) Mars–Maessen/Mars–van Krevelen; or (iii) Eley–Rideal.

The Langmuir–Hinshelwood mechanism involves reaction of two adsorbed species on the catalyst to form the product, as shown:

$$\mathrm{A(g)} \leftrightarrow \mathrm{A(ads)}$$
$$\mathrm{B(g)} \leftrightarrow \mathrm{B(ads)}$$
$$\mathrm{A(ads)} + \mathrm{B(ads)} \xrightarrow{k_{\mathrm{surf}}} \mathrm{AB(ads)}$$
$$\mathrm{AB(ads)} \rightarrow \mathrm{AB(g)}$$

where A could represent mercury and B could represent a halogen such as chlorine.

The Mars–Maessen or Mars–van Krevelen mechanism involves reaction between an adsorbed species (in our case, mercury) and lattice oxygen, or halogen from the catalyst to form the product. The oxygen or halogen is replenished from the gas. The mechanism is depicted here for oxidation of species A by lattice oxygen of the catalyst.

$$\mathrm{A(g)} \leftrightarrow \mathrm{A(ads)}$$
$$\mathrm{A(ads)} + \mathrm{M}_x\mathrm{O}_y \rightarrow \mathrm{AO(ads)} + \mathrm{M}_x\mathrm{O}_{y-1}$$
$$\mathrm{M}_x\mathrm{O}_{y-1} + \frac{1}{2}\mathrm{O}_2 \rightarrow \mathrm{M}_x\mathrm{O}_y$$
$$\mathrm{AO(ads)} \rightarrow \mathrm{AO(g)}$$

The Eley–Rideal mechanism involves a gas-phase species reacting with an adsorbed species to form the product. The mechanism is depicted here.

$$\mathrm{A(g)} \leftrightarrow \mathrm{A(ads)}$$
$$\mathrm{A(ads)} + \mathrm{B(g)} \xrightarrow{k} \mathrm{AB(g)}$$

where A could represent mercury and B could represent a halogen atom such as chlorine.

Niksa and Fujiwara [2] suggest that ammonia and HCl strongly adsorb to the surface of the SCR catalyst, thus creating an environment for surface site adsorption competition. The elemental mercury either in the gas phase contained within the flue gas itself, or as a weakly adsorbed species, eventually contacts the chlorinated sites and the oxidation reaction occurs. The form of this reaction follows the Eley–Rideal rate expression describing the mercury oxidation rate as a function of the ammonia/NO*x* ratio and concentrations of elemental mercury and HCl at the inlet of the SCR as well as catalyst pitch and channel shape, SCR temperature, and the gas space velocity [2]. Other mechanisms suggest that elemental mercury reacts with other constituents either in the gas phase or on the surface of the catalyst or some other solid particle (such as unburned carbon or fly ash), before converting to the more stable $HgCl_2$ form. No one mechanism, however,

has been verified as the primary reaction mechanism for mercury oxidation, possibly because of the multiple components comprising both the catalysts and the flue gas in a real power plant setting. For example, although we may speculate that the tungsten and vanadium species of the SCR catalyst comprise the active phase for mercury oxidation, we must note that there will also typically be catalytically active fly ash particles (containing carbon and numerous metal oxides) present on the catalyst. In addition, if we suggest that a halogen such as adsorbed chlorine on the surface of the catalyst is primarily responsible for the oxidation of mercury, we must note the possibilities (likelihood) of adsorbed oxygen and bromine participating in the oxidation of mercury as well.

15.2.4
SCR Operation-Hg^0 Reaction Effects

Because of the limited knowledge of the exact reaction that occurs during mercury oxidation, little information is available with regard to the effect of operational conditions within the SCR itself. To better understand operational effects, some data has been collected during an array of laboratory and pilot scale tests. One particular test conducted between Southern Company and Gulf Power, Electric Power Research Institute (EPRI) and W.S Hinton and Associates, investigated the mercury oxidation behavior of several different commercial SCR catalysts across various operating conditions. The testing occurred at the 5 MWe Mercury Research Center (MRC) located in Pensacola, FL. at Gulf Power's Plant Crist. Parameters such as halogen content in the flue gas, flue gas flow rate, temperature, and ammonia injection, were all varied to measure the mercury oxidation response to these changes.

Research has demonstrated the inhibitive effect of ammonia on the process of oxidizing mercury. Tests have demonstrated that in a low-ammonia concentration environment, the vast majority of the mercury oxidation was observed to have occurred across the first two layers of the three-layer SCR. In the instance of increasing and subsequent high-ammonia concentrations, the reaction zone for the mercury oxidation tended to shift further down in the SCR reactor occurring in the third layer. In one test program performed at the Mercury Research Center in particular, there was a marked increase in the amount of oxidized mercury further down in the SCR catalyst layers, particularly at lower ammonia injection rates.

Owing to the host unit's fuel source containing a very low level of native chlorine in the coal, opportunity existed to vary the levels of halogens into the flue gas to measure the response of mercury oxidation. For the sake of this particular test, chlorine was injected as HCl gas directly into the flue gas. Injection levels ranged from 0 to 150 ppm of chlorine and to ensure minimal interference from ammonia being injected, a constant alpha ratio of 0.9 (or 90% deNOx) was maintained. It was observed that there was indeed a positive response to mercury oxidation levels as the injection rate of chlorine increased.

A key component of any chemical reaction, temperature was varied to observe the response of the mercury oxidation levels. DeNOx activity tends to improve as

temperature increases. In addition, the conversion of SO_2 to SO_3 also increases with increasing temperature. Conversely, the rate of mercury oxidation decreases as the temperature increases. Typically, for a constant rate of gas flow, given a certain geometry of the catalyst pitch, the temperature change will also result in a volumetric flow change. High- and low-temperature operating conditions were created in conjunction with slightly different ammonia injection rates while increasing the chlorine concentration in the flue gas. Although there were varying conditions affecting data collection, the data do show a decline in mercury oxidation as the temperature is increased. It is noted that mercury is a semi-noble metal, and the thermal decomposition temperatures of its compounds, such as mercuric chloride, are relatively modest, possibly explaining this observed effect.

Although it is observed to not have as large an effect on mercury oxidation as other parameters, the flow rate through the SCR was varied and response to mercury oxidation measured. It was noted that flow rate changes in addition have an effect on residence time (gas contact time across the catalyst), mass transfer, and ammonia slip, thus ultimately affecting mercury oxidation. As the flow rate increased, the rate of mercury oxidation decreased, which could be linked to the lowered residence (contact) time and increased ammonia slip throughout the reactor.

On the basis of the research conducted, some general conclusions can be drawn from the data collected. They include (i) chlorine content has no apparent effect on deNO*x* rate, (ii) chlorine concentrations are effective from 0 to 50 ppm, (iii) mercury oxidation is a function of specific surface area of the catalyst, and (iv) lower temperatures within the SCR reactor increase mercury oxidation rates.

15.2.5
Hg^0 Oxidation and SO_2/SO_3 Conversion

In addition to the deNO*x* and mercury oxidation properties that SCR catalysts possess, there is the ability to oxidize SO_2 (present in the flue gas) to SO_3, with conversion being represented by the following equation:

$$SO_2 + 1/2\ O_2 \rightarrow SO_3 \tag{15.3}$$

The SO_3 produced can then combine with water vapor in the flue gas to produce sulfuric acid. Other potential side reactions that can occur in the presence of excess ammonia include the formation of ammonium sulfate and ammonium bisulfate, which can have adverse reactions on both catalyst performance as well as downstream equipment performance (namely, the air preheater). Through proper operation of the SCR (including minimizing ammonia slip, minimizing SO_2 conversion through catalyst formulations, controlling temperature, etc.), ammonium sulfate and ammonium bisulfate formation can be reduced. Formation reactions are described here:

$$2\ NH_3 + SO_3 + H_2O \rightarrow (NH_4)_2SO_4(\text{Ammonium Sulfate}) \tag{15.4}$$

$$NH_3 + SO_3 + H_2O \rightarrow NH_4HSO_4(\text{Ammonium Bisulfate}) \quad (15.5)$$

In an ideal situation, the SCR catalyst would promote the oxidation of mercury and removal of NO*x* in the flue gas while minimizing the conversion of SO_2 to SO_3. Typical SCR operating conditions have made this balance difficult, especially when it has been observed that SO_2 strongly reduces elemental mercury oxidation at high temperatures (>662 °F) [4]. In laboratory operations, catalyst manufacturer Hitachi has observed that while SO_2 conversion rates of conventional SCR catalysts have decreased, corresponding rates of mercury oxidation have decreased. This suggests a close correlation between both mercury oxidation activity and SO_2 conversion activity. It is noted that vanadium oxides are well-known commercial catalysts for the oxidation of sulfur dioxide to sulfur trioxide, and are also a key component of the SCR catalysts.

By changing the active composition of catalysts, one could also control activity of the catalyst, which would affect all of the chemical reactions. Research has shown that the active metal components contained in the SCR catalyst have demonstrated this direct effect on both the conversion of SO_2 to SO_3 and mercury oxidation. In a test conducted by Schwaemmle *et al.* [5] V_2O_5 and WO_3 concentrations were varied to measure the effects on deNO*x* and $SO_2 - SO_3$ conversion. By reducing the amount of V_2O_5 in the catalyst, a decrease in SO_2 conversion was observed. In addition, the removal of WO_3 and subsequent addition of Cu to the catalyst composition resulted in an increased $SO_2 - SO_3$ conversion and a higher deNO*x* activity. By altering the active catalyst compositions while noting performance, such data can aid manufacturers in catalyst development, achieving high deNO*x* and high mercury oxidation while keeping SO_2-SO_3 conversion relatively low. Both the removal of NO*x* as well as oxidation of elemental mercury occur on the surface of the catalyst, and the SO_2 conversion is a diffusion-limited reaction that occurs within the catalyst itself. According to Gretta *et al.* [4], the reaction rate of SO_2 to SO_3 conversion is slower than the diffusion velocity of SO_2 through the catalyst and the reaction rate of mercury oxidation is faster than the diffusion velocity of the mercury through the catalyst owing to its molecular weight. This means that the SO_2 conversion is controlled by the oxidation rate, which is controlled by the active composition of the SCR catalyst. In order to develop the area of optimizing mercury oxidation using SCR catalysts, design must take into account the amount of active components in the catalyst. By altering the catalyst based on the reaction mechanism, allowing the more active sites to oxidize mercury instead of converting SO_2 to SO_3, higher oxidation rates can be achieved while maintaining low conversion rates [4].

15.3
Conclusions and Future Research

While much research has been done to understand the impacts of SCR operations on mercury oxidation, there is still a need to gain better insight on the actual

reaction mechanism. This need is the key to being able to predict oxidation performance given a plethora of catalyst types and formulations. Given certain SCR inlet conditions as well as catalyst properties, one could essentially predict the fate of the mercury across the SCR as well as in downstream equipment, namely, the ESP and eventually the wFGD.

In terms of operations, it is noted that changes in flow rate did not appear to have significant impact upon mercury oxidation. This is important to note because in the case of a load change, the change in temperature is expected to have the greatest impact, rather than any effects due to flow rate. This holds given a moderate turndown in load (roughly 60%). More extreme turndowns may see larger effects in which flow rate does play a significant role, but facilities should not assume that low load conditions are necessarily beneficial in terms of mercury oxidation, especially in cases where the flue gas temperatures do not change significantly [3]. The data also indicate that changes in ammonia will affect the amount of mercury oxidation through the SCR. From the results found, the total effect of SCR reactor conditions is not well noted, but the relationship between ammonia concentration and mercury oxidation performance has been identified.

Available data can be used in a relative sense to determine how various operational changes will affect mercury-related parameters; however, the industry would benefit from information from other catalyst formulations, such as newer formulations designed to enhance the oxidation of elemental mercury, ultralow SO_2 conversion catalysts, and regenerated and spent catalysts. New information will help utilities develop catalyst management strategies to maximize and maintain high levels of oxidized mercury from outage to outage. From a compliance perspective, being able to predict and optimize mercury oxidation using current air pollution control equipment, namely, the SCR, would provide cost-effective options for electric generating fleets, avoiding higher installation costs of more capital-intensive control technologies in an effort to meet a stringent standard.

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16
Mercury Capture in Wet Flue Gas Desulfurization Systems

Gary Blythe

16.1
Introduction

This section discusses mercury removal by wet flue gas desulfurization (FGD) systems installed to remove sulfur dioxide (SO_2) from coal flue gas. This is often called *co-benefit* mercury removal because wet FGD systems are generally installed to remove SO_2, but many achieve a substantial amount of mercury removal from the flue gas as well.

Wet FGD systems work by circulating an alkaline slurry that contains lime or limestone, or a sodium-based alkaline solution, through a flue gas contactor or "absorber vessel" to remove SO_2 and other acid gases from the flue gas. Figure 16.1 is an illustration of a limestone forced oxidation (LSFO) wet FGD process, showing the main components of reagent preparation, flue gas handling and SO_2 absorption, and by-product dewatering. While most wet FGD systems were not originally designed to remove mercury from flue gas, there can be considerable co-benefit capture of mercury under favorable conditions.

As described in earlier sections, mercury in the gas phase of coal flue gases is present in two main forms: elemental or metallic mercury (Hg^0) and oxidized or ionic mercury (Hg^{2+}), with a small amount present as particulate-bound mercury. Oxidized mercury is believed to be present primarily as mercuric chloride ($HgCl_2$) under most circumstances, but may include mercuric bromide if bromide is added to the coal or flue gas to enhance mercury oxidation.

Of the two major mercury forms in flue gas, the elemental form is exceedingly insoluble in aqueous solutions and therefore is not removed at significant percentages in wet FGD absorbers. In contrast, the oxidized forms, as mercuric chloride or mercuric bromide, are very soluble and absorbed into the FGD scrubbing slurry at high efficiency – at or near the gas-film mass transfer limit of the FGD absorber. In most modern FGD systems, the gas-film limit represents 95–99+% capture of soluble gas-phase species from the FGD inlet flue gas.

Thus, ideally, of the oxidized mercury in the FGD inlet flue gas, a high percentage should be absorbed into the scrubbing slurry. For example, if the total mercury at the FGD inlet is 60% in the oxidized form, approximately 57% to greater than

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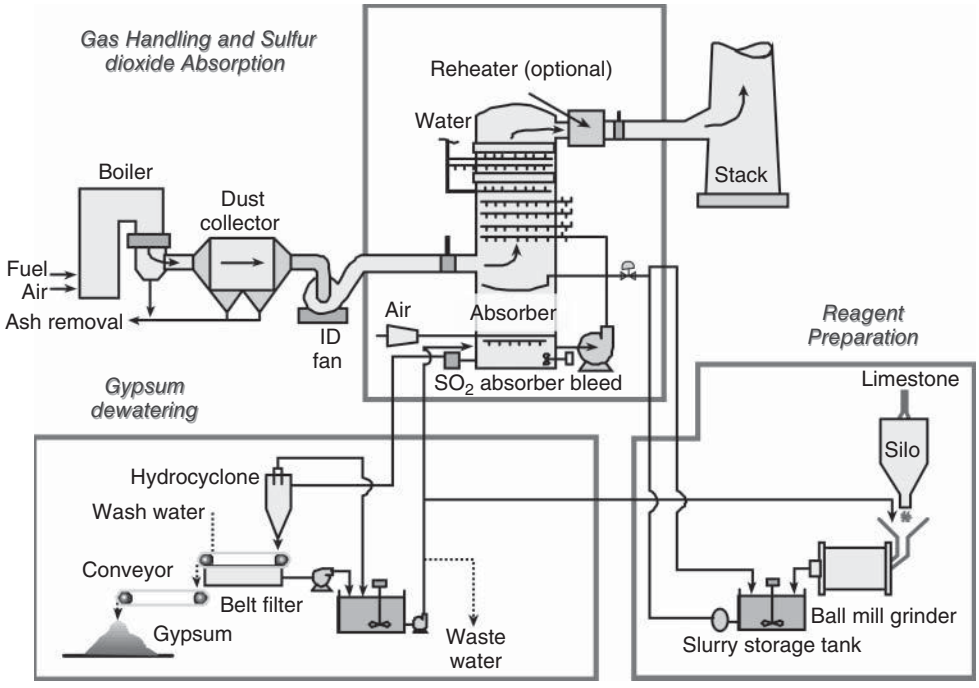

Figure 16.1 Typical limestone forced oxidation wet FGD process.

59% of the total mercury should be absorbed. However, the net removal of oxidized mercury across the FGD system is often limited to lower percentages by a phenomenon called *mercury reemission*, or *reemissions*. In this phenomenon, a portion of the absorbed oxidized mercury undergoes chemical reduction reactions while dissolved in the aqueous phase, and is converted to the relatively insoluble elemental form. Once converted, it is released from the aqueous phase back into the flue gas. Evidence of reemission is seen when the FGD outlet or stack flue gas elemental mercury concentration is measured to be greater than the FGD inlet elemental mercury concentration. Reemissions are discussed in greater detail later in this section.

In the remainder of this section, the capture of oxidized mercury by wet FGD systems is described using two different terminologies to account for the effects of reemissions in limiting net mercury removal. Mercury "absorption" or "capture" is used to describe the transfer of oxidized mercury in the flue gas into the dissolved state in the absorber recirculating slurry, before any reemission reactions. This could be considered the gross capture or removal of oxidized mercury by the FGD system. In contrast, the term *net removal* describes how much oxidized mercury is removed from the inlet flue gas across the FGD system after considering the limitations imposed by reemissions. The initial mercury absorption or capture into the FGD slurry liquor is typically in the range of 95–99+% of the oxidized mercury in the FGD inlet flue gas, while the net removal could be

anywhere in the range of 0–99+%, depending on how significant the reemissions might be. In some cases, the mercury removal across an FGD system can appear to be negative, when in a transient circumstance the inlet mercury concentration to the absorber(s) is lower than the concentration produced by the reemission of mercury from the FGD slurry liquor.

16.2 Fate of Net Mercury Removed by Wet FGD Systems

16.2.1 Phase Partitioning

Mercury is initially absorbed from the flue gas into the liquid phase of the absorber slurry. Once absorbed, it can either remain in the liquor, undergo reemission reactions and be released back into the flue gas as elemental mercury, or be adsorbed or precipitated into the slurry solids.

After being absorbed and dissolved into the aqueous phase of a wet FGD recirculating slurry, oxidized mercury becomes a cationic (positively charged ionic) species. Considering the mercuric salts of the major FGD anionic (negatively charged ionic) species such as sulfate, sulfite, chloride, and carbonate, mercury would be expected to remain in the liquid phase of an FGD slurry; all of these mercuric salts are very soluble. However, the many trace elements present in FGD slurries enter the FGD system by absorption from the flue gas, by capture of fly ash from the flue gas, or from the lime or limestone reagent. Some of these, such as iron (Fe^{3+}) precipitate in FGD slurries, form fine (small particle size) ferri-hydroxides ($Fe_X(OH)_Y$) that can adsorb and/or coprecipitate heavy metals such as mercury. Others such as reduced forms of sulfur (sulfide) and selenium (selenide) form very insoluble salts with oxidized mercury and can result in the precipitation of mercury salts from the aqueous phase into the slurry solid phase. Any or all of these species could be present in FGD slurries in concentrations sufficient to cause a significant phase change of oxidized mercury from the aqueous phase to the solid phase.

The actual mechanism for mercury adsorption/coprecipitation into the solids is not well understood. A number of theories have been considered, and include mercury adsorption/coprecipitation with iron hydroxide fines [1], precipitation as mercuric sulfides [2], or precipitation as mercuric selenides (Bloom, N. (2011) URS Corporation. Personal communication with Gary Blythe, August 2011) and others.

Whether the mercury is found in the slurry solids or liquor is often called the *mercury phase partitioning*. Electric Power Research Institute (EPRI) investigated the phase partitioning of mercury in U.S. wet FGD systems and found that the absorbed mercury can be partitioned over a wide range, from primarily in the slurry liquor to primarily in the slurry solids [3]. Two decades ago, Gutberlet *et al.*, observed that mercury was found primarily dissolved in the liquor phase of LSFO

or gypsum ($CaSO_4 \cdot 2H_2O$) producing wet FGD systems, but primarily in the solid phase of low-oxidation FGD systems that produce calcium sulfite hemihydrate ($CaSO_3 \cdot {}^1/_2H_2O$) as a by-product [4]. At first, this was puzzling to EPRI researchers collecting mercury phase partitioning data on U.S. wet FGD systems, because as mentioned a wide range of mercury partitioning was measured in LSFO systems.

However, on further analysis of the data collected, it was observed that the mercury phase partitioning in forced oxidation FGD systems correlated with the oxidation-reduction potential (ORP) measured in the absorber recirculating slurry. ORP is measured in millivolts and provides a measure of how electrochemically oxidizing or reducing is the chemical environment in an aqueous solution. The more positive the ORP the more oxidizing the environment, while the more negative (or closer to zero) the ORP the more reducing the environment.

ORP measurements are relative to a reference electrode also inserted into the aqueous environment, and each electrode type has its own characteristic electrochemical potential. A "standard hydrogen electrode" (SHE) is defined as having a potential of 0 mV, and this is the defined basis for ORP measurements. Field measurements require a more rugged reference electrode than the SHE, so most FGD ORP measurements are made with a silver/silver chloride electrode in a solution of potassium chloride (Ag/AgCl in KCl), with the KCl solution either 4-M or saturated in concentration. The ORP measurements discussed in this section were all made relative to an Ag/AgCl reference electrode in 4-M KCl, and are reported as measured. These measurement results should have approximately 200-mV added to them to make them equivalent to measurements with a SHE.

Figure 16.2 shows EPRI data for mercury phase partitioning in U.S. wet FGD systems as a function of ORP measured in the absorber slurry. The data for LSFO systems show a consistent trend of increasing percentage of mercury in the liquor phase of the slurry as the ORP increases, although with a few outliers. The linear least-squares fit of the data shown in the plot has an R^2 value of 0.9, indicating a relatively good fit. The LSFO systems show a wide range of mercury partitioning, from virtually all in the solids to greater than 80% in the liquor, over a relatively wide range of ORP from less than 100 to over 600 mV. The underlying mechanism for this apparent correlation with ORP in LSFO systems is not yet fully understood.

The data for low-oxidation (calcium sulfite producing) FGD systems show ORP values of approximately +50 to −50 mV, and the mercury is found primarily in the solid phase. However, the data do not fit the linear correlation made for the LSFO systems, and the reason for the different response to ORP is not apparent.

16.2.2 Mercury in FGD By-product Streams

The recirculating slurry in wet FGD systems contains mostly by-product solids (gypsum in LSFO systems and calcium sulfite in low-oxidation systems) with a small amount of lime or limestone reagent present to provide alkalinity. The reactions with flue gas SO_2 produce solid by-products that must be purged periodically

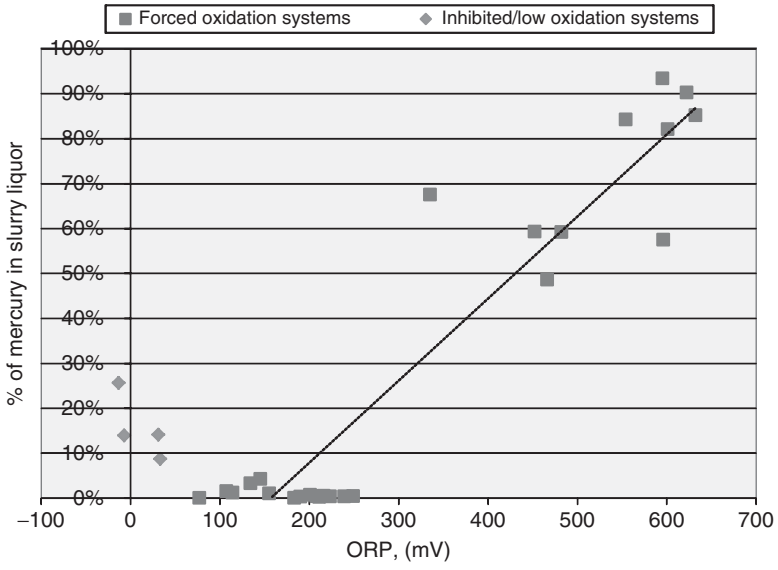

Figure 16.2 Apparent relationship between ORP and phase partitioning of mercury in an FGD absorber slurry. (Reference [5].)

to limit the concentration of suspended solids in the recirculating slurry. This absorber purge stream is dewatered in up to two stages, to produce a damp solid by-product and a low-solid-content liquor stream. In LSFO systems, a portion of the low-solid-content liquor stream is commonly purged to bleed soluble chlorides from the FGD system to prevent excessive chloride concentrations, while the remainder is returned to the absorber. In sulfite-producing wet FGD systems, the sulfite by-product does not dewater as well as gypsum; a separate chloride stream may not be needed, as the water leaving with the dewatered calcium sulfite by-product may adequately control chloride concentrations.

Generally, LSFO systems use hydrocyclones for the first dewatering step, whereas sulfite-producing systems use thickeners (sometimes called *clarifiers*) for the first dewatering step. Figures 16.3 and 16.4 illustrate these two primary dewatering processes. Some early LSFO systems use thickeners for the first step, but hydrocyclones are almost never used in sulfite-producing systems. Both device types produce a low-solid-content liquor overflow and a high-solid-content underflow that can be further dewatered in secondary dewatering processes such as horizontal vacuum belts, drum vacuum filters, or centrifuges. Hydrocyclones produce an overflow that contains approximately 1–5 wt% fine suspended solids, whereas well-performing thickeners produce an overflow with only part-per-million levels of very fine suspended solids. Correspondingly, the two devices produce a different distribution of solids between their overflow and underflow streams.

Hydrocyclones tend to send most of the fine solids in the feed stream to their overflow and most of the coarser solids to their underflow. In contrast,

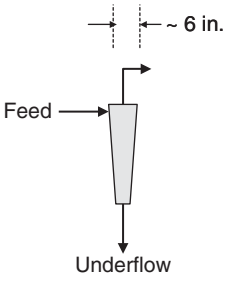

Figure 16.3 Illustration of a hydrocyclone-type FGD primary dewatering system (one of ~10 to 20 per unit is illustrated).

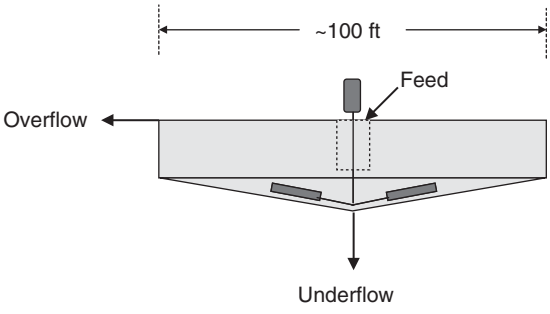

Figure 16.4 Illustration of a thickener-type FGD primary dewatering system (typically one per unit).

well-performing thickeners send almost all of the solids in the feed stream, both fine and coarse, to the underflow. Thus, FGD systems with hydrocyclones tend to recycle an appreciable percentage of fine solids back to the absorber, whereas in systems with thickeners the solids are essentially once through (i.e., no recycle of fine solids).

The sulfite oxidation mode and the types of dewatering devices used in wet FGD systems are described here because they can have a significant impact on how mercury distributes among the solid and liquid by-product streams leaving a wet FGD system. It has generally been observed that mercury is enriched in fine (<20-μm-diameter) solids and is found in a lower concentration in larger solids [5]. This means that in FGD systems with hydrocyclones, the mercury in fine solids tends to get recycled back to the absorber. Because the fine solids have a higher concentration of mercury, the absorber slurry tends to have a higher mercury concentration than the gypsum by-product (hydrocyclone underflow). In systems with thickeners for primary dewatering, the absorber solids tend to have nominally the same mercury concentration as the solid by-product, as the solids are essentially passed through with no size separation.

In systems where most of the mercury is found in the slurry liquor (mostly LSFO systems operated at high ORP), there can be considerable mercury recycle back to the absorber in the hydrocyclone overflow slurry, which is mostly liquor rich in mercury and mostly returned to the absorber. Such a recycle is less common in FGD systems with thickeners, because most are sulfite-producing FGD

systems that operate at low ORP where mercury mostly partitions to the solids, and because it has been observed that liquid-phase mercury concentrations tend to decrease across the thickener. This is likely due to the long residence time in a thickener, during which mercury adsorption and/or precipitation into the solids (or possibly reemission to the atmosphere) can occur.

Correspondingly, in systems that use thickeners for primary dewatering, particularly sulfite-producing wet FGD systems, nearly all of the mercury removed by the wet FGD system leaves with the solid by-product stream. This is largely because in sulfite-producing wet FGD systems, most of the mercury captured by the FGD system is found in the solids. Also, calcium sulfite hemihydrate does not dewater as well as gypsum, so sulfite-producing FGD systems may not require a separate chloride purge stream to control chloride concentrations in the FGD absorber slurry liquor. Thus, there is not a second by-product stream in which mercury can leave the FGD system.

In gypsum-producing wet FGD systems, the mercury removed can be distributed between the gypsum by-product, the chloride purge liquor, and the chloride purge suspended solids. The distribution of mercury among these by-products depends primarily on the ORP at which the absorber(s) operate, the type of primary dewatering device employed, and the weight percent solids in the chloride purge stream. For example, in LSFO systems with a thickener as the primary dewatering device and that operate at low ORP, nearly all of the mercury leaves the FGD system in the gypsum by-product. In contrast, in FGD systems with hydrocyclones for primary dewatering, which operate at high ORP, and/or contain significant fine solids content in the chloride purge stream (e.g., several weight percent solids), the solid and/or liquid portion of the chloride purge stream can represent a significant percentage of the mercury discharge.

16.3 Mercury Reemissions

16.3.1 Definition and Reporting Conventions

As described earlier in this section, mercury reemission describes a phenomenon where oxidized mercury in the flue gas is absorbed in the wet FGD scrubbing slurry, then chemically reduced to the relatively insoluble elemental form and released back into the FGD outlet flue gas. Evidence of reemission is seen when the FGD outlet elemental mercury concentration is greater than the inlet flue gas elemental mercury concentration, when the two concentrations are expressed on a comparable basis (e.g., lb $TBtu^{-1}$ or μg Nm^{-3}@ 3% O_2).

However, it should be noted that making mercury concentration and speciation measurements is sometimes difficult, and FGD inlet and outlet flue gas conditions are much different in terms of temperature and moisture content. Reemissions

are quantified by subtracting one measurement result from another, which often involves subtracting one large number from another to quantify a smaller number by difference. This measurement by difference between two significantly different flue gas matrices can lead to measurement errors. Consequently, it is the author's opinion that reemission levels $<0.5\,\mu g\,Nm^{-3}$@3% O_2 (less than about $0.3\,lb\,TBtu^{-1}$) difference between the FGD inlet and outlet elemental mercury concentrations may be within measurement error. Only if such apparent reemission levels are seen consistently in a series of measurements might such levels be considered "real." Even if the measurement data are consistent, it is possible that apparent reemissions are actually measurement bias artifacts.

Several conventions are used to express reemission levels across an FGD system besides the elemental mercury concentration increase across the FGD system, as described earlier. One is to calculate an observed elemental mercury removal percentage based on FGD inlet and outlet elemental mercury concentrations:

$$\text{Reemission percentage} = (\text{inlet } Hg^0 - \text{outlet } Hg^0) \div \text{inlet } Hg^0 \times 100$$

with reemission being represented by a negative value. However, this percentage can be deceiving because the size of the result is dependent on how large is the inlet elemental mercury concentration. Instead, the author prefers to express reemission levels as a percentage of the inlet oxidized mercury concentration, as it is the oxidized mercury that is removed by the wet FGD system and reduced to the elemental form:

$$\text{Reemission percentage} = (\text{outlet } Hg^0 - \text{inlet } Hg^0) \div \text{inlet } Hg^{2+} \times 100$$

Also, this percentage is a reasonably accurate measure of how much reemission has reduced the overall net mercury removal across the FGD system. However, this percentage result can be misleadingly high when the inlet flue gas contains mostly elemental mercury and/or the inlet oxidized mercury concentration is low. In general, it is best to show reemission levels both as a concentration increase and as a percentage of the inlet oxidized mercury concentration. The two conventions for reporting together provide the best overall measure of how significant the observed reemissions might be.

Table 16.1 illustrates mercury measurements made across an LSFO wet FGD system that was experiencing significant levels of reemissions, both when expressed as an elemental mercury concentration increase across the absorber and as a percentage of the inlet oxidized mercury [6]. In this example, the FGD inlet mercury is 76% in the oxidized form; therefore, in the absence of reemissions approximately 72% to nearly 76% overall mercury capture across the FGD system would be expected. The measured capture percentage of oxidized mercury was high at 95%. However, the measured reemissions (by the Ontario Hydro method [7]) were significant, representing an increase in elemental mercury concentration across the FGD system of $3.4\,\mu g\,Nm^{-3}$ @ 3% O_2, or reemission of 49% of the inlet oxidized mercury. Thus, the net overall mercury capture across the FGD system was limited to only 34% of the FGD inlet total mercury instead of the expected 72–76%.

Table 16.1 Example of reemissions from an LSFO wet FGD system.

Parameter (all Hg concentrations corrected to 3% O_2)	FGD inlet flue gas	Stack flue gas
Hg^0 ($\mu g\,Nm^{-3}$)	2.2	5.7
Hg^{+2} ($\mu g\,Nm^{-3}$)	6.9	0.38
% Oxidized Hg	**76**	—
Total Hg ($\mu g\,Nm^{-3}$)	9.2	6.1
Hg^{+2} capture (%)	—	**95**
Hg^0 reemissions ($\mu g\,Nm^{-3}$)	—	**3.4**
Hg^0 reemissions, % of inlet Hg^{+2}	—	**49**
Overall Hg removal (%)	—	**34**

Source – Ref. [6].

16.3.2 Reemission Chemistry

The primary reaction that produces reemission from FGD systems is believed to be an aqueous oxidation-reduction reaction between absorbed SO_2 and absorbed oxidized mercury. The overall reaction is shown as follows:

$$Hg^{2+}(aq) + HSO_3^-(aq) + H_2O(aq) \leftrightarrow Hg^0 \uparrow (gas) + SO_4^{2-}(aq) + 3\,H^+$$

where HSO_3^- (bisulfite ion) represents absorbed SO_2 in an ionic form at lower pH. However, this reaction is actually the net result of a number of reactions that appear to be kinetically limited at FGD conditions (i.e., they do not always proceed to chemical equilibrium).

The U.S. Department of Energy and EPRI funded a research project to investigate the kinetics of mercury reactions in the aqueous phase of wet FGD slurries, and fundamental studies were conducted in both an ultraviolet/visible spectrophotometer and in a bench-scale wet FGD simulator [8]. Those results showed that in simple simulated FGD solutions, reemission rates slowed as sulfite concentrations increased. This was determined to be the result of the formation of a disulfite complex with oxidized mercury that is more stable than a monosulfite complex with oxidized mercury, according to the following reactions:

$$Hg^{+2} + SO_3^{-2} \leftrightarrow HgSO_3$$
$$HgSO_3 + SO_3^{-2} \leftrightarrow Hg(SO3)_2^{-2}$$

It was determined that the monosulfite complex decomposes to produce the reemission reaction, as follows:

$$HgSO_3 + H_2O \rightarrow Hg^0 \uparrow + SO_4^{-2} + 2\,H^+$$

However, with the addition of chloride to the synthetic FGD liquor, the reemission reaction rates slowed markedly, in proportion to the chloride concentration in the liquor. The effect is apparently the result of the formation of mercuric chloride complexes that are more stable (less likely to produce reemission reactions)

than the mercury-sulfite complexes. Figure 16.5 provides an illustration of the proposed reactions involved in mercury reemissions in a relatively simple aqueous environment containing only mercuric ion, sulfite, and chloride. Bromide and iodide anions were found to form increasingly stronger complexes than chloride (in that order) when compared on a molar concentration basis, but these halogens are much less abundant in U.S. coals than chloride, and are correspondingly found in lower concentrations in wet FGD liquors.

Other FGD variables such as pH were found to have a complex relationship with sulfite and chloride concentration in their effects on reemission rates (i.e., no consistent trends over the typical range of values for FGD systems). Some species found in FGD systems were found to have a direct impact on reemission rates, most likely because they are reducing species themselves and may directly reduce oxidized mercury in the FGD liquor. Examples of this phenomenon include thiosulfate ion (present in inhibited oxidation FGD systems) and some sulfur-nitrogen species (present in many FGD systems, particularly those that do not have a high-efficiency NO_X control system upstream of the FGD).

This research also identified that reemission rates are directly proportional to FGD liquor mercury concentrations. As described, there are mechanisms that result in the transfer of mercury from the liquid phase to the solid phase of the FGD slurry. Reemission reactions occur predominantly in the liquid phase, so mercury precipitated or adsorbed into the solid phase is less likely to reemit. Current research funded by EPRI is focused on developing kinetics for mercury precipitation or adsorption from the liquid phase to the solid phase in FGD slurries, and on identifying the mechanisms for this phase transfer [5].

The species that cause mercury to transfer to the solid phase (e.g., iron hydroxides, sulfide, or selenide) have limited capacity to precipitate or adsorb mercury.

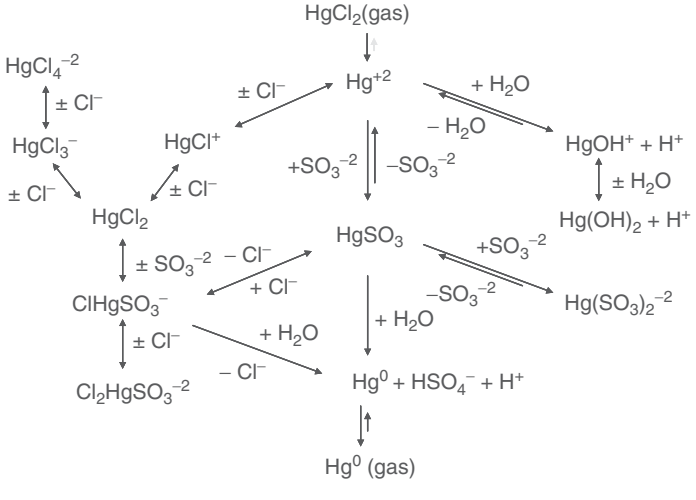

Figure 16.5 Illustration of proposed chemical reactions for mercuric ion, sulfite, and chloride in an aqueous environment [8].

Thus, the ratio of oxidized mercury concentration in the FGD liquor to the concentrations of these species may impact the amount of mercury that remains in the FGD liquor rather than transferring to the solid phase.

The phase change from the liquor to the solids serves as the basis for the so-called FGD reemission additives, which are added to FGD slurries to control reemissions and improve overall co-benefit capture of mercury. Reemission additives are discussed subsequently.

16.3.3 Reemission Additives

A number of vendors offer additives that can be used to limit or even completely eliminate reemissions. Most reemission additives are compounds that contain sulfide (R–S) or thiol (R–S–H) groups (where R represents the remainder of the molecule). Some are based on sodium or calcium molecules, while others have an organic base molecule. Of the organic-based molecules, the base species can either be a single molecule or a polymer.

The principle of operation of reemission additives is that they either precipitate or form very strong complexes with ionic mercury in aqueous solutions. Several of these additives are commonly used in industrial wastewater treatment processes to remove mercury and other metals from waters, and have been adapted for use directly in FGD processes to precipitate mercury. An example is Evonik Degussa's TMT-15, a 15 wt% solution of trimercapto-s-triazine, which has a molecular weight of 243 and has three sulfide groups attached. Evonik Degussa literature cites how extremely insoluble mercuric sulfides are, and that this is the principle of operation of their additive. The additive has been used for some time in industrial wastewater treatment and Evonik Degussa reported its use in European wet FGD systems for reemission control in 2003 [9]. Sulfide-based additives can also precipitate other metals, mostly divalent transition metals, but mercuric sulfide is the least soluble sulfide salt. Degussa cites the relative solubilities of several metal sulfides in the following order:

$$PbS > CdS > CuS >> HgS$$

Besides lead (Pb), cadmium (Cd), copper (Cu) and mercury, nickel (Ni) and zinc (Zn) are also precipitated as low-solubility sulfides. All of these metals tend to be present in FGD liquors, many in concentrations higher than mercury. Thus, these metals can compete with the reemission additives when they are first injected into an FGD system. Over time, with mercury being the least soluble sulfide salt, mercury in the liquor will preferentially precipitate with the additives. But, depending on how fast the reemission reactions occur, these reactions could still produce reemissions before the mercury is precipitated. Therefore, additive dosage and location of injection must be optimized to ensure rapid precipitation of oxidized mercury as it is absorbed into the FGD liquor.

Besides TMT-15, other vendors have reported considerable testing results on U.S. coal plant FGD systems, including Babcock and Wilcox, and the Nalco

Company [10, 11]. Several other companies offer sulfide- or thiol-based reemission additives; one such example is Pravo [12]. Other approaches for controlling reemissions are being offered. For example, Steag offers a technology to add activated carbon to FGD systems to adsorb mercury as it is absorbed from the flue gas [13]. CH2MHill has a patent for a technology to add iron salts to FGD absorbers to remove mercury from the liquor by iron coprecipitation [14]. All of these technologies are adaptations of technologies commonly used to remove mercury and other heavy metals from industrial wastewaters.

Another approach for controlling reemissions from FGD systems may be to optimize FGD operating conditions to minimize reemission rates. However, more research and development is needed to establish this as a well-defined and controllable approach. FGD parameters that could be optimized to control reemissions might include (but may not be limited to) the following:

- ORP (Mitsubishi Heavy Industries has a patent covering ORP control to optimize net mercury capture [15]),
- Iron content in the limestone reagent, and/or process configurations that maximize iron fines recycle to the absorber as part of the slurry dewatering process,
- Chloride concentrations in the FGD liquor (impacts mercury complexation, indirectly impacts the recycle of iron-based mineral fines in FGD reclaim water in systems that employ hydrocyclones),
- Concentrations of other halogens (bromide and iodide) in the FGD liquor that form strong complexes with mercury, and
- Weight percent suspended solids in the absorber slurry (impacts fines concentrations and surface area available for mercury adsorption).

16.4 Effects of Flue Gas Mercury Oxidation Technologies on FGD Capture of Mercury

One way to increase the co-benefit removal of mercury by wet FGD systems is to increase the percent oxidation of the mercury in the flue gas. Other chapters discuss the effects of fuel and flue gas additives, several of which enhance mercury oxidation, and the effects of catalysts, which also can enhance mercury oxidation. Of course, these technologies are not as effective if reemissions limit the net removal of oxidized mercury across the FGD system.

One additive that has been demonstrated to increase mercury oxidation in flue gas is the bromide ion, which can be added to the coal as a salt or injected into the flue gas as a salt or an acid. One impact of bromide injection is that bromine compounds in the flue gas are scrubbed at high efficiency in the FGD system, and the bromide ion is highly soluble in calcium- and sodium-based solutions. Thus, bromide builds up in the FGD system in a manner similar to chloride, to a concentration at which the bromide rate leaving in the water purged from the FGD system equals the rate entering with the coal and the bromide additive.

As the bromide builds to steady-state concentrations in wet FGD systems, it can affect mercury chemistry in the system. One effect was mentioned earlier in this section: bromide forms a relatively strong aqueous complex with oxidized mercury. This complexation can have further effects. As the bromide concentration builds, the mercury tends to remain in the liquor phase rather than transfer to the solids, and is available to participate in aqueous reemission reactions. However, the strength of the mercury–bromide complex tends to slow reemission reaction rates. The net effect of increased bromide concentrations on mercury reemission tendencies can be site specific – in some cases, reemissions are significant, while in one account the presence of elevated bromide concentrations appears to have stopped reemissions [16].

FGD system operators should keep in mind their system's liquid residence time when conducting tests with the bromide additive, as the true performance of the FGD system for net mercury capture may not be realized until steady-state bromide concentrations are achieved. The data plotted in Figure 16.6 show that it took almost 1 week of bromide addition testing at one full-scale wet FGD system to experience a change in mercury partitioning between the FGD liquor and solids. The change was not realized until the liquor bromide concentration exceeded 100 mg l^{-1}. FGD systems with hydrocyclones for primary dewatering, which operate with relatively low chloride concentrations in the FGD liquor and do not have a lot of slurry or liquor storage volume incorporated (e.g., no filter feed tanks or no large reclaim water tanks), tend to reach steady state rapidly, within a matter of days. The FGD liquid residence time is affected by factors such as the total volume of process water in the FGD system, the chloride concentration in the coal, and the chloride concentration in the FGD liquor at blow down. Systems that fire low-chloride coal but operate with elevated chloride concentrations in the absorber liquor, have thickeners for primary dewatering (which have a large liquid volume), and/or systems with other large volumes of water that get returned to the FGD system (e.g., from ponds) can take many days, weeks, or months to reach steady-state bromide concentrations.

Oxidation catalysts that enhance mercury oxidation percentages in the FGD inlet flue gas have generally not been observed to impact mercury behavior in wet FGD systems. That is, catalytically oxidized mercury is generally captured from the flue gas at as high an efficiency as is native oxidized mercury, and is no more or less likely to be reemitted.

However, one possible adverse effect is that by increasing the concentration of oxidized mercury in the flue gas, the ratio of oxidized mercury to species that enhance the transfer of mercury to the solid phase is increased. As this ratio increases, mercury may tend to remain in the liquor, and thus be available for reemission reactions. In contrast, selective catalytic reduction (SCR) catalysts can also oxidize mercury and may have a beneficial effect on mercury chemistry in wet FGD systems. By lowering NO_X concentrations in the FGD inlet flue gas, SCR systems may reduce the formation of "sulfur-nitrogen" compounds in FGD liquors [18]. Some of these compounds are chemically reducing species, and in bench-scale tests have been observed to contribute to mercury reemission

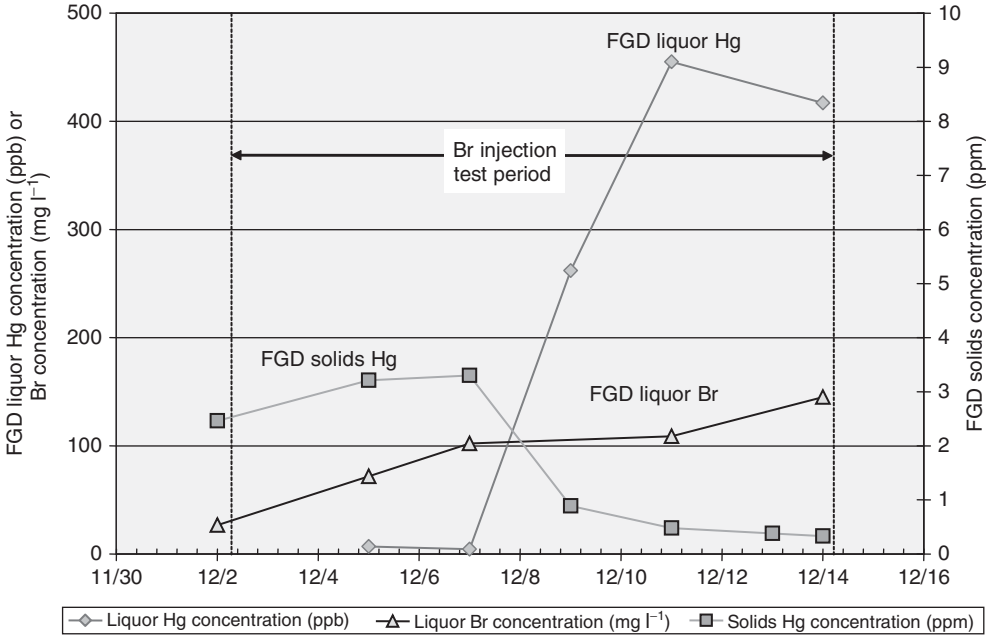

Figure 16.6 Example data showing time dependency of bromide concentration and effects on mercury partitioning in a full-scale wet FGD system. (Reference [17].)

reactions [8]. Thus, SCR catalysts may indirectly lower mercury reemission rates by lowering sulfur-nitrogen compound concentrations.

Some researchers are developing technology to enhance mercury capture by wet FGD systems by *in situ* oxidation of the small amount of elemental mercury that is soluble in wet FGD solutions [19]. Another technology being investigated would use replaceable carbon composite panels in the upper portion of an absorber vessel to absorb mercury from the flue gas [20]. These development efforts may represent future directions for maximizing co-benefit mercury capture by wet FGD systems. At present, these technologies are being investigated at laboratory to demonstration scale.

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17
Introduction to Carbon Sorbents for Pollution Control

Joe Wong

17.1
Carbon Materials

Carbon materials occur in various forms owing to the arrangement of the carbon atom in the structural lattice, which can be characterized as either crystalline or amorphous. Crystalline carbons represent a class of materials whereby the carbon atoms are highly ordered and show a high degree of symmetry in their structural features (Figure 17.1). Crystalline carbon materials include diamond, graphite, and fullerenes. Diamond is considered the most highly ordered crystalline carbon material, having tetrahedrally bonded carbon atoms (sp^3) that form a face-centered cubic structure (Figure 17.2) [1]. Graphite is a highly ordered layered carbon structure with "sheets" of graphene planes (Figure 17.3) [1]. Carbon bond lengths and structural features of crystalline carbons are very regular and well defined.

In contrast, amorphous carbons are carbon materials with less order and/or more defects in the carbon structures. As there is never total disorder of the structure, there exist micro-regions of order or micro-crystallinity in the structure. The irregular carbon arrangement and structural defects give rise to the carbon material's pore structure, surface, and surface area features. Amorphous carbons are further classified into materials derived from coal, charcoal, or lamp black. Activated carbons possess many of the crystal structural features of amorphous carbon materials, and thus are characterized as predominantly amorphous solids.

17.2
Carbon Activation

Activated carbon can be produced from a variety of raw materials, including coal (predominantly bituminous and lignite), lignocellulose (sawdust, nut shells, lignin, pits, etc.), peat, plastics, resins, and petroleum residue. Essentially, any raw material that can be converted to a carbonaceous form can be activated.

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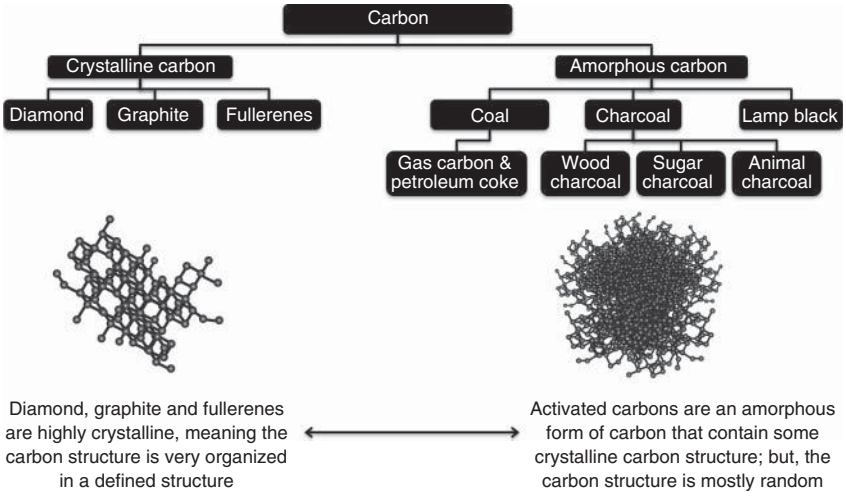


Figure 17.1 Crystalline and amorphous carbon materials.

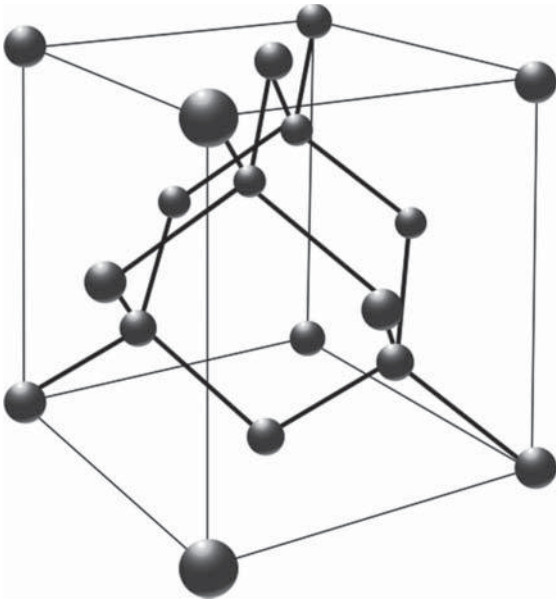


Figure 17.2 Crystalline structure of diamond.

Activation of the carbonaceous raw material is typically conducted either by thermal means or with chemical reactants. Heat treatment equipment ranging from rotary kilns, multihearth furnaces, fluid bed reactors, and batch ovens are employed under a variety of temperature, residence time, and gas composition conditions to achieve desired activated carbon properties. As one can imagine,

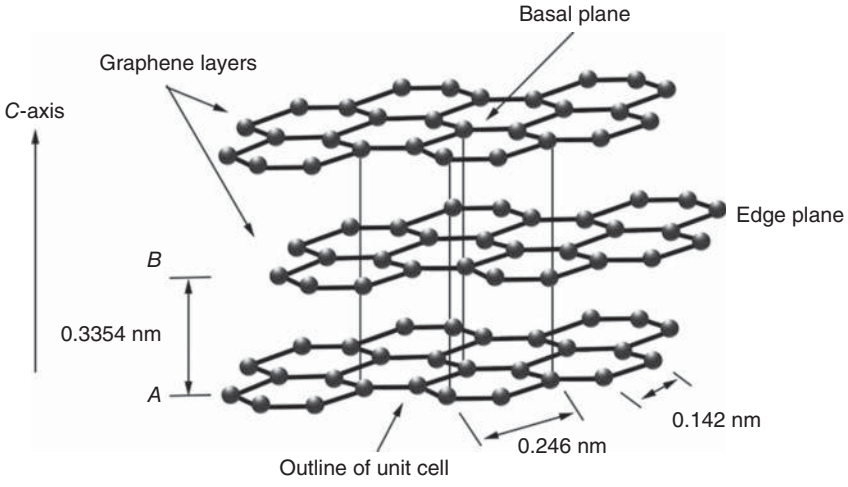


Figure 17.3 Crystalline structure of graphite.

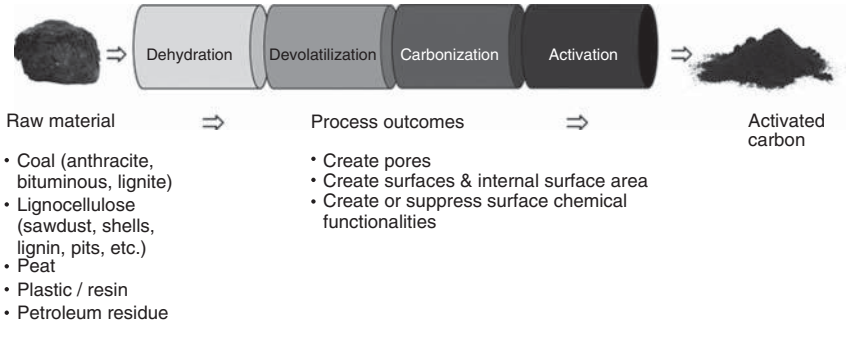


Figure 17.4 Carbon activation.

those in academia and industry and entrepreneurs have defined many activated carbon processing conditions. An Internet search of "Activated Carbon Activation" will return over 37 million hits. Baker, *et al.* [2] describe the various commercial manufacturing processes.

Despite the plethora of activation conditions, there are predominant basic processes occurring in activation, consisting of dehydration, devolatilization, carbonization, and finally activation itself. Figure 17.4 depicts a generalized view of these basic process steps in a thermal activation process. These basic steps are not necessarily discrete steps with fine lines of demarcation, but instead can overlap each other significantly. The first step consists of "dehydration." Most raw materials contain moisture, essentially in the form of free and some bound water, that is initially removed upon heating to about 100–150 °C. The next step is termed *devolatilization* and occurs above 150 °C, whereby free or weakly bound volatile organic constituents begin to evolve from the raw material into the gas phase.

"Carbonization" begins to occur around about 350 °C and proceeds to slightly below 800 °C in an inert or nonoxidizing atmosphere [3]. During carbonization, the non-carbon constituents containing heteroatoms, including oxygen, hydrogen, sulfur, and nitrogen, decompose or volatilize. Some of the organic constituents are not removed and remain in the carbon material as partially charred matter. Elemental carbon is essentially concentrated in the carbon material during carbonization. In addition, the carbon atoms begin to arrange into semirandom amorphous structures. Spaces or interstices of various sizes and shapes begin to form, giving rise to the beginning formation of the material's pores and surfaces. This carbonized material is sometimes referred to as *char*.

Typically, above about 800 and below 1000 °C in the presence of air, steam, carbon dioxide, or another oxidizing agent, the char begins to "activate." During activation, the initial pore structure from carbonization is further developed through oxidation or "burn-off" of the carbon structure and charred organics. Depending on the desired activated carbon "activity," pore development is a trade-off to carbon yield.

During activation and in subsequent cooling steps, the surface chemical functionalities can be manipulated. The oxidative atmosphere during activation typically results in a high oxygen-containing carbon surface. The injection of a "reductive" gas is sometimes employed to cap these oxygen functional groups to obtain desired carbon surface properties.

17.3 Carbon Particle Shapes and Forms

Activated carbons produced from thermal or chemical activation are typically in a combination of powdered and granular particulate form with particle sizes of less than about 2–3 mm in diameter. Additional processing employed by manufacturers can provide smaller or larger particles or shaped forms. Figure 17.5 describes typical activated carbon shapes and forms, which can consist of powdered activated carbon (PAC), granular activated carbon (GAC), shaped carbon, and carbon cloths.

17.3.1 Powdered Activated Carbon (PAC)

The American Society for Testing and Materials (ASTM) classifies PAC as activated carbon material passing through an 80-mesh sieve (0.177 mm or 177 μm) [4]. PAC is produced commercially by comminuting larger activated carbon particles produced during the activation process through one or more types of grinding equipment, including roller mill, hammer mill, ball mill, jet mill, and so on. The comminuted particle is sometimes classified to attain desired sieve mesh size fractions for different application requirements.

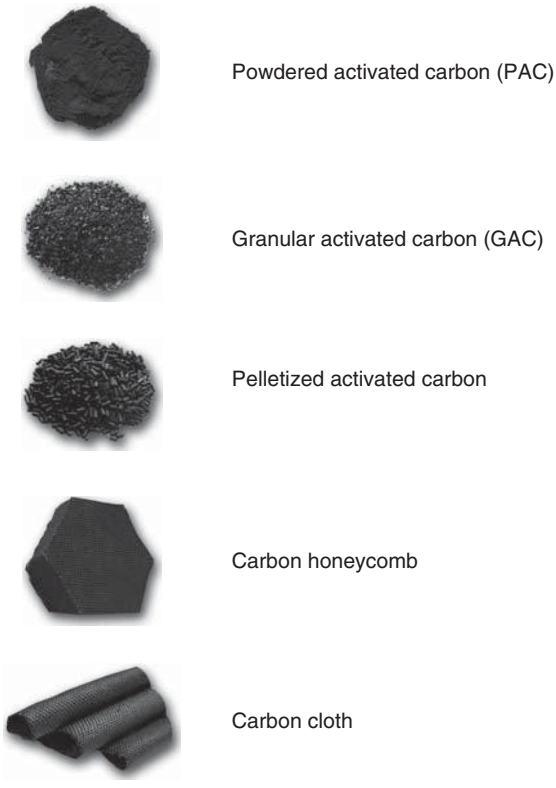


Figure 17.5 Activated carbon shapes and forms.

PAC is used prevalently in liquid-phase purification applications, such as in water treatment and food purification. By the nature of its small particle size, PAC is also a leading candidate for dispersed gas-phase applications. PAC can be designed to be highly dispersible in the gas phase, which allows for enhanced probability of contacting with dilute concentration gaseous pollutants and for rapid capture and uptake of pollutant molecules.

17.3.2 Granular Activated Carbon (GAC)

GAC particles are larger in size than PAC. ASTM classifies GAC as activated carbon particles that are retained on an 80-mesh sieve. The larger particle sized GAC is often used in gas- and liquid-phase applications, whereby the process stream flows through a packed bed of activated carbon. The GAC provides a lower pressure drop, thus allowing higher process stream flow rates, simpler equipment design, and lower energy requirements.

17.3.3
Shaped Activated Carbon

PAC can be mixed with a binder and shaped into different forms, including pellets, beads, honeycombs, and so on. Typical binders include carboxyl methylcellulose, clays, phenolic resins, ceramics, coal tar pitch, or combinations thereof. Depending on the manufacturing process, the binder addition and shaping of the raw material may occur before or after activation.

The manufacture of shaped carbons requires additional equipment and processing beyond carbon activation, thus adding cost to the final activated carbon product. Additional steps include (i) mixing and mulling of the PAC and binder, (ii) extrusion/briquetting/shaping, (iii) low-temperature heat treatment to achieve "green" strength, and (iv) high-temperature heat treatment to "set" the binder.

Shaped activated carbons, including honeycombs (Figure 17.5), are used extensively in gas-phase purification and catalyst support applications. The binder system provides the activated carbon its shape integrity, high mechanical strength, and low dust properties.

17.3.4
Other Activated Carbon Forms

Activated carbons can be impregnated into cloths and fabric, either physically bound or via a coating. These cloths find utility in air filters, chemical warfare suits, or applications requiring a conformal shape.

Other activated carbon forms include fibers and aerogels, which typically tend to be used for high-value, specialized applications.

17.4
Activated Carbon Applications

Activated carbon is a proven, versatile technology for a host of purification and other applications. The ability to tailor performance properties is a key, enabling feature of activated carbons. Although not an encompassing list, Baker, Global Industry Analyst, Freedonia and Roskill [2, 5–7] each describe industrial markets for activated carbon. Figure 17.6 lists some of the larger established and emerging market areas for activated carbon.

The use of activated carbons is well established for waste and potable water treatment, food and pharmaceutical separations and purifications and industrial processes, including solvent recovery. Other specialty applications are also well established, such as for catalyst and catalyst supports. The versatility of activated carbons has garnered much interest in applications for electrode materials for electrical energy storage markets. Other applications in the medical and consumer products arena are also prevalent. Carbon dioxide capture and sequestration are rapidly expanding R&D sectors for activated carbon sorbents.

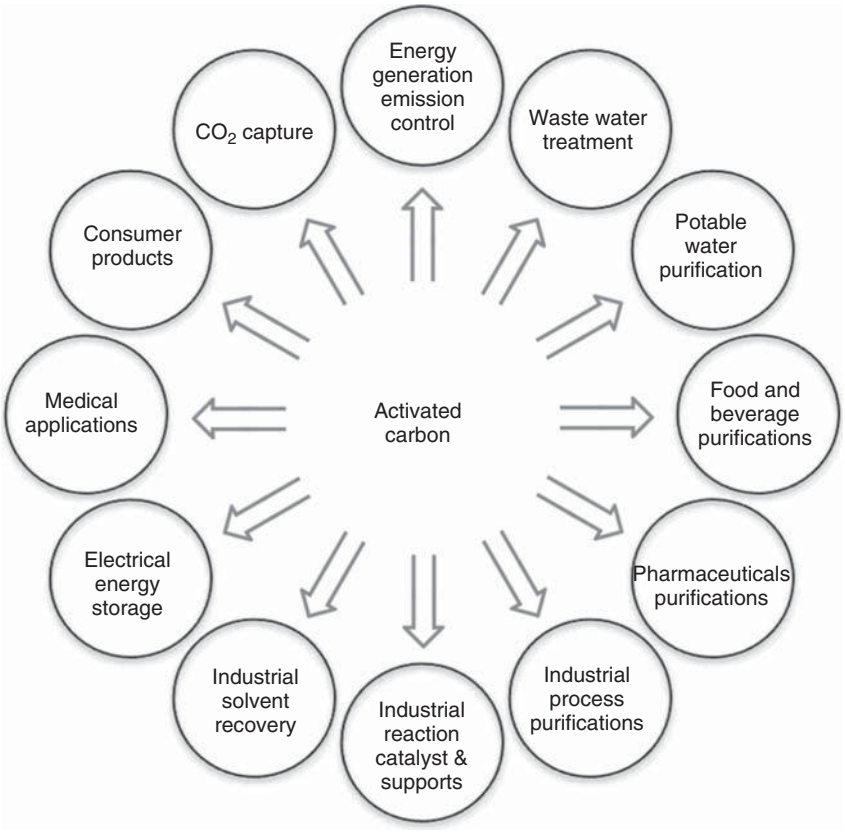


Figure 17.6 Activated carbon market applications.

A significant market interest in activated carbon has come from the energy generation industries, such as coal- and waste-fired power plants, industrial boilers, and cement kilns. These industries are in their initial commercial stages of applying activated carbons in their flue gas treatment steps and are conducting plant trials of improved, specialty activated carbons for mercury and other emission controls. This specialized application of activated carbon technology is establishing ground as the best available, cost-effective technology for mercury capture from flue gas.

17.5
Activated Carbon Properties in Emission Systems

Activated carbons are highly adaptable and can serve multiple purposes in removing organic and inorganic pollutants. Their innate ability to attract and capture

targeted molecules has made activated carbon a viable solution for removing mercury from flue gas streams.

The removal of mercury from power plant flue gas is a complex process, with consideration, to name a few, of the effects of chemical reaction kinetics, flue gas constituents and activated carbon surface interactions, and carbon adsorption capacity, diffusion kinetics, and adsorptive energy distribution. In addition, power plant flue gas emission trains are typically set up differently and thus present a variety of operating conditions from which the activated carbon must perform. Unfortunately, there is no reliable computational model to estimate the individual or collective nature of these factors on mercury removal. However, much work has been conducted to start painting a scientific-based fundamental picture of an ideal model system from which to build upon [8]. Later chapters in this book describe in detail the recent work on mechanisms and models for mercury interaction with carbon surfaces.

It is acknowledged widely that the removal of mercury from flue gas is represented by three predominant mechanisms.

- Conversion of elemental mercury, Hg^0, to an electron-receptive, oxidized state, either Hg^+ or preferably Hg^{2+} to enhance mercury's receptivity to activated carbon;
- Contact of the mercury compound, which is in a very dilute concentration in the flue gas, with the activated carbon;
- Diffusion and capture of the mercury compound in the activated carbon structure by physical adsorption and chemisorption.

The order and influence of these mechanisms and the rate-limiting step have been studied, proposed, and debated; however, it is plausible that all occur in a parallel manner, with one being more pronounced than the others in certain emission train conditions.

Given these mechanisms, activated carbon has three key properties or capabilities that make it effective for emission control applications (Figure 17.7). A meaningful specification for activated carbon for mercury removal in flue gas should factor in each of these characteristics.

- Activated carbons provide a **SURFACE** to host chemical reactants and other functionalities that interact with or affect the pollutant species, both chemically and physically.
- Carbons have **PORES** that adsorb, meaning attract, transport, and capture, molecules to be removed.
- Carbons are **PARTICLES** that are highly dispersible and provide a transport medium to deliver all the desired properties to the right place and at the right time in the emission system.

Each of these properties is discussed here.

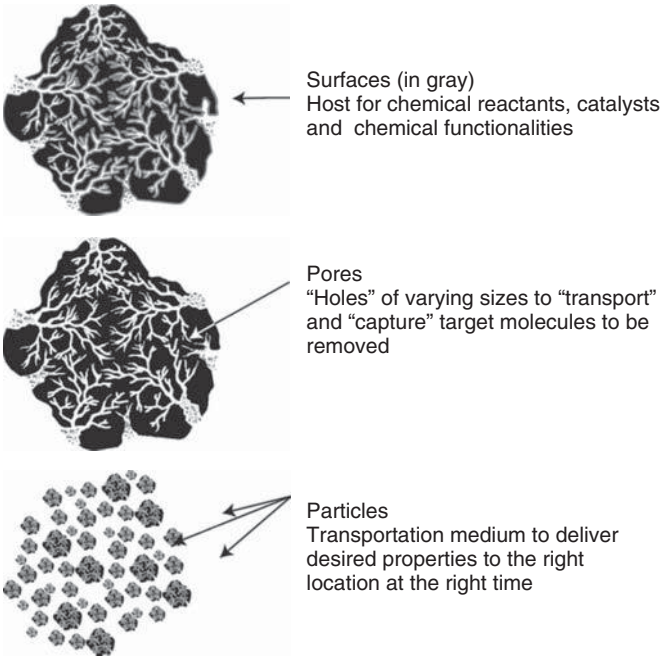


Figure 17.7 Activated carbons are multifunctional.

17.5.1 Activated Carbon Surface

A typical activated carbon designed for power plant flue gas mercury capture contains 500–700 m^2 of surface area per gram of activated carbon. In other words, 1 lb of activated carbon per million actual cubic feet of flue gas (lb/actual cubic feet per minute (ACFM)) injection rate provides enough carbon surface area to cover about 50 football fields if each carbon particle is unfolded completely flat to expose all surfaces. At this level of potential surface area, it is evident that not all of the activated carbon's surfaces are accessible to the mercury and that there are other factors involved. Accordingly, in developing activated carbon specifications specific to mercury capture, specifying surface area alone is insufficient.

Consideration of the role of an activated carbon surface in mercury removal reveals other key surface activities that occur (Figure 17.8).

The carbon surface provides bromine or other halogen forms or an oxidant to facilitate oxidation of elemental mercury to an oxidized, more "adsorbable/soluble" state.

The surface contains and exposes minerals to catalyze the oxidation of mercury. It is well documented that heterogeneous catalysis of mercury in the presence of halogens by precious metals and other minerals is on order of 100 000 times faster than the oxidation of mercury by halogens in a homogeneous gas phase [9, 10]. Having certain minerals present is particularly important when there are only

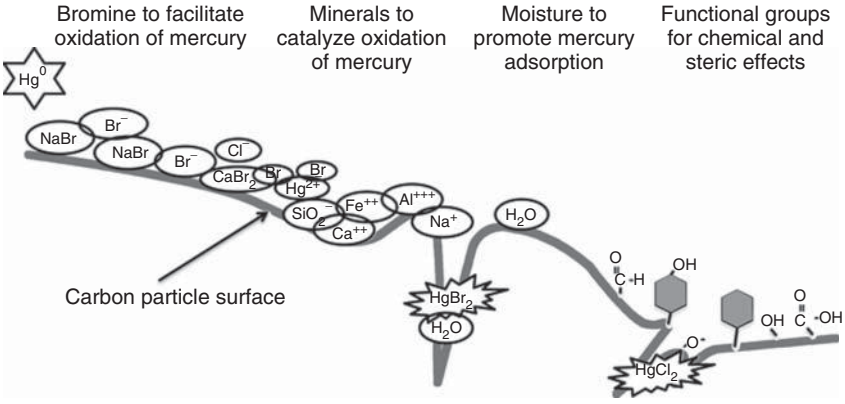


Figure 17.8 Activated carbon surfaces.

seconds of exposure time of the mercury to the halogen in most plant emission systems.

The surface contains moisture to promote mercury adsorption into the pores. The effects of carbon moisture levels have been studied and cited in literature [11]. Moisture plays a role in improving the adsorption of oxidized mercury.

The surface exposes certain chemical functional groups. It is well known that activated carbon surfaces contain a variety of chemical functions, including acidic carboxylic acid functions, phenyl and phenol groups, reactive free radicals, and polar hydroxyl and carbonyl groups [12, 13]. These surface functionalities can enhance or reduce the affinity of the activated carbon for the mercury species [14].

Evaluation of the binding energies of mercury and oxidized mercury species with simulated carbon surfaces has offered insights as to potential surface complex mechanisms, but a definitive or dominate pathway has not been elucidated [15]. However, it has been demonstrated that activated carbon surface features can be tuned to enhance or block specific surface mechanisms to enhance pollutant capture.

17.5.2
Activated Carbon Pores

The pores of an activated carbon are an intricate arrangement of "holes," "passages," and "caves," providing a carbon with its adsorptive properties and the resultant ability to capture targeted mercury molecules in flue gas systems. The characterization of pore structure often includes microscopic analyses and molecular simulations of the morphological (pore shape and size) and topological (pore connectivity) character of carbons [16].

Carbon pores are defined by their shape and size. Pores have been represented in various geometries, ranging in shapes from tapered cylinders to elongated slits. It is commonly acknowledged that the elongated slits provide the best representation of pore shape and function [17–21]. Carbon pore sizes (width) are

Table 17.1 IUPAC classification of pore size.

Classification	Pore diameter (nm) (10^{-9} m)	Pore diameter, Å (10^{-10} m)
Micropore	<2	<20
Mesopore	2–50	20–500
Macropore	>50	>500

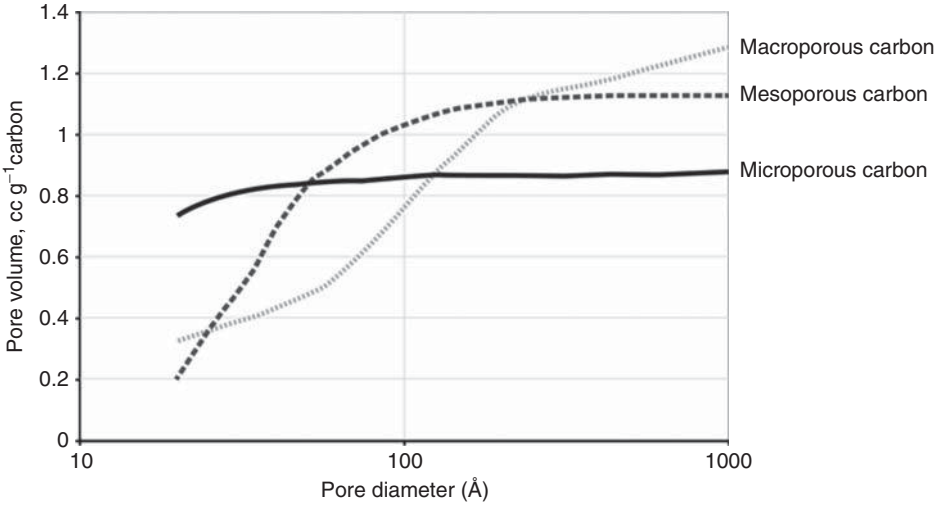


Figure 17.9 Cumulative pore volume and pore size of activated carbons. (Reproduced with permission from MeadWestvaco Corporation.)

classified by the International Union of Pure and Applied Chemistry (IUPAC) as shown in Table 17.1 [22]. Pores with width <2 nm are designated as *micropores.* Pores between 2 and 50 nm are *mesopores.* Pores with width >50 nm are termed *macropores.*

Pore size distributions can be interpreted from gas porosimetry measurements using nitrogen or argon as the adsorbate. Figure 17.9 [23] shows a plot of cumulative pore volume in various pore size ranges for activated carbons possessing high degrees of micropores, mesopores, and macropores. For the microporous carbon, essentially all of the 0.8 cc g^{-1} pore volume is in pores <2 nm in diameter. The mesoporous carbon has minimal pore volume in micropores, and pore volume starts building progressively around 2 to about 30 nm. The macroporous carbon has the majority of its pore volume in pores >25 nm in diameter, building in macropore volume to 100 nm. What is apparent is that activated carbon is not one-size-fits-all, as the pore size distribution can be tuned to some extent to favor one size distribution over another.

Moreover, the molecular size of the target molecule in a particular end-use plays a key role in optimizing the pore size distribution of activated carbon. Because of

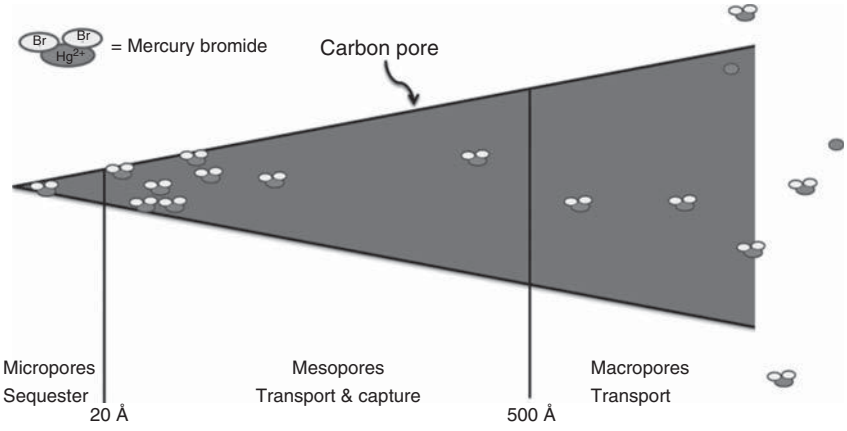


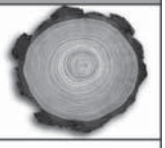
Figure 17.10 Activated carbon pore geometry and size range.

the prevalence of water treatment and food purification applications, traditional liquid- and gas-phase activated carbon pore size design is based on the adsorption performance of small iodine molecules (0.3–0.6 nm or 3–6 Å in molecular size) and large tannins, molasses, or methylene blue color bodies (>2 nm or 20 Å in molecular size). However, in the case of oxidized mercury, a mercury bromide molecule has a molecular size in between those two benchmarks on order of 1.0–1.3 nm (10–13 Å). From that simple analysis, it follows that using traditional activated carbon specifications based on adsorption of smaller molecules or larger color bodies would not be expected to result in the optimal mercury removal performance [24].

Figure 17.10 shows a graphical depiction of the role of each pore size required in capturing mercury. Starting from the right side of Figure 17.10 – in the high-temperature flue gas, highly energetic mercury species need to come in contact with the carbon particle and enter the larger macropores. Once in contact, the macropores transport the molecules into large mesopores. The molecules are eventually captured and sequestered in the small meso and micropores. Because this diffusion, transport, capture, and sequestration occur in a very short amount of time in the emission system, larger pores are required to increase the probability of capturing the gas-phase molecule and enhance pore diffusion/transport, while smaller micropores with high adsorptive energies are required to capture the mercury molecule and prevent diffusion back into the flue gas.

Commercial carbon manufacturers employ a variety of raw materials to produce activated carbon. Invariably, the starting raw material affects the porosity characteristics of the final activated product (Table 17.2). For example, raw coconut shells are hard and dense and produce activated carbons that are typically very high in micropores and have low amounts of mesopores and macropores. Cellulosic precursors, such as wood, are inherently low density and porous, leading to highly meso- and macroporous carbons. Bituminous coal-based carbons lean more toward micropores, while lignite coal carbons are highly mesoporous. It is

Table 17.2 Raw material impact on pore characteristics.

	Coconut activated carbon	Coal activated carbon	Lignite activated carbon	Wood activated carbon
Pore characteristics				
Micropores	High	High	Medium	Low
Mesopores	Low	Medium	High	High
Macropores	Low	Medium	Medium	High

recognized that these are typical porosity descriptions, and that enhanced activation conditions and/or additional processing steps can be added to shift the porosity characteristic from any raw material source. For example, Baker *et al.* [25] developed highly microporous carbons from wood by an intensive second-stage activation of a wood-based carbon with an alkali salt, such as potassium hydroxide.

17.5.3 Activated Carbon Particles

Another important feature of activated carbon is that it is a particle or form that transports key functional properties in and out of the emission system. Specifically, the carbon particle or carbon grain serves an important function as a carrier and disbursement mechanism for bromine or halogen as the mercury oxidant, minerals as oxidation catalyst, surface for other desired chemical functionalities, pores for mercury capture, and a medium to transport mercury out of the emission system through the electrostatic precipitator or filter fabric baghouse.

Knowing the operating conditions of the emission system is critical to maximizing the performance of the activated carbon particle. With such information, the properties of the activated carbon can be tuned to achieve the best performance in various operating configurations. For example, the activated carbon may need to function at high temperatures, such as in the case when injected "hot-side" before the air preheater (as opposed to "cold-side" after the air preheater or after the electrostatic precipitator) or may need to be compatible with other emission control devices (Figure 17.11).

In addition, activated carbon injected into the flue gas may have less than a second of time in order to capture the mercury before being removed from

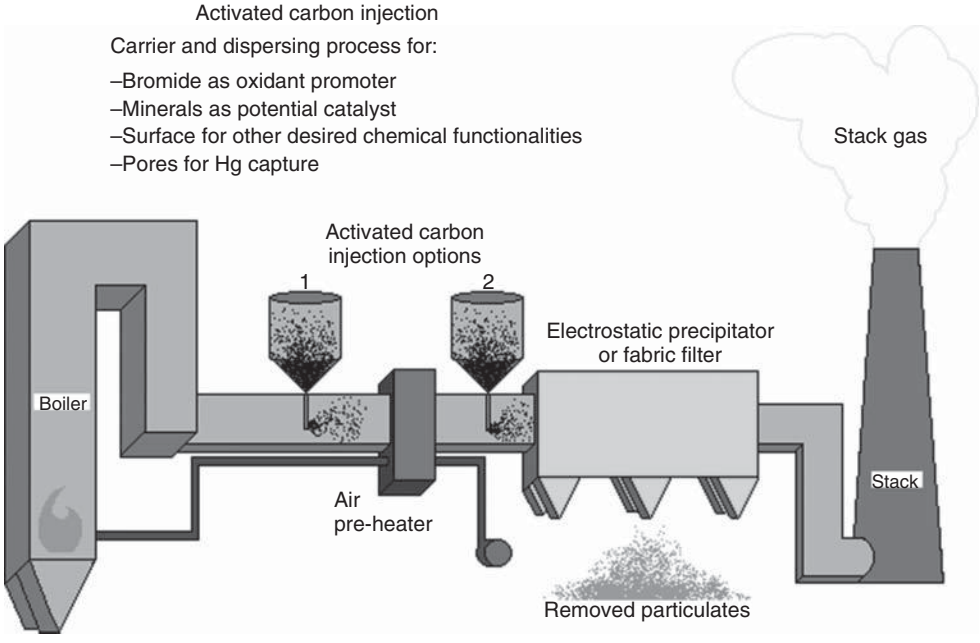


Figure 17.11 Activated carbon particles in emission systems.

the system. Consequently, its effectiveness is highly dependent on diffusional and kinetic considerations with the short residence time of contact between the carbon and the mercury. Much modeling has been conducted to discern drivers and rate-limiting mechanisms, including carbon pore diffusion and restrictions, as well as temperature effects [26].

In view of the kinetic considerations, the industry is trending toward the use of fine activated carbon particles with mean particle diameter $<25-30\,\mu m$. These smaller particles provide a higher propensity of surface for contacting the flue gas than larger carbon particles. However, the handling of these fine carbon particles in a power plant environment requires new particle handling protocols because of different flow characteristics in the injection equipment and removal dynamics in the emission train. Durham and Martin [27] developed a process for onsite size reduction of activated carbon particles to mitigate fine particulate handling issues, but this approach has not yet been adopted widely.

Another benefit of activated carbon particles is that once the mercury species is captured and sequestered on the carbon surfaces and pores, the particles can be readily removed from the emission train. Typical equipment used for this removal includes an electrostatic precipitator or filter fabric baghouse, whereby the spent activated carbon is removed along with the coal fly ash. This fly ash and PAC mixture can be safely land filled or used in producing cement.

17.6 Summary

Activated carbons are customizable adsorbent materials that are key enablers for controlling mercury emissions in power plant flue gas. Advances in understanding and tailoring activated carbon surface, pore, and particle features are providing insights and solutions to tackling the complex adsorptive, catalytic, and diffusional challenges faced in removing mercury in harsh, variable flue gas environments. These insights will help the coal-fired power energy industry move toward more pertinent carbon property specifications, much like the advances that have been made in defining activated carbon specifications for the well-established water treatment, sugar decolorization, and automotive gasoline emission control industries.

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18
Activated Carbon Injection

Sharon M. Sjostrom

18.1
Introduction

Activated carbon (AC) is effective in adsorbing mercury from the flue gas produced by many coal-combustion sources. AC can be installed as a fixed bed of carbon downstream of other pollution control equipment, or ground into a powder and injected upstream of a particulate collection device. This chapter provides information on activated carbon injection (ACI) into flue gas, factors limiting the effectiveness of ACI, and balance-of-plant considerations.

ACI is the most established commercial technology for reducing mercury emissions from coal-fired boiler flue gases. It has been proven through numerous full-scale demonstrations to be an effective, cost-efficient way to reduce mercury emissions from most plants that fire lower sulfur coals. Depending on the type of coal being burned and the type of air pollution control equipment installed on the plant, ACI can reduce mercury emissions by more than 90%, and can offer options for mercury trim at most plants. For plants firing low-halogen fuels, ACI can be used in conjunction with halogen-based coal additives to enhance performance.

ACI technology, which is shown in Figure 18.1, is relatively simple in comparison to typical emission control equipment. An ACI system is shown in Figure 18.1 to the right of an SO_2 scrubber and fabric filter (FF) in the photograph. An ACI system consists of a storage silo for the AC and a pneumatic conveying system that injects the AC at a controlled feed rate at the desired locations in the ductwork before the particulate control device. The mercury reacts with the AC sorbent and then is removed from the flue gas along with the fly ash by the plant's particle control device. Tests have shown that the mercury is not leachable from the sorbent [1] so that it can be disposed of in a landfill without concern for contamination of waterways. Because of their simplicity and small size, ACI systems can be retrofit on virtually any power plant with minimal engineering.

Mercury Control: for Coal-Derived Gas Streams, First Edition.
Edited by Evan J. Granite, Henry W. Pennline and Constance Senior.
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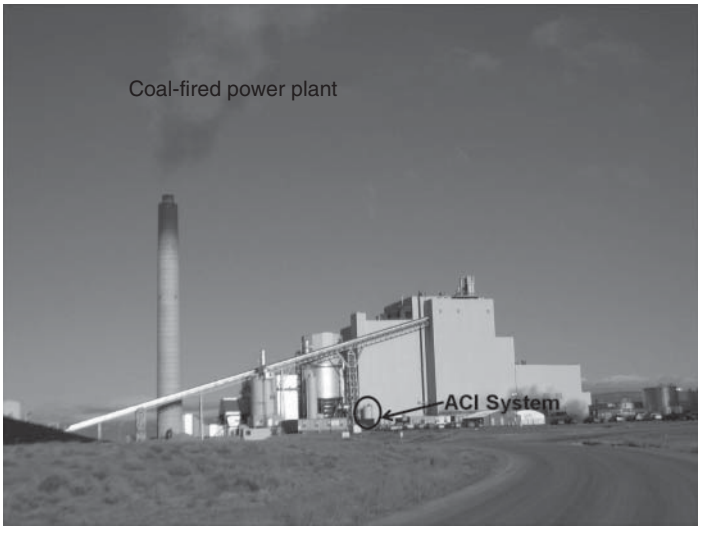

Figure 18.1 Perspective on ACI system in relation to other air pollution control equipment at a coal-fired power plant.

18.2 The Activated Carbon Injection System

Typical ACI system components include a silo to store the powdered activated carbon (PAC) before injection, process equipment to meter and convey the PAC to the injection location, and a distribution grid that includes manifolds and individual injection lances. Figure 18.2 shows a cutaway of a typical ACI system, including the storage module and process equipment, and a photograph of an ACI system installed at a coal-fired power plant. The ACI system shown has a storage silo with an enclosed process equipment room at grade level and a separate motor control building. Although the system appears relatively simple, there are critical aspects of the design that can result in poor control performance or poor reliability if attention is not paid to the details.

18.2.1 Powdered Activated Carbon Storage

The size of the PAC storage system is dependent on the unique needs of the plant. Factors include the projected PAC usage rate and the total days of storage that are required to assure continuous availability. PAC is usually delivered to the plant in a closed truck. The smallest silo for a commercial system typically holds more than a full delivery truck of PAC so that the truck can be unloaded without completely emptying the silo before unloading. This allows continuous availability of the material without demurrage or delays in availability of PAC.

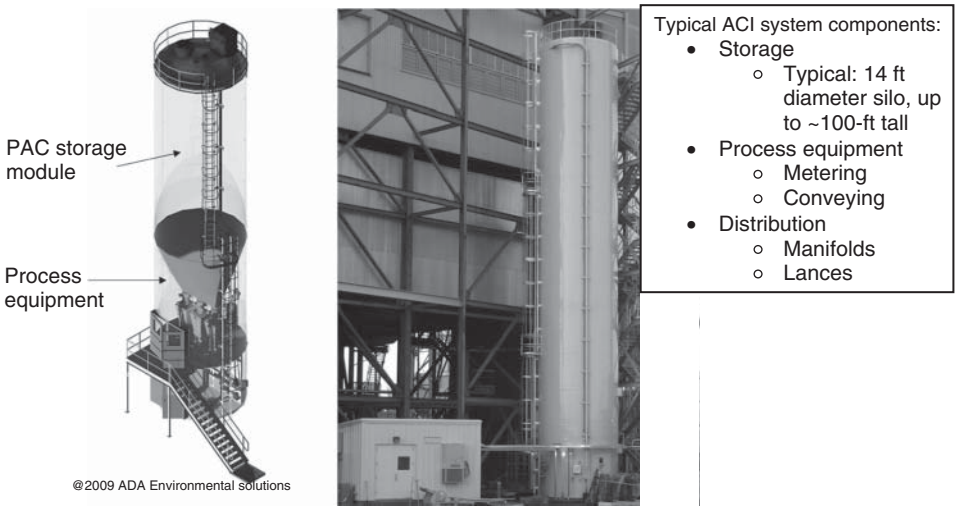

Figure 18.2 Cutaway and photograph of typical ACI system installed at a coal-fired power plant.

18.2.2 Process Equipment

18.2.2.1 Metering

The amount of PAC fed over time can be monitored in real time using either gravimetric or volumetric feeders. Gravimetric feeders are more accurate than volumetric feeders, but are two to three times the cost. One of the main disadvantages of volumetric feeders is that without use of a feedback control loop they may need to be recalibrated whenever a different sorbent with different properties is used. This can be a problem for sites that use multiple sorbents on a frequent basis. For plants that control the PAC feed rate to a set point, accurate calibrations are critical to cost control and to assuring sufficient PAC is being fed to meet mercury emission compliance. Plants that use feedback control from a mercury continuous emissions monitor can often benefit from a gravimetric feeder for inventory control.

18.2.2.2 Conveying

Both regenerative and positive displacement (PD) blowers are used in ACI systems for dilute phase conveying of PAC. The choice of blowers depends on how much PAC is being fed, conveying distance, number of elbows, and change in elevation. PD blowers are more expensive and have a larger footprint, but can provide higher flow and motive force, which is important for installations with long piping runs and many turns. The downstream components must be sized appropriately for the blower to minimize both sorbent fallout and pluggage from low velocities as well as component failures from abrasion due to the high velocities.

18.2.3
PAC Distribution

PAC is conveyed from the silo and feed system through main conveying lines. These are typically hard piped for permanently installed systems to minimize leaks associated with abrasion. The conveying lines terminate at a manifold that distributes the PAC into separate injection lances. These manifolds must be carefully designed to assure that the appropriate amount of PAC is delivered to each lance. There are typically several lances installed at the injection location to assure good distribution across the entire gas path. It is important to assure that all of the flue gas is being treated, especially for plants with electrostatic precipitators (ESPs) where most of the mercury adsorption takes place in-flight. Lance placement can be affected by several factors including access constraints that may limit the ability to install ports.

18.3
Factors Influencing the Effectiveness of Activated Carbon

Coal-combustion facilities that produce steam for electricity or heat fire a range of coals and are configured with a variety of pollution control devices. The effectiveness of ACI for mercury control at these facilities is contingent on several factors. Key factors can be categorized as

1) *Site specific*, including coal characteristics, flue gas temperature, SO_3 concentration in the flue gas, particulate control configuration,
2) *PAC specific*, including characteristics such as PAC quality, chemical treatment, and size distribution, and
3) *ACI system design specific*, including PAC injection location, grid design, and lance design.

18.3.1
Site-Specific Factors

Aside from the difference in heating value between bituminous and subbituminous coals, there are obvious differences in the sulfur and chlorine concentrations, as described in more detail in Chapter 2. In general, ACI is most effective for mercury control on flue gas derived from combustion of coals with lower sulfur contents, such as subbituminous coals, low-sulfur bituminous coals, and many lignite coals. In the United States, most subbituminous coal is mined in the Powder River Basin (PRB). PRB coal typically contains <1% sulfur and $<50\,\mu g\,g^{-1}$ chlorine. Furthermore, ACI is more effective when used in conjunction with an FF, where flue gas must pass through a collected layer of sorbent, than in other particulate collectors, such as ESPs where in-flight capture is more critical. Some plants are installing FFs downstream of an existing ESP, a configuration developed by EPRI (Electric Power Research

Institute) called *TOXECON™* to provide higher efficiency mercury control and particulate trim.

18.3.1.1 Flue Gas Characteristics: Halogens and SO_3

URS Group, University of North Dakota Energy & Environmental Research Center (UNDEERC), and others have studied the effect of hydrogen chloride (HCl) and sulfur in the flue gas on the adsorption capacity of fly ash and AC for mercury in laboratory studies (see, for example, Refs [2, 3] as well as Chapter 25). In general, results from laboratory studies suggest that

- HCl and sulfuric acid (H_2SO_4) accumulate on the surface of carbon.
- HCl increases the mercury removal effectiveness of AC and fly ash for mercury, particularly as the flue gas HCl concentration increases from 1 to nominally 10 ppmv. The relative enhancement in mercury removal performance is not as great above 10 ppmv HCl. In the absence of HCl, the ability of carbon to remove elemental mercury is minimal. Other strong Brønsted acids such as the hydrogen halides HCl, HBr, or HI should have a similar effect. Halogens such as Cl_2 and Br_2 should also be effective in enhancing mercury removal effectiveness, but this may be a result of the halogens reacting directly with mercury rather than the halides promoting the effectiveness of the AC.
- Sulfur dioxide (SO_2) reduces the equilibrium capacity of AC and fly ash for mercury. AC catalyzes the oxidation of SO_2 on the surface of the carbon. Because the concentration of SO_2 is much higher than that of mercury in flue gas, the overall adsorption capacity is likely dependent on the SO_2 concentration in the gas as it forms H_2SO_4 on the surface of the carbon. Thus, the capacity of AC for mercury is higher in flue gas with lower concentrations of SO_2 in the flue gas.

When coal is combusted, mercury contained in the coal is volatized. In the absence of halogens, the resulting vapor-phase mercury will be present primarily in the elemental form. If sufficient halogen is present in the coal, some of the mercury will react with the available halogen and form oxidized mercury. The fraction of oxidized mercury in the gas will be influenced by several factors including the presence of unburned carbon, whether the plant is configured with a selective catalytic reduction system (SCR) for NO_x control, the temperature of the gas where the mercury is measured, and the time–temperature history of the mercury.

Variations in the mercury control effectiveness of injected AC at different plants will be influenced by the speciation of the mercury and variations in the SO_2 and HCl in the flue gases. In 2001, AC-sorbent-based mercury control technology was first applied to full-scale plants burning PRB coals [4]. As noted, PRB fuel typically has very low-halogen content. With ACI, mercury removal for units configured with ESPs was generally limited to roughly 70%. This limitation likely represented the point where available HCl was removed from the gas stream by injected carbon. Excess carbon did not result in additional removal because insufficient HCl was available to promote oxidation and chemisorption of the remaining elemental mercury in the flue gas.

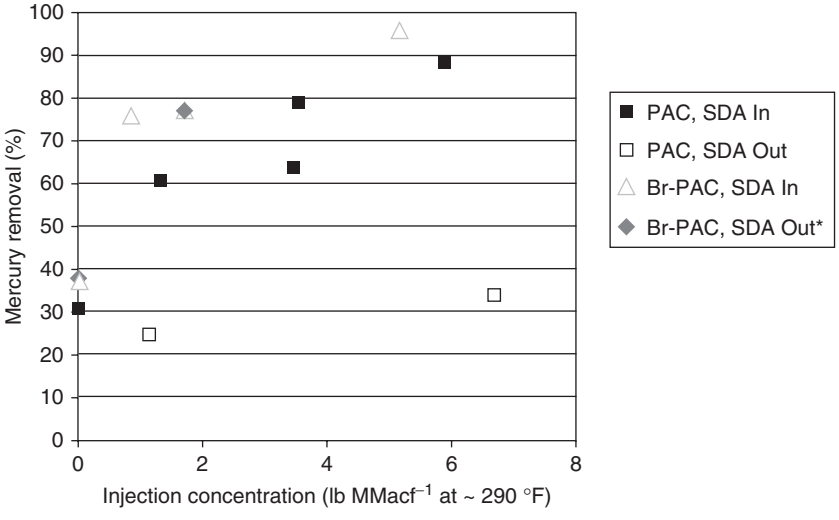

Figure 18.3 Results of injection location tests, Holcomb Station [5] (1 lb MMacf^{-1} = 16 mg m^{-3}).

Results from sites firing PRB and North Dakota lignite coals (low sulfur, low chlorine) configured with a spray dryer absorber (SDA) and an FF also indicate the importance of halogens for capturing elemental mercury using AC. In a typical SDA, slurry of lime is atomized to react with and control emissions of SO_2 and other acid gases. SDAs are very effective in removing HCl. In 2002, tests were conducted at Sunflower Electric's Holcomb Station [5]. The HCl measured at the inlet to the SDA was 0.13–0.61 ppmv. Results from ACI testing at Holcomb is shown in Figure 18.3. During the test, when PAC (DARCO®-Hg) was injected upstream of the Holcomb SDA, the mercury removal was much lower than would have been expected on a site without an SDA. An injection concentration of 91.2 g per actual cubic meter (5.7 lb MMacf^{-1}[1)]) was required to achieve 90% mercury removal. It is likely that the PAC did not fully react with the HCl between the PAC injection location and the SDA inlet before the remaining HCl was removed from the flue gas in the SDA. When PAC was injected downstream of the SDA, the mercury removal suffered further. The mercury removal was limited to <35% at injection concentrations up to 5.7 lb MMacf^{-1}, compared to 90% mercury removal at the inlet location. Most of the HCl was removed in the SDA and was not available to support mercury removal at the SDA outlet injection location [5–7].

On the basis of some of the studies conducted in the early 2000s, PAC vendors developed AC sorbents treated with halogens, typically bromine, to improve mercury control in low-halogen environments. Chapter 20 discusses brominated PAC in more detail. A PAC treated with bromine, DARCO Hg-LH (Norit Americas), was also tested at Holcomb. More than 90% mercury removal was achieved

1) 1 lb/10^6 ft^3 = 16 mg m^{-3}; sorbent loading is typically measured per "actual" volume at the temperature of the particulate control device and is usually denoted as lb MMacf^{-1}.

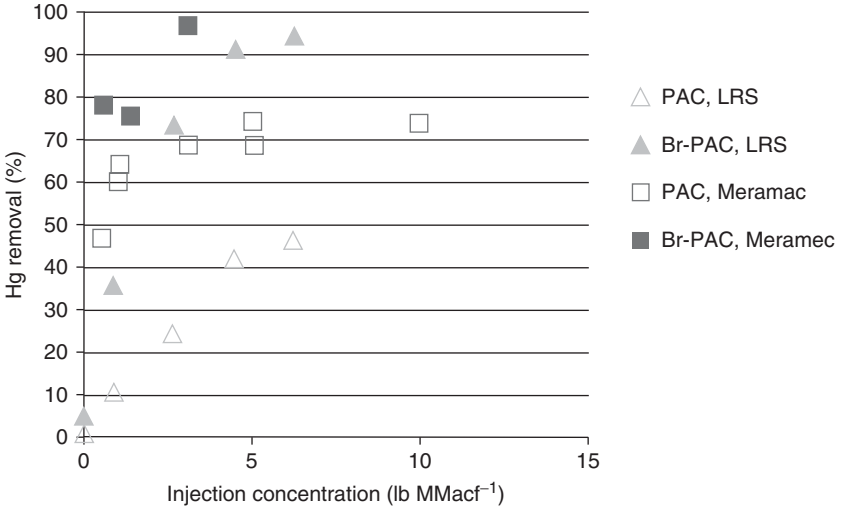

Figure 18.4 Comparison of PAC treated with bromine to nontreated PAC at two PRB-fired sites [8] (1 lb MMacf^{-1} = 16 mg m^{-3}).

at bromine-treated PAC concentrations <2 lb MMacf^{-1} and there was no difference in the performance of the bromine-treated PAC whether injected upstream or downstream of the SDA. These data are also included in Figure 18.3 [5].

Results from tests conducted with ACI at Ameren's Meramec Station and Basin Electric's Laramie River Station (LRS) are presented in Figure 18.4 [8]. Both Meramec and LRS were firing PRB coal during the testing period when both PAC treated with bromine-treated and nontreated PAC was tested. The results indicate that the mercury removal improved dramatically with the treated sorbent. At present, bromine-treated PAC is the standard sorbent for sites firing low-halogen coals. As an alternative, some sites treat the coal with halogens to improve the effectiveness of both unburned carbon and PAC.

Full-scale field tests indicate that standard AC is less efficient in high-sulfur environments. ACI tests were conducted at the University of Illinois' Abbott Power Plant in Champaign, IL in 2001 [9, 10]. This site fires high-sulfur (3.8%) bituminous coal with 2500 μg g^{-1} chlorine. Equilibrium adsorption capacity measurements were conducted on non-bromine-treated PAC samples at this site at temperatures of 191 °C (375 °F) and 163 °C (325 °F). The equilibrium adsorption capacity is measured by flowing flue gas through a fixed bed of PAC, typically mixed with sand to manage the pressure drop through the bed of powder, until the mercury at the inlet to the bed is equal to the outlet, or full breakthrough has been achieved. The equilibrium capacity is calculated as the mass of mercury in the bed to the mass of carbon. The value is often normalized to a mercury concentration in the gas of 50 μg m^{-3} by assuming a linear correlation between capacity and flue gas mercury concentration (i.e., the capacity at 50 μg m^{-3} is five times the capacity at 10 μg m^{-3}). At 191 °C (375 °F), the equilibrium adsorption

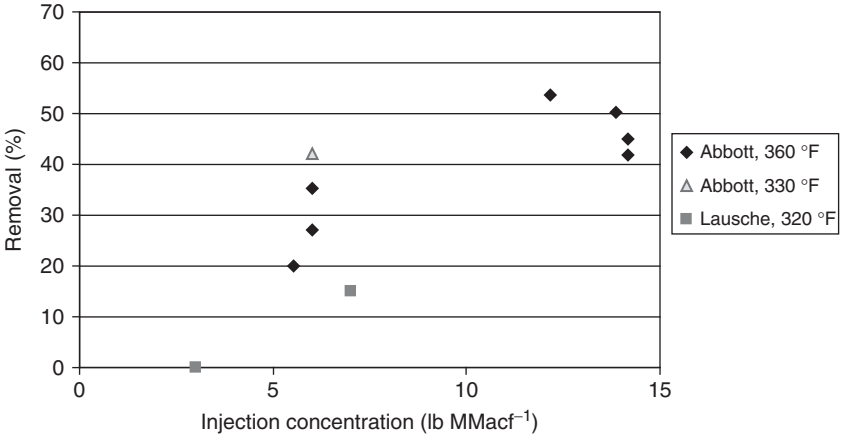

Figure 18.5 Injection test results from Abbott and Lausche Power Plants [9] (1 lb MMacf^{-1} = 16 mg m^{-3}).

capacity was 184 μg g^{-1}. At 163 °C (325 °F), the equilibrium adsorption capacity was 486 μg g^{-1}. Injection tests were conducted at Abbott at two flue gas temperatures: 182 °C (360 °F) and 166 °C (330 °F), and the results suggest a slight increase in the mercury removal performance of non-bromine-treated PAC at the lower temperature. Injection tests were also conducted at the Lausche plant of Ohio University (1000 ppmv SO_2 and 20 ppmv SO_3 in flue gas). Test results from both Abbott and Lausche, shown in Figure 18.5, indicate limited mercury removal performance of non-bromine-treated PAC.

Plants firing low-sulfur fuel may also face mercury control challenges from impacts related to sulfur compounds. For example, SO_3 is used to "condition" the flue gas to improve particulate capture in ESPs. This poses a unique problem because, across the United States, ~25 GW of power is produced by units that fire PRB and low-sulfur bituminous coals and that inject SO_3 to improve ESP performance. Many low-sulfur-fueled sites are also installing SCRs to control NO_x. The SCRs convert a portion of the flue gas SO_2 to SO_3. Low-conversion catalysts are available, but are typically more expensive and are often not considered necessary on low-sulfur applications unless mercury control is a consideration.

We Energies' Pleasant Prairie Power Plant (P4) utilizes SO_3 for flue gas conditioning. Equilibrium adsorption capacity measurements were made at locations upstream and downstream of SO_3 injection [6]. These data indicate a significant impact on the mercury capacity of non-bromine-treated PAC due to both SO_3 and temperature. However, when the PAC was injected into the duct, no difference in performance was noted. In addition, decreasing the temperature at P4 using spray cooling from 149 °C (300 °F) to 121 °C (250 °F) did not improve the mercury removal measured across the ESP when injecting non-bromine-treated PAC for mercury control. This suggests that the threshold capacity, or the capacity at which a change in performance is expected during injection testing, was <425 μg g^{-1} at P4, the equilibrium adsorption capacity measured at 149 °C (300 °F) in the

Table 18.1 Equilibrium adsorption capacities measured at two sites with SO_3 present in flue gas [6].

Site	SO_3	Temperature (°C)	Equilibrium Adsorption Capacity (μg g^{-1}) Normalized to 50 μg Nm^{-3}
P4	None	121	8823
P4	FGC	121	3355
P4 (PAC + lime[a)])	FGC	121	2091
P4	None	149	880
P4	FGC	149	425
P4 (PAC + lime[a)])	FGC	149	>1504
Abbott	Coal	191	148
Abbott	Coal	163	486

FGC, flue gas conditioner.
a) Lime to sorbent ratio was 60 : 1.

presence of SO_3. The equilibrium data also suggests that the capacity can be significantly improved at higher temperatures (149°C) in the presence of SO_3 if the sorbent is mixed with an alkali material such as lime. No improvement was noted at the lower temperature (121 °C). The P4 and Abbott results are presented in Table 18.1.

Full-scale injection testing conducted at Southern Company's Plant Daniel indicated that, unlike Pleasant Prairie, SO_3 used for flue gas conditioning had a negative impact on sorbent performance [11]. Daniel was firing a low sulfur western bituminous coal during the tests and is configured with an ESP for particulate control.

Results from testing conducted at Ameren's Labadie Power Plant [12] clearly show the impact of SO_3 on the mercury control effectiveness of AC. The mercury removal trends for brominated are summarized for 0, 5.4, and 10.7 ppmv SO_3 (0%, 30%, and 60% setting on SO_3 injection system) in Figure 18.6.

SO_3 levels may also be elevated if a selective catalytic reduction system (SCR) is in service to reduce NO_x and if the catalyst converts sufficient SO_2 to SO_3. Public Service of New Hampshire Merrimack Station is configured with an early-vintage SCR. Although the plant was not firing high-sulfur coal, the SO_2 to SO_3 conversion across the SCR was relatively high, resulting in SO_3 concentrations often above 10 ppmv. During long-term ACI testing [13], trona was injected for SO_3 control through four lances between the SCR and the air preheater (APH) at a rate of 550 lb h^{-1} with Br-PAC for mercury control at a rate of 5 lb $MMacf^{-1}$. Under these conditions, 50–55% mercury removal was achieved but could not be sustained because of balance-of-plant impacts. While injecting trona at 550 lb h^{-1}, the APH differential pressure increased 1.2 in. H_2O during the 30 days of injection, indicating deposition of a sodium compound in the APH. These results are shown in Figure 18.7.

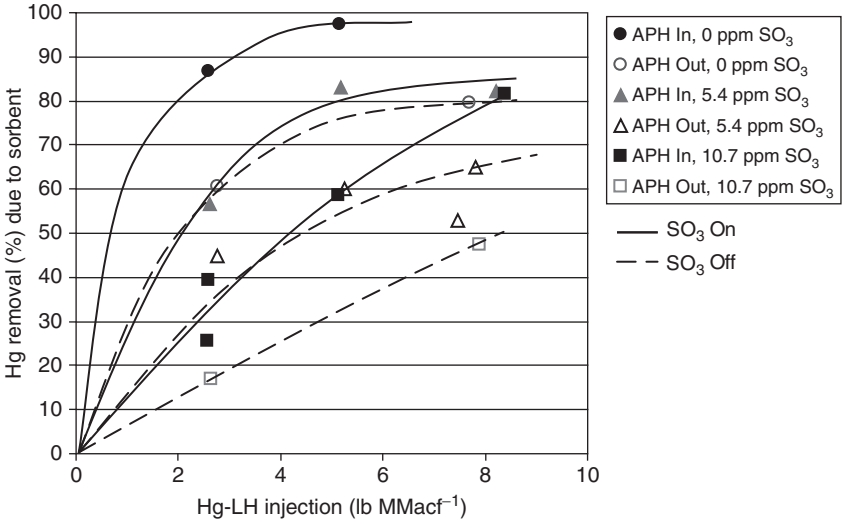

Figure 18.6 Comparison of APH inlet and outlet injection results for Br-PAC [12] (1 lb MMacf^{-1} = 16 mg m^{-3}).

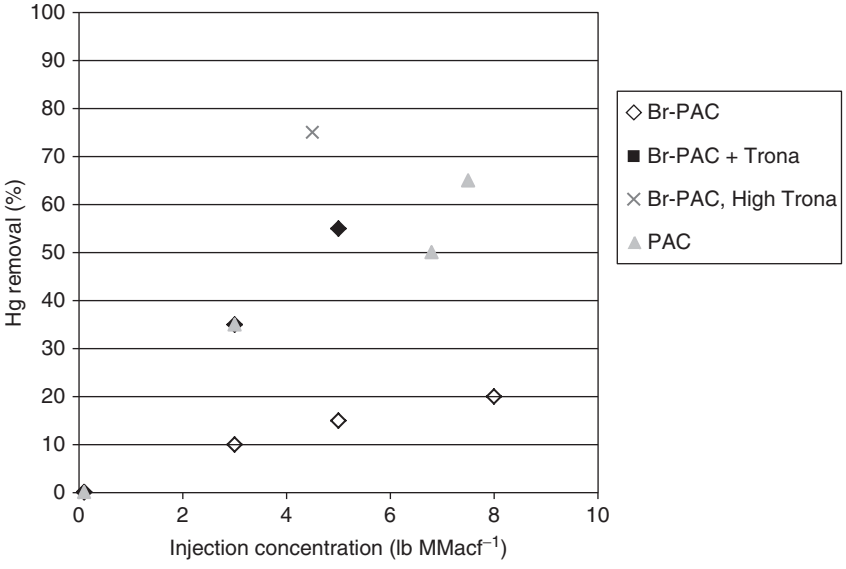

Figure 18.7 Merrimack test results [13] (1 lb MMacf^{-1} = 16 mg m^{-3}).

During a 3-day test, the trona injection rate was increased to 1000 lb h^{-1} to assess the ability to improve mercury removal by lowering the SO_3 concentration. This resulted in an increase in mercury removal up to 75% at a Br-PAC injection concentration of 4.5 lb MMacf^{-1}. These short-term results show that optimizing the trona injection lances for better distribution could improve both SO_3 and

mercury removal, but the data are insufficient to determine long-term balance-of-plant impacts or sustainability.

Techniques to limit the impact of other pollution control devices on PAC effectiveness for mercury control are being developed. For example, chemicals to replace SO_3 for flue gas conditioning are under development and evaluation. For sites firing high-sulfur coal, or when SCR catalysts that convert sufficient SO_2 to SO_3 are in use, the most effective option evaluated to date is lowering the SO_3 concentration using techniques such as trona (sodium sesquicarbonate) or hydrated lime injection. As a result of decreased SO_3 levels, the mercury removal can be significantly increased. Unfortunately, the introduction of trona at some sites has also resulted in other balance-of-plant issues such as an increase in the pressure drop across the APH [13].

18.3.1.2 TOXECON™

The first commercial operation of a mercury-specific control system to the power industry was a TOXECON system installed at the We Energies' Presque Isle Power Plant in Marquette, Michigan [14]. This was as part of a DOE (Department of Energy) Clean Coal Program and significant tests were conducted to characterize performance. Typical of many first installations of emission control technology, some operating problems were encountered during startup. The Presque Isle system achieved 90% mercury control levels for more than a year of continuous operation during the testing program. The operating procedures developed are being implemented with all of the new TOXECON systems being installed.

18.3.2 PAC-Specific Factors

Although ACI is a viable commercial process, technology developers continue to evaluate options to reduce costs and increase removal levels. For example, results from modeling and full-scale ACI tests indicate that reducing the PAC particle size can result in significant improvements in PAC effectiveness. For example, reducing the PAC diameter by a factor of 2 will result in an increase in the particle density of 8 (2^3), and double the available surface area. In 1999, Meserole [15] developed a model for mercury removal with sorbent injection, and the beneficial impact of reduced particle size, given sufficient sorbent capacity, was reported.

PAC milled from a mean diameter of nominally 18–6 μm was evaluated at Ameren's Labadie Station. The milled PAC resulted in a reduction in PAC requirements of more than 50% at a constant mercury reduction percentage, as shown in Figure 18.8 [16].

Most PAC injection systems are designed to feed standard PAC, which typically has a mean diameter between 15 and 25 μm. Fine material has different handling characteristics and may result in ACI system reliability issues. Fine PAC may also reagglomerate, especially if it is stored in the silo for prolonged periods.

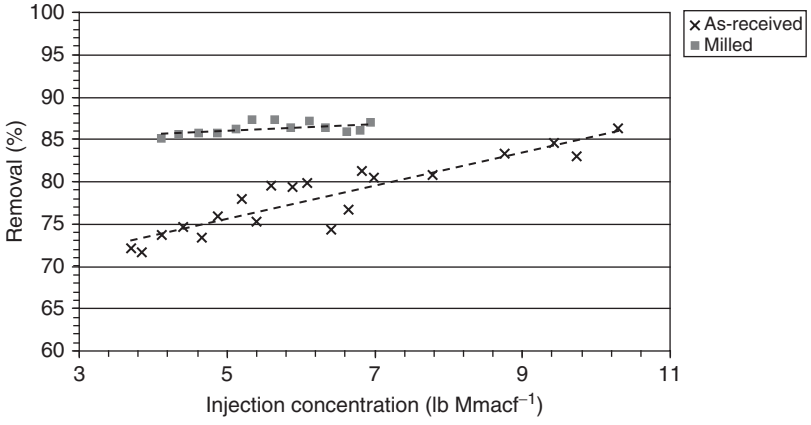

Figure 18.8 Improved mercury control using fine PAC [15] (1 lb MMacf^{-1} = 16 mg m^{-3}).

18.3.3 ACI System Design-Specific Factors

18.3.3.1 Injection Location

Injection location can make a significant difference in the residence time of the PAC in the gas stream, and improve the likelihood of good distribution. For some configurations, the biggest improvement in performance can be attained by moving the injection location from downstream of the APH, where the flue gas temperature is typically between 121 and 205 °C (250 and 400 °F), to upstream of the APH, where temperatures are typically 400–315 °C (750–600 °F). An example of improved mercury removal with PAC injection upstream of the APH is shown in Figure 18.9 [12]. In this case, higher mercury removal was achieved at half the injection rate when injected upstream of the APH. Note that although the *x*-axis presents the data as pound per million actual cubic feet, the actual flue gas volume for the calculation was at the APH downstream temperature in both cases. Although the effectiveness of a carbon for mercury degrades quickly as the temperature increases, injecting PAC upstream of the APH often results in overall improvements in PAC removal effectiveness. This effect is a result of several influences including increased residence time, which can promote both better distribution of the PAC in the duct, reactions between flue gas halogens and PAC, and increased time for reaction as the PAC moves through the APH.

18.3.3.2 Distribution

Either physical flow or computational fluid dynamics (CFD) modeling can be used to predict whether an injection grid is capable of getting PAC into all of the flue gas passages. Flue gas flow and temperature biases are often present. These can develop as a result of boiler design, duct structural members such as turning vanes, or for many plants that use rotary APHs, the rotation of the APH can

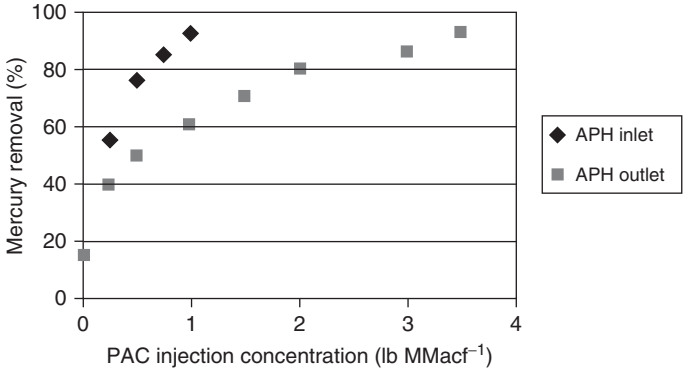

Figure 18.9 Mercury removal when AC was injected upstream and downstream of APH [11] (1 lb MMacf^{-1} = 16 mg m^{-3}).

cause temperature nonhomogeneity. CFD modeling can assist in determining whether additional lances are needed or if PAC injection should be biased into select lances to assure good distribution before the particulate collection device.

Caution should be exercised when designing PAC injection lances to assure that incremental improvements in short-term PAC distribution resulting from complex lance designs do not overshadow long-term maintenance and reliability concerns. Complicated lances, such as those with multiple injection nozzles, may provide enhanced distribution initially, but coal-combustion flue gas is not a forgiving environment. Nozzles can quickly become plugged, resulting in decreased overall distribution compared to simpler, more robust designs.

18.4
Balance-of-Plant Impacts

18.4.1
Coal Combustion By-Products

Fly ash has been used as a replacement for Portland cement in concrete since the 1920s when it was used in the construction of the Hoover Dam, then the largest concrete structure in the world. Air entrained in the concrete matrix improves the durability of the concrete over freeze–thaw cycles. In 2006, more than 72 million tons of fly ash were produced in the United States, 46% of which was used in concrete, concrete products, and grout, with another 6% used to make cement [17]. The remainder was placed in landfills or used in other applications. Fly ash landfilling costs are significant and can become one of the largest operating costs for plants after labor and fuel [18].

Air entrained in the concrete matrix improves the durability of the concrete over freeze/thaw cycles. Air-entraining agents are typically soaplike organic additives.

PAC in fly ash absorbs the organic air-entraining additives and can change the fly ash from a saleable product to a potential landfill liability.

Options to preserve ash sales while using ACI for mercury control include separating the PAC-laden ash from the bulk of the fly ash by using EPRI-patented techniques such as TOXECON, reducing the amount of PAC required through techniques such as using fine PAC, or use of a specialized ash-compatible AC. Chapter 21 discusses concrete-compatible carbons in more detail.

18.4.1.1 Autoignition of PAC in Ash Hoppers

There have been several reports of burning embers in baghouse and ESP ash hoppers collecting ash/PAC mixtures that have relatively high ratios of PAC to ash, such as TOXECON configurations where the majority of ash is removed before injecting PAC into the system [14, 19]. PAC is a relatively good insulator. If a hopper full of PAC is exposed to a localized heat source, such as a hopper heater or a welding spark, it can begin to smolder. PAC can also be oxidized via exothermic reactions in an air- or oxygen-rich environment. When the heat of oxidation increases faster than it can be liberated, temperatures increase, and can ignite the carbon.

Key factors contributing to autoignition are size of the bed or amount of ash/PAC in the hopper, temperature surrounding the bed from hopper heaters or high flue gas temperatures, concentration of carbon in the ash, and oxygen concentration.

Plants where autoignition has occurred have implemented maintenance procedures to prevent future occurrences of autoignition. Successful maintenance procedures include the following:

- Eliminate use of hopper heaters or lower the set point.
- Empty hoppers more frequently to minimize ash in the hopper.
- Ensure complete emptying of ash hoppers because AC becomes sticky when hot.
- Minimize fluidization.

Laboratory oven tests were conducted on different size square containers filled with PAC/ash mixtures collected in the hoppers of the TOXECON baghouse during PAC injection at Presque Isle. Thermocouples were placed in the oven and inserted into the bed of material at different levels to track temperature profiles over time. These tests confirmed that although the ignition temperature of the PAC was 850 °F, sufficient heat was internally generated at 430 °F for the PAC to increase the temperature of the mixture to ignition temperatures.

18.4.1.2 Impacts on Particulate Emissions

PAC is typically injected into flue gas at a rate that typically does not exceed 5% of the fly ash loading, and is often nearer to 1%, except for polishing applications such as TOXECON. There have been few reports of PAC injection negatively impacting particulate emissions [20], and some have reported that Br-PAC injection can improve the operation of the installed ESP [21].

18.4.1.3 Corrosion Issues

Injecting AC for mercury control is not expected to have adverse impacts on corrosion within the ductwork. However, when halogen-treated ACs are used, there is a possibility of inducing corrosion. Recent bench-scale corrosion tests have shown that bromine is capable of accelerating corrosion on metal surfaces [22]. Further investigations into long-term impacts of continuous halogen-treated ACI are under way.

18.5 Future Considerations

Advancements continue to be made in mercury control to assure compliance and minimize costs. PAC vendors are developing materials that are more effective, more tolerant to SO_3 and temperature, less corrosive, and concrete compatible. Equipment providers are required to provide equipment that can assure near-continuous reliability. Integrated solutions that incorporate multiple technologies such as coal additives to provide supplemental halogen, reagents to reduce the SO_3 concentration, catalysts to increase the fraction of oxidized mercury, and chemicals to improve the co-benefit mercury removal in SO_2 scrubbers are being refined. On the basis of its simplicity and cost, ACI will continue to be an important component of the installed mercury control technology base for the US coal-fired fleet.

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19
Halogenated Carbon Sorbents

Robert Nebergall

19.1
Introduction

Activated carbon has been shown over the past several decades to be an effective adsorbent for the removal of mercury from flue gas. The technology was developed in Europe during the late 1980s where municipal waste combustion was a large contributor of anthropogenic (human produced) mercury emissions to the environment. In addition, hazardous waste and medical waste incinerators are also large contributors of mercury emissions to the environment [1]. Municipal, medical, and hazardous wastes typically contain sources of chlorine and hence form chlorine compounds in the flue gas. The chlorine compounds present in the flue gas provide an excellent oxidant in the gas stream for the conversion to oxidized mercury. Standard or untreated activated carbons only effectively remove oxidized mercury from the flue gas. The mercury concentration in the flue gas in these applications was typically relatively high. Owing to the prevalence of mercury in municipal waste and hazardous waste, concentrations of mercury $>200\,\mu g\,m^{-3}$ of flue gas were not uncommon. Activated carbon treatment dosages of 3–6 pounds per million actual cubic feet (lb/MMacf)[1)] or $30–60\,mg\,m^{-3}$ of flue gas were also common [2].

19.2
Application of Activated Carbon for Mercury Control

When injecting activated carbon for mercury control, the mercury capture occurs in the particulate collection device. The two most common particulate collection devices installed at-coal fired power plants are an electrostatic precipitator (ESP) and a fabric filter.

1) $1\,lb/10^6\,ft^3 = 16\,mg\,m^{-3}$; sorbent loading is typically measured per "actual" volume at the temperature of the particulate control device and is usually denoted as lb/MMacf.

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ESPs electrically charge the ash and powdered activated carbon (PAC) particles in the flue gas to collect and remove them [3]. The unit comprises a series of parallel vertical plates through which the flue gas passes. Centered between the plates are charging electrodes that provide the electric field. The collecting plates are typically electrically grounded and are the positive electrode components. The discharge electrodes in the flue-gas stream are connected to a high-voltage power source (typically 55–75 kV DC) with a negative polarity. An electric field is established between the discharge electrodes and the collecting surface. As the flue gas passes through the electric field, the particulate takes on a negative charge, which, depending on particle size, is accomplished by field charging or diffusion.

Dust that has accumulated to a certain thickness on the collection electrode is removed by one of two processes, depending on the type of collection electrode. Collection electrodes in precipitators can be either plates or tubes, with plates being more common. Tubes are usually cleaned by water sprays, while plates can be cleaned either by water sprays or a process called *rapping*. Rapping is a process whereby deposited, dry particles are dislodged from the collection plates by sending mechanical impulses, or vibrations, to the plates. Precipitator plates are rapped periodically while maintaining the continuous flue-gas cleaning process. In other words, the plates are rapped while the ESP is online; the gas flow continues through the precipitator and the applied voltage remains constant. Plates are rapped when the accumulated dust layer is relatively thick (0.03–0.50 in.). This allows the dust layer to fall off the plates as large aggregate sheets and helps eliminate dust re-entrainment.

A fabric filter collects the dry particulate matter and PAC as the cooled gas passes through the filter material [4]. The fabric filter is comprised of a multiple-compartment enclosure, with each compartment containing up to several hundred long vertically supported, small-diameter fabric bags. The gas passes through the porous bag material, which separates the particulate and PAC from the flue gas.

With the typical coal-fired boiler, the PAC-laden flue gas enters the filter inlet plenum, which in turn distributes the gas to each of the compartments for cleaning. An outlet plenum collects the cleaned flue gas from each compartment and directs it toward the induced draft fan and stack. Each compartment has a hopper for particulate and PAC collection. The individual bags are closed at one end and connected to a tube sheet at the other end to permit the gas to pass through the bag assembly. The layer of dust and PAC accumulating on the bag is referred to as the *cake*. As the cake builds and the flue-gas pressure drop across the fabric filter increases, the bags must be cleaned. This occurs after a predetermined operating period or when the pressure drop hits a set point. Each compartment is sequentially cleaned to remove the excess cake and to reduce pressure drop. A residual cake coating is preferred to enhance further collection. Owing to the longer contact time when employing fabric filters, the dosage is up to 75% less than that needed for ESPs.

Table 19.1 Key coal properties [6].

Coal rank	Dry basis	Hg (μg g^{-1})	Cl (μg g^{-1})	S (wt%)	Ash (wt%)	Higher heating value, HHV (MJ kg^{-1})
Bituminous	Average	0.11	1033	1.69	11.10	31
	Range	0.04–0.28	48–2730	0.55–4.1	5.4–27.3	20.11–32.60
Subbituminous	Average	0.07	158	0.50	8.00	28
	Range	0.02–0.14	51–1143	0.22–1.16	4.7–26.7	20.02–20.63
Lignite	Average	>0.11	188	1.30	19.40	23
	Range	—	133–233	0.8–1.42	12.2–24.6	22.07–24.89

19.3 Development of Halogenated Activated Carbon

19.3.1 Motivation

In the United States, the federal Clean Air Mercury Rule (CAMR) was vacated by a Federal Court in February 2008, and a new federal standard for regulation of mercury emissions from power plants (the Mercury and Air Toxics Standards or MATS) has just been finalized. The MATS will not go into effect until 2015, at the earliest; however, as of 2011, 16 states had their own mercury emission regulations [5]. Before the vacatur of CAMR there was a need for the development of mercury control technologies from coal-derived flue-gas streams, and a new challenge for activated carbon. Low-rank coal fuels, including lignite and subbituminous fuels, typically have very low halogen content. As a result, mercury present in the flue gas from low-rank coal combustion is mostly elemental mercury, which provides a challenge for the standard activated carbons.

As discussed in Chapter 2, coal is ranked by age and key characteristics (calorific value, volatile matter, and carbon content). The three main coal ranks, lowest to highest, that power plants in the United States utilize as fuel are lignite, subbituminous, and bituminous. Each of these ranks contains subgroups that provide further differentiation of the key characteristics. Table 19.1 summarizes coal properties by rank relevant to mercury control in coal-fired boilers.

The relationship of coal rank to chlorine content is not easily explained and there are several factors involved over the lifetime of the formation of the coal. In the United States, bituminous coals have higher chlorine content by weight than lower rank coals,[2] with lignite having the least amount of chlorine content by weight.

2) The exception is that beginning with the higher ranked bituminous coals (low volatile and medium volatile), a decrease in chlorine content is seen because of the decreasing sorption capacity of the highly carbonized coal organic matter [17].

Leading up to the 2005 CAMR, much test work was completed in coal-fired power plants with support from the National Energy Technology Laboratory (NETL) division of the Department of Energy (DOE), as discussed in Chapter 10. It was demonstrated early in the plant testing programs that standard activated carbons had limited mercury removal capabilities in flue-gas streams from combustion of low-rank coal fuels. In all, the DOE NETL funded over 40 full-scale field tests for mercury removal with various APCDs (air pollution control devices) [7].

The DOE-sponsored testing program at Pleasant Prairie Power Plant in the early 2000s showed a distinct limitation of standard activated carbons for mercury emission control with Powder River Basin (PRB) subbituminous fuels [8]. Certain levels of mercury removal were possible, but reaching 80% or 90% removal was not achieved with standard PAC. Reduction curves demonstrating diminishing return on additional carbon dosage were developed from that work.

Similar results were achieved at Stanton Station in the same time period on lignite fuel [8, 9]. It was determined that the low halogen level in the low-rank coals was responsible for the low level of oxidized mercury in the flue gas, which prevented effective removal of mercury from the flue-gas stream with PAC.

In the Sunflower Electric testing of 2005 at Holcomb Station, this concept (elemental vs oxidized mercury) was tested at a facility that burned a PRB subbituminous coal and had a pollution control train including a spray dryer absorber and a fabric filter [10]. In this trial, 90% mercury removal efficiency was achieved at ~6 lb of untreated activated carbon injection per million actual cubic feet (MMacf) of gas flow. Correspondingly, 90% removal efficiency was achieved at just over 1 lb $MMacf^{-1}$ of an experimental halogenated activated carbon.

This step forward in technology was later duplicated at Meramec Station near St. Louis, Missouri, in a demonstration that also used a PRB coal fuel [10]. This site had an ESP and also an unusually high level of unburned carbon in the fly ash. Mercury removal levels of 90% were achieved at 3 lb $MMacf^{-1}$ activated carbon injection rate with a halogenated activated carbon. When standard activated carbon (not halogenated) was tested, mercury removal levels did not reach 80%, even at carbon injection rates as high as 15 lb $MMacf^{-1}$.

Since before the beginning of the DOE field test work, there was a great deal of speculation and research on the mechanism of mercury removal from flue gas when utilizing halogenated and nonhalogenated activated carbon. In general, activated carbon is a highly porous adsorption material with a complex structure composed primarily of carbon atoms (see Chapter 17). The structure consists of graphitic-like sheets of carbon atoms joined together by random cross-linkage. Unlike the orderly stacking of layers of carbon atoms in true graphite, an activate carbon has sheets or groups of atoms that are stacked unevenly and disorganized. This randomized bonding of the graphite sheets creates a highly porous structure with myriad nooks and crannies, cracks, and crevices between carbon layers. It is this molecular-size porosity and resulting enormous internal surface area that makes activated carbon such an effective material for adsorbing mercury. Activated carbon's pore surface is a defect structure with a cloud of unpaired electrons.

It contains an array of chemical functional groups containing oxygen that form active sites where adsorption occurs. It is not unreasonable to visualize an active carbon particle as one enormous carbon molecule. It is capable of reacting with, and bonding to, mercury as well as trapping it within its internal structure by electrostatic attraction.

19.3.2 Manufacture

Activated carbons are manufactured by one of two processes: high-temperature steam activation or chemical activation using a strong dehydrating agent. Steam activation is the most commonly used method for activated carbon production. It is performed in a furnace and consists of the following steps:

1) *Drying* – All of the raw materials currently in commercial use contain some residual moisture which must be removed before activation can take place.
2) *Devolatilization* – The lighter boiling organics are driven off the carbon raw material. These volatiles have some fuel value and may be used to reduce the overall energy requirements of the process.
3) *Charring* – The higher molecular weight organics are reduced to carbonaceous char residue. This char becomes the active carbon product during activation.
4) *Activation* – The activation step is generally conducted in a steam atmosphere at temperatures that vary depending on the type of carbon to be produced. Typically, half of the carbonaceous char material entering the activation step will be volatilized during activation to create the desired internal pore structure.

The International Union of Pure and Applied Chemistry IUPAC differentiates carbon pores by size; micropores have diameters <2 nm, mesopore has diameters between 2 and 50 nm, and macropore has diameters >50 nm. The iodine number, bromophenol blue number (BPB), moisture, bulk density, surface area, mesh size as well as bromine concentration are physical properties used to characterize halogenated activated carbon. The iodine number is a relative measure of microporosity. The BPB is a relative measure of range of mesoporosity. The moisture is the weight percent of moisture contained in the activated carbon. The bulk density is defined as the mass of many particles of the material divided by the total volume they occupy. The total volume includes particle volume, interparticle void volume, and internal pore volume. Surface area is the area contained in the particle including pores per gram of the material.

The size of an activated carbon is described by referring to a certain mesh size. By itself, this type of description is somewhat ambiguous. More precise specifications will indicate that a material will pass through some specific mesh (that is, have a maximum size; larger pieces will not fit through this mesh) but will be retained by some specific tighter mesh (that is, a minimum size; pieces smaller than this will have passed through the mesh). This type of description establishes

a range of particle sizes. Bromine percentage is the weight percent of bromine in the activated carbon.

The mechanism by which halogenated activated carbons adsorb elemental mercury is not completely understood at present, and it is a very complex question when considering the differences in activated carbons made from different raw materials and different processes. Chapters 23 and 25 discuss the underlying mechanisms in more detail.

Several different base raw materials including bituminous coal, subbituminous coal, lignite coal, peat, wood, and coconut shells may be used in the production of activated carbon for mercury removal from flue gas. All these raw materials will produce activated carbons with different pore structures, carbon lattices, ash compositions, and internal pore surface functional (oxygen) groups. Furthermore, any individual raw material will also create different surface groups when processed under different activation and cooling conditions.

19.3.3 Performance

It is well known in the industry that halogenation of the activated carbon increases the ability of the activated carbon to adsorb elemental mercury. Figures 19.1 and 19.2 show full-scale data on the removal of mercury across cold-side ESPs (Figure 19.1) and spray dryer plus fabric filter (Figure 19.2). In these figures, Darco Hg is a non-brominated carbon (Norit Americas). The brominated carbons are Darco Hg-LH (Cabot Norit Activated Carbon) and B-PAC (Albemarle).

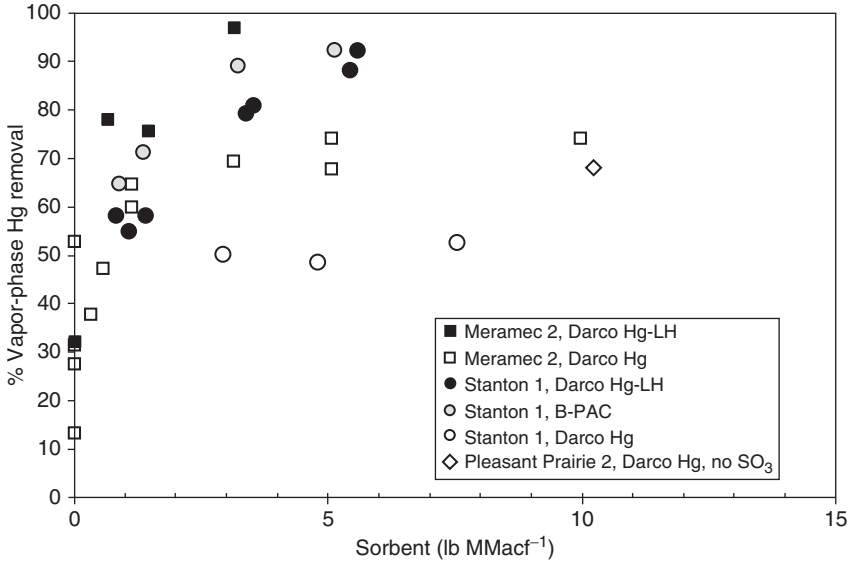

Figure 19.1 Mercury removal across cold-side ESPs at subbituminous-fired boilers; see text for discussion of carbon types [9, 10].

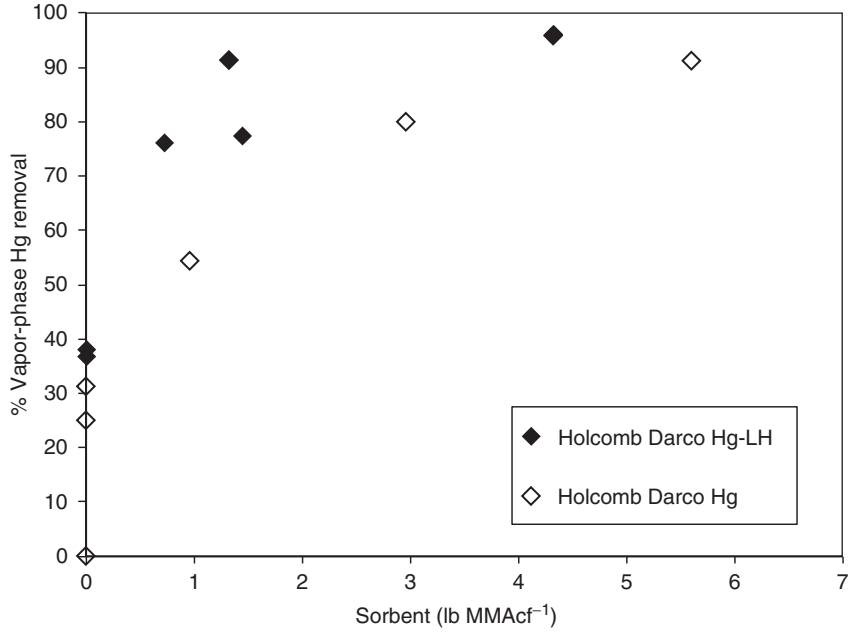

Figure 19.2 Mercury removal across spray dryer–fabric filter at subbituminous-fired boiler; see text for discussion of carbon types [10].

There are different theories as to the actual mechanism principally responsible for the adsorption. Elemental mercury is a highly polarizable atom because of its large number of electrons, which, by theory, should be subject to London dispersion forces [11]. In many activated carbon applications, it is generally believed that van der Waals forces of attraction are part of the mechanism of adsorption. Other theories have their basis in the idea that the surface of the activated carbon effectively acts similar to a Lewis acid through the formation of charge-transfer compounds on the surface of the carbon through halogenations [12].

Studies performed at Energy and Environmental Research Center have examined the effects of flue-gas acid species such as HCl, SO_2, NO, NO_2, on mercury capture as well as mercury binding and oxidation mechanism. In the model they propose, electrons must be accepted by a Lewis acid on activated carbon and then Hg^{2+}, which is a Lewis acid that can bind to Lewis base sites on the surface competing with other acidic species. Chapter 25 provides more detail on this work.

To add to the difficulty of surely identifying the mechanism behind elemental mercury adsorption, one must first address what form the halogen has taken while being applied to the activated carbon. In terms of application, information in the public domain indicates two primary methods of application. Halogen salts (primarily chlorine, bromine, and iodine) have been identified as both fuel additives and treatments for activated carbon. Studies have indicated that the larger the atom added to the surface of the activated carbon, the more effective it would be in oxidizing elemental mercury on the surface of the activated carbon. A lesser used

but also effective method of application is gas-phase impregnation of the activated carbon with gaseous bromine compounds. It is unlikely that the halide salt addition is captured on the internal pore surfaces of the activated carbon in a manner identical to that of a gas-phase treatment. According to X-ray studies, it has been shown that adsorbed mercury is indeed bound on the carbon pore surface in an oxidized form [13]. In addition, adsorbed mercury bound on the activated carbon pore surface appears to be located at halogenated sites, according to the other X-ray studies [14].

As one considers the complexity of a power plant fuel mix, boiler configuration, and its APCDs, it becomes apparent that many variables affect the ability of activated carbon to remove mercury from flue gas. As an example, it is commonly known that relatively high concentrations of sulfur trioxide (SO_3) have a substantial and negative impact on the activated carbon's ability to effectively remove mercury.

The presence of high concentrations of sulfur trioxide in the flue gas can be attributed to two main applications. Intuitively, higher sulfur fuels (typically bituminous) create higher sulfur dioxide flue gases, and hence higher sulfur trioxide levels in the flue gas. In addition, if the APCDs include an SCR (selective catalytic reduction), sulfur trioxide levels will typically be higher, because the SCR catalyst oxidizes some fraction of SO_2 to SO_3 (Chapter 15). In some newer coal-fired power plants burning bituminous fuels, levels of 50 ppmv of sulfur trioxide are found in the flue gas [15]. More commonly, bituminous facilities will have sulfur trioxide levels in the range of 10–20 ppmv.

The other situation in which sulfur trioxide becomes an issue is in flue-gas conditioning for ESP performance improvement. Sulfur trioxide is injected into the flue gas to improve ESP particulate collection performance. Sulfur trioxide is injected into the flue gas to improve ESP particulate collection performance typically at a level of 4–10 ppmv of sulfur trioxide. The flue-gas conditioning treatment, as of this writing, is a very common challenge to the implementation of current mercury control programs using activated carbon injection.

The state of Illinois has implemented the most stringent mercury control regulations to date. Many units located in Illinois were designed for burning high-sulfur, Illinois-basin bituminous coal. These coals have high sulfur and moderate ash contents. Subbituminous coals, although lower in ash than eastern bituminous coals, have much less sulfur and the resistivity of the fly ash is higher.

Resistivity is a measure of the particle's ability to transfer charge. Fly ash resistivity is a function of the particle composition and also the conditions in the flue gas: temperature, moisture, and sulfur trioxide concentration. If the resistivity of fly ash is too high, the ESP will not be able to collect it efficiently. The resistivity of fly ash from a low-sulfur coal is generally higher than that from a high-sulfur coal. Switching from a high-sulfur coal to a low-sulfur coal, therefore, can degrade the efficiency of an ESP. Flue-gas conditioning involves injecting a chemical upstream of the ESP; the chemical lowers the resistivity of the fly ash and improves the collection efficiency of the ESP.

Most units are equipped with ESPs, and thus face the challenge of particulate capture efficiency. Many units need to apply flue-gas conditioning to improve their performance, and sulfur trioxide is a common technology used for this enhancement. Although the mechanism for adsorption of sulfur trioxide has not been well studied, as is the case in many gas-phase applications for activated carbon, capillary condensation is thought to be an important mechanism for the removal of condensable constituents from flue gas. As sulfur trioxide molecules accumulate in the pore structure of the activated carbon, the molecules become closer and closer in proximity and are effectively compressed and condense in the pore. This phenomenon has a higher probability of taking place in smaller diameter pores such as micropores. Correspondingly, it is less likely to take place in mesopores or macropores.

In commercial application, halogenated activated carbons show improved resistance to the mechanism contributing to decreased activated carbon efficiency. The mechanism for this improvement is not well understood.

Another flue-gas variable that affects removal efficiency of activated carbon in general is the temperature. As activated carbon adsorption processes are an equilibrium based on the concentration of the contaminant in the stream, higher temperatures tend to favor desorption rather than adsorption. This has been demonstrated in many of the DOE trial programs. Halogenated activated carbons have demonstrated better mercury capture at higher temperatures [16]. It is speculated that the improved resistance is due to imparting higher charge imbalance on the surface of the activated carbon and hence improving the kinetic equilibrium in favor of adsorption.

19.3.4 Balance-of-Plant Impacts

Mention was made earlier in the chapter about the potential halogens that may be used in this process. Chlorine, bromine, and iodine have all been evaluated through the development of halogenated carbons for mercury removal from flue gas and all are used commercially to at least some degree. Owing to both effectiveness (ability to oxidize mercury) and commercial considerations (price, availability, supply chain reliability), most commercial products have been formulated with the use of bromine or bromine compounds as the preferred halogen. Given the great diversity of flue-gas constituency and potential interactions of a strong oxidant within other compounds in the gas, at least some concern needs to be given to the potential reactions to avoid other undesirable side effects. As an example, ammonia slip in excess may react with sulfur trioxide and form ammonium sulfate precipitate on APCD equipment upon cooling. When SCR work first began, this was not an expected outcome, but had material impacts.

All halogens can have the potential of being corrosive if handled improperly or handled in inappropriately designed equipment. For the handling of halogenated activated carbons, the use of high-grade stainless steel is not uncommon,

particularly in the feeder portion of the systems, to ensure that the equipment is not degraded.

Halogenated activated carbons have been a major technological advance for the mercury removal from coal-derived flue gas. Advancements in the efficiency and method of application are ongoing and sure to be followed by step changes to come.

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20
Concrete-Compatible Activated Carbon

S. Behrooz Ghorishi

20.1
Introduction

The fly ash generated from coal combustion is virtually identical in its composition to volcanic ash and is ideal for concrete use. According to the American Coal Ash Association, the United States produced 65.6 million metric (MM) tons of fly ash in 2008. Replacing cement in concrete is the primary use of fly ash. About 11.5 MM tons of fly ash went to concrete market in 2008 [1]. This is the highest value use of coal combustion fly ash. Reuse of fly ash to partially substitute for cement in concrete is a major success in waste recycling in the US and has significant economic, environmental, and technical benefits. The economic benefits of using fly ash to replace a fraction of the cement in concrete include increased revenue from the sale of the ash, reduced costs for fly ash disposal, and savings from using the ash in place of the more costly cement. Concrete performance benefits include greater resistance to chemical attack, increased strength, and improved workability. Environmental benefits include reduced greenhouse gas emissions, reduced land disposal, and reduced virgin resource use.

Recently the U.S. EPA finalized new federal regulations on coal-fired power plant mercury emissions based on Maximum Achievable Control Technology (MACT). Twenty states have also started controlling the mercury emissions from utilities in their state by 70–90% [2]. For the majority of the coal-fired power plants, the leading technology to comply with the new mercury regulations is activated carbon injection (ACI) [3]. Power plants inject powdered activated carbon (PAC) based mercury sorbents into the flue gas to capture mercury. The carbon sorbent is injected upstream of the plant's existing particulate control device, usually either an electrostatic precipitator (ESP) or a fabric filter (FF) baghouse. Currently, 150 ACI systems have been installed by the coal-fired power plants across the country [4].

The main concern for power plants that sell their fly ash for cement replacement is that PAC-based sorbents make the fly ash incompatible with concrete, causing the fly ash to be landfilled. This is doubly negative, because not only must the fly ash be disposed of rather than beneficially used, but also the opportunity is missed

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to physically and chemically sequester the mercury from release and interactions with the environment by encasing it in the concrete. Mercury that is sequestered in concrete is very stable. Golightly *et al.* [5] measured mercury release during curing of concrete that contained fly ash or fly ash/carbon that had mercury adsorbed on it. The mercury flux from the concrete samples resembled those from natural soils indicating no increase in baseline mercury emission from concrete that is made by inclusion of coal combustion fly ash/PAC. Because of the high surface area of typical PACs and their high adsorption capacity, if even the smallest amount gets mixed in with fly ash, the fly ash can no longer be used in concrete [6]. As shown by Senior *et al.* [6] in their field studies of class C fly ash mixed with activated carbon, the PAC adsorbs the air-entraining admixtures (AEAs) later added to the concrete slurry. These surfactants enable incorporation of the precise amount of air bubbles needed to create the air voids required for concrete workability and freeze-thaw capabilities.

Mercury emissions from cement kilns are also increasingly recognized as a problem. ACI offers the cement kilns a very cost-effective mercury control technology. PACs could similarly be injected into these exhaust gases and be collected in the particulate removal devices that separate the cement kiln dust (CKD) from the exhaust gases. However, because the collected CKD would then contain AEA-adsorbent PACs, it could no longer be sold as cement for air-entrained concretes.

To preserve the sale of fly ash and to continue the use of CKD, "concrete compatible" PAC needs to be developed. Concrete compatible activated-carbon-based mercury sorbent allows power plants to continue to sell their fly ash and cement kilns to continue the use of CKD while also having very good mercury capture performance. There are a number of concrete compatible activated carbon products, one of which is Albemarle Corporation's Concrete-Friendly™, C-PAC™, which is now commercially available. Calgon Carbon Corporation and Norit Americas also offer concrete-compatible products referred to as *FLUEPAC®-CF PLUS* and *DARCO® Hg-CC*, respectively.

Topics covered in this chapter are as follows: new and innovative metrics to define the concrete-compatibility of mercury sorbent, production of concrete-compatible products including C-PAC™, C-PAC™ specifications, commercial application of C-PAC™ in various plants, and the results of concrete test with the resultant fly ash containing C-PAC™.

20.2
Concrete-Compatibility Metrics

Traditionally, the foam index method has been used to determine the concrete compatibility of different fly ashes. The foam index test is a relatively crude method used to predict the relative degree of adsorption of AEAs that a fly ash sample's components, primarily carbon, will have in a concrete slurry. As described before, AEAs are surfactants that are added to concrete mixes to form fine, stable bubbles

that are needed for void volume so that concretes do not crack when interstitial water freezes. Foam index tests are usually done by titrating an AEA solution into a mixture of fly ash and water until a stable foam forms on the surface after agitation. The number of drops of AEA that it takes to saturate the fly ash components so that some is available to form a foam denotes the sample's foam index (FI). Dividing the FI by the amount of carbon in the sample provides a Specific Foam Index (SFI). Unfortunately, there is significant variability and, sometimes, a lack of repeatability in performing foam index measurements. These are the results of operator discretion, the use of different and variable reagents, varying laboratory equipments and "drop" sizes, non-standardized procedures, and the dynamic, nonequilibrium nature of the test. Also the foam index is specific to the AEA used in the particular measurement.

Pederson *et al.* [7] introduced a new method based on dynamic surface tension measurements (using a bubble pressure method) on filtrate from a fly ash and cement suspension. This method is claimed to have less variability as the foam index method. A pure surfactant is added to the suspension as a substitute for a commercial AEA. The surface tension method and the foam index test have been compared on fly ashes acquired from power plants in Denmark and the United States. The results revealed a good relationship between the two methods. This new method and the foam index technique are affected by changes in temperature. The authors stated that the surface tension method requires further work before a finished procedure is accomplished. Stencel *et al.* [8] introduced an automated foam index testing based on detecting acoustic waves emanating from a container in which cement-ash mixture is tested. AEA in water is dosed in the container and agitation is performed using precise computer control. The real-time nature of the acoustic emissions from the container provides dynamic assessment of foam stability. This method removes operator error in the foam index test, but it is still suffers from other drawbacks of this method as mentioned above.

In its development of a concrete-compatible mercury sorbent, Albemarle Corporation needed a standard, repeatable method to gauge the effect that different PACs would have on AEAs in a concrete mix. PACs are similar to the unburned carbon found in fly ash, but they have significantly higher surface area. The lack of reliability and precision encountered when trying to use foam index testing on PAC or PAC/fly ash blends proved unsatisfactory.

Consequently, a standardized and repeatable method for measuring the effect of fly ash carbon or mercury sorbent carbon on AEAs was developed to replace foam index test. This new method is a more accurate indicator of AEA interference than the traditional foam index test. It uses a standard reagent, tested at an equilibrium condition, and eliminates operator discretion in determining when a sample begins to "foam" by utilizing instrumental measurements. Based on this new method, Albemarle Corporation developed its Concrete-Friendly™ mercury sorbent known as *C-PAC™*.

20.2.1
The New and Innovative Concrete-Friendly™ Metrics; the Acid Blue Index

The new method is based on a standard reagent, acid blue 80 (AB80) (CAS 4474-24-2), rather than a non-standard AEA. Numerous dyes were evaluated for their correlations of adsorption with the foam indexes of various AEAs. AB80 provided the best results. Moreover, AB80 has a chemical structure and molecular size similar to some AEAs. Among the other tested dyes, one was methylene blue (CAS 7220-79-3; see Figure 20.1)

Methylene blue has been tried by other researchers for this role, however results indicates that the methylene blue adsorption of several commercially-available PACs does not correlate well with their foam index values, as indicated in Figure 20.2, while AB80 does.

AB80 is one of the anthraquinone type acid dyes (Figure 20.3).

The adsorption spectrum of an AB80 aqueous solution is shown in Figure 20.4. It has three peaks at 626, 581, and 282 nm, respectively. The appearance of several adsorption peaks for a given chromophore is common for a highly conjugated system.

The overall procedure of AB80 adsorption that was developed is very similar to ASTM D 3860-98 Standard Practice for Determination of Adsorptive Capacity of Activated Carbon by Aqueous Phase Isotherm technique. First, the PAC sample is oven-dried at 150 °C for 3 h prior to the test. Different dosages of dried carbon are then added to 50 ml of 100 mg l^{-1} AB80 solution and well stirred. After

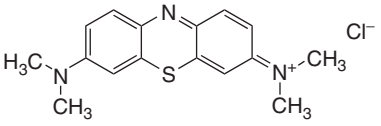

Figure 20.1 Structure of methylene blue.

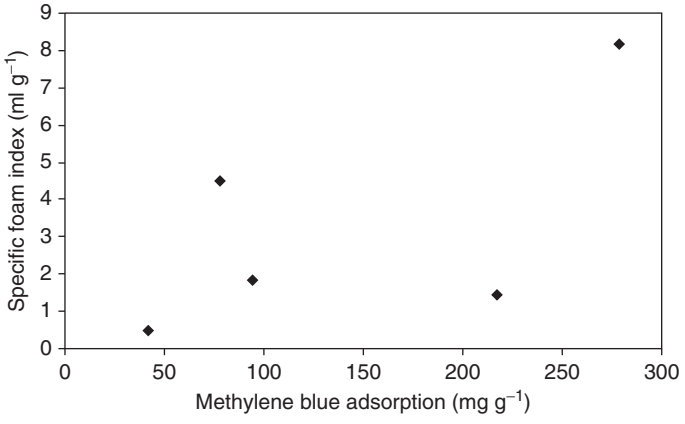

Figure 20.2 Correlation between specific foam index and methylene blue adsorption.

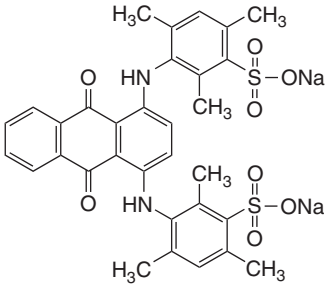

Figure 20.3 Structure of AB80.

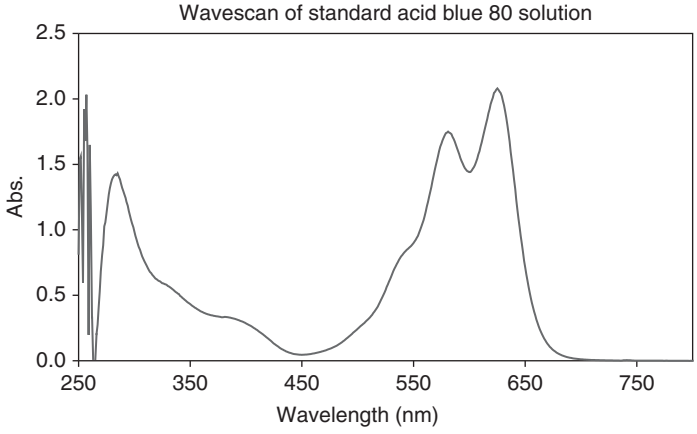

Figure 20.4 Adsorption spectra/wave scan of standard acid blue 80 solution.

the adsorption reaches an equilibrium, the carbon is separated from the AB80 solution by filtration. The concentration of the filtrate is determined, for example, by using Perkin Elmer Lambda EZ201 Spectrophotometer. The amount of AB80 removed by the activated carbon is determined by the relative change of AB80 solution prior to and after contact with activated carbon. The AB80 adsorption of the dosage carbon is then plotted with the equilibrium concentration of AB80 solution. The adsorptive capacity is calculated from a Freundlich isotherm plot at the original concentration of the AB80 solution, which is defined as Acid Blue Index (ABI) in the Albemarle-developed method.

During this method development, it was found that some chemically treated carbons interfere with AB80 adsorption. In order to eliminate this interference, such samples should be prewashed and extracted by deionized or distilled water until none of the impregnation chemicals is detected in the solution. For example, 5 g of B-PAC™ (an Albemarle Corporation's mercury sorbent; a non-concrete compatible brominated PAC) was washed with 250 ml of water, then filtered and rinsed with 1 l of water to properly prepare this brominated carbon for an ABI measurement. The sample weights of the activated carbons used in the

adsorption test may have to be adjusted depending on the adsorptive capacity of the activated carbon. A general guideline is that the concentration of the AB80 solution after contacting activated carbon should fit into the linear range of the AB80 working curve obtained based on the adsorption spectra at different concentrations (see Figure 20.5).

Based on the absorbance at 626 nm, the working curve for AB80 solutions was determined and is displayed in Figure 20.6. It can be used to calculate AB80 concentrations in solutions after adsorption by various activated carbons at various dosages.

The adsorption of AB80 by activated carbon fits well into a Freundlich Adsorption Isotherm, as shown in Figure 20.7. The AB80 adsorption of various activated carbons was determined based on Freundlich isotherms with the original AB80 solution concentration (100 mg l^{-1}) and the adsorption is defined as the ABI.

Depending on the different activation conditions, the pH of PACs can vary from very acidic to basic. Consequently, the effect of pH on the absorbance at 626 nm

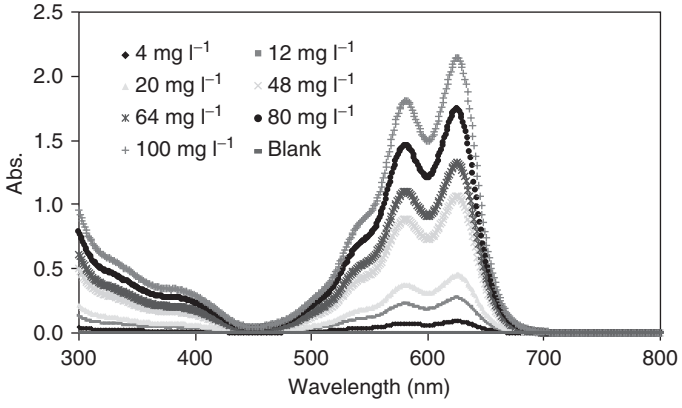

Figure 20.5 AB80 adsorption spectra at different concentrations.

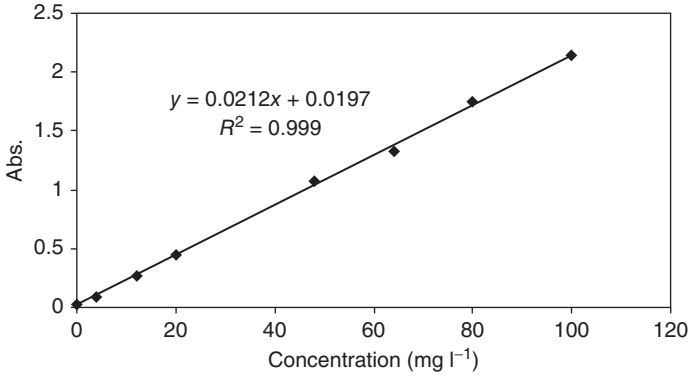

Figure 20.6 Working curve for AB80 solution.

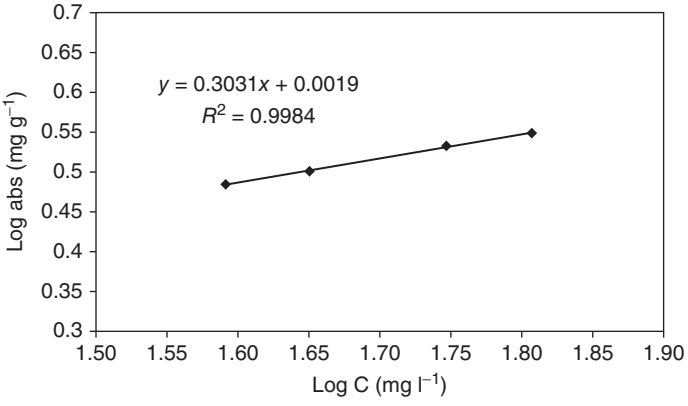

Figure 20.7 Freundlich isotherm for a tested activated carbon.

of AB80 solutions was investigated. The pH of the AB80 solutions was adjusted by H_2SO_4 or NaOH in order to obtain a series of AB80 solutions with different pHs. Within the test pH range of 2–12, the absorbance of the AB solutions vary about ±2%, which suggests that the absorbance of AB80 solution is independent of the pH of solution. The time needed for the adsorption to reach equilibrium is another important parameter in this method. AB80 adsorption progresses relatively quickly, with the adsorption capacity reaching a plateau at about 30 min. This is the recommended time for carrying out the AB80 tests.

The Albemarle-developed ABI method has been extensively tested using a broad variety of carbon-containing materials. These include a series of laboratory-made activated carbons, a range of commercially-available activated carbons from different precursors, and different chemically treated activated carbons, including Albemarle Corporations' B-PAC™ and C-PAC™. A comparison of the ABIs and SFIs of some of these activated carbons using various commercially-available AEAs is shown in Figure 20.8. Use of different AEA compounds result in a wide range of SFI but a very narrow range of ABI, indicating that the ABI is the most appropriate method to determine concrete compatibility of a material. As evident from this figure C-PAC™ has ABI values below 10 mg g^{-1} and very low SFI. The data in this graph is used to set specification for concrete-compatibility of PAC/fly ash mixtures (see the next section).

20.3
Production of Concrete-Compatible Products Including C-PAC™

In C-PAC™ production, a one-step method is used. Before detailing this production technique, a review of a number of other techniques is presented. Fly ash that is mixed with carbon can be treated and passivated with ozone. Hurt *et al.* [9] in US Patent 6 136 089 teaches such method. Chen *et al.* [10] also discusses this technique in their paper. Ozone chemically passivates the surface of carbon in fly ash

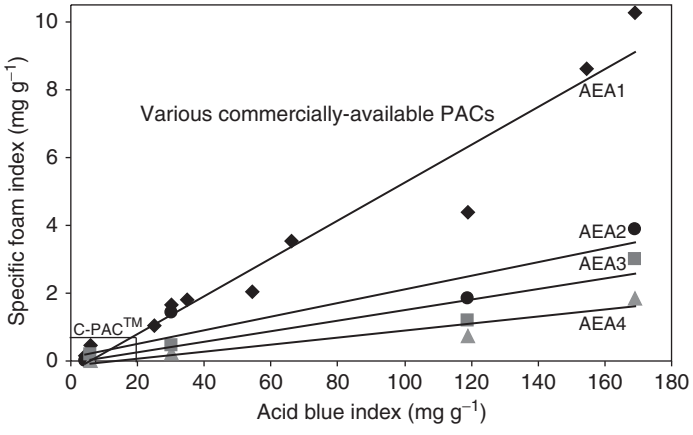

Figure 20.8 Comparison between ABIs and SFI of a number of activated carbons and C-PAC™.

and thus improves the air entrainment characteristic of fly ash. This process leaves the carbon in place, but adds surface oxygen complexes whose presence inhibits adsorption of the surfactant. This procedure requires treating large quantities of fly ash. Nelson [11] teaches a similar method that is only applied to the produced activated carbon before its injection into the flue gas and mixing with the fly ash. This method treats smaller volumes of solid material but still is an additional step in the production of activated carbon.

Jolicoeur *et al.* [12] discuss the use of "sacrificial agents or admixtures" to overcome the negative impact of carbon particles in adsorption of AEAs. The model sacrificial agent used in their study was ethyleneglycolphenylether (EGPE). They showed that addition of EGPE prevents the deleterious carbon effect on air entrainment by altering the surfactant adsorption and the surface energy (wetting behavior) of the carbon particles. They also observed that the addition of excessive dosages of EGPE has no detrimental consequences on air entrainment. However, this method still requires addition of another compound to the cement mixture. Another method to prevent the deleterious effect of carbon in fly ash is by carbon burnout [13]. In this method and before use in concrete mixture, the carbon in fly ash is simply burnt off in a fluidized-bed reactor with temperatures reaching 860 °F. Obviously, this process requires addition of external energy to accomplish carbon burn-off. This is a drawback of this technique.

A low-ABI carbon-based mercury sorbent can be produced by activating carbon using a one-step carbonaceous mercury sorbent precursor consisting of wood, lignite, coconut shell, or coal. The activation temperature and time period should be limited such that the ABI of the activated carbonaceous mercury sorbent does not exceed 15 mg g^{-1} of sorbent (a specification discussed in the next section). This constitutes a one-step production process and no post-treatment processing of the activated carbon is required.

The keys to creating carbonaceous mercury sorbents that can be used together with fly ash in air-entrained concretes are: (i) a minimized PAC mesoporosity and/or (ii) a proper carbon surface chemistry. According to the International Union of Pure and Applied Chemistry's guidance on Reporting Physisorption Data for Gas/Solid Systems, activated carbon pores with widths less than 2 nm are considered micropores. Pores with widths between 2 and 50 nm are considered mesopores and pores with widths exceeding 50 nm are considered macropores. To create a concrete-compatible carbonaceous mercury sorbent, the carbon's mesoporosity must be minimized, while retaining adequate reactive microporosity. AEA compounds are relatively large molecules, on the order of 1 – 3 nm long. By minimizing the number of pores that the AEA molecules can fit into or be transported through, the amount of AEA that can be deleteriously adsorbed from the concrete slurry can also be minimized. The particular surface chemistry of the carbonaceous mercury sorbent is also very important in determining the degree of AEA adsorption on PACs. The presence of particular oxygen functional groups on the surface of the PAC and the net charge of the surface could promote or impede the attachment of AEAs. Oxygen-containing functional groups created during air activation should impart an acidic, hydrophilic character to the carbon surface, which can repel the hydrophilic heads of the AEA molecules. By increasing the hydrophilicity of the PACs the adsorption of AEAs may be retarded, with little deleterious effect on gas-phase mercury adsorption. Additional information regarding production of C-PAC™ can be found elsewhere [14, 15].

20.4 C-PAC™ Specification

Albemarle Corporation has developed a brominated activated-carbon-based mercury sorbent with a very low SFI value, called *C-PAC™*. The ABI of this material is less than 10 mg g^{-1} (see Figure 20.8). ABI is the most important characteristic of this concrete-friendly™ material determining its use in concrete. Based on extensive testing, Albemarle has determined that ABI values of <15 mg g^{-1} are acceptable. There are a number of other specifications that determine the effectiveness of C-PAC™ both for mercury removal and its concrete-friendliness. These values are listed in Table 20.1.

20.4.1 Commercial Application of C-PAC™

In this section, full-scale test results performed with C-PAC™ at a number of utilities and cement plants are presented and discussed. The focus is on the effectiveness of mercury removal using C-PAC™ and the effect of the sorbent on the concrete parameters of the resultant fly ash.

Table 20.1 C-PAC™ specifications.

Property	Value
Acid Blue 80 Index (mg g^{-1})	<15
Bromine (wt%)	7
Moisture (%)	8
Iodine number (mg g^{-1})	>500
Tapped bulk density (g $cm^{-3)}$	0.56
Particle size less than 325 mesh (%)	>95
Ash content (wt%)	<12
Ignition temperature (°C)	>400

20.4.2
Full-Scale C-PAC™ Trials at Midwest Generation's Crawford Station

The goal of the full-scale C-PAC™ injection for mercury control at the Crawford plant was to determine if greater than 70% reduction of mercury could be achieved while maintaining the quality of the fly ash for concrete sales. The Crawford Station Unit 7 fires PRB (Powder River Basin) coal and has an ESP with a specific collection area of 0.4 m^2 per actual cubic meters per minute (120 ft^2 per 1000 actual cubic foot per minute). Much of this plant's fly ash has historically been sold for concrete use. During the month-long continuous test, C-PAC™ was injected at an average rate of 74 mg/m^3 (4.6 pounds of sorbent per million actual cubic feet of flue gas or lb $MMacf^{-1}$). An average total mercury removal rate of over 80% was achieved, as indicated in Figure 20.9.

The sorbent injection rate varied over the course of the trial, as it might in commercial practice, putting varying amounts of the sorbent in the fly ash and

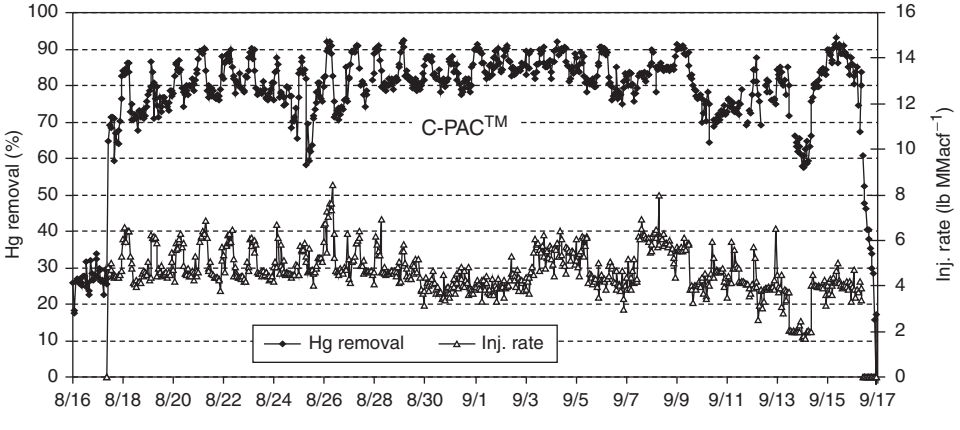

Figure 20.9 Crawford unit 7 mercury removal and injection rates over 30 days (1 lb $MMacf^{-1}$ = 16 mg m^{-3}).

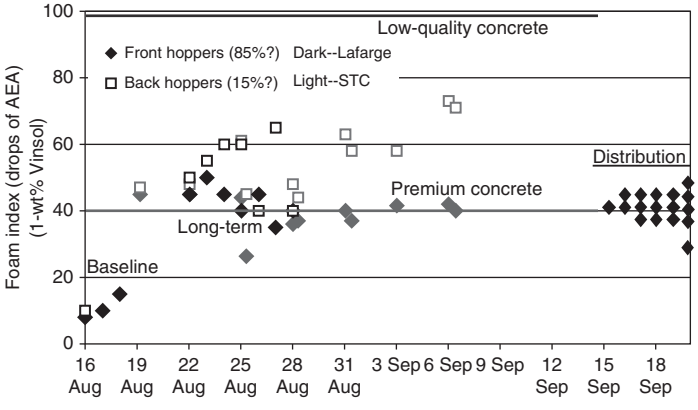

Figure 20.10 Foam index of Crawford fly ash during a 30-days C-PAC injection trial.

challenging the consistency of the fly ash for concrete use. Despite this, the resulting AEA adsorption of the ashes held to a tight band (see Figure 20.10). During the trial, the stack opacity improved, rather than degraded. It was observed that C-PAC™ injection had the co-benefit of improving the particulate collection performance of the ESP.

The resulting fly ash from this unit was usable in concrete. Moreover, fly ash from the front hoppers was usable in premium concrete (Figure 20.10). Using Vinsol® AEA, if the foam index is <40 drops, Crawford's fly ash is considered acceptable for cement replacement in premium concrete. At 99 drops or less, it can be used in standard concrete. The 40-drop cut off for premium concrete is a somewhat arbitrary value, based on the foam index of the unburned carbon and, particularly, on the variation observed in this value. The standard deviation of the C-PAC™-containing ash was only four drops, while that of the baseline control ash was even higher, at five drops.

20.4.3
Full-Scale C-PAC™ Trials the PPL Montana Corette Station

The purpose of the trial conducted at the Corette Steam Generating Station of PPL Montana was to determine whether the injection of C-PAC™ could reduce the mercury emissions by 80% while maintaining the ability to sell the fly ash for use in concrete. Two different continuous mercury monitors (PSA continuous emission monitor (CEM) and Ohio Lumex) and an Appendix K sorbent trap sampler were used for mercury measurements at this site. The injection trial was around the clock beginning at an injection rate of 3 lb MMacf^{-1}, based on an ESP inlet (cold-side) flow basis. In the first phase of the parametric testing, mercury removal rates of >80% were achieved at an injection rate of 3 lb MMacf^{-1} and >90% at an injection rate of 5 lb MMacf^{-1} (see Figure 20.11).

PPL Corette burns a PRB subbituminous coal. The coal samples contained about 30% moisture, <5% ash, and 0.3% sulfur. The coal heat content was slightly

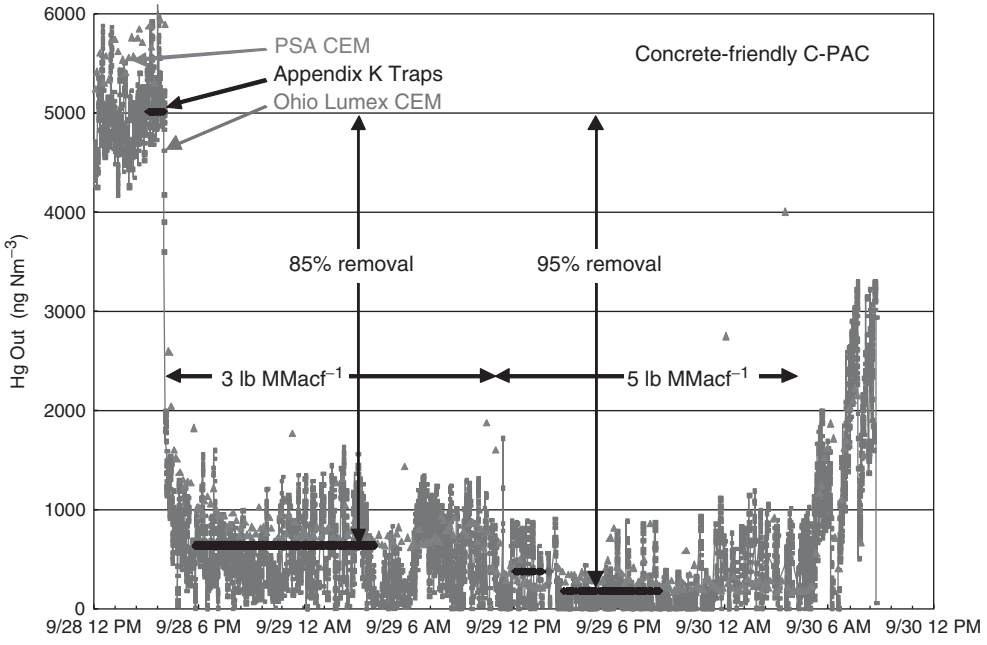

Figure 20.11 Mercury removal and C-PAC™ injection rate at Corette (1 lb MMacf^{-1} = 16 mg m^{-3}).

below 19.8 MJ kg^{-1} (8500 Btu lb^{-1}). The average mercury content of the coal was approximately 0.080 μg g^{-1} on a dry basis. Analysis of the fly ash samples collected during the test confirmed that the proper amount of mercury was being removed from the flue gas and collected in the fly ash. The foam index testing of the resulting fly ash indicated that the fly ash maintained its ability to be used in cement. All of the fly ash generated during the C-PAC™ injection period was transferred into PPL's storage silos and sold for concrete use.

20.4.4 Cement Kiln Mercury Emission Control Using C-PAC™

Portland cement kilns are another major mercury emission source, and the U.S. EPA promulgated in 2010 the final MACT standard for cement plants. One option for the cement plants to meet MACT Hg emission control requirement is to add a polishing baghouse to the kiln at a cost of millions of dollars. An alternative and cost-effective option is the injection of C-PAC™ at the existing baghouse, as illustrated in Figure 20.12.

In this technique, C-PAC™, which is both thermally stable and concrete-compatible, is injected as needed upstream of the primary existing particulate control device to reduce and maintain the mercury emission concentration to an acceptable level. Depending on the site, continuous C-PAC™ injection may

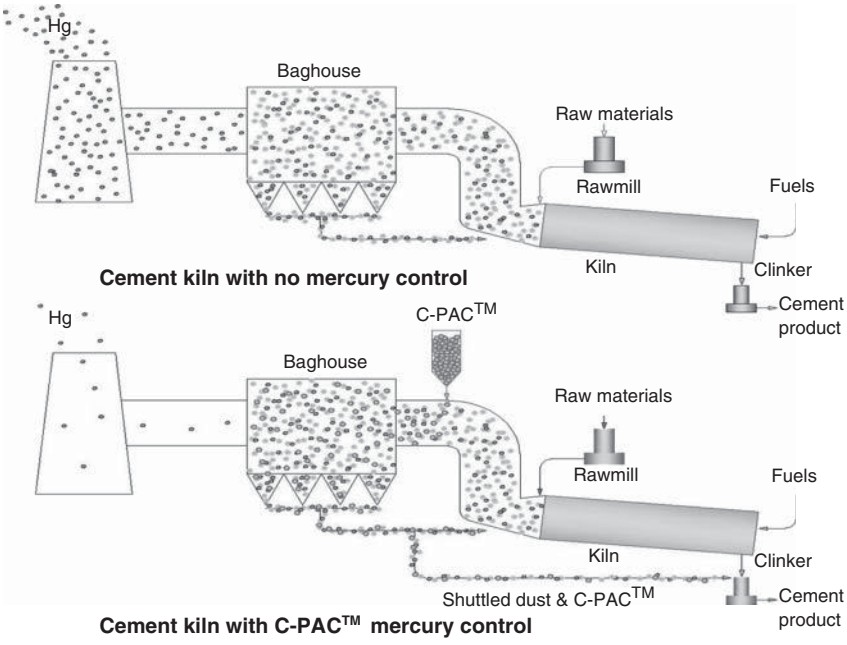

Figure 20.12 Illustration of C-PAC™ injection scheme at a cement plant.

be needed or C-PAC™ injection may only be required when the raw mill is off and Hg is at the highest level. (See Chapter 9 for a detailed discussion of mercury behavior in cement kilns.) Subsequently a percentage of the CKD containing mercury-laden sorbent is shuttled to the finished mill for use in the final cement product. In this way, no waste disposal or loss of the CKD occurs. Very good performance with C-PAC™ has been observed in several demonstrations, as well as commercial applications. The advantages of this in-process Hg control technique for the cement kilns include:

1) Requires only a sorbent injection system (low capital cost).
2) Sorbent is the main additional operating cost.
3) The timeframe for equipment design, procurement, and installation is short.

The sorbent requirements for this technique are that it must be temperature insensitive, concrete-compatible and have a high capability for Hg capture.

20.5 Concrete Compatibility Test – Field Fly Ash/C-PAC™ Mixture

In collaboration with two major fly ash marketers in the United States (Headwater Resources and Lafarge), Albemarle Corporation has examined in more detail the

concrete compatibility of the fly ash generated at Midwest Generation's Crawford Station. The results of these studies are summarized below.

20.5.1 Air Content of Fresh Concrete

The performance of C-PAC™/fly ash was compared with a non-sorbent control (fly ash only) and an alternative commercial PAC/fly ash. To make concrete with 6 vol% voids, about twice the amount of AEA additives was needed for C-PAC™/fly ash, while approximately 10 times the amount of AEA was needed for the alternative PAC/fly ash. Even though somewhat more AEA was required in the C-PAC™ concrete than in the non-sorbent control to achieve the same air content, the dosage still satisfied the contractor specifications. Furthermore, it was found that the properties of fly ash with C-PAC™ were very consistent, even more consistent than the baseline fly ash. The added cost of more AEA is negligible relative to the benefits of utilizing the fly ash in concrete production and eliminating the cost and environmental impact of the landfill.

20.5.2 Unconfined Compressive Strength (UCS)

Compressive strength is the capacity of the concrete to withstand axially directed compressive forces. Concretes produced with fly ash containing C-PAC™ met the target compressive strength of 4000 psi at 14 days (see Figure 20.13). In fact, it appears that the C-PAC™ also improves early strength relative to the control samples (no fly ash or base line fly ash) as shown in Figure 20.13.

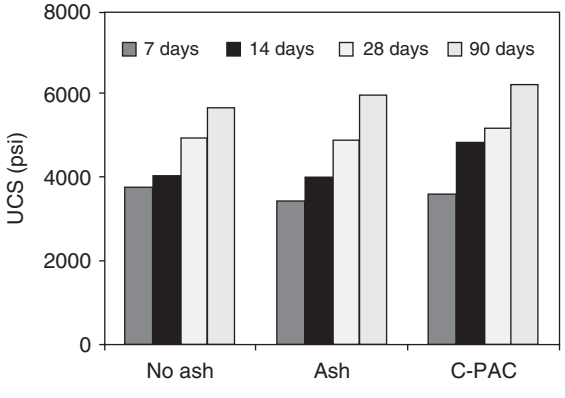

Figure 20.13 UCS of various concretes.

Table 20.2 Mercury leaching of the blank and ACI fly ashes.

Fly ash	Hg content (ng g^{-1})	Hg content in leachate (ng l^{-1})		
		DI water	Acetic acid	Sodium carbonate
Blank extraction solution		11	13	25
Baseline fly ash without mercury sorbent	39	15	9	34
Fly ash with C-PAC™	2004	22	5	14

20.5.3
Stability of Mercury in Fly Ash and Concrete

To assess the effect of C-PAC on the stability of the mercury in fly ash and concrete, the EPA's Toxic Characteristic Leaching Procedure (TCLP) and Synthetic Groundwater Leaching Procedure (SGLP) was applied to a number of samples. The fly ash collected during the Crawford mercury emission control trial was tested and the results are summarized in Table 20.2.

The fly ash samples containing the mercury sorbent generally exhibited a lower rate of mercury release even though it contained as much as two orders of magnitude more mercury. In all cases except for distilled water, the mercury leachate concentration from the long-term fly ash samples was below that of the bland extraction solution. Senior *et al.* [6] also studied leachability of the captured mercury by activated carbon in fly ash and found minimal leaching under various leaching protocols. Liu *et al.* [16] also provides further evidence that the sequestered mercury in concrete is not leachable.

Other properties of concrete with C-PAC™-laden fly ash including air stability, air voids distribution, and setting time were also investigated and it was confirmed that C-PAC™ mercury sorbents at appropriate dosage levels do not deleteriously affect any of the important properties of concrete.

Production of concrete-compatible, carbon-based mercury sorbents according to the procedures outlined in this chapter should result in continuous beneficial use of fly ash in concrete.

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21
Novel Capture Technologies: Non-carbon Sorbents and Photochemical Oxidations

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21.1
Introduction

This chapter focuses on removal of mercury by novel techniques. First, we begin with a brief overview of the pitfalls of current mercury removal strategies and materials that motivate the research, design, and demonstration of non-carbon sorbents. Next we review current non-carbon sorbent materials and photochemical technologies being developed for mercury and other trace contaminant removal from flue gas.

One of the current industrially validated technologies is the removal of oxidized mercury in scrubbers, and this is utilized in approximately 25% of US coal-fired power plants [1]. Elemental mercury is highly insoluble in water, and scrubbing systems are not always effective in removing this form of mercury [2]. Furthermore, the option of scrubber removal of mercury is not available or implemented at all coal-fired boilers, as is the case of western low-sulfur coal-derived flue gas, which does not necessitate further SO*x* removal for compliance [3].

Another industrially validated and well-documented method is powdered activated carbon (PAC) injection, which is introduced into the ductwork upstream of either a cold-side electrostatic precipitator (ESP) or a fabric filter baghouse, in order to remove elemental and oxidized mercury by sorption at temperatures below approximately 400 °F (200 °C) [1, 4]. This retrofit technology is potentially applicable to 75% of coal-fired power plants that are not equipped with scrubbers in the United States [1]. The PAC has a short residence time within the ductwork, and the material must be well dispersed within the flue gas, typically at modest temperatures below 400 °F (200 °C), to achieve high mercury removal. Particle size and proper gas distribution and dispersion play important roles in achieving effective in-flight mercury capture for carbon-based sorbents [4, 5], and PAC injection must take place downstream of hot-side ESP because of the possibility that the carbon may ignite [6]. Carbon sorbents also can ignite in filter baghouses or hopper downstream, adding to a long list of challenges in designing and implementing effective carbon sorbent systems. Furthermore, an increase in flue gas SO_3 concentration results in decreased carbon sorbent effectiveness in removal of

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mercury, and variations in coal type can be detrimental in achieving steady high mercury capture for multiple reasons [7]. The presence of activated carbon in fly ash is detrimental to the utilization of fly ash as a cement additive, and even the use of COHPAC and TOXECON systems (which supply the sorbent injection with its own dust capture system and separates the used sorbent from fly ash) does not sufficiently answer the problems with respect to SO_3 susceptibility or what to do with used PAC sorbent. As carbon sorbents can decrease the efficacy of fly ash as a cement additive, a replacement that is cement additive friendly is desired from both environmental and economic perspectives.

Carbon sorbents are typically used over a lower temperature range for mercury capture. The use of carbon sorbent at higher temperatures results in the volatilization of this captured mercury, with halogenated PAC materials extending this range to some extent. Finding a sorbent candidate that is effective at removing elemental mercury at high temperatures is beneficial as elemental mercury is most prevalent at higher process temperatures, and elemental mercury is the most difficult species to control because of its high volatility relative to other trace contaminants, low reactivity with conventionally used sorbents, and its low solubility in water [8–11]. Many inorganic compounds can react with mercury to facilitate its removal, including metal oxides, metal sulfides, and metal halides. Some of these materials can be utilized as sorbents, and may have advantages over activated carbons. These novel materials are discussed in detail in earlier work from the Department of Energy (DOE) [9, 11]. Sorbents that operate under varying conditions and circumstances are desirable, and here we present several such unique sorbents and their proposed processes.

Photochemical removal of mercury by application of ultraviolet (UV) light has several intriguing advantages over sorbent-based processes. The UV methods are potentially applicable in gases that poison carbon-based sorbents, and are also suitable as potential polishing techniques, ensuring near 100% removal of mercury.

21.2 Non-carbon Sorbents

21.2.1 Amended Silicates, Novinda

21.2.1.1 Background and Motivations

Amended Silicates are inexpensive, non-carbon substrates amended with mercury binding sites. The silicate-based substrate is chemically similar to fly ash; sites react with elemental and oxidized mercury species to bind the mercury to the sorbent. ADA (spun off later as Novinda) wanted to create a sorbent that would not affect fly ash quality for resale as a replacement for Portland cement [12], reduce or remove landfill burying costs associated with PAC and brominated PAC, and prevent the contamination of other high-value materials such as gypsum

[13]. Another major concern was that the use of the mineral sorbent should not interrupt or affect the overall process in any way. Their ideal sorbent would be nonleachable, inflammable, acid-gas resistant, and less corrosive than PAC, while also being overall economically and environmentally attractive. The company has developed several generations of sorbent materials made up of varying substrates and metal sulfides, which achieve these goals and are capable of capturing mercury at higher temperatures and pressures [14, 15]. Here, we discuss the sorbent's mercury capture mechanism and several of the material's sorbent demonstrations at various scales.

21.2.1.2 How Does the Amended Silicates Sorbent Work?

The Amended Silicates material is essentially made of an inexpensive phyllosilicate-type mineral substrate (montmorillonite, vermiculite, allophane) that has been "amended" by a metal sulfide functional group that acts as the active site for mercury capture [13, 16]. The flat sheetlike silicate structure is exposed to a solution of one or more polyvalent metal salts (M = Sn(II), Sn(IV), Fe(II), Fe(III), Ti, Mn, Zn, Mo, etc.), and an ion exchange reaction results in the initial form of the material. This material is then washed with water and subsequently exposed to either a gas or liquid sulfide (Thio-Red®, Na_2S, CaS_x, CS_3^{2-}), and the insoluble metal sulfides precipitate to the surface of the silicate substrate lattice. The resulting material is spray dried, yielding the Amended Silicates material which is characterized by molecularly thin films of layered metal sulfide amendments (transition metal chalcogenides and/or polyvalent metal sulfides) [16]. This layered structure renders the sorbents unaffected by acidic flue gases, likely due to the polar acid gas molecules being unable to break through the interlayer sites (decorated with high-density sulfur atoms) where heavy metals are attracted. The exposure of these metals to the acid gas would otherwise degrade sorbent performance, as is the case for PAC- and zeolite-based sorbents. As the sorbent's active sites are concentrated at the surface, the most expensive part of the material (the metal sulfide) is more fully utilized compared to materials that undergo both internal and external capture mechanisms [16]. Therefore, the capture material is less likely to be limited by residence time requirements or internal diffusion limitations found with other materials.

Initial laboratory-scale packed bed tests reported in 2003 showed Amended Silicates to have a mercury capacity several times that of activated carbon [17], and further pilot testing demonstrated that significantly less Amended Silicates sorbent material is needed to keep mercury stack emissions below MATS limits (compared to PAC)[13]. This additional capacity is attributed to the material's chemisorption capture mechanism, and at elevated temperatures and pressures could be relatively high. Laboratory-scale investigations were performed at conditions as high as 770 °F and 200 psig [17]. At higher pressure, the mercury capacity actually increased by a factor of 5 compared to the sorbent capacity at atmospheric pressure (with sorbent mercury capacity in excess of 3% by weight). A large percentage of mercury remained on the sorbent even after the pressure was reduced

down to 20 psig, and it could only be removed by chemical digestion. Thus, it was determined that the Amended Silicates material is not suited for a regenerable sorbent material, but instead is better suited as a disposable sorbent bed material. This disposable material would be a great Portland cement additive candidate owing to the mercury-sorbent bond stability and could also be disposed of safely as a nonhazardous waste. On the basis of the high capacity at high pressures, it was suggested that 3.5 tons of sorbent in a fixed bed could be used to capture all of the mercury from 1 million tons of coal [17]. Several additional Amended Silicates formulations identified over the past 10 years are top-performing sorbents in varying coal flue gas compositions [14, 16–18]. One of the more recent formulations, AS-022, was found to be resistant to SO_3 poisoning, and retained 95% or greater mercury removal rates even over long periods of time (>20 min) and as much as 20 ppm of SO_3 at laboratory-scale testing [13].

21.2.1.3 Demonstrations

One of the earlier pilot tests performed by ADA was at the 275 MW Xcel Energy Comanche Station Unit 2 in Pueblo, Colorado, between November 2002 and March 2003. ADA designed and built the pilot plant for mercury sorbent testing of various particulate control configurations using a slipstream from the Powder River Basin (PRB) coal burning power plant. The low chloride content of PRB coal results in a larger percentage of elemental vapor-phase mercury, which is typically the more challenging species to remove from flue gas. The pilot plant was configured with a reverse gas baghouse particulate control module, and several injection and sampling ports. The injection rate varied (1.6–9 MMacf), along with the residence time, and injection temperature (200–325 F, with a target range between 280 and 300 °F). Mercury concentrations in the slipstream flue gas ranged from 4 to 8 μg Nm^{-3}, with the fraction of particulate-bound mercury well under 20%. Impinger samples were taken and analyzed, and ADA found that their Amended Silicates resulted in 70–96% mercury capture using injection rates of 1.6–9 lb $MMacf^{-1}$, with 40% or more removed in the first 1 s of residence time. Increasing the injection rates resulted in increased mercury removal [17]. These slipstream tests agreed with another early pilot test where Amended Silicates exhibited rapid removal of vapor-phase mercury, suggesting that the material would perform considerably better than PAC in a plant equipped with an ESP [17]. More recent testing suggests that the Amended Silicates material lowers the bulk resistivity of PRB fly ash and thus can improve the performance of CS-ESPs [14].

Another major demonstration using Amended Silicates was performed at Duke Energy's North Bend, Ohio Miami Fort Unit 6 facility over a 6 week period in early 2006 (funded by DOE and EPA (Environmental Protection Agency)). This facility operates a 175 MW boiler with a cold-side ESP, and burns bituminous coal originating from KY, WV, OH, PA, and IL [12, 19]. Over 75 tons of the Amended Silicates material was made by BASF for this specific demonstration. A baseline was established at the beginning of the trial, where 0–10% of mercury was captured by native fly ash and 1/3 to 2/3 of the total mercury was found to be in

the elemental form [20]. After the baseline period, the Amended Silicates material was injected at various ratios in order to find optimum operating parameters, which was then followed by a 30 day trial at a target Amended Silicates injection ratio of 5–6 lb $MMacf^{-1}$. Afterwards, PAC (NORIT's DARCO HG) was injected for 5 days at several different ratios for comparison purposes. The results from the tests showed that Amended Silicates injection resulted in 40% mercury control, but that this was also achieved with the PAC sorbent, both at injection rates between 5 and 6 lb $MMacf^{-1}$. Increasing injection rates did not result in increased mercury capture for either material, which contradicts the findings from PRB coal slipstream studies. The ESP operating parameters and overall process were not affected by Amended Silicates sorbent injection [12]. Furthermore, tests performed by Boral and Separation Technologies found that Amended Silicates fly ash did not affect the sale of the material as a concrete additive, but that PAC fly ash was rendered unsuitable as a concrete additive material [12].

Changes to the Amended Silicates material were made, and new versions of the material were developed after the Miami Fort tests. The next major demonstration took place between February 2011 and November 2011 at the Gillette Energy Complex of Black Hill's Wygen Units 1, 2, and 3. These units burned PRB coal, utilized pulse jet baghouses for particulate and sorbent collection, selective catalytic reduction catalysts (SCR) for NO*x* reduction, and a spray dryer absorber (SDA) for removal of SO_2 [14]. The sorbent trials were again run using varying Amended Silicates injection rates over short periods, constant Amended Silicates injection rates over longer periods, and PAC/Br-PAC injection for comparison purposes. Test results indicated that steady-state mercury removal was obtained after approximately 24 h of Amended Silicates injection, and that the mercury level was reduced by 70% in the first 90 min to 2 h after injection began. For higher injection rates of 3.3 lb $MMacf^{-1}$, the overall mercury removal was 90–95%, and for lower injection rates of 1.7 lb $MMacf^{-1}$, the overall mercury removal was over 85% [14]. After Amended Silicates injection was stopped, the filter bag cake dust continued to capture mercury, evidenced by the slow recovery of initial stack mercury levels up to 24 h, showing the additional mercury sorbent capture capacity. Not only was the Amended Silicates material capable of being used in the existing dry sorbent injection units (for PAC), but its use did not affect the plant's operation or equipment, nor did it affect fly ash viability for disposal or sale. A neighboring unit (Neil Simpson 2) employing a circulating dry scrubber (CDS) and a CS-ESP was used for testing a different particulate/SO_2 control system with Amended Silicates. The low mercury stack levels meant lower Amended Silicates injection rates were needed, and mercury stack levels well below the EPA/MATS (Mercury and Air Toxics Standard) were achieved. Furthermore, the injection of $CaCl_2$ to promote oxidation of volatile mercury compounds was studied, and it was found that for the baghouse/SDA configuration, a synergistic reduction in mercury was observed when using Amended Silicates. For the case of CS-ESP/CDS, there was no noticeable difference in stack emissions. While the Br-PAC and PAC injections did benefit from $CaCl_2$, neither cases outperformed the Amended Silicates material [14].

The most recent demonstration of ADA/Novinda's most recent Amended Silicates material (AS-022) was performed at the 315 MW Santee Cooper Winyah Station Unit 4, burning eastern bituminous coal and equipped with SCR/CS-ESP and a wet flue gas desulfurization unit (WFGD) [13, 18]. The host site uses their WFGD to generate gypsum that is then sold to wallboard manufacturers, so it was important that the use of Amended Silicates did not affect the salability of the gypsum product. While wanting to demonstrate the efficacy of the AS-022 material, they also wanted to observe the effect of varying the injection locations (temperature and air heater location) and simultaneous hydrated lime injection has on mercury stack emissions.

During pretrial characterization, it was found that a large percentage of SO_3 is removed via condensation at the air heater, so it was decided that AS-022 injection would be best after this point to reduce SO_3 interactions with the sorbent. Furthermore, the largest percentage of mercury removal already occurred at the WFGD, approximately ~90% of which was determined to be almost all Hg^{2+}, which is not surprising as eastern bituminous coal is high in chloride content and, along with SCR catalysts, will promote mercury oxidation. While the WFGD is capable of removing oxidized mercury, the challenge is in removing elemental mercury before it reaches the WFGD using sorbent injection. After AS-022 injection began, it took several days to establish mercury stack emission equilibrium, but this was determined to be a function of the WFGD volume and plant load. However, after that 3- to 4-day period, the majority of mercury was captured at the ESP with the Amended Silicates material, and the amount of dissolved mercury in the WFGD decreased substantially. The hydrated lime injection increased the amount of mercury removed at the ESP, but when the hydrated lime was shut off, the WFGD removed the balance to keep stack emissions under the EPA/MATS limits; any effect that SO_3 would have on the Amended Silicates material mercury capture was essentially controlled by the passive removal of mercury at the WFGD. In addition, the injection of AS-022 before the preheater was found to be optimal owing to increased flue gas and/or AS-022 contact time and more uniform distribution. As the hydrated lime injection was located below the SCR outlet and before the air heater, this was reducing the occurrence of SO_3, which might have otherwise affected the AS-022 performance. Overall, the mercury stack emissions were measured at 0.5 lb $TBtu^{-1}$ (below EPA/MATS 1.2 lb $TBtu^{-1}$ limit), with the majority of mercury capture occurring at the ESP, which decreased the amount of mercury dissolved in WFGD fluid. Not only did the injection of Amended Silicates not affect the gypsum quality but a decrease in AS-022 flow rate kept the stack emissions below the EPA/MATS limit [13, 18].

21.2.1.4 **Conclusions**

The Amended Silicates material is reported to be a cost-competitive alternative to other sorbent materials, such as PAC and Br-PAC. This is a function of the inexpensive, large-scale manufacture of the material and the salability of the fly

ash as a Portland cement additive [13]. In addition, there is little impact to ongoing operation, as the injection of the material uses readily available and demonstrated injection equipment and Amended Silicates have continually been proved to not affect/damage any equipment nor affect any downstream processes [14, 17, 18]. The material's reliable mercury control performance was not affected by low-chlorine coals, moisture, or acid gas constituents. From an environmental perspective, disposal of used Amended Silicates material is much more attractive, as the mercury is tightly bound to the sorbent because of the chemical reaction converting bound mercury to a very stable and insoluble mercuric sulfide that occurs naturally in the Earth's crust, and TLCP fly ash leaching tests consistently report below detection for mercury [13].

21.2.2 MinPlus CDEM Group BV

21.2.2.1 Background and Motivations

MinPlus has been researching cost-effective and widely usable sorbent materials since 1995 for the capture of trace contaminants, as indicated by their wide range of patents for such materials [21–24]. The basis behind the MinPlus sorbent coupled with Mobotec's integrated process is the use of a highly reactive mineral sorbent combined with a highly effective delivery and dispersion system to achieve high-temperature removal of mercury from flue gas. Both MinPlus and Mobotec are interested in high-temperature removal of mercury directly from flue gas in the open radiant furnace itself. The MinPlus sorbent altogether eliminates the need for additional process equipment for mercury removal as it is directly injected into the boiler furnace.

MinPlus can be used upstream of hot-side ESPs because of its high-temperature operating range of 1650–2010 °F (900–1100 °C), removing mercury earlier in the process footprint, and the MinPlus sorbent will not ignite in hoppers or ESPs. MinPlus claims that their sorbent can easily handle variations in mercury concentration. The MinPlus material adds strength to cement as a fly ash additive, and is thus a unique candidate to use in place of carbon-based sorbents where increasing fly ash utilization is vital for cement manufacture. The conservation of the fly ash quality is due to the strong chemical binding of mercury to the MinPlus material and the unique mineral properties of the sorbent. More importantly, though, with respect to mercury capture, is that it takes an extended period of heating time at temperatures above 1700 °F (927 °C) for mercury to begin to be re-released, again supporting the material's stable nature and the chemisorption model [25].

21.2.2.2 How Does the MinPlus Sorbent Work?

The white fly ash like sorbent material is thermally produced from mixing $Ca(OH)_2$, $CaCO_3$, and Al_2O_3-$2SiO_2$-$2H_2O$, (kaolinite/calcite/lime) and is manufactured on the level of metric tons as a by-product from paper recycling residues [6, 26]. The material has a mean particle size of 10 μm based on Malvern particle size distribution analysis [26]. MinPlus is reactive over a wide range

of temperatures, undergoes rapid calcination and chemical transformations when injected into hot flue gas, and these transformations are what control its high-temperature mercury sorption behavior [6]. However, in order for mercury capture to occur in flue gas for this material, the gas mixture needs to contain at least 4000 ppm of oxygen, but the sorbent was reported to still effectively capture mercury in the presence of water [27].

Experimental work using a quartz tube reactor (47 mm I.D × 190 cm) through which varying feed rates of sorbent ($1-6.9\ g\ h^{-1}$) and preheated flue gas mixture ($2.2-4.7\ L\ min^{-1}$) were mixed with a steady supply of elemental mercury ($\sim 25\ \mu g\ m^{-3}$) have shown that MinPlus mercury removal efficiency is sensitive to both sorbent feed rates and to furnace temperature, where increasing either sorbent feed rates or temperature increases mercury capture. This correlation suggests that the mechanism of mercury capture is chemisorption rather than physisorption based. Mercury is predominantly in its elemental form at higher temperatures, and it is this elemental mercury which MinPlus excels at capturing. In fact, between 83% and 90% removal efficiency was observed at temperatures between 1650 and 2010 °F (900–1100 °C) for laboratory-scale tests, yet negligible sorption below 1100 °F (600 °C) [6, 26].

Two types of capture mechanisms were observed, one of which is an "in-flight" capture mechanism with an average residence time of 8 s and optimal mercury capture temperature at approximately 1650 °F (900 °C). The in-flight mechanism involves sorbent initial activation by internal reactions, mercury sorption, and subsequent deactivation if temperatures are too high for too long a period because of a "catastrophic melt" that results in pore closure. Interestingly, analysis of the in-flight deactivated sorbent particles showed that spent solids contained calcium alumino-silicate (Gehlenite) and calcium silicate products, which are specifically formed during activation/calcination at higher temperatures and is likely part of the in-flight mercury capture mechanism and subsequent deactivation [6, 26]. The second type of capture mechanism is characterized by sorbent that formed "scales" on reactor walls and did not appear to undergo deactivation through some sort of wall-stabilization effect. In fact, over a period of time at 2010 °F (1100 °C), the wall-bound sorbent managed to continue capturing mercury without reaching a maximum even after sorbent flow was ceased.

Wendt *et al.* noted that there is an interesting effect that the sorbent interaction with the quartz wall reactor has on mercury capture and uptake, and that it is quite possible that the quartz wall reactor affected capture based on data inconsistencies [27]. Further tests showed that when compared to Inconel reactors, the quartz reactor improved mercury capture, and that adding some form of SiO_2 to the sorbent mixture also stimulates mercury capture [25]. This is postulated to be through the formation of some type of active species that is triggered through the presence of silica but limited by the type of silica content as well as contact time. Additional tests with different types of fly ash with differing types of silica content greatly affected the mercury uptake. This was most evident in full-scale tests that were performed with PRB fly ash, where low to no reactivity with the MinPlus sorbent was detected whatsoever [25].

21.2.2.3 Demonstrations of Sorbent

Successful fixed-bed tests at the University of Arizona and dispersed-phase testing in a 1.75 MW coal-fired pilot plant at the Southern Research Institute in Birmingham, Alabama, led MinPlus to full-scale tests to test the capabilities of their sorbent material. A collaboration with Mobotec's injection and mixing systems were part of this demonstration. These tests were performed at the Richmond Power and Light Whitewater Valley 65 MW Power Plant Unit 2 in Richmond, Indiana, and at a 154 MW power plant in North Carolina. Both plants were equipped with a rotating opposed fired air system (ROFA, supplied by Mobotec), which can generate a highly turbulent mixture of flue gas via asymmetric air nozzle flow. The Mobotec Rotamix system, designed for selective noncatalytic NO*x* reduction (SNCR), coupled with ROFA results in effective direct in-furnace injection mixing and distribution of the MinPlus material that leads to greater utilization of the total furnace volume, optimal sorbent-flue gas contact time, and desirable sorbent temperature profiles [25].

The Richmond Power and Light Whitewater Valley power plant utilized in this demonstration burns bituminous high S Illinois coal, and is a tangentially fired Combustion Engineering pulverized coal-fired 12-boiler with a full load capacity of 65 MW at a steam pressure of 1450 psi and superheat temperature of 1005 °F (541 °C)[2, 7]. This system is equipped with an FSI system that was designed for the delivery of limestone for SO*x* control, but the SNCR and SO*x* control systems were not in service during the MinPlus demonstration. The mixing methodology is important with respect to the contact time and temperature at which the sorbent contacts the flue gas. Eight Rotomix/FSI injection ports, divided into two banks of four ports, were available, and typically either two or four of these ports were used. The MinPlus sorbent was injected pneumatically and fed through the injection ports at over 450 ft s^{-1} directly into the furnace and flue gas (temperature at the injection ports between 2000 and 2200 °F (1093 and 1204 °C)). The demonstration lasted about a week (second week of November 2005), and the results show that the MinPlus sorbent yielded over 95% mercury capture, up to 98%, with mercury stack emission measurements decreasing from 4 μg Nm^{-3} (background; no mercury removal sorbent added) to 0.2 μg Nm^{-3} at 3% O_2 [2]. It is assumed that as elemental mercury is the predominant species at elevated temperatures, the MinPlus sorbent captures mercury in its elemental form. Therefore, any negative effect that plant load, equipment, and coal type have on a sorbent's ability to capture mercury is essentially eliminated with this sorbent material. In addition, mercury was found to be predominantly bound to mineral sorbent, and the wall-bound mercury sorbent capture mechanism appeared to be effective for a period of time after the injection was stopped [2]. There is also an enhanced capture observed over previous testing that occurred at the Southern Research Institute (1.75 MW) coal-fired pilot plant, which resulted in mercury capture rates of approximately 65% [28]. The authors attributed the higher Whitewater Valley mercury capture to a higher injection temperature and better injection/mixing system, where mixing

and distribution of the sorbent in the flue gas is critical [2]. The MinPlus injection did not affect any other aspect of the plant, including fly ash quality and ESP performance.

The next MinPlus sorbent demonstration was at the North Carolina 154 MW Power Plant, a 154 MW, 1956 Combustion Engineering corner-fired design with four levels of pulverized coal burners [7]. This plant also burns eastern bituminous coal, and the demonstration lasted 2 weeks in March 2006. In this plant, the MinPlus sorbent was fed through precalibrated feeding screws from a transportable silo and it was then pneumatically sent to the Rotamix air boxes, mixed into the Rotamix air, and then entered the boiler contacting flue gas at over 450 ft s^{-1}. Similar to the Whitewater test, eight ports were available, and variations of these eight were tested to find the optimal dispersion when using side ports while also using no more than four ports. The temperature of the flue gas it contacted was estimated to be between 1600 and 2670 °F (871 and 1466 °C) [7]. The results showed a 70–80% removal of mercury, where initial mercury measurements of 5 μg Nm^{-3} was reduced to 1 μg Nm^{-3}, measured after ESP. This demonstration also found that use of the MinPlus sorbent did not affect any aspect of the plant, and leaching tests showed that there was complete binding of the mercury on the sorbent material [7].

MinPlus currently operates a full-scale demonstration plant located in Duiven, the Netherlands. This plant is operated as a joint venture between MinPlus-CDEM and a municipal and industrial waste incineration company with a focus on green pollution abatement technology in the paper recycling field.

21.2.2.4 Conclusions

The MinPlus sorbent is an inexpensive recycled material, and the used nonregenerable sorbent material is meant to be combined directly with fly ash. Ash quality measurements of the spent sorbent material mixtures found that the fly ash quality was not affected and could be used for resale as a Portland cement additive [2, 7]. The captured mercury and other trace contaminants do not revolatilize until approximately 1600 °F (871 °C), thus making this another stable mercury capture material that is a possible candidate for safe disposal [25]. The economic advantage of injecting directly into the boiler is that the majority of mercury is bound to sorbent and removed from the process before possible contamination of aluminum equipment downstream from the boiler. Furthermore, tax incentives might also be available for utilizing a process that recycles/reuses paper industry waste [29].

21.2.3 Pahlman Process – Enviroscrub

21.2.3.1 Background and Motivations

The Pahlman process is a closed-loop dry scrubbing process utilizing Pahlmanite™ sorbent, which is made up of low-density oxides of manganese (MnO, Mn_2O_3, and MnO_2) black powder that can adsorb a large percentage of flue gas SO*x* and NO*x* (reported to be >97%) [30]. Upon regeneration, its

sorbent yields raw sulfates and nitrates that are used to manufacture marketable commercial byproducts such as sodium sulfate, ammonium nitrate, and potassium sulfate. The process can remove multiple pollutants by a single-, dual-, or multistage dry process, eliminates undesired waste streams, and ultimately is intended for the replacement of FGD (flue gas desulfurization), SCR, and activated carbon injection technology [31].

21.2.3.2 How Does the Process and Sorbent Work?

The dry sorbent is sprayed into contact with flue gas, mercury vapor is oxidized, and this oxidized via a proprietary mechanism. This oxidized mercury vapor is then adsorbed along with chlorides, SO*x*, and NO*x*. The sorbent has a high affinity for sulfur compounds and this reaction happens relatively quicker compared to mercury and NO*x* adsorption. The temperature at which sulfates and nitrates of manganese decompose dictates the inlet process gas temperature range, and patent literature suggests that a typical temperature range would be 60 - 250 °F (16 - 121 °C), and the temperature should not exceed 350 °F (177 °C) [32–34]. A baghouse collects the sorbent and provides further residence time to contact the sorbent material with the flue gas [30]. Once the sorbent is removed from the baghouse, it is mixed with water and next regenerated via a persulfate oxidant and a base in a separate reactor. The insoluble manganese oxides are insoluble in water and separate out of solution with pollutant salts. A proprietary filter is used to separate trace contaminant metals such as mercury from the solution, which is reported to be a proprietary reaction forming a Mn–Hg complex. It is known that lattice oxygen from manganese oxides can react with elemental mercury to form mercury manganates. The pollutant salts can then be processed with potassium or ammonium to produce sulfate and nitrate salts of high value [30, 32–34].

21.2.3.3 Demonstrations

The first major demonstration of the Pahlman process was performed at the DTE Energy River Rouge Power Station Unit 3 located in Michigan in June 2003. The 290 MW pulverized coal wall-fired boiler plant was burning a PRB/eastern bituminous blend (40 : 60 to 60 : 40), and a 500–1000 SCFM slipstream was diverted to the mobile Enviroscrub pilot unit for processing [30]. The pilot unit used the slipstream to achieve its operating temperature, and subsequently the sorbent was loaded into the baghouse reaction chamber for testing. Inlet and outlet mercury measurements were conducted using the Ontario Hydro method and mercury semicontinuous emission monitors (SCEMs). Concentrations of O_2, NO*x*, SO*x*, CO_2, and CO were also measured during the test. Continuous emission monitoring system (CEMS) data gave an average steady state removal of SO_2 to be ~99.8%, NO*x* removal of ~98.2%, and the Energy and Environmental Research Center from the University of North Dakota reported a mercury removal of ~97% (oxidized, 1.02–0.03 $\mu g\, m^{-3}$) [31].

The second major demonstration of the Pahlman process was performed on a slipstream at the 550 MW Unit 4 at Minnesota Power's Boswell Energy Center in Cohasset, Minnesota, between December 2003 and January 2004. A 500–1000

SCFM slipstream of flue gas was diverted from the coal-fired Combustion Engineering tangentially fired boiler utilizing PRB subbituminous coal to the same mobile Enviroscrub pilot unit that underwent identical processing procedures. CEMS data reported an average steady-state removal of SO_2 to be ~99%, NO*x* removal of ~95.8%, and the Energy and Environmental Research Center from the University of ND reported a mercury removal of ~94.3% (84.4% oxidized, 99.2% elemental) [31].

21.2.3.4 Conclusions

Manganese oxide is inexpensive and abundant, and occurs in over 30 different forms, so acquiring this material easily is quite feasible. On the basis of Enviroscrub's design criteria, the plant runs at approximately 34.1% efficiency, requires about 3.3% of the power it generates in order to operate, and operating expense and capital costs both decrease as a function of plant capacity [31]. The capital cost savings for the Enviroscrub Pahlman process system is between 20% and 50% compared to conventional WFGD/SCR scrubbing technologies because of a decrease in operational equipment and space requirements. Furthermore, operating and maintenance costs decrease by 25–40% when considering the production of marketable byproducts and the removal of waste streams [30, 31]. However, progress still remains to be made on the front of optimization, simulations, and construction of a full-scale pilot plant for further testing and proof of concept at a larger scale than the current mobile unit set-up [35].

21.3 Photochemical Removal of Mercury from Flue Gas

The oxidation of mercury facilitates its capture. Although possessing numerous compounds, mercury is a semi-noble metal, and is exceeding insoluble in water. Ultraviolet light can supply the needed activation energy to induce the reaction of mercury to more amenable compounds for removal. Compounds of mercury tend to condense upon surfaces such as fly ash, and can be captured in a wet scrubber. Photochemical reactions of mercury with various constituents of flue gas can be an attractive alternative or polishing step for sorbent- or scrubber-based processes for mercury capture. There are several potential routes for the photochemical removal of mercury. One method employs short-wave ultraviolet radiation to facilitate the oxidation and removal of mercury. A second technique uses long-wave ultraviolet light in combination with a photocatalyst to oxidize and capture mercury. These techniques are discussed here.

21.3.1 Sensitized Oxidation of Mercury: GP-254 Process

Elemental mercury will absorb or reemit (fluoresce) 253.7 nm ultraviolet light. This ability to absorb or reemit 254 nm light is the basis for detection through

atomic absorption, atomic emission, or atomic fluorescence detectors. In atomic absorption spectroscopy (AAS) detectors, elemental mercury absorbs a photon of 254 nm light and goes to the 6 ($^3P_1$) excited state, denoted as Hg* or Hg 6 ($^3P_1$), and shown here:

$$\text{Hg} + 253.7 \text{ nm radiation} \rightarrow \text{Hg}^* \text{ or Hg } 6\ (^3P_1) \tag{21.1}$$

In atomic emission spectroscopy (AES) detectors for mercury, the atom of excited mercury emits a photon of 254 nm light, and goes back to the ground state.

$$\text{Hg}^* \rightarrow \text{Hg} + 253.7 \text{ nm radiation} \tag{21.2}$$

In atomic fluorescence spectrometry (AFS) detection of mercury, steps (21.1) and (21.2) occur within an infinitesimal fraction of a second, and the intensity of the emitted light (fluorescence) is measured. These processes are the basis for continuous emissions monitors (CEMs) of mercury, and are discussed in Chapter 5.

Dickinson and Sherrill [36] discovered the photochemical formation of mercuric oxide in 1926 described by the reaction:

$$\text{Hg} + 2\ \text{O}_2 + 253.7 - \text{nm light} \rightarrow \text{HgO} + \text{O}_3 \tag{21.3}$$

In the reaction mechanism, elemental mercury serves as a sensitizer for the formation of ozone, and ozone oxidizes mercury to form mercuric oxide. The term *sensitizer* means that elemental mercury in the 6 ($^3P_1$) excited state induces chemical reactions to occur. When the mercury collides with another atom or molecule, it can transfer its energy from the excited state to this species, setting the stage for chemical reactions. Activation energy for chemical reactions are typically supplied by heat, but can also be supplied by light.

The eminent Canadian photochemist Harry Gunning discovered many reactions for which elemental mercury can serve as a sensitizer over five decades spanning the 1940s through 1980s. Some of these sensitized oxidation reactions discovered by Gunning and others [37–43] involve reactants such as moisture, nitrogen oxide, sulfur trioxide, hydrogen chloride, and carbon dioxide that are abundant in coal-derived flue gas, and are present at concentrations that are many orders of magnitude greater than the concentration of mercury (around 1 ppb). Some of these reactions include

$$\text{Hg} + \text{H}_2\text{O} + 253.7\text{-nm light} \rightarrow \text{HgO} + \text{H}_2 \tag{21.4}$$

$$\text{Hg} + \text{HCl} + 253.7\text{-nm light} \rightarrow \text{HgCl} + 1/2\ \text{H}_2 \tag{21.5}$$

$$\text{Hg} + \text{NO}_2 + 253.7\text{-nm light} \rightarrow \text{HgO} + \text{NO} \tag{21.6}$$

$$\text{Hg} + \text{SO}_3 + 253.7\text{-nm light} \rightarrow \text{HgO} + \text{SO}_2 \tag{21.7}$$

$$\text{Hg} + \text{CO}_2 + 253.7\text{-nm light} \rightarrow \text{HgO} + \text{CO} \tag{21.8}$$

Granite and Pennline [44–47] employed reactions (21.3) through (21.8) to facilitate the removal of mercury from flue gases in the laboratory through pilot-scales.

The technology, dubbed GP-254 Process, is available for license through the DOE. The technology could serve as a small and inexpensive polishing step to guarantee near 100% removal of mercury from flue gas. It is noted that even 1 or 2 ppm of SO_3, commonly present within coal-derived flue gases, can severely poison the activated carbons used to capture mercury [48, 49]. Thus, the GP-254 UV Process could serve as a polishing step in these cases by reaction (21.7). It has also been recently suggested that NO_2 can hinder the performance of activated carbons for the capture of mercury [50], and this UV Process could again remove mercury in this case through reaction (21.6).

21.3.2 Photocatalytic Oxidation of Mercury

It is known that certain band-gap semiconductor oxides such as titanium oxide can serve as oxidation catalysts in the presence of long-wave ultraviolet light. Kaluza15 [51] discovered that titanium oxide and other oxides could photo-oxidize mercury to mercuric oxide in 1971. Biswas and coworkers [52–55] studied the capture of mercury in flue gas using titanium oxide particles and ultraviolet light. The ultraviolet light often emanated from the glowing discharge fields of the ESPs, present within many coal-fired power plants. The US DOE [56] studied the photo-catalytic oxidation of mercury to mercuric oxide using 365-nm long-wave ultraviolet light and both titanium oxide powders, as well as titanium oxide coated self-cleaning glasses. The reactions occurring on the titanium oxide surface can be crudely represented through (21.9) and (21.10) as [56]:

$$Hg_{(gas)} + \text{band-gap particle} + \text{light} + O_{2(gas)} \rightarrow HgO_{(ad)} + \text{radicals}_{(surf)} \quad (21.9)$$

$$Hg_{(gas)} + \text{band-gap particle} + \text{light} + H_2O_{(gas)} \rightarrow HgO_{(ad)} + \text{radicals}_{(surf)} \quad (21.10)$$

There are several band-gap semiconductor oxides such as titanium and zinc oxides present in air that can oxidize mercury under the influence of sunlight, potentially impacting the fate of mercury in the environment [56]. Additional research is merited on the use of photocatalysts for the oxidation and capture of mercury from flue gases.

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22
Sorbents for Gasification Processes

Henry W. Pennline and Evan J. Granite

22.1
Introduction

Gasification is a process whereby coal can be decomposed into simpler compounds by reacting it with steam and oxygen at elevated temperatures and pressures. The major product compounds include hydrogen (H_2) and carbon monoxide (CO), which can both be used as a fuel or as building blocks for chemicals (see Chapter 8 also). In chemical production, the $H_2 + CO$ mixture, called *synthesis gas* or *syngas*, can be sent to a catalyst assembly to fabricate various chemicals. Gasoline, diesel fuel, substitute natural gas, and other organic chemicals can be produced in such an operation. In power generation, the $H_2 + CO$ mixture, sometimes referred to as *fuel gas*, can be combusted and expanded in a gas turbine before recovering the heat of combustion in what is called an *integrated gasification combined cycle* (*IGCC*) operation. In either of the above-mentioned cases, the product gas from the gasification process is in a reducing atmosphere and the mercury that was in the coal is typically in the elemental form. With respect to sorbents, mercury removal in the gasification process can occur at either elevated temperatures (149–371 °C; 300–700 °F) or at lower temperatures (ambient to 100 °C). The temperature range is dependent on the final use of the gasification products. In IGCC, elevated temperature removal is desired so that a higher thermal efficiency of the power generation scheme can be maintained. This requirement may not apply to synfuels production. In addition, global warming and the impact that carbon capture and sequestration may have on mitigation of the greenhouse gas carbon dioxide could have a role in determining the process conditions for the removal of mercury. Sorbents for mercury removal can be characterized by the material type, such as activated carbons, stable metal oxides, and noble metals. The mercury removal capabilities with limitations for different families of materials are discussed.

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22.2 Background

A major concern for power systems that use coal as an energy source is the air emissions from the plant. Although certain air emissions are currently regulated in the United States, the emergence of new regulations for other pollutants is on the near horizon. On the basis of a 1998 Report to Congress, the Environmental Protection Agency (EPA) in 2000 had announced its finding that regulation of mercury emissions from utility steam generating units was necessary and appropriate [1]. In addition, the Clear Skies Initiative was proposed in 2002 to dramatically limit the emissions of mercury from coal-utilizing facilities [2]. Emission standards were proposed in 2003 but promulgation did not occur until late 2011. The development of mercury emission regulations will have a direct impact on coal-using power-generation facilities, both conventional steam generating systems as well as IGCC systems.

Gasification is an important strategy for increasing the utilization of abundant domestic coal reserves. Owing to the increase in thermal efficiency for IGCC systems and the potential ability to effectively capture and sequester carbon dioxide emissions, the U.S. Department of Energy envisions increased use of gasification in the United States over the next 20 years [3]. A near-zero emissions goal will be strived for with respect to pollutants, including mercury.

For the gasification process and, in particular, for IGCC, the characterization of the location of mercury within the plant is critical with respect to the eventual capture of the mercury. A total characterization of an advanced gasification technology was conducted in 1995 with Dow Chemical's Louisiana Gasification Technology Inc. [4]. Gas, liquid, and solid streams around the plant were measured for mercury. Although the mercury material closure was poor for the comprehensive study and significant advances in mercury sampling techniques have been made since the study, several important findings were established. The mercury material closure around the plant was poor, possibly suggesting that some of the measurements were in error or that an accumulation of mercury within the plant occurred. Of the gas-phase mercury, over 70% left the plant in the turbine exhaust flue gas.

Later, as part of EPA's Information Collection Request, Tampa Electric's Polk Power Station and PSI Energy's Wabash River Generating Station – both IGCC units – were characterized with respect to mercury air emissions (a full characterization of all streams was not conducted) [4, 5]. In this exercise, the Ontario-Hydro sampling technique was used to speciate the mercury in the flue gas after the turbine combustor. The important conclusions from this data-gathering effort were that near 60% of the mercury in the coal exited in the turbine combustion flue gas and the vast majority of the mercury in this flue gas was in the elemental form. From the information on these units and pertaining to the final disposition of the mercury in the present IGCC systems, it is speculated that a majority of mercury migrates through the system as elemental mercury and that the remainder of the mercury is probably accumulated within one of the scrubbing systems needed to

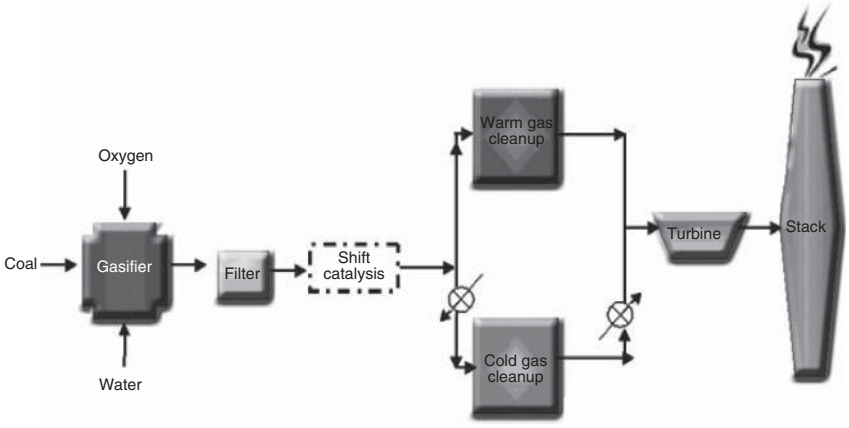

Figure 22.1 Simplistic flow schematic of an IGCC process.

clean the fuel gas before further processing it. In both these facilities, the fuel gas was cooled and then hydrogen sulfide was removed by a liquid solvent scrubbing technique before the gas was sent to the turbine combustor. Further evidence that the mercury in the fuel gas is mostly elemental can be found in gasification thermodynamic modeling or experimental studies [6–9].

Figure 22.1 is a rudimentary flow diagram of an IGCC installation with two options for gas cleanup. The lower path is similar to the one used at the Polk and Wabash Stations where a low temperature (>38 °C; 100 °F) wet scrubbing technique, such as Selexol, is used to remove the hydrogen sulfide. The upper flow path in Figure 22.1 indicates the option where acid gas cleaning occurs within a warm gas cleanup (sometimes called *humid gas cleanup*) system rather than at the previously described cold (lower) temperatures. There are various reasons for opting for the warm gas mercury cleanup as compared to the cold gas cleanup. The main advantage in cleaning the gas in an IGCC application at higher temperature is that the thermal plant efficiency can be as much as 2–3% greater as compared to the lower temperature acid gas cleaning scenario. Provided the temperature is sufficient so that the dew point of the fuel gas is not approached, the moisture content in this warm/humid gas stream remains in the gas phase, as compared to the cold gas cleanup case, and can be used in the turbine expansion. Additional areas of efficiency improvements are that the transfer of heat and latent heat to the more efficient gas turbine cycle are maximized; the capital and operating costs are lowered by reducing the duty on any heat exchangers; and the need for waste water treatment facilities is eliminated [10, 11]. Note that a third option for mercury cleanup could be after the fuel is combusted in the gas turbine. However, the gas is expanded and thus a significantly greater volume of gas would need to be processed.

In addition to the improved IGCC plant thermal efficiency for warm gas cleanup, another reason is that the capability exists for removing a vast majority of the coal-inlet mercury at one location. As seen in the cold gas cleanup systems

at the Polk and Wabash Stations, a substantial amount of the inlet mercury within the feed coal was not accounted for. Although liquid streams were not monitored for mercury in the analysis, it is speculated that the lost mercury is probably within these streams. If mercury removal techniques could be implemented at the elevated warm gas temperature within the process at elevated pressure, then the potential issue of mercury appearing in condensate, wet scrubbing streams, and so on, is eliminated. The partial pressure and thereby the driving force of the gaseous mercury is also higher at the elevated pressure of the system. However, similar issues with potential mercury appearance in wet scrubbing streams occur if the mercury is collected after the combustion of the fuel gas in the turbine combustor exhaust stream. In addition, if Hg removal is left to after the fuel gas is combusted, a much higher volume of gas needs to be processed as compared to the precombustion pressurized case. Cost and equipment size considerations become important.

As in mercury mitigation from flue gas produced by the combustion of coal, the use of a sorbent is a feasible technique to remove mercury within a gasification process. The challenges are many. As mentioned, the temperature options may limit the type of sorbent. Activated carbons generally perform via adsorption of mercury and this is enhanced at a lower temperature as compared to the elevated warm gas temperature case. Conditions can be harsh depending on the location of the removal, as the sorbent could be exposed to various compounds at different concentrations, for example, hydrogen sulfide, moisture, hydrogen chloride, ammonia, and other trace components. Potential deactivation due to poisoning and sintering must be addressed. Although the challenges can be stringent, research in the sorbent area has progressed and thus the sorbents and operating information are addressed in the following sections.

22.3
Warm/Humid Gas Temperature Mercury Sorbent Capture Techniques

There is limited information available on the removal of mercury from high-temperature syngas streams, although there have been some contributions to the general knowledge since 2000. Results from a pilot-scale gasifier suggest that all of the mercury in the coal ends up in the fuel gas [7, 12]. The data from this pilot-scale gasifier suggest that activated carbon and other carbon sorbents will be unsuited for mercury capture from syngas at temperatures greater than 204 °C (400 °F) [7, 12]. Robust high-temperature sorbents, as well as other techniques, are needed for mercury capture from syngas for continued development and proliferation of gasification technology.

In the studies with the various warm gas sorbents, there are some commonalities with respect to the testing. Most of the sorbents tested are in the form of pellets or granular sized materials, although one group has used a monolith design. Sorbents are typically tested in a fixed bed. Elemental mercury permeation tubes are generally used to spike a known gas composition. In many cases, the

sorbent is envisioned as being a multipollutant absorber and besides the removal of mercury, other trace components within the synthesis/fuel gas are desired to be captured, that is, arsine, hydrogen selinide, and so on. Although there are online analyzers for mercury detection in flue gases produced by the combustion of coal, some modification needs to occur so that they can be used in fuel gas applications. Certain analytical techniques have been developed for some of the other trace compounds [13], but reliable continuous, standard, online analysis for mercury in reducing conditions needs to be established. In certain cases, analysis of solids for mercury after the sorbent testing has been used in the determination of the amount of mercury captured on the sorbent. Most studies would be considered laboratory- or bench-scale and have not progressed out of the laboratory setting. However, in certain investigations, the research was actually conducted with real synthesis gas produced from gasification facilities, such as the Power Systems Development Facility (PSDF) in Wilsonville, AL.

As to more mature development of a technology, TDA [14–16] has used their geode sorbent development for multicomponent control. In this novel sorbent design, pockets of active sorbent material are surrounded with a porous but hard, strong shell that provides a wear resistant pellet. This design is similar to a geode as it has a cavity with the desired crystals surrounded by a protective exterior. This structure is very strong because there is a continuous support phase; it effectively contains the sorbent inside small holes in the interior of the pellet, allows the sorbent to expand and contract freely without disrupting the pellet structure, and allows gases to diffuse quickly in and out of the pellet. Copper-based sorbent formulations have been used to remove trace contaminants from fuel gas streams, that is, arsenic [16]. Substrate materials included alumina, titania, or silica. The active material precursors and inert substrates were combined using the geode technology, enabling the incorporation of large quantities of active material into the final sorbent pellet, without plugging the pores of the substrate material and reducing its porosity.

Initial testing in a packed bed of pellets was conducted with simulated gas streams that were spiked with the trace contaminants. The mercury, arsenic, and selenium concentrations at the outlet of the reactor bed were continuously monitored with online analyzers. Breakthrough and saturation capacities of the sorbents were determined for temperatures between 160 and 260 °C and near 450 psig. Mercury capacities were high at the elevated temperatures, and the sorbent has a high capacity for arsenic even in the presence of high concentrations of sulfur. Experiments with multiple trace metals showed that the sorbent could simultaneously remove all these contaminants (mercury, arsenic, and selenium) from syngas in one step [14].

Demonstration tests using actual fuel gas from a gasifier were conducted at two locations: at the PSDF in Wilsonville, AL and at the University of North Dakota Energy and Environmental Research Center (EERC) where lignite and bituminous coals were the feed materials (see Figure 22.2). Overall, the test results indicated that the TDA sorbent was capable of removing multicontaminants in the coal-derived synthesis gas at high temperature. Mercury was successfully removed

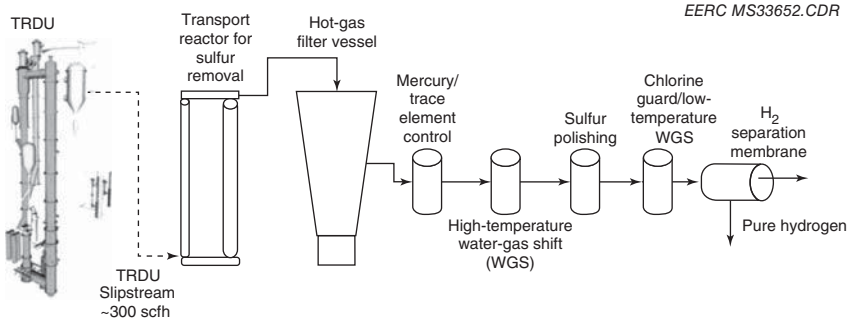

Figure 22.2 Schematic of demonstration unit at UNDEERC [15].

from the synthesis gas streams generated by different gasifiers using different coals at different sites and achieved greater than 95% Hg removal efficiency at 260 °C. This sorbent can be operated in a regenerable manner to remove Hg from the bed, while irreversibly removing all other trace metals including As, Se, and Cd with high capacity. From leaching tests, the fate of the mercury on the sorbent will remain on the sorbent once it is disposed [15].

The Gas Technology Institute (GTI) had developed the Ultra-Clean Process to control various pollutants from syngas, including mercury. The process injects fine sulfur and halide sorbent particles into two stages of barrier filter–reactors integrated in series, coupling efficient particle capture with an effective entrained and filter cake reaction environment. As can be seen in Figure 22.3, sulfur and halides are removed to extremely low levels by injection of various sorbents in the two stages, with the second stage temperature near 288 °C (550 °F). It is projected that for IGCC applications, the mercury removal could be a separate step or incorporated into the second stage of the process, and the mercury could be removed in the temperature range of 149–399 °C (300–750 °F), depending on the moisture content in the fuel gas [17].

Testing for mercury capture occurred in a packed bed reactor system using various simulated fuel gas mixtures and with a PSA Sir Galahad II analyzer. Materials that were tested were based on the oxides of copper, manganese, molybdenum, and zinc as well as mixed oxides and activated carbons. Some sorbents were purchased and others were made by GTI using a modified sol–gel technique or a wet impregnation method. The results with activated carbons were similar to other researchers in that elevated temperature hinders the adsorption of the mercury onto the carbon. With respect to the oxides, copper- and molybdenum-based sorbents, sulfidation of the sorbent is important in the mercury removal performance, possibly by altering the physical/chemical properties of the sorbent with a benefit for the higher loading of sulfur. In either case, the trend was that the effectiveness of the capture decreased as the temperature increased. In more recent work, nanocrystalline metal oxides/sulfides sorbents were evaluated in the temperature range of 150–260 °C, and again a temperature increase appears to have a negative impact on the mercury capacity of the sorbent [18].

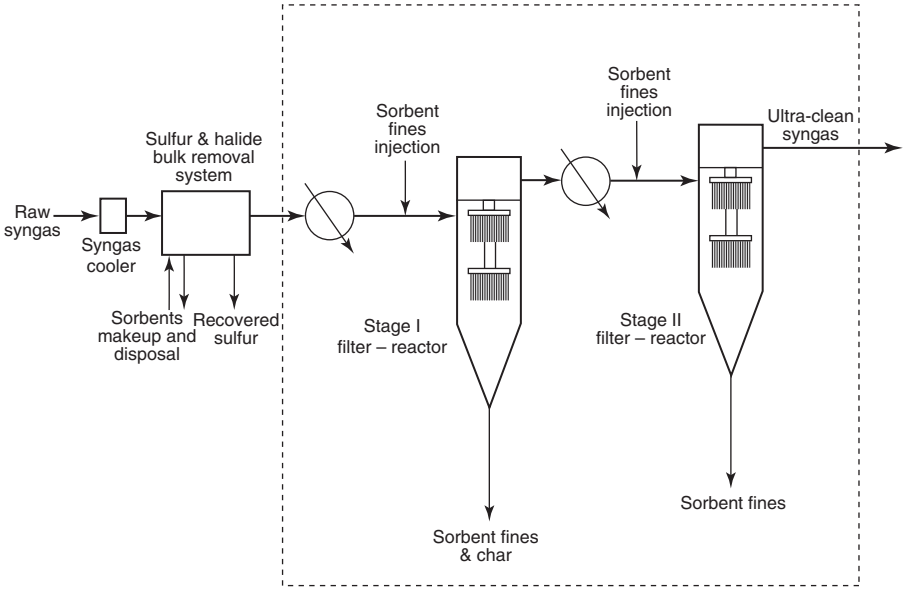

Figure 22.3 Ultra-Clean process flow diagram [17].

In a study conducted at the U.S. Department of Energy's National Energy Technology Laboratory (NETL), thermodynamic considerations followed by actual experimentation were used to screen candidates for mercury removal [19]. Interest was not only in mercury removal but also in the removal of selenium and arsenic. Samples were tested in a laboratory-scale reactor operating at ambient pressure, and capacities for mercury were calculated by flowing a known amount of mercury over the sorbent for a period of time (350 min) and having the spent sorbent solid chemically analyzed for mercury. Platinum and palladium were two candidates that had excellent capacities, even in the presence of simulated fuel gas with other components (hydrogen, carbon monoxide, carbon dioxide, hydrogen sulfide, and moisture). It was noted that the presence of these species impacts the adsorption of mercury as compared to testing under a spiked nitrogen flow. Mercury capacities remained appreciable in the 204–288 °C temperature range. As a noble metal is used, regeneration of the sorbent may be necessary and potential heat or chemical treatments are proposed to rejuvenate the spent sorbent [20].

In a collaboration between NETL and Johnson Matthey, further mercury capture studies with the palladium-alumina-supported sorbent were conducted with different metal loadings ranging from 2 to 9 wt% and over the temperature range of 204–388 °C [21]. The palladium-based sorbent performed better than the platinum-based one, and X-ray diffraction studies indicated a formation of solid solution of mercury within the palladium. Interestingly, a computational study that used *ab initio* methods based on density functional theory predicted material properties in which elemental mercury in the gaseous state would

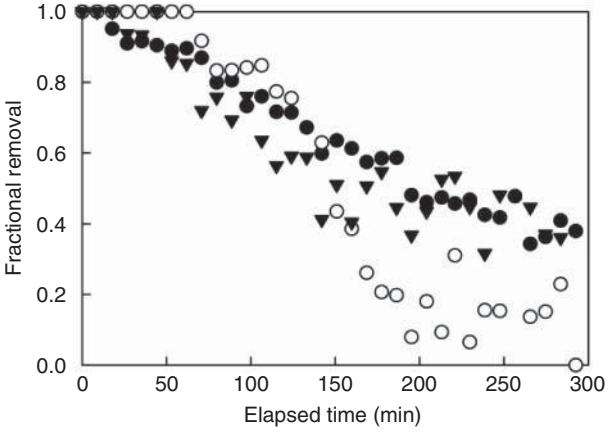

Figure 22.4 Fractional removal with time for 0.7 ppmv PH_3, 2.5 ppmv AsH_3, and 16.7 ppmv H_2Se removal on a 10 mg 5 wt% Pd/Al_2O_3 packed bed at 204 °C in the standard simulated fuel gas. Dark circle – AsH_3; open circle – H_2Se; and triangle – PH_3 [23].

bind to a pure metal to form a binary amalgam [22]. The candidate materials for the highest amalgam formations were the noble metals, of which palladium was highlighted in the computational exercise. In later experimental studies, interest broadened for other contaminant materials to be removed in the fuel gas, including not only mercury but also arsenic, selenium, and phosphorus, which, in the reducing atmosphere, are in the forms of arsine, hydrogen selinide, and phosphine, respectively [23] see Figure 22.4). Tests were conducted using the same reactor system as before, but a gas chromatograph/ion trap mass spectrometer was used for detection of these other compounds [13]. Arsine, phosphine, and hydrogen selenide could be removed from the simulated fuel gas at warm gas cleanup temperatures with the palladium gamma-alumina sorbent.

For these laboratory-scale tests, exposure to the materials of removal interest is usually much larger than what the sorbent would see in an actual situation. This fact would make these sorbents even more amenable to removing trace pollutants as their capacities would most likely increase. Successful testing of the palladium sorbent at real conditions has occurred at the PSDF in Wilsonville, AL [24]. In the slipstream tests, a fixed packed bed of near 10 pounds of sorbent held at 260 °C removed nearly all of the selenium, arsenic, and mercury present within the fuel gas over several weeks. Additional tests with this sorbent in the PSDF have verified the removal capacities.

The University of North Dakota EERC has been investigating promoted monoliths in collaboration with Corning. The monolith is a honeycomb-shaped (parallel-channel) polymeric body with the major ingredient being phenolic resin, fabricated through extrusion, carbonization, and activation processes [25]. The polymer body is carbonized at an elevated temperature in an inert atmosphere, which converts the phenolic resin to graphitic carbon mixed with amorphous carbon domains. It is activated by the removal of the amorphous

carbon by reacting it with carbon dioxide at elevated temperature. Surface areas are typically around 500-$m^2\ g^{-1}$, and additives, such as sulfur, can be introduced before the extrusion step. In the testing rig, simulated fuel gas mixtures spiked with elemental mercury were flowed over the monolith at temperatures between 177 and 260 °C and at elevated pressure. A modified PSA Sir Galahad was used to continuously monitor the mercury. Initial results with these monoliths and incorporating an undisclosed additive were successful in controlling mercury emissions, although with time online, some devolatilization of the mercury occurs but possibly due to the devolatilization of the additive.

Recent testing has also confirmed the ability of the monolith coated with an improved additive to remove mercury at a high level for an extended period of time (see Figure 22.2) [26]. Although the baseline testing occurs at 180 °C, a test at 260 °C (500 °F) did show some decrease in the capacity of the sorbent for mercury removal. One Corning-treated monolith showed effective capture of mercury for over 150 h of testing at 180 °C and was found to be very effective even at pressures up to 600 psig and temperatures up to 370 °C. Additional testing of monoliths and sorbents with various additives revealed that these materials were able to remove other trace components in the fuel gas, that is, arsine and hydrogen selenide, at 204 °C (400 °F) [27].

RTI International is pursuing an approach to mercury removal that is analogous to the one used in their hot gas desulfurization from syngas, which is utilizing a chemically reactive sorbent. They realize that the thermodynamic efficiency of the IGCC cycle is improved if the thermal energy of the fuel gas can be preserved, and thus their sorbent-based desulfurization can be accomplished reliably at 260–316 °C (500–600 °F). Therefore, this temperature range is also targeted for their mercury removal [28].

The experimental approach taken was similar to that of King *et al*. [19]. Performance of the sorbent materials was based on the amount of mercury uptake as measured by offline analysis of the sorbent at the end of an exposure period. Initially, results with sorbents were reported by spiking a stream of nitrogen with elemental mercury. After a test protocol was established, candidate sorbents were typically exposed to the carrier gas/mercury vapor stream for 30-min at 572 °F (300 °C). Mixed metal oxide sorbents, both in sulfide and oxidized forms, were investigated along with commercially available materials. Some of the candidates performed quite well in removing the Hg from the gas stream, although a mechanism for capture was not discussed as the sorbents typically contained multiple components.

In a continuation of these studies [29], composite metal oxides were investigated along with proprietary sorbents and an impregnated activated carbon. The sorbents were selected on the basis of various factors, including surface area, predicted stability in the syngas matrix, expected material costs, and identification of materials that irreversibly bind with elemental mercury at the targeted temperature (typically near 300 °C). The parameters of temperature and gas matrix were of interest with respect to mercury capacity. In general, screening results clearly favored lower temperatures as compared to the 300 °C

baseline. At this temperature and exposed to Hg in nitrogen, the mixed metal oxide sorbents performed adequately. However, in a syngas with or without moisture and without hydrogen sulfide, these sorbents performed poorly. One potential explanation given was that the major syngas components chemically reduced the metal oxide components of the sorbents, thus decreasing the active oxide species responsible for the mercury retention. In addition, the presence of H_2S typically had a deleterious impact on the mercury capacity of the sorbents investigated.

The main thrust for the sorbents discussed was to remove mercury in the warm/humid gas range in an IGCC application. However, certain sorbents can be used in a more elevated temperature range beyond the warm/humid range. The University of Utah has worked with CDEM to demonstrate the MinPlus sorbent, which is an inorganic, mineral-based substance derived from a unique thermal process in which sludge from paper recycling is converted into the desired material [30]. The material serves as a special mineral additive to cement, and the primary constituents are limestone, meta-kaolinite, lime, inerts, and various trace components.

The sorbent was injected into a simulated gas flow in a dispersed-phase entrained bed reactor system. Overall mercury removal efficiency increased with increasing sorbent feed rate and with reaction temperature, suggesting an overall chemisorption mechanism. For the reactor configuration, an overall maximum Hg removal of about 83–90% was achievable at a temperature range of 900–1100 °C. The mercury removal was attributed to an in-flight mechanism as well as to one related to the deposition of the MinPlus sorbent on the reactor walls. It was shown that at 1100 °C, the sorbent ability to capture Hg was greatly diminished, possibly due to a change in composition and/or morphology of the initial material. The impact of the other components in fuel gas, especially hydrogen sulfide, was not discussed in the communication.

22.4 Cold Gas Cleanup of Mercury

From the previous discussion, mercury is most likely in the elemental form after the coal has been gasified. If not removed at elevated temperature in one location, the mercury can be impacted by various processes along the gas cleanup path as related to the final use of the fuel gas or syngas. It should be remembered that although there is a paucity of mercury information in actual commercial gasification systems, past information on actual IGCC units that use gas cleanup at cold temperatures indicate that not all the mercury is accounted for and leads to the speculation that some of the mercury may end up in some of the gas cleanup process streams. However, a substantial amount of mercury still remains in the fuel gas and would need to be removed. At low temperatures (<100 °C), it has been shown that activated carbon can remove the mercury. Other mercury sorbent

materials have also been investigated at these low temperatures. In addition, a wet scrubbing process has also been proposed.

22.4.1 Carbon-Based Materials

Eastman Chemical Company was the first company to operate a commercial coal gasification facility in the United States and has maintained greater that 98% availability for more than two decades [31]. Mercury removal has been commercially demonstrated in this gasification facility. Eastman has developed and successfully applied activated carbon-based mercury control technology at their facility located in Kingsport, TN. Eastman has been operating Chevron Texaco gasifiers at this facility since 1983 to provide syngas for the production of acetyl chemicals [4, 28]. Calgon's HGR-P sulfur-impregnated, pellet-activated carbon beds are utilized with the following performance characteristics:

- Operating conditions: Approximately 30 °C and 900 psi;
- Gas contact time in bed: Near 20 s based on total packed volume;
- Removal efficiency: 90 – 95%;
- Carbon lifetime: 12 – 18 months.

At the lower temperature of operation, this activated carbon technique can be considered proved and is the baseline technology for mercury removal. Various designs for gasification plants, more specifically IGCC, propose to use sulfur-promoted activated carbon beds for mercury control [32 – 34]. Once the efficiency price has been paid by cooling syngas to near 38 °C (100 °F), the incremental cost to remove other components is reduced because the gas cleaning occurs at essentially ambient temperature. Again, the challenge for fuel gas cleanup is to develop gas purification methods that do not require gas cooling that, in turn, lowers overall thermal plant efficiency.

Testing using activated carbons with actual fuel gas did occur at Tampa Electric's Polk Power Station [35]. A packed bed of sulfur impregnated activated carbon (Calgon HGR-P) was fed with a slip stream of syngas containing hydrogen sulfide. Mercury analyses of the gas and the solid followed. Although about half of the feed to the plant was petroleum coke rather than coal, over 90% of the mercury in the feed to the carbon bed was removed.

Various experimental studies with carbon-based materials have also been conducted and have resulted in similar findings. Reed *et al*. [7] obtained samples of fines that were collected in a hot gas filter following a gasifier. The composition of the material was primarily carbon with some sulfur, and the material was collected by a hot gas filer at 580 °C from a 2-MWt gasifier operated on a mixture of coal and sewage sludge. Although further work was needed, the sorbent was able to capture elemental mercury at temperatures below 200 °C, and significant mercury removal was observed at a temperature of 110 °C.

Spanish researchers [36] investigated the importance of sulfur promotion of an activated carbon. A Norit carbon (a peat-based, steam-activated carbon) was

the baseline, and this was impregnated with sulfur compounds to form a second sorbent candidate. Simulated syngas streams with a spike of elemental mercury were passed over beds of the materials. For the gasification case, a better retention of the mercury occurred with the sulfur-containing sorbent as compared to the baseline carbon sorbent, because it was speculated that chemisorptions and/or reaction between sulfur compounds and mercury may occur as compared to just physical adsorption. Surface chemistry was thought to be more important than porous texture in controlling mercury retention in activated carbons.

The impact of gaseous components within syngas was studied [37]. In this experimental study, an activated carbon made from coconut shell was investigated. A simulated syngas flowed over a packed bed of the material at atmospheric pressure and in the temperature range of 80–300 °C. The amount of HCl and H_2S in the gas stream could be varied along with the elemental mercury. It was found that the presence of HCl accelerated the mercury removal rate by the activated carbon. However, the presence of H_2S suppressed the mercury removal in the presence of HCl. The stabilities of the mercury species captured on the activated carbon depended on the presence of the acid gases HCl and H_2S. The effect of temperature was similar to the findings of others where, typically, an increase in temperature has a negative impact on the Hg adsorption capacity of the sorbent. In one of those studies, British researchers [38] investigated a commercial Norit Darco "Hg" activated carbon. Mercury spiked in nitrogen flowed over the packed bed of sorbent in the temperature range of 100–200 °C. As found previously, the capture efficiency is seen to decrease as the temperature is increased. It should be noted that this activated carbon had a high capacity for arsenic removal in the temperature range of 200–400 °C.

22.4.2 Other Materials

Various transition metal sulfides have been proposed as mercury sorbents for fuel gas. In one case, Japanese researchers [39] investigated iron-based sorbents where they envisioned the mercury removal unit to be located just before the wet desulfurization unit in the gas cleanup system. Experimentation was conducted in a thermogravimetric analyzer and packed bed where a simulated fuel gas was spiked with elemental mercury. Unsupported and supported iron oxides that were calcined to different temperatures were tested within the temperature range of 60–100 °C under atmospheric pressure. The effects of temperature and gas composition on the sulfidation of the iron oxides, mercury removal activity, and carbonyl sulfide (COS) formation were investigated. Results indicate that the fabrication of the sorbent, that is, calcination and support, plays an important role in its behavior. Sulfidation of the iron oxide decreased and COS formation decreased with increasing calcination temperature. With decreasing operating temperature, the mercury removal performance increased. For comparison, reagent grade FeS and FeS_2 were active for elemental mercury removal in the simulated fuel gas without forming any COS.

Copper-based mercury sorbents have also been proposed in a fuel gas application at 160 °C [40]. In addition, an effort to clean mercury using copper sulfide from a natural gas stream could have implications for synthesis/fuel gas cleanup. In this study [41], the concern was related to mercury in natural gas and its potential to cause corrosion of downstream aluminum heat exchangers as a result of amalgamation. The sorbent is a mixture of copper sulfide and other materials and was assumed to operate at ambient temperature. On the basis of experience with the material, various precautions were needed to get the sorbent bed up to standard operation, such as removal of oxygen from the inert purge gas during loading of the sorbent. Results indicate that the mercury reduction exceeded the expectations for this copper sulfide sorbent. These results are similar to a previous study [42] with CuS and its ability to remove elemental mercury below 90 °C, although that research effort was not conducted using an atmosphere of reducing gas that would be found in a fuel gas system.

A series of unpromoted and iodine-, bromide-, and/or sulfuric acid-modified chitosan/chitin sorbents were tested in a laboratory-scale fixed-bed reactor system [43]. Elemental mercury was spiked in nitrogen that contained moisture, and temperature of operation was varied from 40 to 135 °C. Although this mixture was to simulate a combustion flue gas, it could also be extrapolated as a simulated fuel gas. Promotion of the chitosan was deemed important with respect to mercury removal, and the presence of moisture can increase the modified chitosan sorbent capacity for mercury uptake. A better mercury uptake capacity and higher mercury removal efficiency occurred at 135 °C as compared to 40 °C and was thought to be associated with a chemisorption mechanism between mercury and the promoters within the sorbent.

Finally, the use of fly ash in mercury removal was investigated by Spanish researchers [44, 45]. In this particular case, fly ashes from different combustion sites were tested in a packed bed reactor by flowing a simulated fuel gas that contained elemental mercury at 120 °C. The mercury retention capacities on the fly ashes in the gasification atmosphere were similar to that found when just nitrogen was spiked with mercury. The nature of the fly ash is determinant in the control of mercury capture. In later studies [45], a temperature programmed decomposition was used to identify the species of mercury that were present on the spent sorbent. Mercury sulfides were determined to be present, and it would be expected in a gasification atmosphere that contained H_2S.

22.4.3
Wet Scrubbing Technique

Typical wet scrubbing processes for the removal of contaminants from fuel gas or syngas do not intentionally remove mercury, although there may be evidence that they unintentionally capture the mercury [28, 35]. One wet scrubbing process that was developed for multicontaminant removal in fuel gas was the University of California Sulfur Recovery Process at High Pressure or (UCSRP-HP) [46, 47]. Research at the University of California coupled with experimental work at

GTI led to the development of an integrated multicontaminant removal process, whereby syngas is sent to a reactor column at a temperature above the melting point and below the polymerization temperature of elemental sulfur at elevated pressure. Desulfurization occurs in the range of 285–300 °F and the process integrates the removal of trace contaminants and heavy metals. The countercurrent-flow reactor column is divided into two sections: a scrub section and the reactor section. In the reactor section, a stream of glycol ether, such as diethylene glycol methyl ether, is used to catalyze a reaction and form a liquid sulfur that can be separated from solvent. In the preceding scrub section, an aqueous glycol ether solvent, such as diethylene glycol, is used to remove hydrogen chloride and the heavy metals mercury, arsenic, and cadmium that will be absorbed to form their respective, very insoluble sulfides. Selenium will be absorbed to form highly soluble ammonium selenide under the conditions of operation. It was proposed that a small slipstream of the diethylene glycol stream be withdrawn for filtration and other treatment to remove the accumulated impurities, especially the mercury-containing one. Laboratory-scale tests indicated that 95% of the mercury could be removed with diethylene glycol as the solvent. Bench scale testing with coal-derived syngas has been proposed [47].

22.5 Summary

Gasification of coal for power generation and chemical production is projected to increase in the future. Many factors could impact this future market, such as the decreased consumption of domestic and foreign oil for chemical fabrication and the potential regulation of the greenhouse gas carbon dioxide. In any event, mercury emissions from gasification-based technologies in the United States will need to be controlled as mandated by law. Similar to post-combustion control of mercury, the use of sorbents is a necessity in the control of mercury. Along the gas cleanup pathway for gasification processes, it is beneficial to remove the mercury at one location and at elevated temperature. Various sorbent results have been discussed where this is applicable. In addition, sorbent investigations have been reported at lower temperatures. Because of the novelty of gasification-based processes and the more recent interest in mercury control, one sorbent-based process for mercury capture is not outstanding. Granted that activated carbon has been shown to be a valid technique at lower temperatures, one clear-cut sorbent technology does not stand out at the beneficial higher temperature of operation. More research and development in this fledgling area is needed.

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Part VI
Modeling of Mercury Chemistry in Air Pollution Control Devices

Mercury Control: for Coal-Derived Gas Streams, First Edition.
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23
Mercury-Carbon Surface Chemistry

Edwin S. Olson

23.1
Nature of the Bonding of Mercury to the Carbon Surface

At low temperatures, elemental mercury is adsorbed to high-surface-area carbons by physisorption mechanisms. The term *physical adsorption* or *physisorption* implies a weak bond involving van der Waals or induced dipole forces between the mercury atom and the carbon surface. This means that the outer 6s electrons in the mercury atom, which are shielded from the nucleus by a lot of inner electrons, become polarized by dipole charges on the carbon surface so that they set up their own dipole moment, resulting in a dipole attraction to the carbon surface.

Although some early reports attributed mercury sorption at higher temperatures in air and flue gas to the physisorption mechanism [1], it is now understood that chemisorption is the primary mechanism in these conditions for mercury capture on carbon; elemental mercury becomes oxidized on the carbon and binds as a Hg(II) compound. Both spectroscopic and reactivity data provide compelling evidence for a chemisorption mechanism for mercury capture on carbons in flue gas at moderate temperatures. An early paper on mercury sorption on a nonimpregnated Saran carbon [2] showed an immediate and complete breakthrough of mercury at 150 °C in an air stream corresponding to a velocity/sorbent ratio of $2.5\,l\,s\,g^{-1}$, indicating that physical adsorption cannot occur at this temperature. Later, using a stopped-flow reactor with activated carbons at temperatures in the range of 100–300 °C, Hall showed that the apparent reaction order for Hg^0 sorption is half order in molecular oxygen [3]. Thus, the carbons are catalyzing the oxidation of mercury with oxygen as the primary oxidant. In a flow-through experiment with a nonimpregnated bituminous carbon at 140 °C in air at a slow flow rate ($0.19\,l\,s^{-1}$), Krishnan *et al.* [4] observed an early breakthrough, but a gradual decrease in capacity. As there did not appear to be any effect of Hg^0 concentration on the capture of Hg, the reaction was zero order with respect to Hg^0 concentration. Thus, the limiting factor was the low number of active sites in the activated carbon. But why did Singha [2] not see any sorption? In more recent flow-through experiments at the EERC with granular carbon (Calgon

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F400 or NORIT GAC1240) beds at 150 °C, we showed that at slow flow rates, the breakthrough time in nitrogen was instantaneous, but was significantly longer in air [5]. With F400 at fast flow rates, breakthrough was instantaneous for both gases; thus, there was clearly a space velocity factor in these experiments. Therefore, only at very slow flow rates can one see sorption occurring in air.

Further evidence for the formation of oxidized mercury on the carbon was obtained from desorption experiments. Heating the spent sorbent beds from a variety of experiments to temperatures over 200 °C resulted in release of mercury. Sometimes temperatures of 750 °C were needed to eliminate the mercury from the sorbent. Although the released mercury in these thermal experiments was mostly elemental, it is unlikely that any Hg^0 existed on the carbon, as Hg^0 volatilized easily at ambient temperatures in an air stream. When heated in a 10% hydrogen stream, the spent sorbents released mercury at 125 °C as Hg^0. This is the reported temperature for reduction of Hg (II) compounds.

Some of the most conclusive evidence for chemisorption comes from an examination of the chemical form of mercury on the spent carbons using X-ray adsorption fine structure (XAFS) spectroscopy. XAFS is a powerful spectroscopic technique that can distinguish elemental and some of the oxidized mercury forms in a solid sample on the basis of the inflection point differences (IPDs) in the energy absorbance curve. Huggins *et al.* [6] showed that the mercury IPD of sorbents exposed to flue gas was not consistent with that of elemental mercury or with mercury bonded to oxygen. Rather, the IPD varied with gas composition and was consistent with a Hg(II) species bonded to a polarizable (soft) element such as chlorine, carbon, or reduced sulfur. This observation also rules out mercury compounds, such as HgO, $HgSO_4$, or $Hg(NO_3)_2$, as well as bonds between Hg and surface oxygen groups, including phenoxide, lactone, or ketone groups that had been previously suggested as binding sites for mercury, and also most mineral surfaces, such as iron or other metal oxides, silicates, and carbonates. Organic and inorganic sulfides are rapidly oxidized to sulfonates and sulfates, respectively [7, 8] and these are also ruled out by the spectroscopic data [6], as they bind via the oxygen rather than the sulfur(VI). When a sorption experiment was carried out with moisture present, but no flue gas, the IPD data for the mercury line indicated that the mercury was bonded to at least one oxygen [9], so there is more than one possible structure resulting from chemisorption, depending on the oxidant, type of sorbent, or conditions, and this structure might include bonds to some combination of carbon, sulfur, oxygen, or halogen.

23.2
Effects of Acid Gases on Mercury Capacities on Carbon

As discussed, activated carbons have little affinity for elemental mercury in air, but the sorption properties of the same carbons change drastically in flue gas. The interactions of the acid gases with the carbon surface determine the reactivity of the carbon to the mercury, as well as the capacity of the carbon for mercury.

The description of this interaction has provided valuable clues to the detailed mechanism of Hg chemisorption and binding on carbon.

An early study on acid gas effects with mercury on a carbon surface was that conducted by Young and Musich, with carbons exposed to gas-phase Hg also containing HCl and SO_2 [10].

Enhanced Hg sorption was observed in gas containing HCl. Because HCl is the major form of halogen in flue gas (see Chapter 7), at least at temperatures at which Hg capture occurs, we need to understand its role in the capture mechanism. Because HCl is not an oxidant, and Hg is oxidized on carbon in the absence of HCl [5], it is clear that neither HCl nor Cl_2 derived from HCl are necessary or independently responsible for oxidation of Hg on the surface.

Two studies published in 1998 [1, 11] pointed out some important effects of flue gas components on mercury sorption; however, many of these effects were not understood until the interactions were later investigated. A large factorial series of tests [12] using powdered activated carbon (Norit Americas flue gas desulfurization (FGD) carbon) was conducted at the EERC in a bench-scale system consisting of a thin fixed-bed reactor in gas streams (100–150 °C) containing 11–15 μg m^{-3} of Hg^0 in various simulated flue gas compositions consisting of acidic (SO_2, NO_2, and HCl) gases plus a base mixture of N_2, O_2, NO, CO_2, and H_2O. The results of these experiments (breakthrough curves) showed that NO_2 or the combination of HCl plus O_2 is required for effective Hg^0 capture, so these represent the primary oxidants or electron acceptors for mercury oxidation. Some acid gases had negative effects on mercury sorption, especially in combination. In one series of tests conducted with constant NO_2 concentration [13], increasing the SO_2 concentration gave shorter mercury breakthrough times (Figure 23.1). When SO_2 was omitted, no breakthrough occurred. In another series of tests at a constant SO_2 concentration, increasing the NO_2 concentration gave shorter mercury breakthrough times (Figure 23.2). Not only was SO_2 retarding the mercury capture, the retarding effect became more important as the NO_2 concentration increased. Thus, understanding of a very important interaction between NO_2, SO_2, and the Hg sorption began to develop. This strong interaction indicated that the NO_2 was oxidizing the SO_2 as well as the mercury on the carbon surface, and the resulting sulfur(VI) was inhibiting the mercury capture and causing the breakthrough. This effect was consistent with previous studies on the carbon-catalyzed oxidation of SO_2 [14]. The water in the flue gas was also needed for breakthrough to occur, which could be attributed to a requirement for the formation of sulfur(VI) [12].

The EERC work [12] also established that the Hg emitted after breakthrough (i.e., when there is no more net Hg sorption on the carbon) was mostly oxidized and can exceed inlet Hg concentration immediately following breakthrough. Olson showed that Hg emitted after breakthrough in the absence of HCl was $Hg(NO_3)_2$ [15], although in the presence of high HCl (50 ppm) concentrations, the emitted oxidized form is undoubtedly $HgCl_2$. This does not mean, however, that either of these two compounds has collected in the carbon before breakthrough. In fact, both forms easily desorb from an inert solid surface at 150 °C [16, 17], and so are not likely to be present on the carbon before breakthrough.

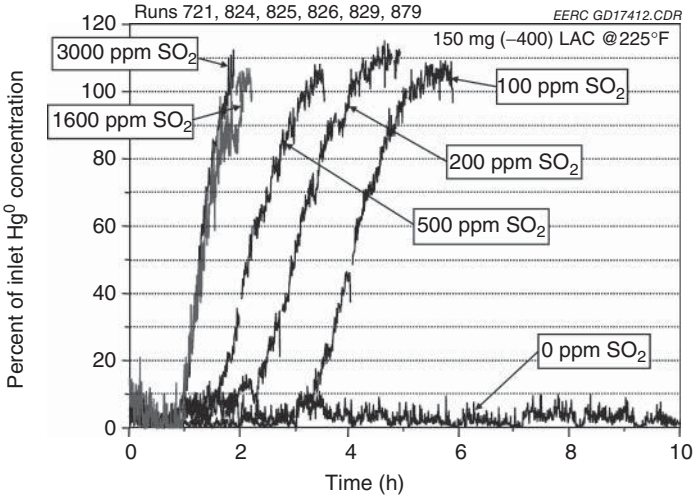

Figure 23.1 Mercury breakthrough curves for set of SO_2 concentrations with 15 μg m^{-3} Hg^0, 50 ppm HCl, 300 ppm NO, 20 ppm NO_2, and other baseline gases [13]. (Used with permission of the Energy and Environmental Center.)

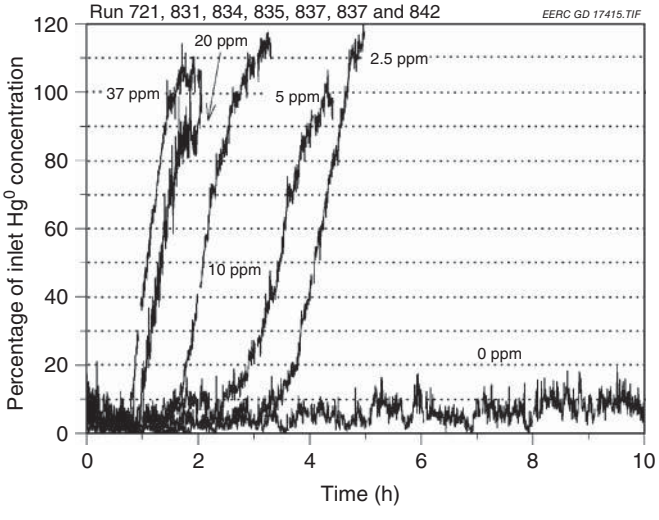

Figure 23.2 Mercury breakthrough curves for set of NO_2 concentrations with 15 μg m^{-3} Hg^0, 50 ppm HCl, 300 ppm NO, 1600 ppm SO_2, and other baseline gases [13]. (Used with permission of the Energy and Environmental Center.)

On the basis of these parametric studies and recognition that mercury is still converted to Hg(II) after breakthrough, an initial mechanism for chemisorption [18] that described the chemisorption mechanism as oxidation and competitive binding of the oxidized mercury with a catalytic carbon site or sites was presented. Oxidation of Hg^0 to form a bound Hg(II) species occurs with the electrons donated

to an electron-accepting (i.e., Lewis acid) site on the carbon. The electrons may be lost to NO_2 or O_2 the primary oxidants. Thus, the carbon plays a catalytic role, but the resulting oxidized mercury is bonded to the carbon structure. A donated electron pair results in formation of a carbon–mercury covalent bond, but this structure is labile, as the parametric tests revealed. An explanation for the SO_2, NO_2, H_2O inhibition of mercury capture is that the breakthrough behavior in the parametric tests was dominated by the competition for binding sites between the Hg(II) and acid components, mainly H_2SO_4 generated from the oxidation of SO_2 on the carbon, which continue to build up on the carbon surface during exposure to flue gas. When the binding sites are completely occupied by acidic species derived from the flue gas, Hg(II) salts are displaced from the binding sites. The equilibrium is shifted toward Hg salt release because of the high concentration and lower volatility of H_2SO_4.

But mercury oxidation still occurs even after complete breakthrough. That is, oxidation occurs in the presence of the bound sulfuric acid, although not always at the same rate as the initial rate. The loss of capacity must not be the result of pore plugging by species resulting from acid gases, as this would stop both oxidation and binding. But pore plugging could slow the oxidation rate.

The competitive inhibition of Hg binding by S(VI) was further demonstrated by Presto and Granite [19]. Halogenated and nonhalogenated carbon samples exposed to SO_3 or impregnated with H_2SO_4 (10 wt%) showed significantly decreased mercury capacity. The effect of water and NO_2 in converting SO_2 on the carbon to sulfuric acid was also confirmed.

Carey *et al.* [1] showed that increasing the inlet Hg concentration resulted in increasing the capacity of the carbon. What is now understood is that the capacity is determined largely by the sulfur(VI) formation and this occurs at the same rate no matter what the mercury concentration is. As the number of active sites for oxidation is very large, the more inlet mercury there is, the more is captured until the binding sites are filled with sulfur VI. Fundamentally, the breakthrough sorption curves that were being drawn did not provide the equilibrium capacity of the sorbent for mercury; instead, they gave an indication of how fast the sorbent was being poisoned by sulfuric acid.

The extensive mineral matter (35%) of the Norit Americas FGD sorbent could contribute basic sites for Hg binding, but a sequential removal of the inorganic matter from the FGD sorbent did not significantly affect the breakthrough behavior [20]. Basic mineral groups, such as CaO present in the FGD sorbent, therefore played no role in the mercury–flue gas interactions that determine the breakthrough capacity. Actually, several activated carbons prepared from pure carbon precursors were perfectly good sorbents. This suggests that the bound Hg is actually an organometallic complex. However, sorption of $HgCl_2$ from a flue gas may not exhibit this exclusivity, because an oxidation site is not needed and any basic site on the sorbent may bind Hg(II).

Further evidence for a competitive binding mechanism for Hg(II) and flue-gas-derived components at a carbon site was provided in a series of studies carried out at the EERC, in which carbons were exposed to various combinations of flue

gases representative of high Cl coals for different times and the spent carbons were analyzed by X-ray photoelectron spectroscopy (XPS) [7, 8]. These studies verified that sulfur(VI) (sulfate, bisulfate, sulfonate, or sulfuric acid) was the major sulfur species on all the exposed sorbent samples, and the longer the exposure to SO_2, the more sulfate was found in the sample. When NO_2 or H_2O was omitted from the flue gas, less sulfate accumulated. Thus, adsorbed SO_2 was clearly oxidized on the sorbent surface to sulfur(VI) species in a process facilitated by NO_2 and H_2O. Additional XPS work [8] with flue gas streams containing low concentrations of HCl typical of western coals, showed that organochlorine intermediates build up on the carbon surface and then disappear along with the bound mercury as the concentration of sulfuric acid increases. The XPS data also indicate that two types of chlorine are present: ionic and covalent, and that both chlorine forms disappeared from the sample at breakthrough. That chlorine is present as both chloride ion and covalent (organic) chlorine indicates that the HCl in the flue gas can donate a hydrogen ion to a basic site, as well as add both hydrogen and chlorine to a basic site to form the organochlorine product. The accumulation of chlorine in the absence of SO_2 as well as the disappearance of chlorine after continued exposure in SO_2 is explained by competition of HCl with bisulfate or sulfuric acid. As more H_2SO_4 is generated from SO_2 at the carbon surface, it displaces the more volatile HCl. Because disappearance of chlorine is coincident with mercury breakthrough, it is clear that Hg(II) is also in competition at the same site. Because of the interference caused by silicon, XPS data could not be obtained for the mercury species present in the exposed sorbents.

23.3 Kinetic HCl Effect

Although the early experiments revealed the nature of the competitive effects of flue gas components on mercury capacity, determining their role in the oxidative portion of the capture mechanism required further analysis. This information would be essential to designing sorbents with faster oxidation. The key to understanding the role of HCl in the oxidation mechanism was provided by testing of carbon sorbents in atmospheres containing low amounts of HCl. In parametric bench-scale tests conducted in very low HCl concentrations, such as those obtained when low-Cl coals (1 ppmv in the flue gas) are burned, the capture efficiency at the start of the run was low (about 50% of inlet concentration), followed by an increase in capture efficiency to the 90–95% capture rate [12]. This effect was also seen in breakthrough curves for a number of sorbents prepared from low-rank coals [21]. This behavior contrasts with the capture of mercury in relatively high HCl concentrations (50 ppm), where capture at the start was always very high (more than 95% of inlet concentration). The higher HCl concentration thus eliminated this induction period during which poor capture is obtained, and, therefore,

a promotional effect of the accumulating HCl on the activity of the carbon in catalyzing the oxidation of mercury was indicated. Ghorishi *et al.* [22] reported an increase in sorbent capacity as a result of pretreating the sorbent with aqueous HCl. Thus, consideration of the effects of HCl on Hg sorption curves led to a concept for understanding how the HCl promotes the mercury oxidation. This promotion was not because the HCl was directly involved in the oxidation, as it is in fact a highly reduced form of chlorine, and it is therefore not thermodynamically feasible to oxidize Hg with HCl.

The possible role of atomic chlorine in surface reactions was briefly examined. For HCl-promoted activated carbon (AC), Hg oxidation was not impeded by the presence of free radical scavengers, indicating that an alternative mechanism involving Cl atoms was not likely [23]. Furthermore, the addition of olefins (cyclohexene and styrene) to an HCl-treated carbon gave no substitution products, which would have resulted from abstraction of hydrogen by any Cl atoms present [24]. In contrast, the addition of HCl to the styrene occurred exclusively via the Markownikoff regioselectivity, indicating a cation mechanism. Thus, all four experiments indicated the absence of a radical or halogen atom pathway.

Several features of the oxidation site were inferred from the HCl promotion and bonding effects that led to development of a detailed chemical mechanism of mercury capture on the carbon surface [23–26]. This mechanism assumes a single carbon site for oxidation and binding but in two different forms and thus offers more detail on the nature of the bonding site and its interaction with flue gases and Hg. The mechanism, shown in Figure 23.3, used the concept proposed by Radovic and Bockrath [27] that zigzag carbene edge structures represent active sites for carbon reactivity. The mechanism for the catalytic role of acids, such as HCl, in the mercury oxidation step proposed addition of HCl and other acids to the carbene edge carbons to form carbenium chloride ion pairs (Lewis acid) that represent an oxidation site [26]. Reactions of the edge carbon with molecular halogens generate similar highly reactive carbenium structures. The

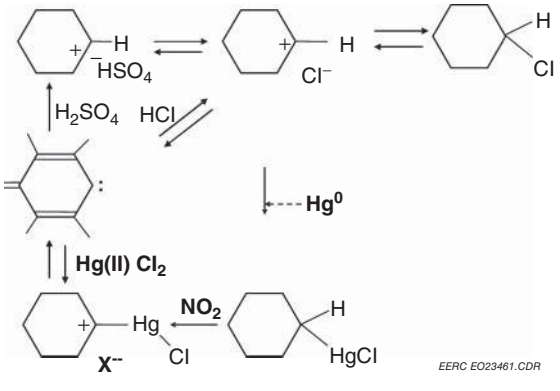

Figure 23.3 Oxidation mechanism – carbenium ion oxidant.

mechanism proceeds with Hg^0 oxidation by the carbenium halide ion pair to form an organomercury intermediate. This intermediate can be subsequently oxidized by NO_2 to a bound Hg^{2+} species. After breakthrough, $HgCl_2$ is continuously released as sulfuric acid competes for the site.

The oxidation of activated carbon is promoted not only by the addition of HCl, but any other acid, including small amounts of sulfuric acid [5, 24]. Comparative testing of a large number of acid-promoted ACs showed that they exhibit a specific acid catalysis, not a general acid catalysis. That is, those acids with polarizable counterions (HI > HBr > HCl) show faster initial rates compared with strong and weak oxyacids and fluoroacids [24]. This finding is consistent with a mechanism where the halide ion proximate to the cation actually can assist in the oxidation mechanism by stabilizing the incipient mercurinium ion forming in the transition state.

Later, the mechanism was somewhat modified to include the role of NO_2 in helping to promote the oxidation site [28]. The combination of HCl and NO_2 in the gas was a very effective promoter of mercury oxidation. The current thought is that multiple charges in the aromatic system may concentrate more of the positive charge and, thus, the oxidation potential at the protonated edge site [29, 30].

The number of active sites on a carbon-based sorbent can be estimated by determining the amount of accumulated sulfate at the time of Hg breakthrough, when essentially all of the binding sites are occupied by sulfate and unavailable for binding Hg. The amount of bound sulfate was calculated from the measured rate of SO_2 oxidation on Norit Americas Darco FGD [31] and the breakthrough time in a fixed-bed bench-scale test. This calculation gave 3.4 mol of potential sites per kilogram of carbon. The question in actual use of the carbon is how fast these sites are promoted to active status.

Early research [1] determined that mercury capacity was inversely related to temperature, and was incorrectly attributed to physisorption. A better explanation for the lower capacity in flue gas at higher temperature is that the rate of oxidation of SO_2 to sulfuric acid increases with temperature, so that the buildup of poisoning H_2SO_4 on the sorbent occurs at a faster rate. It may also be true in general that the rate of loss of $HgCl_2$ from the active sites is faster at high temperature than the rate of oxidation. This is not a true equilibrium as elemental mercury is going on the carbon and oxidized mercury is coming off. The question of temperature dependence of the oxidation was only recently answered. Comparisons of the initial capture efficiency (where kinetic rather than capacity effects predominate) in low-Cl gas at high and low temperature showed that Hg^0 was captured more effectively at the higher temperature. As the rate increases with temperature, the oxidation step is rate controlling and the physisorption reverse reaction is not of importance in controlling the rate. The implications of this finding for control technology are that when contact time is very short and reactivity is important, then higher temperatures will give faster oxidation rates for both mercury and SO_2, but the effect of faster SO_2 reaction to sulfate is not important because binding sites are still abundant in the short time period. For sorbents

collected on a filter bag and in contact with the flue gas for a long time, the capacity will be greater at a lower temperature, because sulfate builds up more slowly at the lower temperature.

Halogenated carbons typically exhibit very high initial rates of mercury oxidation, with no induction period. So they are very effective in mercury capture in utilities where the contact time of the sorbent carbon and the gas phase in the duct is short. However, the capacity of the halogenated carbons may actually be less than that of the nonhalogenated carbons. Presto and Granite demonstrated that in a packed bed reactor with good gas–solid contact, bromination of the carbon does not increase the capacity [19].

Current work involves decoupling the oxidation from the binding steps so that effects of gas components on the oxidation step can be determined, and rate constants derived. These experiments utilize a sorbent bed that has broken through so that most of the inlet Hg^0 is oxidized by the bed in the flue gas, but no mercury is captured [31]. Then, by measuring the Hg^0 and total Hg in the effluent gas simultaneously for a matrix of experiments in which one, two, three, and four components are deleted or reduced, rates of oxidation, and changes in binding chemistry can be determined for each condition. Thus, removal of NO_2 resulted in a significant decrease in oxidation rate, but oxidation was still able to occur (pseudo first order $k = 1.4\,\mathrm{l\,s\,g^{-1}}$ sorbent) with O_2 and NO present. Removal of HCl from the gas composition decreased the oxidation rate, consistent with the specific acid catalysis mechanism, but, because oxidation still occurred, the oxidation can evidently occur via the sulfate-bound carbenium ion.

23.4 Summary

Several factors that determine the amount and rate of Hg capture on carbons have been described. Most important are (i) the competitive interactions of the flue gas components with each other and oxidized mercury on the carbon surface sites in determining mercury capacity on carbon and (ii) the interactions of the acid gases with the carbon surface in determining the reactivity of the carbon for oxidation of mercury. The description and understanding of these interactions has provided valuable clues to the mechanism of Hg chemisorption and binding on carbon. The key to understanding the role of HCl was the finding that sorption experiments conducted in low amounts of or no HCl experienced an induction effect, an initial period of time where the reactivity to Hg oxidation develops [5]. This finding led to the concept of acid promotion of a carbon site to form a carbenium ion that is highly reactive for oxidation, resulting in formation of an organomercury intermediate. The direction in sorbent research recently has been guided by the insight that more reactive or more selective oxidation sites can be generated by varying the carbenium ion structures that are formed.

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24
Atomistic-Level Models

Jennifer Wilcox

24.1
Introduction

Understanding the speciation of mercury throughout the coal-combustion process is crucial to the design of efficient and effective mercury removal technologies. Mercury oxidation takes place through combined homogeneous (i.e., strictly in the gas phase) and heterogeneous (i.e., gas–surface interactions) pathways. Both bench-scale combustion experiments [1] and quantum-chemistry-based theoretical model efforts [2, 3] indicate that homogeneous mercury oxidation is responsible for, at most, 10% of the overall oxidation in a typical coal-fired flue gas with chlorine levels at 500 ppmv (e.g., HCl equivalent). These studies have been additionally confirmed by recent work that compares model predictions to bench-scale experiments, with the simulation predictions dependent on previous kinetic submodels developed specifically for Hg oxidation [4, 5]. Mercury speciation in coal-fired flue gases are extremely complex and depend on many factors, some of which include the mineralogy and chemistry of the coal, combustion conditions, power plant configuration, flue-gas composition, and temperature-time history from the boiler to the stack.

The extent to which particulate-bound mercury (Hg_p), gaseous oxidized mercury (Hg^{2+}), and gaseous elemental mercury (Hg^0) are emitted from the stack is also dependent on the existing pollution controls in a given power plant. The effective removal of Hg through existing flue-gas control technologies acts as a co-benefit (as discussed elsewhere in this book). For instance, electrostatic precipitators (ESPs), in particular cold-side ESPs and hot-side ESPs, capture, on average, 27% and 4% of Hg, while fabric filters (FFs) are more effective with approximately 58% Hg removal [6]. In general, Hg_p or Hg^{2+} is easier to capture using one of these control technologies. In addition, oxidized Hg may also be captured in existing flue-gas desulfurization (FGD) units as the oxidized form is water-soluble. Activated carbon injection (ACI) is a direct method used for Hg capture, in which powdered activated carbon (PAC) is injected into the plant's flue-gas stream where it adsorbs gaseous Hg and is collected in downstream particulate control devices, such as FFs or ESPs. Heterogeneous investigations include both adsorption and

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oxidation mechanisms associated with natural surfaces present in the flue gas such as fly ash, but also include surfaces associated with existing control technologies, such as selective catalytic reduction (SCR) catalysts or specific Hg-control technologies such as activated carbon (AC) or precious-metal sorbents and catalysts. The fundamental model investigations carried out to date may be classified into three major categories: homogeneous Hg oxidation kinetics, chemisorption on AC, and adsorption and amalgamation of Hg with precious metals.

24.2 Homogeneous Mercury Oxidation Kinetics

24.2.1 Mercury–Chlorine Chemistry

Gas-phase oxidation occurs primarily via chlorine species originally present in the coal as the gases cool down through the air preheater and air pollution control devices. Thermodynamic calculations predict that Hg oxidation occurs at temperatures below approximately 700 °C and that Hg will be completely oxidized at or below 450 °C [7]. Regardless of the thermodynamic equilibrium model predictions, experimental evidence has found that not all of the Hg is oxidized in the flue gas, regardless of the chlorine content of the coal. These experimental findings have led the Hg control community to determine that Hg oxidation is kinetically, rather than thermodynamically, limited [7]. For this reason, there has been significant investigation of determining accurate Hg oxidation kinetics from quantum-mechanical-based estimates because of the difficulty of the flue-gas measurements.

Some of the first studies to include quantum chemistry into the examination of the oxidation kinetics of Hg for flue-gas applications are those of Sliger *et al*. [8, 9], in which a homogeneous kinetic model for Hg oxidation via chlorine was determined and coupled with bench-scale combustion experiments. On the basis of these experiments, it was found that oxidation increases with increasing HCl concentration, which is consistent with previous experiments carried out by Hall *et al*. [10, 11] Adding to these initial investigations, the work of Wilcox *et al*. [12–14] and Krishnakumar and Helble [15] provide a fairly complete set of Hg oxidation kinetics via Cl-containing compounds for the following set of reactions:

$$Hg + Cl \leftrightarrow HgCl \tag{R1}$$

$$Hg + O \leftrightarrow HgO \tag{R2}$$

$$Hg + Cl_2 \leftrightarrow HgCl + Cl \tag{R3}$$

$$Hg + Cl_2 \leftrightarrow HgCl_2 \tag{R4}$$

$$Hg + HCl \leftrightarrow HgCl + H \quad \text{(R5)}$$

$$Hg + HOCl \leftrightarrow HgCl + OH \quad \text{(R6)}$$

$$HgCl + Cl \leftrightarrow HgCl_2 \quad \text{(R7)}$$

$$HgCl + Cl_2 \leftrightarrow HgCl_2 + Cl \quad \text{(R8)}$$

$$HgCl + HCl \leftrightarrow HgCl_2 + H \quad \text{(R9)}$$

$$HgCl + HOCl \leftrightarrow HgCl_2 + OH \quad \text{(R10)}$$

Reactions 1, 2, 4, and 7 are all unimolecular decomposition reactions in the reverse direction and are often writing in terms of a collision partner "M" on either side of the reaction. The collision partner is omitted here and as such the rate constants reported herein are in units of $cm^3\,mol\,s^{-1}$ for the forward directions and s^{-1} for the reverse directions. If the concentration of the collision partner is taken into account, the forward direction of the recombination reactions would have units of $cm^6\,mol^2\,s^{-1}$. The remaining reactions are classified as bimolecular with reported units of $cm^3\,mol\,s^{-1}$. A variety of quantum-mechanical-based approaches have been carried out to accurately predict the rate constants of R1–R10. As there are limited experimental data available for these reactions, especially at high temperature, the levels of theory employed have been benchmarked against available experimental structural and thermochemical data. A comparison of predicted to measured vibrational frequency and bond distance data is presented in Tables 24.1 and 24.2, respectively. The levels of theory considered in Tables 24.1 and 24.2 are based on previous high-level kinetics predictions that have relied on these combined methods and basis set choices. The methods that have resulted in the most accurate predictions include B3LYP, MP2, MP4, QCISD, QCISD(T), and CCSD(T), and have been used alongside a variety of basis sets. Owing to the large number of electrons in Hg [16], basis sets incorporating relativistic effects for the inner-core electrons are required. The work of Wilcox *et al*. on Hg oxidation via Cl-containing compounds has relied primarily upon two basis sets, that is, the "60VDZ" basis set of the Stevens *et al*. [17] group and the "60MDF" basis set of the Stuttgart [18] group. Both of these basis sets replace 60 of Hg's atomic core electrons with a relativistic effective core potential. The work of Krishnakumar and Helble [15] has relied upon the "SDD" basis set for Hg, which uses Stuttgart [18] pseodopotentials, in addition to the "CEP-121G" basis set, which uses pseodopotentials developed from the Stevens [17] group. For the non-Hg species, either the D95++(3df,3pd) or the Pople 6-311++G(3pd,3df) basis set was used. Both of these basis sets include diffused and polarization functions on the O, Cl, Br, and H atoms. For the prediction of Hg oxidation via Br-containing compounds, Wilcox and Okano [19] used the augmented correlation-consistent basis set developed by Peterson *et al*. [20, 21], termed *AVTZ*.

Table 24.1 Comparison between experimental and theoretical vibrational frequencies (cm^{-1}) for various mercury-containing compounds.

Molecular species	Vibrational frequency (cm^{-1})		Level of theory[a)]
	Experiment	Prediction	
HgCl	292.61 [22];	244.4	B3LYP/60VDZ
	298.97 [23]	280.6	QCISD(T)/SDD
		285.5	MP4/SDD
		290.3	QCISD/CEP-121G
		290.6	QCISD/60VDZ
		303.0	MP2/CEP-121G
HgBr	188.3 [24]	153.8	CCSD(T)/AVTZ
		162.7	B3LYP/60MDF
HgO	NA	390	QCISD(T)/60VDZ
$HgCl_2$ (symmetric stretch)	313–366 [25, 26]	318	B3LYP/60VDZ
		340	QCISD/60VDZ
(Bend)	100 [27]	92	B3LYP/60VDZ
		97	QCISD/60VDZ
(Asymmetric stretch)	376–413 [28]	374	B3LYP/60VDZ
		394	QCISD/60VDZ
$HgBr_2$ (symmetric stretch)	218–229 [29–32]	201	B3LYP/60MDF
		218	CCSD(T)/AVTZ
(Bend)	68 [27]	60	B3LYP/60MDF
		67	CCSD(T)/AVTZ
(Asymmetric stretch)	293 [33]	271	B3LYP/60MDF
		289	CCSD(T)/AVTZ

a) All predictions from Wilcox *et al.* [12–14, 19] with the exception of SDD and CEP-121G basis sets, which were sourced from Krishnakumar and Helble [15].

The predicted vibrational frequencies of the ground states of HgCl, HgBr, HgO, $HgCl_2$, and $HgBr_2$, have all been compared to experimental data, except in the case of HgO, in which experimental data was unavailable. There have been two experimental reports of the single vibrational mode of HgCl reported in the literature, that is, 292.61 [22] and 298.97 cm^{-1} [23] and a number of experimental investigations [25–28] on the vibrational modes of $HgCl_2$. From Table 24.1 it can be seen that the QCISD (CEP-121G, 60VDZ) and MP2/CEP-121G levels of theory agree best with experiment. In addition, the QCISD/60VDZ level of theory was also able to accurately predict the vibrational frequencies of $HgCl_2$. A number of experimental measurements [24, 27, 29–31, 33] have also been made on HgBr and $HgBr_2$, and a comparison of experiment to prediction shown in Table 24.1 indicates that the CCSD(T)/AVTZ level of theory is the most accurate.

Table 24.1 also includes a comparison of the predicted equilibrium bond distances to available measured data. Experimental measurements [34–36] of HgCl bond distances range from 2.23 to 2.50 Å. All of the levels of theory investigated predict bond distances within this range. The experimental bond distances [34, 38, 39] for $HgCl_2$ range from 2.25 to 2.44, and again, both levels of theory considered

Table 24.2 Comparison between experimental and theoretical bond lengths (Å) for various mercury-containing compounds.

Molecular species	Bond length (Å)		Level of theory[a)]
	Experiment	Prediction	
HgCl	2.23–2.50 [34–36]	2.40	MP4/SDD
		2.41	QCISD (CEP-121G; 60VDZ) QCISD(T)/SDD
		2.48	B3LYP/60VDZ
		2.49	MP2/CEP-121G
HgBr	2.62 [24]	2.62	B3LYP/60VDZ
		2.64	B3LYP/60MDF
		2.70	CCSD(T)/AVTZ
HgO	2.03 [37]	2.07	QCISD(T)/60VDZ
$HgCl_2$	2.25–2.44 [34, 38, 39]	2.30	QCISD/60VDZ
		2.32	B3LYP/60VDZ
$HgBr_2$	2.378 [40]	2.40	CCSD(T)/AVTZ
		2.46	B3LYP (60MDF; 60VDZ)

a) All predictions from Wilcox *et al.* [12–14, 19] with the exception of SDD and CEP-121G basis sets, which were sourced from Krishnakumar and Helble [15].

provide accurate predictions. The QCISD(T)/60VDZ level of theory predicts a bond distance of 2.07 Å for HgO, which agrees reasonably well with the experimental value [37] of 2.03 Å from X-ray diffraction measurements. The HgBr bond distance was measured by Tellinghuisen and Ashmore [24] using emissions spectra photography, with an estimated bond distance of 2.62 Å, which matches exactly with the predicted value from B3LYP/60VDZ. Experimental results of Deyanov *et al.* [40] yield an Hg–Br bond distance within the $HgBr_2$ molecule of 2.378 Å. In general, the CCSD(T)/AVTZ level of theory predicts both the HgBr and $HgBr_2$ geometries reasonably accurately, deviating from experiment by 0.08 and 0.03 Å, respectively.

In addition to the spectroscopic and structure comparison, the enthalpy changes of the reactions of interest have also been predicted and directly compared to available experimental data. Table 24.3 shows both thermochemical and kinetic parameter predictions along with available experimental estimates for reaction enthalpies. In particular, Reaction 1 has received a lot of attention because of the discrepancies reported in the literature and it has been established as the rate-determining step for homogeneous Hg oxidation. The rate constant has been measured experimentally by Donohoue *et al.* [41] using laser-induced fluorescence and by Horne *et al.* [42] using flash photolysis. An effective second-order rate constant of $4.57 \times 10^{11}\,cm^3\,mol\,s^{-1}$ was calculated by Donohoue *et al.* from their reported Arrhenius expression at 260 K and 1 atm. Similarly, the second-order rate constant reported by Horne *et al.* at 393 K and 1 atm is $1.95 \times 10^{13}\,cm^3\,mol\,s^{-1}$. There has been one quantum-based theoretic prediction for the rate constant of the forward recombination pathway of Reaction 1 by

Table 24.3 Comparison between thermochemical (reaction enthalpy) and kinetic (rate constant) parameters of mercury oxidation via chlorine-containing compounds over various levels of theory.

Reaction	*Thermochemistry*		*Kinetics*		Level of theory
	ΔH_{rxn} (kcal mol^{-1}) Experiment [38]	Prediction	A (cm^3 mol s^{-1}) Prediction	E_a (kcal mol^{-1})	
R1. $Hg + Cl \leftrightarrow HgCl$	−24.91	−25.41	2.34[a)][11]	2.12	MP2/CEP-121G [15]
Reverse R1: $HgCl \leftrightarrow Hg + Cl$	24.91	25.27	2.42[b)][8]	15.7	QCISD/60VDZ [14]
R2. $Hg + O \leftrightarrow HgO$	−4.00[43]; −8.92[44]; −13.97[39]; −64.22	−10.58	5.62[c)][5]	3.03	QCISD(T)/60VDZ [13]
R3. $Hg + Cl_2 \leftrightarrow HgCl + Cl$	33.07	31.79	6.15 [13]	43.3	B3LYP/60VDZ [12]
		33.00	4.52 [13]	35.9	QCISD/CEP-121G [15]
R4. $Hg + Cl_2 \leftrightarrow HgCl_2$	−51.63	−55.03	1.77 [5]	8.64	B3LYP/60MDF [13]
R5. $Hg + HCl \leftrightarrow HgCl + H$	78.24	79.00	1.93 [13]	93.3	B3LYP/60VDZ [12]
		79.99	2.76 [15]	79.7	QCISD(T)/SDD [15]
R6. $Hg + HOCl \leftrightarrow HgCl + OH$	31.21	29.65	3.06 [13]	36.6	B3LYP/60VDZ [12]
		30.69	2.69 [14]	31.8	QCISD(T)/SDD [15]
R7. $HgCl + Cl \leftrightarrow HgCl_2$	−82.70	−79.44	7.00[c)][11]	8.567	B3LYP/60MDF [13]
		−83.79	2.02[d)][10]	1.20	MP4/SDD [15]
R8. $HgCl + Cl_2 \leftrightarrow HgCl_2 + Cl$	−24.72	−24.32	1.43 [9] to 2.47 [10]	0	B3LYP/60MDF
		−24.33	5.18[e)][4]	−3.40	B3LYP/MDF60 [15]
R9. $HgCl + HCl \leftrightarrow HgCl_2 + H$	20.46	20.50	1.95 [9]	24.9	QCISD/60MDF [14]
		20.50	2.49 [13]	24.9	B3LYP/MHF60 [15]
R10. $HgCl + HOCl \leftrightarrow HgCl_2 + OH$	−26.60	−26.47	1.74 [9] to 3.48 [10]	0.5	B3LYP/60MDF
		−26.45	3.28[e)][5]	0.3	B3LYP/MDF60 [15]

a) Temperature-dependent rate expression is $k = AT e^{-E_a/RT}$.
b) Units of A are in per second.
c) Temperature-dependent rate expression is $k = A\left(\frac{T}{298}\right)^{-n}$, with n listed in the E_a column.
d) Temperature-dependent rate expression is $k = AT e^{-E_a/RT}$.
e) Temperature-dependent rate expression is $k = AT^{2.4} e^{-E_a/RT}$.
Numbers in parentheses represent powers of 10.

Krishnakumar and Helble [15] at the MP2/CEP-121G level of theory, which is 3.77×10^9 and 1.52×10^{10} cm^3 mol s^{-1} at 260 and 939 K, respectively. The reverse rate constant of Reaction 1 may be estimated on the basis of available experimental equilibrium constant as the equilibrium constant is equal to the ratio of the forward and reverse rate constants. The reverse unimolecular decomposition of HgCl was investigated by Wilcox *et al*. [14] at the QCISD/60DVZ level of theory with a prediction of 1.45×10^4 s^{-1}, compared to the experimentally calculated estimate of 4.31×10^3 s^{-1}, derived from the measurement of Horne *et al*. at 393 K and 1 atm. Both MP2/CEP-121G and QCISD/60VDZ levels of theory predict the heat of reaction for HgCl decomposition accurately to within 1 kcal mol^{-1}, as shown in Table 24.3.

For the HgO formation reaction (R2), both the forward and reverse rate constants have been predicted by Wilcox [13] at 1 atm and over a temperature range of 298–2000 K, with the kinetic parameters of the forward recombination reaction presented in Table 24.3. It is noted that the thermal decomposition temperature of mercuric oxide is 773 K. There are no experimental rate constant data to compare to, but the heat of reaction has been compared against previously reported theoretical and experimental estimates. Estimating the enthalpy of formation of HgO has received a great deal of attention in the literature, and this formation enthalpy is required for accurate estimation of the reaction enthalpy. Theoretical calculations [39, 43, 44] have reported enthalpies of formation ranging between 60.2 and 81.2 kcal mol^{-1}, with an experimental estimate [38] of 10 kcal mol^{-1}. The reaction enthalpy estimates are listed in Table 24.3 and range from −4.00 to −13.97 kcal mol^{-1} based on theory to −64.22 kcal mol^{-1} based on experiment. The QCISD(T)/60VDZ level of theory predicts an enthalpy of reaction of −10.58, which agrees well with previous estimates and was used to determine the temperature-dependent rate constant parameters at 1 atm. Both thermochemical and kinetic parameters are available in Table 24.3 for Reactions 3–10, with the details of comparison and calculation available in the original work of these previous studies. The goal of these fundamental gas-phase submodels is to provide kinetic data to global reaction models that would otherwise be deficient owing to the limited experimental data available over the flue-gas temperature range of interest.

Bench-scale simulated flue-gas experiments have been carried out by Fry *et al*. [45] and Cauch *et al*. [1] to accurately measure Hg oxidation as a function of quench rate. Fry *et al*. [45] carried out experiments to evaluate the effects of quench rate and quartz surface area on Hg oxidation and performed a detailed kinetic modeling analysis of homogeneous Hg oxidation reactions. In their system, Hg and Cl_2 are injected into a natural gas-fired premixed burner to produce a radical pool representative of real combustion systems and passed through a quenching section following the hot temperature region in the furnace as the quench rate of the flue gas can influence the extent of Hg oxidation. Two different temperature profiles were employed, producing quench rates of −210 and −440 K s^{-1}. The Hg concentration in the reactor was 25 μg m^{-3}, while Cl_2 concentrations ranged from 100 to 600 ppmv (equivalent HCl concentration).

At Cl_2 concentrations of 200 ppmv, the larger quench rate resulted in a 52% increase in Hg oxidation compared to the lower quench rate. On the basis of kinetic modeling of the post-flame chlorine species, it was assumed that the Cl_2 molecules are converted to Cl radical species as they pass through the flame and then are subsequently converted predominantly to HCl. When investigating the effect of surface area of the quartz reactor, a threefold increase in surface area resulted in a 19% decrease in Hg oxidation, which is explained by the chlorine radical termination at the surface. It was concluded that quartz surfaces do not catalyze Hg oxidation reactions, but inhibit them, and that these surface interactions are negligible.

Recent experimental results of Cauch *et al*. [1] have shown that previously reported homogeneous Hg oxidation in the presence of chlorine may be exaggerated because of bias when using wet-chemistry measurement techniques. Linak *et al*. [46] have shown that Cl_2, in a simulated flue gas in the absence of SO_2, creates a bias in the Ontario Hydro method and overpredicts the concentrations of oxidized Hg. It has been shown that as little as 1 ppmv Cl_2 is enough to create a bias of 10–20% in the amount of oxidized Hg captured in the KCl solution. Within this study, the bias was eliminated by adding SO_2 to the flue gas or adding sodium thiosulfate ($Na_2S_2O_3$) to the KCl impinger. Similarly, Ryan and Keeney [47], in an actual flue-gas environment, have demonstrated that 10 ppmv Cl_2 added to the flue gas without SO_2 results in 91.5% oxidized Hg, with a decrease to 39% when the KCl impingers are spiked with sodium thiosulfate. A simulation study has been carried out by Gharebaghi *et al*. [4, 5] using the results from the experiments of Cauch *et al*. [1] with the corrected conditioning system to test the performance of the fundamental homogeneous Hg oxidation kinetics. Simulation of Hg speciation was carried out using the PREMIX module of the CHEMKIN II software package [48]. The Arrhenius parameters for the model predictions were taken from a combination of sources, with Reactions 1, 3, 5–10 included in the model in particular. The experimental rate constant determined by Donohoue *et al*. [41] was used for Reaction 1, model predictions from Niksa *et al*. [49] were used for Reactions 3 and 7, and quantum-level theoretical predictions were provided from Wilcox *et al*. [12, 14] for Reactions 5, 6, 8–10. Additional supporting mechanisms include chlorine chemistry from Roesler *et al*. [50], C/H/O mechanism by Dreyer *et al*. [51], and the Leeds SO_x and NO_x mechanism [52], resulting in a global combustion model of 80 species and 361 reactions. Figure 24.1 shows the results of the simulation predictions and their comparison to the bench-scale experiments of Cauch *et al*. [1] The model provides reasonable agreement with the experimental data at the 440 K s^{-1} quench rate, but underpredicts the data at 210 K s^{-1}.

The experimentally derived activation energies and rate constants can have significant errors due to wall effects as well as uncertainties in the determination of mercury and its compounds down to parts per billion and lower levels in flue gas. Noting these potentially large experimental uncertainties introduced by heterogeneous chemistry occurring on the reactor walls, and the measurement uncertainties, the models appear to reasonably reflect the experimental data.

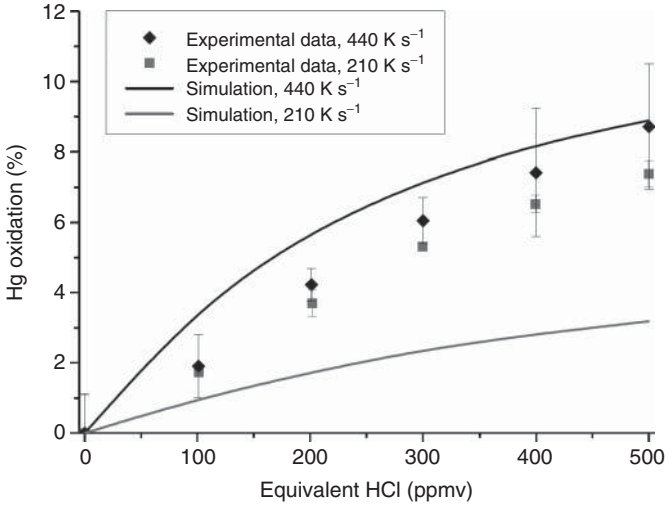

Figure 24.1 Error bars represent the standard deviation from analysis of multiple experiments.

24.2.2 Mercury–Bromine Chemistry

Significant attention has been paid to Hg oxidation via bromine, in addition to chlorine, because of the enhanced Hg oxidation kinetics of Br-containing compounds. Previous investigations report that bromine reacts faster than chlorine toward the production of $HgBr_2$. Similar to the Hg oxidation reactions involving Cl-containing species, Gharebaghi *et al.* [4] have also simulated Hg oxidation based on the following reactions:

$$Hg + Br \leftrightarrow HgBr \quad \text{(R11)}$$

$$Hg + Br_2 \leftrightarrow HgBr + Br \quad \text{(R12)}$$

$$Hg + HBr \leftrightarrow HgBr + H \quad \text{(R13)}$$

$$Hg + HOBr \leftrightarrow HgBr + OH \quad \text{(R14)}$$

$$HgBr + Br \leftrightarrow HgBr_2 \quad \text{(R15)}$$

$$HgBr + Br_2 \leftrightarrow HgBr_2 + Br \quad \text{(R16)}$$

$$HgBr + HBr \leftrightarrow HgBr_2 + H \quad \text{(R17)}$$

$$HgBr + HOBr \leftrightarrow HgBr_2 + OH \quad \text{(R18)}$$

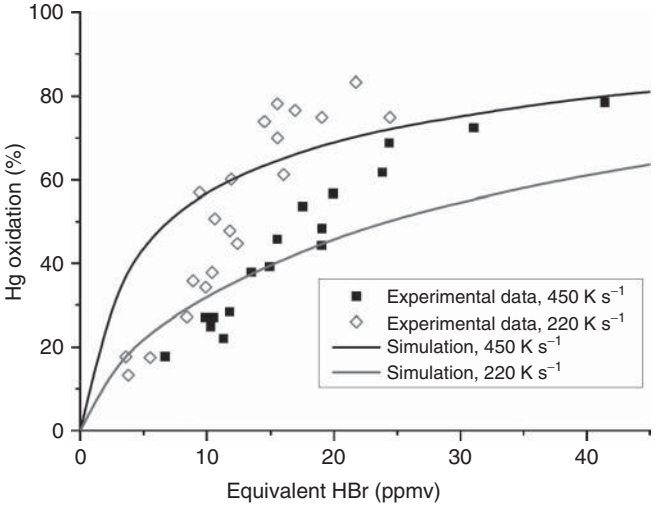

Figure 24.2 Comparison of measured and predicted Hg oxidation with HBr addition at two different reactor temperature quench rates [4].

Similar to the methodology previously discussed, Gharebaghi *et al*. [4] have used a variety of fundamentally derived rate parameters to simulate the global oxidation behavior of these reactions and have directly compared to experimental predictions of Cauch *et al*. [1], as shown in Figure 24.2. The rate parameters of Reaction 11 were taken from the experiments of Donohoue *et al*. [53] using laser-induced fluorescence, while the rate parameters of Reactions 14, 16, and 18 were taken from work carried out by Niksa *et al*. [54] The rate parameters for Reaction 15 was calculated from first principles by Goodsite *et al*. [55], while the parameters for Reactions 12, 13, and 17 were provided by Wilcox and Okano [19] and are based on first-principle quantum mechanical calculations. Table 24.4 provides a fairly complete list of thermochemical and kinetic parameters associated with 8 of the 10 Hg–Br reactions of interest. In previous work, Wilcox and Okano [19] compared their predicted rate data of Reactions 11, 12, and 15 to available experimental [53, 56] and theoretical [55–60] data in the literature. In particular, the theoretical rate constant prediction of 3.84×10^{11} cm^3 mol s^{-1} at the CCSD(T)/AVTZ level of theory for the forward direction of Reaction 11 agrees well with other theoretical [56–59] (ranging between 1.80×10^{11} and 1.92×10^{12} cm^3 mol s^{-1}) and experimental [53] (ranging between 1.08×10^{11} and 3.25×10^{11} cm^3 mol s^{-1}) estimates at 298 K and 1 atm. In addition, for Reaction 12, the theoretical rate constant prediction of 9.9×10^{-8} cm^3 mol s^{-1} at the B3LYP/60VDZ level of theory for the forward direction agrees well with a slight underprediction compared to other theoretical calculations [60], which range between 1.96×10^{-7} and 3.25×10^{-7} cm^3 mol s^{-1} at 298 K and 1 atm. Additional details are available in the manuscript of Wilcox and Okano [19].

Table 24.4 Comparison between thermochemical (reaction enthalpy) and kinetic (rate constant) parameters of mercury oxidation via bromine-containing compounds over various levels of theory.

Reaction	*Thermochemistry*		*Kinetics*		Level of theory [19]
	ΔH_{rxn} (kcal mol^{-1})		A (cm^3 mol s^{-1})	E_a (kcal mol^{-1})	
	Experiment [38]	Prediction	Prediction		
R11. Hg + Br ↔ HgBr	−16.51	−16.72	2.00[a)][12]	1.91	B3LYP/60VDZ
		−15.74	4.00[a)][11]	0.85	CCSD(T)/AVTZ
R12. Hg + Br_2 ↔ HgBr + Br	29.56	28.83	9.76 [14]	26.49	B3LYP/60VDZ
		31.59	1.15 [15]	30.08	CCSD(T)/AVTZ
R13. Hg + HBr ↔ HgBr + H	70.95	67.69	1.86 [13]	71.58	B3LYP/60VDZ
R15. HgBr + Br ↔ $HgBr_2$	−72.02	−71.94	2.00[a)][12]	9.18	CCSD(T)/AVTZ
		−70.13	8.00[a)][10]	7.644	B3LYP/60MDF
R16. HgBr + Br_2 ↔ $HgBr_2$ + Br	−25.95	−24.61	4.02 [11]	0.87	CCSD(T)/AVTZ
R17. HgBr + HBr ↔ $HgBr_2$ + H	15.44	14.28	9.41 [12]	18.68	B3LYP/60MDF

a) Temperature-dependent rate expression is $k = A\left(\frac{T}{298}\right)^{-n}$ with n listed in the E_a column.
Numbers in parentheses represent powers of 10.

The concentration of equivalent HBr was varied between 0 and 45 ppmv compared to a range of 0–500 ppmv of equivalent HCl as HBr dissociates more readily than HCl, resulting in a greater quantity of Br radicals for Hg oxidation. The homogeneous Hg oxidation model via bromine predicts that oxidation begins at a higher temperature than in the case of chlorine, at approximately 1100 K compared to 800 K (chlorine). The simulated results are in reasonable agreement with experiment for the 450 K s^{-1} quench rate above 25 ppmv equivalent HBr, but overestimate oxidation at lower concentrations. On the other hand, for the 220 K s^{-1} quench rate, the simulations underpredict oxidation at high temperature and show reasonable agreement at concentrations less than 10 ppmv equivalent HBr. Owing to the disagreement between the simulation predictions and experiments, it is clear that additional work is still required in this area. It is also noted that there is substantial uncertainty in the experimentally derived kinetic parameters.

From these previous combined modeling-experimental studies it is clear that homogeneous Hg oxidation is only one aspect of the complete mechanism in the complex flue-gas environment. In reality, surfaces are present in the form of unburned carbon, which may serve to both adsorb and oxidize Hg. Oxidized Hg may be captured in existing downstream wet FGD units and Hg^p may be captured via ESPs or FFs. Therefore, understanding the mechanism of Hg reactivity across carbon surfaces is imperative to its effective control.

24.3
Heterogeneous Chemistry

24.3.1
Mercury Adsorption on Activated Carbon

AC has been extensively tested in laboratory- and full-scale systems and has shown the capacity to capture both elemental and oxidized Hg in coal combustion flue gas. A relatively large amount of AC injection is required for the control of Hg from subbituminous-coal- or lignite-combustion flue gas. Depending on the system conditions, an AC-to-mercury mass ratio of at least 3000–20 000 (C/Hg) may be necessary to achieve 90% Hg removal [61–63]. Currently, the design of more effective Hg capture technology is limited by incomplete understanding of the mechanism(s) of Hg oxidation and adsorption on carbon surfaces [64].

The development of accurate fundamental models for Hg–AC reactivity requires careful characterization experiments on materials exposed to well-controlled reaction conditions. Therefore, an overview of such experiments will be discussed before the theoretical model efforts. It is generally accepted that acidic sites on the surface are responsible for elemental Hg capture on AC [65, 66]. In its atomic state, Hg acts as a base in that it has the propensity to oxidize (i.e., donates electrons to a surface or another gas-phase molecule); therefore, Hg will readily interact with acidic sites on the carbon surface. However, once oxidized, and thus acidic in nature, Hg species are thought to compete with acidic gases for the basic sites available on the carbon surface.

The presence of halogens (i.e., bromine, chlorine, and iodine) promotes Hg oxidation on carbon surfaces [66, 67]. Subsequently, AC demonstrates higher Hg removal performance in the flue gas of coals with greater chlorine content, as the combustion of such coal results in a higher concentration of HCl in the flue gas. Hutson *et al*. [68] exposed brominated and chlorinated AC to Hg-laden simulated flue gas and characterized the sorbents using X-ray absorption spectroscopy (XAS) and X-ray photoelectron spectroscopy (XPS). Within this work no evidence was found for homogeneous oxidation of Hg, and no Hg was found present on the AC surface; however, oxidized Hg was found on the surface, present as a chlorinated or brominated species. It is important to note that owing to the low coverage of Hg on the carbon, the speciation of Hg was not determined. Given the results, the authors proposed Hg capture on chlorinated and brominated carbons occurs via surface oxidation of Hg with subsequent adsorption on the carbon surface. Similar to its role in homogeneous Hg oxidation, bromine is thought to have a stronger promotional effect on Hg oxidation/adsorption, but the reason for the difference between bromine and chlorine is not well understood. Recently, the Hg oxidation was demonstrated on a wood-derived Cl-promoted AC in both N_2 and flue gas [69]. The adsorption of Hg on AC was shown to be a chemisorption process, where all Hg was oxidized to Hg^{2+} on the surface as a result of chlorine promotion. While chlorine was consumed, Hg^{2+} was still noted as being present in the outlet gas, indicating that the AC was also capable of catalyzing Hg oxidation.

Huggins *et al*. [70] characterized AC samples after testing in Hg-laden simulated flue-gas conditions using X-ray absorption fine structure (XAFS) spectroscopy. The XAFS results revealed that chlorine and sulfur are adsorbed on the AC surface after exposure to HCl and SO_2, and Hg-anion chemical bonds are formed in the sorbent materials. They suggest that the acidic flue-gas species (e.g., HCl, HNO_3, H_2SO_4) promote the creation of active sites for Hg chemisorption on the carbon surface, and that an oxidation process, either in the gas phase or simultaneously as the Hg atom interacts with the sorbents, is involved in the capture of Hg. Olson *et al*. [66] performed fixed-bed tests with various gas conditions for Hg and $HgCl_2$ adsorption on AC and found that the presence of both HCl and NO_2 reduced the induction period of Hg oxidation, and that in general acid flue-gas components significantly impacted the adsorption of oxidized Hg species. The formation and presence of the oxidized form, $Hg(NO_3)_2$, was observed in the effluent gas in the presence of NO_2, but in the absence of HCl. Laumb *et al*. [71] carried out surface analyses using XPS on ACs exposed to Hg-laden simulated flue gas (e.g., SO_2, NO_2, HCl, H_2O), but were unable to determine the oxidative state of surface-bound Hg due to interference with silicon (Si), which is present at comparable levels to Hg within the carbon matrix. Wilcox *et al*. [72] investigated the binding mechanism of Hg on brominated AC sorbents with a combination of XPS and theoretical modeling. It was found that Hg exists in the oxidized forms on brominated carbon surfaces, as shown in Figure 24.3.

Ab initio electronic structure investigations based on density functional theory (DFT) have been conducted to elucidate the interaction of Hg with AC, using simplified carbon models to represent AC. There have been a limited number of theoretical investigations, and, to the authors' knowledge, the effect of acid flue-gas species on Hg-AC interactions has not been investigated. AC is very difficult to model given its highly inhomogeneous structure. Several initial theoretical investigations have been conducted using cluster models to represent graphene, ranging from single benzene rings [73] to multiple fused rings [74] with embedded halogens as shown in Figure 24.4.

Carbon with Cl-containing functional groups exhibits enhanced Hg adsorption capacity. Furthermore, the most stable Hg surface species was HgCl, while Hg and $HgCl_2$ were found to be thermodynamically unstable on these simplified surfaces of AC [74]. Theoretical calculations by Olson *et al*. [76] supported the role of acidic sites on the AC in Hg capture. They hypothesized that HCl is energetically stable at the cationic zigzag edge sites of AC and proposed three possible models of Hg oxidation:

1) Hg charge transfer complex forms on the cationic center of HCl on AC and is subsequently attacked by Cl^-,
2) elemental Hg interacts simultaneously with the cationic HCl-AC site and Cl^-, or
3) oxidation by the dictation site formed by HCl and NO_2 on AC.

Olsen *et al*. [76] suggested that Hg has the propensity to be oxidized by donating its electrons to a surface or another gas-phase molecule; therefore, in its elemental

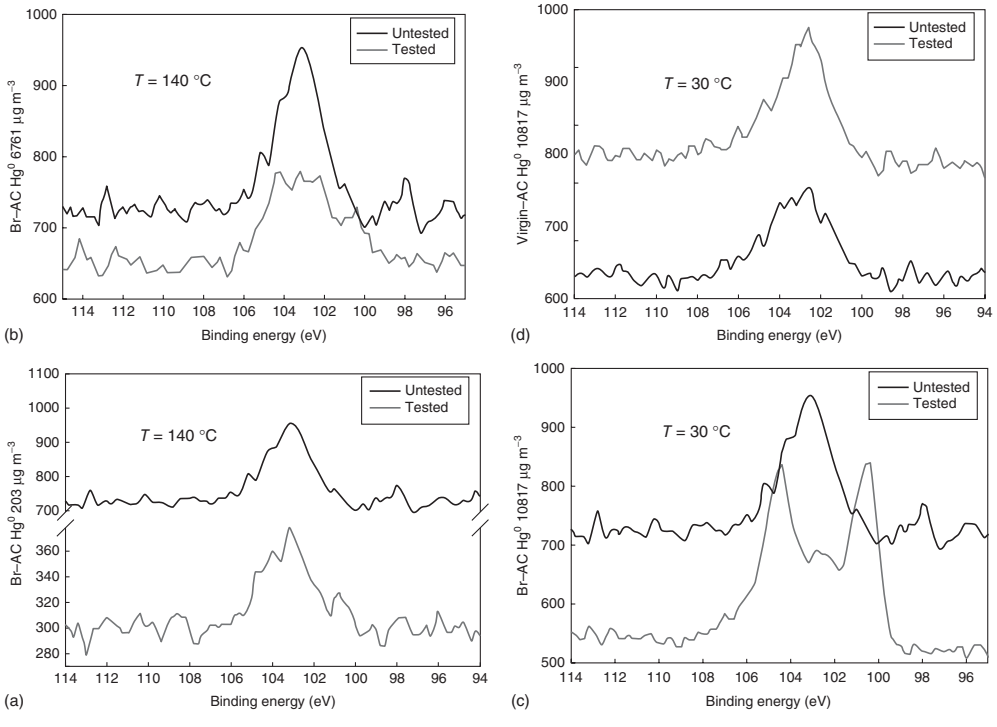

Figure 24.3 Hg 4f core level XPS spectra for activated carbon sorbents at various indicated conditions; (a–c) brominated AC sorbents and (d) virgin AC sorbent [72]. (Reprinted with permission from (Wilcox et al., J Air & Waste Manag. Assoc., 61(4), 418, 2011). Copyright (2011) Taylor & Francis.)

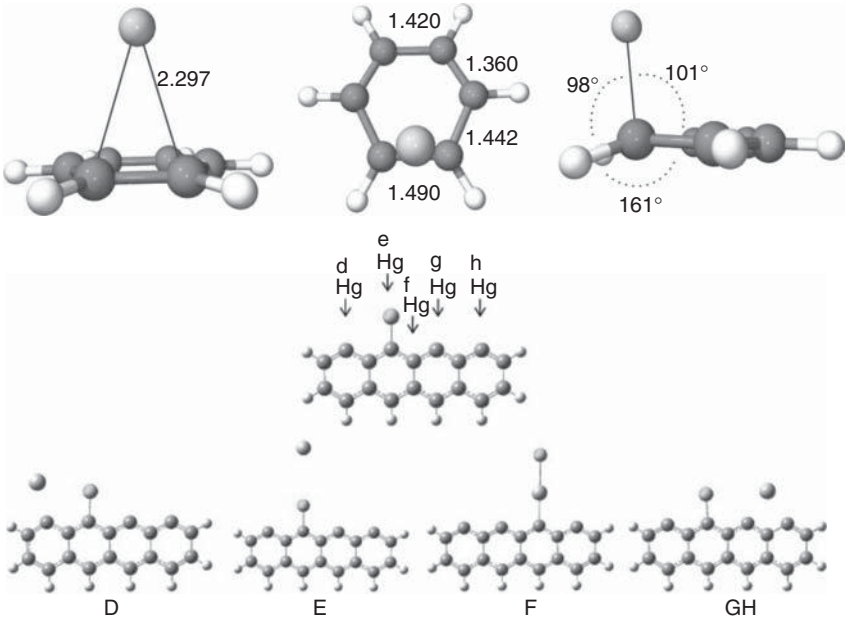

Figure 24.4 Hg–benzene complex investigated at the MP2/AVDZ level of theory (top) [73] (reprinted with permission from (Steckel, Chem. Phys. Lett., 409, 322, 2005). Copyright (2005) Elsevier.) and Hg-halogenated fused rings calculated at the B3LYP/LANL2DZ level of theory (bottom) [75]. (reprinted with permission from (Padak et al., Carbon, 47(12), 2855, 2009). Copyright (2009) Elsevier.)

state, Hg acts as a Lewis base with the desire to interact with an acidic site, thereby forming a strong C–Hg covalent bond on the carbon surface.

More recent investigations have used plane-wave DFT to model AC, which allows for the use of periodic systems such as a graphene. Graphene ribbons with exposed edge sites have been used for investigations of the reactivity of carbonaceous surfaces to various gas species [77]. Several investigations support the zigzag carbene structure model, where the zigzag edge site acts as a Lewis base and reacts with acid gas components thereby serving as a potential adsorption site for oxidized Hg [77, 78]. A recent DFT study [79] on the effect of chemical functional groups on Hg adsorption on carbon surfaces supports this suggestion. The study indicates that an embedded halogen atom promotes chemisorption on the neighboring site, which is consistent with experimental results, and indicative of Hg oxidation. Results also indicate a varying effect of organic groups on Hg adsorption, with lactone, carbonyl, and semiquinone groups promoting Hg chemisorption while phenol and carboxyl functional groups promote physisorption and reduce overall Hg capture. A mechanistic study of Hg oxidation due to halides on carbon materials proposes that the interactions of microcrystalline graphitic structures with halide ions result in the withdrawal of electrons from the graphitic structure, producing a strong Lewis

acid site [80], with Hg adsorption combined with the electron-transfer results in Hg oxidation.

To date, little work has been conducted on the effect of Br on Hg-AC interactions. Wilcox *et al*. [72] investigated the binding mechanism of Hg on brominated AC sorbents with a combination of experimental work, as discussed previously, and quantum-mechanical modeling using a nine-benzene-rings-wide graphene ribbon. Consistent with Padak and Wilcox's [75] results for Hg adsorption in the presence of chlorine, it was found that HgBr species are more stable on the carbon surface than $HgBr_2$ species. Furthermore, DFT and density of states (DOSs) calculations indicate that Hg is more stable when it is bound to the edge C atom interacting with a single Br atom bound atop of Hg. However, while the form of Hg adsorbed on the AC surface may be oxidized, the exact speciation of the adsorbed Hg is remains in question. Furthermore, the Hg adsorption mechanism on the carbon surface and the effects of the flue-gas components are not well understood. Additional work, including closely coupled experimental and theoretical investigations, is required to determine the binding mechanism of Hg on AC sorbents in various flue-gas environments and to further elucidate the adsorption mechanism of Hg on AC.

24.3.2 Mercury Adsorption on Precious Metals

In general, precious metal adsorption of Hg has been applied to Hg capture from fuel gases of coal gasification processes as these metals, in contrast to carbon-based sorbents, may withstand the high temperatures of gasification processes. For gasification applications, the product is termed a *fuel gas*, and consists primarily of H_2, CO_2, and CO, while in the case of traditional coal combustion, the exhaust gas is termed a *flue gas* and is comprised primarily of N_2 and CO_2.

Precious metals, including palladium (Pd), platinum (Pt), gold (Au), iridium (Ir), and rhodium (Rh), have traditionally been used as modifiers for graphite-tube atomic absorption or emission analysis of solid and liquid samples. Among them, Pd has been identified as the best modifier for the adsorption of Hg [16]. In a study carried out by Steckel [81], DFT is used to carry out electronic structure calculations on slab models representing the (001) and (111) surfaces of silver (Ag), Au, copper (Cu), nickel (Ni), Pd, and Pt. Relatively strong binding for all of the metals was noted, with binding energies of ~1 eV for Pt and Pd. However, the DFT method used appears to underestimate the adsorption energy when compared directly to experimental results. Mercury has been predicted to have a stronger bond with the (001) surface, where fourfold hollow sites exist, in contrast to the threefold hollow sites on (111) surfaces. Aboud *et al*. [82] performed a DFT study of Pd alloyed with small amounts Au, Ag, and Cu and found that doping of the Pd surface increased the overall binding energy of Hg, which is beneficial for a sorption process. Furthermore, the binding energy increased the most when the dopants remained subsurface. In a continuation of the work, Sasmaz *et al*. [83] showed that Pd is primarily responsible for interacting with Hg in both alloys and

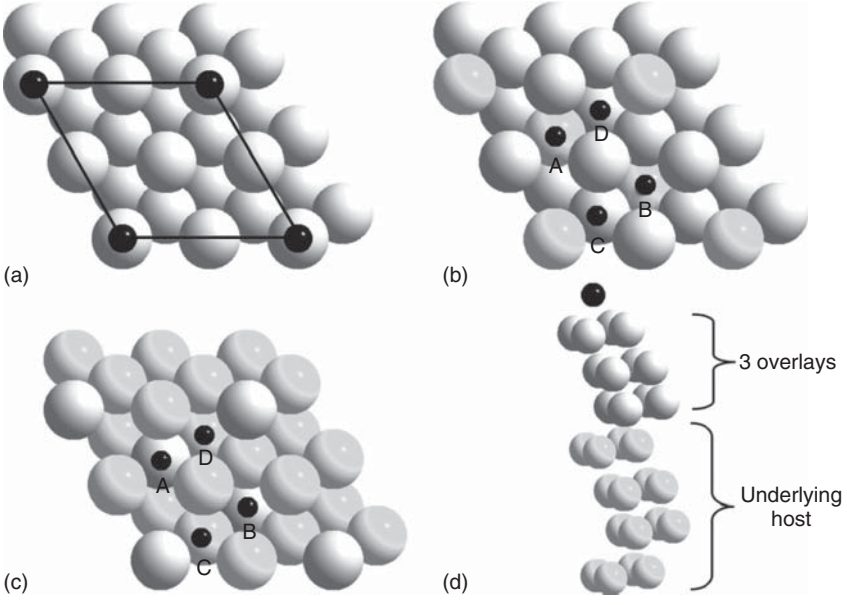

Figure 24.5 (a) Scheme of a supercell of (111) surfaces. (b) Threefold adsorption sites of Pd_3M binary alloys: (A) pure-hexagonal close packed (hcp) site, (B) pure-face-centered cubic (fcc) site, (C) mixed-hcp site, and (D) mixed-fcc site. (c) Threefold adsorption sites of PdM_3 binary alloys: (A) pure-hcp site, (B) pure-fcc site, (C) mixed-hcp site, and (D) mixed-fcc site. (d) Side view of 3Pd/M(111) structure [83]. (Reprinted with permission from (Sasmaz, et al., J. Phys. Chem. C, 113, 7813, 2009). Copyright (2009) American Chemical Society.)

overlays and that the interaction is a result of overlap between the s- and p-states of Pd and the d-state of Hg. Figure 24.5 shows various adsorption sites of Hg on binary alloys and overlays of Pd with other metals, M, such that M represents either gold, silver, or copper.

Jain *et al*. [84] theoretically screened potential high-temperature metal sorbents for Hg capture in syngas streams. Using DFT predictions, the enthalpy of amalgamation and oxidation for metals was evaluated to predict the capability of Hg sorption and oxidation in the gas stream, demonstrating that Pd has the highest amalgamation enthalpy of all metals. Figure 24.6 shows the Hg amalgam formation enthalpy versus the binary oxide formation enthalpy to clarify the tendency of various metals for amalgamation and oxidation. Metals above the O_2 gas chemical potential line (i.e., dashed horizontal line) are estimated to form oxides and metals to the right of the Hg gas chemical potential (i.e., dashed vertical line) are estimated to form amalgams in the syngas stream. Metals satisfying both criteria (i.e., Section (II) in Figure 24.6) were found to form oxides rather than amalgams according to the grand canonical potential predictions. An ideal metal, which amalgamates without oxidizing, is located in Section (IV) of Figure 24.6. No metals are available in the most desirable area, but Pd is the closest to the area, indicating that Pd is the most promising metal for Hg capture.

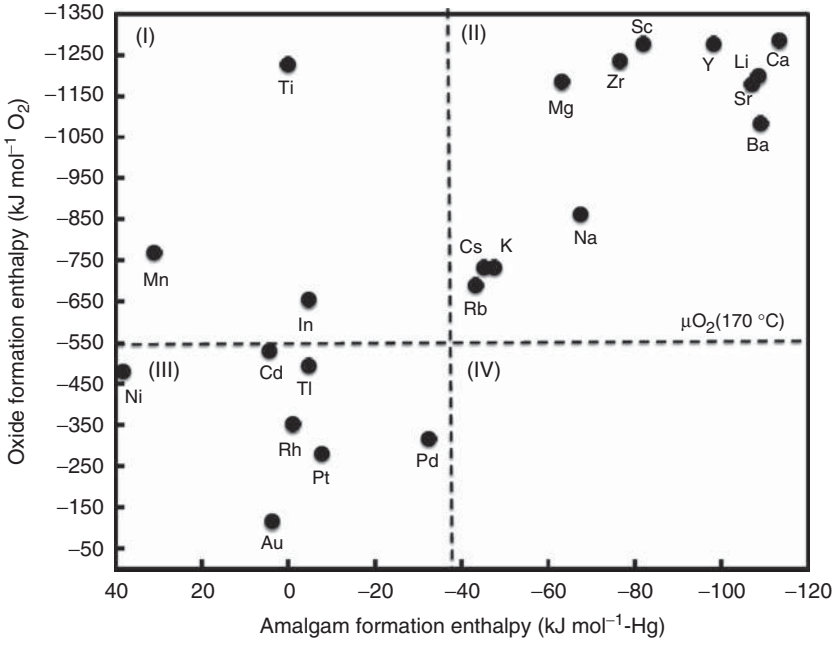

Figure 24.6 Estimated amalgam formation enthalpies of binary Hg amalgam versus binary oxide, normalized per mol of Hg and per mol of O_2, respectively. Dashed horizontal and vertical lines represent the O_2 gas and Hg gas chemical potentials, respectively [84]. (Reprinted with permission from (Jain et al., Chem. Eng. Sci., 65, 3025,2010). Copyright (2010) Elsevier.)

Earlier experiments have validated the mechanisms of reactivity proposed by theory. For example, Baltrus *et al*. [85, 86] showed some evidence of Hg amalgamation on Pd/Al_2O_3. Maximum Hg adsorption on Pd/Al_2O_3 occurs at 204 °C and at low loadings of Pd (<8.5 wt% Pd). An interesting finding is that Hg adsorption is suppressed by an excess of As; however, H_2S in fuel gas can improve this imbalance by moderately inhibiting the As adsorption while enhancing the Hg adsorption [86]. Poulston *et al*. [87] compared the Hg removal capacities of Pd and Pt sorbents supported on alumina and found that Pd is superior to Pt sorbents for Hg removal. This trend is supported by Figure 24.5, which indicates that Pt is located farther from the Section (IV) than Pd. The Hg removal capacity of both Pd and Pt sorbents increase with metal loading but decreases with sorbent temperature. Although most metal sorbent candidates exhibit poor capacities for Hg at temperatures greater than 204 °C, Pd proves to be an attractive sorbent for the Hg removal at elevated temperatures [16]. Fuel-gas substances that may affect the Hg adsorption on metal sorbents may include moisture, H_2S, CO, and H_2 [16]. Baldeck *et al*. [88] presented data on the use of Au traps for the quantitative fuel-gas separation of Hg in the form of an amalgam of Au_2Hg_3. It was suggested that Hg removal on Au is not affected by corrosive substances such as SO_2, H_2S, and organic compounds that may be present in flue gas.

24.4
Conclusions and Future Work

Atomistic modeling efforts have resulted in important insight into the homogeneous and heterogeneous mercury chemistry in power plant flue gases. Future work may focus upon the heterogeneous chemistry of mercury on common fly ash metal oxides, the ductwork walls within the power plants, and the SCR catalysts employed for reduction of NO*x*. Recent and past works [62, 89, 90] hint at a possible important role for iodine and its compounds for promoting the oxidation of mercury in flue gas. It is suggested that further work is merited on the halogens, including both the heterogeneous chemistry on carbon, as well as the gas phase chemistry involving chlorine, bromine, and iodine species.

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25
Predicting Hg Emissions Rates with Device-Level Models and Reaction Mechanisms

Stephen Niksa and Balaji Krishnakumar

25.1
Introduction and Scope

At the turn of the past century, the American utility industry needed to demonstrate which Hg control technologies could be immediately deployed to comply with impending regulations on Hg emissions from coal-fired power plants. This imperative was confounded by the large number of factors that affected Hg emissions, because even Environmental Protection Agency's (EPAs) first Information Collection Request (ICR) testing program had shown that fuel quality, the configuration of units in the gas cleaning system, and numerous gas cleaning conditions affected Hg speciation; hence, the prospects for controlling Hg emissions.

While the bulk of the R&D community was compiling a database of field test measurements that covered the most common fuels, unit configurations, cleaning conditions, and external Hg controls, a small group set out to develop reaction mechanisms and models that could, first, quantitatively interpret the field test database and, ultimately, predict Hg emissions for a particular gas cleaning system as accurately as the Hg speciation could be monitored. Statistical approaches based on regressions of various types of test data never achieved the accuracy needed for strategic compliance planning [1–4]. But some of the approaches based on reaction mechanisms did, and are now being used by both utility companies and original equipment manufacturers to forecast Hg emissions at individual plants and across regional fleets of power stations.

Our collection of reaction mechanisms, called *MercuRator*™ in its commercial implementation, is the basis for this survey of reaction mechanisms that can accurately predict Hg emissions across the entire domain of commercial gas cleaning conditions. Over two dozen previously published articles [5] have evaluated the quantitative accuracy of the model predictions for an assortment of gas cleaning situations, to demonstrate the predictive capabilities. In total, more than 200 field test datasets have been quantitatively interpreted, usually within measurement uncertainties. Here we simply acknowledge that

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MercuRator™ predicts Hg emissions within the measurement uncertainties for any coal in any cleaning configuration across the commercial domain of gas cleaning conditions and, on the basis of that performance, use the mechanisms to assess the most important factors in the practice of Hg emissions control.

25.2 The Reaction System

Our scope covers the properties, compositions, quantities, and operating conditions needed to predict Hg speciation and removals along full-scale flue gas cleaning systems. Pilot-scale gas cleaning systems are also relevant, although the primary reaction systems of interest are commercial. The most important consideration is the distribution of Hg species at all points along the cleaning system; the so-called Hg speciation. Hg vapors are grouped into two forms, elemental (Hg^0) and oxidized (Hg^{2+}), while a single species, particulate Hg (Hg_p), is bound to the unburned carbon (UBC) in fly ash or to injected carbon sorbents. Speciation is crucial to Hg emissions control because Hg^{2+} is completely soluble in flue gas desulfurization (FGD) scrubber solutions (neglecting any reemission of Hg^0 from the FGD solution), whereas Hg^0 is completely insoluble, and Hg_p is removed in any particle collection device (PCD) in proportion to the collection efficiency for UBC, which usually approaches 100%. Consequently, in cleaning systems that effectively capture Hg^{2+} in wet flue gas desulfurization (WFGD) and Hg_p in an electrostatic precipitator (ESP) or fabric (or baghouse) filter (FF), nearly all the Hg leaving the stack will be Hg^0. But in systems without an FGD, the Hg stack emissions will be a mixture of Hg^0 and Hg^{2+} species. Contributions to the stack emissions from Hg_p are almost always negligible for plants with PCDs.

The power plant is first subdivided into a furnace and a gas cleaning system, which are connected at the furnace exit plane upstream of the economizer (ECN). The gas cleaning system is a continuous series of heat exchangers and air pollution control devices (APCDs). Most systems move the flue gas through an ECN into a selective catalytic reduction (SCR) unit, if present; through an air preheater (APH) into a PCD, which is usually a cold-side electrostatic precipitator (ESPc) or FF or mechanical or venturi particle scrubber; and on through a WFGD, if present, and into the stack. One popular variation uses lime injected into a spray drier absorber (SDA) to remove SO_X followed by a FF to recover particulates. Another variation locates the ESP immediately downstream of the ECN (hot-side electrostatic precipitator (ESPh)), and may or may not have a FF downstream of the APH. The gas cleaning configuration is the sequence of units in the cleaning system. Ductwork that connects these units is apportioned to the adjacent units.

The two forms of Hg control are inherent and external. Inherent controls rely on the Hg transformations (and capture) within APCDs primarily devoted to controlling other pollutants, such as an SCR for $deNO_X$ and WFGD and SDA for $deSO_X$. External Hg controls are technologies added to a power plant

specifically to control Hg emissions. The most popular examples are (i) activated carbon injection (ACI) with conventional or brominated carbon sorbents; (ii) addition of halogenation agents to supplement the concentrations of either Cl or Br species in the flue gas; and (iii) additives to WFGDs to ensure that dissolved Hg(II) species are not reemitted into the flue gas as Hg^0. Numerous other control strategies are being developed, including dedicated Hg oxidation units upstream of WFGDs when no SCR is present and various non-carbon sorbents. These are beyond the scope of this article because they are not yet commercially important. Fuel preprocessing to reduce the Hg content, either with froth flotation or density classification schemes or with thermal treatments, are also beyond our scope on the assumption that the Hg content and composition of the fuel fed into a furnace must always be known in advance to forecast the Hg stack emissions.

We assume that flow through the ductwork and heat exchangers in a cleaning system is fully developed and turbulent, so that the concentrations of all flue gas species may be analyzed in a single spatial dimension or in the transit time. Mixing is more important wherever sorbents or halogenation agents are injected into the flow, although the applications community generally appreciates the importance of uniform dispersion of Hg control agents over the flow duct area (notwithstanding several early injector design issues). In contrast, the flows through the channels in an SCR monolith are laminar, by design, as are the flows through the plate spacings within ESPs.

Early analytical work established that the Hg speciation at equilibrium should become dominated by sulfates in the condensed phase at PCD operating temperatures, but these species have never been detected. Instead, measured Hg speciation spans the full gamut from negligible to predominant Hg_p at the PCD, along with negligible to predominant levels of Hg^0 or Hg^{2+}, depending on numerous parametric factors. So equilibrium compositions are irrelevant to Hg emissions prediction. Consequently, our analytical framework will be a time-dependent analysis governed by the chemical reaction kinetics. Such an analysis can only be implemented if supported by an assortment of operating conditions, each specified as a function of the transit time. The most important is the thermal history, which is the mean flue gas temperature as a function of transit time. As seen subsequently, it consists of a series of quench stages for each heat exchanger interrupted by isothermal stages for the SCR, PCD, and WFGD. To incorporate realistic chemical reaction mechanisms, the flue gas composition based on all major species (O_2, H_2O, CO_2, N_2) must be specified, along with several key minor species concentrations (NO, SO_2, SO_3, HCl, total Br, and total Hg). The fly ash loading and its variation in transit time (due to the variable gas density along the quench cycle) must be specified. The UBC level in fly ash is estimated from a measured loss-on-ignition (LOI) level. The UBC specific surface area, in square meters per gram, is also required. Note that the total surface area (and activation) of UBC varies in transit time because the fly ash loading changes, even while LOI and the specific surface area stay the same as the fly ash moves through the cleaning system. Despite many claims to the

contrary in older literature, the participation of any of the mineral phases in fly ash in Hg transformations has never been demonstrated, so we regard UBC as the only reaction substrate in the fly ash. Many other pertinent APCD-specific operating conditions are introduced later, when the Hg transformations through each unit are described.

25.3 Hg Transformations

The following four distinct stages of Hg transformations must be characterized: in-furnace, in-flight, along SCR catalysts, and within WFGDs and SDAs. The in-furnace transformations are rudimentary for Hg, but also cover several much more subtle connections among the ways that pulverized fuels (p.f.s) are injected into furnaces and subsequent Hg conversion throughout gas cleaning systems. In-flight Hg transformations are determined by chemistry in the flue gas stream as it moves through the heat exchangers, ductwork, and PCDs in a cleaning system. The governing chemistry comes in two forms: heterogeneous Hg chemistry occurs via the interaction of select flue gas species and reaction sites on the suspended UBC and sorbent particles in the flow, and on UBC and sorbent deposits on the walls of heat exchangers and, perhaps, ESPs. Homogeneous Hg chemistry involves only gaseous species in the flue gas, with no participation whatsoever by UBC, minerals, or deposits. Transformations along SCR catalysts are restricted to the oxidation of Hg^0 into Hg^{2+} on sites on the promoted V_2O_5 catalysts. However, this Hg^0 oxidation can only be described as an element of a more comprehensive analysis that also describes simultaneous NO reduction, due to essential aspects of a competitive adsorption among NH_3 and the species associated with Hg^0 oxidation. The transformations within WFGDs determine whether any of the aqueous Hg(II) species can be reemitted as Hg^0 into the flue gas and thereby diminish the Hg removal across these units. Each form of the Hg transformations is characterized in turn in succeeding sections.

25.3.1 In-Furnace Transformations

Here we restrict our attention to large utility furnaces fed with whole coals or coal blends in the p.f. size grade. Stoker furnaces, fluidized bed combustors (FBCs), and circulating fluidized bed combustors (CFBCs) are beyond our scope. No chemistry needs to be described in detail within the furnace, because essentially all the Hg and halogens in the fuel are released into the flue gas as vapors, and none of the vapors are scavenged by molten minerals upstream of the furnace exit. Even when pyrite – the densest mineral, by far, which is usually present as extraneous particles – is recovered as bottom ash, it is first heated sufficiently to release its Hg into the flue gas. Similarly, all the Cl and Br in the fuel are released into the flue gas at hundreds of degrees below the

maximum flame temperatures. Chlorine may be incorporated into $CaCl_2$ within molten mineral mixtures with certain low-rank coals and with certain subbituminous/bituminous blends. But, even so, this is always a relatively minor phase that usually sequesters only a small portion of the available Cl, except with some low-rank fuels that have very little inherent Cl to begin with as well as favorable mineral compositions.

On the basis of these observations, the initial condition for the kinetic analysis is the equilibrium flue gas composition at the furnace exit gas temperature (of approximately 1050 °C). To evaluate the equilibrium composition, a furnace stoichiometry is first assigned to match a specified O_2 level in the flue gas at the ECN or, more directly, from specified flow rates for fuel and all the air streams. Such an equilibrium composition cannot accurately estimate the levels of NO, CO, or SO_3 in the flue gas, because the NO and CO concentrations are determined by extremely complex chemistry in the furnace. To circumvent an ambiguous analysis, we stipulate the NO concentration at the ECN as an input parameter. The SO_3 concentration could also be specified as an input parameter but, because it is usually unknown, we use a detailed reaction mechanism in 134 steps that also accounts for heterogeneous production on the Fe-oxides in fly ash and across SCR catalysts [6]. At the furnace exit, all coal-Hg will be present as Hg^0. This equivalence determines the total Hg inventory, which is the Hg concentration that all measured speciation components must sum to, accounting for any Hg removed in downstream APCDs. In practice, there are often very large discrepancies among the estimates based on coal-Hg and summed measured speciation components, because it is always difficult to recover fuel samples that actually represent the fuel properties being converted while the Hg speciation data were recorded. The Cl-species at the furnace exit are completely dominated by HCl, as the concentration of Cl-atoms is on the order of tens of parts per billion and that of Cl_2 is even smaller. But when Br is added to the fuel as an aqueous spray, the concentration of Br-atoms often exceeds that of HBr at the furnace exit, and a detailed homogeneous reaction mechanism is used to describe the Br speciation and its evolution in transit time, as explained subsequently.

Despite the complete vaporization of Hg and halogens in the furnace, it is a mistake to suppose that furnace firing configuration is irrelevant to Hg emissions control, because firing configuration strongly affects the amounts and properties of UBC suspended in the fly ash. Cyclone firing gives the greatest LOI but this LOI is based on the minimum fly ash loadings, owing to the rejection of most coal ash as bottom ash, and its UBC has the minimum specific surface areas [7]. Low-NO_X burners in wall-fired units and low-NO_X controls in T-fired furnaces give more LOI than high-efficiency firing practices [8]. Coal quality is another independent influence on both LOI levels and the specific surface areas of UBC. LOI with low-rank fuels is usually well below 1 wt% of the fly ash, but becomes markedly greater with bituminous coals and, especially, with low-volatility coals. The specific surface area of the LOI from low-rank fuels is several times greater than that with bituminous coals [9], because only bituminous coals melt during

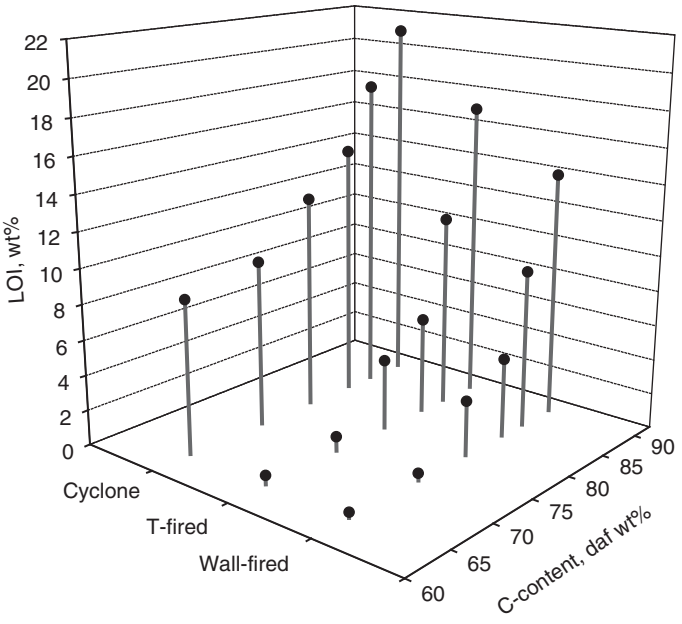

Figure 25.1 Visualization of LOI as a function of the fuel C-content and firing configuration.

the initial stages of combustion and thereby lose most of their internal surface areas.

This rather complicated situation is visualized in 3D in Figure 25.1, which plots LOI for high-efficiency firing practices versus both the C-content of the fuel and the firing configuration. For T- and wall-fired furnaces, the coal quality impact dominates and LOI levels are markedly greater with low-volatility coals than bituminous, and with bituminous than with low-rank coals. The coal quality impact weakens for cyclone firing, although the absolute LOI levels are much greater with this firing configuration than with the other two across the entire range of coal quality. An analogous surface for low-NO_X firing practices would have much greater LOI levels with bituminous and low-volatility coals for T- and wall firing, but similar levels with low-rank coals in all firing configurations and with cyclone firing throughout the range of coal quality. Therefore, the entire surface would be similar except that the LOI with high-rank coals for T- and wall firing would be greater. However, to gauge the impact of these variations on Hg transformations, we must also account for the variations in the specific surface areas. The adjustment between LOI and total UBC surface area for coal quality is about a factor of 7, so that 1 wt% LOI from a subbituminous has a comparable activity to about 7 wt% LOI from a bituminous coal. Of course, LOI is referenced to the total fly ash loading and low-rank coals generally have less mineral matter than high-rank fuels and, therefore, generate less fly ash. But on the basis of equal levels of UBC suspended in flue gas, the UBC from low-rank coals is several times more

active than that from high-rank coals due, in part, to its much greater specific surface area. These observations have great relevance for combustion-modification techniques for enhancing the capture of mercury. We also suspect that the finely dispersed alkali and alkaline earth cations on the UBC from low-rank coals also enhance its chemical activity toward Hg, but this aspect has not yet been characterized in the laboratory.

The impact of coal quality on halogen levels is much simpler. Chlorine is the only significant halogen in the fuel, except in infrequent instances where the Cl-contents in a handful of lignites were so small that the normally negligible levels of coal-Br became relatively significant. In general, low-rank coals generate HCl concentrations in flue gas from single-digit parts per million levels to 20 ppm; high-rank coals generate 25 – 150 ppm; while bituminous coals from the Illinois Basin and from the United Kingdom generate substantially greater concentrations. Aqueous solutions of calcium chlorides and bromides are sometimes sprayed on the fuel to compensate for any natural halogen deficiencies. Perhaps the most important aspect of coal-Cl is its inordinate variability. The testing literature contains instances where coal-Cl varied by as much as a factor of 5 while all other coal properties remained the same during a month-long testing campaign. These variations are completely independent of the primary fuel properties, and can only be accounted for by monitoring coal-Cl on every day of testing, and by running test-specific simulations.

The impact of coal quality and the inherent variability of coal-Hg are much weaker. But the overriding consideration with coal-Hg is that total Hg concentrations in flue gas, at 1 – 10 ppb, are always much too low to affect the concentrations of any other species; in other words, even complete conversion of total Hg leaves the concentrations of all other species unchanged. Of course, coal-Hg and the total Hg concentration in flue gas are scales for the emissions rates and stack Hg concentrations, which are obviously important. But Hg's impact on the process chemistry is severely restricted by its very low absolute concentration. The important implication is that all surface coverages associated with Hg species must be miniscule in the steady state; otherwise, the relaxation times to reach steady states will be incompatible with the reported rapid response times to step changes in the gas cleaning conditions, such as Cl concentrations.

25.3.2 In-Flight Transformations

At the furnace exit, the whole flue gas composition has been specified, including the levels of Hg^0, HCl, HBr, and Br-atoms. The loading and total surface area of UBC in suspension have also been specified. Nearly all the most reactive sites on the UBC have been oxidized but are otherwise accessible. We are now ready to progress forward into the cleaning system, first, to complete the specification of the cleaning conditions and, second, to describe the in-flight Hg transformations.

Regardless of the APCDs in any gas cleaning system, one primary imperative is to extract as much heat as possible from the flue gas before it reaches the stack.

From the furnace exit to the ECN inlet, superheaters reduce the temperature from 1050 to 750 °C in about 1 s, and the ECN cools it to 375 °C in 0.5 s. SCRs operate near-isothermally at 340 – 390 °C with residence times from 1 to 3 s. The APH then quenches the stream to PCD operating temperatures which, for ESPs, vary from 140 to 180 °C with residence times to 15 s and, for FFs, from 120 to 140 °C with times to several seconds. SDAs operate at ESP temperatures, whereas WFGDs operate from 40 to 60 °C. Stack temperatures are usually around 80 °C. A typical thermal history for a cleaning system with only ESPc appears in Figure 25.2. This history is consistent with measured temperatures along several full-scale cleaning systems, although thermal histories for many systems often exhibit large and usually uncharacterized deviations from any baseline thermal history because of differences in the lengths of ductwork and unit sizes. One way to account for these variations is to include detailed specifications on the ductwork in the input requirements. A much less cumbersome way is to adjust the thermal history to match predicted Hg speciation to measured values recorded for baseline operating

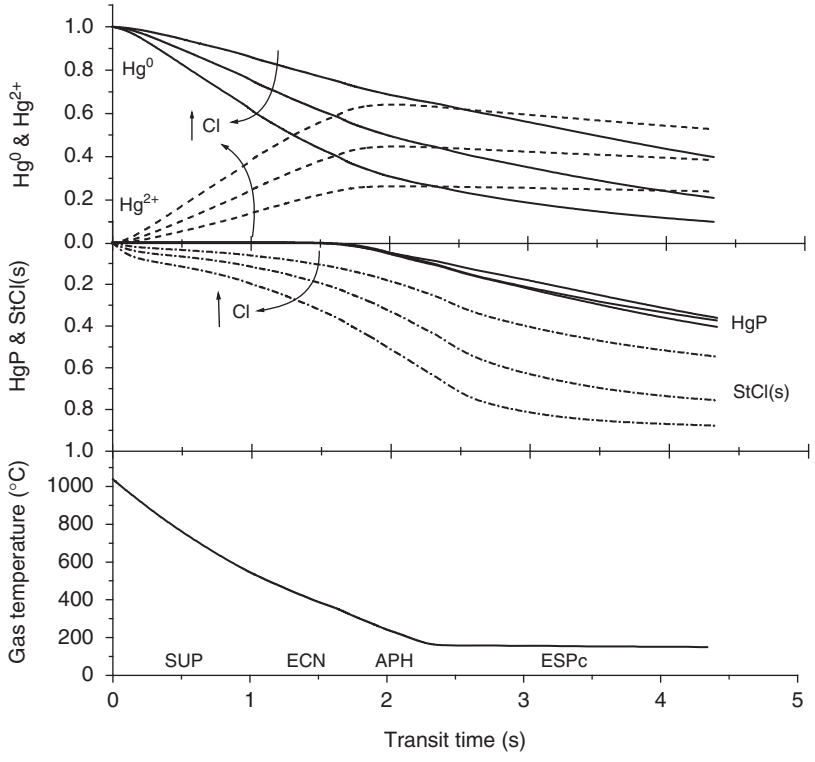

Figure 25.2 MercuRator™ predictions for Hg speciation and (middle panel) the fractional coverage of chlorinated sites on UBC (labeled as StCl(s)) for 7% LOI from a bituminous coal that released 17, 34, and 64 ppm HCl in an ESPc-only cleaning system. The lower panel shows a typical thermal history for commercial gas cleaning systems.

conditions; that is, use the intermediate temperatures in the thermal history to calibrate the analysis to a subject cleaning system. Thermal histories also need to be adjusted as the furnace load is regulated, to account for the longer transit times and cooler operating temperatures under reduced load operation.

These aspects of the thermal history along a cleaning system are important, but the paramount implication from the thermal history in Figure 25.2 reflects the extents of the changes in both temperature and transit time. No process in nature could possibly sustain the same rate-limiting step over such a broad range of temperature; therefore, any proposed reaction mechanism for in-flight Hg transformations must depict several dramatic shifts among the main conversion channels, and these shifts must occur on time scales of only a few seconds. Failure to recognize this essential characteristic of all gas cleaning systems is the main reason that the bulk of testing at laboratory scale is irrelevant to the Hg transformations in commercial cleaning systems. Isothermal laboratory-scale tests can only, at best, be relevant for an instant in the time-temperature pathway of a coal-fired power plant.

Our mechanism for in-flight transformations with only Cl-species has three broad stages, two of which are illustrated in Figure 25.2, and several shifts in the rate-limiting process. In the first stage, the reaction sites on UBC are chlorinated, thereby generating the sites for subsequent Hg chemistry. Such chlorination has never been monitored on coal-derived UBC, but carbon from other sources is known to readily absorb Cl from the gas phase, especially at superheater and ECN operating temperatures [10]. As seen in Table 25.1, we represent this stage as an adsorption equilibrium that balances HCl adsorption, heterogeneous Cl atom recombination, and a hydration reaction. Such a simple adsorption scheme omits the competitive adsorption by S- and N-species, not because they are truly negligible. Rather, these competitions are omitted because the UBC in cleaning systems will always be heavily sulfated and nitrated, so explicitly resolving this competition would add adjustable parameters without improving the fidelity of the surface coverage of the chlorinated sites, which is crucial.

Table 25.1 Heterogeneous Hg conversion mechanism for Cl species on carbon.

Chlorination[a)]	
$StSA(s) + HCl \rightarrow StCl(s) + H$	Chlorination
$StCl(s) + Cl \rightarrow Cl_2 + StSA(s)$	Heterogeneous Cl-atom recombination
$StCl(s) + H_2O \rightarrow HCl + OH + StSA(s)$	Hydration
Hg conversion	
$StCl(s) + Hg^0 \rightarrow StHgCl(s)$	Hg^0 adsorption
$StHgCl(s) + HCl \rightarrow StSA(s) + HgCl_2 + H$	Oxidation with desorption
$StHgCl(s) \rightarrow StSA(s) + HgCl$	Desorption
$StCl(s) + HgCl_2 \rightarrow StHgCl(s) + Cl_2$	Back adsorption

a) Converts open sites (StSA(s)) into chlorinated sites (StCl(s)).

The second stage describes the Hg transformations on the chlorinated sites. Hg adsorption is restricted to the chlorinated sites, because X-ray photoemission spectroscopy (XPS) analysis indicates the presence of Hg–Cl–C bonds on UBC sampled from flue gas [11]. The surface intermediate StHgCl(s) is either chlorinated further and released as $HgCl_2$ or released as HgCl to be fully oxidized in the gas phase. While these two steps are global processes in our mechanism, this stage has been resolved in detail by Olsen and coworkers, as described elsewhere in this volume. Hg^{2+} can also back adsorb onto a chlorinated site on UBC.

The shifts in rate-limiting steps are evident in Figure 25.2 as shifts in the Hg speciation. UBC chlorination dominates through the superheaters and into the ECN. As the appearance of Hg^{2+} without any Hg_p signals the first Hg transformations, the conversion rate is initially adsorption controlled, as expected at high temperatures. Further along the quench cycle, Hg_p appears as evidence of a more balanced conversion under chemical reaction control. Within the APH and into the ESPc, Hg_p continues to accumulate while both vapor species diminish, which signals desorption control. Further into the ESPc, essentially all chlorinated surface area on UBC is removed from the flue gas (although only the maximum accumulation of Hg_p is shown in Figure 25.2) which, along with the low temperature, terminates the Hg transformation chemistry. The time to remove sufficient chlorinated carbon surface from the flue gas to quench Hg chemistry is a small fraction of the total transit time through an ESPc, because most fly ash is recovered in the first and second upstream fields.

The tendency for progressively greater Cl concentrations is also shown in Figure 25.2. Greater Cl levels shift the Cl adsorption equilibrium toward larger populations of chlorinated sites on UBC, which promotes faster Hg^0 oxidation at high temperature but the same accumulation of Hg_p at low temperature, due to the slower adsorption of Hg^{2+} compared to Hg^0. Consequently, the same Hg is removed in the ESPc, and there is substantially less Hg^0 in the stack emissions. The tendency for progressively greater LOI levels would be completely analogous for the vapor species, and more LOI would also enhance Hg_p provided that the flue gas contained sufficient Cl to actually expand the population of chlorinated sites.

This same reaction mechanism describes the markedly enhanced Hg removals for ACI with untreated and brominated carbons with three important differences, two of which are seen in Figure 25.3. The first is that carbon sorbents have surface areas from 500 to 1200 $m^2\,g^{-1}$, which are 2–40 times greater than UBC specific surface areas. The second difference is that the chlorination stage is shifted to much cooler temperatures because ACI is usually positioned immediately downstream or, less frequently, immediately upstream of the APH. As this location is hundreds of degrees cooler than where inherent UBC is chlorinated, we were surprised to see that our chlorination mechanism remained accurate in ACI applications after only very small adjustments to the rate constants. If the sorbent is halogenated before injection, then the chlorination step is simply omitted altogether. The third difference is that progressively greater ACI concentrations generate much more Hg_p at the expense of both Hg^0 and Hg^{2+}. In general, the back

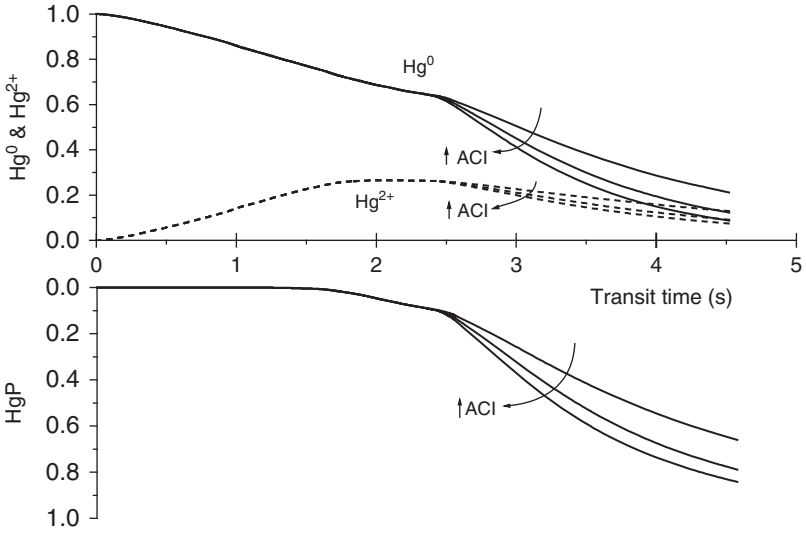

Figure 25.3 MercuRator™ Hg speciation for untreated ACI at 3, 6, and 9 lb/MMacf for 7% LOI from a bituminous coal that released 17 ppm HCl in an ESPc-only cleaning system.

adsorption of Hg^{2+} onto vacant sites tends to be much more important with sorbent than with inherent UBC, simply because the vacant site population is almost always much greater in ACI applications. For this same reason, Cl availability often limits the asymptotic, ultimate removal for even the largest ACI concentrations when applied with low-rank fuels. The asymptotic removals with high-Cl, high-rank fuels tend to approach 95%, where the difference with complete removal is thought to reflect imperfect particle dispersion (mixing of the sorbent) in turbulent flow fields. But asymptotic removals are often no greater than 65–75% with low-rank fuels, because Cl availability limits the size of the population of chlorinated sites. Under these circumstances, further increases in the ACI concentration simply redistributes the same population of chlorinated sites among a larger number of sorbent particles, without increasing the population size.

Another potentially critical limitation of ACI performance is described by the third stage of our in-flight mechanism, inhibition by SO_3. During gas quenching, whenever the local flue gas temperature cools below the SO_3 dew point, sufficient H_2SO_4 – the product of SO_3 hydration – condenses onto any accessible surface to equalize the dew point to the local temperature. According to our analysis [6], the surface area of all fly ash, not just UBC, participates in the condensation. The portion that condenses onto sites on both UBC and carbon sorbents inhibits heterogeneous Hg conversion chemistry. The loss of activity is determined by the condensation of H_2SO_4 onto the population of sites that can potentially be chlorinated on the basis of the total surface area. Once covered by H_2SO_4, these sites no longer participate in any Hg conversion chemistry. SO_3 condensation first diminishes the population of chlorinated sites (just as a lower ACI concentration would) which, in turn, is responsible for less Hg_p; hence, lower Hg removals, as seen in

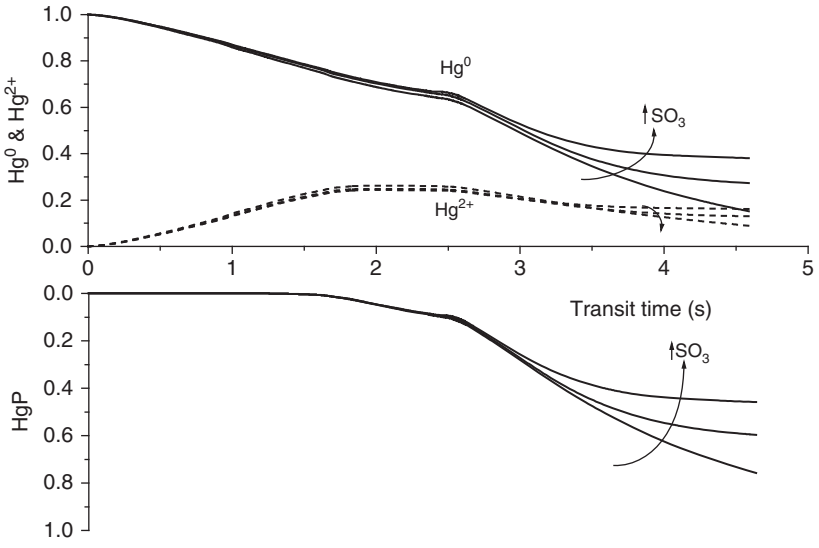

Figure 25.4 MercuRator™ Hg speciation for untreated ACI at 6 lb/MMacf for 7% LOI from a bituminous coal that released 17 ppm HCl in an ESPc-only cleaning system that generated 9.5, 27, and 32 ppm SO_3.

Figure 25.4. Temperatures from the back-end of the APH into the PCD are critical, because Hg removals can be cut in half by this form of inhibition. Accordingly, either ACI is not recommended with high-S fuels, or high sulfur trioxide levels are mitigated possibly through alkaline sorbents or additives.

When a cleaning system uses ESPh instead of ESPc, Hg removals will be markedly lower because an ESPh operates at temperatures well above the onset of Hg_p production; that is, before the mechanism starts shifting toward desorption control. If it uses FF instead of an ESPc, then all Hg transformations upstream of the FF remain the same, but the behavior within the FF is dramatically different, as seen in Figure 25.5. Very little chemistry occurs during the several seconds needed to transport the flue gas into the filtercake on the filter bags. But immediately after the flue gas contacts the filtercake, there are step changes in the levels of Hg_p and Hg^{2+}, with complete elimination of Hg^0 (via enhanced gas-solid contact between flue gas and the sorbent due to formation of a packed bed-type configuration). The exorbitant surface area of the filtercake is responsible for the near-critical behavior because, on a volumetric basis, the surface area of UBC in a filtercake is five orders of magnitude greater than the surface area of suspended UBC in flue gas for a case with 5 wt% LOI from a coal with 10% ash. Preliminary analysis showed that the Hg conversion chemistry is confined to a relatively thin outer layer of the filtercake, across which the Hg speciation relaxed to the composition for an adsorption equilibrium. Because the layer is relatively thin, it is not necessary to resolve the extent of Hg conversion through the filtercake; we simply evaluate the Hg speciation for adsorption equilibrium. The equilibrium

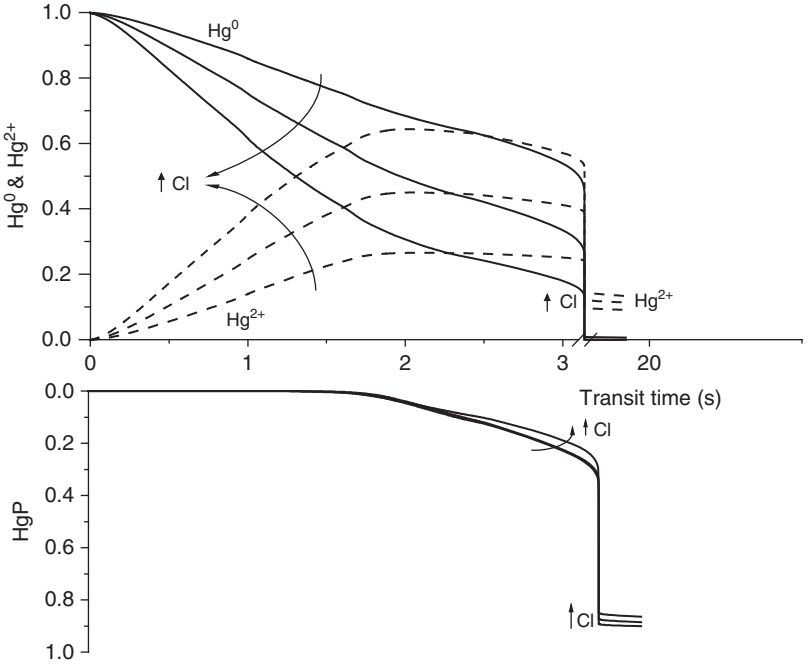

Figure 25.5 MercuRator™ Hg speciation for 7% LOI from a bituminous coal that released 17, 34, and 64 ppm HCl in a FF-only cleaning system.

speciation is not necessarily dominated by Hg_p, because the levels of Cl and carbon surface area determine the proportions of Hg^0, Hg^{2+}, and Hg_p. As seen in Figure 25.5, progressively more Cl shifts the equilibrium speciation toward Hg^{2+} at the expense of Hg_p while Hg^0 is always miniscule.

According to our interpretation, in-flight Hg transformations with Cl species are determined by only the heterogeneous reaction mechanism. This is because the extremely low concentrations of Cl atoms and Cl_2 under commercial gas cleaning conditions cannot drive the two-step, autocatalytic cycle whereby Cl-atoms partially oxidize Hg^0 into HgCl which, in turn, is fully oxidized into $HgCl_2$ by Cl_2 to restore the original Cl atom [12]. Even in homogeneous Hg oxidation mechanisms with somewhat different primary conversion channels, the extent of homogeneous Hg oxidation is negligible compared with measured values under commercial cleaning conditions.

However, in-flight Hg transformations with Br species must be attributed to both homogeneous and heterogeneous reaction mechanisms. As seen in Figure 25.6, simulations with only a homogeneous Hg/Br reaction mechanism [13] demonstrate one of the most distinctive features of Hg oxidation by Br species. For a typical thermal history along a gas cleaning system and with 9.4 ppm Br in flue gas, the predicted extent of Hg oxidation approaches 70%. In contrast, the comparable performance with 20 ppm HCl is no Hg oxidation

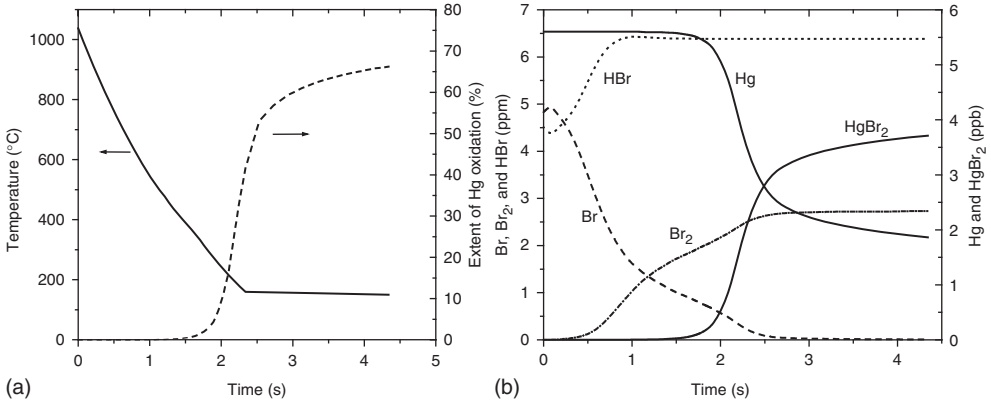

Figure 25.6 (a) Solid curve: typical thermal history for a gas cleaning system whose only APCD is an ESPc and (dashed curve) predicted extent of homogeneous Hg oxidation with 9.4 ppm Br in flue gas. (b) Solid curves: Hg vapor speciation and (dashed curves) Br speciation for the same conditions.

whatsoever. Homogeneous Hg oxidation by Br begins to produce $HgBr_2$ as the flue gas cools below 500 °C and accelerates sharply when the temperature cools below 300 °C. At higher temperatures, the instability of an HgBr intermediate fails to sustain $HgBr_2$ production.

At the furnace exit, Br atoms are present in concentrations that are comparable to HBr levels, in marked contrast to the much lower concentrations of Cl atoms at these conditions. The primary reason that Br is a much more effective Hg oxidizer than Cl is that HBr dissociates into the most reactive atomic species much more extensively than HCl at typical post-flame conditions. As flue gas moves further into the gas cleaning system, Br atoms rapidly recombine through the back-end heat exchangers, first, into HBr, then, into Br_2, so that the HBr concentration plateaus at 600 °C and the Br_2 concentration plateaus at 160 °C. As the flue gas cools in the APH and further downstream, the $HgBr_2$ concentration surges. $HgCl_2$ is not produced because homogeneous Hg oxidation by Cl species is too slow under these conditions. All these species approach ultimate steady concentrations in the ESPc because of the low temperatures.

To account for the impact of variations in UBC levels on Hg transformations by Br species, we supplement the homogeneous reaction mechanism with a heterogeneous mechanism that is completely analogous to the heterogeneous mechanism for Cl species in Table 25.1 [13]. The key difference between the contributions from the in-flight mechanisms on UBC for Br and Cl species is that the much higher concentration of Br atoms promotes heterogeneous recombination into Br_2. This process maintains much smaller populations of brominated sites on the UBC than the chlorinated sites. Consequently, the contribution of heterogeneous in-flight chemistry with Br species is smaller, and much lower levels of Hg_p form at the lowest temperatures of interest. This prediction is consistent with several field test results in which Br addition strongly

enhanced Hg^{2+} levels but left Hg_p levels unchanged. Unfortunately, contradictory findings have also been reported, which are compounded by as-yet unresolved interferences in semi-continuous emissions monitor (SCEM) detectors by Br species. We currently expect Br addition to promote substantial homogeneous Hg^0 oxidation through the ECN and upstream of an SCR with little effect on Hg_p levels, because of the heterogeneous recombination of Br atoms into Br_2. However, such observations must remain tentative until the measurement issues are rectified.

In a similar manner, brominated carbon sorbents are analyzed with the analogous heterogeneous mechanism for Br species, without any bromination stage, and with minimal contributions from homogeneous Hg/Br chemistry, because of the low gas temperatures at ACI locations.

25.3.3 Hg^0 Oxidation across SCR Catalysts

The oxidation of Hg^0 across the promoted V_2O_5 catalysts on SCR monoliths is completely independent of its in-flight oxidation on UBC. In fact, the catalytic oxidation channel often provides the fastest means to oxidize Hg^0, especially in the presence of Br species, which may seem surprising because no SCR has yet been designed or optimized to oxidize Hg^0. Extents of Hg^0 oxidation of 90% or more are routinely recorded in full-scale field tests [14], provided that the flue gas contains abundant Cl- or Br-species and that the SCR provides sufficient reactivity, favorable mass transport rates, and ample residence time for the chemistry to proceed to near completion. When these conditions are satisfied, SCR/ESP/FGD combinations are the technology of choice for Hg control because they require no special operating procedures or reagents to lower Hg emissions, except when Br- and Cl-species are injected to counteract the inherent halogen deficiencies in low-rank coals.

Our first reaction mechanism for catalytic oxidation described simultaneous NO reduction and Hg^0 oxidation in terms of lumped catalyst reactivities that resolved film transport of reactants onto the external catalyst channel wall from an overall chemical reactivity [15]. The key features were a competition between NH_3 and HCl for surface sites, and an Hg^0 oxidation reaction on chlorinated catalyst sites. This competitive adsorption subdivides the catalyst into two stages. An entry stage sustains NO reduction with high concentrations of adsorbed NH_3, but the population of chlorinated sites remains very small as long as the HCl concentration is much lower than the NH_3 concentration. This small population oxidizes small proportions of the Hg^0. Once the NH_3 has been consumed, a trailing stage is chlorinated much more extensively and thereby able to rapidly oxidize Hg^0. This mechanism interpreted extents of Hg^0 oxidation by Cl species in laboratory-, pilot-, and full-scale SCR units for the complete domain of utility gas cleaning conditions, and was recently expanded for oxidation by Br-species [16]. The strong coupling between NO reduction and Hg^0 oxidation via competitive adsorption of

NH_3 and HCl was also independently validated with an extensive series of laboratory tests [17].

Additional modeling work expanded the original lumped analysis in two ways into a legitimate multipollutant analysis [18]. First, simultaneous SO_2 oxidation was incorporated and, second, the analysis resolves internal pore diffusion across the catalyst wall thickness from the intrinsic reactivity of adsorbed species on the catalyst surface with a conventional Thiele analysis, to directly relate catalyst morphology and composition to the multipollutant performance of the SCR reactor. Consequently, the analysis directly relates factors that can be manipulated in the design of SCRs – the size and shape of monolith channels, the composition, and pore size characteristics of the catalyst layer, and the temperature – to the multipollutant performance for specified ranges of flue gas composition and flow rate. It is especially well suited to predicting the performance of a particular SCR across broad domains of flue gas conditions for current and foreseen specifications on fuel quality and furnace firing conditions, and also to optimize SCR design parameters to meet specifications on Hg^0 oxidation with new and replacement SCR catalysts. The goal is to enable plant operators to take better advantage of fuel switching opportunities by calling for additives or operational adjustments that will enhance Hg removals while maintaining high NO_X removals and acceptable SO_3 levels.

The NO reduction mechanism was developed and fully validated for commercial SCR catalysts by Tronconi and coworkers [19], based on submechanisms for film transport, an Ely-Rideal (ER) reaction mechanism with NH_3 chemisorption (gas phase NO reacting with adsorbed NH_3), and pore diffusion. Similarly, the SO_2 oxidation mechanism was also adapted from Tronconi's work [20], albeit with no mediation by any transport phenomena. Our original mechanism for catalytic Hg^0 oxidation has been incorporated into this validated framework to account for the mediation of competitive HCl and NH_3 adsorption by pore diffusion. A simple premise connects NO and SO_2 conversion to the Hg^0 oxidation behavior on SCRs: That HCl, HBr, and Br_2 compete for surface sites with NH_3, and that Hg^0 contacts these halogenated sites either from the gas phase or as a weakly adsorbed species. On the assumption that the competitive adsorption coverages are independent, the rate expression for adsorbed Hg oxidation is given by

$$r_{\mathrm{Hg}} = {}^{\mathrm{Cl}}k_{\mathrm{Hg}} C^{S}_{\mathrm{Hg}} \Theta_{\mathrm{Cl}} + {}^{\mathrm{Br}}k_{\mathrm{Hg}} C^{S}_{\mathrm{Hg}} \Theta_{\mathrm{Br}} = \left[\frac{{}^{\mathrm{Cl}}k_{\mathrm{Hg}} K'_{\mathrm{HCl}} + {}^{\mathrm{Br}}k_{\mathrm{Hg}} K'_{\mathrm{HBr}}}{1 + {}^{H}K'_{\mathrm{NH_3}} C^{S}_{\mathrm{NH_3}}} \right] C^{S}_{\mathrm{Hg}}$$

As the surface coverages of the halide species are independent, the net rate is the sum of independent contributions from Cl and Br, and the original mathematical form of the analysis of only Cl species can be retained. The effective rate constants on the right contain the concentrations of HCl, HBr, and Br_2, which are uniform across the SCR in the steady state.

The common characteristics among the reactivities for NO reduction, SO_2 oxidation, and Hg^0 oxidation are that (i) NH_3 strongly inhibits all three processes and (ii) all rates are directly proportional to the concentrations of the primary reactant.

Otherwise, SO_2 oxidation is weakly promoted by NO and O_2, and weakly inhibited by moisture, whereas Hg^0 oxidizes in proportion to the surface coverages of halide species supplied via adsorption of the halogen vapors. These coverages vary along the catalyst length even while the concentrations of halogen vapors remain uniform because they are not consumed in any chemical process other than Hg^0 oxidation, and the Hg^0 concentration is orders of magnitude smaller than all other reactant concentrations. Several analytical solutions were integrated into the analysis to avoid a computationally expensive 2D simulation along and into the catalyst wall, as elaborated elsewhere [18].

According to both of our analyses, the various SCR design specifications and operating conditions can be understood in terms of how they affect the lengths of the two stages for NO reduction and for the oxidation of Hg^0 and SO_2. Factors that accelerate the transport rates of reactants onto the catalyst walls, such as smaller channel pitches and converting from square to circular channels, shorten the length of the NO reduction stage and thereby promote Hg^0 oxidation. Factors that enhance surface halogenation, such as higher inlet halogen concentrations and lower NH_3/NO ratios, also promote Hg^0 oxidation. Br species dramatically accelerate Hg^0 oxidation rates on some catalysts by as much as a factor of 40 compared to the rates for Cl species [16]. The design analysis also showed that shifting the pore size distribution toward macropores in a final catalyst layer appears to be an effective means to directly enhance Hg^0 oxidation. According to our calculations, this strategy will not increase NH_3 slip, because it raises the effectiveness factor for NO reduction, nor will it increase the extent of SO_2 oxidation by a significant amount, because transport effects are negligible in SO_2 oxidation. But it does have the potential to significantly enhance extents of Hg^0 oxidation, all other SCR operating conditions being the same. Most of these benefits were realized in the increase in macroporosity from 5% to only about 15%, which makes this strategy potentially easier to implement. Increases in the micropore size also enhance Hg^0 oxidation, presumably due to the associated increases in the effective diffusivity of Hg, but the impact is not nearly as large as that for increases in macroporosity.

Perhaps the most important result is that SCR design specifications and operating conditions are at least as important as the halogen concentrations, simply because the domain of these specifications across the industry is enormous. Our database on Hg^0 oxidation across full-scale SCRs covers temperatures from 335 to 395 °C; gas hourly space velocity (GHSV) from 1800 to 4700 h^{-1}; HCl concentrations from 1 to 130 ppm; Br concentrations from 0 to 50 ppm; inlet NO concentrations from 280 to 900 ppm; and NO reduction efficiencies (or NH_3/NO ratios) from 0 (for out-of-service SCRs) to 0.95. SCRs from four catalyst vendors represent plate-monoliths with pitches to 11 mm and honeycomb monoliths with square and triangular channels of pitches to 10 mm. As seen in Figure 25.7, the predictions from the lumped analysis are generally within 10% of the measured values for all cases except EES8U13, even though the measured extents of Hg^0 oxidation vary from 20% to more than 90%. Such performance could not possibly

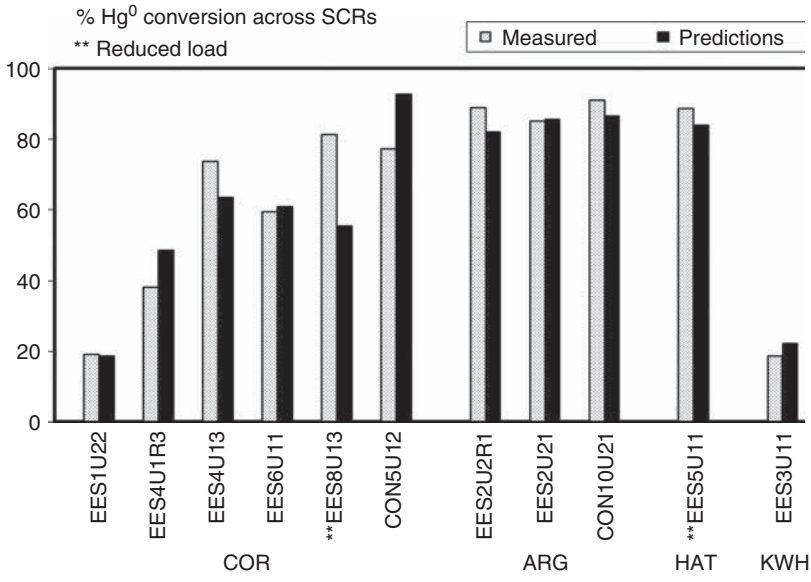

Figure 25.7 Evaluation of extents of Hg^0 oxidation across various full-scale SCRs from MercuRator™ (solid) with measured values representing four catalyst vendors (gray).

be achieved unless the impact of the operating conditions and design specifications was accurately described, in conjunction with the appropriate dependencies on the halogen concentrations.

25.3.4 Hg Transformations within WFGDs

The Hg field-testing literature shows that WFGDs usually capture at least 90% of the Hg^{2+} in flue gas, but virtually none of the Hg^0, because Hg^0 is insoluble in aqueous solutions. However, several full- and bench-scale tests have documented Hg reemission whereby the Hg^0 concentration at the FGD exit is greater than that at the inlet, suggesting that some of the Hg(II) in the scrubber solution must be reduced and reemitted as Hg^0 vapor. Hg reemissions have also been observed in natural waters and atmospheric cloud and rain-water cycles [21–23], where S(IV) species promote the reduction of Hg^{2+}. Bench-scale studies under well-controlled scrubbing conditions showed that Cl^- and O_2 suppress reemission, whereas Ca^{2+} and Mg^{2+} species promote it.

We recently developed a quantitative analysis that identifies and rank-orders the factors involved in Hg reemission during wet FGD scrubbing, to support efforts to mitigate Hg reemission from full-scale, commercial wet FGDs. To simulate Hg transformations WFGD scrubbers, one must first model SO_2 absorption to describe the major solution species (S, Ca, Cl) and their variations with FGD operating conditions (L/G, droplet diameter, T). The conventional simulation strategy

builds numerous equilibrium constraints into a mass transport analysis of the exchange of species from the flue gas into the spray droplets along an absorber tower, with simultaneous limestone dissolution and sulfite oxidation within slurry droplets. Given the absorber temperature and the inlet compositions of flue gas and slurry, the conventional FGD analysis predicts the correct pH and reasonable SO_2 absorption rates along the absorber. It also depicts realistic tendencies for variations in the inlet SO_2 level, and identifies distinctive conditions where elevated HCl levels will reduce SO_2 removal efficiencies by 5–10%, and greater SO_2 removal for smaller slurry droplets, all else the same.

While the conventional FGD analysis relates gross FGD operating conditions to SO_2 absorption efficiencies, it is unsuitable for trace metal transformations, especially for Hg reemission. The reason is that conventional formulations implicitly assume that all oxygen is consumed in sulfite oxidation at the liquid interface on a slurry droplet, and evaluate the rate of sulfite oxidation as an average based on bulk liquid concentrations. The requisite analysis for Hg^{2+} chemistry and, presumably, other trace metal transformations must automatically shift the redox potential of bulk liquid in the spray from oxidizing to reducing through a balance among the finite-rate reagent fluxes that participate in sulfite oxidation. Our SO_2 capture analysis allows oxygen to penetrate through the liquid film and accumulate in the bulk liquid if its concentration exceeds the stoichiometric requirement for bisulfate oxidation. We also propose a finite-rate reaction for Hg(II) reduction that depends on temperature, pH, and S(IV) species which, in the absence of sufficient oxygen, promote Hg(II) reduction to Hg^0 vapor.

The computerized implementation covers the process chemistry occurring in both a counterflow absorber and slurry holding tank [24]. The tank analysis determines the required limestone feed rate for a given tank residence time distribution (RTD) and the solids size distribution into the spray nozzles within the absorber. It also determines how much liquid must be extracted to maintain a target Cl concentration in the tank. The absorber analysis determines the SO_2 capture and the compositions of liquid and solids that return into the holding tank. Given the absorber temperature and the inlet compositions of flue gas and slurry, the analysis predicts the SO_2 capture efficiency, complete slurry composition and flue gas composition, slurry pH, the quantitative enhancement of mass transfer by acid dissociations in the slurry, and the relative contributions of liquid and gas resistances to the overall mass transfer rate. All quantities are resolved as functions of distance along the absorber axis.

For the operating conditions and bulk species concentrations reported for a full-scale limestone WFGD, the analysis correctly predicts that SO_2 was continuously removed along the length of the absorber, whereas most of the Hg was removed in the lower section at a much greater efficiency than SO_2 removal, owing to the high aqueous solubility of $HgCl_2$. For the baseline case with 20% Hg^0, the predicted reemission gradually increased to 20%, and the total Hg removal reached only 65%.

According to the analysis, aqueous Hg species segregate into two groups, Hg–Cl species and Hg–S(IV) species. How variations in the scrubber operating conditions shift the proportions of these two groups is critical, because only the

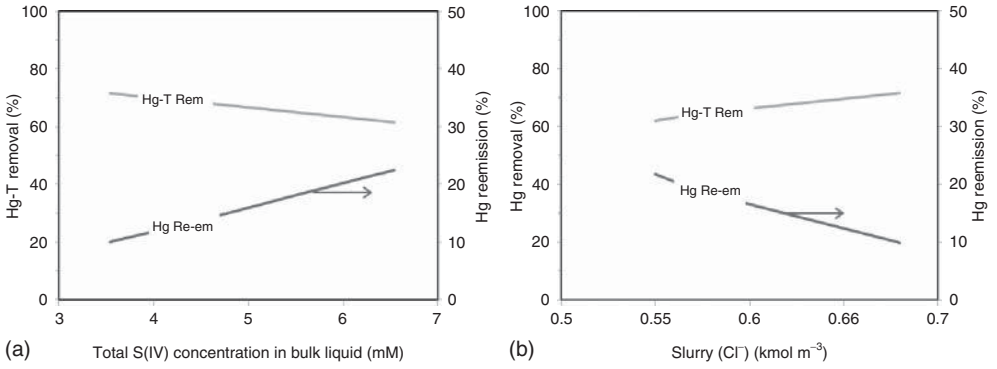

Figure 25.8 Effect of bulk liquid (a) S(IV) and (b) slurry Cl^- concentrations on total Hg removal (left *y*-axis) and percentage Hg reemission (right *y*-axis).

Hg–S(IV) species can be reduced and subsequently reemitted as Hg^0 back into the flue gas. The two most important factors are shown in Figure 25.8, which shows the total Hg removals and extents of Hg^0 reemission for concentration ranges of S(IV) and Cl^- species. As the S(IV) concentration was increased from approximately 3.5 to 6.5 mM, the Hg removal decreased from 72 to 62% with an increase in Hg reemission by a similar percentage. For a twofold increase in S(IV) concentrations, the Hg–S(IV) fraction in the solution at the absorber exit increased from 14 to 36% with a corresponding decrease in Hg–Cl levels. The predicted Hg reemission therefore linearly tracks the Hg–S(IV) levels. Conversely, for progressively greater Cl^- in solution, the Hg(II) species preferentially partition into Hg–Cl complexes that reduce reemission, which is consistent with the observations in bench- and pilot-scale experiments. As the Cl^- concentration was increased from 0.5 to 0.68 kmol m^{-3}, the Hg–Cl ions increased from 66 to 84% with a corresponding decrease in Hg–S(IV) complexes. The change in Cl^- did not affect Hg^{2+} absorption as it was in excess of 99% in all cases. The increased partitioning of Hg(II) into Hg–Cl complexes decreased reemission by 11% and increased the Hg removal from 62 to 72%.

Most additives to control Hg reemission from scrubbers, such as Na_2S_4, TMT-15™, and NaHS, release S(II) ions in the slurry and precipitate Hg as HgS(s). We examined the addition of small amounts of S(II) into the base case scrubber solution and simulated Hg capture. Even at 1 μM concentrations of the additive, all the Hg(II) precipitated as HgS(s), which establishes the maximum Hg^{2+} concentration in the solution as only 10^{-33}. According to our simulations with 80% $HgCl_2$ in the flue gas, essentially all Hg(II) was retained in the solid phase. These predictions are consistent with the B&W tests at Endicott station [25], where the addition of NaHS almost completely suppressed Hg reemission and the extent of reemission did not bear any relation to the additive feed rate. We also simulated the addition of S(II) under oxidizing conditions where the pH was increased to 6.5 and the S(IV) concentration was reduced to the point where oxygen was in excess, to characterize lime-based WFGDs. Under such conditions, equilibrium shifts the added S(II)

species to their oxidized forms, which prevents any precipitation of HgS solids. This is consistent with B&W tests at the Mg/lime WFGD at Zimmer station [25], where adding NaHS did not improve the baseline Hg-T capture efficiency even at high additive feed rates.

At this point in its development, our FGD scrubbing analysis predicts reasonable extents of Hg removals and Hg reemission under realistic FGD operating conditions, without any parameter adjustments. Most Hg^{2+} in flue gas is captured near the flue gas inlet at the bottom of the absorber, but Hg reemission can occur along the entire absorber at a rate that accelerates slightly along the upper elevations. Predicted Hg removals are insensitive to droplet diameter, whereas smaller slurry droplets reemit more Hg because they sustain faster absorption of all the reagent gases involved in Hg(II) reduction. The total S(IV) species concentration in the slurry promotes reemission; conversely, the analysis correctly predicts less reemission for greater Cl^- concentrations in the slurry, in accord with a well-established tendency. Simulations with added S(II) species, as released from commercial additives to suppress Hg reemission, correctly gave complete precipitation of Hg(II) as HgS(s). These predictions are consistent with full-scale field tests where the addition of NaHS almost completely suppressed Hg reemission and the extent of reemission did not bear any relation to the additive feed rate.

25.4 Summary

Collectively, the reaction mechanisms described in this chapter cover all the most common fuels, firing configurations, and gas cleaning configurations, and enable accurate estimates for Hg emissions rates from virtually any commercial power plant. Such estimates are the most expedient and economical means to evaluate potential Hg control technologies, both inherent and external. The fact is that even many individual power plants and, certainly, regional utility operations use so many fuel types that testing all of them becomes a practical impossibility. And such variations will only expand in the foreseeable future as operators develop strategies to comply with new regulations and new fuel sources open up.

Beyond the predictive capabilities resting upon these mechanisms, this level of analysis has clearly exposed the determining factors for Hg emissions. In-flight Hg transformations are determined by halogen concentrations, the halogenated surface area on UBC and carbon sorbents, the type of PCD, and, in ACI applications, the ACI concentration. Unless halogens are added to compensate for low inherent coal-Cl, the enormous inherent variability of coal-Cl levels is a primary consideration, and this variability can only be established by measurements because it is completely independent of all other coal properties. Chlorinated surface areas on UBC reflect the furnace firing configuration, fly ash LOI, and, especially, the coal rank. These influences tend to counteract each other insofar as low-rank coals give UBC with very high specific surface areas but generate very low LOI levels. Conversely, high-rank coals give UBC with low surface areas but generate much

higher LOI levels. Even so, it is impossible to accurately depict in-flight Hg transformations without an accurate account of all three influences on the chlorinated surface area. ACI with untreated carbon sorbents mitigates the inherent variations in chlorinated surface area, but does not necessarily eliminate the halogen dependence. This limitation is clearly seen in the much-lower-than expected asymptotic Hg removals for ACI with many low-rank coals. ACI with brominated carbon is the only current means to completely circumvent these limitations. Unfortunately, even this "universal" solution may be diminished by SO_3 inhibition. Whenever flue gas SO_3 levels are high enough to drive the SO_3 dew point below the local gas temperature in the APH and further downstream, condensed H_2SO_4 will deactivate halogenated sites on UBC and carbon sorbents, whether or not they have been brominated. As this inhibition can cut Hg removals in half, ACI is not recommended with high-S fuels, unless sorbent additives or sulfur trioxide mitigation are implemented.

In cleaning systems that exclusively rely on in-flight Hg transformations to control Hg emissions, relatively very high LOI levels are needed to generate sufficient UBC to produce appreciable Hg_p levels that can be removed in the PCD, even with high-Cl coals. Therefore, impending Hg emission regulations can only be met with ACI. Whether or not the sorbent is brominated, Hg removals for ACI upstream of a FF are significantly greater than ESPc removals, and this scheme requires much lower ACI concentrations to achieve a targeted Hg removal. This is because the enormous volumetric surface area in an FF filtercake brings the Hg speciation to adsorption equilibrium, while ESPs rapidly eliminate all the chlorinated carbon surface area from the flue gas and shut down the Hg conversion chemistry. Our analysis indicates that the only PCD-only cleaning configuration that can match the Hg removal performance of an SCR + ESPc + WFGD configuration is when ACI is positioned between an ESPc and a FF (Toxecon™-I).

The Hg^0 oxidation performance of SCRs is no less variable than the in-flight transformations, because SCR design specifications and operating conditions are at least as important as the halogen concentrations. This variability reflects the fact that none of the SCRs in service were designed, let alone optimized, to oxidize Hg^0. The essential feature is that NH_3 adsorption inhibits the adsorption of the species involved with Hg^0 oxidation, which subdivides the catalyst into two stages. An entry stage sustains NO reduction with high concentrations of adsorbed NH_3 but too few chlorinated sites to sustain Hg^0 oxidation. Once the NH_3 has been consumed, a trailing stage is chlorinated much more extensively and thereby able to rapidly oxidize Hg^0. The various SCR design specifications and operating conditions can be understood in terms of how they affect the lengths of these two stages. Factors that enhance surface halogenation, such as higher inlet halogen concentrations and lower NH_3/NO ratios, also promote Hg^0 oxidation. Br species dramatically accelerate Hg^0 oxidation rates on some catalysts by as much as a factor of 40 compared to the rates for Cl species. The analysis also shows that shifting the pore size distribution toward macropores in a final catalyst layer appears to be an effective means to directly enhance Hg^0 oxidation.

The WFGD analysis predicts Hg reemission along the entire absorber, but not in the slurry holding tank for a limestone, forced oxidation system. The total S(IV) species concentration in the slurry promotes reemission; conversely, the analysis correctly predicts less reemission for greater Cl^- concentrations. Simulations with added S(II) species, as released from commercial additives to suppress Hg reemission, correctly gave complete precipitation of Hg(II) as HgS(s). These predictions are consistent with full-scale field tests where the addition of NaHS almost completely suppressed Hg reemission and the extent of reemission did not bear any relation to the additive feed rate. But this analysis needs additional validation with data from full-scale WFGDs before it can deliver accurate quantitative interpretations.

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The Sources, Distribution, and Trends of Chloride in the Waters of Illinois

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March 2012

Abstract

Chloride (Cl^-) is a major anion found in all natural waters. It occurs naturally and is also a relatively minor contaminant. Chloride concentrations in Illinois range from less than 0.1 milligrams per liter (mg/L) in precipitation to close to 100,000 mg/L in Paleozoic brines. Chloride is non-toxic to humans, although there is a secondary drinking water standard of 250 mg/L. It is, however, deleterious to some plants and aquatic biota, thus the Illinois Environmental Protection Agency (IEPA) has set an acute standard of 500 mg/L for surface waters in Illinois. Chloride is also a very corrosive agent, and elevated levels pose a threat to infrastructure, such as road beds, bridges, and industrial pipes.

Some streams and aquifers in Illinois have naturally elevated Cl^- concentrations due to surface or near-surface discharge of Paleozoic brines. Of greater concern to water resources in Illinois are anthropogenic sources of Cl^-, including road salt runoff, sewage, water conditioning salts, and fertilizer. Chloride concentrations are elevated in most water bodies in the Chicago region, primarily due to road salt runoff. Concentrations have been increasing since approximately the 1960s, and in general, concentrations continue to increase. These elevated Cl^- concentrations may pose a risk to infrastructure as well as aquatic to ecosystems.

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Introduction

Chloride (Cl^-) is a naturally occurring major anion found in all natural waters. Chloride behaves as a conservative ion in most aqueous environments, meaning its movement is not retarded by the interaction of water with soils, sediments, and rocks. As such, it can be used as an indicator of other types of contamination. Anomalously high concentrations can act as an "advance warning" of the presence of other more toxic contaminants. Concentrations of Cl^- in natural waters can range from less than 1 milligram per liter (mg/L) in rainfall and some freshwater aquifers to greater than 100,000 mg/L for very old groundwaters within deep intracratonic basins (Graf et al., 1966; Psenner, 1989). Its concentration in precipitation in mid-continental regions (far from oceans and other salt sources) is almost always less than 1 mg/L, and often less than 0.1 mg/L (NADP, 2011). Upon contacting land surface, Cl^- concentrations in water increase as a result of interaction with soils, rocks, and biota (waste products), as well as the effects of evaporation. Chloride is the most abundant ion in seawater, with a concentration greater than 19,000 mg/L (Stumm and Morgan, 1996). Extremely elevated levels of Cl^- in surface water are generally due to significant evaporation (e.g., the Dead Sea has a Cl^- concentration > 230,000 mg/L).

Chloride is non-toxic to humans, but elevated levels make water unpotable due to the salty taste. In the U.S., there is a secondary (non-enforced) drinking water standard of 250 mg/L, but in areas of the world with water scarcities, drinking water can have considerably greater concentrations of Cl^-. Chloride is corrosive to steel, thus it may corrode pipes in water treatment and industrial plants. Because it imparts a salty taste to water and is corrosive, elevated Cl^- levels in drinking water supplies can lead to increased treatment costs. Elevated Cl^- in surface water has been linked to damage of terrestrial and aquatic plants and aquatic animals at concentrations as low as 210 mg/L (Environment Canada, 2001; Hart et al., 1991; Kaushal et al., 2005; Wilcox, 1986). The U.S. Environmental Protection Agency (USEPA) recommends a chronic criterion for aquatic life of a four-day average Cl^-concentration of 230 mg/L with an occurrence interval of once every three years (USEPA, 1988). The recommended acute criterion is 860 mg/L, which relates to a one-hour average concentration with a recurrence interval of less than once every three years. The Illinois EPA (IEPA) uses an acute criterion of 500 mg/L, but there is no chronic standard. The government of British Columbia has proposed a lower maximum Cl^- concentration of 600 mg/L and a 30-day average concentration of 150 mg/L to protect freshwater life (Nagpal et al., 2003). Increased Cl^- concentrations in some environments have killed off native vegetation and allowed invasive salt-tolerant species to thrive (Panno et al., 1999).

The objective of this report is to characterize the sources, distribution, and trends of Cl^- in the waters of Illinois, including rainwater, lakes, rivers and streams, groundwater, and wetlands.

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Natural Sources of Chloride

Precipitation

Chloride in precipitation and dry deposition originates from marine aerosols or volcanic gases. Naturally-occurring Cl^- concentrations in rainwater and snowmelt can be several mg/L near the coastal regions of the U.S. due to the contribution of seawater aerosols (Figure 1). Chloride concentrations in mid-continental regions are much lower. Concentrations in Illinois are typically less than 0.1 mg/L (NADP, 2011).

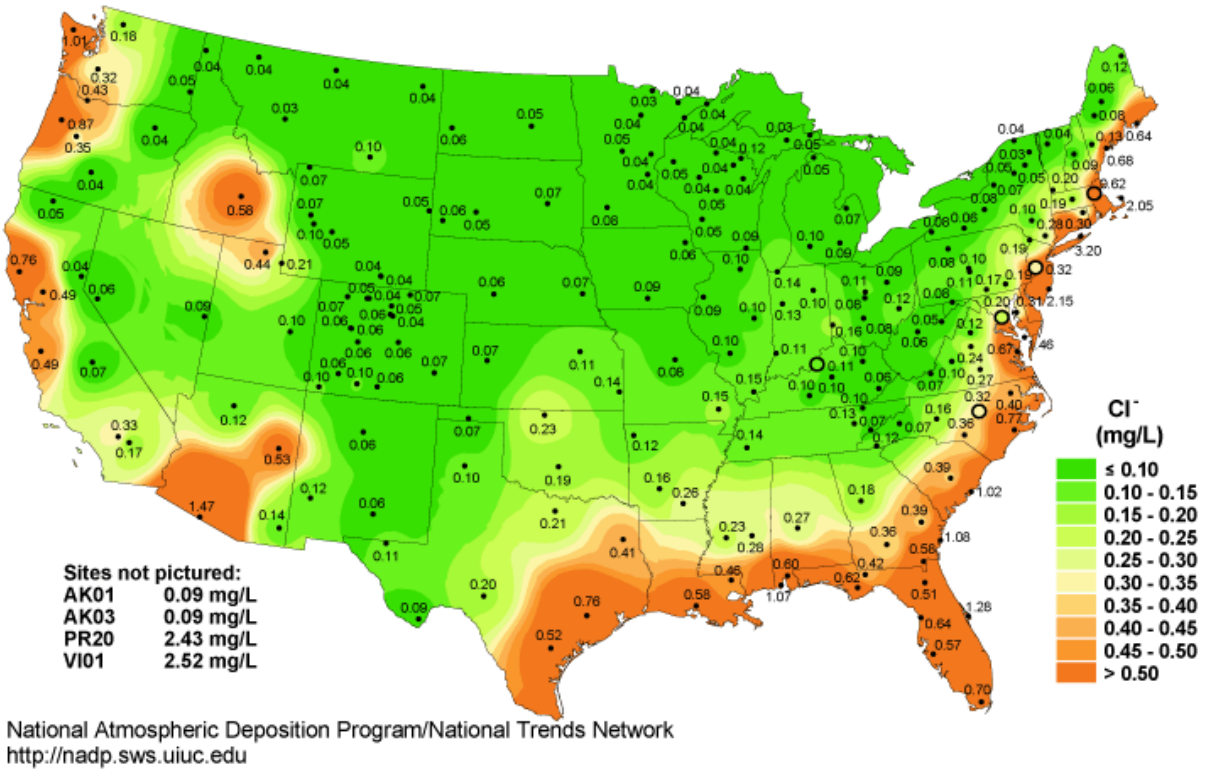

Figure 1. Chloride concentrations in U.S. precipitation for 2009. Map from NADP, 2011.

Rock-Water Interactions

Once rainwater and snow fall to the ground, evaporation and evapotranspiration tend to concentrate the Cl^- in soil water to levels ten or more times their original concentration. Rock-water interactions such as mineral dissolution and desorption within the soil zone and groundwater can further increase Cl^- concentrations.

The largest source of Cl^- in the Earth's crust is the mineral halite (NaCl) in evaporate deposits, which formed over geologic time by the evaporation of seawater. Chloride is also found in other less common salts (e.g., potassium chloride [KCl] and calcium chloride [$CaCl_2$]) associated with these evaporite deposits. Because halite and other chloride salts are extremely soluble, they are not found in areas where there is active circulation of fresh water. There are no known halite deposits in Illinois, although there is evidence from breciated limestone that evaporates may have existed in the geologic past (Willman et al., 1975). Chloride is found in small amounts (1000 to 10,000 parts per million [ppm]) in some silicate and phosphate minerals, including biotite, amphibole, apatite, sodalite, and scapolite (Kamineni, 1987), but these are not common minerals in the sedimentary rocks and sediments of Illinois. Chloride is a minor constituent of sedimentary rocks such as limestone, sandstone, and shale (as well as granitic rocks), but typically at low concentrations. Krauskopf (1979) reported typical Cl^- concentrations of 150, 10, and 200 ppm for limestone, sandstone, and shale, respectively. Chloride is also present within some minerals as fluid inclusions and can have very high concentrations comparable to those of a concentrated brine; however, fluid inclusions are typically very small (a few microns in diameter) and impart very little Cl^- to circulating groundwater. Because of the lack of appreciable amounts of Cl^- in rocks and sediments of Illinois, soils, sediments, and rocks in the shallow subsurface in Illinois would not be expected to have appreciable amounts of naturally-occurring Cl^-.

There are, however, natural brines in Paleozoic sedimentary formations of the Illinois Basin that underlie the southern two-thirds of the state (Figure 2). Meents et al. (1952) sampled over 700 oil field brines in the oil-producing regions of Illinois, primarily in the southeastern quadrant of the state; more than 80 percent of the samples had Cl^- concentrations greater than that of seawater, with a high of ~95,000 mg/L. Panno et al. (2006) summarized data from several studies in the Illinois Basin, and calculated a median Cl^- concentration of 64,600 mg/L, about three times the concentration in seawater.

Naturally saline groundwater in Illinois is very old. The chemical and isotopic compositions of brines in the Illinois Basin suggest they were formed as a result of the partial evaporation of seawater short of the precipitation of halite (Walter et al., 1990; Stueber and Walter, 1991; Kesler et al., 1995). Deeper groundwater in Precambrian granitic bedrock is even more saline, intensified by very long-term rock-water interactions at much warmer conditions than those encountered nearer the surface. Groundwater in the deeper parts of the Paleozoic and crystalline basement bedrock of the Illinois Basin is typically a hypersaline, calcium (Ca)-sodium (Na)-Cl-type brine with total dissolved solids (TDS) concentrations greater than 100,000 to over 250,000 mg/L (Horita, 2005).

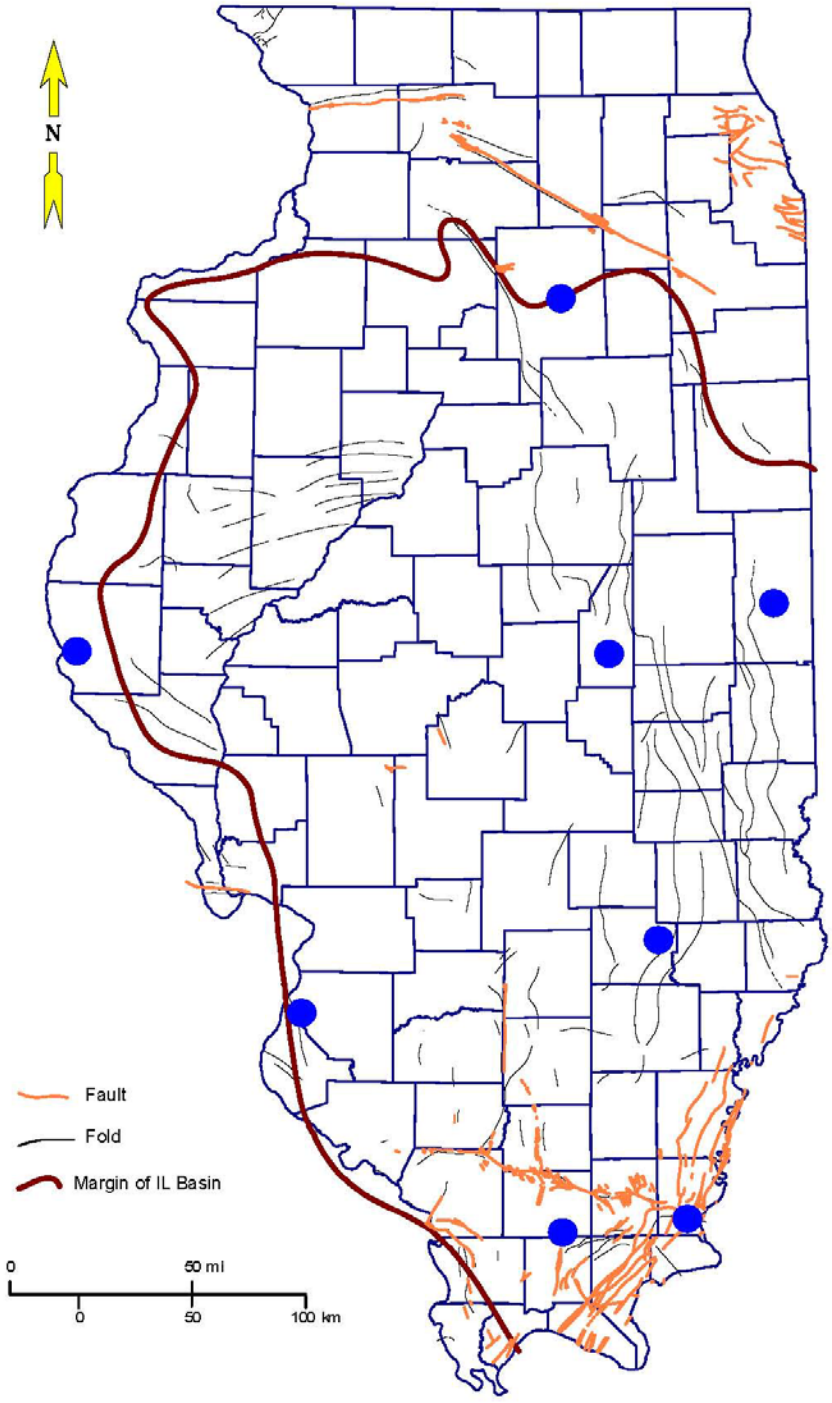

Figure 2. Illinois Basin. Blue circles indicate location of saline springs. Figure from Panno et al. (in preparation).

Saline groundwater in Illinois is under pressure, and at many locations it discharges into shallower aquifers or at the land surface as saline springs (Bartow et al., 1909; Willman et al., 1975; Cartwright, 1970; Panno et al., 1994, 2006). Bedrock discharge into the Mahomet Aquifer in Piatt County in east-central Illinois increases the Cl^- concentration from less than 10 mg/L to concentrations as high as 500 mg/L (Hackley et al., 2010). Thirteen samples of brine-affected groundwater collected by Panno et al. (2006), primarily in the southern part of the state, had a median Cl^- concentration of 474 mg/L. In some parts of Illinois, especially in the south, these deep brines discharge to surface waters, increasing the natural Cl^- concentration. For example, the North Fork of the Saline River in southeastern Illinois, named for its natural saltiness, had a median Cl^- concentration of 109 mg/L between 1978 and 1997 (USGS, 2009).

Background Chloride Concentrations

Despite the existence of saline seeps in Illinois, the vast majority of groundwater has relatively low concentrations of Cl^-, especially in major aquifers. In a study of shallow groundwater (< 100 meters) in northern Illinois, Panno et al. (2006) determined that Cl^- concentrations in shallow aquifers ranged from less than 1 to 15 mg/L. They suggested that concentrations greater than 15 mg/L indicated contamination from human sources. This threshold is probably similar (or lower) for aquifers in the rest of Illinois as well, where urbanization is less (Panno et al., 2005). Prior to human alterations to the landscape, almost all water discharging to surface streams in Illinois passed through the subsurface (i.e., groundwater), and a large majority still does. Thus pristine surface waters in Illinois should have Cl^- concentrations < 15 mg/L. Lusk Creek, for example, which flows through the undeveloped Shawnee National Forest in southern Illinois, had a median Cl^- concentration of 2.3 mg/L between 1978 and 1997 (USGS, 2009).

Anthropogenic Sources

Schlesinger (2004) estimated that more than 140 teragrams (140 trillion kilograms) of Cl^- are annually cycled through various reservoirs on Earth, almost all of it due to human activities. Anthropogenic sources include human sewage, livestock waste, water conditioning salt, synthetic fertilizer (primarily KCl), brine disposal pits associated with oil fields, chemical and other industries, and, in snowy climes, road salt runoff. From a volume standpoint, the most important anthropogenic sources of Cl^- to waters in Illinois are fertilizer, road salt, water conditioning salt, sewage, and livestock waste (Table 1). Chloride concentrations for potential contamination sources of Cl^- in Illinois are shown in Table 2. Once in groundwater, Cl^- and other contaminants can persist for many years if travel times are slow. For example, Howard et al. (1993) estimated that if road salting was stopped immediately in the Toronto area, it would be decades before the Cl^- concentrations returned to pre-1960 levels in shallow groundwater. In rural areas, agricultural sources of Cl^- are of greater importance. Oil field-related contamination problems have occurred primarily in the southern two-thirds of Illinois.

Table 1. Annual Chloride Fluxes in Illinois

Source	*Flux (metric tons)*
Treated Wastewater	
MWRDGC	175,000
Remainder of state	125,000
Atmospheric	18,000
Road Salt	471,000
Water Conditioning Salt	135,000
Fertilizer (KCl)	373,000
Livestock	139,000
Lake Michigan withdrawals	34,000
Groundwater withdrawals	
Public supply wells	12,500
Industrial/commercial	5,300
Irrigation	10,000
Oil-Field Brines	23,000

Note: The treated wastewater fluxes do not include road salt inputs.

Table 2. Chloride Concentrations (mg/L) for Potential Sources in Illinois

Sample Type	*Location*	*Min*	*Median*	*Max*	*Reference*
Tile Drain	Ludlow	10.3	14.5	17.8	Kelly et al. (2010)
	Champaign	23.1	25.4	36.5	Panno et al. (2005)
Treated Wastewater	Stickney (2000-2008)	26.3	145	1,481	MWRDGC
Road Salt Runoff	Willow Springs		8,930		Kelly et al. (2010)
	Pekin		1,572		Kelly et al. (2010)
Agricultural Soil Water	Central Illinois	16.2	17.5	20.8	W. Kelly (unpublished data)
Natural Brine	Central Illinois		6,517		Panno et al. (2006)
	SW Illinois		8,080		Panno et al. (2006)
Illinois Basin Brine		557	64,600	125,000	Panno et al. (2006)
Livestock Manure	Central Illinois	440	847	1,980	Panno et al. (2006)
Septic System Discharge	SW Illinois	20.8	91	5,620	Panno et al. (septic paper)
Landfill Leachate		198	1,284	6,170	Panno et al. (2006)

Human Waste

The median Cl^- concentration in treated wastewater (TWW) discharging from the Stickney wastewater treatment plant (WWTP) in Chicago (the largest in the U.S.) between 2000 and 2008 was 145 mg/L (based on weekly sampling) (MWRDGC, 2010) (Table 2). Kelly et al. (2010) got similar results in samples collected on three dates between 2003 and 2005 from two Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) WWTPs (Stickney and Calumet); they reported a median Cl^- concentration of 141 mg/L. Kelly et al. (2010) also collected samples from the Peoria WWTP, which had Cl^- concentrations that ranged from 113 to 291 mg/L. TWW is generally discharged directly into surface waterways in Illinois.

Livestock Waste

Animal waste contains elevated concentrations of Cl^-; Panno et al. (2006) measured levels as high as 1980 mg/L (Table 2). Because of this, even relatively small concentrations of livestock can create a local problem for shallow groundwater. Large confined animal feeding operations, which can concentrate thousands of animals in a relatively small area, have the potential to produce more widespread contamination of shallow groundwater, streams, and rivers (Wing et al., 2002; Showers et al., 2008).

Road Deicers

The chemical industry and governmental departments handling road ice control are the major importers and consumers of halite in the U.S., accounting for about three-fourths of its total use (Kostick, 2008). Road salt has been linked to groundwater degradation in many urban and roadside areas in snowy climes (Amrhein et al., 1992; Bester et al., 2006; Howard and Haynes, 1993; Huling and Hollocher, 1972; Pilon and Howard, 1987; Williams et al., 2000b). Significant application of road salt began after World War II and accelerated rapidly from the 1960s (Figure 3) (Salt Institute, 2009). Chloride concentrations have been increasing in surface waters and groundwater in urban regions of the northern United States and Canada since the 1960s, primarily due to road salt runoff (Godwin et al., 2003; Howard and Haynes, 1993; Kaushal et al., 2005; Kelly, 2008; Novotny et al., 2009; Kelly et al., 2010).

Two road salt runoff samples collected by Kelly et al. (2010) dripping off road bridges in Pekin and Willow Springs, IL, had very high concentrations of Cl^-: 1572 and 8930 mg/L, respectively (Table 2). Chloride concentrations in road salt runoff samples are extremely variable due to variability in application rates, snowfall amounts, melting rates, etc.; the values measured by Kelly et al. (2010) fall within the range of values reported by others (Amrhein et al., 1992; Environment Canada, 2001; Greb et al., 2000; Pilon and Howard, 1987). Road salt also can increase Cl^- concentrations in precipitation. For example, Williams et al. (2000a) characterized road salt aerosol in suburban areas west and south of Chicago, and measured Cl^- concentrations up to 9.4 mg/L in samples collected after snow events. They also found that Cl^- concentrations in snow samples decreased exponentially with distance from major highways.

Road salt runoff that recharges the soil zone and shallow groundwater can produce very high concentrations of Cl^-. Kelly and Roadcap (1994) measured Cl^- concentrations in excess of 1,000 mg/L in several shallow (< 25 ft; 7.6 m) monitoring wells installed along the uncurbed Interstate 94 in south Chicago, including two exceeding 3,500 mg/L.

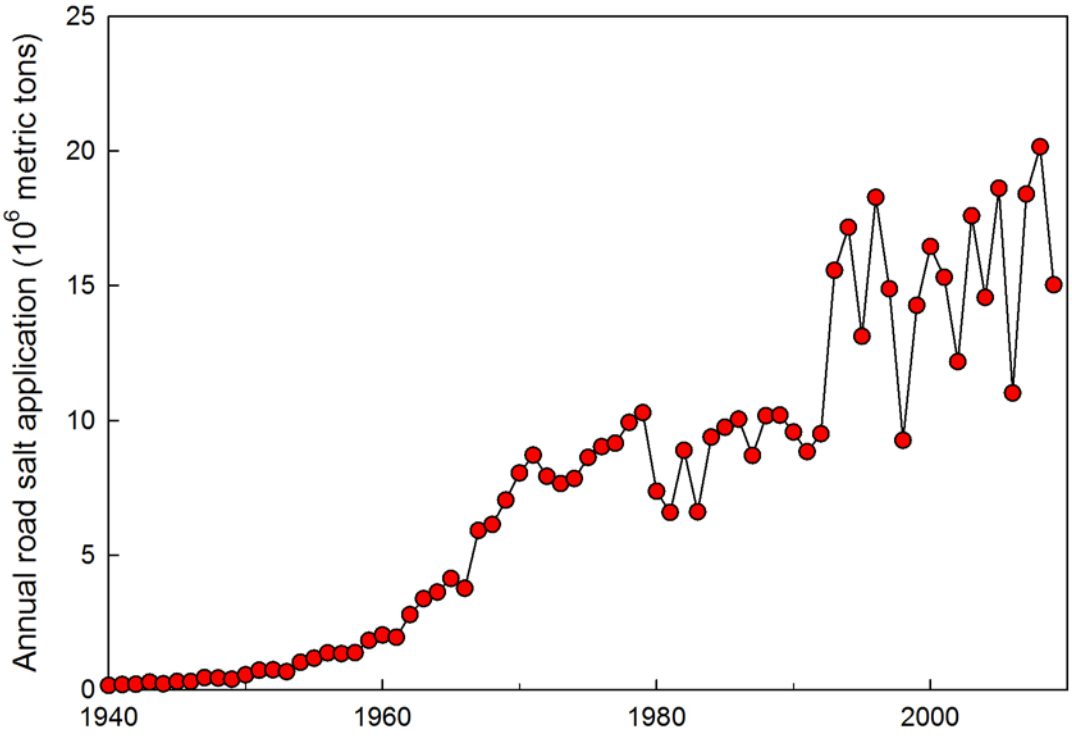

Figure 3. Yearly U.S. highway salt sales. Data from Salt Institute, 2011.

Water Conditioning Salts

In-home water treatment, specifically water softening, typically uses NaCl to recharge ion exchange columns in order to reduce hardness (Ca + Mg) by replacement with Na. For a family of three or four with moderately hard water, the recommended amount of NaCl for water softening is between 1.8 and 2.7 kilograms per day, or 600 to nearly 1000 kg of NaCl per year (Panno et al., 2005, 2007). If a household uses on-site wastewater treatment, the Cl^- is discharged to the shallow groundwater system via the leach field. If the household is connected to a community waste treatment facility, the Cl^- (which is not removed in the treatment process) is generally discharged to streams or rivers.

KCl Fertilizer

Illinois is a major producer of row crops, primarily corn and soybeans. KCl is the most commonly available potassium (K) fertilizer and usually the cheapest, thus it is widely applied in Illinois. Because it is spread over large areas (i.e., non-point source), its impact on soil water and

groundwater quality is less than more concentrated Cl^- applications, such as road salt. In much of Illinois, agricultural fields are tiled to facilitate drainage of soils, and these drain tiles are the major source of water to many streams in Illinois. Panno et al. (2005) and Kelly et al. (2010) collected samples from several tile drains in east-central Illinois, which represent shallow groundwater beneath row crop areas. Chloride concentrations in these tile drain samples ranged from 10 to 37 mg/L (Table 2). This is also approximately the same concentration range found in soil water in agricultural fields in central Illinois (W. Kelly, unpublished data).

Municipal Landfills

Panno et al. (2006) measured Cl^- concentrations in municipal landfill leachate as high as 6,170 mg/L. Roy (1994) reported the greatest Cl^- concentration recorded in municipal landfill leachate to be 27,100 mg/L. Potential sources of Cl^- in landfills include food scraps and pet wastes. Chloride concentrations in landfills are not static, but decrease with the age of the landfill (McGinley and Kmet, 1984; Ham, 1980; Lu et al., 1985). Farquhar (1989) reported that Cl^- concentrations in municipal landfill leachate tend to decrease asymptotically with time, with concentrations 1,000–3,000 mg/L during the first five years, 500–2,000 mg/L during years 5 to 10, 100–500 mg/L during years 10 to 20, and < 100 mg/L after that.

Oil and Gas Exploitation

Leakage of brine-holding ponds associated with oil wells has locally contaminated groundwater with high TDS waters in southeastern Illinois. Hensel and McKenna (1989) installed shallow monitoring wells around two brine-holding ponds in Clay County and measured Cl^- concentrations over 10,000 mg/L in several samples. They identified 384 holding ponds in their study area (~300 mi^2 in southeastern Clay County), so the potential for widespread groundwater contamination is significant and hundreds of acres of farm land were reported to have been made unsuitable for crops due to brine leakage and spillage. However, Hensel and McKenna (1989) found no widespread degradation of groundwater resources in the area.

Identification of Sources of Chloride

There are various methods for determining the source(s) of Cl^- in individual water samples, one of the best being halide ratios. In a recent investigation, Panno et al. (2006) collected more than 100 samples from various Cl^- sources (primarily in Illinois) and, by plotting Cl^- and bromide (Br^-) data on a Cl^- vs. Cl/Br diagram, were able to define domains that distinguish among the sources (Figure 4). TWW can plot outside the septic effluent source domain because there are often multiple sources of Cl^- in TWW. Chicago and many of its suburbs have combined sewers (sewage and storm water), and an average of about 30 percent of the water entering the Stickney WWTP is from storm runoff (J. Wasik, MWRDGC, December 1, 2006, personal communication). The highest Cl/Br ratios in TWW measured by Kelly et al. (2010) were during the winter, which was due to a dominant road salt component.

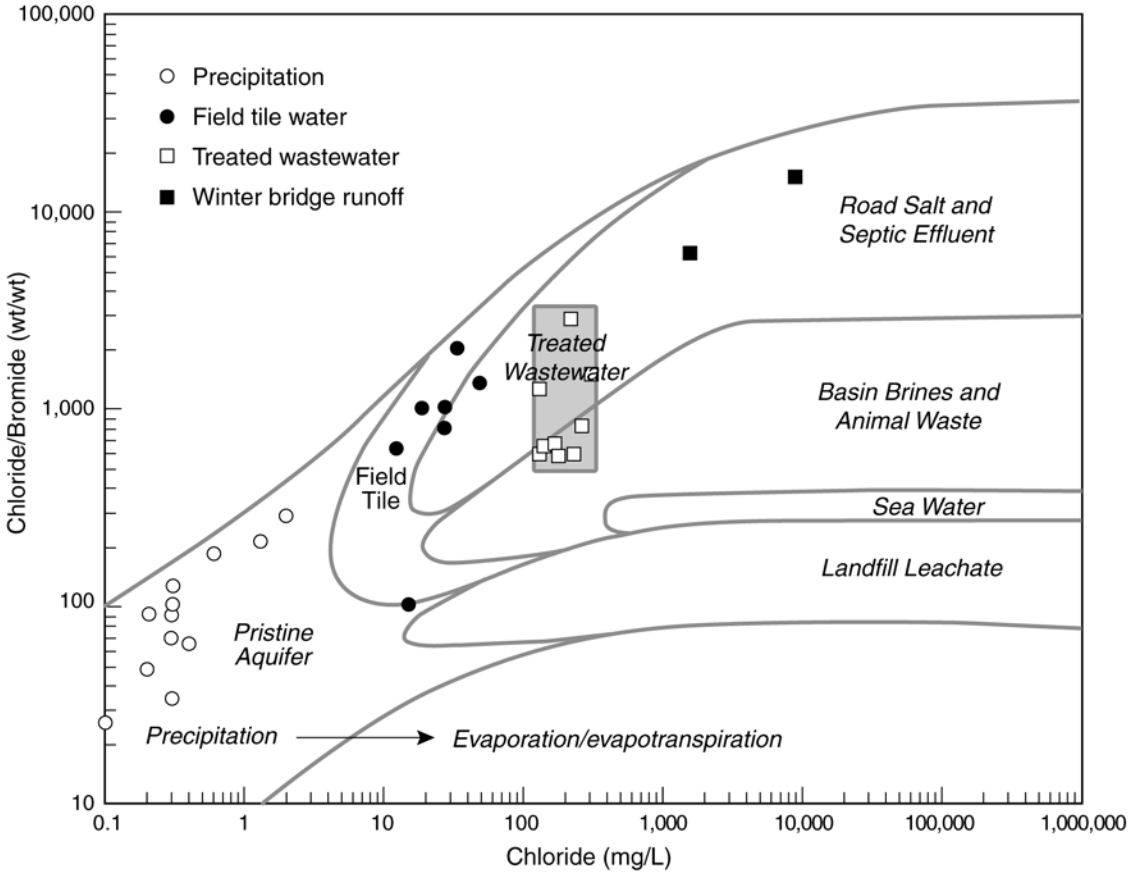

Figure 4. Cl/Br vs. Cl^- plot showing source domains (Kelly et al., 2010)

Annual Fluxes of Chloride in Illinois

The estimated annual flux of Cl^- in Illinois from various sources was determined using the methods of Kelly et al. (2010) (Table 2). They found that Cl^- in the Illinois River Basin was predominantly from road salt, TWW, and KCl fertilizer. An accurate estimate of how much road salt is applied in an average winter is difficult, due to the large number of government agencies and private entities that apply salt to roads and parking lots. Friederici (2004) and Keseley (2006) reported more than 250,000 metric tons of road salt is applied annually in the Chicago metropolitan region, but this is almost certainly an underestimate. Probably the best method for estimating road salt applications is to use road salt sales reported by the Salt Institute (Salt Institute, 2009) as a proxy. Using additional state data from Richter and Kreitler (1993) and Panno et al. (2005), Kelly et al. (2010) estimated that an annual average of 471,000 metric tons of road salt (equivalent to ~283,000 metric tons of Cl^-) were used in Illinois for the years 2002 to 2005, mostly in the Chicago region. Average annual road salt sales have increased since 2005, so the amount of road salt applied in Illinois has undoubtedly increased as well. The amount applied in a particular year generally depends on how much snow and ice fall during winter.

The Cl^- flux for TWW from the Chicago region can be calculated from WWTP discharge and Cl^- concentration data reported by MWRDGC (MWRDGC, 2010), but this calculation is complicated by multiple sources in TWW and the potential for "double counting" of sources. In addition to human waste, TWW includes industrial effluent, water conditioning salt, and road salt, as well as Cl^- present in drinking water sources.

Chloride fluxes from the Chicago WWTPs were calculated using Cohn's equation (Kelly et al., 2010). Road salt contributions were removed from the WWTP loads by assuming that there was no road salt in TWW from May to October. Chloride loads during these months were divided by monthly discharges, and it was assumed that the same load per discharge ratio for non-road salt sources occurred between November and April. The remaining chloride loads between November and April (which varied between 17 percent and 50 percent of the total monthly load) were assumed to come from road salt and were removed from the TWW load calculations.

The seven MWRDGC plants account for almost 60 percent of the TWW discharged to surface water bodies in Illinois. To calculate the Cl^- flux for the remaining TWW, it was assumed that the effluent Cl^- concentration was the same as for the MWRDGC plants, resulting in a flux of 125,000 metric tons.

Human waste actually accounts for a small percentage of Cl^- in TWW. Adult humans excrete between 110 and 250 millimoles of Cl^- per day (3,900–8,860 mg day) (WebMD, 2011). Assuming 5,500 mg of Cl^- per day, a typical value for urine production (1.25 L/day), and a 2010 population of 12.83 million, results in about 32,000 metric tons of Cl^- from human urine annually in Illinois. Another approach taken by Mullaney et al. (2009) is to use per capita salt consumption based on the recommended daily adult sodium intake of 2,300 mg/d, which would include about 3,547 mg of Cl^-. A person on this diet would consume, and release, about 1.3 kg of Cl^- per year, which would be released by wastewater discharge. This would produce almost 17,000 metric tons of Cl^- in Illinois per year. Either estimate represents less than 10 percent of the Cl^- in TWW.

Chloride from water conditioning salt was also estimated from salt sales data. Between 2005 and 2008, approximately 3.2 million metric tons of salt (predominantly NaCl) was sold for water conditioning in the U.S. (Salt Institute, 2009). Assuming that water conditioning salt use was distributed equally across the U.S. based on population, approximately 135,000 metric tons of Cl^- is annually consumed in Illinois by water conditioning.

About 80 percent of corn fields and 30 percent of soybean fields in Illinois receive potassium chloride (KCl) annually (USDA, 2008). The amount of KCl applied in Illinois was estimated from state fertilizer sales data (USDA, 2008). Between 2005 and 2007, an average of 373,000 metric tons of Cl^- from KCl were purchased per year in Illinois.

Between 2005 and 2008, there were approximately 4.23 million pigs and 1.28 million cattle in Illinois (Illinois Agricultural Statistics Service, 2009). A pig produces about 3 gallons of waste a day and a cow produces 14 gal/day. Using Cl^- concentrations of 3,680 mg/L and 3,000 mg/L for pigs and cows, respectively (DeRouchey et al., 2003; Lengemann et al., 1952), an annual total of 139,000 metric tons of Cl^- was calculated to come from livestock.

For Cl^- from precipitation, a Cl^- concentration of 0.12 mg/L and an average annual precipitation of 102 centimeters (cm) were assumed (NAPD, 2011). This gives approximately 18,000 metric tons of Cl^-.

One source of Cl^- that may be overlooked is water extracted from Lake Michigan and groundwater for drinking, industrial, and agricultural purposes. Chicago and many of the inner suburbs obtain drinking water from Lake Michigan, which has a Cl^- concentration of approximately 12 mg/L. Because most of the water Illinois takes from Lake Michigan is discharged outside the Great Lakes Basin, Illinois is limited by U.S. Supreme Court decree to 3,200 cubic feet per second (cfs) (~2,900 billion L/yr) of water from the lake. Assuming Illinois diverts all of this each year, approximately 34,000 metric tons of Cl^- is removed from the lake. Most of this eventually finds its way into wastewater, which would be included in the TWW Cl^- flux, and eventually is discharged down the Illinois River.

Approximately 1,180 million gallons (4,470 million L) of groundwater are withdrawn daily in Illinois (Kenny et al., 2009). About 507 million gallons per day (mgd) (1,920 million L/day) are used for drinking and other household uses, 517 mgd for agriculture (irrigation and livestock), 128 mgd by industrial and commercial applications, 15.5 mgd by mining, and 7.2 mgd for thermoelectric. Most extracted groundwater is not returned to the ground, but eventually finds its way to surface waters. In communities with sewers, most drinking water eventually finds its way into wastewater, which is then discharged to surface streams and rivers, eventually leaving the state. For homes and businesses with private wells and on-site sewage treatment (i.e., septic systems), extracted groundwater is discharged at or just below the ground surface, and most does not recharge underlying aquifers but is either evapotranspired or discharged to nearby streams or other surface waters. The same is true for irrigation water.

Groundwater withdrawal data are available for many public water supply wells and industrial/commercial wells. Of the top 200 pumped public water supply wells, 176 have been sampled sometime in the past 20 years, and the Cl^- concentration and withdrawal data from 2008 were used to calculate the mass of Cl^- removed. In order to not include potential surface contamination sources in shallow wells, it was assumed that the background Cl^- concentration was 15 mg/L in all wells $\leq$ 250 feet deep. These results were then used to estimate Cl^- fluxes

from the other approximately 2,500 public water supply wells for which we have withdrawal data. It was estimated that approximately 12,500 metric tons of Cl^- was extracted from public supply wells.

Sample results were available only for 13 of the top 200 industrial/commercial wells. For 184 of the other 187 wells, samples from a well located near to and at a similar depth to the well in question were found, and the Cl^- concentration from that well was used to calculate Cl^- fluxes. Using these data and the assumption that the background Cl^- concentration was 15 mg/L in all wells $\leq$ 250 feet deep gives an estimate of approximately 5,300 metric tons of Cl^- extracted annually from industrial/commercial wells.

In 2005, the U.S. Geological Survey estimated that approximately 479 million gallons of water were pumped from irrigation wells in Illinois (USGS, 2009). Withdrawal data from individual irrigation wells are lacking in Illinois. Because most irrigation wells are finished in relatively shallow sand and gravel aquifers, it was assumed that the Cl^- concentration was 15 mg/L. This gives a Cl^- flux of approximately 10,000 metric tons from irrigation wells.

It is difficult to get accurate estimates of how much water is withdrawn for oil and gas production. The most recent and most reliable estimates are from the 1980s, when Kirk (1987) reported that 25.5 million gallons per day (~9.3 billion gallons annually) were withdrawn. Almost all of this is reinjected for secondary oil and gas recovery. However, some of this brine was temporarily stored in ponds at the surface, and leakage to surface and shallow subsurface environments has been reported (Hensel and McKenna, 1989). Using the median concentration of 64,600 mg/L reported by Panno et al. (2006), and assuming leakage of 1 percent of the withdrawn brine, gives an annual Cl^- flux of approximately 23,000 metric tons.

Distribution and Trends in Chloride Concentrations in Waters of Illinois

Recent research has suggested that Cl^- concentrations in many water bodies in Illinois are changing (e.g., Kelly [2008] and Kelly et al. [in press]), thus any report on the distribution of Cl^- is a "snapshot in time," subject to change. This is especially true for rivers and shallow groundwater in urban and urbanizing areas, most notably the Chicago region. In order to fully understand the distribution of Cl^- in the waters of Illinois, a discussion of temporal trends must also be included. Trends in Cl^- concentrations in surface water and groundwater can reveal much about the origin, evolution, character, and movement of its sources. Such information is critical to predicting future changes in Cl^- concentrations.

Lakes

As mentioned previously, Lake Michigan currently has an average Cl^- concentration of 12 mg/L, its highest historical level. Concentrations have been slowly increasing since the late 1800s, due to human inputs to the lake (Chapra et al., 2009), with an increase of about 3 mg/L since the 1980s (USEPA, 2011a) (Figure 5). While the increase seems small, it represents an additional annual load of approximately 600,000 metric tons of Cl^- to Lake Michigan.

Natural lakes in Illinois are primarily found in the northern part of the state, especially Lake and McHenry Counties. Most lakes in downstate Illinois are reservoirs created by the

damming of streams and rivers. Their Cl^- concentrations are similar to those found in their stream or river supplies, potentially increasing in summer if there is significant evaporation.

Many lakes in Lake County have been monitored between April and October for dissolved solids since the late 1980s by the Lake County Health Department (LCHD). Chloride concentrations have been routinely monitored only since 2005, but specific conductance, which is highly correlated with Cl^- concentrations, has been monitored from the beginning. Specific conductance values have been increasing with time in most of these lakes (Figure 6). In 2010, the median Cl^- concentration in the 22 lakes being monitored by LCHD was 112 mg/L, with highest concentrations usually measured in the first sample collected (May). Between 2005 and 2010, Cl^- concentrations have generally dropped in many of these lakes, which has been attributed to dilution during the relatively wet summers in recent years (Figure 7) (M. Adams, LCHD, pers. comm.). There is anecdotal evidence that the increasing TDS levels in lakes at golf courses has forced their abandonment as sources of irrigation water due to the deleterious effects on turf. This in turn has led to drilling of new wells, increasing the amount extracted from aquifers in Lake County.

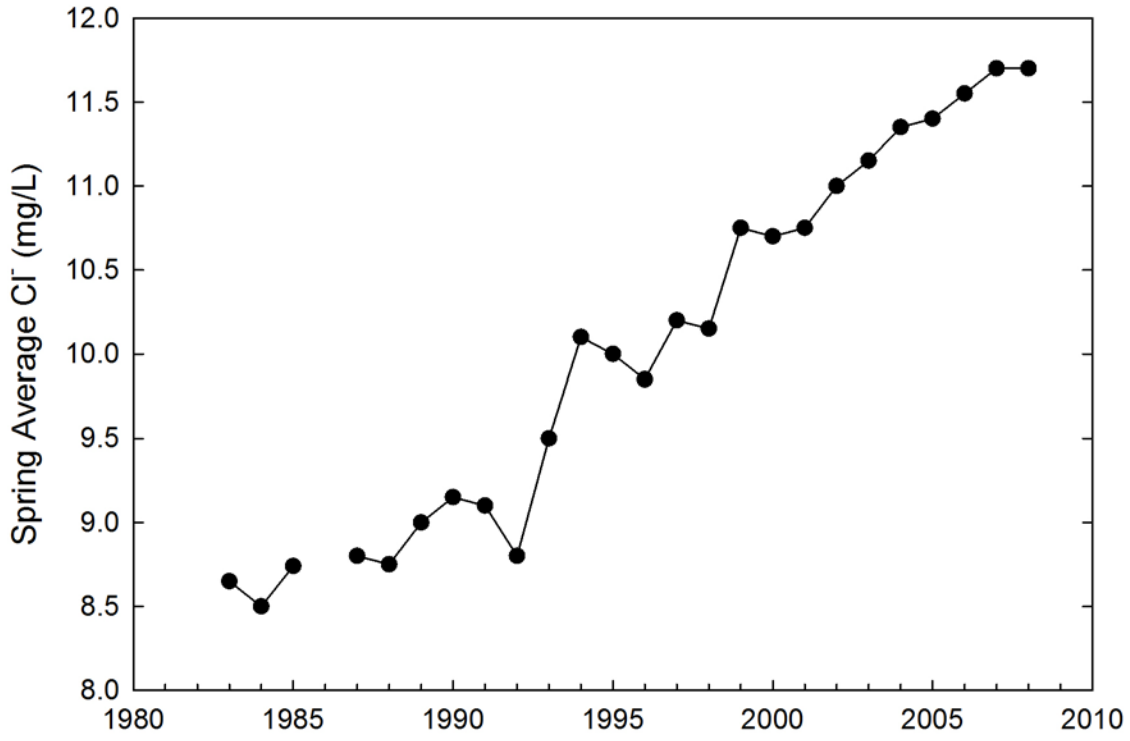

Figure 5. Chloride concentrations in Lake Michigan. Data from USEPA, 2011.

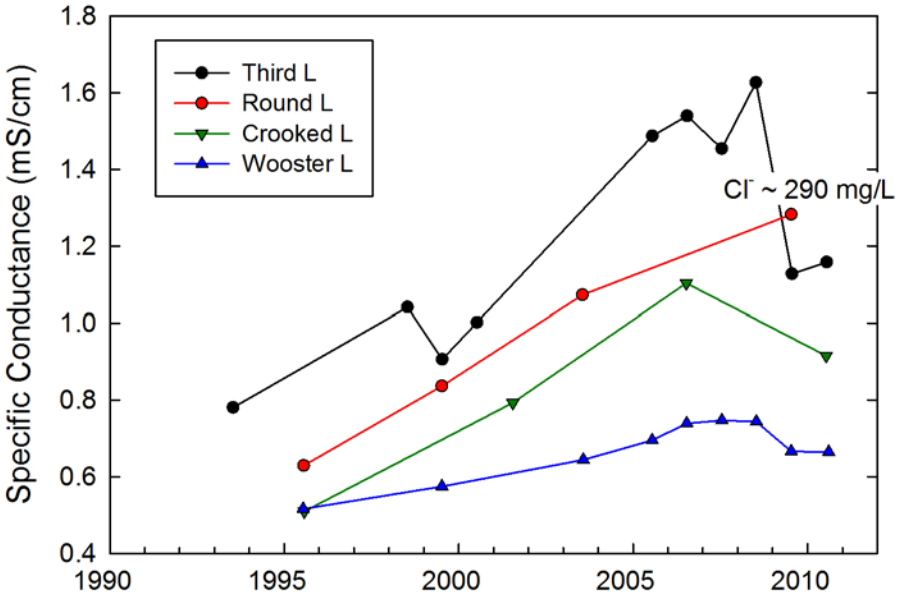

Figure 6. Annual median specific conductance values in selected lakes in Lake County. The chloride concentration for the most recent sample from Crooked Lake is reported. Data from Lake County Health Department.

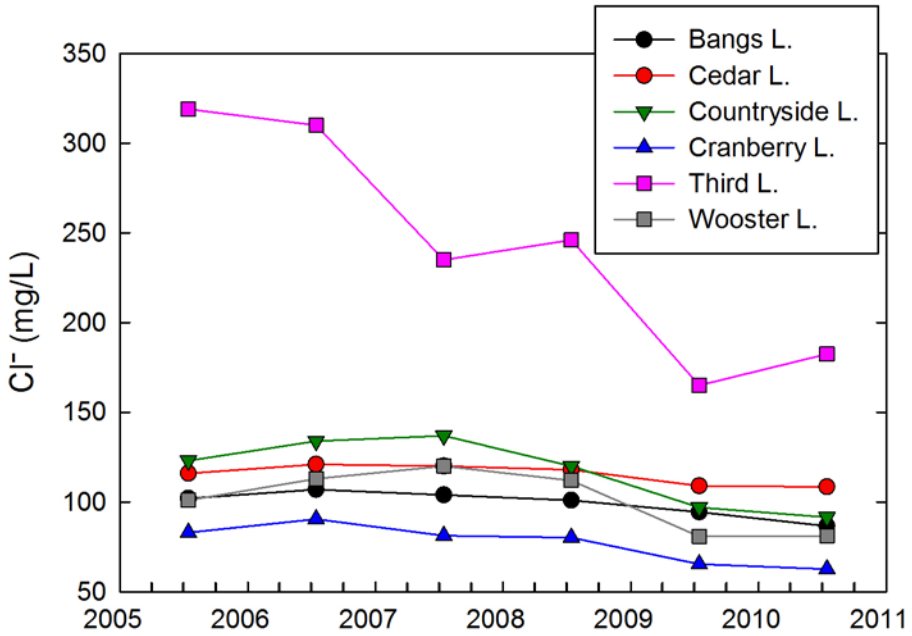

Figure 7. Chloride concentrations in selected lakes in Lake County. Data from Lake County Health Department.

Rivers and Streams

Water quality data for streams and rivers in Illinois are available from several agencies, including the ISWS, USGS, MWRDGC, and IEPA. Chloride concentrations in streams in Illinois are highest in the Chicago region and lowest in streams in forested watersheds in far southern Illinois. The USGS has historical data from a number of streams and rivers throughout Illinois. A comparison of data sets from a time period with the greatest overlap of data (1990–1992) indicates that downstate rivers draining primarily agricultural watersheds (Kankakee, Spoon, La Moine) had median Cl^- concentrations < 30 mg/L (Table 3 and Figure 8). Even though the North Fork of the Saline River drains an agricultural watershed, it has natural sources of Cl^- (geological brine discharge) and thus had a significantly higher median Cl^- concentration (86 mg/L). The Sangamon River, which has several large cities in its watershed (Bloomington-Normal, Decatur, Springfield), had a median concentration (34 mg/L at its most downstream station, Oakford) higher than rivers draining primarily agricultural land. The Fox River, which drains some of the western suburbs of the Chicago region and receives TWW, had an even higher median concentration (70 mg/L at its most downstream station, Dayton). Major Chicago waterways, including the Des Plaines River and the Chicago Sanitary & Ship Canal (CSSC), had median values > 90 mg/L. The median Cl^- concentration in the Illinois River, which receives water from tributaries in the Chicago region as well as down-state, is > 60 mg/L at Peoria and upstream, dropping to around 50 mg/L near its discharge to the Mississippi. Figure 9 shows that there are large annual variations in Cl^- concentrations in rivers throughout Illinois.

The MWRDGC has been monitoring water quality monthly at surface water stations in the Chicago region since 1975, primarily in Cook County but also at a few stations in DuPage and Will Counties (Figure 10). Forty-one stations have been monitored relatively continuously since 1975, with more than 30 others having a shorter period of record. Median Cl^- concentrations in 2008 were > 150 mg/L at about 80 percent of the stations (Figure 11 and Table 4). The highest values tended to be in the smallest streams in northern Cook County, including Higgins Creek, Salt Creek, and Buffalo Creek, as well as the North Branch of the Chicago River. The stream with the lowest values appears to be the North Shore Channel, which receives significant flow from Lake Michigan.

The presence of trends in Cl^- concentrations were determined using Kendall's tau test at the 95 percent confidence level, and annual rates of change were estimated by calculating slope coefficients (β_1) on 5-point running medians (Helsel and Hirsch, 2002). Rivers draining the Chicago region, including the Illinois River, have increasing trends in Cl^- concentrations. Of the 41 stations monitored by MWRDGC since 1975, 35 had statistically significant positive trends in Cl^- concentrations, with a median increase of 2.7 mg/L per year (Table 5). Five stations had increases of greater than 5 mg/L/yr; two of these stations were in the North Branch of the Chicago River. Of a total of 78 USGS stations tested throughout the entire state, 36 had significant positive trends in Cl^- concentrations, and 10 had significant negative trends (Table 6). The positive stations included almost all the Chicago region rivers and canals (Des Plaines River, Fox River, Chicago River, Addison Creek, CSSC), as well as a number of down-state rivers, including the Kankakee, Rock, and Sangamon Rivers. All of the Illinois River stations, as well as those on the Mississippi and Ohio, had positive trends. The stations with negative trends were scattered throughout the state.

Table 3. Median Cl^- Values (mg/L) for Rivers in Illinois for Water Years 1991–1992 at USGS stations. For Rivers with More Than One Station (Ordered from Upstream to Downstream)

River	*Location*	*Station*	*Median*		*River*	*Location*	*Station*	*Median*
Big Muddy	Murphysboro	5599500	31		La Moine	Colmar	5585000	17
Cache	Forman	3612000	10		Little Wabash	Effingham	3378635	30
Cal Sag Channel	Sag Bridge	5536700	105		Little Wabash	Carmi	3381495	34
Casey Fork	Mt Vernon	5595830	67		Lusk Ck	Eddyville	3384450	2.3
CSSC	Romeoville	5536995	109		Md Fk Vermilion	Oakwood	3336645	24
CSSC	Lockport	5537000	91		N Branch Chicago	Deerfield	5534500	131
Crab Orchard Ck	Carbondale	5598245	13		N Branch Chicago	Niles	5536000	146
Des Plaines	Riverside	5532500	158		N Fork Saline	Texas City	3382325	86
Des Plaines	Joliet	5537980	99		Pecatonica	Freeport	5435500	20
Embarras	Camargo	3343395	30		Richland Ck	Hecker	5595200	65
Embarras	Diona	3344000	29		Rock	Rockton	5437500	24
Embarras	Billett	3346550	30		Rock	Como	5443500	38
Fox	Channel Lk	5546700	65		S Fork Saline	Crab Orchard	3382055	32
Fox	S Elgin	5551000	75		S Fork Saline	Carrier Mills	3382100	19
Fox	Montgomery	5551540	85		Saline Branch	Mayview	3337700	51
Fox	Dayton	5552500	70		Salt Fork	St Joseph	3336900	39
Green	Geneseo	5447500	25		Sangamon	Allerton Park	5572125	44
Illinois	Marseilles	5543500	63		Sangamon	Oakford	5583000	34
Illinois	Peoria	5559900	59		Sangamon S Fork	Kincaid	5575500	50
Illinois	Valley City	5586100	52		Spoon	Seville	5570000	31
Iroquois	Chebanse	5526000	40		Sugar Ck (Saline)	Stonefort	3382090	5.9
Kankakee	Wilmington	5527500	27		Sugar Ck (Lk Springfield)	Springfield	5576250	56
Kaskaskia	Cooks Mills	5591200	33		Sugar Ck (Salt Ck)	Hartsburg	5581500	48
Kaskaskia	Venedy Station	5594100	27		Thorn Ck	Thornton	5536275	130
Kishwaukee	Perryville	5440000	43					

Table 4. Median Cl^- Values (mg/L) for 2008 at River Stations Monitored by MWRDGC

Station	*River*	*Location*	*Cl^-*		*Station*	*River*	*Location*	*Cl^-*
12	Buffalo Ck	Lake-Cook Rd	286		34	N Br Chicago	Dempster St	231
43	Cal-Sag Channel	Rte 83	186		37	N Br Chicago	Wilson Ave	166
58	Cal-Sag Channel	Ashland Ave	176		46	N Br Chicago	Grand Ave	159
59	Cal-Sag Channel	Cicero Ave	173		73	N Br Chicago	Diversey Ave	159
49	Calumet	Ewing St	33.5		96	N Br Chicago	Albany Ave	236
55	Calumet	130th St	156		104	N Br Chicago	Glenview Rd	204
74	Calumet	Lake Shore Dr	45.5		31	N Br Chicago (Md Fk)	Lake-Cook Rd	277
100	Chicago	Wells St	105		103	N Br Chicago (W Fk)	Golf Rd	288
40	CSSC	Damen Ave	143		106	N Br Chicago (W Fk)	Dundee Rd	350
41	CSSC	Harlem Ave	175		35	N Shore Channel	Central Ave	21.5
42	CSSC	Rte 83	169		36	N Shore Channel	Touhy Ave	135
48	CSSC	Stephen St	167		101	N Shore Channel	Foster Ave	140
75	CSSC	Cicero	169		102	N Shore Channel	Oakton Ave	72.0
92	CSSC	Lockport	162		39	S Br Chicago	Madison St	134
13	Des Plaines	Lake-Cook Rd	182		108	S Br Chicago	Loomis St	136
17	Des Plaines	Oakton St	196		99	S Br Chicago (S Fk)	Archer Ave	170
19	Des Plaines	Belmont Ave	196		18	Salt Ck	Devon Ave	241
20	Des Plaines	Roosevelt Rd	195		24	Salt Ck	Wolf Rd	252
22	Des Plaines	Ogden Ave	197		79	Salt Ck	Higgins Rd	388
23	Des Plaines	Willow Springs Rd	209		80	Salt Ck	Arlington Hts Rd	235
29	Des Plaines	Stephen St	198		90	Salt Ck	Rte 19	252
91	Des Plaines	Material Service Rd	193		109	Salt Ck	Brookfield Ave	256
86	Grand Calumet	Burnham Ave	138		32	Skokie	Lake-Cook Rd	247
77	Higgins Ck	Elmhurst Rd	452		105	Skokie	W Frontage Rd	181
78	Higgins Ck	Wille Rd	187		54	Thorn Ck	Joe Orr Rd	160
52	Little Calumet	Wentworth Ave	168		97	Thorn Ck	170th St	182
56	Little Calumet	Indiana Ave	172		64	W Br DuPage	Lake St	168
57	Little Calumet	Ashland Ave	191		89	W Br DuPage	Walnut Ln	151
76	Little Calumet	Halsted Ave	170		110	W Br DuPage	Springinsguth Rd	297
					50	Wolf Lake	127th St	64.9

Table 5. Trends Determined by Kendall Tau Statistic and β_1 Values (Reported as Yearly Change in Cl^-) for MWRDGC Stations with Monitoring Data from 1975 to 2008. Kendall Tau Significance Determined at 95% Confidence Level. β_1 Values Reported for All Data (total) as Well as Seasonally.

		Kendall Tau	β_1 (mg/L/yr)				
Station	*River*	*Significant?*	*Total*	*Jan-Mar*	*Apr-Jun*	*Jul-Sep*	*Oct-Dec*
12	Buffalo Creek	Y	5.8	13.2	6.9	1.4	3.0
13	Des Plaines R	Y	3.4	6.9	3.4	2.1	2.0
17	Des Plaines R	Y	3.8	8.2	3.9	2.6	2.7
18	Salt Creek	Y	2.1	6.7	6.4	-0.1	-1.2
19	Des Plaines R	Y	3.7	8.2	3.4	1.6	2.8
20	Des Plaines R	Y	4.1	8.6	3.7	2.2	3.0
22	Des Plaines R	Y	3.3	2.6	3.8	1.2	1.2
23	Des Plaines R	Y	3.4	8.9	4.0	1.1	2.0
24	Salt Creek	N					
29	Des Plaines R	Y	3.3	8.7	3.8	1.0	1.5
31	N Branch Chicago R (Md Fk)	Y	5.2	7.1	5.9	4.8	3.5
32	Skokie R	Y	4.6	5.5	6.3	4.3	3.5
34	N Branch Chicago R	Y	5.5	9.7	6.3	3.5	3.9
35	N Shore Channel	Y	0.17	5.4	2.0	-0.3	0.3
36	N Shore Channel	Y	1.9	5.2	2.1	0.9	2.7
37	N Branch Chicago R	Y	2.7	6.8	2.9	1.3	3.4
39	S Branch Chicago R	Y	2.6	6.4	2.5	0.5	3.0
40	CSSC	Y	2.7	6.4	2.7	0.4	3.2
41	CSSC	Y	2.5	5.2	2.2	1.0	4.2
42	CSSC	Y	2.7	7.0	2.4	1.1	2.3
43	Cal-Sag Channel	Y	1.4	5.2	1.8	0.1	0.0
46	N Branch Chicago R	Y	2.7	6.8	3.2	1.4	2.7
48	CSSC	Y	2.4	5.2	2.5	0.9	1.9
49	Calumet R	Y	0.76	1.7	0.5	-0.1	0.8
50	Wolf Lake	Y	0.51	0.4	0.7	0.6	0.4
52	Little Calumet R	Y	1.9	3.6	2.5	0.4	0.5
54	Thorn Creek	Y*	-4.8	-1.3	-2.8	-6.1	-7.7
55	Calumet R	N					
56	Little Calumet R	N					
57	Little Calumet R	Y	0.07	5.2	1.8	-2.3	-2.5
58	Cal-Sag Channel	Y	1.2	5.0	0.9	-0.1	1.4
59	Cal-Sag Channel	Y	1.2	4.3	1.8	-0.2	0.2
64	W Branch DuPage R	Y	-0.93	4.4	1.7	-2.2	-3.1
73	N Branch Chicago R	Y	2.5	6.7	2.5	1.0	2.6
74	Chicago R	Y	1.1	6.0	2.7	0.0	1.4
75	CSSC	Y	2.9	7.0	1.5	0.6	3.3
76	Little Calumet R	Y	1.4	4.7	10.1	0.6	1.4
78	Higgins Creek	Y	1.6	3.8	9.9	1.0	1.4
79	Salt Creek	Y	7.3	15.9	6.4	5.8	4.6
80	Salt Creek	Y	2.0	6.6	2.3	0.3	-0.6
90	Salt Creek	Y	6.8	12.8	11.1	4.4	3.7

* Negative trend.

Table 6. Trends Determined by Kendall Tau Statistic and β_1 Values (Reported as Yearly Change in Cl^-, mg/L/yr) for USGS Stations. Data Start in 1984, and End between 1997 and 2008. Kendall Tau Significance Determined at 95% Confidence.

Station	*River*	*KT sign.*	β_1		*Station*	*River*	*KT sign.*	β_1
5532000	Addison Creek	Y	9.33		3384450	Lusk Creek	N	
5599500	Big Muddy	N			3336645	Middle Fork Vermilion	N	
3378000	Bonpas Creek	Y*	-1.08		7022000	Mississippi	Y	0.21
3612000	Cache	Y*	0.07		5587455	Mississippi	Y	0.48
5536700	Cal Sag Channel	N			5534500	N Branch Chicago	Y	7.13
5595830	Casey Fork	N			5536000	N Branch Chicago	Y	5.74
5598245	Crab Orchard Creek	N			3346000	N Fork Embarras	Y*	-2.00
5593520	Crooked Creek	Y*	-3.17		3382325	N Fork Saline	N	
5537000	CSSC	Y	3.84		3338780	N Fork Vermilion	Y*	-0.29
5536995	CSSC	Y	5.64		3612500	Ohio	Y	0.23
5528000	Des Plaines	Y	6.00		5435500	Pecatonica	Y*	-0.15
5529000	Des Plaines	Y	6.03		5550500	Poplar Creek	Y	14.2
5532500	Des Plaines	Y	2.11		5595200	Richland Creek	Y	0.99
5537980	Des Plaines	N			5437500	Rock	Y	1.00
5540500	DuPage	Y*	-2.63		5443500	Rock	Y	0.99
3344000	Embarras	N			5446500	Rock	Y	0.98
3345500	Embarras	Y*	-0.40		3337700	Saline Branch	Y	1.63
3343395	Embarras	N			5531500	Salt Creek	N	
3346550	Embarras	N			3336900	Salt Fork	N	
5551000	Fox	Y	5.89		5576500	Sangamon	N	
5551540	Fox	Y	7.11		5583000	Sangamon	Y	0.58
5552500	Fox	Y	1.76		5572000	Sangamon	N	
5550000	Fox	Y	5.56		5573540	Sangamon	N	
5546700	Fox	Y	2.94		5572125	Sangamon	N	
5447500	Green	N			3382100	S Fork Saline	N	
5539000	Hickory Creek	Y	6.52		3382055	S Fork Saline	N	
5543500	Illinois	Y	1.24		5575500	S Fork Sangamon	N	
5559900	Illinois	Y	2.54		3380500	Skillet Fork	N	
5586100	Illinois	Y	0.90		5594450	Silver Creek	Y	2.04
5526000	Iroquois	Y	0.32		5594800	Silver Creek	N	
5520500	Kankakee	Y	0.36		3382090	Sugar Creek	Y*	-0.59
5527500	Kankakee	Y	0.07		5576250	Sugar Creek	Y	2.53
5594100	Kaskaskia	N			5581500	Sugar Creek	Y	1.18
5592500	Kaskaskia	Y*	-2.08		5536275	Thorn Creek	N	
5591200	Kaskaskia	Y	1.68		3339000	Vermilion	N	
5440000	Kishwuakee	Y	0.98		5539900	W Branch DuPage	Y	4.23
5584500	La Moine	N			5540095	W Branch DuPage	N	
5585000	La Moine	N						
3378635	Little Wabash	N						
3379500	Little Wabash	N						
3381495	Little Wabash	N						

* Negative trend.

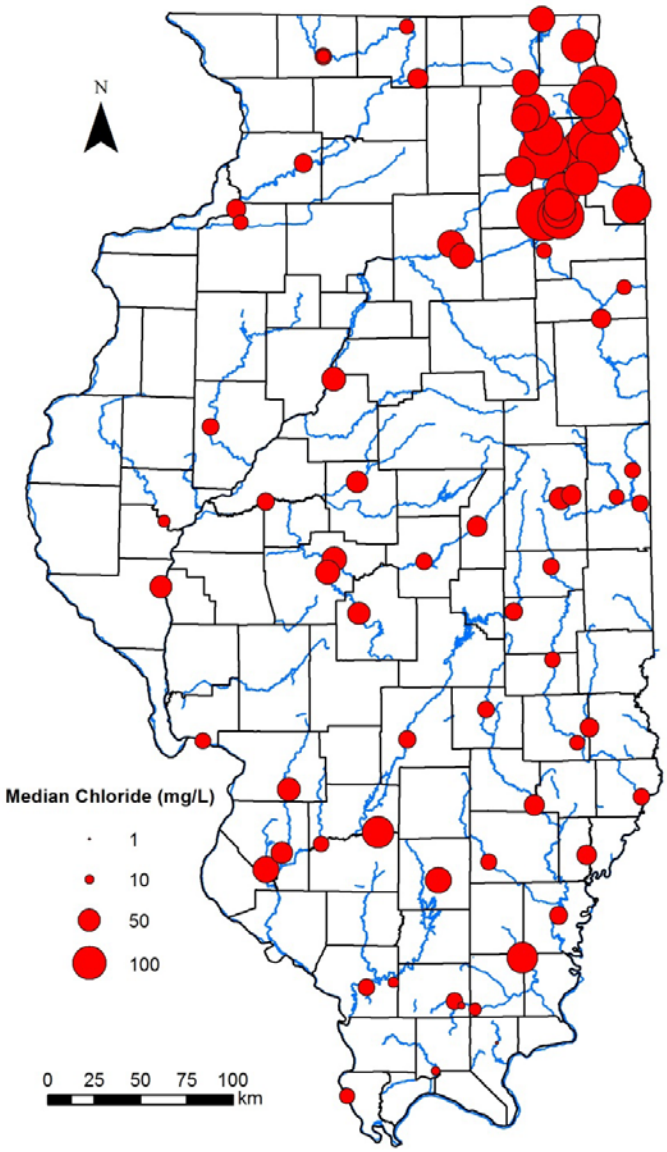

Figure 8. Median Cl^- values in streams and rivers of Illinois for the Water Years 1991-1992 for USGS monitoring stations

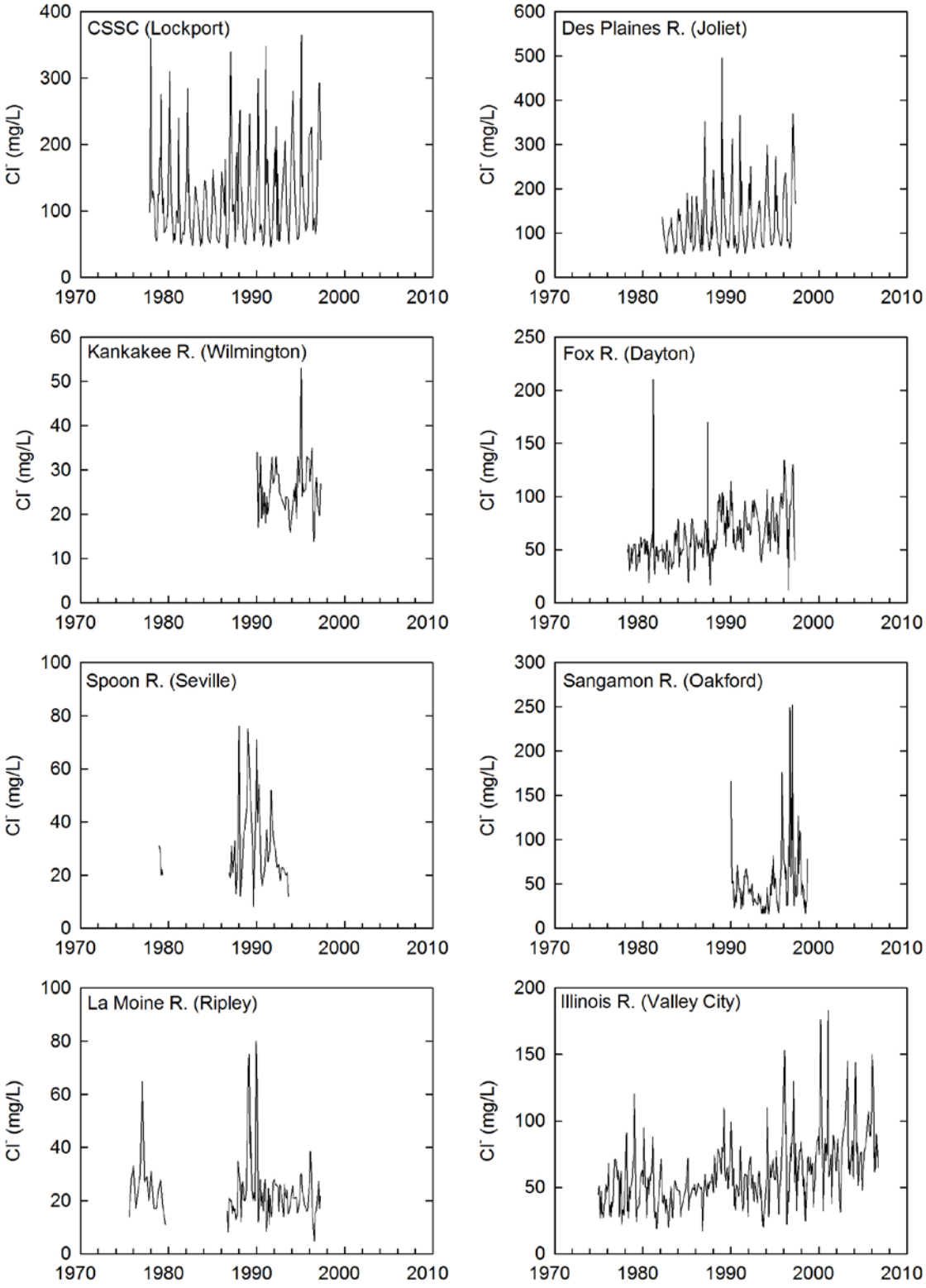

Figure 9. Chloride concentrations at selected USGS monitoring stations in Illinois

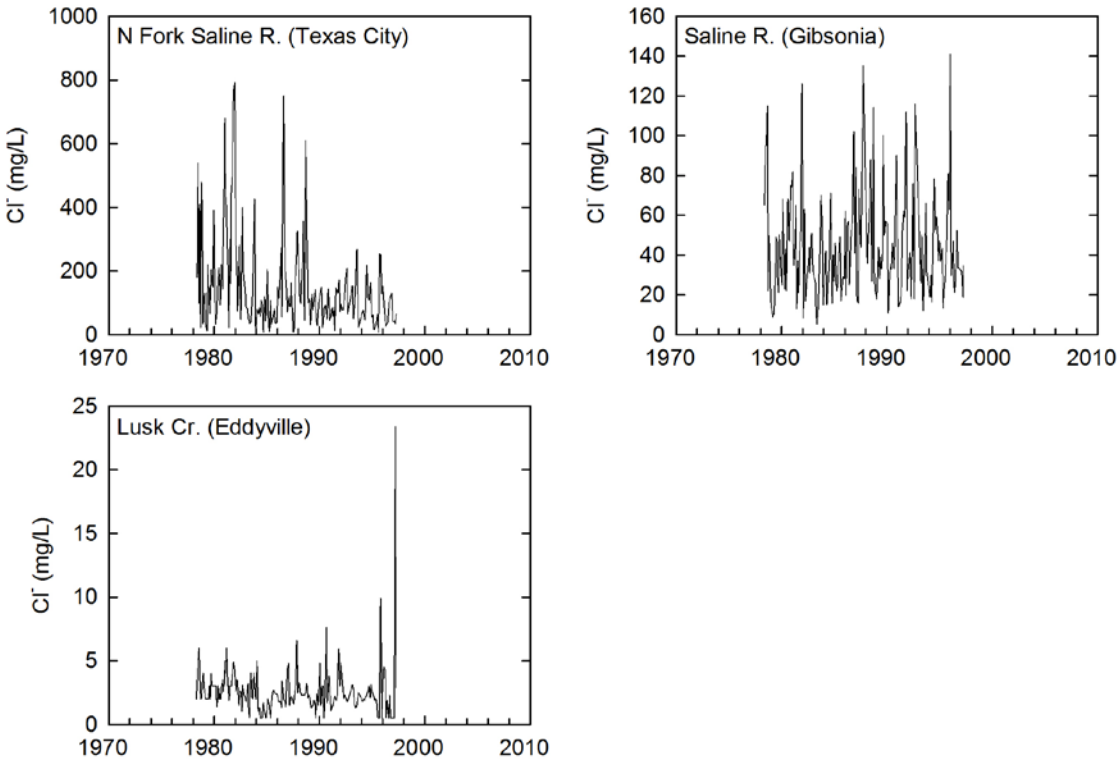

Figure 9. Continued

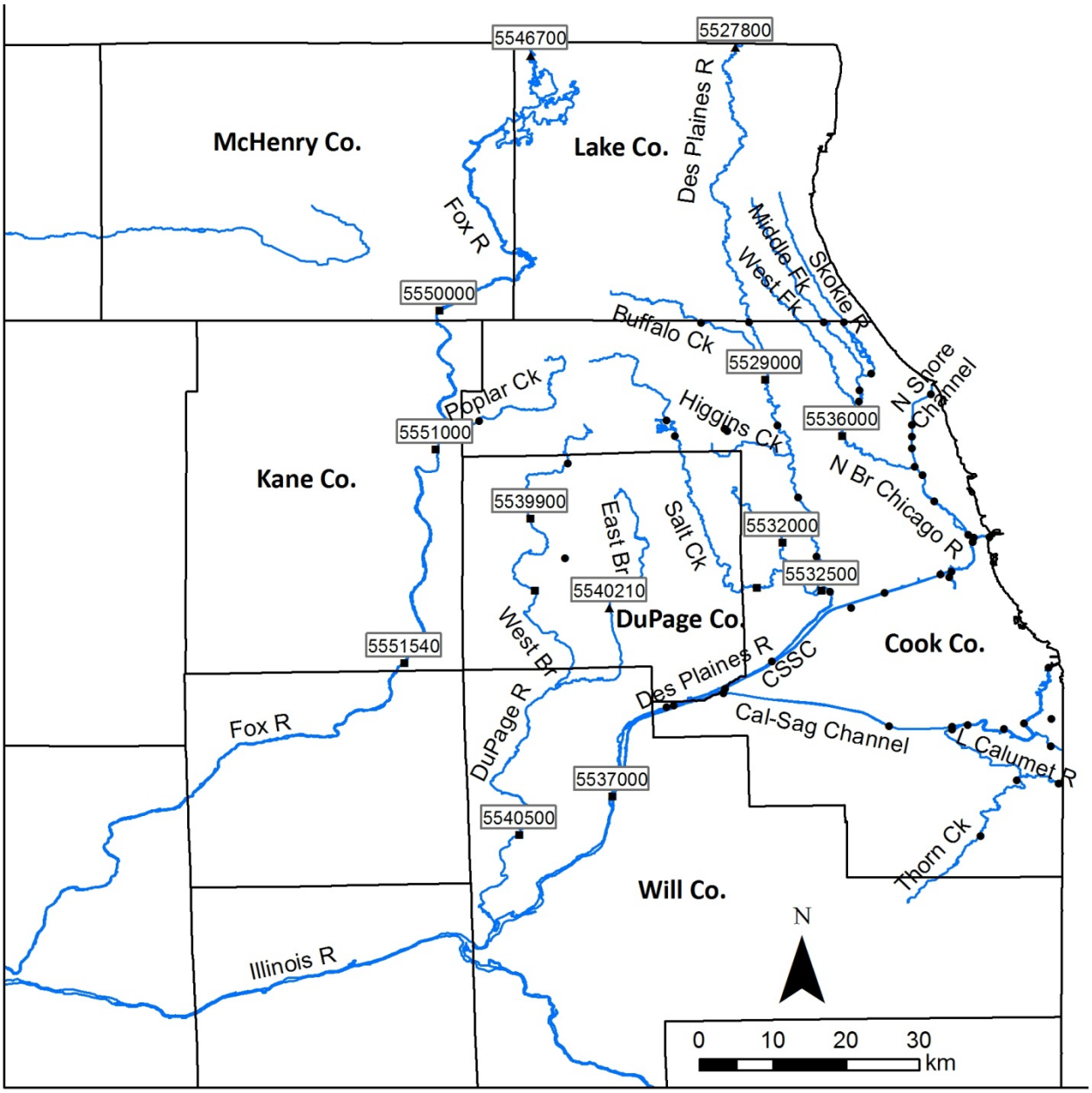

Figure 10. MWRDGC and USGS surface water monitoring stations evaluated in this study. Seven-digit numbers are USGS stations.

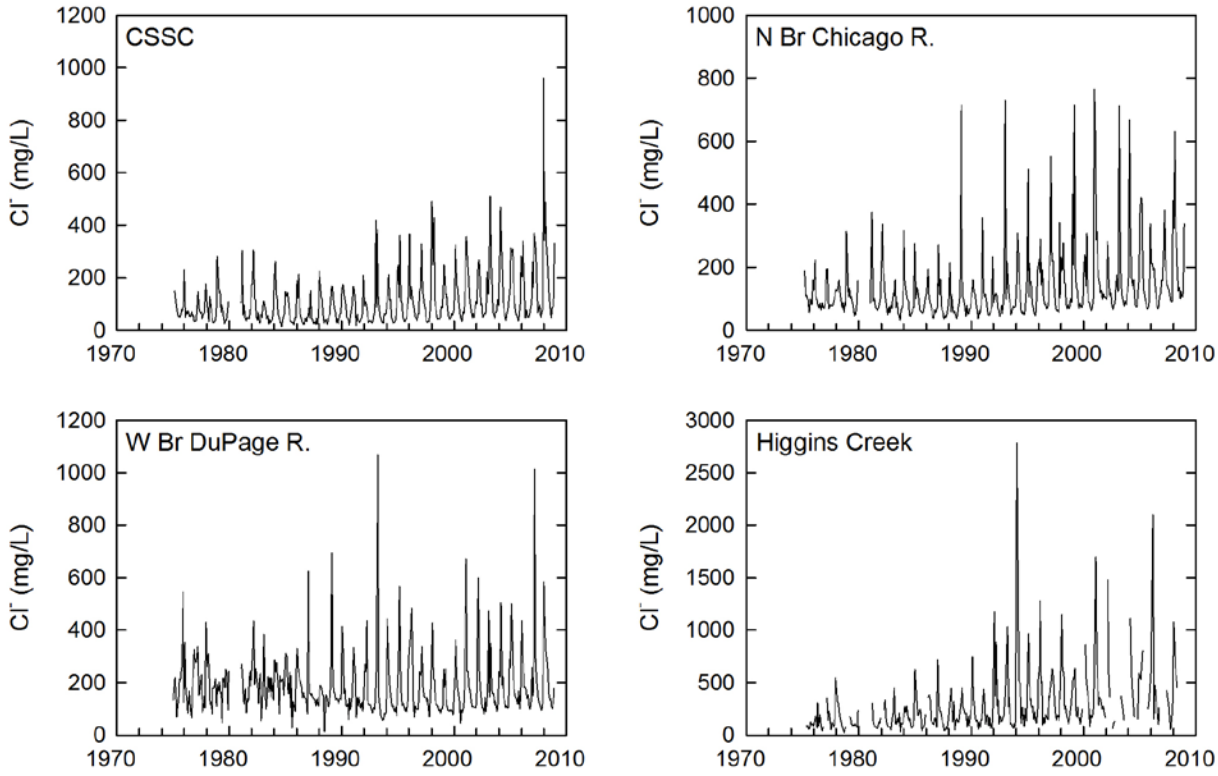

Figure 11. Chloride concentrations at selected MWRDGC monitoring stations in the Chicago region

There are clear seasonal differences in Cl^- concentrations for rivers where concentrations are increasing, with highest values between January and March (Figure 12). At 97 percent of the MWRDGC stations, the largest Cl^- concentrations were in the winter (January–March). At 83 percent of these stations, the winter concentrations were significantly greater (determined by ANOVA on ranks) than each of the other three seasons, and for 16 percent of these stations, concentrations were significantly greater than two of the other seasons. The spring months (April–June) generally had the second highest concentrations (88 percent of the stations), and for 53 percent of these stations spring concentrations were significantly greater than fall or summer. Concentrations were usually lowest in the summer (88 percent of stations). This seasonality is obviously due to road salt runoff. In snowy winters, large applications of NaCl produce Cl^- concentrations and loads in streams and rivers considerably higher than in winters with low snowfalls (Figure 13). It should be noted that during the months when Cl^- concentrations are lowest in the Chicago region (July–October), concentrations still are typically greater than 100 mg/L.

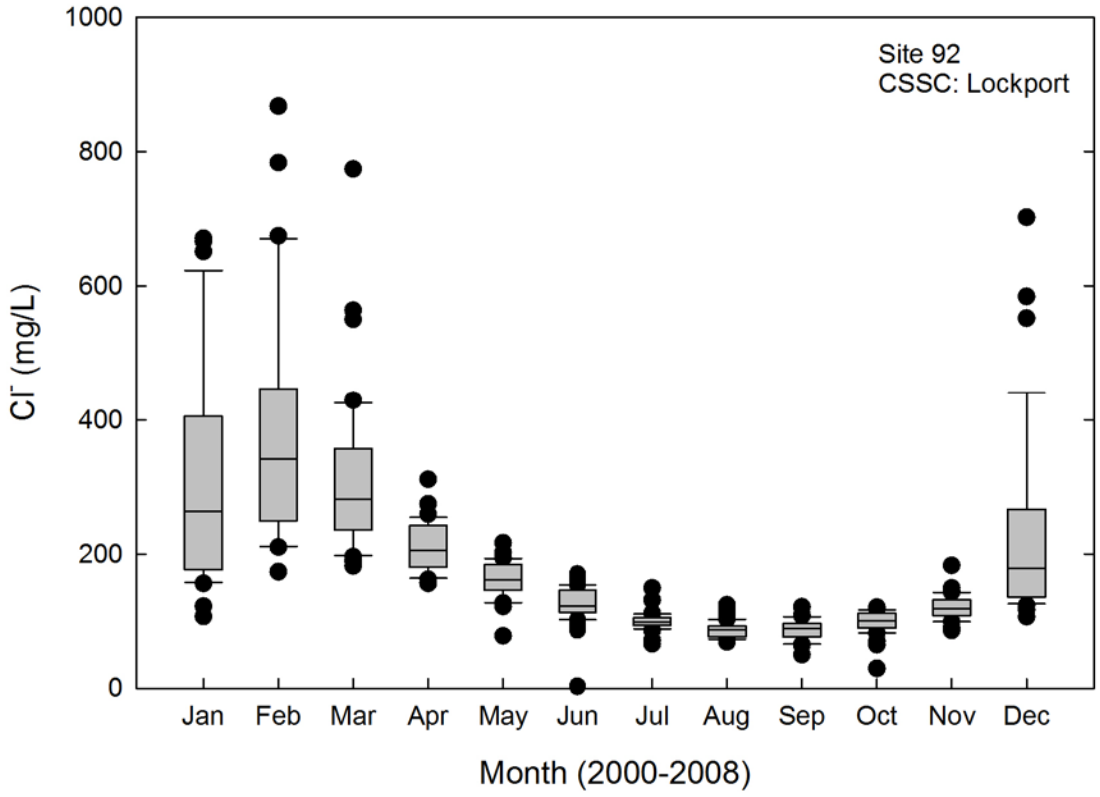

Figure 12. Chloride concentrations by month for MWRDGC station 92 (CSSC at Lockport) between 2000 and 2008. The site was sampled weekly.

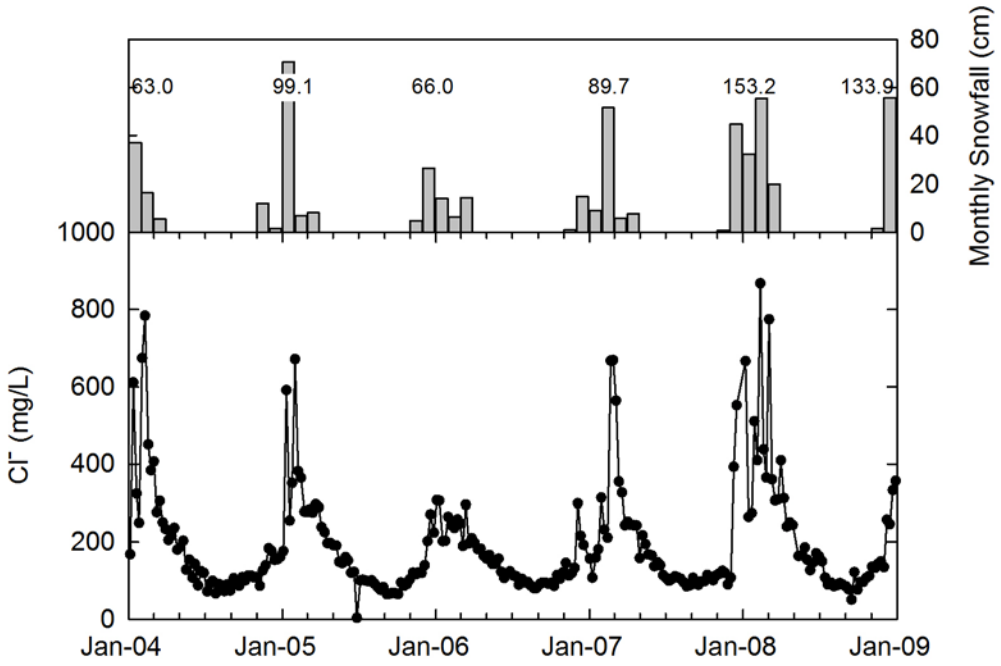

Figure 13. Chloride concentrations at MWRDGC station 92 on the CSSC at Lockport, IL, and monthly snowfall totals in Chicago (winter totals shown above bar). Snowfall data from NOAA, 2010.

Increasing trends in Cl^- concentrations are observed in all seasons at the MWRDGC stations, with the rates of increase following the same seasonal pattern as the concentration data, i.e., greatest increases in the winter and smallest in the summer (Figure 14 and Table 5). This is additional evidence that increases in Cl^- concentrations are the result of road salt runoff.

Rivers outside the Chicago region tended to have different seasonal patterns. Chloride concentrations in the Fox River were significantly lower between April and June than for both autumn and winter samples, and in the Sangamon River, concentrations were significantly lower between April and June than in all other seasons. For both these rivers, the highest Cl^- concentrations were typically measured between October and December. This may be due to leaching of fertilizer, which is typically applied in Illinois in the autumn after harvest. There were no significant seasonal differences for the Kankakee, Spoon, and La Moine Rivers.

Kelly et al. (2010) reported that chloride concentrations were significantly higher when river discharge was low, regardless of season. The USGS data sets showed the influence of discharge on Cl^- concentrations (Figure 15). For every station except CSSC reported by Kelly et al. (2010), Cl^- concentrations at low discharge (bottom 25^{th} percentile) were significantly greater than at high (top 25^{th} percentile) and intermediate (middle 50^{th} percentile) discharges, and concentrations at intermediate discharge were almost always significantly greater than at high discharge. For CSSC, Cl^- concentrations at low discharge were significantly greater than at intermediate discharge.

For the most part, discharge from tributaries to the Illinois River downstream of Chicago dilutes the concentrations of Cl^- and other ions originating from TWW and road salt. Road salt inputs are seasonally variable, with fluxes highest in the winter and early spring; the flux of contaminants from TWW should be less seasonally affected. Thus when the Illinois River discharge is low, there is less dilution of TWW downstream of Chicago. Therefore, Cl^-, which is elevated in TWW, becomes relatively elevated in the river because there is less dilution by downstream tributaries. This relationship can be seen in Figure 16, which shows the fraction of the Cl^- load at Peoria attributable to the load in the CSSC as a function of river discharge at Peoria. When discharge is low, it is not uncommon for more than 60 percent of the Cl^- load at Peoria to be attributable to what is coming out of the CSSC, which is predominantly TWW.

The longest record of data is the Illinois River at Peoria, which indicates that Cl^- concentrations have been steadily increasing since the 1960s (Figure 17). The annual increase since 1960 (from β_1 calculation) is 1.0 mg/L per year (mg/L/yr), and 3.1 mg/L/yr since 1990. Concentrations are highest in the winter and early spring months, and the variability in concentrations during these months has been increasing. The overall temporal increase in Cl^- concentrations is mostly due to increases during January through April; concentrations have increased at rates greater than 4.0 mg/L/yr in all these months since 1990. However, there were positive trends in all months except June, indicating that increases in Cl^- concentrations are due to factors other than just direct road salt runoff. Shallow groundwater in much of the Chicago region has elevated Cl^- due to road salt (Kelly, 2008), and most of this groundwater discharges to tributaries of the Illinois Waterway throughout the year, not just in winter. In addition, the increasing population and concomitant increase in residential acreage and sewage in the Chicago region is likely increasing the Cl^- load to the Illinois Waterway via TWW discharge. The influence of river discharge on Cl^- concentrations can also be seen in Figure 17. Concentrations were relatively low during flood years (e.g., 1972, 1993), and relatively high during droughts (1963–1964, 1977, 1980, 1988–1989).

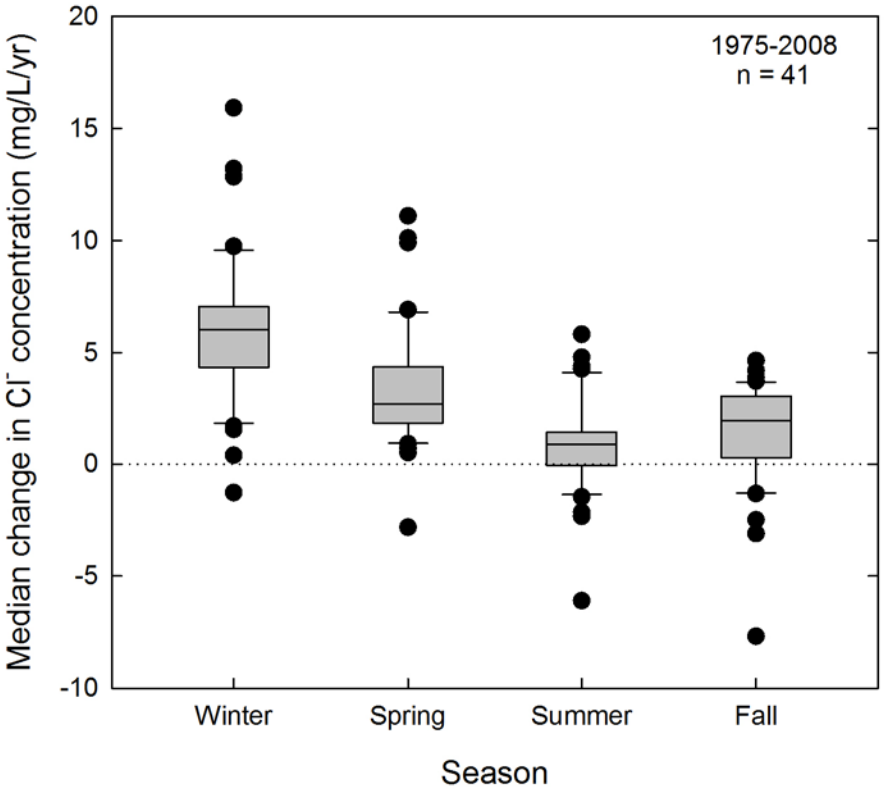

Figure 14. Box and whisker plot of median changes in chloride concentrations for 41 MWRDGC stations monitored between 1975 and 2008, divided by season. Changes calculated from slope statistic ($^{2}_{1}$) for linear regressions. Changes were significantly greater for winter compared to all other seasons, and for spring compared to summer and fall (ANOVA on ranks).

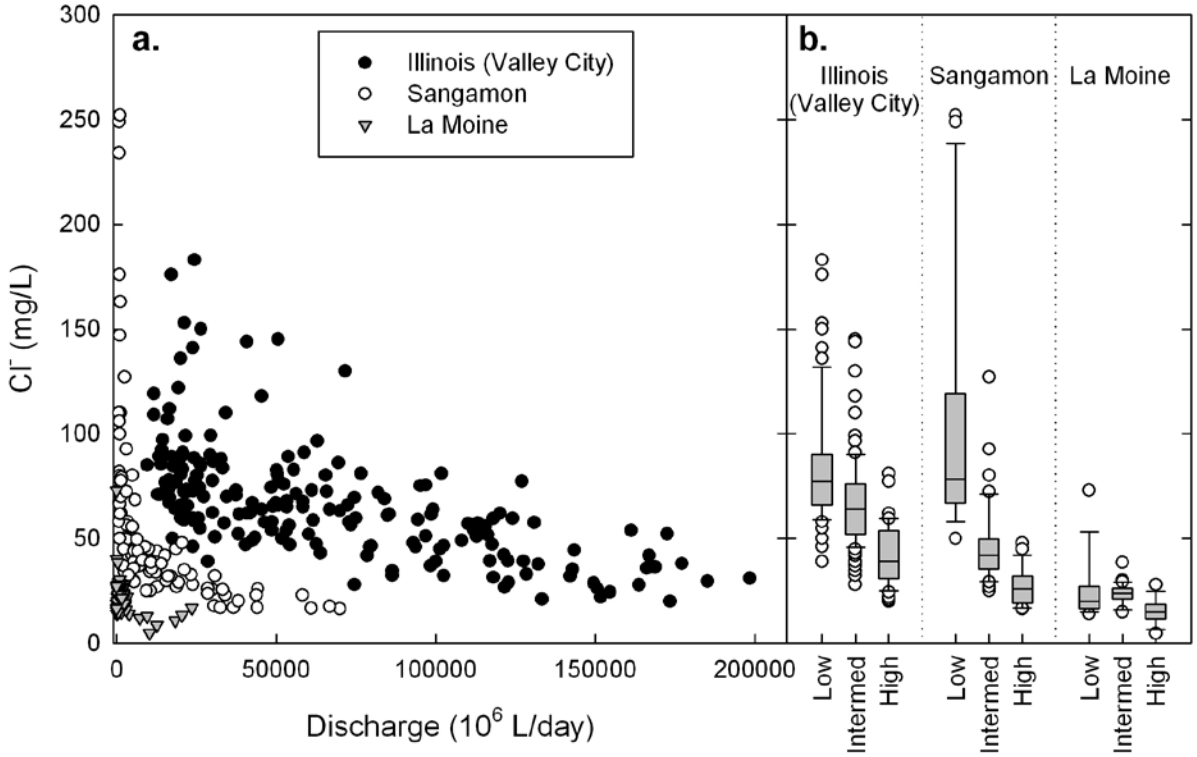

Figure 15. (a) Chloride concentration as a function of discharge for the Illinois River (Valley City), Sangamon River (Oakford), and La Moine River (Ripley). (b) Box plots showing same data as a function of river discharge category; circles are all outliers (< 10%, > 90%). Figure from Kelly et al. (2010), data from USGS (2008).

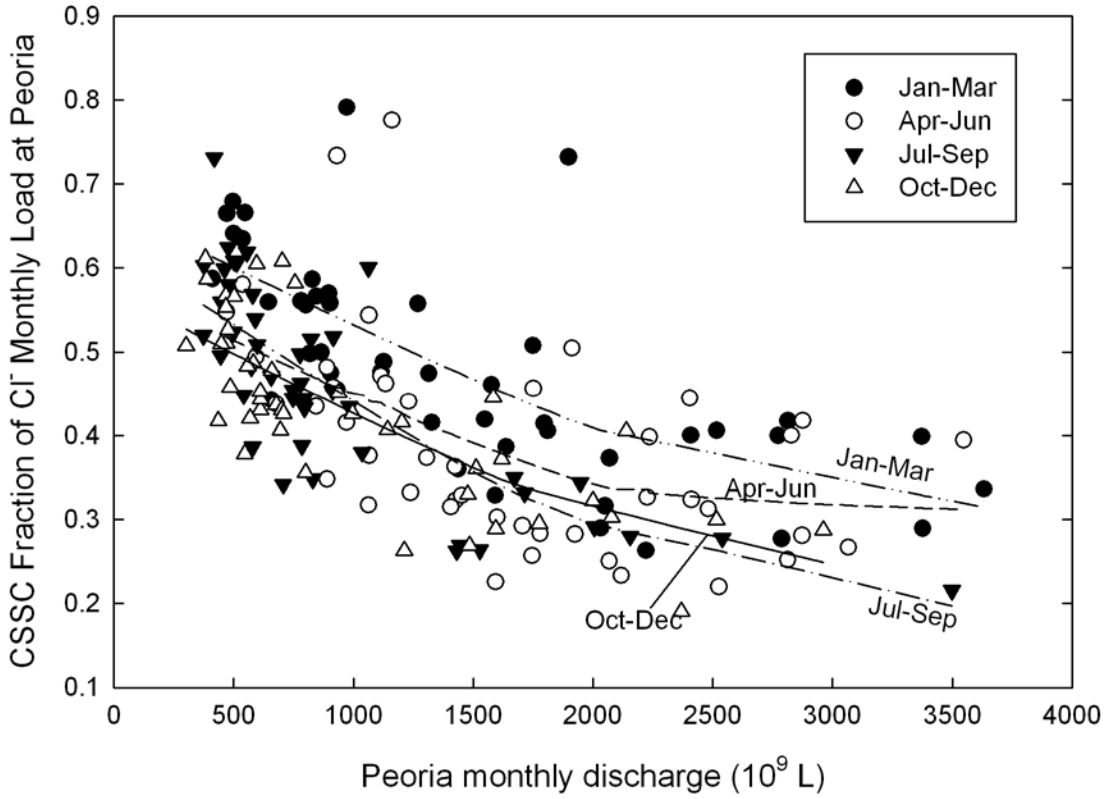

Figure 16. Fractions of the chloride monthly loads in the Illinois River at Peoria that can be attributable to discharge from the CSSC (Romeoville) as a function of monthly discharge at Peoria (1987–2001) Lines are smoothed regressions using LOWESS. Figure from Kelly et al. (2010), data from USGS (2008).

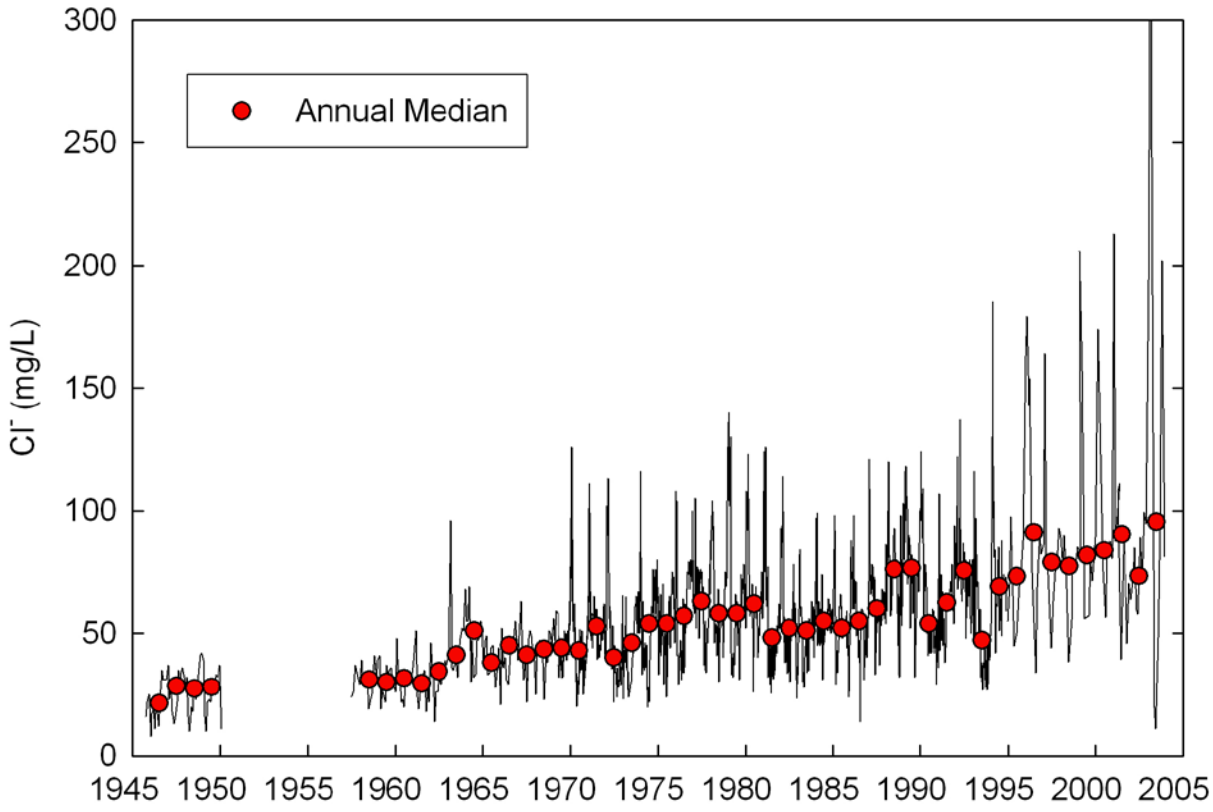

Figure 17. Chloride concentrations in Illinois River at Peoria. Data from ISWS and USGS.

Groundwater

In this report, we use the hydrostratigraphic nomenclature developed by Meyer et al. (2009) to differentiate among aquifers in Illinois. In most of the state, the aquifers closest to the land surface are Quaternary in age. These are composed of unconsolidated sands and gravels deposited by glacial and alluvial processes. Bedrock aquifers in Illinois are all sedimentary rocks (sandstones and carbonates) of Paleozoic age, the youngest being Pennsylvanian and the oldest Cambrian. We divided the bedrock aquifers into three groups (Figure 18), from youngest to oldest: (1) the upper bedrock unit, primarily sandstones of Pennsylvanian and Mississippian age; (2) the Silurian-Devonian carbonate unit, primarily fractured dolomites; and (3) the Cambrian-Ordovician aquifers, which are primarily sandstones. The Cambrian-Ordovician group comprises several aquifers, but because wells are commonly open to more than one of these aquifers, we chose to group them together.

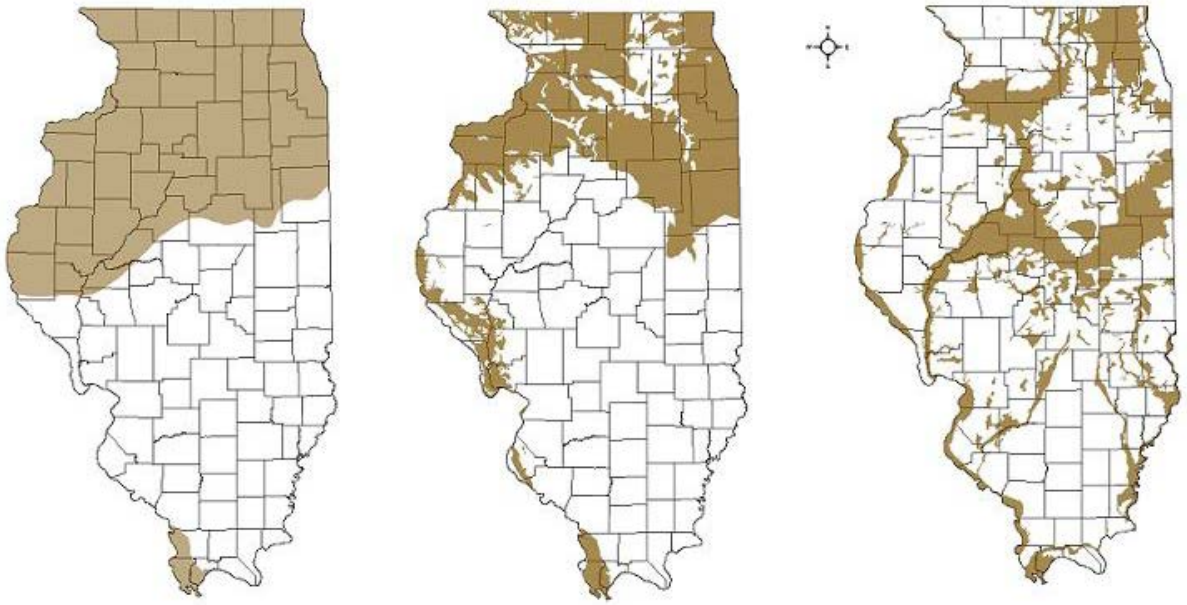

Figure 18. Extents of principal aquifer systems in Illinois (a) Cambrian-Ordovician bedrock; (b) shallow bedrock (Silurian-Pennsylvanian); (c) unconsolidated

Quaternary Aquifers

Sand and gravel Quaternary aquifers are found throughout Illinois (Figure 18c). Alluvial aquifers are found in river valleys; most aquifers in the southern third of Illinois are of this type. Glacial aquifers include buried bedrock valleys filled with sand and gravels and sand and gravel lenses within till deposits. The largest buried bedrock valley aquifer is the Mahomet Aquifer in central Illinois, and other major glacial aquifers are found in the northern half of the state. Chloride concentrations vary greatly in these aquifers (Figure 19).

In the Mahomet Aquifer (Figure 20), chloride concentrations are extremely low in the eastern part of the aquifer, and are < 1 mg/L in parts of Champaign County. Hackley et al. (2010) suggested that recharge from glacial meltwaters recharging the Mahomet aquifer in Champaign County near the end of the Wisconsin Glacial Episode (about 11,500 years BP) leached the fine sediments and sand and gravel of the recharge zone and the aquifer. This resulted in the anomalously low Cl^- concentrations. Near the border between Champaign and Piatt Counties, Cl^- concentrations abruptly increase, due to discharge of brine from Pennsylvanian bedrock. Concentrations then decrease gradually to the west due to dilution. In the western region of the Mahomet aquifer (Piatt, Macon, and DeWitt Counties) where Cl^- concentrations are highest, concentrations along the bedrock valley walls tend to be higher than in the central, thalweg part of the valley. This is likely due to proximity to bedrock discharge along the valley walls and greater dilution in the thalweg. The Mahomet is confined through most of its central and eastern extent, thus surface activities generally do not impact its water quality. In the Sankoty-Mahomet section (Mason and western Tazewell Counties), the Sankoty-Mahomet is unconfined and

surface activities can impact water quality. Elevated Cl^- concentrations in the East Peoria and Pekin regions are probably due to road salt runoff in those urban areas.

Other buried bedrock valley aquifers in Illinois include the Mackinaw and Princeton bedrock valleys northwest of the Mahomet Aquifer. Chloride concentrations are generally low in these aquifers. Burch (2004) reported a median Cl^- concentration of 10.8 mg/L (N = 30) in samples from the Princeton bedrock valley, which included several samples impacted by road salt runoff.

Chloride concentrations in glacial aquifers within till deposits vary greatly. For example, the Glasford Aquifer in central Illinois has Cl^- concentrations ranging from < 1 to about 100 mg/L. Sand and gravel aquifers in northeastern Illinois have been heavily impacted by human activities, with the most obvious sign being increasing Cl^- concentrations. Kelly (2008) showed that Cl^- concentrations in shallow groundwater in the Chicago region have been increasing since the 1960s when road salt began being used in earnest. Over half of the public supply wells finished in sand and gravel aquifers have statistically significant increasing trends in Cl^- concentrations. Widespread sampling of shallow aquifers (< 250 feet deep) in Kane County in 2003 indicated the role of urbanization on shallow groundwater quality (Kelly, 2005). Chloride concentrations were significantly higher in the eastern urban corridor compared with the remainder of the county, which was primarily rural (Figure 21). Figure 21 clearly shows that urban land use increases Cl^- concentrations but rural land uses do not.

Mullaney et al. (2009) reported on Cl^- in unconsolidated glacial aquifers of the U.S. and found that land use significantly affected Cl^- concentrations. Shallow monitoring wells in urban areas had significantly greater Cl^- concentrations (median = 46 mg/L, n = 317) than in agricultural areas (median = 12 mg/L, n = 430), and both were significantly higher than wells in forested areas (median = 2.9 mg/L, n = 50). Their source analysis suggested that Cl^- in urban settings was dominated by deicing and/or water softening salt.

Chloride concentrations in alluvial aquifers in southern Illinois are generally low (< 30 mg/L), with a few exceptions. The Rock River valley in Rockford has higher Cl^- concentrations (generally > 50 mg/L), reflecting greater urbanization and heavier amounts of snow and thus road salt runoff. Chloride concentrations also are higher in the American Bottoms area across the Mississippi River from St. Louis, again reflecting the large degree of urbanization. In areas where there are no aquifers, primarily the southern half of Illinois, large-diameter dug and bored wells are used. These wells are vulnerable to surface contamination. Chloride concentrations in these areas vary widely, probably reflecting the local land use activities that impact the wells.

An important control on Cl^- concentrations in Quaternary aquifers is depth. In general, the shallower the aquifer, the more vulnerable it is to surface-derived contamination. Figure 22 shows Cl^- concentrations for wells 50 feet or less. In contrast, Figure 23 shows Cl^- concentrations for wells greater than 250 feet. Figure 24 shows a box-and-whisker diagram of Cl^- concentrations as a function of depth. Results from ANOVA testing indicated that Cl^- concentrations in each depth range were significantly greater than all deeper groups.

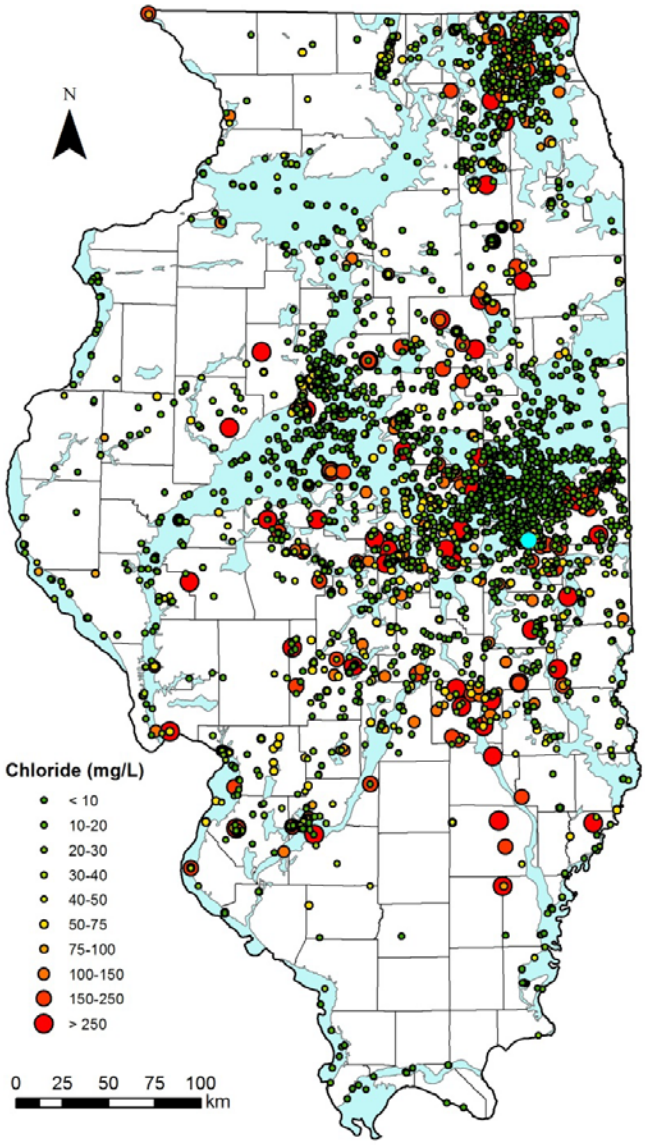

Figure 19. Chloride concentrations in wells open to Quaternary sand-and-gravel aquifers. Locations of significant Quaternary sand-and-gravel aquifers indicated by light blue.

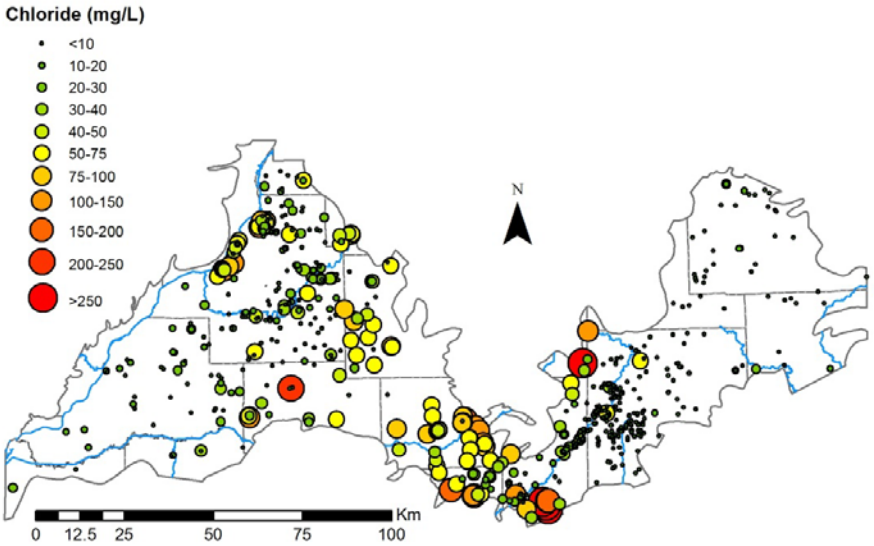

Figure 20. Chloride concentrations in the Mahomet Aquifer

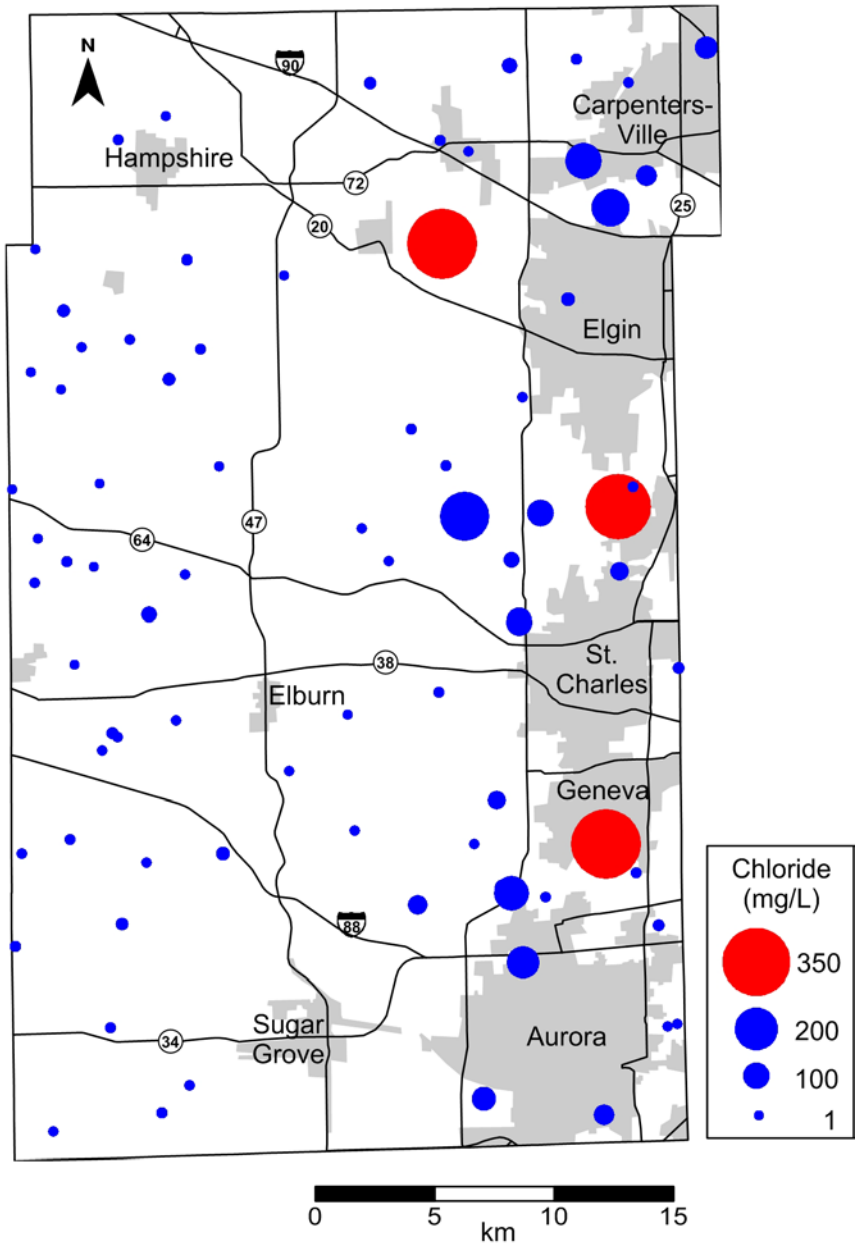

Figure 21. Chloride concentrations in samples collected from shallow wells (< 250 feet) in Kane County in 2003. Size of circle represents Cl^- concentration, with red circles indicating values > 250 mg/L. Gray areas represent municipalities. Major roads shown. Figure from Kelly, 2005.

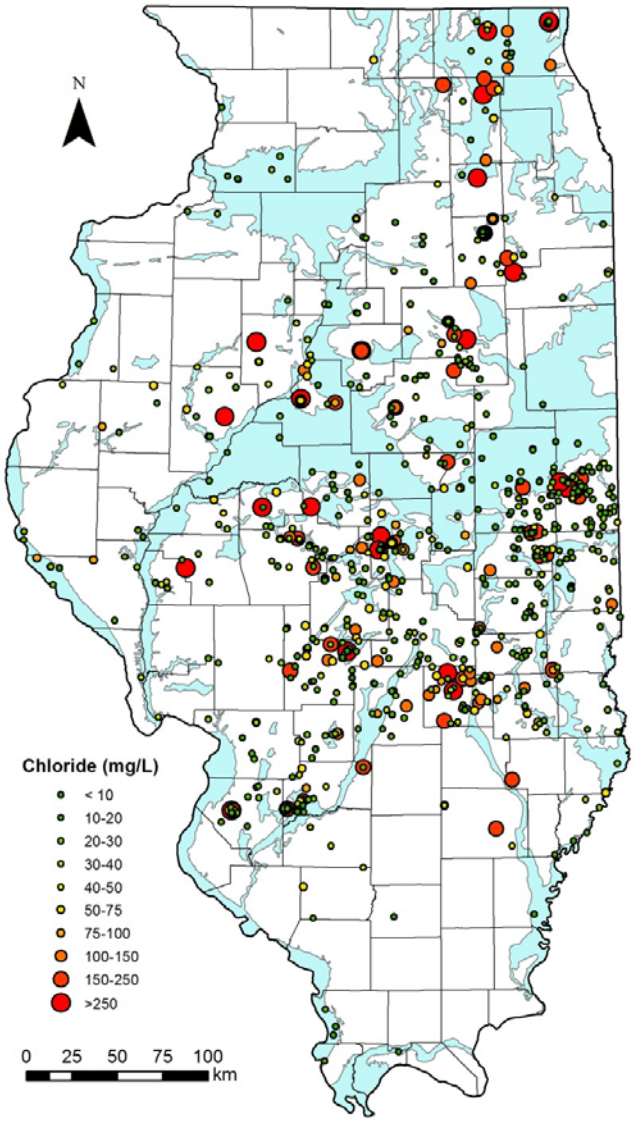

Figure 22. Chloride concentrations in wells 50 feet deep or less open to Quaternary sand-and-gravel aquifers. Locations of significant Quaternary sand-and-gravel aquifers indicated by light blue.

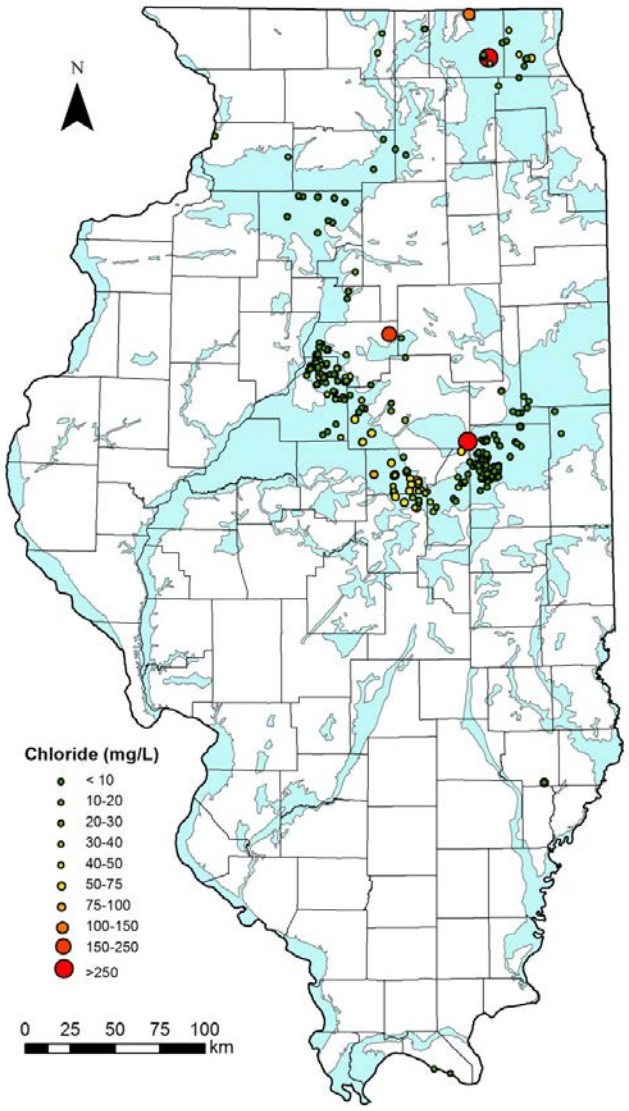

Figure 23. Chloride concentrations in wells equal to or greater than 250 feet open to Quaternary sand-and-gravel aquifers. Locations of significant Quaternary sand-and-gravel aquifers indicated by light blue.

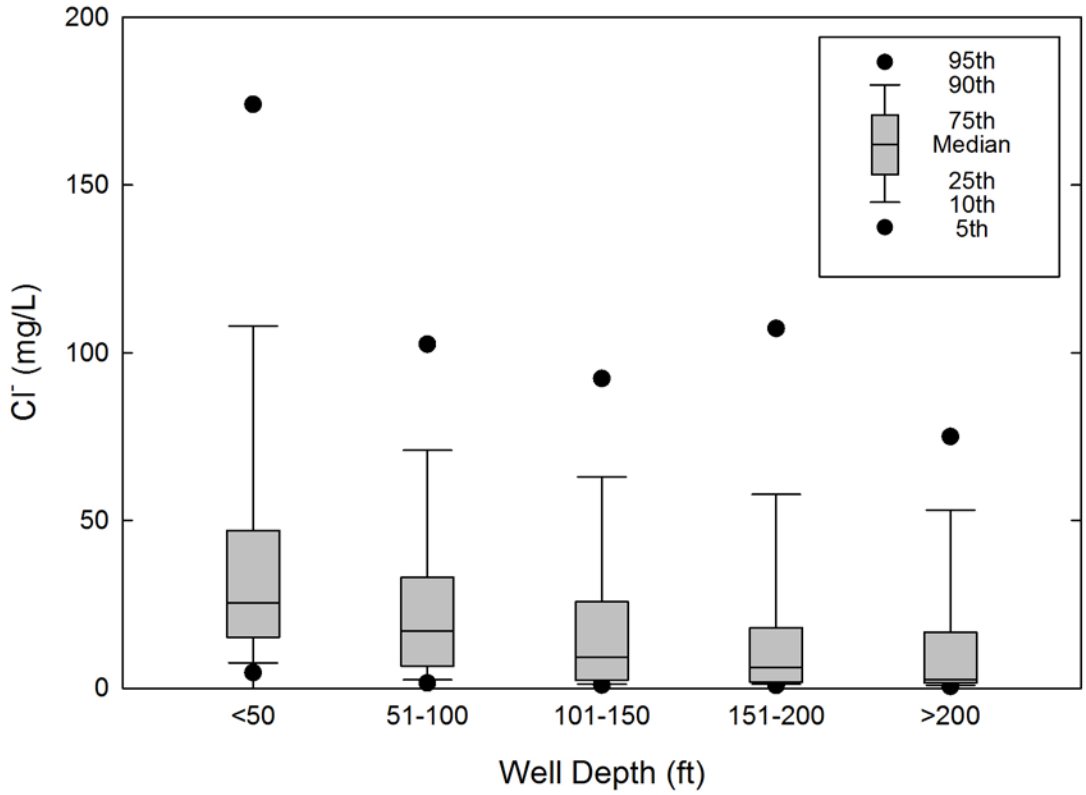

Figure 24. Box-and-whisker diagram for Cl^- concentrations in Quaternary aquifers in Illinois as a function of well depth. Concentrations are significantly greater for each depth group compared to all deeper groups.

Bedrock Aquifers

Bedrock aquifers in Illinois are found in the northern third of the state and along the Mississippi River (Figure 18). Aquifers in the upper bedrock unit are used in the southern two-thirds of Illinois. Chloride concentrations vary widely (Figures 25 and 26), and primarily appear to be a function of depth, i.e., the deeper the well, the higher the concentration (Figure 27). Very high concentrations are likely primarily due to natural sources, i.e., recharge from brines; Pennsylvanian formations are the primary oil producing units in Illinois. Some of these wells may also be exhibiting contamination from leaky brine holding ponds commonly associated with oil drilling activities (Hensel and McKenna, 1989). In the sinkhole plain of southwestern Illinois (Monroe, Randolph, and St. Clair Counties), Mississippian limestones exhibit karst features (sinkholes, caves). These aquifers are extremely vulnerable to surface contamination, but Cl^- is not an important contaminant in this primarily rural region.

Devonian and Silurian Age aquifers are important aquifers in Illinois, heavily used in northeastern and northwestern Illinois (Figure 26). They are primarily of carbonate lithology, the most productive being fractured dolomites. The heaviest use of these aquifers is in the Chicago

region, in DuPage, northern Will, southern and western Cook, and western Lake Counties. These bedrock units dip towards the south, and Cl^- concentrations are significantly greater in areas where the Devonian-Silurian aquifers are deeper (Figures 26 and 27). In northeastern Illinois, the tops of the bedrock aquifers are often in contact with sand and gravel glacial units. Wells are often screened in this interval due to its large hydraulic conductivity. These Silurian bedrock aquifers also show the increasing trend in Cl^- concentrations seen in the sand and gravel aquifers due to road salt runoff (Kelly, 2008). More than half of public supply wells finished in these aquifers tested by Kelly (2008) have statistically significant increasing trends in Cl^- concentrations.

The oldest aquifers in Illinois are found in the northern third of the state and are Cambrian and Ordovician aged. These aquifers are primarily sandstones and are heavily used in the northern part of Illinois, especially centered around Joliet and Aurora south and west of Chicago, respectively. In general, the salinity of water in the Cambrian-Ordovician aquifers is lowest in north-central and northwestern Illinois where the Ancell Aquifer outcrops at the surface and recharge is occurring (Figure 28). Salinity generally increases to the east and south in the direction of flow and stratigraphic dip. Below a latitude of about 40° the water in these aquifers is unpotable due to high TDS levels. Chloride concentrations tend to increase with well depth (Figure 29).

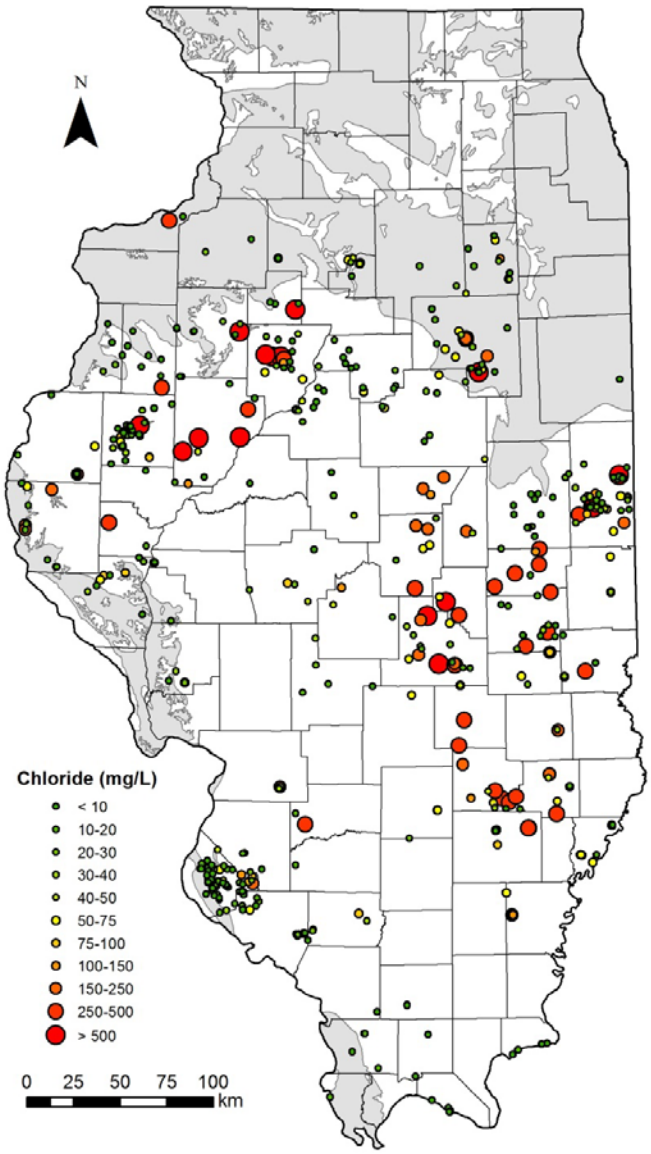

Figure 25. Chloride concentrations in wells open to upper bedrock aquifers (Pennsylvanian-Mississippian). Extent of Silurian-Pennsylvanian aquifers indicated by gray.

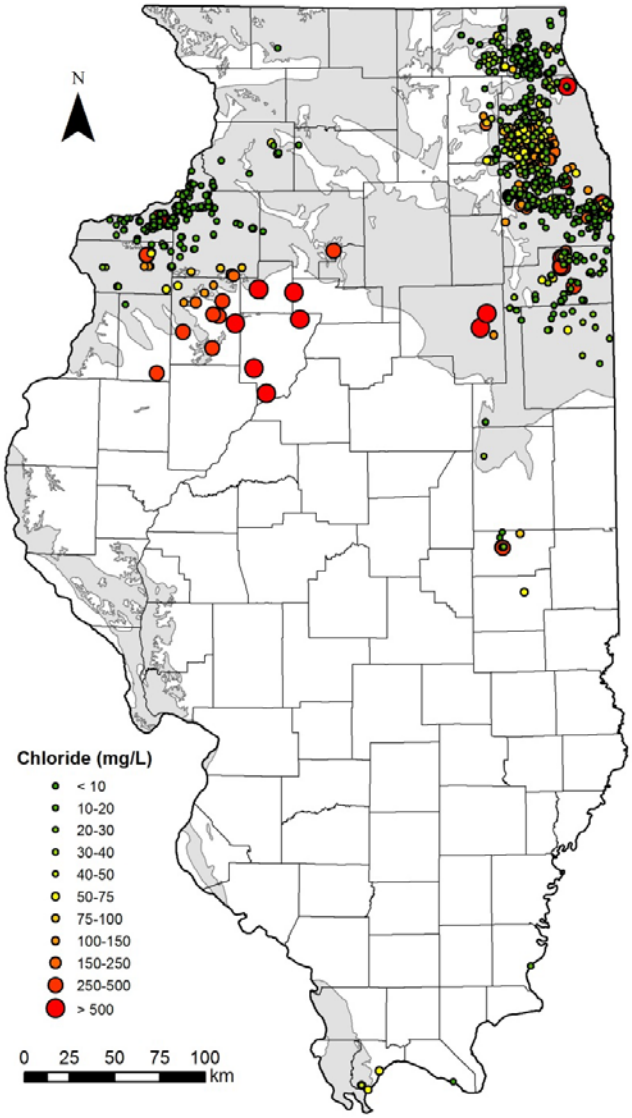

Figure 26. Chloride concentrations in wells open to Devonian-Silurian bedrock aquifers. Extent of Silurian-Pennsylvanian aquifers indicated by gray.

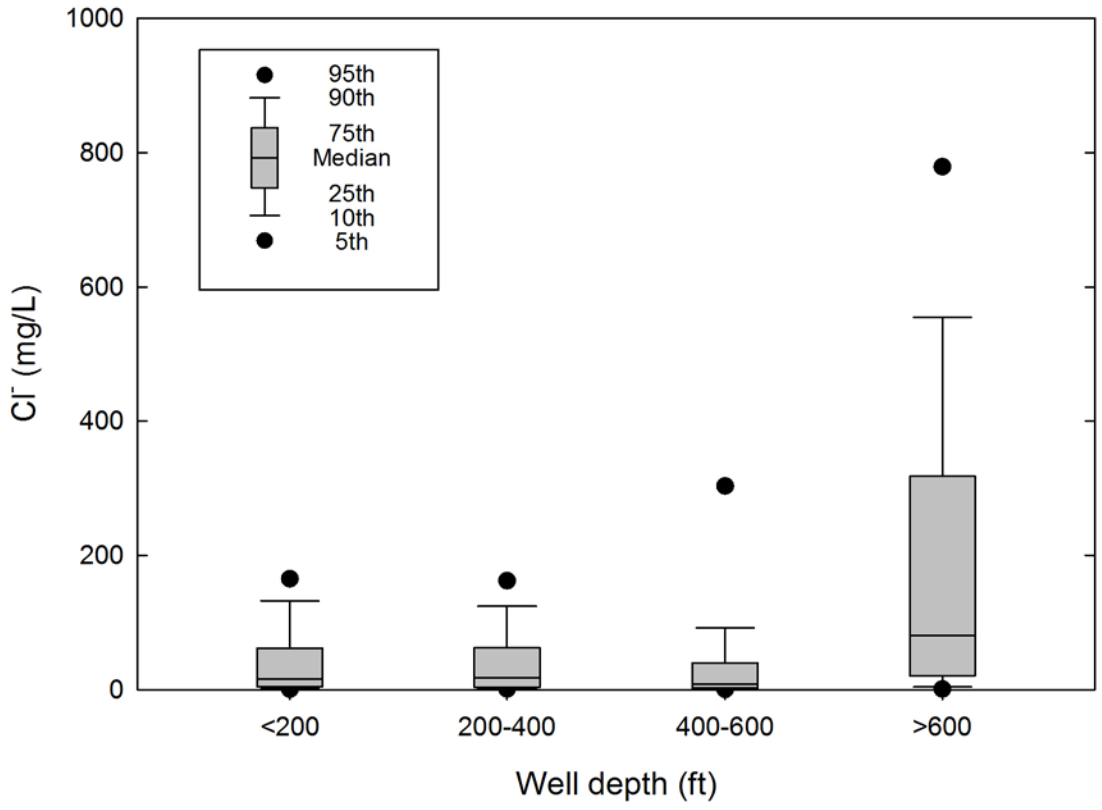

Figure 27. Chloride concentrations as a function of depth for wells completed in Silurian-Devonian bedrock aquifers. The deepest group has significantly greater concentrations than all three shallower groups (ANOVA on ranks).

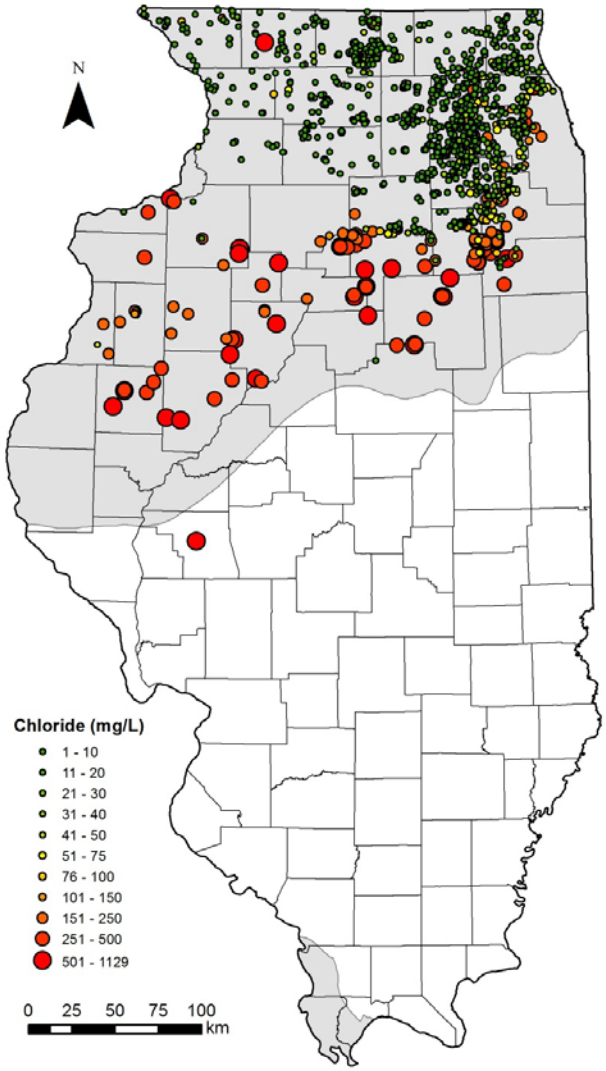

Figure 28. Chloride concentrations in wells open to Cambrian-Ordovician aquifers. Extent of Cambrian-Ordovician aquifers indicated by gray.

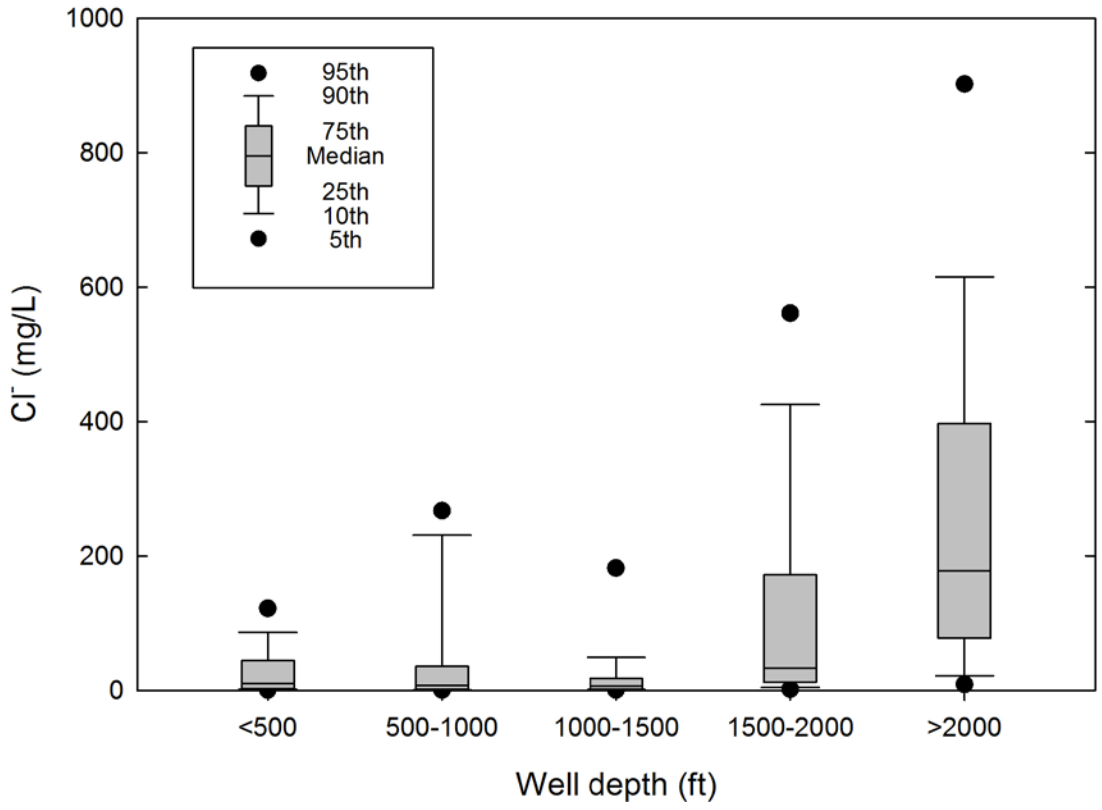

Figure 29. Chloride concentrations as a function of depth for wells completed in Cambrian-Ordovician bedrock aquifers. The two deepest groups have significantly greater concentrations than all three shallower groups (ANOVA on ranks).

Saline Springs

Panno et al. (2010) reported that there are about 30 saline springs throughout the Illinois Basin (most of which are in Illinois) that are coincident with geologic structures within and at the margins of the basin (Figure 2). Saline springs in Illinois have been identified by others (i.e., Bartow et al., 1909; Willman and Payne 1941; Panno et al., 1994, 2006, 2011). Discharge of saline groundwater may be found along the LaSalle Anticlinorium in the form of shallow wells, salt marshes, and springs at Starved Rock, Matheson, and Kickapoo Creek State Parks, and as bedrock seeps into the Mahomet aquifer in east central Illinois (Panno et al., 1994, 2006). Similar saline springs are found in southern Illinois along the Rough Creek-Shawneetown Fault Zone near Equality, and many of these sites are historic in that they were used by Native Americans and early settlers as a source of salt for meat preservation and other uses (Panno et al., 2006, 2010). Chloride concentrations in these springs can range from several hundred to greater than 30,000 mg/L in the case of the Vermilion Salines in Kickapoo Creek State Park (Panno et al., ISGS, unpublished data). The sources of these saline springs range from Cambrian- to Pennsylvanian-age formations (Panno et al., 2010).

Trend Analysis

Shallow aquifers in northeastern Illinois have been heavily impacted by human activities, with the most obvious sign being increasing Cl^- concentrations. Kelly (2008) showed that Cl^- concentrations in shallow groundwater in the Chicago region have been increasing since the 1960s. Over half of the shallow (< 200 ft; 60 m) public supply wells evaluated (N = 239) had statistically significant increasing trends in Cl^- concentrations, and there did not appear to be a leveling off of trends for the most recent samples (1990–2005).

Chloride concentrations have been increasing in shallow aquifers since the 1950s–1960s (Figure 30). The median Cl^- concentration steadily increased from 6 mg/L prior to 1950 to nearly 20 mg/L in samples from 1990 to 2005, and each time period had significantly greater concentrations than the previous time period except for the 1990–2005 group compared to the 1980s. The spread in concentrations has also been increasing, indicating spatial variability in sources of Cl^- contamination. Chloride had greater concentrations in the shallower (< 100 ft) wells than the deeper (100–200 ft) ones for all date groupings (Figure 31). These differences were statistically significant at most time periods for Cl^-. Concentration trends were generally the same for both the shallower and deeper wells. There were increasing trends for Cl^- concentrations for both shallower and deeper wells, with the median concentration increasing from 8 to 36 mg/L in the shallower wells and from 5 to 17 mg/L in the deeper wells from prior to 1950s–1960s to 1990–2005.

For individual counties, the greatest temporal changes for Cl^- were generally found in the western counties, DuPage, Kane, McHenry, and, to a lesser extent, Will County to the south (Figure 31) (Kelly, 2008). In DuPage County, the median values of all major ions tended to increase, especially Cl^-, which increased from 4 mg/L prior to 1950 to 101 mg/L in the 1990s and later, an increase of more than 2500 percent. Chloride in Cook County was highest in the 1990–2005 data group, but there was little change in the previous groups. No significant change occurred in Cl^- concentrations in Lake County during the entire time span.

Kelly (2008) reported there were significant temporal increases in Cl^- concentrations for the majority of the municipal wells tested (55 percent), and significant positive slope values were calculated for 57 percent of the wells (Figure 32). Chloride trends varied spatially; Lake and Cook Counties had relatively low percentages of wells with increasing Cl^- trends (39 to 45 percent) and slope values, while DuPage, Kane, and McHenry Counties had much higher percentages of wells with positive trends (55 to 71 percent) and slope values. Almost half (112 of 239) of the individual public supply wells tested had at least one sample collected between 1990 and 2005. The same trends for Cl^- were observed for the wells with the most recent data compared to the entire group of wells, suggesting that there has not been a leveling off in Cl^- concentrations in the 1990s or later (Kelly, 2008).

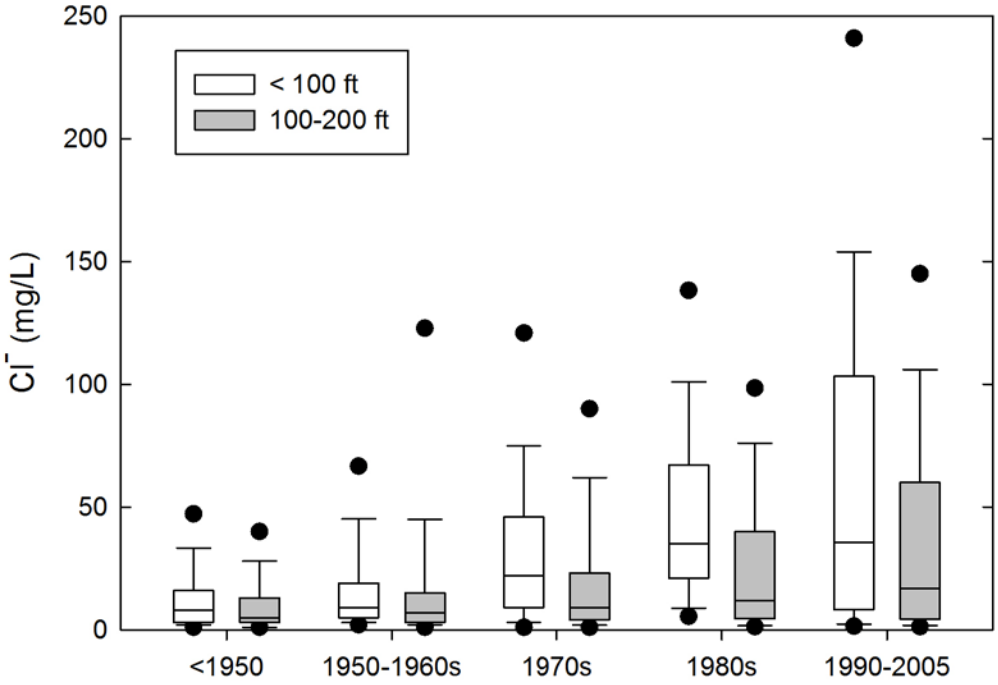

Figure 30. Box plots of Cl^- concentrations in shallow aquifers in the Chicago region. Circles show 5th and 95th percentile data. Figure from Kelly (2008).

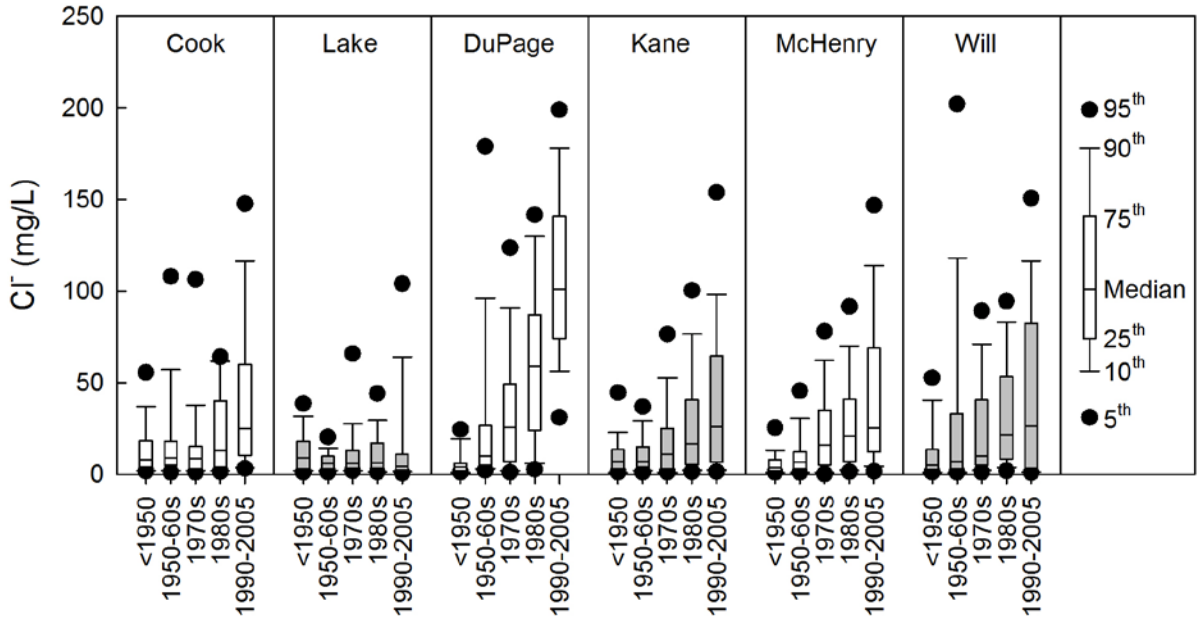

Figure 31. Box plots of Cl^- concentrations in shallow aquifers in the Chicago region by county. Figure from Kelly, 2008.

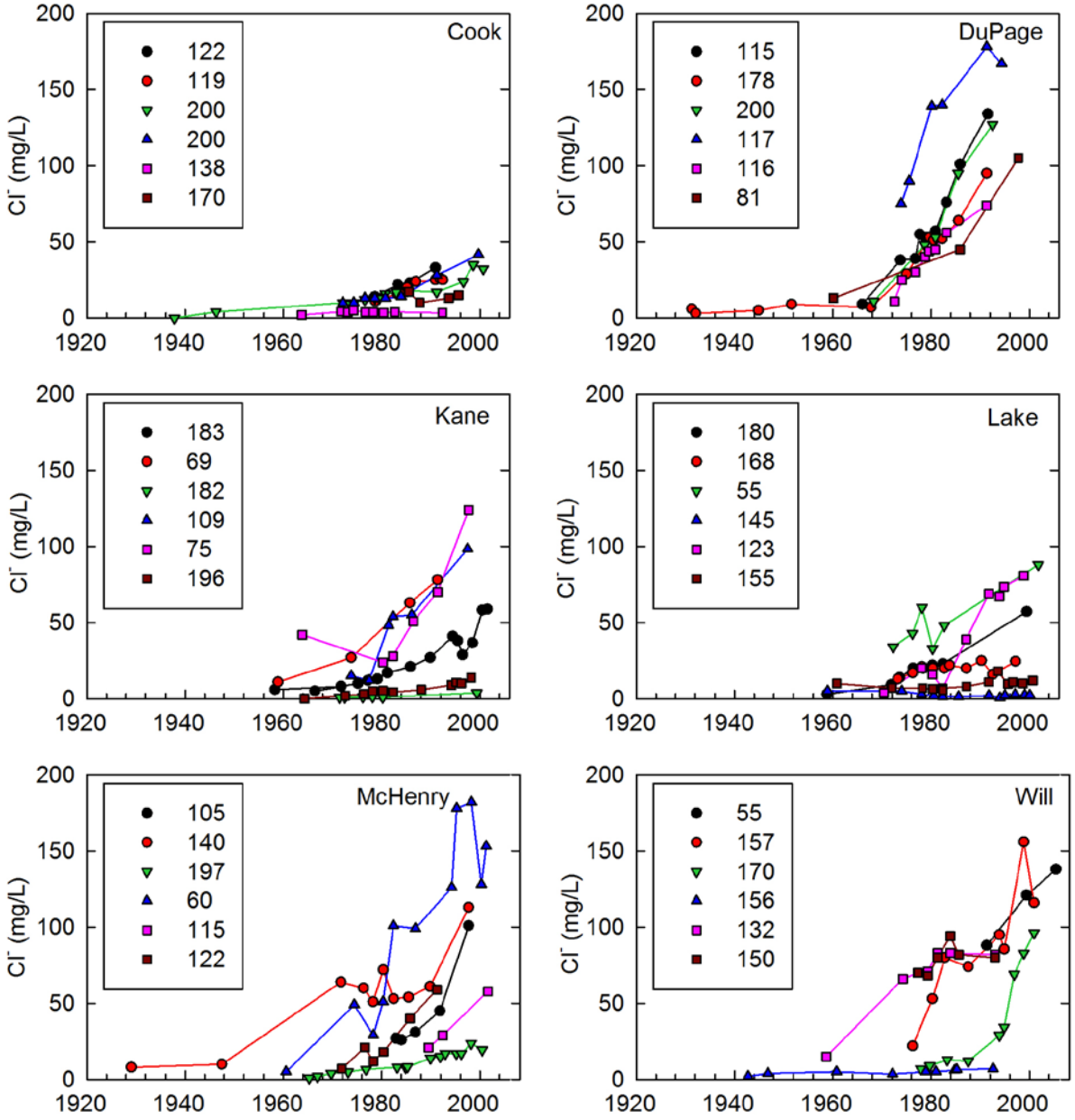

Figure 32. Chloride concentrations as a function of time for selected public supply wells in the Chicago region. Well depths (feet) in legends. Figure from Kelly, 2008.

Wetlands

Wetlands are defined as lands that transition between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water (U.S. Fish and Wildlife, 2011). Wetland substrates can be either predominantly undrained hydric soils or nonsoils that are saturated or covered by shallow water at some time during the growing season. Wetland types found in Illinois include marshes, swamps, bogs, and fens (USEPA, 2011b). Water quality in wetlands should generally reflect their source water, whether it is shallow groundwater or surface runoff, but land use activities adjacent to wetlands can strongly influence concentrations of Cl^- and other aqueous species within the wetlands.

There have been few published studies that include water quality data, and specifically Cl^-, for wetlands in Illinois. There are some published data for fens and bogs in northeastern Illinois. Fens are essentially springs that receive a very hard Ca-HCO_3-type groundwater, while bogs receive surface water from more dilute runoff. Both types of wetlands are common in northeastern Illinois. Fens at Sterne's Woods State Natural Area near Crystal Lake and South Elgin Fen near South Elgin were found to be contaminated with road salt and septic effluent (Panno et al., 1999, 2006). One part of a fen at Sterne's Woods that was reported to be in near pristine condition had Cl^- concentrations between 8.8 and 44 mg/L. Two other fens affected by septic effluent and road salt had Cl^- concentrations as high as 339 mg/L and 283 mg/L, respectively. Septic effluent and road salt discharged into South Elgin Fen increased the Cl^- concentration to 116 mg/L (Panno et al., 2005). In cases where septic effluent discharged into fens, the diverse fen-wetland vegetation was replaced by a more salt-tolerant monoculture of cattails (*Typhaangustifolia*). Panno et al. (1999) reported that fen vegetation diversity was profoundly reduced when Cl^- concentrations exceeded 45 mg/L. Road salt runoff has reduced plant diversity in wetlands of northern Illinois, where very high Cl^- concentrations have produced wetlands that can only support cattails and other halophilic vegetation (e.g., *Phragmitesaustralis*).

Discussion and Conclusions

Prior to major settlements in Illinois, Cl^- concentrations in most shallow groundwater and rivers and streams were very low, probably < 10 mg/L, and in many cases much lower. The exceptions were areas where natural brines in Paleozoic sedimentary rocks discharged at or near the land surface. There were numerous saline springs that were exploited by Native Americans and early settlers for making salt. There are numerous streams and rivers in Illinois with names such as Salt Creek or Saline Branch, named because of the discharge of saline water in or near these streams.

Once Illinois became settled as the population grew, contamination of water began. Chloride was not an important component of contamination sources in the 19th century, with the possible exception of livestock waste. It wasn't until around the middle of the 20th century that the important sources of Cl^- contamination, i.e., water conditioning salt, KCl fertilizer, and road deicers, began to be used in large amounts in Illinois. Since that time, there has been an increase

in Cl^- concentrations in many water bodies in Illinois, and there does not yet appear to be any slackening in its increase in groundwater or surface waters (Kelly, 2008; Kelly et al., in press).

One of the most likely results of increasing Cl^- concentrations in surface waters is degradation of aquatic biota. We are unaware of any systematic studies of the effects of elevated levels of Cl^- on aquatic biota in the Chicago area, but it seems certain that there would be negative effects. Corsi et al. (2010) reported that seven of 13 streams in the Milwaukee, WI, area exhibited toxicity to water fleas (*Ceriodaphniadubia*) and fathead minnows (*Pimephalespromelas*) due to road salt runoff. They measured very high Cl^- concentrations in some of the streams (commonly > 1,000 mg/L and up to 7,730 mg/L).While these are higher than typically found in stations monitored in Chicago, some of the smaller streams occasionally had Cl^- concentrations > 1,000 mg/L, and smaller streams that are unmonitored undoubtedly experience even higher concentrations.

Chicago, many of its suburbs, and many other cities in Illinois have combined sewer systems, with storm water runoff being collected and treated at WWTPs. A large percentage of road salt runoff in the most urban parts of the Chicago region thus does not enter shallow groundwater but is diverted to streams and rivers in discharge from WWTPs. The rapid transfer of saline snow melt to streams and rivers in Chicago produces very high Cl^- concentrations in the winter. However, some road salt runoff ends up in the soil zone and shallow groundwater, and this could represent a relatively long-term source of Cl^- and other ions to surface water.

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Methods and Advances in the Forensic Analysis of Contaminated Rivers

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Abstract. Trace metals and metalloids are a common and persistent form of riverine (river) contamination and are derived from a wide variety of sources, including mining and milling operations, industrial activities, urban runoff, agricultural chemicals, and atmospheric pollution, among a host of others. Documentation of trace metal sources and dispersal pathways in riverine ecosystems is essential to mitigate their potentially harmful effects to human and ecosystem health and is often required from a legal (environmental forensic) perspective to assess liability for the costs of remediation. Unfortunately, documenting the sources and source contributions of trace metals in rivers has proven difficult, time-intensive, and costly. Herein, a four-component, interdisciplinary framework is proposed to efficiently identify the sources and source contributions of trace metals in alluvial sediments where multiple natural and/or anthropogenic sources exist. The components include (1) the analysis of the river's alluvial stratigraphic architecture and geomorphic history, (2) the temporal correlation of geochemically characterized alluvial deposits to potential anthropogenic trace metal sources, (3) the analysis of the spatial variations in selected geochemical parameters, and (4) the use of geochemical and/or isotopic tracers to quantitatively estimate the contributions of trace metals from the defined natural and anthropogenic sources. The four components are *not* intended to be exhaustive; the framework may require modification following multiple lines of evidence approach, in which additional methods and data are added to the investigation until there is confidence that all trace metal sources and their contributions have been effectively defined.

Keywords: **Environmental Forensics; Trace Metals; Contaminated Rivers.**

1 Introduction

Trace metals and metalloids (herein referred to collectively as trace metals) are one of the most common and persistent contaminants in riverine ecosystems[1–6]. In rivers characterized by "normal" Eh and pH conditions, trace metals are primarily sorbed onto sediments, particularly fine-grained, chemically reactive sediments, composed of clay minerals, iron (Fe) and manganese (Mn) oxides and hydroxides, and organic matter. As a result, 90% or more of the total trace metal load is typically transported with particulates by physical processes [7,8], and incorporated into channel bed, floodplain, and other types of alluvial (river) deposits [9,10]. These alluvial deposits, then, contain a record of the spatial and temporal variations in the quantity of trace metal inputs into, and transported through, the river system, and their analysis can provide insights into the degree to which anthropogenic activities including mining, agriculture, urbanization, and industry, among others, have contaminated the aquatic environment. Moreover, the river (riverine) sediments can be used to determine the source of trace metals within the river.

The determination of trace metal sources has become one of the most important components of river cleanup for two primary reasons. First, the success of a remediation program depends on identifying where the contaminants are coming from, and then reducing or eliminating their input into the aquatic environment. In fact, the improvements in water quality in many countries since the 1970s have primarily been related to the implementation of environmental regulations that restrict the input of contaminants to water bodies from identified sources, particularly those related to industrial or mining activities. Second, the determination of trace metal sources is often driven by the polluter-pays-principal in which the polluter is required by law to pay for the cleanup of the river such that it is returned a close approximation of its previous condition.

In the U.S., for example, the Comprehensive Environmental Compensation, Response and Liability Act (CERCLA), frequently referred to as the Superfund Program, was enacted in 1980 at the federal level to address the most contaminated sites across the country. State governments have also enacted hazardous waste site remediation programs largely patterned after CERCLA. The developed legislation at both the federal and state levels allows for the allocation of liability to potentially responsible parties (PRPs). These PRPs may include single or multiple person(s) and entity(ies) such as current and past site owners or operators, generators of chemical wastes, and those involved in or responsible for the transport of wastes between sites [11].

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Across Europe, recent environmental legislation has largely been derived from European Union (EU) Directives. These directives do not specify the manner in which the laws are to be written, but direct Member States of the EU to develop regulations to achieve a particularly set of outcomes [12]. Of particular importance to our current discussion is the Environmental Liability Directive of 2004 that was intended to prevent and remedy environmental damage to both land and water resources that pose a threat to the ecosystem and human health [12]. The Directive enhances the 'polluter-pays-principle' in that it specifies that polluters should be responsible for implementing measures that prevent damage to natural resources and for remediating the damage that they have caused to the environment.

In order to carry out legislation based on the polluter-pays-principle, the source of the contaminant(s) must be identified and linked to the responsible party(ies). In some cases, such as where a single source of a non-naturally occurring chemical is dispersed by a limited number of processes, it may be a relatively easy task to identify the polluter. More commonly, however, water resources are contaminated by multiple entities that discharged varying quantities of contaminants to the environment. Some of these entities may no longer exist but were a historic waste generator. Further complicating the issue is that toxic trace metals occur naturally in the environment, raising the question as to what the contaminant level was prior to pollution, and for which the PRPs should not be held liable [13]. A fallout of these complex, legal cases is that a waste generator may not only question whether they are a responsible polluter, but whether they should be held responsible for all of the damage to a particular resource [13].

While scientists have been conducting investigations into contaminant liability issues for decades, the increasing need to apply their investigative techniques to legal issues led in the 1990s to the field of *environmental forensics*. Wenning and Simmons [14] defined environmental forensics as the "systematic examination of environmental information to determine sources of chemical contamination, the timing of releases to the environment, the spatial distribution of contamination, and the potential responsible party(ies)".

The field of environmental forensics has grown over the past 20-years into a scientific subdiscipline in and of itself. During this time, it has become clear that the determination of contaminant sources to riverine ecosystems is a difficult, and potentially expensive, task. Even where the contaminant source appears obvious, detailed investigations have shown that additional, unexpected sources of trace metals may exist. For example, numerous studies during the 1970s through the 1990s found increased inputs of mercury (Hg) to aquatic ecosystems in the Amazonian rainforest [15–18]. The assumption was that the increase in Hg inputs was related to widespread Hg amalgamation mining of placer gold deposits. Amalgamation mining involved the use of Hg to capture fine gold particles by forming dense amalgam grains that could be separated from the hydraulically lighter sediments. These amalgam grains were then heated (roasted), driving Hg off as a vapor and leaving a "purer form of the gold. In the process, Hg was lost to the riverine ecosystem. Malm [18], in fact, estimated that approximately 240 tons of Hg were released into the environment annually during the 1990s from mining operations in the Amazon of Brazil Amazon, Venezuela, Colombia, and Bolivia. Mercury was also found to be elevated in biota, including human hair, blood, and urine [15,16,19]. While gold amalgamation mining clearly contributed Hg to rivers in the Amazon (and many other places around the world), more detailed studies found that mining was not the sole source, or even the predominant source, of increased Hg inputs [20–23]. In fact, within some river basins, such as the Tapajós, Hg inputs were found to come primarily from the erosion of surface soils that had been enriched naturally by means of atmospheric deposition over geological time scales. The observed increases in Hg inputs to the studied rivers were induced, in part, by deforestation; only about 3% was derived from mining operations [22]. The point here is that while the termination of all Hg amalgamation mining may have slightly improved sediment and water quality, improvements would have been minimal because much of the Hg was derived from a separate, unexpected source.

The remediation of Contaminant Rivers is a major undertaking. In fact, rivers represent some of the largest Superfund sites in the U.S., and the costs of remediation are often in the hundreds of millions of dollars (US). As a result, significant effort has gone into developing methods to determine the source of contaminants, including trace metals, in rivers, most recently in the context of environmental forensics. The majority of the developed techniques rely on fingerprinting techniques that attempt to define trace metal sources by identifying one or more unique physical, mineralogical and/or chemical parameters that can uniquely distinguish a suspected source in the basin from all other sources. Fingerprinting techniques, however, are not the only methods that can be used to assess trace metal sources or their relative contributions to a river. A common question that arises, then, during the development of a remediation program is which methods are most effective at identifying trace metal sources in terms of both time and costs. Underlying this question is the understanding that whatever methods are used must withstand the scrutiny of legal debate which is often associated with remedial activities.

In this paper, a multidisciplinary four-component approach to the effective identification of the predominant sources of trace metals to river sediments is put forth. The approach is intended to integrate geomorphic, alluvial stratigraphic, and geochemical data that not only allows for the assessment of trace metal sources but insights into their transport and ultimate depositional locations of trace metals along the river valley.

2 Methodological Approach

Herein, it is argued that four types of analyses provide a time and cost-effective framework for the identification of trace metal sources and their relative contributions to aquatic environments. They include (1) the analysis of the river's recent alluvial stratigraphic architecture and

geomorphic history, (2) the temporal correlation of geochemically characterized alluvial deposits to potential anthropogenic trace metal sources, (3) the analysis of the spatial variations in selected geochemical parameters, and (4) the use of geochemical and/or isotopic tracers to quantitatively estimate the contributions of trace metals from the defined natural and anthropogenic sources (Fig. 1). The four included components are *not* intended to be exhaustive. In fact, the approach utilized at any given site should be based on the multiple lines of evidence concept, in which additional methods and data (not described herein) are added to the investigation until there is "sufficient" confidence that all trace metal sources and their contributions have been effectively defined.

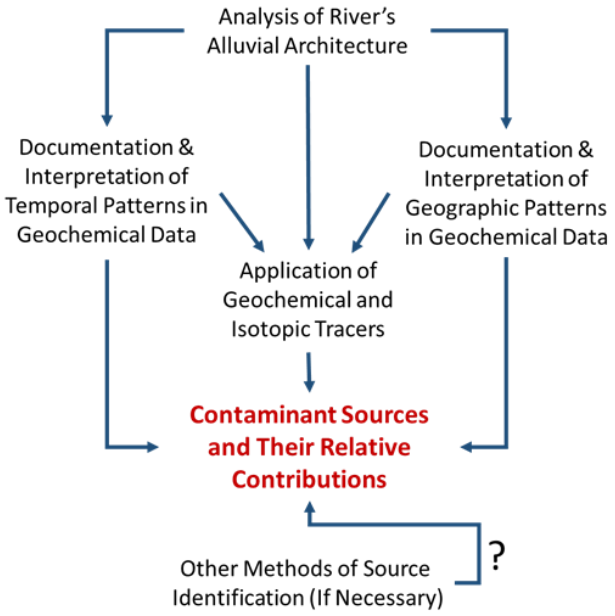

Fig. 1. Schematic diagram of the framework proposed for the assessment of trace metal sources and source contributions.

2.1 Analysis of a River's Alluvial Architecture and Geomorphic History

Rivers can be viewed, somewhat simplistically, as a network of channels that carry water and sediment from upland areas of a catchment to the basin mouth. Rather than being simple conduits, however, rivers continually erode and deposit sediments, both within the channel and, during floods, on the adjacent floodplain. These geomorphic processes create alluvial stratigraphic units (deposits) that not only consist of the sediments that enter the channel but sediment-associated trace metals. These alluvial (river) deposits, therefore, contain a record of trace metal inputs to the river [9,24,25].

Historically, the sampling of contaminated rivers largely ignored the fact that these alluvial deposits vary in terms of their sedimentological characteristics or age. However, more recent studies have shown that attempts to distinguish the relative proportions of trace metals derived from natural and anthropogenic sources are complicated by physical and biogeochemical processes that act on source materials as they are transported downstream through the river system. A particularly important process is hydraulic sorting that partitions the sediments, and the trace metal(s) they are carrying, into specific depositional environments within and along the river based on grain size and density [9]. Fine-grained sediments tend to be deposited in areas of low velocity, whereas coarser sediments in zones of higher velocity. The net effect of these processes is for trace metals to become partitioned during transport such that they are deposited into stratigraphic units characterized by distinct sedimentological traits that are characterized by concentrations that are significantly higher or lower than in the original source materials. In addition to hydraulic sorting, the original composition of the source materials may be affected by the addition of non-reactive constituents (e.g., organic matter, carbonates) into the deposited sediment, or by geochemical transformation processes including reductive/oxidative reactions (that may, for example, allow grains to be coated with Fe and Mn oxides and hydroxides). These processes are element-specific, and depend on the local climatic, hydrologic, and geomorphic setting [9,26]

The preferential deposition of source materials also occurs over larger spatial scales. For example, relatively narrow, steep valley reaches have been shown to produce zones of limited sediment deposition (referred to as transport zones), whereas wide, low-gradient reaches produce zones of deposition and contaminant storage (depositional zones). Thus, in some environments, trace metal concentrations and storage may vary downstream as a function of the river's overall geomorphology, and the geomorphic processes that occur along Specific River reach.

The primary goal of analyzing the river's alluvial stratigraphic architecture and history is to identify, characterize and map the distribution of distinct, sedimentary deposits along the river valley. These deposits can subsequently be dated, as described below. Provided that sediment-trace metal relationships are known, the collected information provides insights into where sediment-associated metals from a specific source are likely to be deposited. For example, mine and mill tailings from Cu, Pb, and Zn ores commonly contain significant quantities of sulfide minerals (e.g., galena, sphalerite, and pyrite). These relatively dense mineral grains are typically deposited with coarse-grained alluvial sediments. In fact, these sulfide minerals may form contaminant placer deposits along the river [9]. The same holds true for Au or Ag amalgam grains associated with amalgamation mining. In contrast, trace metals associated with chemically reactive, fine-grained sediments will likely be deposited in areas of relatively low flow, such as on floodplains or in oxbow lakes (Fig. 2). Therefore, by characterizing the sedimentology and distribution of the deposits, it is possible to hypothesize as to where trace metals from a potential source are likely to be concentrated.

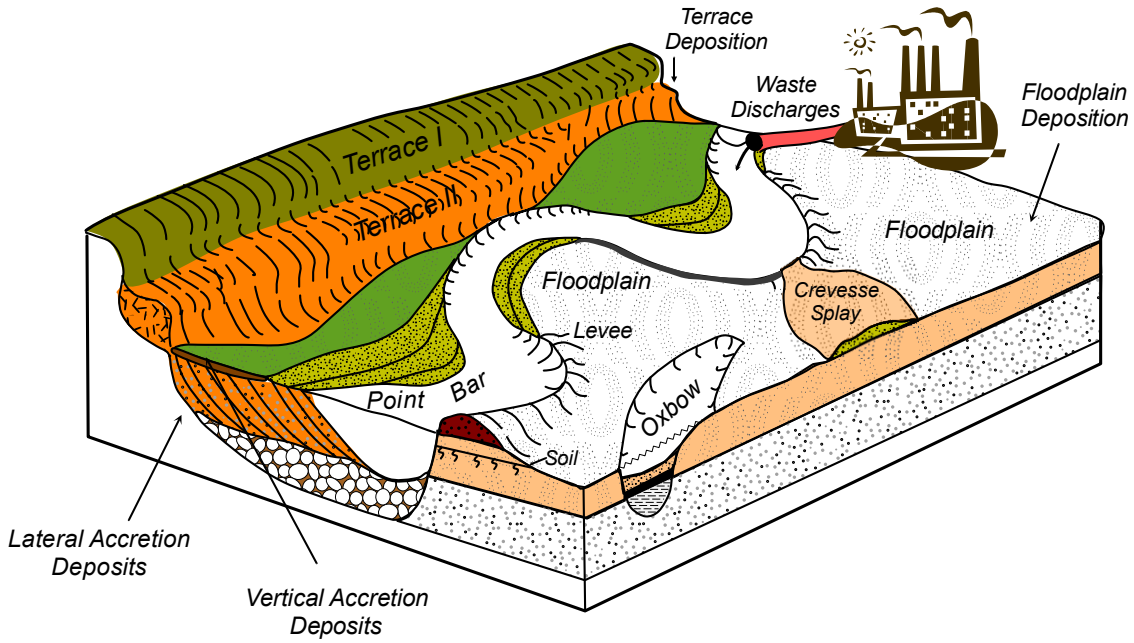

Fig. 2. Common types of alluvial deposits located along meandering streams. Each deposit (stratigraphic unit) possesses a unique sedimentology and, thus, trace metal content (figure modified from Miller et al. [37]).

In addition to the above, documentation of the river's alluvial architecture and history provides the foundation for the development of the temporal and spatial analyses described below. Thus, while such geomorphic and stratigraphic studies are often ignored in contaminant source analyses, they are critical components that should not be overlooked.

2.2. Temporal Studies

Once the alluvial stratigraphic deposits within the river valley have been defined and sedimentological and geochemically characterized, they can often be dated to determine their approximate age. Historically, absolute dating of the deposits primarily relied on radiocarbon methods characterized by a rather poor temporal resolution. However, deposit dating has significantly improved in recent years, and may include the use of other methods including ^{137}Cs and ^{210}Pb analyses, dendrochronology techniques, the analysis of historic artifacts and sequential aerial imagery, and, perhaps of most significance, optically stimulated luminescence (OSL) techniques, to mention a few (see Stokes and Walling, [27] for a more detailed review). As a result, it is often possible to constrain the age of alluvial stratigraphic deposits to a few years. This makes it possible to compare the geochemical (trace metal) content of the deposits, both temporally and geographically, to the location and history of suspected anthropogenic trace metal sources. As an illustration, the hypothetical stratigraphy of a river valley containing two potential sources of lead (Pb), is shown in Fig. 3. Stratigraphic units A1-A3 possess similar and relatively low Pb concentrations. The highest concentrations of Pb are found in unit A5, which was deposited between approximately 1900-1960, during which time an upstream industrial site (#1) was operating. This temporal correlation between high Pb concentrations in unit 5 and the industrial site #1 suggests that it contributed at least some of the increased Pb observed in unit A5. Given that industrial site #2 had yet to be built and was located downstream of cross-section B-B', it could not have contributed Pb to the site. Note, however, that the increase in Pb concentrations began to occur in unit A4, which predates the operation of industrial site #1, suggesting that another, unidentified source of Pb may have existed upstream of the cross-section B-B'. The illustration shows that it is important to develop chronologies of trace metal inputs for multiple locations. Selection of these sites should minimize the number of locations needed to effectively define inputs to the river from all potential trace metal sources. The historical record should also extend into the past for hundreds of years, if possible, to ensure that natural variations in trace metal inputs are adequately characterized.

The methods, assumptions, and uncertainties inherent in developing a record of the temporal variations in trace metal inputs to a river can be found in Macklin and Klimek [28], Hudson-Edwards et al. [29], Tobin et al. [30], Miller and Orbock Miller [9], Pease et al. [31], Du Laing et al. [32], Matys Grygr et al. [33,34], and Ferrand et al. [35]. In general, it involves three primary tasks, including the stratigraphic and sedimentological characterization of the river deposits, the sampling and geochemical analysis of the deposits for trace metals and other parameters, and the application of absolute dating methods to determine the approximate age of the deposits in "calendar" years.

Contaminant chronologies can be developed using any undisturbed sequence of river sediments, as well as sediments obtained from wetlands, lakes, and reservoirs that are physically linked to the river. Perhaps the most detailed chronological records have been developed using reservoir deposits and overbank floodplain deposits. The

latter deposits (also referred to as vertical accretion deposits) are characterized by successive thin layers of sediment produced by the deposition of suspended sediments from floodwaters that inundate the floodplain surface (Fig. 2). The process results in a sequence of layers in which younger sediments overlie older sediments producing a trend in which the age of the sediment systematically increases with depth. Unfortunately, the relationship between depth and unit age is not perfect because deposition only occurs during floods. Nonetheless, detailed records of trace metal loadings, as shown in Fig. 3, have been produced [28,35,34].

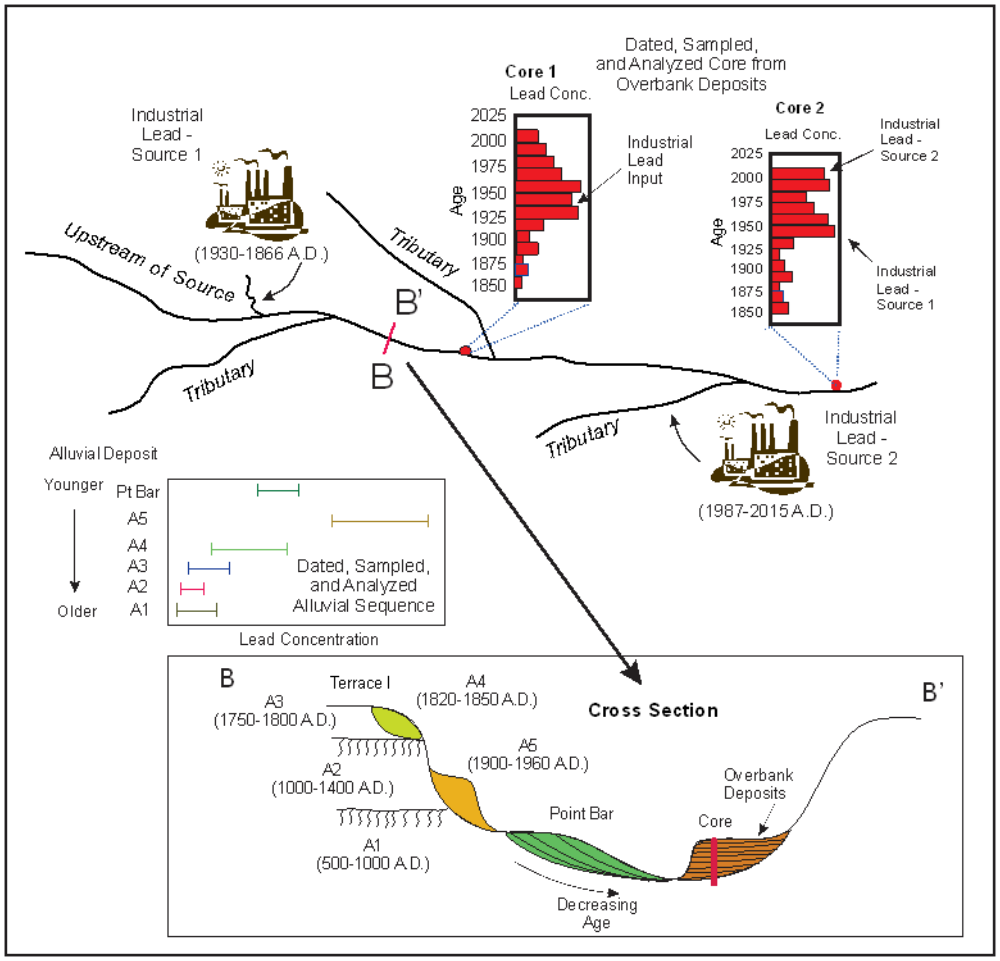

Fig. 3. Illustration of the spatial and temporal correlation of between alluvial stratigraphic units and industrial sources (figure modified from National Academy of Sciences [36].

2.3. Spatial Studies

One of the oldest and most extensively utilized methods of determining a point source of trace metal contamination is to examine its spatial distribution along the river. In most instances, the spatial distribution of the trace metal is examined in terms of its concentration in the channel bed or floodplain sediments. The presumption is that the highest concentrations of the metal will be located closest to the source, and decrease with distance from the site. In general, the spatial approach to source determination along rivers involves the collection and analysis of samples from multiple sites distributed along the channel and its associated features, and the subsequent plotting of the derived concentration data to document geographical patterns in elemental content. Point sources can then be identified by a distinctive trend in which low concentrations occur upstream of a source and abruptly increase in concentration where the trace metal(s) enter the channel. Concentrations subsequently decrease semi-systematically downstream from the source as a result of (1) the hydraulic sorting of contaminated particles, (2) dilution resulting from the mixing of contaminated particles with "clean" sediment from tributaries and eroded banks, and the dispersal of sediment-borne contaminants over a larger area, and/or (3) the deposition and subsequent storage of the contaminants within the channel bed or floodplain, a process that removes the contaminants from further transport. In addition, geographical patterns in alluvial sediments are often influenced by geochemical processes, such as precipitation, sorption on to reactive particles, and/or the oxidation/reduction of mineral grains. The accumulation of a contaminant in biota also has been cited as a control, but its influence is typically negligible along most rivers. In many cases, input from the identified source is supported by a comparison of the concentration of the contaminant within the suspected source materials. As an illustration, Fig. 4 shows the distribution of Pb and

Barium (Ba) along the Big River in southeastern Missouri. The abrupt upstream increase in Pb was interpreted to result from the influx of mining and milling wastes within the St. Francois mining district. Secondary increases in Pb spatially correspond to increases in Ba, which have been interpreted to represent the influence of Pb from earlier mining operations within the Barite mining district [38].

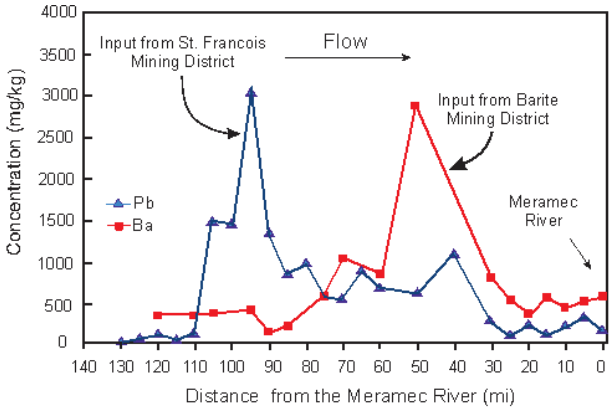

Fig. 4. Downstream trends in lead and barium concentration along the Big River, Missouri, USA. Abrupt increases in concentration reflect input of metals from mining operations (figure modified from Integral [38].

Although the spatial analysis of trace metal concentrations is easy to use and often provides important insights into the sources of trace metals to a river, the approach is plagued by the fact that the influx of trace metals from multiple sources can create overlapping spatial patterns that make it difficult to identify where the metals are derived. Such overlapping patterns are particularly common in mineralized river basins where metals may be derived from both mining wastes and mineralized rocks that underlie the basin. In fact, exploration geochemists often analyze spatial trends in trace metal concentrations in rivers to identify the location and grade of ore deposits. To help alleviate this problem, downstream variations in the ratios of trace metal concentrations may be used. For example, within the Rio Loa basin of northern Chile, Cu/Sb ratios were effective at differentiating between mining and geogenic trace metal sources. High Cu concentrations were associated with waste materials from local Cu mines, whereas elevated Sb concentrations were associated with natural mineralized rocks, particularly sediments derived from the El Tatio Geyser Basin [39]. In other instances, it may be possible to utilize the unique element or mineral associated with a specific source. The use of Ba along the Big River in Missouri is an example, as barite was not particularly prevalent in the mine wastes from the St. Francois mining district. Alternately, spatial trends in local enrichment factors (LEFs, see below) can be used to filter out the input of trace metals from natural sources, along with changes in the grain size and lithology of the source materials during transport through the river.

Another potential problem encountered while interpreting spatial data is that the deposition of sediment and sediment-associated trace metals may not decrease systematically downstream, but may reflect changes in flow conditions along with the drainage network (as observed for transport and sedimentation zones). Moreover, in mining areas, the influx of trace metals from mineralized rocks may produce downstream trends characterized by highly variable trace metal concentrations or ratios, as well as the preferential deposition of trace metals in deposits of specific grain size or density.

To compensate for the influence of grain size, density, or natural geogenic variability, spatial variations in concentration within the overbank deposits is often examined for a specific grain size fraction (such as the silt and clay-sized, <63 µm fraction), or a bulk concentration normalized by the percent of fine sediment in the sample [40]. An alternative approach used to differentiate between natural and anthropogenic sources of trace metals is to examine spatial variations in enrichment factors (EFs).

One of the most common methods of calculating EF values is the "double-normalization" technique, mathematically expressed as:

$$EF = (M/M_{ref})/(M/M_{ref})_{bc} \quad (1)$$

where M is the target trace metal of interest, M*ref* is a conservative reference element, and *bc* refers to the average concentrations of the target metal and reference element in uncontaminated background materials. Commonly utilized reference elements include Al, Fe, Li, Rb, Si, Ti, and, more recently, Co. Theoretically, the method addresses variations in both grain size and particle mineralogy. Aluminum, for example, is a significant element in aluminosilicate minerals, including fine-grained (<~2 µm) clay minerals, and therefore reflects both grain size and elemental composition of the sediment [26,41,42].

Historically, elemental average concentrations were based on those measured in continental crustal rocks (*bc,* Equation 1 [26,43,44]. More recent studies have shown, however, that the use of these elemental averages tends to result in large errors [44] because (1) the elemental concentrations determined from continental crustal rocks do not adequately represent that rocks that underlie the basin of study, and (2) the metal concentrations measured in the source metals rocks) will be altered by physical and/or biogeochemical processes, thereby changing the nature of the source sediments as they are transported downstream (as described earlier). Given these shortcomings, more recent studies have argued for the use of local enrichment factor (LEF) [26,43,44], in which:

$$LEF = M_S/M_{BG} \quad (2)$$

where M_S is the concentration of the target metal of concern in the sample, and M_{BG} is the concentration of the metal of concern in local, non-anthropogenically polluted, background sediments. M_{BG} is empirically predicted using a background function, such that:

$$M_{BG} = f(M_{ref}). \quad (3)$$

In most instances, background functions are defined by bivariate regression equations between the concentrations of the target metal in the unpolluted sediments and a parameter that accounts for changes in metal concentrations during sediment transport and deposition. The most common functions involve grain size, organic matter content, or the concentration of a conservative reference element. An advantage of calculating and using local enrichment factors in the development of trace metal chronologies is that they not only provide insights in when contamination occurred but the relative magnitude of the contamination that occurred in comparison to local background values.

It is important to recognize that the resolution of the spatial variations in downstream trends in trace metal concentrations, elemental ratios, and LEFs values depends on both the number and location of the samples that have been collected along the river. Differences in sampling frequencies and locations may yield differing results. It is therefore advantageous to collect as many samples as possible, particularly up and downstream of major tributaries.

2.4. Use of Geochemical Tracers to Determine Source Contributions

The approaches described above identify contaminant source(s) by spatially or temporally linking elevated concentrations (or differences in elemental ratios or LEFs) to suspected contaminant sources. Where multiple sources exist, the assumption is that the magnitude of the increases or decreases in metal values will provide *qualitative* insights into the relative contributions of contaminants from each of the delineated sources. While the approach is logically intuitive and easily understood, more quantitative estimates are often required, particularly when the analysis is being conducted as part of an environmental forensic investigation. During the past decade, there has been a dramatic increase in the use of environmental tracers to assess the provenance (source), movement, and fate of sediment and sediment-associated contaminants within rivers. With regards to alluvial sediments, a *tracer* is defined as a unique sediment-associated parameter or set of parameters that can distinguish a particular sediment type from other sediments in the basin. The tracer can, therefore, be used to track the movement and cycling of specific sediments from their point of origin through the river over varying temporal and spatial scales [37]. The term 'tracer' is often used synonymously with *fingerprint*. However, the term fingerprint is used in the geomorphological literature refer to a specific type of analysis (referred to as fingerprinting studies), which are described below. With regards to environmental forensic studies of contaminated rivers, the application of tracers or fingerprints has evolved significantly over the past decade and has now become the predominant method for *quantitatively* determining source contributions. With regards to alluvial (river) sediments, two types of analyses have evolved over the past two decades and, unfortunately, there has been little integration in the development of the two approaches. One approach involves the use of the concentration of multiple elements to create unique source area fingerprints and then applies statistically-based mixing models to the data. The second approach relies on the use of stable isotopic data, which is typically combined with analytical mixing models. Both types of investigation have benefitted greatly from recent scientific advances in analytical chemistry, which allows for the rapid analysis of large numbers of samples for a wide range of elements and measurements of isotopes that could not be analyzed in the past. Another important advantage of using geochemical tracers/fingerprints is that the analysis can be completed relatively quickly in comparison to many techniques, and can be applied to historic sedimentary deposits retrospectively to determine changes in sediment and contaminant provenance at a site through time.

2.4.1. Multi-elemental Fingerprinting Analyses

As the name implies, multi-elemental fingerprinting studies utilize variations in the concentration of multiple elements to develop a unique fingerprint for a specific sediment source and then allow sediment from that source to be distinguished from other sediment sources in the basin. It is worth noting that the method tracks the sediments associated with a trace metal source and not the trace metal of concern. Fingerprinting studies are most often applied to diffuse sources of sediment in the basin, although their application to other types of problems is increasing. Conceptually, fingerprinting studies are based on the fact that upland areas of a catchment can be spatially subdivided into specific sediment sources on the basis of its underlying geology or soil types. Each of these sediment sources can be eroded, after which the generated sediments are transported, often intermittently, to the river channel. As the sediments are transported downstream through the channel to a depositional point, the particles from all of the source areas are combined such that the sediments within the depositional unit represent a mixture of particles from all of the source areas in the basin. The physical and geochemical composition of this sediment mixture (which we will refer to as river sediment) depends on the composition of the source area sediments and the relative amount of sediment that is contributed to the deposit from each source area; if both are known, it is possible to predict what the composition of the mixture will be. In our case, however, the objective is to determine the relative amount of sediment, and sediment-associated trace metals, that a particular sediment source contributed to the deposit. This type of calculation represents a linear inverse problem [45]. The problem is typically solved using some form of inverse or unmixing model that requires that the composition of both the source and river sediments be known for a selected set of parameters, and then defines the mixing proportions from each source by adjusting the contributions such that the values of the parameters most closely match the values observed in the studied river sediment [45].

In general, the fingerprinting method involves five key steps (after Zhang et al. [46]): (1) delineation and

characterization of sediment sources within the basin, (2) the selection of the fingerprinting parameters (elements) that most effectively discriminate between sediments of the defined sources, (3) the collection of river sediment on the basis of the timeframe under consideration, and its subsequent characterization for the selected fingerprinting properties, (4) the determination of sediment provenance (source) using numerical modeling procedures, and (5) assessment of the uncertainty inherent in the modeling results. Although a wide range of physical, mineralogical, and geochemical parameters have been used as fingerprinting parameters to determine the source of the sediments and their associated metals [37, 47], most environmental forensic analyses utilize the concentration of multiple, conservative elements to develop an effective fingerprint.

Geochemical fingerprinting studies have been applied to a wide range of river sediments, and the river sediments that are selected determine the timeframe of the source analysis. The timeframe may range from recent, instantaneous suspended sediment samples collected during a specific part of a flood event to river sediments deposited within floodplains or riparian wetlands during an entire flood and that may be hundreds or even thousands of years old. In addition, overbank floodplain deposits or reservoir sediments can be incrementally collected and analyzed to determine changes in sediment source through time (Fig. 5).

The overwhelming majority of fingerprint studies have been conducted to determine the source of sediments and sediment-associated contaminants from diffuse sources located throughout a river basin. The approach, then, is perhaps most applicable to the assessment of trace metals from natural mineralized rocks as well as urban pollutants and agricultural chemicals (e.g, fertilizers, pesticides, sewage amendments). It is possible, however, to include point sources of trace metals in the analysis to determine their contribution to a river. Moreover, the approach has been used to assess the relative inputs from a point source by characterizing changes in elemental concentrations from up- to downstream of a contaminant input point. In most instances, the point in contaminant influx is taken to be the mouth of a tributary [48, 49].

A common criticism in the application of multi-elemental fingerprinting studies is that the statistical mixing models used to estimate the relative contributions of sediment from each of the defined sources resulted in values that were not unique. Rather, the results represented statistical estimates, for which there was an infinite number of possibilities. This problem has been referred to as the equifinality problem. Moreover, the results were often considered to possess considerable, but unquantifiable error, particularly where one source contributed little (~0 %) or all (100 %) of the sediment. During the past decade, considerable progress has been made in addressing this problem, and most statistical fingerprinting approaches are now able to quantify the uncertainty in the modeling results. In addition, the influence of grain size, organic matter content, and other factors on elemental concentrations has also been reduced. As a result, it can be argued that multi-element fingerprinting methods are highly effective.

2.4.2. Source Analysis using Isotopic Tracers

A wide range of stable isotopes have been applied to hydrological and geological investigations. The isotopes that have, perhaps, been most widely used are H, C, N, O, S, and Si. However, with regards to sediments, and the analysis of sediment and trace metal sources, radiogenic isotopes (e.g., Sr, Nd, and Pb) have historically been of most importance. Radiogenic isotopes are the daughter products of the decay of a radioactive parent. Their use as effective tracers stems from several key characteristics: (1) they can be accurately and precisely determined, (2) they exhibit isotopic abundances that vary widely within geological materials, allowing for the fingerprinting of both natural and anthropogenic materials, and (3) they are not significantly fractionated by physical, chemical or biological processes. This latter trait is important because the isotopic ratios (fingerprints) of the source sediments will remain largely intact during the erosion, transport, deposition, and diagensis of the sediment, allowing the isotopic composition of river sediments to reflect the mixing of materials from all of its sources within a river basin. With regards to environmental forensic investigations, the radiogenic isotopes of Pb have been the most extensively utilized. In fact, lead isotopes have been extensively used to determine the sources of Pb in a wide range of media, including air and aerosols, snow and ice, soils, lacustrine and reservoir deposits, wetlands and peat, plants, mosses, and tree rings, human tissues and blood and other biota (see Miller et al. [37] for extensive list of references). Moreover, because Pb is commonly associated in both Earth materials and man-made products with other toxic trace metals, Pb isotopes can often be used to assess the source of these other metals. A key advantage of using radiogenic isotopes, including those of Pb, is that they can provide quantitative estimates of the contribution of Pb in sediment as well as the other media of interest. It is for this reason that where possible, radiogenic isotopes, particularly those of Pb, should be applied in the forensic investigation of contaminated river sediments.

Given its widespread application, and its effectiveness at tracking sediment-associated Pb, Pb isotopes are discussed below as an example of how isotopic tracers can be applied to determine the source(s) and source contributions of Pb in river basins. More detailed reviews of the use of radiogenic isotopes in the environmental forensic investigation of contaminated rivers can be found in Miller et al. [37], whereas Bird [50] reviews the application of Pb isotopes to riverine environments.

Lead has three radiogenic isotopes, ^{206}Pb, ^{207}Pb, and ^{208}Pb, derived from the radioactive decay of ^{238}U, ^{235}U, and ^{232}Th, respectively; ^{204}Pb, has no known radiogenic parent. The isotopic abundances of Pb in geological materials are reported in terms of ratios (e.g., ^{206}Pb /^{204}Pb). For most environmental studies, only the radiogenic isotopes of Pb are used as geochemical tracers, in part, because the abundance of ^{204}Pb is relatively low, making it difficult to accurately measure. The analyses of sediment-associated Pb sources presume that the analyzed river sediment contains a mixture of Pb from all of the

potential Pb sources in the basin and that the relative abundance of the radiogenic Pb isotopes in the sediment depends on the relative contributions of Pb from each source. This assumption is nearly always met as the fractionation of Pb isotopes by physical, chemical and biological processes is negligible.

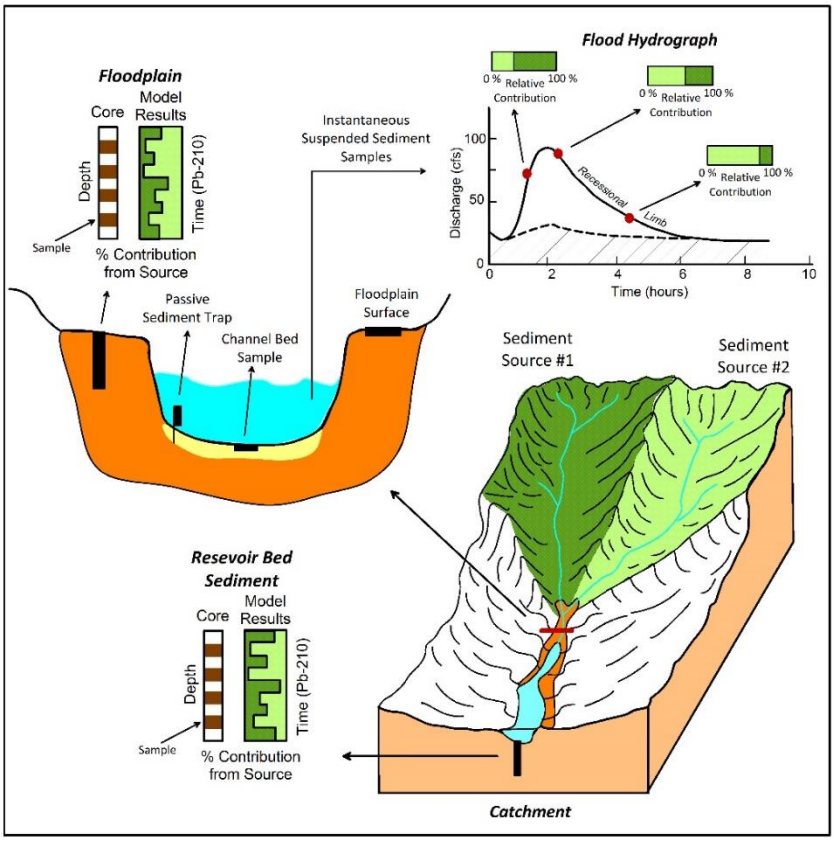

Fig. 5. Summary of commonly used sediments for the analysis of trace metal sources using multi-elemental fingerprinting methods (figure from Miller et al. [37]).

The quantification of Pb contributions from a particular source is often initiated by plotting the isotopic data collected from suspected Pb sources and the river sediments of interest on three-component (bivariate) scatter diagrams depicting differences between two isotopic ratios (Fig. 6) [51,52,50]. Ideally, Pb sources will exhibit a narrow range of isotopic ratios, which differ from the other suspected sources and from the sediments collected from within the river. In this case, the Pb isotopic ratios serve as effective fingerprints (tracers) of the suspected Pb sources. Moreover, if the isotopic ratios of the river sediments plot along a linear trend between two of these isotopic end-members, then the trend is interpreted as a mixing curve, and the Pb within the river sediments is assumed to be primarily derived from the sources that form the two end-members of the line. In many cases, one end-member of the mixing curve represents Pb from the bedrock that underlies the river basin, whereas the other represents Pb from a significant anthropogenic source [50]. The average signature of the "geogenic" Pb sources can be determined by analyzing uncontaminated alluvial sediments in the basin, such as sediments found in uncontaminated alluvial terraces (comprised of pre-historic sediments) [52], floodplain sediment found at depth within a sediment core that pre-dates anthropogenic contamination [48], or the direct analysis of the underlying bedrock [52].

As mentioned earlier, a significant advantage of using Pb isotopes as tracers is that accurate estimates of the relative contributions of Pb can be determined analytically. When there are only two sources of Pb, and the mixing curve is linear, the contributions from the two end member sources can be calculated using a simple binary model [48,53] that takes the form of:

$$\%A = \frac{\left(^{20x}Pb/^{20x}Pb\right)_S - \left(^{20x}Pb/^{20x}Pb\right)_A}{\left(^{20x}Pb/^{20x}Pb\right)_B - \left(^{20x}Pb/^{20x}Pb\right)_B} \qquad (4)$$

where $\%A$ is the contribution of source A in a sample and $^{20x}Pb/^{20x}Pb$ and $^{20x}Pb/^{20x}Pb$ are the average ratios in the sample (S) and the two end-member sources, A and B.

Within larger river systems contaminated by multiple anthropogenic Pb sources, well-defined mixing lines do not exist on binary scatter plots. In these cases, it is likely that multiple geogenic or anthropogenic Pb sources exist. As a result, estimating the relative contribution of Pb in the alluvial sediments of the river from the identified sources becomes more difficult. This problem has been overcome by subdividing and analyzing the data on the basis of located geographical areas or time periods (ref). In addition, the use of isotopic tracers can be combined with the multi-elemental approach describe above. For example, Bird et al. [54] used a two-tiered approach to assess the origins of Pb within sediments of the River Maritsa catchment of Bulgaria and Turkey. Lead isotopic

data were used to assess the contributions of Pb to the channel from mining operations within smaller tributary basins. However, at a larger spatial scale, where highly variable Pb isotopic values inhibited the use of a binary isotopic approach, the sources of the Pb were determined using multi-element geochemical fingerprinting methods (described in the section above).

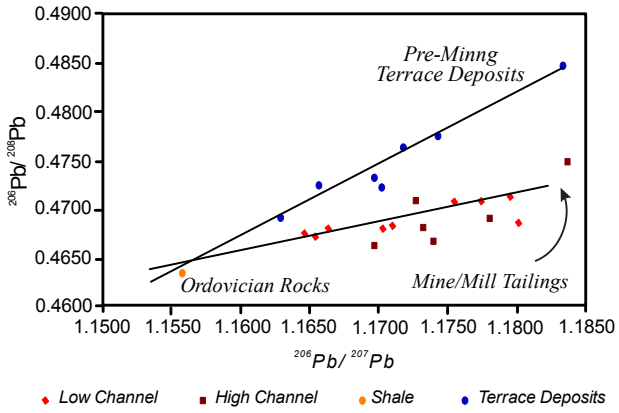

Fig. 6. Bivariate plot of lead isotopes. Background lead was characterized using samples from alluvial terrace deposits that predate mining. The onset of mining results in the influx of Pb from mine and mill tailings. The influx is reflected in a new source of Pb in the channel bed. Thus, samples plot along a new mixing line (figure modified from Miller et al. [52]).

Lead isotopic data are often combined with Pb concentration data (see, for example, Shepard et al. [55]). In doing so, it is possible to assess both changes the source of the Pb as well as the degree to which the Pb sources have contaminated the river. Moreover, because the predominant sources of Pb also served as the predominant sources of other toxic trace metals (e.g., As, Cd, Ni, Zn), Pb isotopes can be used to determine the sources of these metals as well. However, this is not always the case, and in some instances, the isotopic composition of Pb in contaminant sources cannot be distinguished from Pb naturally found in the underlying Earth materials. For example, within the Rio Loa basin of northern Chile, the Pb isotopic composition of Cu mine tailings and ore deposits was similar to that found in other rock types in the basin, including those associated with a local geyser basin, inhibiting the use of Pb isotopes as an effective tracer.

Before the 1990s, the investigation of many of the other isotopic systems (e.g., those associated with the transition and post-transition elements) was hindered by an inability to precisely measure their abundance in Earth materials. However, recent advances in analytical chemistry, including the advent of the MC-ICP-MS, have led to the precise measurement of a wide range of non-traditional stable isotopes, or non-CHONS (referred to because they are not one of the five most studied isotopic systems) [56]. The ability to accurately measure the isotopic abundances of these non-traditional isotopes in geological materials has opened up a whole new field of research into their use as tracers of contamination and to gain insights into biogeochemical processes. The intent with regards to environmental forensics is to develop direct methods to determine the source and cycling of toxic metals in sediments, soils, and water.

The application of these non-traditional isotopes as tracers of contaminant source in river sediments is much more complicated than that of Pb, and most other radiogenic isotopes. In the case of Pb, isotopic fractionation by industrial or biological processes is negligible; the Pb isotopic composition of man-made materials (e.g., as a battery) reflects the ore deposits from which the Pb was derived. Given that the Pb isotopic signature of the ores deposits typically differs from most other types of rocks, the Pb in man-made products is often unique. Moreover, Pb isotopic ratios measured within a sample of river sediment is a function only of the mixing of Pb from different sources, allowing for the relatively easy assessment of Pb contributions from each source. In contrast, the use of the non-traditional isotopes as a tracer is complicated by multiple physical and biological fractionation processes, which not only vary between elements, but the environmental conditions that exist within the river, and the physical, chemical and biological processes to which the metals were subjected. Thus, detailed investigations into the cycling of the utilized isotopes are required for their effective application. Nevertheless, several isotopic systems appear to hold significant promise with regards to the assessment of contaminated river sediments, including Cu, Hg, and Zn [37].

As an example, interest in the use of Zn isotopes as a forensic tracer in rivers stems from that fact that: (1) Zn occurs in a wide range of materials including mining and refining products and wastes, steel processing plants, coal-fired power plants, vehicles, urban waste incinerators, car tires, and other constituents in urban runoff , and (2) Zn is often associated with Cd and Pb in natural and anthropogenic materials, and can therefore be used to determine the source of these trace metals. The potential to use Zn isotopes to determine to the source of Zn in sediments and soils rests, in part, on the fact that the Zn isotopic composition of some anthropogenically produced materials can be distinguished from that occurring naturally in rocks and minerals. In addition, the fractionation of Zn is dominated by mass-dependent processes, such as evaporation, condensation, and electroplating, which when associated with industrial activities, can be measured. Fractionation may also occur at low temperatures during its biogenic uptake by micro-organisms and other biotas [57,58], diffusion processes [59], adsorption onto inorganic and organic surfaces[58,60], and mineralization [61,62] (Table 6.1). If these new isotopic abundances (following fractionation) can be linked to a specific industrial process, then it is possible to use Zn isotopes to determine where the Zn from that process is currently located along a river and how much of the total Zn was derived from it [63–65].

The use of these non-traditional isotopes as tracers of metals in riverine sediments is still in the developmental stages, and in spite of some notable successes, their use will likely be limited to a supportive role in environmental forensic investigations during the near future. Nonetheless, the fact that these non-traditional isotopic systems can provide a wealth of information on the

source, dispersal, and biogeochemical cycling of toxic trace metals that cannot otherwise be obtained, suggesting that their use is likely to grow exponentially in the coming years.

3 Conclusion

Environmental forensic investigations have increasingly relied on the use of geochemical and isotopic fingerprinting methods to determine the source and source contributions of trace metals in contaminated rivers. Recent advances in analytical chemistry have enhanced by the application of geochemical fingerprinting by allowing for the rapid, multi-elemental analysis of sediment samples, and by continually improving upon the accuracy and precision of measuring the isotopic abundances in Earth materials. In addition, it is now possible to determine the abundance of non-traditional isotopes in sediments. Although fractionation makes the use of these isotopic systems more complicated to use for source determination, recent studies show that some isotopes (e.g., those of Cu, Hg, and Zn) hold considerable promise with respect to river sediments. In light of the above, geochemical and isotopic fingerprinting techniques are likely to remain the method of choice to determine trace metal sources and source contributions riverine sediments. However, the use of fingerprinting techniques requires an understanding of the natural and anthropogenic sources that exist within the basin; sources cannot be fingerprinted if they have not been tentatively defined. Potential sources of trace metals within the basin can be qualitatively identified using the widely used and accepted, but underutilized spatial and temporal methods described herein. These temporal and spatial methods, when combined with an analysis of the river valley's alluvial architecture, not only provide insights into potential trace metal sources, but (1) the potential partitioning of source materials into specific depositional environments, (2) the distances and rates of trace metal transport, and (3) the location of geochemical hotspots along the river valley.

Where the above methods do not fully identify the sources or source contributions for trace metals to a river, it will be necessary to utilized other types of physical or mineralogical tracers or source attribution methods, such as the occurrence of unique minerals within a source materials, geochemical speciation data, particle size or microtextures, and/or geomagnetic information (see D'Daen et al. [47], for examples).

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Geological Influences on Groundwater Quality

19

Samuel V. Panno and Keith C. Hackley

Introduction

The quality of groundwater is determined by the type and concentration of its chemical and biological constituents. These constituents, depending on their nature and concentrations, can produce water that is unsafe to drink or that has an objectionable taste or odor. Because naturally occurring substances are dissolved in or suspended as fine-grained solids in groundwater, in many cases, some water treatment is necessary before groundwater quality becomes acceptable for drinking purposes or industrial uses. This chapter discusses these naturally occurring substances, their common sources, and the general quality of the groundwater observed within the different aquifers in Illinois.

As municipal and industrial water supplies grew in importance during the early twentieth century, scientists began to study the chemical composition of groundwater and its relationship to the geological framework and associations with the host sediment or bedrock aquifers. The chemical interactions between aquifers and groundwater were identified during the first half of the century and rigorously examined during the latter half (Back and Freeze 1983). Water quality of municipal and private water supplies in Illinois has been routinely analyzed by the Illinois State Water Survey since its founding in 1895 as a means of tracing waterborne diseases (Illinois State Water Survey 2003). Today, studies of the chemical composition of groundwater are routinely performed on both public and private water supplies. The composition of groundwater is used to determine its potability and serves as a tool to determine the sources of naturally occurring and human-related contaminants.

Groundwater is derived from precipitation, such as rainfall or snow melt. Precipitation contains very low concentrations of dissolved minerals (approaching that of distilled water). The major ions—or electrically charged particles—present in rainwater and snow melt are calcium, magnesium, sodium, silica (as $Si(OH)_4$), sulfate, chloride, and nitrogen compounds (nitrate, ammonium, and organic nitrogen). The total concentration of all constituents typically is less than 5 to 10 mg/L (parts per million) (Table 19-1). The natural sources of these ions include airborne dust (calcium, magnesium, and silica) and aerosols from seawater (sodium and chloride), which are highest near the coastal areas (Drever 1997). The majority of the remaining ions are typically from airborne particulate matter and gases from industrial emissions, automobile exhaust, and the evaporation of volatile chemicals (e.g., anhydrous ammonia fertilizers). These latter constituents are discussed in Chapter 28, Karst Terrane.

Once rainfall and snowmelt seep into the ground, the water begins its journey to the water table through the connected pores and crevices in soil, unconsolidated sediment, and rocks. The water table is the elevation at which the geological sediments and rocks become saturated with water. Permeable sediments and bedrock below the water table constitute aquifers. Aquifers supply private citizens and municipalities with potable water and are also used as a source of water for irrigation and industrial purposes throughout much of the state.

Water is a solvent and, as such, is capable of dissolving and interacting with organic and inorganic components of soils, the minerals that make up unconsolidated deposits (e.g., sand and gravel), and with various types of bedrock. Dissolution of minerals within the soil, sediment, and bedrock is a slow process that can take days, years, or eons, depending on the solubility of the materials. These materials contribute to the amount of total dissolved solids (TDS) that are present in all groundwater. Major dissolved constituents of groundwater include the cations (positively charged ions) sodium, potassium, calcium, magnesium, and silica and the anions (negatively charged ions) bicarbonate, sulfate, chloride, and nitrate (Table 19-1). When trace-level ions, such as ammonium, iron, manganese, and arsenic, are present in relatively high concentrations, they create water-quality problems. These constituents come from the dissolution of rocks such as limestone and dolomite, the weathering of less-soluble rocks such as granite, the degradation of organic debris in the soil zone (e.g., trees and leaves), and man-made contaminants (discussed in Chapter 29, Pollution of Natural Waters).

In general, the chemistry of groundwater is controlled by the type of geological materials through which the water flows and the amount of time the water is in contact with these materials. For example, precipitation percolating into a limestone aquifer would dissolve the limestone (made of calcium carbonate), and the water (now groundwater) would contain predominantly calcium and bicarbonate ions. The dominant cations and anions are used to describe the gen-

eral chemical composition, or "type," of groundwater. For example, limestone aquifers contain "calcium bicarbonate type" groundwater, and deep, granitic rock eventually produces "sodium chloride type" groundwater.

Aquifers and Aquitards: Effects on Groundwater Quality

Aquifers in Illinois are made up of two types of material: (1) sand and gravel deposits found in association with glacial till or along stream valleys, and (2) porous and permeable bedrock units. Sand and gravel aquifers are scattered throughout the state, but the largest deposits occur in northeastern and central Illinois. Bedrock aquifers containing usable groundwater are located throughout the state, but potable water is found only in the bedrock aquifers of the northern third and, to a lesser extent, the western and southern parts of the state. For example, fresh groundwater with less than 1,000 mg of TDS/L can be pumped from wells over 1,000 feet (305 m) deep in the northern part of the state, but saline (salty) groundwater is encountered several hundred feet or less below the surface in southern Illinois (Lloyd and Lyke 1995). Groundwater from bedrock found in the southern two-thirds of the state is usually too saline for human use (Figure 19-1). Salinity of groundwater generally increases with depth. Bedrock aquifers in the northern portion include shallow carbonate rocks (dolomite and limestone) as well as deep sandstones that are primarily made up of quartz and silicate minerals. The bedrock aquifers in the western and southern parts of the state are primarily shallow carbonate rocks.

Sand and gravel deposits typically contain abundant clasts (i.e., sand grains, pebbles, and cobbles) of limestone and dolomite that dissolve much faster than do clasts of other composition (e.g., quartz). Consequently, calcite and dolomite, once dissolved, dominate the chemical composition of the groundwater in these aquifers, forming a calcium-magnesium bicarbonate type of groundwater (Table 19-1). Similarly, bedrock aquifers are often made of fractured limestone and dolomite, resulting in groundwater with the same general chemical composition as that found in sand and gravel aquifers. Groundwater circulating through fractured sandstone aquifers, such as the Aux Vases Sandstone in southwestern Illinois, typically form a sodium bicarbon-

Table 19-1 Chemical composition[1] of averaged rainwater samples and single samples of different types of groundwater in Illinois. All parameters are reported in milligrams per liter except pH.

		Groundwater type								
	Rain[2]	Ca-Mg bicarbonate[3]	Na bicarbonate[4]	High NaCl[5]	High F[6]	High As[7]	High Mn, Fe[8]	High ammonium[9]	High sulfate[10]	Seawater[11]
pH	4.5	7.2	8.6	6.6	6.8	7.4	7.49	7.2	7.1	8.0
SC	21.1*	688	2,100	—	694	515	750	670	2,000	58,500*
Na	0.08	27.4	559	44,923	27.4	17.4	47.6	15.8	104	10,556
K	0.03	<1	<2	—	<2	1.74	1.82	3	4	380
Ca	0.24	90.1	6.0	5,740	109	67.9	82.3	82.3	279	400
Mg	0.04	33.9	3.1	2,173	20.5	32.9	41.8	36.6	96.7	1,272
SiO_2	—	19.1	8.6	15	14.8	18.1	21.8	22.7	20.1	6.43
HCO_3	—	443	1,108	61	385	479	560	480	301	140
SO_4	2.28	33.1	165	329	25.3	<0.09	16.3	0.34	981	2,649
Cl	0.15	7.4	37	85,569	25.1	1.1	41.8	0.55	8.5	18,908
F	—	0.37	—	—	1.46	0.2	0.1	—	0.28	1
NO_3	1.46	<1.9	0.26	0.0	0.09	<0.02	<0.2	0.35	<1.7	<0.5
NH_4	0.40	0.98	—	64	—	2.8	3.7	6.02	—	<0.5
Fe	—	1.89	<0.01	20	1.65	4.57	3.67	4.32	0.27	0.01
Mn	—	<0.03	<0.01	2.0	0.76	0.04	0.21	0.03	1.2	0.002
As	—	—	—	—	—	0.096	—	—	—	0.003
TDS	4.68*	661*	1,887*	142,194	611*	626*	821*	652*	1,796	34,477

[1]Abbreviations: SC, specific conductance; Na, sodium; K, potassium; Ca, calcium; Mg, magnesium; SiO_2, silicon dioxide, or silica; HCO_3, bicarbonate; SO_4, sulfate; Cl, chlorine; F, fluorine; NO_3, nitrate; NH_4, ammonia; Fe, iron; Mn, manganese; As, arsenic; TDS, total dissolved solids. Values followed by asterisk were calculated. —, data are unavailable.
[2]Average values from six active collection sites throughout Illinois from 1980 to 2003 (http://www.nadp.isws.illinois.edu).
[3]Hackley (2002); sample WRD-55, Mahomet aquifer, Champaign County.
[4]Panno (unpublished data 1995); Aux Vases Sandstone, Monroe County.
[5]Meents et al. (1952); sample 930, Ste. Genevieve Formation, Wayne County.
[6]Panno and Hackley (1997a); Valmeyeran Series limestones, Rosiclare, Hardin County.
[7]Holm (1995); sample 93-24A, Mackinaw Valley aquifer, Tazewell County.
[8]Holm (1995); sample 93-14, Mackinaw Valley aquifer, Tazewell County.
[9]Hackley (unpublished data); Mahomet aquifer, Mc Lean County.
[10]Hackley (2002); sample VER-94b, Mahomet aquifer, Vermilion County.
[11]Mason (1966).

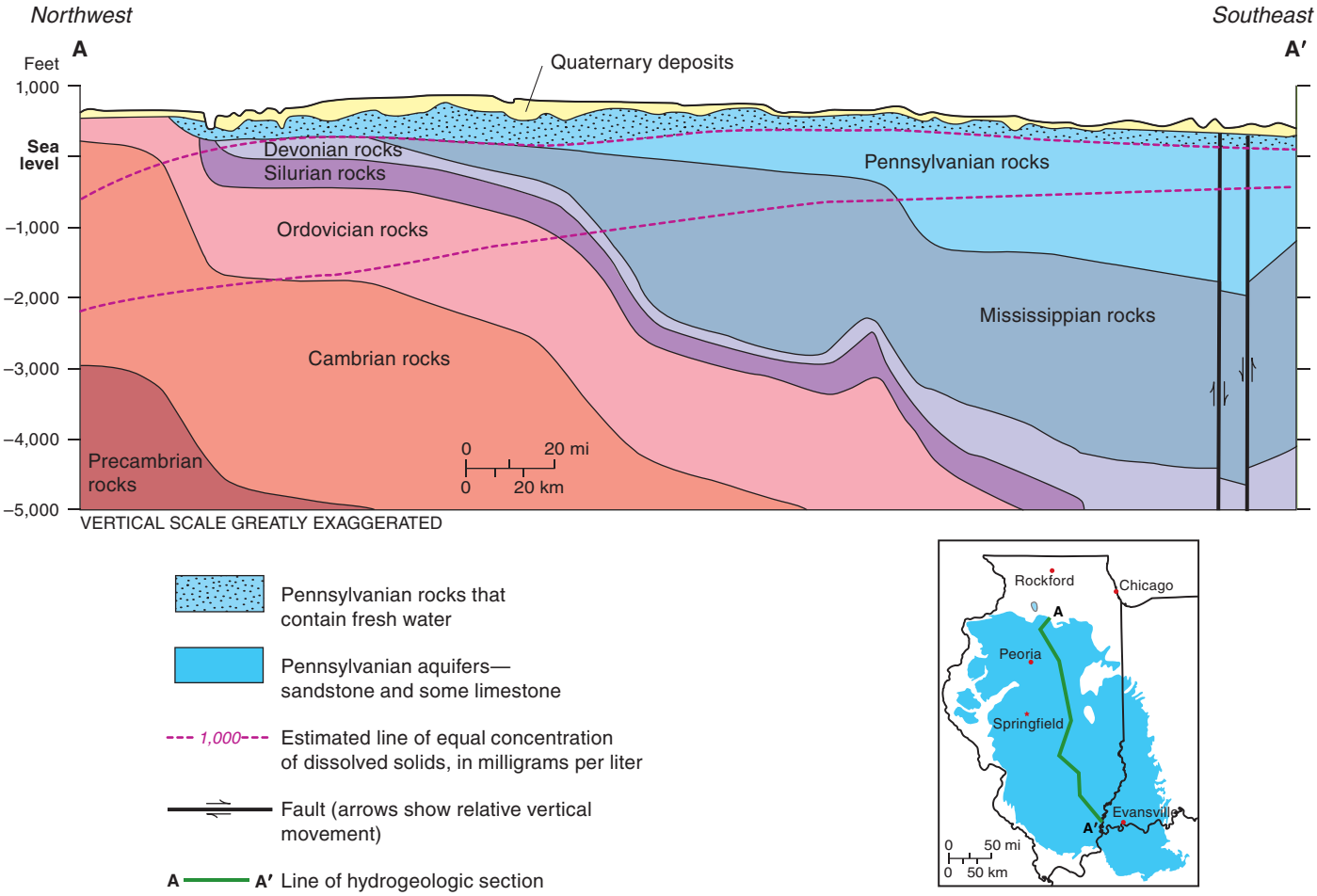

Figure 19-1 North-south cross section of Illinois showing estimated lines of equal concentration of total dissolved solids in groundwater (Lloyd and Lyke 1995).

ate type groundwater (Table 19-1). One way such groundwater is formed is for calcium bicarbonate groundwater to enter the sandstone, and, through ion exchange, calcium ions replace sodium ions on clay minerals (sodium is often present due to degradation of feldspars in the sandstone). This process is similar to that occurring when a water softener causes calcium and magnesium to exchange positions on a resin within the softener; the result in both cases is a "soft" sodium bicarbonate water.

Aquitards are those deposits or rocks that do not allow recharge water or groundwater to penetrate very easily (e.g., clay-rich glacial till and shale) (Chapter 18, Aquifers). These deposits or rock units protect groundwater from surface-borne contaminants, isolate groundwater from the atmosphere, and confine groundwater to a single aquifer or channel it to a series of connected aquifers. The isolation of groundwater for hundreds to thousands to tens of thousands of years can affect its chemistry by fostering reducing conditions, as is discussed later in this chapter. Additionally, the interaction of groundwater with the minerals of an aquitard can alter the chemical composition of the groundwater flowing through it and the chemical composition of adjacent aquifers. For example, recharge water interacting with the shale that bounds an aquifer often encounters the mineral pyrite (iron sulfide), which can be easily oxidized to form groundwater that has very high concentrations of sulfate (perhaps hundreds to thousands of milligrams per liter) (Table 19-1). Such sulfate-enriched groundwater, as it enters an underlying aquifer, can enrich the aquifer with sulfate even though there may have been no mineralogical source of sulfate in the aquifer.

Chemical Composition

There are a number of constituents that can be found in groundwater, and water quality depends on the type and concentration of these constituents. For example, groundwater in some locations is immediately potable; elsewhere it may have an objectionable taste and/or odor and may even be unsafe to drink. The U.S. Environmental Protection Agency (U.S. EPA) has developed a list of acceptable concentrations of natural and man-made contaminants for municipal drinking water. These standards, the National Pri-

mary Drinking Water Regulations (NPDWR), are enforced by the U.S. EPA (1991, 2009). National Secondary Drinking Water Regulations (NSDWR) are U.S. EPA guidelines pertaining to constituents of drinking water based on cosmetic effects, taste, odor, and appearance. Both guidelines may be found on the U.S. EPA (2009) Web site.

The chemical components that are typically measured to help determine the general quality of groundwater include suspended solids, hardness, sodium, chloride, fluoride, sulfate, chemicals associated with reduction-oxidation (e.g., arsenic, iron, manganese, nitrate, and ammonium), assorted minor and trace constituents, dissolved gases (e.g., air, carbon dioxide, methane, and hydrogen sulfide), and stable and radioactive isotopes. Some of these constituents are occasionally referred to as "contaminants," but they can be naturally occurring.

Suspended Solids

Suspended solids in groundwater are occasionally observed in wells tapping aquifers that have relatively large porosity and permeability (e.g., sand and gravel, karst limestone/dolomite). Suspended solids include soil and other fine-grained material (e.g., clay, silt, and organic debris) small enough to pass through the tiny spaces between sand and gravel and through crevices in carbonate rock. Suspended solids can also include compounds that may precipitate in the water as it is withdrawn from the aquifer due to dramatic changes in temperature, pressure, pH, or oxygen content. Examples of dissolved constituents that can emerge from apparently clear water are calcium carbonate, which forms small white flakes when dissolved carbon dioxide is released from the water, and iron and manganese oxides, which form orange and black granules or coatings when water is exposed to oxygen. Such materials can make the water cloudy and can affect its taste unfavorably.

An extreme example of suspended solids in groundwater comes from the karst aquifers of southwestern Illinois. Karst aquifers have large crevices and conduits that can carry relatively large concentrations of suspended solids in the water. Several wells in one subdivision in southwestern Illinois intersected crevices that were in direct contact with at least one large sinkhole. During and following large rainstorms, soil washed into the sinkhole(s) and through the crevices that led to the wells. Pumps in the wells sent the sediment-laden water, now a muddy slurry, into the plumbing systems of several houses, and mud oozed from the fixtures (Figure 19-2) (Panno et al. 1996). In most cases, however, suspended solids in groundwater are not so extreme and can be removed by commercially available filters.

Figure 19-2 Examples of muddy tap water from a residential home in southwestern Illinois' karst region. Left and center: Water containing sediment from erosion of cropland adjacent to a sinkhole during and following relatively large rainfall events (1 inch [2.5 cm] or greater). Right: Fireplace ashes in water caused by dumping fireplace ashes into the sinkhole in the home's backyard. (Photograph by Joel M. Dexter.)

Rock-Water Interaction

The chemical characteristics of groundwater are determined by the interaction between groundwater and the minerals that make up the rock or sediment through which the water is moving (Figure 19-3). That is, the materials of the soil zone and the aquifer are dissolved and incorporated into the water moving through them. Some components may provide a characteristic taste to the water and some may make the water undrinkable based on taste, toxicity, or both.

Calcium, Magnesium, Bicarbonate, and Hardness

In areas where bedrock is dominated by limestone and/or dolomite or where sand and gravel aquifers contain abundant clasts of these carbonate minerals, the groundwater is typically a calcium bicarbonate type or calcium-magnesium bicarbonate type (Table 19-1; Figure 19-4). These rocks are dominated by calcite (calcium carbonate) and dolomite (calcium-magnesium carbonate), and both are soluble in slightly acidic rainwater (Table 19-1) and snowmelt and in carbon dioxide-enriched soil water (soil water made more acidic by the generation of carbon dioxide from root respiration and microbial degradation of organic debris). Carbonate minerals dissolve relatively fast when exposed to carbon dioxide-enriched waters.

Groundwater from aquifers made up of or containing carbonate rock is often referred to as "hard." Hard water contains calcium and magnesium that react with soap and produce soap scum or react with other anions to produce a solid scale or coating when the water is boiled and evapo-

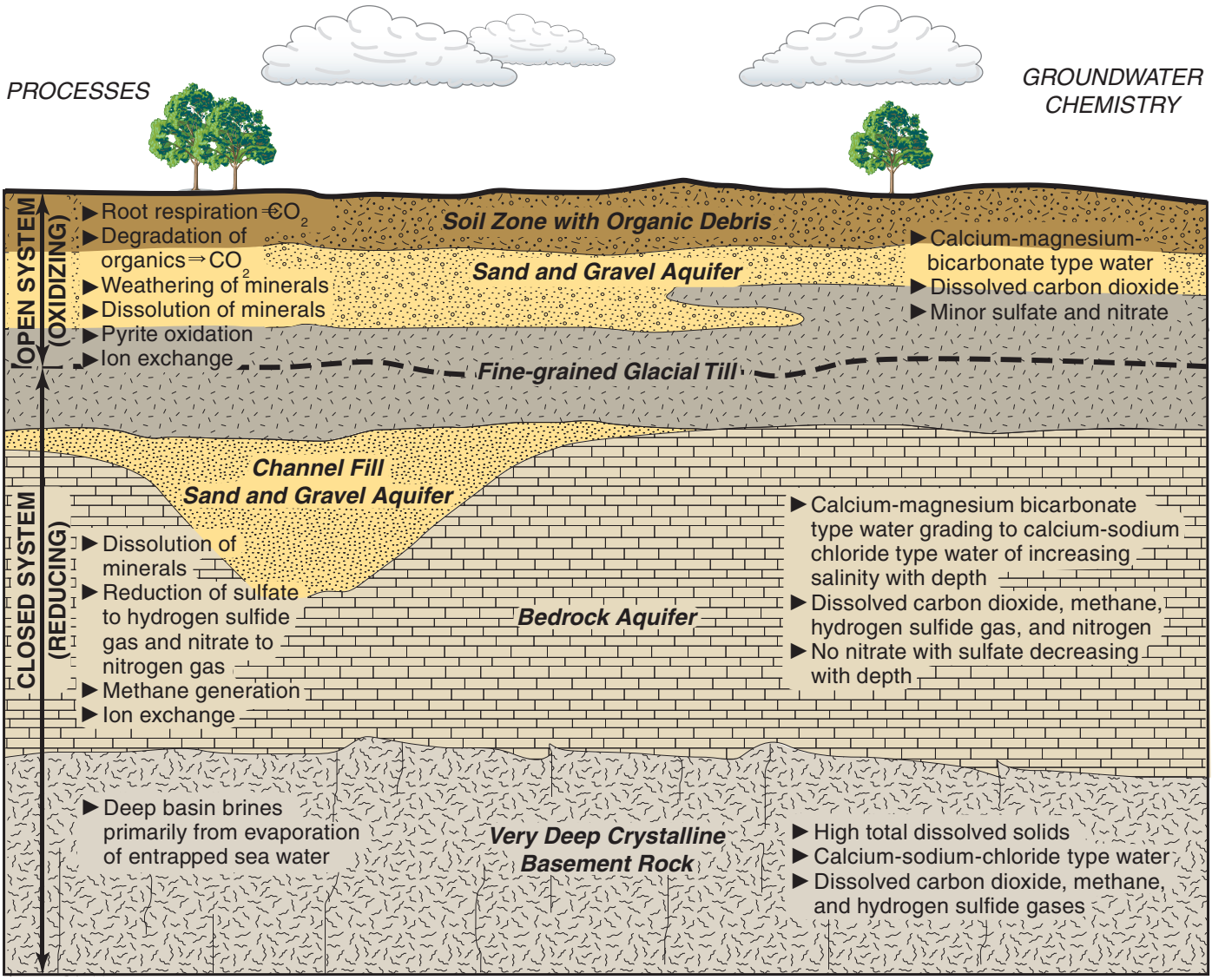

Figure 19-3 Conceptual model of the processes and chemical composition of groundwater in Illinois. Abbreviation: CO_2, carbon dioxide.

rated. Hardness and its components are not toxic, have no offensive taste or odor, and are under no U.S. EPA guidelines. Chemically, hardness is defined (Freeze and Cherry 1979) as (total calcium concentration × 2.5) + (magnesium × 4.1) and is expressed as milligrams per liter, or parts per million. For example, if water contains 5 mg of calcium/L and 5 mg of magnesium/L, then the hardness is 33 mg/L. Water with a hardness value greater than 120 mg/L is considered to be hard, and greater than 180 mg/L is considered to be very hard (Lehr et al. 1980). Because the presence of these minerals controls water chemistry, groundwater from carbonate mineral-rich aquifers is typically very hard. For example, the average hardness value for the groundwater of the karst limestone aquifers of Illinois is about 230 mg/L (Panno et al. 1996, 1997). Groundwater from sand and gravel aquifers in northern Illinois has hardness values of over 300 to 400 mg/L (Panno et al. 2005a).

The scale or coating from these dissolved minerals that can be found in pots used for boiling hard water and on the bottom of hot water heaters is a deposit of carbonate minerals. In some cases, hard water may be desirable because it tends to coat the interior of metal pipes containing copper or lead or joined by lead-bearing solder, thereby protecting the metals from leaching into the water supply (Lehr et al. 1980). However, continued coating of pipes with scale may eventually (after tens of years) constrict the interior of water pipes so that the water flow slows to a trickle. Hardness can be treated easily by commercially available water softening treatment systems. Water softeners typically consist of an ion-exchange system that exchanges sodium for calcium and magnesium. What enters the water softener as a hard, calcium-magnesium bicarbonate water discharges as a soft, sodium bicarbonate water.

Figure 19-4 Groundwater discharging from a spring at Weldon Springs State Park near Clinton, Illinois. The dilute, calcium-bicarbonate groundwater that is recharged in the higher elevations to the north percolates into and flows through a sand and gravel layer in glacial till and discharges as springs in the low-lying area of the park. A pipe was inserted into this spring's discharge point and channeled to this facade; unlike its Wyoming namesake, Illinois' Old Faithful flows constantly (Panno and Hackley 2001b). (Photograph by Samuel V. Panno.)

Sodium and Chloride

Water may be classified according to its TDS content (Table 19-2). In Illinois, most groundwater from shallow aquifers is fresh, whereas relatively deep groundwater from within the Illinois Basin is saline to briney. Water containing chloride concentrations of approximately 250 mg/L or greater may have a salty taste. This concentration is the U.S. EPA recommended limit for drinking water (U.S. EPA 1991, 2009); chloride concentrations exceeding 1,000 mg/L may be unsafe for human consumption (Lin 1977, Lehr et al. 1980, U.S. EPA 1991). Sodium concentrations are not regulated by the U.S. EPA. However, high-sodium intake may be associated with hypertension in some individuals (U.S. EPA 1991), and the sodium concentration in drinking water should be considered by those for whom dietary sodium is a concern (Haman and Bottcher 1986).

Most shallow groundwater is relatively fresh and typically has little sodium and chloride dissolved in it. Usually, naturally occurring sodium and chloride concentrations in sand and gravel aquifers in Illinois are between about 1 and 15 mg/L (Panno et al. 2006a). However, sodium chloride is present in large concentrations in groundwater from deep aquifers of northern Illinois, in parts of central Illinois, and many parts of southern Illinois (Clayton et al. 1966).

Table 19-2 Classification of groundwater relative to total dissolved solids (TDS) contents (Hem 1986).

Water classification	TDS (mg/L)
Fresh	<1,000
Slightly saline	1,000 to 3,000
Moderately saline	3,000 to 10,000
Very saline	10,000 to 35,000
Brine	>35,000

Much of the bedrock in Illinois, however, is part of an underlying midcontinental sedimentary basin known as the Illinois Basin. Sedimentary basins such as this contain abundant saline groundwater that typically increases in salinity with depth (Figures 19-1 and 19-3); in the case of the Illinois Basin, salinity increases to a depth of about 1.2 miles (2 km) or so before it levels out (McIntosh et al. 2002). The source of the salinity of this groundwater has generated much interest. Walter et al. (1990) and Steuber et al. (1991, 1993) suggested that the salinity was due to the evaporation of seawater short of the precipitation of halite in Silurian and Devonian strata and a mixture of evaporated seawater and dissolution of evaporites in shallower Mississippian and Pennsylvanian strata. Recent work by Hanor and McIntosh (2006) suggests that saline groundwater of the Illinois Basin underwent extensive alteration as a result of rock-water interaction and were transformed from sodium chloride brines to calcium-sodium chloride brines with salinities up to 200,000 mg/L TDS.

Saline springs can be seen along structural features, such as along folds and faults in the Starved Rock area (the Old Salt Well) in La Salle County, in southwestern Illinois in the vicinity of oil fields near Columbia in Monroe County, and in southern Illinois near the Equality Fault Zone and the town of Equality in Saline County (Figure 19-5). Water from these springs is about as saline as seawater with about 35,000 mg/L TDS and is dominated by sodium and chloride; seawater is dominated by sodium and chloride and contains about 34,477 mg/L TDS (Table 19-1).

Saline groundwater and brines can be brought near or to the land surface by natural conditions, such as migrating up prominent fractures and/or faults in bedrock, or by anthropogenic activities, such as exploration for and exploitation of petroleum. The mixing of upward-migrating saline groundwater with fresh groundwater from shallow aquifers can make groundwater from private wells undrinkable and can present a very expensive problem for municipalities. An example of saline groundwater seeping into a freshwater aquifer can be found in east-central Illinois where the Mahomet aquifer crosses a major, roughly north-south–trending structural feature called the La Salle Anticlinorium (Figure 19-6). Saline water seeps up into the base of the aquifer from bedrock at a depth of about 300 feet (91 m) below the land surface near the Champaign-Piatt County line. Groundwater that normally has chloride concentra-

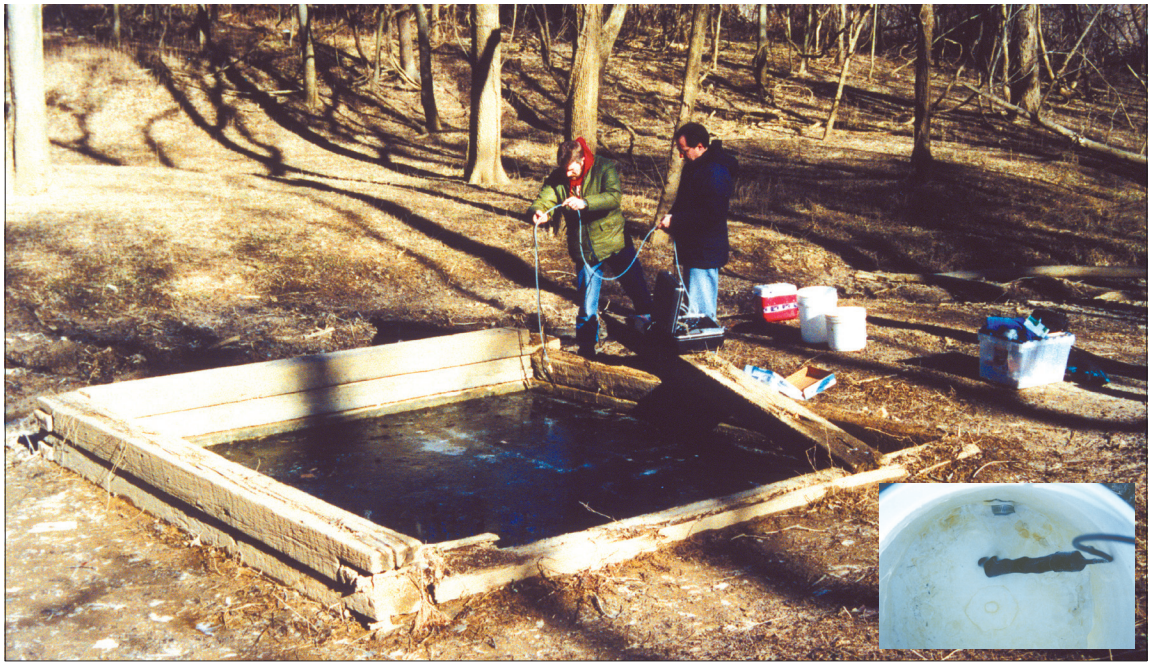

Figure 19-5 Equality Spring in Saline County in southern Illinois is a saline spring containing over 13,000 mg/L of sodium and chloride. The spring is over 6 feet deep (2 m), is encased by railroad ties, and was used as a commercial source of salt by early settlers of Illinois. (Photograph by Samuel V. Panno.)

tions less than or about 1 mg/L here exceeds 300 mg/L (Panno et al. 1994). Samples of groundwater from bedrock beneath the sand and gravel aquifer have chloride concentrations in the thousands of milligrams per liter (Panno et al. 2005a).

In addition, naturally saline springs in northern (e.g., Starved Rock State Park) and southern Illinois, usually located along fault zones or structural folds, discharge highly saline water into surface streams (Panno et al. 2005a, 2006a). Streams in areas where there are saline seeps have names such as the Saline River (Saline County) and the Salt Fork of the Vermilion River (Vermilion County). Because salt was an important commodity during early Illinois settlement by Europeans during the early 1800s, such seeps and their "salt works," initially used by Native Americans, became the nucleus of early settlements. Saline water was boiled in large iron kettles, and the residual salt was harvested and sold (Fliege 2002).

Fluoride

Fluoride typically is added to municipal water supplies because of its protective effects on teeth. However, fluoride in drinking water at concentrations greater than 3 mg/L can cause problems with tooth mottling, brown staining, and pitting in the teeth (dental fluorosis) in children with developing teeth (U.S. EPA 2009). The primary U.S. EPA drinking water standard is 4 mg/L. Fluoride concentrations greater than 4 mg/L can result in bone disease and bone and joint deformation (skeletal fluorosis) (Appelo and Postma 1994). The NSDWR for fluoride in drinking water is 2.0 mg/L (U.S. EPA 1991, 2009).

Groundwater from wells in most aquifers in Illinois has relatively low fluoride concentrations (usually about 0.5 mg/L) (Panno, unpublished data). Fluoride concentrations in groundwater are a function of the chemical composition of the groundwater and the presence or absence of fluorine-bearing minerals within an aquifer. Fluorine-bearing minerals include apatite (calcium phosphate), fluorite (calcium fluoride), and minerals that can exchange hydroxyl ions for fluoride ions (hornblende, mica, and clay minerals) (Hem 1986). Conrad et al. (1999) found that the greatest fluoride concentrations in Kentucky were associated with relatively deep, sodium bicarbonate-type groundwater with pH values between 7.6 and 8.0. The fluoride concentrations in Illinois aquifers are relatively low, in part, because calcium bicarbonate-type groundwater (found in limestone and sand and gravel aquifers of northern Illinois) limits the amount of the fluorite that can be dissolved (Hem 1986). Fluorite (calcium fluoride) deposits are found in southeastern Illinois within and near the town of Rosiclare, in Hardin County, site of the largest known fluorite deposits in the United States. Groundwater samples drawn from limestone for Rosiclare's municipal water supply contained 1.5 mg of fluoride/L (Panno and Hackley 2001a) (Table 19-1). Private wells that tapped into the groundwater of the Aux Vases Sandstone in southern Illinois have intersected groundwa-

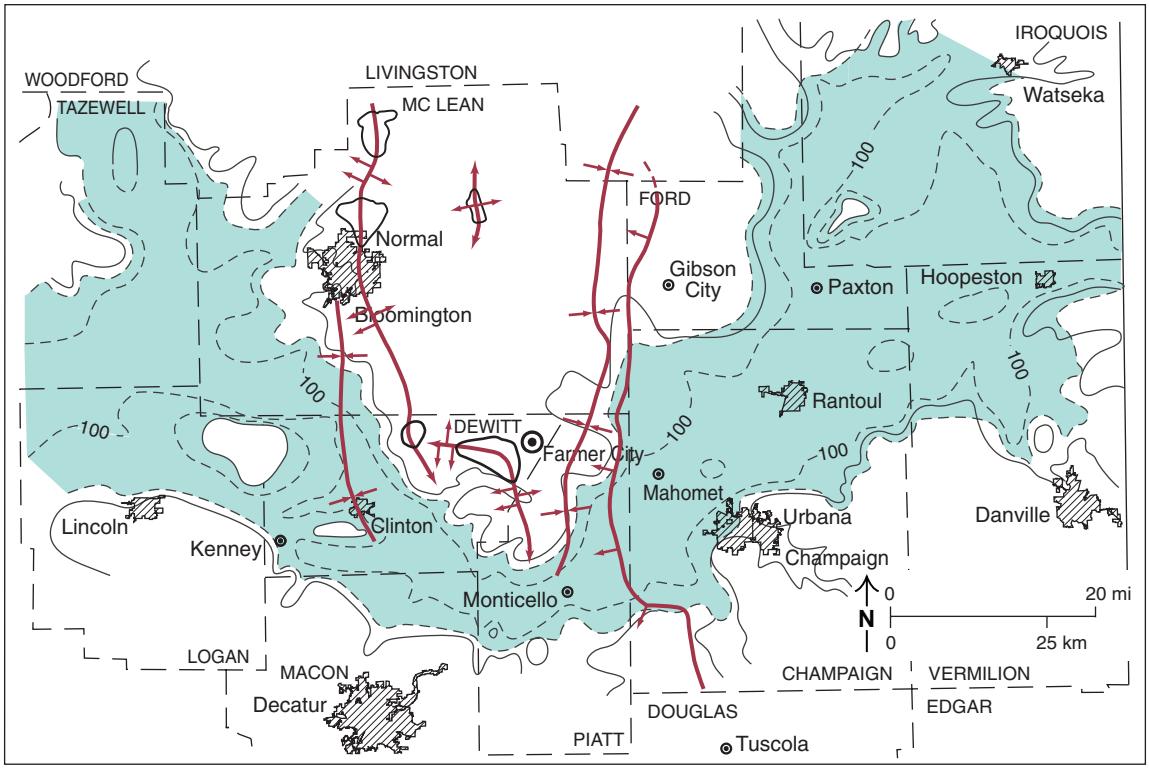

Figure 19-6 Saline groundwater can seep into a freshwater aquifer to contaminate it. Such a situation occurs in east-central Illinois where the Mahomet aquifer crosses the north-south cluster of folds known as the La Salle Anticlinorium. Dashed lines are thickness contours (in feet). (Modified from Panno et al. 1994.)

ter with fluoride concentrations as high as 9 mg/L (J. Bade, former sanitarian with the Monroe-Randolph Bi-County Health Department, personal communications 1997).

Sensitivity to Reduction-Oxidation

Oxygen

Oxygen, one of the most abundant elements on earth, very commonly combines with other elements. Depending on the nature of the bond, the bonded element is either reduced or oxidized. In simplest terms, reduction-oxidation (commonly shortened to redox) involves the gaining (reduction) or losing (oxidation) of electrons between elements, one of which is oxygen. The term "reduction" refers to the charge; an atom, molecule, or ion that gains an electron now has a reduced, or negative, charge. The loss of electrons through oxidation results in a positive charge. Redox reactions happen in pairs; there is no oxidation without a concurrent reduction. Redox-sensitive elements are those that either precipitate or dissolve in the presence or absence of dissolved oxygen and other electron-bearing, often oxygen-bearing, ions (e.g., nitrate and sulfate). The abundance of dissolved oxygen (and oxygen-bearing ions) usually decreases with depth and confinement of an aquifer. Groundwater in shallow, unconfined aquifers typically has dissolved oxygen contents similar to that of surface water (about 8 mg/L). Groundwater in deeper aquifers and shallow, confined aquifers has little or no dissolved oxygen because it is readily used up by bacterial activity and other oxygen- and electron-consuming chemical reactions that occur within the aquifers (e.g., decomposition of organic matter and oxidation of pyrite); such groundwater is referred to as being under reducing conditions. Consequently, redox-sensitive elements are more readily dissolved in deeper, oxygen-depleted groundwater.

Arsenic

Arsenic is an element that is soluble in water, is redox-sensitive, and occurs naturally in minute concentrations in groundwater. The routine ingestion of water containing very low concentrations of arsenic has been linked to skin disease and cancer (Smith et al. 1992). The arsenic standard for community supply wells has been lowered by the U.S. EPA from 50 to 10 µg/L (parts per billion) for finished drinking water (Vorman 2001). Health problems, such as arsenic-induced cancers, have resulted, in other parts of the world, from drinking water with relatively large concentrations of arsenic (e.g., Bagla and Kaiser 1996). Arsenic concentrations of shallow glacial and alluvial aquifers of Illinois range from less than 1 to as high as 107 µg/L; the greatest arsenic concentrations are in the southern part of the state and in the Mahomet aquifer (glacial drift aquifer) (Table 19-1) (Figure 19-7) (Warner et al. 2003).

Iron and Manganese

The solubilities of iron and manganese, metals that are commonly present in groundwater, are sensitive to changes in redox conditions. The concentrations of these metals are low in groundwater from shallow aquifers because the presence of dissolved oxygen in the water causes these metals to precipitate from solution. However, in deeper aquifers where dissolved oxygen has long been consumed by biological and chemical reactions, groundwater often contains abundant concentrations of dissolved iron and manganese (Table 19-1).

Groundwater containing relatively high concentrations of these dissolved metals may appear to turn yellow rapidly (within minutes) in a container. Such water can form orange to black coatings on porcelain fixtures and laundry due to precipitation of manganese oxides and iron oxyhydroxides upon exposure to oxygen (Figure 19-8). The presence of these metals in water can thus be a nuisance. Iron and manganese also can precipitate on well screens and eventually plug them. Such plugging is very likely one of the causes for reduced efficiency of a municipal well in an east-central Illinois municipal well field (Panno et al. 2005b). Iron and manganese can impart a metallic taste to water. The U.S. EPA limits for iron and manganese are 0.30 and 0.05 mg/L, respectively. The U.S. EPA limit is an NSDWR, based on taste and the problems just mentioned rather than on health risk (U.S. EPA 1991). Commercially available water softeners with salt and filters can effectively remove these metals.

Figure 19-8 Falling Springs, located near Dupo, in St. Clair County in southwestern Illinois, is an example of reduced groundwater. The spring discharges from a cave located 50 feet above the base of a cliff. As the groundwater is oxygenated, it precipitates manganese oxide and iron oxyhydroxide intermixed with calcite to form a black apron on the cliff. (Photograph by Joel M. Dexter.)

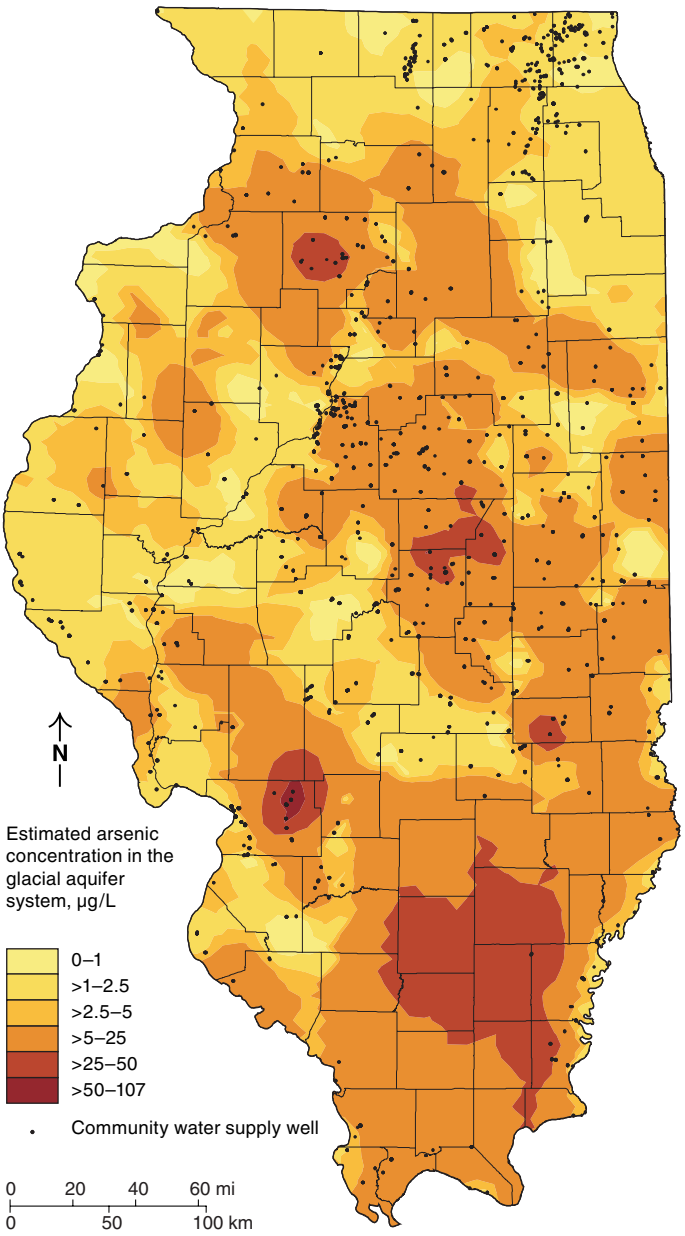

Figure 19-7 Contour map of estimated arsenic concentrations in Illinois groundwater (Warner et al. 2003).

Nitrogen Compounds

Nitrogen compounds (nitrate, nitrite, ammonium, and

organic nitrogen) are naturally occurring components of groundwater. Nitrate is the most common dissolved nitrogen compound in surface and shallow groundwater environments where the water is relatively oxidized. Usually the concentrations of these compounds are small. Naturally occurring nitrate concentrations (NO_3-N) are typically between 2.0 mg/L and 2.5 mg/L (Panno et al. 2006b). However, groundwater in some shallow aquifers in Illinois exceeds the U.S. EPA NPDWR of 10 mg of NO_3-N/L; water with concentrations at or exceeding 10 mg of NO_3-N/L may pose health problems. The potential sources of such high-nitrate concentrations are discussed in Chapter 29, Pollution of Natural Waters. Nitrate concentrations can be naturally reduced through denitrification, a process by which denitrifying bacteria convert nitrate to nitrogen gas. As a result, nitrate in groundwater is often stratified or layered; the greatest concentrations occur near the top of the water table and continually decrease with depth. Ammonium becomes more prevalent in the reducing conditions of deeper and confined aquifers. For example, the Mahomet aquifer of east-central Illinois has ammonium concentrations up to 6 mg/L (Table 19-1) (Hackley 2002). Roy et al. (2003) indicated that the source of ammonium in a deep sand and gravel of the Mahomet aquifer in east-central Illinois is the subsurface degradation of organic materials present in buried ancient soils (paleosols).

Sulfate

Sulfate is typically present in groundwater at concentrations in the tens of milligrams per liter, but it can be much higher. Sulfate concentrations of 250 mg/L or greater is a U.S. EPA NSDWR. Drinking water with such high sulfate concentrations may have objectionable taste and odor; however, there is no evidence of ill effects from drinking such water (Centers for Disease Control, U.S. EPA 1999). In Illinois, sulfate concentrations of several hundred to 2,000 mg/L were found from the deep bedrock Cambrian and Ordovician aquifers in northeastern Illinois (Gilkeson et al. 1981) and in east-central Illinois in the unconsolidated sands and gravels of the Onarga Valley portion of the Mahomet aquifer (Hamdan 1970). Gilkeson et al. (1981) determined that the large sulfate concentrations found in the Cambrian and Ordovician aquifers were from the dissolution of marine evaporites (the calcium sulfate mineral gypsum). Sulfate in the Onarga Valley is due to circulation of groundwater through the bedrock and the leaching of secondary sulfate minerals produced from pyrite oxidation (Table 19-1) (Panno et al. 1994, Hackley 2002).

Dissolved Gases

A variety of dissolved gases are commonly associated with groundwater (Figure 19-3): nitrogen, oxygen, carbon dioxide, methane, and hydrogen sulfide. Other gases that are often present but usually in low concentrations are the noble (inert) gases, hydrogen, chlorofluorocarbons, and radon. As water penetrates into the ground, gases typically found in the atmosphere are dissolved in the water. Thus, nitrogen is common in groundwater. Nitrogen also may be produced from microbial denitrification reactions. Due to biochemical reactions within the aquifers, oxygen is quickly consumed during oxidation of organic matter and other reduced compounds such as the sulfides found in the soils and deeper sediments. Carbon dioxide is added to the infiltrating water in the soil zone due to root respiration and oxidation of organic matter. The addition of carbon dioxide increases the carbonic acid, lowering the water's pH, which has important impacts on the solubility of the rocks and minerals through which the groundwater flows.

In reducing environments, hydrogen sulfide and methane become more prevalent. Hydrogen sulfide results in a rotten egg odor that is sometimes present in well water. The sources of hydrogen sulfide include the bacterial reduction of naturally occurring sulfate dissolved in groundwater and decomposing organic matter within confined aquifers or in aquitards. Although the odor is objectionable, the concentrations of hydrogen sulfide gas typically found in drinking water do not pose a health problem. Hydrogen sulfide can be tasted at concentrations at or exceeding 0.05 mg/L (Lehr et al. 1980). At concentrations of 0.2 mg/L, hydrogen sulfide can be corrosive to silverware, fixtures, and plumbing (Lin 1977). Most water treatment companies can install equipment capable of removing hydrogen sulfide from domestic water supplies using oxidation, chlorination, aeration, and filtration or ion exchange with chemically active compounds (Lemley et al. 1999, Ross et al. 1999).

Dissolved methane is quite common in Illinois groundwater (Figure 19-9). Methane occurs naturally from the microbial degradation of buried organic debris present in the glacial drift deposits throughout much of central and northeastern Illinois (Meents 1958, 1960; Coleman 1976). Many residents of Illinois have used this "drift gas" to run appliances or heat their homes (Meents 1960). Using isotope geochemistry, methane from glacial drift deposits can be distinguished from other sources, such as thermogenic methane associated with petroleum formation or generated in landfills (Coleman et al. 1977, 1988, 1995; Hackley et al. 1996). The ability to determine these differences is important when exploring possible environmental problems from methane-generating sources such as landfills.

Total Dissolved Solids

Total dissolved solids, or TDS, refers to the total mass

of all dissolved constituents (as ions) present in groundwater. The U.S. EPA's NSDWR puts a suggested limit of 500 mg/L on this parameter. The TDS can easily be approximated by using a specific conductance or electrical conductance meter to measure the electrical conductivity of water (its ability to conduct electricity). Conductivity has the following relationship with TDS (Hem 1986):

TDS = specific conductance × 0.59.

Distilled water, having almost no dissolved minerals, would have a specific conductance of near zero. Rainwater is very dilute with a low specific conductance of about 20 microsiemens per centimeter (μS/cm), and water with a large TDS load (such as seawater) has a very high value (close to 60,000 μS/cm in the case of seawater) (Table 19-2). The specific conductance of the 500 mg/L standard would be about 850 μS/cm.

ENVIRONMENTAL ISOTOPES

Isotopes are atoms of an element that have a different number of neutrons in the nucleus. Isotopes can be stable or radioactive. Because the number of protons and the electron configuration are the same as other atoms of that element, isotopes of a particular element behave similarly during chemical reactions. However, because the atomic weights are different, the isotopes of an element react at different rates, which results in different concentrations of isotopes in the coexisting phases of a compound or in the reaction products of chemical, physical, and biological processes. This natural partitioning process is very important in the field of stable isotope geochemistry and is quite useful for determining the source of water or certain dissolved constituents and for figuring out the geochemical processes that have occurred to give the present-day chemical composition of a certain groundwater. The use of environmental isotopes can help solve groundwater quality problems by establishing the source of contaminants (natural or human-induced). The isotopes can also be used to protect groundwater by helping to identify groundwater recharge areas and groundwater flow velocities. Elements with stable isotopes that are commonly used in groundwater studies include oxygen, hydrogen, carbon, sulfur, nitrogen, and, to a lesser degree, chlorine, strontium, helium, and beryllium.

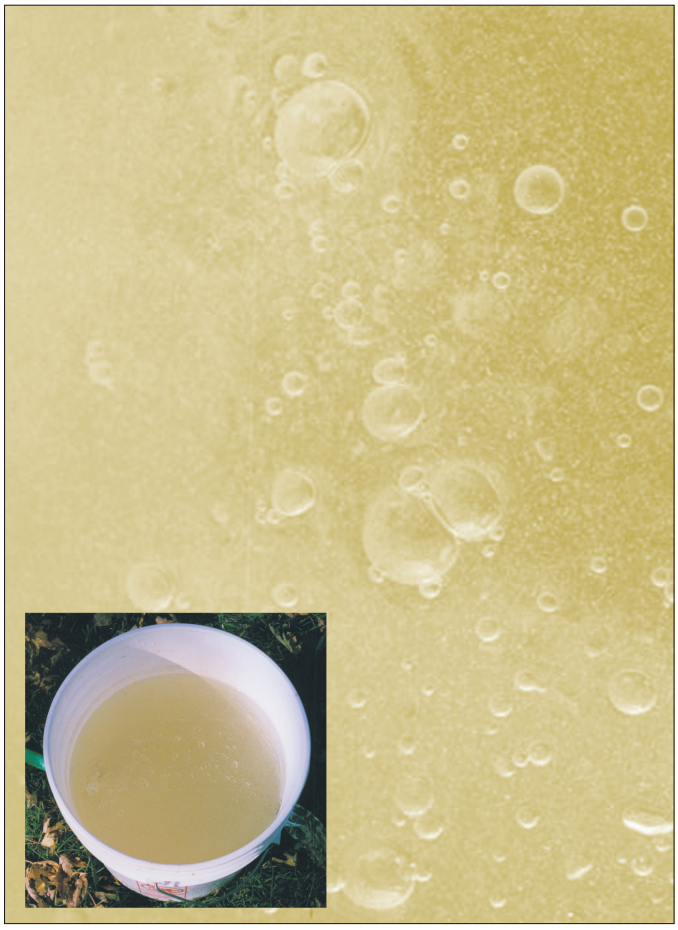

Figure 19-9 Gas (predominantly methane) bubbling out of groundwater pumped from the Mahomet aquifer in central Illinois. The largest bubbles were up to 1 inch (2.54 cm) in diameter. The presence of methane indicates reducing conditions within the aquifer. (Photographs by Samuel V. Panno.)

Radioactive isotopes have unstable nuclei and change into different atomic elements through spontaneous decay involving the emission of particles and energy. The rates of decay differ widely for the various radioactive isotopes, ranging from a fraction of a second to billions of years. The rate of decay is usually referred to as the half-life, the time needed for the concentration of the radioactive isotope to decrease by one-half. In hydrology, radioactive isotopes are typically used to determine the relative age of water and as tracers to help determine the source of water or of dissolved constituents in the water. Several radioactive isotopes are used in groundwater research; however, the most common are tritium (^{3}H), with a 12.3-year half-life, and carbon-14 (^{14}C), which has a 5,730-year half-life.

Two very good sources for information about isotope geochemistry applied to groundwater hydrology are Clark and Fritz (1997) and Kendall and McDonnell (1998). Examples of the use of isotope geochemistry applied to Illinois groundwater include the determination of origin of high-sulfate concentrations in deep aquifers of northern Illinois (Gilkeson et al. 1981), the processes controlling the enrichment of radium-226 and uranium-234 in the Cambrian and Ordovician aquifers of northern Illinois (Gilkeson et al. 1983), the origin of methane in glacial drift and Paleozoic bedrock (Coleman et al. 1988), detection of the impacts of landfill leachate and gases on local groundwater chemistry (Hackley et al. 1996, 1999), determination of sources of elevated nitrate concentrations (Panno et al. 2001, Hackley et

al. 2007, Roadcap et al. 2002, Hwang et al. 2003), the origin of the Illinois Basin brines and Mississippi Valley-type ore deposits (Clayton et al. 1966, Richardson et al. 1988, Stueber and Walter 1991), and the age of groundwater in a buried bedrock valley of central Illinois (Hackley 2002).

Although the concentrations of most radioactive isotopes measured in Illinois groundwater are low and do not detrimentally affect groundwater quality, dissolved radium from the deep Cambrian and Ordovician aquifers of northern Illinois is often present in relatively high concentrations. More than 300 wells in this area exceeded the U.S. EPA NPDWR for radium (Gilkeson et al. 1983). Radium-226 and radium-228 concentrations in groundwater ranged from 2.3 to 50.2 picocuries per liter (pCi/L); the U.S. EPA regulatory limit for the two radionuclides is 5.0 pCi/L (U.S. EPA 1991, 2009). The source of the radium in the aquifers is thought to be fine-grained materials such as the shale layers that form the bounds of the sandstone aquifers.

Conclusion

The quality of groundwater in Illinois changes with depth and location of the aquifer. Shallow surficial aquifers, such as glacially deposited sand and gravel or bedrock units near the land surface in the northern third of the state, contain relatively dilute groundwater compared with groundwater from deeper bedrock aquifers in the central and southern two-thirds of the state. Most of the aquifers in Illinois are made up of carbonate rock or contain considerable amounts of carbonate rock fragments, resulting in an almost ubiquitous problem with hard water. Many of the unconsolidated sand and gravel aquifers are deposited within fine-grained glacial tills and are confined aquifers that are under reducing conditions. The reducing conditions result in considerable amounts of dissolved iron and manganese and, in some cases, methane (drift gas). Most private wells in rural areas of Illinois use water softeners to extract iron and decrease the hardness of the groundwater. Groundwater pumped from wells in the central and southern parts of the state quickly become more saline as depths of wells increase and penetrate into the Pennsylvanian and deeper Paleozoic aquifers. Sodium and chloride concentrations tend to increase as depth increases.

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Groundwater

Recharge and Groundwater Flow Within an Intracratonic Basin, Midwestern United States

by Samuel V. Panno[1], Zohreh Askari[2], Walton R. Kelly[3], Thomas M. Parris[4], and Keith C. Hackley[5]

Abstract

The conservative nature of chloride (Cl^-) in groundwater and the abundance of geochemical data from various sources (both published and unpublished) provided a means of developing, for the first time, a representation of the hydrogeology of the Illinois Basin on a basin-wide scale. The creation of Cl^- isocons superimposed on plan view maps of selected formations and on cross sections across the Illinois Basin yielded a conceptual model on a basin-wide scale of recharge into, groundwater flow within and through the Illinois Basin. The maps and cross sections reveal the infiltration and movement of freshwater into the basin and dilution of brines within various geologic strata occurring at basin margins and along geologic structures. Cross-formational movement of brines is also seen in the northern part of the basin. The maps and cross sections also show barriers to groundwater movement created by aquitards resulting in areas of apparent isolation/stagnation of concentrated brines within the basin. The distribution of Cl^- within the Illinois Basin suggests that the current chemical composition of groundwater and distribution of brines within the basin is dependent on five parameters: (1) presence of bedrock exposures along basin margins; (2) permeability of geologic strata and their distribution relative to one another; (3) presence or absence of major geologic structures; (4) intersection of major waterways with geologic structures, basin margins, and permeable bedrock exposures; and (5) isolation of brines within the basin due to aquitards, inhomogeneous permeability, and, in the case of the deepest part of the basin, brine density effects.

Introduction

The geochemical origin and the movement of brines within intracratonic sedimentary basins have been the subject of numerous studies for much of the latter half of the 20th century (e.g., Bethke et al. 1988; Hanor 1994). An understanding of these influences on the groundwater chemistry within the basin is important for water resource evaluation and natural resource exploitation. Moreover, reservoirs in intracratonic basins have been used for storage of natural gas, and the disposal of a variety of industrial, oil field, and other types of wastes (e.g., Bergstrom 1968). The magnitude of this disposal has increased considerably with injection of flow-back waters from unconventional oil and gas reservoirs and could increase with geologic carbon sequestration (Locke et al. 2013).

The Illinois Basin in the U.S. Midwest (Figure 1) is an anomaly among intracratonic basins because it contains no known halite-bearing evaporite sequences that could contribute to brine formation. The chemical composition and origin of brines in the Illinois Basin have been shown to be unique for Cambrian, Ordovician, Silurian–Devonian, and Mississippian–Pennsylvanian strata (Stueber et al. 1987; Walter et al. 1990; Stueber and Walter 1991, 1994; Panno et al. 2013). Groundwater movement within the Illinois Basin was studied by Cartwright (1970) using thermal anomalies in the southern half of Illinois and by Siegel (1989) using stable isotopes in northern Illinois. Both concluded that groundwater flows toward the center of the basin becoming more sluggish with depth, and discharges upward across confining units. Cartwright (1970) further suggested that upward movement of groundwater should occur along fractures associated with geologic structures.

Total dissolved solids (TDS) and chloride (Cl^-) concentrations of brines within intracratonic basins typically increase with depth (Domenico 1972). Within the Illinois Basin, Cl^- concentrations range from about 1 mg/L in shallow aquifers to over 200,000 mg/L for the deepest Paleozoic strata (Panno et al. 2013). Variable permeability and hydraulic gradients within Paleozoic

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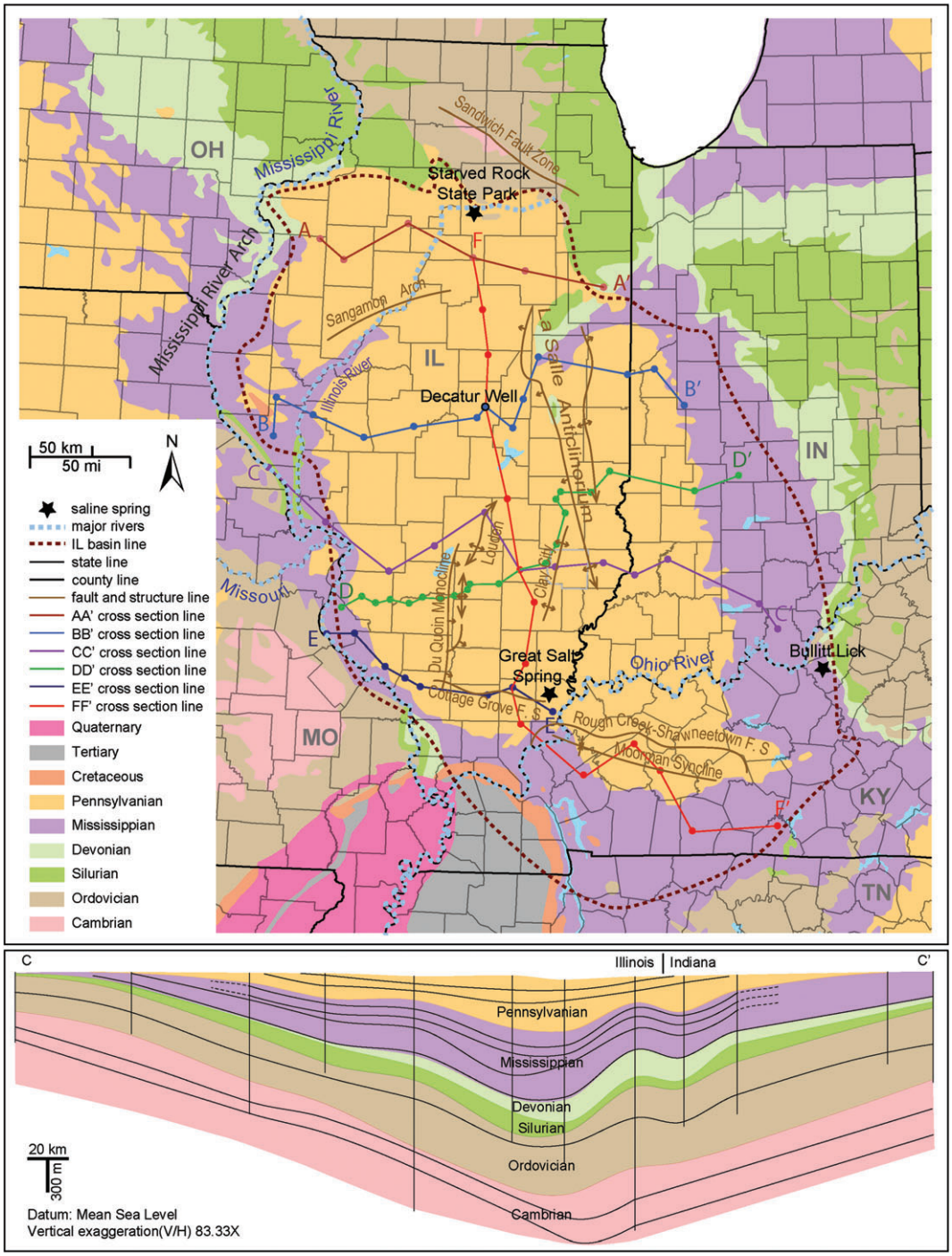

Figure 1. Cross section location map showing bedrock geology and structural features within the Illinois Basin. The bedrock geology was modified from Young (1992). East-west cross section C–C′ (at the bottom of the figure) shows the major strata, by age, of the basin.

strata, freshwater recharge at the margins of the basin and along zones of high permeability, and migration of brines through fractures associated with structural features all can cause departures from a monotonic increase in TDS and Cl^- concentrations with depth. Given the absence of halite-containing evaporites within the Illinois Basin, the conservative nature of Cl^- should allow it to act as a natural tracer revealing zones of recharge and preferential groundwater flow paths into, through, and out of the Illinois Basin (Figure 1). Chloride distribution should also indicate zones of low and high permeability, as well as zones of low flow, stagnation, or both. Mapping the distribution of Cl^- concentration in cross sections provides an efficient means of identifying dilution of basin brines within Paleozoic strata, mixing between aquifers, the isolating effects of aquitards, and potential flow paths along geologic structures (e.g., Panno et al. 1994).

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Whereas, there has been a great deal of research on the Illinois Basin, previous studies have focused on selected formations and only portions of the basin. No basin-wide scale study has been done that would provide a comprehensive understanding of the hydrogeology of the Illinois Basin. Consequently, there is limited information regarding groundwater movement within and only speculation regarding discharge from the basin. The purpose of this investigation was to develop a conceptual model of recharge to, groundwater movement within, and discharge from the Illinois Basin on a basin-wide scale. To do this, we created plan-view maps of selected formations and detailed cross sections extending across the Illinois Basin and added Cl^- concentration data from oil and gas wells, municipal and private water wells, gas-injection wells, and published data. The Cl^- concentrations are represented with symbols and isocons on maps and cross sections that yield information regarding the current hydrogeologic state of the basin. This is important because recharge, groundwater movement within, and discharge from the basin can have a direct bearing on the transport of hydrocarbons, the feasibility of the sequestration of CO_2, and maintaining groundwater quality in those areas affected by basin brines and could provide insight into the source or flow paths of brines for the formation of Mississippi Valley-type ore deposits.

Geology and Hydrogeology of the Illinois Basin

The geology of the Illinois Basin is summarized from Collinson et al. (1988) and Kolata and Nelson (2010). Briefly, the Illinois Basin developed on Precambrian crystalline basement and now underlies most of the state of Illinois, western and southwestern Indiana, western Kentucky, and a portion of northwestern Tennessee (Figure 1). The basin is filled with Paleozoic marine sedimentary rocks ranging from Cambrian through Pennsylvanian that gently dip toward the center of the basin and extend to a depth of up to 9144 m along the Rough Creek Graben in western Kentucky (Goetz et al. 1992; Figure 1). The geometry, distribution, and interrelationships of the carbonate rocks, sandstones, and shales of the basin play a key role in recharge to and groundwater flow within the basin. Paleozoic sandstones and carbonate rocks whose groundwater is brackish to saline elsewhere in the basin, constitute productive aquifers in the northern-most part and along the eastern and western margins of the Illinois Basin, and shales constitute effective aquitards within the basin.

Cambrian and Ordovician aquifers are used extensively as a source of potable water in the northern third of Illinois (Larson and Herzog 2004). The Cambrian Mount Simon Sandstone is rarely used because it is only potable in the northern one-fifth of the state and has a moderately low permeability due to its well-cemented nature. Shale, siltstone, and dolomite of the overlying Eau Claire Formation act as a confining unit. The overlying Ironton-Galesville Sandstone is made up of a well-sorted and fine-grained sandstone, confined by overlying dolomites, shales and some sandstones, and provides a reliable potable water source. The Ordovician Glenwood-St. Peter Sandstone and overlying fractured and creviced Galena-Platteville Dolomite constitute major aquifers for northern Illinois. Because of their close proximity, these aquifers and are often combined into a single hydrogeologic unit referred to as the Cambrian-Ordovician aquifer. The St. Peter Sandstone is a relatively thick, well-sorted, fine-to medium-grained and loosely cemented sandstone of marine origin and belongs to the Ancell Group, which includes the overlying Glenwood Formation made up of sandstone, dolomite, and shale (Willman et al. 1975). In addition to being a prolific aquifer, the St. Peter Sandstone has long been known as a source of high-quality pure quartz sand in northern Illinois where it is exposed at the surface near, within, and north of Starved Rock State Park (Lamar 1928). The St. Peter Sandstone ranges from 1 to up to 275 m thick, averages between 30 and 100 m thick throughout the Illinois Basin (Willman et al. 1975), and is either exposed or shallowly buried in northern Illinois and at the northern margin of the basin. In this article, we focused on the water quality data from the St. Peter Sandstone. The Upper Ordovician Maquoketa Shale constitutes a confining unit between the underlying Cambrian-Ordovician aquifer and overlying Silurian strata.

Silurian strata consist of mostly fractured and creviced dolomite in the northern part of the basin and limestone in the southern part of the basin. Because of its karst nature, water yields range from small to very large. Devonian strata are predominantly limestone with some dolomite and shale; these strata are not present in the northern part of the basin because of erosion. These strata yield only small to moderate volumes of groundwater and are confined from the overlying Mississippian strata by the New Albany Shale (Larson and Herzog 2004).

Similarly, Mississippian strata are missing from the northern part of the basin because of erosion and are made up of limestone, with lesser amounts of dolomite, shale, siltstone, and sandstone. These strata are exposed on the margins of the Illinois Basin in western and southwestern Illinois and on the eastern margin in central Indiana, and are well known for their karst nature. Overlying Pennsylvanian strata are made up of predominantly shale with beds of sandstone, siltstone and limestone, and coal measures. These strata are thin to missing in the extreme northern part of the Illinois Basin due to erosion. Pennsylvanian strata typically constitute an aquitard, although some of its sandstone and limestone layers can yield small amounts of potable groundwater in the vicinity of outcrop areas. In much of Illinois and Indiana, Paleozoic rocks are capped by a thick layer of Pleistocene glacial drift that includes thick sand and gravel layers that are typically sandwiched between clay-rich tills. The sand and gravel deposits are used extensively in these states as freshwater aquifers; the Mahomet aquifer is a classic example of a glacial drift aquifer (e.g., Kempton et al. 1991).

Groundwater of the Illinois Basin ranges from extremely fresh $Ca\text{-}HCO_3^-$ type water at the near surface to concentrated mixed-cation-Cl^- brines at the deepest

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part of the basin where Cl^- concentrations can be hundreds of grams per liter (Clayton et al. 1966). The salinity of the groundwater within the basin is typically stratified (Panno and Hackley 2010) with most shallow groundwater containing Na and Cl^- concentrations in sand and gravel aquifers between 1 and 15 mg/L for each ion (Panno et al. 2006). The sources of the Na-Ca-Cl-type brines of the Illinois Basin were studied by Stueber et al. (1987), Walter et al. (1990), Stueber and Walter (1991, 1994), Panno et al. (2013), and Labotka et al. (2015, 2016). These studies suggested, based on halide–halide and halide–cation ratios, and stable isotopes ($^{87}Sr/^{86}Sr$, δD and $\delta^{18}O$), that brines of the Illinois Basin originated as evaporated seawater and are composed of four geochemically distinct fluid regimes (Cambrian, Ordovician, Silurian–Devonian, and Mississippian–Pennsylvanian). Petroleum is found in Ordovician through Pennsylvanian rocks in the central and southern parts of the basin, and groundwater within these strata is highly saline. Because of the high salinity, few systematic hydrogeological studies have been conducted in these regions.

Methodology

Five east-west and one north-south cross section were constructed to illustrate the subsurface distribution of Cl^- in the Illinois Basin (Figure 1). The geologic data for the cross sections were compiled from geophysical logs from the Illinois State Geological Survey (ISGS) database and imported to GeoGraphix Discovery v5000 software (LMK Resources Inc., Houston, Texas) to create the cross sections and index maps. Boreholes that provided geologic data are represented as vertical lines in the cross sections; geologic structures were compiled from Nelson (1995).

The cross sections were populated with more than 600 Cl^- concentrations for groundwater samples from Cambrian through Pennsylvanian strata. Chloride concentration data are from Bartow et al. (1909), Meents (1952), Keller (1983), McIntosh et al. (2002), Panno et al. (2013), the Illinois State Water Survey (ISWS) Groundwater Quality Database (data available from ISWS on request), and the Kentucky Geological Survey (unpublished data). Well depths and screened intervals (or formation[s] from which groundwater was accessed) are available from these sources. Where brine data were acquired from oil fields, we used only samples collected before the onset of waterflood operations in oil fields to avoid possible contamination by mixing of brines or fresher waters from different stratigraphic units or dilution/contamination from drilling fluids. The Cl^- concentrations are represented with symbols, and by hand-contoured isocons, which represent locations of equal Cl^- concentrations. Adobe Illustrator CC 2015 (Adobe Systems, Incorporated, San Jose, California) was used for final editing and adding Cl^- concentration data for cross sections.

Chloride and TDS concentrations are highly correlated for these samples. The following equations developed by the authors of this article from data collected from fresh water aquifers, NaCl-enriched groundwater, and oil field brines in Illinois, were used to convert TDS concentrations to Cl^- concentrations (both in mg/L). Equations 1 and 2 were used for samples with TDS concentrations less than and greater than or equal to 5000 mg/L, respectively:

$$< 5000\,\text{mg/L} : Cl^- = 0.0022 \times TDS^{1.5328} \quad (R^2 = 0.895) \tag{1}$$

$$\geq 5000\,\text{mg/L} : \; Cl^- = 0.637 \times TDS \quad (R^2 = 0.989) \tag{2}$$

The relationship between TDS and Cl^- is supported by others working with a spectrum of water ranging from fresh to concentrated brines (Frape et al. 1984). For this article, the conversion was used for a direct comparison of Cl^- concentrations in cross sections and plan-view maps.

In addition to the cross sections, Cl^- isocon maps using simple interpolation were prepared for the Cambrian Mount Simon Sandstone (Figure 2) and the Ordovician St. Peter Sandstone (Figure 3). It is not clear, based on the sources of our data, whether the wells intersected both the Glenwood and St. Peter Sandstones or just the St. Peter Sandstone. Given their close proximity, and for our purposes we refer to the aquifer as the St. Peter Sandstone. The shaded counties contain one or more data points used in creating and contouring the St. Peter Sandstone map. A similar map, prepared for the Mount Simon Sandstone based on TDS data reported by Mehnert and Weberling, (2014; Figure 2), allowed comparison of Cl^- isocons with those of the St. Peter Sandstone (Figure 3). Not all cross sections and plan-view maps have the same density of data; consequently, some uncertainty/bias may be present in the interpretations. However, given the drilling activity in searching for fresh groundwater in the Illinois Basin, it is unlikely that formations containing potable groundwater would have gone undiscovered for more than a century.

Results and Discussion

Here we present, for the first time, plan view maps of selected formations and cross sections of the Illinois Basin containing Cl^- concentrations and isocons whose variability and patterns reflect the effects of freshwater recharge into and within a brine-dominated flow system. These patterns may be used as indicators of recharge, freshwater-brine mixing, cross-formational and flow-through movement of groundwater, and areas of brine stagnation within the basin.

Cambrian–Ordovician Aquifers

The aquifers of the Cambrian Mount Simon Sandstone, and the Ordovician Ironton-Galesville Sandstone, Glenwood-St. Peter Sandstone and Galena-Platteville Dolomite were referred to as the Cambrian-Ordovician Aquifer by Siegel and Mandel (1984) and Siegel (1989). However, they did not include the lowermost Mount

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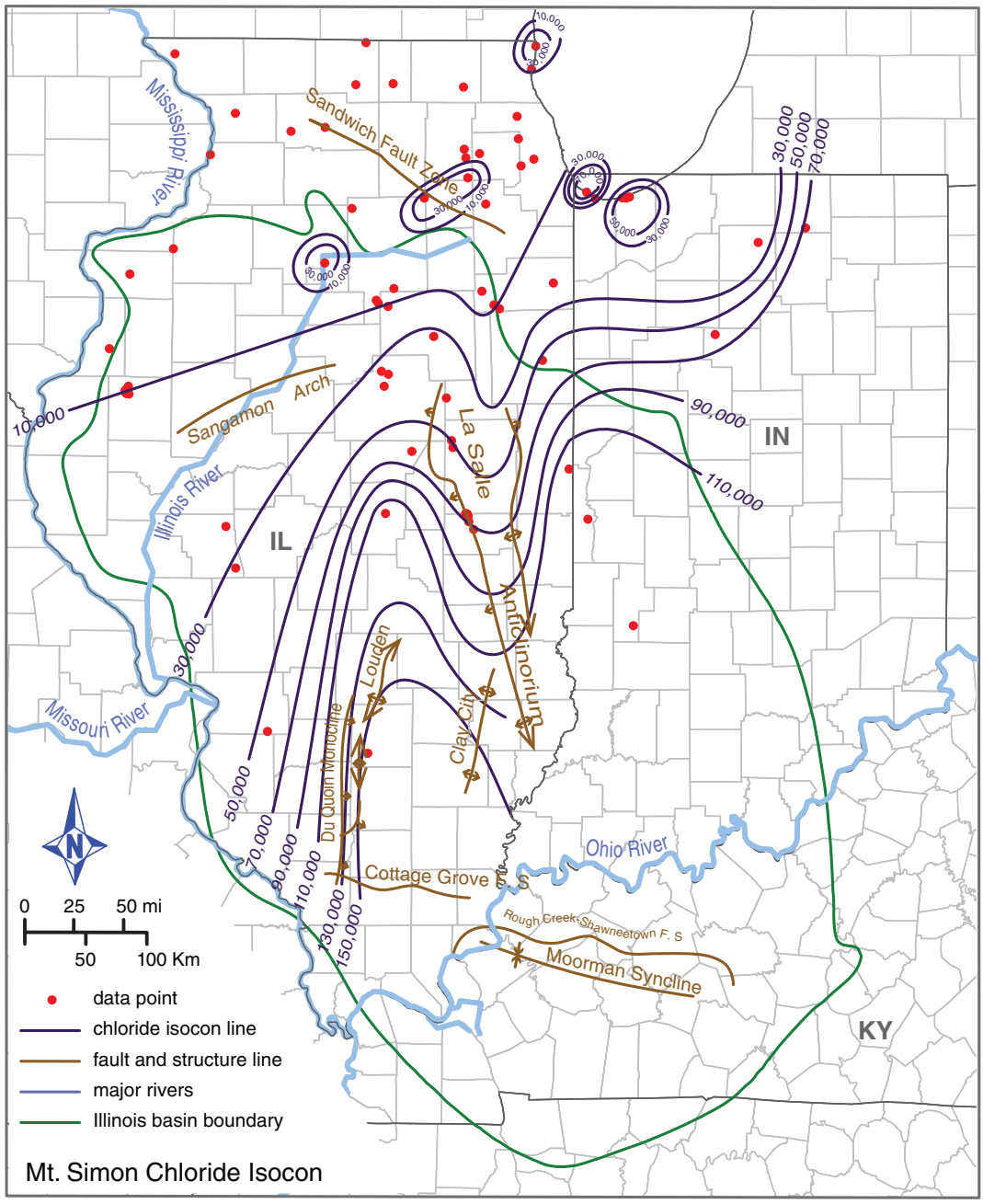

Figure 2. Chloride isocons in groundwater for the Mount Simon Sandstone. Water quality data (as TDS) are from Mehnert and Weberling (2014) and were converted to Cl^- concentrations using Equations 1 and 2.

Simon Formation because of the relatively high salinity of groundwater within this sandstone. These formations are used extensively in the northern third of Illinois for potable groundwater by municipalities and industries with wells that are often open to multiple aquifers (Larson and Herzog 2004).

Mount Simon Sandstone

The Mount Simon Sandstone represents the base of the Paleozoic sedimentary rock sequence that makes up the Illinois Basin. Unlike the St. Peter Sandstone, the Mount Simon Sandstone is rarely used as a freshwater resource because of its elevated TDS throughout the Illinois Basin. Mehnert and Weberling (2014) prepared a map of the distribution of TDS of brines within the Mount Simon Sandstone for much of the Illinois Basin. The data for this formation are from wells that are screened only within the Mount Simon Sandstone. We converted the TDS into Cl^- concentrations (for consistency within this investigation), contoured the data by hand, and added the Illinois River and pertinent geologic structures for interpretation purposes (Figure 2).

The Mount Simon isocon map shows preferential recharge from the northern, northwestern, and western boundaries of the Illinois Basin, and from north to south along the LaSalle Anticlinorium. The map also shows

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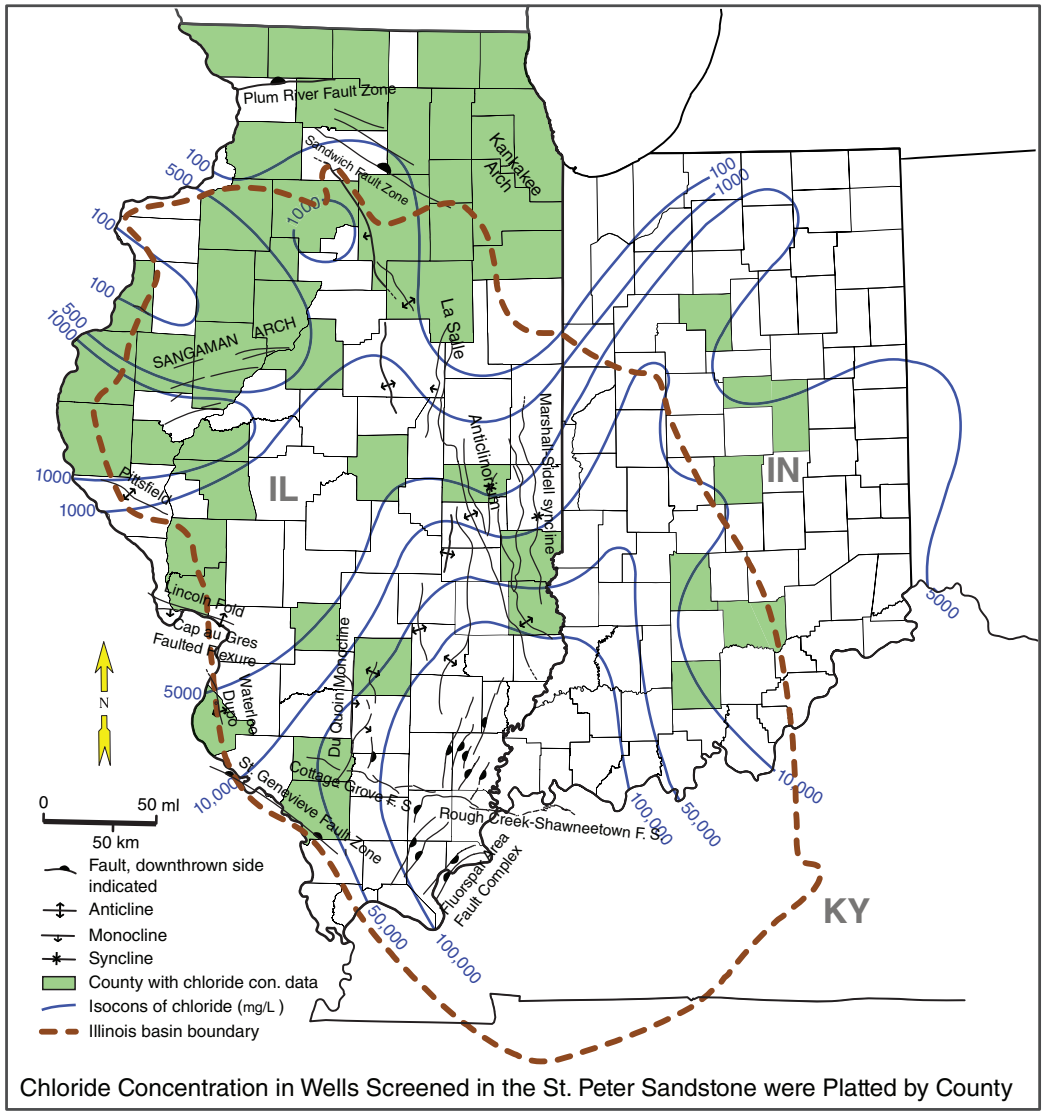

Figure 3. Chloride isocons in groundwater for the St. Peter Sandstone. Water quality data are from groundwater samples from wells screened in the St. Peter Sandstone. All concentrations are from published data and were plotted by county.

the presence of concentrated brines in the center of the basin in southern Illinois. Preferential recharge along the LaSalle Anticlinorium is of particular interest. The LaSalle Anticlinorium is a large geologic feature made up of numerous subparallel structures that collectively extend from southeastern Illinois to north-central Illinois and include anticlines, domes, monoclines, and synclines (Nelson 1995). Uplift of the LaSalle Anticlinorium occurred primarily during the late Paleozoic Era (Late Mississippian) but before the Pennsylvanian, and resumed after the Pennsylvanian. The anticlinorium was interpreted by Nelson (1995) to be the result of fault movement and displacement within the crystalline basement during the Late Paleozoic Era. Nelson (1995) suggests that the faults die out as they cut upward into the sedimentary rocks, and the structures of the LaSalle Anticlinorium become essentially drape folds. Recent seismic-reflection profiles by Kamp et al. (2016) suggest that the anticlinorium may be a fault system with strike-slip displacement.

The Mount Simon Cl^- isocon map (Figure 2) shows that salinity anomalies in the northern part of the basin and around the edge of Lake Michigan coincide with the Illinois River and the Sandwich Fault Zone. The saline anomaly farthest west and along the Illinois River (within and near Starved Rock State Park) contains nearly 40,000 mg/L of Cl^-. Just north and south of the anomaly, Cl^- concentrations are only 319 mg/L or less, and 7000 mg/L or less, respectively. This saline anomaly is coincident with the Illinois River and is probably associated with saline springs (Willman and Payne 1942) and relatively shallow saline wells (Panno, ISGS, unpublished data) of the Starved Rock State Park and surrounding area. The very low Cl/Br mass ratio of this groundwater (149 to 216; Panno, ISGS, unpublished data) suggests that the salinity originates from a mixture of brines from the underlying Cambrian and Ordovician strata, and perhaps crystalline basement brines (Table S1, Supporting Information). The upwelling of crystalline basement brines at

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least into lower Cambrian strata is likely, based on work by Panno et al. (2013) and Labotka et al. (2015, 2016).

St. Peter Sandstone

The distribution of Cl^- on the isocon map for the St. Peter Sandstone suggests that recharge takes place along the northwestern (from Iowa) and central and northeastern parts (from northern Illinois) of the margins of the Illinois Basin (Figure 3). Recharge in these areas and groundwater flow into the Illinois Basin within this formation is consistent with groundwater flow directions for the northern and northeastern portion of the Illinois Basin identified by Siegel (1989) and Young (1992) based on predevelopment potentiometric surface data. Stable isotope data were determined from saline water samples from the St. Peter Sandstone collected from a well near Decatur, IL located about 160 km south of Starved Rock State Park (Figure 1), about 50 km south of Siegel's (1989) study area. The Decatur, Illinois, sample showed isotopically light (δD and δ^{18}O of −61.7 and −9.13, respectively) indicating a component of Pleistocene glacial meltwater (Panno and Fanta, unpublished report, Electronic Supplement). These data are consistent with those of samples collected from wells within the St. Peter Sandstone located in the vicinity of the Decatur well (Kelly, ISWS, and Panno, ISGS, unpublished data; Figure 1).

The Cl^- isocons also show that enhanced recharge is occurring horizontally along the LaSalle Anticlinorium (Figure 3) similar to that of the Mount Simon Sandstone (Figure 2). Dilation of fractures along faults and folds associated with the anticlinorium could provide preferential groundwater flow paths for groundwater (e.g., Bethke 1986). The Cl^- isocons of the St. Peter Sandstone (Figure 3) reveal that enhanced recharge is occurring horizontally along the LaSalle Anticlinorium (Figure 3) very similar to that of the Mount Simon Sandstone (Figure 2). We suggest, based on these isocon maps, that the LaSalle Anticlinorium provides structural controls on recharge and groundwater movement within the Illinois Basin and serves as a preferential flow path from north to south probably along fractures and faults associated with the anticlinorium. Stueber and Walter (1994) noted that the δ^{18}O of brines from the Ordovician Galena Formation had a meteoric-water signature for only those samples collected along the LaSalle Anticlinorium. These data support the concept of its role as a zone of enhanced anisotropic permeability with greater and/or more rapid recharge and groundwater movement along this structure within at least Cambrian and Ordovician strata. This structure also has been identified as the location of thermal anomalies and saline springs (Cartwright 1970; Panno et al. 1994; Panno, ISGS, unpublished data) suggesting the anticlinorium is a zone of enhanced permeability throughout the entire Paleozoic sequence. In addition, the LaSalle Anticlinorium has been described by Bethke (1986) as a structure that may have "funneled" ore-forming solutions from the southern part of the Illinois Basin to the host rocks of the Upper Mississippi Valley ore district to the north (Figure 1) in post-Pennsylvanian time. Finally, whereas Devonian rocks are exposed in isolated locations along the LaSalle Anticlinorium, it is unlikely that recharge via these "windows" through the Pennsylvanian strata is responsible for the preferential flow patterns in the St. Peter Sandstone or the Mount Simon Sandstone.

Cross Sections of the Illinois Basin

Chloride isocons on the cross sections (Figures 4–8 and S1) reveal patterns of recharge, stratification, paths of preferential groundwater flow, zones of near stagnation, and flow directions within and through the basin. The isocons often reveal strong contrasts in groundwater Cl^- concentrations in adjacent stratigraphic units, which suggests areas with limited to negligible vertical mixing and near stagnant brines. Some of the cross sections also show the effects of the LaSalle Anticlinorium on enhanced recharge into the basin. In addition, the isocons show that the shales of the Pennsylvanian strata, where present, provide a low flow boundary for recharge into the underlying strata. The cross sections are discussed in detail further.

The northernmost part of the Illinois Basin is characterized by exposures of Cambrian and Ordovician strata. Consequently, these strata are more easily recharged and groundwater in this area contains the lowest concentrations of Cl^- in the Illinois Basin (Figure 4). As a result, some of the lowest Cl^- values (e.g., all values are below that of average seawater of 19,800 mg/L; Table S1) are found in this part of the basin. Here, the shallowest bedrock (Pennsylvanian strata) contains Cl^- concentrations that are typically less than 100 mg/L, and concentrations barely exceed 20,000 mg/L in the deeper, typically briny, Mount Simon Sandstone. The isocons of A–A′ (Figure 4) indicate recharge of low Cl^- water to all Paleozoic formations along the northernmost margins of the Illinois Basin where the Ordovician St. Peter Sandstone is exposed at and near Starved Rock State Park. The low Cl^- concentrations in this area are consistent with findings by Siegel (1989, 1991) and Panno et al. (2013), who showed, using groundwater chemistry and stable isotopes, that Pleistocene recharge extended into the Illinois Basin from the north and west. McIntosh et al. (2002) showed a similar recharge into Devonian and Mississippian strata from the east. As cross section A–A′ (Figure 4) shows evidence of several isolated/narrow plumes of groundwater with elevated Cl^- concentrations, it is likely that there is an upward hydraulic gradient where deeper, saline groundwater is welling up to the surface. The widespread saline anomaly within and in the vicinity of Starved Rock State Park (Willman and Payne 1942; Panno, ISGS, unpublished data) is coincident with these plumes. The sporadic occurrence of saline wells, springs, and plumes of saline groundwater in this area suggest the upward movement of saline groundwater along faults and fractures.

Farther south, freshwater recharge is evident along the western margin of the basin and along the LaSalle Anticlinorium where Pennsylvanian shale is thin to absent (Figure 5). The greatest recharge appears to have been to

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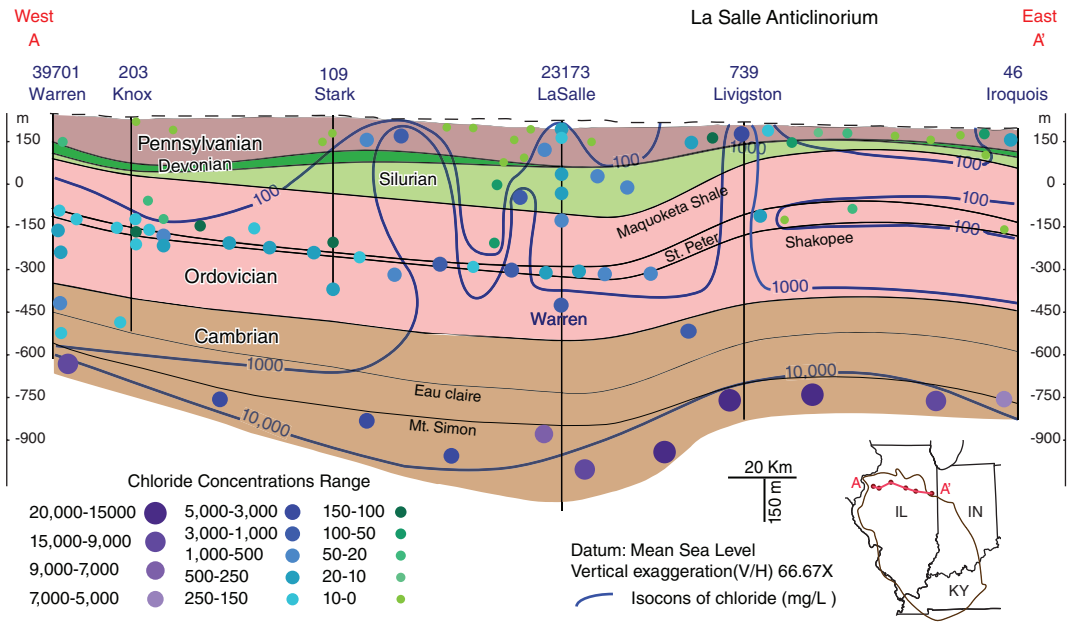

Figure 4. Cross section A–A′ extending east-west across northern Illinois. The most dilute groundwater in the Illinois Basin is found in the northern part of the basin because of the shallowness or exposure of the formations in this area, or both. Recharge is apparent from dilution effects from the west and east, and an upward movement of brines near the center of the cross section in the vicinity of the Illinois River.

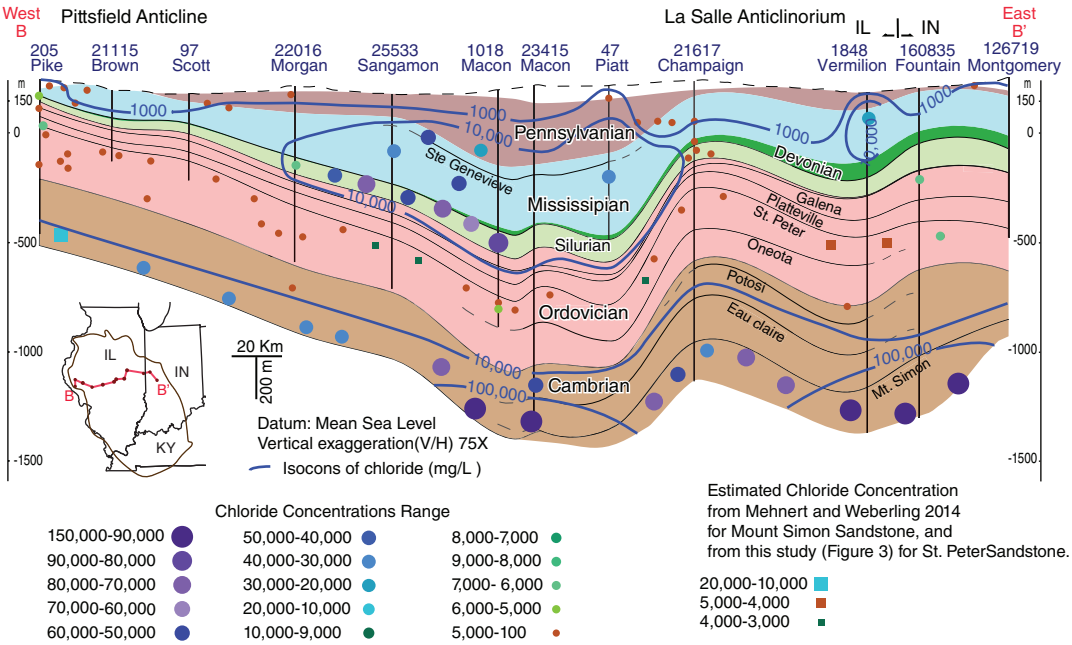

Figure 5. Cross section B–B′ extending east-west across central Illinois and central Indiana. The effects of freshwater recharge are apparent where Pennsylvanian strata are thin or absent and along the western and eastern margins of the basin and along the LaSalle Anticlinorium. Residual brines are present near the center of the cross section in Silurian–Devonian and Mississippian strata. The most concentrated brines are present near the center and far western part of the Cambrian strata.

Ordovician strata, primarily into the St. Peter Sandstone. Some of the lowest Cl^- concentrations are located along the LaSalle Anticlinorium. In the central region of cross section B–B′ (Figure 5), pools of dilute groundwater within the St. Peter Sandstone extend below pools of basin brines where Pennsylvanian strata are thickest. Greater concentrations of Cl^- lie within the Silurian, Mississippian, and Pennsylvanian strata above (many greater than 50,000 mg/L) and the Cambrian strata below (some greater than 100,000 mg/L). The greatest Cl^- concentrations are found within Cambrian strata on either side of the LaSalle Anticlinorium probably related to the effects of north to south fresh-water recharge within the Cambrian along the anticlinorium (Figure 2).

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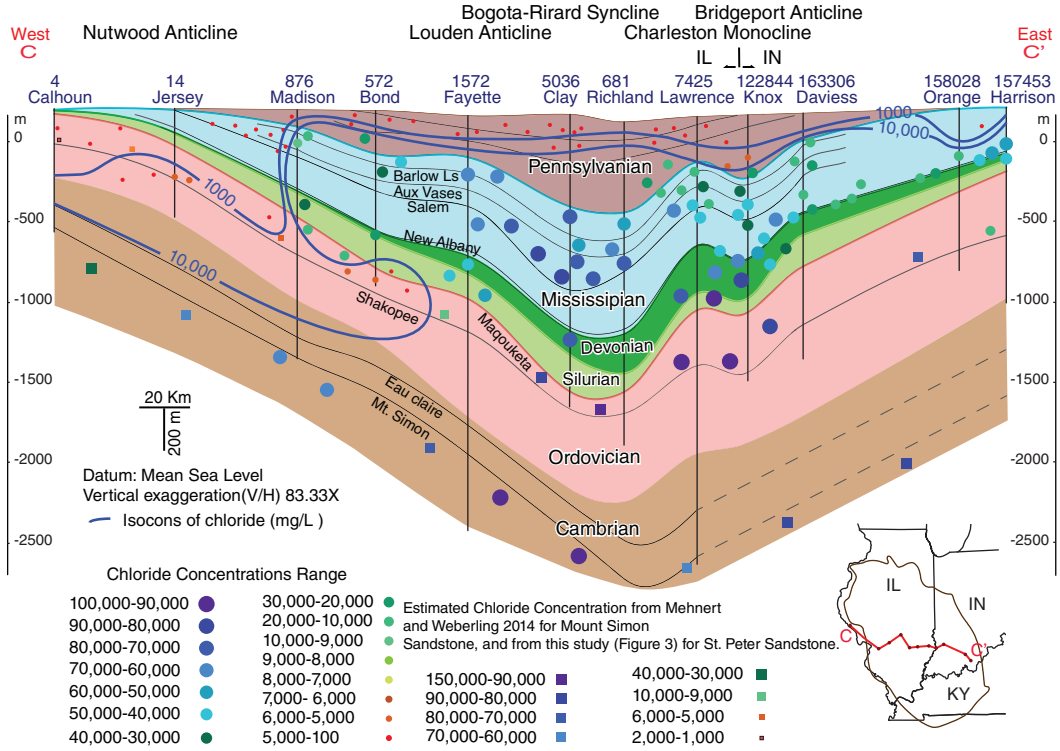

Figure 6. Cross section C–C′ extending east-west across southern Illinois and southern Indiana. The effects of freshwater recharge are most prominent at the western edge of the basin and in upper 200 m of Pennsylvanian strata. The most concentrated brines are present in the Cambrian Mount Simon Formation near the center of the basin.

Across the central portion of the Illinois Basin, cross section C–C′ reveals dilution of brines along zones of recharge at the western and, to a lesser extent, at the eastern edges of the basin where Pennsylvanian strata have been eroded (Figure 6). A relatively large plume of freshwater from the west has penetrated deep into the basin along Ordovician strata. The exposure of Ordovician, Silurian–Devonian, and Mississippian strata along the Mississippi River is a likely location for focused recharge, probably from glacial meltwaters during the Pleistocene Epoch. As the plume approaches the deepest part of the basin, it is bounded above by the Maquoketa Shale, below by the Eau Claire Formation, as well as above and below by brines with greater Cl^- concentrations. Dilution of brine within the Mount Simon Sandstone is also present from both the west and east, but to a lesser extent.

Freshwater recharge is indicated for much of the Pennsylvanian strata where Cl^- concentrations are less than 100 mg/L for the upper 50 to 100 m. Conversely, Cl^- concentrations in Mississippian through Silurian strata near the center of the basin exceed 50,000 mg/L where they are bounded above by thick Pennsylvanian strata and below by the New Albany Shale. Brines within these dominantly carbonate rock strata are diluted by freshwater recharge from both the west and east (Figure 6).

Just south of cross section C–C′, cross section D–D′ reveals similar conditions, but extends no deeper than Ordovician strata due to the paucity of geologic and geochemical data in this area (Figure 7). As with cross section C–C′, Cl^- concentrations suggest active recharge from the west and east where Pennsylvanian strata are thin or absent. Recharge from the east and west extends into Paleozoic strata from both sides of the basin. The eastern portion of the cross section within Indiana reveals greater recharge from the east within Silurian through Mississippian strata. This is supported by McIntosh et al. (2002) who found that the Silurian–Devonian strata provided a hydrologic pathway for recharging Pleistocene meltwater to depths up to 1 km across the eastern margin of the basin, and recharge from Mississippian strata, through underlying fractured New Albany Shale, and into Silurian–Devonian strata in the southeastern part of the Illinois Basin. Cross section D–D′ suggests recharge from the west is entering exposed Ordovician and Mississippian strata along the Mississippi River Arch (Figure 7).

Freshwater recharge is limited within the center of the basin where Pennsylvanian strata are thick (more than 600 m). Dilution of Cl^- concentrations of 1000 mg/L or less is consistent across Pennsylvanian strata to a depth of 60 to 120 m; however, limited data suggests that Cl^- concentrations rapidly increase, with depth, to greater than 10,000 mg/L within Pennsylvanian strata. Chloride concentrations within the center of cross section D–D′ (along the deepest part of the basin) reveal the presence of concentrated brines within all strata. Freshwater recharge from the north is apparent within the LaSalle Anticlinorium in the eastern half of the cross section and occurs within Upper Ordovician through Mississippian strata.

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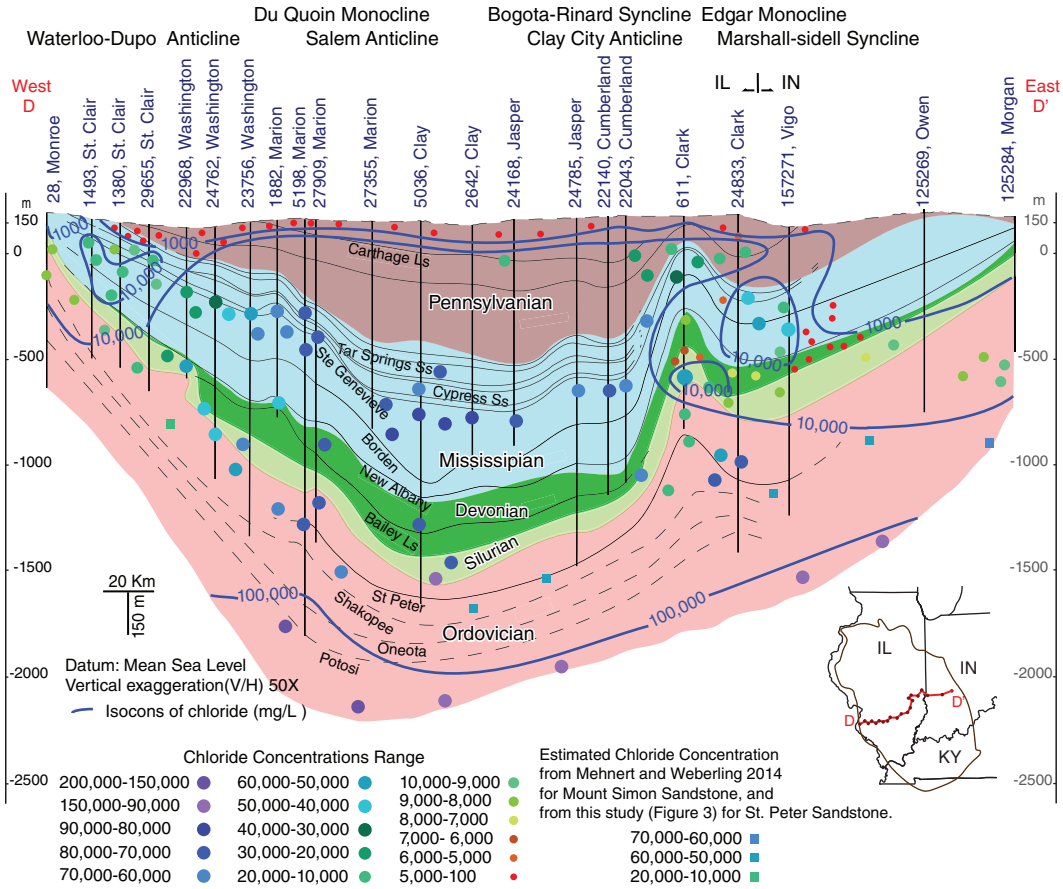

Figure 7. Cross section D–D′ extending east-west across southern Illinois and southern Indiana. Freshwater recharge affects the western and eastern margins of the basin, but not to the extent seen in cross sections farther north. Brines are also diluted along the LaSalle Anticlinorium (groundwater movement toward the reader). Again, the most concentrated brines are present in the Cambrian strata.

Farther south, cross section E–E′ does not extend beyond the Illinois-Indiana border and does not extend below Ordovician strata because of the paucity of geologic data (Figure S1). As with the cross sections C–C′ and D–D′, to the north, Cl^- concentrations show a plume of dilute water extending into the basin from the west. The absence of Pennsylvanian shale in the west has facilitated groundwater recharge where Ordovician through Mississippian strata are exposed along the Mississippi River Arch and in southwestern Illinois.

Constructed along the long axis of the Illinois Basin, cross section F–F′ reveals the effects of recharge, groundwater flow, and zones of stagnation within nearly the entire basin. It was used, in conjunction with the plan-view maps and east-west cross sections, as a conceptual model of recharge into, distribution of brines and brine-freshwater mixing within, and groundwater flow within and through the Illinois Basin. Based on the Cl^- concentrations and associated isocons, freshwater recharge is entering all Paleozoic formations including Cambrian strata in northern Illinois as seen in cross section A–A′ and B–B′ (Figures 4 and 5), and from the east and west (Figures 6, 7, and S1). Along the northern basin margin, Cl^- concentrations reveal a pool of dilute groundwater extending from Pennsylvanian strata at the surface downward into the Cambrian Mt. Simon Sandstone (Figure 8). The effects of freshwater recharge along the LaSalle Anticlinorium are seen in a short segment of the Mount Simon Formation about 200 km from the northern edge of the cross section. Here, Cl^- concentrations of Mount Simon brines are diluted below 100,000 mg/L. The overall distribution of isocons and Cl^- concentrations indicates groundwater flow from north to south through Ordovician strata with preferential recharge to and groundwater movement through the St. Peter Sandstone. The isocons also reveal a pattern of increasing Cl^- concentrations with distance from northern and western recharge areas about two thirds of the way to the southern end of the basin. Beyond the recharge zone to the north, thick Pennsylvanian strata protect brines within Silurian–Devonian and Mississippian strata from dilution by recharge; this is in contrast to the dilution of brines seen in these formations in the southern part of the basin where Pennsylvanian strata are thin to absent.

The separation of the 100,000 mg/L isocon within Cambrian strata in the northern third of cross section F–F′ is associated with dilution of brines along the LaSalle Anticlinorium. The deepest part of the basin contains the greatest concentration of Cl^- (and TDS) that extends from

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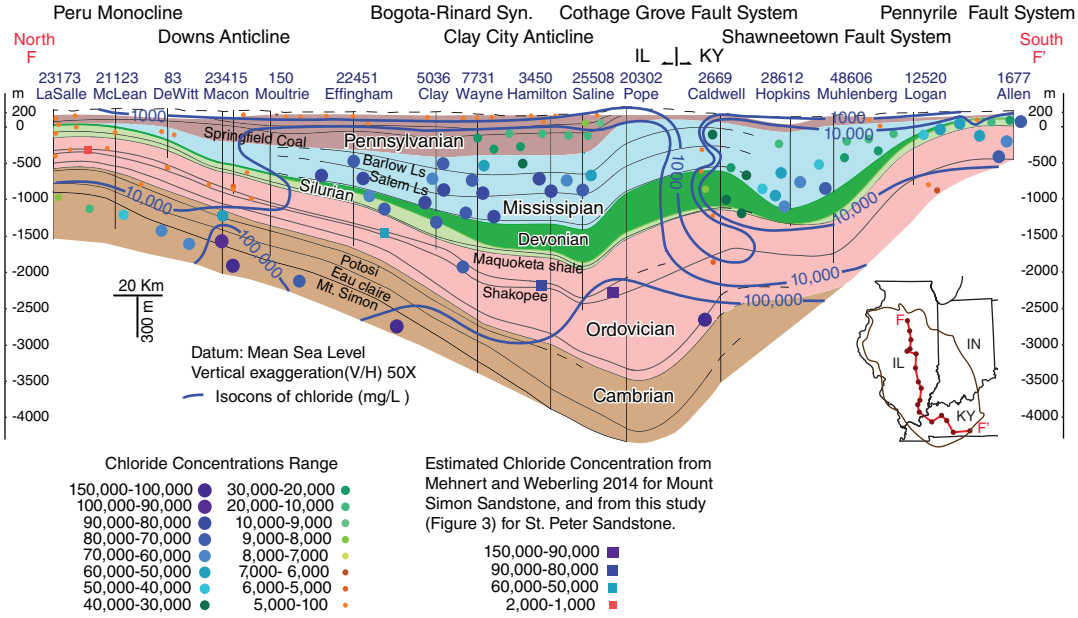

Figure 8. Cross section F–F′ extending north-south from northern Illinois to southwestern Kentucky. This cross section reveals the effects of freshwater recharge in the northern part of the basin, where much of the Paleozoic strata are exposed or near surface. The greatest dilution is apparent in the St. Peter Sandstone aquifer, and the most concentrated brines are present in Cambrian strata and up into Ordovician strata at the center of the basin. Focused recharge deep into Ordovician strata is apparent in the vicinity of the Ohio River near the Rough Creek-Shawneetown Fault System, where Pennsylvania strata is thin to absent.

Cambrian strata up into Ordovician strata. Cartwright (1970) and Siegel (1989) suggested that discharge of concentrated brines in southern Illinois may be by upward migration across leaky confining units. The area in this cross section where the greatest Cl^- concentrations extend into Ordovician strata is immediately beneath the Great Salt Spring located near Equality, Illinois with saline springs on either side of the Saline River indicating points of discharge. However, the saline water of the Great Salt Spring appears to be characteristic of Pennsylvanian strata based on Cl/Br mass ratios and not derived from Cambrian and Ordovician strata (Panno, ISGS, unpublished data). The saline springs in this area may suggest an upward hydraulic gradient, perhaps with mixing of the brines prior to reaching the surface. In addition, it is possible that concentrated crystalline basement brines are upwelling into the original brines of the Cambrian Mount Simon Formation near the center of the basin as was observed in the Decatur well to the north by Panno et al. (2013) and Labotka et al. (2015, 2016).

The inferred pattern of north-to-south brine migration is interrupted in the southern part of the basin at or near the Ohio River (Figure 1). Here, recharge occurs where the Ohio River intersects the Rough Creek-Shawneetown Fault System. In this area, Pennsylvanian strata are thin or missing and Cl^- contours indicate the presence of a fresh-water plume, presumably from the Ohio River (perhaps including Pleistocene glacial meltwaters) recharging carbonate bedrock aquifers. Surface waters are probably recharging underlying aquifers as they flow through Mississippian and Silurian–Devonian strata, and into Ordovician strata. The Cl^- isocons further suggest that the freshwater recharge within Ordovician strata flows to the south-southeast into Kentucky toward the southern end of the Illinois Basin. The freshwater recharge is probably mixing with basin brines as it flows through Ordovician strata. We speculate that the resulting saline groundwater from the southeastern margin of the Illinois Basin may be discharging to the numerous salt licks found in northern and central Kentucky (e.g., Bullitt's Lick; Figure 1). These salt licks were used by Native Americans and frontiersmen as a source of salt and as hunting spots where herds of bison, deer, and elk would frequent the area and where bison "licked out deep trenches in the salt-impregnated clay" (McDowell 1956). Based on the Cl/Br mass ratio of Bullitt's Lick (189), one of many salt licks located just southeast of Louisville, Kentucky, the saline water is Cambrian-Ordovician in origin (Panno, ISGS, unpublished data), which is consistent with the inferred flow patterns and groundwater mixing within the Illinois Basin.

Conclusions

We develop, for the first time, a conceptual model of the hydrogeology of the Illinois Basin on a basin-wide scale. This model, based on Cl^- isocons on plan-view maps of selected formations and cross sections across the basin, reveal the infiltration and movement of freshwater recharge into the basin and dilution of brines within all of the Paleozoic strata, inter-formational interactions, and groundwater flow within and through the Illinois Basin. Pathways of greater permeability (e.g., highly conductive

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lithologies and fractures associated with geologic structures) resulted in zones of dilute groundwater migrating through areas bounded on all sides by brines. Restrictions or barriers created by aquitards have created areas of near isolation/stagnation of concentrated brines within the basin. The Cl^- isocons suggest that the current chemical composition of groundwater and distribution of brines within the Illinois Basin is dependent on five parameters: (1) the presence of bedrock exposures along basin margins; (2) the permeability of geologic strata and their distribution relative to one another; (3) the presence or absence of major geologic structures; (4) the intersection of major rivers with geologic structures, basin margins, and permeable bedrock exposures; and (5) the isolation of brines within the basin resulting from aquitards, inhomogeneous permeability, and, in the case of the deepest part of the basin, brine density effects.

Cambrian Mount Simon Sandstone is bounded below by crystalline basement and above by the Eau Claire Formation and contains original brines (as determined by Labotka et al. 2016). Groundwater within the deepest part of the basin located in far southern Illinois may be under near stagnant conditions, or at least that part of the basin constitutes a zone of low flow within Cambrian and lower Ordovician strata. Based on previous work by McIntosh et al. (2002); Siegel (1989, 1991), and this study, groundwater flow through the basin appears to be from the northern, eastern, and western margins of the basin and dominantly through the Ordovician St. Peter Sandstone, and carbonate rocks of the Silurian–Devonian and Mississippian strata. Silurian–Devonian strata, consisting of mostly carbonate rocks, are bounded by the underlying Ordovician Maquoketa Shale and the overlying Devonian New Albany Shale. Similarly, the carbonate rocks of the Mississippian strata are bounded below and above by the New Albany Shale and the shale-dominated Pennsylvanian strata, respectively, where remnant brines remain. Our findings are consistent with Stueber and Walter (1994) who suggested that the remnant brines within the Silurian–Devonian and Mississippian strata are due to the bounding shale layers. We suggest that the inhomogeneous hydraulic characteristics of the Silurian–Devonian and Mississippian strata (i.e., dual porosity) probably help maintain brine compositions within these strata.

Pennsylvanian strata, where present, act as a confining unit to protect brines of the underlying Mississippian strata from freshwater recharge. Where Pennsylvanian strata are thin or absent, brines of the Mississippian strata have been diluted to various degrees, and, in some cases, to potable groundwater. Exposures of formations near basin margins allow recharge from meteoric water and, in the past, glacial meltwaters. Where the Mississippi River intersects bedrock exposures along the Mississippi River Arch (western margin of the Illinois Basin), enhanced recharge is likely responsible for freshwater plumes that extend deep into the basin from the west. The intersection of major rivers with major geologic structures is responsible for relatively rapid fresh-water recharge and movement of groundwater through the Illinois Basin. Evidence of Pleistocene meltwater recharge is observed along the LaSalle Anticlinorium where associated faults and fractures have created a zone of enhanced anisotropic permeability. Glacial meltwaters appear to have flushed out much of the brines within the St. Peter Sandstone within the northern part of the Illinois Basin during the Pleistocene based on data by Siegel (1989, 1991) and this study. Subsequently, deep-seated brines welled up along fault and fracture planes and created saline springs and the sporadic occurrence of saline wells near the Illinois River.

Chloride isocons within the Cambrian Mount Simon Sandstone and the St. Peter Sandstone reveal a marked dilution along the LaSalle Anticlinorium that extends into southern Illinois. This pattern of dilution also was observed in younger formations along the anticlinorium in the cross sections. In far southern Illinois, the intersection of the Rough Creek–Shawneetown Fault System (a major fault zone across the southern part of the basin) and the Ohio River has resulted in enhanced recharge deep into the Illinois Basin extending from surficial Mississippian strata, through Devonian and Silurian strata, and continuing to near the base of Ordovician strata. Within Ordovician strata, we speculate that the freshwater plume joins groundwater flowing through Ordovician strata via the St. Peter Sandstone and continues south into Kentucky where it discharges to numerous salt licks and saline springs near and south of Louisville and perhaps into northern Tennessee. These observations are consistent with an overall north to south flow of groundwater within the Illinois Basin and discharge along its southern boundaries.

Acknowledgments

The authors thank Chris Korose (ISGS) for his assistance with the geology/cross section location map. This paper was greatly improved through the comments and suggestions of Randy Locke, Dana Labotka (ISGS), Executive Editor Kristine Uhlman, and an anonymous reviewer, and editing by Susan Krusmark (ISGS). This work was supported by grant from the U.S. Environmental Protection Agency (Star Grant EPA-G2008-STAR-H1) and by the Illinois State Geological Survey of the Prairie Research Institute, University of Illinois.

Supporting Information

Additional Supporting Information may be found in the online version of this article. Supporting Information is generally *not* peer reviewed.

Appendix S1. Chloride Content and Cl/Br Ratios of Brines of the Illinois Basin and References.

Table S1. Maximum Cl^- concentrations and median Cl/Br ratios (the ± refers to range) reported for geologic strata within the Illinois Basin. The Cl^- concentrations of

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seawater and Precambrian Shield brines are added for comparison.

Figure S1. Cross section E–E′ extending east-west across far southern Illinois. Because this cross section is truncated at the Illinois–Indiana state boundary, the effects of freshwater recharge are only seen along the western margin of the basin.

Appendix S2. Illinois State Geological Survey Unpublished Report.

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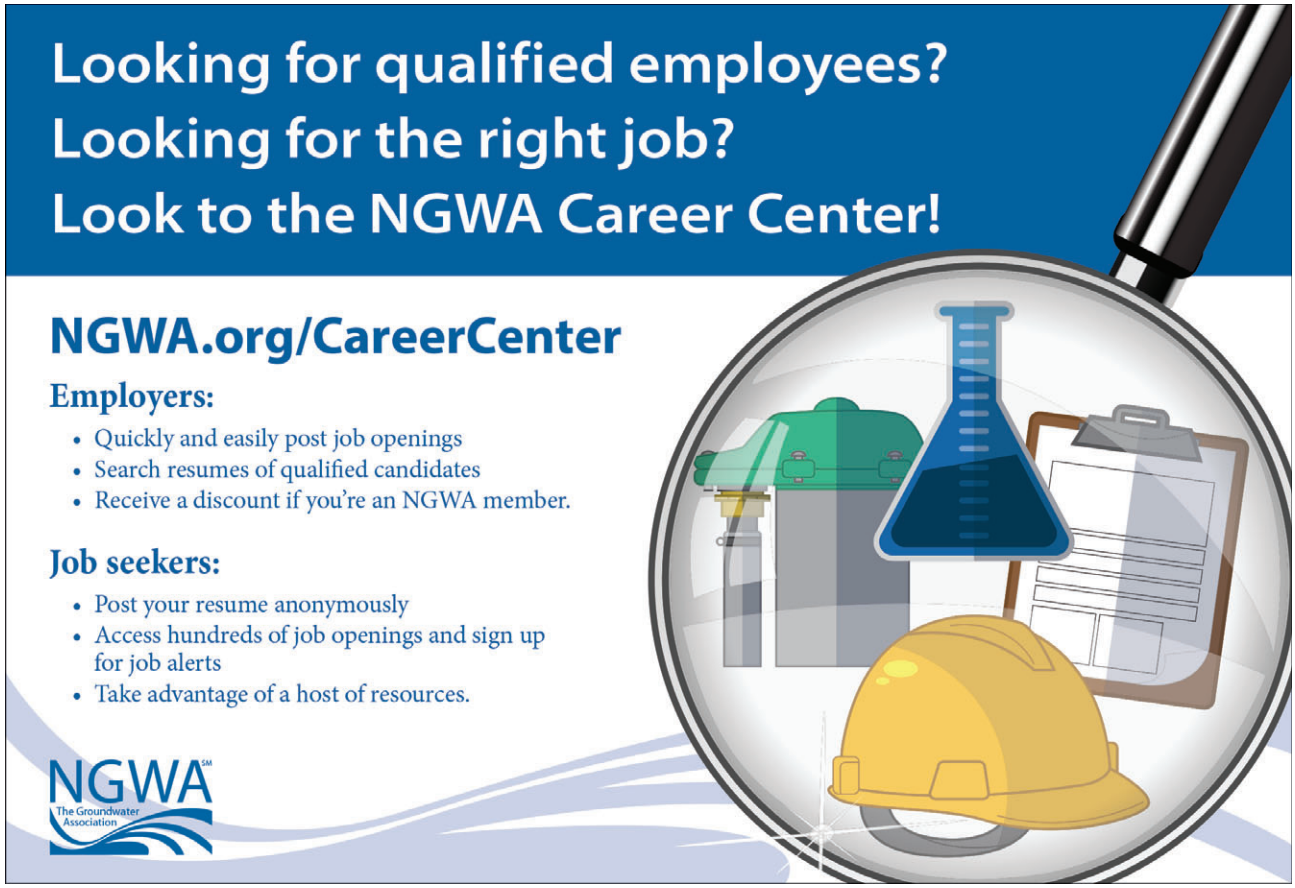

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Document 14

Ramboll, 35 I.A.C. § 845.610(B)(3)(D) Groundwater Monitoring Data and Detected Exceedances; Quarter 2 2023; Primary Ash Pond, Newton Power Plant, Newton Illinois (August 7, 2023).

Luminant

Illinois Power Generating Company
1500 Eastport Plaza Drive
Collinsville, IL 62234

August 7, 2023
Illinois Environmental Protection Agency
DWPC – Permits MC#15
Attn: Part 845 Coal Combustion Residual Rule Submittal
1021 North Grand Avenue East
Springfield, IL 62794

Re: Newton Power Plant Primary Ash Pond; IEPA ID # W0798070001-01

Dear Mr. LeCrone:

In accordance with Title 35 of the Illinois Administrative Code (35 I.A.C.) Section (§) 845.610(b)(3)(D), Illinois Power Generating Company (IPGC) is submitting groundwater monitoring data for the Quarter 2 2023 sampling event at the Newton Power Plant Primary Ash Pond, identified by Illinois Environmental Protection Agency (IEPA) ID No. W0798070001-01. This data is being submitted and placed in the facility's operating record as required by 35 I.A.C. § 845.800(d)(15) within 60 days of receiving final laboratory analytical data. Results were compared with the groundwater protection standards (GWPSs) described in 35 I.A.C. § 845.600 to determine exceedances of the GWPS.

The date of this submittal is considered to be the date that exceedances of the GWPS were detected. This notification of exceedances of the GWPSs in 35 I.A.C. § 845.600 will be placed in the facility's operating record within 30 days as required by 35 I.A.C. § 845.800(d)(16). As allowed in 35 I.A.C. § 845.650(e), an alternate source demonstration (ASD) will be evaluated for the detected exceedances of the GWPS and, if successfully completed, the ASD will be submitted to IEPA within 60 days of this transmittal.

Sincerely,

Phil Morris, PE
Senior Director, Environmental

Enclosures

Groundwater Monitoring Data and Detected Exceedances, Quarter 2 2023, Primary Ash Pond, Newton Power Plant, Newton, Illinois

RAMBOLL

ENVIRONMENT
& HEALTH

35 I.A.C. § 845.610(B)(3)(D)
GROUNDWATER MONITORING DATA AND DETECTED EXCEEDANCES
QUARTER 2 2023
PRIMARY ASH POND, NEWTON POWER PLANT, NEWTON, ILLINOIS

August 7, 2023

Samples were collected between April 25 and April 28, 2023 and analyzed for the parameters listed in Title 35 of the Illinois Administrative Code (35 I.A.C) Section (§) 845.600(a), calcium, and turbidity. Final laboratory analytical data were received on June 8, 2023.

The monitoring well locations are included in **Figure 1**. **Attachment A** summarizes the groundwater elevation data for the Quarter 2 2023 sampling event. **Table 1** is a summary of the field parameters and analytical results. **Attachment B** contains the associated laboratory analytical reports and field data sheets for the Quarter 2 2023 sampling event.

Statistical procedures used to evaluate groundwater results are provided in Appendix A of the Groundwater Monitoring Plan[1] provided in the operating permit application. In accordance with 35 I.A.C. § 845.610(b)(3)(B), the Quarter 2 2023 groundwater monitoring data were evaluated for statistically significant levels (SSLs) over background levels for the constituents listed in 35 I.A.C. § 845.600. **Attachment C** shows the statistically derived values compared to background levels.

In accordance with 35 I.A.C. § 845.610(b)(3)(C), the statistically derived values identified as Statistical Results in **Table 2** were compared with the groundwater protection standards (GWPSs) described in 35 I.A.C. § 845.600 to determine exceedances of the GWPS, as shown in **Table 2**. The date of this submittal is considered to be the date that the exceedances of the GPWS were detected.

As allowed in 35 I.A.C. § 845.650(e), an alternate source demonstration (ASD) will be evaluated for the detected exceedances of the GWPS and, if successfully completed, the ASD will be submitted to Illinois Environmental Protection Agency (IEPA) within 60 days of this transmittal.

TABLES

Table 1 Field Parameters and Analytical Results - Quarter 2, 2023
Table 2 Comparison of Statistical Results to GWPS - Quarter 2, 2023

FIGURES

Figure 1 Monitoring Well Location Map

ATTACHMENTS

Attachment A Groundwater Elevation Data - Quarter 2, 2023
Attachment B Laboratory Reports and Field Data Sheets - Quarter 2, 2023
Attachment C Comparison of Statistical Results to Background - Quarter 2, 2023

[1] Ramboll Americas Engineering Solutions, Inc. (Ramboll), 2021. *Groundwater Monitoring Plan. Primary Ash Pond. Newton Power Plant. Newton, Illinois. October 25, 2021.*

TABLES

TABLE 1.
FIELD PARAMETERS AND ANALYTICAL RESULTS - QUARTER 2, 2023
845 QUARTERLY REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

Well ID	Well Type	Event	Date	Parameter	Result	Unit
APW05	Background	E001	04/27/2023	Antimony, total	0.00043 U	mg/L
APW05	Background	E001	04/27/2023	Arsenic, total	0.0300	mg/L
APW05	Background	E001	04/27/2023	Barium, total	0.250	mg/L
APW05	Background	E001	04/27/2023	Beryllium, total	0.00059 U	mg/L
APW05	Background	E001	04/27/2023	Boron, total	0.0920	mg/L
APW05	Background	E001	04/27/2023	Cadmium, total	0.00074 U	mg/L
APW05	Background	E001	04/27/2023	Calcium, total	49.0	mg/L
APW05	Background	E001	04/27/2023	Chloride, total	46.0	mg/L
APW05	Background	E001	04/27/2023	Chromium, total	0.0037 J	mg/L
APW05	Background	E001	04/27/2023	Cobalt, total	0.00048 J	mg/L
APW05	Background	E001	04/27/2023	Dissolved Oxygen	18.0	mg/L
APW05	Background	E001	04/27/2023	Fluoride, total	0.498	mg/L
APW05	Background	E001	04/27/2023	Lead, total	0.00068 J	mg/L
APW05	Background	E001	04/27/2023	Lithium, total	0.0087 J	mg/L
APW05	Background	E001	04/27/2023	Mercury, total	0.00014 U	mg/L
APW05	Background	E001	04/27/2023	Molybdenum, total	0.00910	mg/L
APW05	Background	E001	04/27/2023	Oxidation Reduction Potential	-124	mV
APW05	Background	E001	04/27/2023	Radium 226 + Radium 228, total	0.841	pCi/L
APW05	Background	E001	04/27/2023	Selenium, total	0.00074 U	mg/L
APW05	Background	E001	04/27/2023	Specific Conductance @ 25C (field)	819	micromhos/cm
APW05	Background	E001	04/27/2023	Sulfate, total	0.97 J	mg/L
APW05	Background	E001	04/27/2023	Temperature	14.5	degrees C
APW05	Background	E001	04/27/2023	Thallium, total	0.00038 U	mg/L
APW05	Background	E001	04/27/2023	Total Dissolved Solids	560	mg/L
APW05	Background	E001	04/27/2023	Turbidity, field	40.1	NTU
APW05	Background	E001	04/27/2023	pH (field)	7.1	SU
APW06	Background	E001	04/26/2023	Antimony, total	0.00043 U	mg/L
APW06	Background	E001	04/26/2023	Arsenic, total	0.00920	mg/L
APW06	Background	E001	04/26/2023	Barium, total	0.240	mg/L
APW06	Background	E001	04/26/2023	Beryllium, total	0.00059 U	mg/L
APW06	Background	E001	04/26/2023	Boron, total	0.0870 J+	mg/L
APW06	Background	E001	04/26/2023	Cadmium, total	0.00074 U	mg/L
APW06	Background	E001	04/26/2023	Calcium, total	58.0	mg/L
APW06	Background	E001	04/26/2023	Chloride, total	26.0	mg/L
APW06	Background	E001	04/26/2023	Chromium, total	0.00790 J+	mg/L
APW06	Background	E001	04/26/2023	Cobalt, total	0.0011 J	mg/L
APW06	Background	E001	04/26/2023	Dissolved Oxygen	11.0	mg/L
APW06	Background	E001	04/26/2023	Fluoride, total	0.489	mg/L
APW06	Background	E001	04/26/2023	Lead, total	0.00170	mg/L
APW06	Background	E001	04/26/2023	Lithium, total	0.012 J	mg/L
APW06	Background	E001	04/26/2023	Mercury, total	0.00019 J	mg/L
APW06	Background	E001	04/26/2023	Molybdenum, total	0.00770	mg/L
APW06	Background	E001	04/26/2023	Oxidation Reduction Potential	-128	mV
APW06	Background	E001	04/26/2023	Radium 226 + Radium 228, total	1.20	pCi/L
APW06	Background	E001	04/26/2023	Selenium, total	0.00074 U	mg/L
APW06	Background	E001	04/26/2023	Specific Conductance @ 25C (field)	796	micromhos/cm

TABLE 1.
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Well ID	Well Type	Event	Date	Parameter	Result	Unit
APW06	Background	E001	04/26/2023	Sulfate, total	7.60	mg/L
APW06	Background	E001	04/26/2023	Temperature	17.6	degrees C
APW06	Background	E001	04/26/2023	Thallium, total	0.00038 U	mg/L
APW06	Background	E001	04/26/2023	Total Dissolved Solids	500 J+	mg/L
APW06	Background	E001	04/26/2023	Turbidity, field	471	NTU
APW06	Background	E001	04/26/2023	pH (field)	7.3	SU
APW02	Compliance	E001	04/27/2023	Antimony, total	0.00043 U	mg/L
APW02	Compliance	E001	04/27/2023	Arsenic, total	0.00140	mg/L
APW02	Compliance	E001	04/27/2023	Barium, total	0.0240	mg/L
APW02	Compliance	E001	04/27/2023	Beryllium, total	0.00059 U	mg/L
APW02	Compliance	E001	04/27/2023	Boron, total	0.120 J+	mg/L
APW02	Compliance	E001	04/27/2023	Cadmium, total	0.00074 U	mg/L
APW02	Compliance	E001	04/27/2023	Calcium, total	460	mg/L
APW02	Compliance	E001	04/27/2023	Chloride, total	110	mg/L
APW02	Compliance	E001	04/27/2023	Chromium, total	0.00400	mg/L
APW02	Compliance	E001	04/27/2023	Cobalt, total	0.0012 J	mg/L
APW02	Compliance	E001	04/27/2023	Dissolved Oxygen	1.20	mg/L
APW02	Compliance	E001	04/27/2023	Fluoride, total	0.172 J	mg/L
APW02	Compliance	E001	04/27/2023	Lead, total	0.00039 J	mg/L
APW02	Compliance	E001	04/27/2023	Lithium, total	0.0980	mg/L
APW02	Compliance	E001	04/27/2023	Mercury, total	0.00018 J	mg/L
APW02	Compliance	E001	04/27/2023	Molybdenum, total	0.00160	mg/L
APW02	Compliance	E001	04/27/2023	Oxidation Reduction Potential	80.8	mV
APW02	Compliance	E001	04/27/2023	Radium 226 + Radium 228, total	0.768	pCi/L
APW02	Compliance	E001	04/27/2023	Selenium, total	0.00074 U	mg/L
APW02	Compliance	E001	04/27/2023	Specific Conductance @ 25C (field)	5,217	micromhos/cm
APW02	Compliance	E001	04/27/2023	Sulfate, total	3,100	mg/L
APW02	Compliance	E001	04/27/2023	Temperature	15.6	degrees C
APW02	Compliance	E001	04/27/2023	Thallium, total	0.00038 U	mg/L
APW02	Compliance	E001	04/27/2023	Total Dissolved Solids	5,400	mg/L
APW02	Compliance	E001	04/27/2023	Turbidity, field	25.0	NTU
APW02	Compliance	E001	04/27/2023	pH (field)	6.7	SU
APW03	Compliance	E001	04/25/2023	Antimony, total	0.00043 U	mg/L
APW03	Compliance	E001	04/25/2023	Arsenic, total	0.00069 U	mg/L
APW03	Compliance	E001	04/25/2023	Barium, total	0.0780	mg/L
APW03	Compliance	E001	04/25/2023	Beryllium, total	0.00059 U	mg/L
APW03	Compliance	E001	04/25/2023	Boron, total	0.370	mg/L
APW03	Compliance	E001	04/25/2023	Cadmium, total	0.00074 U	mg/L
APW03	Compliance	E001	04/25/2023	Calcium, total	96.0	mg/L
APW03	Compliance	E001	04/25/2023	Chloride, total	6.90	mg/L
APW03	Compliance	E001	04/25/2023	Chromium, total	0.00720	mg/L
APW03	Compliance	E001	04/25/2023	Cobalt, total	0.00048 U	mg/L
APW03	Compliance	E001	04/25/2023	Dissolved Oxygen	2.20	mg/L
APW03	Compliance	E001	04/25/2023	Fluoride, total	0.04 U	mg/L
APW03	Compliance	E001	04/25/2023	Lead, total	0.00022 U	mg/L
APW03	Compliance	E001	04/25/2023	Lithium, total	0.01 J	mg/L

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APW03	Compliance	E001	04/25/2023	Mercury, total	0.00014 U	mg/L
APW03	Compliance	E001	04/25/2023	Molybdenum, total	0.0008 J	mg/L
APW03	Compliance	E001	04/25/2023	Oxidation Reduction Potential	141	mV
APW03	Compliance	E001	04/25/2023	Radium 226 + Radium 228, total	1.02	pCi/L
APW03	Compliance	E001	04/25/2023	Selenium, total	0.00074 U	mg/L
APW03	Compliance	E001	04/25/2023	Specific Conductance @ 25C (field)	925	micromhos/cm
APW03	Compliance	E001	04/25/2023	Sulfate, total	120	mg/L
APW03	Compliance	E001	04/25/2023	Temperature	17.0	degrees C
APW03	Compliance	E001	04/25/2023	Thallium, total	0.00038 U	mg/L
APW03	Compliance	E001	04/25/2023	Total Dissolved Solids	740	mg/L
APW03	Compliance	E001	04/25/2023	Turbidity, field	0 U	NTU
APW03	Compliance	E001	04/25/2023	pH (field)	7.0	SU
APW04	Compliance	E001	04/25/2023	Antimony, total	0.00043 U	mg/L
APW04	Compliance	E001	04/25/2023	Arsenic, total	0.00089 J	mg/L
APW04	Compliance	E001	04/25/2023	Barium, total	0.0220	mg/L
APW04	Compliance	E001	04/25/2023	Beryllium, total	0.00059 U	mg/L
APW04	Compliance	E001	04/25/2023	Boron, total	0.0240	mg/L
APW04	Compliance	E001	04/25/2023	Cadmium, total	0.00074 U	mg/L
APW04	Compliance	E001	04/25/2023	Calcium, total	210	mg/L
APW04	Compliance	E001	04/25/2023	Chloride, total	34.0	mg/L
APW04	Compliance	E001	04/25/2023	Chromium, total	0.0440	mg/L
APW04	Compliance	E001	04/25/2023	Cobalt, total	0.00081 J	mg/L
APW04	Compliance	E001	04/25/2023	Dissolved Oxygen	0.930	mg/L
APW04	Compliance	E001	04/25/2023	Fluoride, total	0.051 J	mg/L
APW04	Compliance	E001	04/25/2023	Lead, total	0.00063 J	mg/L
APW04	Compliance	E001	04/25/2023	Lithium, total	0.018 J	mg/L
APW04	Compliance	E001	04/25/2023	Mercury, total	0.00014 U	mg/L
APW04	Compliance	E001	04/25/2023	Molybdenum, total	0.00180	mg/L
APW04	Compliance	E001	04/25/2023	Oxidation Reduction Potential	171	mV
APW04	Compliance	E001	04/25/2023	Radium 226 + Radium 228, total	1.00	pCi/L
APW04	Compliance	E001	04/25/2023	Selenium, total	0.00074 U	mg/L
APW04	Compliance	E001	04/25/2023	Specific Conductance @ 25C (field)	1,830	micromhos/cm
APW04	Compliance	E001	04/25/2023	Sulfate, total	840	mg/L
APW04	Compliance	E001	04/25/2023	Temperature	11.8	degrees C
APW04	Compliance	E001	04/25/2023	Thallium, total	0.00038 U	mg/L
APW04	Compliance	E001	04/25/2023	Total Dissolved Solids	1,800	mg/L
APW04	Compliance	E001	04/25/2023	Turbidity, field	178	NTU
APW04	Compliance	E001	04/25/2023	pH (field)	6.9	SU
APW05S	Compliance	E001	04/26/2023	Antimony, total	0.00043 U	mg/L
APW05S	Compliance	E001	04/26/2023	Arsenic, total	0.00093 J	mg/L
APW05S	Compliance	E001	04/26/2023	Barium, total	0.0350	mg/L
APW05S	Compliance	E001	04/26/2023	Beryllium, total	0.00059 U	mg/L
APW05S	Compliance	E001	04/26/2023	Boron, total	0.0540 J+	mg/L
APW05S	Compliance	E001	04/26/2023	Cadmium, total	0.00074 U	mg/L
APW05S	Compliance	E001	04/26/2023	Calcium, total	390	mg/L
APW05S	Compliance	E001	04/26/2023	Chloride, total	200	mg/L

TABLE 1.
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Well ID	Well Type	Event	Date	Parameter	Result	Unit
APW05S	Compliance	E001	04/26/2023	Chromium, total	0.0031 J+	mg/L
APW05S	Compliance	E001	04/26/2023	Cobalt, total	0.00083 J	mg/L
APW05S	Compliance	E001	04/26/2023	Dissolved Oxygen	3.50	mg/L
APW05S	Compliance	E001	04/26/2023	Fluoride, total	0.365	mg/L
APW05S	Compliance	E001	04/26/2023	Lead, total	0.00022 J	mg/L
APW05S	Compliance	E001	04/26/2023	Lithium, total	0.0330	mg/L
APW05S	Compliance	E001	04/26/2023	Mercury, total	0.00014 U	mg/L
APW05S	Compliance	E001	04/26/2023	Molybdenum, total	0.00130	mg/L
APW05S	Compliance	E001	04/26/2023	Oxidation Reduction Potential	97.0	mV
APW05S	Compliance	E001	04/26/2023	Radium 226 + Radium 228, total	0.141	pCi/L
APW05S	Compliance	E001	04/26/2023	Selenium, total	0.00074 U	mg/L
APW05S	Compliance	E001	04/26/2023	Specific Conductance @ 25C (field)	3,930	micromhos/cm
APW05S	Compliance	E001	04/26/2023	Sulfate, total	2,100	mg/L
APW05S	Compliance	E001	04/26/2023	Temperature	16.4	degrees C
APW05S	Compliance	E001	04/26/2023	Thallium, total	0.00038 U	mg/L
APW05S	Compliance	E001	04/26/2023	Total Dissolved Solids	3,800 J+	mg/L
APW05S	Compliance	E001	04/26/2023	Turbidity, field	220	NTU
APW05S	Compliance	E001	04/26/2023	pH (field)	6.6	SU
APW07	Compliance	E001	04/27/2023	Antimony, total	0.00043 U	mg/L
APW07	Compliance	E001	04/27/2023	Arsenic, total	0.0180	mg/L
APW07	Compliance	E001	04/27/2023	Barium, total	0.510	mg/L
APW07	Compliance	E001	04/27/2023	Beryllium, total	0.00059 U	mg/L
APW07	Compliance	E001	04/27/2023	Boron, total	0.0850 J+	mg/L
APW07	Compliance	E001	04/27/2023	Cadmium, total	0.00074 U	mg/L
APW07	Compliance	E001	04/27/2023	Calcium, total	100	mg/L
APW07	Compliance	E001	04/27/2023	Chloride, total	63.0	mg/L
APW07	Compliance	E001	04/27/2023	Chromium, total	0.0170	mg/L
APW07	Compliance	E001	04/27/2023	Cobalt, total	0.00360	mg/L
APW07	Compliance	E001	04/27/2023	Dissolved Oxygen	0.510	mg/L
APW07	Compliance	E001	04/27/2023	Fluoride, total	0.409	mg/L
APW07	Compliance	E001	04/27/2023	Lead, total	0.00550	mg/L
APW07	Compliance	E001	04/27/2023	Lithium, total	0.0058 J	mg/L
APW07	Compliance	E001	04/27/2023	Mercury, total	0.00014 U	mg/L
APW07	Compliance	E001	04/27/2023	Molybdenum, total	0.00340	mg/L
APW07	Compliance	E001	04/27/2023	Oxidation Reduction Potential	-116	mV
APW07	Compliance	E001	04/27/2023	Radium 226 + Radium 228, total	2.09	pCi/L
APW07	Compliance	E001	04/27/2023	Selenium, total	0.00074 U	mg/L
APW07	Compliance	E001	04/27/2023	Specific Conductance @ 25C (field)	1,051	micromhos/cm
APW07	Compliance	E001	04/27/2023	Sulfate, total	14.0	mg/L
APW07	Compliance	E001	04/27/2023	Temperature	14.5	degrees C
APW07	Compliance	E001	04/27/2023	Thallium, total	0.00038 U	mg/L
APW07	Compliance	E001	04/27/2023	Total Dissolved Solids	590	mg/L
APW07	Compliance	E001	04/27/2023	Turbidity, field	621	NTU
APW07	Compliance	E001	04/27/2023	pH (field)	7.4	SU
APW08	Compliance	E001	04/26/2023	Antimony, total	0.00043 U	mg/L
APW08	Compliance	E001	04/26/2023	Arsenic, total	0.0260	mg/L

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Well ID	Well Type	Event	Date	Parameter	Result	Unit
APW08	Compliance	E001	04/26/2023	Barium, total	0.470	mg/L
APW08	Compliance	E001	04/26/2023	Beryllium, total	0.00059 U	mg/L
APW08	Compliance	E001	04/26/2023	Boron, total	0.0870 J+	mg/L
APW08	Compliance	E001	04/26/2023	Cadmium, total	0.00074 U	mg/L
APW08	Compliance	E001	04/26/2023	Calcium, total	110	mg/L
APW08	Compliance	E001	04/26/2023	Chloride, total	58.0	mg/L
APW08	Compliance	E001	04/26/2023	Chromium, total	0.00760 J+	mg/L
APW08	Compliance	E001	04/26/2023	Cobalt, total	0.00220	mg/L
APW08	Compliance	E001	04/26/2023	Dissolved Oxygen	1.70	mg/L
APW08	Compliance	E001	04/26/2023	Fluoride, total	0.404	mg/L
APW08	Compliance	E001	04/26/2023	Lead, total	0.00330	mg/L
APW08	Compliance	E001	04/26/2023	Lithium, total	0.0057 J	mg/L
APW08	Compliance	E001	04/26/2023	Mercury, total	0.00015 J	mg/L
APW08	Compliance	E001	04/26/2023	Molybdenum, total	0.00440	mg/L
APW08	Compliance	E001	04/26/2023	Oxidation Reduction Potential	-118	mV
APW08	Compliance	E001	04/26/2023	Radium 226 + Radium 228, total	0.941	pCi/L
APW08	Compliance	E001	04/26/2023	Selenium, total	0.00074 U	mg/L
APW08	Compliance	E001	04/26/2023	Specific Conductance @ 25C (field)	1,100	micromhos/cm
APW08	Compliance	E001	04/26/2023	Sulfate, total	48.0	mg/L
APW08	Compliance	E001	04/26/2023	Temperature	14.2	degrees C
APW08	Compliance	E001	04/26/2023	Thallium, total	0.00038 U	mg/L
APW08	Compliance	E001	04/26/2023	Total Dissolved Solids	640 J+	mg/L
APW08	Compliance	E001	04/26/2023	Turbidity, field	17.7	NTU
APW08	Compliance	E001	04/26/2023	pH (field)	7.5	SU
APW09	Compliance	E001	04/27/2023	Antimony, total	0.00043 U	mg/L
APW09	Compliance	E001	04/27/2023	Arsenic, total	0.0290	mg/L
APW09	Compliance	E001	04/27/2023	Barium, total	0.430	mg/L
APW09	Compliance	E001	04/27/2023	Beryllium, total	0.00059 U	mg/L
APW09	Compliance	E001	04/27/2023	Boron, total	0.0990 J+	mg/L
APW09	Compliance	E001	04/27/2023	Cadmium, total	0.00074 U	mg/L
APW09	Compliance	E001	04/27/2023	Calcium, total	76.0	mg/L
APW09	Compliance	E001	04/27/2023	Chloride, total	130	mg/L
APW09	Compliance	E001	04/27/2023	Chromium, total	0.00420	mg/L
APW09	Compliance	E001	04/27/2023	Cobalt, total	0.00068 J	mg/L
APW09	Compliance	E001	04/27/2023	Dissolved Oxygen	0.470	mg/L
APW09	Compliance	E001	04/27/2023	Fluoride, total	0.482	mg/L
APW09	Compliance	E001	04/27/2023	Lead, total	0.00130	mg/L
APW09	Compliance	E001	04/27/2023	Lithium, total	0.0072 J	mg/L
APW09	Compliance	E001	04/27/2023	Mercury, total	0.00014 U	mg/L
APW09	Compliance	E001	04/27/2023	Molybdenum, total	0.00390	mg/L
APW09	Compliance	E001	04/27/2023	Oxidation Reduction Potential	-137	mV
APW09	Compliance	E001	04/27/2023	Radium 226 + Radium 228, total	2.00	pCi/L
APW09	Compliance	E001	04/27/2023	Selenium, total	0.00074 U	mg/L
APW09	Compliance	E001	04/27/2023	Specific Conductance @ 25C (field)	1,356	micromhos/cm
APW09	Compliance	E001	04/27/2023	Sulfate, total	9.40	mg/L
APW09	Compliance	E001	04/27/2023	Temperature	16.5	degrees C

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APW09	Compliance	E001	04/27/2023	Thallium, total	0.00038 U	mg/L
APW09	Compliance	E001	04/27/2023	Total Dissolved Solids	840	mg/L
APW09	Compliance	E001	04/27/2023	Turbidity, field	117	NTU
APW09	Compliance	E001	04/27/2023	pH (field)	7.5	SU
APW10	Compliance	E001	04/27/2023	Antimony, total	0.00043 U	mg/L
APW10	Compliance	E001	04/27/2023	Arsenic, total	0.00780	mg/L
APW10	Compliance	E001	04/27/2023	Barium, total	0.0260	mg/L
APW10	Compliance	E001	04/27/2023	Beryllium, total	0.00059 U	mg/L
APW10	Compliance	E001	04/27/2023	Boron, total	0.0770 J+	mg/L
APW10	Compliance	E001	04/27/2023	Cadmium, total	0.00074 U	mg/L
APW10	Compliance	E001	04/27/2023	Calcium, total	140	mg/L
APW10	Compliance	E001	04/27/2023	Chloride, total	46.0	mg/L
APW10	Compliance	E001	04/27/2023	Chromium, total	0.0028 U	mg/L
APW10	Compliance	E001	04/27/2023	Cobalt, total	0.00048 U	mg/L
APW10	Compliance	E001	04/27/2023	Dissolved Oxygen	3.40	mg/L
APW10	Compliance	E001	04/27/2023	Fluoride, total	0.217 J	mg/L
APW10	Compliance	E001	04/27/2023	Lead, total	0.00022 U	mg/L
APW10	Compliance	E001	04/27/2023	Lithium, total	0.018 J	mg/L
APW10	Compliance	E001	04/27/2023	Mercury, total	0.00014 U	mg/L
APW10	Compliance	E001	04/27/2023	Molybdenum, total	0.00650	mg/L
APW10	Compliance	E001	04/27/2023	Oxidation Reduction Potential	77.5	mV
APW10	Compliance	E001	04/27/2023	Radium 226 + Radium 228, total	0.316	pCi/L
APW10	Compliance	E001	04/27/2023	Selenium, total	0.00074 U	mg/L
APW10	Compliance	E001	04/27/2023	Specific Conductance @ 25C (field)	1,461	micromhos/cm
APW10	Compliance	E001	04/27/2023	Sulfate, total	410	mg/L
APW10	Compliance	E001	04/27/2023	Temperature	15.1	degrees C
APW10	Compliance	E001	04/27/2023	Thallium, total	0.00038 U	mg/L
APW10	Compliance	E001	04/27/2023	Total Dissolved Solids	1,100	mg/L
APW10	Compliance	E001	04/27/2023	Turbidity, field	0 U	NTU
APW10	Compliance	E001	04/27/2023	pH (field)	7.4	SU
APW11	Compliance	E001	04/26/2023	Antimony, total	0.00043 U	mg/L
APW11	Compliance	E001	04/26/2023	Arsenic, total	0.00440	mg/L
APW11	Compliance	E001	04/26/2023	Barium, total	0.0430	mg/L
APW11	Compliance	E001	04/26/2023	Beryllium, total	0.00059 U	mg/L
APW11	Compliance	E001	04/26/2023	Boron, total	0.0640 J+	mg/L
APW11	Compliance	E001	04/26/2023	Cadmium, total	0.00074 U	mg/L
APW11	Compliance	E001	04/26/2023	Calcium, total	120	mg/L
APW11	Compliance	E001	04/26/2023	Chloride, total	26.0	mg/L
APW11	Compliance	E001	04/26/2023	Chromium, total	0.00700 J+	mg/L
APW11	Compliance	E001	04/26/2023	Cobalt, total	0.00210	mg/L
APW11	Compliance	E001	04/26/2023	Dissolved Oxygen	0.640	mg/L
APW11	Compliance	E001	04/26/2023	Fluoride, total	0.283	mg/L
APW11	Compliance	E001	04/26/2023	Lead, total	0.00630	mg/L
APW11	Compliance	E001	04/26/2023	Lithium, total	0.0200	mg/L
APW11	Compliance	E001	04/26/2023	Mercury, total	0.00014 J	mg/L
APW11	Compliance	E001	04/26/2023	Molybdenum, total	0.00430	mg/L

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Well ID	Well Type	Event	Date	Parameter	Result	Unit
APW11	Compliance	E001	04/26/2023	Oxidation Reduction Potential	-17.8	mV
APW11	Compliance	E001	04/26/2023	Radium 226 + Radium 228, total	2.17 J	pCi/L
APW11	Compliance	E001	04/26/2023	Selenium, total	0.00074 U	mg/L
APW11	Compliance	E001	04/26/2023	Specific Conductance @ 25C (field)	1,252	micromhos/cm
APW11	Compliance	E001	04/26/2023	Sulfate, total	260	mg/L
APW11	Compliance	E001	04/26/2023	Temperature	15.5	degrees C
APW11	Compliance	E001	04/26/2023	Thallium, total	0.00038 U	mg/L
APW11	Compliance	E001	04/26/2023	Total Dissolved Solids	920 J+	mg/L
APW11	Compliance	E001	04/26/2023	Turbidity, field	446	NTU
APW11	Compliance	E001	04/26/2023	pH (field)	7.2	SU
APW12	Compliance	E001	04/26/2023	Antimony, total	0.00043 U	mg/L
APW12	Compliance	E001	04/26/2023	Arsenic, total	0.00140	mg/L
APW12	Compliance	E001	04/26/2023	Barium, total	0.0280	mg/L
APW12	Compliance	E001	04/26/2023	Beryllium, total	0.00059 U	mg/L
APW12	Compliance	E001	04/26/2023	Boron, total	0.440	mg/L
APW12	Compliance	E001	04/26/2023	Cadmium, total	0.00074 U	mg/L
APW12	Compliance	E001	04/26/2023	Calcium, total	230	mg/L
APW12	Compliance	E001	04/26/2023	Chloride, total	23.0	mg/L
APW12	Compliance	E001	04/26/2023	Chromium, total	0.003 U	mg/L
APW12	Compliance	E001	04/26/2023	Cobalt, total	0.0012 J	mg/L
APW12	Compliance	E001	04/26/2023	Dissolved Oxygen	0.980	mg/L
APW12	Compliance	E001	04/26/2023	Fluoride, total	0.04 U	mg/L
APW12	Compliance	E001	04/26/2023	Lead, total	0.00022 U	mg/L
APW12	Compliance	E001	04/26/2023	Lithium, total	0.0240	mg/L
APW12	Compliance	E001	04/26/2023	Mercury, total	0.00014 U	mg/L
APW12	Compliance	E001	04/26/2023	Molybdenum, total	0.00074 U	mg/L
APW12	Compliance	E001	04/26/2023	Oxidation Reduction Potential	107	mV
APW12	Compliance	E001	04/26/2023	Radium 226 + Radium 228, total	0.0586	pCi/L
APW12	Compliance	E001	04/26/2023	Selenium, total	0.00074 U	mg/L
APW12	Compliance	E001	04/26/2023	Specific Conductance @ 25C (field)	1,831	micromhos/cm
APW12	Compliance	E001	04/26/2023	Sulfate, total	540	mg/L
APW12	Compliance	E001	04/26/2023	Temperature	14.6	degrees C
APW12	Compliance	E001	04/26/2023	Thallium, total	0.00038 U	mg/L
APW12	Compliance	E001	04/26/2023	Total Dissolved Solids	1,500 J+	mg/L
APW12	Compliance	E001	04/26/2023	Turbidity, field	0.520	NTU
APW12	Compliance	E001	04/26/2023	pH (field)	6.5	SU
APW13	Compliance	E001	04/27/2023	Antimony, total	0.00043 U	mg/L
APW13	Compliance	E001	04/27/2023	Arsenic, total	0.00400	mg/L
APW13	Compliance	E001	04/27/2023	Barium, total	0.0500	mg/L
APW13	Compliance	E001	04/27/2023	Beryllium, total	0.00059 U	mg/L
APW13	Compliance	E001	04/27/2023	Boron, total	0.110 J+	mg/L
APW13	Compliance	E001	04/27/2023	Cadmium, total	0.00074 U	mg/L
APW13	Compliance	E001	04/27/2023	Calcium, total	120	mg/L
APW13	Compliance	E001	04/27/2023	Chloride, total	51.0	mg/L
APW13	Compliance	E001	04/27/2023	Chromium, total	0.0028 U	mg/L
APW13	Compliance	E001	04/27/2023	Cobalt, total	0.00048 U	mg/L

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APW13	Compliance	E001	04/27/2023	Dissolved Oxygen	1.60	mg/L
APW13	Compliance	E001	04/27/2023	Fluoride, total	0.394	mg/L
APW13	Compliance	E001	04/27/2023	Lead, total	0.00022 U	mg/L
APW13	Compliance	E001	04/27/2023	Lithium, total	0.0210	mg/L
APW13	Compliance	E001	04/27/2023	Mercury, total	0.00014 U	mg/L
APW13	Compliance	E001	04/27/2023	Molybdenum, total	0.00670	mg/L
APW13	Compliance	E001	04/27/2023	Oxidation Reduction Potential	-25.3	mV
APW13	Compliance	E001	04/27/2023	Radium 226 + Radium 228, total	0.651	pCi/L
APW13	Compliance	E001	04/27/2023	Selenium, total	0.00074 U	mg/L
APW13	Compliance	E001	04/27/2023	Specific Conductance @ 25C (field)	1,360	micromhos/cm
APW13	Compliance	E001	04/27/2023	Sulfate, total	250	mg/L
APW13	Compliance	E001	04/27/2023	Temperature	14.3	degrees C
APW13	Compliance	E001	04/27/2023	Thallium, total	0.00038 U	mg/L
APW13	Compliance	E001	04/27/2023	Total Dissolved Solids	940	mg/L
APW13	Compliance	E001	04/27/2023	Turbidity, field	0 U	NTU
APW13	Compliance	E001	04/27/2023	pH (field)	7.3	SU
APW14	Compliance	E001	04/28/2023	Antimony, total	0.00043 U	mg/L
APW14	Compliance	E001	04/28/2023	Arsenic, total	0.00550	mg/L
APW14	Compliance	E001	04/28/2023	Barium, total	0.0650	mg/L
APW14	Compliance	E001	04/28/2023	Beryllium, total	0.00059 U	mg/L
APW14	Compliance	E001	04/28/2023	Boron, total	0.100 J+	mg/L
APW14	Compliance	E001	04/28/2023	Cadmium, total	0.00074 U	mg/L
APW14	Compliance	E001	04/28/2023	Calcium, total	130	mg/L
APW14	Compliance	E001	04/28/2023	Chloride, total	46.0	mg/L
APW14	Compliance	E001	04/28/2023	Chromium, total	0.0028 U	mg/L
APW14	Compliance	E001	04/28/2023	Cobalt, total	0.00048 U	mg/L
APW14	Compliance	E001	04/28/2023	Dissolved Oxygen	1.20	mg/L
APW14	Compliance	E001	04/28/2023	Fluoride, total	0.243 J	mg/L
APW14	Compliance	E001	04/28/2023	Lead, total	0.00022 U	mg/L
APW14	Compliance	E001	04/28/2023	Lithium, total	0.016 J	mg/L
APW14	Compliance	E001	04/28/2023	Mercury, total	0.00014 U	mg/L
APW14	Compliance	E001	04/28/2023	Molybdenum, total	0.00400	mg/L
APW14	Compliance	E001	04/28/2023	Oxidation Reduction Potential	-95.0	mV
APW14	Compliance	E001	04/28/2023	Radium 226 + Radium 228, total	0.381 J	pCi/L
APW14	Compliance	E001	04/28/2023	Selenium, total	0.00074 U	mg/L
APW14	Compliance	E001	04/28/2023	Specific Conductance @ 25C (field)	1,480	micromhos/cm
APW14	Compliance	E001	04/28/2023	Sulfate, total	380	mg/L
APW14	Compliance	E001	04/28/2023	Temperature	14.8	degrees C
APW14	Compliance	E001	04/28/2023	Thallium, total	0.00038 U	mg/L
APW14	Compliance	E001	04/28/2023	Total Dissolved Solids	980	mg/L
APW14	Compliance	E001	04/28/2023	Turbidity, field	8.81	NTU
APW14	Compliance	E001	04/28/2023	pH (field)	7.3	SU
APW15	Compliance	E001	04/26/2023	Antimony, total	0.00043 U	mg/L
APW15	Compliance	E001	04/26/2023	Arsenic, total	0.0210	mg/L
APW15	Compliance	E001	04/26/2023	Barium, total	0.530	mg/L
APW15	Compliance	E001	04/26/2023	Beryllium, total	0.00059 U	mg/L

TABLE 1.
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Well ID	Well Type	Event	Date	Parameter	Result	Unit
APW15	Compliance	E001	04/26/2023	Boron, total	0.130	mg/L
APW15	Compliance	E001	04/26/2023	Cadmium, total	0.00074 U	mg/L
APW15	Compliance	E001	04/26/2023	Calcium, total	91.0	mg/L
APW15	Compliance	E001	04/26/2023	Chloride, total	270	mg/L
APW15	Compliance	E001	04/26/2023	Chromium, total	0.00640 J+	mg/L
APW15	Compliance	E001	04/26/2023	Cobalt, total	0.0011 J	mg/L
APW15	Compliance	E001	04/26/2023	Dissolved Oxygen	0.320	mg/L
APW15	Compliance	E001	04/26/2023	Fluoride, total	0.402	mg/L
APW15	Compliance	E001	04/26/2023	Lead, total	0.00120	mg/L
APW15	Compliance	E001	04/26/2023	Lithium, total	0.0064 J	mg/L
APW15	Compliance	E001	04/26/2023	Mercury, total	0.00014 U	mg/L
APW15	Compliance	E001	04/26/2023	Molybdenum, total	0.00650	mg/L
APW15	Compliance	E001	04/26/2023	Oxidation Reduction Potential	-126	mV
APW15	Compliance	E001	04/26/2023	Radium 226 + Radium 228, total	1.97	pCi/L
APW15	Compliance	E001	04/26/2023	Selenium, total	0.00074 U	mg/L
APW15	Compliance	E001	04/26/2023	Specific Conductance @ 25C (field)	1,682	micromhos/cm
APW15	Compliance	E001	04/26/2023	Sulfate, total	0.4 J	mg/L
APW15	Compliance	E001	04/26/2023	Temperature	15.3	degrees C
APW15	Compliance	E001	04/26/2023	Thallium, total	0.00038 U	mg/L
APW15	Compliance	E001	04/26/2023	Total Dissolved Solids	1,100 J+	mg/L
APW15	Compliance	E001	04/26/2023	Turbidity, field	51.6	NTU
APW15	Compliance	E001	04/26/2023	pH (field)	7.2	SU
APW16	Compliance	E001	04/25/2023	Antimony, total	0.00043 U	mg/L
APW16	Compliance	E001	04/25/2023	Arsenic, total	0.0210	mg/L
APW16	Compliance	E001	04/25/2023	Barium, total	0.540	mg/L
APW16	Compliance	E001	04/25/2023	Beryllium, total	0.00059 U	mg/L
APW16	Compliance	E001	04/25/2023	Boron, total	0.130	mg/L
APW16	Compliance	E001	04/25/2023	Cadmium, total	0.00074 U	mg/L
APW16	Compliance	E001	04/25/2023	Calcium, total	96.0	mg/L
APW16	Compliance	E001	04/25/2023	Chloride, total	71.0	mg/L
APW16	Compliance	E001	04/25/2023	Chromium, total	0.0028 U	mg/L
APW16	Compliance	E001	04/25/2023	Cobalt, total	0.00048 U	mg/L
APW16	Compliance	E001	04/25/2023	Dissolved Oxygen	1.20	mg/L
APW16	Compliance	E001	04/25/2023	Fluoride, total	0.606	mg/L
APW16	Compliance	E001	04/25/2023	Lead, total	0.00036 J	mg/L
APW16	Compliance	E001	04/25/2023	Lithium, total	0.005 U	mg/L
APW16	Compliance	E001	04/25/2023	Mercury, total	0.00014 U	mg/L
APW16	Compliance	E001	04/25/2023	Molybdenum, total	0.00074 U	mg/L
APW16	Compliance	E001	04/25/2023	Oxidation Reduction Potential	-104	mV
APW16	Compliance	E001	04/25/2023	Radium 226 + Radium 228, total	2.05	pCi/L
APW16	Compliance	E001	04/25/2023	Selenium, total	0.00074 U	mg/L
APW16	Compliance	E001	04/25/2023	Specific Conductance @ 25C (field)	953	micromhos/cm
APW16	Compliance	E001	04/25/2023	Sulfate, total	0.65 J	mg/L
APW16	Compliance	E001	04/25/2023	Temperature	14.0	degrees C
APW16	Compliance	E001	04/25/2023	Thallium, total	0.00038 U	mg/L
APW16	Compliance	E001	04/25/2023	Total Dissolved Solids	800	mg/L

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Well ID	Well Type	Event	Date	Parameter	Result	Unit
APW16	Compliance	E001	04/25/2023	Turbidity, field	0.210	NTU
APW16	Compliance	E001	04/25/2023	pH (field)	7.7	SU
APW17	Compliance	E001	04/25/2023	Antimony, total	0.00043 U	mg/L
APW17	Compliance	E001	04/25/2023	Arsenic, total	0.0200	mg/L
APW17	Compliance	E001	04/25/2023	Barium, total	0.550	mg/L
APW17	Compliance	E001	04/25/2023	Beryllium, total	0.00059 U	mg/L
APW17	Compliance	E001	04/25/2023	Boron, total	0.0830	mg/L
APW17	Compliance	E001	04/25/2023	Cadmium, total	0.00074 U	mg/L
APW17	Compliance	E001	04/25/2023	Calcium, total	110	mg/L
APW17	Compliance	E001	04/25/2023	Chloride, total	56.0	mg/L
APW17	Compliance	E001	04/25/2023	Chromium, total	0.0028 U	mg/L
APW17	Compliance	E001	04/25/2023	Cobalt, total	0.00048 U	mg/L
APW17	Compliance	E001	04/25/2023	Dissolved Oxygen	1.20	mg/L
APW17	Compliance	E001	04/25/2023	Fluoride, total	0.483	mg/L
APW17	Compliance	E001	04/25/2023	Lead, total	0.00022 U	mg/L
APW17	Compliance	E001	04/25/2023	Lithium, total	0.005 U	mg/L
APW17	Compliance	E001	04/25/2023	Mercury, total	0.00014 U	mg/L
APW17	Compliance	E001	04/25/2023	Molybdenum, total	0.00530	mg/L
APW17	Compliance	E001	04/25/2023	Oxidation Reduction Potential	-97.2	mV
APW17	Compliance	E001	04/25/2023	Radium 226 + Radium 228, total	1.42	pCi/L
APW17	Compliance	E001	04/25/2023	Selenium, total	0.00074 U	mg/L
APW17	Compliance	E001	04/25/2023	Specific Conductance @ 25C (field)	1,162	micromhos/cm
APW17	Compliance	E001	04/25/2023	Sulfate, total	52.0	mg/L
APW17	Compliance	E001	04/25/2023	Temperature	15.2	degrees C
APW17	Compliance	E001	04/25/2023	Thallium, total	0.00038 U	mg/L
APW17	Compliance	E001	04/25/2023	Total Dissolved Solids	700	mg/L
APW17	Compliance	E001	04/25/2023	Turbidity, field	3.82	NTU
APW17	Compliance	E001	04/25/2023	pH (field)	7.6	SU
APW18	Compliance	E001	04/25/2023	Antimony, total	0.00043 U	mg/L
APW18	Compliance	E001	04/25/2023	Arsenic, total	0.00270	mg/L
APW18	Compliance	E001	04/25/2023	Barium, total	0.350	mg/L
APW18	Compliance	E001	04/25/2023	Beryllium, total	0.00059 U	mg/L
APW18	Compliance	E001	04/25/2023	Boron, total	0.100	mg/L
APW18	Compliance	E001	04/25/2023	Cadmium, total	0.00074 U	mg/L
APW18	Compliance	E001	04/25/2023	Calcium, total	75.0	mg/L
APW18	Compliance	E001	04/25/2023	Chloride, total	24.0	mg/L
APW18	Compliance	E001	04/25/2023	Chromium, total	0.0028 U	mg/L
APW18	Compliance	E001	04/25/2023	Cobalt, total	0.00048 U	mg/L
APW18	Compliance	E001	04/25/2023	Dissolved Oxygen	1.00	mg/L
APW18	Compliance	E001	04/25/2023	Fluoride, total	0.518	mg/L
APW18	Compliance	E001	04/25/2023	Lead, total	0.00022 U	mg/L
APW18	Compliance	E001	04/25/2023	Lithium, total	0.0052 J	mg/L
APW18	Compliance	E001	04/25/2023	Mercury, total	0.00014 U	mg/L
APW18	Compliance	E001	04/25/2023	Molybdenum, total	0.00290	mg/L
APW18	Compliance	E001	04/25/2023	Oxidation Reduction Potential	-137	mV
APW18	Compliance	E001	04/25/2023	Radium 226 + Radium 228, total	1.33	pCi/L

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Well ID	Well Type	Event	Date	Parameter	Result	Unit
APW18	Compliance	E001	04/25/2023	Selenium, total	0.00074 U	mg/L
APW18	Compliance	E001	04/25/2023	Specific Conductance @ 25C (field)	1,012	micromhos/cm
APW18	Compliance	E001	04/25/2023	Sulfate, total	52.0	mg/L
APW18	Compliance	E001	04/25/2023	Temperature	15.2	degrees C
APW18	Compliance	E001	04/25/2023	Thallium, total	0.00038 U	mg/L
APW18	Compliance	E001	04/25/2023	Total Dissolved Solids	660	mg/L
APW18	Compliance	E001	04/25/2023	Turbidity, field	5.01	NTU
APW18	Compliance	E001	04/25/2023	pH (field)	7.8	SU

Notes:
C = Celsius
cm = centimeter
mg/L = milligrams per liter
mV = millivolts
NTU = Nephelometric Turbidity Units
pCi/L = picocuries per liter
SU = Standard Units
J = The result is an estimated quantity. The associated numerical value is the approximate concentration of the analyte in the sample.
J+ = The result is an estimated quantity, but the result may be biased high.
U = The analyte was analyzed for, but was not detected above the level of the adjusted detection limit or quantitation limit, as appropriate.

TABLE 2.
COMPARISON OF STATISTICAL RESULTS TO GWPS - QUARTER 2, 2023
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Well ID	HSU	Event	Parameter	Units	Date Range	Sample Count	Percent ND	Statistical Calculation	Statistical Result	GWPS	GWPS Source	Exceedance Type
APW02	UD	E001	Antimony, total	mg/L	02/17/21 - 04/27/23	10	100	All ND - Last	0.003	0.006	Standard	No Exceedance
APW02	UD	E001	Arsenic, total	mg/L	02/17/21 - 04/27/23	10	70	CI around median	0.001	0.059	Background	No Exceedance
APW02	UD	E001	Barium, total	mg/L	02/17/21 - 04/27/23	10	0	CB around linear reg	0.00275	2	Standard	No Exceedance
APW02	UD	E001	Beryllium, total	mg/L	02/17/21 - 04/27/23	10	100	All ND - Last	0.001	0.004	Standard	No Exceedance
APW02	UD	E001	Boron, total	mg/L	02/17/21 - 04/27/23	10	0	CI around geomean	0.105	2	Standard	No Exceedance
APW02	UD	E001	Cadmium, total	mg/L	02/17/21 - 04/27/23	10	100	All ND - Last	0.001	0.005	Standard	No Exceedance
APW02	UD	E001	Chloride, total	mg/L	02/17/21 - 04/27/23	10	0	CI around mean	100	200	Standard	No Exceedance
APW02	UD	E001	Chromium, total	mg/L	02/17/21 - 04/27/23	10	90	Most recent sample	0.004	0.1	Standard	No Exceedance
APW02	UD	E001	Cobalt, total	mg/L	02/17/21 - 04/27/23	10	100	All ND - Last	0.002	0.006	Standard	No Exceedance
APW02	UD	E001	Fluoride, total	mg/L	02/17/21 - 04/27/23	10	100	All ND - Last	0.25	4	Standard	No Exceedance
APW02	UD	E001	Lead, total	mg/L	02/17/21 - 04/27/23	10	90	CI around median	0.001	0.0075	Standard	No Exceedance
APW02	UD	E001	Lithium, total	mg/L	02/17/21 - 04/27/23	10	0	CI around geomean	0.0888	0.04	Standard	Determined
APW02	UD	E001	Mercury, total	mg/L	02/17/21 - 04/27/23	10	100	All ND - Last	0.0002	0.002	Standard	No Exceedance
APW02	UD	E001	Molybdenum, total	mg/L	02/17/21 - 04/27/23	9	67	CI around median	0.001	0.1	Standard	No Exceedance
APW02	UD	E001	Radium 226 + Radium 228, total	pCi/L	02/17/21 - 04/27/23	9	0	CI around mean	0.227	6.9	Background	No Exceedance
APW02	UD	E001	Selenium, total	mg/L	02/17/21 - 04/27/23	10	100	All ND - Last	0.001	0.05	Standard	No Exceedance
APW02	UD	E001	Sulfate, total	mg/L	02/17/21 - 04/27/23	10	0	CI around median	2,900	400	Standard	Determined
APW02	UD	E001	Thallium, total	mg/L	02/17/21 - 04/27/23	10	100	All ND - Last	0.001	0.002	Standard	No Exceedance
APW02	UD	E001	Total Dissolved Solids	mg/L	02/17/21 - 04/27/23	16	0	CB around linear reg	5,180	1,200	Standard	Determined
APW02	UD	E001	pH (field)	SU	02/17/21 - 04/27/23	16	0	CI around mean	6.6/6.8	6.4/9	Background/Standard	No Exceedance
APW03	UD	E001	Antimony, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.003	0.006	Standard	No Exceedance
APW03	UD	E001	Arsenic, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.001	0.059	Background	No Exceedance
APW03	UD	E001	Barium, total	mg/L	02/18/21 - 04/25/23	10	0	CI around mean	0.0648	2	Standard	No Exceedance
APW03	UD	E001	Beryllium, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.001	0.004	Standard	No Exceedance
APW03	UD	E001	Boron, total	mg/L	02/18/21 - 04/25/23	10	0	CI around geomean	0.377	2	Standard	No Exceedance
APW03	UD	E001	Cadmium, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.001	0.005	Standard	No Exceedance
APW03	UD	E001	Chloride, total	mg/L	02/18/21 - 04/25/23	10	0	CI around mean	7.35	200	Standard	No Exceedance

TABLE 2.
COMPARISON OF STATISTICAL RESULTS TO GWPS - QUARTER 2, 2023
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NEWTON, IL

Well ID	HSU	Event	Parameter	Units	Date Range	Sample Count	Percent ND	Statistical Calculation	Statistical Result	GWPS	GWPS Source	Exceedance Type
APW03	UD	E001	Chromium, total	mg/L	02/18/21 - 04/25/23	10	90	CI around median	0.004	0.1	Standard	No Exceedance
APW03	UD	E001	Cobalt, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.002	0.006	Standard	No Exceedance
APW03	UD	E001	Fluoride, total	mg/L	02/18/21 - 04/25/23	10	90	CI around median	0.25	4	Standard	No Exceedance
APW03	UD	E001	Lead, total	mg/L	02/18/21 - 04/25/23	10	90	CI around median	0.001	0.0075	Standard	No Exceedance
APW03	UD	E001	Lithium, total	mg/L	02/18/21 - 04/25/23	10	40	CI around median	0.02	0.04	Standard	No Exceedance
APW03	UD	E001	Mercury, total	mg/L	02/18/21 - 04/25/23	10	90	CI around median	0.0002	0.002	Standard	No Exceedance
APW03	UD	E001	Molybdenum, total	mg/L	02/18/21 - 04/25/23	9	11	CI around mean	0.000992	0.1	Standard	No Exceedance
APW03	UD	E001	Radium 226 + Radium 228, total	pCi/L	02/18/21 - 04/25/23	9	0	CI around mean	0.123	6.9	Background	No Exceedance
APW03	UD	E001	Selenium, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.001	0.05	Standard	No Exceedance
APW03	UD	E001	Sulfate, total	mg/L	02/18/21 - 04/25/23	10	0	CI around mean	139	400	Standard	No Exceedance
APW03	UD	E001	Thallium, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.001	0.002	Standard	No Exceedance
APW03	UD	E001	Total Dissolved Solids	mg/L	02/18/21 - 04/25/23	16	0	CI around mean	628	1,200	Standard	No Exceedance
APW03	UD	E001	pH (field)	SU	02/18/21 - 04/25/23	16	0	CI around mean	6.8/7.2	6.4/9	Background/Standard	No Exceedance
APW04	UD	E001	Antimony, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.003	0.006	Standard	No Exceedance
APW04	UD	E001	Arsenic, total	mg/L	02/18/21 - 04/25/23	10	40	CI around geomean	0.000941	0.059	Background	No Exceedance
APW04	UD	E001	Barium, total	mg/L	02/18/21 - 04/25/23	10	0	CI around mean	0.0181	2	Standard	No Exceedance
APW04	UD	E001	Beryllium, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.001	0.004	Standard	No Exceedance
APW04	UD	E001	Boron, total	mg/L	02/18/21 - 04/25/23	10	0	CI around median	0.024	2	Standard	No Exceedance
APW04	UD	E001	Cadmium, total	mg/L	02/18/21 - 04/25/23	10	90	CI around median	0.001	0.005	Standard	No Exceedance
APW04	UD	E001	Chloride, total	mg/L	02/18/21 - 04/25/23	10	0	CI around mean	29.3	200	Standard	No Exceedance
APW04	UD	E001	Chromium, total	mg/L	02/18/21 - 04/25/23	10	90	CI around median	0.004	0.1	Standard	No Exceedance
APW04	UD	E001	Cobalt, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.002	0.006	Standard	No Exceedance
APW04	UD	E001	Fluoride, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.25	4	Standard	No Exceedance
APW04	UD	E001	Lead, total	mg/L	02/18/21 - 04/25/23	10	60	CI around median	0.001	0.0075	Standard	No Exceedance
APW04	UD	E001	Lithium, total	mg/L	02/18/21 - 04/25/23	10	30	CI around median	0.02	0.04	Standard	No Exceedance
APW04	UD	E001	Mercury, total	mg/L	02/18/21 - 04/25/23	10	90	CI around median	0.0002	0.002	Standard	No Exceedance
APW04	UD	E001	Molybdenum, total	mg/L	02/18/21 - 04/25/23	9	89	CI around median	0.001	0.1	Standard	No Exceedance

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Well ID	HSU	Event	Parameter	Units	Date Range	Sample Count	Percent ND	Statistical Calculation	Statistical Result	GWPS	GWPS Source	Exceedance Type
APW04	UD	E001	Radium 226 + Radium 228, total	pCi/L	02/18/21 - 04/25/23	9	0	CI around mean	0.0207	6.9	Background	No Exceedance
APW04	UD	E001	Selenium, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.001	0.05	Standard	No Exceedance
APW04	UD	E001	Sulfate, total	mg/L	02/18/21 - 04/25/23	10	0	CI around mean	844	400	Standard	Determined
APW04	UD	E001	Thallium, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.001	0.002	Standard	No Exceedance
APW04	UD	E001	Total Dissolved Solids	mg/L	02/18/21 - 04/25/23	16	0	CI around mean	1,710	1,200	Standard	Determined
APW04	UD	E001	pH (field)	SU	02/18/21 - 04/25/23	16	0	CB around linear reg	6.9/8.0	6.4/9	Background/Standard	No Exceedance
APW05S	UD	E001	Antimony, total	mg/L	02/17/21 - 04/26/23	9	100	All ND - Last	0.003	0.006	Standard	No Exceedance
APW05S	UD	E001	Arsenic, total	mg/L	02/17/21 - 04/26/23	9	33	CI around mean	0.00105	0.059	Background	No Exceedance
APW05S	UD	E001	Barium, total	mg/L	02/17/21 - 04/26/23	9	0	CI around median	0.048	2	Standard	No Exceedance
APW05S	UD	E001	Beryllium, total	mg/L	02/17/21 - 04/26/23	9	100	All ND - Last	0.001	0.004	Standard	No Exceedance
APW05S	UD	E001	Boron, total	mg/L	02/17/21 - 04/26/23	9	0	CI around median	0.04	2	Standard	No Exceedance
APW05S	UD	E001	Cadmium, total	mg/L	02/17/21 - 04/26/23	9	89	CI around median	0.001	0.005	Standard	No Exceedance
APW05S	UD	E001	Chloride, total	mg/L	02/17/21 - 04/26/23	9	0	CI around median	190	200	Standard	No Exceedance
APW05S	UD	E001	Chromium, total	mg/L	02/17/21 - 04/26/23	9	89	CI around median	0.004	0.1	Standard	No Exceedance
APW05S	UD	E001	Cobalt, total	mg/L	02/17/21 - 04/26/23	9	33	CI around geomean	0.00185	0.006	Standard	No Exceedance
APW05S	UD	E001	Fluoride, total	mg/L	02/17/21 - 04/26/23	9	0	CI around mean	0.349	4	Standard	No Exceedance
APW05S	UD	E001	Lead, total	mg/L	02/17/21 - 04/26/23	9	89	CI around median	0.001	0.0075	Standard	No Exceedance
APW05S	UD	E001	Lithium, total	mg/L	02/17/21 - 04/26/23	9	0	CI around geomean	0.0332	0.04	Standard	No Exceedance
APW05S	UD	E001	Mercury, total	mg/L	02/17/21 - 04/26/23	9	100	All ND - Last	0.0002	0.002	Standard	No Exceedance
APW05S	UD	E001	Molybdenum, total	mg/L	02/17/21 - 04/26/23	8	0	CB around linear reg	-0.000835	0.1	Standard	No Exceedance
APW05S	UD	E001	Radium 226 + Radium 228, total	pCi/L	02/17/21 - 04/26/23	8	0	CI around geomean	0.128	6.9	Background	No Exceedance
APW05S	UD	E001	Selenium, total	mg/L	02/17/21 - 04/26/23	9	100	All ND - Last	0.001	0.05	Standard	No Exceedance
APW05S	UD	E001	Sulfate, total	mg/L	02/17/21 - 04/26/23	9	0	CI around median	640	400	Standard	Determined
APW05S	UD	E001	Thallium, total	mg/L	02/17/21 - 04/26/23	9	100	All ND - Last	0.001	0.002	Standard	No Exceedance
APW05S	UD	E001	Total Dissolved Solids	mg/L	02/17/21 - 04/26/23	9	0	CI around mean	3,450	1,200	Standard	Determined
APW05S	UD	E001	pH (field)	SU	02/17/21 - 04/26/23	9	0	CI around mean	6.7/7.0	6.4/9	Background/Standard	No Exceedance
APW07	UA	E001	Antimony, total	mg/L	12/15/15 - 04/27/23	11	100	All ND - Last	0.003	0.006	Standard	No Exceedance

TABLE 2.
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Well ID	HSU	Event	Parameter	Units	Date Range	Sample Count	Percent ND	Statistical Calculation	Statistical Result	GWPS	GWPS Source	Exceedance Type
APW07	UA	E001	Arsenic, total	mg/L	12/15/15 - 04/27/23	12	0	CB around linear reg	0.0127	0.059	Background	No Exceedance
APW07	UA	E001	Barium, total	mg/L	12/15/15 - 04/27/23	12	0	CB around linear reg	0.465	2	Standard	No Exceedance
APW07	UA	E001	Beryllium, total	mg/L	12/15/15 - 04/27/23	11	100	All ND - Last	0.001	0.004	Standard	No Exceedance
APW07	UA	E001	Boron, total	mg/L	12/15/15 - 04/27/23	22	0	CB around T-S line	0.0841	2	Standard	No Exceedance
APW07	UA	E001	Cadmium, total	mg/L	12/15/15 - 04/27/23	11	100	All ND - Last	0.001	0.005	Standard	No Exceedance
APW07	UA	E001	Chloride, total	mg/L	12/15/15 - 04/27/23	24	0	CB around T-S line	57.5	200	Standard	No Exceedance
APW07	UA	E001	Chromium, total	mg/L	12/15/15 - 04/27/23	12	75	CI around median	0.004	0.1	Standard	No Exceedance
APW07	UA	E001	Cobalt, total	mg/L	12/15/15 - 04/27/23	11	82	CI around median	0.002	0.006	Standard	No Exceedance
APW07	UA	E001	Fluoride, total	mg/L	12/15/15 - 04/27/23	22	4	CI around mean	0.36	4	Standard	No Exceedance
APW07	UA	E001	Lead, total	mg/L	12/15/15 - 04/27/23	12	58	CI around median	0.001	0.0075	Standard	No Exceedance
APW07	UA	E001	Lithium, total	mg/L	12/15/15 - 04/27/23	12	100	All ND - Last	0.02	0.04	Standard	No Exceedance
APW07	UA	E001	Mercury, total	mg/L	12/15/15 - 04/27/23	12	100	All ND - Last	0.0002	0.002	Standard	No Exceedance
APW07	UA	E001	Molybdenum, total	mg/L	12/15/15 - 04/27/23	11	0	CB around linear reg	-0.00442	0.1	Standard	No Exceedance
APW07	UA	E001	Radium 226 + Radium 228, total	pCi/L	12/15/15 - 04/27/23	12	0	CI around mean	1.31	6.9	Background	No Exceedance
APW07	UA	E001	Selenium, total	mg/L	12/15/15 - 04/27/23	12	100	All ND - Last	0.001	0.05	Standard	No Exceedance
APW07	UA	E001	Sulfate, total	mg/L	12/15/15 - 04/27/23	23	17	CB around T-S line	6.15	400	Standard	No Exceedance
APW07	UA	E001	Thallium, total	mg/L	12/15/15 - 04/27/23	11	100	All ND - Last	0.001	0.002	Standard	No Exceedance
APW07	UA	E001	Total Dissolved Solids	mg/L	12/15/15 - 04/27/23	22	0	CI around mean	486	1,200	Standard	No Exceedance
APW07	UA	E001	pH (field)	SU	12/15/15 - 04/27/23	24	0	CI around mean	7.1/7.3	6.4/9	Background/Standard	No Exceedance
APW08	UA	E001	Antimony, total	mg/L	12/15/15 - 04/26/23	11	100	All ND - Last	0.003	0.006	Standard	No Exceedance
APW08	UA	E001	Arsenic, total	mg/L	12/15/15 - 04/26/23	12	0	CB around linear reg	0.0188	0.059	Background	No Exceedance
APW08	UA	E001	Barium, total	mg/L	12/15/15 - 04/26/23	12	0	CB around linear reg	0.444	2	Standard	No Exceedance
APW08	UA	E001	Beryllium, total	mg/L	12/15/15 - 04/26/23	11	100	All ND - Last	0.001	0.004	Standard	No Exceedance
APW08	UA	E001	Boron, total	mg/L	12/15/15 - 04/26/23	22	0	CI around geomean	0.0816	2	Standard	No Exceedance
APW08	UA	E001	Cadmium, total	mg/L	12/15/15 - 04/26/23	11	100	All ND - Last	0.001	0.005	Standard	No Exceedance
APW08	UA	E001	Chloride, total	mg/L	12/15/15 - 04/26/23	24	0	CI around mean	54.7	200	Standard	No Exceedance
APW08	UA	E001	Chromium, total	mg/L	12/15/15 - 04/26/23	12	58	CI around median	0.004	0.1	Standard	No Exceedance

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Well ID	HSU	Event	Parameter	Units	Date Range	Sample Count	Percent ND	Statistical Calculation	Statistical Result	GWPS	GWPS Source	Exceedance Type
APW08	UA	E001	Cobalt, total	mg/L	12/15/15 - 04/26/23	11	73	CI around median	0.002	0.006	Standard	No Exceedance
APW08	UA	E001	Fluoride, total	mg/L	12/15/15 - 04/26/23	22	9	CI around median	0.373	4	Standard	No Exceedance
APW08	UA	E001	Lead, total	mg/L	12/15/15 - 04/26/23	12	50	CI around median	0.001	0.0075	Standard	No Exceedance
APW08	UA	E001	Lithium, total	mg/L	12/15/15 - 04/26/23	12	67	CI around median	0.01	0.04	Standard	No Exceedance
APW08	UA	E001	Mercury, total	mg/L	12/15/15 - 04/26/23	12	100	All ND - Last	0.0002	0.002	Standard	No Exceedance
APW08	UA	E001	Molybdenum, total	mg/L	12/15/15 - 04/26/23	11	0	CI around mean	0.00453	0.1	Standard	No Exceedance
APW08	UA	E001	Radium 226 + Radium 228, total	pCi/L	12/15/15 - 04/26/23	12	0	CI around mean	1.03	6.9	Background	No Exceedance
APW08	UA	E001	Selenium, total	mg/L	12/15/15 - 04/26/23	12	92	CI around median	0.001	0.05	Standard	No Exceedance
APW08	UA	E001	Sulfate, total	mg/L	12/15/15 - 04/26/23	23	0	CB around linear reg	44	400	Standard	No Exceedance
APW08	UA	E001	Thallium, total	mg/L	12/15/15 - 04/26/23	11	100	All ND - Last	0.001	0.002	Standard	No Exceedance
APW08	UA	E001	Total Dissolved Solids	mg/L	12/15/15 - 04/26/23	22	0	CB around linear reg	592	1,200	Standard	No Exceedance
APW08	UA	E001	pH (field)	SU	12/15/15 - 04/26/23	25	0	CI around mean	7.2/7.4	6.4/9	Background/Standard	No Exceedance
APW09	UA	E001	Antimony, total	mg/L	12/15/15 - 04/27/23	11	100	All ND - Last	0.003	0.006	Standard	No Exceedance
APW09	UA	E001	Arsenic, total	mg/L	12/15/15 - 04/27/23	12	0	CB around linear reg	0.0223	0.059	Background	No Exceedance
APW09	UA	E001	Barium, total	mg/L	12/15/15 - 04/27/23	12	0	CI around mean	0.277	2	Standard	No Exceedance
APW09	UA	E001	Beryllium, total	mg/L	12/15/15 - 04/27/23	11	100	All ND - Last	0.001	0.004	Standard	No Exceedance
APW09	UA	E001	Boron, total	mg/L	12/15/15 - 04/27/23	22	0	CB around T-S line	0.0809	2	Standard	No Exceedance
APW09	UA	E001	Cadmium, total	mg/L	12/15/15 - 04/27/23	11	100	All ND - Last	0.001	0.005	Standard	No Exceedance
APW09	UA	E001	Chloride, total	mg/L	12/15/15 - 04/27/23	24	0	CI around median	95	200	Standard	No Exceedance
APW09	UA	E001	Chromium, total	mg/L	12/15/15 - 04/27/23	12	67	CB around T-S line	0.004	0.1	Standard	No Exceedance
APW09	UA	E001	Cobalt, total	mg/L	12/15/15 - 04/27/23	11	91	CI around median	0.002	0.006	Standard	No Exceedance
APW09	UA	E001	Fluoride, total	mg/L	12/15/15 - 04/27/23	22	4	CI around mean	0.438	4	Standard	No Exceedance
APW09	UA	E001	Lead, total	mg/L	12/15/15 - 04/27/23	12	50	CI around median	0.001	0.0075	Standard	No Exceedance
APW09	UA	E001	Lithium, total	mg/L	12/15/15 - 04/27/23	12	100	All ND - Last	0.02	0.04	Standard	No Exceedance
APW09	UA	E001	Mercury, total	mg/L	12/15/15 - 04/27/23	12	83	CI around median	0.0002	0.002	Standard	No Exceedance
APW09	UA	E001	Molybdenum, total	mg/L	12/15/15 - 04/27/23	11	0	CB around linear reg	-0.00854	0.1	Standard	No Exceedance
APW09	UA	E001	Radium 226 + Radium 228, total	pCi/L	12/15/15 - 04/27/23	12	0	CI around geomean	0.828	6.9	Background	No Exceedance

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Well ID	HSU	Event	Parameter	Units	Date Range	Sample Count	Percent ND	Statistical Calculation	Statistical Result	GWPS	GWPS Source	Exceedance Type
APW09	UA	E001	Selenium, total	mg/L	12/15/15 - 04/27/23	12	92	CI around median	0.001	0.05	Standard	No Exceedance
APW09	UA	E001	Sulfate, total	mg/L	12/15/15 - 04/27/23	23	9	CI around geomean	4	400	Standard	No Exceedance
APW09	UA	E001	Thallium, total	mg/L	12/15/15 - 04/27/23	11	100	All ND - Last	0.001	0.002	Standard	No Exceedance
APW09	UA	E001	Total Dissolved Solids	mg/L	12/15/15 - 04/27/23	23	0	CB around T-S line	734	1,200	Standard	No Exceedance
APW09	UA	E001	pH (field)	SU	12/15/15 - 04/27/23	24	0	CI around median	7.4/7.5	6.4/9	Background/Standard	No Exceedance
APW10	UA	E001	Antimony, total	mg/L	12/16/15 - 04/27/23	13	100	All ND - Last	0.003	0.006	Standard	No Exceedance
APW10	UA	E001	Arsenic, total	mg/L	12/16/15 - 04/27/23	14	0	CI around mean	0.0059	0.059	Background	No Exceedance
APW10	UA	E001	Barium, total	mg/L	12/16/15 - 04/27/23	14	0	CI around mean	0.0286	2	Standard	No Exceedance
APW10	UA	E001	Beryllium, total	mg/L	12/16/15 - 04/27/23	13	100	All ND - Last	0.001	0.004	Standard	No Exceedance
APW10	UA	E001	Boron, total	mg/L	12/16/15 - 04/27/23	24	0	CB around linear reg	0.0764	2	Standard	No Exceedance
APW10	UA	E001	Cadmium, total	mg/L	12/16/15 - 04/27/23	13	100	All ND - Last	0.001	0.005	Standard	No Exceedance
APW10	UA	E001	Chloride, total	mg/L	12/16/15 - 04/27/23	25	0	CI around mean	45.4	200	Standard	No Exceedance
APW10	UA	E001	Chromium, total	mg/L	12/16/15 - 04/27/23	14	100	All ND - Last	0.004	0.1	Standard	No Exceedance
APW10	UA	E001	Cobalt, total	mg/L	12/16/15 - 04/27/23	13	92	CI around median	0.002	0.006	Standard	No Exceedance
APW10	UA	E001	Fluoride, total	mg/L	12/16/15 - 04/27/23	24	21	CI around mean	0.298	4	Standard	No Exceedance
APW10	UA	E001	Lead, total	mg/L	12/16/15 - 04/27/23	14	86	CI around median	0.001	0.0075	Standard	No Exceedance
APW10	UA	E001	Lithium, total	mg/L	12/16/15 - 04/27/23	14	7	CB around linear reg	0.0132	0.04	Standard	No Exceedance
APW10	UA	E001	Mercury, total	mg/L	12/16/15 - 04/27/23	14	100	All ND - Last	0.0002	0.002	Standard	No Exceedance
APW10	UA	E001	Molybdenum, total	mg/L	12/16/15 - 04/27/23	13	0	CB around linear reg	0.00524	0.1	Standard	No Exceedance
APW10	UA	E001	Radium 226 + Radium 228, total	pCi/L	12/16/15 - 04/27/23	14	0	CI around mean	0.442	6.9	Background	No Exceedance
APW10	UA	E001	Selenium, total	mg/L	12/16/15 - 04/27/23	14	100	All ND - Last	0.001	0.05	Standard	No Exceedance
APW10	UA	E001	Sulfate, total	mg/L	12/16/15 - 04/27/23	25	0	CI around median	410	400	Standard	Determined
APW10	UA	E001	Thallium, total	mg/L	12/16/15 - 04/27/23	13	100	All ND - Last	0.001	0.002	Standard	No Exceedance
APW10	UA	E001	Total Dissolved Solids	mg/L	12/16/15 - 04/27/23	26	0	CB around linear reg	1,030	1,200	Standard	No Exceedance
APW10	UA	E001	pH (field)	SU	12/16/15 - 04/27/23	27	0	CB around linear reg	7.2/7.5	6.4/9	Background/Standard	No Exceedance
APW11	UA	E001	Antimony, total	mg/L	02/18/21 - 04/26/23	10	100	All ND - Last	0.003	0.006	Standard	No Exceedance
APW11	UA	E001	Arsenic, total	mg/L	02/18/21 - 04/26/23	10	0	CI around mean	0.0015	0.059	Background	No Exceedance

TABLE 2.
COMPARISON OF STATISTICAL RESULTS TO GWPS - QUARTER 2, 2023
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NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

Well ID	HSU	Event	Parameter	Units	Date Range	Sample Count	Percent ND	Statistical Calculation	Statistical Result	GWPS	GWPS Source	Exceedance Type
APW11	UA	E001	Barium, total	mg/L	02/18/21 - 04/26/23	10	0	CB around T-S line	-0.566	2	Standard	No Exceedance
APW11	UA	E001	Beryllium, total	mg/L	02/18/21 - 04/26/23	10	100	All ND - Last	0.001	0.004	Standard	No Exceedance
APW11	UA	E001	Boron, total	mg/L	02/18/21 - 04/26/23	10	0	CI around median	0.063	2	Standard	No Exceedance
APW11	UA	E001	Cadmium, total	mg/L	02/18/21 - 04/26/23	10	100	All ND - Last	0.001	0.005	Standard	No Exceedance
APW11	UA	E001	Chloride, total	mg/L	02/18/21 - 04/26/23	10	0	CI around median	26	200	Standard	No Exceedance
APW11	UA	E001	Chromium, total	mg/L	02/18/21 - 04/26/23	10	70	CI around median	0.004	0.1	Standard	No Exceedance
APW11	UA	E001	Cobalt, total	mg/L	02/18/21 - 04/26/23	10	70	CI around median	0.002	0.006	Standard	No Exceedance
APW11	UA	E001	Fluoride, total	mg/L	02/18/21 - 04/26/23	10	50	CI around geomean	0.245	4	Standard	No Exceedance
APW11	UA	E001	Lead, total	mg/L	02/18/21 - 04/26/23	10	60	CI around median	0.001	0.0075	Standard	No Exceedance
APW11	UA	E001	Lithium, total	mg/L	02/18/21 - 04/26/23	10	10	CI around mean	0.0175	0.04	Standard	No Exceedance
APW11	UA	E001	Mercury, total	mg/L	02/18/21 - 04/26/23	10	80	CI around median	0.0002	0.002	Standard	No Exceedance
APW11	UA	E001	Molybdenum, total	mg/L	02/18/21 - 04/26/23	9	0	CB around T-S line	-0.0661	0.1	Standard	No Exceedance
APW11	UA	E001	Radium 226 + Radium 228, total	pCi/L	02/18/21 - 04/26/23	9	0	CI around mean	0.424	6.9	Background	No Exceedance
APW11	UA	E001	Selenium, total	mg/L	02/18/21 - 04/26/23	10	80	CI around median	0.001	0.05	Standard	No Exceedance
APW11	UA	E001	Sulfate, total	mg/L	02/18/21 - 04/26/23	10	0	CI around median	260	400	Standard	No Exceedance
APW11	UA	E001	Thallium, total	mg/L	02/18/21 - 04/26/23	10	90	CI around median	0.001	0.002	Standard	No Exceedance
APW11	UA	E001	Total Dissolved Solids	mg/L	02/18/21 - 04/26/23	10	0	CI around mean	809	1,200	Standard	No Exceedance
APW11	UA	E001	pH (field)	SU	02/18/21 - 04/26/23	10	0	CI around median	6.6/7.2	6.4/9	Background/Standard	No Exceedance
APW12	UD	E001	Antimony, total	mg/L	02/17/21 - 04/26/23	10	100	All ND - Last	0.003	0.006	Standard	No Exceedance
APW12	UD	E001	Arsenic, total	mg/L	02/17/21 - 04/26/23	10	0	CI around mean	0.00155	0.059	Background	No Exceedance
APW12	UD	E001	Barium, total	mg/L	02/17/21 - 04/26/23	10	0	CB around linear reg	0.0133	2	Standard	No Exceedance
APW12	UD	E001	Beryllium, total	mg/L	02/17/21 - 04/26/23	10	100	All ND - Last	0.001	0.004	Standard	No Exceedance
APW12	UD	E001	Boron, total	mg/L	02/17/21 - 04/26/23	10	0	CI around mean	0.18	2	Standard	No Exceedance
APW12	UD	E001	Cadmium, total	mg/L	02/17/21 - 04/26/23	10	100	All ND - Last	0.001	0.005	Standard	No Exceedance
APW12	UD	E001	Chloride, total	mg/L	02/17/21 - 04/26/23	10	0	CI around mean	21.3	200	Standard	No Exceedance
APW12	UD	E001	Chromium, total	mg/L	02/17/21 - 04/26/23	10	100	All ND - Last	0.004	0.1	Standard	No Exceedance
APW12	UD	E001	Cobalt, total	mg/L	02/17/21 - 04/26/23	10	20	CB around linear reg	-0.00198	0.006	Standard	No Exceedance

TABLE 2.
COMPARISON OF STATISTICAL RESULTS TO GWPS - QUARTER 2, 2023
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NEWTON, IL

Well ID	HSU	Event	Parameter	Units	Date Range	Sample Count	Percent ND	Statistical Calculation	Statistical Result	GWPS	GWPS Source	Exceedance Type
APW12	UD	E001	Fluoride, total	mg/L	02/17/21 - 04/26/23	10	100	All ND - Last	0.25	4	Standard	No Exceedance
APW12	UD	E001	Lead, total	mg/L	02/17/21 - 04/26/23	10	90	CI around median	0.001	0.0075	Standard	No Exceedance
APW12	UD	E001	Lithium, total	mg/L	02/17/21 - 04/26/23	10	0	CI around geomean	0.0244	0.04	Standard	No Exceedance
APW12	UD	E001	Mercury, total	mg/L	02/17/21 - 04/26/23	10	90	CI around median	0.0002	0.002	Standard	No Exceedance
APW12	UD	E001	Molybdenum, total	mg/L	02/17/21 - 04/26/23	9	44	CI around geomean	0.000964	0.1	Standard	No Exceedance
APW12	UD	E001	Radium 226 + Radium 228, total	pCi/L	02/17/21 - 04/26/23	9	0	CI around geomean	0.14	6.9	Background	No Exceedance
APW12	UD	E001	Selenium, total	mg/L	02/17/21 - 04/26/23	10	100	All ND - Last	0.001	0.05	Standard	No Exceedance
APW12	UD	E001	Sulfate, total	mg/L	02/17/21 - 04/26/23	10	0	CI around mean	253	400	Standard	No Exceedance
APW12	UD	E001	Thallium, total	mg/L	02/17/21 - 04/26/23	10	100	All ND - Last	0.001	0.002	Standard	No Exceedance
APW12	UD	E001	Total Dissolved Solids	mg/L	02/17/21 - 04/26/23	10	0	CI around mean	1,160	1,200	Standard	No Exceedance
APW12	UD	E001	pH (field)	SU	02/17/21 - 04/26/23	10	0	CI around mean	6.2/6.6	6.4/9	Background/Standard	No Exceedance
APW13	UA	E001	Antimony, total	mg/L	02/22/21 - 04/27/23	10	100	All ND - Last	0.003	0.006	Standard	No Exceedance
APW13	UA	E001	Arsenic, total	mg/L	02/22/21 - 04/27/23	10	0	CI around mean	0.00314	0.059	Background	No Exceedance
APW13	UA	E001	Barium, total	mg/L	02/22/21 - 04/27/23	10	0	CI around mean	0.05	2	Standard	No Exceedance
APW13	UA	E001	Beryllium, total	mg/L	02/22/21 - 04/27/23	10	100	All ND - Last	0.001	0.004	Standard	No Exceedance
APW13	UA	E001	Boron, total	mg/L	02/22/21 - 04/27/23	10	0	CI around mean	0.105	2	Standard	No Exceedance
APW13	UA	E001	Cadmium, total	mg/L	02/22/21 - 04/27/23	10	100	All ND - Last	0.001	0.005	Standard	No Exceedance
APW13	UA	E001	Chloride, total	mg/L	02/22/21 - 04/27/23	10	0	CI around mean	46.2	200	Standard	No Exceedance
APW13	UA	E001	Chromium, total	mg/L	02/22/21 - 04/27/23	10	100	All ND - Last	0.004	0.1	Standard	No Exceedance
APW13	UA	E001	Cobalt, total	mg/L	02/22/21 - 04/27/23	10	100	All ND - Last	0.002	0.006	Standard	No Exceedance
APW13	UA	E001	Fluoride, total	mg/L	02/22/21 - 04/27/23	10	10	CI around mean	0.285	4	Standard	No Exceedance
APW13	UA	E001	Lead, total	mg/L	02/22/21 - 04/27/23	10	100	All ND - Last	0.001	0.0075	Standard	No Exceedance
APW13	UA	E001	Lithium, total	mg/L	02/22/21 - 04/27/23	10	0	CI around mean	0.0262	0.04	Standard	No Exceedance
APW13	UA	E001	Mercury, total	mg/L	02/22/21 - 04/27/23	10	100	All ND - Last	0.0002	0.002	Standard	No Exceedance
APW13	UA	E001	Molybdenum, total	mg/L	02/22/21 - 04/27/23	9	0	CB around linear reg	-0.00498	0.1	Standard	No Exceedance
APW13	UA	E001	Radium 226 + Radium 228, total	pCi/L	02/22/21 - 04/27/23	9	0	CI around mean	0.245	6.9	Background	No Exceedance
APW13	UA	E001	Selenium, total	mg/L	02/22/21 - 04/27/23	10	100	All ND - Last	0.001	0.05	Standard	No Exceedance

TABLE 2.
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Well ID	HSU	Event	Parameter	Units	Date Range	Sample Count	Percent ND	Statistical Calculation	Statistical Result	GWPS	GWPS Source	Exceedance Type
APW13	UA	E001	Sulfate, total	mg/L	02/22/21 - 04/27/23	10	0	CI around mean	210	400	Standard	No Exceedance
APW13	UA	E001	Thallium, total	mg/L	02/22/21 - 04/27/23	10	100	All ND - Last	0.001	0.002	Standard	No Exceedance
APW13	UA	E001	Total Dissolved Solids	mg/L	02/22/21 - 04/27/23	10	0	CI around mean	801	1,200	Standard	No Exceedance
APW13	UA	E001	pH (field)	SU	02/22/21 - 04/27/23	10	0	CI around median	7.1/7.3	6.4/9	Background/Standard	No Exceedance
APW14	UA	E001	Antimony, total	mg/L	02/22/21 - 04/28/23	10	100	All ND - Last	0.003	0.006	Standard	No Exceedance
APW14	UA	E001	Arsenic, total	mg/L	02/22/21 - 04/28/23	10	0	CI around mean	0.00506	0.059	Background	No Exceedance
APW14	UA	E001	Barium, total	mg/L	02/22/21 - 04/28/23	10	0	CI around mean	0.0752	2	Standard	No Exceedance
APW14	UA	E001	Beryllium, total	mg/L	02/22/21 - 04/28/23	10	100	All ND - Last	0.001	0.004	Standard	No Exceedance
APW14	UA	E001	Boron, total	mg/L	02/22/21 - 04/28/23	10	0	CI around mean	0.0949	2	Standard	No Exceedance
APW14	UA	E001	Cadmium, total	mg/L	02/22/21 - 04/28/23	10	100	All ND - Last	0.001	0.005	Standard	No Exceedance
APW14	UA	E001	Chloride, total	mg/L	02/22/21 - 04/28/23	10	0	CI around mean	41.8	200	Standard	No Exceedance
APW14	UA	E001	Chromium, total	mg/L	02/22/21 - 04/28/23	10	90	CI around median	0.004	0.1	Standard	No Exceedance
APW14	UA	E001	Cobalt, total	mg/L	02/22/21 - 04/28/23	10	90	CI around median	0.002	0.006	Standard	No Exceedance
APW14	UA	E001	Fluoride, total	mg/L	02/22/21 - 04/28/23	10	30	CI around mean	0.266	4	Standard	No Exceedance
APW14	UA	E001	Lead, total	mg/L	02/22/21 - 04/28/23	10	70	CI around median	0.001	0.0075	Standard	No Exceedance
APW14	UA	E001	Lithium, total	mg/L	02/22/21 - 04/28/23	10	20	CB around linear reg	-0.00217	0.04	Standard	No Exceedance
APW14	UA	E001	Mercury, total	mg/L	02/22/21 - 04/28/23	10	100	All ND - Last	0.0002	0.002	Standard	No Exceedance
APW14	UA	E001	Molybdenum, total	mg/L	02/22/21 - 04/28/23	9	0	CB around linear reg	-0.0066	0.1	Standard	No Exceedance
APW14	UA	E001	Radium 226 + Radium 228, total	pCi/L	02/22/21 - 04/28/23	9	0	CI around mean	0.372	6.9	Background	No Exceedance
APW14	UA	E001	Selenium, total	mg/L	02/22/21 - 04/28/23	10	100	All ND - Last	0.001	0.05	Standard	No Exceedance
APW14	UA	E001	Sulfate, total	mg/L	02/22/21 - 04/28/23	10	0	CI around median	320	400	Standard	No Exceedance
APW14	UA	E001	Thallium, total	mg/L	02/22/21 - 04/28/23	10	100	All ND - Last	0.001	0.002	Standard	No Exceedance
APW14	UA	E001	Total Dissolved Solids	mg/L	02/22/21 - 04/28/23	10	0	CI around mean	892	1,200	Standard	No Exceedance
APW14	UA	E001	pH (field)	SU	02/22/21 - 04/28/23	10	0	CI around median	7.3/7.5	6.4/9	Background/Standard	No Exceedance
APW15	UA	E001	Antimony, total	mg/L	02/23/21 - 04/26/23	10	100	All ND - Last	0.003	0.006	Standard	No Exceedance
APW15	UA	E001	Arsenic, total	mg/L	02/23/21 - 04/26/23	10	0	CI around mean	0.0166	0.059	Background	No Exceedance
APW15	UA	E001	Barium, total	mg/L	02/23/21 - 04/26/23	10	0	CI around mean	0.559	2	Standard	No Exceedance

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Well ID	HSU	Event	Parameter	Units	Date Range	Sample Count	Percent ND	Statistical Calculation	Statistical Result	GWPS	GWPS Source	Exceedance Type
APW15	UA	E001	Beryllium, total	mg/L	02/23/21 - 04/26/23	10	100	All ND - Last	0.001	0.004	Standard	No Exceedance
APW15	UA	E001	Boron, total	mg/L	02/23/21 - 04/26/23	10	0	CI around mean	0.128	2	Standard	No Exceedance
APW15	UA	E001	Cadmium, total	mg/L	02/23/21 - 04/26/23	10	100	All ND - Last	0.001	0.005	Standard	No Exceedance
APW15	UA	E001	Chloride, total	mg/L	02/23/21 - 04/26/23	10	0	CI around median	230	200	Standard	Determined
APW15	UA	E001	Chromium, total	mg/L	02/23/21 - 04/26/23	10	80	CI around median	0.004	0.1	Standard	No Exceedance
APW15	UA	E001	Cobalt, total	mg/L	02/23/21 - 04/26/23	10	80	CI around median	0.002	0.006	Standard	No Exceedance
APW15	UA	E001	Fluoride, total	mg/L	02/23/21 - 04/26/23	10	0	CI around geomean	0.6	4	Standard	No Exceedance
APW15	UA	E001	Lead, total	mg/L	02/23/21 - 04/26/23	10	50	CI around median	0.001	0.0075	Standard	No Exceedance
APW15	UA	E001	Lithium, total	mg/L	02/23/21 - 04/26/23	10	80	CI around median	0.02	0.04	Standard	No Exceedance
APW15	UA	E001	Mercury, total	mg/L	02/23/21 - 04/26/23	10	100	All ND - Last	0.0002	0.002	Standard	No Exceedance
APW15	UA	E001	Molybdenum, total	mg/L	02/23/21 - 04/26/23	9	0	CI around mean	0.00846	0.1	Standard	No Exceedance
APW15	UA	E001	Radium 226 + Radium 228, total	pCi/L	02/23/21 - 04/26/23	9	0	CI around mean	1.5	6.9	Background	No Exceedance
APW15	UA	E001	Selenium, total	mg/L	02/23/21 - 04/26/23	10	100	All ND - Last	0.001	0.05	Standard	No Exceedance
APW15	UA	E001	Sulfate, total	mg/L	02/23/21 - 04/26/23	10	100	All ND - Last	1	400	Standard	No Exceedance
APW15	UA	E001	Thallium, total	mg/L	02/23/21 - 04/26/23	10	100	All ND - Last	0.001	0.002	Standard	No Exceedance
APW15	UA	E001	Total Dissolved Solids	mg/L	02/23/21 - 04/26/23	10	0	CI around mean	1,020	1,200	Standard	No Exceedance
APW15	UA	E001	pH (field)	SU	02/23/21 - 04/26/23	10	0	CI around median	7.0/7.3	6.4/9	Background/Standard	No Exceedance
APW16	UA	E001	Antimony, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.003	0.006	Standard	No Exceedance
APW16	UA	E001	Arsenic, total	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	0.00767	0.059	Background	No Exceedance
APW16	UA	E001	Barium, total	mg/L	02/23/21 - 04/25/23	10	0	CB around linear reg	0.434	2	Standard	No Exceedance
APW16	UA	E001	Beryllium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.001	0.004	Standard	No Exceedance
APW16	UA	E001	Boron, total	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	0.128	2	Standard	No Exceedance
APW16	UA	E001	Cadmium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.001	0.005	Standard	No Exceedance
APW16	UA	E001	Chloride, total	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	66.1	200	Standard	No Exceedance
APW16	UA	E001	Chromium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.004	0.1	Standard	No Exceedance
APW16	UA	E001	Cobalt, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.002	0.006	Standard	No Exceedance
APW16	UA	E001	Fluoride, total	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	0.605	4	Standard	No Exceedance

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Well ID	HSU	Event	Parameter	Units	Date Range	Sample Count	Percent ND	Statistical Calculation	Statistical Result	GWPS	GWPS Source	Exceedance Type
APW16	UA	E001	Lead, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.001	0.0075	Standard	No Exceedance
APW16	UA	E001	Lithium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.02	0.04	Standard	No Exceedance
APW16	UA	E001	Mercury, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.0002	0.002	Standard	No Exceedance
APW16	UA	E001	Molybdenum, total	mg/L	02/23/21 - 04/25/23	9	44	CB around linear reg	-0.00408	0.1	Standard	No Exceedance
APW16	UA	E001	Radium 226 + Radium 228, total	pCi/L	02/23/21 - 04/25/23	9	0	CI around geomean	1.22	6.9	Background	No Exceedance
APW16	UA	E001	Selenium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.001	0.05	Standard	No Exceedance
APW16	UA	E001	Sulfate, total	mg/L	02/23/21 - 04/25/23	10	90	CI around median	1	400	Standard	No Exceedance
APW16	UA	E001	Thallium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.001	0.002	Standard	No Exceedance
APW16	UA	E001	Total Dissolved Solids	mg/L	02/23/21 - 04/25/23	10	0	CI around median	690	1,200	Standard	No Exceedance
APW16	UA	E001	pH (field)	SU	02/23/21 - 04/25/23	10	0	CI around mean	7.2/7.6	6.4/9	Background/Standard	No Exceedance
APW17	UA	E001	Antimony, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.003	0.006	Standard	No Exceedance
APW17	UA	E001	Arsenic, total	mg/L	02/23/21 - 04/25/23	10	0	CB around linear reg	0.0181	0.059	Background	No Exceedance
APW17	UA	E001	Barium, total	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	0.565	2	Standard	No Exceedance
APW17	UA	E001	Beryllium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.001	0.004	Standard	No Exceedance
APW17	UA	E001	Boron, total	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	0.0839	2	Standard	No Exceedance
APW17	UA	E001	Cadmium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.001	0.005	Standard	No Exceedance
APW17	UA	E001	Chloride, total	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	43.9	200	Standard	No Exceedance
APW17	UA	E001	Chromium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.004	0.1	Standard	No Exceedance
APW17	UA	E001	Cobalt, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.002	0.006	Standard	No Exceedance
APW17	UA	E001	Fluoride, total	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	0.394	4	Standard	No Exceedance
APW17	UA	E001	Lead, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.001	0.0075	Standard	No Exceedance
APW17	UA	E001	Lithium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.02	0.04	Standard	No Exceedance
APW17	UA	E001	Mercury, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.0002	0.002	Standard	No Exceedance
APW17	UA	E001	Molybdenum, total	mg/L	02/23/21 - 04/25/23	9	0	CI around median	0.0048	0.1	Standard	No Exceedance
APW17	UA	E001	Radium 226 + Radium 228, total	pCi/L	02/23/21 - 04/25/23	9	0	CI around mean	0.644	6.9	Background	No Exceedance
APW17	UA	E001	Selenium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.001	0.05	Standard	No Exceedance
APW17	UA	E001	Sulfate, total	mg/L	02/23/21 - 04/25/23	10	10	CI around mean	26.7	400	Standard	No Exceedance

TABLE 2.
COMPARISON OF STATISTICAL RESULTS TO GWPS - QUARTER 2, 2023
845 QUARTERLY REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

Well ID	HSU	Event	Parameter	Units	Date Range	Sample Count	Percent ND	Statistical Calculation	Statistical Result	GWPS	GWPS Source	Exceedance Type
APW17	UA	E001	Thallium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.001	0.002	Standard	No Exceedance
APW17	UA	E001	Total Dissolved Solids	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	631	1,200	Standard	No Exceedance
APW17	UA	E001	pH (field)	SU	02/23/21 - 04/25/23	10	0	CI around mean	7.3/7.6	6.4/9	Background/Standard	No Exceedance
APW18	UA	E001	Antimony, total	mg/L	02/23/21 - 04/25/23	10	90	CI around median	0.003	0.006	Standard	No Exceedance
APW18	UA	E001	Arsenic, total	mg/L	02/23/21 - 04/25/23	10	10	CI around mean	0.00144	0.059	Background	No Exceedance
APW18	UA	E001	Barium, total	mg/L	02/23/21 - 04/25/23	10	0	CI around median	0.33	2	Standard	No Exceedance
APW18	UA	E001	Beryllium, total	mg/L	02/23/21 - 04/25/23	10	90	CI around median	0.001	0.004	Standard	No Exceedance
APW18	UA	E001	Boron, total	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	0.103	2	Standard	No Exceedance
APW18	UA	E001	Cadmium, total	mg/L	02/23/21 - 04/25/23	10	90	CI around median	0.001	0.005	Standard	No Exceedance
APW18	UA	E001	Chloride, total	mg/L	02/23/21 - 04/25/23	10	0	CB around T-S line	-243	200	Standard	No Exceedance
APW18	UA	E001	Chromium, total	mg/L	02/23/21 - 04/25/23	10	70	CI around median	0.004	0.1	Standard	No Exceedance
APW18	UA	E001	Cobalt, total	mg/L	02/23/21 - 04/25/23	10	70	CI around median	0.002	0.006	Standard	No Exceedance
APW18	UA	E001	Fluoride, total	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	0.677	4	Standard	No Exceedance
APW18	UA	E001	Lead, total	mg/L	02/23/21 - 04/25/23	10	50	CB around linear reg	-0.00473	0.0075	Standard	No Exceedance
APW18	UA	E001	Lithium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.02	0.04	Standard	No Exceedance
APW18	UA	E001	Mercury, total	mg/L	02/23/21 - 04/25/23	10	90	CI around median	0.0002	0.002	Standard	No Exceedance
APW18	UA	E001	Molybdenum, total	mg/L	02/23/21 - 04/25/23	9	0	CB around linear reg	-0.0288	0.1	Standard	No Exceedance
APW18	UA	E001	Radium 226 + Radium 228, total	pCi/L	02/23/21 - 04/25/23	9	0	CI around mean	1.38	6.9	Background	No Exceedance
APW18	UA	E001	Selenium, total	mg/L	02/23/21 - 04/25/23	10	90	CI around median	0.001	0.05	Standard	No Exceedance
APW18	UA	E001	Sulfate, total	mg/L	02/23/21 - 04/25/23	10	20	CI around geomean	1.82	400	Standard	No Exceedance
APW18	UA	E001	Thallium, total	mg/L	02/23/21 - 04/25/23	10	80	CI around median	0.001	0.002	Standard	No Exceedance
APW18	UA	E001	Total Dissolved Solids	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	508	1,200	Standard	No Exceedance
APW18	UA	E001	pH (field)	SU	02/23/21 - 04/25/23	10	0	CI around mean	7.5/7.8	6.4/9	Background/Standard	No Exceedance

TABLE 2.
COMPARISON OF STATISTICAL RESULTS TO GWPS - QUARTER 2, 2023
845 QUARTERLY REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

Notes:
Determined: An exceedance was determined upon without resampling
HSU = hydrostratigraphic unit:

- UA = Uppermost Aquifer
- UD = Upper Drift

mg/L = milligrams per liter
ND = non-detect
pCi/L = picocuries per liter
SU = standard units
Sample Count = number of samples from Sampled Date Range used to calculate the Statistical Result
Statistical Calculation = method used to calculate the statistical result:

- All ND - Last = All results were below the reporting limit, and the last determined reporting limit is shown
- CB around T-S line = Confidence band around Thiel-Sen line
- CB around linear reg = Confidence band around linear regression
- CI around geomean = Confidence interval around the geometric mean
- CI around mean = Confidence interval around the mean
- CI around median = Confidence interval around the median
- Most recent sample = Result for the most recently collected sample used due to insufficient data

Statistical Result = calculated in accordance with Statistical Analysis Plan using constituent concentrations observed at monitoring well during all sampling events within the specified date range
For pH, the values presented are the lower / upper limits
GWPS = Groundwater Protection Standard
GWPS Source:

- Standard = standard specified in 35 I.A.C. § 845.600(a)(1)
- Background = background concentration (see cover page for additional information)

FIGURES

COMPLIANCE WELL
BACKGROUND WELL
STAFF GAUGE
REGULATED UNIT (SUBJECT UNIT)
SITE FEATURE
PROPERTY BOUNDARY

0 500 1,000
Feet

35 I.A.C. § 845 GROUNDWATER MONITORING WELL NETWORK

PRIMARY ASH POND
NEWTON POWER PLANT
NEWTON, ILLINOIS

FIGURE 1

RAMBOLL AMERICAS
ENGINEERING SOLUTIONS, INC.

RAMBOLL

Y:\Mapping\Projects\222285MXD\845_Operating_Permit\Newton\GMP\Figure 2-1_Proposed Monitoring Well Network.mxd

PROJECT: 169000XXXX | DATED: 10/20/2021 | DESIGNER: STOLZSD

ATTACHMENTS

ATTACHMENT A
GROUNDWATER ELEVATION DATA
QUARTER 2 2023

ATTACHMENT A.
GROUNDWATER ELEVATION DATA - QUARTER 2, 2023
845 QUARTERLY REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

Well ID	Well Type	Date	Depth to Groundwater (feet BMP)	Groundwater Elevation (feet NAVD88)
APW02	Compliance	04/24/2023	4.09	529.52
APW03	Compliance	04/24/2023	11.92	520.49
APW04	Compliance	04/24/2023	5.27	519.79
APW05	Background	04/24/2023	14.08	529.99
APW05S	Compliance	04/24/2023	11.78	532.16
APW06	Background	04/24/2023	19.17	526.90
APW07	Compliance	04/24/2023	46.18	492.19
APW08	Compliance	04/24/2023	36.99	490.80
APW09	Compliance	04/24/2023	26.55	504.97
APW10	Compliance	04/24/2023	17.60	506.65
APW11	Compliance	04/24/2023	24.26	514.37
APW12	Compliance	04/24/2023	14.59	531.70
APW13	Compliance	04/24/2023	32.00	505.99
APW14	Compliance	04/24/2023	20.89	505.40
APW15	Compliance	04/24/2023	21.51	503.18
APW16	Compliance	04/24/2023	40.22	490.96
APW17	Compliance	04/24/2023	41.16	491.36
APW18	Compliance	04/24/2023	51.91	491.36
XSG01	Water Level	04/24/2023	2.17	534.00
SG02	Water Level	04/24/2023	2.11	504.78

Notes:
BMP = below measuring point
NAVD88 = North American Vertical Datum of 1988

ATTACHMENT B
LABORATORY REPORTS AND FIELD DATA SHEETS
QUARTER 2 2023

Pace Analytical Services, LLC
2231 W. Altorfer Drive
Peoria, IL 61615
(800)752-6651

June 07, 2023

Terry Hanratty
Vistra - Newton
Newton Energy Center 6725 N. 500th St
Newton, IL 62448

Dear Terry Hanratty:

Please find enclosed the analytical results for the sample(s) the laboratory received. All testing is performed according to our current TNI accreditations unless otherwise noted. This report cannot be reproduced, except in full, without the written permission of Pace Analytical Services, LLC.

If you have any questions regarding your report, please contact your project manager. Quality and timely data is of the utmost importance to us.

Pace Analytical Services appreciates the opportunity to provide you with analytical expertise. We are always trying to improve our customer service and we welcome you to contact the General Manager, Lisa Grant, with any feedback you have about your experience with our laboratory at 309-683-1764 or lisa.grant@pacelabs.com.

Sincerely,

Gail Schindler
Project Manager
(309) 692-9688 x1716
gail.schindler@pacelabs.com

Pace Analytical Services, LLC
2231 W. Altorfer Drive
Peoria, IL 61615
(800)752-6651

SAMPLE RECEIPT CHECK LIST

Items not applicable will be marked as in compliance

Work Order GD04461

YES	Samples received within temperature compliance when applicable
YES	COC present upon sample receipt
YES	COC completed & legible
YES	Sampler name & signature present
YES	Unique sample IDs assigned
YES	Sample collection location recorded
YES	Date & time collected recorded on COC
YES	Relinquished by client signature on COC
YES	COC & labels match
YES	Sample labels are legible
YES	Appropriate bottle(s) received
YES	Sufficient sample volume received
YES	Sample containers received undamaged
YES	Zero headspace, <6 mm present in VOA vials
NO	Trip blank(s) received
YES	All non-field analyses received within holding times
YES	Short hold time analysis
YES	Current PDC COC submitted
NO	Case narrative provided

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Work Order GD04746

YES	Samples received within temperature compliance when applicable
YES	COC present upon sample receipt
YES	COC completed & legible
YES	Sampler name & signature present
YES	Unique sample IDs assigned
YES	Sample collection location recorded
YES	Date & time collected recorded on COC
YES	Relinquished by client signature on COC
YES	COC & labels match
YES	Sample labels are legible
YES	Appropriate bottle(s) received
YES	Sufficient sample volume received
YES	Sample containers received undamaged
YES	Zero headspace, <6 mm present in VOA vials
NO	Trip blank(s) received
YES	All non-field analyses received within holding times
YES	Short hold time analysis
YES	Current PDC COC submitted
YES	Case narrative provided

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Work Order GD04839

YES	Samples received within temperature compliance when applicable
YES	COC present upon sample receipt
YES	COC completed & legible
YES	Sampler name & signature present
YES	Unique sample IDs assigned
YES	Sample collection location recorded
YES	Date & time collected recorded on COC
YES	Relinquished by client signature on COC
YES	COC & labels match
YES	Sample labels are legible
YES	Appropriate bottle(s) received
YES	Sufficient sample volume received
YES	Sample containers received undamaged
YES	Zero headspace, <6 mm present in VOA vials
NO	Trip blank(s) received
YES	All non-field analyses received within holding times
YES	Short hold time analysis
YES	Current PDC COC submitted
NO	Case narrative provided

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Work Order GD04919

YES	Samples received within temperature compliance when applicable
YES	COC present upon sample receipt
YES	COC completed & legible
YES	Sampler name & signature present
YES	Unique sample IDs assigned
YES	Sample collection location recorded
YES	Date & time collected recorded on COC
YES	Relinquished by client signature on COC
YES	COC & labels match
YES	Sample labels are legible
YES	Appropriate bottle(s) received
YES	Sufficient sample volume received
YES	Sample containers received undamaged
YES	Zero headspace, <6 mm present in VOA vials
NO	Trip blank(s) received
YES	All non-field analyses received within holding times
YES	Short hold time analysis
YES	Current PDC COC submitted
NO	Case narrative provided

Pace Analytical Services, LLC
2231 W. Altorfer Drive
Peoria, IL 61615
(800)752-6651

ANALYTICAL RESULTS

Sample: GD04461-01
Name: APW03
Matrix: Ground Water - Grab

Sampled: 04/25/23 13:20
Received: 04/26/23 14:08

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	6.9	mg/L		04/26/23 20:03	1	1.0	04/26/23 20:03	CRD	EPA 300.0 REV 2.1
Fluoride	< 0.250	mg/L		04/26/23 20:03	1	0.250	04/26/23 20:03	CRD	EPA 300.0 REV 2.1
Sulfate	120	mg/L		04/26/23 20:21	25	25	04/26/23 20:21	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	11.94	Feet		04/25/23 13:20	1		04/25/23 13:20	FIELD	Field*
Dissolved oxygen, Field	2.2	mg/L		04/25/23 13:20	1		04/25/23 13:20	FIELD	Field*
Oxidation Reduction Potential	141	mV		04/25/23 13:20	1	-500	04/25/23 13:20	FIELD	Field*
pH, Field Measured	7.01	pH Units		04/25/23 13:20	1		04/25/23 13:20	FIELD	Field*
Specific Conductance, Field Measured	925.0	umhos/cm		04/25/23 13:20	1		04/25/23 13:20	FIELD	Field*
Temperature, Field Measured	17.0	°C		04/25/23 13:20	1		04/25/23 13:20	FIELD	Field*
Turbidity, Field Measured	< 0.00	NTU		04/25/23 13:20	1	0.00	04/25/23 13:20	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	390	mg/L		05/04/23 10:11	1	10	05/04/23 10:11	CPS	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	< 10	mg/L		05/04/23 10:11	1	10	05/04/23 10:11	CPS	SM 2320B 1997*
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	740	mg/L		04/28/23 14:40	1	26	04/28/23 16:47	HRF	SM 2540C
Total Metals - PIA									
Antimony	< 3.0	ug/L		05/03/23 09:07	5	3.0	05/04/23 09:27	JMW	EPA 6020A
Arsenic	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:27	JMW	EPA 6020A
Barium	78	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:27	JMW	EPA 6020A
Beryllium	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:27	JMW	EPA 6020A
Boron	370	ug/L		05/03/23 09:07	5	10	05/05/23 08:18	JMW	EPA 6020A
Cadmium	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:27	JMW	EPA 6020A
Calcium	96	mg/L		05/03/23 09:07	5	0.20	05/04/23 09:27	JMW	EPA 6020A
Chromium	7.2	ug/L		05/03/23 09:07	5	4.0	05/04/23 09:27	JMW	EPA 6020A
Cobalt	< 2.0	ug/L		05/03/23 09:07	5	2.0	05/04/23 09:27	JMW	EPA 6020A
Lead	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:27	JMW	EPA 6020A
Magnesium	58	mg/L		05/03/23 09:07	5	0.10	05/04/23 09:27	JMW	EPA 6020A
Mercury	< 0.20	ug/L		05/03/23 09:07	5	0.20	05/05/23 08:18	JMW	EPA 6020A
Molybdenum	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:27	JMW	EPA 6020A
Potassium	0.31	mg/L		05/03/23 09:07	5	0.10	05/04/23 09:27	JMW	EPA 6020A

Pace Analytical Services, LLC
2231 W. Altorfer Drive
Peoria, IL 61615
(800)752-6651

ANALYTICAL RESULTS

Sample: GD04461-01
Name: APW03
Matrix: Ground Water - Grab

Sampled: 04/25/23 13:20
Received: 04/26/23 14:08

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Selenium	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:27	JMW	EPA 6020A
Sodium	61	mg/L		05/03/23 09:07	5	0.10	05/04/23 09:27	JMW	EPA 6020A
Thallium	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:27	JMW	EPA 6020A
Lithium	< 0.020	mg/L		05/03/23 09:07	1	0.020	05/09/23 10:16	TJJ	EPA 6010B

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ANALYTICAL RESULTS

Sample: GD04461-02
Name: APW04
Matrix: Ground Water - Grab

Sampled: 04/25/23 16:42
Received: 04/26/23 14:08

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	34	mg/L		04/26/23 20:57	10	10	04/26/23 20:57	CRD	EPA 300.0 REV 2.1
Fluoride	< 0.250	mg/L		04/26/23 20:39	1	0.250	04/26/23 20:39	CRD	EPA 300.0 REV 2.1
Sulfate	840	mg/L		04/26/23 21:51	100	100	04/26/23 21:51	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	5.1	Feet		04/25/23 16:42	1		04/25/23 16:42	FIELD	Field*
Dissolved oxygen, Field	0.93	mg/L		04/25/23 16:42	1		04/25/23 16:42	FIELD	Field*
Oxidation Reduction Potential	171	mV		04/25/23 16:42	1	-500	04/25/23 16:42	FIELD	Field*
pH, Field Measured	6.93	pH Units		04/25/23 16:42	1		04/25/23 16:42	FIELD	Field*
Specific Conductance, Field Measured	1830	umhos/cm		04/25/23 16:42	1		04/25/23 16:42	FIELD	Field*
Temperature, Field Measured	11.8	°C		04/25/23 16:42	1		04/25/23 16:42	FIELD	Field*
Turbidity, Field Measured	178	NTU		04/25/23 16:42	1	0.00	04/25/23 16:42	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	440	mg/L		05/04/23 10:11	1	10	05/04/23 10:11	CPS	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	< 10	mg/L		05/04/23 10:11	1	10	05/04/23 10:11	CPS	SM 2320B 1997*
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	1800	mg/L		04/28/23 14:40	1	26	04/28/23 16:47	HRF	SM 2540C
Total Metals - PIA									
Antimony	< 3.0	ug/L		05/03/23 09:07	5	3.0	05/04/23 09:31	JMW	EPA 6020A
Arsenic	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:31	JMW	EPA 6020A
Barium	22	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:31	JMW	EPA 6020A
Beryllium	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:31	JMW	EPA 6020A
Boron	24	ug/L		05/03/23 09:07	5	10	05/05/23 08:21	JMW	EPA 6020A
Cadmium	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:31	JMW	EPA 6020A
Calcium	210	mg/L		05/03/23 09:07	5	0.20	05/04/23 09:31	JMW	EPA 6020A
Chromium	44	ug/L		05/03/23 09:07	5	4.0	05/04/23 09:31	JMW	EPA 6020A
Cobalt	< 2.0	ug/L		05/03/23 09:07	5	2.0	05/04/23 09:31	JMW	EPA 6020A
Lead	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:31	JMW	EPA 6020A
Magnesium	170	mg/L		05/03/23 09:07	5	0.10	05/04/23 09:31	JMW	EPA 6020A
Mercury	< 0.20	ug/L		05/03/23 09:07	5	0.20	05/05/23 08:21	JMW	EPA 6020A
Molybdenum	1.8	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:31	JMW	EPA 6020A
Potassium	1.3	mg/L		05/03/23 09:07	5	0.10	05/04/23 09:31	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04461-02
Name: APW04
Matrix: Ground Water - Grab

Sampled: 04/25/23 16:42
Received: 04/26/23 14:08

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Selenium	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:31	JMW	EPA 6020A
Sodium	90	mg/L		05/03/23 09:07	5	0.10	05/04/23 09:31	JMW	EPA 6020A
Thallium	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:31	JMW	EPA 6020A
Lithium	< 0.020	mg/L		05/03/23 09:07	1	0.020	05/09/23 10:17	TJJ	EPA 6010B

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ANALYTICAL RESULTS

Sample: GD04461-03
Name: APW16
Matrix: Ground Water - Grab

Sampled: 04/25/23 13:26
Received: 04/26/23 14:08

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	71	mg/L	Q4	04/26/23 23:03	10	10	04/26/23 23:03	CRD	EPA 300.0 REV 2.1
Fluoride	0.606	mg/L		04/26/23 22:09	1	0.250	04/26/23 22:09	CRD	EPA 300.0 REV 2.1
Sulfate	< 1.0	mg/L		04/26/23 22:09	1	1.0	04/26/23 22:09	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	40.15	Feet		04/25/23 13:26	1		04/25/23 13:26	FIELD	Field*
Dissolved oxygen, Field	1.2	mg/L		04/25/23 13:26	1		04/25/23 13:26	FIELD	Field*
Oxidation Reduction Potential	-104	mV		04/25/23 13:26	1	-500	04/25/23 13:26	FIELD	Field*
pH, Field Measured	7.65	pH Units		04/25/23 13:26	1		04/25/23 13:26	FIELD	Field*
Specific Conductance, Field Measured	953.0	umhos/cm		04/25/23 13:26	1		04/25/23 13:26	FIELD	Field*
Temperature, Field Measured	14.0	°C		04/25/23 13:26	1		04/25/23 13:26	FIELD	Field*
Turbidity, Field Measured	0.210	NTU		04/25/23 13:26	1	0.00	04/25/23 13:26	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	560	mg/L		05/04/23 10:11	1	10	05/04/23 10:11	CPS	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	< 10	mg/L		05/04/23 10:11	1	10	05/04/23 10:11	CPS	SM 2320B 1997*
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	800	mg/L		04/28/23 14:40	1	26	04/28/23 16:47	HRF	SM 2540C
Total Metals - PIA									
Antimony	< 3.0	ug/L		05/03/23 09:07	5	3.0	05/04/23 09:34	JMW	EPA 6020A
Arsenic	21	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:34	JMW	EPA 6020A
Barium	540	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:34	JMW	EPA 6020A
Beryllium	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:34	JMW	EPA 6020A
Boron	130	ug/L		05/03/23 09:07	5	10	05/05/23 08:24	JMW	EPA 6020A
Cadmium	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:34	JMW	EPA 6020A
Calcium	96	mg/L	Q4	05/03/23 09:07	5	0.20	05/04/23 09:34	JMW	EPA 6020A
Chromium	< 4.0	ug/L		05/03/23 09:07	5	4.0	05/04/23 09:34	JMW	EPA 6020A
Cobalt	< 2.0	ug/L		05/03/23 09:07	5	2.0	05/04/23 09:34	JMW	EPA 6020A
Lead	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:34	JMW	EPA 6020A
Magnesium	44	mg/L	Q4	05/03/23 09:07	5	0.10	05/04/23 09:34	JMW	EPA 6020A
Mercury	< 0.20	ug/L		05/03/23 09:07	5	0.20	05/05/23 08:24	JMW	EPA 6020A
Molybdenum	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:34	JMW	EPA 6020A
Potassium	1.8	mg/L		05/03/23 09:07	5	0.10	05/04/23 09:34	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04461-03
Name: APW16
Matrix: Ground Water - Grab

Sampled: 04/25/23 13:26
Received: 04/26/23 14:08

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Selenium	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:34	JMW	EPA 6020A
Sodium	140	mg/L	Q4	05/03/23 09:07	5	0.10	05/04/23 09:34	JMW	EPA 6020A
Thallium	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:34	JMW	EPA 6020A
Lithium	< 0.020	mg/L		05/03/23 09:07	1	0.020	05/09/23 10:19	TJJ	EPA 6010B

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ANALYTICAL RESULTS

Sample: GD04461-04
Name: APW17
Matrix: Ground Water - Grab

Sampled: 04/25/23 16:50
Received: 04/26/23 14:08

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	56	mg/L		04/26/23 23:40	10	10	04/26/23 23:40	CRD	EPA 300.0 REV 2.1
Fluoride	0.483	mg/L		04/26/23 23:22	1	0.250	04/26/23 23:22	CRD	EPA 300.0 REV 2.1
Sulfate	52	mg/L		04/26/23 23:40	10	10	04/26/23 23:40	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	41.09	Feet		04/25/23 16:50	1		04/25/23 16:50	FIELD	Field*
Dissolved oxygen, Field	1.2	mg/L		04/25/23 16:50	1		04/25/23 16:50	FIELD	Field*
Oxidation Reduction Potential	-97.2	mV		04/25/23 16:50	1	-500	04/25/23 16:50	FIELD	Field*
pH, Field Measured	7.62	pH Units		04/25/23 16:50	1		04/25/23 16:50	FIELD	Field*
Specific Conductance, Field Measured	1162	umhos/cm		04/25/23 16:50	1		04/25/23 16:50	FIELD	Field*
Temperature, Field Measured	15.2	°C		04/25/23 16:50	1		04/25/23 16:50	FIELD	Field*
Turbidity, Field Measured	3.82	NTU		04/25/23 16:50	1	0.00	04/25/23 16:50	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	450	mg/L		05/04/23 10:11	1	10	05/04/23 10:11	CPS	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	< 10	mg/L		05/04/23 10:11	1	10	05/04/23 10:11	CPS	SM 2320B 1997*
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	700	mg/L		04/28/23 14:40	1	26	04/28/23 16:47	HRF	SM 2540C
Total Metals - PIA									
Antimony	< 3.0	ug/L		05/03/23 09:07	5	3.0	05/04/23 09:38	JMW	EPA 6020A
Arsenic	20	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:38	JMW	EPA 6020A
Barium	550	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:38	JMW	EPA 6020A
Beryllium	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:38	JMW	EPA 6020A
Boron	83	ug/L		05/03/23 09:07	5	10	05/05/23 08:27	JMW	EPA 6020A
Cadmium	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:38	JMW	EPA 6020A
Calcium	110	mg/L		05/03/23 09:07	5	0.20	05/04/23 09:38	JMW	EPA 6020A
Chromium	< 4.0	ug/L		05/03/23 09:07	5	4.0	05/04/23 09:38	JMW	EPA 6020A
Cobalt	< 2.0	ug/L		05/03/23 09:07	5	2.0	05/04/23 09:38	JMW	EPA 6020A
Lead	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:38	JMW	EPA 6020A
Magnesium	47	mg/L		05/03/23 09:07	5	0.10	05/04/23 09:38	JMW	EPA 6020A
Mercury	< 0.20	ug/L		05/03/23 09:07	5	0.20	05/05/23 08:27	JMW	EPA 6020A
Molybdenum	5.3	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:38	JMW	EPA 6020A
Potassium	1.6	mg/L		05/03/23 09:07	5	0.10	05/04/23 09:38	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04461-04
Name: APW17
Matrix: Ground Water - Grab

Sampled: 04/25/23 16:50
Received: 04/26/23 14:08

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Selenium	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:38	JMW	EPA 6020A
Sodium	93	mg/L		05/03/23 09:07	5	0.10	05/04/23 09:38	JMW	EPA 6020A
Thallium	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:38	JMW	EPA 6020A
Lithium	< 0.020	mg/L		05/03/23 09:07	1	0.020	05/09/23 10:22	TJJ	EPA 6010B

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ANALYTICAL RESULTS

Sample: GD04461-05
Name: APW18
Matrix: Ground Water - Grab

Sampled: 04/25/23 15:03
Received: 04/26/23 14:08

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	24	mg/L		04/27/23 00:16	10	10	04/27/23 00:16	CRD	EPA 300.0 REV 2.1
Fluoride	0.518	mg/L		04/26/23 23:58	1	0.250	04/26/23 23:58	CRD	EPA 300.0 REV 2.1
Sulfate	52	mg/L		04/27/23 00:16	10	10	04/27/23 00:16	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	51.63	Feet		04/25/23 15:03	1		04/25/23 15:03	FIELD	Field*
Dissolved oxygen, Field	1.0	mg/L		04/25/23 15:03	1		04/25/23 15:03	FIELD	Field*
Oxidation Reduction Potential	-137	mV		04/25/23 15:03	1	-500	04/25/23 15:03	FIELD	Field*
pH, Field Measured	7.78	pH Units		04/25/23 15:03	1		04/25/23 15:03	FIELD	Field*
Specific Conductance, Field Measured	1012	umhos/cm		04/25/23 15:03	1		04/25/23 15:03	FIELD	Field*
Temperature, Field Measured	15.2	°C		04/25/23 15:03	1		04/25/23 15:03	FIELD	Field*
Turbidity, Field Measured	5.01	NTU		04/25/23 15:03	1	0.00	04/25/23 15:03	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	440	mg/L		05/04/23 10:11	1	10	05/04/23 10:11	CPS	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	< 10	mg/L		05/04/23 10:11	1	10	05/04/23 10:11	CPS	SM 2320B 1997*
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	660	mg/L		04/28/23 14:40	1	26	04/28/23 16:47	HRF	SM 2540C
Total Metals - PIA									
Antimony	< 3.0	ug/L		05/03/23 09:07	5	3.0	05/04/23 09:42	JMW	EPA 6020A
Arsenic	2.7	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:42	JMW	EPA 6020A
Barium	350	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:42	JMW	EPA 6020A
Beryllium	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:42	JMW	EPA 6020A
Boron	100	ug/L		05/03/23 09:07	5	10	05/05/23 08:30	JMW	EPA 6020A
Cadmium	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:42	JMW	EPA 6020A
Calcium	75	mg/L		05/03/23 09:07	5	0.20	05/04/23 09:42	JMW	EPA 6020A
Chromium	< 4.0	ug/L		05/03/23 09:07	5	4.0	05/04/23 09:42	JMW	EPA 6020A
Cobalt	< 2.0	ug/L		05/03/23 09:07	5	2.0	05/04/23 09:42	JMW	EPA 6020A
Lead	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:42	JMW	EPA 6020A
Magnesium	40	mg/L		05/03/23 09:07	5	0.10	05/04/23 09:42	JMW	EPA 6020A
Mercury	< 0.20	ug/L		05/03/23 09:07	5	0.20	05/05/23 08:30	JMW	EPA 6020A
Molybdenum	2.9	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:42	JMW	EPA 6020A
Potassium	2.6	mg/L		05/03/23 09:07	5	0.10	05/04/23 09:42	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04461-05
Name: APW18
Matrix: Ground Water - Grab

Sampled: 04/25/23 15:03
Received: 04/26/23 14:08

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Selenium	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:42	JMW	EPA 6020A
Sodium	110	mg/L		05/03/23 09:07	5	0.10	05/04/23 09:42	JMW	EPA 6020A
Thallium	< 1.0	ug/L		05/03/23 09:07	5	1.0	05/04/23 09:42	JMW	EPA 6020A
Lithium	< 0.020	mg/L		05/03/23 09:07	1	0.020	05/09/23 10:23	TJJ	EPA 6010B

Sample: GD04461-27
Name: XSG01
Matrix: Ground Water

Sampled: 04/24/23 17:16
Received: 04/26/23 14:08

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Field - PIA									
Depth, From Measuring Point	5.34	Feet		04/24/23 17:16	1		04/24/23 17:16	FIELD	Field*

Sample: GD04461-28
Name: SG02
Matrix: Ground Water

Sampled: 04/24/23 14:44
Received: 04/26/23 14:08

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Field - PIA									
Depth, From Measuring Point	2.11	Feet		04/24/23 14:44	1		04/24/23 14:44	FIELD	Field*

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ANALYTICAL RESULTS

Sample: GD04746-02
Name: APW05S
Matrix: Ground Water - Grab

Sampled: 04/26/23 17:40
Received: 04/27/23 14:20

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	200	mg/L		04/29/23 21:22	100	100	04/29/23 21:22	CRD	EPA 300.0 REV 2.1
Sulfate	2100	mg/L		04/27/23 21:31	250	250	04/27/23 21:31	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	9.46	Feet		04/26/23 17:40	1		04/26/23 17:40	FIELD	Field*
Dissolved oxygen, Field	3.5	mg/L		04/26/23 17:40	1		04/26/23 17:40	FIELD	Field*
Oxidation Reduction Potential	97.0	mV		04/26/23 17:40	1	-500	04/26/23 17:40	FIELD	Field*
pH, Field Measured	6.60	pH Units		04/26/23 17:40	1		04/26/23 17:40	FIELD	Field*
Specific Conductance, Field Measured	3930	umhos/cm		04/26/23 17:40	1		04/26/23 17:40	FIELD	Field*
Temperature, Field Measured	16.4	°C		04/26/23 17:40	1		04/26/23 17:40	FIELD	Field*
Turbidity, Field Measured	220	NTU		04/26/23 17:40	1	0.00	04/26/23 17:40	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	520	mg/L		05/05/23 09:44	1	10	05/05/23 09:44	HRF	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	< 10	mg/L		05/05/23 09:44	1	10	05/05/23 09:44	HRF	SM 2320B 1997*
Fluoride	0.365	mg/L		05/05/23 16:50	1	0.250	05/05/23 16:50	TTH	SM 4500F C 1997
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	3800	mg/L		05/01/23 11:30	1	26	05/01/23 15:30	HRF	SM 2540C
Total Metals - PIA									
Antimony	< 3.0	ug/L		05/04/23 09:03	5	3.0	05/09/23 07:20	JMW	EPA 6020A
Arsenic	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/10/23 07:33	JMW	EPA 6020A
Barium	35	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:20	JMW	EPA 6020A
Beryllium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:20	JMW	EPA 6020A
Boron	54	ug/L		05/04/23 09:03	5	10	05/09/23 07:20	JMW	EPA 6020A
Cadmium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:20	JMW	EPA 6020A
Calcium	390	mg/L	Q4	05/04/23 09:03	5	0.20	05/09/23 07:20	JMW	EPA 6020A
Chromium	< 4.0	ug/L		05/04/23 09:03	5	4.0	05/09/23 07:20	JMW	EPA 6020A
Cobalt	< 2.0	ug/L		05/04/23 09:03	5	2.0	05/09/23 07:20	JMW	EPA 6020A
Lead	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:20	JMW	EPA 6020A
Magnesium	300	mg/L	Q4	05/04/23 09:03	5	0.10	05/09/23 07:20	JMW	EPA 6020A
Mercury	< 0.20	ug/L		05/04/23 09:03	5	0.20	05/09/23 07:58	JMW	EPA 6020A
Molybdenum	1.3	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:20	JMW	EPA 6020A
Potassium	1.8	mg/L		05/04/23 09:03	5	0.10	05/09/23 07:20	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04746-02
Name: APW05S
Matrix: Ground Water - Grab

Sampled: 04/26/23 17:40
Received: 04/27/23 14:20

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Selenium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:20	JMW	EPA 6020A
Sodium	260	mg/L	Q4	05/04/23 09:03	5	0.10	05/09/23 07:20	JMW	EPA 6020A
Thallium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:20	JMW	EPA 6020A
Lithium	0.033	mg/L		05/04/23 09:03	1	0.020	05/09/23 10:31	TJJ	EPA 6010B

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ANALYTICAL RESULTS

Sample: GD04746-03
Name: APW06
Matrix: Ground Water - Grab

Sampled: 04/26/23 16:00
Received: 04/27/23 14:20

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	26	mg/L		04/27/23 22:07	10	10	04/27/23 22:07	CRD	EPA 300.0 REV 2.1
Fluoride	0.489	mg/L		04/27/23 21:49	1	0.250	04/27/23 21:49	CRD	EPA 300.0 REV 2.1
Sulfate	7.6	mg/L		04/27/23 21:49	1	1.0	04/27/23 21:49	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	19.33	Feet		04/26/23 16:00	1		04/26/23 16:00	FIELD	Field*
Dissolved oxygen, Field	11	mg/L		04/26/23 16:00	1		04/26/23 16:00	FIELD	Field*
Oxidation Reduction Potential	-128	mV		04/26/23 16:00	1	-500	04/26/23 16:00	FIELD	Field*
pH, Field Measured	7.35	pH Units		04/26/23 16:00	1		04/26/23 16:00	FIELD	Field*
Specific Conductance, Field Measured	796.0	umhos/cm		04/26/23 16:00	1		04/26/23 16:00	FIELD	Field*
Temperature, Field Measured	17.6	°C		04/26/23 16:00	1		04/26/23 16:00	FIELD	Field*
Turbidity, Field Measured	471	NTU		04/26/23 16:00	1	0.00	04/26/23 16:00	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	380	mg/L		05/05/23 09:44	1	10	05/05/23 09:44	HRF	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	< 10	mg/L		05/05/23 09:44	1	10	05/05/23 09:44	HRF	SM 2320B 1997*
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	500	mg/L		05/01/23 11:30	1	26	05/01/23 15:30	HRF	SM 2540C
Total Metals - PIA									
Antimony	< 3.0	ug/L		05/04/23 09:03	5	3.0	05/09/23 07:24	JMW	EPA 6020A
Arsenic	9.2	ug/L		05/04/23 09:03	5	1.0	05/10/23 07:42	JMW	EPA 6020A
Barium	240	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:24	JMW	EPA 6020A
Beryllium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:24	JMW	EPA 6020A
Boron	87	ug/L		05/04/23 09:03	5	10	05/09/23 07:24	JMW	EPA 6020A
Cadmium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:24	JMW	EPA 6020A
Calcium	58	mg/L		05/04/23 09:03	5	0.20	05/09/23 07:24	JMW	EPA 6020A
Chromium	7.9	ug/L		05/04/23 09:03	5	4.0	05/09/23 07:24	JMW	EPA 6020A
Cobalt	< 2.0	ug/L		05/04/23 09:03	5	2.0	05/09/23 07:24	JMW	EPA 6020A
Lead	1.7	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:24	JMW	EPA 6020A
Magnesium	27	mg/L		05/04/23 09:03	5	0.10	05/09/23 07:24	JMW	EPA 6020A
Mercury	< 0.20	ug/L		05/04/23 09:03	5	0.20	05/09/23 07:24	JMW	EPA 6020A
Molybdenum	7.7	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:24	JMW	EPA 6020A
Potassium	1.5	mg/L		05/04/23 09:03	5	0.10	05/09/23 07:24	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04746-03
Name: APW06
Matrix: Ground Water - Grab

Sampled: 04/26/23 16:00
Received: 04/27/23 14:20

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Selenium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:24	JMW	EPA 6020A
Sodium	120	mg/L		05/04/23 09:03	5	0.10	05/09/23 07:24	JMW	EPA 6020A
Thallium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:24	JMW	EPA 6020A
Lithium	< 0.020	mg/L		05/04/23 09:03	1	0.020	05/09/23 10:34	TJJ	EPA 6010B

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ANALYTICAL RESULTS

Sample: GD04746-04
Name: APW08
Matrix: Ground Water - Grab

Sampled: 04/26/23 12:11
Received: 04/27/23 14:20

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	58	mg/L		04/27/23 22:43	10	10	04/27/23 22:43	CRD	EPA 300.0 REV 2.1
Fluoride	0.404	mg/L		04/27/23 22:25	1	0.250	04/27/23 22:25	CRD	EPA 300.0 REV 2.1
Sulfate	48	mg/L		04/27/23 22:43	10	10	04/27/23 22:43	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	37.56	Feet		04/26/23 12:11	1		04/26/23 12:11	FIELD	Field*
Dissolved oxygen, Field	1.7	mg/L		04/26/23 12:11	1		04/26/23 12:11	FIELD	Field*
Oxidation Reduction Potential	-118	mV		04/26/23 12:11	1	-500	04/26/23 12:11	FIELD	Field*
pH, Field Measured	7.52	pH Units		04/26/23 12:11	1		04/26/23 12:11	FIELD	Field*
Specific Conductance, Field Measured	1100	umhos/cm		04/26/23 12:11	1		04/26/23 12:11	FIELD	Field*
Temperature, Field Measured	14.2	°C		04/26/23 12:11	1		04/26/23 12:11	FIELD	Field*
Turbidity, Field Measured	17.7	NTU		04/26/23 12:11	1	0.00	04/26/23 12:11	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	410	mg/L		05/05/23 09:44	1	10	05/05/23 09:44	HRF	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	< 10	mg/L		05/05/23 09:44	1	10	05/05/23 09:44	HRF	SM 2320B 1997*
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	640	mg/L		05/01/23 11:30	1	26	05/01/23 15:30	HRF	SM 2540C
Total Metals - PIA									
Antimony	< 3.0	ug/L		05/04/23 09:03	5	3.0	05/09/23 07:27	JMW	EPA 6020A
Arsenic	26	ug/L		05/04/23 09:03	5	1.0	05/10/23 07:45	JMW	EPA 6020A
Barium	470	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:27	JMW	EPA 6020A
Beryllium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:27	JMW	EPA 6020A
Boron	87	ug/L		05/04/23 09:03	5	10	05/09/23 07:27	JMW	EPA 6020A
Cadmium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:27	JMW	EPA 6020A
Calcium	110	mg/L		05/04/23 09:03	5	0.20	05/09/23 07:27	JMW	EPA 6020A
Chromium	7.6	ug/L		05/04/23 09:03	5	4.0	05/09/23 07:27	JMW	EPA 6020A
Cobalt	2.2	ug/L		05/04/23 09:03	5	2.0	05/09/23 07:27	JMW	EPA 6020A
Lead	3.3	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:27	JMW	EPA 6020A
Magnesium	45	mg/L		05/04/23 09:03	5	0.10	05/09/23 07:27	JMW	EPA 6020A
Mercury	< 0.20	ug/L		05/04/23 09:03	5	0.20	05/09/23 07:27	JMW	EPA 6020A
Molybdenum	4.4	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:27	JMW	EPA 6020A
Potassium	2.0	mg/L		05/04/23 09:03	5	0.10	05/09/23 07:27	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04746-04
Name: APW08
Matrix: Ground Water - Grab

Sampled: 04/26/23 12:11
Received: 04/27/23 14:20

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Selenium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:27	JMW	EPA 6020A
Sodium	91	mg/L		05/04/23 09:03	5	0.10	05/09/23 07:27	JMW	EPA 6020A
Thallium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:27	JMW	EPA 6020A
Lithium	< 0.020	mg/L		05/04/23 09:03	1	0.020	05/09/23 10:35	TJJ	EPA 6010B

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ANALYTICAL RESULTS

Sample: GD04746-05
Name: APW11
Matrix: Ground Water - Grab

Sampled: 04/26/23 15:43
Received: 04/27/23 14:20

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	26	mg/L		04/27/23 23:19	5	5.0	04/27/23 23:19	CRD	EPA 300.0 REV 2.1
Fluoride	0.283	mg/L		04/27/23 23:01	1	0.250	04/27/23 23:01	CRD	EPA 300.0 REV 2.1
Sulfate	260	mg/L		04/27/23 23:37	50	50	04/27/23 23:37	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	24.27	Feet		04/26/23 15:43	1		04/26/23 15:43	FIELD	Field*
Dissolved oxygen, Field	0.64	mg/L		04/26/23 15:43	1		04/26/23 15:43	FIELD	Field*
Oxidation Reduction Potential	-17.8	mV		04/26/23 15:43	1	-500	04/26/23 15:43	FIELD	Field*
pH, Field Measured	7.15	pH Units		04/26/23 15:43	1		04/26/23 15:43	FIELD	Field*
Specific Conductance, Field Measured	1252	umhos/cm		04/26/23 15:43	1		04/26/23 15:43	FIELD	Field*
Temperature, Field Measured	15.5	°C		04/26/23 15:43	1		04/26/23 15:43	FIELD	Field*
Turbidity, Field Measured	446	NTU		04/26/23 15:43	1	0.00	04/26/23 15:43	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	350	mg/L		05/05/23 09:44	1	10	05/05/23 09:44	HRF	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	< 10	mg/L		05/05/23 09:44	1	10	05/05/23 09:44	HRF	SM 2320B 1997*
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	920	mg/L		05/01/23 11:30	1	26	05/01/23 15:30	HRF	SM 2540C
Total Metals - PIA									
Antimony	< 3.0	ug/L		05/04/23 09:03	5	3.0	05/09/23 07:31	JMW	EPA 6020A
Arsenic	4.4	ug/L		05/04/23 09:03	5	1.0	05/10/23 07:48	JMW	EPA 6020A
Barium	43	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:31	JMW	EPA 6020A
Beryllium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:31	JMW	EPA 6020A
Boron	64	ug/L		05/04/23 09:03	5	10	05/09/23 07:31	JMW	EPA 6020A
Cadmium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:31	JMW	EPA 6020A
Calcium	120	mg/L		05/04/23 09:03	5	0.20	05/09/23 07:31	JMW	EPA 6020A
Chromium	7.0	ug/L		05/04/23 09:03	5	4.0	05/09/23 07:31	JMW	EPA 6020A
Cobalt	2.1	ug/L		05/04/23 09:03	5	2.0	05/09/23 07:31	JMW	EPA 6020A
Lead	6.3	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:31	JMW	EPA 6020A
Magnesium	57	mg/L		05/04/23 09:03	5	0.10	05/09/23 07:31	JMW	EPA 6020A
Mercury	< 0.20	ug/L		05/04/23 09:03	5	0.20	05/09/23 07:31	JMW	EPA 6020A
Molybdenum	4.3	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:31	JMW	EPA 6020A
Potassium	1.9	mg/L		05/04/23 09:03	5	0.10	05/09/23 07:31	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04746-05
Name: APW11
Matrix: Ground Water - Grab

Sampled: 04/26/23 15:43
Received: 04/27/23 14:20

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Selenium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:31	JMW	EPA 6020A
Sodium	93	mg/L		05/04/23 09:03	5	0.10	05/09/23 07:31	JMW	EPA 6020A
Thallium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:31	JMW	EPA 6020A
Lithium	< 0.020	mg/L		05/04/23 09:03	1	0.020	05/09/23 10:36	TJJ	EPA 6010B

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ANALYTICAL RESULTS

Sample: GD04746-06
Name: APW12
Matrix: Ground Water - Grab

Sampled: 04/26/23 13:56
Received: 04/27/23 14:20

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	23	mg/L		04/28/23 00:13	5	5.0	04/28/23 00:13	CRD	EPA 300.0 REV 2.1
Fluoride	< 0.250	mg/L		04/28/23 00:13	1	0.250	04/28/23 00:13	CRD	EPA 300.0 REV 2.1
Sulfate	540	mg/L		04/29/23 21:58	100	100	04/29/23 21:58	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	14.56	Feet		04/26/23 13:56	1		04/26/23 13:56	FIELD	Field*
Dissolved oxygen, Field	0.98	mg/L		04/26/23 13:56	1		04/26/23 13:56	FIELD	Field*
Oxidation Reduction Potential	107	mV		04/26/23 13:56	1	-500	04/26/23 13:56	FIELD	Field*
pH, Field Measured	6.52	pH Units		04/26/23 13:56	1		04/26/23 13:56	FIELD	Field*
Specific Conductance, Field Measured	1831	umhos/cm		04/26/23 13:56	1		04/26/23 13:56	FIELD	Field*
Temperature, Field Measured	14.6	°C		04/26/23 13:56	1		04/26/23 13:56	FIELD	Field*
Turbidity, Field Measured	0.520	NTU		04/26/23 13:56	1	0.00	04/26/23 13:56	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	520	mg/L		05/05/23 09:44	1	10	05/05/23 09:44	HRF	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	< 10	mg/L		05/05/23 09:44	1	10	05/05/23 09:44	HRF	SM 2320B 1997*
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	1500	mg/L		05/01/23 11:30	1	26	05/01/23 15:30	HRF	SM 2540C
Total Metals - PIA									
Antimony	< 3.0	ug/L		05/04/23 09:03	5	3.0	05/09/23 07:35	JMW	EPA 6020A
Arsenic	1.4	ug/L		05/04/23 09:03	5	1.0	05/10/23 07:50	JMW	EPA 6020A
Barium	28	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:35	JMW	EPA 6020A
Beryllium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:35	JMW	EPA 6020A
Boron	440	ug/L		05/04/23 09:03	5	10	05/09/23 07:35	JMW	EPA 6020A
Cadmium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:35	JMW	EPA 6020A
Calcium	230	mg/L		05/04/23 09:03	5	0.20	05/09/23 07:35	JMW	EPA 6020A
Chromium	< 4.0	ug/L		05/04/23 09:03	5	4.0	05/09/23 07:35	JMW	EPA 6020A
Cobalt	< 2.0	ug/L		05/04/23 09:03	5	2.0	05/09/23 07:35	JMW	EPA 6020A
Lead	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:35	JMW	EPA 6020A
Magnesium	110	mg/L		05/04/23 09:03	5	0.10	05/09/23 07:35	JMW	EPA 6020A
Mercury	< 0.20	ug/L		05/04/23 09:03	5	0.20	05/09/23 07:35	JMW	EPA 6020A
Molybdenum	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:35	JMW	EPA 6020A
Potassium	0.94	mg/L		05/04/23 09:03	5	0.10	05/09/23 07:35	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04746-06
Name: APW12
Matrix: Ground Water - Grab

Sampled: 04/26/23 13:56
Received: 04/27/23 14:20

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Selenium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:35	JMW	EPA 6020A
Sodium	120	mg/L		05/04/23 09:03	5	0.10	05/09/23 07:35	JMW	EPA 6020A
Thallium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:35	JMW	EPA 6020A
Lithium	0.024	mg/L		05/04/23 09:03	1	0.020	05/09/23 10:38	TJJ	EPA 6010B

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ANALYTICAL RESULTS

Sample: GD04746-07
Name: APW15
Matrix: Ground Water - Grab

Sampled: 04/26/23 17:23
Received: 04/27/23 14:20

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	270	mg/L		04/29/23 22:34	50	50	04/29/23 22:34	CRD	EPA 300.0 REV 2.1
Fluoride	0.402	mg/L		04/28/23 01:27	1	0.250	04/28/23 01:27	CRD	EPA 300.0 REV 2.1
Sulfate	< 1.0	mg/L		04/28/23 01:27	1	1.0	04/28/23 01:27	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	21.43	Feet		04/26/23 17:23	1		04/26/23 17:23	FIELD	Field*
Dissolved oxygen, Field	0.32	mg/L		04/26/23 17:23	1		04/26/23 17:23	FIELD	Field*
Oxidation Reduction Potential	-126	mV		04/26/23 17:23	1	-500	04/26/23 17:23	FIELD	Field*
pH, Field Measured	7.25	pH Units		04/26/23 17:23	1		04/26/23 17:23	FIELD	Field*
Specific Conductance, Field Measured	1682	umhos/cm		04/26/23 17:23	1		04/26/23 17:23	FIELD	Field*
Temperature, Field Measured	15.3	°C		04/26/23 17:23	1		04/26/23 17:23	FIELD	Field*
Turbidity, Field Measured	51.6	NTU		04/26/23 17:23	1	0.00	04/26/23 17:23	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	590	mg/L		05/05/23 09:44	1	10	05/05/23 09:44	HRF	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	< 10	mg/L		05/05/23 09:44	1	10	05/05/23 09:44	HRF	SM 2320B 1997*
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	1100	mg/L		05/01/23 11:30	1	26	05/01/23 15:30	HRF	SM 2540C
Total Metals - PIA									
Antimony	< 3.0	ug/L		05/04/23 09:03	5	3.0	05/09/23 07:39	JMW	EPA 6020A
Arsenic	21	ug/L		05/04/23 09:03	5	1.0	05/10/23 07:53	JMW	EPA 6020A
Barium	530	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:39	JMW	EPA 6020A
Beryllium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:39	JMW	EPA 6020A
Boron	130	ug/L		05/04/23 09:03	5	10	05/09/23 07:39	JMW	EPA 6020A
Cadmium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:39	JMW	EPA 6020A
Calcium	91	mg/L		05/04/23 09:03	5	0.20	05/09/23 07:39	JMW	EPA 6020A
Chromium	6.4	ug/L		05/04/23 09:03	5	4.0	05/09/23 07:39	JMW	EPA 6020A
Cobalt	< 2.0	ug/L		05/04/23 09:03	5	2.0	05/09/23 07:39	JMW	EPA 6020A
Lead	1.2	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:39	JMW	EPA 6020A
Magnesium	38	mg/L		05/04/23 09:03	5	0.10	05/09/23 07:39	JMW	EPA 6020A
Mercury	< 0.20	ug/L		05/04/23 09:03	5	0.20	05/09/23 07:39	JMW	EPA 6020A
Molybdenum	6.5	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:39	JMW	EPA 6020A
Potassium	3.0	mg/L		05/04/23 09:03	5	0.10	05/09/23 07:39	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04746-07
Name: APW15
Matrix: Ground Water - Grab

Sampled: 04/26/23 17:23
Received: 04/27/23 14:20

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Selenium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:39	JMW	EPA 6020A
Sodium	290	mg/L		05/04/23 09:03	5	0.10	05/09/23 07:39	JMW	EPA 6020A
Thallium	< 1.0	ug/L		05/04/23 09:03	5	1.0	05/09/23 07:39	JMW	EPA 6020A
Lithium	< 0.020	mg/L		05/04/23 09:03	1	0.020	05/09/23 10:39	TJJ	EPA 6010B

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ANALYTICAL RESULTS

Sample: GD04839-03
Name: APW02
Matrix: Ground Water - Grab

Sampled: 04/27/23 12:17
Received: 04/28/23 12:45

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	110	mg/L		04/28/23 19:45	25	25	04/28/23 19:45	CRD	EPA 300.0 REV 2.1
Sulfate	3100	mg/L		04/28/23 20:03	500	500	04/28/23 20:03	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	3.72	Feet		04/27/23 12:17	1		04/27/23 12:17	FIELD	Field*
Dissolved oxygen, Field	1.2	mg/L		04/27/23 12:17	1		04/27/23 12:17	FIELD	Field*
Oxidation Reduction Potential	80.8	mV		04/27/23 12:17	1	-500	04/27/23 12:17	FIELD	Field*
pH, Field Measured	6.71	pH Units		04/27/23 12:17	1		04/27/23 12:17	FIELD	Field*
Specific Conductance, Field Measured	5217	umhos/cm		04/27/23 12:17	1		04/27/23 12:17	FIELD	Field*
Temperature, Field Measured	15.6	°C		04/27/23 12:17	1		04/27/23 12:17	FIELD	Field*
Turbidity, Field Measured	25.0	NTU		04/27/23 12:17	1	0.00	04/27/23 12:17	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	640	mg/L		05/08/23 13:35	1	10	05/08/23 13:35	CPS	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	< 10	mg/L		05/08/23 13:35	1	10	05/08/23 13:35	CPS	SM 2320B 1997*
Fluoride	< 0.250	mg/L		05/05/23 16:47	1	0.250	05/05/23 16:47	TTH	SM 4500F C 1997
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	5400	mg/L		05/02/23 12:44	1	26	05/03/23 11:06	HRF	SM 2540C
Total Metals - PIA									
Antimony	< 3.0	ug/L		05/08/23 09:07	5	3.0	05/09/23 12:38	JMW	EPA 6020A
Arsenic	1.4	ug/L		05/08/23 09:07	5	1.0	05/10/23 09:18	JMW	EPA 6020A
Barium	24	ug/L		05/08/23 09:07	5	1.0	05/09/23 12:38	JMW	EPA 6020A
Beryllium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 09:54	JMW	EPA 6020A
Boron	120	ug/L		05/08/23 09:07	5	10	05/09/23 09:54	JMW	EPA 6020A
Cadmium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 12:38	JMW	EPA 6020A
Calcium	460	mg/L		05/08/23 09:07	5	0.20	05/09/23 09:54	JMW	EPA 6020A
Chromium	< 4.0	ug/L		05/08/23 09:07	5	4.0	05/09/23 09:54	JMW	EPA 6020A
Cobalt	< 2.0	ug/L		05/08/23 09:07	5	2.0	05/09/23 09:54	JMW	EPA 6020A
Lead	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 09:54	JMW	EPA 6020A
Magnesium	430	mg/L		05/08/23 09:07	5	0.10	05/09/23 09:54	JMW	EPA 6020A
Mercury	< 0.20	ug/L		05/08/23 09:07	5	0.20	05/09/23 12:38	JMW	EPA 6020A
Molybdenum	1.6	ug/L		05/08/23 09:07	5	1.0	05/09/23 12:38	JMW	EPA 6020A
Potassium	5.8	mg/L		05/08/23 09:07	5	0.10	05/09/23 09:54	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04839-03
Name: APW02
Matrix: Ground Water - Grab

Sampled: 04/27/23 12:17
Received: 04/28/23 12:45

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Selenium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 09:54	JMW	EPA 6020A
Sodium	360	mg/L		05/08/23 09:07	5	0.10	05/09/23 09:54	JMW	EPA 6020A
Thallium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 09:54	JMW	EPA 6020A
Lithium	0.098	mg/L		05/08/23 09:07	1	0.020	05/09/23 10:47	TJJ	EPA 6010B

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ANALYTICAL RESULTS

Sample: GD04839-04
Name: APW05
Matrix: Ground Water - Grab

Sampled: 04/27/23 12:40
Received: 04/28/23 12:45

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	46	mg/L	Q4	04/28/23 17:02	10	10	04/28/23 17:02	CRD	EPA 300.0 REV 2.1
Fluoride	0.498	mg/L		04/28/23 16:08	1	0.250	04/28/23 16:08	CRD	EPA 300.0 REV 2.1
Sulfate	< 1.0	mg/L		04/28/23 16:08	1	1.0	04/28/23 16:08	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	14.01	Feet		04/27/23 12:40	1		04/27/23 12:40	FIELD	Field*
Dissolved oxygen, Field	18	mg/L		04/27/23 12:40	1		04/27/23 12:40	FIELD	Field*
Oxidation Reduction Potential	-124	mV		04/27/23 12:40	1	-500	04/27/23 12:40	FIELD	Field*
pH, Field Measured	7.10	pH Units		04/27/23 12:40	1		04/27/23 12:40	FIELD	Field*
Specific Conductance, Field Measured	819.0	umhos/cm		04/27/23 12:40	1		04/27/23 12:40	FIELD	Field*
Temperature, Field Measured	14.5	°C		04/27/23 12:40	1		04/27/23 12:40	FIELD	Field*
Turbidity, Field Measured	40.1	NTU		04/27/23 12:40	1	0.00	04/27/23 12:40	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	480	mg/L		05/08/23 13:35	1	10	05/08/23 13:35	CPS	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	< 10	mg/L		05/08/23 13:35	1	10	05/08/23 13:35	CPS	SM 2320B 1997*
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	560	mg/L		05/02/23 12:44	1	26	05/03/23 11:06	HRF	SM 2540C
Total Metals - PIA									
Antimony	< 3.0	ug/L		05/08/23 09:07	5	3.0	05/09/23 12:42	JMW	EPA 6020A
Arsenic	30	ug/L		05/08/23 09:07	5	1.0	05/10/23 09:21	JMW	EPA 6020A
Barium	250	ug/L		05/08/23 09:07	5	1.0	05/09/23 12:42	JMW	EPA 6020A
Beryllium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 09:58	JMW	EPA 6020A
Boron	92	ug/L		05/08/23 09:07	5	10	05/09/23 09:58	JMW	EPA 6020A
Cadmium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 12:42	JMW	EPA 6020A
Calcium	49	mg/L		05/08/23 09:07	5	0.20	05/09/23 09:58	JMW	EPA 6020A
Chromium	< 4.0	ug/L		05/08/23 09:07	5	4.0	05/09/23 09:58	JMW	EPA 6020A
Cobalt	< 2.0	ug/L		05/08/23 09:07	5	2.0	05/09/23 09:58	JMW	EPA 6020A
Lead	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 09:58	JMW	EPA 6020A
Magnesium	26	mg/L		05/08/23 09:07	5	0.10	05/09/23 09:58	JMW	EPA 6020A
Mercury	< 0.20	ug/L		05/08/23 09:07	5	0.20	05/09/23 12:42	JMW	EPA 6020A
Molybdenum	9.1	ug/L		05/08/23 09:07	5	1.0	05/09/23 12:42	JMW	EPA 6020A
Potassium	1.4	mg/L		05/08/23 09:07	5	0.10	05/09/23 09:58	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04839-04
Name: APW05
Matrix: Ground Water - Grab

Sampled: 04/27/23 12:40
Received: 04/28/23 12:45

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Selenium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 09:58	JMW	EPA 6020A
Sodium	130	mg/L		05/08/23 09:07	5	0.10	05/09/23 09:58	JMW	EPA 6020A
Thallium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 09:58	JMW	EPA 6020A
Lithium	< 0.020	mg/L		05/08/23 09:07	1	0.020	05/09/23 10:48	TJJ	EPA 6010B

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ANALYTICAL RESULTS

Sample: GD04839-05
Name: APW07
Matrix: Ground Water - Grab

Sampled: 04/27/23 10:35
Received: 04/28/23 12:45

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	63	mg/L		04/28/23 17:38	10	10	04/28/23 17:38	CRD	EPA 300.0 REV 2.1
Fluoride	0.409	mg/L		04/28/23 17:20	1	0.250	04/28/23 17:20	CRD	EPA 300.0 REV 2.1
Sulfate	14	mg/L		04/28/23 17:38	10	10	04/28/23 17:38	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	46.59	Feet		04/27/23 10:35	1		04/27/23 10:35	FIELD	Field*
Dissolved oxygen, Field	0.51	mg/L		04/27/23 10:35	1		04/27/23 10:35	FIELD	Field*
Oxidation Reduction Potential	-116	mV		04/27/23 10:35	1	-500	04/27/23 10:35	FIELD	Field*
pH, Field Measured	7.39	pH Units		04/27/23 10:35	1		04/27/23 10:35	FIELD	Field*
Specific Conductance, Field Measured	1051	umhos/cm		04/27/23 10:35	1		04/27/23 10:35	FIELD	Field*
Temperature, Field Measured	14.5	°C		04/27/23 10:35	1		04/27/23 10:35	FIELD	Field*
Turbidity, Field Measured	621	NTU		04/27/23 10:35	1	0.00	04/27/23 10:35	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	500	mg/L		05/08/23 13:35	1	10	05/08/23 13:35	CPS	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	< 10	mg/L		05/08/23 13:35	1	10	05/08/23 13:35	CPS	SM 2320B 1997*
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	590	mg/L		05/02/23 12:44	1	26	05/03/23 11:06	HRF	SM 2540C
Total Metals - PIA									
Antimony	< 3.0	ug/L		05/08/23 09:07	5	3.0	05/09/23 12:46	JMW	EPA 6020A
Arsenic	18	ug/L		05/08/23 09:07	5	1.0	05/10/23 09:24	JMW	EPA 6020A
Barium	510	ug/L		05/08/23 09:07	5	1.0	05/09/23 12:46	JMW	EPA 6020A
Beryllium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 10:02	JMW	EPA 6020A
Boron	85	ug/L		05/08/23 09:07	5	10	05/09/23 10:02	JMW	EPA 6020A
Cadmium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 12:46	JMW	EPA 6020A
Calcium	100	mg/L		05/08/23 09:07	5	0.20	05/09/23 10:02	JMW	EPA 6020A
Chromium	17	ug/L		05/08/23 09:07	5	4.0	05/09/23 10:02	JMW	EPA 6020A
Cobalt	3.6	ug/L		05/08/23 09:07	5	2.0	05/09/23 10:02	JMW	EPA 6020A
Lead	5.5	ug/L		05/08/23 09:07	5	1.0	05/09/23 10:02	JMW	EPA 6020A
Magnesium	40	mg/L		05/08/23 09:07	5	0.10	05/09/23 10:02	JMW	EPA 6020A
Mercury	< 0.20	ug/L		05/08/23 09:07	5	0.20	05/09/23 12:46	JMW	EPA 6020A
Molybdenum	3.4	ug/L		05/08/23 09:07	5	1.0	05/09/23 12:46	JMW	EPA 6020A
Potassium	2.5	mg/L		05/08/23 09:07	5	0.10	05/09/23 10:02	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04839-05
Name: APW07
Matrix: Ground Water - Grab

Sampled: 04/27/23 10:35
Received: 04/28/23 12:45

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Selenium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 10:02	JMW	EPA 6020A
Sodium	93	mg/L		05/08/23 09:07	5	0.10	05/09/23 10:02	JMW	EPA 6020A
Thallium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 10:02	JMW	EPA 6020A
Lithium	< 0.020	mg/L		05/08/23 09:07	1	0.020	05/09/23 10:49	TJJ	EPA 6010B

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ANALYTICAL RESULTS

Sample: GD04839-06
Name: APW09
Matrix: Ground Water - Grab

Sampled: 04/27/23 14:05
Received: 04/28/23 12:45

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	130	mg/L		04/28/23 19:09	25	25	04/28/23 19:09	CRD	EPA 300.0 REV 2.1
Fluoride	0.482	mg/L		04/28/23 17:57	1	0.250	04/28/23 17:57	CRD	EPA 300.0 REV 2.1
Sulfate	9.4	mg/L		04/28/23 18:51	5	5.0	04/28/23 18:51	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	26.56	Feet		04/27/23 14:05	1		04/27/23 14:05	FIELD	Field*
Dissolved oxygen, Field	0.47	mg/L		04/27/23 14:05	1		04/27/23 14:05	FIELD	Field*
Oxidation Reduction Potential	-137	mV		04/27/23 14:05	1	-500	04/27/23 14:05	FIELD	Field*
pH, Field Measured	7.53	pH Units		04/27/23 14:05	1		04/27/23 14:05	FIELD	Field*
Specific Conductance, Field Measured	1356	umhos/cm		04/27/23 14:05	1		04/27/23 14:05	FIELD	Field*
Temperature, Field Measured	16.5	°C		04/27/23 14:05	1		04/27/23 14:05	FIELD	Field*
Turbidity, Field Measured	117	NTU		04/27/23 14:05	1	0.00	04/27/23 14:05	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	600	mg/L		05/08/23 13:35	1	10	05/08/23 13:35	CPS	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	< 10	mg/L		05/08/23 13:35	1	10	05/08/23 13:35	CPS	SM 2320B 1997*
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	840	mg/L		05/02/23 12:44	1	26	05/03/23 11:06	HRF	SM 2540C
Total Metals - PIA									
Antimony	< 3.0	ug/L		05/08/23 09:07	5	3.0	05/09/23 12:50	JMW	EPA 6020A
Arsenic	29	ug/L		05/08/23 09:07	5	1.0	05/10/23 09:27	JMW	EPA 6020A
Barium	430	ug/L		05/08/23 09:07	5	1.0	05/09/23 12:50	JMW	EPA 6020A
Beryllium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 10:06	JMW	EPA 6020A
Boron	99	ug/L		05/08/23 09:07	5	10	05/09/23 10:06	JMW	EPA 6020A
Cadmium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 12:50	JMW	EPA 6020A
Calcium	76	mg/L		05/08/23 09:07	5	0.20	05/09/23 10:06	JMW	EPA 6020A
Chromium	4.2	ug/L		05/08/23 09:07	5	4.0	05/09/23 10:06	JMW	EPA 6020A
Cobalt	< 2.0	ug/L		05/08/23 09:07	5	2.0	05/09/23 10:06	JMW	EPA 6020A
Lead	1.3	ug/L		05/08/23 09:07	5	1.0	05/09/23 10:06	JMW	EPA 6020A
Magnesium	38	mg/L		05/08/23 09:07	5	0.10	05/09/23 10:06	JMW	EPA 6020A
Mercury	< 0.20	ug/L		05/08/23 09:07	5	0.20	05/09/23 12:50	JMW	EPA 6020A
Molybdenum	3.9	ug/L		05/08/23 09:07	5	1.0	05/09/23 12:50	JMW	EPA 6020A
Potassium	1.7	mg/L		05/08/23 09:07	5	0.10	05/09/23 10:06	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04839-06
Name: APW09
Matrix: Ground Water - Grab

Sampled: 04/27/23 14:05
Received: 04/28/23 12:45

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Selenium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 10:06	JMW	EPA 6020A
Sodium	190	mg/L		05/08/23 09:07	5	0.10	05/09/23 10:06	JMW	EPA 6020A
Thallium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 10:06	JMW	EPA 6020A
Lithium	< 0.020	mg/L		05/08/23 09:07	1	0.020	05/09/23 10:50	TJJ	EPA 6010B

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ANALYTICAL RESULTS

Sample: GD04839-07
Name: APW10
Matrix: Ground Water - Grab

Sampled: 04/27/23 15:47
Received: 04/28/23 12:45

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	46	mg/L		04/29/23 13:25	10	10	04/29/23 13:25	CRD	EPA 300.0 REV 2.1
Fluoride	< 0.250	mg/L		04/29/23 13:07	1	0.250	04/29/23 13:07	CRD	EPA 300.0 REV 2.1
Sulfate	410	mg/L		04/29/23 13:43	100	100	04/29/23 13:43	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	17.53	Feet		04/27/23 15:47	1		04/27/23 15:47	FIELD	Field*
Dissolved oxygen, Field	3.4	mg/L		04/27/23 15:47	1		04/27/23 15:47	FIELD	Field*
Oxidation Reduction Potential	77.5	mV		04/27/23 15:47	1	-500	04/27/23 15:47	FIELD	Field*
pH, Field Measured	7.36	pH Units		04/27/23 15:47	1		04/27/23 15:47	FIELD	Field*
Specific Conductance, Field Measured	1461	umhos/cm		04/27/23 15:47	1		04/27/23 15:47	FIELD	Field*
Temperature, Field Measured	15.1	°C		04/27/23 15:47	1		04/27/23 15:47	FIELD	Field*
Turbidity, Field Measured	< 0.00	NTU		04/27/23 15:47	1	0.00	04/27/23 15:47	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	420	mg/L		05/08/23 13:35	1	10	05/08/23 13:35	CPS	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	< 10	mg/L		05/08/23 13:35	1	10	05/08/23 13:35	CPS	SM 2320B 1997*
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	1100	mg/L		05/02/23 12:44	1	26	05/03/23 11:06	HRF	SM 2540C
Total Metals - PIA									
Antimony	< 3.0	ug/L		05/08/23 09:07	5	3.0	05/09/23 13:09	JMW	EPA 6020A
Arsenic	7.8	ug/L		05/08/23 09:07	5	1.0	05/10/23 09:30	JMW	EPA 6020A
Barium	26	ug/L		05/08/23 09:07	5	1.0	05/09/23 13:09	JMW	EPA 6020A
Beryllium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 10:10	JMW	EPA 6020A
Boron	77	ug/L		05/08/23 09:07	5	10	05/09/23 10:10	JMW	EPA 6020A
Cadmium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 13:09	JMW	EPA 6020A
Calcium	140	mg/L		05/08/23 09:07	5	0.20	05/09/23 10:10	JMW	EPA 6020A
Chromium	< 4.0	ug/L		05/08/23 09:07	5	4.0	05/09/23 10:10	JMW	EPA 6020A
Cobalt	< 2.0	ug/L		05/08/23 09:07	5	2.0	05/09/23 10:10	JMW	EPA 6020A
Lead	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 10:10	JMW	EPA 6020A
Magnesium	68	mg/L		05/08/23 09:07	5	0.10	05/09/23 10:10	JMW	EPA 6020A
Mercury	< 0.20	ug/L		05/08/23 09:07	5	0.20	05/09/23 13:09	JMW	EPA 6020A
Molybdenum	6.5	ug/L		05/08/23 09:07	5	1.0	05/09/23 13:09	JMW	EPA 6020A
Potassium	1.5	mg/L		05/08/23 09:07	5	0.10	05/09/23 10:10	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04839-07
Name: APW10
Matrix: Ground Water - Grab

Sampled: 04/27/23 15:47
Received: 04/28/23 12:45

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Selenium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 10:10	JMW	EPA 6020A
Sodium	120	mg/L		05/08/23 09:07	5	0.10	05/09/23 10:10	JMW	EPA 6020A
Thallium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 10:10	JMW	EPA 6020A
Lithium	< 0.020	mg/L		05/08/23 09:07	1	0.020	05/09/23 10:52	TJJ	EPA 6010B

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ANALYTICAL RESULTS

Sample: GD04839-08
Name: APW13
Matrix: Ground Water - Grab

Sampled: 04/27/23 17:16
Received: 04/28/23 12:45

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	51	mg/L		04/28/23 20:39	10	10	04/28/23 20:39	CRD	EPA 300.0 REV 2.1
Fluoride	0.394	mg/L		04/28/23 20:21	1	0.250	04/28/23 20:21	CRD	EPA 300.0 REV 2.1
Sulfate	250	mg/L		04/28/23 20:57	100	100	04/28/23 20:57	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	32.05	Feet		04/27/23 17:16	1		04/27/23 17:16	FIELD	Field*
Dissolved oxygen, Field	1.6	mg/L		04/27/23 17:16	1		04/27/23 17:16	FIELD	Field*
Oxidation Reduction Potential	-25.3	mV		04/27/23 17:16	1	-500	04/27/23 17:16	FIELD	Field*
pH, Field Measured	7.26	pH Units		04/27/23 17:16	1		04/27/23 17:16	FIELD	Field*
Specific Conductance, Field Measured	1360	umhos/cm		04/27/23 17:16	1		04/27/23 17:16	FIELD	Field*
Temperature, Field Measured	14.3	°C		04/27/23 17:16	1		04/27/23 17:16	FIELD	Field*
Turbidity, Field Measured	< 0.00	NTU		04/27/23 17:16	1	0.00	04/27/23 17:16	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	490	mg/L		05/08/23 13:35	1	10	05/08/23 13:35	CPS	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	< 10	mg/L		05/08/23 13:35	1	10	05/08/23 13:35	CPS	SM 2320B 1997*
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	940	mg/L		05/02/23 12:44	1	26	05/03/23 11:06	HRF	SM 2540C
Total Metals - PIA									
Antimony	< 3.0	ug/L		05/08/23 09:07	5	3.0	05/09/23 13:13	JMW	EPA 6020A
Arsenic	4.0	ug/L		05/08/23 09:07	5	1.0	05/10/23 09:33	JMW	EPA 6020A
Barium	50	ug/L		05/08/23 09:07	5	1.0	05/09/23 13:13	JMW	EPA 6020A
Beryllium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 10:13	JMW	EPA 6020A
Boron	110	ug/L		05/08/23 09:07	5	10	05/09/23 10:13	JMW	EPA 6020A
Cadmium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 13:13	JMW	EPA 6020A
Calcium	120	mg/L		05/08/23 09:07	5	0.20	05/09/23 10:13	JMW	EPA 6020A
Chromium	< 4.0	ug/L		05/08/23 09:07	5	4.0	05/09/23 10:13	JMW	EPA 6020A
Cobalt	< 2.0	ug/L		05/08/23 09:07	5	2.0	05/09/23 10:13	JMW	EPA 6020A
Lead	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 10:13	JMW	EPA 6020A
Magnesium	61	mg/L		05/08/23 09:07	5	0.10	05/09/23 10:13	JMW	EPA 6020A
Mercury	< 0.20	ug/L		05/08/23 09:07	5	0.20	05/09/23 13:13	JMW	EPA 6020A
Molybdenum	6.7	ug/L		05/08/23 09:07	5	1.0	05/09/23 13:13	JMW	EPA 6020A
Potassium	1.8	mg/L		05/08/23 09:07	5	0.10	05/09/23 10:13	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04839-08
Name: APW13
Matrix: Ground Water - Grab

Sampled: 04/27/23 17:16
Received: 04/28/23 12:45

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Selenium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 10:13	JMW	EPA 6020A
Sodium	120	mg/L		05/08/23 09:07	5	0.10	05/09/23 10:13	JMW	EPA 6020A
Thallium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 10:13	JMW	EPA 6020A
Lithium	0.021	mg/L		05/08/23 09:07	1	0.020	05/09/23 10:53	TJJ	EPA 6010B

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ANALYTICAL RESULTS

Sample: GD04839-18
Name: XPW01
Matrix: Ground Water - Grab

Sampled: 04/27/23 14:07
Received: 04/28/23 12:45

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	8.1	mg/L		04/29/23 11:36	5	5.0	04/29/23 11:36	CRD	EPA 300.0 REV 2.1
Fluoride	5.34	mg/L		04/29/23 11:36	5	1.25	04/29/23 11:36	CRD	EPA 300.0 REV 2.1
Sulfate	2900	mg/L		05/04/23 21:21	1000	1000	05/04/23 21:21	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	11.06	Feet		04/27/23 14:07	1		04/27/23 14:07	FIELD	Field*
Dissolved oxygen, Field	4.3	mg/L		04/27/23 14:07	1		04/27/23 14:07	FIELD	Field*
Oxidation Reduction Potential	-379	mV		04/27/23 14:07	1	-500	04/27/23 14:07	FIELD	Field*
pH, Field Measured	12.2	pH Units		04/27/23 14:07	1		04/27/23 14:07	FIELD	Field*
Specific Conductance, Field Measured	10500	umhos/cm		04/27/23 14:07	1		04/27/23 14:07	FIELD	Field*
Temperature, Field Measured	18.4	°C		04/27/23 14:07	1		04/27/23 14:07	FIELD	Field*
Turbidity, Field Measured	>1000:	NTU		04/27/23 14:07	1	0.00	04/27/23 14:07	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	< 10	mg/L		05/08/23 13:35	1	10	05/08/23 13:35	CPS	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	700	mg/L		05/08/23 13:35	1	10	05/08/23 13:35	CPS	SM 2320B 1997*
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	6900	mg/L		05/02/23 12:44	1	26	05/03/23 11:06	HRF	SM 2540C
Total Metals - PIA									
Boron	14000	ug/L		05/08/23 09:07	100	200	05/09/23 12:33	JMW	EPA 6020A
Calcium	36	mg/L		05/08/23 09:07	5	0.20	05/09/23 10:25	JMW	EPA 6020A
Magnesium	8.7	mg/L		05/08/23 09:07	5	0.10	05/09/23 10:25	JMW	EPA 6020A
Potassium	47	mg/L		05/08/23 09:07	5	0.10	05/09/23 10:25	JMW	EPA 6020A
Sodium	2400	mg/L		05/08/23 09:07	100	2.0	05/09/23 12:33	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04839-19
Name: XPW02
Matrix: Ground Water - Grab

Sampled: 04/27/23 15:29
Received: 04/28/23 12:45

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	8.8	mg/L		04/29/23 12:12	1	1.0	04/29/23 12:12	CRD	EPA 300.0 REV 2.1
Fluoride	0.536	mg/L		04/29/23 12:12	1	0.250	04/29/23 12:12	CRD	EPA 300.0 REV 2.1
Sulfate	150	mg/L		04/29/23 12:48	25	25	04/29/23 12:48	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	7.39	Feet		04/27/23 15:29	1		04/27/23 15:29	FIELD	Field*
Dissolved oxygen, Field	4.8	mg/L		04/27/23 15:29	1		04/27/23 15:29	FIELD	Field*
Oxidation Reduction Potential	-237	mV		04/27/23 15:29	1	-500	04/27/23 15:29	FIELD	Field*
pH, Field Measured	9.58	pH Units		04/27/23 15:29	1		04/27/23 15:29	FIELD	Field*
Specific Conductance, Field Measured	400.0	umhos/cm		04/27/23 15:29	1		04/27/23 15:29	FIELD	Field*
Temperature, Field Measured	17.6	°C		04/27/23 15:29	1		04/27/23 15:29	FIELD	Field*
Turbidity, Field Measured	39.1	NTU		04/27/23 15:29	1	0.00	04/27/23 15:29	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	12	mg/L	M	05/08/23 16:02	1	10	05/08/23 16:02	CPS	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	35	mg/L		05/08/23 16:02	1	10	05/08/23 16:02	CPS	SM 2320B 1997*
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	290	mg/L		05/02/23 12:44	1	26	05/03/23 11:06	HRF	SM 2540C
Total Metals - PIA									
Boron	2300	ug/L		05/08/23 09:07	5	10	05/09/23 13:28	JMW	EPA 6020A
Calcium	23	mg/L		05/08/23 09:07	5	0.20	05/09/23 13:28	JMW	EPA 6020A
Magnesium	0.19	mg/L		05/08/23 09:07	5	0.10	05/09/23 13:28	JMW	EPA 6020A
Potassium	14	mg/L		05/08/23 09:07	5	0.10	05/09/23 13:28	JMW	EPA 6020A
Sodium	64	mg/L		05/08/23 09:07	5	0.10	05/09/23 13:28	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04839-20
Name: XPW03
Matrix: Ground Water - Grab

Sampled: 04/27/23 17:00
Received: 04/28/23 12:45

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	9.7	mg/L		04/29/23 15:49	5	5.0	04/29/23 15:49	CRD	EPA 300.0 REV 2.1
Fluoride	1.03	mg/L		04/29/23 15:31	1	0.250	04/29/23 15:31	CRD	EPA 300.0 REV 2.1
Sulfate	120	mg/L		04/29/23 16:07	25	25	04/29/23 16:07	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	10.81	Feet		04/27/23 17:00	1		04/27/23 17:00	FIELD	Field*
Dissolved oxygen, Field	0.70	mg/L		04/27/23 17:00	1		04/27/23 17:00	FIELD	Field*
Oxidation Reduction Potential	-273	mV		04/27/23 17:00	1	-500	04/27/23 17:00	FIELD	Field*
pH, Field Measured	11.5	pH Units		04/27/23 17:00	1		04/27/23 17:00	FIELD	Field*
Specific Conductance, Field Measured	1430	umhos/cm		04/27/23 17:00	1		04/27/23 17:00	FIELD	Field*
Temperature, Field Measured	17.1	°C		04/27/23 17:00	1		04/27/23 17:00	FIELD	Field*
Turbidity, Field Measured	119	NTU		04/27/23 17:00	1	0.00	04/27/23 17:00	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	< 10	mg/L		05/08/23 13:35	1	10	05/08/23 13:35	CPS	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	200	mg/L		05/08/23 13:35	1	10	05/08/23 13:35	CPS	SM 2320B 1997*
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	620	mg/L		05/02/23 12:44	1	26	05/03/23 11:06	HRF	SM 2540C
Total Metals - PIA									
Boron	1800	ug/L		05/08/23 09:07	5	10	05/09/23 13:32	JMW	EPA 6020A
Calcium	26	mg/L		05/08/23 09:07	5	0.20	05/09/23 13:32	JMW	EPA 6020A
Magnesium	0.69	mg/L		05/08/23 09:07	5	0.10	05/09/23 13:32	JMW	EPA 6020A
Potassium	18	mg/L		05/08/23 09:07	5	0.10	05/09/23 13:32	JMW	EPA 6020A
Sodium	190	mg/L		05/08/23 09:07	5	0.10	05/09/23 13:32	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04919-02
Name: XPW04
Matrix: Ground Water - Grab

Sampled: 04/28/23 10:23
Received: 04/28/23 16:12

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	59	mg/L		04/29/23 17:45	10	10	04/29/23 17:45	CRD	EPA 300.0 REV 2.1
Sulfate	9500	mg/L		04/29/23 18:03	1000	1000	04/29/23 18:03	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	12.49	Feet		04/28/23 10:23	1		04/28/23 10:23	FIELD	Field*
Dissolved oxygen, Field	1.8	mg/L		04/28/23 10:23	1		04/28/23 10:23	FIELD	Field*
Oxidation Reduction Potential	-255	mV		04/28/23 10:23	1	-500	04/28/23 10:23	FIELD	Field*
pH, Field Measured	11.6	pH Units		04/28/23 10:23	1		04/28/23 10:23	FIELD	Field*
Specific Conductance, Field Measured	11900	umhos/cm		04/28/23 10:23	1		04/28/23 10:23	FIELD	Field*
Temperature, Field Measured	16.2	°C		04/28/23 10:23	1		04/28/23 10:23	FIELD	Field*
Turbidity, Field Measured	75.5	NTU		04/28/23 10:23	1	0.00	04/28/23 10:23	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	< 10	mg/L		05/09/23 10:18	1	10	05/09/23 10:18	CPS	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	220	mg/L		05/09/23 10:18	1	10	05/09/23 10:18	CPS	SM 2320B 1997*
Fluoride	0.985	mg/L		05/05/23 17:00	1	0.250	05/05/23 17:00	TTH	SM 4500F C 1997
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	14000	mg/L	H	05/05/23 17:14	1	51	05/08/23 10:59	CPS	SM 2540C
Total Metals - PIA									
Boron	4000	ug/L		05/08/23 09:07	5	10	05/09/23 13:40	JMW	EPA 6020A
Calcium	100	mg/L		05/08/23 09:07	5	0.20	05/09/23 13:40	JMW	EPA 6020A
Magnesium	0.50	mg/L		05/08/23 09:07	5	0.10	05/09/23 13:40	JMW	EPA 6020A
Potassium	89	mg/L		05/08/23 09:07	5	0.10	05/09/23 13:40	JMW	EPA 6020A
Sodium	4700	mg/L		05/08/23 09:07	100	2.0	05/09/23 14:32	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04919-03
Name: APW14
Matrix: Ground Water - Grab

Sampled: 04/28/23 11:29
Received: 04/28/23 16:12

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	46	mg/L		04/29/23 18:39	10	10	04/29/23 18:39	CRD	EPA 300.0 REV 2.1
Fluoride	< 0.250	mg/L		04/29/23 18:21	1	0.250	04/29/23 18:21	CRD	EPA 300.0 REV 2.1
Sulfate	380	mg/L		04/29/23 18:57	50	50	04/29/23 18:57	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	20.72	Feet		04/28/23 11:29	1		04/28/23 11:29	FIELD	Field*
Dissolved oxygen, Field	1.2	mg/L		04/28/23 11:29	1		04/28/23 11:29	FIELD	Field*
Oxidation Reduction Potential	-95.0	mV		04/28/23 11:29	1	-500	04/28/23 11:29	FIELD	Field*
pH, Field Measured	7.34	pH Units		04/28/23 11:29	1		04/28/23 11:29	FIELD	Field*
Specific Conductance, Field Measured	1480	umhos/cm		04/28/23 11:29	1		04/28/23 11:29	FIELD	Field*
Temperature, Field Measured	14.8	°C		04/28/23 11:29	1		04/28/23 11:29	FIELD	Field*
Turbidity, Field Measured	8.81	NTU		04/28/23 11:29	1	0.00	04/28/23 11:29	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	460	mg/L		05/09/23 10:18	1	10	05/09/23 10:18	CPS	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	< 10	mg/L		05/09/23 10:18	1	10	05/09/23 10:18	CPS	SM 2320B 1997*
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	980	mg/L		05/03/23 12:09	1	26	05/03/23 15:21	CPS	SM 2540C
Total Metals - PIA									
Antimony	< 3.0	ug/L		05/08/23 09:07	5	3.0	05/09/23 14:10	JMW	EPA 6020A
Arsenic	5.5	ug/L		05/08/23 09:07	5	1.0	05/10/23 09:51	JMW	EPA 6020A
Barium	65	ug/L		05/08/23 09:07	5	1.0	05/09/23 14:10	JMW	EPA 6020A
Beryllium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 14:10	JMW	EPA 6020A
Boron	100	ug/L		05/08/23 09:07	5	10	05/09/23 14:10	JMW	EPA 6020A
Cadmium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 14:10	JMW	EPA 6020A
Calcium	130	mg/L		05/08/23 09:07	5	0.20	05/09/23 14:10	JMW	EPA 6020A
Chromium	< 4.0	ug/L		05/08/23 09:07	5	4.0	05/09/23 14:10	JMW	EPA 6020A
Cobalt	< 2.0	ug/L		05/08/23 09:07	5	2.0	05/09/23 14:10	JMW	EPA 6020A
Lead	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 14:10	JMW	EPA 6020A
Magnesium	66	mg/L		05/08/23 09:07	5	0.10	05/09/23 14:10	JMW	EPA 6020A
Mercury	< 0.20	ug/L		05/08/23 09:07	5	0.20	05/09/23 14:10	JMW	EPA 6020A
Molybdenum	4.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 14:10	JMW	EPA 6020A
Potassium	1.6	mg/L		05/08/23 09:07	5	0.10	05/09/23 14:10	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04919-03
Name: APW14
Matrix: Ground Water - Grab

Sampled: 04/28/23 11:29
Received: 04/28/23 16:12

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Selenium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 14:10	JMW	EPA 6020A
Sodium	130	mg/L		05/08/23 09:07	5	0.10	05/09/23 14:10	JMW	EPA 6020A
Thallium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 14:10	JMW	EPA 6020A
Lithium	< 0.020	mg/L		05/08/23 09:07	1	0.020	05/09/23 10:54	TJJ	EPA 6010B

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ANALYTICAL RESULTS

Sample: GD04919-04
Name: APW14 DUP
Matrix: Ground Water - Grab

Sampled: 04/28/23 11:29
Received: 04/28/23 16:12

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Anions - PIA									
Chloride	48	mg/L	Q4	04/29/23 20:45	10	10	04/29/23 20:45	CRD	EPA 300.0 REV 2.1
Fluoride	< 0.250	mg/L		04/29/23 19:15	1	0.250	04/29/23 19:15	CRD	EPA 300.0 REV 2.1
Sulfate	370	mg/L	Q4	04/29/23 21:03	50	50	04/29/23 21:03	CRD	EPA 300.0 REV 2.1
Field - PIA									
Depth, From Measuring Point	20.72	Feet		04/28/23 11:29	1		04/28/23 11:29	FIELD	Field*
Dissolved oxygen, Field	1.2	mg/L		04/28/23 11:29	1		04/28/23 11:29	FIELD	Field*
Oxidation Reduction Potential	-95.0	mV		04/28/23 11:29	1	-500	04/28/23 11:29	FIELD	Field*
pH, Field Measured	7.34	pH Units		04/28/23 11:29	1		04/28/23 11:29	FIELD	Field*
Specific Conductance, Field Measured	1480	umhos/cm		04/28/23 11:29	1		04/28/23 11:29	FIELD	Field*
Temperature, Field Measured	14.8	°C		04/28/23 11:29	1		04/28/23 11:29	FIELD	Field*
Turbidity, Field Measured	8.81	NTU		04/28/23 11:29	1	0.00	04/28/23 11:29	FIELD	Field*
General Chemistry - PIA									
Alkalinity - bicarbonate as CaCO3	450	mg/L		05/09/23 10:18	1	10	05/09/23 10:18	CPS	SM 2320B 1997*
Alkalinity - carbonate as CaCO3	< 10	mg/L		05/09/23 10:18	1	10	05/09/23 10:18	CPS	SM 2320B 1997*
Soluble General Chemistry - PIA									
Solids - total dissolved solids (TDS)	1000	mg/L		05/03/23 12:09	1	26	05/03/23 15:21	CPS	SM 2540C
Total Metals - PIA									
Antimony	< 3.0	ug/L		05/08/23 09:07	5	3.0	05/09/23 14:13	JMW	EPA 6020A
Arsenic	5.6	ug/L		05/08/23 09:07	5	1.0	05/10/23 09:54	JMW	EPA 6020A
Barium	64	ug/L		05/08/23 09:07	5	1.0	05/09/23 14:13	JMW	EPA 6020A
Beryllium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 14:13	JMW	EPA 6020A
Boron	100	ug/L		05/08/23 09:07	5	10	05/09/23 14:13	JMW	EPA 6020A
Cadmium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 14:13	JMW	EPA 6020A
Calcium	130	mg/L		05/08/23 09:07	5	0.20	05/09/23 14:13	JMW	EPA 6020A
Chromium	< 4.0	ug/L		05/08/23 09:07	5	4.0	05/09/23 14:13	JMW	EPA 6020A
Cobalt	< 2.0	ug/L		05/08/23 09:07	5	2.0	05/09/23 14:13	JMW	EPA 6020A
Lead	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 14:13	JMW	EPA 6020A
Magnesium	65	mg/L		05/08/23 09:07	5	0.10	05/09/23 14:13	JMW	EPA 6020A
Mercury	< 0.20	ug/L		05/08/23 09:07	5	0.20	05/09/23 14:13	JMW	EPA 6020A
Molybdenum	3.9	ug/L		05/08/23 09:07	5	1.0	05/09/23 14:13	JMW	EPA 6020A
Potassium	1.6	mg/L		05/08/23 09:07	5	0.10	05/09/23 14:13	JMW	EPA 6020A

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ANALYTICAL RESULTS

Sample: GD04919-04
Name: APW14 DUP
Matrix: Ground Water - Grab

Sampled: 04/28/23 11:29
Received: 04/28/23 16:12

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Selenium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 14:13	JMW	EPA 6020A
Sodium	130	mg/L		05/08/23 09:07	5	0.10	05/09/23 14:13	JMW	EPA 6020A
Thallium	< 1.0	ug/L		05/08/23 09:07	5	1.0	05/09/23 14:13	JMW	EPA 6020A
Lithium	< 0.020	mg/L		05/08/23 09:07	1	0.020	05/09/23 11:10	TJJ	EPA 6010B

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QC SAMPLE RESULTS

Parameter	Result	Unit	Qual	Spike Level	Source Result	%REC	%REC Limits	RPD	RPD Limit
Batch B331846 - IC No Prep - EPA 300.0 REV 2.1									
Matrix Spike (B331846-MS2)	**Sample: GD04461-03**			Prepared & Analyzed: 04/26/23					
Chloride	1.0E9	mg/L	Q4	1.500	71	NR	80-120		
Fluoride	2.19	mg/L		1.500	0.606	106	80-120		
Sulfate	2.25	mg/L		1.500	0.650	107	80-120		
Matrix Spike Dup (B331846-MSD2)	**Sample: GD04461-03**			Prepared & Analyzed: 04/26/23					
Chloride	1.0E9	mg/L	Q4	1.500	71	NR	80-120	0	20
Fluoride	2.18	mg/L		1.500	0.606	105	80-120	0.2	20
Sulfate	2.25	mg/L		1.500	0.650	106	80-120	0.08	20
Batch B331995 - No Prep - SM 2540C									
Blank (B331995-BLK1)				Prepared & Analyzed: 04/28/23					
Solids - total dissolved solids (TDS)	< 17	mg/L							
LCS (B331995-BS1)				Prepared & Analyzed: 04/28/23					
Solids - total dissolved solids (TDS)	963	mg/L		1000		96	84.9-109		
Duplicate (B331995-DUP1)	**Sample: GD04461-03**			Prepared & Analyzed: 04/28/23					
Solids - total dissolved solids (TDS)	795	mg/L			795			0	5
Batch B332031 - IC No Prep - EPA 300.0 REV 2.1									
Matrix Spike (B332031-MS1)	**Sample: GD04839-04**			Prepared & Analyzed: 04/28/23					
Fluoride	2.01	mg/L		1.500	0.498	101	80-120		
Sulfate	2.58	mg/L		1.500	0.975	107	80-120		
Chloride	1.0E9	mg/L	Q4	1.500	46	NR	80-120		
Matrix Spike Dup (B332031-MSD1)	**Sample: GD04839-04**			Prepared & Analyzed: 04/28/23					
Fluoride	2.02	mg/L		1.500	0.498	101	80-120	0.6	20
Sulfate	2.58	mg/L		1.500	0.975	107	80-120	0.1	20
Chloride	1.0E9	mg/L	Q4	1.500	46	NR	80-120	0	20
Batch B332081 - No Prep - SM 2540C									
Blank (B332081-BLK1)				Prepared & Analyzed: 05/01/23					
Solids - total dissolved solids (TDS)	< 17	mg/L							
LCS (B332081-BS1)				Prepared & Analyzed: 05/01/23					
Solids - total dissolved solids (TDS)	947	mg/L		1000		95	84.9-109		
Duplicate (B332081-DUP2)	**Sample: GD04746-02**			Prepared & Analyzed: 05/01/23					
Solids - total dissolved solids (TDS)	3720	mg/L			3800			2	5
Batch B332085 - IC No Prep - EPA 300.0 REV 2.1									
Matrix Spike (B332085-MS1)	**Sample: GD04919-04**			Prepared & Analyzed: 04/29/23					
Sulfate	1.00E9	mg/L	Q4	1.500	370	NR	80-120		
Fluoride	1.70	mg/L		1.500	0.247	97	80-120		
Chloride	1.0E9	mg/L	Q4	1.500	48	NR	80-120		
Matrix Spike Dup (B332085-MSD1)	**Sample: GD04919-04**			Prepared & Analyzed: 04/29/23					
Fluoride	1.73	mg/L		1.500	0.247	99	80-120	2	20
Sulfate	1.00E9	mg/L	Q4	1.500	370	NR	80-120	0	20
Chloride	1.0E9	mg/L	Q4	1.500	48	NR	80-120	0	20
Batch B332218 - No Prep - SM 2540C									

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QC SAMPLE RESULTS

Parameter	Result	Unit	Qual	Spike Level	Source Result	%REC	%REC Limits	RPD	RPD Limit
Blank (B332218-BLK1)				Prepared: 05/02/23 Analyzed: 05/03/23					
Solids - total dissolved solids (TDS)	< 17	mg/L							
LCS (B332218-BS1)				Prepared: 05/02/23 Analyzed: 05/03/23					
Solids - total dissolved solids (TDS)	1000	mg/L		1000		100	84.9-109		
Batch B332309 - SW 3015 - EPA 6010B									
Blank (B332309-BLK1)				Prepared: 05/03/23 Analyzed: 05/09/23					
Lithium	< 0.020	mg/L							
LCS (B332309-BS1)				Prepared: 05/03/23 Analyzed: 05/09/23					
Lithium	0.565	mg/L		0.5556		102	80-120		
Matrix Spike (B332309-MS1)	**Sample: GD04461-03**			Prepared: 05/03/23 Analyzed: 05/09/23					
Lithium	0.561	mg/L		0.5556	ND	101	75-125		
Matrix Spike Dup (B332309-MSD1)	**Sample: GD04461-03**			Prepared: 05/03/23 Analyzed: 05/09/23					
Lithium	0.543	mg/L		0.5556	ND	98	75-125	3	20
Batch B332309 - SW 3015 - EPA 6020A									
Blank (B332309-BLK1)				Prepared: 05/03/23 Analyzed: 05/04/23					
Antimony	< 3.0	ug/L							
Arsenic	< 1.0	ug/L							
Barium	< 1.0	ug/L							
Beryllium	< 1.0	ug/L							
Boron	< 10	ug/L							
Cadmium	< 1.0	ug/L							
Calcium	< 0.20	mg/L							
Chromium	< 4.0	ug/L							
Cobalt	< 2.0	ug/L							
Lead	< 1.0	ug/L							
Magnesium	< 0.10	mg/L							
Mercury	< 0.20	ug/L							
Molybdenum	< 1.0	ug/L							
Potassium	< 0.10	mg/L							
Selenium	< 1.0	ug/L							
Sodium	< 0.10	mg/L							
Thallium	< 1.0	ug/L							
LCS (B332309-BS1)				Prepared: 05/03/23 Analyzed: 05/04/23					
Antimony	539	ug/L		555.6		97	80-120		
Arsenic	538	ug/L		555.6		97	80-120		
Barium	540	ug/L		555.6		97	80-120		
Beryllium	557	ug/L		555.6		100	80-120		
Boron	568	ug/L		555.6		102	80-120		
Cadmium	529	ug/L		555.6		95	80-120		
Calcium	5.40	mg/L		5.556		97	80-120		
Chromium	582	ug/L		555.6		105	80-120		
Cobalt	576	ug/L		555.6		104	80-120		
Lead	557	ug/L		555.6		100	80-120		
Magnesium	5.64	mg/L		5.556		102	80-120		
Mercury	55.7	ug/L		55.56		100	80-120		
Molybdenum	527	ug/L		555.6		95	80-120		

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QC SAMPLE RESULTS

Parameter	Result	Unit	Qual	Spike Level	Source Result	%REC	%REC Limits	RPD	RPD Limit
LCS (B332309-BS1)				Prepared: 05/03/23 Analyzed: 05/04/23					
Potassium	5.54	mg/L		5.556		100	80-120		
Selenium	549	ug/L		555.6		99	80-120		
Sodium	5.54	mg/L		5.556		100	80-120		
Thallium	585	ug/L		555.6		105	80-120		
Matrix Spike (B332309-MS1)	**Sample: GD04461-03**			Prepared: 05/03/23 Analyzed: 05/04/23					
Antimony	530	ug/L		555.6	ND	95	75-125		
Arsenic	548	ug/L		555.6	21.0	95	75-125		
Barium	1070	ug/L		555.6	541	95	75-125		
Beryllium	550	ug/L		555.6	ND	99	75-125		
Boron	691	ug/L		555.6	129	101	75-125		
Cadmium	522	ug/L		555.6	ND	94	75-125		
Calcium	98.1	mg/L	Q4	5.556	96.3	32	75-125		
Chromium	562	ug/L		555.6	ND	101	75-125		
Cobalt	552	ug/L		555.6	ND	99	75-125		
Lead	531	ug/L		555.6	0.356	95	75-125		
Magnesium	47.9	mg/L	Q4	5.556	44.3	65	75-125		
Mercury	57.8	ug/L		55.56	ND	104	75-125		
Molybdenum	533	ug/L		555.6	ND	96	75-125		
Potassium	7.16	mg/L		5.556	1.80	97	75-125		
Selenium	543	ug/L		555.6	ND	98	75-125		
Sodium	144	mg/L	Q4	5.556	143	10	75-125		
Thallium	561	ug/L		555.6	ND	101	75-125		
Matrix Spike Dup (B332309-MSD1)	**Sample: GD04461-03**			Prepared: 05/03/23 Analyzed: 05/04/23					
Antimony	534	ug/L		555.6	ND	96	75-125	0.8	20
Arsenic	560	ug/L		555.6	21.0	97	75-125	2	20
Barium	1070	ug/L		555.6	541	96	75-125	0.2	20
Beryllium	561	ug/L		555.6	ND	101	75-125	2	20
Boron	707	ug/L		555.6	129	104	75-125	2	20
Cadmium	532	ug/L		555.6	ND	96	75-125	2	20
Calcium	100	mg/L	Q4	5.556	96.3	72	75-125	2	20
Chromium	575	ug/L		555.6	ND	103	75-125	2	20
Cobalt	566	ug/L		555.6	ND	102	75-125	2	20
Lead	536	ug/L		555.6	0.356	96	75-125	1	20
Magnesium	49.1	mg/L	Q4	5.556	44.3	87	75-125	2	20
Mercury	59.4	ug/L		55.56	ND	107	75-125	3	20
Molybdenum	542	ug/L		555.6	ND	98	75-125	2	20
Potassium	7.32	mg/L		5.556	1.80	99	75-125	2	20
Selenium	552	ug/L		555.6	ND	99	75-125	2	20
Sodium	147	mg/L	Q4	5.556	143	66	75-125	2	20
Thallium	565	ug/L		555.6	ND	102	75-125	0.8	20
Batch B332343 - No Prep - SM 2540C									
Blank (B332343-BLK1)				Prepared & Analyzed: 05/03/23					
Solids - total dissolved solids (TDS)	< 17	mg/L							
LCS (B332343-BS1)				Prepared & Analyzed: 05/03/23					
Solids - total dissolved solids (TDS)	950	mg/L		1000		95	84.9-109		

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QC SAMPLE RESULTS

Parameter	Result	Unit	Qual	Spike Level	Source Result	%REC	%REC Limits	RPD	RPD Limit
Batch B332419 - SW 3015 - EPA 6010B									
Blank (B332419-BLK1)				Prepared: 05/04/23 Analyzed: 05/09/23					
Lithium	< 0.020	mg/L							
LCS (B332419-BS1)				Prepared: 05/04/23 Analyzed: 05/09/23					
Lithium	0.564	mg/L		0.5556		102	80-120		
Matrix Spike (B332419-MS1)	**Sample: GD04746-02**			Prepared: 05/04/23 Analyzed: 05/09/23					
Lithium	0.572	mg/L		0.5556	0.0326	97	75-125		
Matrix Spike Dup (B332419-MSD1)	**Sample: GD04746-02**			Prepared: 05/04/23 Analyzed: 05/09/23					
Lithium	0.575	mg/L		0.5556	0.0326	98	75-125	0.5	20
Batch B332419 - SW 3015 - EPA 6020A									
Blank (B332419-BLK1)				Prepared: 05/04/23 Analyzed: 05/09/23					
Antimony	< 3.0	ug/L							
Arsenic	< 1.0	ug/L							
Barium	< 1.0	ug/L							
Beryllium	< 1.0	ug/L							
Boron	< 10	ug/L							
Cadmium	< 1.0	ug/L							
Calcium	< 0.20	mg/L							
Chromium	< 4.0	ug/L							
Cobalt	< 2.0	ug/L							
Lead	< 1.0	ug/L							
Magnesium	< 0.10	mg/L							
Mercury	< 0.20	ug/L							
Molybdenum	< 1.0	ug/L							
Potassium	< 0.10	mg/L							
Selenium	< 1.0	ug/L							
Sodium	< 0.10	mg/L							
Thallium	< 1.0	ug/L							
LCS (B332419-BS1)				Prepared: 05/04/23 Analyzed: 05/09/23					
Antimony	546	ug/L		555.6		98	80-120		
Arsenic	608	ug/L		555.6		109	80-120		
Barium	548	ug/L		555.6		99	80-120		
Beryllium	549	ug/L		555.6		99	80-120		
Boron	548	ug/L		555.6		99	80-120		
Cadmium	547	ug/L		555.6		99	80-120		
Calcium	5.47	mg/L		5.556		98	80-120		
Chromium	578	ug/L		555.6		104	80-120		
Cobalt	558	ug/L		555.6		100	80-120		
Lead	555	ug/L		555.6		100	80-120		
Magnesium	5.53	mg/L		5.556		100	80-120		
Mercury	56.5	ug/L		55.56		102	80-120		
Molybdenum	532	ug/L		555.6		96	80-120		
Potassium	5.57	mg/L		5.556		100	80-120		
Selenium	562	ug/L		555.6		101	80-120		
Sodium	5.52	mg/L		5.556		99	80-120		
Thallium	550	ug/L		555.6		99	80-120		

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QC SAMPLE RESULTS

Parameter	Result	Unit	Qual	Spike Level	Source Result	%REC	%REC Limits	RPD	RPD Limit
Matrix Spike (B332419-MS1)	**Sample: GD04746-02**			Prepared: 05/04/23 Analyzed: 05/09/23					
Antimony	523	ug/L		555.6	ND	94	75-125		
Arsenic	593	ug/L		555.6	0.933	107	75-125		
Barium	548	ug/L		555.6	34.8	92	75-125		
Beryllium	515	ug/L		555.6	ND	93	75-125		
Boron	577	ug/L		555.6	53.5	94	75-125		
Cadmium	518	ug/L		555.6	ND	93	75-125		
Calcium	379	mg/L	Q4	5.556	389	NR	75-125		
Chromium	538	ug/L		555.6	3.12	96	75-125		
Cobalt	518	ug/L		555.6	0.828	93	75-125		
Lead	509	ug/L		555.6	0.222	92	75-125		
Magnesium	285	mg/L	Q4	5.556	298	NR	75-125		
Mercury	56.8	ug/L		55.56	ND	102	75-125		
Molybdenum	527	ug/L		555.6	1.26	95	75-125		
Potassium	7.02	mg/L		5.556	1.83	94	75-125		
Selenium	544	ug/L		555.6	ND	98	75-125		
Sodium	248	mg/L	Q4	5.556	259	NR	75-125		
Thallium	509	ug/L		555.6	ND	92	75-125		
Matrix Spike Dup (B332419-MSD1)	**Sample: GD04746-02**			Prepared: 05/04/23 Analyzed: 05/09/23					
Antimony	522	ug/L		555.6	ND	94	75-125	0.2	20
Arsenic	592	ug/L		555.6	0.933	106	75-125	0.2	20
Barium	552	ug/L		555.6	34.8	93	75-125	0.6	20
Beryllium	523	ug/L		555.6	ND	94	75-125	2	20
Boron	586	ug/L		555.6	53.5	96	75-125	2	20
Cadmium	525	ug/L		555.6	ND	94	75-125	1	20
Calcium	385	mg/L	Q4	5.556	389	NR	75-125	2	20
Chromium	546	ug/L		555.6	3.12	98	75-125	1	20
Cobalt	530	ug/L		555.6	0.828	95	75-125	2	20
Lead	517	ug/L		555.6	0.222	93	75-125	1	20
Magnesium	290	mg/L	Q4	5.556	298	NR	75-125	2	20
Mercury	57.0	ug/L		55.56	ND	103	75-125	0.5	20
Molybdenum	534	ug/L		555.6	1.26	96	75-125	1	20
Potassium	7.12	mg/L		5.556	1.83	95	75-125	1	20
Selenium	554	ug/L		555.6	ND	100	75-125	2	20
Sodium	254	mg/L	Q4	5.556	259	NR	75-125	2	20
Thallium	517	ug/L		555.6	ND	93	75-125	2	20
Batch B332511 - No Prep - SM 2320B 1997									
Blank (B332511-BLK1)				Prepared & Analyzed: 05/04/23					
Alkalinity - carbonate as CaCO3	2.50	mg/L							
Alkalinity - bicarbonate as CaCO3	2.50	mg/L							
Blank (B332511-BLK2)				Prepared & Analyzed: 05/04/23					
Alkalinity - bicarbonate as CaCO3	2.50	mg/L							
Alkalinity - carbonate as CaCO3	2.50	mg/L							
Duplicate (B332511-DUP1)	**Sample: GD04461-03**			Prepared & Analyzed: 05/04/23					
Alkalinity - carbonate as CaCO3	< 10	mg/L			ND				10
Alkalinity - bicarbonate as CaCO3	600	mg/L			562			6	10
Duplicate (B332511-DUP2)	**Sample: GD04461-03**			Prepared & Analyzed: 05/04/23					

Pace Analytical Services, LLC
2231 W. Altorfer Drive
Peoria, IL 61615
(800)752-6651

QC SAMPLE RESULTS

Parameter	Result	Unit	Qual	Spike Level	Source Result	%REC	%REC Limits	RPD	RPD Limit
Duplicate (B332511-DUP2)	**Sample: GD04461-03**			Prepared & Analyzed: 05/04/23					
Alkalinity - carbonate as CaCO3	< 10	mg/L			ND				10
Alkalinity - bicarbonate as CaCO3	575	mg/L			562			2	10
Batch B332653 - No Prep - SM 4500F C 1997									
Matrix Spike (B332653-MS2)	**Sample: GD04746-02**			Prepared & Analyzed: 05/05/23					
Fluoride	1.38	mg/L		1.000	0.365	102	80-120		
Matrix Spike Dup (B332653-MSD2)	**Sample: GD04746-02**			Prepared & Analyzed: 05/05/23					
Fluoride	1.36	mg/L		1.000	0.365	99	80-120	2	20
Batch B332659 - No Prep - SM 2320B 1997									
Duplicate (B332659-DUP3)	**Sample: GD04746-02**			Prepared & Analyzed: 05/05/23					
Alkalinity - bicarbonate as CaCO3	525	mg/L			525			0	10
Alkalinity - carbonate as CaCO3	< 10	mg/L			ND				10
Batch B332663 - No Prep - SM 2540C									
Blank (B332663-BLK1)				Prepared: 05/05/23 Analyzed: 05/08/23					
Solids - total dissolved solids (TDS)	< 17	mg/L							
LCS (B332663-BS1)				Prepared: 05/05/23 Analyzed: 05/08/23					
Solids - total dissolved solids (TDS)	1010	mg/L		1000		101	84.9-109		
Batch B332692 - SW 3015 - EPA 6010B									
Blank (B332692-BLK1)				Prepared: 05/08/23 Analyzed: 05/09/23					
Lithium	< 0.020	mg/L							
LCS (B332692-BS1)				Prepared: 05/08/23 Analyzed: 05/09/23					
Lithium	0.558	mg/L		0.5556		100	80-120		
Batch B332692 - SW 3015 - EPA 6020A									
Blank (B332692-BLK1)				Prepared: 05/08/23 Analyzed: 05/09/23					
Antimony	< 3.0	ug/L							
Arsenic	< 1.0	ug/L							
Barium	< 1.0	ug/L							
Beryllium	< 1.0	ug/L							
Boron	< 10	ug/L							
Cadmium	< 1.0	ug/L							
Calcium	< 0.20	mg/L							
Chromium	< 4.0	ug/L							
Cobalt	< 2.0	ug/L							
Lead	< 1.0	ug/L							
Magnesium	< 0.10	mg/L							
Mercury	< 0.20	ug/L							
Molybdenum	< 1.0	ug/L							
Potassium	< 0.10	mg/L							
Selenium	< 1.0	ug/L							
Sodium	< 0.10	mg/L							
Thallium	< 1.0	ug/L							
LCS (B332692-BS1)				Prepared: 05/08/23 Analyzed: 05/09/23					
Antimony	512	ug/L		555.6		92	80-120		

Pace Analytical Services, LLC
2231 W. Altorfer Drive
Peoria, IL 61615
(800)752-6651

QC SAMPLE RESULTS

Parameter	Result	Unit	Qual	Spike Level	Source Result	%REC	%REC Limits	RPD	RPD Limit
LCS (B332692-BS1)				Prepared: 05/08/23 Analyzed: 05/10/23					
Arsenic	595	ug/L		555.6		107	80-120		
Barium	527	ug/L		555.6		95	80-120		
Beryllium	534	ug/L		555.6		96	80-120		
Boron	531	ug/L		555.6		96	80-120		
Cadmium	525	ug/L		555.6		95	80-120		
Calcium	5.13	mg/L		5.556		92	80-120		
Chromium	545	ug/L		555.6		98	80-120		
Cobalt	542	ug/L		555.6		98	80-120		
Lead	523	ug/L		555.6		94	80-120		
Magnesium	5.36	mg/L		5.556		96	80-120		
Mercury	49.7	ug/L		55.56		89	80-120		
Molybdenum	510	ug/L		555.6		92	80-120		
Potassium	5.37	mg/L		5.556		97	80-120		
Selenium	535	ug/L		555.6		96	80-120		
Sodium	5.38	mg/L		5.556		97	80-120		
Thallium	520	ug/L		555.6		94	80-120		
Batch B332796 - No Prep - SM 2320B 1997									
Duplicate (B332796-DUP2)	**Sample: GD04839-07**			Prepared & Analyzed: 05/08/23					
Alkalinity - carbonate as CaCO3	< 10	mg/L			ND				10
Alkalinity - bicarbonate as CaCO3	438	mg/L			425			3	10
Batch B332797 - No Prep - SM 2320B 1997									
Duplicate (B332797-DUP1)	**Sample: GD04839-19**			Prepared & Analyzed: 05/08/23					
Alkalinity - bicarbonate as CaCO3	10.0	mg/L	M		12.5			22	10
Alkalinity - carbonate as CaCO3	35.0	mg/L			35.0			0	10

Pace Analytical Services, LLC
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Peoria, IL 61615
(800)752-6651

NOTES

Specifications regarding method revisions, method modifications, and calculations used for analysis are available upon request. Please contact your project manager.

* Not a TNI accredited analyte

Certifications

CHI - McHenry, IL - 4314-A W. Crystal Lake Road, McHenry, IL 60050
TNI Accreditation for Drinking Water and Wastewater Fields of Testing through IL EPA Accreditation No. 100279
Illinois Department of Public Health Bacterial Analysis in Drinking Water Approved Laboratory Registry No. 17556

PIA - Peoria, IL - 2231 W. Altorfer Drive, Peoria, IL 61615
TNI Accreditation for Drinking Water, Wastewater, Solid and Hazardous Material Fields of Testing through IL EPA Accreditation No. 100230
Illinois Department of Public Health Bacterial Analysis in Drinking Water Approved Laboratory Registry No. 17553
Drinking Water Certifications/Accreditations: Iowa (240); Kansas (E-10338); Missouri (870)
Wastewater Certifications/Accreditations: Arkansas (88-0677); Iowa (240); Kansas (E-10338)
Solid and Hazardous Material Certifications/Accreditations: Arkansas (88-0677); Iowa (240); Kansas (E-10338)

SPMO - Springfield, MO - 1805 W Sunset Street, Springfield, MO 65807
USEPA DMR-QA Program

STL - Hazelwood, MO - 944 Anglum Rd, Hazelwood, MO 63042
TNI Accreditation for Wastewater, Solid and Hazardous Material Fields of Testing through KS KDHE Certification No. E-10389
TNI Accreditation for Wastewater, Solid and Hazardous Material Fields of Testing through IL EPA Accreditation No. - 200080
Illinois Department of Public Health Bacterial Analysis in Drinking Water Approved Laboratory, Registry No. 171050
Missouri Department of Natural Resources - Certificate of Approval for Microbiological Laboratory Service - No. 1050

Qualifiers

H	Test performed after the expiration of the appropriate regulatory/advisory maximum allowable hold time.
M	Analyte failed to meet the required acceptance criteria for duplicate analysis.
Q4	The matrix spike recovery result is unusable since the analyte concentration in the sample is greater than four times the spike level. The associated blank spike was acceptable.

Gail J Schindler

Certified by: Gail Schindler, Project Manager

GD04461
VMW 4-26-23

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES | GROUND WATER | DRINKING WATER
UST | RCRA | OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test Y/N: NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_A213																						
2	NEW_A214																						
3	NEW_A215																						
4	NEW_APW02																						
5	NEW_APW03			4/25/23	1326		11	X	X	X													
6	NEW_APW04			4/25/23	1642		11	X	X	X													
7	NEW_APW05																						
8	NEW_APW05#S																						
9	NEW_APW06																						
10	NEW_APW07																						
11	NEW_APW08																						
12	NEW_APW09																						
13	NEW_APW10																						
14	NEW_APW11																						
15	NEW_APW12																						
16	NEW_APW13																						

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME
NEW-23Q2 Rev 0		4/26/23	706		4-26-23	1020
		4-26-23	1310		4-26-23	1330

SAMPLER NAME AND SIGNATURE
PRINT Name of SAMPLER: Aaron Pemberton
SIGNATURE of SAMPLER:
DATE Signed (MM/DD/YY): 04/25/23

SAMPLE CONDITIONS

Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
5	Y	N	Y

4-26 1020 5.33

EMS 5-3-23

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

GD04461
VMW 4-26-23

CHAIN-OF-CUSTODY / Analytical Request Document

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Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES | GROUND WATER | DRINKING WATER
UST | RCRA | OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test Y/N	NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_APW14																								
2	NEW_APW15																								
3	NEW_APW16			4/25/23	1326		22	X	X	X															
4	NEW_APW17			4/25/23	1650		11	X	X	X															
5	NEW_APW18			4/25/23	1503		11	X	X	X															
6	04/26/23 NEW_G104 + Dup			4/25/23	1652		8	X	X	X		X													
7	NEW_G104#S DTW																								
8	NEW_G104&D																								
9	NEW_G105																								
10	NEW_G106			4/25/23	1131		4	X	X	X		X													
11	NEW_G108																								
12	NEW_G109 DTW																								
13	NEW_G110 DTW																								
14	NEW_G111 DTW																								
15	NEW_G112 DTW																								
16	NEW_G113 DTW																								

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME	SAMPLE CONDITIONS
NEW-23Q2 Rev 0		4/26/23	0706		4-26-23	1020	
		4-26-23	1310		4-26-23	1330	1.5 / Y / N / Y

Temp in °C | Received on Ice (Y/N) | Custody Sealed Cooler (Y/N) | Samples Intact (Y/N)

SAMPLER NAME AND SIGNATURE
PRINT Name of SAMPLER: Aaron Rambelon
SIGNATURE of SAMPLER:
DATE Signed (MM/DD/YY): 04/25/2023

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

GD04461
Vmw 4-26-23

CHAIN-OF-CUSTODY / Analytical Request Document

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Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES | GROUND WATER | DRINKING WATER
UST | RCRA | OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test Y/N	NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_G114																								
2	NEW_G114&D			4/25/23	1804		2	X		X															
3	NEW_G115 DTW																								
4	NEW_G116																								
5	NEW_G117 DTW																								
6	NEW_G118																								
7	NEW_G119 DTW																								
8	NEW_G120 DTW																								
9	NEW_G125																								
10	NEW_G128																								
11	NEW_G130																								
12	NEW_G133																								
13	NEW_G136																								
14	NEW_G139																								
15	NEW_G141																								
16	NEW_G201			4/25/23	1527		4	X	X	X		X													

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME	SAMPLE CONDITIONS
NEW-23Q2 Rev 0		4/26/23	0706		4-26-23	1020	
		4-26-23	1320		4-26-23	1330	1.5 / Y / N / Y

SAMPLER NAME AND SIGNATURE

PRINT Name of SAMPLER: Aaron Ambeaon

SIGNATURE of SAMPLER:

DATE Signed (MM/DD/YY): 04/25/23

Temp in °C | Received on Ice (Y/N) | Custody Sealed Cooler (Y/N) | Samples Intact (Y/N)

EMS 5-3-23

GD044461
Vmw 4-26-23

CHAIN-OF-CUSTODY / Analytical Request Document

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Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES GROUND WATER DRINKING WATER
UST RCRA OTHER

Site Location STATE: IL

Section D Required Client Information

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test ↓ Y/N	NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	05/06/23 NEW_G202 - Duplicate			4/25/23	1208		8	X	X	X		X													
2	NEW_G217#S																								
3	NEW_G221																								
4	NEW_G225																								
5	NEW_G230																								
6	NEW_G231																								
7	NEW_G232																								
8	NEW_G233																								
9	NEW_G234			4/25/23	1542		11	X	X	X	X	X													
10	NEW_L1R_leachate																								
11	NEW_L201_leachate DTW																								
12	NEW_L202_leachate DTW																								
13	NEW_L203_leachate DTW																								
14	NEW_L204_leachate DTW																								
15	NEW_L205_leachate DTW																								
16	NEW_L301_leachate																								

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME
NEW-23Q2 Rev 0		4/26/23	0706		4-26-23	1020
		4-26-23	1330	Vmw Wagner	4-26-23	1330

SAMPLER NAME AND SIGNATURE

PRINT Name of SAMPLER: Aaron Pemberton

SIGNATURE of SAMPLER: DATE Signed (MM/DD/YY): 04/25/23

SAMPLE CONDITIONS			
Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
15	Y	N	Y

EMS 5-3-23

GD04461
VMW 4-26-23

CHAIN-OF-CUSTODY / Analytical Request Document

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Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES | GROUND WATER | DRINKING WATER
UST | RCRA | OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
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AIR	AR
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ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test Y/N	NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_LREP_leachate																								
2	NEW_MW34&D																								
3	NEW_MW35&D																								
4	NEW_MW43&D																								
5	NEW_MW46&D																								
6	NEW_R201			4/25/23	1424		4	X	X	X		X													
7	NEW_R202			4/25/23	1311		2	X	X	X		X													
8	NEW_R217&D						3	4/25																	
9	NEW_R219																								
10	~~NEW_T101~~ EB-01 (04-25-23)			4/25/23	1715		9																		
11	NEW_T102																								
12	NEW_XPW01_pore																								
13	NEW_XPW02_pore																								
14	NEW_XPW03_pore																								
15	NEW_XPW04_pore																								
16	NEW_XSG01 - DTW																								

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME
NEW-23Q2 Rev 0		4/26/23	0706		4-26-23	1020
		4-26-23	1330		4-26-23	1330

SAMPLE CONDITIONS

Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
1.5	Y	N	Y

SAMPLER NAME AND SIGNATURE

PRINT Name of SAMPLER: Aaron Pemberton

SIGNATURE of SAMPLER: DATE Signed (MM/DD/YY): 04/25/23

EMS 5-3-23

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

6D04746 ge

Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES GROUND WATER DRINKING WATER
UST RCRA OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID
(A-Z, 0-9 / ,-)
Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
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SOIL/SOLID	SL
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TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Requested Analysis Filtered (Y/N)	Residual Chlorine (Y/N)	Project No./ Lab I.D.
	Analysis Test ↓						Y/N ↓	NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000				
1	NEW_A213																	
2	NEW_A214																	
3	NEW_A215			4/26/23	1640		9	X	X	X	X	X						
4	NEW_APW02																	
5	NEW_APW03																	
6	NEW_APW04																	
7	NEW_APW05S			4/26/23	1740		11	X	X	X								
8	NEW_APW05#S																	
9	NEW_APW06			4/26/23	1600		11	X	X	X								
10	NEW_APW07																	
11	NEW_APW08			4/26/23	1211		11	X	X	X								
12	NEW_APW09																	
13	NEW_APW10																	
14	NEW_APW11			4/26/23	1543		11	X	X	X								
15	NEW_APW12			4/26/23	1356		11	X	X	X								
16	NEW_APW13																	

ADDITIONAL COMMENTS: **NEW-23Q2 Rev 0**

RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME
Joseph R Reed	4/27/23	713		4-27	1030
	4-27	1426		4/27/23	14:20

SAMPLER NAME AND SIGNATURE

PRINT Name of SAMPLER: James David

SIGNATURE of SAMPLER: James D

DATE Signed (MM/DD/YY): 4/26/23

SAMPLE CONDITIONS

Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
5	Y	N	Y
0	Y		

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES GROUND WATER DRINKING WATER
UST RCRA OTHER

Site Location STATE: IL

Section D Required Client Information

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Requested Analysis Filtered (Y/N) Y/N	Analysis Test ↓ NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_APW14																								
2	NEW_APW15																								
3	NEW_APW16			4/26/23	1723		11	X	X	X															
4	NEW_APW17																								
5	NEW_APW18																								
6	NEW_G104																								
7	NEW_G104#S DTW																								
8	NEW_G104&D																								
9	NEW_G105																								
10	NEW_G106																								
11	NEW_G108																								
12	NEW_G109 DTW																								
13	NEW_G110 DTW																								
14	NEW_G111 DTW																								
15	NEW_G112 DTW																								
16	NEW_G113 DTW																								

ADDITIONAL COMMENTS: **NEW-23Q2 Rev 0**

RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME
Joseph R Reed	4/27/23	1030		4-27	1030
	4-27	1420		4/27/23	14:20

SAMPLER NAME AND SIGNATURE

PRINT Name of SAMPLER: James David

SIGNATURE of SAMPLER:

DATE Signed (MM/DD/YY): 4/26/23

SAMPLE CONDITIONS

Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
5	Y	N	Y

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES GROUND WATER DRINKING WATER
UST RCRA OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test Y/N	NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_G114																								
2	NEW_G114&D																								
3	NEW_G115 DTW																								
4	NEW_G116																								
5	NEW_G117 DTW																								
6	NEW_G118																								
7	NEW_G119 DTW																								
8	NEW_G120 DTW																								
9	NEW_G125																								
10	NEW_G128 + dup 4-27-23			4/26/23	1500		12	X	X	X		X													
11	NEW_G130																								
12	NEW_G133			4/26/23	1609		6	X	X	X		X													
13	NEW_G136			4/26/23	1702		4	X	X	X		X													
14	NEW_G139																								
15	NEW_G141																								
16	NEW_G201																								

Requested Analysis Filtered (Y/N)

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME
NEW-23Q2 Rev 0	Joseph A Reed	4/27/23	1030		4-27	1030
		4-27	1420		4/27/23	14:20

SAMPLER NAME AND SIGNATURE

PRINT Name of SAMPLER: James David

SIGNATURE of SAMPLER:

DATE Signed (MM/DD/YY): 4/26/23

SAMPLE CONDITIONS

Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
0.7	Y	Y	Y

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES GROUND WATER DRINKING WATER
UST RCRA OTHER

Site Location STATE: IL

Section D Required Client Information

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test ↓ Y/N	NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_G202																								
2	NEW_G217#S			4/26/23	1303		9	X	X	X	X	X														
3	NEW_G221																								
4	NEW_G225																								
5	NEW_G230			4/26/23	1151		9	X	X	X	X	X														
6	NEW_G231			4/26/23	1310		9	X	X	X	X	X														
7	NEW_G232			4/26/23	1416		9	X	X	X	X	X														
8	NEW_G233			4/26/23	1526		9	X	X	X	X	X														
9	NEW_G234																								
10	NEW_L1R_leachate																								
11	NEW_L201_leachate DTW																								
12	NEW_L202_leachate DTW																								
13	NEW_L203_leachate DTW																								
14	NEW_L204_leachate DTW																								
15	NEW_L205_leachate DTW																								
16	NEW_L301_leachate																								

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME
NEW-23Q2 Rev 0	James David	4/27/23	1030		4-27	1030
		4.27	1420		4/27/23	14:20

SAMPLER NAME AND SIGNATURE

PRINT Name of SAMPLER: James David

SIGNATURE of SAMPLER: James David

DATE Signed (MM/DD/YY): 4/26/23

SAMPLE CONDITIONS			
Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
0.7	Y	N	Y

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES GROUND WATER DRINKING WATER
UST RCRA OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test Y/N: NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_LREP_leachate																						
2	NEW_MW34&D																						
3	NEW_MW35&D																						
4	NEW_MW43&D																						
5	NEW_MW46&D																						
6	NEW_R201																						
7	NEW_R202																						
8	NEW_R217&D			4/26/23	1143		9	X	X	X	X	X												
9	NEW_R219																						
10	NEW_T101																						
11	NEW_T102																						
12	NEW_XPW01_pore																						
13	NEW_XPW02_pore																						
14	NEW_XPW03_pore																						
15	NEW_XPW04_pore																						
16	NEW_XSG01 - DIW																						

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME
NEW-23Q2 Rev 0	Joseph R Ford	4/27/23	1030		4-27	1030
		4-27	1420	grace Jackson	4/27/23	14:20

SAMPLER NAME AND SIGNATURE
PRINT Name of SAMPLER: James David
SIGNATURE of SAMPLER: James David
DATE Signed (MM/DD/YY): 4/26/23

SAMPLE CONDITIONS			
Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
0.7	Y	N	Y

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

Section A Required Client Information:

Company: Vistra Corp
Address: 13498 E. 900th St
Email To: Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911 Fax:
Requested Due Date/TAT: 10 day

Section B Required Project Information:

Report To: Brian Voelker
Copy To: Jason Stuckey
Purchase Order No.:
Project Name:
Project Number: 2285

Section C Invoice Information:

Attention: Jason Stuckey
Company Name: Vistra Corp
Address: see Section A
Quote Reference:
Project Manager:
Profile #:

REGULATORY AGENCY

NPDES GROUND WATER DRINKING WATER
UST RCRA OTHER
Site Location STATE: IL

Section D Required Client Information

SAMPLE ID
(A-Z, 0-9 / ,-)
Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test ↓ Y/N	NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_YSG02 DTW																								
2	NEW_YSW_S101			4/26/23	1803		9	X	X	X															
3	NEW_YSW_S102			4/26/23	1743		9	X	X	X															
4	4/26/23 EB-02			4/26/23	1630																				
5																									
6																									
7																									
8																									
9																									
10																									
11																									
12																									
13																									
14																									
15																									
16																									

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME	SAMPLE CONDITIONS: Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
NEW-23Q2 Rev 0		4/27/23	1030		4-27	1020	5	Y	N	Y
		4-27	1420		4/27/23	14:20	0			

SAMPLER NAME AND SIGNATURE
PRINT Name of SAMPLER: James David
SIGNATURE of SAMPLER:
DATE Signed (MM/DD/YY): 4/26/23

courier

6D04839
gej

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES GROUND WATER DRINKING WATER
UST RCRA OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID
(A-Z, 0-9 / ,-)
Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test ↓ Y/N	NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_A213	WT	G	4/27/23	1209		9	X	X	X	X	X													
2	NEW_A214	WT	G	4/27/23	1432		9	X	X	X	X	X													
3	NEW_A215																								
4	NEW_APW02	WT	G	4/27/23	1217		11	X	X	X															
5	NEW_APW03																								
6	NEW_APW04																								
7	NEW_APW05	WT	G	4/27/23	1240		11	X	X	X															
8	NEW_APW05#S																								
9	NEW_APW06																								
10	NEW_APW07	WT	G	4/27/23	1035		11	X	X	X															
11	NEW_APW08																								
12	NEW_APW09	WT	G	4/27/23	1405		11	X	X	X															
13	NEW_APW10	WT	G	4/27/23	1547		11	X	X	X															
14	NEW_APW11																								
15	NEW_APW12																								
16	NEW_APW13	WT	G	4/27/23	1716		11	X	X	X															

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME
NEW-23Q2 Rev 0		4/28/23	0705	Brenden Herman	4/28/23	0705
	Brenden Herman	4/28/23	1245	Grace	4/28/23	12:45

SAMPLER NAME AND SIGNATURE
PRINT Name of SAMPLER: Aaron Pemberton
SIGNATURE of SAMPLER:
DATE Signed (MM/DD/YY): 04/27/2023

SAMPLE CONDITIONS	Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
	5°	Y	N	Y

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES GROUND WATER DRINKING WATER
UST RCRA OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test Y/N	NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_APW14																								
2	NEW_APW15																								
3	NEW_APW16																								
4	NEW_APW17																								
5	NEW_APW18																								
6	NEW_G104																								
7	NEW_G104#S DTW																								
8	NEW_G104&D																								
9	NEW_G105 + Dup	WT	G	4/27/23	1207		8	X	X	X	X														
10	NEW_G106																								
11	NEW_G108																								
12	NEW_G109 DTW																								
13	NEW_G110 DTW																								
14	NEW_G111 DTW																								
15	NEW_G112 DTW																								
16	NEW_G113 DTW																								

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME
NEW-23Q2 Rev 0		4/28/23	0705	Brendan Heiman	4/28/23	0705
	Brendan Heiman	4/28/23	1245		4/28/23	12:45

SAMPLER NAME AND SIGNATURE

PRINT Name of SAMPLER: Aaron Armbruster

SIGNATURE of SAMPLER: DATE Signed (MM/DD/YY): 04/27/23

SAMPLE CONDITIONS			
Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
5	Y	N	Y

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES GROUND WATER DRINKING WATER
UST RCRA OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test ↓ Y/N: NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_G114																						
2	NEW_G114&D																						
3	NEW_G115 DTW																						
4	NEW_G116																						
5	NEW_G117 DTW																						
6	NEW_G118																						
7	NEW_G119 DTW																						
8	NEW_G120 DTW																						
9	NEW_G125 + Dup	WT	G	4/27/23	1639		8	x	x	x					x								
10	NEW_G128																						
11	NEW_G130	WT	G	4/27/23	1020	6	6	x	x	x					x								
12	NEW_G133																						
13	NEW_G136																						
14	NEW_G139																						
15	NEW_G141	WT	G	4/27/23	1511		4	x	x	x					x								
16	NEW_G201																						

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME	SAMPLE CONDITIONS
NEW-23Q2 Rev 0		4/28/23	0705	Brandon Hinn	4/28/23	0705	0
	Brandon Hinn	4/28/23	1245	grace	4/28/23	12:45	6

App 4/27/23

SAMPLER NAME AND SIGNATURE
PRINT Name of SAMPLER: Aaron Ankerlen
SIGNATURE of SAMPLER:
DATE Signed (MM/DD/YY): 04/27/23

Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
6	Y		Y

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES | GROUND WATER | DRINKING WATER
UST | RCRA | OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test ↓ Y/N	NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_G202																								
2	NEW_G217#S																								
3	NEW_G221	WT	G	4/27/23	1027		9	X	X	X	X	X													
4	NEW_G225	WT	G	4/27/23	1335		9	X	X	X	X	X													
5	NEW_G230																								
6	NEW_G231																								
7	NEW_G232																								
8	NEW_G233																								
9	NEW_G234																								
10	NEW_L1R_leachate	WT	G	4/27/23	1309		9	X	X	X															
11	NEW_L201_leachate DTW																								
12	NEW_L202_leachate DTW																								
13	NEW_L203_leachate DTW																								
14	NEW_L204_leachate DTW																								
15	NEW_L205_leachate DTW																								
16	NEW_L301_leachate																								

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME
NEW-23Q2 Rev 0		4/28/23	0705	Brenden Johnson	4/28/23	0705
	Brenden Johnson	4/28/23	1245		4/28/23	12:45

SAMPLER NAME AND SIGNATURE
PRINT Name of SAMPLER: Aaron Pemberton
SIGNATURE of SAMPLER:
DATE Signed (MM/DD/YY): 04/27/23

SAMPLE CONDITIONS			
Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
0	Y	N	Y
6	Y		Y

CHAIN-OF-CUSTODY / Analytical Request Document

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Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES | GROUND WATER | DRINKING WATER
UST | RCRA | OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test Y/N: NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_LREP_leachate																						
2	NEW_MW34&D																						
3	NEW_MW35&D																						
4	NEW_MW43&D																						
5	NEW_MW46&D																						
6	NEW_R201																						
7	NEW_R202																						
8	NEW_R217&D																						
9	NEW_R219																						
10	NEW_T101	WT	G	4/27/23	1604		9	X	X	X													
11	NEW_T102																						
12	NEW_XPW01_pore	WT	G	4/27/23	1407		10	X	X	X													
13	NEW_XPW02_pore	WT	G	4/27/23	1529		10	X	X	X													
14	NEW_XPW03_pore	WT	G	4/27/23	1700		10	X	X	X													
15	~~NEW_XPW04_pore~~ EB-03	WT	G	4/27/23	1435		10	X	X	X													
16	NEW_XSG01 - DTW																						

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME
NEW-23Q2 Rev 0		4/28/23	0705		4/28/23	0705
		4/28/23	1245		4/28/23	1245

SAMPLER NAME AND SIGNATURE
PRINT Name of SAMPLER: Aaron Pemberton
SIGNATURE of SAMPLER: DATE Signed (MM/DD/YY): 04/27/23

SAMPLE CONDITIONS			
Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
5.0	Y	N	Y

CHAIN-OF-CUSTODY / Analytical Request Document

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Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES | GROUND WATER | DRINKING WATER
UST | RCRA | OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test Y/N	NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_LREP_leachate																								
2	NEW_MW34&D																								
3	NEW_MW35&D																								
4	NEW_MW43&D																								
5	NEW_MW46&D																								
6	NEW_R201																								
7	NEW_R202																								
8	NEW_R217&D																								
9	NEW_R219	WT	G	4/28/23	1134		9																		
10	NEW_T101																								
11	NEW_T102																								
12	NEW_XPW01_pore																								
13	NEW_XPW02_pore																								
14	NEW_XPW03_pore																								
15	NEW_XPW04_pore	WT	G	4/28/23	1023		10																		
16	NEW_XSG01 - DUP																								

Requested Analysis Filtered (Y/N)

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME
NEW-23Q2 Rev 0	Joe Reed	4/28/23			4/28/23	16:12

SAMPLE CONDITIONS

Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
5.7	Y		Y

SAMPLER NAME AND SIGNATURE

PRINT Name of SAMPLER: Joe Reed

SIGNATURE of SAMPLER: Joe Reed

DATE Signed (MM/DD/YY): 4/28/23

GD04919 gd

CHAIN-OF-CUSTODY / Analytical Request Document

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Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES GROUND WATER DRINKING WATER
UST RCRA OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test Y/N	NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	GS 5-2-23 NEW_APW14 + dup	WT	G	4/28/23	1129		22																		
2	NEW_APW15																								
3	NEW_APW16																								
4	NEW_APW17																								
5	NEW_APW18																								
6	NEW_G104																								
7	NEW_G104#S DTW																								
8	NEW_G104&D																								
9	NEW_G105																								
10	NEW_G106																								
11	NEW_G108																								
12	NEW_G109 DTW																								
13	NEW_G110 DTW																								
14	NEW_G111 DTW																								
15	NEW_G112 DTW																								
16	NEW_G113 DTW																								

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME
NEW-23Q2 Rev 0	Joseph R Reed	4/28/23	16 12	grace Just	4/28/23	16:12

SAMPLER NAME AND SIGNATURE

PRINT Name of SAMPLER: Joe Reed

SIGNATURE of SAMPLER: Joseph R Reed

DATE Signed (MM/DD/YY): 4/28/23

SAMPLE CONDITIONS			
Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
4	Y	2	Y

CHAIN-OF-CUSTODY / Analytical Request Document

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Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES GROUND WATER DRINKING WATER
UST RCRA OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test ↓ Y/N	NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_G114																								
2	NEW_G114&D																								
3	NEW_G115 DTW																								
4	NEW_G116	WT	G	4/28/23	1010		4																		
5	NEW_G117 DTW																								
6	6/5 6/6/23 NEW_G118 + DUP	WT	G	4/28/23	1004		4																		
7	NEW_G119 DTW																								
8	NEW_G120 DTW																								
9	NEW_G125																								
10	NEW_G128																								
11	NEW_G130																								
12	NEW_G133																								
13	NEW_G136																								
14	6/5 6/6/23 NEW_G139 + DUP	WT	G	4/28/23	1128		8																		
15	NEW_G141																								
16	~~NEW_G201~~ EB-04	WT	G	4/28/23	1200		2																		

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME	SAMPLE CONDITIONS
NEW-23Q2 Rev 0	Joe Reed	4/28/23	1612	grace Jones	4128/23	16:12	4.4 / Y / 2 / Y

SAMPLER NAME AND SIGNATURE

PRINT Name of SAMPLER: Joe Reed

SIGNATURE of SAMPLER: Joe Reed DATE Signed (MM/DD/YY): 4/28/23

Temp in °C | Received on Ice (Y/N) | Custody Sealed Cooler (Y/N) | Samples Intact (Y/N)

SAR-3: Depth to Groundwater Measurements

Plant: NEWTON POWER PLANT
Unit: PRIMARY ASH POND
Event: NEWTON, IL

Well	Unique ID	Date	Time	Depth to Water, ft bmp		Transducer			Initials	Notes
				Manual	Transducer	Serial No.	Batt %	DL		
A207	NEW_A207	4/24/23	1541	X	36.00	NA	NA	NA	JMD	
A213	NEW_A213		1544	X	18.63				KL	
A214	NEW_A214		1531	X	40.90				KL	
A215	NEW_A215		1527	X	44.03				KL	
G06D	NEW_G006&D		1459	X	28.92				JMD	
G104	NEW_G104		1804	X	4.51				JMD	
G104D	NEW_G104&D		1810	X	50.37				JMD	TD = 89.31
G104S	NEW_G104#S		1806	X	4.68				JMD	TD = 26.04
G105	NEW_G105		1833	X	7.10				JMD	TD = 26.20
G106	NEW_G106		1857	X	20.37				AP	
G109	NEW_G109		1647	X	5.11				JMD	TD = 24.97
G111	NEW_G111		1815	X	5.97				JMD	TD = 22.75
G112	NEW_G112		1823	X	4.38				JMD	TD = 24.62
G113	NEW_G113		1908	X	17.09				JMD	TD = 33.33
G114	NEW_G114		1723	X	13.45				JR	
G114D	NEW_G114&D		1556	X	42.69				JR	
G115	NEW_G115		1612	X	4.04				JR	No Lock, no pump
G116	NEW_G116		1933	X	6.00				JMD	
G117	NEW_G117		1845	X	7.08				JMD	TD = 21.90
G118	NEW_G118		1608	X	6.32				JMD	TD = 22.59
G119	NEW_G119		1654	X	4.10				JMD	TD = 23.85
G120	NEW_G120		1632	X	7.33				JMD	TD = 23.38
G125	NEW_G125		1457	X	2.84	JMD 4/24			KL	
G128	NEW_G128		~~1531~~ 1511	X	~~19.75~~	3.96			JMD	
G130	NEW_G130		1704	X	4.34				JMD	TD = 22.69
G133	NEW_G133		1658	X	8.84				JMD	TD = 27.32
G136	NEW_G136		1643	X	6.69				JMD	TD = 22.20
G139	NEW_G139		1639	X	6.15				JMD	TD = 23.05
G141	NEW_G141		1515	X	10.99				JMD	TD = 25.16
G201	NEW_G201		1742	X	17.50				JMD	
G202	NEW_G202		1828	X	47.84				JMD	

SAR-3: Depth to Groundwater Measurements
Plant: NEW
Event: NEW 2Q23

Well	Unique ID	Date	Time	Depth to Water, ft bmp		Transducer			Initials	Notes
				Manual	Transducer	Serial No.	Batt %	DL		
G203	NEW_G203	4/24/23	1536	X	41.39	NA	NA	NA	JR	No lock
G208	NEW_G208	"	1534	X	24.02	"	"	"	JMD	
G217S	NEW_G217#S	"	1439	X	6.20	"	"	"	KL	
G218	NEW_G218	"	1839	X	19.78	"	"	"	JMD	
G220	NEW_G220	"	1525	X	17.03	"	"	"	JMD	
G221	NEW_G221	"	1521	X	21.34	"	"	"	JMD	
G222	NEW_G222	"	1518	X	15.13	"	"	"	JMD	
G223	NEW_G223	"	1515	X	33.13	"	"	"	KL	Well has incorrect sign, says G233
G224	NEW_G224	"	1503	X	42.56	"	"	"	KL	
G225	NEW_G225	"	1511	X	7.27	"	"	"	JMD	TD= 24.99
G230	NEW_G230	"	1500	X	47.99	"	"	"	JR	
G231	NEW_G231	"	1504	X	47.36	"	"	"	JR	
G232	NEW_G232	"	1509	X	45.73	"	"	"	JR	
G233	NEW_G233	"	1516	X	41.67	"	"	"	JR	
G234	NEW_G234	"	1532	X	43.18	"	"	"	JR	
G48MG	NEW_G048MG	"	1826	X	18.99	"	"	"	JR	TD = 80.07
L1R	NEW_L1R_leachate	"	1716	X	52.80	"	"	"	KL	
L201	NEW_L201_leachate	"	1720	X	13.30	"	"	"	KL	Dry
L202	NEW_L202_leachate	"	1643	X	15.30	"	"	"	KL	Dry
L203	NEW_L203_leachate	"	1650	X	9.60	"	"	"	KL	Dry
L204	NEW_L204_leachate	"	1709	X	15.42	"	"	"	KL	
L205	NEW_L205_leachate	"	1701	X	0.97	"	"	"	KL	
L301	NEW_L301_leachate	"	NA	X	NA	"	"	"	JMD	No depth to measure
L302	NEW_L302_leachate	"	NA	X	NA	"	"	"	JMD	Not a well
M25-1	NEW_M25-1	"	1556	X	2.15	"	"	"	KL	
M25-2	NEW_M25-2	"	1557	X	1.42	"	"	"	KL	
M25-3	NEW_M25-3	"	1558	X	1.63	"	"	"	KL	
M25-4	NEW_M25-4	"	1559	X	2.43	"	"	"	KL	
M25-5	NEW_M25-5	"	1601	X	5.67	"	"	"	KL	
M25-6	NEW_M25-6	"	1602	X	12.28	"	"	"	KL	
M25-7	NEW_M25-7	"	1602	X	18.52	"	"	"	KL	

SAR-3: Depth to Groundwater Measurements
Plant: NEWTON POWER PLANT
Event: PRIMARY ASH POND
NEW T2Q2

Well	Unique ID	Date	Time	Depth to Water, ft bmp		Transducer			Initials	Notes
				Manual	Transducer	Serial No.	Batt %	DL		
M26-1	NEW_M26-1	4/24/23	1806	X	2.80	NA	NA	NA	KL	
M26-2	NEW_M26-2		1807	X	23.02				KL	
M26-3	NEW_M26-3		1808	X	23.19				KL	
M26-4	NEW_M26-4		1809	X	NA				KL	Obstruction in well at depth 1.17'
M26-5	NEW_M26-5		1810	X	1.22				KL	
M26-6	NEW_M26-6		1811	X	1.21				KL	
M26-7	NEW_M26-7		1812	X	40.76				KL	
MW31S	NEW_MW31#S		19:35	X	6.00				JMD	TD = 18.69
MW33S	NEW_MW33#S		1600	X	8.32				AP	TD = 29.59
MW34D	NEW_MW34&D		1655	X	14.85				AP	TD = 58.73, unable to close casing
MW35D	NEW_MW35&D		1438	X	26.24				AP	TD = 53.73
MW35S	NEW_MW35#S		1737	X	2.99				JMD	TD = 16.28
MW36S	NEW_MW36#S		1623	X	3.35				AP	TD = 15.49
MW43D	NEW_MW43&D		1812	X	5.73				AP	TD = 40.80
MW46D	NEW_MW46&D		1619	X	16.82				JR	
MW48S	NEW_MW48#S		1833	X	3.52				JR	13.49 = TD
R201	NEW_R201		1445	X	47.56				JR	
R202	NEW_R202		1912	X	47.55					
R216	NEW_R216		1455	X	43.33				KL	
R217D	NEW_R217&D		1444	X	19.15				KL	
R219	NEW_R219		1528	X	20.08				JMD	
T101	NEW_T101		1700	X	5.84				JR	
T102	NEW_T102		1712	X	6.00				JR	
APW02	NEW_APW02				X	21521987				
APW03	NEW_APW03				X	21521988				
APW04	NEW_APW04				X	21503517				
APW05	NEW_APW05				X	21615053				
APW05S	NEW_APW05#S				X	21503536				
APW06	NEW_APW06				X	21615054				
APW07	NEW_APW07				X	21615033				
APW08	NEW_APW08				X	21615032				

SAR-3: Depth to Groundwater Measurements
Plant: Newton
Event: NEW_2023_Q2

Well	Unique ID	Date	Time	Depth to Water, ft bmp		Transducer			Initials	Notes
				Manual	Transducer	Serial No.	Batt %	DL		
APW09	NEW_APW09				X	21522025	NA	NA		
APW10	NEW_APW10				X	21558058				
APW11	NEW_APW11				X	21558059				
APW12	NEW_APW12				X	21503535				
APW13	NEW_APW13				X	21522024				
APW14	NEW_APW14				X	21522035				
APW15	NEW_APW15				X	21522034				
APW16	NEW_APW16				X	21522033				
APW17	NEW_APW17				X	21522023				
APW18	NEW_APW18				X	21522026				
SG02	NEW_YSG02	4/24/23	1444	2.11	X	TBD			AP	
XPW01	NEW_XPW01_pore				X	21503518				
XPW02	NEW_XPW02_pore				X	21522010				
XPW03	NEW_XPW03_pore				X	21503520				
XPW04	NEW_XPW04_pore				X	21503519				
XSG01	NEW_XSG01	4/24/23	1716	534	X	TBD			AP	Staff gauge says 534
MW31D		4/24/23	1936	8.64						TD = 43.20
MW32S			1545	4.93						TD = 22.20
MW32D			1536	15.55						TD = 63.12
MW33D			1557	12.30						TD = 51.71
MW34S			1659	3.58						TD = 18.66
MW36D			1618	7.52						TD = 35.07
MW43S			1812	4.79						TD = 16.54
MW46S			1623	4.28						
MW48D			1831	4.98						TD = 41.54

Lake Levels
4/26/23 11:02 2.15'
4/26/23 8:11 2.19'
4/27/23 17:00 2.20'
4/28/23 7:58 2.17'
5/1/23 15:36 2.05'

GW08 - well removed Jan 2023

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

NEWTON

WELL/SAMPLE POINT APW02 **Purge Method:** Submersible pump

Date: 4/27/23 Start Time: 1056 Finish/Sample Time: 1217

Well Depth (Bottom) From MP: 24.03 ft Min. Purge Volume: 2 Gal (L)

Depth to Water From MP: 3.72 ft Total Purge Volume: 4 Gal (L)

Total Drawdown: 3.11 ft

Reading (Units)	Time	Depth (ft.)	Flow Rate (mL/min)	pH (s.u.)	Spec Cond (umhos/cm)	Temp (deg C)	ORP (mV)	DO (mg/L)	Turb (NTU)
1	1118	6.83	100	6.72	5213.3	15.55	80.6	1.23	24.51
2	1120	6.83	100	6.72	5216.1	15.58	80.7	1.23	23.97
3	1121	6.83	100	6.71	5217.2	15.62	80.8	1.23	25.04
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Aquatroll 600

Sample Appearance:

Odor: ☑ None ☐ Slight ☐ Mod. ☐ Strong

Color ☑ None ☐ Slight ☐ Mod. ☐ Strong

Turb: ☑ None ☐ Slight ☐ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	/	
Casing locked/secure	/	
Well cap fits securely.	/	
Good seal/drainage	/	
Well has weep holes	/	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
	General (P, 250 mL)
1	P 2.5L HNO3
1	P 1000 mL

Filtered	
Qty	Bottles
1	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
	General (P,500mL)
3	AV 40mL H2SO4
1	P 1000 mL
0.165 ppm	Soluble Iron +2

Comments APW02 next to APW07. HOBO connect SNs 21615523 and 21615614
FDTW = 6.83

Sampler's Signature:

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

Newton

WELL/SAMPLE POINT APW03 **Purge Method:** non dedicated pump

Date: 4/25/23 Start Time: 1145 Finish/Sample Time: 1320

Well Depth (Bottom) From MP: 23.47 ft Min. Purge Volume: 2 Gal / (L)

Depth to Water From MP: 11.94 ft Total Purge Volume: 2 Gal / (L)

Total Drawdown: 0.65 ft

Reading (Units)	Time	Depth (ft.)	Flow Rate (mL/min)	pH (s.u.)	Spec Cond (umhos/cm)	Temp (deg C)	ORP (mV)	DO (mg/L)	Turb (NTU)
1	1223	11.34	100	7.02	925	16.94	141	2.50	0.0
2	1224	11.39	100	7.01	925	16.91	140	2.45	0.0
3	1225	11.41	100	7.01	925	16.97	140	2.32	0.0
4	1226	11.47	100	7.01	925	16.97	141	2.25	0.0
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Horiba

Sample Appearance:

Odor: ☒ None ☐ Slight ☐ Mod. ☐ Strong

Color ☒ None ☐ Slight ☐ Mod. ☐ Strong

Turb: ☒ None ☐ Slight ☐ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	✓	
Casing locked/secure	✓	
Well cap fits securely.	✓	
Good seal/drainage	✓	
Well has weep holes	✓	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
1	General (P, ~~250~~ mL) 1000mL
1	2.5 L

Filtered	
Qty	Bottles
1	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
1	General (P,500mL)
3	4 V 40mL H_2SO_4

Comments 0.106 ppm Soluble iron +2 Final DTW 12.59 FL
Transducer S/N - 216155 24

Sampler's Signature: for Joe Reed

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

NEWTON

WELL/SAMPLE POINT APW04 **Purge Method:** Submersible pump

Date: 4/25/23 Start Time: 1450 Finish/Sample Time: 1642

Well Depth (Bottom) From MP: ~~22.63~~ ft Min. Purge Volume: 2 Gal (L)

Depth to Water From MP: 5.10 ft Total Purge Volume: 2.1 Gal / L

Total Drawdown: 6.21 ft

Reading	Time	Depth	Flow Rate	pH	Spec Cond	Temp	ORP	DO	Turb
(Units)		(ft.)	(mL/min)	(s.u.)	(umhos/cm)	(deg C)	(mV)	(mg/L)	(NTU)
1	1528	9.16	100	6.93	1830	11.79	172	0.93	203
2	1529	9.17	100	6.93	1830	11.79	172	0.93	204
3	1530	9.18	100	6.93	1830	11.79	171	0.93	178
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Horiba

Sample Appearance:

Odor: ☒ None ☐ Slight ☐ Mod. ☐ Strong

Color ☒ None ☐ Slight ☐ Mod. ☐ Strong

Turb: ☐ None ☒ Slight ☐ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	✓	
Casing locked/secure	✓	
Well cap fits securely.	✓	
Good seal/drainage	✓	
Well has weep holes	✓	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
1	General (P, ~~250~~ mL) 1000 mL
1	2.5 L HNO3

Filtered	
Qty	Bottles
1	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
1	General (P, ~~500~~ mL) 1000 mL
3	TOC

Comments S/n 21615483 0.155 ppm soluble iron +2

Sampler's Signature: Joseph R Rad

End DTW 11.31

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

Newton

WELL/SAMPLE POINT APW-055 (MW) **Purge Method:** Bladder pump/low flow

Date: 4/27/23 Start Time: 1110 JR Finish/Sample Time: 1240

Well Depth (Bottom) From MP: NM ft pump Min. Purge Volume: 2 Gal / L

Depth to Water From MP: 14.01 ft Total Purge Volume: 2.3 Gal / L

End DTW 14.05 ft

Total Drawdown: 0.04 ft

Reading	Time	Depth	Flow Rate	pH	Spec Cond	Temp	ORP	DO	Turb
(Units)		(ft.)	(mL/min)	(s.u.)	(umhos/cm)	(deg C)	(mV)	(mg/L)	(NTU)
1	1149	14.05	100	7.06	824	14.53	-120	17.70	30.0
2	1150	14.05	100	7.08	822	14.50	-122	17.78	36.0
3	1151	14.05	100	7.10	819	14.51	-124	17.70	40.1
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Horiba

Sample Appearance:

Odor: ☒ None ☐ Slight ☐ Mod. ☐ Strong

Color ☒ None ☐ Slight ☐ Mod. ☐ Strong

Turb: ☐ None ☒ Slight ☐ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	X	
Casing locked/secure	X	
Well cap fits securely.	X	
Good seal/drainage	X	
Well has weep holes	X	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
1	General (P, [illegible] mL) S/1000mL
1	2.5L HNO3

Filtered	
Qty	Bottles
1	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2SO4)
1	General (P, [illegible] mL) S/1000mL
3	TOC 40mL

Comments S/n - 21629308 Dis. Iron +2 = 1.151 ppm

Sampler's Signature: Joseph R Reed

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

NEWTON

WELL/SAMPLE POINT APW05S (UA) **Purge Method:** Submersible pump

Date: 4/26/23 Start Time: 1633 Finish/Sample Time: 1740

Well Depth (Bottom) From MP: 23.24 ft Min. Purge Volume: 2 Gal / L

Depth to Water From MP: 9.46 ft Total Purge Volume: 2.3 Gal / L

End DTW 10.23

Total Drawdown: 0.77 ft

Reading (Units)	Time	Depth (ft.)	Flow Rate (mL/min)	pH (s.u.)	Spec Cond (umhos/cm)	Temp (deg C)	ORP (mV)	DO (mg/L)	Turb (NTU)
1	1655	10.17	100	6.64	3940	16.35	101	3.61	225
2	56	10.17	100	6.62	3940	16.36	100	3.58	230
3	57	10.17	100	6.60	3930	16.35	97	3.53	220
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Horiba

Sample Appearance:

Odor: ☒ None ☐ Slight ☐ Mod. ☐ Strong

Color ☒ None ☐ Slight ☐ Mod. ☐ Strong

Turb: ☐ None ☒ Slight ☐ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	X	
Casing locked/secure	X	
Well cap fits securely.	X	
Good seal/drainage	X	
Well has weep holes	X	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
1	General (P, 250 mL)
1	2.5L HNO3

Filtered	
Qty	Bottles
1	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
1	General (P, ~~500mL~~) 1000mL
3	TOC 40mL

Comments S/N-21615502 Disolved Iron^{+2} = 0.259 ppm

Sampler's Signature: Joseph R Reed

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

NEWTON

WELL/SAMPLE POINT APW06 **Purge Method:** Submersible pump

Date: 4/26/23 Start Time: 1443 Finish/Sample Time: 1600

Well Depth (Bottom) From MP: 75.76 ft Min. Purge Volume: 2 Gal (L)

Depth to Water From MP: 19.33 ft Total Purge Volume: 2.3 Gal / L

End DTW 19.45

Total Drawdown: 0.12 ft

Reading (Units)	Time	Depth (ft.)	Flow Rate (mL/min)	pH (s.u.)	Spec Cond (umhos/cm)	Temp (deg C)	ORP (mV)	DO (mg/L)	Turb (NTU)
1	1510	19.45	100	7.36	795	17.55	-126	10.71	400
2	1511	19.45	100	7.35	797	17.55	-128	10.70	436
3	1512	19.45	100	7.35	796	17.55	-128	10.71	471
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Horiba

Sample Appearance:

Odor: ☒ None ☐ Slight ☐ Mod. ☐ Strong

Color ☒ None ☐ Slight ☐ Mod. ☐ Strong

Turb: ☐ None ☐ Slight ☒ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	X	
Casing locked/secure	X	
Well cap fits securely.	X	
Good seal/drainage	X	
Well has weep holes	X	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
1	General (P, ~~250~~mL) 1000 mL
1	2.5 L HNO3

Filtered	
Qty	Bottles
1	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
1	General (P, ~~500~~mL) 1000mL
3	40mL TOC

Comments Disolved Iron #2 = 0.904 ppm
S/N- 216 29309

Sampler's Signature: Joseph R Reed

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

Newton

WELL/SAMPLE POINT APW07 **Purge Method:** Submersible pump

Date: 4/27/23 Start Time: 0919 Finish/Sample Time: 1035

Well Depth (Bottom) From MP: 85.77 ft Min. Purge Volume: 2 Gal (L)

Depth to Water From MP: 46.59 ft Total Purge Volume: 7 Gal (L)

Total Drawdown: 0.00 ft

Reading	Time	Depth	Flow Rate	pH	Spec Cond	Temp	ORP	DO	Turb
(Units)		(ft.)	(mL/min)	(s.u.)	(umhos/cm)	(deg C)	(mV)	(mg/L)	(NTU)
1	0946	46.59	100	7.39	1050.9	14.41	-117.0	0.47	625.73
2	0947	46.59	100	7.40	1051.9	14.46	-117.0	0.48	648.42
3	0949	46.59	100	7.39	1050.7	14.50	-115.6	0.51	620.77
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Aquatroll 600

Sample Appearance:

Odor: ☐ None ☑ Slight ☐ Mod. ☐ Strong

Color ☐ None ☐ Slight ☑ Mod. ☐ Strong

Turb: ☐ None ☐ Slight ☑ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	✓	
Casing locked/secure	✓	
Well cap fits securely.	✓	
Good seal/drainage	✓	
Well has weep holes	✓	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
	General (P, 250 mL)
1	P 2.5L HNO3
1	P 1000 mL

Filtered	
Qty	Bottles
1	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
	General (P,500mL)
3	AV 40mL H2SO4
1	P 1000 mL
1.103 ppm	Soluble Iron $^{+2}$

Comments HOBO correct SN 21629296
Dedicated pump wasn't working properly. It discharges all the water in the tubing and then air. Pulled pump and used portable pump.

Sampler's Signature:

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

NEWTON

WELL/SAMPLE POINT APW08 **Purge Method:** Dedicated pump

Date: 4/26/23 Start Time: 1048 Finish/Sample Time: 1211

Well Depth (Bottom) From MP: NM ft Min. Purge Volume: 2.4 Gal (L)

Depth to Water From MP: 37.56 ft Total Purge Volume: 2.4 Gal (L)

Total Drawdown: 0.00 ft

Reading (Units)	Time	Depth (ft.)	Flow Rate (mL/min)	pH (s.u.)	Spec Cond (umhos/cm)	Temp (deg C)	ORP (mV)	DO (mg/L)	Turb (NTU)
1	1110	37.56	100	7.52	1105.4	14.24	-118.1	1.63	14.80
2	1111	37.56	100	7.53	1115.9	14.27	-117.2	1.67	16.76
3	1113	37.56	100	7.52	1100.0	14.23	-118.0	1.66	17.73
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Aquatroll 600

Sample Appearance:

Odor: ☐ None ☑ Slight ☐ Mod. ☐ Strong

Color ☑ None ☐ Slight ☐ Mod. ☐ Strong

Turb: ☑ None ☐ Slight ☐ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	✓	
Casing locked/secure	✓	
Well cap fits securely.	✓	
Good seal/drainage	✓	
Well has weep holes	✓	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
	General (P, 250 mL)
1	P 1000 mL
1	P 2.5L HNO3

Filtered	
Qty	Bottles
1	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
	General (P,500mL)
3	AV 40mL H2SO4
1	P 1000 mL
2.641 ppm	Soluble Iron +2

Comments HOBO connect SN 21629295

Sampler's Signature:

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

Newton

WELL/SAMPLE POINT APW09 **Purge Method:** Submersible pump

Date: 4/27/23 Start Time: 1240 Finish/Sample Time: 1405

Well Depth (Bottom) From MP: 57.97 ft Min. Purge Volume: 2 Gal / (L)

Depth to Water From MP: 26.56 ft Total Purge Volume: 6 Gal / (L)

Total Drawdown: 0.00 ft

Reading	Time	Depth	Flow Rate	pH	Spec Cond	Temp	ORP	DO	Turb
(Units)		(ft.)	(mL/min)	(s.u.)	(umhos/cm)	(deg C)	(mV)	(mg/L)	(NTU)
1	1304	26.56	100	7.53	1357.2	16.47	-134.6	0.53	93.33
2	1306	26.56	100	7.53	1357.4	16.51	-136.0	0.50	100.42
3	1307	26.56	100	7.53	1356.5	16.54	-137.0	0.47	116.74
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Aquaroll 600

Sample Appearance:

Odor: ☒ None ☐ Slight ☐ Mod. ☐ Strong

Color ☐ None ☒ Slight ☐ Mod. ☐ Strong

Turb: ☐ None ☐ Slight ☒ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	/	
Casing locked/secure	/	
Well cap fits securely.	/	
Good seal/drainage	/	
Well has weep holes	/	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
	General (P, 250 mL)
1	P 2.5L HNO3
1	P 1000 mL

Filtered	
Qty	Bottles
1	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
	General (P,500mL)
3	AV 40 ml H2SO4
1	P 1000 mL
2.279 ppm	Soluble Iron +2

Comments APW09 next to APW03. HOBOconnect SNs 21615616 and 21615524
Dedicated pump isn't pumping water at all. Pulled pump and used portable pump

Sampler's Signature:

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

NEWTON

WELL/SAMPLE POINT APW10 **Purge Method:** Dedicated pump

Date: 4/27/23 Start Time: 1420 Finish/Sample Time: 1547

Well Depth (Bottom) From MP: 48.55 ft Min. Purge Volume: 2 Gal (L)

Depth to Water From MP: 17.53 ft Total Purge Volume: 2.3 Gal (L)

Total Drawdown: 0.11 ft

Reading	Time	Depth	Flow Rate	pH	Spec Cond	Temp	ORP	DO	Turb
(Units)		(ft.)	(mL/min)	(s.u.)	(umhos/cm)	(deg C)	(mV)	(mg/L)	(NTU)
1	1442	17.59	100	7.36	1463.9	15.14	77.4	3.38	0.00
2	1443	17.59	100	7.36	1466.9	15.17	77.5	3.37	0.00
3	1445	17.59	100	7.36	1461.2	15.13	77.5	3.39	0.00
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Aquatroll 600

Sample Appearance:

Odor: ☑ None ☐ Slight ☐ Mod. ☐ Strong

Color ☑ None ☐ Slight ☐ Mod. ☐ Strong

Turb: ☑ None ☐ Slight ☐ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	✓	
Casing locked/secure	✓	
Well cap fits securely.		✓
Good seal/drainage	✓	
Well has weep holes	✓	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
	General (P, 250 mL)
1	P 2.5L HNO3
1	P 1000 mL

Filtered	
Qty	Bottles
1	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
	General (P,500mL)
3	AV 40 mL H2SO4
1	P 1000 mL
0.025 ppm	Soluble Iron +2

Comments APW10 reset to APW04. HOBOconnect SNs 21615483 and 21615555
Top 3 feet of pump tubing is folded in well. Needs to be cut off and reattached to wellhead adapter. Folded tubing has caused holes and leaks.

Sampler's Signature:

FDTW = 17.64'

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

NEWTON

WELL/SAMPLE POINT APW11 **Purge Method:** Dedicated pump

Date: 4/26/23 Start Time: 1406 Finish/Sample Time: 1543

Well Depth (Bottom) From MP: NM ft Min. Purge Volume: 2 Gal (L)

Depth to Water From MP: 24.27 ft Total Purge Volume: 2.3 Gal (L)

Total Drawdown: 0.09 ft

Reading (Units)	Time	Depth (ft.)	Flow Rate (mL/min)	pH (s.u.)	Spec Cond (umhos/cm)	Temp (deg C)	ORP (mV)	DO (mg/L)	Turb (NTU)
1	1432	24.32	100	7.14	1253.8	15.52	-13.8	0.67	471.71
2	1433	24.32	100	7.14	1252.4	15.56	-15.5	0.66	456.53
3	1435	24.32	100	7.15	1252.5	15.51	-17.8	0.64	445.59
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Aquatroll 600

Sample Appearance:

Odor: ☑ None ☐ Slight ☐ Mod. ☐ Strong

Color ☐ None ☐ Slight ☑ Mod. ☐ Strong

Turb: ☐ None ☐ Slight ☑ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	✓	
Casing locked/secure	✓	
Well cap fits securely.	✓	
Good seal/drainage	✓	
Well has weep holes	✓	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
	General (P, 250 mL)
1	P 1000mL
1	P 2.5L HNO3

Filtered	
Qty	Bottles
1	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
	General (P,500mL)
3	AV 40mL H2SO4
1	P 1000mL
0.721 ppm	Soluble Iron +2

Comments HOBO connect SN 21615556
Final DTW = 24.36

Sampler's Signature:

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

NEWTON

WELL/SAMPLE POINT APW12 **Purge Method:** Dedicated pump

Date: 4/26/23 Start Time: 1229 Finish/Sample Time: 1356

Well Depth (Bottom) From MP: NM ft Min. Purge Volume: 2 Gal /(L)

Depth to Water From MP: 14.56 ft Total Purge Volume: 2.3 Gal /(L)

Total Drawdown: 0.02 ft

Reading	Time	Depth	Flow Rate	pH	Spec Cond	Temp	ORP	DO	Turb
(Units)		(ft.)	(mL/min)	(s.u.)	(umhos/cm)	(deg C)	(mV)	(mg/L)	(NTU)
1	1252	14.58	100	6.51	1817.1	14.64	107.5	1.04	1.02
2	1253	14.58	100	6.52	1817.1	14.66	108.7	1.02	0.62
3	1255	14.58	100	6.52	1831.4	14.65	107.4	0.98	0.52
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Aquatroll 600

Sample Appearance:

Odor: ☑ None ☐ Slight ☐ Mod. ☐ Strong

Color ☑ None ☐ Slight ☐ Mod. ☐ Strong

Turb: ☑ None ☐ Slight ☐ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	✓	
Casing locked/secure	✓	
Well cap fits securely.	✓	
Good seal/drainage	✓	
Well has weep holes	✓	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
	General (P, 250 mL)
1	P 1000mL
1	P 2.5L HNO3

Filtered	
Qty	Bottles
1	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
	General (P,500mL)
3	AV 40mL H2SO4
1	P 1000mL
0.107 ppm	Soluble Iron +2

3rd 4/26

Comments HOBO connect SN 5 21615501

Sampler's Signature:

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

NEWTON

WELL/SAMPLE POINT APW13 **Purge Method:** Dedicated pump

Date: 4/27/23 Start Time: 1554 Finish/Sample Time: 1716

Well Depth (Bottom) From MP: NM ft Min. Purge Volume: 2 Gal /(L)

Depth to Water From MP: 32.05 ft Total Purge Volume: 2.3 Gal /(L)

Total Drawdown: 0.10 ft

Reading (Units)	Time	Depth (ft.)	Flow Rate (mL/min)	pH (s.u.)	Spec Cond (umhos/cm)	Temp (deg C)	ORP (mV)	DO (mg/L)	Turb (NTU)
1	1616	32.15	100	7.26	1376.7	14.29	-22.8	1.58	0.00
2	1617	32.15	100	7.26	1377.2	14.33	-24.1	1.61	0.00
3	1619	32.15	100	7.26	1360.1	14.28	-25.3	1.63	0.00
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Aquatroll 600

Sample Appearance:

Odor: ☑ None ☐ Slight ☐ Mod. ☐ Strong

Color ☑ None ☐ Slight ☐ Mod. ☐ Strong

Turb: ☑ None ☐ Slight ☐ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	✓	
Casing locked/secure	✓	
Well cap fits securely.	✓	
Good seal/drainage	✓	
Well has weep holes	✓	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
	General (P, 250 mL)
1	P 2.5L HNO3
1	P 1000 mL

Filtered	
Qty	Bottles
1	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
	General (P,500mL)
3	AV 40 mL H2S04
1	P 1000 mL
1.316 ppm	Soluble Iron+2

Comments HOBOconnect SN 21615615

Sampler's Signature: [signature]

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

NEWTON

WELL/SAMPLE POINT APW14 **Purge Method:** Dedicated pump

Date: 4/28/23 Start Time: 0908 Finish/Sample Time: ~~0~~ 2nd 4/28 1129

Well Depth (Bottom) From MP: NM ft Min. Purge Volume: 2 Gal / (L)

Depth to Water From MP: 20.72 ft Total Purge Volume: 2.4 Gal / (L)

Total Drawdown: 0.08 ft

Reading	Time	Depth	Flow Rate	pH	Spec Cond	Temp	ORP	DO	Turb
(Units)		(ft.)	(mL/min)	(s.u.)	(umhos/cm)	(deg C)	(mV)	(mg/L)	(NTU)
1	0930	20.76	100	7.35	1481.3	14.87	-93.3	1.28	12.43
2	0931	20.76	100	7.34	1473.8	14.85	-94.0	1.25	6.05
3	0933	20.76	100	7.34	1480.5	14.84	-95.0	1.22	8.81
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Aquatroll 600

Sample Appearance:

Odor: ☑ None ☐ Slight ☐ Mod. ☐ Strong

Color ☑ None ☐ Slight ☐ Mod. ☐ Strong

Turb: ☑ None ☐ Slight ☐ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	✓	
Casing locked/secure	✓	
Well cap fits securely.	✓	
Good seal/drainage	✓	
Well has weep holes	✓	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3 + 3 dup	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1 + 1 dup	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
	General (P, 250 mL)
1 + 1 dup	P 2.5 L HNO3
1 + 1 dup	P 1000 mL

Filtered	
Qty	Bottles
1 + 1 dup	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
	General (P,500mL)
3 + 3 dup	AV 40 mL H2SO4
1 + 1 dup	P 1000 mL
3.827 ppm	Soluble Iron **

Comments HOBO connect SN 21C15626
Field dup
FDTU: 20.80

Sampler's Signature:

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

NEWTON

WELL/SAMPLE POINT APW15 **Purge Method:** Dedicated pump

Date: 4/26/23 Start Time: 1601 Finish/Sample Time: 1723

Well Depth (Bottom) From MP: NM ft Min. Purge Volume: 2 Gal (L)

Depth to Water From MP: 21.43 ft Total Purge Volume: 2.3 Gal (L)

Total Drawdown: 0.72 ft

Reading (Units)	Time	Depth (ft.)	Flow Rate (mL/min)	pH (s.u.)	Spec Cond (umhos/cm)	Temp (deg C)	ORP (mV)	DO (mg/L)	Turb (NTU)
1	1623	22.05	100	7.26	1694.5	15.26	-125.3	0.34	63.37
2	1625	22.05	100	7.25	1658.2	15.28	-125.5	0.33	56.78
3	1626	22.05	100	7.25	1682.1	15.32	-125.6	0.32	51.55
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Aquatroll 600

Sample Appearance:

Odor: ☐ None ☒ Slight ☐ Mod. ☐ Strong

Color ☐ None ☐ Slight ☒ Mod. ☐ Strong

Turb: ☐ None ☐ Slight ☒ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	✓	
Casing locked/secure	✓	
Well cap fits securely.	✓	
Good seal/drainage	✓	
Well has weep holes	✓	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
	General (P, 250 mL)
1	P 1000 mL
1	P 2.5 HNO3

Filtered	
Qty	Bottles
1	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
	General (P,500mL)
3	AV 40 mL H2SO4
1	P 1000 mL
Overread	Soluble Iron ++

>6 ppm

Comments HOBO connect SN 21615625 Soluble Iron ++ reading was over the limit of 6 ppm
Final DTW = 22.15'

Sampler's Signature:

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

NEWTON

WELL/SAMPLE POINT APW16 **Purge Method:** Dedicated pump

Date: 4/25/23 Start Time: 1108 Finish/Sample Time: 1326

Well Depth (Bottom) From MP: NM ft Min. Purge Volume: 2 Gal (L)

Depth to Water From MP: 40.15 ft Total Purge Volume: 2 Gal (L)

Total Drawdown: 0.00 ft

Reading	Time	Depth	Flow Rate	pH	Spec Cond	Temp	ORP	DO	Turb
(Units)		(ft.)	(mL/min)	(s.u.)	(umhos/cm)	(deg C)	(mV)	(mg/L)	(NTU)
1	1137	40.15	100	7.64	947.82	14.10	-100.7	1.24	0.78
2	1138	40.15	100	7.65	949.58	14.04	-102.3	1.21	0.02
3	1140	40.15	100	7.65	953.00	14.04	-103.5	1.20	0.21
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Aquatroll 600

Sample Appearance:

Odor: ☐ None ☑ Slight ☐ Mod. ☐ Strong

Color ☑ None ☐ Slight ☐ Mod. ☐ Strong

Turb: ☑ None ☐ Slight ☐ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	✓	
Casing locked/secure	✓	
Well cap fits securely.	✓	
Good seal/drainage	✓	
Well has weep holes	✓	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
6	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
2	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
2	General (P, 250 mL) 1000 mL
1	P 2.5L HNO3
1	P 1000mL HNO3

Filtered	
Qty	Bottles
2	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
	General (P,500mL)
6	AV 40mL H2SO4
2	P 1000mL
2.271 ppm	Soluble Iron Fe

Comments HOBO connect SN 21615624
MS/MSD

Sampler's Signature:

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

NEWTON

WELL/SAMPLE POINT APW17 **Purge Method:** Dedicated Pump

Date: 4/25/23 Start Time: 1527 Finish/Sample Time: 1650

Well Depth (Bottom) From MP: NM ft Min. Purge Volume: 2.2 Gal (L)

Depth to Water From MP: 41.09 ft Total Purge Volume: 2.2 Gal (L)

Total Drawdown: 0.00 ft

Reading (Units)	Time	Depth (ft.)	Flow Rate (mL/min)	pH (s.u.)	Spec Cond (umhos/cm)	Temp (deg C)	ORP (mV)	DO (mg/L)	Turb (NTU)
1	1552	41.09	100	7.62	1161.9	15.13	-95.4	1.24	3.04
2	1553	41.09	100	7.62	1161.8	15.14	-96.3	1.22	2.84
3	1555	41.09	100	7.62	1162.3	15.17	-97.2	1.20	3.82
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Aquatroll 600

Sample Appearance:

Odor: ☐ None ☑ Slight ☐ Mod. ☐ Strong

Color ☑ None ☐ Slight ☐ Mod. ☐ Strong

Turb: ☑ None ☐ Slight ☐ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	/	
Casing locked/secure	/	
Well cap fits securely.	/	
Good seal/drainage	/	
Well has weep holes	/	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
	General (P, 250 mL)
1	P 2.5L HNO3
1	P 1000 mL

Filtered	
Qty	Bottles
1	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
	General (P,500mL)
3	4V 40mL H2S04
1	P 1000 mL
1.933 ppm	Soluble Iron Fe

Comments APW17 next to APW02. HOBOconnect SNs 21615523 and 21615614

Sampler's Signature:

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

NEWTON

WELL/SAMPLE POINT APW18 **Purge Method:** Dedicated pump

Date: 4/25/23 Start Time: 1340 Finish/Sample Time: 1503

Well Depth (Bottom) From MP: NM ft Min. Purge Volume: 2 Gal (L)

Depth to Water From MP: 51.63 ft Total Purge Volume: 2 Gal (L)

Total Drawdown: 0.00 ft

Reading (Units)	Time	Depth (ft.)	Flow Rate (mL/min)	pH (s.u.)	Spec Cond (umhos/cm)	Temp (deg C)	ORP (mV)	DO (mg/L)	Turb (NTU)
1	1405	51.63	100	7.77	1019.1	15.20	-134.0	1.10	10.57
2	1406	51.63	100	7.77	1015.5	15.17	-135.3	1.07	6.27
3	1408	51.63	100	7.78	1012.4	15.18	-136.7	1.05	5.01
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Aquatroll 600

Sample Appearance:

Odor: ☑ None ☐ Slight ☐ Mod. ☐ Strong

Color ☑ None ☐ Slight ☐ Mod. ☐ Strong

Turb: ☑ None ☐ Slight ☐ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	✓	
Casing locked/secure	✓	
Well cap fits securely.	✓	
Good seal/drainage	✓	
Well has weep holes	✓	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
	General (P, 250 mL)
1	P 2.5L HNO3
1	P 1000 mL

Filtered	
Qty	Bottles
1	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
	General (P,500mL)
3	AV 40mL H2SO4
1	P 1000 mL
1.328 ppm	Soluble Iron +2

Comments HOBO connect SN 21615617

Sampler's Signature:

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

NEWTON

WELL/SAMPLE POINT XPW01 **Purge Method:** Bladder Pump / low flow

Date: 4/27/23 Start Time: 1300 Finish/Sample Time: 1407

Well Depth (Bottom) From MP: 17.47 ft Min. Purge Volume: 2 Gal (V)

Depth to Water From MP: 11.06 ft Total Purge Volume: 2.3 Gal (L)

End DTW 11.07

Total Drawdown: 0.01 ft

Reading	Time	Depth	Flow Rate	pH	Spec Cond	Temp	ORP	DO	Turb
(Units)		(ft.)	(mL/min)	(s.u.)	(umhos/cm)	(deg C)	(mV)	(mg/L)	(NTU)
1	1326	11.07	100	12.20	10500	18.54	-378	4.43	>1000
2	1327	11.07	100	12.20	10500	18.40	-378	4.36	>1000
3	1328	11.07	100	12.19	10500	18.38	-379	427	>1000
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Horiba

Sample Appearance:

Odor: ☒ None ☐ Slight ☐ Mod. ☐ Strong

Color ☐ None ☐ Slight ☐ Mod. ☒ Strong

Turb: ☐ None ☐ Slight ☐ Mod ☒ Strong

Well Integrity	Yes	No
Well has ID sign	X	
Casing locked/secure	X	
Well cap fits securely.	X	
Good seal/drainage	X	
Well has weep holes	X	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
1	General (P, ~~250~~ mL) 1000mL

Filtered	
Qty	Bottles
1	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
1	General (P, ~~500~~mL) 1000mL
3	TOC 40mL

Comments S/n – 21615484 Dis. $Iron^{+2}$ = 0.508 ppm

Sampler's Signature: Joseph R Reed

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

NEWTON

WELL/SAMPLE POINT XPW02 **Purge Method:** Bladder pump / low flow

Date: 4/27/23 Start Time: 1413 Finish/Sample Time: 1529

Well Depth (Bottom) From MP: 16.49 ft Min. Purge Volume: 2 Gal (L)

Depth to Water From MP: 7.39 ft Total Purge Volume: 2.3 Gal (L)

End DTW 7.39

Total Drawdown: 0.0 ft

Reading	Time	Depth	Flow Rate	pH	Spec Cond	Temp	ORP	DO	Turb
(Units)		(ft.)	(mL/min)	(s.u.)	(umhos/cm)	(deg C)	(mV)	(mg/L)	(NTU)
1	1443	7.45	100	9.59	400	17.55	-236	4.86	40.8
2	1444	7.45	100	9.58	400	17.56	-235	4.80	43.1
3	1445	7.45	100	9.58	400	17.56	-237	4.80	39.1
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Horiba

Sample Appearance:

Odor: ☐ None ☒ Slight ☐ Mod. ☐ Strong

Color ☒ None ☐ Slight ☐ Mod. ☐ Strong

Turb: ☒ None ☐ Slight ☐ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	X	
Casing locked/secure	X	
Well cap fits securely.	X	
Good seal/drainage	X	
Well has weep holes	X	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3 4 JR	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
1	General (P, ~~250mL~~ 1000mL)

Filtered	
Qty	Bottles
1	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
1	General (P, ~~500mL~~ 1000mL)
3	TOC 40mL

Comments S/n - 21615544 Dis. Iron $^{+2}$ = 0.163 ppm

Sampler's Signature: Joseph R Redl

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

NEWTON

WELL/SAMPLE POINT XPW03 **Purge Method:** Bladder pump / low flow

Date: 4/27/23 Start Time: 1546 Finish/Sample Time: 1700

Well Depth (Bottom) From MP: 20.43 ft

Depth to Water From MP: 10.81 ft

Min. Purge Volume: 2.0 Gal / L

Total Purge Volume: 2.3 Gal / L

End DTW 10.81 ft

Total Drawdown: 0.0 ft

Reading	Time	Depth	Flow Rate	pH	Spec Cond	Temp	ORP	DO	Turb
(Units)		(ft.)	(mL/min)	(s.u.)	(umhos/cm)	(deg C)	(mV)	(mg/L)	(NTU)
1	1620	10.81	100	11.51	1440	17.16	-272	0.69	146
2	1621	10.81	100	11.51	1440	17.13	-272	0.72	132
3	1622	10.81	100	11.51	1430	17.09	-273	0.70	119
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Horiba

Sample Appearance:

Odor: ☒ None ☐ Slight ☐ Mod. ☐ Strong

Color ☒ None ☐ Slight ☐ Mod. ☐ Strong

Turb: ☒ None ☐ Slight ☐ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	X	
Casing locked/secure	X	
Well cap fits securely.	X	
Good seal/drainage	X	
Well has weep holes	X	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
1	General (P, ~~250 mL~~ 1000 mL)

Filtered	
Qty	Bottles
1	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
1	General (P, ~~500mL~~ 1000 mL)
3	TOC 49 mL

Comments S/N 21615486 Dis. Iron $^{+2}$ = 0.127 ppm

Sampler's Signature: Joseph R Rad

ATTACHMENT B.
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

NEWTON

WELL/SAMPLE POINT XPW04 **Purge Method:** Bladder Pump/Low Flow

Date: 4/28/23 Start Time: 918 Finish/Sample Time: 1023

Well Depth (Bottom) From MP: 20.40 ft Min. Purge Volume: 2.0 Gal (L)

Depth to Water From MP: 12.49 ft Total Purge Volume: 2.3 Gal (L)

End DTW 12.50

Total Drawdown: 0.01 ft

Reading (Units)	Time	Depth (ft.)	Flow Rate (mL/min)	pH (s.u.)	Spec Cond (umhos/cm)	Temp (deg C)	ORP (mV)	DO (mg/L)	Turb (NTU)
1	939	12.50	100	11.59	11900	12.26	-246	1.99	88.4
2	940	12.50	100	11.59	11900	16.19	-251	1.85	75.0
3	941	12.50	100	11.59	11900	16.20	-255	1.78	75.5
4									
5									
Stabilization	NA	NA	NA	± 0.2	± 3%	± 0.2	± 20	± 10% or 0.2	NA

Field Meter: Horiba

Sample Appearance:

Odor: ☒ None ☐ Slight ☐ Mod. ☐ Strong

Color ☐ None ☒ Slight ☐ Mod. ☐ Strong

Turb: ☒ None ☐ Slight ☐ Mod ☐ Strong

Well Integrity	Yes	No
Well has ID sign	X	
Casing locked/secure	X	
Well cap fits securely.	X	
Good seal/drainage	X	
Well has weep holes	X	

BOTTLE INFORMATION:

Unfiltered	
Qty	Bottles
	VOAs (C,V, 40mL, HCL)
	VOAS (C,V, 40mL)
	Organics (A,G,U 1000mL)
	Organics (A,G,U 500mL)
3	TOC (A,V 40mL, H2SO4)
	TOX (A,G 250mL, H2SO4)
1	Metals (P,250mL, HNO3)
	Cyanide (P, 250mL, NaOH)
	Phenols (A,G,250mL, H2SO4)
1	General (P, ~~500~~mL) 1000mL

Filtered	
Qty	Bottles
1	Metals (P,250mL, HNO3)
	Ammonia (P,250mL, H2S04)
1	General (P, ~~500~~mL) 1000mL
3	TOC 40mL

Comments S/N - 21615485 Dis. Iron = 0.367 ppm

Sampler's Signature: Joseph R Reed

Multiparameter Meter Field Calibration Checklist

Field Personnel:	JD	Location:	Vistra Newton
Weather:	43-62°F p.cloudy wind W 5-10mph	Environment:	grass, dirt rock roads

Multiparameter Water Meter	Make:	Aquatroll	Model:	600	Serial Number: 762215
Water Level Meter	Make:	Heron	Model:	Dipper-T	Serial Number: 3717-T

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.11	s.u.	±0.1 s.u.	Fail	Yes	4.06	MSI	L344-09	12/14/2023
pH 7.00a	6.86	s.u.	±0.1 s.u.	Fail	Yes	7.06	MSI	L343-07	12/9/2023
pH 10.00a	9.89	s.u.	±0.1 s.u.	Fail	Yes	10.08	MSI	M082-04	3/25/2024
SC Zero (DI)	12.13	µS/cm	0<25 µS/cm	Pass	No	NA	Pace Labs	N/A (DI)	N/A (DI)
SC 2000	2023.0	µS/cm	±5%	Pass	No	NA	Geotech	2GE1442	May-23
ORP	244.3	mV	±15 mV	Pass	No	NA	InSitu	2G1762	Jun-23
DO (Zero pt)	0.08	mg/L	±0.1	Pass	No	NA	Macron	#000228049	8/26/2025
DO (Saturated)	90.87	%	97-100%	Fail	Yes	99.73	Pace Labs	N/A (DI)	N/A (DI)
Turbidity (DI)	0.00	NTU	<2 NTU	Pass	No	NA	Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

ICV (Initial Calibration Verification)					Time: 10:16			
Buffer	Check Value	Units	Range	Pass/Fail	Action Taken?	Manufacturer	Lot#	Exp.
pH 4.00b	4.03	s.u.	±0.15 s.u.	Pass	NA	Geotech	2GC243	Mar-24
pH 7.00b	7.07	s.u.	±0.15 s.u.	Pass	NA	Geotech	2GC931	Mar-24
pH 10.00b	10.07	s.u.	±0.15 s.u.	Pass	NA	Geotech	2GE820	May-24
SC 1000	965.05	µS/cm	±5%	Pass	NA	Ricca	4205H64	May-24

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):					Time: 1731				
Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.07	s.u.	±0.1 s.u.	pass	No	NA	MSI	L315-04	11/22/2023
pH 7.00a	7.07	s.u.	±0.1 s.u.	pass	No	NA	MSI	L172-33	6/23/2023
pH 10.00a	10.16	s.u.	±0.1 s.u.	pass	No	NA	MSI	L354-22	1/5/2024
SC 1000	969.37	µS/cm	±5%	pass	No	NA	Ricca	2108D48	Jul-23
DO (Zero pt)	0.07	mg/L	±0.1 mg/L	pass	No	NA	Macron	#000228049	8/26/2025
Turbidity (DI)	0.00	NTU	<2 NTU	pass	No	NA	Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):					Time:				
Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
4.00a		s.u.	±0.1 s.u.				MSI	L315-04	11/22/2023
7.00a		s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
10.00a		s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000		µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)		mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)		NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Comments:

Signature:	[signature]	Date:	4/25/23

Multiparameter Meter Field Calibration Checklist

Field Personnel:	Kyle Lane	Location:	Newton Power
Weather:	46° to 65° cloudy	Environment:	Dry
Multiparameter Water Meter	Make: Horiba	Model: U-5000	Serial Number: VL9KJ9HR
Water Level Meter	Make: Huron	Model: water tape	Serial Number: 19FF2111192HB

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.01	s.u.	±0.1 s.u.	P	N/a	N/a	MSI	L344-09	12/14/2023
pH 7.00a	6.97	s.u.	±0.1 s.u.				MSI	L343-07	12/9/2023
pH 10.00a	10.01	s.u.	±0.1 s.u.				MSI	M082-04	3/25/2024
SC Zero (DI)	35.00	µS/cm	0<25 µS/cm				Pace Labs	N/A (DI)	N/A (DI)
SC 2000	1994	µS/cm	±5%				Geotech	2GE1442	May-23
ORP	238	mV	±15 mV				InSitu	2G1762	Jun-23
DO (Zero pt)	0.08	mg/L	±0.1				Macron	#000228049	8/26/2025
DO (Saturated)	97.48	%	97-100%				Pace Labs	N/A (DI)	N/A (DI)
Turbidity (DI)	0.84	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

ICV (Initial Calibration Verification)

Time: 10:21

Buffer	Check Value	Units	Range	Pass/Fail	Action Taken?	Manufacturer	Lot#	Exp.
pH 4.00b	4.00	s.u.	±0.15 s.u.		NA	Geotech	2GC243	Mar-24
pH 7.00b	7.00	s.u.	±0.15 s.u.			Geotech	2GC931	Mar-24
pH 10.00b	9.91	s.u.	±0.15 s.u.			Geotech	2GE820	May-24
SC 1000 9778	978	µS/cm	±5%			Ricca	4205H64	May-24

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):

Time:

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a		s.u.	±0.1 s.u.				MSI	L315-04	11/22/2023
pH 7.00a		s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
pH 10.00a		s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000		µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)		mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)		NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):

Time: 17:45

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
4.00a	4.07	s.u.	±0.1 s.u.	P	N/a	N/a	MSI	L315-04	11/22/2023
7.00a	6.94	s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
10.00a	9.97	s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000	1016	µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)	0.00	mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)	1.80	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Comments:

Signature:	[signature]	Date:	4-25-23

Multiparameter Meter Field Calibration Checklist

Field Personnel:	Joe Reed	Location:	Newton Power Station
Weather:	40-65° Mostly sunny wind 5-10 mph	Environment:	Grassy, gravel road
Multiparameter Water Meter	Make: Horiba	Model: U-5000	Serial Number: U4UIEVTF
Water Level Meter	Make: Heron	Model: Dipper T	Serial Number: 19FF2202131 ML

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.02	s.u.	±0.1 s.u.	P	Y		MSI	L344-09	12/14/2023
pH 7.00a	7.04	s.u.	±0.1 s.u.				MSI	L343-07	12/9/2023
pH 10.00a	10.05	s.u.	±0.1 s.u.				MSI	M082-04	3/25/2024
SC Zero (DI)	8	µS/cm	0<25 µS/cm				Pace Labs	N/A (DI)	N/A (DI)
SC 2000	2050	µS/cm	±5%				Geotech	2GE1442	May-23
ORP	244	mV	±15 mV				InSitu	2G1762	Jun-23
DO (Zero pt)	0.05	mg/L	±0.1				Macron	#000228049	8/26/2025
DO (Saturated)	97.8	%	97-100%				Pace Labs	N/A (DI)	N/A (DI)
Turbidity (DI)	0.0	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

12.64°C

Approx. every 4 hrs, unless only one well

ICV (Initial Calibration Verification)					Time: 1010			
Buffer	Check Value	Units	Range	Pass/Fail	Action Taken?	Manufacturer	Lot#	Exp.
pH 4.00b	4.07	s.u.	±0.15 s.u.	P	NA	Geotech	2GC243	Mar-24
pH 7.00b	6.97	s.u.	±0.15 s.u.			Geotech	2GC931	Mar-24
pH 10.00b	9.95	s.u.	±0.15 s.u.			Geotech	2GE820	May-24
SC 1000	1010	µS/cm	±5%			Ricca	4205H64	May-24

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):					Time: 1815			
Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.05	s.u.	±0.1 s.u.	P	N		MSI	L315-04	11/22/2023
pH 7.00a	7.04	s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
pH 10.00a	10.06	s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000	1010	µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)	0.05	mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)	0.5	NTU	<2 NTU				Race Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):					Time:				
Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
4.00a		s.u.	±0.1 s.u.				MSI	L315-04	11/22/2023
7.00a		s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
10.00a		s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000		µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)		mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)		NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Comments:

Signature:	Joseph R Reed	Date:	4/25/23

Multiparameter Meter Field Calibration Checklist

Field Personnel:	Aaron Rembecka	Location:	Newton
Weather:	45°-63°F cloudy wind SE 3mph	Environment:	grass, dirt, woods

Multiparameter Water Meter	Make: AT	Model: 600	Serial Number:	762193	
Water Level Meter	Make: Heron	Model: Dipper i	Serial Number:	11SF220930SMC	

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.09	s.u.	±0.1 s.u.	P	NO	N/A	MSI	L344-09	12/14/2023
pH 7.00a	7.08	s.u.	±0.1 s.u.	P	NO	N/A	MSI	L343-07	12/9/2023
pH 10.00a	10.08	s.u.	±0.1 s.u.	P	NO	N/A	MSI	M082-04	3/25/2024
SC Zero (DI)	21.07	µS/cm	0<25 µS/cm	P	NO	N/A	Pace Labs	N/A (DI)	N/A (DI)
SC 2000	2044.7	µS/cm	±5%	P	NO	N/A	Geotech	2GE1442	May-23
ORP	236.9	mV	±15 mV	P	NO	N/A	InSitu	2G1762	Jun-23
DO (Zero pt)	0.08	mg/L	±0.1	P	NO	N/A	Macron	#000228049	8/26/2025
DO (Saturated)	83.74	%	97-100%	P	yes	~~1000~~ 100	Pace Labs	N/A (DI)	N/A (DI)
Turbidity (DI)	2.72	NTU	<2 NTU	P	yes	0.00	Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

App 4/25/23

2HZ @ 15°C

ICV (Initial Calibration Verification)					Time: 0915				
Buffer	Check Value	Units	Range	Pass/Fail	Action Taken?		Manufacturer	Lot#	Exp.
pH 4.00b	4.09	s.u.	±0.15 s.u.	P	N/A		Geotech	2GC243	Mar-24
pH 7.00b	6.93	s.u.	±0.15 s.u.	P	N/A		Geotech	2GC931	Mar-24
pH 10.00b	10.01	s.u.	±0.15 s.u.	P	N/A		Geotech	2GE820	May-24
SC 1000	986.4	µS/cm	±5%	P	N/A		Ricca	4205H64	May-24

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):					Time: 1831				
Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.08	s.u.	±0.1 s.u.	P	NO	N/A	MSI	L315-04	11/22/2023
pH 7.00a	7.08	s.u.	±0.1 s.u.	P	NO	N/A	MSI	L172-33	6/23/2023
pH 10.00a	10.07	s.u.	±0.1 s.u.	P	NO	N/A	MSI	L354-22	1/5/2024
SC 1000	1024	µS/cm	±5%	P	NO	N/A	Ricca	2108D48	Jul-23
DO (Zero pt)	0.09	mg/L	±0.1 mg/L	P	NO	N/A	Macron	#000228049	8/26/2025
Turbidity (DI)	1.81	NTU	<2 NTU	P	NO	N/A	Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):					Time:				
Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
4.00a		s.u.	±0.1 s.u.				MSI	L315-04	11/22/2023
7.00a		s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
10.00a		s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000		µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)		mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)		NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Comments:

Signature:		Date:	4/25/2023

Multiparameter Meter Field Calibration Checklist

Field Personnel:	JD	Location:	Vistra Newton
Weather:	42-62°F partly cloudy wind NW 5mph	Environment:	grassy

Multiparameter Water Meter	Make: Aquatroll	Model: 600	Serial Number:	762215	
Water Level Meter	Make: Heron	Model: Dipper-T	Serial Number:	3717-T	

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	3.98	s.u.	±0.1 s.u.	pass	No	NA	MSI	L344-09	12/14/2023
pH 7.00a	7.06	s.u.	±0.1 s.u.	↓	↓	↓	MSI	L343-07	12/9/2023
pH 10.00a	10.07	s.u.	±0.1 s.u.	↓	↓	↓	MSI	M082-04	3/25/2024
SC Zero (DI)	14.62	µS/cm	0<25 µS/cm	↓	↓	↓	Pace Labs	N/A (DI)	N/A (DI)
SC 2000	1937.2	µS/cm	±5%	↓	↓	↓	Geotech	2GE1442	May-23
ORP	252.0	mV	±15 mV	↓	↓	↓	InSitu	2G1762	Jun-23
DO (Zero pt)	0.05	mg/L	±0.1	↓	↓	↓	Macron	#000228049	8/26/2025
DO (Saturated)	98.13	%	97-100%	↓	↓	↓	Pace Labs	N/A (DI)	N/A (DI)
Turbidity (DI)	0.00	NTU	<2 NTU	↓	↓	↓	Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

ICV (Initial Calibration Verification)					Time: 0916			
Buffer	Check Value	Units	Range	Pass/Fail	Action Taken?	Manufacturer	Lot#	Exp.
pH 4.00b	4.07	s.u.	±0.15 s.u.	pass	NA	Geotech	2GC243	Mar-24
pH 7.00b	6.91	s.u.	±0.15 s.u.	↓	↓	Geotech	2GC931	Mar-24
pH 10.00b	9.92	s.u.	±0.15 s.u.	↓	↓	Geotech	2GE820	May-24
SC 1000	981.01	µS/cm	±5%	↓	↓	Ricca	4205H64	May-24

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):					Time: 1740				
Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.08	s.u.	±0.1 s.u.	pass	No	NA	MSI	L315-04	11/22/2023
pH 7.00a	7.07	s.u.	±0.1 s.u.	↓	↓	↓	MSI	L172-33	6/23/2023
pH 10.00a	10.02	s.u.	±0.1 s.u.	↓	↓	↓	MSI	L354-22	1/5/2024
SC 1000	955.42	µS/cm	±5%	↓	↓	↓	Ricca	2108D48	Jul-23
DO (Zero pt)	0.09	mg/L	±0.1 mg/L	↓	↓	↓	Macron	#000228049	8/26/2025
Turbidity (DI)	0.00	NTU	<2 NTU	↓	↓	↓	Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):					Time:				
Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
4.00a		s.u.	±0.1 s.u.				MSI	L315-04	11/22/2023
7.00a		s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
10.00a		s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000		µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)		mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)		NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Comments:

Signature:	[signature]	Date:	4/26/23

Multiparameter Meter Field Calibration Checklist

Field Personnel:	Aaron Pemberton	Location:	Newton
Weather:	52°-63°F Sunny Wind NE 5mph	Environment:	grass, dirt

Multiparameter Water Meter	Make: AT	Model: 600	Serial Number:	762193	
Water Level Meter	Make: Heron	Model: Dipper T	Serial Number:	11ff2209305ML	

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.05	s.u.	±0.1 s.u.	P	NO	N/A	MSI	L344-09	12/14/2023
pH 7.00a	7.04	s.u.	±0.1 s.u.				MSI	L343-07	12/9/2023
pH 10.00a	10.04	s.u.	±0.1 s.u.				MSI	M082-04	3/25/2024
SC Zero (DI)	3.93	µS/cm	0<25 µS/cm				Pace Labs	N/A (DI)	N/A (DI)
SC 2000	2025.1	µS/cm	±5%				Geotech	2GE1442	May-23
ORP	240.0	mV	±15 mV				InSitu	2G1762	Jun-23
DO (Zero pt)	0.08	mg/L	±0.1				Macron	#000228049	8/26/2025
DO (Saturated)	97.6	%	97-100%				Pace Labs	N/A (DI)	N/A (DI)
Turbidity (DI)	1.15	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

236 @ 20°C

ICV (Initial Calibration Verification)					Time: 0952			
Buffer	Check Value	Units	Range	Pass/Fail	Action Taken?	Manufacturer	Lot#	Exp.
pH 4.00b	4.01	s.u.	±0.15 s.u.	P	N/A	Geotech	2GC243	Mar-24
pH 7.00b	6.89	s.u.	±0.15 s.u.			Geotech	2GC931	Mar-24
pH 10.00b	10.00	s.u.	±0.15 s.u.			Geotech	2GE820	May-24
SC 1000	1000.0	µS/cm	±5%			Ricca	4205H64	May-24

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):					Time: 1720				
Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.07	s.u.	±0.1 s.u.	P	NO	N/A	MSI	L315-04	11/22/2023
pH 7.00a	7.02	s.u.	±0.1 s.u.	P			MSI	L172-33	6/23/2023
pH 10.00a	10.05	s.u.	±0.1 s.u.	P			MSI	L354-22	1/5/2024
SC 1000	999.72	µS/cm	±5%	P			Ricca	2108D48	Jul-23
DO (Zero pt)	0.09	mg/L	±0.1 mg/L	P			Macron	#000228049	8/26/2025
Turbidity (DI)	1.03	NTU	<2 NTU	P			Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):					Time:				
Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
4.00a		s.u.	±0.1 s.u.				MSI	L315-04	11/22/2023
7.00a		s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
10.00a		s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000		µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)		mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)		NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Comments:

Signature:	[signature]	Date:	4/26/2023

Multiparameter Meter Field Calibration Checklist

Field Personnel:	Kyle Lane	Location:	Newton Power
Weather:	41° to 63° Sunny cloudy	Environment:	Dry

Multiparameter Water Meter	Make:	Horiba	Model:	U-5000	Serial Number:	419KJ9Ha
Water Level Meter	Make:	Heron	Model:	Water tape	Serial Number:	19FF2111192HB

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.00	s.u.	±0.1 s.u.	P	N/a	N/a	MSI	L344-09	12/14/2023
pH 7.00a	6.81	s.u.	±0.1 s.u.	F	7.00	7.00	MSI	L343-07	12/9/2023
pH 10.00a	10.09	s.u.	±0.1 s.u.	P	N/a	N/a	MSI	M082-04	3/25/2024
SC Zero (DI)	13.00	µS/cm	0<25 µS/cm	P	N/a	N/a	Pace Labs	N/A (DI)	N/A (DI)
SC 2000	1790	µS/cm	±5%	F	2000	2,000	Geotech	2GE1442	May-23
ORP	243	mV	±15 mV	P	N/a	N/a	InSitu	2G1762	Jun-23
DO (Zero pt)	0.65	mg/L	±0.1	P	N/a	N/a	Macron	#000228049	8/26/2025
DO (Saturated)	97.46	%	97-100%	P	N/a	N/a	Pace Labs	N/A (DI)	N/A (DI)
Turbidity (DI)	1.90	NTU	<2 NTU	P	N/a	N/a	Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

ICV (Initial Calibration Verification)

Time: 10:04

Buffer	Check Value	Units	Range	Pass/Fail	Action Taken?	Manufacturer	Lot#	Exp.
pH 4.00b	3.95	s.u.	±0.15 s.u.	P	N/a	Geotech	2GC243	Mar-24
pH 7.00b	7.00	s.u.	±0.15 s.u.			Geotech	2GC931	Mar-24
pH 10.00b	10.13	s.u.	±0.15 s.u.			Geotech	2GE820	May-24
SC 1000	990	µS/cm	±5%			Ricca	4205H64	May-24

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):

Time:

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a		s.u.	±0.1 s.u.				MSI	L315-04	11/22/2023
pH 7.00a		s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
pH 10.00a		s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000		µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)		mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)		NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):

Time: 18:48

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
4.00a	4.08	s.u.	±0.1 s.u.	P	N/a	N/a	MSI	L315-04	11/22/2023
7.00a	7.01	s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
10.00a	10.03	s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000	1048	µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)	0.07	mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)	1.40	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Comments:

Signature:	Kyle Lane	Date:	4-26-2023

Multiparameter Meter Field Calibration Checklist

Field Personnel:	Joe Reed	Location:	Newton Power
Weather:	54-63° sunny w 4-7mph	Environment:	Dusty road / grass
Multiparameter Water Meter	Make: Horiba	Model: U5000	Serial Number: U4U1FVTF
Water Level Meter	Make: Heron	Model: Dipper-T	Serial Number: 3717-T

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	3.99	s.u.	±0.1 s.u.	P	N		MSI	L344-09	12/14/2023
pH 7.00a	7.01	s.u.	±0.1 s.u.				MSI	L343-07	12/9/2023
pH 10.00a	9.99	s.u.	±0.1 s.u.				MSI	M082-04	3/25/2024
SC Zero (DI)	5	µS/cm	0<25 µS/cm				Pace Labs	N/A (DI)	N/A (DI)
SC 2000	2010	µS/cm	±5%				Geotech	2GE1442	May-23
ORP	235	mV	±15 mV				InSitu	2G1762	Jun-23
DO (Zero pt)	0.04	mg/L	±0.1				Macron	#000228049	8/26/2025
DO (Saturated)	99.1	%	97-100%				Pace Labs	N/A (DI)	N/A (DI)
Turbidity (DI)	0.40	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

19.25°C

Approx. every 4 hrs, unless only one well

ICV (Initial Calibration Verification)					Time: 1236			
Buffer	Check Value	Units	Range	Pass/Fail	Action Taken?	Manufacturer	Lot#	Exp.
pH 4.00b	4.00	s.u.	±0.15 s.u.	P	N	Geotech	2GC243	Mar-24
pH 7.00b	6.95	s.u.	±0.15 s.u.			Geotech	2GC931	Mar-24
pH 10.00b	9.97	s.u.	±0.15 s.u.			Geotech	2GE820	May-24
SC 1000	1030	µS/cm	±5%			Ricca	4205H64	May-24

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):					Time: 1858				
Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.03	s.u.	±0.1 s.u.	P	N		MSI	L315-04	11/22/2023
pH 7.00a	7.05	s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
pH 10.00a	10.03	s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000	1010	µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)	0.05	mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)	0.6	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):					Time:				
Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
4.00a		s.u.	±0.1 s.u.				MSI	L315-04	11/22/2023
7.00a		s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
10.00a		s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000		µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)		mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)		NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Comments:

Signature:	Joseph R Reed	Date:	4/26/23

Multiparameter Meter Field Calibration Checklist

Field Personnel:	Aaron Pemberton	Location:	Newton
Weather:	brkn clouds, WNW NE 7 mph	Environment:	grass, dirt, woods

Multiparameter Water Meter	Make: AT	Model: 600	Serial Number:	762193	
Water Level Meter	Make: Heron	Model: Dipper-T	Serial Number:	11ff220930SMC	

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.04	s.u.	±0.1 s.u.	P	NO	N/A	MSI	L344-09	12/14/2023
pH 7.00a	7.02	s.u.	±0.1 s.u.				MSI	L343-07	12/9/2023
pH 10.00a	10.06	s.u.	±0.1 s.u.				MSI	M082-04	3/25/2024
SC Zero (DI)	3.52	µS/cm	0<25 µS/cm				Pace Labs	N/A (DI)	N/A (DI)
SC 2000	2022.2	µS/cm	±5%				Geotech	2GE1442	May-23
ORP	234	mV	±15 mV				InSitu	2G1762	Jun-23
DO (Zero pt)	0.09	mg/L	±0.1				Macron	#000228049	8/26/2025
DO (Saturated)	98.72	%	97-100%				Pace Labs	N/A (DI)	N/A (DI)
Turbidity (DI)	0.00	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

24 Z @ 15°C

ICV (Initial Calibration Verification)

Time: 0903

Buffer	Check Value	Units	Range	Pass/Fail	Action Taken?	Manufacturer	Lot#	Exp.
pH 4.00b	4.01	s.u.	±0.15 s.u.	P	N/A	Geotech	2GC243	Mar-24
pH 7.00b	6.89	s.u.	±0.15 s.u.			Geotech	2GC931	Mar-24
pH 10.00b	10.04	s.u.	±0.15 s.u.			Geotech	2GE820	May-24
SC 1000	994.75	µS/cm	±5%			Ricca	4205H64	May-23

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):

Time: 1200

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.08	s.u.	±0.1 s.u.	P	NO	N/A	MSI	L315-04	11/22/2023
pH 7.00a	7.06	s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
pH 10.00a	10.03	s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000	995.1	µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)	0.00	mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)	0.00	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

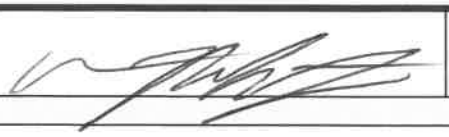
Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):

Time:

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
4.00a		s.u.	±0.1 s.u.				MSI	L315-04	11/22/2023
7.00a		s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
10.00a		s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000		µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)		mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)		NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Comments:

Signature:		Date:	4/27/2023

Multiparameter Meter Field Calibration Checklist

Field Personnel:	Joe Reed	Location:	Newton
Weather:	50-69° partcloudy windmph	Environment:	Dusty grassy
Multiparameter Water Meter	Make: Horiba	Model: U-5000	Serial Number: U4U1FVTF
Water Level Meter	Make: Heron	Model: Dipper	Serial Number: 19FF2111192HB

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.00	s.u.	±0.1 s.u.	P	Y		MSI	L344-09	12/14/2023
pH 7.00a	6.99	s.u.	±0.1 s.u.				MSI	L343-07	12/9/2023
pH 10.00a	10.00	s.u.	±0.1 s.u.				MSI	M082-04	3/25/2024
SC Zero (DI)	0.5	µS/cm	0<25 µS/cm				Pace Labs	N/A (DI)	N/A (DI)
SC 2000	2010	µS/cm	±5%				Geotech	2GE1442	May-23
ORP	234	mV	±15 mV				InSitu	2G1762	Jun-23
DO (Zero pt)	0.05	mg/L	±0.1				Macron	#000228049	8/26/2025
DO (Saturated)	98.1	%	97-100%				Pace Labs	N/A (DI)	N/A (DI)
Turbidity (DI)	0.0	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

ICV (Initial Calibration Verification)					Time:			
Buffer	Check Value	Units	Range	Pass/Fail	Action Taken?	Manufacturer	Lot#	Exp.
pH 4.00b	4.00	s.u.	±0.15 s.u.	P	N	Geotech	2GC243	Mar-24
pH 7.00b	7.01	s.u.	±0.15 s.u.			Geotech	2GC931	Mar-24
pH 10.00b	10.02	s.u.	±0.15 s.u.			Geotech	2GE820	May-24
SC 1000	1010	µS/cm	±5%			Ricca	4205H64	May-24

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):					Time:				
Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.02	s.u.	±0.1 s.u.	P	Y		MSI	L315-04	11/22/2023
pH 7.00a	7.01	s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
pH 10.00a	10.00	s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000	1020	µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)	0.05	mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)	0.0	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):					Time:				
Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
4.00a		s.u.	±0.1 s.u.				MSI	L315-04	11/22/2023
7.00a		s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
10.00a		s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000		µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)		mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)		NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Comments:

Signature:	Joe Reed	Date:	4/27/23

Multiparameter Meter Field Calibration Checklist

Field Personnel:	JD	Location:	Vistra Newton
Weather:	40-69°F wind NE 5mph	Environment:	grassy, rock road

Multiparameter Water Meter	Make: Aquatroll	Model: 600	Serial Number:	762215	
Water Level Meter	Make: Heron	Model: Dipper-T	Serial Number:	3717-T	

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.04	s.u.	±0.1 s.u.	Pass	No	NA	MSI	L344-09	12/14/2023
pH 7.00a	7.01	s.u.	±0.1 s.u.				MSI	L343-07	12/9/2023
pH 10.00a	10.01	s.u.	±0.1 s.u.				MSI	M082-04	3/25/2024
SC Zero (DI)	7.25	µS/cm	0<25 µS/cm				Pace Labs	N/A (DI)	N/A (DI)
SC 2000	1914.8	µS/cm	±5%				Geotech	2GE1442	May-23
ORP	255.8	mV	±15 mV				InSitu	2G1762	Jun-23
DO (Zero pt)	0.07	mg/L	±0.1				Macron	#000228049	8/26/2025
DO (Saturated)	97.49	%	97-100%				Pace Labs	N/A (DI)	N/A (DI)
Turbidity (DI)	0.00	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

ICV (Initial Calibration Verification) — Time: 0849

Buffer	Check Value	Units	Range	Pass/Fail	Action Taken?	Manufacturer	Lot#	Exp.
pH 4.00b	4.10	s.u.	±0.15 s.u.	Pass	NA	Geotech	2GC243	Mar-24
pH 7.00b	6.92	s.u.	±0.15 s.u.			Geotech	2GC931	Mar-24
pH 10.00b	9.94	s.u.	±0.15 s.u.			Geotech	2GE820	May-24
SC 1000	962.41	µS/cm	±5%			Ricca	4205H64	May-24

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification): — Time: 1739

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.05	s.u.	±0.1 s.u.	Pass	No	NA	MSI	L315-04	11/22/2023
pH 7.00a	7.06	s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
pH 10.00a	10.05	s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000	965.34	µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)	0.06	mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)	0.00	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification): — Time:

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
4.00a		s.u.	±0.1 s.u.				MSI	L315-04	11/22/2023
7.00a		s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
10.00a		s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000		µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)		mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)		NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Comments:

Signature:	JD	Date:	4/27/23

Multiparameter Meter Field Calibration Checklist

Field Personnel:	Kyle Lane	Location:	Newton Power
Weather:	45° to 70° Sunny	Environment:	Dry

Multiparameter Water Meter	Make: Horiba	Model: U-5000	Serial Number:	9L9KJ#Ha	
Water Level Meter	Make: Heron	Model: Water tape	Serial Number:	IIFF2209305 Mi	

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.00	s.u.	±0.1 s.u.	P	N/A	N/A	MSI	L344-09	12/14/2023
pH 7.00a	7.00	s.u.	±0.1 s.u.				MSI	L343-07	12/9/2023
pH 10.00a	10.01	s.u.	±0.1 s.u.				MSI	M082-04	3/25/2024
SC Zero (DI)	12.14	µS/cm	0<25 µS/cm				Pace Labs	N/A (DI)	N/A (DI)
SC 2000	1978	µS/cm	±5%				Geotech	2GE1442	May-23
ORP	241	mV	±15 mV				InSitu	2G1762	Jun-23
DO (Zero pt)	0.06	mg/L	±0.1				Macron	#000228049	8/26/2025
DO (Saturated)	97.49	%	97-100%				Pace Labs	N/A (DI)	N/A (DI)
Turbidity (DI)	1.30	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

ICV (Initial Calibration Verification)					Time: 08:47			
Buffer	Check Value	Units	Range	Pass/Fail	Action Taken?	Manufacturer	Lot#	Exp.
pH 4.00b	4.01	s.u.	±0.15 s.u.	P	N/a	Geotech	2GC243	Mar-24
pH 7.00b	6.98	s.u.	±0.15 s.u.			Geotech	2GC931	Mar-24
pH 10.00b	9.91	s.u.	±0.15 s.u.			Geotech	2GE820	May-24
SC 1000	968 4.68	µS/cm	±5%			Ricca	4205H64	May-24

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):					Time:				
Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a		s.u.	±0.1 s.u.				MSI	L315-04	11/22/2023
pH 7.00a		s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
pH 10.00a		s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000		µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)		mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)		NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):					Time: 12:34				
Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
4.00a	4.03	s.u.	±0.1 s.u.	P	N/a	N/a	MSI	L315-04	11/22/2023
7.00a	7.02	s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
10.00a	10.07	s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000	1020	µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)	0.00	mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)	1.10	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Comments:

Signature:		Date:	4-27-23

Multiparameter Meter Field Calibration Checklist

Field Personnel:	Kyle Lane	Location:	Newton Power
Weather:	56° to 70° sunny	Environment:	Wet

Multiparameter Water Meter	Make: Horiba	Model: U-52	Serial Number:	YL 9KJ9Ha	
Water Level Meter	Make: Heron	Model: Water tape	Serial Number:	19FF22023 1ML	

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.35	s.u.	±0.1 s.u.	F	Y	4.00	MSI	L344-09	12/14/2023
pH 7.00a	6.96	s.u.	±0.1 s.u.	P	N/a	N/a	MSI	L343-07	12/9/2023
pH 10.00a	10.00	s.u.	±0.1 s.u.				MSI	M082-04	3/25/2024
SC Zero (DI)	20.10	µS/cm	0<25 µS/cm				Pace Labs	N/A (DI)	N/A (DI)
SC 2000	1,970	µS/cm	±5%				Geotech	2GE1442	May-23
ORP	215	mV	±15 mV				InSitu	2G1762	Jun-23
DO (Zero pt)	0.00	mg/L	±0.1				Macron	#000228049	8/26/2025
DO (Saturated)	98.00	%	97-100%				Pace Labs	N/A (DI)	N/A (DI)
Turbidity (DI)	1.60	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

ICV (Initial Calibration Verification) — Time: 08:45

Buffer	Check Value	Units	Range	Pass/Fail	Action Taken?	Manufacturer	Lot#	Exp.
pH 4.00b	3.98	s.u.	±0.15 s.u.	P	N/a	Geotech	2GC243	Mar-24
pH 7.00b	6.87	s.u.	±0.15 s.u.			Geotech	2GC931	Mar-24
pH 10.00b	9.96	s.u.	±0.15 s.u.			Geotech	2GE820	May-24
SC 1000	960	µS/cm	±5%			Ricca	4205H64	May-24

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification): — Time:

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a		s.u.	±0.1 s.u.				MSI	L315-04	11/22/2023
pH 7.00a		s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
pH 10.00a		s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000		µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)		mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)		NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification): — Time: 12:04

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
4.00a	4.02	s.u.	±0.1 s.u.	P	N/a	N/a	MSI	L315-04	11/22/2023
7.00a	6.98	s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
10.00a	9.92	s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000	1,030	µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)	0.00	mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)	1.30	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Comments:

Signature:	[signature]	Date:	4-28-23

Multiparameter Meter Field Calibration Checklist

Field Personnel:	Aaron Remberton	Location:	Newton
Weather:	55°-61°F Sunny Wind: NNW	Environment:	grass, gravel, dirt
Multiparameter Water Meter	Make: AT	Model: 600	Serial Number: 762193
Water Level Meter	Make: Heron	Model: Dipper T	Serial Number: 11FF220930SM2

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.07	s.u.	±0.1 s.u.	P	NO	NA	MSI	L344-09	12/14/2023
pH 7.00a	7.06	s.u.	±0.1 s.u.				MSI	L343-07	12/9/2023
pH 10.00a	10.02	s.u.	±0.1 s.u.				MSI	M082-04	3/25/2024
SC Zero (DI)	21.21	µS/cm	0<25 µS/cm				Pace Labs	N/A (DI)	N/A (DI)
SC 2000	2024.1	µS/cm	±5%				Geotech	2GE1442	May-23
ORP	237.1	mV	±15 mV				InSitu	2G1762	Jun-23
DO (Zero pt)	0.09	mg/L	±0.1				Macron	#000228049	8/26/2025
DO (Saturated)	100.8%	%	97-100%				Pace Labs	N/A (DI)	N/A (DI)
Turbidity (DI)	1.03	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

242 @ 15°C

ICV (Initial Calibration Verification) Time: 0829

Buffer	Check Value	Units	Range	Pass/Fail	Action Taken?	Manufacturer	Lot#	Exp.
pH 4.00b	4.04	s.u.	±0.15 s.u.	P	NA	Geotech	2GC243	Mar-24
pH 7.00b	6.92	s.u.	±0.15 s.u.			Geotech	2GC931	Mar-24
pH 10.00b	9.98	s.u.	±0.15 s.u.			Geotech	2GE820	May-24
SC 1000	1089.19	µS/cm	±5%			Ricca	4205H64	May-24

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification): Time:

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a		s.u.	±0.1 s.u.				MSI	L315-04	11/22/2023
pH 7.00a		s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
pH 10.00a		s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000		µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)		mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)		NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification): Time:

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
4.00a		s.u.	±0.1 s.u.				MSI	L315-04	11/22/2023
7.00a		s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
10.00a		s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000		µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)		mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)		NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Comments:

Signature: Date: 4/28/2023

Multiparameter Meter Field Calibration Checklist

Field Personnel:	JD	Location:	Vistra Newton
Weather:	52-70°F p.sunny wind NE 10mph	Environment:	grassy

Multiparameter Water Meter	Make: Aquatroll	Model: 600	Serial Number:	762215	
Water Level Meter	Make: Heron	Model: Dipper-T	Serial Number:	3717-T	

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.07	s.u.	±0.1 s.u.	pass	No	NA	MSI	L344-09	12/14/2023
pH 7.00a	7.05	s.u.	±0.1 s.u.				MSI	L343-07	12/9/2023
pH 10.00a	10.02	s.u.	±0.1 s.u.				MSI	M082-04	3/25/2024
SC Zero (DI)	19.34	µS/cm	0<25 µS/cm				Pace Labs	N/A (DI)	N/A (DI)
SC 2000	1982.7	µS/cm	±5%				Geotech	2GE1442	May-23
ORP	250.9	mV	±15 mV				InSitu	2G1762	Jun-23
DO (Zero pt)	0.06	mg/L	±0.1				Macron	#000228049	8/26/2025
DO (Saturated)	99.48	%	97-100%				Pace Labs	N/A (DI)	N/A (DI)
Turbidity (DI)	0.00	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

ICV (Initial Calibration Verification)					Time: 0845			
Buffer	Check Value	Units	Range	Pass/Fail	Action Taken?	Manufacturer	Lot#	Exp.
pH 4.00b	4.10	s.u.	±0.15 s.u.	pass	NA	Geotech	2GC243	Mar-24
pH 7.00b	6.89	s.u.	±0.15 s.u.			Geotech	2GC931	Mar-24
pH 10.00b	9.92	s.u.	±0.15 s.u.			Geotech	2GE820	May-24
SC 1000	954.22	µS/cm	±5%			Ricca	4205H64	May-24

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):					Time: 1200				
Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.09	s.u.	±0.1 s.u.	pass	No	NA	MSI	L315-04	11/22/2023
pH 7.00a	7.05	s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
pH 10.00a	10.03	s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000	969.19	µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)	0.07	mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)	0.00	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):					Time:				
Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
4.00a		s.u.	±0.1 s.u.				MSI	L315-04	11/22/2023
7.00a		s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
10.00a		s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000		µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)		mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)		NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Comments:

Signature:	[signature]	Date:	4/28/23

Multiparameter Meter Field Calibration Checklist

Field Personnel:	Joe Reed	Location:	Newton Power
Weather:	56-74 partcloudy wind 10mph	Environment:	grassy
Multiparameter Water Meter	Make: Horiba	Model: U-5000	Serial Number: V4UIFVTF
Water Level Meter	Make: Heron	Model: Dipper T	Serial Number: 9FF2202131M2

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.00	s.u.	±0.1 s.u.	P	N		MSI	L344-09	12/14/2023
pH 7.00a	6.99	s.u.	±0.1 s.u.				MSI	L343-07	12/9/2023
pH 10.00a	10.00	s.u.	±0.1 s.u.				MSI	M082-04	3/25/2024
SC Zero (DI)	10	µS/cm	0<25 µS/cm				Pace Labs	N/A (DI)	N/A (DI)
SC 2000	2010	µS/cm	±5%				Geotech	2GE1442	May-23
ORP	240	mV	±15 mV				InSitu	2G1762	Jun-23
DO (Zero pt)	0.05	mg/L	±0.1				Macron	#000228049	8/26/2025
DO (Saturated)	99.3	%	97-100%				Pace Labs	N/A (DI)	N/A (DI)
Turbidity (DI)	0.0	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

ICV (Initial Calibration Verification)

Time: 830

Buffer	Check Value	Units	Range	Pass/Fail	Action Taken?	Manufacturer	Lot#	Exp.
pH 4.00b	4.02	s.u.	±0.15 s.u.	P	N	Geotech	2GC243	Mar-24
pH 7.00b	6.99	s.u.	±0.15 s.u.			Geotech	2GC931	Mar-24
pH 10.00b	9.99	s.u.	±0.15 s.u.			Geotech	2GE820	May-24
SC 1000	1010	µS/cm	±5%			Ricca	4205H64	May-24

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):

Time: 1217

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
pH 4.00a	4.03	s.u.	±0.1 s.u.	P	N		MSI	L315-04	11/22/2023
pH 7.00a	7.01	s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
pH 10.00a	10.01	s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000	1020	µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)	0.05	mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)	0.0	NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Approx. every 4 hrs, unless only one well

CCV (Continued Calibration Verification):

Time:

Buffer	Check Value	Units	Range	Pass/Fail	Calibrate?	Adjusted Reading	Manufacturer	Lot#	Exp.
4.00a		s.u.	±0.1 s.u.				MSI	L315-04	11/22/2023
7.00a		s.u.	±0.1 s.u.				MSI	L172-33	6/23/2023
10.00a		s.u.	±0.1 s.u.				MSI	L354-22	1/5/2024
SC 1000		µS/cm	±5%				Ricca	2108D48	Jul-23
DO (Zero pt)		mg/L	±0.1 mg/L				Macron	#000228049	8/26/2025
Turbidity (DI)		NTU	<2 NTU				Pace Labs	N/A (DI)	N/A (DI)

Comments:

Signature:	Joseph E Reed	Date:	4/28/23

Pace Analytical Services, LLC
2231 W. Altorfer Drive
Peoria, IL 61615
(800)752-6651

June 08, 2023

Terry Hanratty
Vistra - Newton
Newton Energy Center 6725 N. 500th St
Newton, IL 62448

Dear Terry Hanratty:

Please find enclosed the analytical results for the sample(s) the laboratory received. All testing is performed according to our current TNI accreditations unless otherwise noted. This report cannot be reproduced, except in full, without the written permission of Pace Analytical Services, LLC.

If you have any questions regarding your report, please contact your project manager. Quality and timely data is of the utmost importance to us.

Pace Analytical Services appreciates the opportunity to provide you with analytical expertise. We are always trying to improve our customer service and we welcome you to contact the General Manager, Lisa Grant, with any feedback you have about your experience with our laboratory at 309-683-1764 or lisa.grant@pacelabs.com.

Sincerely,

Gail Schindler

Gail Schindler
Project Manager
(309) 692-9688 x1716
gail.schindler@pacelabs.com

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SAMPLE RECEIPT CHECK LIST

Items not applicable will be marked as in compliance

Work Order GD04486

YES	Samples received within temperature compliance when applicable
YES	COC present upon sample receipt
YES	COC completed & legible
YES	Sampler name & signature present
YES	Unique sample IDs assigned
YES	Sample collection location recorded
YES	Date & time collected recorded on COC
YES	Relinquished by client signature on COC
YES	COC & labels match
YES	Sample labels are legible
YES	Appropriate bottle(s) received
YES	Sufficient sample volume received
YES	Sample containers received undamaged
NO	Zero headspace, <6 mm present in VOA vials
NO	Trip blank(s) received
YES	All non-field analyses received within holding times
NO	Short hold time analysis
YES	Current PDC COC submitted
NO	Case narrative provided

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Work Order GD04770

YES	Samples received within temperature compliance when applicable
YES	COC present upon sample receipt
YES	COC completed & legible
YES	Sampler name & signature present
YES	Unique sample IDs assigned
YES	Sample collection location recorded
YES	Date & time collected recorded on COC
YES	Relinquished by client signature on COC
YES	COC & labels match
YES	Sample labels are legible
YES	Appropriate bottle(s) received
YES	Sufficient sample volume received
YES	Sample containers received undamaged
NO	Zero headspace, <6 mm present in VOA vials
NO	Trip blank(s) received
YES	All non-field analyses received within holding times
NO	Short hold time analysis
YES	Current PDC COC submitted
NO	Case narrative provided

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Work Order GD04853

YES	Samples received within temperature compliance when applicable
YES	COC present upon sample receipt
YES	COC completed & legible
YES	Sampler name & signature present
YES	Unique sample IDs assigned
YES	Sample collection location recorded
YES	Date & time collected recorded on COC
YES	Relinquished by client signature on COC
YES	COC & labels match
YES	Sample labels are legible
YES	Appropriate bottle(s) received
YES	Sufficient sample volume received
YES	Sample containers received undamaged
NO	Zero headspace, <6 mm present in VOA vials
NO	Trip blank(s) received
YES	All non-field analyses received within holding times
NO	Short hold time analysis
YES	Current PDC COC submitted
NO	Case narrative provided

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Work Order GD04926

YES	Samples received within temperature compliance when applicable
YES	COC present upon sample receipt
YES	COC completed & legible
YES	Sampler name & signature present
YES	Unique sample IDs assigned
YES	Sample collection location recorded
YES	Date & time collected recorded on COC
YES	Relinquished by client signature on COC
YES	COC & labels match
YES	Sample labels are legible
YES	Appropriate bottle(s) received
YES	Sufficient sample volume received
YES	Sample containers received undamaged
NO	Zero headspace, <6 mm present in VOA vials
NO	Trip blank(s) received
YES	All non-field analyses received within holding times
NO	Short hold time analysis
YES	Current PDC COC submitted
NO	Case narrative provided

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ANALYTICAL RESULTS

Sample: GD04486-01 **Sampled:** 04/25/23 13:20
Name: APW03 **Received:** 04/26/23 13:30
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	1.02	pCi/L			1	0.598	05/19/23 14:32		904.0 903.0

Sample: GD04486-02 **Sampled:** 04/25/23 16:42
Name: APW04 **Received:** 04/26/23 13:30
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	1	pCi/L			1	0.518	05/19/23 14:32		904.0 903.0

Sample: GD04486-03 **Sampled:** 04/25/23 13:26
Name: APW16 **Received:** 04/26/23 13:30
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	2.05	pCi/L			1	0.472	05/19/23 14:32		904.0 903.0

Sample: GD04486-04 **Sampled:** 04/25/23 16:50
Name: APW17 **Received:** 04/26/23 13:30
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	1.42	pCi/L			1	0.493	05/19/23 14:32		904.0 903.0

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ANALYTICAL RESULTS

Sample: GD04486-05 **Sampled:** 04/25/23 15:03
Name: APW18 **Received:** 04/26/23 13:30
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	1.33	pCi/L			1	0.476	05/19/23 14:32		904.0 903.0

Sample: GD04486-06 **Sampled:** 04/25/23 17:15
Name: EB-01 **Received:** 04/26/23 13:30
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	0.426 J	pCi/L			1	0.652	05/19/23 14:32		904.0 903.0

Sample: GD04770-01 **Sampled:** 04/26/23 17:40
Name: APW05S **Received:** 04/27/23 14:20
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	0.141 U	pCi/L			1	0.784	05/31/23 08:55		904.0 903.0

Sample: GD04770-02 **Sampled:** 04/26/23 16:00
Name: APW06 **Received:** 04/27/23 14:20
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	1.2	pCi/L			1	0.686	05/31/23 08:55		904.0 903.0

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ANALYTICAL RESULTS

Sample: GD04770-03 **Sampled:** 04/26/23 12:11
Name: APW08 **Received:** 04/27/23 14:20
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	0.941	pCi/L			1	0.628	05/31/23 08:55		904.0 903.0

Sample: GD04770-04 **Sampled:** 04/26/23 15:43
Name: APW11 **Received:** 04/27/23 14:20
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	2.17	pCi/L			1	0.566	05/31/23 08:55		904.0 903.0

Sample: GD04770-05 **Sampled:** 04/26/23 13:56
Name: APW12 **Received:** 04/27/23 14:20
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	0.0586 U	pCi/L			1	0.697	05/31/23 08:55		904.0 903.0

Sample: GD04770-06 **Sampled:** 04/26/23 17:23
Name: APW15 **Received:** 04/27/23 14:20
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	1.97	pCi/L			1	0.696	05/31/23 08:55		904.0 903.0

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ANALYTICAL RESULTS

Sample: GD04770-07 **Sampled:** 04/26/23 16:30
Name: EB-02 **Received:** 04/27/23 14:20
Matrix: Ground Water - Equipment Blank

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	0.142 U	pCi/L			1	0.528	05/31/23 08:55		904.0 903.0

Sample: GD04853-01 **Sampled:** 04/27/23 12:17
Name: APW02 **Received:** 04/28/23 12:45
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	0.768	pCi/L			1	0.551	05/19/23 14:32		904.0 903.0

Sample: GD04853-02 **Sampled:** 04/27/23 12:40
Name: APW05 **Received:** 04/28/23 12:45
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	0.841	pCi/L			1	0.471	05/19/23 14:32		904.0 903.0

Sample: GD04853-03 **Sampled:** 04/27/23 10:35
Name: APW07 **Received:** 04/28/23 12:45
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	2.09	pCi/L			1	0.546	05/19/23 14:32		904.0 903.0

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ANALYTICAL RESULTS

Sample: GD04853-04 **Sampled:** 04/27/23 14:05
Name: APW09 **Received:** 04/28/23 12:45
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	2	pCi/L			1	0.449	05/19/23 14:32		904.0 903.0

Sample: GD04853-05 **Sampled:** 04/27/23 15:47
Name: APW10 **Received:** 04/28/23 12:45
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	0.316 J	pCi/L			1	0.562	05/19/23 14:32		904.0 903.0

Sample: GD04853-06 **Sampled:** 04/27/23 17:16
Name: APW13 **Received:** 04/28/23 12:45
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	0.651	pCi/L			1	0.485	05/19/23 14:32		904.0 903.0

Sample: GD04853-07 **Sampled:** 04/27/23 14:35
Name: EB-03 **Received:** 04/28/23 12:45
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	0.418 J	pCi/L			1	0.513	05/19/23 14:32		904.0 903.0

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ANALYTICAL RESULTS

Sample: GD04926-01
Name: APW14
Alias: NEW_811_502

Sampled: 04/28/23 11:29
Received: 04/28/23 16:12
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	0.381 J	pCi/L			1	0.465	05/24/23 00:32		904.0 903.0

Sample: GD04926-02
Name: APW14 DUP
Alias: NEW_811_502

Sampled: 04/28/23 11:29
Received: 04/28/23 16:12
Matrix: Ground Water - Grab

Parameter	Result	Unit	Qualifier	Prepared	Dilution	MRL	Analyzed	Analyst	Method
Miscellaneous - Pace Analytical - Mt Juliet, Tn									
Rad 226 and 228-Subcontract	1.71	pCi/L			1	0.584	05/31/23 08:55		904.0 903.0

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QC SAMPLE RESULTS

Parameter	Result	Unit	Qual	Spike Level	Source Result	%REC	%REC Limits	RPD	RPD Limit

Pace Analytical Services, LLC
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Peoria, IL 61615
(800)752-6651

NOTES

Specifications regarding method revisions, method modifications, and calculations used for analysis are available upon request. Please contact your project manager.

* Not a TNI accredited analyte

Certifications

CHI - McHenry, IL - 4314-A W. Crystal Lake Road, McHenry, IL 60050
TNI Accreditation for Drinking Water and Wastewater Fields of Testing through IL EPA Accreditation No. 100279
Illinois Department of Public Health Bacterial Analysis in Drinking Water Approved Laboratory Registry No. 17556

PIA - Peoria, IL - 2231 W. Altorfer Drive, Peoria, IL 61615
TNI Accreditation for Drinking Water, Wastewater, Solid and Hazardous Material Fields of Testing through IL EPA Accreditation No. 100230
Illinois Department of Public Health Bacterial Analysis in Drinking Water Approved Laboratory Registry No. 17553
Drinking Water Certifications/Accreditations: Iowa (240); Kansas (E-10338); Missouri (870)
Wastewater Certifications/Accreditations: Arkansas (88-0677); Iowa (240); Kansas (E-10338)
Solid and Hazardous Material Certifications/Accreditations: Arkansas (88-0677); Iowa (240); Kansas (E-10338)

SPMO - Springfield, MO - 1805 W Sunset Street, Springfield, MO 65807
USEPA DMR-QA Program

STL - Hazelwood, MO - 944 Anglum Rd, Hazelwood, MO 63042
TNI Accreditation for Wastewater, Solid and Hazardous Material Fields of Testing through KS KDHE Certification No. E-10389
TNI Accreditation for Wastewater, Solid and Hazardous Material Fields of Testing through IL EPA Accreditation No. - 200080
Illinois Department of Public Health Bacterial Analysis in Drinking Water Approved Laboratory, Registry No. 171050
Missouri Department of Natural Resources - Certificate of Approval for Microbiological Laboratory Service - No. 1050

Gail J Schindler

Certified by: Gail Schindler, Project Manager

ANALYTICAL REPORT

June 01, 2023

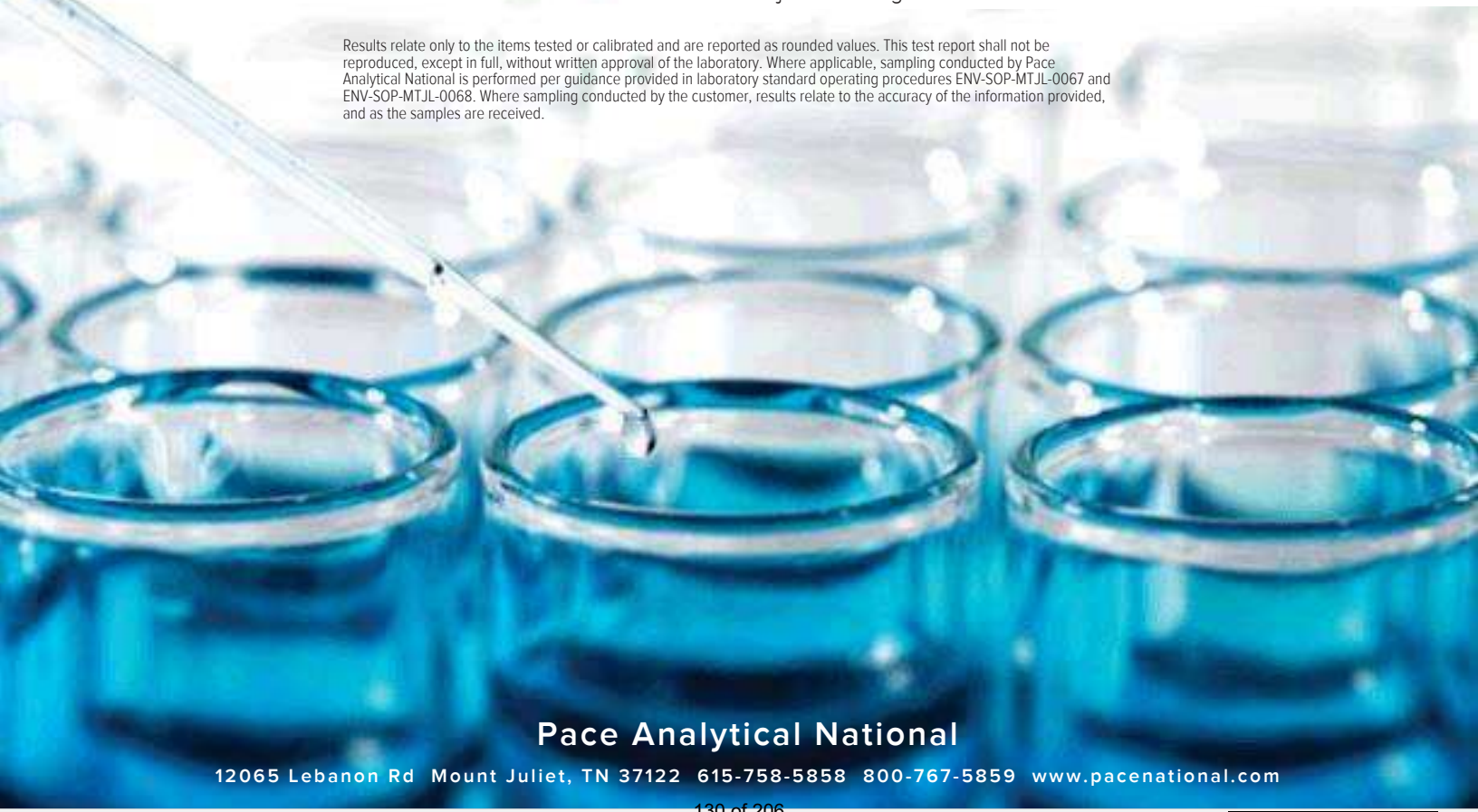
Pace IR - Peoria, IL

Sample Delivery Group:	L1611854
Samples Received:	05/03/2023
Project Number:	GD04486
Description:	Vistra-Newton
Site:	001
Report To:	Gail Schindler 2231 W. Altorfer Drive Peoria, IL 61615

Entire Report Reviewed By:

Haley Torrence
Project Manager

Results relate only to the items tested or calibrated and are reported as rounded values. This test report shall not be reproduced, except in full, without written approval of the laboratory. Where applicable, sampling conducted by Pace Analytical National is performed per guidance provided in laboratory standard operating procedures ENV-SOP-MTJL-0067 and ENV-SOP-MTJL-0068. Where sampling conducted by the customer, results relate to the accuracy of the information provided, and as the samples are received.



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SAMPLE SUMMARY

APW03 L1611854-01 Non-Potable Water

Collected by | Collected date/time 04/25/23 13:20 | Received date/time 05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061003	1	05/16/23 23:23	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058951	1	05/17/23 16:27	05/19/23 14:32	RRE	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058951	1	05/17/23 16:27	05/18/23 18:05	RRE	Mt. Juliet, TN

APW04 L1611854-02 Non-Potable Water

Collected by | Collected date/time 04/25/23 16:42 | Received date/time 05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061003	1	05/16/23 23:23	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058951	1	05/17/23 16:27	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058951	1	05/17/23 16:27	05/18/23 18:05	RGT	Mt. Juliet, TN

APW16 L1611854-03 Non-Potable Water

Collected by | Collected date/time 04/25/23 13:26 | Received date/time 05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061003	1	05/16/23 23:23	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058951	1	05/17/23 16:27	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058951	1	05/17/23 16:27	05/18/23 18:05	RGT	Mt. Juliet, TN

APW17 L1611854-04 Non-Potable Water

Collected by | Collected date/time 04/25/23 16:50 | Received date/time 05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061003	1	05/16/23 23:23	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058951	1	05/17/23 16:27	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058951	1	05/17/23 16:27	05/18/23 18:05	RGT	Mt. Juliet, TN

APW18 L1611854-05 Non-Potable Water

Collected by | Collected date/time 04/25/23 15:03 | Received date/time 05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061003	1	05/16/23 23:23	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058951	1	05/17/23 16:27	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058951	1	05/17/23 16:27	05/18/23 18:05	RGT	Mt. Juliet, TN

EB-01 L1611854-06 Non-Potable Water

Collected by | Collected date/time 04/25/23 17:15 | Received date/time 05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061003	1	05/16/23 23:23	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058951	1	05/17/23 16:27	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058951	1	05/17/23 16:27	05/18/23 18:05	RGT	Mt. Juliet, TN

CASE NARRATIVE

All sample aliquots were received at the correct temperature, in the proper containers, with the appropriate preservatives, and within method specified holding times, unless qualified or notated within the report. Where applicable, all MDL (LOD) and RDL (LOQ) values reported for environmental samples have been corrected for the dilution factor used in the analysis. All radiochemical sample results for solids are reported on a dry weight basis with the exception of tritium, carbon-14 and radon, unless wet weight was requested by the client. All Method and Batch Quality Control are within established criteria except where addressed in this case narrative, a non-conformance form or properly qualified within the sample results. By my digital signature below, I affirm to the best of my knowledge, all problems/anomalies observed by the laboratory as having the potential to affect the quality of the data have been identified by the laboratory, and no information or data have been knowingly withheld that would affect the quality of the data.

Haley Torrence

Haley Torrence
Project Manager

APW03 SAMPLE RESULTS - 01
Collected date/time: 04/25/23 13:20 L1611854

Radiochemistry by Method 904/9320

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-228	0.267	J	0.241	0.432	05/19/2023 14:32	WG2061003
(T) Barium	*109*			*30.0-143*	*05/19/2023 14:32*	WG2061003
(T) Yttrium	*90.0*			*30.0-136*	*05/19/2023 14:32*	WG2061003

Radiochemistry by Method Calculation

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
Combined Radium	1.02		0.551	0.598	05/19/2023 14:32	WG2058951

Radiochemistry by Method SM7500Ra B M

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-226	0.754		0.496	0.414	05/18/2023 18:05	WG2058951
(T) Barium-133	*39.3*			*30.0-143*	*05/18/2023 18:05*	WG2058951

APW04 SAMPLE RESULTS - 02
Collected date/time: 04/25/23 16:42 L1611854

Radiochemistry by Method 904/9320

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-228	0.543		0.253	0.444	05/19/2023 14:32	WG2061003
(T) Barium	*109*			*30.0-143*	*05/19/2023 14:32*	WG2061003
(T) Yttrium	*112*			*30.0-136*	*05/19/2023 14:32*	WG2061003

Radiochemistry by Method Calculation

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
Combined Radium	1.00		0.379	0.518	05/19/2023 14:32	WG2058951

Radiochemistry by Method SM7500Ra B M

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-226	0.462		0.282	0.266	05/18/2023 18:05	WG2058951
(T) Barium-133	*95.1*			*30.0-143*	*05/18/2023 18:05*	WG2058951

APW16
Collected date/time: 04/25/23 13:26

SAMPLE RESULTS - 03
L1611854

Radiochemistry by Method 904/9320

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-228	1.28		0.264	0.442	05/19/2023 14:32	WG2061003
(T) Barium	*118*			*30.0-143*	*05/19/2023 14:32*	WG2061003
(T) Yttrium	*105*			*30.0-136*	*05/19/2023 14:32*	WG2061003

Radiochemistry by Method Calculation

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
Combined Radium	2.05		0.408	0.472	05/19/2023 14:32	WG2058951

Radiochemistry by Method SM7500Ra B M

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-226	0.774		0.311	0.166	05/18/2023 18:05	WG2058951
(T) Barium-133	*91.0*			*30.0-143*	*05/18/2023 18:05*	WG2058951

APW17 SAMPLE RESULTS - 04
Collected date/time: 04/25/23 16:50 L1611854

Radiochemistry by Method 904/9320

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-228	0.696		0.244	0.423	05/19/2023 14:32	WG2061003
(T) Barium	*110*			*30.0-143*	*05/19/2023 14:32*	WG2061003
(T) Yttrium	*100*			*30.0-136*	*05/19/2023 14:32*	WG2061003

Radiochemistry by Method Calculation

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
Combined Radium	1.42		0.417	0.493	05/19/2023 14:32	WG2058951

Radiochemistry by Method SM7500Ra B M

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-226	0.725		0.338	0.254	05/18/2023 18:05	WG2058951
(T) Barium-133	*87.1*			*30.0-143*	*05/18/2023 18:05*	WG2058951

APW18 SAMPLE RESULTS - 05
Collected date/time: 04/25/23 15:03 L1611854

Radiochemistry by Method 904/9320

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-228	0.515		0.238	0.417	05/19/2023 14:32	WG2061003
(T) Barium	*108*			*30.0-143*	*05/19/2023 14:32*	WG2061003
(T) Yttrium	*94.8*			*30.0-136*	*05/19/2023 14:32*	WG2061003

Radiochemistry by Method Calculation

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
Combined Radium	1.33		0.413	0.476	05/19/2023 14:32	WG2058951

Radiochemistry by Method SM7500Ra B M

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-226	0.819		0.338	0.230	05/18/2023 18:05	WG2058951
(T) Barium-133	*118*			*30.0-143*	*05/18/2023 18:05*	WG2058951

EB-01 SAMPLE RESULTS - 06
Collected date/time: 04/25/23 17:15 L1611854

Radiochemistry by Method 904/9320

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-228	-0.653	U	0.262	0.500	05/19/2023 14:32	WG2061003
(T) Barium	*105*			*30.0-143*	*05/19/2023 14:32*	WG2061003
(T) Yttrium	*114*			*30.0-136*	*05/19/2023 14:32*	WG2061003

Radiochemistry by Method Calculation

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
Combined Radium	0.426	J	0.434	0.652	05/19/2023 14:32	WG2058951

Radiochemistry by Method SM7500Ra B M

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-226	0.426		0.346	0.419	05/18/2023 18:05	WG2058951
(T) Barium-133	*89.5*			*30.0-143*	*05/18/2023 18:05*	WG2058951

WG2061903

Radiochemistry by Method 904.0/9320

QUALITY CONTROL SUMMARY

L1611854-01,02,03,04,05,06

Method Blank (MB)

(MB) R3929806-1 05/19/23 14:32

Analyte	MB Result pCi/l	MB Qualifier	MB Uncertainty + / - pCi/l	MB MDA pCi/l
Radium-228	-0.357	U	0.173	0.324
(T) Barium	*108*		*108*	
(T) Yttrium	*101*		*101*	

L1611854-01 Original Sample (OS) • Duplicate (DUP)

(OS) L1611854-01 05/19/23 14:32 • (DUP) R3929806-5 05/19/23 14:32

Analyte	Original Result pCi/l	Original Uncertainty + / -	Original MDA pCi/l	DUP Result pCi/l	DUP Uncertainty + / -	DUP MDA pCi/l	Dilution	DUP RPD %	DUP RER	DUP Qualifier	DUP RPD Limits %	DUP RER Limit
Radium-228	0.267	0.241	0.432	-0.527	0.396	0.432	1	200	1.71	U	20	3
(T) Barium	*109*			*114*	*114*							
(T) Yttrium	*90.0*			*116*	*116*							

Laboratory Control Sample (LCS)

(LCS) R3929806-2 05/19/23 14:32

Analyte	Spike Amount pCi/l	LCS Result pCi/l	LCS Rec. %	Rec. Limits %	LCS Qualifier
Radium-228	5.00	4.97	99.4	80.0-120	
(T) Barium			*116*		
(T) Yttrium			*112*		

L1606733-01 Original Sample (OS) • Matrix Spike (MS) • Matrix Spike Duplicate (MSD)

(OS) L1606733-01 05/19/23 14:32 • (MS) R3929806-3 05/19/23 14:32 • (MSD) R3929806-4 05/19/23 14:32

Analyte	Spike Amount pCi/l	Original Result pCi/l	MS Result pCi/l	MSD Result pCi/l	MS Rec. %	MSD Rec. %	Dilution	Rec. Limits %	MS Qualifier	MSD Qualifier	RPD %	MS RER	RPD Limits %
Radium-228	10.0	0.855	10.4	10.0	95.1	91.7	1	70.0-130			3.34		20
(T) Barium		*121*			*120*	*116*							
(T) Yttrium		*108*			*111*	*98.4*							

WG2058991

Radiochemistry by Method SM 7500Ra B M

QUALITY CONTROL SUMMARY

L1611854-01,02,03,04,05,06

Method Blank (MB)

(MB) R3927911-5 05/18/23 18:22

Analyte	MB Result pCi/l	MB Qualifier	MB Uncertainty + / - pCi/l	MB MDA pCi/l
Radium-226	-0.0127	U	0.0290	0.0632
(T) Barium-133	*74.5*		*74.5*	

L1611860-01 Original Sample (OS) • Duplicate (DUP)

(OS) L1611860-01 05/18/23 18:05 • (DUP) R3927911-4 05/18/23 18:05

Analyte	Original Result pCi/l	Original Uncertainty + / -	Original MDA pCi/l	DUP Result pCi/l	DUP Uncertainty + / -	DUP MDA pCi/l	Dilution	DUP RPD %	DUP RER	DUP Qualifier	DUP RPD Limits %	DUP RER Limit
Radium-226	0.688	0.371	0.320	0.0912	0.205	0.320	1	153	1.41	U	20	3
(T) Barium-133	*85.0*			*87.1*	*87.1*							

Laboratory Control Sample (LCS)

(LCS) R3927911-1 05/18/23 18:05

Analyte	Spike Amount pCi/l	LCS Result pCi/l	LCS Rec. %	Rec. Limits %	LCS Qualifier
Radium-226	5.01	5.13	102	80.0-120	
(T) Barium-133			*77.2*		

L1611860-07 Original Sample (OS) • Matrix Spike (MS) • Matrix Spike Duplicate (MSD)

(OS) L1611860-07 05/18/23 18:05 • (MS) R3927911-2 05/18/23 18:05 • (MSD) R3927911-3 05/18/23 18:05

Analyte	Spike Amount pCi/l	Original Result pCi/l	MS Result pCi/l	MSD Result pCi/l	MS Rec. %	MSD Rec. %	Dilution	Rec. Limits %	MS Qualifier	MSD Qualifier	RPD %	MS RER	RPD Limits %
Radium-226	20.0	0.0721	19.7	19.7	98.2	97.9	1	75.0-125			0.305		20
(T) Barium-133		*79.2*			*84.7*	*72.7*							

GLOSSARY OF TERMS

Guide to Reading and Understanding Your Laboratory Report

The information below is designed to better explain the various terms used in your report of analytical results from the Laboratory. This is not intended as a comprehensive explanation, and if you have additional questions please contact your project representative.

Results Disclaimer - Information that may be provided by the customer, and contained within this report, include Permit Limits, Project Name, Sample ID, Sample Matrix, Sample Preservation, Field Blanks, Field Spikes, Field Duplicates, On-Site Data, Sampling Collection Dates/Times, and Sampling Location. Results relate to the accuracy of this information provided, and as the samples are received.

Abbreviations and Definitions

MDA	Minimum Detectable Activity.
Rec.	Recovery.
RER	Replicate Error Ratio.
RPD	Relative Percent Difference.
SDG	Sample Delivery Group.
(T)	Tracer - A radioisotope of known concentration added to a solution of chemically equivalent radioisotopes at a known concentration to assist in monitoring the yield of the chemical separation.
Analyte	The name of the particular compound or analysis performed. Some Analyses and Methods will have multiple analytes reported.
Dilution	If the sample matrix contains an interfering material, the sample preparation volume or weight values differ from the standard, or if concentrations of analytes in the sample are higher than the highest limit of concentration that the laboratory can accurately report, the sample may be diluted for analysis. If a value different than 1 is used in this field, the result reported has already been corrected for this factor.
Limits	These are the target % recovery ranges or % difference value that the laboratory has historically determined as normal for the method and analyte being reported. Successful QC Sample analysis will target all analytes recovered or duplicated within these ranges.
Original Sample	The non-spiked sample in the prep batch used to determine the Relative Percent Difference (RPD) from a quality control sample. The Original Sample may not be included within the reported SDG.
Qualifier	This column provides a letter and/or number designation that corresponds to additional information concerning the result reported. If a Qualifier is present, a definition per Qualifier is provided within the Glossary and Definitions page and potentially a discussion of possible implications of the Qualifier in the Case Narrative if applicable.
Result	The actual analytical final result (corrected for any sample specific characteristics) reported for your sample. If there was no measurable result returned for a specific analyte, the result in this column may state “ND” (Not Detected) or “BDL” (Below Detectable Levels). The information in the results column should always be accompanied by either an MDL (Method Detection Limit) or RDL (Reporting Detection Limit) that defines the lowest value that the laboratory could detect or report for this analyte.
Uncertainty (Radiochemistry)	Confidence level of 2 sigma.
Case Narrative (Cn)	A brief discussion about the included sample results, including a discussion of any non-conformances to protocol observed either at sample receipt by the laboratory from the field or during the analytical process. If present, there will be a section in the Case Narrative to discuss the meaning of any data qualifiers used in the report.
Quality Control Summary (Qc)	This section of the report includes the results of the laboratory quality control analyses required by procedure or analytical methods to assist in evaluating the validity of the results reported for your samples. These analyses are not being performed on your samples typically, but on laboratory generated material.
Sample Chain of Custody (Sc)	This is the document created in the field when your samples were initially collected. This is used to verify the time and date of collection, the person collecting the samples, and the analyses that the laboratory is requested to perform. This chain of custody also documents all persons (excluding commercial shippers) that have had control or possession of the samples from the time of collection until delivery to the laboratory for analysis.
Sample Results (Sr)	This section of your report will provide the results of all testing performed on your samples. These results are provided by sample ID and are separated by the analyses performed on each sample. The header line of each analysis section for each sample will provide the name and method number for the analysis reported.
Sample Summary (Ss)	This section of the Analytical Report defines the specific analyses performed for each sample ID, including the dates and times of preparation and/or analysis.

Qualifier	Description
J	The identification of the analyte is acceptable; the reported value is an estimate.
U	Below Detectable Limits: Indicates that the analyte was not detected.

1 Cp
2 Tc
3 Ss
4 Cn
5 Sr
6 Qc
7 Gl
8 Al
9 Sc

ACCREDITATIONS & LOCATIONS

Pace Analytical National 12065 Lebanon Rd Mount Juliet, TN 37122

Alabama	40660	Nebraska	NE-OS-15-05
Alaska	17-026	Nevada	TN000032021-1
Arizona	AZ0612	New Hampshire	2975
Arkansas	88-0469	New Jersey–NELAP	TN002
California	2932	New Mexico [1]	TN00003
Colorado	TN00003	New York	11742
Connecticut	PH-0197	North Carolina	Env375
Florida	E87487	North Carolina [1]	DW21704
Georgia	NELAP	North Carolina [3]	41
Georgia [1]	923	North Dakota	R-140
Idaho	TN00003	Ohio–VAP	CL0069
Illinois	200008	Oklahoma	9915
Indiana	C-TN-01	Oregon	TN200002
Iowa	364	Pennsylvania	68-02979
Kansas	E-10277	Rhode Island	LAO000356
Kentucky [1 6]	KY90010	South Carolina	84004002
Kentucky [2]	16	South Dakota	n/a
Louisiana	AI30792	Tennessee [1 4]	2006
Louisiana	LA018	Texas	T104704245-20-18
Maine	TN00003	Texas [5]	LAB0152
Maryland	324	Utah	TN000032021-11
Massachusetts	M-TN003	Vermont	VT2006
Michigan	9958	Virginia	110033
Minnesota	047-999-395	Washington	C847
Mississippi	TN00003	West Virginia	233
Missouri	340	Wisconsin	998093910
Montana	CERT0086	Wyoming	A2LA
A2LA – ISO 17025	1461.01	AIHA-LAP,LLC EMLAP	100789
A2LA – ISO 17025 [5]	1461.02	DOD	1461.01
Canada	1461.01	USDA	P330-15-00234
EPA–Crypto	TN00003		

[1] Drinking Water [2] Underground Storage Tanks [3] Aquatic Toxicity [4] Chemical/Microbiological [5] Mold [6] Wastewater n/a Accreditation not applicable

* Not all certifications held by the laboratory are applicable to the results reported in the attached report.

* Accreditation is only applicable to the test methods specified on each scope of accreditation held by Pace Analytical.

A133

Internal Transfer Chain of Custody

Pace Analytical®
www.pacelabs.com

State of Origin: IL
Cert. Needed: [X] YES [ ] NO

GD04486 **Workorder Name:** VISTRA - NEWTON **Owner Received Date:** 4/26/2023 **Results Requ By:** 5/15/2023

Report To:	Subcontract To:
Gail Schindler Pace Analytical - IL/MO 2231 W. Altorfer Drive Peoria, IL 61615 800-752-6651	Pace Analytical - Mt Juliet 12065 Lebanon Rd Mt Juliet TN 37122

Item	Sample ID	Sample Type	Collect Date/Time	Lab ID	Matrix	Preserved Containers	Requested Analysis: Radium 226	Requested Analysis: Radium 228	LAB USE ONLY
1	APW03	GRAB	4/25/2023 13:20	GD04486-01	GW		X	X	-01
2	APW04	GRAB	4/25/2023 16:42	GD04486-02	GW		X	X	-02
3	APW16	GRAB	4/25/2023 13:26	GD04486-03	GW		X	X	-03
4	APW17	GRAB	4/25/2023 16:50	GD04486-04	GW		X	X	-04
5	APW18	GRAB	4/25/2023 15:03	GD04486-05	GW		X	X	-05
6	EB-01	GRAB	4/25/2023 17:15	GD04486-06	DI		X	X	-06

LLD1854

Transfers	3/14/2023 14:31	Date/Time	Received By	Date/Time	Comments
1	Camden Pennett	5-2-23 14:42	Hayley Robertson	5/3/23 0900	Needs 226, 228 and combined Include QC summary and edd 10 day TAT
2					
3					

HR 5/3

Cooler Temperature on Receipt _____ °C	Custody Seal Y or N	Received on Ice Y or N	Sample Intact Y or N

***In order to maintain client confidentiality, location/name of the sampling site, sampler's name and signature may not be provided on this COC document. This chain of custody is considered complete as is since this information is available in the owner laboratory.

FMT-ALL-C-002rev.00 24March2009

Page 1 of 2

Sample Receipt Checklist

COC Seal Present/Intact:	Y / N	If Applicable	
COC Signed/Accurate:	Y / N	VOA Zero Headspace:	Y / N
Bottles arrive intact:	Y / N	Pres.Correct/Check:	Y / N
Correct bottles used:	Y / N		
Sufficient volume sent:	Y / N		
RAD Screen <0.5 mR/hr:	Y / N		

17.7±0=17.7 NS AG

6319597 8519

L1611854

Pace Analytical
www.pacelabs.com

Ship to :
Pace Analytical Services, LLC
12065 Lebanon Rd
Mt Juliet TN 37122

(615)758-5858

INTER_LABORATORY WORK ORDER # GD04486
(To be complete by sending lab)

Sending Project No:	GD04486
Receiving Project No:	
Check Box for Consolidated Invoice:	
Date Prepared:	5/2/2023
REQUESTED COMPLETION DATE:	5/15/2023

Sending Region	IR72-IL/MO	Sending Project Mgr.	Gail Schindler
Receiving Region	MT JULIET	External Client	VISTRA - NEWTON
State of Sample Origin	IL	QC Deliverable	**STD Report**

All questions should be addressed to sending project manager.

Requested Reportable Units _____ Report Wet or Dry Weight? _____ Cert Needed: IL

WORK REQUESTED						
Method Description	**Container Type**	**Quantity of**	**Preservative**	**Quantity of**	**Unit Price**	**Amount**
Radium 226		6		6	$100.00	$600.00
Radium 228		6		6	$100.00	$600.00
		1		1		$0.00
					TOTAL	$1,200.00

Special Requirements: Report as 226, 228 & combined 226/228. Include QC summary & edd

Receiving Reqion Department	Acctg. Code	Totals from above	Revenue Allocation	
			Receiving Region (80%)	Client Services Dept.
radiological	38	$1,200.00	$960.00	$240.00
		TOTAL	$960.00	$240.00

* Custom Revenue Allocation

FOR ANALYTICAL WORK COMPLETED THIS SECTION ALSO

Return Samples to Sending Region: [ ] Yes [X] No

CONFIRMATION OF WORK COMPLETED

Date Completed: _____ Receiving Project Manager: _____

Original sent to the receiving lab - Copy kept at the sending lab.

When work completed: Original sent to the ABM at the receiving laboratory. Copies are made to corporate as needed.

FMT-ALL-C-001 rev.00 24March2009 Page 1 of 1

ATTACHMENT B,
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

ANALYTICAL REPORT

June 06, 2023

Pace IR - Peoria, IL

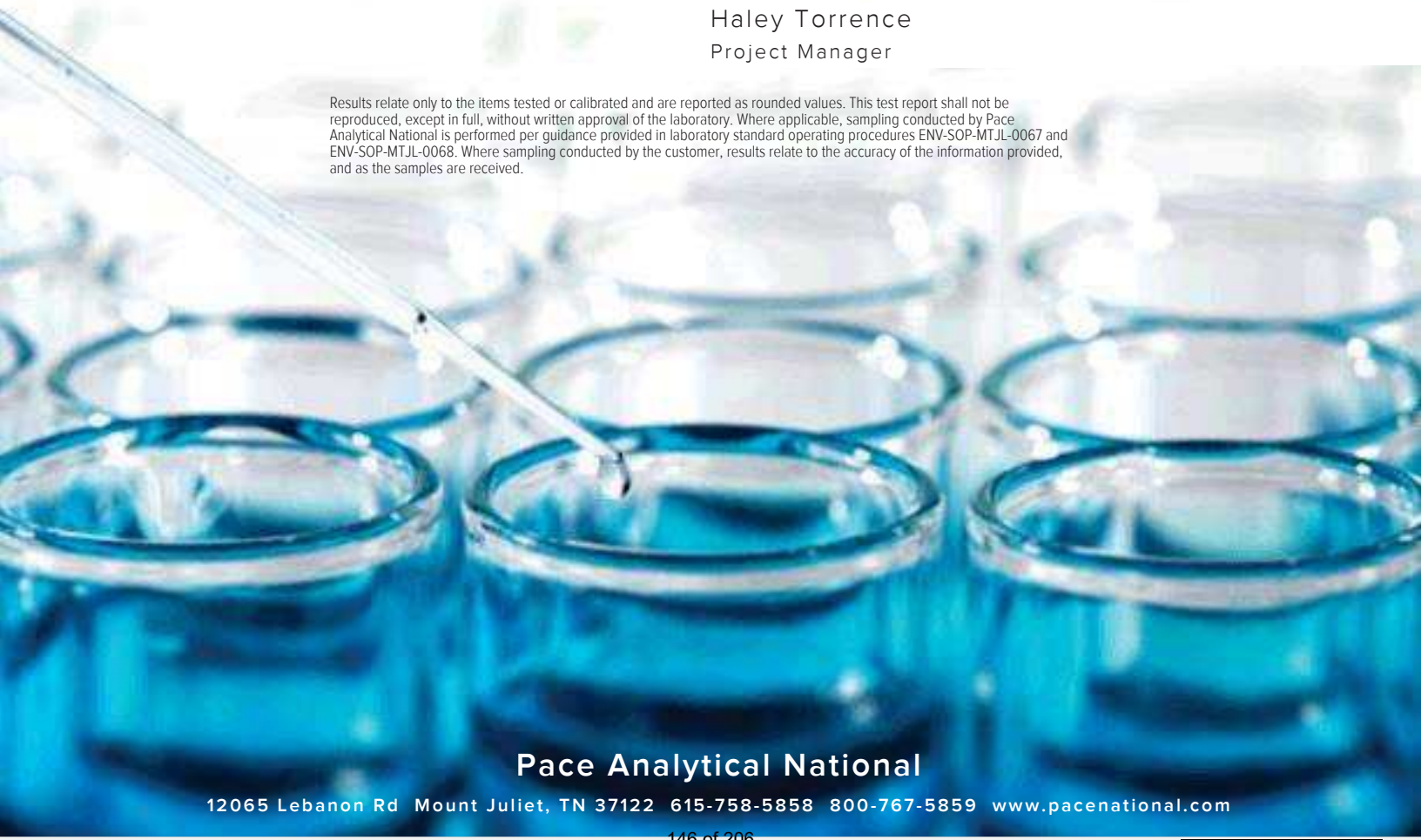
Sample Delivery Group:	L1611866
Samples Received:	05/03/2023
Project Number:	GD04770
Description:	Vistra-Newton
Site:	001
Report To:	Gail Schindler
	2231 W. Altorfer Drive
	Peoria, IL 61615

Entire Report Reviewed By:

Haley Torrence

Haley Torrence
Project Manager

Results relate only to the items tested or calibrated and are reported as rounded values. This test report shall not be reproduced, except in full, without written approval of the laboratory. Where applicable, sampling conducted by Pace Analytical National is performed per guidance provided in laboratory standard operating procedures ENV-SOP-MTJL-0067 and ENV-SOP-MTJL-0068. Where sampling conducted by the customer, results relate to the accuracy of the information provided, and as the samples are received.



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SAMPLE SUMMARY

APW05S L1611866-01 Non-Potable Water

Collected by | Collected date/time 04/26/23 17:40 | Received date/time 05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061735	1	05/17/23 20:19	05/31/23 08:55	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058953	1	05/22/23 11:11	05/31/23 08:55	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058953	1	05/22/23 11:11	05/24/23 13:18	RGT	Mt. Juliet, TN

APW06 L1611866-02 Non-Potable Water

Collected by | Collected date/time 04/26/23 16:00 | Received date/time 05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061735	1	05/17/23 20:19	05/31/23 08:55	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058953	1	05/22/23 11:11	05/31/23 08:55	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058953	1	05/22/23 11:11	05/24/23 13:18	RRE	Mt. Juliet, TN

APW08 L1611866-03 Non-Potable Water

Collected by | Collected date/time 04/26/23 12:11 | Received date/time 05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061735	1	05/17/23 20:19	05/31/23 08:55	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058953	1	05/22/23 11:11	05/31/23 08:55	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058953	1	05/22/23 11:11	05/24/23 13:18	RGT	Mt. Juliet, TN

APW11 L1611866-04 Non-Potable Water

Collected by | Collected date/time 04/26/23 15:43 | Received date/time 05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061735	1	05/17/23 20:19	05/31/23 08:55	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058953	1	05/22/23 11:11	05/31/23 08:55	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058953	1	05/22/23 11:11	05/24/23 13:18	RGT	Mt. Juliet, TN

APW12 L1611866-05 Non-Potable Water

Collected by | Collected date/time 04/26/23 13:56 | Received date/time 05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061735	1	05/17/23 20:19	05/31/23 08:55	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058953	1	05/22/23 11:11	05/31/23 08:55	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058953	1	05/22/23 11:11	05/24/23 13:18	RGT	Mt. Juliet, TN

APW15 L1611866-06 Non-Potable Water

Collected by | Collected date/time 04/26/23 17:23 | Received date/time 05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061735	1	05/17/23 20:19	05/31/23 08:55	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058953	1	05/22/23 11:11	05/31/23 08:55	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058953	1	05/22/23 11:11	05/24/23 13:18	RGT	Mt. Juliet, TN

SAMPLE SUMMARY

EB-02 L1611866-07 Non-Potable Water

Collected by	Collected date/time	Received date/time
	04/26/23 16:30	05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061735	1	05/17/23 20:19	05/31/23 08:55	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058953	1	05/22/23 11:11	05/31/23 08:55	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058953	1	05/22/23 11:11	05/24/23 13:18	RGT	Mt. Juliet, TN

CASE NARRATIVE

All sample aliquots were received at the correct temperature, in the proper containers, with the appropriate preservatives, and within method specified holding times, unless qualified or notated within the report. Where applicable, all MDL (LOD) and RDL (LOQ) values reported for environmental samples have been corrected for the dilution factor used in the analysis. All radiochemical sample results for solids are reported on a dry weight basis with the exception of tritium, carbon-14 and radon, unless wet weight was requested by the client. All Method and Batch Quality Control are within established criteria except where addressed in this case narrative, a non-conformance form or properly qualified within the sample results. By my digital signature below, I affirm to the best of my knowledge, all problems/anomalies observed by the laboratory as having the potential to affect the quality of the data have been identified by the laboratory, and no information or data have been knowingly withheld that would affect the quality of the data.

Haley Torrence

Haley Torrence
Project Manager

APW05S SAMPLE RESULTS - 01
Collected date/time: 04/26/23 17:40 L1611866

Radiochemistry by Method 904/9320

Analyte	Result	Qualifier	Uncertainty	MDA	Analysis Date	Batch
	pCi/l		+ / -	pCi/l	date / time	
RADIUM-228	-1.07	U	0.400	0.755	05/31/2023 08:55	WG2061735
(T) Barium	*80.2*			*30.0-143*	*05/31/2023 08:55*	WG2061735
(T) Yttrium	*88.7*			*30.0-136*	*05/31/2023 08:55*	WG2061735

Radiochemistry by Method Calculation

Analyte	Result	Qualifier	Uncertainty	MDA	Analysis Date	Batch
	pCi/l		+ / -	pCi/l	date / time	
Combined Radium	0.141	U	0.430	0.784	05/31/2023 08:55	WG2058953

Radiochemistry by Method SM7500Ra B M

Analyte	Result	Qualifier	Uncertainty	MDA	Analysis Date	Batch
	pCi/l		+ / -	pCi/l	date / time	
RADIUM-226	0.141	J	0.159	0.210	05/24/2023 13:18	WG2058953
(T) Barium-133	*101*			*30.0-143*	*05/24/2023 13:18*	WG2058953

Radiochemistry by Method 904/9320

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-228	0.574	J	0.336	0.595	05/31/2023 08:55	WG2061735
(T) Barium	*78.6*			*30.0-143*	*05/31/2023 08:55*	WG2061735
(T) Yttrium	*127*			*30.0-136*	*05/31/2023 08:55*	WG2061735

Radiochemistry by Method Calculation

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
Combined Radium	1.20		0.487	0.686	05/31/2023 08:55	WG2058953

Radiochemistry by Method SM7500Ra B M

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-226	0.621		0.353	0.342	05/24/2023 13:18	WG2058953
(T) Barium-133	*96.0*			*30.0-143*	*05/24/2023 13:18*	WG2058953

Radiochemistry by Method 904/9320

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-228	0.337	J	0.293	0.524	05/31/2023 08:55	WG2061735
(T) Barium	*93.7*			*30.0-143*	*05/31/2023 08:55*	WG2061735
(T) Yttrium	*88.5*			*30.0-136*	*05/31/2023 08:55*	WG2061735

Radiochemistry by Method Calculation

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
Combined Radium	0.941		0.456	0.628	05/31/2023 08:55	WG2058953

Radiochemistry by Method SM7500Ra B M

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-226	0.604		0.349	0.346	05/24/2023 13:18	WG2058953
(T) Barium-133	*84.4*			*30.0-143*	*05/24/2023 13:18*	WG2058953

APW11
Collected date/time: 04/26/23 15:43

SAMPLE RESULTS - 04

L1611866

Radiochemistry by Method 904/9320

Analyte	Result	Qualifier	Uncertainty	MDA	Analysis Date	Batch
	pCi/l		+ / -	pCi/l	date / time	
RADIUM-228	1.64		0.303	0.496	05/31/2023 08:55	WG2061735
(T) Barium	*78.2*			*30.0-143*	*05/31/2023 08:55*	WG2061735
(T) Yttrium	*95.5*			*30.0-136*	*05/31/2023 08:55*	WG2061735

Radiochemistry by Method Calculation

Analyte	Result	Qualifier	Uncertainty	MDA	Analysis Date	Batch
	pCi/l		+ / -	pCi/l	date / time	
Combined Radium	2.17		0.424	0.566	05/31/2023 08:55	WG2058953

Radiochemistry by Method SM7500Ra B M

Analyte	Result	Qualifier	Uncertainty	MDA	Analysis Date	Batch
	pCi/l		+ / -	pCi/l	date / time	
RADIUM-226	0.530		0.296	0.273	05/24/2023 13:18	WG2058953
(T) Barium-133	*101*			*30.0-143*	*05/24/2023 13:18*	WG2058953

APW12 SAMPLE RESULTS - 05
Collected date/time: 04/26/23 13:56 L1611866

Radiochemistry by Method 904/9320

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-228	-1.05	U	0.345	0.659	05/31/2023 08:55	WG2061735
(T) Barium	*85.3*			*30.0-143*	*05/31/2023 08:55*	WG2061735
(T) Yttrium	*127*			*30.0-136*	*05/31/2023 08:55*	WG2061735

Radiochemistry by Method Calculation

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
Combined Radium	0.0586	U	0.369	0.697	05/31/2023 08:55	WG2058953

Radiochemistry by Method SM7500Ra B M

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-226	0.0586	U	0.131	0.226	05/24/2023 13:18	WG2058953
(T) Barium-133	*97.0*			*30.0-143*	*05/24/2023 13:18*	WG2058953

Radiochemistry by Method 904/9320

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-228	1.38		0.390	0.665	05/31/2023 08:55	WG2061735
(T) Barium	*78.6*			*30.0-143*	*05/31/2023 08:55*	WG2061735
(T) Yttrium	*83.7*			*30.0-136*	*05/31/2023 08:55*	WG2061735

Radiochemistry by Method Calculation

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
Combined Radium	1.97		0.488	0.696	05/31/2023 08:55	WG2058953

Radiochemistry by Method SM7500Ra B M

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-226	0.586		0.294	0.207	05/24/2023 13:18	WG2058953
(T) Barium-133	*98.0*			*30.0-143*	*05/24/2023 13:18*	WG2058953

EB-02
Collected date/time: 04/26/23 16:30

SAMPLE RESULTS - 07
L1611866

Radiochemistry by Method 904/9320

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-228	-0.0858	U	0.272	0.502	05/31/2023 08:55	WG2061735
(T) Barium	*82.0*			*30.0-143*	*05/31/2023 08:55*	WG2061735
(T) Yttrium	*139*	C1		*30.0-136*	*05/31/2023 08:55*	WG2061735

Radiochemistry by Method Calculation

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
Combined Radium	0.142	U	0.306	0.528	05/31/2023 08:55	WG2058953

Radiochemistry by Method SM7500Ra B M

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-226	0.142	J	0.140	0.163	05/24/2023 13:18	WG2058953
(T) Barium-133	*100*			*30.0-143*	*05/24/2023 13:18*	WG2058953

1 Cp
2 Tc
3 Ss
4 Cn
5 Sr
6 Qc
7 Gl
8 Al
9 Sc

Method Blank (MB)

(MB) R3932968-2 05/31/23 08:55

Analyte	MB Result pCi/l	MB Qualifier	MB Uncertainty + / - pCi/l	MB MDA pCi/l
Radium-228	0.510		0.175	0.303
(T) Barium	*80.6*		*80.6*	
(T) Yttrium	*117*		*117*	

L1611866-05 Original Sample (OS) • Duplicate (DUP)

(OS) L1611866-05 05/31/23 08:55 • (DUP) R3932968-5 05/31/23 08:55

Analyte	Original Result pCi/l	Original Uncertainty + / -	Original MDA pCi/l	DUP Result pCi/l	DUP Uncertainty + / -	DUP MDA pCi/l	Dilution	DUP RPD %	DUP RER	DUP Qualifier	DUP RPD Limits %	DUP RER Limit
Radium-228	-1.05	0.345	0.659	-1.23	0.448	0.659	1	0.000	0.313	U	20	3
(T) Barium	*85.3*			*81.0*	*81.0*							
(T) Yttrium	*127*			*143*	*143*					C1		

Laboratory Control Sample (LCS)

(LCS) R3932968-1 05/26/23 09:50

Analyte	Spike Amount pCi/l	LCS Result pCi/l	LCS Rec. %	Rec. Limits %	LCS Qualifier
Radium-228	5.00	5.89	118	80.0-120	
(T) Barium			*94.2*		
(T) Yttrium			*74.8*		

L1607413-01 Original Sample (OS) • Matrix Spike (MS) • Matrix Spike Duplicate (MSD)

(OS) L1607413-01 05/31/23 08:55 • (MS) R3932968-3 05/31/23 08:55 • (MSD) R3932968-4 05/31/23 08:55

Analyte	Spike Amount pCi/l	Original Result pCi/l	MS Result pCi/l	MSD Result pCi/l	MS Rec. %	MSD Rec. %	Dilution	Rec. Limits %	MS Qualifier	MSD Qualifier	RPD %	MS RER	RPD Limits %
Radium-228	10.0	4.03	11.0	11.8	69.2	77.2	1	70.0-130	J6		7.05		20
(T) Barium		*80.5*			*88.9*	*84.4*							
(T) Yttrium		*87.6*			*117*	*116*							

WG2058993

Radiochemistry by Method SM 7500Ra B M

QUALITY CONTROL SUMMARY

L1611866-01,02,03,04,05,06,07

Method Blank (MB)

(MB) R3929001-1 05/24/23 00:32

Analyte	MB Result pCi/l	MB Qualifier	MB Uncertainty + / - pCi/l	MB MDA pCi/l
Radium-226	-0.0131	U	0.0300	0.0654
(T) Barium-133	*72.0*		*72.0*	

L1611866-07 Original Sample (OS) • Duplicate (DUP)

(OS) L1611866-07 05/24/23 13:18 • (DUP) R3929001-5 05/24/23 13:18

Analyte	Original Result pCi/l	Original Uncertainty + / -	Original MDA pCi/l	DUP Result pCi/l	DUP Uncertainty + / -	DUP MDA pCi/l	Dilution	DUP RPD %	DUP RER	DUP Qualifier	DUP RPD Limits %	DUP RER Limit
Radium-226	0.142	0.140	0.163	0.130	0.254	0.163	1	8.91	0.0417	U	20	3
(T) Barium-133	*100*			*83.2*	*83.2*							

Laboratory Control Sample (LCS)

(LCS) R3929001-2 05/24/23 13:18

Analyte	Spike Amount pCi/l	LCS Result pCi/l	LCS Rec. %	Rec. Limits %	LCS Qualifier
Radium-226	5.01	5.10	102	80.0-120	
(T) Barium-133			*94.0*		

L1611864-01 Original Sample (OS) • Matrix Spike (MS) • Matrix Spike Duplicate (MSD)

(OS) L1611864-01 05/24/23 00:32 • (MS) R3929001-3 05/24/23 13:18 • (MSD) R3929001-4 05/24/23 13:18

Analyte	Spike Amount pCi/l	Original Result pCi/l	MS Result pCi/l	MSD Result pCi/l	MS Rec. %	MSD Rec. %	Dilution	Rec. Limits %	MS Qualifier	MSD Qualifier	RPD %	MS RER	RPD Limits %
Radium-226	20.0	0.153	19.5	18.2	96.6	90.2	1	75.0-125			6.74		20
(T) Barium-133		*99.5*			*97.5*	*94.4*							

1 Cp
2 Tc
3 Ss
4 Cn
5 Sr
6 Qc
7 Gl
8 Al
9 Sc

GLOSSARY OF TERMS

Guide to Reading and Understanding Your Laboratory Report

The information below is designed to better explain the various terms used in your report of analytical results from the Laboratory. This is not intended as a comprehensive explanation, and if you have additional questions please contact your project representative.

Results Disclaimer - Information that may be provided by the customer, and contained within this report, include Permit Limits, Project Name, Sample ID, Sample Matrix, Sample Preservation, Field Blanks, Field Spikes, Field Duplicates, On-Site Data, Sampling Collection Dates/Times, and Sampling Location. Results relate to the accuracy of this information provided, and as the samples are received.

Abbreviations and Definitions

MDA	Minimum Detectable Activity.
Rec.	Recovery.
RER	Replicate Error Ratio.
RPD	Relative Percent Difference.
SDG	Sample Delivery Group.
(T)	Tracer - A radioisotope of known concentration added to a solution of chemically equivalent radioisotopes at a known concentration to assist in monitoring the yield of the chemical separation.
Analyte	The name of the particular compound or analysis performed. Some Analyses and Methods will have multiple analytes reported.
Dilution	If the sample matrix contains an interfering material, the sample preparation volume or weight values differ from the standard, or if concentrations of analytes in the sample are higher than the highest limit of concentration that the laboratory can accurately report, the sample may be diluted for analysis. If a value different than 1 is used in this field, the result reported has already been corrected for this factor.
Limits	These are the target % recovery ranges or % difference value that the laboratory has historically determined as normal for the method and analyte being reported. Successful QC Sample analysis will target all analytes recovered or duplicated within these ranges.
Original Sample	The non-spiked sample in the prep batch used to determine the Relative Percent Difference (RPD) from a quality control sample. The Original Sample may not be included within the reported SDG.
Qualifier	This column provides a letter and/or number designation that corresponds to additional information concerning the result reported. If a Qualifier is present, a definition per Qualifier is provided within the Glossary and Definitions page and potentially a discussion of possible implications of the Qualifier in the Case Narrative if applicable.
Result	The actual analytical final result (corrected for any sample specific characteristics) reported for your sample. If there was no measurable result returned for a specific analyte, the result in this column may state “ND” (Not Detected) or “BDL” (Below Detectable Levels). The information in the results column should always be accompanied by either an MDL (Method Detection Limit) or RDL (Reporting Detection Limit) that defines the lowest value that the laboratory could detect or report for this analyte.
Uncertainty (Radiochemistry)	Confidence level of 2 sigma.
Case Narrative (Cn)	A brief discussion about the included sample results, including a discussion of any non-conformances to protocol observed either at sample receipt by the laboratory from the field or during the analytical process. If present, there will be a section in the Case Narrative to discuss the meaning of any data qualifiers used in the report.
Quality Control Summary (Qc)	This section of the report includes the results of the laboratory quality control analyses required by procedure or analytical methods to assist in evaluating the validity of the results reported for your samples. These analyses are not being performed on your samples typically, but on laboratory generated material.
Sample Chain of Custody (Sc)	This is the document created in the field when your samples were initially collected. This is used to verify the time and date of collection, the person collecting the samples, and the analyses that the laboratory is requested to perform. This chain of custody also documents all persons (excluding commercial shippers) that have had control or possession of the samples from the time of collection until delivery to the laboratory for analysis.
Sample Results (Sr)	This section of your report will provide the results of all testing performed on your samples. These results are provided by sample ID and are separated by the analyses performed on each sample. The header line of each analysis section for each sample will provide the name and method number for the analysis reported.
Sample Summary (Ss)	This section of the Analytical Report defines the specific analyses performed for each sample ID, including the dates and times of preparation and/or analysis.

Qualifier	Description
C1	Tracer recovery limits have been exceeded; values are outside upper control limits.
J	The identification of the analyte is acceptable; the reported value is an estimate.
J6	The sample matrix interfered with the ability to make any accurate determination; spike value is low.
U	Below Detectable Limits: Indicates that the analyte was not detected.

ACCREDITATIONS & LOCATIONS

Pace Analytical National 12065 Lebanon Rd Mount Juliet, TN 37122

Alabama	40660	Nebraska	NE-OS-15-05
Alaska	17-026	Nevada	TN000032021-1
Arizona	AZ0612	New Hampshire	2975
Arkansas	88-0469	New Jersey–NELAP	TN002
California	2932	New Mexico [1]	TN00003
Colorado	TN00003	New York	11742
Connecticut	PH-0197	North Carolina	Env375
Florida	E87487	North Carolina [1]	DW21704
Georgia	NELAP	North Carolina [3]	41
Georgia [1]	923	North Dakota	R-140
Idaho	TN00003	Ohio–VAP	CL0069
Illinois	200008	Oklahoma	9915
Indiana	C-TN-01	Oregon	TN200002
Iowa	364	Pennsylvania	68-02979
Kansas	E-10277	Rhode Island	LAO000356
Kentucky [1 6]	KY90010	South Carolina	84004002
Kentucky [2]	16	South Dakota	n/a
Louisiana	AI30792	Tennessee [1 4]	2006
Louisiana	LA018	Texas	T104704245-20-18
Maine	TN00003	Texas [5]	LAB0152
Maryland	324	Utah	TN000032021-11
Massachusetts	M-TN003	Vermont	VT2006
Michigan	9958	Virginia	110033
Minnesota	047-999-395	Washington	C847
Mississippi	TN00003	West Virginia	233
Missouri	340	Wisconsin	998093910
Montana	CERT0086	Wyoming	A2LA
A2LA – ISO 17025	1461.01	AIHA-LAP,LLC EMLAP	100789
A2LA – ISO 17025 [5]	1461.02	DOD	1461.01
Canada	1461.01	USDA	P330-15-00234
EPA–Crypto	TN00003		

[1] Drinking Water [2] Underground Storage Tanks [3] Aquatic Toxicity [4] Chemical/Microbiological [5] Mold [6] Wastewater n/a Accreditation not applicable

* Not all certifications held by the laboratory are applicable to the results reported in the attached report.

* Accreditation is only applicable to the test methods specified on each scope of accreditation held by Pace Analytical.

Internal Transfer Chain of Custody

Pace Analytical® A130

State of Origin: IL
Cert. Needed: [X] YES [ ] NO

Owner Received Date: 4/27/2023

Results Requ By: 5/15/2023

GD04770 Workorder Name: VISTRA - NEWTON

Report To:	Subcontract To:
Gail Schindler Pace Analytical - IL/MO 2231 W. Altorfer Drive Peoria, IL 61615 800-752-6651	Pace Analytical - Mt Juliet 12065 Lebanon Rd Mt Juliet TN 37122

Item	Sample ID	Sample Type	Collect Date/Time	Lab ID	Matrix	Preserved Containers	Requested Analysis: Radium 226	Requested Analysis: Radium 228	LAB USE ONLY
1	APW05s	GRAB	4/26/2023 17:40	GD04770-01	GW		X	X	-01
2	APW06	GRAB	4/26/2023 16:00	GD04770-02	GW		X	X	-02
3	APW08	GRAB	4/26/2023 12:11	GD04770-03	GW		X	X	-03
4	APW11	GRAB	4/26/2023 15:43	GD04770-04	GW		X	X	-04
5	APW12	GRAB	4/26/2023 13:56	GD04770-05	GW		X	X	-05
6	APW15	GRAB	4/26/2023 17:23	GD04770-06	GW		X	X	-06
7	EB-02	GRAB	4/26/2023 16:30	GD04770-07	DI		X	X	-07

U611866

Transfers	3/14/2023 14:31	Date/Time	Received By	Date/Time	Comments
1	Carolyn Bennett	5-2-23 14:42	Hayley Barlow	5/3/23 0900	Needs 226, 228 and combined Include QC summary and edd 10 day TAT
2					
3					

Cooler Temperature on Receipt _____ °C | Custody Seal Y or N | Received on Ice Y or N | Sample Intact Y or N

***In order to maintain client confidentiality, location/name of the sampling site, sampler's name and signature may not be provided on this COC document.
This chain of custody is considered complete as is since this information is available in the owner laboratory.

Sample Receipt Checklist

COC Seal Present/Intact:	Y N	If Applicable	
COC Signed/Accurate:	Y N	VOA Zero Headspace:	Y N
Bottles arrive intact:	Y N	Pres.Correct/Check:	Y N
Correct bottles used:	Y N		
Sufficient volume sent:	Y N		
RAD Screen <0.5 mR/hr:	Y N		

18.8±0=18.5 NS 17

6319 5997 8493

L161864

Pace Analytical
www.pacelabs.com

Ship to :
Pace Analytical Services, LLC
12065 Lebanon Rd
Mt Juliet TN 37122

(615)758-5858

INTER_LABORATORY WORK ORDER # GD04770
(To be complete by sending lab)

Sending Project No:	GD04770
Receiving Project No:	
Check Box for Consolidated Invoice:	
Date Prepared:	5/2/2023
REQUESTED COMPLETION DATE:	5/15/2023

Sending Region	IR72-IL/MO	Sending Project Mgr.	Gail Schindler
Receiving Region	MT JULIET	External Client	VISTRA - NEWTON
State of Sample Origin	IL	QC Deliverable	**STD Report**

All questions should be addressed to sending project manager.

Requested Reportable Units _____ Report Wet or Dry Weight? _____ Cert Needed: IL

WORK REQUESTED						
Method Description	**Container Type**	**Quantity of**	**Preservative**	**Quantity of**	**Unit Price**	**Amount**
Radium 226		7		7	$100.00	$700.00
Radium 228		7		7	$100.00	$700.00
		1		1		$0.00
					TOTAL	$1,400.00

Special Requirements: Report as 226, 228 & combined 226/228. Include QC summary & edd

Receiving Reqion Department	Acctg. Code	Totals from above	Revenue Allocation	
			Receiving Region (80%)	Client Services Dept.
radiological	38	$1,400.00	$1,120.00	$280.00
		TOTAL	$1,120.00	$280.00

* Custom Revenue Allocation

FOR ANALYTICAL WORK COMPLETED THIS SECTION ALSO

Return Samples to Sending Region: [ ] Yes [X] No

CONFIRMATION OF WORK COMPLETED

Date Completed: _____ Receiving Project Manager: _____

Original sent to the receiving lab - Copy kept at the sending lab.

When work completed: Original sent to the ABM at the receiving laboratory. Copies are made to corporate as needed.

FMT-ALL-C-001 rev.00 24March2009 Page 1 of 1

ATTACHMENT B
845 QUARTERLY REPORT - QUARTER 2, 2023
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

ANALYTICAL REPORT

May 26, 2023

Pace IR - Peoria, IL

Sample Delivery Group:	L1611860
Samples Received:	05/03/2023
Project Number:	GD04853
Description:	Vistra-Newton
Site:	001
Report To:	Gail Schindler
	2231 W. Altorfer Drive
	Peoria, IL 61615

Entire Report Reviewed By:

Haley Torrence

Haley Torrence
Project Manager

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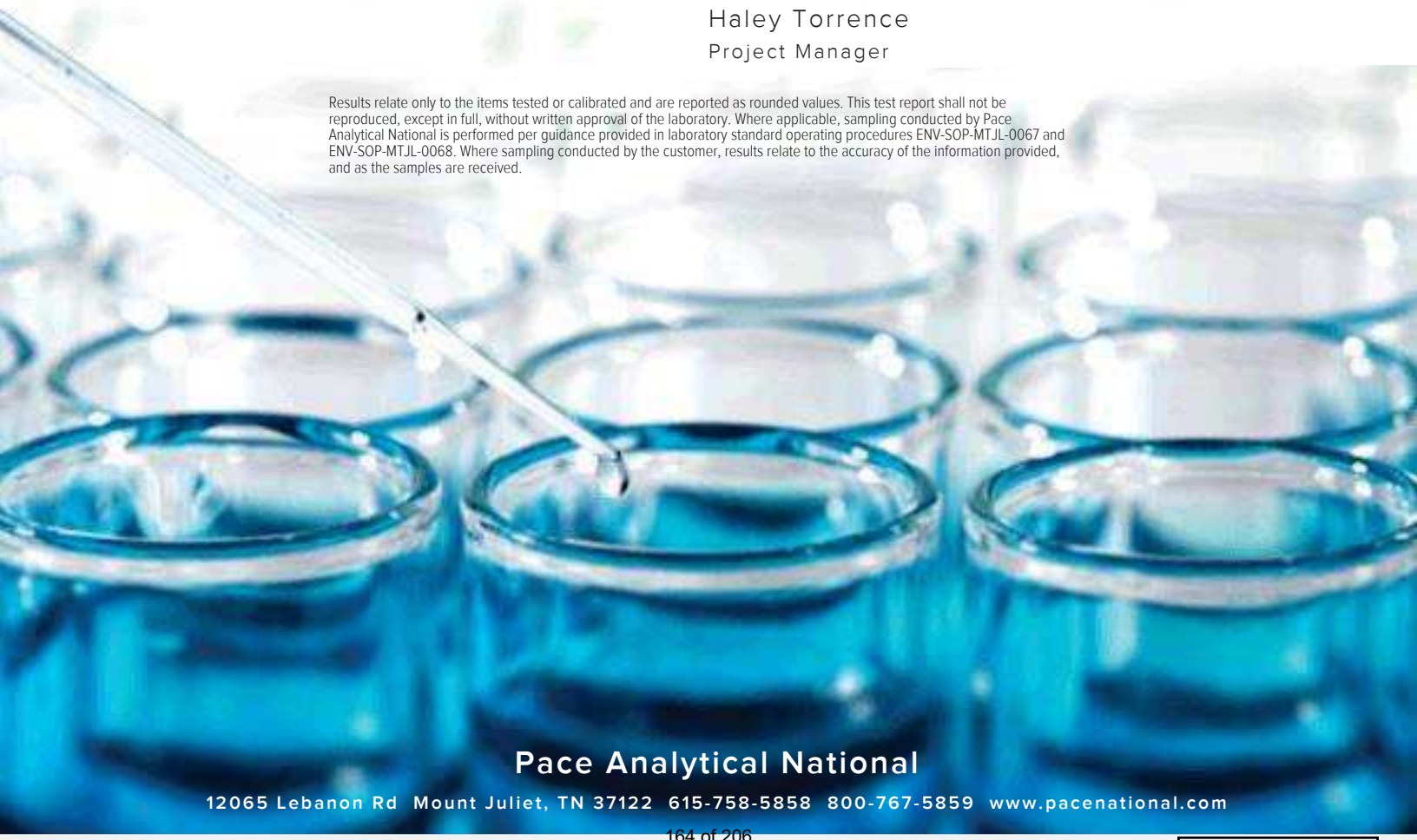

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SAMPLE SUMMARY

APW02 L1611860-01 Non-Potable Water

Collected by | Collected date/time 04/27/23 12:17 | Received date/time 05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061003	1	05/16/23 23:23	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058951	1	05/17/23 16:27	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058951	1	05/17/23 16:27	05/18/23 18:05	RGT	Mt. Juliet, TN

APW05 L1611860-02 Non-Potable Water

Collected by | Collected date/time 04/27/23 12:40 | Received date/time 05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061003	1	05/16/23 23:23	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058951	1	05/17/23 16:27	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058951	1	05/17/23 16:27	05/18/23 18:05	RGT	Mt. Juliet, TN

APW07 L1611860-03 Non-Potable Water

Collected by | Collected date/time 04/27/23 10:35 | Received date/time 05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061003	1	05/16/23 23:23	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058951	1	05/17/23 16:27	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058951	1	05/17/23 16:27	05/18/23 18:05	RGT	Mt. Juliet, TN

APW09 L1611860-04 Non-Potable Water

Collected by | Collected date/time 04/27/23 14:05 | Received date/time 05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061003	1	05/16/23 23:23	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058951	1	05/17/23 16:27	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058951	1	05/17/23 16:27	05/18/23 18:05	RGT	Mt. Juliet, TN

APW10 L1611860-05 Non-Potable Water

Collected by | Collected date/time 04/27/23 15:47 | Received date/time 05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061003	1	05/16/23 23:23	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058951	1	05/17/23 16:27	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058951	1	05/17/23 16:27	05/18/23 18:05	RGT	Mt. Juliet, TN

APW13 L1611860-06 Non-Potable Water

Collected by | Collected date/time 04/27/23 17:16 | Received date/time 05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061003	1	05/16/23 23:23	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058951	1	05/17/23 16:27	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058951	1	05/17/23 16:27	05/18/23 18:05	RGT	Mt. Juliet, TN

1 Cp
2 Tc
3 Ss
4 Cn
5 Sr
6 Qc
7 Gl
8 Al
9 Sc

SAMPLE SUMMARY

EB-03 L1611860-07 Non-Potable Water

	Collected by	Collected date/time	Received date/time
		04/27/23 14:35	05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061003	1	05/16/23 23:23	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058951	1	05/17/23 16:27	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058951	1	05/17/23 16:27	05/18/23 18:05	RGT	Mt. Juliet, TN

CASE NARRATIVE

All sample aliquots were received at the correct temperature, in the proper containers, with the appropriate preservatives, and within method specified holding times, unless qualified or notated within the report. Where applicable, all MDL (LOD) and RDL (LOQ) values reported for environmental samples have been corrected for the dilution factor used in the analysis. All radiochemical sample results for solids are reported on a dry weight basis with the exception of tritium, carbon-14 and radon, unless wet weight was requested by the client. All Method and Batch Quality Control are within established criteria except where addressed in this case narrative, a non-conformance form or properly qualified within the sample results. By my digital signature below, I affirm to the best of my knowledge, all problems/anomalies observed by the laboratory as having the potential to affect the quality of the data have been identified by the laboratory, and no information or data have been knowingly withheld that would affect the quality of the data.

Haley Torrence

Haley Torrence
Project Manager

APW02 SAMPLE RESULTS - 01
Collected date/time: 04/27/23 12:17 L1611860

Radiochemistry by Method 904/9320

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-228	0.0802	U	0.245	0.448	05/19/2023 14:32	WG2061003
(T) Barium	*106*			*30.0-143*	*05/19/2023 14:32*	WG2061003
(T) Yttrium	*127*			*30.0-136*	*05/19/2023 14:32*	WG2061003

Radiochemistry by Method Calculation

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
Combined Radium	0.768		0.445	0.551	05/19/2023 14:32	WG2058951

Radiochemistry by Method SM7500Ra B M

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-226	0.688		0.371	0.320	05/18/2023 18:05	WG2058951
(T) Barium-133	*85.0*			*30.0-143*	*05/18/2023 18:05*	WG2058951

APW05 SAMPLE RESULTS - 02
Collected date/time: 04/27/23 12:40 L1611860

Radiochemistry by Method 904/9320

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-228	0.606		0.211	0.365	05/19/2023 14:32	WG2061003
(T) Barium	*118*			*30.0-143*	*05/19/2023 14:32*	WG2061003
(T) Yttrium	*114*			*30.0-136*	*05/19/2023 14:32*	WG2061003

Radiochemistry by Method Calculation

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
Combined Radium	0.841		0.314	0.471	05/19/2023 14:32	WG2058951

Radiochemistry by Method SM7500Ra B M

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-226	0.236	J	0.233	0.298	05/18/2023 18:05	WG2058951
(T) Barium-133	*99.0*			*30.0-143*	*05/18/2023 18:05*	WG2058951

APW07 SAMPLE RESULTS - 03
Collected date/time: 04/27/23 10:35 L1611860

Radiochemistry by Method 904/9320

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-228	1.07		0.274	0.467	05/19/2023 14:32	WG2061003
(T) Barium	*110*			*30.0-143*	*05/19/2023 14:32*	WG2061003
(T) Yttrium	*109*			*30.0-136*	*05/19/2023 14:32*	WG2061003

Radiochemistry by Method Calculation

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
Combined Radium	2.09		0.488	0.546	05/19/2023 14:32	WG2058951

Radiochemistry by Method SM7500Ra B M

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-226	1.02		0.404	0.282	05/18/2023 18:05	WG2058951
(T) Barium-133	*91.3*			*30.0-143*	*05/18/2023 18:05*	WG2058951

1 Cp
2 Tc
3 Ss
4 Cn
5 Sr
6 Qc
7 Gl
8 Al
9 Sc

APW09 SAMPLE RESULTS - 04
Collected date/time: 04/27/23 14:05 L1611860

Radiochemistry by Method 904/9320

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-228	0.920		0.237	0.402	05/19/2023 14:32	WG2061003
(T) Barium	*125*			*30.0-143*	*05/19/2023 14:32*	WG2061003
(T) Yttrium	*119*			*30.0-136*	*05/19/2023 14:32*	WG2061003

Radiochemistry by Method Calculation

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
Combined Radium	2.00		0.465	0.449	05/19/2023 14:32	WG2058951

Radiochemistry by Method SM7500Ra B M

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-226	1.08		0.400	0.199	05/18/2023 18:05	WG2058951
(T) Barium-133	*96.8*			*30.0-143*	*05/18/2023 18:05*	WG2058951

APW10
Collected date/time: 04/27/23 15:47

SAMPLE RESULTS - 05

L1611860

Radiochemistry by Method 904/9320

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-228	-0.384	U	0.250	0.469	05/19/2023 14:32	WG2061003
(T) Barium	*108*			*30.0-143*	*05/19/2023 14:32*	WG2061003
(T) Yttrium	*107*			*30.0-136*	*05/19/2023 14:32*	WG2061003

Radiochemistry by Method Calculation

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
Combined Radium	0.316	J	0.360	0.562	05/19/2023 14:32	WG2058951

Radiochemistry by Method SM7500Ra B M

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-226	0.316		0.259	0.310	05/18/2023 18:05	WG2058951
(T) Barium-133	*92.1*			*30.0-143*	*05/18/2023 18:05*	WG2058951

APW13 SAMPLE RESULTS - 06
Collected date/time: 04/27/23 17:16 L1611860

Radiochemistry by Method 904/9320

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-228	0.413	J	0.242	0.430	05/19/2023 14:32	WG2061003
(T) Barium	*95.4*			*30.0-143*	*05/19/2023 14:32*	WG2061003
(T) Yttrium	*111*			*30.0-136*	*05/19/2023 14:32*	WG2061003

Radiochemistry by Method Calculation

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
Combined Radium	0.651		0.314	0.485	05/19/2023 14:32	WG2058951

Radiochemistry by Method SM7500Ra B M

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-226	0.238		0.200	0.225	05/18/2023 18:05	WG2058951
(T) Barium-133	*83.9*			*30.0-143*	*05/18/2023 18:05*	WG2058951

1 Cp
2 Tc
3 Ss
4 Cn
5 Sr
6 Qc
7 Gl
8 Al
9 Sc

EB-03
Collected date/time: 04/27/23 14:35

SAMPLE RESULTS - 07
L1611860

Radiochemistry by Method 904/9320

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-228	0.346	J	0.218	0.389	05/19/2023 14:32	WG2061003
(T) Barium	*116*			*30.0-143*	*05/19/2023 14:32*	WG2061003
(T) Yttrium	*113*			*30.0-136*	*05/19/2023 14:32*	WG2061003

Radiochemistry by Method Calculation

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
Combined Radium	0.418	J	0.292	0.513	05/19/2023 14:32	WG2058951

Radiochemistry by Method SM7500Ra B M

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-226	0.0721	U	0.195	0.334	05/18/2023 18:05	WG2058951
(T) Barium-133	*79.2*			*30.0-143*	*05/18/2023 18:05*	WG2058951

WG2061903

Radiochemistry by Method 904.0/9320

QUALITY CONTROL SUMMARY

L1611860-01,02,03,04,05,06,07

Method Blank (MB)

(MB) R3929806-1 05/19/23 14:32

Analyte	MB Result pCi/l	MB Qualifier	MB Uncertainty + / - pCi/l	MB MDA pCi/l
Radium-228	-0.357	U	0.173	0.324
(T) Barium	*108*		*108*	
(T) Yttrium	*101*		*101*	

L1611854-01 Original Sample (OS) • Duplicate (DUP)

(OS) L1611854-01 05/19/23 14:32 • (DUP) R3929806-5 05/19/23 14:32

Analyte	Original Result pCi/l	Original Uncertainty + / -	Original MDA pCi/l	DUP Result pCi/l	DUP Uncertainty + / -	DUP MDA pCi/l	Dilution	DUP RPD %	DUP RER	DUP Qualifier	DUP RPD Limits %	DUP RER Limit
Radium-228	0.267	0.241	0.432	-0.527	0.396	0.432	1	200	1.71	U	20	3
(T) Barium	*109*			*114*	*114*							
(T) Yttrium	*90.0*			*116*	*116*							

Laboratory Control Sample (LCS)

(LCS) R3929806-2 05/19/23 14:32

Analyte	Spike Amount pCi/l	LCS Result pCi/l	LCS Rec. %	Rec. Limits %	LCS Qualifier
Radium-228	5.00	4.97	99.4	80.0-120	
(T) Barium			*116*		
(T) Yttrium			*112*		

L1606733-01 Original Sample (OS) • Matrix Spike (MS) • Matrix Spike Duplicate (MSD)

(OS) L1606733-01 05/19/23 14:32 • (MS) R3929806-3 05/19/23 14:32 • (MSD) R3929806-4 05/19/23 14:32

Analyte	Spike Amount pCi/l	Original Result pCi/l	MS Result pCi/l	MSD Result pCi/l	MS Rec. %	MSD Rec. %	Dilution	Rec. Limits %	MS Qualifier	MSD Qualifier	RPD %	MS RER	RPD Limits %
Radium-228	10.0	0.855	10.4	10.0	95.1	91.7	1	70.0-130			3.34		20
(T) Barium		*121*			*120*	*116*							
(T) Yttrium		*108*			*111*	*98.4*							

WG2058991

Radiochemistry by Method SW7500Ra B M

QUALITY CONTROL SUMMARY

L1611860-01,02,03,04,05,06,07

Method Blank (MB)

(MB) R3927911-5 05/18/23 18:22

Analyte	MB Result pCi/l	MB Qualifier	MB Uncertainty + / - pCi/l	MB MDA pCi/l
Radium-226	-0.0127	U	0.0290	0.0632
(T) Barium-133	*74.5*		*74.5*	

L1611860-01 Original Sample (OS) • Duplicate (DUP)

(OS) L1611860-01 05/18/23 18:05 • (DUP) R3927911-4 05/18/23 18:05

Analyte	Original Result pCi/l	Original Uncertainty + / -	Original MDA pCi/l	DUP Result pCi/l	DUP Uncertainty + / -	DUP MDA pCi/l	Dilution	DUP RPD %	DUP RER	DUP Qualifier	DUP RPD Limits %	DUP RER Limit
Radium-226	0.688	0.371	0.320	0.0912	0.205	0.320	1	153	1.41	U	20	3
(T) Barium-133	*85.0*			*87.1*	*87.1*							

Laboratory Control Sample (LCS)

(LCS) R3927911-1 05/18/23 18:05

Analyte	Spike Amount pCi/l	LCS Result pCi/l	LCS Rec. %	Rec. Limits %	LCS Qualifier
Radium-226	5.01	5.13	102	80.0-120	
(T) Barium-133			*77.2*		

L1611860-07 Original Sample (OS) • Matrix Spike (MS) • Matrix Spike Duplicate (MSD)

(OS) L1611860-07 05/18/23 18:05 • (MS) R3927911-2 05/18/23 18:05 • (MSD) R3927911-3 05/18/23 18:05

Analyte	Spike Amount pCi/l	Original Result pCi/l	MS Result pCi/l	MSD Result pCi/l	MS Rec. %	MSD Rec. %	Dilution	Rec. Limits %	MS Qualifier	MSD Qualifier	RPD %	MS RER	RPD Limits %
Radium-226	20.0	0.0721	19.7	19.7	98.2	97.9	1	75.0-125			0.305		20
(T) Barium-133		*79.2*			*84.7*	*72.7*							

GLOSSARY OF TERMS

Guide to Reading and Understanding Your Laboratory Report

The information below is designed to better explain the various terms used in your report of analytical results from the Laboratory. This is not intended as a comprehensive explanation, and if you have additional questions please contact your project representative.

Results Disclaimer - Information that may be provided by the customer, and contained within this report, include Permit Limits, Project Name, Sample ID, Sample Matrix, Sample Preservation, Field Blanks, Field Spikes, Field Duplicates, On-Site Data, Sampling Collection Dates/Times, and Sampling Location. Results relate to the accuracy of this information provided, and as the samples are received.

Abbreviations and Definitions

MDA	Minimum Detectable Activity.
Rec.	Recovery.
RER	Replicate Error Ratio.
RPD	Relative Percent Difference.
SDG	Sample Delivery Group.
(T)	Tracer - A radioisotope of known concentration added to a solution of chemically equivalent radioisotopes at a known concentration to assist in monitoring the yield of the chemical separation.
Analyte	The name of the particular compound or analysis performed. Some Analyses and Methods will have multiple analytes reported.
Dilution	If the sample matrix contains an interfering material, the sample preparation volume or weight values differ from the standard, or if concentrations of analytes in the sample are higher than the highest limit of concentration that the laboratory can accurately report, the sample may be diluted for analysis. If a value different than 1 is used in this field, the result reported has already been corrected for this factor.
Limits	These are the target % recovery ranges or % difference value that the laboratory has historically determined as normal for the method and analyte being reported. Successful QC Sample analysis will target all analytes recovered or duplicated within these ranges.
Original Sample	The non-spiked sample in the prep batch used to determine the Relative Percent Difference (RPD) from a quality control sample. The Original Sample may not be included within the reported SDG.
Qualifier	This column provides a letter and/or number designation that corresponds to additional information concerning the result reported. If a Qualifier is present, a definition per Qualifier is provided within the Glossary and Definitions page and potentially a discussion of possible implications of the Qualifier in the Case Narrative if applicable.
Result	The actual analytical final result (corrected for any sample specific characteristics) reported for your sample. If there was no measurable result returned for a specific analyte, the result in this column may state “ND” (Not Detected) or “BDL” (Below Detectable Levels). The information in the results column should always be accompanied by either an MDL (Method Detection Limit) or RDL (Reporting Detection Limit) that defines the lowest value that the laboratory could detect or report for this analyte.
Uncertainty (Radiochemistry)	Confidence level of 2 sigma.
Case Narrative (Cn)	A brief discussion about the included sample results, including a discussion of any non-conformances to protocol observed either at sample receipt by the laboratory from the field or during the analytical process. If present, there will be a section in the Case Narrative to discuss the meaning of any data qualifiers used in the report.
Quality Control Summary (Qc)	This section of the report includes the results of the laboratory quality control analyses required by procedure or analytical methods to assist in evaluating the validity of the results reported for your samples. These analyses are not being performed on your samples typically, but on laboratory generated material.
Sample Chain of Custody (Sc)	This is the document created in the field when your samples were initially collected. This is used to verify the time and date of collection, the person collecting the samples, and the analyses that the laboratory is requested to perform. This chain of custody also documents all persons (excluding commercial shippers) that have had control or possession of the samples from the time of collection until delivery to the laboratory for analysis.
Sample Results (Sr)	This section of your report will provide the results of all testing performed on your samples. These results are provided by sample ID and are separated by the analyses performed on each sample. The header line of each analysis section for each sample will provide the name and method number for the analysis reported.
Sample Summary (Ss)	This section of the Analytical Report defines the specific analyses performed for each sample ID, including the dates and times of preparation and/or analysis.

Qualifier	Description
J	The identification of the analyte is acceptable; the reported value is an estimate.
U	Below Detectable Limits: Indicates that the analyte was not detected.

ACCREDITATIONS & LOCATIONS

Pace Analytical National 12065 Lebanon Rd Mount Juliet, TN 37122

Alabama	40660	Nebraska	NE-OS-15-05
Alaska	17-026	Nevada	TN000032021-1
Arizona	AZ0612	New Hampshire	2975
Arkansas	88-0469	New Jersey–NELAP	TN002
California	2932	New Mexico [1]	TN00003
Colorado	TN00003	New York	11742
Connecticut	PH-0197	North Carolina	Env375
Florida	E87487	North Carolina [1]	DW21704
Georgia	NELAP	North Carolina [3]	41
Georgia [1]	923	North Dakota	R-140
Idaho	TN00003	Ohio–VAP	CL0069
Illinois	200008	Oklahoma	9915
Indiana	C-TN-01	Oregon	TN200002
Iowa	364	Pennsylvania	68-02979
Kansas	E-10277	Rhode Island	LAO000356
Kentucky [1 6]	KY90010	South Carolina	84004002
Kentucky [2]	16	South Dakota	n/a
Louisiana	AI30792	Tennessee [1 4]	2006
Louisiana	LA018	Texas	T104704245-20-18
Maine	TN00003	Texas [5]	LAB0152
Maryland	324	Utah	TN000032021-11
Massachusetts	M-TN003	Vermont	VT2006
Michigan	9958	Virginia	110033
Minnesota	047-999-395	Washington	C847
Mississippi	TN00003	West Virginia	233
Missouri	340	Wisconsin	998093910
Montana	CERT0086	Wyoming	A2LA
A2LA – ISO 17025	1461.01	AIHA-LAP,LLC EMLAP	100789
A2LA – ISO 17025 [5]	1461.02	DOD	1461.01
Canada	1461.01	USDA	P330-15-00234
EPA–Crypto	TN00003		

[1] Drinking Water [2] Underground Storage Tanks [3] Aquatic Toxicity [4] Chemical/Microbiological [5] Mold [6] Wastewater n/a Accreditation not applicable

* Not all certifications held by the laboratory are applicable to the results reported in the attached report.

* Accreditation is only applicable to the test methods specified on each scope of accreditation held by Pace Analytical.

A132

Internal Transfer Chain of Custody

Pace Analytical®
www.pacelabs.com

State of Origin: IL
Cert. Needed: [X] YES [ ] NO

Owner Received Date: 4/28/2023
Results Requ By: 5/15/2023

GD04853 **Workorder Name:** VISTRA - NEWTON

Report To:	Subcontract To:
Gail Schindler Pace Analytical - IL/MO 2231 W. Altorfer Drive Peoria, IL 61615 800-752-6651	Pace Analytical - Mt Juliet 12065 Lebanon Rd Mt Juliet TN 37122

Item	Sample ID	Sample Type	Collect Date/Time	Lab ID	Matrix	Preserved Containers	Requested Analysis: Radium 226	Requested Analysis: Radium 228	LAB USE ONLY
1	APW02	GRAB	4/27/2023 12:17	GD04853-01	GW		X	X	-01
2	APW05	GRAB	4/27/2023 12:40	GD04853-02	GW		X	X	-02
3	APW07	GRAB	4/27/2023 10:35	GD04853-03	GW		X	X	-03
4	APW09	GRAB	4/27/2023 14:05	GD04853-04	GW		X	X	-04
5	APW10	GRAB	4/27/2023 15:47	GD04853-05	GW		X	X	-05
6	APW13	GRAB	4/27/2023 17:16	GD04853-06	GW		X	X	-06
7	EB-03	GRAB	4/27/2023 14:35	GD04853-07	DI		X	X	-07

U1d8160

Transfers		Date/Time	Received By	Date/Time	Comments
1	Camden Bennett	5-2-23 14:42	Harley Balutar	5/3/23 0900	Needs 226, 228 and combined Include QC summary and edd 10 day TAT
2					
3					

Cooler Temperature on Receipt _____ °C | **Custody Seal** Y or N | **Received on Ice** Y or N | **Sample Intact** Y or N

***In order to maintain client confidentiality, location/name of the sampling site, sampler's name and signature may not be provided on this COC document.
This chain of custody is considered complete as is since this information is available in the owner laboratory.

Sample Receipt Checklist
COC Seal Present/Intact: Y N
COC Signed/Accurate: Y N
Bottles arrive intact: Y N
Correct bottles used: Y N
Sufficient volume sent: Y N
RAD Screen <0.5 mR/hr: Y N
If Applicable
VOA Zero Headspace: Y N
Pres.Correct/Check: Y N

16.5+0=16.5 NS A7

6319 5997 8530

L1618160

Pace Analytical
www.pacelabs.com

Ship to :
Pace Analytical Services, LLC
12065 Lebanon Rd
Mt Juliet TN 37122

(615)758-5858

INTER_LABORATORY WORK ORDER # GD4853
(To be complete by sending lab)

Sending Project No:	GD4853
Receiving Project No:	
Check Box for Consolidated Invoice:	
Date Prepared:	5/2/2023
REQUESTED COMPLETION DATE:	5/15/2023

Sending Region	IR72-IL/MO	Sending Project Mgr.	Gail Schindler
Receiving Region	MT JULIET	External Client	VISTRA - NEWTON
State of Sample Origin	IL	QC Deliverable	**STD Report**

All questions should be addressed to sending project manager.

Requested Reportable Units _____ Report Wet or Dry Weight? _____ Cert Needed: IL

WORK REQUESTED						
Method Description	**Container Type**	**Quantity of**	**Preservative**	**Quantity of**	**Unit Price**	**Amount**
Radium 226		7		7	$100.00	$700.00
Radium 228		7		7	$100.00	$700.00
		1		1		$0.00
					TOTAL	$1,400.00

Special Requirements: Report as 226, 228 & combined 226/228. Include QC summary & edd

Receiving Reqion Department	Acctg. Code	Totals from above	Revenue Allocation	
			Receiving Region (80%)	Client Services Dept.
radiological	38	$1,400.00	$1,120.00	$280.00
* Custom Revenue Allocation		TOTAL	$1,120.00	$280.00

FOR ANALYTICAL WORK COMPLETED THIS SECTION ALSO

Return Samples to Sending Region: [ ] Yes [X] No

CONFIRMATION OF WORK COMPLETED

Date Completed: _____ Receiving Project Manager: _____

Original sent to the receiving lab - Copy kept at the sending lab.
When work completed: Original sent to the ABM at the receiving laboratory. Copies are made to corporate as needed.

FMT-ALL-C-001 rev.00 24March2009 Page 1 of 1

ANALYTICAL REPORT

June 06, 2023

Pace IR - Peoria, IL

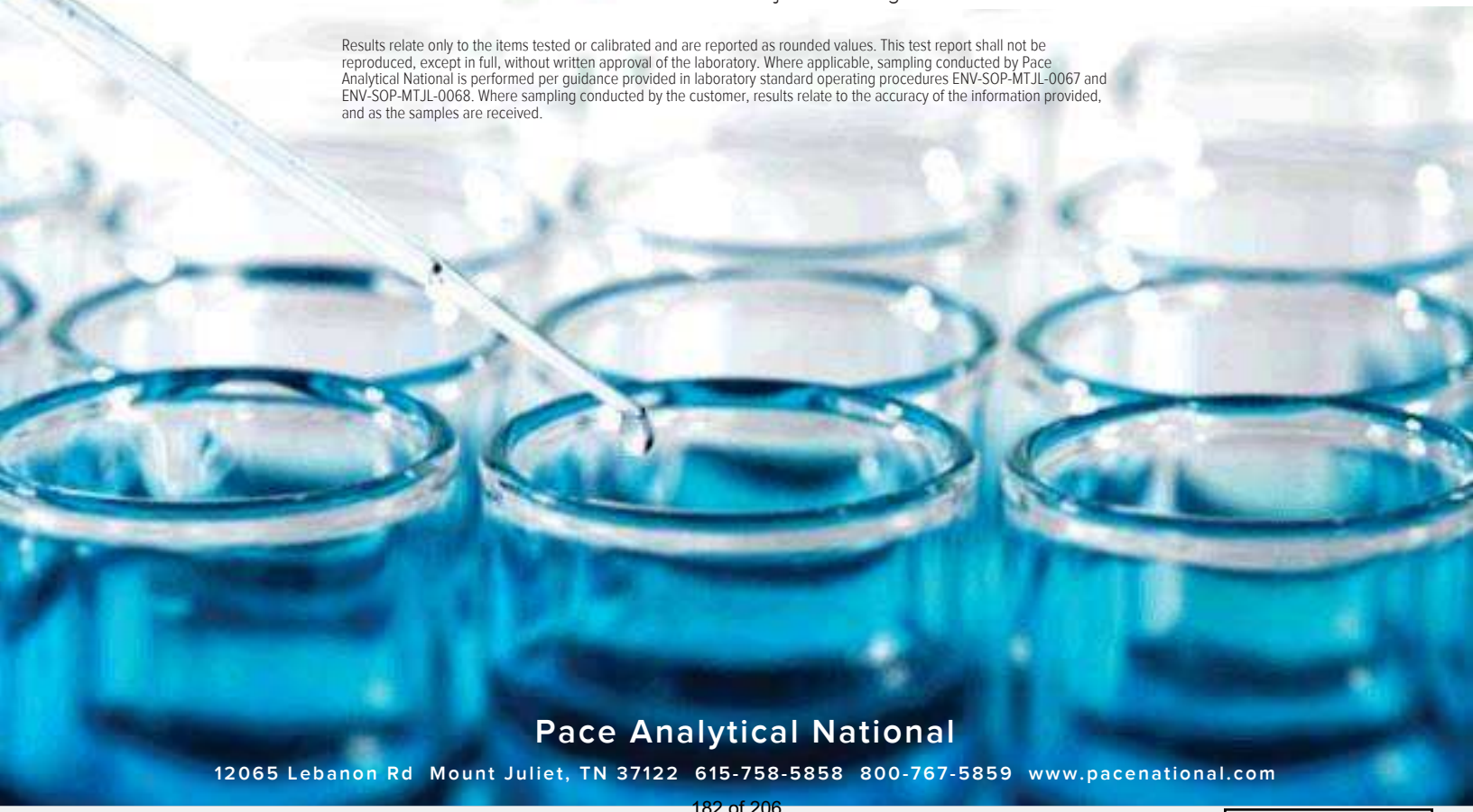
Sample Delivery Group:	L1611864
Samples Received:	05/03/2023
Project Number:	GD04926
Description:	Vistra-Newton
Site:	001
Report To:	Gail Schindler
	2231 W. Altorfer Drive
	Peoria, IL 61615

Entire Report Reviewed By:

Haley Torrence

Haley Torrence
Project Manager

Results relate only to the items tested or calibrated and are reported as rounded values. This test report shall not be reproduced, except in full, without written approval of the laboratory. Where applicable, sampling conducted by Pace Analytical National is performed per guidance provided in laboratory standard operating procedures ENV-SOP-MTJL-0067 and ENV-SOP-MTJL-0068. Where sampling conducted by the customer, results relate to the accuracy of the information provided, and as the samples are received.



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SAMPLE SUMMARY

APW14 L1611864-01 Non-Potable Water

	Collected by	Collected date/time	Received date/time
		04/28/23 11:29	05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061003	1	05/16/23 23:23	05/19/23 14:32	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058953	1	05/22/23 11:11	05/24/23 00:32	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058953	1	05/22/23 11:11	05/24/23 00:32	RGT	Mt. Juliet, TN

APW14 DUP L1611864-02 Non-Potable Water

	Collected by	Collected date/time	Received date/time
		04/28/23 11:29	05/03/23 09:00

Method	Batch	Dilution	Preparation date/time	Analysis date/time	Analyst	Location
Radiochemistry by Method 904/9320	WG2061735	1	05/17/23 20:19	05/31/23 08:55	SNR	Mt. Juliet, TN
Radiochemistry by Method Calculation	WG2058953	1	05/22/23 11:11	05/31/23 08:55	SNR	Mt. Juliet, TN
Radiochemistry by Method SM7500Ra B M	WG2058953	1	05/22/23 11:11	05/24/23 00:32	RGT	Mt. Juliet, TN

CASE NARRATIVE

All sample aliquots were received at the correct temperature, in the proper containers, with the appropriate preservatives, and within method specified holding times, unless qualified or notated within the report. Where applicable, all MDL (LOD) and RDL (LOQ) values reported for environmental samples have been corrected for the dilution factor used in the analysis. All radiochemical sample results for solids are reported on a dry weight basis with the exception of tritium, carbon-14 and radon, unless wet weight was requested by the client. All Method and Batch Quality Control are within established criteria except where addressed in this case narrative, a non-conformance form or properly qualified within the sample results. By my digital signature below, I affirm to the best of my knowledge, all problems/anomalies observed by the laboratory as having the potential to affect the quality of the data have been identified by the laboratory, and no information or data have been knowingly withheld that would affect the quality of the data.

Haley Torrence

Haley Torrence
Project Manager

APW14 SAMPLE RESULTS - 01
Collected date/time: 04/28/23 11:29 L1611864

Radiochemistry by Method 904/9320

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-228	0.228	J	0.217	0.391	05/19/2023 14:32	WG2061003
(T) Barium	*109*			*30.0-143*	*05/19/2023 14:32*	WG2061003
(T) Yttrium	*108*			*30.0-136*	*05/19/2023 14:32*	WG2061003

Radiochemistry by Method Calculation

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
Combined Radium	0.381	J	0.285	0.465	05/24/2023 00:32	WG2058953

Radiochemistry by Method SM7500Ra B M

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-226	0.153	J	0.184	0.252	05/24/2023 00:32	WG2058953
(T) Barium-133	*99.5*			*30.0-143*	*05/24/2023 00:32*	WG2058953

APW14 DUP - SAMPLE RESULTS - 02

Collected date/time: 04/28/23 11:29 L1611864

Radiochemistry by Method 904/9320

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-228	1.28		0.291	0.489	05/31/2023 08:55	WG2061735
(T) Barium	*77.9*			*30.0-143*	*05/31/2023 08:55*	WG2061735
(T) Yttrium	*123*			*30.0-136*	*05/31/2023 08:55*	WG2061735

Radiochemistry by Method Calculation

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
Combined Radium	1.71		0.417	0.584	05/31/2023 08:55	WG2058953

Radiochemistry by Method SM7500Ra B M

Analyte	Result pCi/l	Qualifier	Uncertainty + / -	MDA pCi/l	Analysis Date date / time	Batch
RADIUM-226	0.433		0.299	0.319	05/24/2023 00:32	WG2058953
(T) Barium-133	*96.7*			*30.0-143*	*05/24/2023 00:32*	WG2058953

WG2061903

Radiochemistry by Method 904.0/9320

QUALITY CONTROL SUMMARY

L1611864-01

Method Blank (MB)

(MB) R3929806-1 05/19/23 14:32

Analyte	MB Result pCi/l	MB Qualifier	MB Uncertainty + / - pCi/l	MB MDA pCi/l
Radium-228	-0.357	U	0.173	0.324
(T) Barium	*108*		*108*	
(T) Yttrium	*101*		*101*	

L1611854-01 Original Sample (OS) • Duplicate (DUP)

(OS) L1611854-01 05/19/23 14:32 • (DUP) R3929806-5 05/19/23 14:32

Analyte	Original Result pCi/l	Original Uncertainty + / -	Original MDA pCi/l	DUP Result pCi/l	DUP Uncertainty + / -	DUP MDA pCi/l	Dilution	DUP RPD %	DUP RER	DUP Qualifier	DUP RPD Limits %	DUP RER Limit
Radium-228	0.267	0.241	0.432	-0.527	0.396	0.432	1	200	1.71	U	20	3
(T) Barium	*109*			*114*	*114*							
(T) Yttrium	*90.0*			*116*	*116*							

Laboratory Control Sample (LCS)

(LCS) R3929806-2 05/19/23 14:32

Analyte	Spike Amount pCi/l	LCS Result pCi/l	LCS Rec. %	Rec. Limits %	LCS Qualifier
Radium-228	5.00	4.97	99.4	80.0-120	
(T) Barium			*116*		
(T) Yttrium			*112*		

L1606733-01 Original Sample (OS) • Matrix Spike (MS) • Matrix Spike Duplicate (MSD)

(OS) L1606733-01 05/19/23 14:32 • (MS) R3929806-3 05/19/23 14:32 • (MSD) R3929806-4 05/19/23 14:32

Analyte	Spike Amount pCi/l	Original Result pCi/l	MS Result pCi/l	MSD Result pCi/l	MS Rec. %	MSD Rec. %	Dilution	Rec. Limits %	MS Qualifier	MSD Qualifier	RPD %	MS RER	RPD Limits %
Radium-228	10.0	0.855	10.4	10.0	95.1	91.7	1	70.0-130			3.34		20
(T) Barium		*121*			*120*	*116*							
(T) Yttrium		*108*			*111*	*98.4*							

WG2061739

Radiochemistry by Method 904.0/9320

QUALITY CONTROL SUMMARY

L1611864-02

Method Blank (MB)

(MB) R3932968-2 05/31/23 08:55

Analyte	MB Result pCi/l	MB Qualifier	MB Uncertainty + / - pCi/l	MB MDA pCi/l
Radium-228	0.510		0.175	0.303
(T) Barium	*80.6*		*80.6*	
(T) Yttrium	*117*		*117*	

L1611866-05 Original Sample (OS) • Duplicate (DUP)

(OS) L1611866-05 05/31/23 08:55 • (DUP) R3932968-5 05/31/23 08:55

Analyte	Original Result pCi/l	Original Uncertainty + / -	Original MDA pCi/l	DUP Result pCi/l	DUP Uncertainty + / -	DUP MDA pCi/l	Dilution	DUP RPD %	DUP RER	DUP Qualifier	DUP RPD Limits %	DUP RER Limit
Radium-228	-1.05	0.345	0.659	-1.23	0.448	0.659	1	0.000	0.313	U	20	3
(T) Barium	*85.3*			*81.0*	*81.0*							
(T) Yttrium	*127*			*143*	*143*					C1		

Laboratory Control Sample (LCS)

(LCS) R3932968-1 05/26/23 09:50

Analyte	Spike Amount pCi/l	LCS Result pCi/l	LCS Rec. %	Rec. Limits %	LCS Qualifier
Radium-228	5.00	5.89	118	80.0-120	
(T) Barium			*94.2*		
(T) Yttrium			*74.8*		

L1607413-01 Original Sample (OS) • Matrix Spike (MS) • Matrix Spike Duplicate (MSD)

(OS) L1607413-01 05/31/23 08:55 • (MS) R3932968-3 05/31/23 08:55 • (MSD) R3932968-4 05/31/23 08:55

Analyte	Spike Amount pCi/l	Original Result pCi/l	MS Result pCi/l	MSD Result pCi/l	MS Rec. %	MSD Rec. %	Dilution	Rec. Limits %	MS Qualifier	MSD Qualifier	RPD %	MS RER	RPD Limits %
Radium-228	10.0	4.03	11.0	11.8	69.2	77.2	1	70.0-130	J6		7.05		20
(T) Barium		*80.5*			*88.9*	*84.4*							
(T) Yttrium		*87.6*			*117*	*116*							

WG2058993

Radiochemistry by Method SW7500Ra B M

QUALITY CONTROL SUMMARY

L1611864-01,02

Method Blank (MB)

(MB) R3929001-1 05/24/23 00:32

Analyte	MB Result pCi/l	MB Qualifier	MB Uncertainty + / - pCi/l	MB MDA pCi/l
Radium-226	-0.0131	U	0.0300	0.0654
(T) Barium-133	*72.0*		*72.0*	

L1611866-07 Original Sample (OS) • Duplicate (DUP)

(OS) L1611866-07 05/24/23 13:18 • (DUP) R3929001-5 05/24/23 13:18

Analyte	Original Result pCi/l	Original Uncertainty + / -	Original MDA pCi/l	DUP Result pCi/l	DUP Uncertainty + / -	DUP MDA pCi/l	Dilution	DUP RPD %	DUP RER	DUP Qualifier	DUP RPD Limits %	DUP RER Limit
Radium-226	0.142	0.140	0.163	0.130	0.254	0.163	1	8.91	0.0417	U	20	3
(T) Barium-133	*100*			*83.2*	*83.2*							

Laboratory Control Sample (LCS)

(LCS) R3929001-2 05/24/23 13:18

Analyte	Spike Amount pCi/l	LCS Result pCi/l	LCS Rec. %	Rec. Limits %	LCS Qualifier
Radium-226	5.01	5.10	102	80.0-120	
(T) Barium-133			*94.0*		

L1611864-01 Original Sample (OS) • Matrix Spike (MS) • Matrix Spike Duplicate (MSD)

(OS) L1611864-01 05/24/23 00:32 • (MS) R3929001-3 05/24/23 13:18 • (MSD) R3929001-4 05/24/23 13:18

Analyte	Spike Amount pCi/l	Original Result pCi/l	MS Result pCi/l	MSD Result pCi/l	MS Rec. %	MSD Rec. %	Dilution	Rec. Limits %	MS Qualifier	MSD Qualifier	RPD %	MS RER	RPD Limits %
Radium-226	20.0	0.153	19.5	18.2	96.6	90.2	1	75.0-125			6.74		20
(T) Barium-133		*99.5*			*97.5*	*94.4*							

1 Cp
2 Tc
3 Ss
4 Cn
5 Sr
6 Qc
7 Gl
8 Al
9 Sc

GLOSSARY OF TERMS

Guide to Reading and Understanding Your Laboratory Report

The information below is designed to better explain the various terms used in your report of analytical results from the Laboratory. This is not intended as a comprehensive explanation, and if you have additional questions please contact your project representative.

Results Disclaimer - Information that may be provided by the customer, and contained within this report, include Permit Limits, Project Name, Sample ID, Sample Matrix, Sample Preservation, Field Blanks, Field Spikes, Field Duplicates, On-Site Data, Sampling Collection Dates/Times, and Sampling Location. Results relate to the accuracy of this information provided, and as the samples are received.

Abbreviations and Definitions

MDA	Minimum Detectable Activity.
Rec.	Recovery.
RER	Replicate Error Ratio.
RPD	Relative Percent Difference.
SDG	Sample Delivery Group.
(T)	Tracer - A radioisotope of known concentration added to a solution of chemically equivalent radioisotopes at a known concentration to assist in monitoring the yield of the chemical separation.
Analyte	The name of the particular compound or analysis performed. Some Analyses and Methods will have multiple analytes reported.
Dilution	If the sample matrix contains an interfering material, the sample preparation volume or weight values differ from the standard, or if concentrations of analytes in the sample are higher than the highest limit of concentration that the laboratory can accurately report, the sample may be diluted for analysis. If a value different than 1 is used in this field, the result reported has already been corrected for this factor.
Limits	These are the target % recovery ranges or % difference value that the laboratory has historically determined as normal for the method and analyte being reported. Successful QC Sample analysis will target all analytes recovered or duplicated within these ranges.
Original Sample	The non-spiked sample in the prep batch used to determine the Relative Percent Difference (RPD) from a quality control sample. The Original Sample may not be included within the reported SDG.
Qualifier	This column provides a letter and/or number designation that corresponds to additional information concerning the result reported. If a Qualifier is present, a definition per Qualifier is provided within the Glossary and Definitions page and potentially a discussion of possible implications of the Qualifier in the Case Narrative if applicable.
Result	The actual analytical final result (corrected for any sample specific characteristics) reported for your sample. If there was no measurable result returned for a specific analyte, the result in this column may state “ND” (Not Detected) or “BDL” (Below Detectable Levels). The information in the results column should always be accompanied by either an MDL (Method Detection Limit) or RDL (Reporting Detection Limit) that defines the lowest value that the laboratory could detect or report for this analyte.
Uncertainty (Radiochemistry)	Confidence level of 2 sigma.
Case Narrative (Cn)	A brief discussion about the included sample results, including a discussion of any non-conformances to protocol observed either at sample receipt by the laboratory from the field or during the analytical process. If present, there will be a section in the Case Narrative to discuss the meaning of any data qualifiers used in the report.
Quality Control Summary (Qc)	This section of the report includes the results of the laboratory quality control analyses required by procedure or analytical methods to assist in evaluating the validity of the results reported for your samples. These analyses are not being performed on your samples typically, but on laboratory generated material.
Sample Chain of Custody (Sc)	This is the document created in the field when your samples were initially collected. This is used to verify the time and date of collection, the person collecting the samples, and the analyses that the laboratory is requested to perform. This chain of custody also documents all persons (excluding commercial shippers) that have had control or possession of the samples from the time of collection until delivery to the laboratory for analysis.
Sample Results (Sr)	This section of your report will provide the results of all testing performed on your samples. These results are provided by sample ID and are separated by the analyses performed on each sample. The header line of each analysis section for each sample will provide the name and method number for the analysis reported.
Sample Summary (Ss)	This section of the Analytical Report defines the specific analyses performed for each sample ID, including the dates and times of preparation and/or analysis.

Qualifier	Description
C1	Tracer recovery limits have been exceeded; values are outside upper control limits.
J	The identification of the analyte is acceptable; the reported value is an estimate.
J6	The sample matrix interfered with the ability to make any accurate determination; spike value is low.
U	Below Detectable Limits: Indicates that the analyte was not detected.

ACCREDITATIONS & LOCATIONS

Pace Analytical National 12065 Lebanon Rd Mount Juliet, TN 37122

Alabama	40660	Nebraska	NE-OS-15-05
Alaska	17-026	Nevada	TN000032021-1
Arizona	AZ0612	New Hampshire	2975
Arkansas	88-0469	New Jersey–NELAP	TN002
California	2932	New Mexico [1]	TN00003
Colorado	TN00003	New York	11742
Connecticut	PH-0197	North Carolina	Env375
Florida	E87487	North Carolina [1]	DW21704
Georgia	NELAP	North Carolina [3]	41
Georgia [1]	923	North Dakota	R-140
Idaho	TN00003	Ohio–VAP	CL0069
Illinois	200008	Oklahoma	9915
Indiana	C-TN-01	Oregon	TN200002
Iowa	364	Pennsylvania	68-02979
Kansas	E-10277	Rhode Island	LAO000356
Kentucky [1 6]	KY90010	South Carolina	84004002
Kentucky [2]	16	South Dakota	n/a
Louisiana	AI30792	Tennessee [1 4]	2006
Louisiana	LA018	Texas	T104704245-20-18
Maine	TN00003	Texas [5]	LAB0152
Maryland	324	Utah	TN000032021-11
Massachusetts	M-TN003	Vermont	VT2006
Michigan	9958	Virginia	110033
Minnesota	047-999-395	Washington	C847
Mississippi	TN00003	West Virginia	233
Missouri	340	Wisconsin	998093910
Montana	CERT0086	Wyoming	A2LA
A2LA – ISO 17025	1461.01	AIHA-LAP,LLC EMLAP	100789
A2LA – ISO 17025 [5]	1461.02	DOD	1461.01
Canada	1461.01	USDA	P330-15-00234
EPA–Crypto	TN00003		

[1] Drinking Water [2] Underground Storage Tanks [3] Aquatic Toxicity [4] Chemical/Microbiological [5] Mold [6] Wastewater n/a Accreditation not applicable

* Not all certifications held by the laboratory are applicable to the results reported in the attached report.

* Accreditation is only applicable to the test methods specified on each scope of accreditation held by Pace Analytical.

A131

Internal Transfer Chain of Custody

Pace Analytical®
www.pacelabs.com

State of Origin: IL
Cert. Needed: [X] YES [ ] NO

Owner Received Date: 4/29/2023
Results Requ By: 5/15/2023

GD04926 Workorder Name: VISTRA - NEWTON

Report To:	Subcontract To:
Gail Schindler Pace Analytical - IL/MO 2231 W. Altorfer Drive Peoria, IL 61615 800-752-6651	Pace Analytical - Mt Juliet 12065 Lebanon Rd Mt Juliet TN 37122

Item	Sample ID	Sample Type	Collect Date/Time	Lab ID	Matrix	Preserved Containers	Requested Analysis: Radium 226	Requested Analysis: Radium 228	LAB USE ONLY
1	APW14	GRAB	4/28/2023 11:29	GD04926-01	GW		X	X	4618164
2	APW14 DUP	GRAB	4/28/2023 11:29	GD04926-02	GW		X	X	

Transfers	3/14/2023 14:31	Date/Time	Received By	Date/Time	Comments
1	Camden Bennett	5-2-23 14:42	Hanley Baltz	5/3/23 0900	Needs 226, 228 and combined Include QC summary and edd 10 day TAT
2					
3					

Cooler Temperature on Receipt _____ °C | Custody Seal Y or N | Received on Ice Y or N | Sample Intact Y or N

***In order to maintain client confidentiality, location/name of the sampling site, sampler's name and signature may not be provided on this COC document.
This chain of custody is considered complete as is since this information is available in the owner laboratory.

Sample Receipt Checklist

		If Applicable	
COC Seal Present/Intact:	Y N	VOA Zero Headspace:	Y N
COC Signed/Accurate:	Y N	Pres.Correct/Check:	Y N
Bottles arrive intact:	Y N		
Correct bottles used:	Y N		
Sufficient volume sent:	Y N		
RAD Screen <0.5 mR/hr:	Y N		

18.8 ± 0 = 18.8 NS AT

6319 5997 8493

L1618864

Pace Analytical
www.pacelabs.com

Ship to :
Pace Analytical Services, LLC
12065 Lebanon Rd
Mt Juliet TN 37122

(615)758-5858

INTER_LABORATORY WORK ORDER # GD04926
(To be complete by sending lab)

Sending Project No:	GD04926
Receiving Project No:	
Check Box for Consolidated Invoice:	
Date Prepared:	5/2/2023
REQUESTED COMPLETION DATE:	5/15/2023

Sending Region	IR72-IL/MO	Sending Project Mgr.	Gail Schindler
Receiving Region	MT JULIET	External Client	VISTRA - NEWTON
State of Sample Origin	IL	QC Deliverable	**STD Report**

All questions should be addressed to sending project manager.

Requested Reportable Units _____ Report Wet or Dry Weight? _____ Cert Needed: IL

WORK REQUESTED						
Method Description	**Container Type**	**Quantity of**	**Preservative**	**Quantity of**	**Unit Price**	**Amount**
Radium 226		2		2	$100.00	$200.00
Radium 228		2		2	$100.00	$200.00
		1		1		$0.00
					TOTAL	$400.00

Special Requirements: Report as 226, 228 & combined 226/228. Include QC summary & edd

Receiving Reqion Department	Acctg. Code	Totals from above	Revenue Allocation	
			Receiving Region (80%)	Client Services Dept.
radiological	38	$400.00	$320.00	$80.00
* Custom Revenue Allocation		TOTAL	$320.00	$80.00

FOR ANALYTICAL WORK COMPLETED THIS SECTION ALSO

Return Samples to Sending Region: [ ] Yes [X] No

CONFIRMATION OF WORK COMPLETED

Date Completed: _____ Receiving Project Manager: _____

Original sent to the receiving lab - Copy kept at the sending lab.
When work completed: Original sent to the ABM at the receiving laboratory. Copies are made to corporate as needed.

~~GD04461~~ VMW
GD04486
VMW 4-26-23

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES GROUND WATER DRINKING WATER
UST RCRA OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID
(A-Z, 0-9 / ,-)
Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test ↓ Y/N	NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_A213																							
2	NEW_A214																							
3	NEW_A215																							
4	NEW_APW02																							
5	NEW_APW03			4/25/23	1326		11	X	X	X															
6	NEW_APW04			4/25/23	1642		11	X	X	X															
7	NEW_APW05																							
8	NEW_APW05#S																							
9	NEW_APW06																							
10	NEW_APW07																							
11	NEW_APW08																							
12	NEW_APW09																							
13	NEW_APW10																							
14	NEW_APW11																							
15	NEW_APW12																							
16	NEW_APW13																							

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME	SAMPLE CONDITIONS
NEW-23Q2 Rev 0		4/26/23	1706		4-26-23	1020	
		4-26-23	1330		4-26-23	1330	1.5 / Y / N / Y

SAMPLER NAME AND SIGNATURE
PRINT Name of SAMPLER: Aaron Pennington
SIGNATURE of SAMPLER:
DATE Signed (MM/DD/YY): 04/25/23

Temp in °C | Received on Ice (Y/N) | Custody Sealed Cooler (Y/N) | Samples Intact (Y/N)

~~4-26~~ ~~1020~~ EMS 5-3-23

GD04486
VMW 4-26-23

CHAIN-OF-CUSTODY / Analytical Request Document

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Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES GROUND WATER DRINKING WATER
UST RCRA OTHER
Site Location STATE: IL

Section D Required Client Information

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test Y/N	NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_APW14																								
2	NEW_APW15																								
3	NEW_APW16			4/25/23	1326		22	X	X	X															
4	NEW_APW17			4/25/23	1650		11	X	X	X															
5	NEW_APW18			4/25/23	1503		11	X	X	X															
6	NEW_G104			4/25/23	1652		8	X	X	X		X													
7	NEW_G104#S DTW																								
8	NEW_G104&D																								
9	NEW_G105																								
10	NEW_G106			4/25/23	1131		4	X	X	X		X													
11	9/26/23 ~~NEW_G108~~ EB-01			4/25/23	1715																				
12	NEW_G109 DTW																								
13	NEW_G110 DTW																								
14	NEW_G111 DTW																								
15	NEW_G112 DTW																								
16	NEW_G113 DTW																								

Requested Analysis Filtered (Y/N)

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME	SAMPLE CONDITIONS
NEW-23Q2 Rev 0		4/26/23	0706		4-26-23	1020	
		4-26-23	1330.		4-26-23	1330	1.5 / Y / N / Y

SAMPLER NAME AND SIGNATURE
PRINT Name of SAMPLER: Aaron Rebertson
SIGNATURE of SAMPLER:
DATE Signed (MM/DD/YY): 04/25/2023

Temp in °C | Received on Ice (Y/N) | Custody Sealed Cooler (Y/N) | Samples Intact (Y/N)

CHAIN-OF-CUSTODY / Analytical Request Document

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6D04746 ge

Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES GROUND WATER DRINKING WATER
UST RCRA OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID
(A-Z, 0-9 / ,-)
Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Requested Analysis Filtered (Y/N)	Residual Chlorine (Y/N)	Project No./ Lab I.D.
	Analysis Test ↓															Y/N ↓		
	NEW_257_501																	
	NEW_257_502																	
	NEW_811_502																	
	NEW_811_503																	
	NEW_845_501																	
	NEW_NPDES_501																	
	NEW_SUP_000																	
1	NEW_A213																	
2	NEW_A214																	
3	NEW_A215			4/26/23	1640		9	X	X	X	X	X						
4	NEW_APW02																	
5	NEW_APW03																	
6	NEW_APW04																	
7	NEW_APW05			4/26/23	1740		11	X	X	X								
8	NEW_APW05#S																	
9	NEW_APW06			4/26/23	1600		11	X	X	X								
10	NEW_APW07																	
11	NEW_APW08			4/26/23	1211		11	X	X	X								
12	NEW_APW09																	
13	NEW_APW10																	
14	NEW_APW11			4/26/23	1543		11	X	X	X								
15	NEW_APW12			4/26/23	1356		11	X	X	X								
16	NEW_APW13																	

4-27-23

ADDITIONAL COMMENTS: **NEW-23Q2 Rev 0**

RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME
	4/27/23	713		4-27	1030
	4-27	1426		4/27/23	14:20

SAMPLER NAME AND SIGNATURE

PRINT Name of SAMPLER: James David

SIGNATURE of SAMPLER: James D

DATE Signed (MM/DD/YY): 4/26/23

SAMPLE CONDITIONS

Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
5.0	Y	N	Y

CHAIN-OF-CUSTODY / Analytical Request Document

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Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES GROUND WATER DRINKING WATER
UST RCRA OTHER

Site Location STATE: IL

Section D Required Client Information

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test ↓ Y/N: NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_APW14																						
2	NEW_APW15																						
3	NEW_APW16			4/26/23	1723		11	X	X	X													
4	NEW_APW17																						
5	NEW_APW18																						
6	NEW_G104																						
7	NEW_G104#S DTW																						
8	NEW_G104&D																						
9	NEW_G105																						
10	NEW_G106																						
11	NEW_G108																						
12	NEW_G109 DTW																						
13	NEW_G110 DTW																						
14	NEW_G111 DTW																						
15	NEW_G112 DTW																						
16	NEW_G113 DTW																						

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME
NEW-23Q2 Rev 0	Joseph R Reed	4/27/23	1030		4-27	1030
		4-27	1420		4/27/23	14:20

SAMPLER NAME AND SIGNATURE

PRINT Name of SAMPLER: James David

SIGNATURE of SAMPLER:

DATE Signed (MM/DD/YY): 4/26/23

SAMPLE CONDITIONS			
Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
0	Y	N	Y

CHAIN-OF-CUSTODY / Analytical Request Document

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Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES GROUND WATER DRINKING WATER
UST RCRA OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID (A-Z, 0-9 / , -) Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test Y/N	NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_YSG02 DTW																								
2	NEW_YSW_S101			4/26/23	1803		9	X	X	X															
3	NEW_YSW_S102			4/26/23	1743		9	X	X	X															
4	4/26/23 EB-02			4/26/23	1630																				
5																									
6																									
7																									
8																									
9																									
10																									
11																									
12																									
13																									
14																									
15																									
16																									

Requested Analysis Filtered (Y/N)

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME	SAMPLE CONDITIONS
NEW-23Q2 Rev 0	Joseph R Rod	4/27/23	1030		4-27	1020	L
		4-27	1420	gracelynn	4/27/23	14:20	0.1 / Y / N / Y

SAMPLER NAME AND SIGNATURE

PRINT Name of SAMPLER: James David

SIGNATURE of SAMPLER: James David

DATE Signed (MM/DD/YY): 4/26/23

Temp in °C | Received on Ice (Y/N) | Custody Sealed Cooler (Y/N) | Samples Intact (Y/N)

courier

GD04853-07 gef

CHAIN-OF-CUSTODY / Analytical Request Document

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Page: 1 of 6

Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES GROUND WATER DRINKING WATER
UST RCRA OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID
(A-Z, 0-9 / ,-)
Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test Y/N	NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_A213	WT	G	4/27/23	1209		9	X	X	X	X	X													
2	NEW_A214	WT	G	4/27/23	1432		9	X	X	X	X	X													
3	NEW_A215																								
4	NEW_APW02	WT	G	4/27/23	1217		11	X	X	X															
5	NEW_APW03																								
6	NEW_APW04																								
7	NEW_APW05	WT	G	4/27/23	1240		11	X	X	X															
8	NEW_APW05#S																								
9	NEW_APW06																								
10	NEW_APW07	WT	G	4/27/23	1035		11	X	X	X															
11	NEW_APW08																								
12	NEW_APW09	WT	G	4/27/23	1405		11	X	X	X															
13	NEW_APW10	WT	G	4/27/23	1547		11	X	X	X															
14	NEW_APW11																								
15	NEW_APW12																								
16	NEW_APW13	WT	G	4/27/23	1716		11	X	X	X															

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME	SAMPLE CONDITIONS
NEW-23Q2 Rev 0		4/28/23	0705		4/28/23	0705	6.0 / T / N / Y
		4/28/23	1245		4/28/23	12:45	

SAMPLER NAME AND SIGNATURE
PRINT Name of SAMPLER: Aaron Pemberton
SIGNATURE of SAMPLER:
DATE Signed (MM/DD/YY): 04/27/2023

Temp in °C | Received on Ice (Y/N) | Custody Sealed Cooler (Y/N) | Samples Intact (Y/N)

CHAIN-OF-CUSTODY / Analytical Request Document

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Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES | GROUND WATER | DRINKING WATER
UST | RCRA | OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test ↓ Y/N	NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	NEW_LREP_leachate																								
2	NEW_MW34&D																								
3	NEW_MW35&D																								
4	NEW_MW43&D																								
5	NEW_MW46&D																								
6	NEW_R201																								
7	NEW_R202																								
8	NEW_R217&D																								
9	NEW_R219																								
10	NEW_T101	WT	G	4/27/23	1604		9	X	X	X															
11	NEW_T102																								
12	NEW_XPW01_pore	WT	G	4/27/23	1407		10	X	X	X															
13	NEW_XPW02_pore	WT	G	4/27/23	1529		10	X	X	X															
14	NEW_XPW03_pore	WT	G	4/27/23	1700		10	X	X	X															
15	~~NEW_XPW04_pore~~ EB-03	WT	G	4/27/23	1435		10	X	X	X															
16	NEW_XSG01 - DTW																								

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME	SAMPLE CONDITIONS
NEW-23Q2 Rev 0		4/28/23	0705	Brenden Klemm	4/28/23	0705	0.5
	Brenden Klemm	4/28/23	1245		4/28/23	1245	Y

SAMPLER NAME AND SIGNATURE

PRINT Name of SAMPLER: Aaron Pemberton

SIGNATURE of SAMPLER: DATE Signed (MM/DD/YY): 04/27/23

Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
0.5	Y		Y

GD04926

CHAIN-OF-CUSTODY / Analytical Request Document

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Section A Required Client Information:

Company:	Vistra Corp
Address:	13498 E. 900th St
Email To:	Brian.Voelker@VistraCorp.com
Phone: (217) 753-8911	Fax:
Requested Due Date/TAT:	10 day

Section B Required Project Information:

Report To:	Brian Voelker
Copy To:	Jason Stuckey
Purchase Order No.:	
Project Name:	
Project Number:	2285

Section C Invoice Information:

Attention:	Jason Stuckey
Company Name:	Vistra Corp
Address:	see Section A
Quote Reference:	
Project Manager:	
Profile #:	

REGULATORY AGENCY

NPDES | GROUND WATER | DRINKING WATER
UST | RCRA | OTHER

Site Location STATE: IL

Section D Required Client Information

SAMPLE ID
(A-Z, 0-9 / ,-)
Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED DATE	COLLECTED TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test Y/N	NEW_257_501	NEW_257_502	NEW_811_502	NEW_811_503	NEW_845_501	NEW_NPDES_501	NEW_SUP_000	Residual Chlorine (Y/N)	Project No./ Lab I.D.
1	04/5/23 NEW_APW14 + dup	WT	G	4/28/23	1129		22																		
2	NEW_APW15																								
3	NEW_APW16																								
4	NEW_APW17																								
5	NEW_APW18																								
6	NEW_G104																								
7	NEW_G104#S DTW																								
8	NEW_G104&D																								
9	NEW_G105																								
10	NEW_G106																								
11	NEW_G108																								
12	NEW_G109 DTW																								
13	NEW_G110 DTW																								
14	NEW_G111 DTW																								
15	NEW_G112 DTW																								
16	NEW_G113 DTW																								

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME	SAMPLE CONDITIONS
NEW-23Q2 Rev 0	Joseph R Reed	4/28/23	16:12		4/28/23	16:12	4 / Y / 2 / Y

SAMPLER NAME AND SIGNATURE
PRINT Name of SAMPLER: Joe Reed
SIGNATURE of SAMPLER: Joseph R Reed
DATE Signed (MM/DD/YY): 4/28/23

Temp in °C | Received on Ice (Y/N) | Custody Sealed Cooler (Y/N) | Samples Intact (Y/N)

SAR-3: Depth to Groundwater Measurements
Plant: NEW
Event: NEW 2302

NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

Well	Unique ID	Date	Time	Depth to Water, ft bmp		Transducer			Initials	Notes
				Manual	Transducer	Serial No.	Batt %	DL		
A207	NEW_A207	4/24/23	1541	X	36.00	NA	NA	NA	JMD	
A213	NEW_A213		1544	X	18.63				KL	
A214	NEW_A214		1531	X	40.90				KL	
A215	NEW_A215		1527	X	44.03				KL	
G06D	NEW_G006&D		1459	X	28.92				JMD	
G104	NEW_G104		1804	X	4.51				JMD	
G104D	NEW_G104&D		1810	X	50.37				JMD	TD = 89.31
G104S	NEW_G104#S		1806	X	4.68				JMD	TD = 26.04
G105	NEW_G105		1833	X	7.10				JMD	TD = 26.20
G106	NEW_G106		1857	X	20.37				AP	
G109	NEW_G109		1647	X	5.11				JMD	TD = 24.97
G111	NEW_G111		1815	X	5.97				JMD	TD = 22.75
G112	NEW_G112		1823	X	4.38				JMD	TD = 24.62
G113	NEW_G113		1908	X	17.09				JMD	TD = 33.33
G114	NEW_G114		1723	X	13.45				JR	
G114D	NEW_G114&D		1556	X	42.69				JR	
G115	NEW_G115		1612	X	4.04				JR	No Lock, no pump
G116	NEW_G116		1933	X	6.00				JMD	
G117	NEW_G117		1845	X	7.08				JMD	TD = 21.90
G118	NEW_G118		1608	X	6.32				JMD	TD = 22.59
G119	NEW_G119		1654	X	4.10				JMD	TD = 23.85
G120	NEW_G120		1632	X	7.33				JMD	TD = 23.38
G125	NEW_G125		1457 JMD 4/24	X	2.84 JMD 4/24				KL	
G128	NEW_G128		~~1531~~ 1511	X	~~19.75~~ 3.96				JMD	
G130	NEW_G130		1704	X	4.34				JMD	TD = 22.69
G133	NEW_G133		1658	X	8.84				JMD	TD = 27.32
G136	NEW_G136		1643	X	6.69				JMD	TD = 22.20
G139	NEW_G139		1639	X	6.15				JMD	TD = 23.05
G141	NEW_G141		1515	X	10.99				JMD	TD = 25.16
G201	NEW_G201		1742	X	17.50				JMD	
G202	NEW_G202		1828	X	47.84				JMD	

SAR-3: Depth to Groundwater Measurements
Plant: NEW
Event: NEWTON_2Q

Well	Unique ID	Date	Time	Depth to Water, ft bmp		Transducer			Initials	Notes
				Manual	Transducer	Serial No.	Batt %	DL		
G203	NEW_G203	4/24/23	1536	x	41.39	NA	NA	NA	JR	No lock
G208	NEW_G208		1534	x	24.02				JMD	
G217S	NEW_G217#S		1439	x	6.20				KL	
G218	NEW_G218		1839	x	19.78				JMD	
G220	NEW_G220		1525	x	17.03				JMD	
G221	NEW_G221		1521	x	21.34				JMD	
G222	NEW_G222		1518	x	15.13				JMD	
G223	NEW_G223		1515	x	33.13				KL	Well has incorrect sign, says G233
G224	NEW_G224		1503	x	42.56				KL	
G225	NEW_G225		1511	x	7.27				JMD	TD= 24.99
G230	NEW_G230		1500	x	47.99				JR	
G231	NEW_G231		1504	x	47.36				JR	
G232	NEW_G232		1509	x	45.73				JR	
G233	NEW_G233		1516	x	41.67				JR	
G234	NEW_G234		1532	x	43.18				JR	
G48MG	NEW_G048MG		1826	x	18.99				JR	TD= 80.07
L1R	NEW_L1R_leachate		1716	x	52.80				KL	
L201	NEW_L201_leachate		1720	x	13.30				KL	Dry
L202	NEW_L202_leachate		1643	x	15.30				KL	Dry
L203	NEW_L203_leachate		1650	x	9.60				KL	Dry
L204	NEW_L204_leachate		1709	x	15.42				KL	
L205	NEW_L205_leachate		1701	x	0.97				KL	
L301	NEW_L301_leachate		NA	x	NA				JMD	No depth to measure
L302	NEW_L302_leachate		NA	x	NA				JMD	Not a well
M25-1	NEW_M25-1		1556	x	2.15				KL	
M25-2	NEW_M25-2		1557	x	1.42				KL	
M25-3	NEW_M25-3		1558	x	1.63				KL	
M25-4	NEW_M25-4		1559	x	2.43				KL	
M25-5	NEW_M25-5		1601	x	5.67				KL	
M25-6	NEW_M25-6		1602	x	12.28				KL	
M25-7	NEW_M25-7		1602	x	18.52				KL	

SAR-3: Depth to Groundwater Measurements
Plant: NEW PRIMARY ASH POND
Event: NEW-2302 NEWTON, IL

Well	Unique ID	Date	Time	Depth to Water, ft bmp		Transducer			Initials	Notes
				Manual	Transducer	Serial No.	Batt %	DL		
M26-1	NEW_M26-1	4/24/23	1806	X	2.80	NA	NA	NA	KL	
M26-2	NEW_M26-2		1807	X	23.02				KL	
M26-3	NEW_M26-3		1808	X	23.19				KL	
M26-4	NEW_M26-4		1809	X	NA				KL	Obstruction in well at depth 1.17'
M26-5	NEW_M26-5		1810	X	1.22				KL	
M26-6	NEW_M26-6		1811	X	1.21				KL	
M26-7	NEW_M26-7		1812	X	40.76				KL	
MW31S	NEW_MW31#S		19:35	X	6.00				JMD	TD = 18.69
MW33S	NEW_MW33#S		1600	X	8.32				AP	TD = 29.59
MW34D	NEW_MW34&D		1655	X	14.85				AP	TD = 58.73, unable to close casing
MW35D	NEW_MW35&D		1438	X	26.24				AP	TD = 53.73
MW35S	NEW_MW35#S		1737	X	2.99				JMD	TD = 16.28
MW36S	NEW_MW36#S		1623	X	3.35				AP	TD = 15.49
MW43D	NEW_MW43&D		1812	X	5.73				AP	TD = 40.80
MW46D	NEW_MW46&D		1619	X	16.82				JR	
MW48S	NEW_MW48#S		1833	X	3.52				JR	13.49 = TD
R201	NEW_R201		1445	X	47.56				JR	
R202	NEW_R202		1912	X	47.55					
R216	NEW_R216		1455	X	43.33				KL	
R217D	NEW_R217&D		1444	X	19.15				KL	
R219	NEW_R219		1528	X	20.08				JMD	
T101	NEW_T101		1700	X	5.84				JR	
T102	NEW_T102		1712	X	6.00				JR	
APW02	NEW_APW02				X	21521987				
APW03	NEW_APW03				X	21521988				
APW04	NEW_APW04				X	21503517				
APW05	NEW_APW05				X	21615053				
APW05S	NEW_APW05#S				X	21503536				
APW06	NEW_APW06				X	21615054				
APW07	NEW_APW07				X	21615033				
APW08	NEW_APW08				X	21615032				

SAR-3: DANIEL ...TON POWER PLANT
Plant: NEW
Event: NEW 2302

NEW Groundwater Measurements
PRIMARY ASH POND
NEWTON, IL

Well	Unique ID	Date	Time	Depth to Water, ft bmp		Transducer			Initials	Notes
				Manual	Transducer	Serial No.	Batt %	DL		
APW09	NEW_APW09				X	21522025	NA	NA		
APW10	NEW_APW10				X	21558058				
APW11	NEW_APW11				X	21558059				
APW12	NEW_APW12				X	21503535				
APW13	NEW_APW13				X	21522024				
APW14	NEW_APW14				X	21522035				
APW15	NEW_APW15				X	21522034				
APW16	NEW_APW16				X	21522033				
APW17	NEW_APW17				X	21522023				
APW18	NEW_APW18				X	21522026				
SG02	NEW_YSG02	4/24/23	1444	2.11	X	TBD			AP	
XPW01	NEW_XPW01_pore				X	21503518				
XPW02	NEW_XPW02_pore				X	21522010				
XPW03	NEW_XPW03_pore				X	21503520				
XPW04	NEW_XPW04_pore				X	21503519				
XSG01	NEW_XSG01	4/24/23	1716	534	X	TBD			AP	Staff gauge says 534
MW31D		4/24/23	1936	8.64						TD = 43.20
MW32S			1545	4.93						TD = 22.20
MW32D			1536	15.55						TD = 63.12
MW33D			1557	12.30						TD = 51.71
MW34S			1659	3.58						TD = 18.66
MW36D			1618	7.52						TD = 35.07
MW43S			1812	4.79						TD = 16.54
MW46S			1623	4.28						
MW48D			1831	4.98						TD = 41.54

Lake Levels
4/25/23 11:02 2.15'
4/26/23 8:11 2.19'
4/27/23 17:00 2.20'
4/28/23 7:58 2.17'
5/1/23 15:36 2.05'

G108 - well removed Jan 2023

ATTACHMENT C
COMPARISON OF STATISTICAL RESULTS TO BACKGROUND
QUARTER 2 2023

ATTACHMENT C.
COMPARISON OF STATISTICAL RESULTS TO BACKGROUND - QUARTER 2, 2023
845 QUARTERLY REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

Well ID	HSU	Event	Parameter	Units	Date Range	Sample Count	Percent ND	Statistical Calculation	Statistical Result	Background
APW02	UD	E001	Antimony, total	mg/L	02/17/21 - 04/27/23	10	100	All ND - Last	0.003	0.003
APW02	UD	E001	Arsenic, total	mg/L	02/17/21 - 04/27/23	10	70	CI around median	0.001	0.059
APW02	UD	E001	Barium, total	mg/L	02/17/21 - 04/27/23	10	0	CB around linear reg	0.00275	0.3
APW02	UD	E001	Beryllium, total	mg/L	02/17/21 - 04/27/23	10	100	All ND - Last	0.001	0.001
APW02	UD	E001	Boron, total	mg/L	02/17/21 - 04/27/23	10	0	CI around geomean	0.105	0.26
APW02	UD	E001	Cadmium, total	mg/L	02/17/21 - 04/27/23	10	100	All ND - Last	0.001	0.001
APW02	UD	E001	Chloride, total	mg/L	02/17/21 - 04/27/23	10	0	CI around mean	100	52
APW02	UD	E001	Chromium, total	mg/L	02/17/21 - 04/27/23	10	90	Most recent sample	0.004	0.011
APW02	UD	E001	Cobalt, total	mg/L	02/17/21 - 04/27/23	10	100	All ND - Last	0.002	0.0043
APW02	UD	E001	Fluoride, total	mg/L	02/17/21 - 04/27/23	10	100	All ND - Last	0.25	0.633
APW02	UD	E001	Lead, total	mg/L	02/17/21 - 04/27/23	10	90	CI around median	0.001	0.0074
APW02	UD	E001	Lithium, total	mg/L	02/17/21 - 04/27/23	10	0	CI around geomean	0.0888	0.03
APW02	UD	E001	Mercury, total	mg/L	02/17/21 - 04/27/23	10	100	All ND - Last	0.0002	0.0002
APW02	UD	E001	Molybdenum, total	mg/L	02/17/21 - 04/27/23	9	67	CI around median	0.001	0.018
APW02	UD	E001	Radium 226 + Radium 228, total	pCi/L	02/17/21 - 04/27/23	9	0	CI around mean	0.227	6.9
APW02	UD	E001	Selenium, total	mg/L	02/17/21 - 04/27/23	10	100	All ND - Last	0.001	0.001
APW02	UD	E001	Sulfate, total	mg/L	02/17/21 - 04/27/23	10	0	CI around median	2,900	35.84
APW02	UD	E001	Thallium, total	mg/L	02/17/21 - 04/27/23	10	100	All ND - Last	0.001	0.001
APW02	UD	E001	Total Dissolved Solids	mg/L	02/17/21 - 04/27/23	16	0	CB around linear reg	5,180	628
APW02	UD	E001	pH (field)	SU	02/17/21 - 04/27/23	16	0	CI around mean	6.6/6.8	6.4/7.8
APW03	UD	E001	Antimony, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.003	0.003
APW03	UD	E001	Arsenic, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.001	0.059
APW03	UD	E001	Barium, total	mg/L	02/18/21 - 04/25/23	10	0	CI around mean	0.0648	0.3
APW03	UD	E001	Beryllium, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.001	0.001
APW03	UD	E001	Boron, total	mg/L	02/18/21 - 04/25/23	10	0	CI around geomean	0.377	0.26
APW03	UD	E001	Cadmium, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.001	0.001
APW03	UD	E001	Chloride, total	mg/L	02/18/21 - 04/25/23	10	0	CI around mean	7.35	52

ATTACHMENT C.
COMPARISON OF STATISTICAL RESULTS TO BACKGROUND - QUARTER 2, 2023
845 QUARTERLY REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

Well ID	HSU	Event	Parameter	Units	Date Range	Sample Count	Percent ND	Statistical Calculation	Statistical Result	Background
APW03	UD	E001	Chromium, total	mg/L	02/18/21 - 04/25/23	10	90	CI around median	0.004	0.011
APW03	UD	E001	Cobalt, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.002	0.0043
APW03	UD	E001	Fluoride, total	mg/L	02/18/21 - 04/25/23	10	90	CI around median	0.25	0.633
APW03	UD	E001	Lead, total	mg/L	02/18/21 - 04/25/23	10	90	CI around median	0.001	0.0074
APW03	UD	E001	Lithium, total	mg/L	02/18/21 - 04/25/23	10	40	CI around median	0.02	0.03
APW03	UD	E001	Mercury, total	mg/L	02/18/21 - 04/25/23	10	90	CI around median	0.0002	0.0002
APW03	UD	E001	Molybdenum, total	mg/L	02/18/21 - 04/25/23	9	11	CI around mean	0.000992	0.018
APW03	UD	E001	Radium 226 + Radium 228, total	pCi/L	02/18/21 - 04/25/23	9	0	CI around mean	0.123	6.9
APW03	UD	E001	Selenium, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.001	0.001
APW03	UD	E001	Sulfate, total	mg/L	02/18/21 - 04/25/23	10	0	CI around mean	139	35.84
APW03	UD	E001	Thallium, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.001	0.001
APW03	UD	E001	Total Dissolved Solids	mg/L	02/18/21 - 04/25/23	16	0	CI around mean	628	628
APW03	UD	E001	pH (field)	SU	02/18/21 - 04/25/23	16	0	CI around mean	6.8/7.2	6.4/7.8
APW04	UD	E001	Antimony, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.003	0.003
APW04	UD	E001	Arsenic, total	mg/L	02/18/21 - 04/25/23	10	40	CI around geomean	0.000941	0.059
APW04	UD	E001	Barium, total	mg/L	02/18/21 - 04/25/23	10	0	CI around mean	0.0181	0.3
APW04	UD	E001	Beryllium, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.001	0.001
APW04	UD	E001	Boron, total	mg/L	02/18/21 - 04/25/23	10	0	CI around median	0.024	0.26
APW04	UD	E001	Cadmium, total	mg/L	02/18/21 - 04/25/23	10	90	CI around median	0.001	0.001
APW04	UD	E001	Chloride, total	mg/L	02/18/21 - 04/25/23	10	0	CI around mean	29.3	52
APW04	UD	E001	Chromium, total	mg/L	02/18/21 - 04/25/23	10	90	CI around median	0.004	0.011
APW04	UD	E001	Cobalt, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.002	0.0043
APW04	UD	E001	Fluoride, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.25	0.633
APW04	UD	E001	Lead, total	mg/L	02/18/21 - 04/25/23	10	60	CI around median	0.001	0.0074
APW04	UD	E001	Lithium, total	mg/L	02/18/21 - 04/25/23	10	30	CI around median	0.02	0.03
APW04	UD	E001	Mercury, total	mg/L	02/18/21 - 04/25/23	10	90	CI around median	0.0002	0.0002
APW04	UD	E001	Molybdenum, total	mg/L	02/18/21 - 04/25/23	9	89	CI around median	0.001	0.018

ATTACHMENT C.
COMPARISON OF STATISTICAL RESULTS TO BACKGROUND - QUARTER 2, 2023
845 QUARTERLY REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

Well ID	HSU	Event	Parameter	Units	Date Range	Sample Count	Percent ND	Statistical Calculation	Statistical Result	Background
APW04	UD	E001	Radium 226 + Radium 228, total	pCi/L	02/18/21 - 04/25/23	9	0	CI around mean	0.0207	6.9
APW04	UD	E001	Selenium, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.001	0.001
APW04	UD	E001	Sulfate, total	mg/L	02/18/21 - 04/25/23	10	0	CI around mean	844	35.84
APW04	UD	E001	Thallium, total	mg/L	02/18/21 - 04/25/23	10	100	All ND - Last	0.001	0.001
APW04	UD	E001	Total Dissolved Solids	mg/L	02/18/21 - 04/25/23	16	0	CI around mean	1,710	628
APW04	UD	E001	pH (field)	SU	02/18/21 - 04/25/23	16	0	CB around linear reg	6.9/8.0	6.4/7.8
APW05S	UD	E001	Antimony, total	mg/L	02/17/21 - 04/26/23	9	100	All ND - Last	0.003	0.003
APW05S	UD	E001	Arsenic, total	mg/L	02/17/21 - 04/26/23	9	33	CI around mean	0.00105	0.059
APW05S	UD	E001	Barium, total	mg/L	02/17/21 - 04/26/23	9	0	CI around median	0.048	0.3
APW05S	UD	E001	Beryllium, total	mg/L	02/17/21 - 04/26/23	9	100	All ND - Last	0.001	0.001
APW05S	UD	E001	Boron, total	mg/L	02/17/21 - 04/26/23	9	0	CI around median	0.04	0.26
APW05S	UD	E001	Cadmium, total	mg/L	02/17/21 - 04/26/23	9	89	CI around median	0.001	0.001
APW05S	UD	E001	Chloride, total	mg/L	02/17/21 - 04/26/23	9	0	CI around median	190	52
APW05S	UD	E001	Chromium, total	mg/L	02/17/21 - 04/26/23	9	89	CI around median	0.004	0.011
APW05S	UD	E001	Cobalt, total	mg/L	02/17/21 - 04/26/23	9	33	CI around geomean	0.00185	0.0043
APW05S	UD	E001	Fluoride, total	mg/L	02/17/21 - 04/26/23	9	0	CI around mean	0.349	0.633
APW05S	UD	E001	Lead, total	mg/L	02/17/21 - 04/26/23	9	89	CI around median	0.001	0.0074
APW05S	UD	E001	Lithium, total	mg/L	02/17/21 - 04/26/23	9	0	CI around geomean	0.0332	0.03
APW05S	UD	E001	Mercury, total	mg/L	02/17/21 - 04/26/23	9	100	All ND - Last	0.0002	0.0002
APW05S	UD	E001	Molybdenum, total	mg/L	02/17/21 - 04/26/23	8	0	CB around linear reg	-0.000835	0.018
APW05S	UD	E001	Radium 226 + Radium 228, total	pCi/L	02/17/21 - 04/26/23	8	0	CI around geomean	0.128	6.9
APW05S	UD	E001	Selenium, total	mg/L	02/17/21 - 04/26/23	9	100	All ND - Last	0.001	0.001
APW05S	UD	E001	Sulfate, total	mg/L	02/17/21 - 04/26/23	9	0	CI around median	640	35.84
APW05S	UD	E001	Thallium, total	mg/L	02/17/21 - 04/26/23	9	100	All ND - Last	0.001	0.001
APW05S	UD	E001	Total Dissolved Solids	mg/L	02/17/21 - 04/26/23	9	0	CI around mean	3,450	628
APW05S	UD	E001	pH (field)	SU	02/17/21 - 04/26/23	9	0	CI around mean	6.7/7.0	6.4/7.8
APW07	UA	E001	Antimony, total	mg/L	12/15/15 - 04/27/23	11	100	All ND - Last	0.003	0.003

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APW07	UA	E001	Arsenic, total	mg/L	12/15/15 - 04/27/23	12	0	CB around linear reg	0.0127	0.059
APW07	UA	E001	Barium, total	mg/L	12/15/15 - 04/27/23	12	0	CB around linear reg	0.465	0.3
APW07	UA	E001	Beryllium, total	mg/L	12/15/15 - 04/27/23	11	100	All ND - Last	0.001	0.001
APW07	UA	E001	Boron, total	mg/L	12/15/15 - 04/27/23	22	0	CB around T-S line	0.0841	0.26
APW07	UA	E001	Cadmium, total	mg/L	12/15/15 - 04/27/23	11	100	All ND - Last	0.001	0.001
APW07	UA	E001	Chloride, total	mg/L	12/15/15 - 04/27/23	24	0	CB around T-S line	57.5	52
APW07	UA	E001	Chromium, total	mg/L	12/15/15 - 04/27/23	12	75	CI around median	0.004	0.011
APW07	UA	E001	Cobalt, total	mg/L	12/15/15 - 04/27/23	11	82	CI around median	0.002	0.0043
APW07	UA	E001	Fluoride, total	mg/L	12/15/15 - 04/27/23	22	4	CI around mean	0.36	0.633
APW07	UA	E001	Lead, total	mg/L	12/15/15 - 04/27/23	12	58	CI around median	0.001	0.0074
APW07	UA	E001	Lithium, total	mg/L	12/15/15 - 04/27/23	12	100	All ND - Last	0.02	0.03
APW07	UA	E001	Mercury, total	mg/L	12/15/15 - 04/27/23	12	100	All ND - Last	0.0002	0.0002
APW07	UA	E001	Molybdenum, total	mg/L	12/15/15 - 04/27/23	11	0	CB around linear reg	-0.00442	0.018
APW07	UA	E001	Radium 226 + Radium 228, total	pCi/L	12/15/15 - 04/27/23	12	0	CI around mean	1.31	6.9
APW07	UA	E001	Selenium, total	mg/L	12/15/15 - 04/27/23	12	100	All ND - Last	0.001	0.001
APW07	UA	E001	Sulfate, total	mg/L	12/15/15 - 04/27/23	23	17	CB around T-S line	6.15	35.84
APW07	UA	E001	Thallium, total	mg/L	12/15/15 - 04/27/23	11	100	All ND - Last	0.001	0.001
APW07	UA	E001	Total Dissolved Solids	mg/L	12/15/15 - 04/27/23	22	0	CI around mean	486	628
APW07	UA	E001	pH (field)	SU	12/15/15 - 04/27/23	24	0	CI around mean	7.1/7.3	6.4/7.8
APW08	UA	E001	Antimony, total	mg/L	12/15/15 - 04/26/23	11	100	All ND - Last	0.003	0.003
APW08	UA	E001	Arsenic, total	mg/L	12/15/15 - 04/26/23	12	0	CB around linear reg	0.0188	0.059
APW08	UA	E001	Barium, total	mg/L	12/15/15 - 04/26/23	12	0	CB around linear reg	0.444	0.3
APW08	UA	E001	Beryllium, total	mg/L	12/15/15 - 04/26/23	11	100	All ND - Last	0.001	0.001
APW08	UA	E001	Boron, total	mg/L	12/15/15 - 04/26/23	22	0	CI around geomean	0.0816	0.26
APW08	UA	E001	Cadmium, total	mg/L	12/15/15 - 04/26/23	11	100	All ND - Last	0.001	0.001
APW08	UA	E001	Chloride, total	mg/L	12/15/15 - 04/26/23	24	0	CI around mean	54.7	52
APW08	UA	E001	Chromium, total	mg/L	12/15/15 - 04/26/23	12	58	CI around median	0.004	0.011

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APW08	UA	E001	Cobalt, total	mg/L	12/15/15 - 04/26/23	11	73	CI around median	0.002	0.0043
APW08	UA	E001	Fluoride, total	mg/L	12/15/15 - 04/26/23	22	9	CI around median	0.373	0.633
APW08	UA	E001	Lead, total	mg/L	12/15/15 - 04/26/23	12	50	CI around median	0.001	0.0074
APW08	UA	E001	Lithium, total	mg/L	12/15/15 - 04/26/23	12	67	CI around median	0.01	0.03
APW08	UA	E001	Mercury, total	mg/L	12/15/15 - 04/26/23	12	100	All ND - Last	0.0002	0.0002
APW08	UA	E001	Molybdenum, total	mg/L	12/15/15 - 04/26/23	11	0	CI around mean	0.00453	0.018
APW08	UA	E001	Radium 226 + Radium 228, total	pCi/L	12/15/15 - 04/26/23	12	0	CI around mean	1.03	6.9
APW08	UA	E001	Selenium, total	mg/L	12/15/15 - 04/26/23	12	92	CI around median	0.001	0.001
APW08	UA	E001	Sulfate, total	mg/L	12/15/15 - 04/26/23	23	0	CB around linear reg	44	35.84
APW08	UA	E001	Thallium, total	mg/L	12/15/15 - 04/26/23	11	100	All ND - Last	0.001	0.001
APW08	UA	E001	Total Dissolved Solids	mg/L	12/15/15 - 04/26/23	22	0	CB around linear reg	592	628
APW08	UA	E001	pH (field)	SU	12/15/15 - 04/26/23	25	0	CI around mean	7.2/7.4	6.4/7.8
APW09	UA	E001	Antimony, total	mg/L	12/15/15 - 04/27/23	11	100	All ND - Last	0.003	0.003
APW09	UA	E001	Arsenic, total	mg/L	12/15/15 - 04/27/23	12	0	CB around linear reg	0.0223	0.059
APW09	UA	E001	Barium, total	mg/L	12/15/15 - 04/27/23	12	0	CI around mean	0.277	0.3
APW09	UA	E001	Beryllium, total	mg/L	12/15/15 - 04/27/23	11	100	All ND - Last	0.001	0.001
APW09	UA	E001	Boron, total	mg/L	12/15/15 - 04/27/23	22	0	CB around T-S line	0.0809	0.26
APW09	UA	E001	Cadmium, total	mg/L	12/15/15 - 04/27/23	11	100	All ND - Last	0.001	0.001
APW09	UA	E001	Chloride, total	mg/L	12/15/15 - 04/27/23	24	0	CI around median	95	52
APW09	UA	E001	Chromium, total	mg/L	12/15/15 - 04/27/23	12	67	CB around T-S line	0.004	0.011
APW09	UA	E001	Cobalt, total	mg/L	12/15/15 - 04/27/23	11	91	CI around median	0.002	0.0043
APW09	UA	E001	Fluoride, total	mg/L	12/15/15 - 04/27/23	22	4	CI around mean	0.438	0.633
APW09	UA	E001	Lead, total	mg/L	12/15/15 - 04/27/23	12	50	CI around median	0.001	0.0074
APW09	UA	E001	Lithium, total	mg/L	12/15/15 - 04/27/23	12	100	All ND - Last	0.02	0.03
APW09	UA	E001	Mercury, total	mg/L	12/15/15 - 04/27/23	12	83	CI around median	0.0002	0.0002
APW09	UA	E001	Molybdenum, total	mg/L	12/15/15 - 04/27/23	11	0	CB around linear reg	-0.00854	0.018
APW09	UA	E001	Radium 226 + Radium 228, total	pCi/L	12/15/15 - 04/27/23	12	0	CI around geomean	0.828	6.9

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APW09	UA	E001	Selenium, total	mg/L	12/15/15 - 04/27/23	12	92	CI around median	0.001	0.001
APW09	UA	E001	Sulfate, total	mg/L	12/15/15 - 04/27/23	23	9	CI around geomean	4	35.84
APW09	UA	E001	Thallium, total	mg/L	12/15/15 - 04/27/23	11	100	All ND - Last	0.001	0.001
APW09	UA	E001	Total Dissolved Solids	mg/L	12/15/15 - 04/27/23	23	0	CB around T-S line	734	628
APW09	UA	E001	pH (field)	SU	12/15/15 - 04/27/23	24	0	CI around median	7.4/7.5	6.4/7.8
APW10	UA	E001	Antimony, total	mg/L	12/16/15 - 04/27/23	13	100	All ND - Last	0.003	0.003
APW10	UA	E001	Arsenic, total	mg/L	12/16/15 - 04/27/23	14	0	CI around mean	0.0059	0.059
APW10	UA	E001	Barium, total	mg/L	12/16/15 - 04/27/23	14	0	CI around mean	0.0286	0.3
APW10	UA	E001	Beryllium, total	mg/L	12/16/15 - 04/27/23	13	100	All ND - Last	0.001	0.001
APW10	UA	E001	Boron, total	mg/L	12/16/15 - 04/27/23	24	0	CB around linear reg	0.0764	0.26
APW10	UA	E001	Cadmium, total	mg/L	12/16/15 - 04/27/23	13	100	All ND - Last	0.001	0.001
APW10	UA	E001	Chloride, total	mg/L	12/16/15 - 04/27/23	25	0	CI around mean	45.4	52
APW10	UA	E001	Chromium, total	mg/L	12/16/15 - 04/27/23	14	100	All ND - Last	0.004	0.011
APW10	UA	E001	Cobalt, total	mg/L	12/16/15 - 04/27/23	13	92	CI around median	0.002	0.0043
APW10	UA	E001	Fluoride, total	mg/L	12/16/15 - 04/27/23	24	21	CI around mean	0.298	0.633
APW10	UA	E001	Lead, total	mg/L	12/16/15 - 04/27/23	14	86	CI around median	0.001	0.0074
APW10	UA	E001	Lithium, total	mg/L	12/16/15 - 04/27/23	14	7	CB around linear reg	0.0132	0.03
APW10	UA	E001	Mercury, total	mg/L	12/16/15 - 04/27/23	14	100	All ND - Last	0.0002	0.0002
APW10	UA	E001	Molybdenum, total	mg/L	12/16/15 - 04/27/23	13	0	CB around linear reg	0.00524	0.018
APW10	UA	E001	Radium 226 + Radium 228, total	pCi/L	12/16/15 - 04/27/23	14	0	CI around mean	0.442	6.9
APW10	UA	E001	Selenium, total	mg/L	12/16/15 - 04/27/23	14	100	All ND - Last	0.001	0.001
APW10	UA	E001	Sulfate, total	mg/L	12/16/15 - 04/27/23	25	0	CI around median	410	35.84
APW10	UA	E001	Thallium, total	mg/L	12/16/15 - 04/27/23	13	100	All ND - Last	0.001	0.001
APW10	UA	E001	Total Dissolved Solids	mg/L	12/16/15 - 04/27/23	26	0	CB around linear reg	1,030	628
APW10	UA	E001	pH (field)	SU	12/16/15 - 04/27/23	27	0	CB around linear reg	7.2/7.5	6.4/7.8
APW11	UA	E001	Antimony, total	mg/L	02/18/21 - 04/26/23	10	100	All ND - Last	0.003	0.003
APW11	UA	E001	Arsenic, total	mg/L	02/18/21 - 04/26/23	10	0	CI around mean	0.0015	0.059

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APW11	UA	E001	Barium, total	mg/L	02/18/21 - 04/26/23	10	0	CB around T-S line	-0.566	0.3
APW11	UA	E001	Beryllium, total	mg/L	02/18/21 - 04/26/23	10	100	All ND - Last	0.001	0.001
APW11	UA	E001	Boron, total	mg/L	02/18/21 - 04/26/23	10	0	CI around median	0.063	0.26
APW11	UA	E001	Cadmium, total	mg/L	02/18/21 - 04/26/23	10	100	All ND - Last	0.001	0.001
APW11	UA	E001	Chloride, total	mg/L	02/18/21 - 04/26/23	10	0	CI around median	26	52
APW11	UA	E001	Chromium, total	mg/L	02/18/21 - 04/26/23	10	70	CI around median	0.004	0.011
APW11	UA	E001	Cobalt, total	mg/L	02/18/21 - 04/26/23	10	70	CI around median	0.002	0.0043
APW11	UA	E001	Fluoride, total	mg/L	02/18/21 - 04/26/23	10	50	CI around geomean	0.245	0.633
APW11	UA	E001	Lead, total	mg/L	02/18/21 - 04/26/23	10	60	CI around median	0.001	0.0074
APW11	UA	E001	Lithium, total	mg/L	02/18/21 - 04/26/23	10	10	CI around mean	0.0175	0.03
APW11	UA	E001	Mercury, total	mg/L	02/18/21 - 04/26/23	10	80	CI around median	0.0002	0.0002
APW11	UA	E001	Molybdenum, total	mg/L	02/18/21 - 04/26/23	9	0	CB around T-S line	-0.0661	0.018
APW11	UA	E001	Radium 226 + Radium 228, total	pCi/L	02/18/21 - 04/26/23	9	0	CI around mean	0.424	6.9
APW11	UA	E001	Selenium, total	mg/L	02/18/21 - 04/26/23	10	80	CI around median	0.001	0.001
APW11	UA	E001	Sulfate, total	mg/L	02/18/21 - 04/26/23	10	0	CI around median	260	35.84
APW11	UA	E001	Thallium, total	mg/L	02/18/21 - 04/26/23	10	90	CI around median	0.001	0.001
APW11	UA	E001	Total Dissolved Solids	mg/L	02/18/21 - 04/26/23	10	0	CI around mean	809	628
APW11	UA	E001	pH (field)	SU	02/18/21 - 04/26/23	10	0	CI around median	6.6/7.2	6.4/7.8
APW12	UD	E001	Antimony, total	mg/L	02/17/21 - 04/26/23	10	100	All ND - Last	0.003	0.003
APW12	UD	E001	Arsenic, total	mg/L	02/17/21 - 04/26/23	10	0	CI around mean	0.00155	0.059
APW12	UD	E001	Barium, total	mg/L	02/17/21 - 04/26/23	10	0	CB around linear reg	0.0133	0.3
APW12	UD	E001	Beryllium, total	mg/L	02/17/21 - 04/26/23	10	100	All ND - Last	0.001	0.001
APW12	UD	E001	Boron, total	mg/L	02/17/21 - 04/26/23	10	0	CI around mean	0.18	0.26
APW12	UD	E001	Cadmium, total	mg/L	02/17/21 - 04/26/23	10	100	All ND - Last	0.001	0.001
APW12	UD	E001	Chloride, total	mg/L	02/17/21 - 04/26/23	10	0	CI around mean	21.3	52
APW12	UD	E001	Chromium, total	mg/L	02/17/21 - 04/26/23	10	100	All ND - Last	0.004	0.011
APW12	UD	E001	Cobalt, total	mg/L	02/17/21 - 04/26/23	10	20	CB around linear reg	-0.00198	0.0043

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APW12	UD	E001	Fluoride, total	mg/L	02/17/21 - 04/26/23	10	100	All ND - Last	0.25	0.633
APW12	UD	E001	Lead, total	mg/L	02/17/21 - 04/26/23	10	90	CI around median	0.001	0.0074
APW12	UD	E001	Lithium, total	mg/L	02/17/21 - 04/26/23	10	0	CI around geomean	0.0244	0.03
APW12	UD	E001	Mercury, total	mg/L	02/17/21 - 04/26/23	10	90	CI around median	0.0002	0.0002
APW12	UD	E001	Molybdenum, total	mg/L	02/17/21 - 04/26/23	9	44	CI around geomean	0.000964	0.018
APW12	UD	E001	Radium 226 + Radium 228, total	pCi/L	02/17/21 - 04/26/23	9	0	CI around geomean	0.14	6.9
APW12	UD	E001	Selenium, total	mg/L	02/17/21 - 04/26/23	10	100	All ND - Last	0.001	0.001
APW12	UD	E001	Sulfate, total	mg/L	02/17/21 - 04/26/23	10	0	CI around mean	253	35.84
APW12	UD	E001	Thallium, total	mg/L	02/17/21 - 04/26/23	10	100	All ND - Last	0.001	0.001
APW12	UD	E001	Total Dissolved Solids	mg/L	02/17/21 - 04/26/23	10	0	CI around mean	1,160	628
APW12	UD	E001	pH (field)	SU	02/17/21 - 04/26/23	10	0	CI around mean	6.2/6.6	6.4/7.8
APW13	UA	E001	Antimony, total	mg/L	02/22/21 - 04/27/23	10	100	All ND - Last	0.003	0.003
APW13	UA	E001	Arsenic, total	mg/L	02/22/21 - 04/27/23	10	0	CI around mean	0.00314	0.059
APW13	UA	E001	Barium, total	mg/L	02/22/21 - 04/27/23	10	0	CI around mean	0.05	0.3
APW13	UA	E001	Beryllium, total	mg/L	02/22/21 - 04/27/23	10	100	All ND - Last	0.001	0.001
APW13	UA	E001	Boron, total	mg/L	02/22/21 - 04/27/23	10	0	CI around mean	0.105	0.26
APW13	UA	E001	Cadmium, total	mg/L	02/22/21 - 04/27/23	10	100	All ND - Last	0.001	0.001
APW13	UA	E001	Chloride, total	mg/L	02/22/21 - 04/27/23	10	0	CI around mean	46.2	52
APW13	UA	E001	Chromium, total	mg/L	02/22/21 - 04/27/23	10	100	All ND - Last	0.004	0.011
APW13	UA	E001	Cobalt, total	mg/L	02/22/21 - 04/27/23	10	100	All ND - Last	0.002	0.0043
APW13	UA	E001	Fluoride, total	mg/L	02/22/21 - 04/27/23	10	10	CI around mean	0.285	0.633
APW13	UA	E001	Lead, total	mg/L	02/22/21 - 04/27/23	10	100	All ND - Last	0.001	0.0074
APW13	UA	E001	Lithium, total	mg/L	02/22/21 - 04/27/23	10	0	CI around mean	0.0262	0.03
APW13	UA	E001	Mercury, total	mg/L	02/22/21 - 04/27/23	10	100	All ND - Last	0.0002	0.0002
APW13	UA	E001	Molybdenum, total	mg/L	02/22/21 - 04/27/23	9	0	CB around linear reg	-0.00498	0.018
APW13	UA	E001	Radium 226 + Radium 228, total	pCi/L	02/22/21 - 04/27/23	9	0	CI around mean	0.245	6.9
APW13	UA	E001	Selenium, total	mg/L	02/22/21 - 04/27/23	10	100	All ND - Last	0.001	0.001

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APW13	UA	E001	Sulfate, total	mg/L	02/22/21 - 04/27/23	10	0	CI around mean	210	35.84
APW13	UA	E001	Thallium, total	mg/L	02/22/21 - 04/27/23	10	100	All ND - Last	0.001	0.001
APW13	UA	E001	Total Dissolved Solids	mg/L	02/22/21 - 04/27/23	10	0	CI around mean	801	628
APW13	UA	E001	pH (field)	SU	02/22/21 - 04/27/23	10	0	CI around median	7.1/7.3	6.4/7.8
APW14	UA	E001	Antimony, total	mg/L	02/22/21 - 04/28/23	10	100	All ND - Last	0.003	0.003
APW14	UA	E001	Arsenic, total	mg/L	02/22/21 - 04/28/23	10	0	CI around mean	0.00506	0.059
APW14	UA	E001	Barium, total	mg/L	02/22/21 - 04/28/23	10	0	CI around mean	0.0752	0.3
APW14	UA	E001	Beryllium, total	mg/L	02/22/21 - 04/28/23	10	100	All ND - Last	0.001	0.001
APW14	UA	E001	Boron, total	mg/L	02/22/21 - 04/28/23	10	0	CI around mean	0.0949	0.26
APW14	UA	E001	Cadmium, total	mg/L	02/22/21 - 04/28/23	10	100	All ND - Last	0.001	0.001
APW14	UA	E001	Chloride, total	mg/L	02/22/21 - 04/28/23	10	0	CI around mean	41.8	52
APW14	UA	E001	Chromium, total	mg/L	02/22/21 - 04/28/23	10	90	CI around median	0.004	0.011
APW14	UA	E001	Cobalt, total	mg/L	02/22/21 - 04/28/23	10	90	CI around median	0.002	0.0043
APW14	UA	E001	Fluoride, total	mg/L	02/22/21 - 04/28/23	10	30	CI around mean	0.266	0.633
APW14	UA	E001	Lead, total	mg/L	02/22/21 - 04/28/23	10	70	CI around median	0.001	0.0074
APW14	UA	E001	Lithium, total	mg/L	02/22/21 - 04/28/23	10	20	CB around linear reg	-0.00217	0.03
APW14	UA	E001	Mercury, total	mg/L	02/22/21 - 04/28/23	10	100	All ND - Last	0.0002	0.0002
APW14	UA	E001	Molybdenum, total	mg/L	02/22/21 - 04/28/23	9	0	CB around linear reg	-0.0066	0.018
APW14	UA	E001	Radium 226 + Radium 228, total	pCi/L	02/22/21 - 04/28/23	9	0	CI around mean	0.372	6.9
APW14	UA	E001	Selenium, total	mg/L	02/22/21 - 04/28/23	10	100	All ND - Last	0.001	0.001
APW14	UA	E001	Sulfate, total	mg/L	02/22/21 - 04/28/23	10	0	CI around median	320	35.84
APW14	UA	E001	Thallium, total	mg/L	02/22/21 - 04/28/23	10	100	All ND - Last	0.001	0.001
APW14	UA	E001	Total Dissolved Solids	mg/L	02/22/21 - 04/28/23	10	0	CI around mean	892	628
APW14	UA	E001	pH (field)	SU	02/22/21 - 04/28/23	10	0	CI around median	7.3/7.5	6.4/7.8
APW15	UA	E001	Antimony, total	mg/L	02/23/21 - 04/26/23	10	100	All ND - Last	0.003	0.003
APW15	UA	E001	Arsenic, total	mg/L	02/23/21 - 04/26/23	10	0	CI around mean	0.0166	0.059
APW15	UA	E001	Barium, total	mg/L	02/23/21 - 04/26/23	10	0	CI around mean	0.559	0.3

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PRIMARY ASH POND
NEWTON, IL

Well ID	HSU	Event	Parameter	Units	Date Range	Sample Count	Percent ND	Statistical Calculation	Statistical Result	Background
APW15	UA	E001	Beryllium, total	mg/L	02/23/21 - 04/26/23	10	100	All ND - Last	0.001	0.001
APW15	UA	E001	Boron, total	mg/L	02/23/21 - 04/26/23	10	0	CI around mean	0.128	0.26
APW15	UA	E001	Cadmium, total	mg/L	02/23/21 - 04/26/23	10	100	All ND - Last	0.001	0.001
APW15	UA	E001	Chloride, total	mg/L	02/23/21 - 04/26/23	10	0	CI around median	230	52
APW15	UA	E001	Chromium, total	mg/L	02/23/21 - 04/26/23	10	80	CI around median	0.004	0.011
APW15	UA	E001	Cobalt, total	mg/L	02/23/21 - 04/26/23	10	80	CI around median	0.002	0.0043
APW15	UA	E001	Fluoride, total	mg/L	02/23/21 - 04/26/23	10	0	CI around geomean	0.6	0.633
APW15	UA	E001	Lead, total	mg/L	02/23/21 - 04/26/23	10	50	CI around median	0.001	0.0074
APW15	UA	E001	Lithium, total	mg/L	02/23/21 - 04/26/23	10	80	CI around median	0.02	0.03
APW15	UA	E001	Mercury, total	mg/L	02/23/21 - 04/26/23	10	100	All ND - Last	0.0002	0.0002
APW15	UA	E001	Molybdenum, total	mg/L	02/23/21 - 04/26/23	9	0	CI around mean	0.00846	0.018
APW15	UA	E001	Radium 226 + Radium 228, total	pCi/L	02/23/21 - 04/26/23	9	0	CI around mean	1.5	6.9
APW15	UA	E001	Selenium, total	mg/L	02/23/21 - 04/26/23	10	100	All ND - Last	0.001	0.001
APW15	UA	E001	Sulfate, total	mg/L	02/23/21 - 04/26/23	10	100	All ND - Last	1	35.84
APW15	UA	E001	Thallium, total	mg/L	02/23/21 - 04/26/23	10	100	All ND - Last	0.001	0.001
APW15	UA	E001	Total Dissolved Solids	mg/L	02/23/21 - 04/26/23	10	0	CI around mean	1,020	628
APW15	UA	E001	pH (field)	SU	02/23/21 - 04/26/23	10	0	CI around median	7.0/7.3	6.4/7.8
APW16	UA	E001	Antimony, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.003	0.003
APW16	UA	E001	Arsenic, total	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	0.00767	0.059
APW16	UA	E001	Barium, total	mg/L	02/23/21 - 04/25/23	10	0	CB around linear reg	0.434	0.3
APW16	UA	E001	Beryllium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.001	0.001
APW16	UA	E001	Boron, total	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	0.128	0.26
APW16	UA	E001	Cadmium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.001	0.001
APW16	UA	E001	Chloride, total	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	66.1	52
APW16	UA	E001	Chromium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.004	0.011
APW16	UA	E001	Cobalt, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.002	0.0043
APW16	UA	E001	Fluoride, total	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	0.605	0.633

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PRIMARY ASH POND
NEWTON, IL

Well ID	HSU	Event	Parameter	Units	Date Range	Sample Count	Percent ND	Statistical Calculation	Statistical Result	Background
APW16	UA	E001	Lead, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.001	0.0074
APW16	UA	E001	Lithium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.02	0.03
APW16	UA	E001	Mercury, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.0002	0.0002
APW16	UA	E001	Molybdenum, total	mg/L	02/23/21 - 04/25/23	9	44	CB around linear reg	-0.00408	0.018
APW16	UA	E001	Radium 226 + Radium 228, total	pCi/L	02/23/21 - 04/25/23	9	0	CI around geomean	1.22	6.9
APW16	UA	E001	Selenium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.001	0.001
APW16	UA	E001	Sulfate, total	mg/L	02/23/21 - 04/25/23	10	90	CI around median	1	35.84
APW16	UA	E001	Thallium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.001	0.001
APW16	UA	E001	Total Dissolved Solids	mg/L	02/23/21 - 04/25/23	10	0	CI around median	690	628
APW16	UA	E001	pH (field)	SU	02/23/21 - 04/25/23	10	0	CI around mean	7.2/7.6	6.4/7.8
APW17	UA	E001	Antimony, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.003	0.003
APW17	UA	E001	Arsenic, total	mg/L	02/23/21 - 04/25/23	10	0	CB around linear reg	0.0181	0.059
APW17	UA	E001	Barium, total	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	0.565	0.3
APW17	UA	E001	Beryllium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.001	0.001
APW17	UA	E001	Boron, total	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	0.0839	0.26
APW17	UA	E001	Cadmium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.001	0.001
APW17	UA	E001	Chloride, total	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	43.9	52
APW17	UA	E001	Chromium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.004	0.011
APW17	UA	E001	Cobalt, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.002	0.0043
APW17	UA	E001	Fluoride, total	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	0.394	0.633
APW17	UA	E001	Lead, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.001	0.0074
APW17	UA	E001	Lithium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.02	0.03
APW17	UA	E001	Mercury, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.0002	0.0002
APW17	UA	E001	Molybdenum, total	mg/L	02/23/21 - 04/25/23	9	0	CI around median	0.0048	0.018
APW17	UA	E001	Radium 226 + Radium 228, total	pCi/L	02/23/21 - 04/25/23	9	0	CI around mean	0.644	6.9
APW17	UA	E001	Selenium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.001	0.001
APW17	UA	E001	Sulfate, total	mg/L	02/23/21 - 04/25/23	10	10	CI around mean	26.7	35.84

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NEWTON, IL

Well ID	HSU	Event	Parameter	Units	Date Range	Sample Count	Percent ND	Statistical Calculation	Statistical Result	Background
APW17	UA	E001	Thallium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.001	0.001
APW17	UA	E001	Total Dissolved Solids	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	631	628
APW17	UA	E001	pH (field)	SU	02/23/21 - 04/25/23	10	0	CI around mean	7.3/7.6	6.4/7.8
APW18	UA	E001	Antimony, total	mg/L	02/23/21 - 04/25/23	10	90	CI around median	0.003	0.003
APW18	UA	E001	Arsenic, total	mg/L	02/23/21 - 04/25/23	10	10	CI around mean	0.00144	0.059
APW18	UA	E001	Barium, total	mg/L	02/23/21 - 04/25/23	10	0	CI around median	0.33	0.3
APW18	UA	E001	Beryllium, total	mg/L	02/23/21 - 04/25/23	10	90	CI around median	0.001	0.001
APW18	UA	E001	Boron, total	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	0.103	0.26
APW18	UA	E001	Cadmium, total	mg/L	02/23/21 - 04/25/23	10	90	CI around median	0.001	0.001
APW18	UA	E001	Chloride, total	mg/L	02/23/21 - 04/25/23	10	0	CB around T-S line	-243	52
APW18	UA	E001	Chromium, total	mg/L	02/23/21 - 04/25/23	10	70	CI around median	0.004	0.011
APW18	UA	E001	Cobalt, total	mg/L	02/23/21 - 04/25/23	10	70	CI around median	0.002	0.0043
APW18	UA	E001	Fluoride, total	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	0.677	0.633
APW18	UA	E001	Lead, total	mg/L	02/23/21 - 04/25/23	10	50	CB around linear reg	-0.00473	0.0074
APW18	UA	E001	Lithium, total	mg/L	02/23/21 - 04/25/23	10	100	All ND - Last	0.02	0.03
APW18	UA	E001	Mercury, total	mg/L	02/23/21 - 04/25/23	10	90	CI around median	0.0002	0.0002
APW18	UA	E001	Molybdenum, total	mg/L	02/23/21 - 04/25/23	9	0	CB around linear reg	-0.0288	0.018
APW18	UA	E001	Radium 226 + Radium 228, total	pCi/L	02/23/21 - 04/25/23	9	0	CI around mean	1.38	6.9
APW18	UA	E001	Selenium, total	mg/L	02/23/21 - 04/25/23	10	90	CI around median	0.001	0.001
APW18	UA	E001	Sulfate, total	mg/L	02/23/21 - 04/25/23	10	20	CI around geomean	1.82	35.84
APW18	UA	E001	Thallium, total	mg/L	02/23/21 - 04/25/23	10	80	CI around median	0.001	0.001
APW18	UA	E001	Total Dissolved Solids	mg/L	02/23/21 - 04/25/23	10	0	CI around mean	508	628
APW18	UA	E001	pH (field)	SU	02/23/21 - 04/25/23	10	0	CI around mean	7.5/7.8	6.4/7.8

ATTACHMENT C.
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NEWTON, IL

Notes:
Lower Confidence Limit (LCL) or Upper Confidence Limit (UCL) exceeded the statistical background value
HSU = hydrostratigraphic unit:

UA = Uppermost Aquifer

UD = Upper Drift

mg/L = milligrams per liter
ND = non-detect
pCi/L = picocuries per liter
SU = standard units
Sample Count = number of samples from Sampled Date Range used to calculate the Statistical Result
Statistical Calculation = method used to calculate the statistical result:

All ND - Last = All results were below the reporting limit, and the last determined reporting limit is shown

CB around T-S line = Confidence band around Thiel-Sen line

CB around linear reg = Confidence band around linear regression

CI around geomean = Confidence interval around the geometric mean

CI around mean = Confidence interval around the mean

CI around median = Confidence interval around the median

Most recent sample = Result for the most recently collected sample used due to insufficient data

Statistical Result = calculated in accordance with Statistical Analysis Plan using constituent concentrations observed at monitoring well during all sampling events within the specified date range
For pH, the values presented are the lower / upper limits of the background determination

Document 16

Siegel, D.I., 1989. Geochemistry of the Cambrian-Ordovician Aquifer System in the Northern Midwest, U.S. Geological Survey Professional Paper 1405-D, 76p.

GEOCHEMISTRY OF THE CAMBRIAN-ORDOVICIAN AQUIFER SYSTEM IN THE NORTHERN MIDWEST, UNITED STATES

REGIONAL AQUIFER-SYSTEM ANALYSIS

U. S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1405 – D

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Geochemistry of the Cambrian–Ordovician Aquifer System in the Northern Midwest, United States

By D.I. SIEGEL

REGIONAL AQUIFER–SYSTEM ANALYSIS—
NORTHERN MIDWEST AQUIFER SYSTEM

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1405–D

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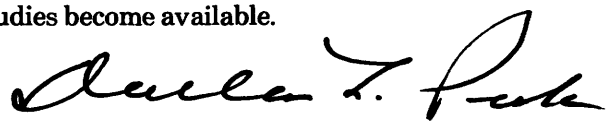
FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) Program was started in 1978 following a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which in aggregate underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number, and where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretive products of subsequent studies become available.



Dallas L. Peck
Director

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ENGLISH-TO-METRIC UNITS CONVERSION FACTORS AND ABBREVIATIONS

For readers who prefer to use metric (International System) units rather than the inch-pound units used in this report, conversion factors are listed below.

Multiply inch-pound unit	*By*	*To obtain metric unit*
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow	
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per square mile per year [$(ft^3/mi^2)/yr$]	0.01093	cubic meter per square kilometer per year [$(m^3/km^2)/yr$]
	Temperature	
degree Fahrenheit (°F)	0.5556 (°F−32)	degree Celsius (°C)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

SYMBOLS AND DEFINITIONS

δ	Isotopic composition expressed as permil differences in the measured isotopic ratios of sample and standard.
$\delta^{13}C$	Standard expression of the ratio of the ^{13}C ion with respect to the ^{12}C ion.
δD	Standard expression of the ratio of the ^{2}H ion (deuterium) with respect to the ^{1}H ion.
$\delta^{18}O$	Standard expression of the ratio of the ^{18}O ion with respect to the ^{16}O ion.
$\delta^{34}S$	Standard expression of the ratio of the ^{34}S ion with respect to the ^{32}S ion.
$\mu g/L$	Micrograms per liter.
Eh	Oxidation potential, log activity of e^1.
e^1	Electron.
(g)	Gaseous.
meq/L	Milliequivalents per liter.
mg/L	Milligrams per liter.
P_{CO_2}	Partial pressure of carbon dioxide.
PDB	PeeDee belemnite ^{13}C isotopic standard.
pCi/L	Picocuries per liter.
pH	Negative log activity of H^+.
ppm	Parts per million.
SI	Saturation index.
SMOW	Standard Mean Ocean Water ^{18}O and ^{2}H isotopic standard.
(s)	Solid.

GEOCHEMISTRY OF THE CAMBRIAN-ORDOVICIAN AQUIFER SYSTEM IN THE NORTHERN MIDWEST, UNITED STATES

By D.I. SIEGEL

ABSTRACT

Distributions of solutes in aquifers of Cambrian and Ordovician age were studied in Minnesota, Wisconsin, Iowa, Illinois, northwestern Indiana, and northern Missouri to determine the sources of solutes and the probable chemical mechanisms that control regional variations in water quality. This work is part of the Northern Midwest Regional Aquifer-System Analysis project, whose objective is to describe and model the regional hydrogeology of the Cambrian-Ordovician aquifer system in the study region. The data base used included more than 3,000 ground-water-quality analyses from all major aquifers, but especially from the St. Peter, Jordan, and Mount Simon Sandstones and their equivalents. Regional variations in the water chemistry of glacial drift and other sedimentary units that overlie the Cambrian-Ordovician aquifer system in recharge areas in Minnesota, Iowa, Wisconsin, and Illinois were also studied, but to a lesser degree.

The most important chemical variation in the aquifer is the change in water type from calcium-sodium-sulfate-bicarbonate water to sodium-calcium-sulfate-bicarbonate and sodium-chloride waters along the longest regional flow path from northwestern Iowa to the Illinois basin. Sodium predominance downgradient from the recharge area is probably related to mechanisms of ion exchange and shale-membrane filtration near the Illinois and Forest City basins.

The most striking aspect of the distribution of dissolved solids and carbon isotopic content of bicarbonate is the increase in concentration and isotopic enrichment from southwestern Wisconsin, southern Minnesota, and northwestern Illinois south toward Missouri. This trend is perpendicular to the present hydraulic gradient that trends from northwestern Iowa southeastward to the Illinois basin. The distribution of dissolved solids defines a "plume" of dilute water having a dissolved-solids concentration of about 500 milligrams per liter, compared with surrounding concentrations more than twice as large. Distribution of the isotopic content of oxygen ($\delta^{18}O$) and hydrogen (δD) in water closely parallels that of dissolved solids and shows covariance similar to modern meteoric water. The isotopic contents are more depleted (lighter) toward the south, perpendicular to the direction of current hydraulic gradients. The degree of depletion, compared with the isotopic content of modern recharge water, indicates that the plume and a significant fraction of the ground water in Iowa, northern Missouri, and possibly central Illinois may have originated as recharge during Pleistocene time.

Distributions of dissolved trace constituents in the aquifers probably are related to the proximity to mineralogic sources as well as chemical and hydraulic mechanisms. For example, concentrations of some constituents, such as cadmium and arsenic, are largest in the vicinity of the Dakota Formation in northwestern Iowa. Other constituents, such as beryllium and vanadium, have larger concentrations near the edge of the Forest City basin in southwestern Iowa and northwestern Missouri. Strontium and fluoride concentrations generally increase from north to south, which suggests the input of these trace constituents during the recharge events. However, concentrations of bromide, radium-226, and lithium show distribution patterns similar to the "plume" defined by dissolved solids and isotopes of water, suggesting dilution of concentrations of trace constituents by Pleistocene recharge. Concentrations of other constituents are partly controlled by aquifer temperature, such as silica in south-central Iowa, and solubility controls, such as barium in northeastern Illinois. Additional information on the chemical and mineralogical composition of the aquifer matrix and the isotopically lightest ground water is needed to evaluate the hypothesis of Pleistocene mixing before more quantitative studies can be done to evaluate the different proposed mechanisms that have controlled and modified the water chemistry over time. This study, however, indicates that the ground water in the region is thousands of years old. The study also indicates that the major chemical trends in the aquifers probably are related as much to paleohydrogeologic flow systems during Pleistocene time as to the present flow system, which may postdate the retreat of the last ice sheet about 12,000 years ago.

INTRODUCTION

Sandstone and dolomite strata of Cambrian and Ordovician age make up much of the sedimentary rocks overlying the Precambrian basement in the northern Midwest and form the major aquifer system of that area. In October 1978, the U.S. Geological Survey began a regional assessment of the Cambrian-Ordovician aquifer system in that area (Steinhilber and Young, 1979) as part of its national Regional Aquifer-System Analysis (RASA) program (Bennett, 1979). The major goals of the RASA program are to (1) gain an understanding of the hydrogeologic system in each region, including the nature of the hydrogeologic units, ground-water flow system, and chemical quality of the water, and (2) describe the regional interaction of components of the system, especially as affected by large-scale withdrawal of ground water. The latter goal is accomplished by constructing digital-computer models that simulate the ground-water flow system.

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PURPOSE AND SCOPE

This report describes the hydrologic and geochemical mechanisms that cause regional differences in groundwater quality in the northern Midwest. Other regional reports on the aquifer system are being published as chapters of U.S. Geological Survey Professional Paper 1405. They include chapter A, a summary of the Northern Midwest RASA (H.L. Young, U.S. Geological Survey, written commun., 1988), chapter B, which describes the regional hydrogeology and water quality (Young, in press), chapter C, which describes a regional three-dimensional ground-water model of the study area (Mandle and Kontis, in press), and chapter E, which describes a detailed three-dimensional ground-water flow model of the Chicago-Milwaukee area (H.L. Young and A.J. MacKenzie, U.S. Geological Survey, written commun., 1988).

The study covers about 161,000 mi^2 in northern Illinois, northwestern Indiana, Iowa, southeastern Minnesota, northern Missouri, and Wisconsin (fig. 1). The border of the study area delimits either the natural physical or hydrologic boundaries of the aquifer system or places where the aquifers are not used because of poor water quality. The northern boundary, from northwestern Iowa to northeastern Wisconsin, delineates the erosional edge of Cambrian rocks overlying crystalline basement rocks of Precambrian age. The Missouri River is a discharge line and forms the western and southwestern boundary. Beyond the eastern and southeastern boundary in Michigan, Illinois, and Indiana, water in the aquifer is too highly mineralized to be used. As a first approximation, the brine-saltwater interface at about 30,000 mg/L is assumed to be a minimal-flow boundary.

The primary subject of the study is the Cambrian- and Ordovician-age rocks that form the dominant aquifer system in the study area. However, because some wells developed in the Cambrian-Ordovician aquifer system are also open to the overlying carbonate rocks of the Silurian-Devonian aquifer, the latter, although only a minor aquifer regionally, is included in the study.

ACKNOWLEDGMENTS

I express my appreciation to many U.S. Geological Survey colleagues for their assistance in this study. Special thanks go to E.C. Alexander, Jr., and H.E. Wright, Jr., University of Minnesota, and to E.G. Perry, Jr., Northern Illinois University, for discussions on Pleistocene geology and environmental isotope geochemistry in the study area, and to the many geologists in State agencies with whom I had helpful conversations.

HYDROGEOLOGIC SETTING

The regional hydrogeology of the Cambrian-Ordovician aquifer system in the northern Midwest is summarized in Professional Paper 1405-B. The following is a brief regional synopsis of the structural, lithologic, and hydrologic features of the geologic formations in the study area and a description of the vertical discretization of geologic units into layers used in the regional flow model. Detailed accounts of the geology and hydrology of each of the States in the study area can be found in publications of State agencies and the U.S. Geological Survey referenced in Professional Paper 1405-B. The nomenclature used in this report was established for the Northern Midwest RASA (see Professional Paper 1405-B) and does not necessarily coincide with that previously accepted by the U.S. Geological Survey. It follows usage prevalent in the majority of the study area, or usage of a particular State, where appropriate.

The consolidated sedimentary rocks in the northern Midwest consist of sandstone, carbonate, and shale sequences that range in age from Precambrian to Cretaceous (fig. 2). They overlie the eroded surface of the Precambrian basement complex, which consists of crystalline igneous and metamorphic rocks. This basement complex forms the North American craton, the more permanent nucleus of the continent. The widespread sedimentary rocks were deposited in the midcontinental interior by a series of transgressions and regressions of the epeiric Sauk and Tippicanoe seas (King, 1959) as the craton subsided. Irregular subsidence resulted in the formation of the Illinois, Michigan, and Forest City basins, beginning in Early Cambrian time. The major structurally high areas, the Kankakee, Transcontinental, and Wisconsin arches, also began developing during Cambrian time (fig. 2). Cambrian and Ordovician rocks presently crop out or subcrop beneath Pleistocene drift and Holocene sediments in southeastern Minnesota, northeastern Iowa, northern Illinois, and southern Wisconsin. A band of Silurian and Devonian rocks subcrop beneath glacial drift along the trend of the Kankakee arch between Michigan and Illinois, along the eastern part of Wisconsin, and in northeastern Iowa (fig. 2). Mississippian and younger rocks border the major sedimentary basins and are present southwest and east of the Silurian rocks.

The Cambrian and Ordovician rocks in the northern Midwest have long been divided into rock-stratigraphic units on the basis of lithology and lateral continuity. For this study, the units were grouped into five aquifer layers and four confining layers on the basis of their hydrologic properties. Figure 3 is a generalized geologic

FIGURE 1.—Location and general features of the Northern Midwest Regional Aquifer-System Analysis area.

section from Missouri to Wisconsin, which shows this hydrogeologic grouping. The first and deepest hydrogeologic unit, the Mount Simon aquifer (aquifer layer 1), is composed mainly of the Mount Simon Sandstone and its equivalents. This basal sandstone rests on the Precambrian basement complex in much of the study area, but on older Precambrian red clastic rocks in Minnesota and western Wisconsin. The latter are included in aquifer layer 1. The Mount Simon Sandstone is a marine, fine- to coarse-grained conglomeratic sandstone and ranges in thickness from less than 100 ft in Minnesota and Wisconsin to more than 2,500 ft in the northern part of the Illinois basin. In the northern part of the area it is overlain by shale, dolomitic sandstone, siltstone, and dolomite of the Eau Claire Formation, which constitutes a regional confining unit. The Eau Claire is predominantly a fine-grained sandstone in Wisconsin but has varying amounts of shale. The Eau

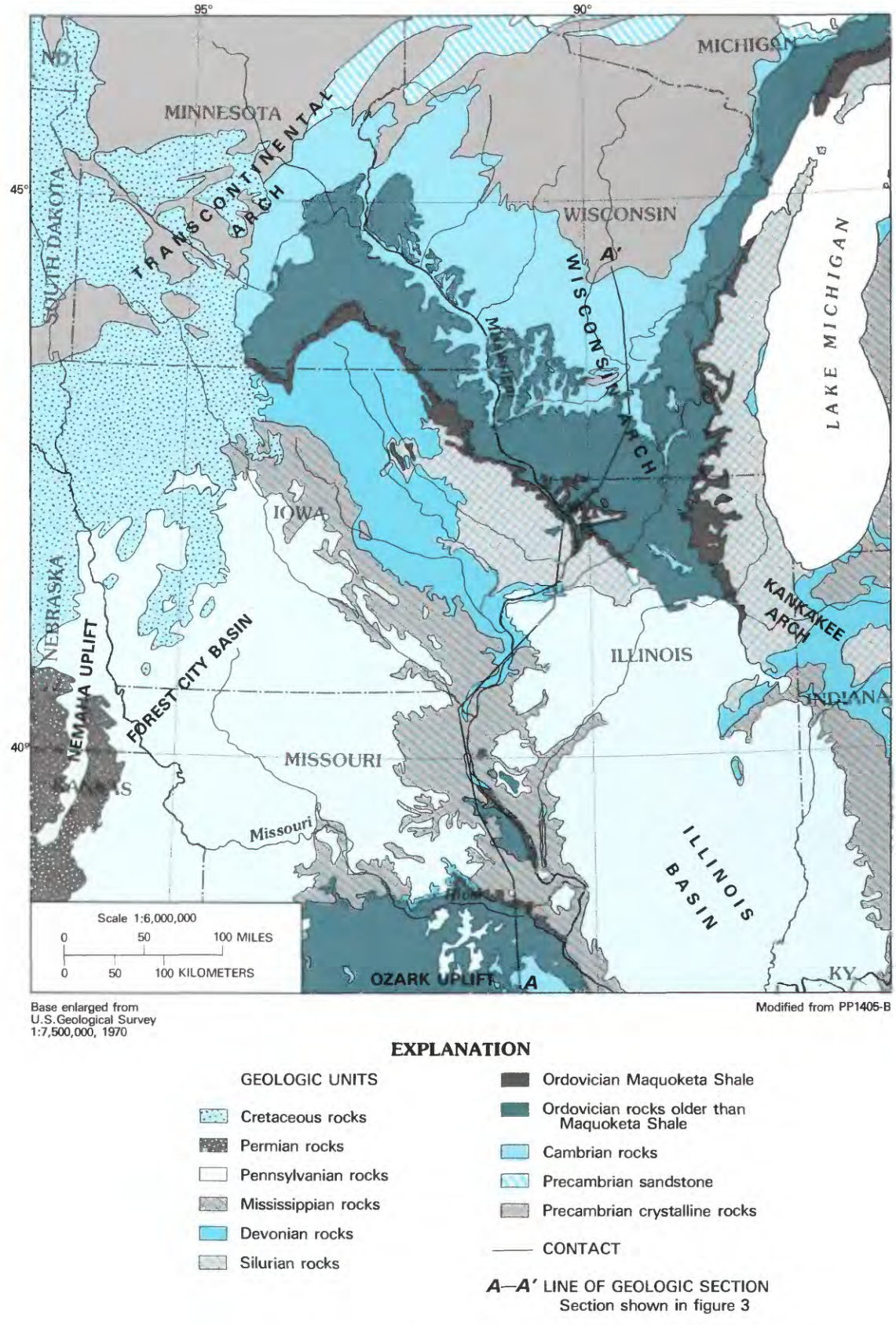
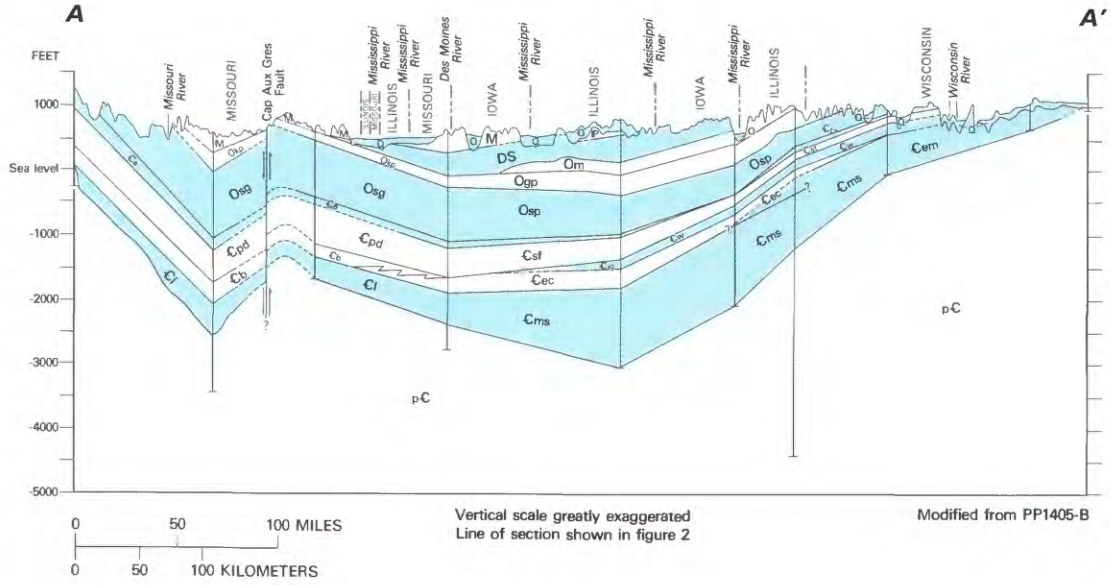


FIGURE 2.—General bedrock geology of the northern Midwest. (Modified from Young, in press.)



EXPLANATION

CORRELATION OF GEOLOGIC UNITS AND AQUIFER LAYERS (shown in blue)

Designated aquifer layers			
5	Q	Pleistocene	QUATERNARY
	P		PENNSYLVANIAN
	M		MISSISSIPPIAN
4	DS		DEVONIAN and SILURIAN
	Om, Okp, Ogp, Osg, Osp	Upper Ordovician; Middle Ordovician; Middle and Lower Ordovician	ORDOVICIAN
3			
2	Ce, Cj, Csf, Cst, Cpd, Cig, Cw, Cb, Cec, Cem	Upper Cambrian	CAMBRIAN
1	Cl, Cms		
	pC		PRECAMBRIAN

DESCRIPTION OF UNITS (aquifers shown in blue)

- Q — Pleistocene deposits
- P — Pennsylvanian rocks
- M — Mississippian rocks
- DS — Devonian and Silurian rocks
- Om — Maquoketa Shale
- Okp — Kimmswick, Decorah, and Plattin Formations
- Ogp — Galena Dolomite, Decorah and Platteville Formations
- Osg — St. Peter Sandstone; Smithville Formation; Powell, Cotter, and Jefferson City Dolomites; Roubidoux Formation; Gasconade Dolomite
- Osp — St. Peter Sandstone, Prairie du Chien Group
- Ce — Eminence Dolomite
- Cj — Jordan Sandstone
- Csf — St. Lawrence Formation, Potosi Dolomite, Franconia Formation
- Cst — St. Lawrence Formation, Tunnel City Group in Iowa and Wisconsin
- Cpd — Potosi and Derby-Doerun Dolomites, Davis Formation
- Cb — Bonneterre Formation
- Cl — Lamotte Sandstone
- Cem — Elk Mound Group, undifferentiated—Where differentiated, consists of Ironton and Galesville Sandstone Members of the Wonewoc Sandstone, Eau Claire Formation, Mount Simon Sandstone in Iowa and Wisconsin
- Cig — Ironton and Galesville Sandstones
- Cw — Wonewoc Sandstone in Iowa and Wisconsin
- Cec — Eau Claire Formation
- Cms — Mount Simon Sandstone
- pC — Precambrian crystalline rocks

CONTACT—Dashed where approximate

FAULT—Arrows indicate relative vertical movement

FIGURE 3.—Geologic section from Missouri to Wisconsin. (Modified from Young, in press.)

Claire is not strongly confining in much of Wisconsin and is hydrologically connected with the underlying Mount Simon Sandstone and the overlying Ironton and Galesville Sandstones, except toward the south where the upper part becomes more shaly. To the south in Missouri, the Eau Claire grades into dolomite of the Bonneterre Formation. In northern Illinois, the lower part of the Eau Claire, the Elmhurst Sandstone Member, is included in aquifer layer 1, which is locally termed the "basal sandstone aquifer." In south-central Minnesota, the Eau Claire Formation consists, in part, of glauconitic "greensands."

Aquifer layer 2, the Ironton-Galesville aquifer, is the combined Ironton and Galesville Sandstones and, in Iowa and Wisconsin, the equivalent Wonewoc Formation. It is generally less than 100 ft thick but exceeds 200 ft in the Illinois basin. It consists of calcareous to dolomitic sandstone in Minnesota, Wisconsin, and northern Illinois. The aquifer layer is absent in southern Illinois and is thin or absent and grades into carbonate rocks of the lower part of the Davis Formation in southwestern Iowa and Missouri. Shaly sandstones of the Franconia Formation and limestone and dolomite of the St. Lawrence Formation overlie and confine the Ironton-Galesville aquifer in the north. The southern equivalent of the St. Lawrence-Franconia confining unit is the upper Davis Formation through Potosi Dolomite interval.

The composition of the third aquifer layer varies with its geographic location. In most of the study area it consists of, from oldest to youngest, the Jordan Sandstone, the overlying Prairie du Chien Group, and the St. Peter Sandstone. In Missouri, the Gasconade Dolomite-Smithville Formation sequence is a general equivalent and replaces the Prairie du Chien Group. Also, the Jordan Sandstone is replaced by the Eminence Dolomite in Missouri and all but the extreme northwestern part of Illinois. These formations are generally in hydrologic connection. They are treated as a single unit because fractures commonly penetrate through the Prairie du Chien Group.

The Jordan Sandstone is a coarse- to medium-grained orthoquartzite to dolomitic sandstone in Minnesota, Wisconsin, and Iowa, grading into sandy dolomite and dolomite in southern Iowa, northern Missouri, and all but the extreme northwestern part of Illinois. The Prairie du Chien Group consists of fossiliferous dolomite and limestone interbedded with thin, discontinuous beds of sandstone, siltstone, and shale. Aquifer layers 1 and 3 generally range from 200 to 600 ft in thickness in the northern half of the study area but thicken to more than 1,500 ft in the Illinois basin. The St. Peter Sandstone is a laterally persistent clean and friable orthoquartzite, generally 100 to 200 ft thick except locally in northern Illinois, where thickness exceeds 700 ft upon pre-St. Peter karstic topography.

The Maquoketa Shale forms a very effective confining unit above aquifer layer 3 over much of the study area. The Maquoketa consists of thick pyritic shales except in western Iowa and Minnesota, where the shales grade into interbedded dolomitic limestones and shaly dolomites that provide a hydraulic connection with overlying and underlying carbonates. The shaly dolomites, which make up the Galena Dolomite and Decorah and Platteville Formations or equivalents, are generally of low permeability where overlain by the Maquoketa and are included as part of the confining unit. The base of the confining unit is the Glenwood Formation, which consists generally of shale and silty, shaly sandstone. Extensive phosphatic beds are present within the Maquoketa in Iowa. The Cambrian-Ordovician aquifer system is further confined by thick sequences of younger Paleozoic rocks south of the outcrop of the Maquoketa Shale.

Aquifer layer 4 consists of the carbonate rocks of the Silurian through Middle Devonian and is termed the Silurian-Devonian aquifer for this study. The rocks are dominantly thick- to thinly bedded dolomites, limestones, and shales that are hydraulically connected by fractures. Where not eroded, they generally range in thickness from 200 to 500 ft, but they are more than 1,000 ft thick in the Illinois basin. The excellent confinement of the Maquoketa Shale, which separates aquifer layer 4 from aquifer layer 3, limits the potential of water in aquifer layer 4 to affect the chemistry of water in the Cambrian-Ordovician aquifer system. However, the opposite may be true where the Maquoketa is mainly a fractured carbonate. The very thick sequence of younger consolidated rocks from the Upper Devonian through the Pennsylvanian contains little aquifer material and, for the purposes of this study, is considered to be a confining unit between aquifer layers 4 and 5. In Iowa, the Mississippian is classified as a separate aquifer (Horick and Steinhilber, 1973).

Aquifer layer 5 consists of the combined Holocene surficial deposits, Pleistocene glacial drift, or Cretaceous rocks that form the land surface over most of the study area. This layer directly overlies the units of the Cambrian-Ordovician aquifer system in much of the Cambrian-Ordovician outcrop areas in Minnesota, Iowa, Wisconsin, and Illinois. Most drift is calcareous because of carbonate minerals derived from the glacial erosion of Paleozoic limestones and dolomites in Manitoba and Michigan and within the study area. Except for the Driftless Area of southwestern Wisconsin and adjacent small areas in Illinois and Iowa, the entire study area was glaciated during the Pleistocene. Cretaceous rocks that overlie the Cambrian and Ordovician rocks in western Minnesota and Iowa consist of varicolored marine shales, siltstones, and lignitic sandstones of the Dakota Formation, which commonly contains disseminated pyrite in its basal part.

The ground-water reservoir is recharged by infiltration of precipitation through the soil into the underlying rock. Because glacial deposits are the surficial rocks in most of the northern Midwest, they receive most of the initial recharge. Aquifer layers 1 through 4 also are recharged by infiltration of precipitation where they crop out at the land surface, such as in the Driftless

Area. These aquifers also receive recharge by vertical seepage across confining beds, where they subcrop beneath aquifer layer 5 and where they are penetrated by buried bedrock valleys eroded by glacial meltwater streams during Pleistocene time. Both field observation and steady-state simulation of the ground-water flow system (Mandle and Kontis, in press) indicate that vertical head gradients in the Cambrian-Ordovician aquifers (aquifer layers 1 through 3) are generally upward where overlain by the Maquoketa Shale in Iowa, Illinois, and Wisconsin (fig. 4). Vertical head gradients are downward in the Cambrian-Ordovician outcrop areas in much of south-central Minnesota, south-central Wisconsin, and northern Iowa.

Ground water flows from topographically high recharge areas to low discharge areas. Most of the ground water in aquifer layer 5 moves within local flow systems of a few miles in length and discharges to small first- and second-order tributaries of the major rivers. Ground-water movement in the unconfined parts of the Cambrian-Ordovician aquifer system is similar, but the flow systems are larger and discharge is toward the major river valleys. Figure 5 is a representation of the original predevelopment potentiometric surface of aquifer layer 3, for which the most data are available, and is generally representative of the predevelopment potentiometric heads in the lower aquifer layers. The more localized flow systems in the unconfined areas are shown by the topographic control and steeper gradient of the contours there. In the confined areas, ground water moves toward the Illinois and Michigan basins but can discharge only as upward leakage across confining units. Thus the rate of lateral flow into the basins is greatly decreased. The longest flow paths in the aquifer system (more than 300 mi) extend from recharge areas in northwestern Iowa to the center of the Illinois basin (fig. 5). Shorter flow paths (less than 50 mi) in the northern part of the area extend from recharge areas: in central Minnesota to the Minnesota River; in central Wisconsin, central Minnesota, northeastern Iowa, and northwestern Illinois to the Mississippi River; and in eastern Wisconsin and northeastern Illinois toward Lake Michigan. Penetration of aquifer layers by the Mississippi River valley during the Pleistocene causes the flow system in the northern part of the study area to have shorter flow paths. This effect of the Mississippi River is most pronounced in aquifer layers 3 and 4 and is less pronounced in layers 1 and 2. For example, flow in layer 3 discharges to the Mississippi River as far south as about 50 mi south of the Wisconsin-Illinois State line, but the direct influence of the river on aquifer layer 1 extends only as far as the Minnesota-Iowa State line. Aquifer layer 4 discharges toward the Mississippi River downstream from northeastern Iowa.

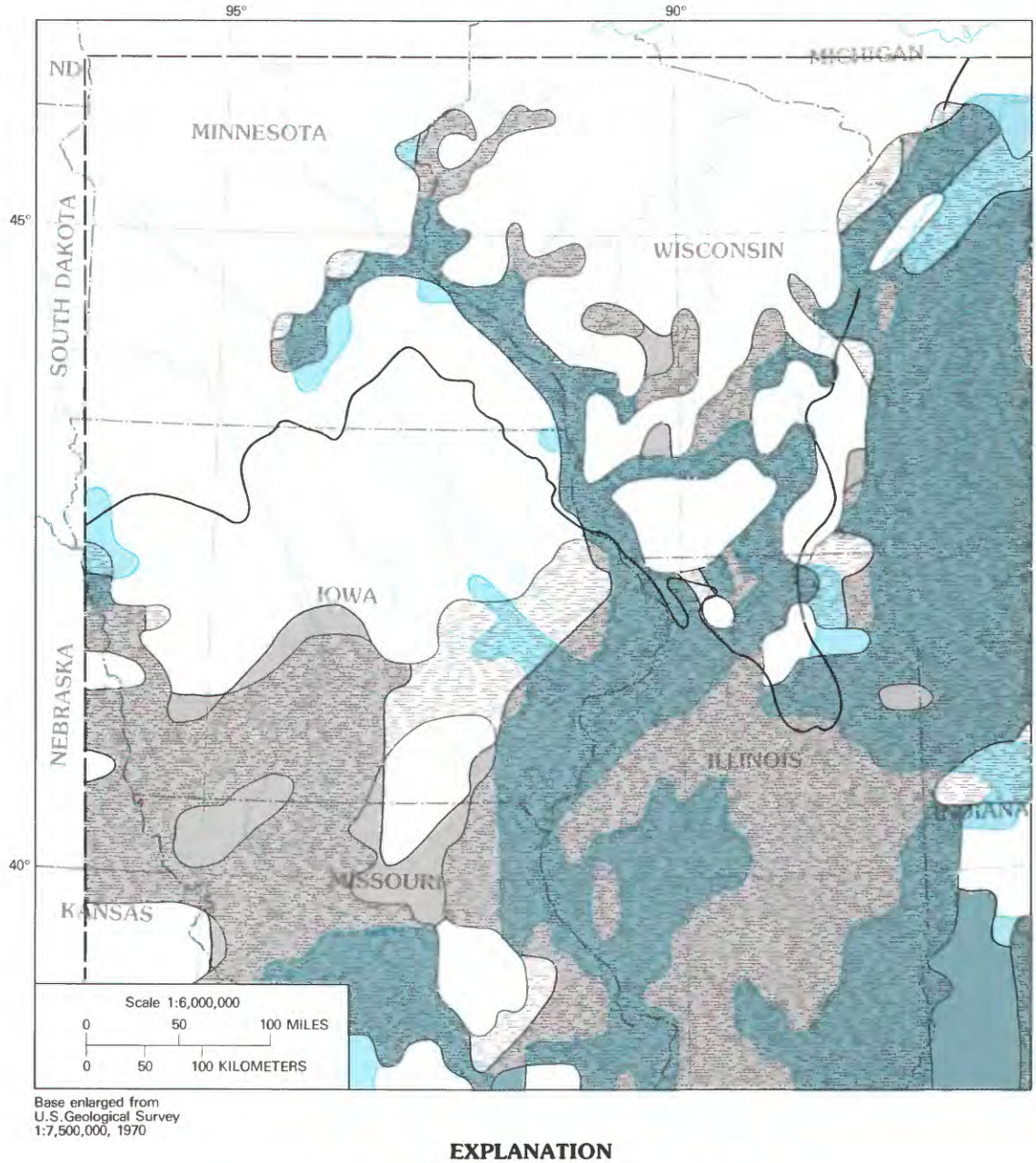
GEOCHEMISTRY

METHODS OF INVESTIGATION

The interpretation of regional ground-water quality is based on a synthesis of more than 3,000 chemical analyses of ground water available from the U.S. Geological Survey WATSTORE (Water Data Storage and Retrieval System) data base, publications of State and Federal agencies, and scientific journals. Published descriptions of the water chemistry of parts of the Cambrian-Ordovician aquifer system were reviewed, particularly in the following references (grouped by State): Minnesota—Winter (1974), Norvitch and others (1973), and Maderak (1965); Wisconsin—Kammerer (1981), Holt and Skinner (1973), and Ryling (1961); Iowa—Horick and Steinhilber (1978); Missouri—Feder (1979) and Gann and others (1971, 1973); and Illinois—Larson (1963), Gibb and O'Hearn (1980), and Schicht and others (1976). Description and analyses of brines in Cambrian-Ordovician aquifer units were obtained from Meents and others (1952), Graf and others (1965, 1966), Bond (1972), and the files of the Indiana and Michigan Geological Surveys and the Illinois State Water Survey.

Mean concentrations are used where multiple analyses are available. In general, analyses that did not balance electrochemically within 5 percent were deleted from the data base. Some partial analyses of brines include data for only dissolved solids and chloride, but these analyses were used to complete the areal distribution of dissolved solids along the southeastern boundary of the study area. Thus, the lines of equal concentration there should be considered approximate.

One hundred and sixty-four ground-water samples were collected for the study during the period 1980–82 to determine the concentrations of trace constituents and radiochemical species as well as stable isotope ratios. Seventy-five samples were collected to determine the isotopic composition of oxygen and hydrogen in the ground water and of carbon in bicarbonate. The isotopic composition of sulfur in sulfate was determined for selected samples. Field pH, alkalinity, and temperature of the water were measured at critical sample locations along ground-water flow paths to enable calculation of chemical species at equilibrium. Analyses were made using methods described in American Public Health Association (1980) and Skougstad and others (1979). Isotopic composition of water, carbon in inorganic carbon, and sulfur in sulfate was determined by standard methods. By convention, the isotopic variations are expressed as $\pm \delta$ values in parts per thousand (permil) differences in the measured isotopic ratios in a sample and in appropriate standards: Standard Mean Ocean Water (SMOW) for oxygen ($\delta^{18}O$) and

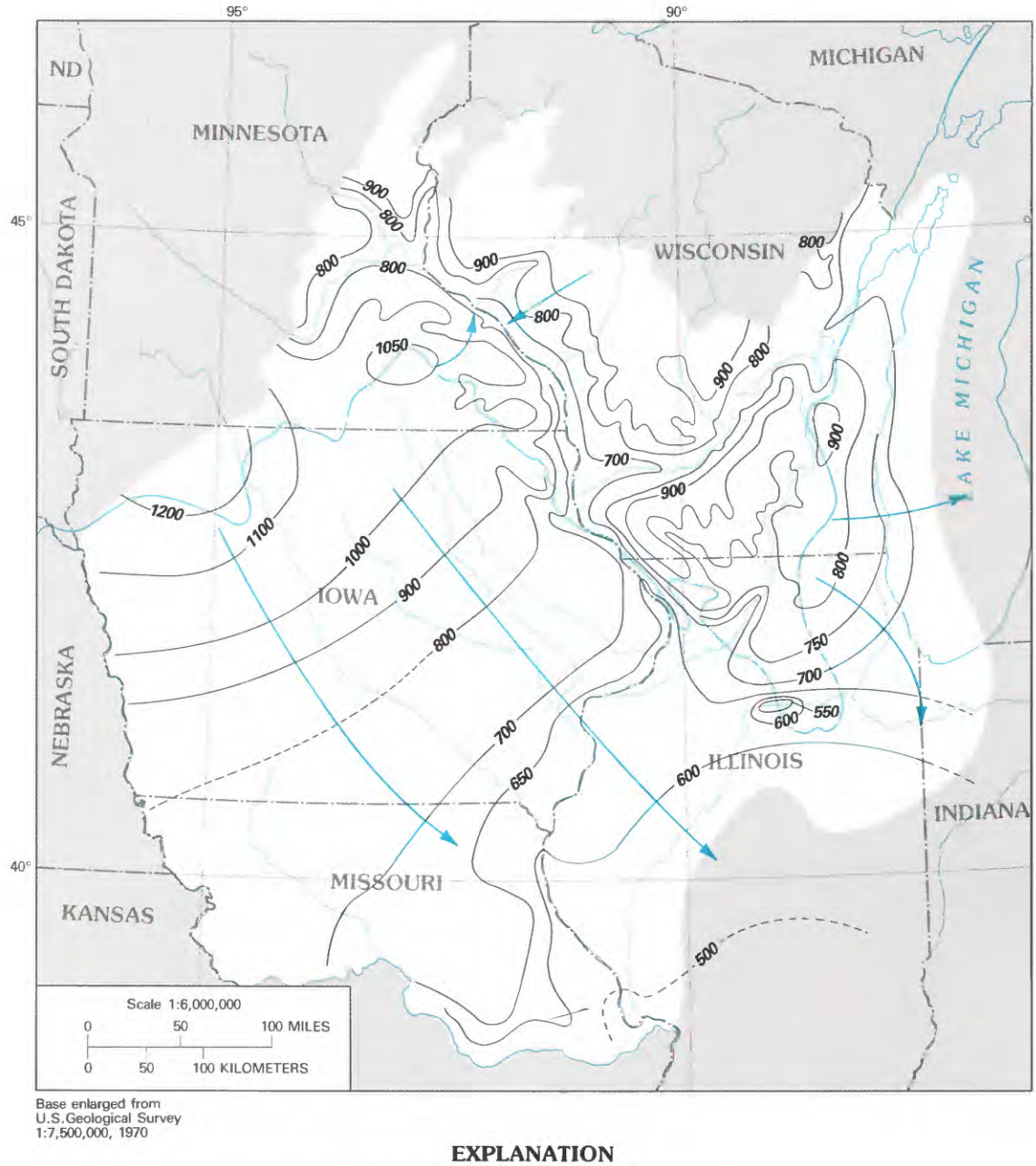


EXPLANATION

SIMULATED DISCHARGE AREA—Shows area where the ground-water flow model indicates upward flow from the aquifer layer for predevelopment conditions

- Aquifer layer 3
- Aquifer layer 2
- Aquifer layer 1
- NORTHERN BOUNDARY OF MAQUOKETA SHALE
- BOUNDARY OF GROUND-WATER FLOW MODEL

FIGURE 4.—Simulated predevelopment discharge areas for aquifer layers 1, 2, and 3. (Modified from Mandle and Kontis, in press.)



EXPLANATION

600 — POTENTIOMETRIC CONTOUR—Shows altitude of predevelopment potentiometric surface for aquifer layer 3. Dashed where approximate. Interval, in feet, is variable. Datum is sea level

DIRECTION OF GROUND-WATER MOVEMENT

NORTHERN BOUNDARY OF MAQUOKETA SHALE

FIGURE 5.—Approximate predevelopment potentiometric surface for aquifer layer 3. (Modified from Young, in press.)

hydrogen (δD) in water, Canyon Diablo troilite for sulfur (δ^{34}S), and PeeDee belemnite (PDB standard) for carbon (δ^{13}C). Results of the analyses for the study are given in tables 1, 2, and 3 (at the end of the report). Figure 6 shows the locations of the wells in aquifer layers 1, 3, and 5 sampled for this study and the locations of selected wells in aquifer layers 1 and 3 with WATSTORE and published analyses. Data distribution for aquifer layer 5 was dense throughout the recharge areas of Wisconsin, Minnesota, Iowa, and Illinois; consequently, the locations of only new data for this aquifer layer are shown in figure 6. In subsequent figures that show areal distribution of solutes, only locations of data collected during this study are plotted.

Maps showing the areal distribution of solutes were derived from a composite of data from aquifer layers 1 and 3, for which there is significant regional coverage. It is recognized that because the lithologies of these layers are different, the chemistry may be different. However, the composited data are used as a first approximation in describing the regional chemical patterns for the following reasons:

1. The chemical quality of ground water in aquifer layers 1 and 3 is essentially the same in outcrop areas in Minnesota, Wisconsin, Illinois, and Iowa.
2. In the major confined areas in Iowa, Missouri, Illinois, and eastern Wisconsin, all but a few data points are from aquifer layer 3 (fig. 6).

The maps of areal solute distribution in this report, therefore, represent mainly aquifer layer 3 in the confined part of the aquifer and aquifer layers 1, 2, and 3 in outcrop areas. Where data distribution was dense, maps of concentrations of dissolved solids and particular ions were prepared, in part, by data-management techniques described by Kontis and Mandle (1980).

The detailed evaluation of the water quality of the Cambrian-Ordovician aquifer system was restricted to aquifer layers 3 and 5, for which the areal distribution of data was considered sufficient to evaluate regional trends and variations in concentrations of major dissolved constituents. In most of Wisconsin and north-central Illinois, aquifer layers 1, 2, and 3 are unconfined and are hydraulically connected; thus water quality in those aquifer layers is probably similar. All statistical calculations were made using computer methods of the Statistical Analysis System (SAS Institute, Inc., 1979).

DISSOLVED SOLIDS

The chemical quality of the water in the Cambrian-Ordovician aquifer system varies widely from recharge areas to discharge areas. Dissolved-solids concentrations range from less than 200 mg/L in the outcrop areas in Wisconsin and southeastern Minnesota to more than 200,000 mg/L in the Illinois basin. The 500-mg/L line of equal dissolved solids (isopleth) in figure 7 roughly outlines the extent of the predominantly unconfined flow systems in the northern half of the study area. The 500-mg/L line also is approximately parallel to the outcrop pattern of the Maquoketa Shale in Illinois and Wisconsin, the major confining unit between the Cambrian-Ordovician aquifer system and the overlying units. Dissolved solids generally increase in the direction of the hydraulic gradient.

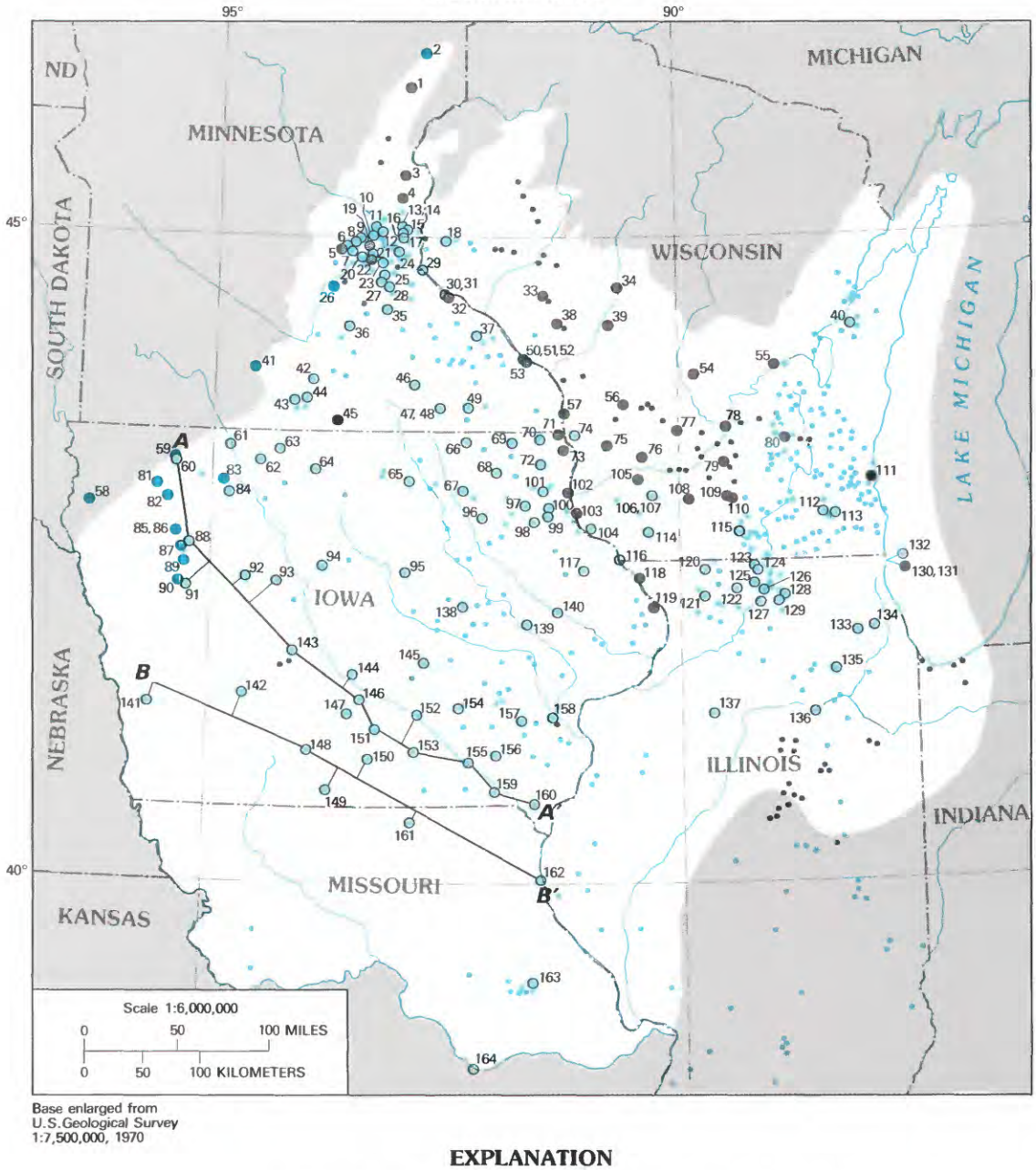
In Iowa, the 500-mg/L line shows a plume-shaped zone of fresher water trending from the northeast to the south-southwest across the Maquoketa Shale outcrop (figs. 2, 7). In both Iowa and Missouri, the gradient toward increasing dissolved solids (fig. 7) varies but is generally perpendicular to the direction of the hydraulic gradient shown in figure 5. For example, along the flow path that is approximately coincident with geochemical section A–A' (fig. 6), dissolved solids decrease from 2,400 mg/L at well 59 (Hibbing, Iowa) to 440 mg/L at well 144 (Altoona, Iowa) in the south-central part of the State. Dissolved solids increase southeast of Altoona to more than 100,000 mg/L in the Illinois basin (fig. 7). Dissolved solids normally increase along the hydraulic gradient because as the residence time of water in the aquifer increases, the water has a longer period of interaction with the rock minerals (Chebotarev, 1955; Back and Hanshaw, 1965). The discordance of increasing dissolved-solids distribution with the hydraulic gradient in the central part of the study area is an abnormal occurrence and poses a major geochemical anomaly that is examined and discussed in a later section, "Hypothetical Geochemical Models."

CHEMICAL CLASSIFICATION

Water chemistry in the aquifer system was classified by calculating percentages of equivalents per liter for major cations and anions. Maps were prepared showing the areal distribution of water types according to the method described by Back (1966). These maps were used to relate water chemistry to lithologic changes in aquifers and to evaluate possible geochemical and hydrologic processes that control the evolution of water chemistry along and across the hydraulic gradients.

A wide range of water types is present in the Cambrian-Ordovician aquifer system. Water recharged to the system through aquifer layer 5 ranges from a Ca-Mg-HCO_3 type in the northern part of the area to a Ca-Na-SO_4-HCO_3 type in northwestern Iowa and southwestern Minnesota (fig. 8). Dissolved solids in aquifer layer 5 range from less than 300 to more than 2,000 mg/L in Minnesota, Wisconsin, and northwestern Iowa.

Water chemistry in the Cambrian-Ordovician aquifer system in recharge areas in Minnesota, Wisconsin, Illinois, and Iowa is very similar to that in the overlying



Base enlarged from
U.S.Geological Survey
1:7,500,000, 1970

EXPLANATION

WELL WITH CHEMICAL ANALYSIS—Sample collected during this study. Numbers refer to tables 1, 2 and 3

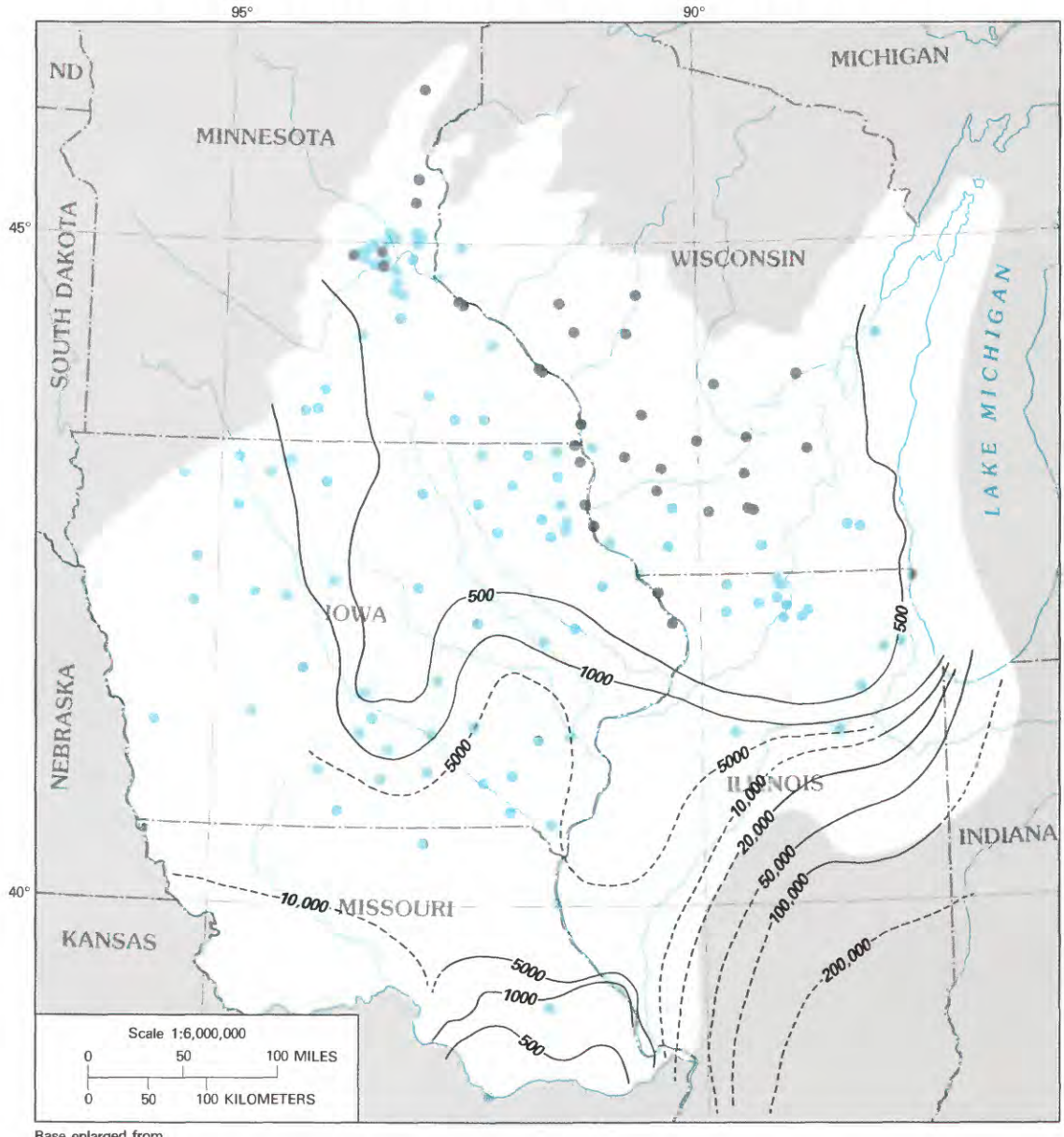
- 39 — Mount Simon aquifer
- 65 — St. Peter-Prairie du Chien-Jordan aquifer
- 45 — Silurian-Devonian aquifer
- 89 — Drift or Cretaceous aquifer

WATSTORE and published data

- Mount Simon aquifer
- St. Peter-Prairie du Chien-Jordan aquifer

B——*B*′ LINE OF GEOCHEMICAL SECTION—Sections shown in figures 17 and 18

FIGURE 6.—Location of wells with water-quality analyses and location of geochemical sections *A-A*′ and *B-B*′.



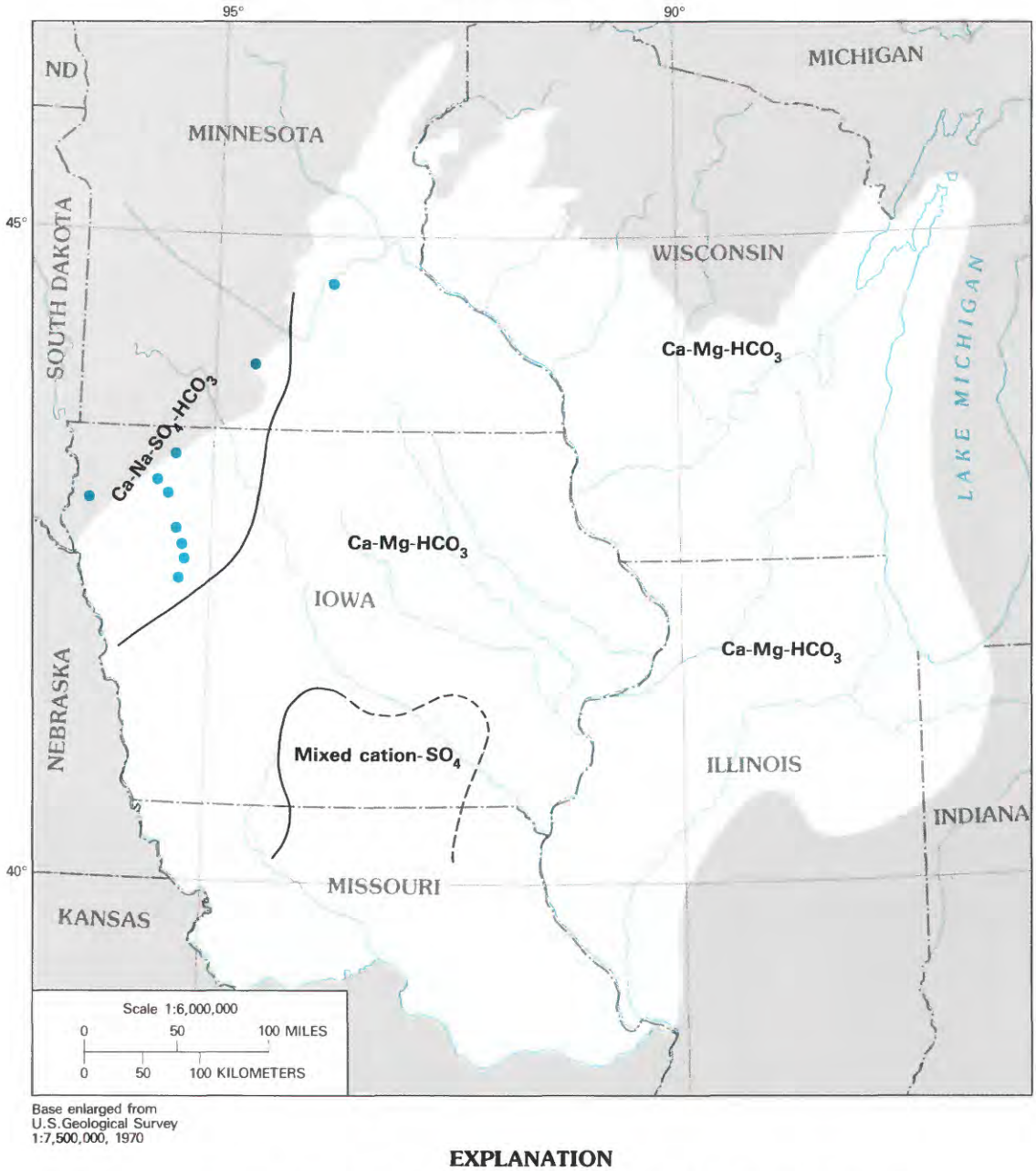
EXPLANATION

—500--- LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATION—Dashed where approximate. Interval, in milligrams per liter, is variable

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

- Open to aquifer layer 1
- Open to aquifer layer 3

FIGURE 7.—Dissolved-solids distribution in aquifer layers 1 and 3. (Modified from Young, in press.)

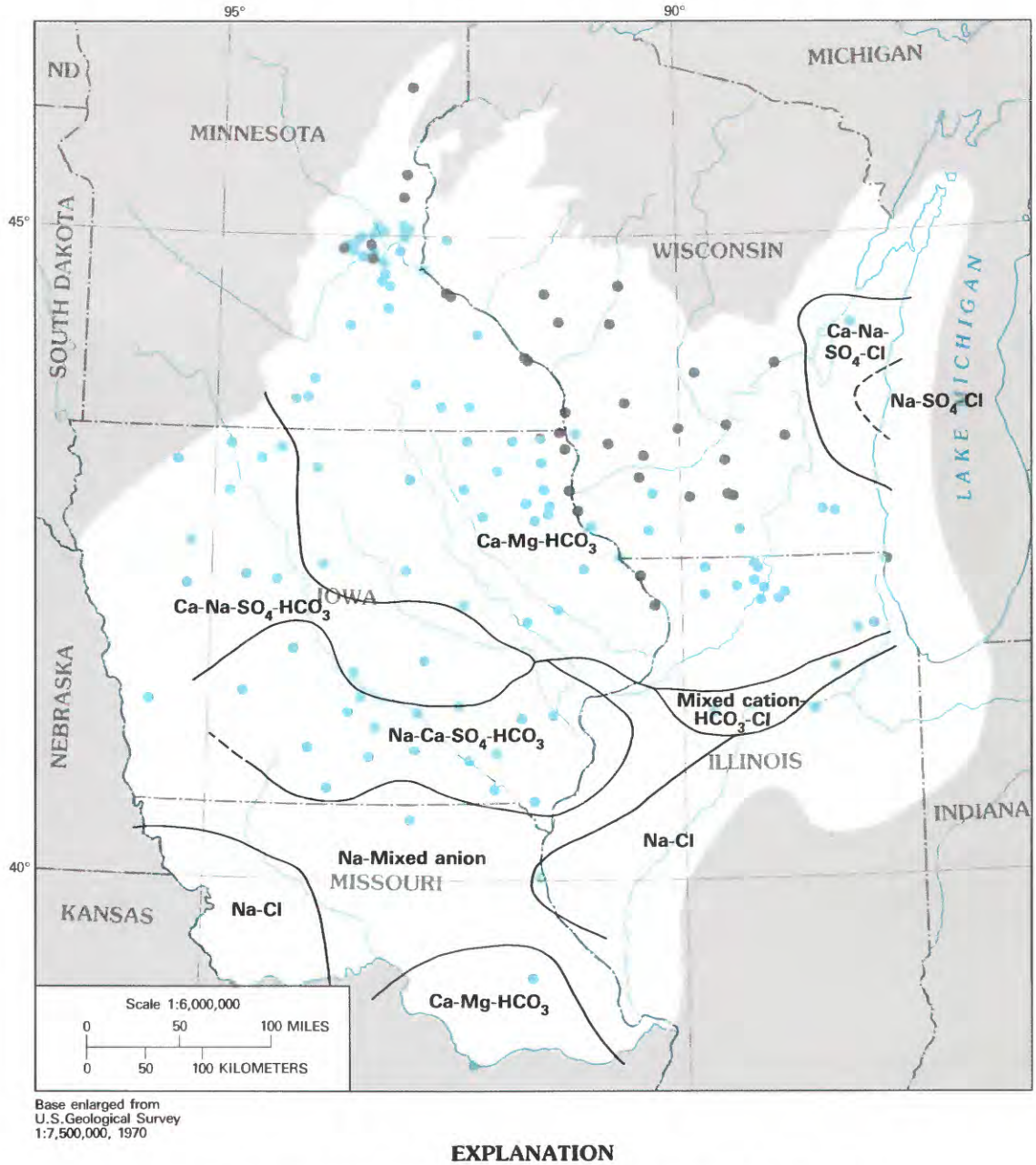


EXPLANATION

HYDROCHEMICAL FACIES ZONE BOUNDARY—Dashed where approximate

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY
Open to aquifer layer 5

FIGURE 8.—Hydrochemical facies of ground water in aquifer layer 5.



EXPLANATION

HYDROCHEMICAL FACIES ZONE BOUNDARY—Dashed where approximate

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

- Open to aquifer layer 1
- Open to aquifer layer 3

FIGURE 9.—Hydrochemical facies of ground water in aquifer layers 1 and 3.

aquifer layer 5. Water in both aquifer layers 1 and 3 in the northern part of the study area is a Ca-Mg-HCO_3 type, but water in northwestern Iowa and southwestern Minnesota is a Ca-Na-SO_4-HCO_3 type (fig. 9).

The most pronounced geochemical changes occur in the confined parts of the aquifer system. Along flow paths confined by the Maquoketa Shale from eastern Wisconsin east toward the Michigan basin, water chemistry changes from Ca-Mg-HCO_3 to Ca-Na-SO_4 and Na-Cl-SO_4 waters, a transition to the Ca-SO_4 and Ca-Cl_2 types of brines in the Michigan basin (fig. 9). From northern Illinois to central Illinois also, the water changes from a Ca-Mg-HCO_3 type to a Na-Cl type similar to the brines in the Illinois basin.

The largest variability in water chemistry occurs along confined flow paths in the aquifer system from northwestern Iowa to central Illinois. Water type evolves along the hydraulic gradient to the Illinois basin from the Ca-Na-SO_4-HCO_3 water that typically is present in the Dakota Formation and overlying drift of aquifer layer 5 to Na-Ca-SO_4-HCO_3, Na-anion (no dominant anion), and Na-Cl water. This change occurs in aquifer layer 3 even though the dissolved-solids concentration decreases along the central part of the flow path. South of the Na-Ca-SO_4-HCO_3 facies in south-central Iowa, the water is of either the Na-Cl or the Na-anion type.

Few generalizations can be made about variations in water types in aquifer layers 1 and 2 or with depth in individual aquifer layers because of the scant data on the areal distribution of the major solutes in aquifer layers 1, 2, and 4. Saline water is present in aquifer layer 1 at several locations along the Mississippi River valley. Chemical data from municipal wells in aquifer layer 1 at Red Wing, Minn. (fig. 1), indicate that the water type changes from Ca-Mg-HCO_3 to Na-Cl at depth (table 4). This change in water quality with depth can occur with increases of dissolved solids from less than 500 to several thousand milligrams per liter (Hall and others, 1911; Thiel, 1944). A similar increase in dissolved solids and change in water type in aquifer layer 1 occurs near Lake Michigan, where high salinity makes aquifer layer 1 nonpotable in some places. Samples collected from aquifer layer 1 in a deep test well drilled for this study at Zion, Ill. (fig. 1), illustrate the increase in salinity with depth (table 4). This increase in salinity is also found in aquifer layer 1 within the Illinois basin in central Illinois and eastern Indiana (Meents and others, 1952; R.J. Shedlock, U.S. Geological Survey, written commun., 1983). These data plus scant data from wells in south-central Iowa (fig. 6) suggest that the Na-Cl water type in Iowa in aquifer layer 1 may be present much farther up the hydraulic gradient than in aquifer layer 3.

TABLE 4.—*Selected chemical data that show variation of water quality with depth in aquifer layer 1*

[Results in milligrams per liter, except as indicated. Map number is location in figure 6]

	Well name			
	USGS test well Zion, Illinois		Red Wing no. 1 west, Minnesota	Red Wing no. 3, Minnesota
Map number	130	131	30	32
Date of collection	12–10–80	1–14–81	2–12–80	2–13–80
Field pH (standard units)	7.2	—	7.4	7.4
Dissolved solids, residue on evaporation	2,800	58,300	410	1,110
Calcium, Ca	311	1,000	64	80
Magnesium, Mg	39	930	27	44
Sodium, Na	440	15,000	53	250
Potassium, K	16	270	6.8	7.9
Sulfate, SO_4	1,300	1,400	34	36
Chloride, Cl	370	37,000	80	550
Interval sampled (feet below land surface)	1,775–1,935	3,120–3,475	350–630	385–770

GEOCHEMICAL PROCESSES

CALCIUM-MAGNESIUM-BICARBONATE WATER TYPE

The major geochemical and hydrologic processes that cause the changes in dissolved-solids concentrations and water types in the Cambrian-Ordovician aquifer system can be evaluated at different levels of complexity. Qualitatively, the Ca-Mg-HCO_3 water in all layers probably reflects the dissolution of calcite ($CaCO_3$) and dolomite [$CaMg(CO_3)_2$] in the aquifer matrix and overlying drift. The chemical reactions involved in the dissolution of carbonate minerals are a combination of hydrolysis and dissociation. The major source of acidity in the northern part of the study area is probably carbon dioxide in the atmosphere and soil. The pertinent reactions for the dissolution of calcite by carbonic acid may be expressed by

$$CO_{2(g)}+H_2O=H_2CO_3, \quad (1)$$

$$H_2CO_3=H^++HCO_3^-, \quad (2)$$

$$HCO_3^{-1}=H^++CO_3^{2-}, \quad (3)$$

and

$$(Ca_{1-x}Mg_x)CO_{3(s)}+2H^+=(1-x)Ca^{2+}+xMg^{2+}+2HCO_3^-. \quad (4)$$

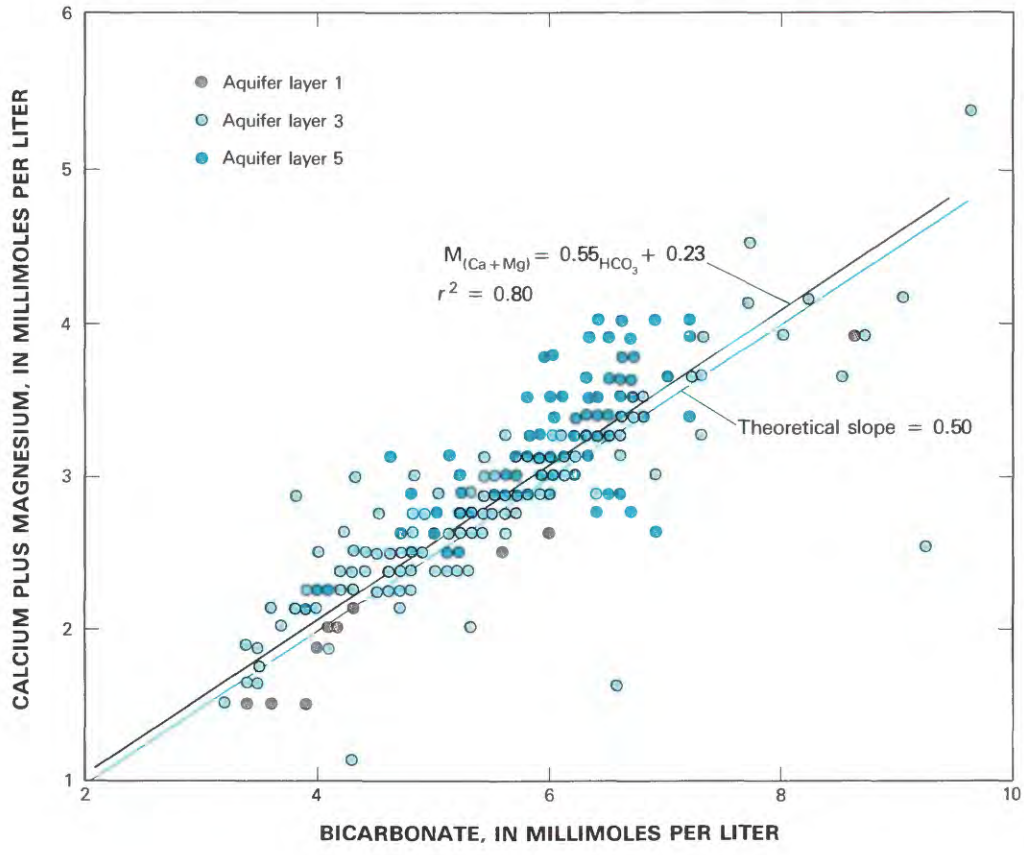


FIGURE 10.—Correlation of calcium plus magnesium and bicarbonate in ground water from the Ca-Mg-HCO_3 facies in aquifer layers 1, 3, and 5 in the northern outcrop area of the Cambrian-Ordovician aquifer system.

Combining equations 1 through 4 and neglecting CO_3^{2-} because of the near-neutral pH conditions in the aquifer,

$$(Ca_{1-x}Mg_x)CO_{3(s)} + H_2O + CO_{2(g)} = (1-x)Ca^{2+} + xMg^{2+} + 2HCO_3^- . \quad (5)$$

Little information exists on the mole fractions of calcium and magnesium in the major carbonate minerals in either the Cambrian-Ordovician aquifer system or the overlying units in aquifer layer 5. A large number of rock analyses of carbonate units from Minnesota obtained from the Cambrian-Ordovician aquifer system are available—for example, Prokopovich and Schwartz (1956), Thiel and Stauffer (1947), and Stauffer (1950)—and show that there is both wide vertical and wide areal variability in the CaO and MgO content of the aquifer carbonate rocks and confining units. It is likely that there is a similar variability in calcium and magnesium content of the carbonate rocks elsewhere in the study area.

However, if dissolved calcium, magnesium, and bicarbonate in the ground water result mainly from the dissolution of carbonate minerals according to equation 5, then the molar proportions of $(Ca^{2+}+Mg^{2+})$ to HCO_3^- should be linear with a slope of 0.5. Calcium and magnesium are summed because of variability of the mole fractions within the carbonate minerals. The line of regression (fig. 10) of $(Ca^{2+}+Mg^{2+})$ versus HCO_3^- for ground-water samples in aquifer layers 1, 3, and 5 in the northern outcrop area of the Cambrian-Ordovician aquifer system in Minnesota, Wisconsin, and northeastern Iowa has a slope of 0.55. The coefficient of correlation (r^2) is 0.80, which indicates a good fit between the carbonate-dissolution model and field data.

The state of equilibrium between ground water and carbonate minerals can be tested by use of saturation indices (*SI*), expressed as

$$SI_{\text{mineral}} = \log \frac{IAP}{K_{sp}}, \quad (6)$$

where *IAP* is the ion-activity product calculated from analytical data and K_{sp} is the solubility product, an

equilibrium constant for ions in a saturated solution in contact with excess solid phases.

A saturation index of 0.0 indicates that *IAP* and K_{sp} are equal and that thermodynamic equilibrium of the solution exists with the solid phase in question; a negative or positive index indicates undersaturation and oversaturation, respectively. Saturation indices for calcite and dolomite in selected water samples from aquifer layer 3 in Iowa and northeastern Missouri were determined by use of WATEQF, a U.S. Geological Survey water chemical-equilibrium calculation program (Truesdell and Jones, 1974; Plummer and others, 1976). Saturation indices calculated for calcite and dolomite range generally from about 0.0 to +0.6 and from −0.2 to +1.0, respectively (fig. 11), for wells in Iowa and northeastern Missouri.

The accuracy of the saturation index for determining equilibrium between solution and carbonate minerals depends largely on the accuracy of field measurements of pH and alkalinity. The most accurate method of measuring pH is by using a flow-through cell or bath until pH is constant for at least 15 minutes (Thorstenson and others, 1979). Precision by this method can be within 0.05 pH unit. Unfortunately, during this study the general accuracy of field pH measurements may have been within only ±0.1 pH unit. Accurate field measurements of alkalinity should be done by potentiometric titration to inflection points rather than to specified end points (Barnes, 1964), which was the method used during this study. The combined errors in pH measurements and alkalinity determinations could result in errors in saturation indices for carbonate dissolution reactions within a range of 20 percent. Within these error limits, ground water in the Cambrian-Ordovician aquifer system seems to be nearly saturated or oversaturated with respect to calcite and dolomite (fig. 11).

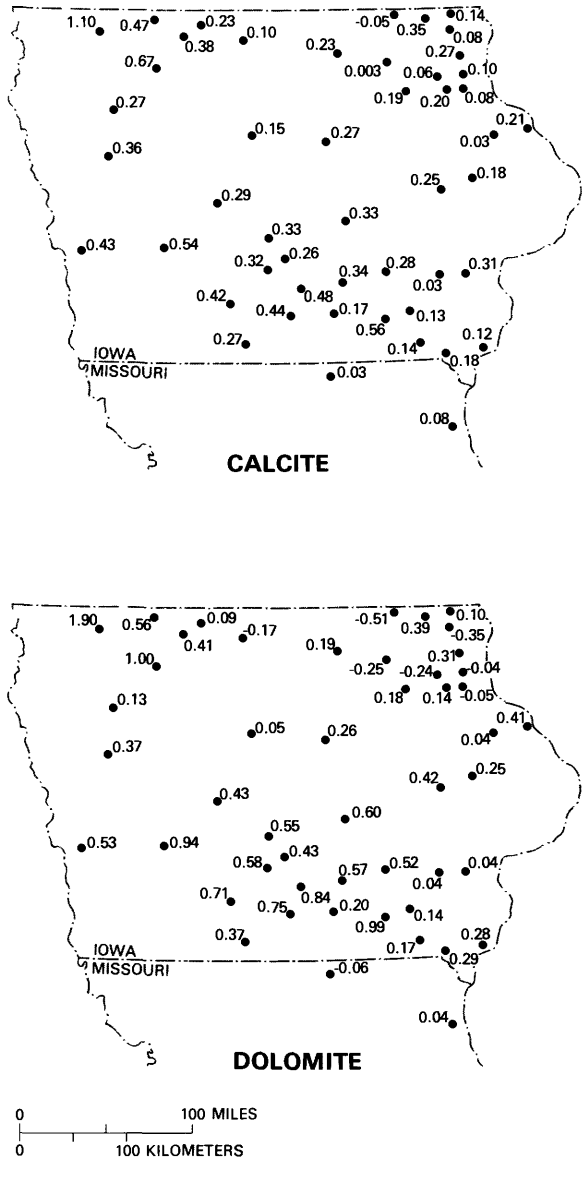


FIGURE 11.—Saturation indices for calcite and dolomite in water from selected wells in aquifer layer 3 in Iowa and northeastern Missouri.

CALCIUM-SODIUM-SULFATE-BICARBONATE WATER TYPE

Ca-Na-SO_4-HCO_3 water is common in the drift and the Dakota Formation (table 5) and is present in all aquifer layers that subcrop beneath the Dakota Formation. For instance, samples of water collected at "nests" of vertically spaced observation wells (piezometers) in aquifer layers 1, 2, and 3 in southwestern Minnesota are all of the Ca-Na-SO_4-HCO_3 type (table 6). The relative chemical uniformity of water in aquifer layers 1, 2, and 3 observed in the piezometers in southwestern Minnesota is an important factor in evaluating chemical and hydrologic mechanisms that affect changes in chemistry southeastward along the major direction of groundwater flow in Iowa. Water-quality data are scant for aquifer layers 1, 2, and 4. If the chemistry of water recharging these aquifer layers is similar to the chemistry of the ground water in aquifer layer 3, one can probably assume that the major geochemical mechanisms that control the water chemistry in all aquifer layers in the recharge areas are generally similar.

The origin of Ca-Na-SO_4-HCO_3 water in the Dakota Formation, the Quaternary drift, and the Cambrian-

TABLE 5.—*Selected chemical analyses of water from the Dakota Formation in northwestern Iowa*

[Map number is location in figure 6]

	Well name				
	Sutherland no. 3	Primghar	Arthur no. 4	Schaller no. 3	Ruthven no. 5
Map number	82	81	90	89	83
Date of collection	2-23-82	2-23-82	2-22-82	2-22-82	2-23-82
Temperature (°C)	9.9	11.1	11.9	7.1	12.3
Field pH (standard units)	7.3	7.4	7.4	7.5	7.5
Calcium, Ca (mg/L)	320	—	260	310	220
Magnesium, Mg (mg/L)	80	—	63	100	58
Sodium, Na (mg/L)	96	—	140	190	100
Lab alkalinity, as HCO_3 (mg/L)	341	412	285	415	404
Sulfate, SO_4 (mg/L)	930	1,000	850	1,200	520
Chloride, Cl (mg/L)	6.7	20	8.5	16	5.0
Dissolved solids, residue on evaporation (mg/L)	1,790	—	1,560	2,340	1,160
Arsenic, As (μg/L)	<50	<50	<50	<50	<50
Barium, Ba (μg/L)	9	9	10	8	13
Cadmium, Cd (μg/L)	<2	<2	<2	<2	<2
Chromium, Cr (μg/L)	<5	<5	<5	<5	<5
Silica, SiO_2 (mg/L)	11	10	5	12	11
Sulfide, S (μg/L)	<3	<3	<3	<3	<3
Selenium, Se (μg/L)	<5	<5	<5	<5	<5
Copper, Cu (μg/L)	6	2	4	3	4
Iron, Fe (μg/L)	2,900	1,400	2,900	71	4,200
Manganese, Mn (μg/L)	640	—	460	2,600	270
Nickel, Ni (μg/L)	<10	—	<10	<10	<10
Lead, Pb (μg/L)	<50	—	<50	<50	<50

Ordovician aquifer system in northwestern Iowa and southwestern Minnesota is related to both the oxidation of pyrite and the dissolution of carbonate minerals. Oxidation of pyrite produces sulfuric acid that dissociates to sulfate and hydrogen ions as follows:

$$FeS_{2(s)} + 7/2 O_{2(g)} + H_2O = Fe^{2+} + 2SO_4^{2-} + 2H^+. \quad (7)$$

Depending on the Eh (redox potential) and pH of the water, the resultant ferrous iron may then be oxidized to ferric iron,

$$Fe^{2+} + 1/4 O_2 + H^+ = Fe^{3+} + 1/2 H_2O, \quad (8)$$

which hydrolyzes to form insoluble iron oxides or hydroxide, for example,

$$Fe^{3+} + 3H_2O = Fe(OH)_{3(s)} + 3H^+. \quad (9)$$

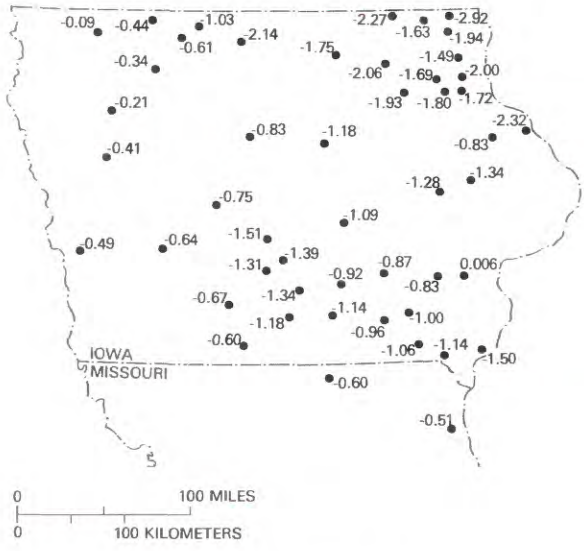
TABLE 6.—*Water-quality data for water samples obtained from piezometers at Schroeder and Kingstrom sites, Goodhue County, Minn., January 1980*

[Results in milligrams per liter, except as indicated. Analyses by Minnesota Department of Health]

	Well name					
	Schroeder no. 5	Schroeder no. 2	Schroeder no. 4	Kingstrom no. 1	Kingstrom no. 3	Kingstrom no. 4
Aquifer layer	1	2	3	1	2	3
Field pH (standard units)	7.1	7.3	7.2	7.2	7.3	7.1
Calcium, Ca	148	136	116	140	140	136
Magnesium, Mg	41	51	56	63	51	39
Sodium, Na	52	62	111	149	74	51
Potassium, K	10	19	24	20	26	9.7
Silica, SiO_2	6.6	6.3	6.7	6.4	5.7	6.6
Manganese, Mn (μg/L)	69	89	48	240	97	59
Iron, Fe (μg/L)	1,900	4,500	2,600	4,600	3,500	50
Alkalinity, as $CACO_3$	306	320	317	328	315	317
Sulfate, SO_4	300	370	317	490	400	290
Chloride, Cl	5.5	9.3	33	49	13	8.6
Dissolved solids, sum of constituents	860	960	1,000	1,300	1,000	800

Acidity produced in the oxidation process may be neutralized by carbonate minerals (eq. 5) that are found as part of the matrix in the Dakota Formation and the underlying aquifer units.

Sulfate in the Dakota Formation and other aquifers in northwestern Iowa and southwestern Minnesota has also been attributed to possible dissolution of either gypsum ($CaSO_4 \cdot 2H_2O$) or anhydrite ($CaSO_4$) (Winter, 1974; Munter and others, 1983). No petrographic evidence of primary evaporite minerals has been noted in the literature, however. Dissolution of gypsum proceeds rapidy compared with dissolution of carbonates and other common minerals in the aquifer matrix. The hydraulic conductivity of the Dakota Formation is generally low owing to bedded shale and siltstone. Therefore, the residence time of ground water in the Dakota probably is long. This is supported by the carbon-14 dates for water in the Dakota ranging from 22,000 to more than 35,000 years B.P. (before present) (D.L. Iles, South Dakota Geological Survey, written commun., 1982). Because of this long residence time, ground water in the Dakota Formation should be in equilibrium with gypsum, if gypsum is present, as should the ground water in aquifer layer 3, where the ground water is recharged from the Dakota. However, negative saturation indices for gypsum in ground water in aquifer layer 3 in northwestern Iowa (fig. 12) show the water to be undersaturated with respect to gypsum, and this indi-



EXPLANATION

-0.75 • WELL LOCATION—Number is saturation index, *SI* (see text for discussion)

FIGURE 12.—Saturation indices for gypsum in water from selected wells in aquifer layer 3 in Iowa and northeastern Missouri.

rectly indicates that there is not enough gypsum in the Dakota Formation to be the source of sulfate, as suggested by other investigators.

Data on the isotopic composition of sulfur in sulfate is another way to test independently whether the sulfur is from the oxidation of pyrite (FeS_2) or the dissolution of gypsum or anhydrite. Negative $\delta^{34}S$ values typically indicate that the source of sulfur is weathered sulfide from shales, whereas positive values generally indicate an evaporitic mineral source (Holser and Kaplan, 1966; Hitchon and Krouse, 1972; Hoefs, 1980).

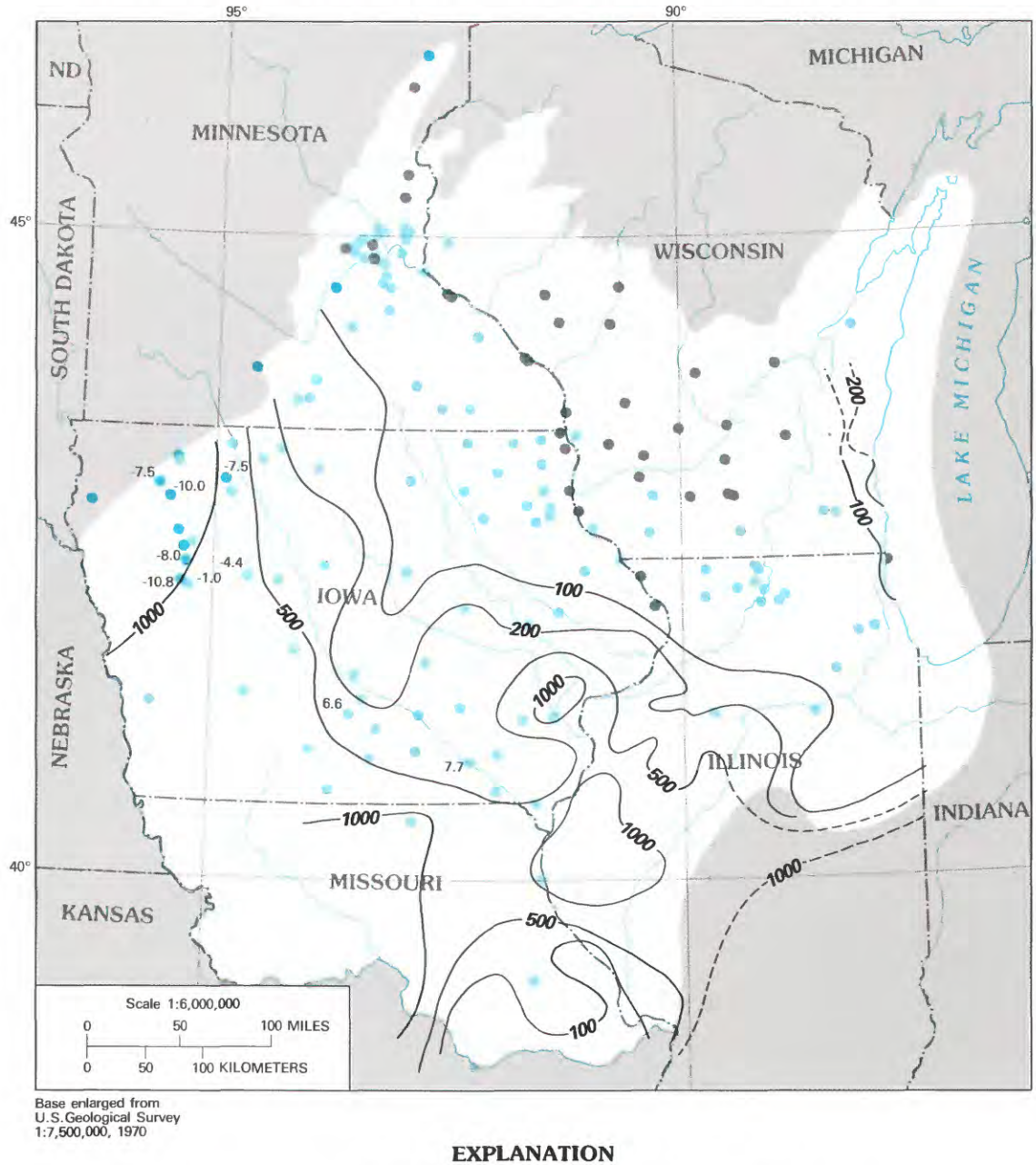
The $\delta^{34}S$ in sulfate from the Cambrian-Ordovician aquifer system and the Dakota Formation in northwestern Iowa (fig. 13) ranges from −10.8 to −1.0 permil (parts per thousand, written o/oo), considerably lighter than $\delta^{34}S$ associated with marine evaporites in the Cretaceous Period (Claypool and others, 1980). $\delta^{34}S$ of pyrite and other disseminated sulfide minerals in shales tends to be less than +10 o/oo, the lower limit for evaporitic sulfate (Holser and Kaplan, 1966). These values are similar to isotopic sulfur ratios in streams that drain basins underlain by marine Cretaceous rock, roughly similar to the Dakota Formation, in the MacKenzie River Basin of Canada (Hitchon and Krouse, 1972). The values of $\delta^{34}S$ indicate that the original source of sulfur was probably pyrite in the Dakota Formation.

The isotopic composition of the sulfur in sulfate reflects the isotopic composition of the sulfur in the original pyrite and depends on many factors. Sulfur isotopes approach equilibrium at earth temperatures and pressures very slowly (Pearson and Rightmire, 1980). Most differences in sulfur isotope content in aqueous sulfur compounds are caused by kinetic fractionation accompanying inorganic or bacterial reduction or by oxidation of sulfur compounds (Kaplan and Rittenburg, 1964; Goldhaber and Kaplan, 1974). Hydrogen sulfide degassing is a common problem in many wells in the Dakota Formation; this indicates that reducing conditions do exist locally in the formation (U.S. Geolgical Survey, unpub. data; Burkart, 1984). In southwestern Minnesota, methane is also common in both drift and the underlying Cambrian-Ordovician aquifer system (Coleman, 1978, 1979).

$\delta^{34}S$ in sulfate in aquifer layer 3 is enriched downgradient from the northwestern recharge area in central Iowa but is still less than +10 o/oo (fig. 13). The $\delta^{34}S$ enrichment may be related to the preferential bacterial reduction and consequent loss of sulfur-32 in H_2S or metal sulfide precipitates. Although sulfide in solution is present in the aquifer system in central Iowa (fig. 14), data are insufficient to document the presence of such possible bacteriological mediation of the reduction process. The low concentrations of sulfide may reflect precipitation of pyrite or other metal sulfides. Calculations from the WATEQF program show that sulfide-bearing solutions are supersaturated with respect to pyrite.

Some input of sulfur to the aquifer system could have been from the oxidation of pyrite in the Maquoketa Shale along the outcrop area in northeastern Iowa. However, the scant data on the isotopic content of sulfur in sulfate in central Iowa (fig. 13) show $\delta^{34}S$ greater than +5 o/oo, which is considerably heavier than that of the sulfur in sulfate derived from either the oxidation of pyrite in northwestern Iowa or from the Maquoketa Shale in northeastern Iowa.

Elsewhere in the aquifer system, $\delta^{34}S$ in sulfate may indicate a sulfur source from evaporite minerals. East of the Maquoketa confining unit in northern Illinois, $\delta^{34}S$ in sulfate in oxidized water is about +20 o/oo and is too enriched to be derived solely from the oxidation of sulfide minerals (Perry and others, 1982). Gilkeson and others (1981) proposed that some of the sulfate may have been placed in the aquifer system during Pleistocene glaciations and may be related to Michigan basin evaporites. Hydraulic gradients in Illinois, at least during the Wisconsin ice advances, could have been from east to west, reversed from current hydraulic gradients, because of the pressure head from the weight of the ice sheets that periodically covered the Lake Michigan



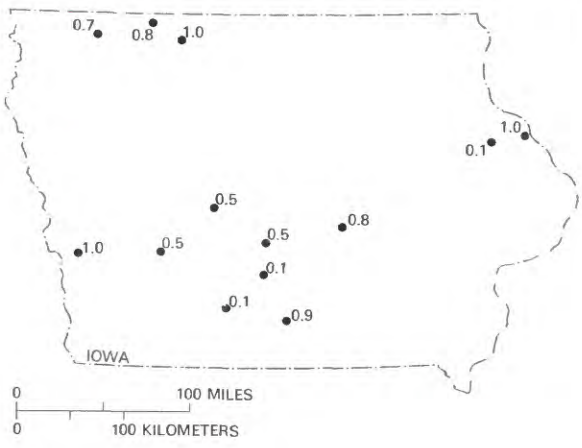
EXPLANATION

—500— LINE OF EQUAL CONCENTRATION OF SULFATE—Dashed where approximate. Interval, in milligrams per liter, is variable

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY
Number is isotopic composition of sulfur in sulfate, $\delta^{34}S$, permil

- Open to aquifer layer 1
- -4.4 Open to aquifer layer 3
- -7.5 Open to aquifer layer 5

FIGURE 13.—Sulfate distribution in aquifer layers 1 and 3 and sulfur isotopic composition in sulfate in water from selected wells in aquifer layer 3 and aquifer layer 5 (Dakota Formation).



EXPLANATION

1.0 WELL LOCATION—Number is sulfide concentration in milligrams per liter

FIGURE 14.—Sulfide distribution in water from selected wells in aquifer layer 3 in Iowa.

basin (Gilkeson and others, 1981; Filley and Parizek, 1983; Siegel and Mandle, 1983). The influence of Pleistocene glaciations on the water chemistry of the Cambrian-Ordovician aquifer system was profound and is discussed in a later section, "Isotopic Composition of Water and Pleistocene Recharge Model."

SODIUM-MIXED ANION WATER TYPE

The evolution of Ca-Na-SO_4-HCO_3 water to Na-Ca-SO_4-HCO_3 and Na-Cl water is well illustrated in figure 15, a plot of analyses in terms of equivalent weights on the trilinear diagram of Piper (1944). Data from wells along geochemical sections A–A' and B–B' indicate a trend toward sodium predominance on the cation plot, and toward chloride predominance on the anion plot. The increase in sodium and the decrease in calcium and magnesium along the flow path could be the result of several processes.

Sodium could be contributed by dissolution of sodium-bearing silicate or evaporite minerals in the aquifer system. However, no petrographic evidence exists to indicate the presence of halite (NaCl) in the aquifer system, and the dissolution rate of sodic plagioclase ($NaAlSi_3O_8$) is much too slow to account for the concentrations of sodium found in central Iowa.

The inverse relationship between concentrations of sodium and alkaline-earth metals could also be explained by ion exchange, which has been identified in many aquifer systems elsewhere (for example, Foster, 1950; Krothe and Parizek, 1979; Thorstenson and others, 1979; Krothe and Bergeron, 1981; Chapelle and Knobel, 1983). Exchange would follow the generalized reaction

$$M^{2+} + Na_2\text{-Clay} = 2Na^+ + M\text{-Clay}, \qquad (10)$$

where M^{2+} is $Ca^{2+} + Mg^{2+}$ or other alkaline-earth metals.

Micaceous clays such as illite and glauconite are more common in the Cambrian-Ordovician aquifer system than are mixed-layered clays such as montmorillonite and smectite, which are usually associated with cation exchange. Major clay minerals in the Ordovician Decorah Formation and Glenwood Formation, which are part of the Maquoketa confining unit that separates aquifer layer 3 from aquifer layer 4, are kaolinite and illite (Parham and Austin, 1967, 1969). However, distinctive beds of potassium montmorillonite have been identified in the Decorah Formation and other Ordovician formations throughout the study area (Mossler and Hayes, 1966). Although the presence of montmorillonite in Ordovician and Cambrian rocks suggests that significant cation-exchange capacity may be present in the aquifers, such exchange probably cannot completely account for the linear plot of the cations (fig. 15). If cation exchange were the dominant mechanism, the plot would trend more parallel to the calcium-sodium axis rather than toward the sodium apex (Piper, 1944), unless exchange of calcium and magnesium for sodium occurred at rates that would maintain similar Ca:Mg molar ratios along the flow path. Covariance of the molality of sodium to molality of (Ca+Mg) has a low coefficient of correlation (r^2) of 0.3 and a slope of +2.1. If ion exchange were a major process, r^2 would be closer to unity and the slope would be close to −2 (Chapelle, 1983). Given the areal variability and probable scarcity of clays having high cation-exchange capacity for calcium and magnesium in the aquifer system, it is unlikely that much ion exchange occurs except in recharge areas underlain by clayey till and the Dakota Formation.

Mixtures of two waters will also plot on straight lines if all solutes remain in solution and do not increase or decrease as a result of chemical reactions. The linearity of the cation plot (fig. 15) may indicate simple mixing of Na-mixed anion water with Ca-Na-mixed anion water, but the curvilinear fit of the anion data indicates sources and sinks along the flow path with respect to bicarbonate and sulfate.

Although cation trends on the trilinear diagrams could indicate mixing of two types of water, sodium and chloride concentrations along the major southeastward direction of ground-water flow across Iowa probably

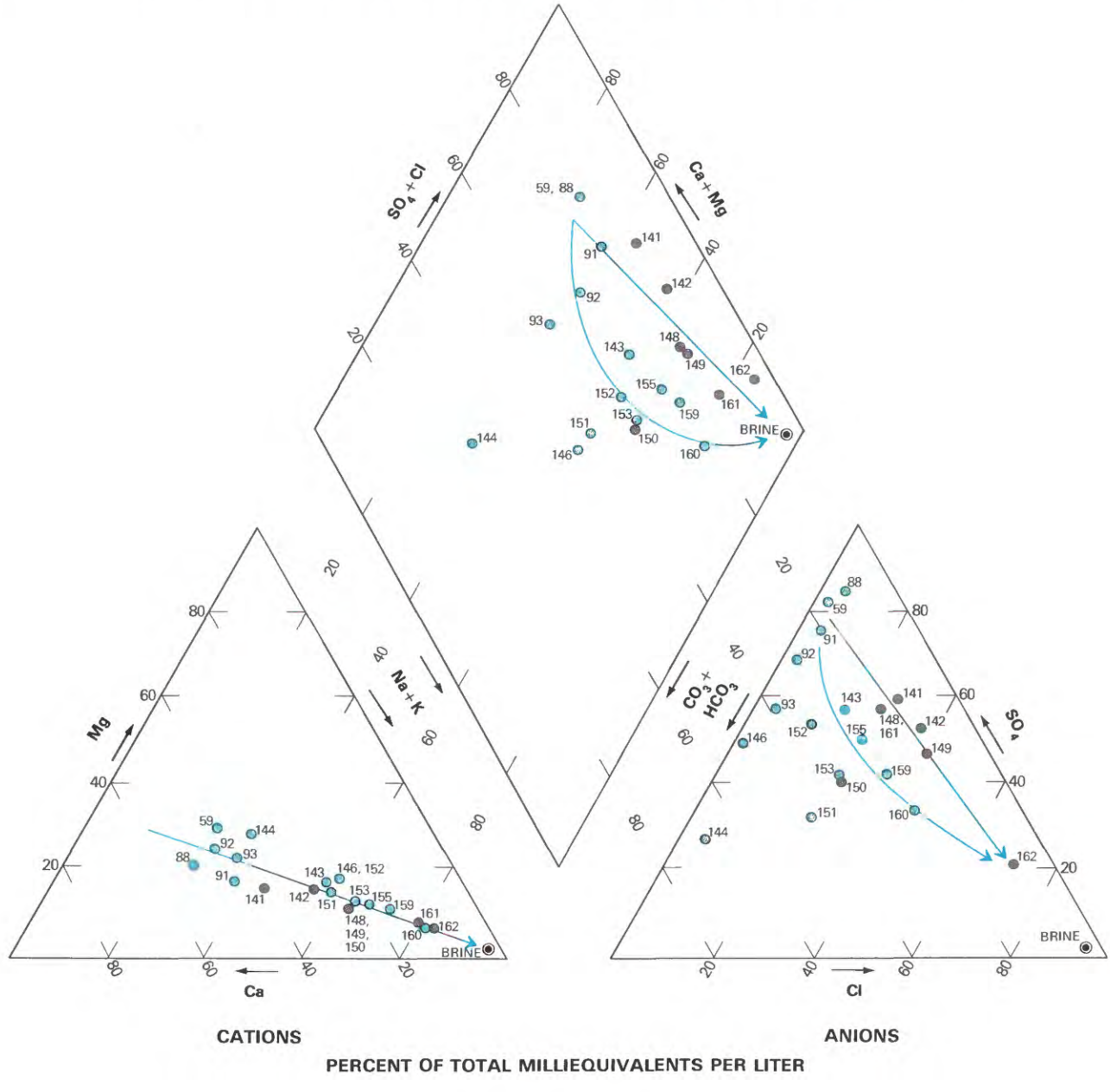


FIGURE 15.—Trilinear diagram of water chemistry along geochemical sections *A-A′* and *B-B′*.

reflect a gradual mineralization of the waters as they approach the Na-Cl brines of the Illinois basin. The origin of the brines is related to reverse chemical osmosis and membrane filtration (Graf and others, 1965; Clayton and others, 1966; Hanshaw and Coplen, 1973; Graf, 1982). The combined effects of these processes that concentrate sodium and chloride probably extend upgradient in the Cambrian-Ordovician aquifer system outside the Illinois basin proper. For example, chloride concentrations increase to more than 100 mg/L in southern Iowa, halfway down the regional flow paths from northwestern and western Iowa to southeastern Iowa (fig. 16). The overall trend toward more chloride-rich waters occurs even in central Iowa within the plume of low-dissolved-solids water, where concentrations of chloride are several times greater than to the northeast (figs. 7, 16). Figures 17 and 18 show concentrations of major constituents along geochemical sections A–A' and B–B'. Concentrations of chloride and sodium begin to increase from south-central Iowa down the major flow paths to the southeast toward the Illinois basin.

The trilinear plot of anions (fig. 15) shows that, although chloride is less than 10 percent, sulfate decreases from about 80 percent at the recharge area in western Iowa to about 55 percent near the Mississippi River. Bicarbonate plus carbonate increases from less than 20 percent to more than 40 percent. The apparent inverse relationship between equivalents of these constituents suggests that sulfate is possibly being reduced to sulfide along the hydraulic gradient, probably with an associated loss of oxygen, in the presence of a reducing agent such as organic material.

If the reducing agent is organic material, the following reactions are possible:

$$15CH_2O+2Fe_2O_3+8SO_4^{2-}+H_2CO_3 = 4FeS_2+16HCO_3^-+8H_2O \quad (11)$$

or

$$SO_4^{2-}+2CH_2O+2H^+ = H_2S+2CO_2+2H_2O. \quad (12)$$

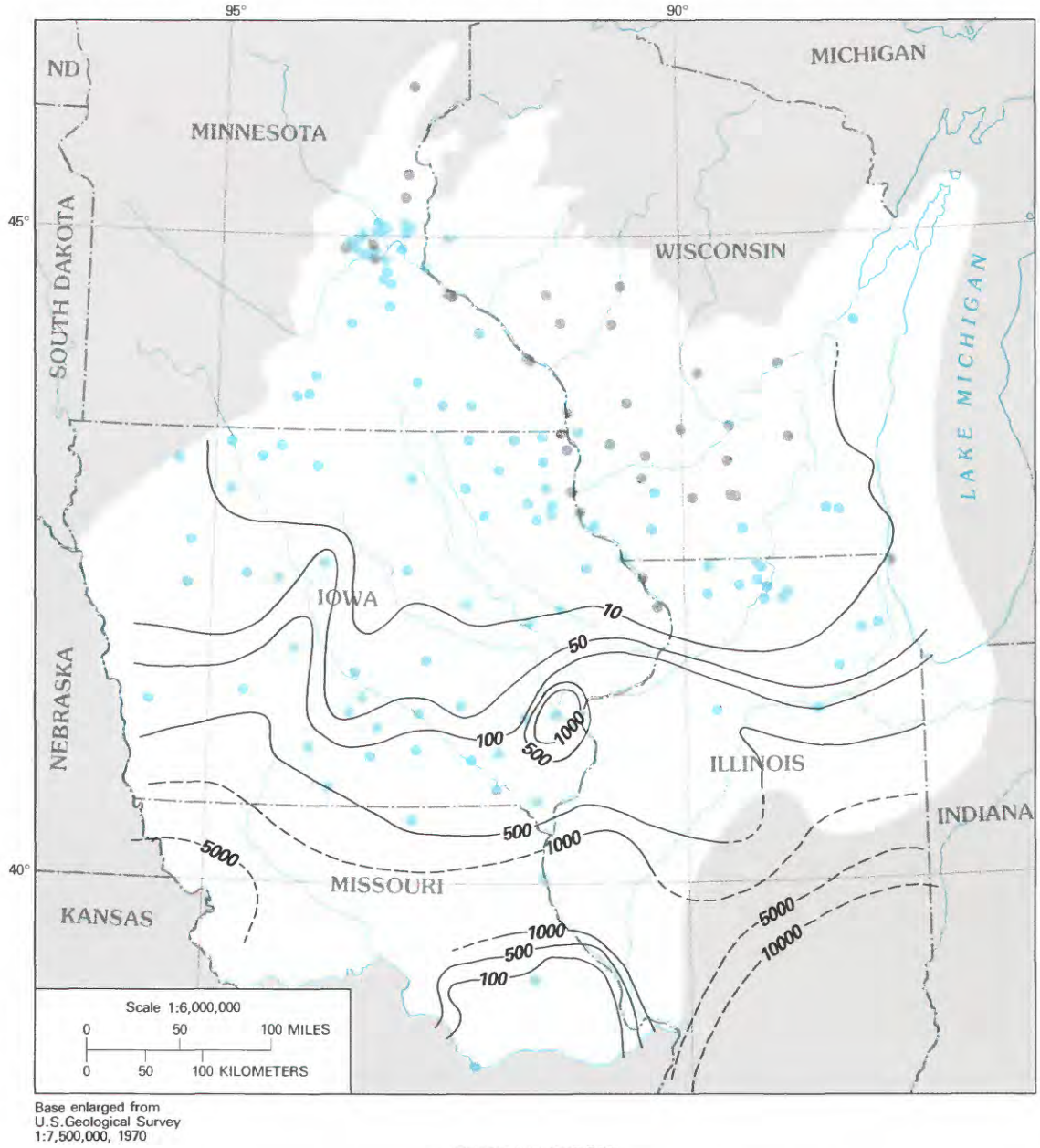
Hematite (Fe_2O_3) and ferric oxyhydroxide [FeO(OH)] are common in the Cambrian-Ordovician aquifer system. Organic material is less common, but bacteriogenic decomposition of organic material occurs within the overlying Dakota Formation. Thus, recharge from the Dakota Formation and possible reduction of organic material in shales associated with aquifer layer 3 could produce bacteriogenic methane in water. Methane concentrations of as much as 15 ppm in aquifer layer 3 and 7 ppm in aquifer layers 2 and 1 were identified in southwestern Minnesota (Coleman, 1978; Minnesota Department of Natural Resources, written commun., 1981).

The equivalent weight of sulfate lost should approximately equal that of bicarbonate gained if the reactions are a reasonable explanation for the observed chemical changes (eqs. 11, 12). A plot of equivalents of sulfate against bicarbonate for sections A–A' and B–B' shows the contrary (fig. 19); as sulfate decreases, bicarbonate remains the same, at about 5 meq/L. Furthermore, saturation indices indicate that the ground water is oversaturated or is nearly in equilibrium with calcite and dolomite (fig. 11). Bicarbonate concentrations remain constant even in the vicinity of the dilute plume in central Iowa. If the dilute plume is caused by dilution of ground water with recharge water of low dissolved-solids content, the uniform bicarbonate concentrations and saturation indices would suggest that ground water has reequilibrated with carbonate minerals in the aquifer since the dilution episode or episodes. The mechanism, timing, and amount of such recharge can be explained hypothetically by glacial advances during the Pleistocene and are discussed later in the section "Isotopic Composition of Water and Pleistocene Recharge Model."

TRACE AND MINOR CONSTITUENTS

The areal distribution of many trace constituents in the aquifer system is related approximately to the availability of the constituents in the source rocks. Although specific data on the trace-element content of the aquifer matrix is lacking, compilation of the average distribution of elements in major rock types (Turekian and Wedepohl, 1961; Drever, 1982) indicates that higher concentrations of many transition metals are found in shales rather than in carbonate rocks or sandstones. Concentrations of the alkaline earth strontium and of halogens, such as bromine and fluorine, are more variable with respect to rock type.

The areal distribution of the transitional metals cadmium and arsenic in the aquifer system may be related to the proximity of the argillaceous Dakota Formation. Concentrations of these metals are generally less than 5 μg/L, except where the aquifer subcrops beneath the Dakota Formation in northwestern Iowa and southwestern Minnesota (fig. 20). Scant data suggest that selenium concentrations are less than 5 μg/L except at one location beneath the Dakota Formation. Cadmium concentrations may also increase to more than 5 μg/L in southeastern Iowa and northeastern Missouri on the edge of the Illinois basin. Concentrations of iron and manganese increase where the aquifer is overlain by the Dakota Formation and by drift derived from the Dakota (fig. 21). For example, concentrations of iron



EXPLANATION

-50- - - LINE OF EQUAL CHLORIDE CONCENTRATION— Dashed where approximate. Interval, in milligrams per liter, is variable

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

Open to aquifer layer 1

Open to aquifer layer 3

FIGURE 16.—Chloride distribution in aquifer layers 1 and 3.

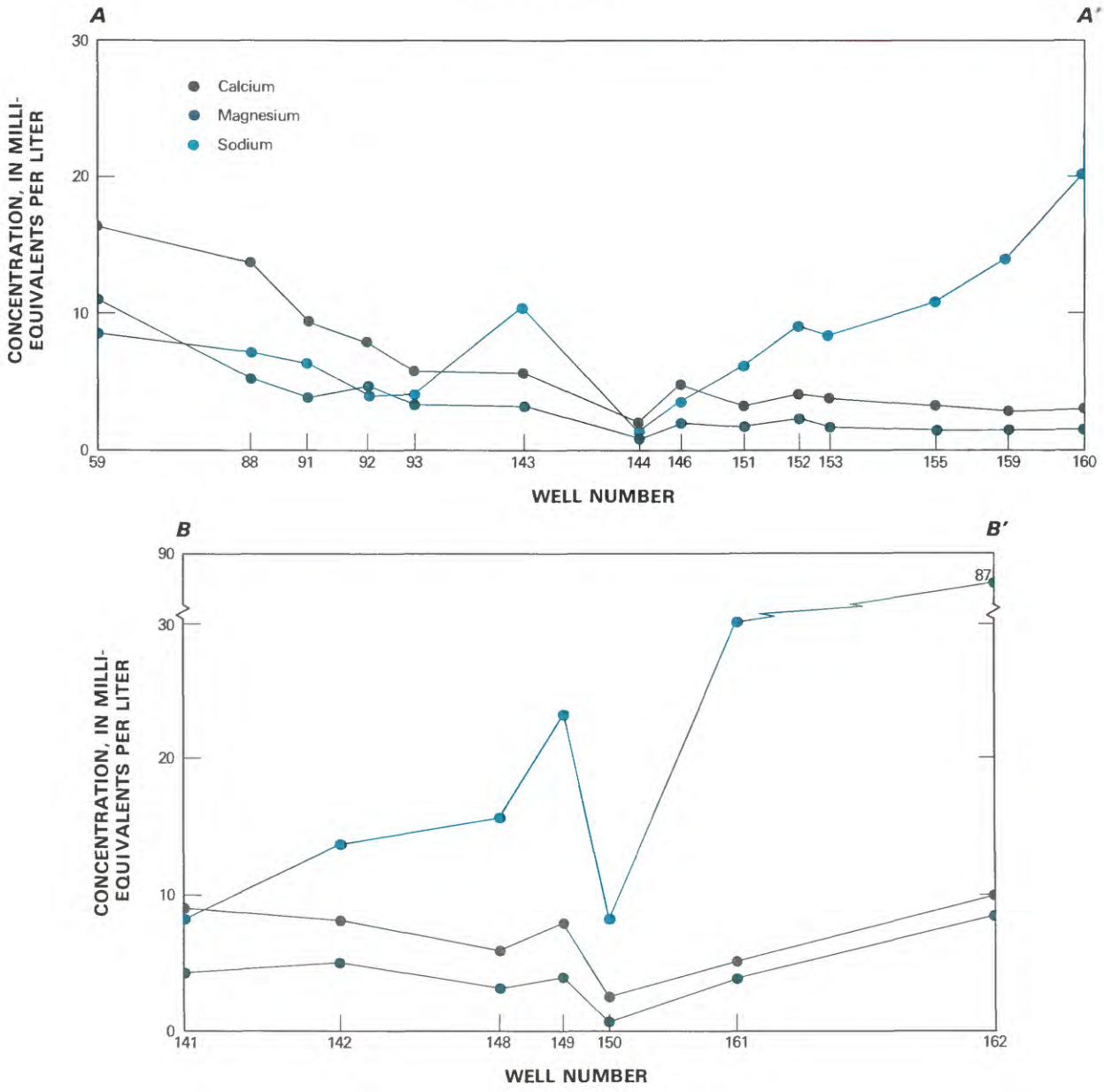


FIGURE 17.—Concentrations of major cations in water from wells in aquifer layers 1 and 3 along geochemical sections *A-A'* and *B-B'*. (Location of wells shown in fig. 6.)

and manganese exceed 1,000 μg/L and 100 μg/L, respectively, in northwestern Iowa. Concentrations of iron, manganese, copper, lead, and cobalt increase in southwestern Iowa near the margin of the Forest City basin (figs. 21, 22). Concentrations of cadmium and copper are more than 5 and 20 μg/L, respectively, in southeastern Iowa near the western flank of the Illinois basin (figs. 20, 22).

The controls on the concentrations of these and other trace metals are complicated and are related as much to complexation of metals by organic and inorganic ligands, sorption of metals onto solids, and oxidation-reduction potential of the water as to the metal content of the source rock (Garrels and Christ, 1965; Stumm and Morgan, 1981; Eichenberger and Chen, 1982; Hem, 1985). The influence of these processes on the trace-metal content of the water cannot be evaluated at the present time because the detection limits of the analyses for the metals were at reconnaissance levels and because information on the composition of dissolved organic carbon in the water and regional mineralogical and trace-metal composition of the aquifer matrix are

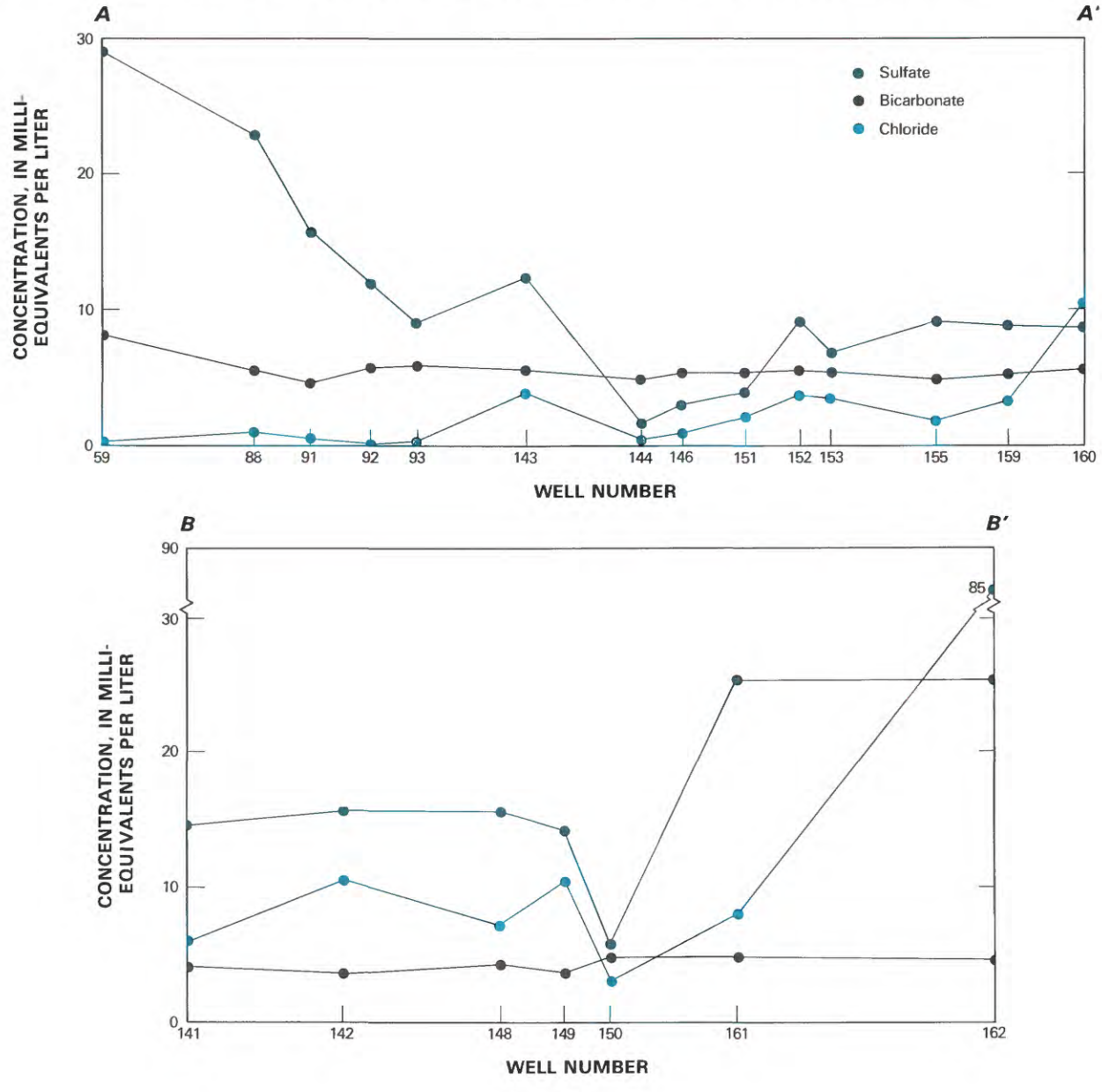


FIGURE 18.—Concentrations of major anions in water from wells in aquifer layers 1 and 3 along geochemical sections *A-A'* and *B-B'*. (Location of wells shown in fig. 6.)

lacking. Some trace metals, such as iron, can be reduced by bacteria at the pH values prevalent in the aquifer. Reducing conditions, identified by measurable dissolved sulfide, are present throughout the aquifer where it is confined by the Maquoketa Shale (fig. 14) and locally in the Dakota Formation (Burkart, 1984), and they probably are a major control on trace-metal concentrations in western Iowa.

The relationship between some trace-metal concentrations in ground water and proximity to the Forest City basin may be indicated by concentrations of beryllium and molybdenum of more than 1 and 10 μg/L, respectively, in southwestern Iowa (fig. 23). Concentrations of these and other metals may increase near the Illinois basin. However, no trace-metal data for water from the Cambrian-Ordovician aquifer system are available for that area. Several wells in northeastern and north-central Iowa inexplicably have molybdenum concentrations of more than 10 μg/L.

Some trace constituents that have relatively similar average concentrations in different sedimentary rock types show increases in concentration in ground water

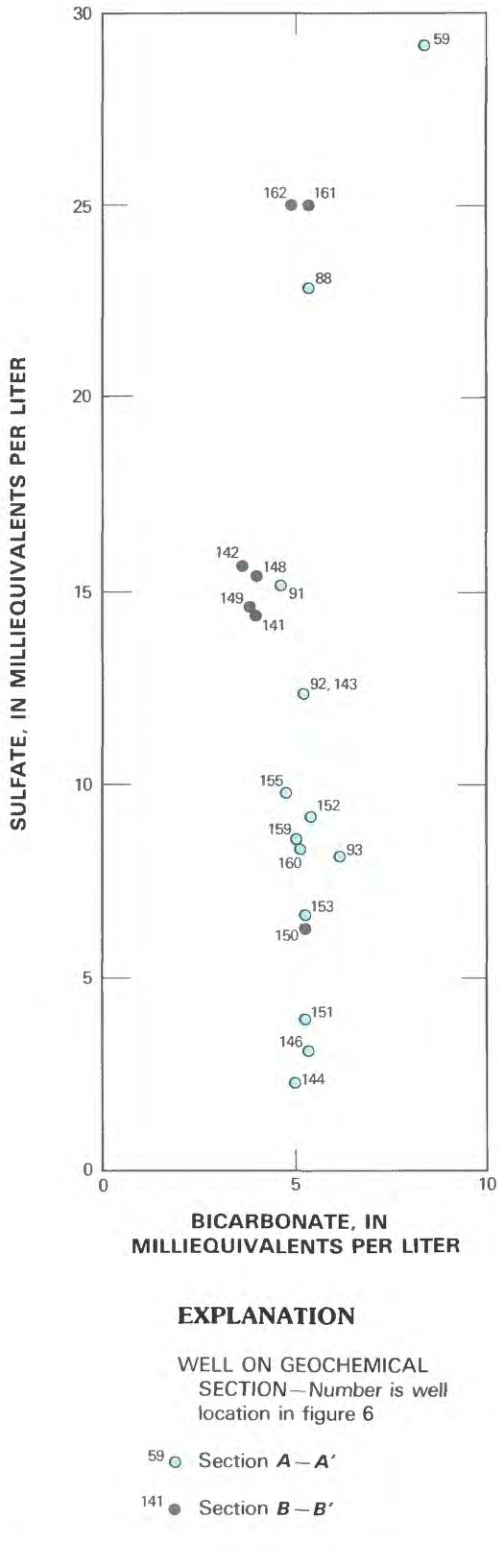


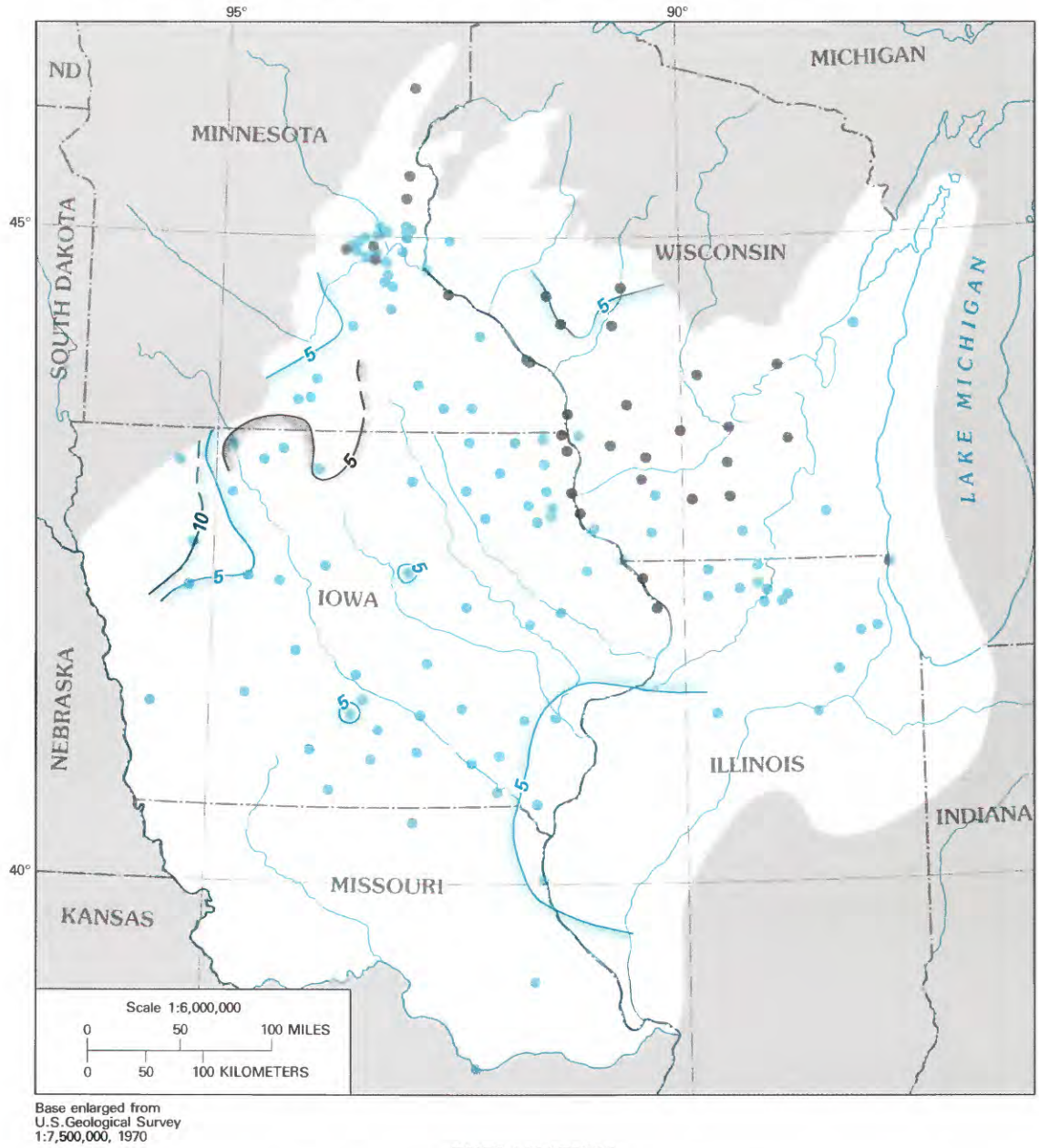
FIGURE 19.—Sulfate-bicarbonate relationship along geochemical sections *A-A′* and *B-B′*.

southwestward across Iowa and eastward across Wisconsin. For example, fluoride concentrations increase from less than 1 to more than 2 mg/L, lithium from less than 10 to more than 400 μg/L, boron from less than 200 to more than 2,000 μg/L, and strontium from less than 1,000 to more than 6,000 μg/L across Iowa (figs. 24–27). Strontium concentrations exceed 1,000 μg/L in eastern Wisconsin where dissolved solids generally exceed 500 mg/L (Nichols and McNall, 1957; Kammerer, 1981). Boron concentrations exceed 5,000 μg/L near the western edge of the Illinois basin (fig. 26).

There is no identifiable plume of dilute concentration of trace constituents in Iowa (as there is for dissolved solids), with the exception of bromide (fig. 28) and possibly lithium (fig. 25). Bromide concentrations in the aquifer are generally less than 0.5 mg/L except near the western edge of the Illinois basin, where concentrations approach 10 mg/L. In central and southern Iowa, a broad zone of bromide concentration of less than 0.5 mg/L is surrounded by areas of bromide concentrations of greater than 1.0 mg/L (fig. 28). This distribution roughly matches the dilution shown by the dissolved-solids distribution (fig. 7). Bromide is a conservative, relatively nonreactive constituent and therefore is a good indicator of hydrological processes that involve mixing of different water types. The lack of similar dilution plumes in the distribution of strontium, fluoride, and boron suggests that chemical processes other than mixing have controlled the distribution of these trace constituents, thus masking the reacharge plume(s).

Concentrations of barium in the ground water are related both to source and to geochemical processes. Gilkeson and others (1981) showed that barium concentrations or more than 1 mg/L in northeastern Illinois are due to a zone of reducing conditions in the confined Cambrian-Ordovician aquifer system. Sulfate ion is reduced to sulfide, thereby allowing concentrations of barium to increase until the solubility limit of barite ($BaSO_4$) is reached. Concentrations exceeding 100 μg/L in the northwestern part of the study area are probably due to barium contained in shales of the Dakota Formation (fig. 29). Concentrations also exceed 100 μg/L in the northeastern corner of Iowa near the Mississippi River. The cause of the higher barium concentrations in Iowa is unknown. Higher barium concentrations also are present in the aquifer in southeastern Wisconsin along the strike of the Maquoketa Shale, apparently an extension of the conditions in northeastern Illinois. Additional work is needed to determine whether the solubility of barite controls the high barium concentrations in these waters.

Text continues on p. D39.



EXPLANATION

LINES OF EQUAL CONCENTRATION—Stippled in direction of lower concentration. Dashed where approximate. Interval, in micrograms per liter, is variable

—5— Cadmium

– – 5 – – Arsenic

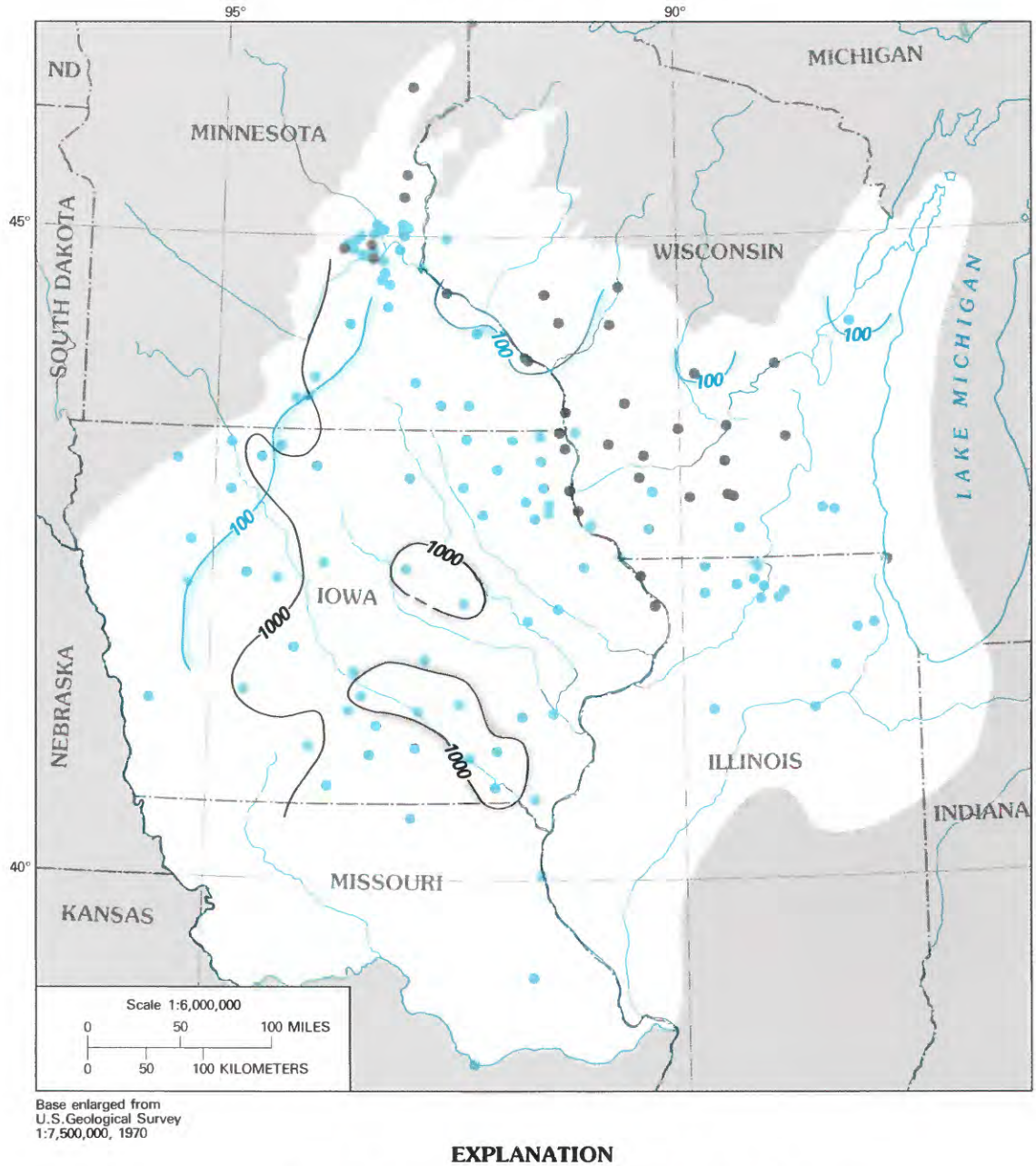
– · – 10 – · – Selenium

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

● Open to aquifer layer 1

● Open to aquifer layer 3

FIGURE 20.—Distribution of dissolved cadmium, arsenic, and selenium in aquifer layers 1 and 3.



EXPLANATION

LINES OF EQUAL CONCENTRATION—Stippled in direction of lower concentration. Dashed where approximate. Interval, in micrograms per liter, is variable

--1000-- Iron

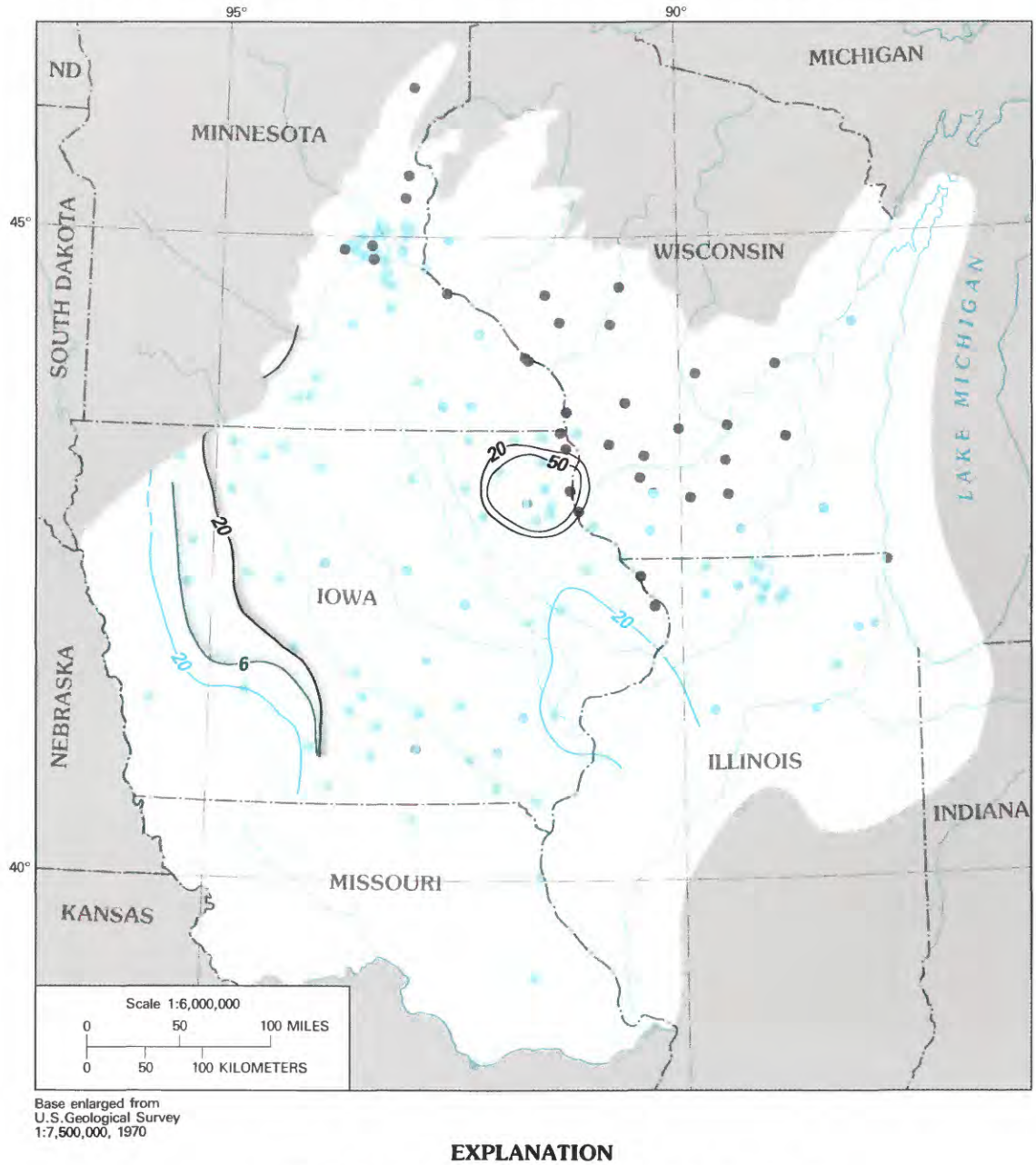
—100— Manganese

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

Open to aquifer layer 1

Open to aquifer layer 3

FIGURE 21.—Distribution of dissolved iron and manganese in aquifer layers 1 and 3.



EXPLANATION

LINES OF EQUAL CONCENTRATION—Stippled in direction of lower concentration. Dashed where approximate. Interval, in micrograms per liter, is variable

—20— Copper

—20— Lead

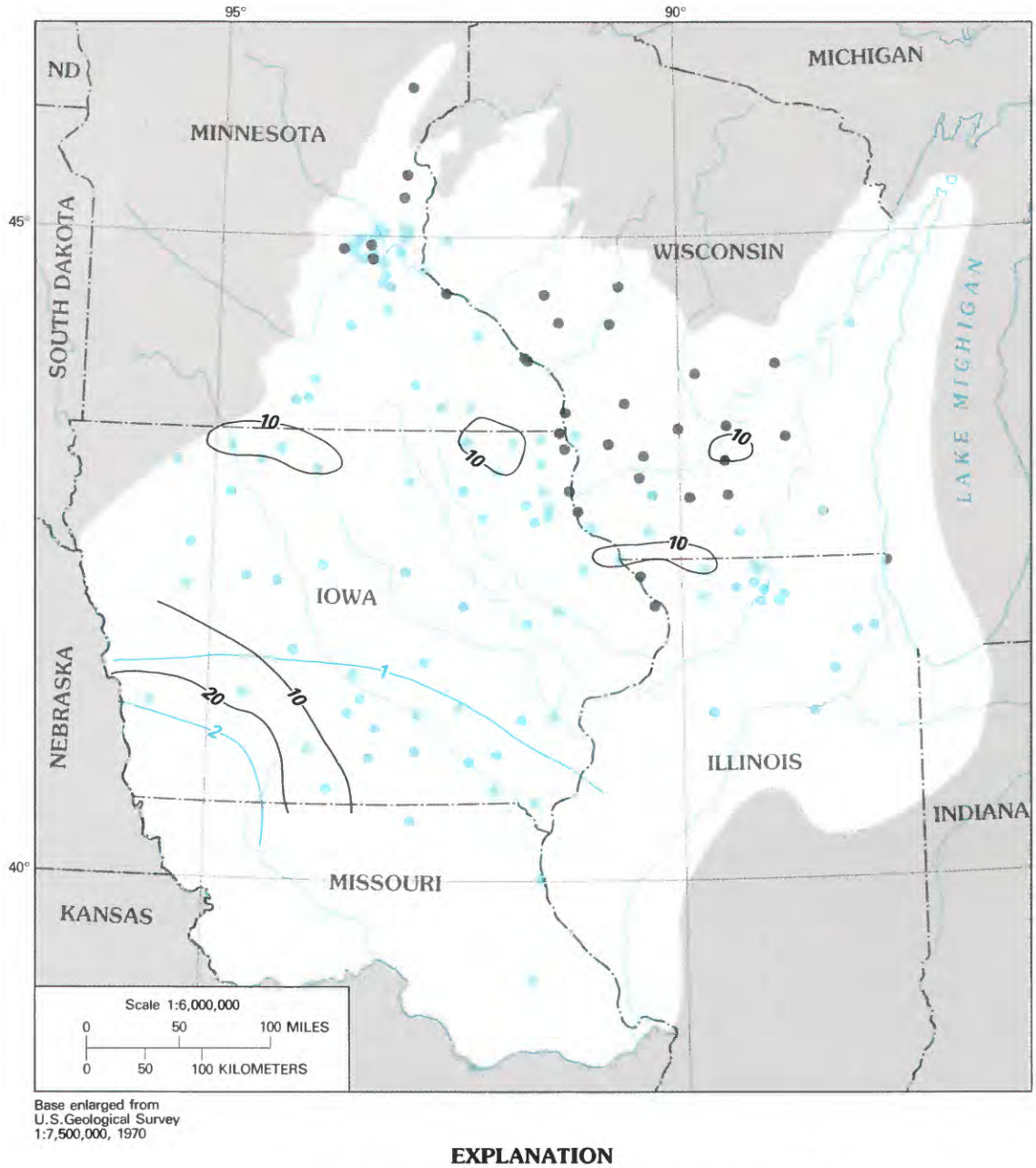
—6— Cobalt

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

● Open to aquifer layer 1

● Open to aquifer layer 3

FIGURE 22.—Distribution of dissolved copper, lead, and cobalt in aquifer layers 1 and 3.



EXPLANATION

LINES OF EQUAL CONCENTRATION—Interval, in micrograms per liter, is variable

—10— Molybdenum

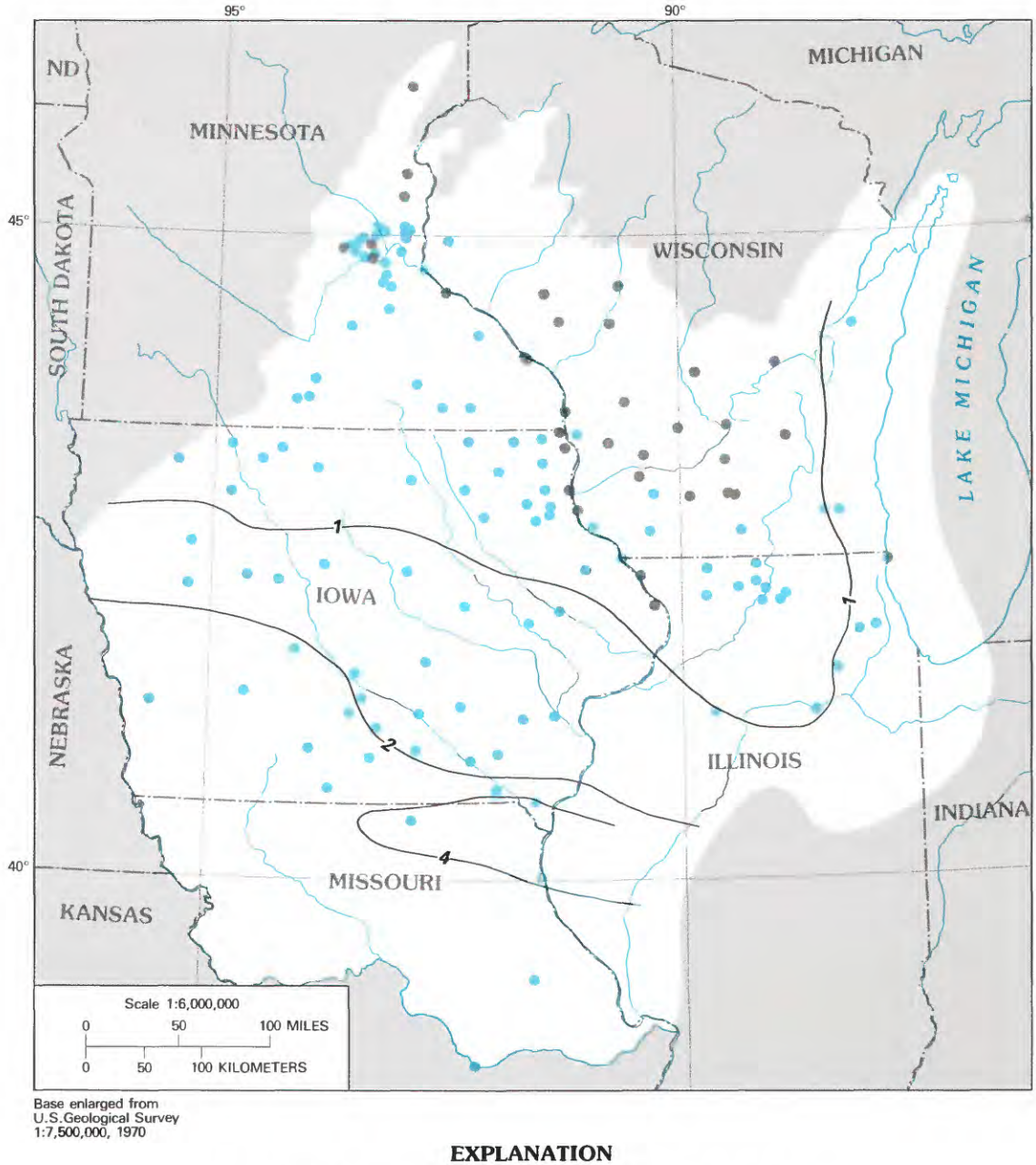
—2— Beryllium

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

Open to aquifer layer 1

Open to aquifer layer 3

FIGURE 23.—Distribution of dissolved molybdenum and beryllium in aquifer layers 1 and 3.



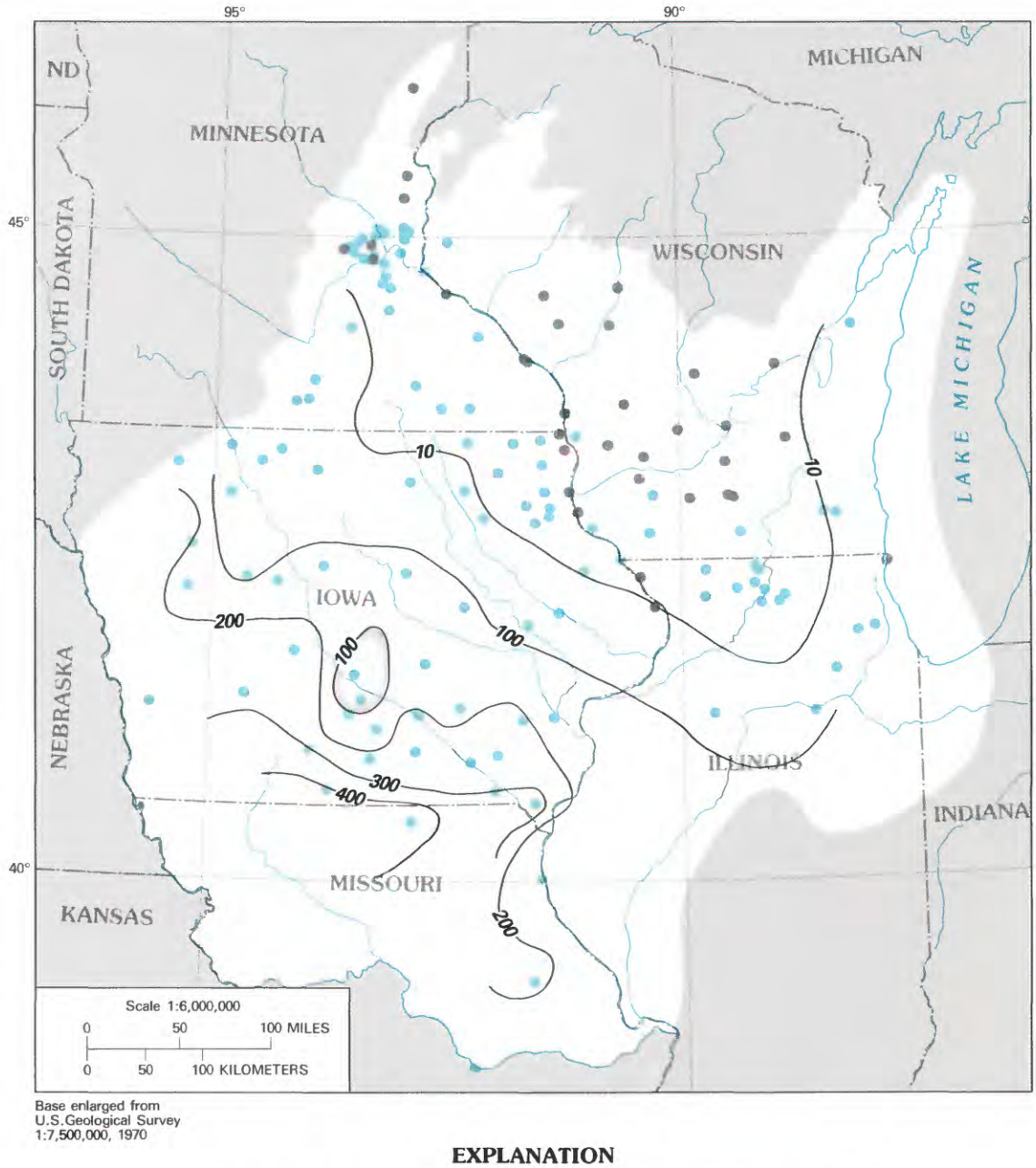
EXPLANATION

—4— LINE OF EQUAL FLUORIDE CONCENTRATION—Interval, in milligrams per liter, is variable

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

- Open to aquifer layer 1
- Open to aquifer layer 3

FIGURE 24.—Distribution of dissolved fluoride in aquifer layers 1 and 3.



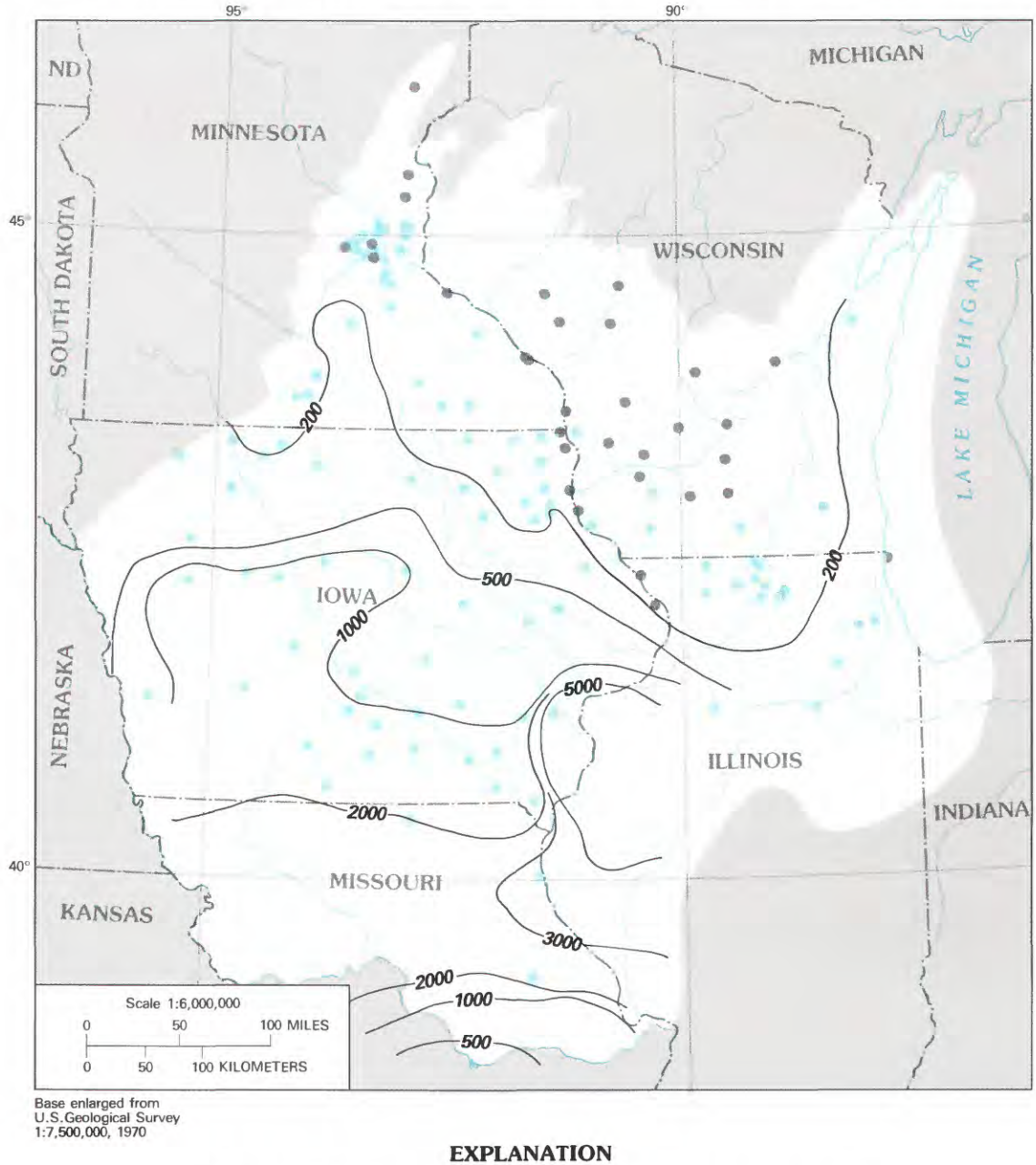
EXPLANATION

—100— LINE OF EQUAL DISSOLVED LITHIUM CONCENTRATION—Stippled in direction of lower concentration. Interval, in micrograms per liter, is variable

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

- Open to aquifer layer 1
- Open to aquifer layer 3

FIGURE 25.—Distribution of dissolved lithium in aquifer layers 1 and 3.



EXPLANATION

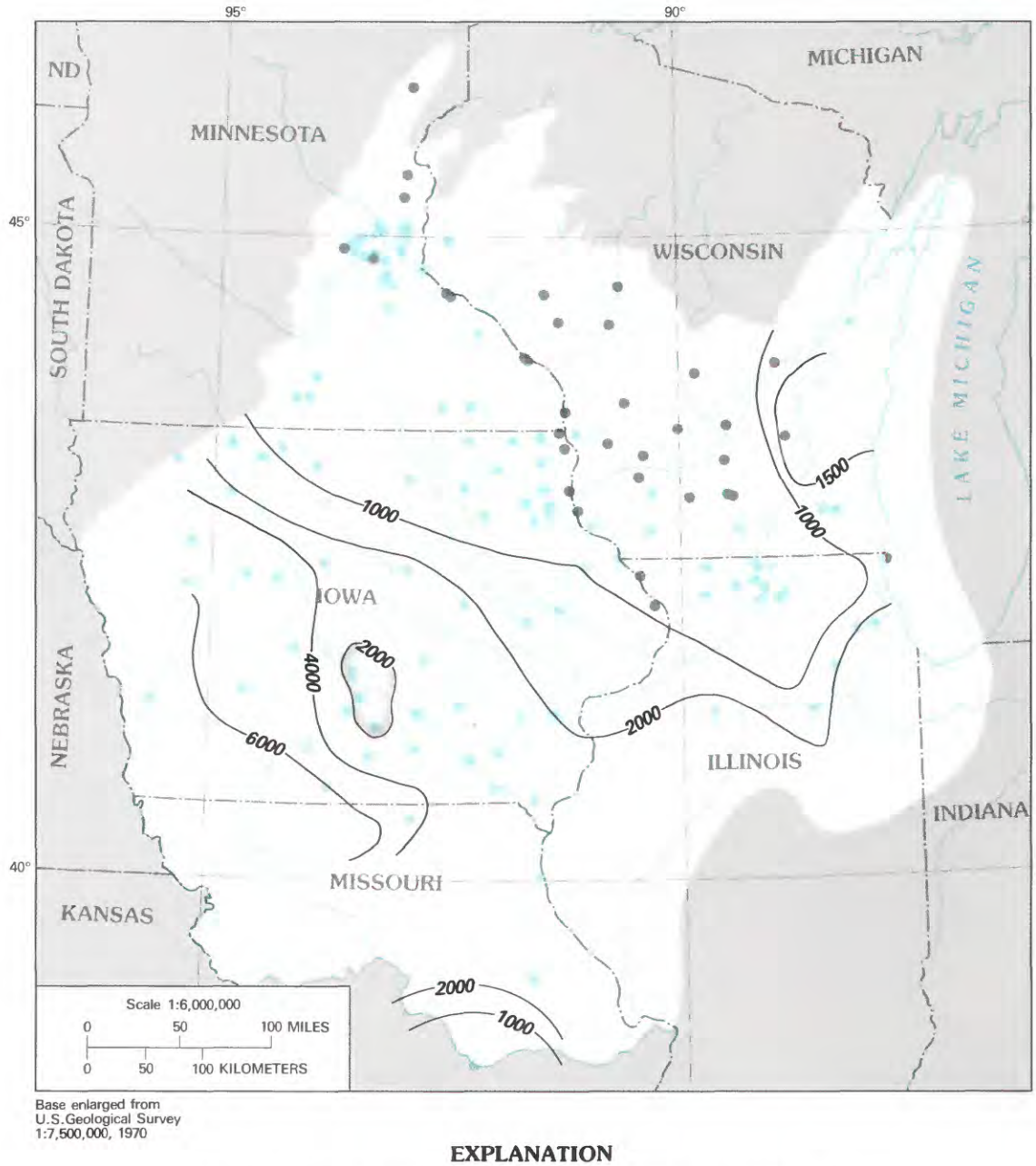
—200— LINE OF EQUAL BORON CONCENTRATION—Interval, in micrograms per liter, is variable

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

Open to aquifer layer 1

Open to aquifer layer 3

FIGURE 26.—Distribution of dissolved boron in aquifer layers 1 and 3.



EXPLANATION

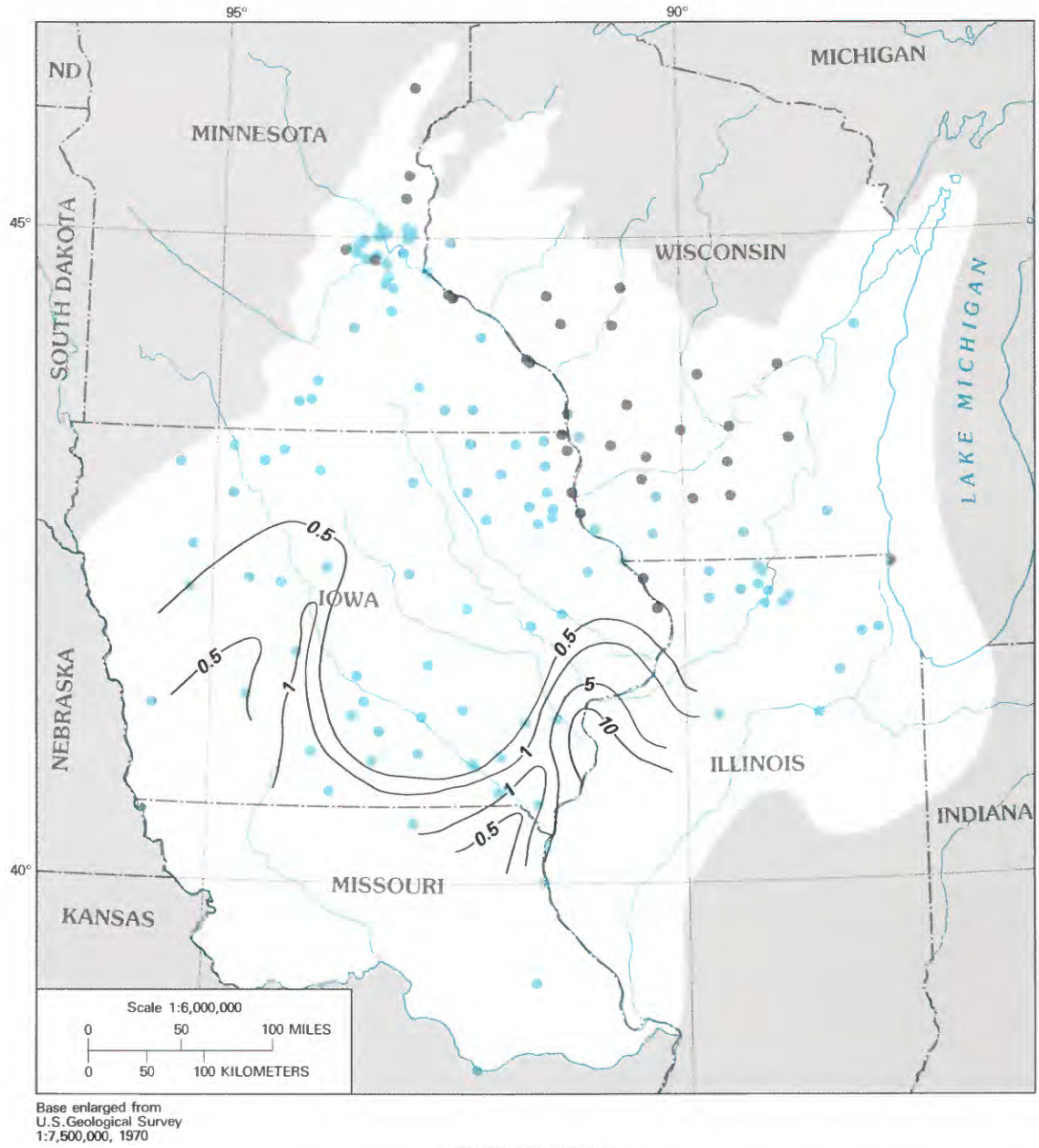
—1000— LINE OF EQUAL DISSOLVED STRONTIUM CONCENTRATION—Stippled in direction of lower concentration. Interval, in micrograms per liter, is variable

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

Open to aquifer layer 1

Open to aquifer layer 3

FIGURE 27.—Distribution of dissolved strontium in aquifer layers 1 and 3.



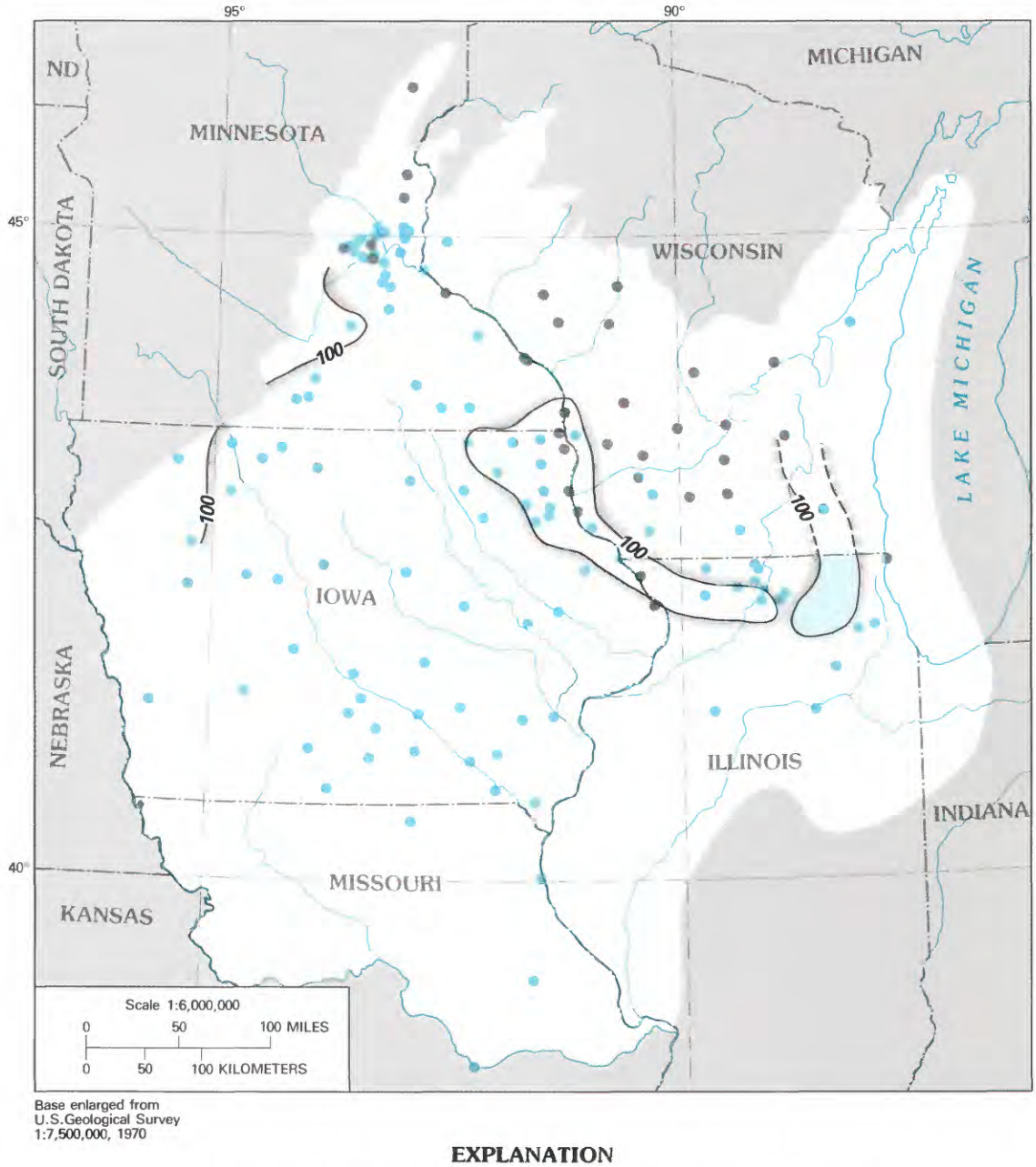
EXPLANATION

—5— LINE OF EQUAL BROMIDE CONCENTRATION—Interval, in milligrams per liter, is variable

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

- Open to aquifer layer 1
- Open to aquifer layer 3

FIGURE 28.—Distribution of dissolved bromide in aquifer layers 1 and 3.



EXPLANATION

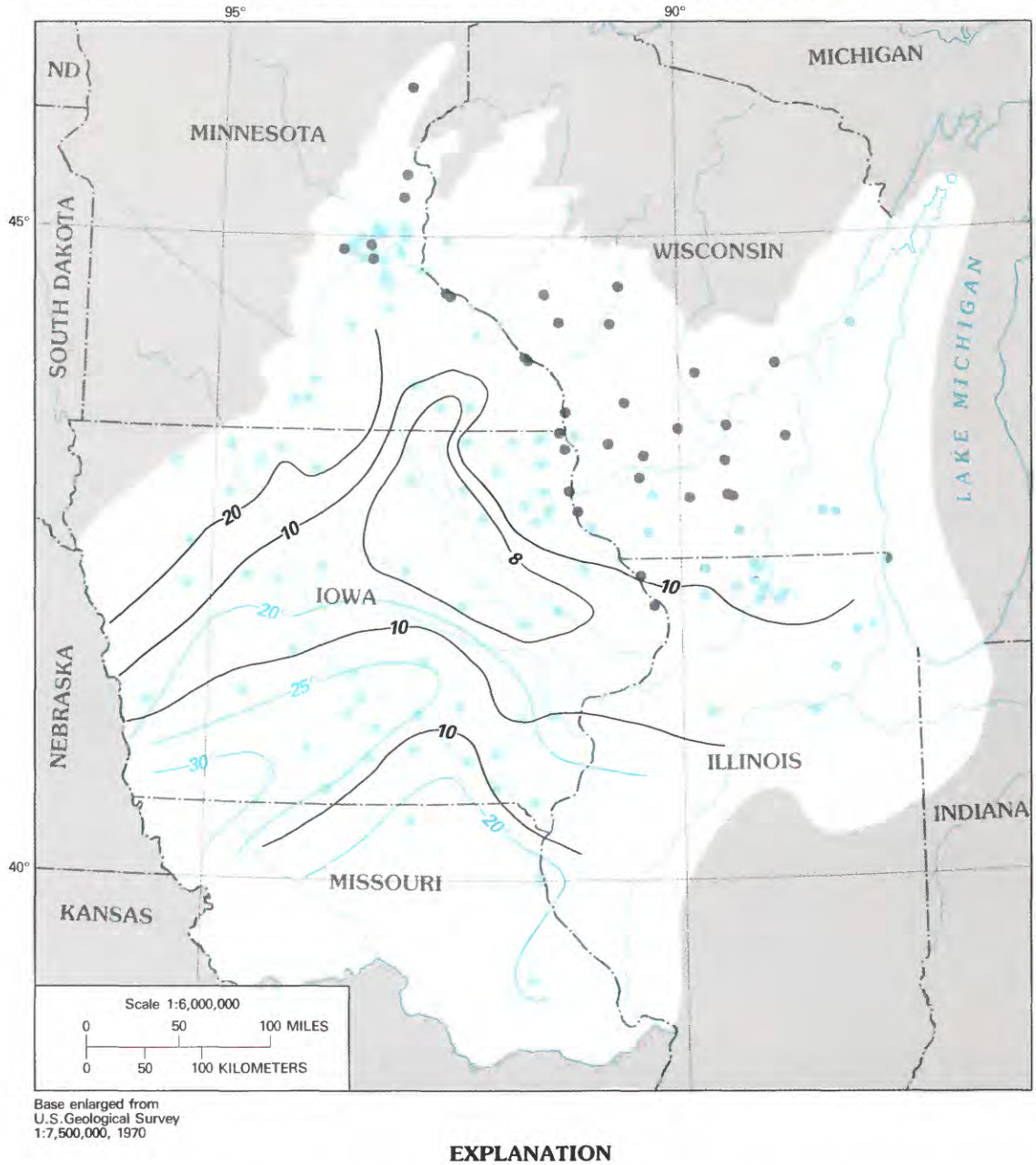
—100-- LINE OF EQUAL DISSOLVED BARIUM CONCENTRATION—Stippled in direction of lower concentration. Dashed where approximate. Interval 100 micrograms per liter

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

- Open to aquifer layer 1
- Open to aquifer layer 3

DATA FROM GILKESON AND OTHERS (1981)

FIGURE 29.—Distribution of dissolved barium in aquifer layers 1 and 3.



EXPLANATION

—20— LINE OF EQUAL DISSOLVED SILICA CONCENTRATION—Interval, in milligrams per liter, is variable

—20— LINE OF EQUAL GROUND-WATER TEMPERATURE—Interval 5 degrees Celsius

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

● Open to aquifer layer 1

● Open to aquifer layer 3

FIGURE 30.—Distribution of dissolved silica and ground-water temperature in aquifer layers 1 and 3.

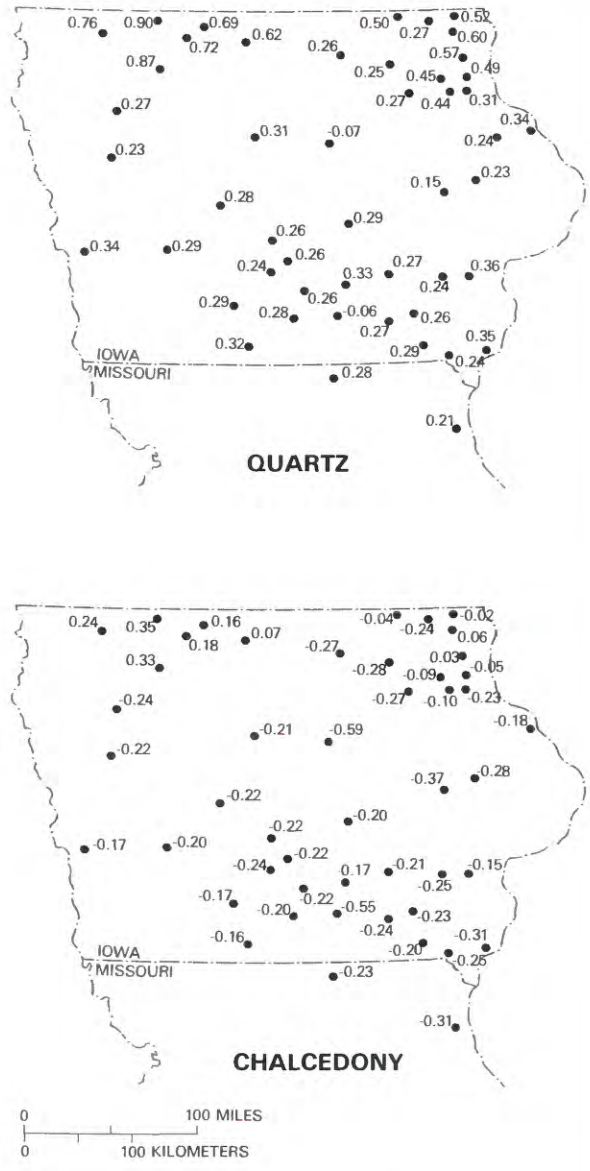


FIGURE 31.—Saturation indices for quartz and chalcedony in water from selected wells in aquifer layer 3 in Iowa and northeastern Missouri.

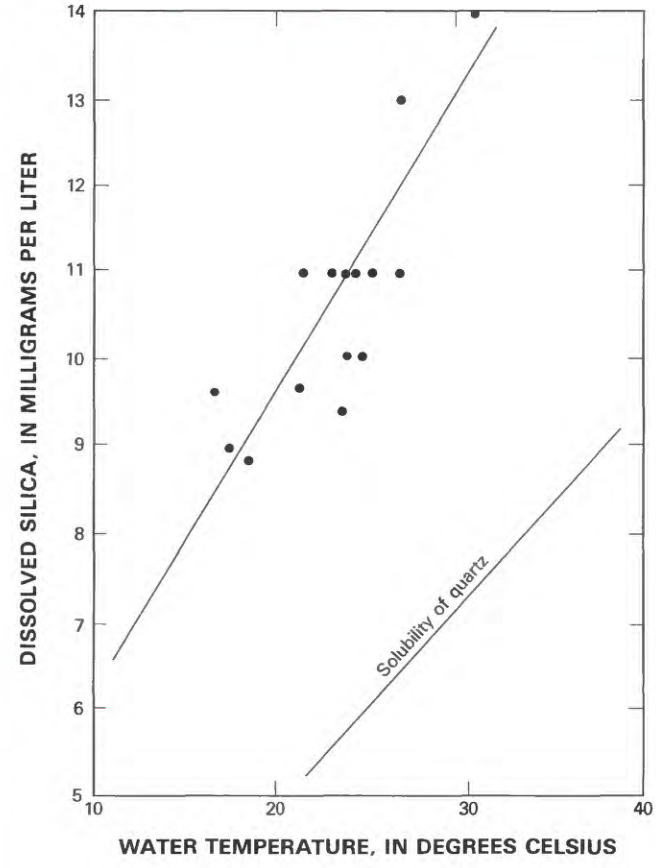
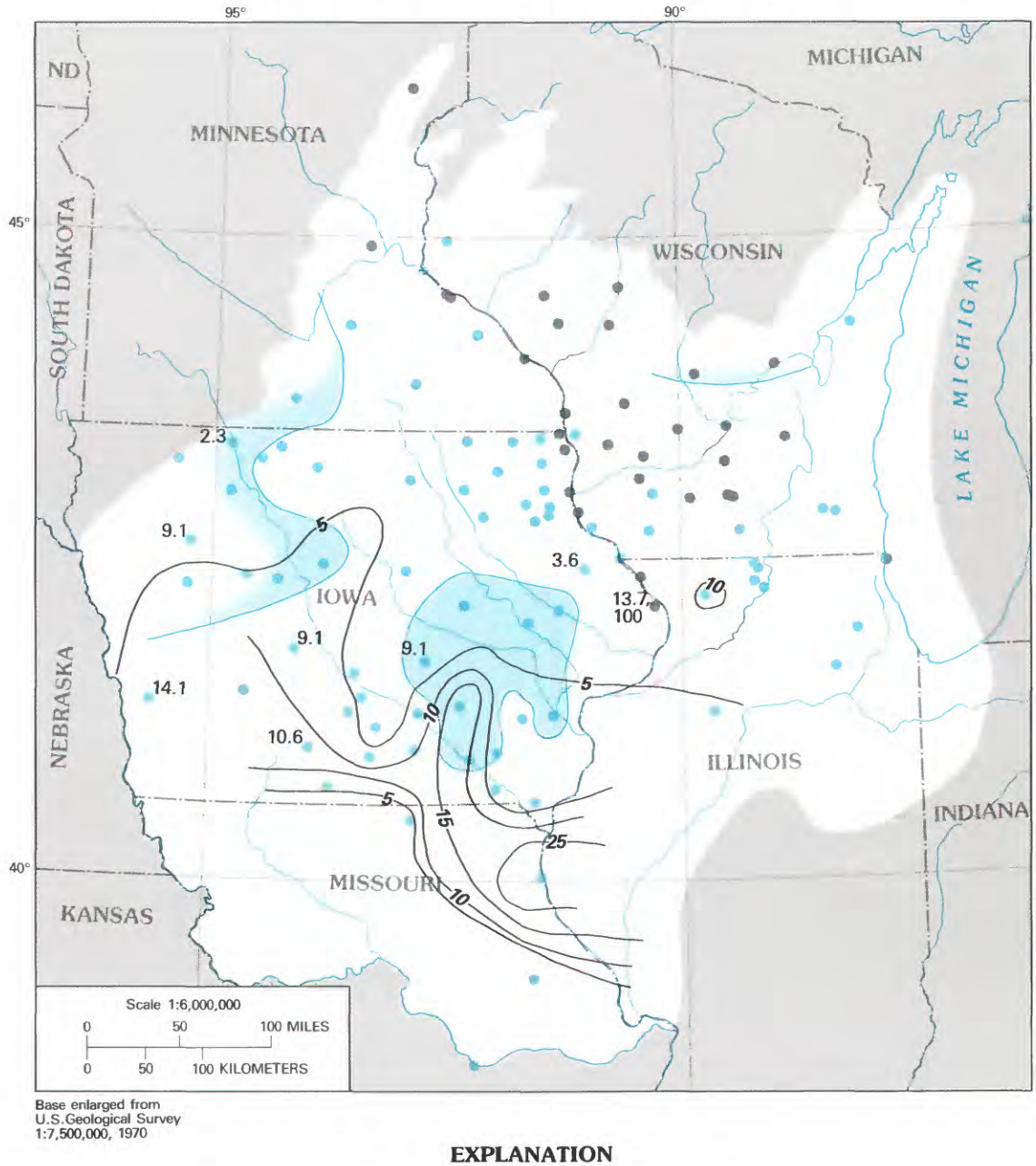


FIGURE 32.—Comparison of dissolved silica concentration and the solubility of quartz with water temperature in southwestern and southern Iowa and northeastern Missouri.

Concentrations of silica in the aquifer system range from less than 8 to more than 20 mg/L (fig. 30). The differences in silica content are related to the solubility of silicate phases in the aquifer matrix. Saturation indices show oversaturation of quartz and undersaturation of chalcedony (fig. 31); this is a typical occurrence in many waters. The solubility of silica in surface and ground water is related to solid-phase products of aluminosilicate mineral dissolution, but no aluminum data are available to test the thermodynamic models of such dissolution in a formal sense.

Concentrations of silica greater than 20 mg/L are present in the recharge area in northwestern Iowa, where the Dakota Formation and the overlying drift contain siliceous shales. Concentrations decrease downgradient to less than 10 mg/L in central Iowa, increase to more than 10 mg/L in south-central Iowa, and then decrease to less than 10 mg/L in southeastern Iowa. The distribution patterns of silica and temperature are very similar, showing the direct relationship of silica solubility to water temperature. However, the data in figure 32 indicate that the relationship of quartz solubility with temperature is not the control on dissolved silica (Helgeson, 1969). This suggests that silica phases other than quartz are contributing silica to the ground water.



EXPLANATION

—10— LINE OF EQUAL RADIUM-226 CONCENTRATION—Interval, in picocuries per liter, is variable

AREA WHERE DISSOLVED URANIUM CONCENTRATION EXCEEDS 1 MICROGRAM PER LITER

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY
Number is activity ratio of $^{234}U/^{238}U$

13.7 Open to aquifer layer 1

9.1 Open to aquifer layer 3

FIGURE 33.—Distribution of dissolved uranium and radium-226 in aquifer layers 1 and 3.

The distribution of uranium and radium-226 in the aquifer system shows the effects of the dilution plume in Iowa (fig. 33) on the concentration of these constituents. Uranium exceeds 1 μg/L in northwestern and southeastern Iowa but is less than 1 μg/L in central and southern Iowa and in northern Missouri in the vicinity of the plume of low dissolved solids. The 5-pCi/L line of radium-226 activity clearly defines the shape of the plume. Activity increases to more than 15 pCi/L southward near the Iowa-Missouri border, but the scant available data show a decrease to 5 pCi/L in northern Missouri.

High radium activities have been identified in Iowa (Brown and Morris, 1959; Lucas, 1960, 1985; Morris and Klinsky, 1962; Horick and Steinhilber, 1978; Cochran and Hahne, 1979), eastern Wisconsin (Lucas, 1960, 1985; Hahn, 1984), and northeastern Illinois (Lucas and Ilcewicz, 1958; Krause, 1959, 1960; Larson and Weatherford, 1960; Lucas, 1960, 1985; Emrich and Lucas, 1963; Kristoff and others, 1975; Gilkeson and Cowart, 1982; Gilkeson and others, 1983).

The sources of the high radium concentrations in the ground water are probably related to uranium-238 and thorium-232 in the aquifer matrix. These radioisotopes decay to radium-226 and 228, respectively. In Illinois, Gilkeson and others (1978) used radium-226 and radium-228 concentrations in 33 samples of Cambrian and Ordovician rocks to estimate the equivalent amounts of uranium-238 and thorium-232, assuming equilibrium between the parent-daughter nuclides. Calculated average uranium-238 concentrations ranged from about 1 ppm in sandstone to about 3 ppm in shale. Direct determinations of uranium-238 indicated that uranium-238 and radium-226 are in equilibrium or near equilibrium in the Cambrian-Ordovician rocks.

The activity of radium-226 and concentrations of uranium in solution may not be directly correlated, however, because of restraints on the solubility of uranium in different redox (reduction-oxidation) environments. Uranium is mobile in oxidizing environments and immobile in reducing environments (Hostetler and Garrels, 1962; Langmuir, 1978). Gilkeson and Cowart (1982) observed a decrease in total uranium concentrations from a few tenths μg/L to less than 0.01 μg/L across a reduction front along a flow path in the Cambrian-Ordovician aquifer system in northeastern Illinois. Downgradient from the reduction front, however, uranium increased to more than 0.3 μg/L under oxidizing conditions. The decrease in uranium in the central part of Iowa also could be due partly to more reducing conditions along the major flow paths. The increase in uranium in southeastern Iowa, however, probably is not caused by increased uranium solubility in oxidizing conditions, because other chemical constituents, such as dissolved sulfide, indicate probable reducing conditions.

Radium-226 activity can be increased in the ground water along a reducing front because of decay of uranium in the water and uranium previously precipitated in the aquifer matrix. The decrease in uranium in Iowa is not accompanied by an increase in radium-226 from northeast to southwest. Therefore, concentrations of uranium and radium-226 in central Iowa seem to be related more to the dilution events than to geochemical processes in the aquifer system.

The activity ratio of $^{234}U/^{238}U$ generally increases across a reducing front because of alpha-recoil transfer (Kronfeld and others, 1975; Cowart and Osmond, 1977). No such increase in the activity ratio is apparent from the data in central Iowa. However, to relate redox relationships to uranium and radium in ground water, more detailed sampling is necessary at a closer spacing than for the reconnaissance purposes of this study. Defining sources and sinks for radium and uranium in the study area would require more detailed information on the concentrations and isotopic variability of these constituents and thorium in aquifer matrices and ground water. For example, in a more detailed study, Gilkeson and Cowart (1982) determined $^{234}U/^{238}U$ alpha-activity ratios in ground water from the aquifer system along a flow path from the unconfined to confined system in northeastern Illinois. Where the aquifer is confined by the Maquoketa Shale, ratios exceed 20, but in the unconfined area, ratios are generally less than 5. The disequilibrium in the confined area is pronounced, and Gilkeson and Cowart (1982) suggest that dissolved uranium was emplaced in the aquifer during Pleistocene glaciation when flow directions may have been different from those of today. Uranium-234 could then have been leached from glacial till and the Maquoketa Shale. However, the observed disequilibrium still is problematical, because the role of geochemical and radiogenic mechanisms in enriching the isotopic ratio is not fully understood (Gilkeson and others, 1978).

Similar disequilibria are found in selected samples of water from aquifer layer 3 in Iowa. $^{234}U/^{238}U$ activity ratios determined from a few selected water samples showed disequilibrium and range from 2.3 to 14.1 with no discernible pattern (fig. 33). For example, the ratio is 9.1 for water in the northwest recharge area associated with the Dakota Formation as well as for water in the central dilute plume area. The scant data suggest that the ratio in Iowa increases generally toward the south, but additional data are needed to verify the trend.

A water sample from a 2,673-ft-deep test well drilled during this study at Green Island in extreme eastern Iowa is of particular interest. The sample from the interval 1,741 to 2,673 ft in the Mount Simon Sand-

stone had the extraordinarily high ratio of 100 (fig. 33). This may be the largest known uranium disequilibrium in an aquifer system. Gilkeson and Cowart (1982) indicate that the highest reported ratio prior to their work was 12.3. They measured activity ratios as high as 28.6 in the Cambrian-Ordovician aquifer system in northeastern Illinois and activity ratios "greater than 40" in the aquifer system in other parts of Illinois.

Gilkson and Cowart (1982) hypothesize that such extreme disequilibrium may be related to influx of uranium-234-enriched uranium derived from fine-grained materials during the emplacement of glacial meltwater during the Pleistocene. The uranium-234-enriched ground water could be further enriched by isotopic fractionation caused by precipitation of the uranium in the reducing zone downgradient from the meltwater recharge front. Unfortunately, the scant areal distribution of the uranium isotope data for this study is not sufficient to evaluate this hypothesis further, and the causes of the isotopic enrichment are still unknown.

ISOTOPIC COMPOSITION OF WATER AND PLEISTOCENE RECHARGE MODEL

The direction of the dilute plume, from northeastern Iowa to south-southwestern Iowa, suggests a flow system having recharge areas in southeastern Minnesota and northeastern Iowa and discharge areas in Missouri or farther south. The study region was glaciated numerous times during the Pleistocene Epoch. Work by Boellstorff (1976, 1980) indicates that at least Nebraska and Iowa were glaciated as long ago as 2.5 m.y. (million years) and that the classic Nebraskan-Kansan sequence of glaciation—now referred to as Pre-Illinoian (Richmond and Fullerton, 1986)—occurred 1.0 to 0.4 m.y. ago. At least five ice advances occurred in Iowa and Nebraska during this time. No similar sequence of glaciation has been identified in Wisconsin and Illinois to date, but evidence of such glaciation could be obscured by glaciation during Illinoian and Wisconsin time, from about 100,000 to 12,000 yr B.P. (years before present).

The extent of major glaciations (fig. 34) has been estimated from the stratigraphic relationships among glacial deposits (Flint, 1972). Pre-Illinoian advances extended almost to the Missouri River and covered much of the study area. Later advances during Illinoian time covered most of Illinois and parts of Wisconsin. During Wisconsin time, numerous ice lobes advanced into Wisconsin, Minnesota, Iowa, and Illinois.

Theoretical reconstructions of the temperature distribution in continental Pleistocene glaciers have indicated that a pressure-melting zone probably was extensive in the basal part of the ablation zone. The zone may have extended upgradient for a few hundred miles from frozen ice margins (Hooke, 1977; Sugden, 1977; Moran and others, 1980). Glacial movement in these unfrozen areas involved basal sliding (Weertman, 1957, 1961, 1964; Clayton and Moran, 1974). Landforms such as drumlins, tunnel valleys, and streamlined ridges are field evidence for basal melting (Wright, 1973; Clayton and Moran, 1974; Moran and others, 1980) where meltwater under high hydrostatic head could have recharged the Cambrian-Ordovician aquifer system in outcrop areas.

The isotopic composition of oxygen and hydrogen in the ground water in the aquifer system is important geochemical evidence for such recharge. The distribution of $\delta^{18}O$ and δD in modern precipitation shows excellent covariation with both mean annual air temperature and latitude because of isotope fractionation by the Raleigh distillation effect (Dansgaard, 1964). Covariation between $\delta^{18}O$ and δD of modern precipitation defines an average meteoric water line (Craig, 1961), expressed as

$$\delta D = 8\,\delta^{18}O + 10, \qquad (13)$$

to which the isotopic content of ground water can be compared. If past ground-water recharge occurred under climatic conditions similar to those of today, then the isotopic composition of the ground water should be similar to that of modern recharge. However, if the ground water originally precipitated at temperatures colder than today, its isotopic composition should be lighter than modern recharge but should still plot near the meteoric water line (eq. 13). Deviations of the data from the trend of the line indicate that geochemical processes, such as water-rock interaction, evaporation, or ultrafiltration, have modified the isotopic composition of the water.

The relationship of $\delta^{18}O$ to δD in ground water in the Cambrian-Ordovician aquifer system exclusive of the Illinois basin is similar to the isotopic composition of modern precipitation (fig. 35). This indicates that the water in the Cambrian-Ordovician aquifer system outside the Illinois basin retains its meteoric nature and has been relatively unaltered by significant reactions with the aquifer matrix. Water in the Illinois basin is enriched in oxygen-18 because of probable exchanges between carbonate rock and water at temperatures more than twice the temperature in the fresher and shallower parts of the aquifer system (Clayton and others, 1966). The average $\delta^{18}O$ and δD of modern precipitation in the study area ranges from about −8 to −6 ‰ and from −70 to −50 ‰, respectively, from

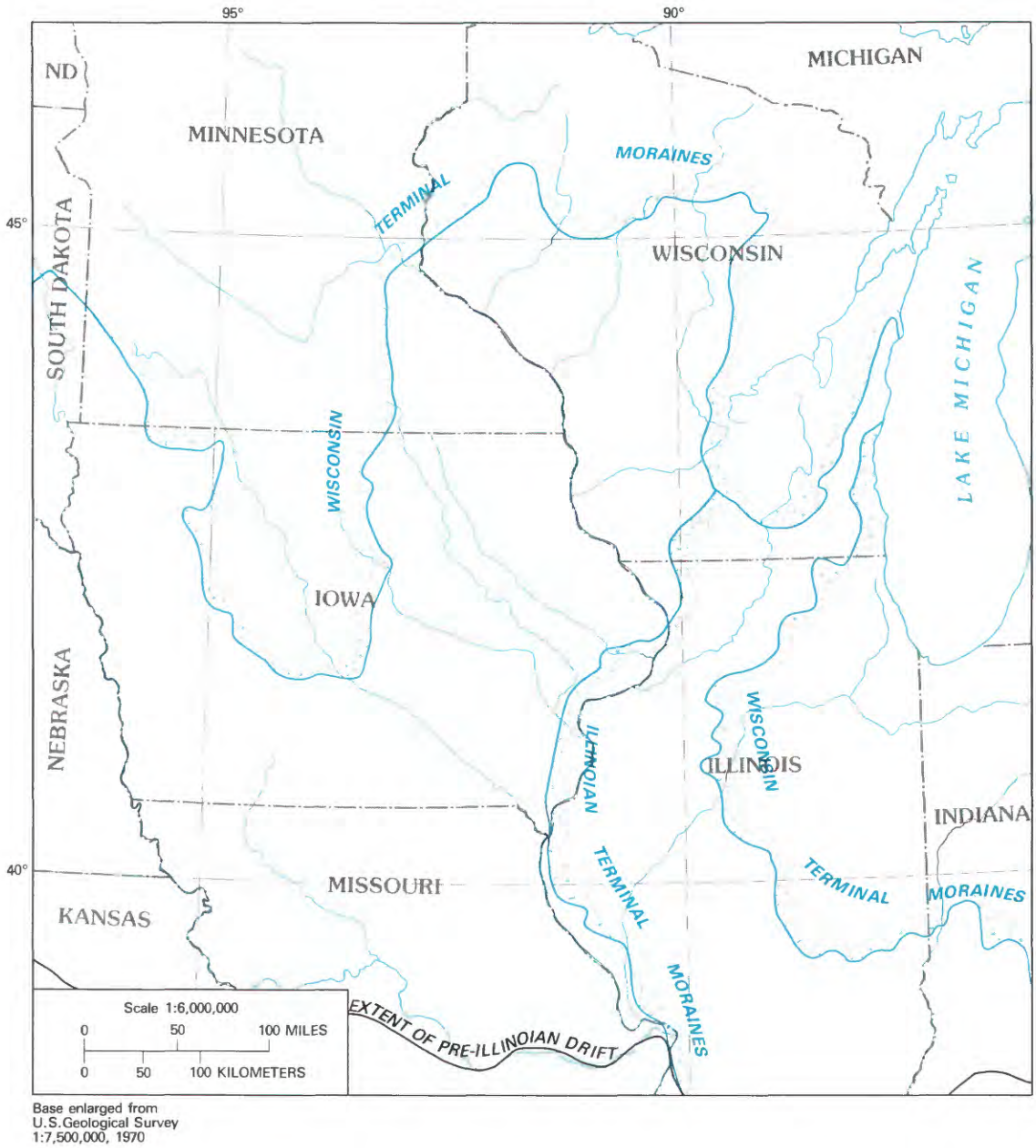


FIGURE 34.—Extent of major glaciations in the northern Midwest during the Pleistocene Epoch.

north to south (Yurtsever, 1975). The difference in $\delta^{18}O$ and δD between water in the aquifer and in modern precipitation, as much as −9 and −70 o/oo, respectively, indicates past recharge to the aquifer system that is isotopically similar to water now precipitated at colder latitudes hundreds of miles north of the study area. No shift occurs in the isotopic content of water across the Holocene-Pleistocene boundary in regional aquifers unaffected by glaciation (Hanshaw and others, 1978). This suggests that the light isotopic composition of the ground water is not a result of continental differences in the isotopic composition of interstadial precipitation.

Isotopically light ground water in the aquifer system in northern Illinois has been described previously and explained as Pleistocene recharge (Clayton and others, 1966; Gilkeson and others, 1981; Perry and others, 1982). Regional distribution of the isotopic composition of water in the aquifer system (figs. 36, 37) closely approximates the distribution of dissolved solids (fig.

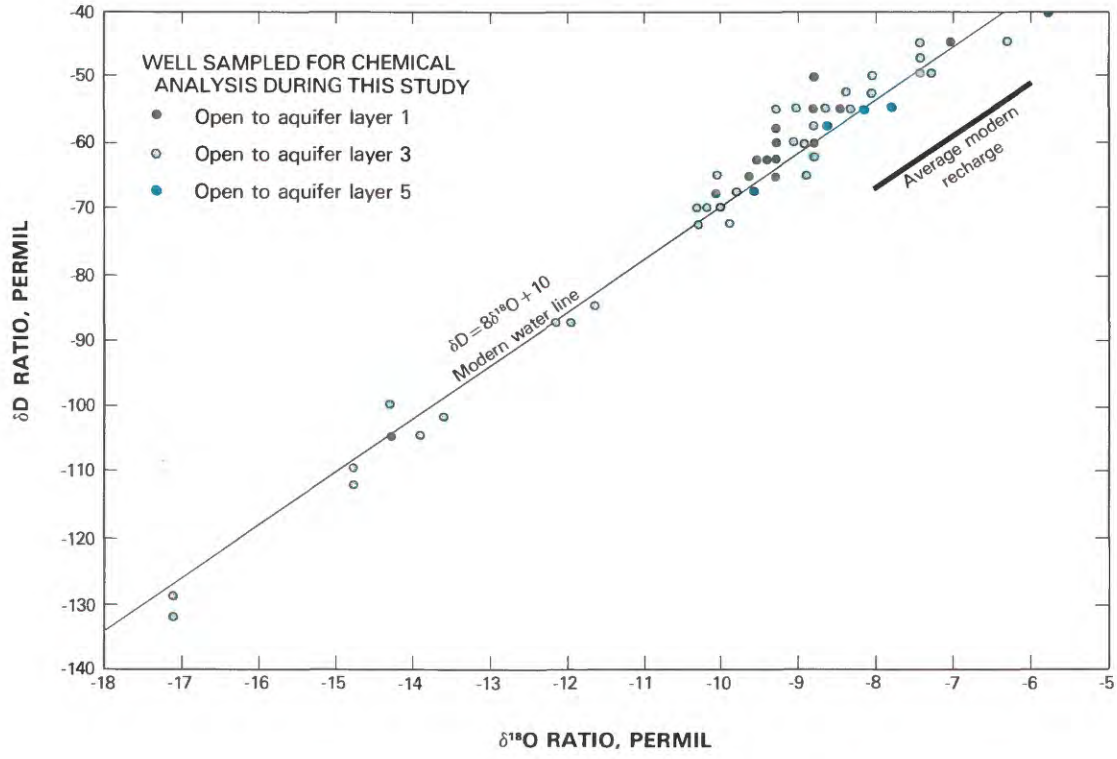


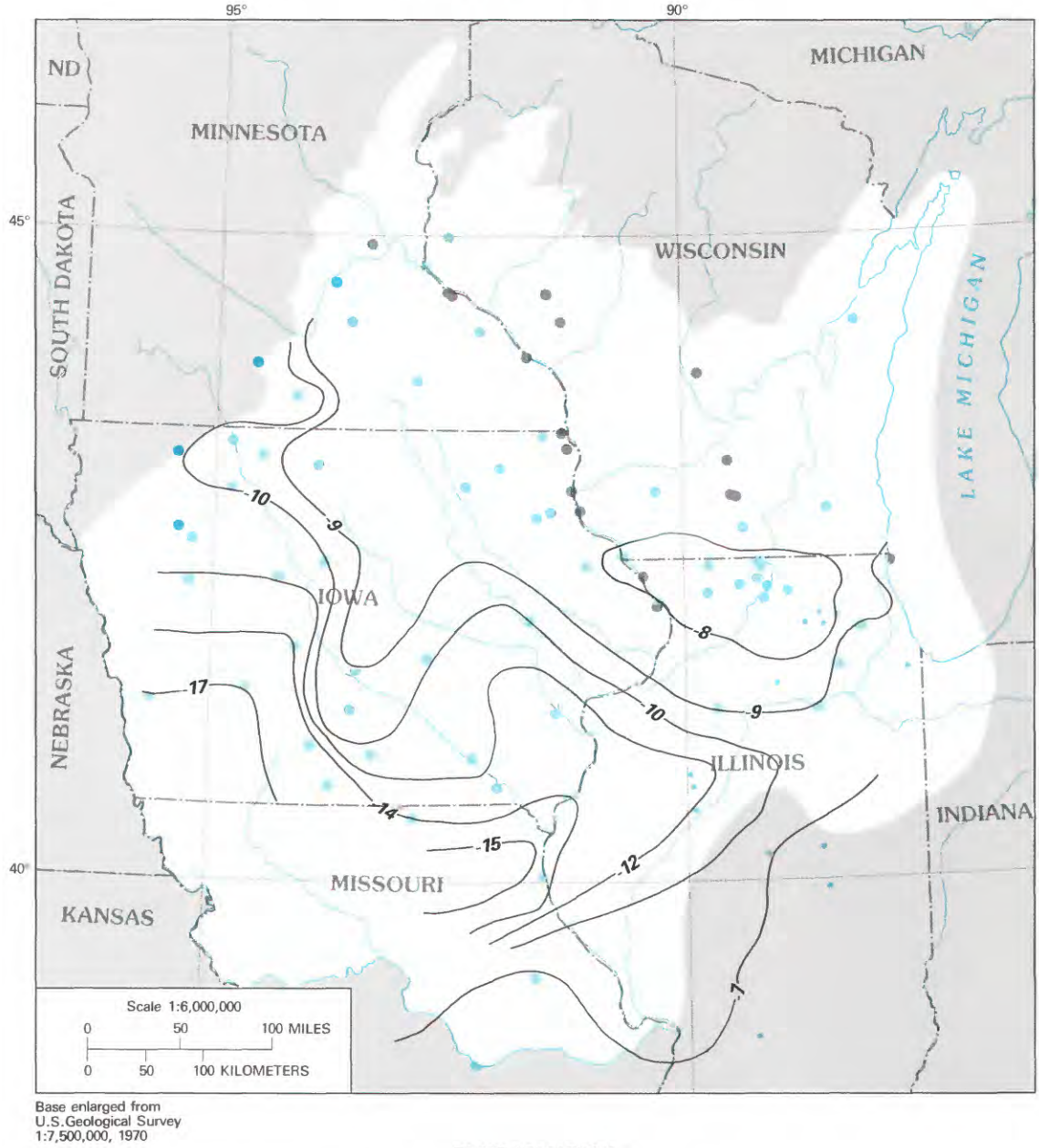
FIGURE 35.—$\delta^{18}O$-δD relationship for ground water in the northern Midwest.

7). In Iowa and Missouri, ground water is isotopically lighter toward the south, approximately perpendicular to the direction of the modern hydraulic gradient. The boundary of the dilute plume in central Iowa is coincident with the −10 o/oo $\delta^{18}O$ isoline. The plume, although isotopically about 2 to 4 o/oo lighter with respect to $\delta^{18}O$ than modern recharge at the same latitude, is isotopically heavier than surrounding ground water. The extension of the −10 o/oo line into south-central Iowa and the distribution of dissolved solids suggest a ground-water flow direction approximately perpendicular to that of today.

The $\delta^{18}O$ content of North American ice sheets could have ranged from about −40 o/oo (Dansgaard and Tauber, 1969) to −9 o/oo (Emiliani, 1971). Yapp and Epstein (1977), using calculations from δD of cellulose in plant material entrained in drift, suggest an intermediate $\delta^{18}O$ of −15 o/oo for the ice of the latest Wisconsin advance. If the isotopically lightest water in the aquifer system in southern Iowa were emplaced during this time, virtually all the ground water in the southwestern part of the study area would be recharged from glacial meltwater. This is unlikely because the dissolution of carbonate and silicate minerals at aquifer temperatures (less than 40 °C) would not produce concentrations of dissolved solids exceeding 2,500 mg/L or the large equivalent percentages of chloride and sodium found in the southwestern part of the aquifer. Therefore, the isotopic content of the ground water probably represents a mixture of meltwater with $\delta^{18}O$ depleted to less than −17 o/oo and pre-Pleistocene ground water with $\delta^{18}O$ enriched to more than −17 o/oo, and perhaps similar to the isotopic content of modern recharge.

The shape of the dilute plume looks similar to the shape of the Des Moines lobe which covered part of north-central Iowa during the last advance of Wisconsin ice. This suggests that the plume may be related to this ice advance. The isotopic content of water in the dilute plume would be lighter than −10 o/oo if the plume were caused by meltwater recharge under the lobe through the outcrop area in southern Minnesota. However, the possible displacement of ground water having low dissolved solids from overlying Paleozoic aquifers to aquifer layer 3 by vertical leakage of subglacial meltwater cannot be ruled out unequivocally at this time.

Scant data indicate that dissolved-solids concentrations in aquifer layer 4 are generally more than 1,000 mg/L where the aquifer is overlain by Mississippian rocks in central Iowa but are generally less than 500 mg/L in outcrop areas north of the Mississippian erosional edge (U.S. Geological Survey, unpub. data).



EXPLANATION

—8— LINE OF EQUAL $\delta^{18}O$ RATIO— Interval, permil, is variable

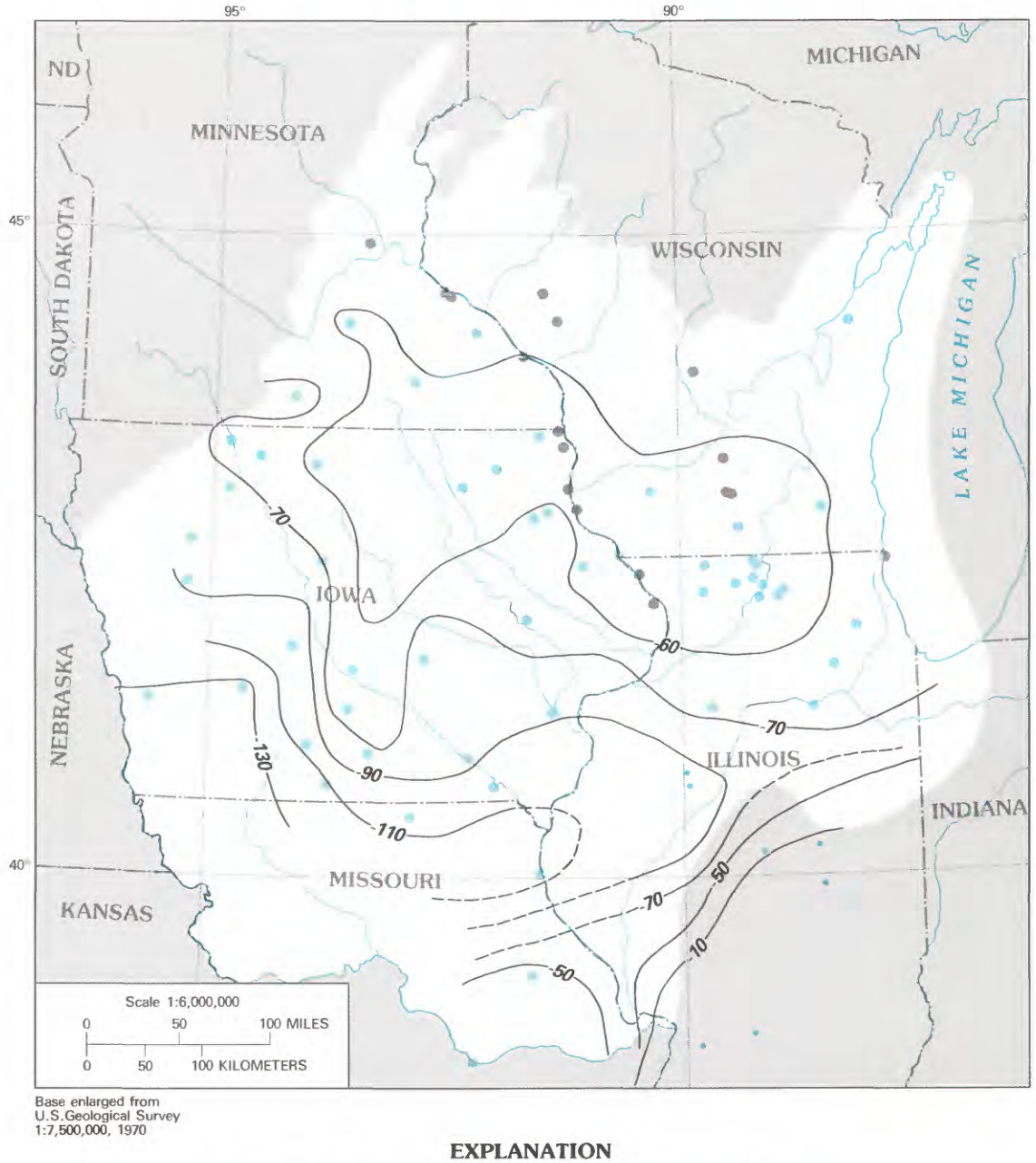
WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

- Open to aquifer layer 1
- Open to aquifer layer 3
- Open to aquifer layer 5

WELL WITH ANALYSIS FROM OTHER SOURCE

- Open to aquifer layer 3

FIGURE 36.—Distribution of $\delta^{18}O$ ratio in aquifer layers 1, 3, and 5.



EXPLANATION

--70— LINE OF EQUAL δD RATIO—Dashed where approximate. Interval, permil, is variable

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

Open to aquifer layer 1

Open to aquifer layer 3

WELL WITH ANALYSIS FROM OTHER SOURCE

Open to aquifer layer 3

FIGURE 37.—Distribution of δD ratio in aquifer layers 1 and 3.

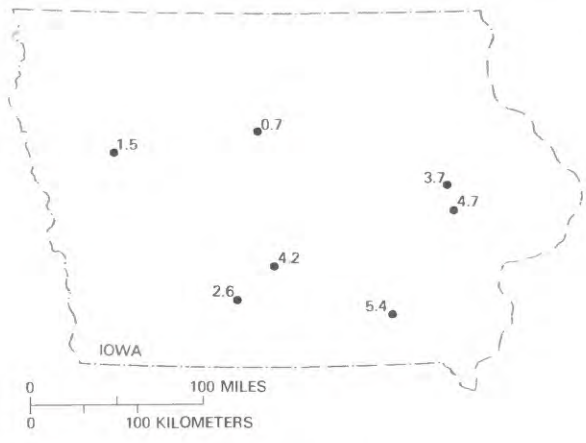


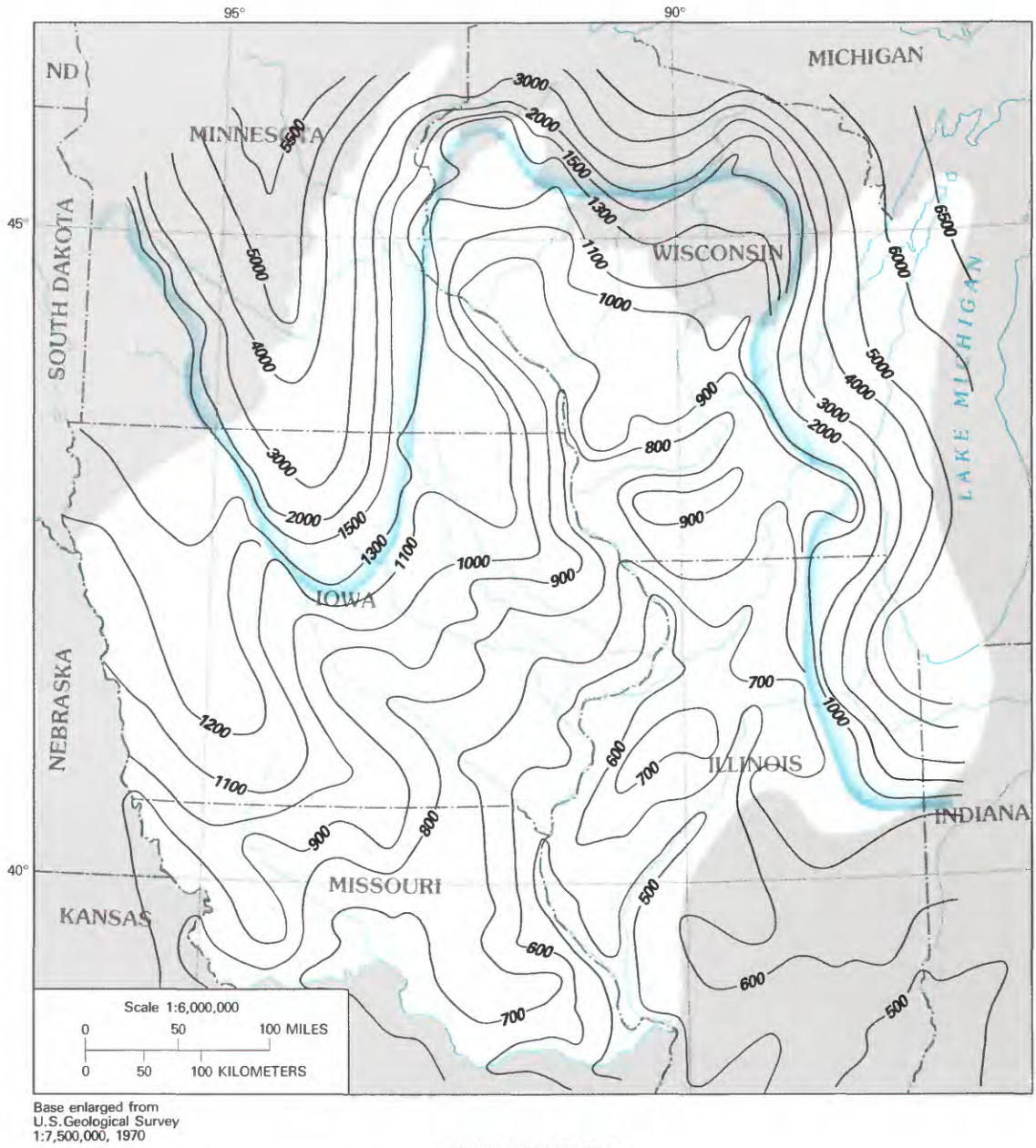
FIGURE 38.—Carbon-14 data for water from selected wells in aquifer layer 3 in Iowa.

Dissolved-solids concentration in ground water from Mississippian rocks in north-central Iowa is more than 500 mg/L. The 1,000-mg/L isoline of dissolved solids in the Mississippian rocks roughly outlines a dilute plume trending from north-central to southwestern Iowa (Horick and Steinhilber, 1973), similar to the plume in aquifer layer 3.

Downward movement of meltwater from the base of the Des Moines lobe into the Mississippian rocks could have started a series of downward displacements of water from layer to layer: recharge of water with low dissolved solids into the Mississippian; higher disolved-solids water (more than 1,000 mg/L) from the Mississippian into aquifer layer 4; and water with low dissolved solids from aquifer layer 4 into aquifer layer 3, forming the dilute plume. Water in aquifer layer 4 could have had a $\delta^{18}O$ content ranging from −8 to −6 o/oo if it were not mixed with meltwater recharge from previous glaciations. Downward flow of water from aquifer layer 4 to aquifer layer 3 could have resulted in both dilution and isotopic enrichment. However, additional isotopic data for ground water from aquifer layer 4 and the Mississippian in central Iowa are needed to evaluate better the influence of the Des Moines lobe on the Cambrian-Ordovician aquifer system.

The time, or times, of meltwater emplacement is unknown. Seven carbon-14 analyses of ground water from aquifer layer 3 in Iowa have a range of 0.7 to 5.4 percent modern carbon (fig. 38). These values correspond to apparent ages ranging from more than 30,000 to about 15,000 yr B.P., respectively, corrected for isotopic dilution by dissolution of carbonate aquifer minerals. The smallest amount of modern carbon occurs in central Iowa within the dilute plume. This could reflect either the age of water in aquifer layer 3 or a composite age of water from aquifer layers 3 and 4, if vertical recharge occurred beneath the ice of the Des Moines lobe. A small amount of modern carbon may have been introduced in the sampling procedure at other sites as contamination from atmospheric carbon dioxide (E.C. Alexander, University of Minnesota, written commun., 1982; L.N. Plummer, U.S. Geological Survey, oral commun., 1982). Water in aquifer layer 1 at St. Paul, Minn., has an apparent age of more than 35,000 yr B.P. (Alexander and others, 1983), and very likely water in the Cambrian-Ordovician aquifer system in southern Iowa and northern Missouri also contains little or no measurable carbon-14 because flow paths are many times longer than in Minnesota.

The possible emplacement of meltwater during the late Pleistocene was independently tested using the steady-state three-dimensional ground-water flow model of Mandle and Kontis (in press) to simulate the Cambrian-Ordovician aquifer system under the pressure head caused by the weight of the glacial ice about 18,000 yr B.P. The head values for the water-table aquifer (aquifer layer 5) in the ice-covered areas (fig. 39) were estimated as the sum of the elevation head at the land surface and the pressure head from the ice. The water-table aquifer is represented by constant-head nodes in the model and provides the hydraulic driving force to simulate ground-water flow. An average Wisconsin glacial ice-sheet configuration was assumed similar to that described by Denton and Hughes (1981). The static steady-state topography of the ice sheets at maximum advance calculated by Denton and Hughes (1981) was based on the modern analog of the Greenland and Antarctic ice sheets. This may be incorrect because geologic evidence suggests that the Laurentide ice sheet did not attain a steady-state profile everywhere but may have been highly dynamic (Clark, 1980; Andrews, 1982). Nevertheless, the Denton and Hughes (1981) model is probably a first approximation for the general morphometry of the major ice lobes that entered the northern Midwest during Wisconsin time. Hydraulic parameters, boundaries, and nodal distribution for all aquifer layers were those used in a steady-state flow model of the modern Cambrian-Ordovician aquifer system described by Mandle and Kontis (in press). The position of the ancestral Mississippi River was assumed to be similar to its present position. Although the ancestral Mississippi River was displaced in some areas during the late Pleistocene, the displacement did not significantly alter the general drainage pattern from



EXPLANATION

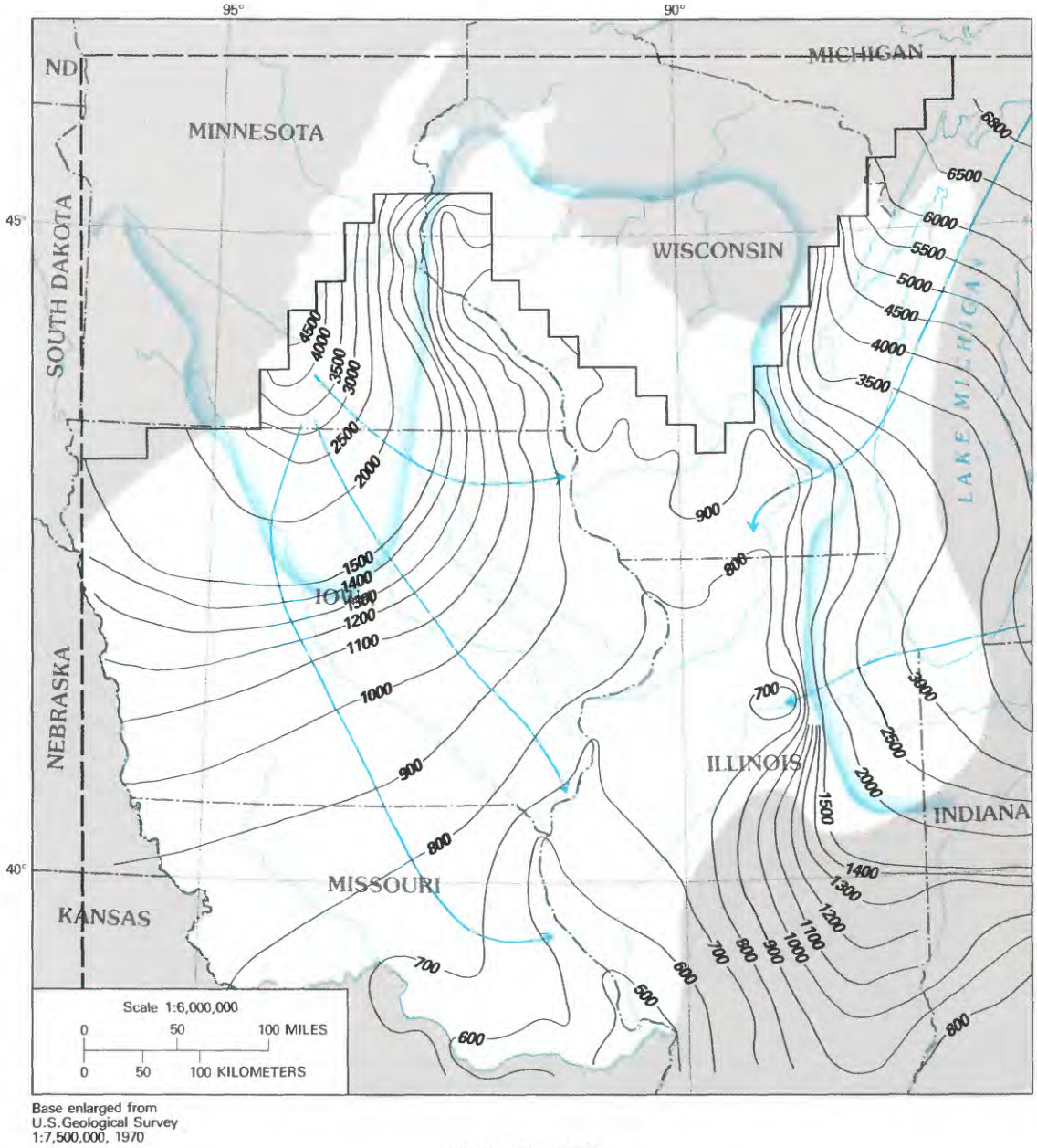
—800— POTENTIOMETRIC CONTOUR—Shows altitude of assumed potentiometric surface for aquifer layer 5, 18,000 years B.P. Contour interval, in feet, is variable. Datum is sea level

APPROXIMATE ICE MARGIN

FIGURE 39.—Assumed hydraulic head for aquifer layer 5 incorporating effects of ice thickness at the average advance of ice, about 18,000 yr B.P., during late Wisconsin time.

north to south near the border of Iowa and Illinois (Flint, 1972).

Results of the steady-state flow model show that the distribution of ice at the average Wisconsin advance probably did not significantly change the direction of ground-water flow in most of Iowa and Missouri (fig. 40). Ground-water flow paths, in general, were from northwestern Iowa southeastward to the Illinois basin.



EXPLANATION

—900— POTENTIOMETRIC CONTOUR—Shows altitude of simulated potentiometric surface for aquifer layer 3, 18,000 years B.P. Contour interval, in feet, is variable. Datum is sea level

APPROXIMATE ICE MARGIN

GENERALIZED GROUND-WATER FLOW PATH

MODELED LAYER 3 BOUNDARY

BOUNDARY OF GROUND-WATER FLOW MODEL

FIGURE 40.—Simulated hydraulic head in aquifer layer 3 at the average advance of ice, about 18,000 yr B.P., during late Wisconsin time.

Some ground-water flow was diverted from central to northeastern Iowa from a local ground-water divide that is symmetrical with the axis of the Des Moines lobe in Iowa. In eastern Wisconsin and Illinois, simulated ground-water flow was opposite from that of today: ground-water recharge zones were in the vicinity of Lake Michigan, and discharge zones were the outcrop areas in Wisconsin, northeastern Iowa, southeastern Minnesota, and northern Illinois. Results of the flow model show that, during late Wisconsin time, the net movement of ground water was not in the direction of the dilute plume, from northeastern to southwestern Iowa. Much of the outcrop area of the aquifer in Wisconsin, Iowa, and Illinois was probably a discharge zone, as suggested by the results of the flow model, and not a recharge zone, as suggested by the geochemical data.

Model-calculated horizontal flow rates of the present flow system in Iowa are extremely slow, ranging from a few feet per year in the recharge area in northwestern Iowa to less than 1 ft/yr in deeper parts of the aquifer (Mandle and Kontis, in press). These flow rates indicate that residence time for most of the water in the aquifer system could be tens of thousands to hundreds of thousands of years. The slow flow rates compare favorably with the carbon-14 date of more than 35,000 yr B.P. for water in aquifer layer 1 from a well in St. Paul, Minn. (Alexander and others, 1983).

Model-calculated horizontal flow rates under the Des Moines lobe are about 10 times larger than present flow rates. Model-calculated vertical leakage from aquifer layer 4 to aquifer layer 3 in the confined part of Iowa is less than 5,000 (ft^3/mi^2)/yr, even under simulated glacial head from the Des Moines lobe. This amount of vertical leakage is insignificant with respect to the total amount of water in aquifer layer 5. The volume of water per square mile in aquifer layer 3 is approximately 2×10^9 ft^3, assuming an average thickness of 300 ft and a porosity of 0.25. Only about 2.5 percent of the water in the aquifer would be replaced in 10,000 yr at the maximum calculated flow rates owing to glacial-ice loading.

This computed result suggests that downward leakage from younger Paleozoic rocks to aquifer layer 3 probably did not cause the dilute (low dissolved solids) plume in Iowa. However, fracture permeability in younger confining units and in the carbonate rocks of the aquifer system was not specifically addressed in the model because of the paucity of field data needed to define fracture locations and patterns. Consequently, the possibility of larger amounts of vertical leakage during glaciation still exists and needs to be tested by additional isotopic data, as discussed previously.

An alternative hypothesis to explain the isotopically defined plume in Iowa is a southerly displacement of ground water having an isotopic content similar to that of modern recharge from the outcrop area in southern Minnesota. Model-calculated flow rates in aquifer layer 3 for the average ice advance in south-central Minnesota range from 10^{-6} to 10^{-5} ft/s. At the fastest rate, meltwater would move downgradient about 60 mi in 1,000 yr. The Des Moines lobe probably was on the outcrop area in southern Minnesota for 2,000 yr, from about 16,000 to 14,000 yr B.P. (Wright, 1972), so the model results indicate that it is possible to have had significant meltwater displacement of ground water ($\delta^{18}O$ content of about −8 o/oo) toward Iowa. The meltwater that replaced the ambient ground water would be isotopically very light. This characteristic should be identifiable today in southern Minnesota, where the aquifer is confined and flow rates are low. On the contrary, $\delta^{18}O$ content of water in aquifer layer 3 in south-central Minnesota is about −9 o/oo; this $\delta^{18}O$ content is only slightly depleted relative to modern recharge and is not characteristic of isotopically depleted water, such as is found in southern Iowa and central Illinois.

The hypothetical steady-state model of the ground-water flow system at the maximum glacial advance during Wisconsin time shows that flow rates are increased significantly only under, and immediately next to, the ice sheets. The simulated effect of the additional pressure head on the potentiometric gradient contributed by the ice sheets is dampened considerably within 30 to 50 mi from the edge of the ice (fig. 40). The steady-state model simulations of predevelopment conditions and with glacial-ice loading during Wisconsin time suggest that the time necessary for a unit volume of recharge in northeastern Iowa and in southern Minnesota to reach north-central Missouri would have been at least tens of thousands of years. Confinement by the ice could accelerate flow rates in Iowa south of the Maquoketa Shale outcrop.

HYPOTHETICAL GEOCHEMICAL MODELS

Previous studies of the chemistry of regional aquifer systems have used mass-balance and reaction models to evalute, at least semiquantitatively, the extent of chemical mass transfer from solid to aqueous phases and the evolution of different water types—for example, Thorstenson and others (1979), Plummer (1977), Chapelle (1983), Plummer and Back (1980), and Plummer and others (1983). These models have been particularly useful for evaluating chemical changes associ-

ated with mixing of different water types—for example, Plummer (1975) and Wigley and Plummer (1976).

The extent to which these approaches can be successfully used in the present study of the geochemistry of the Cambrian-Ordovician aquifer system is limited, because critical data are still unavailable on the solid phases in the aquifer, the isotopic composition of Pleistocene glacial meltwater and precipitation, the pre-Pleistocene topography and water table, and local values for hydraulic characteristics.

The chemical composition of major solid phases, such as calcite, in the aquifer matrices in central Iowa is unknown. Information on bulk chemistry of the rocks and petrographic information on the type and nature of cementation in the rocks are necessary to check the accuracy of mass-balance calculations of net dissolution or precipitation of carbonate minerals (Chapelle, 1983). Identification of clay minerals in the aquifer matrix also is needed to determine appropriate ion-exchange selectivity coefficients for use in thermodynamic models of reaction progress. Estimates of ion-exchange selectivity coefficients from water chemistry (Thorstenson and others, 1979) are not applicable because of possible multiple sources and mechanisms for observed increases in sodium concentrations in southern Iowa and northern Missouri. No direct information is available on the isotopic composition of carbon in the aquifer matrix. Such data are critical to the use of $\delta^{13}C$ information to check the mass-balance models. Furthermore, detailed mass-transfer models that have been used to evaluate carbon isotopes in other aquifer systems (Wigley and others, 1978) cannot be applied to the Cambrian-Ordovician aquifer system because location and magnitude of past recharge were pulselike, depending on the configuration, timing, and duration of the ice sheets during the Pleistocene. Present-day concentrations of solutes may not represent steady-state conditions, and effects of hydrodynamic dispersion on the isotopic composition of ground water during recharge events cannot be excluded.

The $\delta^{18}O$ and δD composition of ground water in the Cambrian-Ordovician aquifer system is probably a composite derived from numerous episodes of Pleistocene recharge to the aquifer system. Assuming that the isotopic composition of the water is conservative, based on the clustering of data around the modern meteoric water line discussed previously (fig. 35), a mixing model can be prepared. However, to prepare such a model, the isotopic composition of both the pre-Pleistocene ground water and the Pleistocene recharge must be known. Within the aquifer system, the isotopic gradient toward lighter water from central to southwestern Iowa shows *no reversal* in trend (figs. 36, 37). The isotopically lightest water may, consequently, be even more depleted in $\delta^{18}O$ than −17 o/oo. Estimation of the $\delta^{18}O$ of Pleistocene recharge is also difficult because the $\delta^{18}O$ of meltwater from glacial ice could have ranged at least from −40 to −15 o/oo. The isotopic composition of precipitation in the region during the Pleistocene may have been different from what it is today.

A mixing model of a chemically conservative constituent is made using the generalized equation

$$C_1(1-Q_2)+ C_2Q_2=C_{mixture}, \quad (14)$$

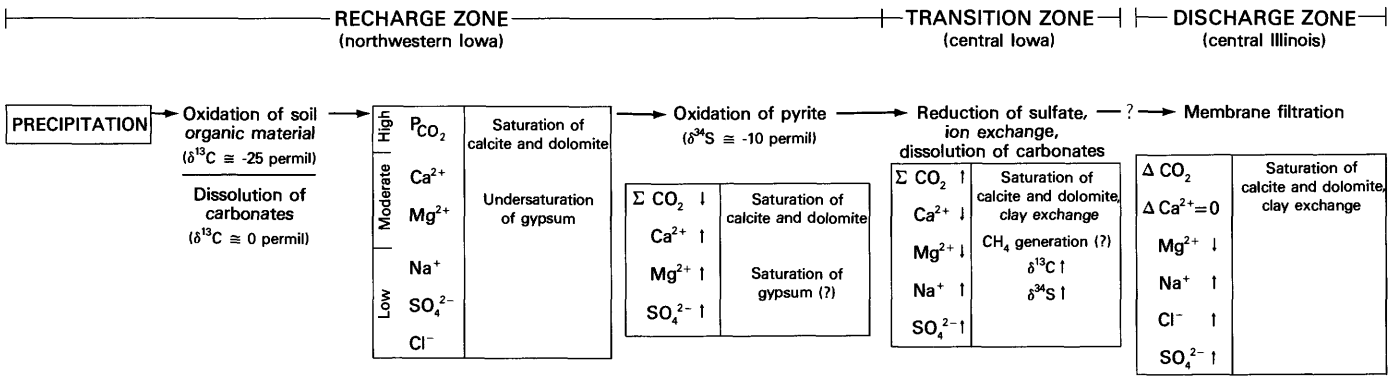
where

C_1=concentration in water 1,
C_2=concentration in water 2, and
Q_2=fraction of water 2 in the mixture.

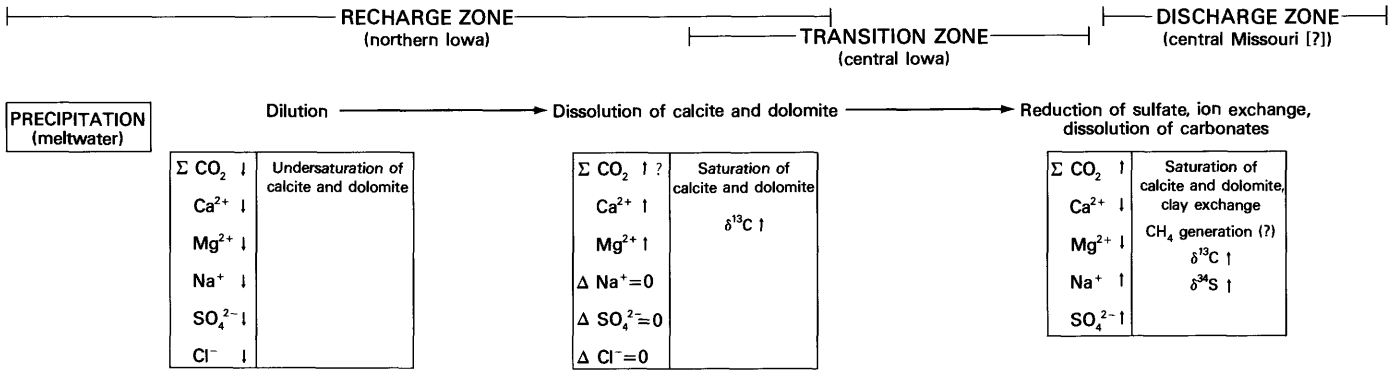
As an example of a mixing model, the following conditions were assumed:

1. Pre-Pleistocene ground water had an istotopic composition similar to the present-day recharge water of about −7 o/oo of $\delta^{18}O$.
2. Glacial meltwater entered the aquifer, resulting in a $\delta^{18}O$ of −17 o/oo, the most isotopically depleted water identified.
3. Subsequent recharge southwestward caused the plume outlined by the −10 o/oo line of $\delta^{18}O$. This recharge water is assumed to have a $\delta^{18}O$ value of −8 o/oo, which is about 1 o/oo lighter than modern recharge.

It follows from these assumptions and for equation 14 that a 1:2.3 mixture of meltwater ($\delta^{18}O$ of −40 o/oo) and pre-Pleistocene ground water ($\delta^{18}O$ of −7 o/oo) would produce an observed $\delta^{18}O$ of −17 o/oo. This first-phase mixture subsequently would have had to be mixed with Pleistocene recharge ($\delta^{18}O$ of −8 o/oo) at ratios of up to 1:9 to produce the present isotopically heavier plume in central Iowa. If the $\delta^{18}O$ of the first mixture were lighter than −17 o/oo, the second-phase dilution would be larger. If recharge in the second mixing phase was isotopically heavier, that is, derived from precipitation during warm interstadial periods (Emiliani, 1955; Ruddiman and McIntyre, 1976), a smaller volume of recharge would have been required. For example, if in the hypothesized second mixing phase $\delta^{18}O$ of Pleistocene recharge in the plume area was about 1 o/oo heavier than in modern precipitation (−6 rather than −7 o/oo), the mixing ratio of ground water with $\delta^{18}O$ of −17 o/oo and recharge with −6 o/oo would have been about 1:2 to produce the heavier plume. These exercises indicate that the amount of Pleistocene meltwater currently in the plume area of aquifer layer 3 could be as much as 90 percent, depending on which isotopic values were chosen in the calculations. If the



EVOLUTION OF WATER CHEMISTRY FROM NORMAL RECHARGE



EVOLUTION OF WATER CHEMISTRY FROM MELTWATER RECHARGE

FIGURE 41.—Hypothetical geochemical models for the evolution of water chemistry in the Cambrian-Ordovician aquifer system.

$\delta^{18}O$ of the pre-Pleistocene ground water was heavier than that of modern precipitation, the total percentage of Pleistocene glacial meltwater in the aquifer system would be less.

The hypothetical hydrologic and geochemical processes that may have affected the water quality of the Cambrian-Ordovician aquifer system are illustrated in figure 41. Preglacial water quality in the major recharge areas in Wisconsin, Minnesota, and northeastern Iowa may be controlled by dissolution of carbonate minerals in the aquifer matrix. Dissolution of carbonate minerals, ion exchange, and oxidation of pyrite may modify the water quality in northwestern Iowa and southwestern Minnesota. Oxidation of pyrite in the Dakota Formation and in glacial till derived from the Dakota Formation produces sulfuric acid (eq. 7) that would increase both the dissolution of carbonate minerals and the concentration of sulfate. Activities of sulfate and calcium may locally approach the solubility of gypsum, although, generally, ground water in the aquifer system and the overlying Dakota Formation and glacial drift is undersaturated with respect to gypsum and other evaporite minerals. Sulfate reduction, oxidation of organic material, and methane generation decrease concentrations of sulfate and increase inorganic carbon content. Downgradient into the transition zones of Ca-Na-SO_4-HCO_3 and Na-Ca-SO_4-HCO_3 facies in Iowa, additional sulfate reduction, unaccompanied by ion exchange, could cause carbonate precipitation. Membrane filtration near and in the Illinois basin may have caused precipitation of calcite, possible dolomitization of the aquifer matrix in the Illinois basin (Graf and

others, 1966; Nesbitt, 1980; R. Shedlock, U.S. Geological Survey, written commun., 1982), and increases in sodium and chloride concentrations.

Glaciation and emplacement of Pleistocene meltwater in the aquifer system in Iowa and Missouri could cause dilution of all ground-water solutes. Although concentrations of conservative solutes, such as bromide and chloride, remained low, redissolution of carbonate minerals in the aquifer matrix increased the bicarbonate, calcium, and magnesium until equilibrium with the carbonate minerals was reestablished. This dilution and reequilibration process could have occurred many times. Glaciation also could temporarily enhance the extent of pyrite oxidation in Iowa because additional pyrite was exposed to the atmosphere by glacial erosion of the Dakota Formation.

The hypothetical model can be tested by evaluating the variations in $\delta^{13}C$ in dissolved inorganic carbon. $\delta^{13}C$ inorganic carbon in ground water from wells in aquifer layer 1 in southeastern Minnesota, southern Wisconsin, and northeastern Iowa ranges from about −14 to −8 o/oo (fig. 42). $\delta^{13}C$ is more than −9 o/oo in aquifer layer 3 in northern Illinois and less than −17 o/oo in northwestern Iowa. Of major interest is the enrichment of $\delta^{13}C$ from about −11 to more than −8 o/oo from northeast to southwest in Iowa, approximately perpendicular to the direction of the present hydraulic gradient.

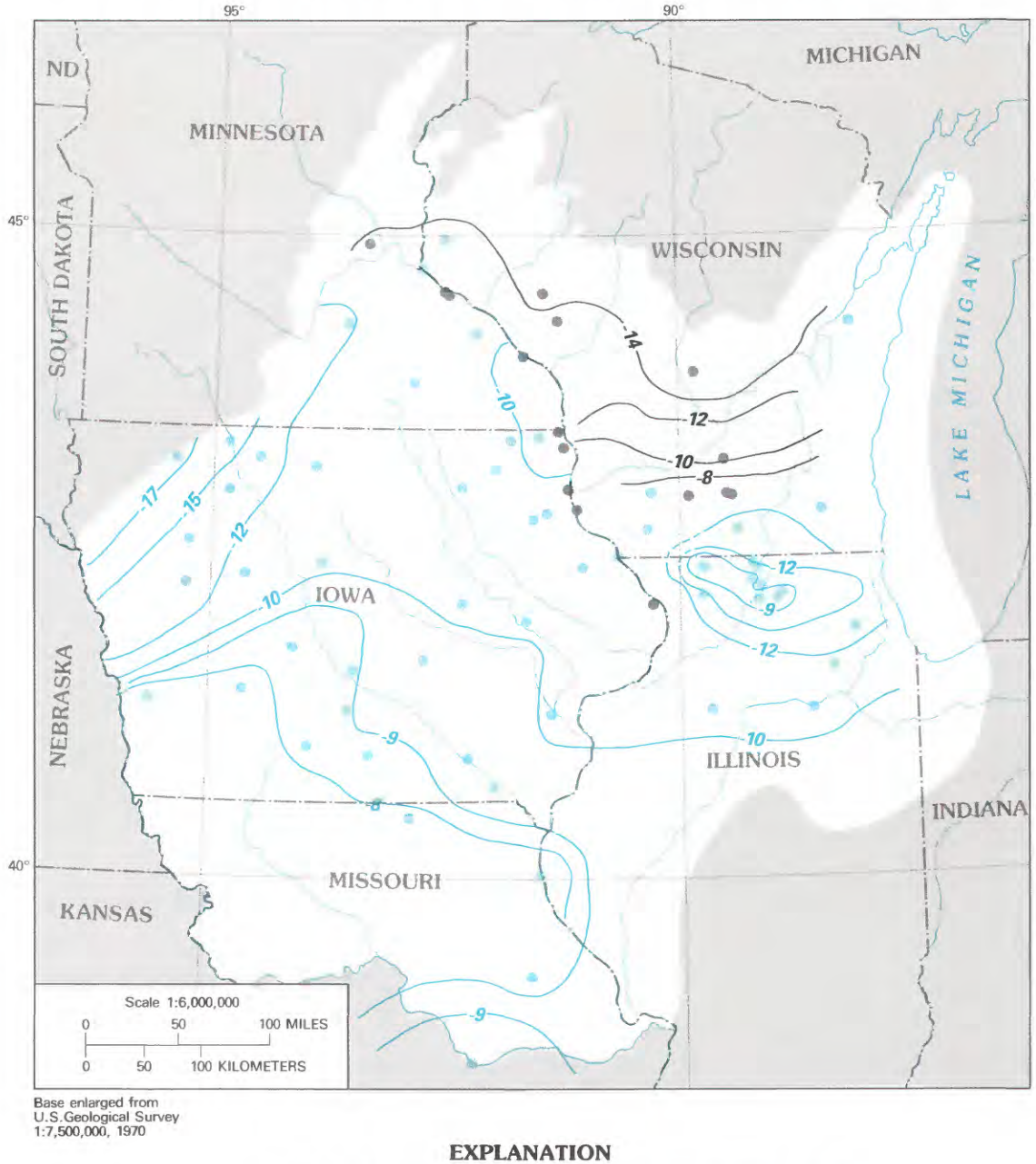
The average of $\delta^{13}C$ in the major recharge areas in Minnesota and Wisconsin is close to −12 o/oo in aquifer layer 1, a value that is typically obtained by the simple closed-system dissolution of carbonate minerals with $\delta^{13}C$ of 0 o/oo (Wigley and others, 1978) by soil carbon dioxide with $\delta^{13}C$ of about −25 o/oo. Recharge to the aquifer system through the Dakota Formation in northwestern Iowa would obtain dissolved carbon from the oxidation of isotopically depleted organic material from both soils and lignite. The $\delta^{13}C$ of the lignite is also probably about −25 o/oo, and consequently the observed −17 to −18 o/oo $\delta^{13}C$ of inorganic carbon in the ground water in aquifer layer 3 is probably caused by fractionation processes. One likely process is bacterially mediated oxidation of methane, which would produce isotopically depleted carbon dioxide with $\delta^{13}C$ of less than −25 o/oo (Fenchel and Blackburn, 1979), and ultimately result in $\delta^{13}C$ of dissolved inorganic carbon in the ground water of less than −12 o/oo. However, sulfate reduction followed by methane production can also enrich the $\delta^{13}C$ of inorganic carbon (Nissenbaum and others, 1972; Claypool and Kaplan, 1974).

The enrichment in $\delta^{13}C$ in aquifer layer 3 from about −11 o/oo in northeastern Iowa to more than −8 o/oo in southwestern Iowa can be explained by successive episodes of glacial-meltwater dilution, dissolution of carbonate minerals in the aquifer matrix, and reequilibration of ground water with respect to the carbonate system. However, it is necessary to assume that the inorganic carbon in the meltwater that recharged the aquifer system had a $\delta^{13}C$ of more than −10 o/oo. The involvement of organic carbon in the dissolution of carbonate rock beneath modern glaciers is minimal, although the presence of atmospheric carbon dioxide in meltwater cannot be overlooked (Hanshaw and Hallet, 1978). The $\delta^{13}C$ of modern atmospheric carbon dioxide is about −7 o/oo (Hoefs, 1980). If most of the meltwater recharge occurred subglacially and if the carbon isotopic composition of Pleistocene atmospheric carbon dioxide was similar to that of today, then the observed enrichment of $\delta^{13}C$ from −11 to −8 o/oo of the dissolved inorganic carbon in the ground water would be conceptually consistent with the meltwater recharge model. During glacial-meltwater emplacement, $\delta^{13}C$ of inorganic carbon also could be enriched by sulfate reduction followed by methane production, as discussed earlier.

Infiltration of meltwater through soils could result in soil carbon dioxide of varying isotopic composition depending on the type of vegetation (Fontes, 1980; Hoefs, 1980). Studies of plant succession after the latest Wisconsin glacial retreat in the Midwest indicate that many stages in plant succession can occur after glaciation and could range from black spruce forests to open woodlands (Wright, 1976). These vegetation types can develop even on the mantle of rock debris that covers stagnant ice. The simplest interpretation of the succession in central Minnesota, for example, is probably that the earlier colonization of herb tundra vegetation was followed by shrub and forest tundra, spruce forest, and, ultimately, pine (Birks, 1975; Gordon and Birks, 1982). These types of vegetation, as well as prairie grasses, have $\delta^{13}C$ values between about −37 and −24 o/oo (Hoefs, 1980). The isotopic composition of carbon dioxide derived from the oxidation of this vegetation would not be too different from that of modern soils. Repeated dissolution of carbonate minerals by meltwater with such dissolved soil carbon dioxide would result in $\delta^{13}C$ of dissolved inorganic carbon of about −12 o/oo, rather than the observed enriched values of carbon-13.

SUMMARY AND CONCLUSIONS

The evolution of the water quality in the Cambrian-Ordovician aquifer system in the northern Midwest United States is complicated because of many possible geochemical processes and the probable effects of Pleistocene glaciation on the aquifer system. Modern



EXPLANATION

LINES OF EQUAL $\delta^{13}C$ RATIO—Dashed where uncertain. Interval, permil, is variable

—10— Aquifer layer 1

--12-- Aquifer layer 3

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

Open to aquifer layer 1

Open to aquifer layer 3

FIGURE 42.—Distribution of $\delta^{13}C$ ratio in aquifer layers 1 and 3.

ground-water types may be, in part, a result of ground-water types prior to Pleistocene ice advances.

Ground water in recharge areas in Wisconsin, southern Minnesota, northeastern Iowa, and north-central Illinois is the Ca-Mg-HCO_3 type and is identical in both the glacial drift and the underlying Cambrian-Ordovician aquifer system. Dissolved-solids concentrations are less than 500 mg/L, and the major geochemical process probably is dissolution of carbonate minerals by soil carbon dioxide. In northwestern Iowa and southwestern Minnesota, however, the ground-water type in both the drift and the Cambrian-Ordovician aquifer system is Ca-Na-SO_4-HCO_3 because of the oxidation of pyrite in the Dakota Formation that overlies the aquifer system. Ground water is generally undersaturated with gypsum, and the negative $\delta^{34}S$ values in sulfate indicate that pyrite is a primary sulfur source. Dissolved-solids concentrations in places exceed 1,000 mg/L.

Ground-water type changes from Na-Ca-SO_4-HCO_3 to Na-Cl along the major flow path from northwestern Iowa to the Illinois basin. This is probably due to membrane filtration that would result in calcite precipitation coincident with increases in sodium and chloride.

A plume of dilute water containing less than 500 mg/L of dissolved solids trends north to south in central Iowa under the confining Maquoketa Shale. The plume suggests that paleo-ground-water flow probably was perpendicular to the present hydraulic gradient. This interpretation also is suggested by the general trend of increasing dissolved solids perpendicular to the present hydraulic gradient in Iowa and Missouri.

Ground water in southern Iowa and northern Missouri is considerably more depleted in the heavier stable isotopes, oxygen-18 and hydrogen-2, than is modern recharge water. This evidence may suggest a Pleistocene, and probably a glacial-meltwater, origin of recharge. A plume of ground water isotopically heavier than ground water in southern Iowa, but isotopically lighter than modern recharge, is coincident with the plume of low-dissolved-solids water in central Iowa. It is hypothesized that the isotopic content and dilution of ground water in Iowa and Missouri probably was caused by glacial meltwater emplaced in the aquifer system when glacial ice covered the present recharge areas in northeastern Iowa and southern Minnesota. The emplaced water extends hundreds of miles from the recharge areas. This may suggest that some of the recharge occurred subglacially, under considerably steeper hydraulic gradients than those of the present.

Dilution by the emplaced water decreased the concentrations of solutes such as chloride and sulfate in central Iowa, but bicarbonate concentrations remained about the same. Reequilibration of ground water with carbonate minerals in aquifer matrices, suggested by marked enrichment of $\delta^{13}C$ in dissolved inorganic carbon, could have maintained the level of bicarbonate concentrations. Dilution and re-reaction of the water with the aquifer matrix did not significantly change the ground-water types that are present down the modern hydraulic gradient. The overall chemical character of the ground water in the aquifer system in Iowa was probably established prior to glaciation and the recharge of meltwater.

Reconnaissance data on the distribution of trace solutes show that concentrations of cadmium, arsenic, and selenium seem to be related to the proximity of the Dakota Formation, which onlaps the western edge of the aquifer system in northwestern Iowa and southwestern Minnesota. Iron, manganese, cobalt, cadmium, copper, and lead concentrations are higher in proximity to the Dakota Formation in northwestern Iowa and on the edge of the Forest City basin in southwestern Iowa. Concentrations of beryllium and molybdenum are generally higher near the Forest City basin than elsewhere in the aquifer system. Silica concentrations correlate roughly with ground-water temperature in south-central Iowa and northern Missouri; however, the solid phases controlling the solubility of silica are unknown.

Concentrations of lithium, strontium, boron, and fluoride increase from north to south in Iowa and northern Missouri in a direction perpendicular to the present hydraulic gradient. Distributions of lithium, radium-226, and bromide show a plume of lower concentration similar to the plumes of low dissolved solids and the distribution of stable isotopes of water. Uranium isotopes are at disequilibrium and show activity ratios of uranium-234 to uranium-238 as large as 100. High barium concentrations in northern Illinois and eastern Wisconsin are probably due to a zone of reducing conditions that markedly lower the sulfate concentration. Thus, barium concentrations increase until the solubility limit of barite is reached. Increased concentrations of sulfate and positive $\delta^{34}S$ values of sulfur in sulfate east of the reducing zone in eastern Wisconsin and northeastern Illinois probably indicate emplacement of sulfate derived from evaporitic gypsum. This may have occurred during Pleistocene glaciation, when the load of glacial ice could have reversed ground-water flow from east to west. Ground water from the Michigan basin could have discharged through the present recharge area in central Wisconsin and northern Illinois, where the aquifer either crops out at the land surface or subcrops beneath glacial drift.

It is possible to derive scenarios for the net dilution and dissolution process from calculations using data on the stable isotopes of the water. Such calculations are

nonunique and are used only for the hypothetical interpretation of geochemical data because (1) the number of glacial advances in Wisconsin and Minnesota prior to Wisconsin time is uncertain, (2) the pre-Pleistocene regional ground-water flow system and topography are unknown, (3) information on the chemical and clay-mineral composition of the aquifer matrix in central Iowa is scant, (4) estimates of the isotopic composition of Pleistocene ice sheets have a large range, (5) different interpretations are made of the shape of the continental ice lobes, (6) no direct information is available on the leakance of younger rocks that overlie the aquifer south of the Maquoketa Shale outcrop, and (7) the extent of isotopic depletion in ground water south of the study area is unknown.

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CHEMICAL AND ISOTOPIC ANALYSES OF GROUND WATER SAMPLED DURING THE STUDY (TABLES 1-3)

TABLE 1.—*Chemical analyses of major constituents in water from wells sampled for this study*

[Results in milligrams per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Site identification number	Date of collection	Field pH (standard units)	Calcium, Ca	Magnesium, Mg	Sodium, Na	Potassium, K	Field alkalinity, as HCO_3	Sulfate, SO_4	Chloride, Cl	Silica, SiO_2	Dissolved solids, sum of constituents
						Aquifer layer 1, Illinois						
118	422418090255501	10-23-80	7.4	50	26	1.3	2.8	--	5.9	1.3	7.7	230
130	422803087475303	12-10-80	7.2	310	39	440	16	--	1300	370	7.5	2600
131	422803087475304	01-14-81	--	1000	930	15000	270	--	1400	37000	4.4	56000
						Aquifer layer 1, Iowa						
71	432953091172001	06-24-80	7.5	37	45	2.7	1.9	317	19	2.9	8.2	270
73	432206091130301	06-10-80	7.9	31	18	99	4.7	245	52	45	8.0	410
102	430240091110001	06-09-80	7.7	62	27	55	4.0	323	52	59	8.6	430
119	420842090165702	05-15-81	7.6	57	37	9.3	5.9	366	20	8.7	10	330
						Aquifer layer 1, Minnesota						
1	461209093550701	02-21-80	6.5	13	4.4	3.8	1.3	50	5.2	--	19	--
3	453038092584301	05-13-80	7.0	64	22	9.6	2.4	340	<5.0	2.7	20	--
4	452008092595001	05-13-80	7.3	52	14	5.0	1.6	241	<5.0	1.0	13	--
5	445648093395101	05-19-80	7.4	68	24	23	5.4	368	30	6.5	11	350
19	445704093215611	09-04-80	7.8	58	19	33	7.6	244	47	33	7.2	330
21	445153093202101	05-20-80	--	39	13	29	6.7	239	<5.0	20	7.6	--
30	443354092323201	02-12-80	6.7	64	27	53	6.8	276	34	80	8.3	410
31	443407092315501	02-12-80	6.8	40	19	79	4.4	250	27	98	9.2	400
32	443300092302901	02-12-80	7.0	80	44	250	7.9	262	36	550	8.6	1100
50	440324091404001	02-13-80	7.4	56	20	130	8.1	364	85	99	7.0	590
51	440324091401501	02-13-80	7.0	60	21	180	9.0	362	180	140	7.4	760
52	440318091388180	02-13-80	6.9	52	20	80	6.3	351	57	56	8.4	450
53	440312091381201	02-13-80	7.2	56	21	49	6.2	312	37	28	8.3	360
						Aquifer layer 1, Wisconsin						
33	443436091281401	08-06-80	6.8	13	5.9	2.0	1.7	65	11	1.2	16	84
34	443841090393001	08-20-80	6.7	34	8.9	7.7	1.0	99	14	17	20	180
38	442141091185601	08-13-80	7.2	16	6.7	3.8	3.6	68	19	4.2	17	110
39	442045090453601	08-20-80	6.4	2.8	1.2	1.2	1.4	16	6.1	1.3	11	36
54	435743089485701	08-21-80	7.8	21	9.0	1.6	.4	110	4.2	.7	8.9	100
55	440219088555701	08-19-80	8.0	27	34	15	1.8	256	27	2.3	21	260
56	434312090353901	08-22-80	7.8	51	27	1.2	1.0	268	19	1.0	9.8	240
57	433921091132101	10-08-81	7.6	45	29	1.9	1.3	294	11	2.6	9.9	250
75	432336090460601	08-28-80	7.6	50	28	1.7	1.0	268	17	.9	11	240
76	432042090231701	08-28-80	7.7	55	26	2.7	1.0	232	18	3.2	12	230
77	433144089595901	09-05-80	7.2	22	11	3.9	2.5	--	13	7.1	11	--
78	433220089282601	09-05-80	7.4	65	42	1.8	.6	378	32	5.0	7.1	340
79	431849089311002	07-24-80	7.7	51	29	2.5	.9	329	3.0	.8	13	260
80	432717088501701	09-05-80	7.3	60	31	3.7	1.7	--	21	3.7	9.4	--
103	425246091042101	08-19-81	7.3	180	40	140	12	280	370	180	8.7	1100
105	431108090263101	08-29-80	7.4	57	32	5.2	1.5	305	6.0	5.3	12	270
108	430055089534001	07-18-80	7.3	67	37	6.0	1.0	354	28	13	6.7	360
110	430058089251401	07-22-80	7.6	54	31	2.9	1.8	329	6.4	1.8	9.0	270
						Aquifer layer 3, Illinois						
120	422606089434501	08-29-80	7.6	66	34	3.2	.6	341	5.2	.6	13	290
121	421331089442201	08-29-80	7.4	74	42	9.8	3.0	329	3.2	1.1	9.5	330
122	421658089235101	08-20-80	7.4	110	50	25	1.5	256	86	39	21	530
123	422738089114601	08-23-80	7.1	81	41	3.5	1.8	402	29	7.2	11	390
124	422545089103301	08-23-80	7.4	91	49	5.7	.6	451	32	20	8.7	440
125	421855089121601	08-23-80	7.3	62	29	2.9	.7	329	11	.8	12	280
126	421614089062301	09-03-80	6.7	120	57	59	4.9	232	140	120	16	650
127	420953089080501	09-05-80	7.4	65	32	5.0	.5	232	16	2.3	15	250
128	421025088564401	09-04-80	7.0	67	34	3.7	1.0	244	14	1.9	14	260
129	421329088531701	09-05-80	7.1	95	47	14	1.8	207	74	38	13	440
132	422803087475306	09-01-81	7.2	94	23	41	11	--	150	13	8.0	510
133	415632088071201	06-21-80	8.3	74	23	52	18	597	170	18	7.0	660
134	415818087565201	05-02-80	--	24	7.2	85	4.3	268	44	22	7.1	330
135	413847088214801	08-27-80	7.3	54	27	64	1.9	280	69	20	7.5	390
136	411858088363401	08-28-80	7.4	71	35	97	12	195	110	90	7.8	520
137	411933089403701	08-28-80	7.0	38	19	370	12	317	200	350	9.3	1200

TABLE 1.—*Chemical analyses of major constituents in water from wells sampled for this study*—Continued

[Results in milligrams per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Site identification number	Date of collection	Field pH (standard units)	Calcium, Ca	Magnesium, Mg	Sodium, Na	Potassium, K	Field alkalinity, as HCO_3	Sulfate, SO_4	Chloride, Cl	Silica, SiO_2	Dissolved solids, sum of constituents
						Aquifer layer 3, Iowa						
59	431620095250201	09-03-80	8.0	340	130	190	10	505	1400	26	22	2400
61	432412094503301	09-09-81	7.3	240	74	50	6.0	841	570	2.6	27	1400
62	431750094303001	09-08-81	7.4	180	61	63	5.0	744	440	2.3	18	1100
63	432256094183301	06-25-80	7.3	110	35	58	3.1	441	200	1.9	18	650
64	431350093544201	06-25-80	7.3	78	27	19	4.0	421	17	1.1	14	370
65	430800092540301	06-26-80	7.8	66	26	16	6.8	317	48	2.0	7.0	330
66	432650092170201	06-24-80	7.4	60	18	4.2	1.7	274	14	1.3	11	250
67	430337092190701	06-25-80	7.5	52	21	6.9	4.3	263	27	.9	6.8	250
68	431216091572001	06-23-80	7.5	69	29	3.5	1.1	297	37	9.4	11	320
69	432606091470301	06-23-80	7.2	93	24	5.0	1.6	386	10	9.4	18	370
70	432800091295301	06-24-80	7.5	56	28	3.5	.8	366	3.6	2.1	12	300
72	431638091284102	06-24-80	7.3	86	21	3.2	.9	341	24	6.5	14	330
84	430210094500001	09-08-81	7.6	240	78	100	7.3	744	800	6.6	26	1600
88	423840095135001	09-04-80	7.2	280	64	170	43	329	1100	30	8.3	1900
91	421831095152101	09-04-80	7.5	190	48	150	32	282	730	32	9.3	1300
92	422339094375101	09-02-80	7.2	170	59	98	26	317	590	14	9.0	1100
93	422136094173401	09-05-80	7.5	120	44	92	25	372	390	20	9.0	890
94	422855093481501	09-02-80	7.3	120	43	140	20	363	370	71	8.4	960
95	422611092552501	09-02-80	7.4	78	32	74	21	329	180	11	8.0	570
96	425049092063801	06-11-80	7.7	50	24	15	6.6	293	39	1.3	6.6	290
97	425708091383001	06-10-80	7.3	82	27	6.0	2.6	347	47	13	10	370
98	424820091324001	06-09-80	7.6	65	27	4.5	1.6	293	43	8.9	10	310
99	425138091234901	06-09-80	7.5	62	29	6.7	5.0	293	54	1.7	7.4	310
100	425550091233001	06-09-80	7.5	60	27	4.6	2.8	317	28	1.9	11	290
101	430330091264301	06-24-80	7.5	87	39	7.4	1.2	366	75	14	13	420
116	423141090385801	08-26-81	7.6	52	33	2.2	2.2	329	16	2.5	9.5	280
117	422640091002701	08-26-81	7.8	50	24	62	11	329	90	21	8.3	430
138	421010092180301	06-23-80	7.5	83	40	73	14	400	200	6.8	7.2	630
139	420200091363001	07-21-80	7.4	59	31	74	13	341	170	10	7.8	540
140	420718091165401	07-23-80	7.5	62	30	68	13	341	160	14	7.9	530
141	412407095391201	09-02-81	7.7	190	55	210	36	244	690	240	9.7	1600
142	413015094391302	09-02-81	7.8	170	63	330	35	219	750	380	11	1900
143	415021094072801	09-02-81	7.5	110	44	240	28	317	590	140	9.7	1300
144	413931093292001	09-01-81	7.6	58	24	53	12	305	110	14	11	440
145	414430092433001	09-01-81	7.5	79	37	100	16	354	270	21	11	710
146	412736093241201	07-30-81	7.5	61	26	83	13	329	150	28	11	540
147	412025093322201	06-10-81	7.7	55	22	140	17	305	240	30	12	670
148	410235093564901	06-10-81	7.6	130	44	360	28	244	740	250	14	1700
149	404422093445602	07-28-81	7.4	170	56	520	26	232	700	410	13	2000
150	405858093175701	06-10-81	7.8	60	23	200	19	317	300	110	11	890
151	411332093142101	06-10-81	7.8	57	22	140	17	317	190	75	11	680
152	412020092471001	08-12-81	7.6	86	37	200	22	329	440	62	11	1000
153	410305092490701	07-28-81	7.5	65	26	190	17	317	320	130	4.8	910
154	412356092211001	07-30-81	7.4	100	46	150	15	341	430	34	11	960
155	405750092142001	06-09-81	8.0	74	32	250	20	293	470	140	8.7	1100
156	410115091571801	06-09-81	7.5	75	31	240	20	280	470	130	10	1100
157	411812091412601	08-05-80	7.3	93	46	240	20	286	550	63	10	1200
158	411907091220001	10-29-80	7.2	530	78	2500	70	295	2200	3600	10	9200
159	404421091575801	06-09-81	7.5	69	28	330	20	305	410	250	11	1300
160	403839091333801	08-05-80	7.6	62	28	490	17	312	400	370	9.5	1500
						Aquifer layer 3, Minnesota						
6	445607093364701	05-19-80	7.6	84	44	25	3.8	535	26	.9	20	470
7	445409093342801	05-19-80	7.7	52	29	4.1	4.0	312	<5.0	2.9	17	--
8	445831093305701	05-19-80	7.5	80	34	6.4	2.2	406	8.0	6.2	23	360
9	450015093280001	05-14-80	7.6	76	34	3.7	2.2	358	28	5.5	23	350
10	450127093204201	05-14-80	7.3	88	41	5.3	2.6	447	12	.50	20	390
11	450510093172501	05-14-80	--	64	24	5.6	1.8	302	9.5	3.1	21	280
12	450337093130901	05-14-80	6.8	68	29	5.4	1.5	269	61	8.2	19	330
13	450532093000301	05-12-80	7.3	48	17	4.1	1.8	213	8.0	3.2	15	200
14	450532093000302	05-12-80	7.2	56	18	7.9	3.7	233	<5.0	1.7	8.9	--
15	450417092570401	05-12-80	--	40	16	3.2	1.2	212	<5.0	<.5	15	--
16	450238093000401	05-12-80	7.0	56	18	5.4	1.8	219	8.3	4.7	16	220
17	450039092594501	05-14-80	6.8	56	19	7.9	1.7	232	35	6.2	19	260

TABLE 1.—*Chemical analyses of major constituents in water from wells sampled for this study*—Continued

[Results in milligrams per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Site identification number	Date of collection	Field pH (standard units)	Calcium, Ca	Magnesium, Mg	Sodium, Na	Potassium, K	Field alkalinity, as HCO_3	Sulfate, SO_4	Chloride, Cl	Silica, SiO_2	Dissolved solids, sum of constituents
20	445124093270801	05-20-80	7.6	68	27	5.5	1.7	347	12	2.9	22	310
22	445153093202102	05-20-80	7.6	76	32	5.2	1.4	371	11	3.3	17	330
23	444825093125001	05-22-80	--	68	27	3.7	1.7	--	11	<.5	23	--
24	445348093022901	05-21-80	--	100	36	14	1.9	--	71	45	22	470
25	444227093125201	05-21-80	--	65	20	4.8	1.1	305	10	.5	14	260
27	443849093143601	01-30-80	6.6	140	36	45	11	394	300	7.8	21	760
28	443806093085901	05-21-80	7.6	68	24	2.8	1.1	322	10	<.5	15	--
35	442648093091301	05-21-80	--	76	29	3.0	1.3	--	35	.6	15	930
36	441851093341801	09-03-80	--	90	35	22	4.2	378	33	1.6	22	400
37	441454092101001	02-12-80	--	72	27	9.1	.8	--	18	24	17	310
42	435542093570501	02-29-80	7.0	140	41	65	4.3	452	340	1.3	15	830
43	434547094095802	01-29-80	7.5	160	44	68	4.9	428	450	1.5	15	960
44	434601094010001	02-29-80	7.4	110	32	30	4.6	472	69	.6	23	510
46	435333092503901	09-02-80	--	72	20	4.3	3.1	317	21	1.1	7.6	290
47	434221092341701	05-07-80	--	60	22	3.1	2.8	260	34	.9	7.6	260
48	434235092340201	05-07-80	--	64	22	3.0	2.5	269	34	.8	8.3	270
49	434242092160503	05-06-80	--	56	21	2.3	1.1	262	12	2.6	9.3	230
					Aquifer layer 3, Missouri							
161	402842092511801	04-07-81	7.4	110	49	710	25	319	1200	450	8.6	2700
162	400217091295201	04-07-81	7.3	210	100	2000	46	300	1200	3000	6.7	6700
163	391622091343301	04-06-81	7.5	72	36	280	19	450	280	190	8.5	1100
164	383543092103001	04-06-81	7.4	51	23	43	5.6	360	36	27	8.0	370
					Aquifer layer 3, Wisconsin							
18	445910092331301	08-04-80	7.8	36	20	2.9	.8	195	6.5	3.5	19	200
29	444504092473601	08-14-80	7.5	13	5.8	2.5	.8	46	13	2.3	19	94
40	441849088051801	08-08-80	7.3	300	48	110	15	195	870	170	9.8	1600
74	432800091062501	11-10-81	7.7	61	35	4.2	.6	304	8.0	8.6	18	290
104	424423090552801	08-26-80	7.1	120	57	17	.7	439	47	41	26	640
106	430117090173201	08-27-80	7.6	63	33	2.3	.8	329	16	4.5	13	310
107	430132090172601	08-27-80	6.8	12	6.1	3.2	.7	51	13	2.8	22	89
109	430136089274301	05-12-80	7.5	94	49	21	1.1	390	34	91	20	520
112	425245088274701	05-29-80	7.5	56	28	4.4	1.8	305	2.2	1.3	9.9	260
113	425153088195501	10-21-82	7.6	53	22	7.0	1.6	266	19	1.7	10	250
114	424407090200001	08-26-80	7.6	66	37	3.8	.5	341	19	3.1	11	310
115	424404089204701	09-04-80	7.5	57	30	20	3.9	280	31	41	15	340
					Aquifer layer 4, Minnesota							
45	433615093403001	09-02-80	--	58	20	100	2.6	512	66	2.1	22	520
					Aquifer layer 4, Wisconsin							
111	430618087571001	11-21-80	7.7	68	28	35	2.6	--	240	15	9.8	510
					Aquifer layer 5, Iowa							
58	425526096210711	09-03-80	8.0	250	97	170	16	305	1100	21	14	1800
60	431620095250511	09-03-80	8.0	300	110	150	8.8	442	1200	30	23	2000
81	430512095371801	02-23-82	7.4	--	--	--	--	--	--	--	10	--
82	425824095300901	02-23-82	7.3	320	80	96	--	--	930	6.7	11	--
83	430745094541101	02-23-82	7.5	220	58	100	--	--	520	5.0	11	--
85	424348095231601	04-15-80	8.0	120	38	74	9.9	355	260	18	9.0	710
86	424348095231602	09-04-80	8.1	97	35	25	3.0	396	170	1.6	27	560
87	423618095194511	09-04-80	8.0	180	42	28	3.7	397	370	1.1	24	850
89	422950095174301	02-22-82	7.5	310	100	190	--	1200	16	12	--	--
90	422009095210101	02-22-82	7.4	260	63	140	--	850	8.5	5.0	--	--
					Aquifer layer 5, Minnesota							
2	462710092454001	02-21-80	--	60	15	13	1.7	--	15	39	19	270
26	443710093453501	09-03-80	--	82	35	80	3.6	378	100	36	24	550
41	440026094355401	09-03-80	--	87	24	18	2.2	268	130	5.0	29	430

TABLE 2.—*Chemical analyses of selected trace constituents in water from wells sampled for this study*

[Results in micrograms per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Site identification number	Date of sample	Arsenic, As	Boron, B	Barium, Ba	Bromide, Br (mg/L)	Cadmium, Cd	Cobalt, Co	Chromium, Cr	Copper, Cu
					Aquifer layer 1, Illinois					
118	422418090255501	10-23-80	<1	20	160	.20	<1	4	--	<10
130	422803087475303	12-10-80	<1	1000	10	1.4	5	6	--	<10
131	422803087475304	01-14-81	2	11000	50	.20	10	<3	--	36
					Aquifer layer 1, Iowa					
71	432953091172001	06-24-80	1	30	130	<.10	2	<3	--	<10
73	432206091130301	06-10-80	2	220	60	<.10	<1	<3	--	13
102	430240091110001	06-09-80	1	160	80	<.10	2	<3	--	<10
119	420842090165702	05-15-81	1	10	160	<.10	<1	<3	--	<10
					Aquifer layer 1, Minnesota					
1	461209093550701	02-21-80	<1	<50	18	--	<1	<3	<1	<10
3	453038092584301	05-13-80	<1	60	48	--	<1	<3	<1	<10
4	452008092595001	05-13-80	<1	<50	37	--	<1	<3	<1	<10
5	445648093395101	05-19-80	1	250	150	--	<1	<3	<1	11
19	445704093215611	09-04-80	1	210	150	.30	8	<3	--	<10
21	445153093202101	05-20-80	<1	20	280	--	<1	<1	<1	<10
30	443354092323201	02-12-80	<1	210	520	--	<1	<3	<1	<10
31	443407092315501	02-12-80	<1	--	33	--	2	<3	2	<10
50	440324091404001	02-13-80	<1	620	32	--	<1	<3	<1	20
51	440324091401501	02-13-80	<1	80	37	--	<1	<3	<1	<10
52	440318091388180	02-13-80	<1	43	33	--	<1	<3	<1	<10
53	440312091381201	02-13-80	<1	32	40	--	<1	<3	<1	1
					Aquifer layer 1, Wisconsin					
33	443436091281401	08-06-80	1	<20	20	.40	5	<3	--	10
34	443841090393001	08-20-80	1	10	60	.10	6	<3	--	10
38	442141091185601	08-13-80	<1	40	20	.70	5	<3	--	<10
39	442045090453601	08-20-80	2	10	20	<.10	2	<3	--	<10
54	435743089485701	08-21-80	1	<20	40	<.10	2	<3	--	<10
55	440219088555701	08-19-80	6	50	80	.20	3	<3	--	<10
56	434312090353901	08-22-80	1	<20	20	.30	<1	<3	--	<10
57	433921091132101	10-08-81	1	10	40	.10	1	10	--	10
75	432336090460601	08-28-80	1	20	50	.30	3	<3	--	<10
76	432042090231701	08-28-80	2	30	30	.20	4	<3	--	<10
77	433144089595901	09-05-80	1	20	40	.40	2	<3	--	<10
78	433220089282601	09-05-80	1	<20	40	.40	3	<3	--	11
79	431849089311002	07-24-80	4	<20	30	.20	3	<3	--	<10
80	432717088501701	09-05-80	1	30	250	.30	2	<3	--	<10
103	425246091042101	08-19-81	1	190	20	.90	2	10	--	10
105	431108090263101	08-29-80	1	50	50	.20	3	<3	--	<10
108	430055089534001	07-18-80	1	<20	60	.90	3	<3	--	<10
110	430058089251401	07-22-80	2	30	20	.30	<1	<3	--	<10
					Aquifer layer 3, Illinois					
120	422606089434501	08-29-80	1	20	20	.20	4	<3	--	<10
121	421331089442201	08-29-80	2	80	21000	.20	3	<3	--	<10
122	421658089235101	08-20-80	1	40	110	.60	3	<3	--	<10
123	422738089114601	08-23-80	<1	<20	40	.10	<2	<3	--	<20
124	422545089103301	08-23-80	<1	--	40	.10	<2	<3	--	<20
125	421855089121601	08-23-80	1	<20	130	.20	<2	<3	--	<20
126	421614089062301	09-03-80	1	270	80	.60	4	<3	10	<10
127	420953089080501	09-05-80	2	20	100	.70	3	<3	--	<10
128	421025088564401	09-04-80	1	50	110	.30	4	<3	--	<10

TABLE 2.—*Chemical analyses of selected trace constituents in water from wells sampled for this study*—Continued

[Results in micrograms per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Fluoride, F (mg/L)	Iron, Fe	Lithium, Li	Manganese, Mn	Molybdenum, Mo	Lead, Pb	Selenium, Se	Strontium, Sr	Vanadium, Va	Beryllium, Be	Sulfide, S (mg/L)
					Aquifer layer 1, Illinois						
118	.30	670	<4	10	<10	<10	<1	46	<6	<.7	--
130	1.0	2700	180	190	<10	17	<1	13000	<6	<.7	<.1
131	.30	8500	2100	9800	<10	170	<1	100000	<6	<1.0	<.1
					Aquifer layer 1, Iowa						
71	.20	220	7	9	<10	<10	<1	100	<6	<.7	--
73	.20	170	15	15	<10	<10	<1	230	<6	.7	--
102	.30	250	18	14	<10	62	<1	360	<6	<.7	--
119	.10	11	13	14	<10	<10	<1	960	<6	<1.0	--
					Aquifer layer 1, Minnesota						
1	.10	4800	2	450	<1	<10	<1	--	--	--	--
3	.26	1100	5	70	2	<10	<1	--	--	--	--
4	.20	550	4	90	2	<10	<1	--	--	--	--
5	.72	2200	11	30	<1	<10	1	--	--	--	--
19	.40	610	20	14	<10	34	<10	690	<6	<.7	--
21	.30	380	18	20	<1	<1	2	--	--	--	--
30	.18	<50	29	59	2	<1	3	--	--	--	--
31	.28	300	20	38	<1	<10	--	--	--	--	--
50	.56	200	56	25	<1	<1	<1	--	--	--	--
51	.04	580	63	<20	<1	<1	<1	--	--	--	--
52	1.3	340	31	21	<1	<1	1	--	--	--	--
53	.39	340	22	24	<1	30	4	--	--	--	--
					Aquifer layer 1, Wisconsin						
33	.50	6	0	210	0	10	<1	24	<6	<.7	<.1
34	.20	<3	5	5	<10	13	<1	58	<6	<.7	<.1
38	.60	6500	<4	190	<10	<10	<1	20	<6	2.0	<.1
39	.10	<3	<4	2	<10	<10	<1	12	<6	3.0	<.1
54	.20	<3	<4	260	<10	<10	<1	39	<6	3.0	<.1
55	.40	50	7	11	<10	<10	<1	1100	<6	2.0	<.1
56	.20	40	<4	29	<10	16	<1	36	<6	4.0	--
57	<.10	440	4	17	10	10	<1	59	6	1.0	--
75	.10	310	<4	14	<10	17	<1	40	<6	<.7	<.1
76	.10	150	<4	16	<10	<10	<1	45	<6	1.0	<.1
77	.10	10	<4	45	<10	<10	<1	41	<6	<.7	.2
78	.10	9	<4	5	<10	<10	<1	44	<6	<.7	<.1
79	.10	<3	<4	<1	<10	<10	<1	46	<6	<.7	<.1
80	.30	840	<4	49	<10	<10	<1	1700	<6	<.7	<.1
103	.20	1700	50	16	11	10	<1	4400	6	1.0	<.1
105	.20	750	5	26	<10	<10	<1	58	<6	<.7	.2
108	.10	8	<4	<1	10	13	<1	38	<6	<.7	<.1
110	.10	140	<4	16	<10	<10	<1	76	<6	.8	.1
					Aquifer layer 3, Illinois						
120	.20	1500	<4	28	13	18	<1	61	<6	<.7	--
121	.30	270	5	13	<10	12	<1	540	<6	<.7	--
122	.20	100	5	<1	<10	14	1	110	<6	1.0	--
123	.10	3	5	<1	<10	21	<1	48	<6	<.7	--
124	.10	16	6	<1	<10	<10	<1	43	<6	<.7	--
125	.10	21	4	5	<10	<10	<1	48	<6	<.7	--
126	.20	330	6	58	<10	11	<1	160	<6	<.7	--
127	.20	1700	<4	44	<10	<10	<1	120	<6	<.7	--
128	.20	<3	<4	<1	<10	<10	<1	72	<6	<.7	--

TABLE 2.—*Chemical analyses of selected trace constituents in water from wells sampled for this study*—Continued

[Results in micrograms per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Site identification number	Date of sample	Arsenic, As	Boron, B	Barium, Ba	Bromide, Br (mg/L)	Cadmium, Cd	Cobalt, Co	Chromium, Cr	Copper, Cu
129	421329088531701	09-05-80	1	30	50	.50	3	<3	--	<10
132	422803087475306	09-01-81	1	290	2	.10	1	3	--	10
133	415632088071201	06-21-80	1	560	80	.20	1	<3	--	<10
134	415818087565201	05-02-80	1	910	20	.20	<1	<3	--	11
135	413847088214801	08-27-80	1	470	30	.40	<1	<3	--	<10
136	411858088363401	08-28-80	1	270	30	.70	2	<3	--	<10
137	411933089403701	08-28-80	<1	850	20	1.0	5	<3	--	<10
				Aquifer layer 3, Iowa						
59	431620095250201	09-03-80	3	300	20	.20	7	<3	--	<10
61	432412094503301	09-09-81	2	300	23	.10	1	<3	--	<10
62	431750094303001	09-08-81	2	210	21	<.10	1	4	--	<10
63	432256094183301	06-25-80	1	140	60	<.10	<1	<3	--	<10
64	431350093544201	06-25-80	1	70	140	<.10	<1	<3	--	<10
65	430800092540301	06-26-80	1	250	60	<.10	3	<3	--	<10
66	432650092170201	06-24-80	1	70	140	.10	<1	<3	--	<10
67	430337092190701	06-25-80	<10	310	70	<.10	<1	<3	--	<10
68	431216091572001	06-23-80	1	60	140	.10	<1	<3	--	<10
69	432606091470301	06-23-80	1	20	120	.10	<1	<3	--	<10
70	432800091295301	06-24-80	<10	<20	60	.10	2	<3	--	<10
72	431638091284102	06-24-80	<10	30	80	<.10	<1	<3	--	<10
84	430210094500001	09-08-81	1	360	31	<.10	1	<3	--	<10
88	423840095135001	09-04-80	1	2200	20	.90	6	<3	--	<10
91	421831095152101	09-04-80	1	1100	30	.50	4	<3	--	<10
92	422339094375101	09-02-80	1	990	20	.80	5	<3	--	<10
93	422136094173401	09-05-80	1	1200	20	.80	3	<3	--	<10
94	422855093481501	09-02-80	2	1100	20	.90	4	<3	--	<10
95	422611092552501	09-02-80	1	1100	30	.40	4	<3	--	<10
96	425049092063801	06-11-80	<10	220	70	<.10	<1	<3	--	<10
97	425708091383001	06-10-80	4	50	110	.10	<1	<3	--	<10
98	424820091324001	06-09-80	1	140	140	<.10	1	<3	--	<10
99	425138091234901	06-09-80	2	180	60	<.10	<1	<3	--	<10
100	425550091233001	06-09-80	<10	130	100	<.10	<1	<3	--	<10
101	430330091264301	06-24-80	<10	80	100	.10	2	<3	--	<10
116	423141090385801	08-26-81	2	<20	150	<.10	<1	<3	--	<10
117	422640091002701	08-26-81	1	460	40	.10	<1	<3	--	<10
138	421010092180301	06-23-80	<10	590	30	.10	3	<3	--	<10
139	420200091363001	07-21-80	1	610	30	.30	<1	<3	--	<10
140	420718091165401	07-23-80	1	570	40	.30	2	<3	--	<10
141	412407095391201	09-02-81	<10	820	17	.90	<2	<6	--	<20
142	413015094391302	09-02-81	1	1300	23	.20	<2	<6	--	<20
143	415021094072801	09-02-81	1	1700	21	.60	<1	<3	--	<10
144	413931093292001	09-01-81	<10	600	48	.10	<1	<3	--	<10
145	414430092433001	09-01-81	<10	1100	27	.10	<1	<3	--	<10
146	412736093241201	07-30-81	2	760	40	.20	<1	<3	--	<10
147	412025093322201	06-10-81	<10	1200	170	.20	<1	<3	--	<10
148	410235093564901	06-10-81	1	1600	310	.90	<2	<6	--	<20
149	404422093445602	07-28-81	1	1900	20	1.5	<1	<3	--	<10
150	405858093175701	06-10-81	1	1500	130	.40	<1	<3	--	<10
151	411332093142101	06-10-81	1	1100	120	.30	<1	<3	--	<10
152	412020092471001	08-12-81	1	1400	30	.30	<1	<3	--	<10
153	410305092490701	07-28-81	1	1400	30	.40	<1	<3	--	<10
154	412356092211001	07-30-81	2	870	30	.20	<1	<3	--	<10
155	405750092142001	06-09-81	1	1400	130	.50	<1	<3	--	<10
156	410115091571801	06-09-81	1	1300	100	.50	<1	<3	--	<10
157	411812091412601	08-05-80	2	670	30	.40	4	<3	--	<10
158	411907091220001	10-29-80	1	5700	30	9.8	6	10	--	24
159	404421091575801	06-09-81	1	1700	140	.80	<1	<3	--	<10
160	403839091333801	08-05-80	3	1600	30	.50	5	<3	--	<10

TABLE 2.—*Chemical analyses of selected trace constituents in water from wells sampled for this study*—Continued

[Results in micrograms per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Fluoride, F (mg/L)	Iron, Fe	Lithium, Li	Manganese, Mn	Molybdenum, Mo	Lead, Pb	Selenium, Se	Strontium, Sr	Vanadium, Va	Beryllium, Be	Sulfide, S (mg/L)
129	.20	<3	<4	<1	<10	<10	<1	83	<6	<.7	--
132	1.4	650	24	14	10	10	<1	8300	6	1.0	<.1
133	1.1	22	49	13	<10	54	<1	3900	<6	2.0	--
134	3.5	200	73	11	12	<10	<1	710	<6	4.0	--
135	1.1	4	59	48	<10	21	<1	1800	<6	<.7	--
136	.70	9	67	10	<10	18	<1	1300	<6	<.7	--
137	1.5	580	220	9	<10	<10	<1	2700	<6	<.7	--
					Aquifer layer 3, Iowa						
59	.30	82	140	550	<10	26	<1	3000	<6	<.7	--
61	.30	1500	70	330	20	<10	<1	1100	<6	<1.0	.8
62	.40	99	51	130	<10	10	<1	1100	<6	<1.0	1.0
63	.30	2600	30	36	25	<10	<1	350	<6	<.7	--
64	.40	260	23	25	17	<10	<1	320	<6	<.7	--
65	.70	380	31	8	21	<10	<1	510	<6	<.7	--
66	.60	630	10	10	<10	<10	<1	150	<6	<.7	--
67	.60	91	14	5	<10	17	<1	280	<6	<.7	--
68	.30	<3	7	2	17	<10	1	220	<6	<.7	--
69	.20	7	7	25	16	<10	<1	100	<6	<.7	--
70	.10	<3	<4	2	<10	<10	<1	52	<6	<.7	--
72	.20	15	5	3	15	<10	<1	97	<6	<.7	--
84	.30	2500	72	170	<10	10	<1	1900	<6	<1.0	.7
88	1.7	1300	210	59	<10	24	<1	9100	<6	<.7	--
91	2.0	3700	170	57	<10	22	<1	6000	<6	<.7	--
92	1.5	2100	95	39	<10	18	<1	4400	<6	<.7	--
93	1.6	2600	150	33	<10	14	<1	5200	<6	<.7	--
94	1.3	210	130	14	<10	13	<1	4000	<6	<.7	--
95	1.2	1200	120	18	<10	10	<1	2200	<6	<.7	--
96	.80	150	24	8	<10	<10	<1	530	<6	<.7	--
97	.40	6	5	4	<10	66	1	250	<6	<.7	--
98	.50	7	<4	37	<10	<10	2	150	<6	<.7	--
99	.40	22	14	8	11	78	<1	370	<6	<.7	--
100	.50	260	9	9	<10	87	<1	270	<6	2.0	--
101	.30	210	9	9	16	<10	<1	120	<6	<.7	--
116	.20	170	7	10	<10	<10	<1	92	<6	<1.0	<.1
117	.90	280	77	8	<10	<10	<1	1100	<6	<1.0	.1
138	1.1	1400	110	19	<10	<10	<1	1900	<6	<.7	--
139	1.3	170	90	3	<10	<10	<1	1500	<6	<.7	--
140	1.2	120	79	4	<10	<10	<1	1600	<6	<.7	--
141	2.9	2500	240	120	<20	<20	<1	6300	<12	<2.0	1.0
142	2.7	370	280	17	<20	<20	<1	5800	<12	<2.0	.5
143	2.3	440	270	8	<10	<10	<1	4700	<6	<1.0	.5
144	1.7	120	63	4	<10	<10	<1	1300	<6	<1.0	.5
145	1.4	320	140	5	<10	<10	<1	2300	<6	<1.0	.8
146	1.7	2000	86	18	<10	<10	<1	1700	<6	<1.0	--
147	2.7	210	150	3	<10	<10	<1	2100	<6	<1.0	.1
148	2.7	1300	350	18	<20	<20	<1	5700	<6	<2.0	.1
149	2.8	720	420	10	<10	<10	<1	6000	<6	<1.0	<.1
150	2.7	840	200	8	<10	<10	<1	2400	<6	<1.0	.9
151	2.2	800	130	12	<10	<10	<1	1800	<6	<1.0	<.1
152	1.2	2300	210	32	<10	<10	<1	2500	<6	<1.0	.2
153	1.6	51	4	<1	<10	<10	<1	44	<6	<1.0	<.1
154	1.3	2200	170	18	<10	<10	<1	2300	<6	<1.0	--
155	1.7	2100	260	91	<10	<10	<1	2700	<6	<1.0	<.1
156	1.6	530	240	8	<10	<10	<1	2500	<6	<1.0	<.1
157	1.3	290	220	4	<10	16	<1	2500	<6	<.7	--
158	1.5	10000	620	130	<10	17	<1	19000	5	<1.0	--
159	2.3	1200	290	12	<10	<10	<1	2500	<6	<1.0	<.1
160	4.1	770	360	8	<10	<10	<1	2600	<6	1.0	--

TABLE 2.—*Chemical analyses of selected trace constituents in water from wells sampled for this study*—Continued

[Results in micrograms per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Site identification number	Date of sample	Arsenic, As	Boron, B	Barium, Ba	Bromide, Br (mg/L)	Cadmium, Cd	Cobalt, Co	Chromium, Cr	Copper, Cu
			Aquifer layer 3, Minnesota							
6	445607093364701	05-19-80	<1	210	110	--	<1	<3	<1	<10
7	445409093342801	05-19-80	<1	10	160	--	<1	<3	<1	21
8	445831093305701	05-19-80	11	10	270	--	<1	<3	<1	15
9	450015093280001	05-14-80	<1	80	75	--	<1	<3	<1	11
10	450127093204201	05-14-80	<1	110	11	--	<1	<3	<1	<10
11	450510093172501	05-14-80	<1	100	90	--	<1	<3	<1	<10
12	450337093130901	05-14-80	<1	80	63	--	<1	<3	<1	12
13	450532093000301	05-12-80	--	--	--	--	--	--	--	--
14	450532093000302	05-12-80	<1	<50	59	--	<1	<3	<1	<10
15	450417092570401	05-12-80	<1	<50	13	--	<1	<3	<1	<10
16	450238093000401	05-12-80	<1	<50	25	--	<1	<3	<1	<10
17	450039092594501	05-14-80	<1	90	110	--	<1	<3	<1	<10
20	445124093270801	05-20-80	1	70	190	--	<1	<3	8	<10
22	445153093202102	05-20-80	1	240	150	--	<1	<3	7.9	<10
23	444825093125001	05-22-80	2	80	190	--	<1	<3	<1	--
24	445348093022901	05-21-80	<1	80	53	--	<1	<3	<1	<10
25	444227093125201	05-21-80	<1	110	120	--	--	--	--	--
27	443849093143601	01-30-80	2	400	17	--	<1	<3	<1	<10
28	443806093085901	05-21-80	<1	70	91	--	<1	<3	<1	<10
35	442648093091301	05-21-80	<1	90	50	--	<1	<3	<1	<10
36	441851093341801	09-03-80	1	30	110	--	10	<3	--	<10
37	441454092101001	02-12-80	<1	<50	57	--	<1	<3	1	<10
42	435542093570501	02-29-80	5	20	46	--	<1	<3	1	<10
43	434547094095802	01-29-80	6	270	47	--	<1	<3	<1	<10
44	434601094010001	02-29-80	6	20	44	--	<1	<3	<1	<10
46	435333092503901	09-02-80	1	90	80	--	10	<3	<1	30
47	434221092341701	05-07-80	<1	120	48	--	<1	<3	<1	<10
48	434235092340201	05-07-80	1	80	44	--	<1	<3	--	<10
49	434242092160503	05-06-80	<1	<50	35	--	<1	<3	<1	16
			Aquifer layer 3, Missouri							
161	402842092511801	04-07-81	0	2100	30	3.0	2	<3	--	0
162	400217091295201	04-07-81	0	3100	30	5.6	13	<3	--	0
163	391622091343301	04-06-81	0	2200	40	1.0	1	<3	--	0
164	383543092103001	04-06-81	0	320	100	.10	3	<3	--	0
			Aquifer layer 3, Wisconsin							
18	445910092331301	08-04-80	0	<20	20	.60	2	<3	--	<10
29	444504092473601	08-14-80	1	<20	20	.90	4	<3	--	<10
40	441849088051801	08-08-80	7	400	20	.90	4	<3	--	<10
74	432800091062501	11-10-81	0	<20	30	<.10	1	3	--	10
104	424423090552801	08-26-80	1	30	160	.40	4	<3	--	<10
106	430117090173201	08-27-80	1	30	30	.30	6	4	--	<10
107	430132090172601	08-27-80	1	30	30	.30	3	<3	--	<10
109	430136089274301	05-12-80	2	30	90	<.10	6	<3	--	<10
112	425245088274701	05-29-80	0	80	950	<.10	<1	<3	--	<10
113	425153088195501	10-21-82	--	--	150	--	--	--	--	--
114	424407090200001	08-26-80	1	30	40	.10	5	4	--	<10
115	424404089204701	09-04-80	1	80	40	.30	3	<3	--	<10
			Aquifer layer 4, Minnesota							
45	433615093403001	09-02-80	5	250	60	.10	11	<3	--	<10
			Aquifer layer 4, Wisconsin							
111	430618087571001	11-21-80	3	180	30	.30	2	<3	--	<10

TABLE 2.—*Chemical analyses of selected trace constituents in water from wells sampled for this study*—Continued

[Results in micrograms per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Fluoride, F (mg/L)	Iron, Fe	Lithium, Li	Manganese, Mn	Molybdenum, Mo	Lead, Pb	Selenium, Se	Strontium, Sr	Vanadium, Va	Beryllium, Be	Sulfide, S (mg/L)
					Aquifer layer 3, Minnesota						
6	.30	330	14	190	<10	<10	1	--	--	--	--
7	.20	1200	11	230	<10	<10	<1	--	--	--	--
8	.20	1200	6	<20	<10	<10	<1	--	--	--	--
9	.24	<50	6	320	<10	<10	1	--	--	--	--
10	.26	430	8	470	<10	--	<1	--	--	--	--
11	.18	<50	4	280	<10	<10	<1	--	--	--	--
12	.20	<50	3	320	<10	<10	<1	--	--	--	--
13	--	--	3	--	<10	<10	<1	--	--	--	--
14	.27	640	7	30	<10	<10	<1	--	--	--	--
15	.18	<50	2	70	<10	<10	<1	--	--	--	--
16	.19	50	4	<20	<10	<10	<1	--	--	--	--
17	.18	<50	2	<50	<1	--	<1	--	--	--	--
20	.18	590	5	70	3	<10	<1	--	--	--	--
22	.24	430	5	30	3	<10	<1	--	--	--	--
23	.12	<50	5	140	2	<10	<1	--	--	--	--
24	.12	<50	12	20	1	<10	2	--	--	--	--
25	.14	130	7	1000	<1	<10	<1	--	--	--	--
27	.15	1120	7	22	<1	<10	1	--	--	--	--
28	.12	200	5	40	2	<10	<1	--	--	--	--
35	.14	160	7	90	<10	<10	<1	--	--	--	--
36	.40	39	29	330	<10	44	<1	450	<6	<.7	--
37	.17	<50	5	<20	<1	<10	<1	--	--	--	--
42	.43	660	29	190	15	<10	3	--	--	--	--
43	.18	2200	29	200	2	<10	2	--	--	--	--
44	.28	2400	17	300	4	<10	2	--	--	--	--
46	.40	200	8	22	<10	51	1	320	<6	<.7	--
47	.37	320	8	20	<1	<10	<1	--	--	--	--
48	.40	150	8	20	1	<10	1	--	--	--	--
49	.24	240	3	20	<1	1	<1	--	--	--	--
					Aquifer layer 3, Missouri						
161	5.1	110	390	21	0	<10	<1	4500	0	<.7	--
162	4.7	12	680	19	0	25	<1	9300	0	<.7	--
163	2.7	140	230	9	0	<10	<1	2400	0	<.7	--
164	1.2	130	37	18	0	<10	<1	570	0	<.7	--
					Aquifer layer 3, Wisconsin						
18	.20	<3	<4	<1	<10	<10	<1	34	<6	<.7	<.1
29	.10	<3	<4	1	<10	14	<1	21	<6	2.0	<.1
40	1.3	2500	90	65	<10	18	<1	15000	<6	<.7	<.1
74	.10	6	4	1	10	10	<1	62	6	1.0	<.1
104	.20	<3	5	2	<10	13	<1	120	<6	<.7	<.1
106	.20	7	<4	1	<10	17	<1	50	<6	<.7	<.1
107	.10	45	<4	7	<10	<10	<1	15	<6	<.7	<.1
109	.10	14	<4	2	21	<10	<1	78	<6	<.7	--
112	.30	440	8	6	<10	<10	<1	1200	<6	<.7	.6
113	.30	120	4	21	--	--	--	1200	--	--	--
114	.20	3	<4	2	<10	<10	<1	58	<6	<.7	<.1
115	.10	59	<4	190	<10	<10	<1	58	<6	<.7	<.1
					Aquifer layer 4, Minnesota						
45	.30	210	22	100	<10	55	<1	190	<6	<.7	--
					Aquifer layer 4, Wisconsin						
111	.90	150	12	12	12	16	1	13000	<6	<1.0	.2

TABLE 2.—*Chemical analyses of selected trace constituents in water from wells sampled for this study*—Continued

[Results in micrograms per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Site identification number	Date of sample	Arsenic, As	Boron, B	Barium, Ba	Bromide, Br (mg/L)	Cadmium, Cd	Cobalt, Co	Chromium, Cr	Copper, Cu
					Aquifer layer 5, Iowa					
58	425526096210711	09-03-80	2	480	20	.60	6	<3	--	<10
60	431620095250511	09-03-80	3	280	20	.10	6	<3	--	13
81	430512095371801	02-23-82	<50	--	9	--	<2	--	<5	<10
82	425824095300901	02-23-82	<50	--	9	--	<2	--	<5	<10
83	430745094541101	02-23-82	<50	--	13	--	<2	--	<5	<10
85	424348095231601	04-15-80	<10	--	<100	--	1	--	<1	<10
86	424348095231602	09-04-80	2	150	30	<.10	4	<3	--	<10
87	423618095194511	09-04-80	10	340	30	.20	6	6	--	<10
89	422950095174301	02-22-82	<50	--	8	--	<2	--	<5	<10
90	422009095210101	02-22-82	<50	--	10	--	<2	--	<5	<10
					Aquifer layer 5, Minnesota					
2	462710092454001	02-21-80	<1	120	49	--	<1	<3	<1	<10
26	443710093453501	09-03-80	5	220	70	.40	9	<3	--	<10
41	440026094355401	09-03-80	9	110	160	<.10	11	<3	--	<10

TABLE 2.—*Chemical analyses of selected trace constituents in water from wells sampled for this study*—Continued

[Results in micrograms per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Fluoride, F (mg/L)	Iron, Fe	Lithium, Li	Manganese, Mn	Molybdenum, Mo	Lead, Pb	Selenium, Se	Strontium, Sr	Vanadium, Va	Beryllium, Be	Sulfide, S (mg/L)
					Aquifer layer 5, Iowa						
58	.80	140	170	230	<10	22	<1	4300	<6	<.7	--
60	.30	78	110	720	<10	28	<1	2600	<6	<.7	--
81	--	1400	--	--	--	--	<5	--	--	--	<.1
82	.57	2500	--	640	--	<50	<5	--	--	--	<.1
83	.36	4200	--	270	--	<50	<5	--	--	--	<.1
85	2.0	30	--	130	--	<10	<10	--	--	--	--
86	.40	34	33	210	<10	20	<1	770	<6	<.7	--
87	.50	27	45	220	<10	20	<1	1100	<6	<.7	--
89	.43	71	--	2600	--	<50	<5	--	--	--	<.1
90	.82	2900	--	460	--	<50	<5	--	--	--	<.1
					Aquifer layer 5, Minnesota						
2	.15	<0	6	<0	<1	<10	3	--	--	--	--
26	.30	1500	20	710	<10	34	0	370	<6	<.7	--
41	.20	1800	17	320	<10	34	1	240	<6	<.7	--

TABLE 3.—*Analyses of stable isotopes, uranium, and radium-226 in water from selected wells sampled for this study*

[Analyses by U.S. Geological Survey. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Site identification number	Date of collection	Stable isotope ratios (permil) $\delta^{18}O$	δD	$\delta^{13}C$	$\delta^{34}S$	Uranium, U (µg/L)	Radium-226, Ra (pCi/L)	Carbon-14 (percent modern)
			Aquifer layer 1, Illinois						
118	422418090255501	10-23-80	-8.4	-54.0	--	--	<.6	1.1	--
130	422803087475303	12-10-80	-9.3	-63.0	--	8.7	<.6	6.9	--
131	422803087475304	01-14-81	-9.0	-57.5	--	--	28.9	99	--
			Aquifer layer 1, Iowa						
71	432953091172001	06-24-80	-8.4	-55.0	-11.7	--	<.3	1.4	--
73	432206091130301	06-10-80	-8.8	-54.5	-11.3	--	.5	2.0	--
102	430240091110001	06-09-80	-9.2	-56.5	-10.0	--	<.5	2.0	--
119	420842090165702	05-15-81	-8.4	-58.0	-11.1	--	<.6	2.2	--
			Aquifer layer 1, Minnesota						
1	461209093550701	02-21-80	--	--	--	--	<.6	1.7	--
19	445704093215611	09-04-80	-9.6	-64.5	-13.2	--	<.5	2.8	--
30	443354092323201	02-12-80	-10.0	-67.0	-9.9	--	<.6	5.5	--
32	443300092302901	02-12-80	-10.2	-68.0	-10.2	--	<.6	11	--
51	440324091401501	02-13-80	-9.2	-60.5	-12.4	--	<.5	4.6	--
52	440318091388180	02-13-80	-9.5	-61.5	-12.5	--	<.6	2.8	--
			Aquifer layer 1, Wisconsin						
33	443436091281401	08-06-80	-9.2	-65.5	-14.4	--	<.6	.2	--
34	443841090393001	08-20-80	--	--	--	--	<.6	.4	--
38	442141091185601	08-13-80	-9.2	-63.0	-12.3	--	<.7	.5	--
39	442045090453601	08-20-80	--	--	--	--	<.6	.3	--
54	435743089485701	08-21-80	-9.4	-62.5	-14.2	--	2.0	.5	--
55	440219088555701	08-19-80	--	--	--	--	3.7	.5	--
56	434312090353901	08-22-80	--	--	--	--	<.5	.2	--
57	433921091132101	10-08-81	--	--	--	--	<.6	2.2	--
75	432336090460601	08-28-80	--	--	--	--	<.6	.9	--
76	432042090231701	08-28-80	--	--	--	--	<.6	.7	--
77	433144089595901	09-05-80	--	--	--	--	<.6	.5	--
78	433220089282601	09-05-80	--	--	--	--	<.6	.2	--
79	431849089311002	07-24-80	-8.8	-60.0	-8.2	--	.9	<.1	--
80	432717088501701	09-05-80	--	--	--	--	<.6	5.9	--
103	425246091042101	08-19-81	-8.6	-56.5	-11.0	--	.7	2.8	--
105	431108090263101	08-29-80	--	--	--	--	<.5	1.7	--
108	430055089534001	07-18-80	--	--	--	--	.7	.8	--
109	430136089274301	05-12-80	-9.4	-60.0	-13.1	--	22	<.1	--
110	430058089251401	07-22-80	-8.8	-51.0	-8.6	--	.8	1.2	--
			Aquifer layer 3, Illinois						
120	422606089434501	08-29-80	-7.4	-47.5	-8.4	--	--	--	--
121	421331089442201	08-29-80	-8.0	-50.5	-12.6	--	<.6	13	--
122	421658089235101	08-20-80	-8.4	-52.5	--	--	--	--	--
123	422738089114601	08-23-80	-8.8	-58.0	-14.0	--	<.6	.1	--
124	422545089103301	08-23-80	-8.6	-56.0	-12.3	--	<.6	.1	--
125	421855089121601	08-23-80	-7.4	-49.5	-7.3	--	<.6	.8	--
126	421614089062301	09-03-80	-8.4	-54.5	-14.0	--	.9	.5	--
127	420953089080501	09-05-80	-7.4	-46.0	-8.2	--	--	--	--
128	421025088564401	09-04-80	--	--	-7.9	--	--	--	--
129	421329088531701	09-05-80	-8.4	-51.5	-9.4	--	--	--	--
132	422803087475306	09-01-81	-9.6	-68.5	--	15.5	.7	6.0	--
133	415632088071201	06-21-80	-8.9	-64.0	-14.6	--	<1.6	2.7	--
135	413847088214801	08-27-80	-9.5	-61.5	-11.8	--	<.6	2.2	--
136	411858088363401	08-28-80	-9.0	-60.5	-10.6	--	--	--	--
137	411933089403701	08-28-80	-9.4	-61.5	-11.3	--	<.6	5.8	--

TABLE 3—*Analyses of stable isotopes, uranium, and radium-226 in water from selected wells sampled for this study*—Continued

[Analyses by U.S. Geological Survey. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Site identification number	Date of collection	Stable isotope ratios (permil) $\delta^{18}O$	δD	$\delta^{13}C$	$\delta^{34}S$	Uranium, U (µg/L)	Radium-226, Ra (pCi/L)	Carbon-14 (percent modern)
			Aquifer layer 3, Iowa						
59	431620095250201	09-03-80	-10.2	-71.5	-17.2	--	3.7	2.7	--
61	432412094503301	09-09-81	-9.4	-68.5	-13.8	-10.0	2.6	5.8	--
62	431750094303001	09-08-81	-9.0	-64.5	-16.0	-9.9	<.6	1.9	--
63	432256094183301	06-25-80	--	--	--	--	.6	1.6	--
64	431350093544201	06-25-80	-6.3	-45.5	-11.2	--	<.6	1.2	--
65	430800092540301	06-26-80	--	--	--	--	<.5	2.0	--
66	432650092170201	06-24-80	--	--	--	--	<.5	.4	--
67	430337092190701	06-25-80	-8.3	-54.5	-10.2	--	.4	1.1	--
68	431216091572001	06-23-80	-9.2	-54.0	-10.6	--	.8	.3	--
69	432606091470301	06-23-80	--	--	--	--	.9	<.1	--
70	432800091295301	06-24-80	-8.9	-59.5	-10.0	--	.7	<.1	--
72	431638091284102	06-24-80	--	--	--	--	.5	.2	--
84	430210094500001	09-08-81	-9.9	-70.0	-18.8	-8.5	<.7	.4	--
88	423840095135001	09-04-80	--	--	--	--	.7	8.0	--
		09-08-81	-10.8	-78.5	-14.7	-9.2	--	--	--
91	421831095152101	09-04-80	-12.0	-87.0	-12.5	-1.1	.6	7.3	1.5
92	422339094375101	09-02-80	--	--	-10.1	-4.4	1.2	5.0	--
93	422136094173401	09-05-80	-12.3	--	--	-1.0	1.1	9.1	--
94	422855093481501	09-02-80	-10.0	-70.0	-11.4	--	1.2	6.5	<0.7
95	422611092552501	09-02-80	--	--	--	--	.7	3.6	--
96	425049092063801	06-11-80	--	--	--	--	.5	2.4	--
97	425708091383001	06-10-80	--	--	--	--	2.4	.6	--
98	424820091324001	06-09-80	-8.6	-54.0	-10.0	--	4.9	.8	--
99	425138091234901	06-09-80	-9.0	-54.5	-11.2	--	<.5	1.8	--
100	425550091233001	06-09-80	--	--	--	--	.4	1.7	--
101	430330091264301	06-24-80	--	--	--	--	1.4	1.4	--
116	423141090385801	08-26-81	-8.2	-54.5	-11.2	3.9	.8	2.0	--
117	422640091002701	08-26-81	-8.8	-61.5	-10.2	-8.4	<.6	1.8	--
138	421010092180301	06-23-80	--	--	-10.1	--	1.1	2.7	--
139	420200091363001	07-21-80	-10.0	-66.0	-10.1	--	<7.0	2.8	3.7
140	420718091165401	07-23-80	--	--	--	--	1.6	1.8	--
141	412407095391201	09-02-81	-17.1	-131.0	-7.3	11.8	<.6	6.2	--
142	413015094391302	09-02-81	-17.1	-132.0	-6.9	13.6	<.5	12	--
143	415021094072801	09-02-81	-13.6	-103.0	-8.6	6.5	.7	9.4	--
144	413931093292001	09-01-81	--	--	-8.9	--	<.6	6.5	--
		09-08-81	-8.6	-61.0	-9.2	2.5	--	--	--
145	414430092433001	09-01-81	-9.9	-72.5	-9.3	1.8	<1.1	3.2	--
146	412736093241201	07-30-81	--	--	--	--	<.6	3.3	--
147	412025093322201	06-10-81	-9.6	-64.5	-9.0	6.6	<.5	4.7	4.2
148	410235093564901	06-10-81	-14.7	-109.0	-8.1	-2.0	<.5	13	2.6
149	404422093445602	07-28-81	-16.5	-124.0	-7.7	16.2	<.6	7.1	--
150	405858093175701	06-10-81	-10.3	-72.0	-8.9	-4.6	<.5	5.8	--
151	411332093142101	06-10-81	--	--	--	--	<.6	3.9	--
152	412020092471001	08-12-81	--	--	--	--	<.6	9.0	--
153	410305092490701	07-28-81	--	--	--	--	<.5	11	--
154	412356092211001	07-30-81	--	--	--	--	.9	17	--
155	405750092142001	06-09-81	-12.1	-88.5	-9.3	7.7	1.2	16	5.4
156	410115091571801	06-09-81	--	--	--	--	1.3	9.6	--
157	411812091412601	08-05-80	--	--	--	--	<.5	7.1	--
158	411907091220001	10-29-80	-19.4	-86.5	-10.6	--	<1.6	8.2	--
160	403839091333801	08-05-80	--	--	--	--	.9	9.9	--
			Aquifer layer 3, Minnesota						
36	441851093341801	09-03-80	-7.6	-54.5	-12.4	--	3.1	.4	--
37	441454092101001	02-12-80	-9.5	-62.5	-9.0	--	1.2	.3	--
43	434547094095802	01-29-80	-10.2	-70.0	--	--	1.0	3.7	--
46	435333092503901	09-02-80	-9.0	-59.0	-11.4	--	<.5	.8	--

TABLE 3—*Analyses of stable isotopes, uranium, and radium-226 in water from selected wells sampled for this study*—Continued

[Analyses by U.S. Geological Survey. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Site identification number	Date of collection	Stable isotope ratios (permil) $\delta^{18}O$	δD	$\delta^{13}C$	$\delta^{34}S$	Uranium, U (µg/L)	Radium-226, Ra (pCi/L)	Carbon-14 (percent modern)
			Aquifer layer 3, Missouri						
161	402842092511801	04-07-81	-13.9	-104.0	-6.2	--	<.6	3.3	--
162	400217091295201	04-07-81	-14.8	-112.0	-6.1	--	<.6	31	--
163	391622091343301	04-06-81	-7.2	-49.0	-7.6	--	1.9	3.4	--
164	383543092103001	04-06-81	-7.0	-46.0	-9.0	--	.8	2.1	--
			Aquifer layer 3, Wisconsin						
18	445910092331301	08-04-80	-10.5	--	-13.4	--	<.6	<.1	--
29	444504092473601	08-14-80	-9.4	--	-6.2	--	1.5	.5	--
40	441849088051801	08-08-80	-14.0	-98.0	-12.6	--	1.4	8.9	--
74	432800091062501	11-10-81	--	--	--	--	<.6	<.1	--
104	424423090552801	08-26-80	--	--	--	--	.9	<.1	--
106	430117090173201	08-27-80	-9.0	-59.0	-10.7	--	<.5	<.1	--
107	430132090172601	08-27-80	--	--	-6.2	--	<.6	.2	--
112	425245088274701	05-29-80	-8.6	-56.5	-9.0	--	<.5	3.3	--
113	425153088195501	10-21-82	--	--	--	--	--	3.0	--
114	424407090200001	08-26-80	--	--	-6.1	--	1.0	.5	--
115	424404089204701	09-04-80	-9.2	-62.0	-13.0	--	<.6	.1	--
			Aquifer layer 4, Minnesota						
45	433615093403001	09-02-80	-9.6	-63.0	-14.4	--	1.2	.3	--
			Aquifer layer 4, Wisconsin						
111	430618087571001	11-21-80	--	--	--	--	.8	.3	--
			Aquifer layer 5, Iowa						
58	425526096210711	09-03-80	--	--	--	--	<.5	.8	--
60	431620095250511	09-03-80	--	--	--	--	1.6	.8	--
81	430512095371801	02=23-82	--	--	--	-7.5	--	--	--
82	425824095300901	02-23-82	--	--	--	-10.0	--	--	--
83	430745094541101	02-23-82	--	--	--	-7.5	--	--	--
85	424348095231601	09-04-80	-8.1	-55.5	-14.2	--	<.5	.1	--
86	424348095231602	09-04-80	-8.6	-57.5	-7.6	--	6.1	.1	--
87	423618095194511	09-04-80	--	--	--	--	1.3	.3	--
89	422950095174301	02-22-82	--	--	--	-8.0	--	--	--
90	422009095210101	02-22-82	--	--	--	-10.8	--	--	--
			Aquifer layer 5, Minnesota						
2	462710092454001	02-20-80	--	--	--	--	1.1	.1	--
26	443710093453501	09-03-80	-7.8	-55.5	-13.8	--	3.2	.2	--
41	440026094355401	09-03-80	-9.5	-67.0	-10.2	--	<.6	.2	--

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Document 16

U.S. EPA, Office of Solid Waste and Emergency Response, OSWER Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor in Indoor Air, June 2015.

OSWER Publication 9200.2-154

OSWER TECHNICAL GUIDE FOR ASSESSING AND MITIGATING THE VAPOR INTRUSION PATHWAY FROM SUBSURFACE VAPOR SOURCES TO INDOOR AIR

U.S. Environmental Protection Agency

Office of Solid Waste and Emergency Response

June 2015

DISCLAIMER

This document presents current technical recommendations of the U.S. Environmental Protection Agency (EPA) based on our current understanding of vapor intrusion into indoor air from subsurface vapor sources. This guidance document does not impose any requirements or obligations on the EPA, the states or tribal governments, or the regulated community. Rather, the sources of authority and requirements for addressing subsurface vapor intrusion are the relevant statutes and regulations. Decisions regarding a particular situation should be made based upon statutory and regulatory authority. EPA decision-makers retain the discretion to adopt or approve approaches on a case-by-case basis that differ from this guidance document, where appropriate, as long as the administrative record supporting its decision provides an adequate basis and reasoned explanation for doing so.

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ACRONYMS AND ABBREVIATIONS

ACH	air changes per hour (air exchanges per hour)
ADT	active depressurization technology
AER	air exchange rate
ANSI	American National Standards Institute
ASQ	American Society for Quality
ASTM	American Society for Testing and Materials
ASTSWMO	Association of State and Territorial Solid Waste Management Officials
ATSDR	Agency for Toxic Substances and Disease Registry
BTEX	benzene, toluene, ethylbenzene, xylenes
BWD	block-wall depressurization
CalEPA	California Environmental Protection Agency
CASRN	Chemical Abstracts Service Registry Number
CEI	Community Engagement Initiative
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CHC	chlorinated hydrocarbon
CIC	Community Involvement Coordinator
CIO	Chief Information Officer
CIP	community involvement plan
CMS	corrective measures study
CSM	conceptual site model
DCE	dichloroethylene, or equivalently dichloroethene
DNAPL	dense non-aqueous-phase liquid
DoD	U.S. Department of Defense
DoN	U.S. Department of Navy
DQO	data quality objective
DTD	drain-tile depressurization
EI	environmental indicator
EPA	U.S. Environmental Protection Agency
ERT	Environmental Response Team
FR	Federal Register
FS	feasibility study

FYR	five-year review
HI	Hazard Index
HQ	Hazard Quotient
HVAC	heating, ventilation and air conditioning
IC	institutional control
ICIAP	Institutional Controls Implementation and Assurance Plan
IDLH	immediately dangerous to life or health
ITRC	Interstate Technology and Regulatory Council
LCR	lifetime cancer risk
LEL	lower explosive limit
LEP	limited English proficiency
LNAPL	light non-aqueous-phase liquid
LTS	long-term stewardship
MADEP	Massachusetts Department of Environmental Protection
NAPL	non-aqueous-phase liquid
NAS	National Academy of Sciences
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NFA	No Further Action
NIST	National Institute of Standards and Technology
NPL	National Priorities List
NRC	National Research Council
NIOSH	National Institute for Occupational Safety and Health
NYSDOH	New York State Department of Health
O&M	operation and maintenance
OIG	Office of the Inspector General
OSC	on-scene coordinator
OSHA	Occupational Safety and Health Administration
OSWER	Office of Solid Waste and Emergency Response
OUST	Office of Underground Storage Tanks
PAH	polycyclic aromatic hydrocarbon
PCB	polychlorinated biphenyl
PCE	tetrachloroethylene, or equivalently tetrachloroethene
PEM	preemptive mitigation
PID	photoionization detector

P.E.	Professional Engineer
ppbv	parts per billion by volume
PRP	potentially responsible party
QAPP	quality assurance project plan
QMP	quality management plan
RCRA	Resource Conservation and Recovery Act
RfC	inhalation reference concentration
RFI	RCRA facility investigation
RI	remedial investigation
RME	reasonable maximum exposure
ROD	Record of Decision
RPM	remedial project manager
SMD	sub-membrane depressurization
SSD	sub-slab depressurization
TAGA	trace atmospheric gas analyzer
TCE	trichloroethylene, or equivalently trichloroethene
UFP-QAPP	Uniform Federal Policy for Quality Assurance Project Plans
UECA	Uniform Environmental Covenants Act
USPS	U.S. Postal Service
UST	underground storage tank
UU/UE	unlimited use/unrestricted exposure
VI	vapor intrusion
VISL	vapor intrusion screening level
VOC	volatile organic compound

EXECUTIVE SUMMARY

Definition and Description of Vapor Intrusion

Vapor intrusion is the general term given to migration of hazardous vapors from any subsurface vapor source, such as contaminated soil or groundwater, through the soil and into an overlying building or structure. These vapors can enter buildings through cracks in `basements and foundations, as well as through conduits and other openings in the building envelope. Vapors can also enter structures that are not intended for human occupancy (e.g., sewers, drain lines, access vaults, storage sheds, pump houses) through cracks and other openings.

All types of buildings, regardless of foundation type (e.g., basement, crawl space, slab-on-grade), have openings that render them potentially vulnerable to vapor intrusion. Buildings subject to vapor intrusion include, but are not limited to, residential buildings (e.g., detached single-family homes, trailer or 'mobile' homes, multi-unit apartments and condominiums), commercial workplaces (e.g., office buildings, retail establishments), educational and recreational buildings (e.g., schools and gyms), and industrial facilities (e.g., manufacturing plants).

Vapor intrusion is a potential human exposure pathway -- a way that people may come into contact with hazardous vapors while performing their day-to-day indoor activities. For purposes of this Technical Guide, the vapor intrusion pathway is referred to as "complete" for a specific building or collection of buildings when the following five conditions are met under current conditions:

1) A subsurface source of vapor-forming chemicals is present (e.g., in the soil or in groundwater) underneath or near the building(s) (see Sections 2.1, 5.3, 6.2.1, and 6.3.1);

2) Vapors form and have a route along which to migrate (be transported) toward the building (see Sections 2.2 and 6.3.2);

3) The building(s) is(are) susceptible to soil gas entry, which means openings exist for the vapors to enter the building and driving 'forces' (e.g., air pressure differences between the building and the subsurface environment) exist to draw the vapors from the subsurface through the openings into the building(s) (see Sections 2.3 and 6.3.3);

4) One or more vapor-forming chemicals comprising the subsurface vapor source(s) is(are) present in the indoor environment (see Sections 6.3.4 and 6.4.1); and

5) The building(s)[1] is(are) occupied by one or more individuals when the vapor-forming chemical(s) is(are) present indoors.

[1] For purposes of this Technical Guide and its recommendations for evaluating human health risk posed by vapor-forming chemicals, "building" refers to a structure that is intended for occupancy and use by humans. This would include, for instance, homes, offices, stores, commercial and industrial buildings, etc., but would not normally include sheds, carports, pump houses, or other structures that are not intended for human occupancy.

A complete vapor intrusion pathway indicates that there is an opportunity for human exposure, which warrants further analysis (see Section 7.4) to determine whether there is a basis for undertaking a response action(s) (see Section 7.7). Depending upon building- and site-specific circumstances, concentrations of chemical vapors indoors arising from a complete vapor intrusion pathway may threaten the health of building occupants (e.g., residents, workers, etc.), which may warrant a response action(s).

On the other hand and for purposes of this Technical Guide, if one (or more) of the five foregoing conditions is currently absent and is reasonably expected to be absent in the future (e.g., vapor migration is significantly and persistently impeded by natural geologic, hydrologic, or biochemical (e.g., biodegradation) processes and conditions), the vapor intrusion pathway is referred to as "incomplete." EPA recommends that any determination that the vapor intrusion pathway is incomplete be supported by site-specific evidence to demonstrate that the nature and extent of vapor-forming chemical contamination in the subsurface has been well characterized (Section 6.3.1) and the types of vapor sources and the conditions of the vadose zone and surrounding infrastructure do not present opportunities for unattenuated or enhanced transport of vapors (Sections 5.4 and 6.5.2) toward and into any building (see Section 7.3 for further discussion). When the vapor intrusion pathway is determined to be incomplete, then vapor intrusion mitigation is not generally warranted.

EPA recommends that site managers also evaluate whether subsurface vapor sources that remain have the potential to pose unacceptable human health risks due to vapor intrusion in the future[2] if site conditions were to change. The vapor intrusion pathway is referred to as 'potentially complete' for a building when:

- a subsurface source of vapor-forming chemicals is present underneath or near an existing building or a building that is reasonably expected to be constructed in the future;
- vapors can form from this source(s) and have a route along which to migrate (be transported) toward the building; and
- three additional conditions are reasonably expected to all be met in the future, which may not all be met currently; i.e.,
    - the building is susceptible to soil gas entry, which means openings exist for the vapors to enter the building and driving forces exist to draw the vapors from the subsurface through the openings into the building;
    - one or more vapor-forming chemicals comprising the subsurface vapor source(s) is (or will be) present in the indoor environment; and
    - the building is or will be occupied by one or more individuals when the vapor-forming chemical(s) is (or are) present indoors.

[2] "Both current and reasonably likely future risks need to be considered in order to demonstrate that a site does not present an unacceptable risk to human health and the environment." (EPA 1991a).

In addition to their toxicity threats, methane and certain other vapor-forming chemicals can also pose explosion hazards depending upon structure-, building-, and site-specific circumstances. Explosion hazards may pose an imminent and substantial danger to human health and public welfare.

Technical Guide Development and Recommended Uses

To help assess the subsurface vapor intrusion pathway, the Office of Solid Waste and Emergency Response (OSWER) released in November 2002 for comment EPA's *Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils* ("Draft VI Guidance"). Since the Draft VI Guidance was released, EPA's knowledge of and experience with assessment and mitigation of the vapor intrusion pathway has increased considerably, leading to an improved understanding of and enhanced approaches for evaluating and managing vapor intrusion. In addition, EPA received hundreds of comments from the public since 2002 on the Draft VI Guidance, on a public review draft issued in April 2013, and on emerging practices and science considerations.

This Technical Guide presents current technical recommendations of the EPA based on our current understanding of vapor intrusion into indoor air from subsurface vapor sources. One of its main purposes is to promote national consistency in assessing the vapor intrusion pathway.[3] At the same time, it provides a flexible science-based approach to assessment that accommodates the different circumstances (e.g., stage of the cleanup process) in which vapor intrusion is first considered at a site and differences among pertinent EPA programs. This Technical Guide is intended for use at any site (and any building or structure on a site) being evaluated by EPA pursuant to the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) or the corrective action provisions of the Resource Conservation and Recovery Act (RCRA), EPA's brownfield grantees, or state agencies acting pursuant to CERCLA or an authorized RCRA corrective action program where vapor intrusion may be of potential concern. This document and the accompanying *Technical Guide For Addressing Petroleum Vapor Intrusion At Leaking Underground Storage Tank Sites* (EPA 2015b)[4] supersede and replace the Draft VI Guidance.

Although this Technical Guide is intended for use at any site subject to federal statutes, regulations, and rules, it is not intended to alter existing requirements, guidance, or practices among OSWER's programs about development, selection, or documentation of final remediation[5] plans (addressing subsurface vapor sources, for example).

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[3] If EPA staff wish to consider using any specific guidance that is not explicitly recommended in this Technical Guide, they should consult with Headquarters.

[4] For petroleum hydrocarbons that arise from petroleum that has been released from Subtitle I UST systems, EPA has developed a companion to this Technical Guide (*Technical Guide For Addressing Petroleum Vapor Intrusion At Leaking Underground Storage Tank Sites* (EPA 2015b)), which provides information and guidance about how EPA recommends vapor intrusion be assessed for petroleum hydrocarbons in these settings.

[5] For purposes of this Technical Guide, "remediation" is intended to apply to interim and final cleanups, whether conducted pursuant to RCRA corrective action, the CERCLA removal or remedial programs, or using EPA brownfield grant funds with oversight by state and tribal response programs. In addition to permanent remedies for subsurface vapor sources, site remediation may also entail implementation of institutional controls and construction and operation of engineered systems for exposure control.

Document Content and Key Recommendations

This document is comprised of eleven sections and three appendices, including a list of acronyms, which precedes this summary, and a glossary of terms in Section 10. Section 3 provides an overview of the entire Technical Guide and can be further summarized as follows:

- Broadly speaking, two general levels of vapor intrusion assessments can be distinguished:

  1) A preliminary analysis, which utilizes available and readily ascertainable information to develop an *initial* understanding of the potential for human health risks to be posed by vapor intrusion, which would typically be performed as part of an initial site assessment (Section 5).

  2) A detailed investigation (Section 6), which is generally recommended when the preliminary analysis (e.g., Section 5.3) indicates that subsurface contamination with vapor-forming chemicals may be present underlying or near buildings. A detailed investigation of the vapor intrusion pathway is typically performed as part of the site investigation stage.

  The approach for assessing vapor intrusion will vary from site to site, because each site will differ in the available data when vapor intrusion is being evaluated. This Technical Guide, therefore, recommends a framework for planning and conducting vapor intrusion investigations, rather than a prescriptive step-by-step approach to be applied at every site.

- Response actions to address vapor intrusion when it poses unacceptable human health risks (Sections 7.7 and 8) typically entail a combination of:

  - remediation to reduce or eliminate subsurface vapor sources (Section 8.1);
  - engineered exposure controls for specific buildings to reduce vapor intrusion or reduce concentrations of vapor-forming chemicals that have already entered the building (Section 8.2);
  - monitoring to assess and verify the performance and effectiveness of the remediation systems and engineered exposure controls (Section 8.4); and
  - institutional controls (ICs) to restrict land use and/or to alert parties (e.g., prospective developers, owners, and municipalities) of the presence of subsurface sources of vapor-forming chemicals and to foster operation, maintenance, and monitoring of the remediation systems and engineered exposure controls (Section 8.6).

  Additional response actions to avoid or reduce human exposure may also warrant consideration in circumstances where “early” or prompt response action is appropriate to address indoor air exposure conditions or a potential for explosion hazards.

Additional key recommendations and policies comprising this document include the following:

Planning, Scoping and Conducting Investigations (see Sections 5.4 and 6.2 for further information)

- Consider site and building access agreements, equipment security, and locations of underground utilities and piping, such as storm and sewer lines within buildings, when planning vapor intrusion investigations (Section 6.2).

- Develop an initial conceptual site model, use this model to guide planning and scoping of the investigation, and update this model as additional information and insights are generated (Sections 5.4, 7.1, and 7.2).

- Generally limit chemical analyses to those vapor-forming chemicals known or reasonably expected to be present in the subsurface environment.

- Consider a "worst first" approach to prioritize buildings for investigation at sites where numerous buildings are potentially subject to vapor intrusion (Section 6.2.2).

- To the extent practical, plan and implement investigations within buildings and on individual properties with the goal of limiting return visits, which can cause disruption and inconvenience for building occupants and owners (Section 6.2).

- Generally assess the vapor intrusion pathway by collecting, weighing, and evaluating multiple lines of evidence (Sections 6.3, 7.1, and 7.2).

- Utilize 100 feet to define an initial lateral inclusion zone for vapor intrusion assessment (i.e., for identifying buildings that are 'near' a subsurface vapor source and generally warrant assessment) for purposes of a preliminary analysis). Investigate soil vapor migration distance (e.g., define inclusion zone(s) for assessing vapor intrusion in specific buildings) on a site-specific basis. That is, distances larger or smaller than 100 feet (i.e., beyond or within an initial 100-foot inclusion zone) may need to be considered when developing objectives for detailed vapor intrusion investigations and interpreting the resulting data (Section 6.2.1).

- To support evaluations of sources of indoor air concentrations, identify in individual buildings known or suspected indoor sources of the vapor-forming chemicals also found in the subsurface and characterize ambient air quality in the site vicinity for these same chemicals (Sections 6.3.5 and 6.4).

- Select sampling and analytical methods that are capable of obtaining reliable analytical detections of concentrations less than project-appropriate, risk-based screening levels (e.g., vapor intrusion screening levels, or VISLs).

- When groundwater is a subsurface source of vapors, collect groundwater samples from wells screened across the top of the water table to characterize the source strength for vapor intrusion (Sections 6.3.1 and 6.4.5).

- Collect indoor air samples to characterize exposure levels in indoor air, account for seasonal variations in climate and the habits of building occupants, and ensure that

related risk management decisions are based upon a consideration of a reasonable maximum vapor intrusion condition for a given building (Sections 6.3.4 and 6.4.1).

- When sampling indoor air,
  - employ time-integrated sampling methods (e.g., evacuated canisters, sorbent-based sampling devices). Indoor air concentrations can be temporally variable and time-integrated exposure estimates over appropriate exposure durations (e.g., chronic typically; less-than-chronic in some cases) are generally most useful for exposure and human health risk assessment (Sections 6.4.1 and 7.4);
  - remove potential indoor sources[6] of vapor-forming chemicals from the building to strive to ensure that the concentrations measured in the indoor air samples are attributable to the vapor intrusion pathway (Sections 6.3.5 and 6.4.1); and
  - measure the pressure difference between the indoors and the subsurface, which provides a complementary line of evidence to support data evaluation and interpretation (Section 6.4.1) and is a more direct means of assessing building under-pressurization than is monitoring weather/climate factors (e.g., air temperature, wind speed).
- Mathematical modeling of vapor intrusion is most appropriately used in conjunction with other lines of evidence (Section 6.6).
- Confirm the reliability of modeling results, especially when limited site-specific data are available as inputs (Section 6.6).
- Collect and evaluate appropriate site-specific information to demonstrate that the property fulfills the conditions and assumptions of the generic conceptual model underlying the vapor intrusion screening levels (Section 6.5.2).

Data Evaluation and Decision-making

- Assess (and seek) concordance among the lines of evidence to more confidently support decision-making (Sections 7.1, 7.2, and 7.3).[7] Multiple lines of evidence are generally recommended for supporting conclusions, such as the following:
  - The subsurface vapor source(s) at a specific site has the potential to pose an unacceptable vapor intrusion exposure under current or reasonably expected future conditions, due to its vapor strength (Section 6.5) and proximity relative to one or more existing buildings or a building that may be constructed in the future (Section 6.2.1).

[6] As mentioned in Section 6.3.5, indoor sources can sometimes be identified and located using portable instruments.

[7] Confidence in the assessment and risk management decisions is expected to be higher when multiple independent lines of evidence come together to provide mutually supporting evidence for a common understanding of the site conditions/scenarios and the potential for vapor intrusion (EPA 2010b).

- The vapor intrusion pathway is complete for one or more buildings under current or reasonably expected future conditions (Section 7.3).

- The vapor intrusion pathway is incomplete for one or more buildings near a subsurface source of vapor-forming chemicals (Section 7.3), due to

  - inadequate source strength (i.e., chemicals comprising subsurface contamination and/or their potential vapor concentrations cannot pose an unacceptable human health risk via the vapor intrusion pathway) (Section 6.5); or

  - geologic, hydrologic, and/or biochemical (e.g., biodegradation) processes that provide substantial and persistent attenuation of vapors extending laterally over large distances relative to the footprint of the building(s) and the extent of the vapor source (Section 6.3.2).

- Indoor air concentrations attributable to vapor intrusion pose (or, alternatively, are unlikely to pose) an unacceptable human health risk in one or more existing buildings under current or reasonably expected future conditions, based upon currently available information about a chemical's toxicity (Section 7.4).

- Indoor air concentrations measured in one or more buildings can (or alternatively, cannot) be reasonably attributed to indoor or ambient air sources (i.e., background – see Glossary) (Sections 6.3.5 and 7.4.2).

Multiple lines of evidence are particularly important for supporting "no-further-action" decisions regarding the vapor intrusion pathway (e.g., pathway incomplete determinations) to reduce the chance of reaching a false-negative conclusion (i.e., concluding vapor intrusion does not pose unacceptable human health risk, when it actually poses an unacceptable human health risk). Collecting and weighing multiple lines of evidence can also reduce the chance of reaching a false-positive conclusion (i.e., concluding vapor intrusion poses unacceptable human health risk, when it does not). On the other hand, parties may implement engineered exposure controls for vapor intrusion, even though only limited lines of evidence or measurements may be available to characterize the overall vapor intrusion pathway.

- Consider reasonably expected future conditions, in addition to current conditions, when reaching conclusions about the vapor intrusion pathway (Sections 3.2 and 7.3). For example, EPA recommends that vapor intrusion be evaluated for reasonably expected future land use conditions, including new building construction and new uses and occupants for uninhabited buildings.

- Identify any conditions that warrant prompt action (Section 7.5) and respond, consistent with applicable statutes and regulations and considering EPA guidance, with actions that eliminate, avoid, reduce or otherwise address the human health risk posed by vapor intrusion (Sections 7.7 and 8.2):

  - Explosive conditions and threats that warrant prompt action (Section 7.5.1) are reasonably suspected to exist when measured concentrations of vapors in the building, utility conduits, sumps, subsurface drains, or other structure directly

connected to the building exceed one-tenth (10%) of the lower explosive limit (LEL).[8] EPA recommends evacuation of buildings with potential explosion and fire hazards, along with notification to the local fire department about the situation.

- o Conditions posing health concerns that warrant prompt action are reasonably suspected to exist when estimated exposure concentrations of vapors in the building exceed health-protective concentrations for short-term or acute exposure (Section 7.5.2).

- When making decisions pertaining to the assessment of vapor intrusion at nonresidential buildings, consider the characteristics of the populations potentially exposed to vapor-forming chemicals in the indoor air, the relative contributions of vapors from background (including anthropogenic background), and any existing or planned engineering or institutional controls for the building, in addition to the potential for vapor intrusion (Sections 4, 6.3.5, 6.4.1 and 7.4.2).

- When evaluating environmental sampling results to assess the vapor intrusion pathway, first determine that the samples were collected appropriately (Sections 5.5 and 6.4).

- Before conducting risk-based screening, verify that the site fulfills the conditions and assumptions of the generic conceptual model underlying the VISLs (Section 6.5.2).

- Compare groundwater concentrations to the VISLs (Section 6.5) for groundwater to estimate the boundaries of the plume, when contaminated groundwater is the subsurface vapor source for vapor intrusion (Section 6.2.1).

- Generally support the decision to collect indoor air data (Section 6.4.1) by lines of site- or building-specific evidence that demonstrate vapor intrusion has the potential to pose a significant human exposure [e.g., data on strength and proximity of subsurface vapor source(s) (Sections 6.2.1, 6.3.1, and 6.5), or preferential vapor migration in the vadose zone or into buildings (Sections 5.4, 6.3.2, and 6.3.3)].

- Consider variability in laboratory analyses when evaluating sampling data.

- Generally conduct a human health risk assessment to determine whether the potential human health risks posed to building occupants are within or exceed acceptable levels consistent with applicable statutes and considering EPA guidance (Section 7.4).

- Consider the potential for adverse non-cancer health effects from short-duration exposures (i.e., acute, short-term, or subchronic exposure durations), as well as longer term exposure (i.e., chronic exposure) conditions, and select toxicity values considering OSWER's preferred hierarchy of sources (EPA 2003) (Sections 7.4 and 7.5.2).

[8] The Occupational Safety and Health Administration of the U.S. Department of Labor (OSHA) considers concentrations in excess of one-tenth of the LEL to be a hazardous atmosphere in confined spaces [29 CFR 1910.146(b)]. The National Institute for Occupational Safety and Health (NIOSH) has designated such concentrations as immediately dangerous to life or health (IDLH).

- Consider collecting multiple rounds of indoor air samples,[9] using time-integrated measurements (Section 6.4.1) to estimate exposure concentrations appropriate for the exposure (occupancy) scenario being evaluated (e.g., residential versus commercial), when the risk assessment for an existing building would support a conclusion that the human health risks are acceptable (Section 7.4).[10]

- In the risk characterization of the human health risk assessment, discuss 'background' contributions to indoor air exposure and associated human health risks (Section 7.4.2). (For purposes of this Guide, 'background' refers to a vapor-forming chemical(s) or location(s) that is(are) not influenced by the releases from a site – see Glossary). Information on 'background' contributions of site-related, vapor-forming chemicals in indoor air is important to risk managers because generally EPA does not clean up to concentrations below natural or anthropogenic background levels[11] (EPA 2002e).

- If data are available, distinguish the contribution of 'background' to total exposure concentration(s). With such information, EPA can help advise affected individuals about the environmental and human health risks they face. Other parties, including building owners and operators, may help with risk communication.

- If background vapor sources (see Glossary) are found to be primarily responsible for indoor air concentrations (see Section 6.3.5), then response actions for vapor intrusion would generally not be warranted for current conditions.

<u>Engineered Exposure Controls and Building Mitigation</u>

- When vapor intrusion has been determined to pose unacceptable human health risks,

    - Aim to achieve a permanent remedy by eliminating or substantially reducing the level(s) of vapor-forming chemical(s) in the subsurface source medium (e.g., groundwater, subsurface soil, sewer lines) (Sections 7.7 and 8.1); and
    - In cases where subsurface vapor sources cannot be remediated quickly, implement engineered exposure controls to reduce or eliminate vapor intrusion in buildings (i.e., "mitigate" vapor intrusion) or reduce indoor air exposure levels (Sections 7.7 and 8.2).

[9] Because weather conditions and building operations can lead to time-variable contributions from vapor intrusion and ambient air infiltration, indoor air concentrations of vapor-forming chemicals can be expected to vary over time (see, for example, Section 2.6). An individual sample (or single round of sampling) would be insufficient to characterize seasonal variability, or variability at any other time scale.

[10] EPA recommends basing the decision about whether to undertake response action for vapor intrusion (i.e., a component of risk management; see Section 7.4) on a consideration of a reasonable maximum exposure (e.g., EPA 1989, 1991a), which is a semi-quantitative term, referring to the lower portion of the high end of the exposure distribution (see Glossary).

[11] With respect to vapor intrusion mitigation (see Sections 3.5 and 8.2), some options for reducing indoor air exposure levels (e.g., ventilation, indoor air treatment) unavoidably act on background concentrations arising from indoor or outdoor sources, as well as vapor concentrations arising from vapor intrusion. Most options for interrupting the vapor intrusion pathway (e.g., active depressurization technologies – see Section 8.2) unavoidably interrupt the intrusion of naturally occurring radon also. It should also be noted that some EPA regulations (e.g., indoor radon standards under 40 CFR 192.12) are inclusive of background.

- When developing monitoring programs to assess effectiveness of building mitigation, consider the degree of human health risk or hazard being mitigated, the building use, the technology used to mitigate vapor intrusion, and coordination with site remediation efforts.

- Establish cleanup levels and criteria for terminating engineered exposure controls and other building mitigation methods, institutional controls, and remediation systems for subsurface vapor sources (Sections 7.6 and 8.7).

Document Activities and Decisions

- Document objectives and methods of vapor intrusion investigations, preferably in a vapor intrusion work plan (Section 6.2).

- Base decisions upon data and information in the administrative record.

- Base decisions to undertake response actions on lines of site- or building-specific evidence (e.g., characterization of subsurface vapor source(s) strength and proximity to building(s); building conditions) that demonstrate that vapor intrusion has the potential to pose an unacceptable human health risk (Section 7).

- Document, consistent with statutory requirements and considering prevailing guidance for the respective land restoration program (e.g., CERCLA, RCRA corrective action, brownfields, etc.), any and all decisions pertaining to vapor intrusion, including decisions to undertake (or not to undertake) investigation or mitigation of specific buildings at a contaminated site.

- Prepare and publish system manuals to document building mitigation and remediation systems (Section 8.5).

- Prepare and implement operations and maintenance manuals and practices to foster continued effective operation and performance of engineered exposure controls and remediation systems for subsurface vapor sources (Section 8.5).

- Document monitoring programs that assess the performance and effectiveness of remediation and mitigation systems.

Community Outreach and Involvement (Section 9)

- Develop or refine a community involvement or public participation plan while planning a vapor intrusion investigation and implement this plan throughout the assessment, remediation, and mitigation phases.

- Conduct building-by-building contact and communication as means of educating the community and obtaining access needed to assess, mitigate, and monitor the vapor intrusion pathway. Personal contact is further recommended to establish a good working relationship with each building owner or occupant and to build trust.

- Generally provide validated results and interpretations (e.g., chemicals of concern, associated risk assessment implications) to property owners and occupants in a timely manner (e.g., within approximately 30 days of receiving these results).

- Provide adequate opportunities for public participation (including potentially affected landowners and communities) when considering appropriate use of ICs.

The science and technology to assess and mitigate vapor intrusion have evolved significantly over the past decade. EPA will continue to monitor these evolving developments and will update these recommendations in the future, if and as appropriate.

1.0 INTRODUCTION

This technical guide was prepared by the U.S. Environmental Protection Agency (EPA) through the cooperative efforts of a team of EPA Headquarters and Regional staff, known as the Vapor Intrusion Intra-Agency Workgroup (Workgroup). Drafts of this document were subjected to a comprehensive, consultative peer-input process in 2012, as described in EPA's *Peer Review Handbook* (EPA-SPC 2006), which included comments and other contributions from Workgroup members representing several EPA offices and the EPA's Vapor Intrusion Forum.[12] Public comments submitted from 2002 through 2013 and recommendations of the Office of Inspector General (OIG) were also considered in developing this document.

This document comprises EPA's 'final' vapor intrusion technical guide[13] and is referred to herein as "this Technical Guide." It describes a recommended framework for assessing vapor intrusion that relies upon collecting and evaluating multiple lines of evidence to support risk management decisions. It also provides technical recommendations about monitoring and terminating building mitigation systems.

This Technical Guide relied upon a large body of scientific information found in the peer-reviewed literature. Additionally, EPA developed three technical support documents that were externally peer reviewed (EPA 2011a, 2012a, 2012b). This approach is consistent with EPA's peer review handbook and policy (EPA-SPC 2006). Peer-reviewed literature, peer-reviewed technical reports, existing and relevant EPA guidance (e.g., for conducting human health risk assessment; for planning and conducting investigations of environmental contamination), and other pertinent information that support development or implementation of this Technical Guide are cited within.

This introductory section: defines the term "vapor intrusion"; summarizes EPA's statutory authorities to protect human health from vapor intrusion; summarizes the intended uses of this Technical Guide, including its applicability to petroleum hydrocarbons and other potentially biodegradable chemicals and to nonresidential buildings; identifies key technical resources that facilitate consideration of its recommendations; provides a concise historical accounting of its development; describes how the public was involved in its development; and provides an overview of its organization.

1.1 Definition of Vapor Intrusion

Certain chemicals that are released into the subsurface[14] as liquids or solids may form hazardous vapors that migrate or are transported through the vadose zone[15] and eventually

[12] The EPA Vapor Intrusion Forum is an intra-Agency group engaged in sharing information, technical resources, and perspectives pertaining to vapor intrusion assessment and mitigation.

[13] This document is intended to fulfill EPA's commitment to the OIG to issue "updated, revised, and finalized" vapor intrusion guidance (EPA 2009a, Appendix B; EPA 2010b).

[14] For purposes of this Technical Guide, the phrases 'released into the subsurface' and 'release to the subsurface' are intended to encompass any and all mechanisms by which chemical contamination arises in the subsurface, including, for example, spills and releases above the ground surface that result in subsurface (e.g., soil and groundwater) contamination.

enter buildings as a component of a gas[16] by migrating (being transported) through cracks, seams, interstices, and gaps in basement floors, walls, or foundations ("adventitious openings"), through intentional openings (e.g., perforations due to utility conduits, sump pits), and/or within conduits (e.g., drain and sewer lines). Vapor intrusion is the general term given to migration of hazardous vapors from any subsurface contaminant source, such as contaminated soil or groundwater or contaminated conduit(s), into an overlying building or unoccupied structure via any opening or conduit.

Recognition of soil vapor intrusion to buildings and other enclosed spaces occurred in the 1980s with concerns over radon intrusion.[17] Subsequently, there was an increasing awareness that anthropogenic chemicals (e.g., petroleum hydrocarbons and chlorinated solvents) in soil and ground water could also pose threats to indoor air quality via the vapor intrusion pathway (Little et al. 1992; Moseley and Meyer 1992).

Vapor intrusion can occur in a broad range of land use settings, including residential, commercial, and industrial, and affect buildings with virtually any foundation type (e.g., basement, crawl space(s), or slab on grade). In the last 20 years, vapor intrusion impacts have been demonstrated in occupied buildings at a number of sites across the country (e.g., Little et al. 1992). As a result, vapor intrusion is widely recognized as a potential pathway of human exposure to "volatile" hazardous chemicals in indoor spaces. When and where vapor intrusion occurs, concentrations of vapors can increase gradually in amount in buildings or structures as time passes (i.e., "accumulate"). Depending upon site- and building-specific circumstances, vapors of potentially toxic chemicals may accumulate to a point where the health of the occupants (e.g., residents, workers, etc.) in those buildings could be threatened.

In addition to their toxicity threats, methane and certain other vapor-forming chemicals can pose explosion hazards depending upon structure-, building-, and site-specific circumstances. Explosion hazards may pose an imminent and substantial danger to human health and public welfare.

Careful consideration of the vapor intrusion pathway is warranted at all sites where vapor-forming chemicals are present in the soil or groundwater aquifer (NRC 2013).

Section 2.0 describes the vapor intrusion pathway in greater detail.

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[15] The 'vadose zone' is the soil zone between land surface and the groundwater table within which the moisture content is less than saturation (except in the capillary fringe). It is also referred to as the "unsaturated zone."

[16] The terms 'gas' and 'vapor' refer the gaseous state, as distinguished from the liquid or solid state, of matter. Whereas "vapor' refers to a volatile chemical that may comprise only a portion of the total volume, 'gas' refers to the entire volume. For economy of words, this Technical Guide refers to vapor concentrations in soil gas as "soil gas concentrations."

[17] Radon is a colorless, odorless, radioactive gas that is formed from the decay of radium, a radioactive element that occurs naturally in the soil and bedrock in many areas of the United States. Radon can also be emitted from certain uranium- or radium-containing products and wastes. For more information about radon, see: http://www.epa.gov/radon/index.html.

1.2 Statutory Authorities

Protection of human health is a critical mandate underlying several federal statutes, including the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended,[18] and the Resource Conservation and Recovery Act (RCRA), as amended.[19] Protection of human health is also a critical objective of the National Oil and Hazardous Substances Pollution Contingency Plan (NCP), which is the federal government's blueprint for responding to oil spills and releases of hazardous substances, pollutants, or contaminants.

The sources of authority and requirements for addressing subsurface vapor intrusion are the relevant statutes and regulations. On this basis, the EPA has broad authority and distinct responsibilities[20] to assess and, if warranted, mitigate vapor intrusion in residential and nonresidential[21] settings arising from a chemical release that causes subsurface contamination by volatile hazardous chemicals.[22] These actions may include sampling indoor air to assess exposure levels of building occupants to subsurface vapors and implementing interim mitigation measures to control, reduce, or eliminate exposure indoors to vapors emanating from subsurface vapor sources. Where such subsurface contamination includes vapor-forming chemicals (see Section 3.1) and underlies or is near buildings, EPA recommends that the potential for human health risk from vapor intrusion be evaluated throughout the cleanup life

[18] Amendments to CERCLA include the Small Business Liability Relief and Brownfields Revitalization Act.

[19] Application of these statutory authorities to a particular situation generally entails site- and fact-specific analysis.

[20] On January 23, 1987, the President of the United States signed Executive Order 12580 entitled, "Superfund Implementation," which delegates to a number of Federal departments and agencies the authority and responsibility to implement certain provisions of CERCLA. The policies and procedures for implementing these provisions (e.g., carrying out response actions) are spelled out in the NCP. The provisions of Executive Order 12580 appear at 52 *Federal Register* 2923.

[21] The EPA and the Occupational Safety and Health Administration (OSHA) of the Department of Labor each have a distinct statutory responsibility to ensure the safety and health of America's workforce through the timely and effective implementation of a number of federal laws and implementing regulations. On November 23, 1990, the Secretary of the Department of Labor and Administration of the EPA signed a Memorandum of Understanding (MOU) with the goal of establishing a program for improved environmental and workplace health and safety, which continues in effect. Implementation of the MOU is intended "to improve the combined efforts of the agencies to achieve protection of workers, the public, and the environment at facilities subject to EPA and OSHA jurisdiction; to delineate the general areas of responsibility of each agency; and to provide guidelines for coordination of interface activities between the two agencies with the overall goal of identifying and minimizing environmental or workplace hazards." An additional MOU was signed in February 1991 to establish a process and framework for notification, consultation and coordination between EPA and OSHA to aid both agencies in identifying environmental and workplace health and safety problems and to more effectively implement enforcement of their respective national environmental and workplace statutes. For additional information, see https://www.osha.gov/pls/oshaweb/owasrch.search_form?p_doc_type=MOU&p_toc_level=1&p_keyvalue=Agency&p_status=CURRENT.

EPA's recommended approach for evaluating vapor intrusion exposures is based upon its existing risk assessment guidance, as summarized in Section 7.4.

[22] Section 3.1 of this Technical Guide describes technical criteria for identifying which specific chemicals are sufficiently volatile and hazardous to generally warrant routine evaluation during vapor intrusion assessments, when they are present as subsurface contaminants. These sufficiently volatile and hazardous chemicals are referred to as "vapor-forming chemicals" for purposes of this Technical Guide.

cycle (i.e., initial site assessment, site investigation, interim and final response actions,[23] and periodic reviews of the selected remedy), as described in Sections 5 and 6 of this Guide.

Although this Technical Guide is intended for use at any site subject to federal statutes, regulations, and rules, it is not intended to alter existing requirements, guidance, or practices among OSWER's programs about development, selection, or documentation of final remediation[24] plans (addressing subsurface vapor sources, for example).

EPA may need access to private property to conduct investigations, studies and response actions pursuant to CERCLA and RCRA, as amended. The Superfund Amendments and Reauthorization Act of 1986 and RCRA explicitly grant EPA the authority to enter property for these purposes (EPA 1986, 1987, 2010a). EPA generally prefers to obtain access through consent and cooperation. If consent is denied, however, EPA can use the judicial process or an administrative order to gain access. Application of legal doctrines to a particular access situation warrants site- and fact-specific analysis.

Provisions under CERCLA, RCRA, federal regulations, and federal guidance also provide authority and support for taking early actions to mitigate actual and potential human health risks, as discussed below. In the context of vapor intrusion, "early action" may include response measures such as engineered exposure controls to reduce or eliminate vapor intrusion in buildings (i.e., "mitigate" vapor intrusion) or reduce indoor air exposure levels (see Sections 7.8 and 8.2) and 'prompt' response actions to address more urgent threats to human health or public welfare (see Section 7.5).

1.2.1 Taking Action with Limited Data under CERCLA and the NCP

CERCLA and the NCP both contain provisions that support and encourage taking early actions to mitigate actual and potential threats to human health associated with vapor intrusion. For example, CERCLA sections 104 and 106 provide the federal government with broad authority to take response action(s) to address a release or threatened release of hazardous substances that "may present" a human health risk. Similarly, the preamble to the final NCP issued in the *Federal Register* on March 8, 1990 (55 FR 8704), states, "EPA expects to take early action at sites where appropriate, and to remediate sites in phases using operable units as early actions to eliminate, reduce or control the hazards posed by a site or to expedite the completion of total site cleanup. In deciding whether to take early actions, EPA balances a number of considerations, including the desire to definitively characterize site risks and analyze alternative remedial approaches for addressing those threats in great detail with the desire to implement protective measures quickly. EPA intends to perform this balancing with a bias for initiating

[23] The words "response action" or "response" are used generically in this Technical Guide to include remedial and removal actions under CERCLA as amended and similar actions under RCRA as amended.

[24] For purposes of this Technical Guide, "remediation" is intended to apply to interim and final cleanups, whether conducted pursuant to RCRA corrective action, the CERCLA removal or remedial programs, or using EPA brownfield grant funds with oversight by state and tribal response programs. In addition to permanent remedies for subsurface vapor sources, site remediation may also entail implementation of institutional controls and construction and operation of engineered systems.

response actions necessary or appropriate to eliminate, reduce, or control hazards posed by a site as early as possible."[25]

For sites that are not on the National Priorities List (NPL), EPA may use its removal authority under CERCLA to undertake early action to mitigate vapor intrusion threats. For sites that are on the NPL, EPA's Superfund program may use its remedial or removal authority under CERCLA to undertake early action to ensure the protection of human health during existing or future property uses that could be affected by vapor intrusion. Building mitigation, control of subsurface vapor source(s), and associated ICs could be part of a final remedy selected for the site, or where appropriate, could represent an early action that (1) is evaluated and selected on a faster track and (2) complements the anticipated final remedial action for the site.

Because of state cost-share consequences, EPA recommends that state concurrence be sought for any Fund-lead mitigation under CERCLA where there is a reasonable expectation that the state will need to take over responsibility for operations and maintenance (O&M) as part of a long-term, final remedy.

EPA's guidance for preparing Superfund decision documents states: "An interim action is limited in scope and only addresses areas/media that also will be addressed by a final site/operable unit ROD [Record of Decision]….Early actions can be taken throughout the RI/FS [remedial investigation/feasibility study] process to initiate risk reduction activities…. "Early" in this case is simply a description of when the action is taken in the Superfund process. Thus, an early action is one that is taken before the RI/FS for the site or operable unit has been completed. Hence, early actions may be either interim or final" (EPA 1999b). The primary goals of an early action are to "achieve prompt risk reduction and increase the efficiency of the overall site response" (EPA 1992b). Although preparation of an RI/FS Report is not essential for an early action, documentation that supports the rationale for the action and becomes part of Administrative Record is recommended, consistent with the NCP and CERCLA. For interim actions, EPA's guidance for preparing Superfund decision documents states: "A summary of site data collected during field investigations should be sufficient to document a problem in need of response. In addition, a short analysis of remedial alternatives considered, those rejected, and the basis for the evaluation (as is done in a focused FS) should be summarized to support the selected action" (EPA 1999b).

For response actions selected in an Action Memorandum or Record of Decision which are carried out by potentially responsible parties (PRPs), and where the PRP(s) agree to implement preemptive mitigation (PEM) for vapor intrusion, EPA recommends that PRP commitments to proceed with response action (including early action) be obtained through settlements or other enforcement documents (for example, administrative orders). Such response action commitments could include performance of O&M and monitoring. EPA recommends that settlement with PRPs concerning PEM/early action response actions specify that PRPs agree not to challenge the basis of the response based on inadequate characterization.

[25] So, for example, EPA cited the NCP in its *Compilation of Information Relating to Early/Interim Actions at Superfund Sites and the TCE IRIS Assessment* (EPA 2014b).

1.2.2 Taking Action with Limited Data under RCRA Corrective Action

EPA has emphasized the importance of interim actions and site stabilization in the RCRA corrective action program to control or abate "ongoing risks" to human health and the environment while site characterization is underway or before a final remedy is selected (see the *Federal Register* of May 1, 1996 [61 FR 19446]). Interim actions encompass a wide range of institutional and physical corrective action activities to achieve stabilization and can be implemented at any time during the corrective action process. EPA recommends that interim actions, including PEM, be employed as early in the corrective action process as possible, consistent with the human health and environmental protection objectives and priorities for the site. EPA recommends that, as further information is collected, program implementers continue to look for opportunities to conduct additional interim response actions.

1.3 Scope and Recommended Uses of this Technical Guide

This Technical Guide presents EPA's current recommendations for how to identify and consider key factors when assessing vapor intrusion, making risk management decisions, and implementing mitigation pertaining to this potential human exposure pathway. This Technical Guide and the accompanying *Technical Guide For Addressing Petroleum Vapor Intrusion At Leaking Underground Storage Tank Sites* (EPA 2015b) supersede and replace EPA's *Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils* (EPA 2002c) ("Draft VI Guidance"). One of the main purposes of this Technical Guide is to promote national consistency in assessing the vapor intrusion pathway.[26] At the same time, it provides a flexible science-based approach to assessment that accommodates the different circumstances (e.g., stage of the cleanup process) at a site and differences among pertinent EPA programs.

This Technical Guide is intended for use at any site[27] being evaluated by EPA pursuant to CERCLA or RCRA corrective action, EPA's brownfield grantees, or state agencies acting

[26] If EPA staff wish to consider using any specific guidance that is not explicitly recommended in this Technical Guide, they should consult with Headquarters.

[27] The term "site" is used generically in this Technical Guide to represent areas of contamination managed in a cleanup project under CERCLA as amended, under RCRA as amended, at a federal facility, or pursuant to an EPA Brownfields grant.

pursuant to CERCLA or an authorized RCRA corrective action program[28] where vapor intrusion may be of potential concern. EPA recommends consideration of this Technical Guide when:

- Making "Current Human Exposures Under Control" environmental indicator (EI) determinations at RCRA corrective action facilities (EPA 1999a, 2002b)[29] and National Priorities List (NPL) sites under CERCLA (EPA 2008b);

- Undertaking removal actions, remedial actions, pre-remedial investigations,[30] remedial investigations, and five-year reviews (FYRs)[31] and selecting remedies under CERCLA; and

- Undertaking RCRA facility investigations and corrective actions and site investigations and cleanups at federal facilities and brownfield sites.

This Technical Guide addresses both residential and nonresidential buildings that may be impacted by vapor intrusion from subsurface vapor sources.

The broad concepts of this Technical Guide generally may be appropriate when evaluating any of a large number and broad range of vapor-forming chemicals— described in Section 3.1 — that potentially can provide subsurface sources for vapor intrusion into buildings. These chemicals include, for example, chlorinated hydrocarbons (CHCs), petroleum hydrocarbons, other types of both halogenated and non-halogenated volatile organic compounds (VOCs),

[28] EPA believes that states, tribes, and local governments will find this Technical Guide useful for their respective programs. EPA recommends that state agencies that have delegated authority to implement CERCLA or RCRA consider this Technical Guide when implementing their state-specific guidance for vapor intrusion assessment and mitigation, if any, (e.g., ensure they incorporate features such as: using multiple lines of evidence to support pathway-incomplete determinations and "no-further-action" decisions; collecting multiple rounds of indoor air sampling to characterize exposure levels in indoor air in existing buildings and reduce the chance of reaching a false-negative conclusion (i.e., concluding exposure is at an acceptable risk level when it is not) or a false-positive conclusion (i.e., concluding vapor intrusion poses unacceptable human health risk, when it does not); focusing lab analyses of indoor air, ambient air, and sub-slab soil gas samples on vapor-forming chemicals known or suspected to be released to the subsurface environment; invoking the recommended criteria described in Section 6.5.2 as a condition for using risk-based screening levels for vapor intrusion; assessing human health risk posed by less-than-chronic exposure durations; and considering reasonably expected future conditions, as well as current conditions, when making risk management decisions and selecting cleanup and building mitigation plans).

[29] Also see http://www.epa.gov/osw/hazard/correctiveaction/eis/faqs.htm.

[30] CERCLA authorizes the EPA to identify and prioritize which sites warrant further investigation to ascertain whether remedial action is needed. The Hazard Ranking System (HRS) is the statutorily required method for evaluating and identifying sites for placement on the NPL.

[31] Section 121 of CERCLA specifies that remedial actions that result in any hazardous substances, pollutants, or contaminants remaining at the site be re-evaluated every five years to ensure that the remedy is and will continue to be protective of human health and the environment. OSWER Directive 9200.2-84 (*Assessing Protectiveness at Sites for Vapor Intrusion: Supplemental Guidance to the Comprehensive Five-Year Review Guidance* (EPA 2012c)) provides supplemental guidance for considering vapor intrusion while evaluating remedy protectiveness in the context of the Superfund five-year review process (even if vapor intrusion was not addressed as part of the original remedial action).

elemental mercury, and radon when it arises from uranium- or radium-bearing solid wastes in the subsurface.[32]

This Technical Guide addresses risk management (e.g., exposure control or avoidance methods) for indoor air contamination that arises from vapor intrusion from subsurface sources of these vapor-forming chemicals. It is not intended as a guide for assessing or mitigating indoor air exposures that arise solely from other sources (e.g., indoor use and storage of certain consumer products[33]).

The exposure route of general interest for vapor intrusion is inhalation[34] of vapors present in indoor air that have entered via soil gas entry from the subsurface.[35] Other human exposure routes that may warrant consideration during site investigations of subsurface contamination (e.g., ingestion of soil or water, dermal contact with soil or water, inhalation of particulate material, inhalation of vapors while outdoors, and inhalation of vapors while showering or washing with contaminated groundwater while indoors) are not addressed in this Technical Guide.

EPA recommends that risk management and response action decisions for the vapor intrusion pathway generally consider reasonably expected future conditions, which may differ from current conditions due to changes in land use, building and infrastructure construction and conditions, and vadose zone hydrology and oxygenation, among other factors. This Technical Guide provides general information regarding how these factors may enhance or impede vapor intrusion. It also provides recommendations for institutional controls and monitoring where a subsurface vapor source(s) is(are) present and has the potential to pose unacceptable human health risks.

Although this Technical Guide is intended for use at any site subject to federal statutes, regulations, and rules, it is not intended to alter existing requirements, guidance, or practices among OSWER's programs about circumstances for reviewing past risk management and cleanup decisions. As noted, remedy reviews are required by Section 121 of CERCLA when

[32] Radon emanating from natural geological materials may also affect indoor air quality in occupied buildings, but is not a subject of this Technical Guide. According to EPA estimates, inhalation of toxic radon decay products is the leading cause of lung cancer among non-smokers. For more information about radon emanating from natural geological materials, see: http://www.epa.gov/radon/index.html.

[33] Indoor air in most buildings will contain detectable levels of a number of volatile compounds, whether or not the building overlies a subsurface source of vapor-forming chemicals (EPA 2011a). As discussed further in Section 2.7 of this Technical Guide, these chemicals originate from indoor uses of chemical-containing products (e.g., household or consumer products) and from outdoor (ambient) air. EPA's indoor air quality program provides useful advice for control of indoor air exposures (see http://www.epa.gov/iaq/).

[34] Among human exposure pathways involving contamination of land and water, vapor intrusion is distinct. Whereas contact with contaminated surface soil, contaminated fish, and contaminated drinking water generally can be readily avoided for prolonged periods, breathing cannot.

[35] In addition, certain hazardous chemicals (e.g., methane) can pose explosion hazards when they gradually increase in amount in structures (e.g., confined spaces) or buildings as time passes to a point where there is an imminent and substantial danger to human health and public welfare.

hazardous substances remain on site.[36] EPA's other land restoration programs (e.g., RCRA corrective action, brownfield redevelopment) will continue to rely upon their existing, respective practices to address the need, if any, for periodic reviews of cleanup decisions, including consideration of the vapor intrusion pathway.

Finally, this Technical Guide does not aim or intend to:

- Offer recommendations for vapor intrusion assessments that private parties choose to conduct as part of real estate transactions;
- Modify existing guidance regarding landowner liability protection (e.g., all appropriate inquiries, the *bona fide* prospective purchaser provision); or
- Offer recommendations for responding to leaks from natural gas transmission lines.

1.3.1 Petroleum Hydrocarbons

The approaches in this Technical Guide are recommended for evaluating the vapor intrusion pathway pursuant to CERCLA or RCRA corrective action for petroleum hydrocarbons that are mixed with other types of volatile hazardous chemicals or are the result of releases from sources other than Subtitle I underground storage tank (UST) systems.[37] For petroleum hydrocarbons that arise from petroleum that has been released from Subtitle I UST systems, EPA has developed a companion to this Technical Guide (*Technical Guide For Addressing Petroleum Vapor Intrusion At Leaking Underground Storage Tank Sites* (EPA 2015b)), which provides information and guidance about assessing vapor intrusion from petroleum hydrocarbons in these settings and may also be useful in informing decisions about vapor intrusion and petroleum hydrocarbons at non-UST sites that are similar in size to a typical Subtitle I UST release.

Many petroleum hydrocarbons may naturally biodegrade in the vadose zone through the actions of microorganisms found naturally in soil. When oxygen supply from the atmosphere is sufficient, biodegradation of petroleum hydrocarbons can occur relatively quickly, will generally produce less harmful compounds (i.e., biodegradation products), and can result in substantial attenuation of petroleum hydrocarbon vapors over relatively short distances in the vadose zone.

Numerous site-specific factors can influence the biodegradation rate of petroleum hydrocarbons (and other biodegradable vapor-forming chemicals) in the vadose zone. These factors include quantities, distribution, types, and mixtures of vapor-forming chemicals, which can differ substantially among sites where petroleum hydrocarbons are released to the subsurface

[36] The NCP states [40 *CFR* 300.430(f)(4)(ii)]: "If a remedial action is selected that results in hazardous substances, pollutants, or contaminants remaining at the site above levels that allow for unlimited use and unrestricted exposure, the lead agency shall review such action no less often than every five years after initiation of the selected remedial action." For further information, see, for example, http://www.epa.gov/superfund/cleanup/postconstruction/5yr.htm

[37] For example, the approaches in this Technical Guide are recommended for evaluating the vapor intrusion pathway associated with subsurface releases of petroleum, petroleum derivatives, and petroleum hydrocarbons from refineries, bulk storage facilities, oil exploration and production sites, pipelines and transportation, chemical manufacturing facilities, former manufactured gas plants, creosote (wood-treating) facilities, large-scale fueling and storage operations at federal facilities, and dry cleaners that use petroleum solvents.

environment. This Technical Guide allows site-specific observations of the effects of biodegradation to be considered in its approach for petroleum hydrocarbons (and any other biodegradable, vapor-forming chemical). Sections 6.3.2 and 7.3 expand on EPA's recommended approach to evaluating biodegradation of vapor-forming chemicals in the vadose zone at sites with subsurface contamination.

1.3.2 Nonresidential Buildings

EPA has broad authority and distinct responsibilities to assess and, if warranted, mitigate vapor intrusion in nonresidential settings arising from a chemical release that causes subsurface contamination by volatile hazardous chemicals (see Section 1.2). EPA[38] is authorized to take all appropriate actions to protect human health and the environment from subsurface vapor sources of chemical exposure consistent with applicable federal statutes[39,40] and regulations and considering EPA guidance,[41] taking into account the nonresidential setting. These actions may include sampling indoor air to assess exposure levels of building occupants to subsurface vapor sources and implementing interim mitigation measures to control, reduce, or eliminate exposure indoors to vapors emanating from a subsurface vapor source(s).

As used in this Technical Guide, the phrase "nonresidential buildings" may include, but is not limited to, institutional buildings (e.g., schools, libraries, hospitals, community centers and other enclosed structures for gathering, gyms and other enclosed structures for recreation); commercial buildings (e.g., hotels, office buildings, many (but not all) day care facilities, and retail establishments); and industrial buildings where vapor-forming chemicals may or may not be routinely used or stored. Section 4.0 expands on EPA's recommended approach to evaluating and mitigating vapor intrusion in nonresidential buildings.

1.4 Companion Documents and Technical Resources

Technical information pertaining to vapor intrusion has also been prepared to support development of and facilitate implementation of the technical approaches and recommendations in this Technical Guide. Key technical information is described in this section and can be found on OSWER's vapor intrusion website (see Section 11.0 for citations and internet links).

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[38] On January 23, 1987, the President of the United States signed Executive Order 12580 entitled, "Superfund Implementation," which delegates to a number of Federal departments and agencies the authority and responsibility to implement certain provisions of CERCLA. The policies and procedures for implementing these provisions (e.g., carrying out response actions) are spelled out in the NCP. The provisions of Executive Order 12580 appear at 52 *Federal Register* 2923. At federal facilities on the NPL, EPA may not be the lead agency, but does have oversight responsibilities pursuant to CERCLA Section 120.

[39] CERCLA and RCRA authorize EPA to protect human health and the environment, as summarized in Section 1.2 of this Technical Guide. The NCP also addresses protection of human health and the environment.

[40] See, for example, CERCLA Section 101(22).

[41] See, for example, OSWER Directive 9355.0-30 (*Role of the Baseline Risk Assessment in Superfund Remedy Selection Decisions*) (EPA 1991a) and *Rules of Thumb for Superfund Remedy Selection,* OSWER Directive 9355.0-69, August 1997 (EPA 1997).

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1.4.1 Vapor Intrusion Screening Level Calculator

The Vapor Intrusion Screening Level (VISL) Calculator (2015a) is a technical resource, developed by EPA that:

(1) Identifies chemicals considered to be typically vapor-forming and known to pose a potential cancer risk or noncancer hazard through the inhalation pathway (as described further in Section 3.1 herein);

(2) Provides generally recommended screening-level concentrations for groundwater, near-source soil gas (exterior to buildings), sub-slab soil gas, and indoor air based upon default residential or nonresidential exposure scenarios, a target cancer risk level of one per million (10^{-6}), and a target hazard quotient of one for potential non-cancer effects; and

(3) Facilitates calculation of site-specific screening levels (see Section 6.5) and/or candidate cleanup levels (see Section 7.6) based on user-defined target risk levels, exposure scenarios, and semi-site-specific (Appendix A) or site-specific (Section 7.6) attenuation factors.

The VISL Calculator is comprised of an MS Excel workbook. It can be used in evaluating whether the vapor intrusion pathway has the potential to pose a human health risk by helping to:

(1) Identify whether volatile hazardous chemicals that can pose a threat through vapor intrusion are present;

(2) Determine if those volatile hazardous chemicals are present at potentially explosive levels;

(3) Compare subsurface or indoor data against recommended screening levels provided in the VISL Calculator; and

(4) Prioritize buildings and sites for investigation and response action.

The recommended screening-level concentrations in the spreadsheet are calculated using the recommended approaches in existing EPA guidance for human health risk assessment, as described further in Sections 6.5.2 and 6.5.3 herein, and are based on current understanding of the vapor intrusion pathway.

1.4.2 Technical Support Documents

Key technical documents supporting development of the technical approaches and recommendations in this Technical Guide include:

Background Indoor Air Concentrations of Volatile Organic Compounds in North American Residences (1990-2005): A Compilation of Statistics for Assessing Vapor Intrusion (EPA 2011a): This technical report presents (1) a summary of indoor air studies that measured background concentrations of VOCs in the indoor air of thousands of North American residences and (2) an evaluation and compilation of the statistical information reported in these studies. The objective of this compilation is to illustrate the ranges and variability of

VOC concentrations in indoor air during the study period (1990-2005), resulting from sources other than vapor intrusion. This technical report was externally peer reviewed, consistent with EPA's peer review policy (EPA-SPC 2006) for scientific and technically based work products that are intended to inform Agency decisions.

EPA's Vapor Intrusion Database: Evaluation and Characterization of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings (EPA 2012a): This technical report presents technical information about sites in the U.S. that have been investigated for vapor intrusion. The primary focus of the report is the evaluation of concentrations of chlorinated VOCs in and underneath residential buildings based upon the EPA's vapor intrusion database as of 2010. This report provides the technical basis for the generic and semi-site-specific attenuation factors recommended in this Technical Guide to calculate vapor intrusion screening levels (see Section 6.5 and Appendix A). This technical report was externally peer reviewed, consistent with EPA's peer review policy (EPA-SPC 2006) for scientific and technically based work products that are intended to inform Agency decisions.

Conceptual Model Scenarios for the Vapor Intrusion Pathway (EPA 2012b): This technical report provides simplified simulation examples to illustrate graphically how subsurface conditions and building-specific characteristics determine: (1) the distribution of vapor-forming chemicals in the subsurface; and (2) the indoor air concentration relative to a source concentration. It was prepared to help environmental practitioners gain insights into the processes and variables involved in the vapor intrusion pathway and to provide a theoretical framework with which to draw inferences about and better understand the complex vapor fate and transport conditions typically encountered at actual, contaminated sites. This technical report was externally peer reviewed, consistent with EPA's peer review policy (EPA-SPC 2006) for scientific and technically based work products that are intended to inform Agency decisions.

These technical tools and documents, as well as others, can be found at http://www.epa.gov/oswer/vaporintrusion, a website developed to support the development of this Technical Guide and enhance public communication about the topic. This website also allows certain sections of this Technical Guide to be more dynamic and facilitates updates to information.

Technical documents intended to facilitate consideration of the recommendations in the *Technical Guide For Addressing Petroleum Vapor Intrusion At Leaking Underground Storage Tank Sites* (EPA 2015b) can be found at http://www.epa.gov/oust/cat/pvi/.

1.5 Historical Context

To help assess the subsurface vapor intrusion pathway, the Office of Solid Waste and Emergency Response (OSWER) released in November 2002 for comment EPA's Draft VI Guidance, which presents EPA's technical information and recommendations for evaluating subsurface vapor intrusion, based on the understanding of vapor intrusion at that time (EPA 2002c). This Technical Guide and the accompanying *Technical Guide For Addressing Petroleum Vapor Intrusion At Leaking Underground Storage Tank Sites* (EPA 2015b) supersede and replace the Draft VI Guidance.

Since the Draft VI Guidance was released, EPA's knowledge of and experience with assessment and mitigation of the vapor intrusion pathway has increased considerably, leading to an improved understanding of and enhanced approaches for evaluating and managing vapor intrusion. In addition:

- Other federal agencies with responsibilities and obligations for environmental cleanup or for response to reports of vapor intrusion have developed vapor intrusion guides for their respective programs (e.g., ATSDR 2008; DoD 2009; DoN 2011a; USPS 2009).

- A number of state agencies involved with environmental quality or public health protection have developed vapor intrusion guides for their programs, which they may continue to implement under their respective statutory authorities (e.g., see ASTSWMO [2009], a compilation).

- The Interstate Technology & Regulatory Council (ITRC), a state-led coalition of environmental regulatory professionals, prepared three guidelines for assessing the vapor intrusion pathway (ITRC 2007ab, 2014).

EPA has considered these guides in developing this Technical Guide.

In addition, in December 2009, the OIG made recommendations regarding EPA's Draft VI Guidance, which are documented in the evaluation report *Lack of Final Guidance on Vapor Intrusion Impedes Efforts to Address Indoor Air Risks* (Report No. 10-P-042; EPA 2009a). Among other things, the OIG recommended that the final guidance incorporate:

- Updated toxicity values.

- A recommendation(s) to collect and weigh multiple lines of evidence in evaluating and making decisions about human health risks posed by vapor intrusion.

- How risks from petroleum hydrocarbon vapors should be addressed.

- How the guidance applies to Superfund FYRs.

- When or whether preemptive mitigation is appropriate.

- Operations, maintenance, and termination of mitigation systems.

- When institutional controls are appropriate.

In its response letter dated March 11, 2010, OSWER generally agreed with OIG's recommendations to finalize guidance on vapor intrusion. In addition, the OIG recommended

that EPA identify and publicly report the portions of its Draft VI Guidance that remain valid and the portions that would be updated.[42]

This Technical Guide and the companion documents identified in Sections 1.3 and 1.4 fulfill EPA's commitment to address the OIG's recommendations. Table 1-1 identifies specific updates prepared by EPA in response to OIG's specific recommendations. Table 1-2 describes additional updates identified and publicly announced by EPA (EPA 2010b).

TABLE 1-1
DIRECTORY TO UPDATES IN THIS TECHNICAL GUIDE ADDRESSING RECOMMENDATIONS OF EPA OFFICE OF INSPECTOR GENERAL (EPA 2009A)

Topics to Be Addressed	Location Within This Technical Guide	Companion Documents
Update toxicity values		*VISL Calculator* (EPA 2015a)
Use of multiple lines of evidence in evaluating and making decisions about risks from vapor intrusion	Sections 5, 6, and 7	
How risks from petroleum hydrocarbon vapors should be addressed	Sections 1.3.1, 6.3.2 and 7.3	*Technical Guide for Addressing Petroleum Vapor Intrusion at Leaking Underground Storage Tank Sites* (EPA 2015b)
How this Technical Guide applies to Superfund Five-year Reviews (FYRs)		*Assessing Protectiveness at Sites for Vapor Intrusion: Supplemental Guidance to the Comprehensive Five-Year Review Guidance* (EPA 2012c)
When or whether preemptive mitigation/early action is appropriate	Sections 3.3 and 7.8	
Operations and maintenance of mitigation systems	Section 8.3	
Termination of mitigation systems	Section 8.7	
When ICs and deed restrictions are appropriate.	Section 8.6	

[42] OSWER carried out this recommendation by issuing a memorandum in August 2010, entitled *Review of the Draft 2002 Subsurface Vapor Intrusion Guidance* (EPA 2010b). The guidance reflected in this memorandum is incorporated in this Technical Guide.

TABLE 1-2
DIRECTORY TO ADDITIONAL UPDATES IN THIS TECHNICAL GUIDE PUBLICLY IDENTIFIED BY OSWER (EPA 2010B)

Topics to Be Updated, Including References to the Draft VI Guidance	Location Within This Technical Guide	Companion Technical Document or Resource
Updated a few chemical-specific physical parameters used for identifying the vapor-forming chemicals of concern.	Section 3.1	VISL Calculator (EPA 2015a)
Updated the toxicity-based criteria in Table D-1 in the draft guidance.	Section 3.1	VISL Calculator (EPA 2015a)
Observation-based conservative attenuation factors have been updated with a larger database. The generic attenuation factor for external soil gas has been updated, as well as the Reliability Assessment, using the newer available data.	Section 6.5.3 and Appendix A	*U.S. EPA's Vapor Intrusion Database: Evaluation of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings* (EPA 2012a)
Observational data since 2002 indicates that the "single line of evidence" approach with site-estimated attenuation factors is generally not appropriate for external soil gas samples.	Section 6.4.4 and Appendix A	
Experiences since 2002 illustrate the value of collecting indoor air samples earlier in the investigations. The "indoor air last" approach has been updated, which will allow more flexibility in the sequencing of subsurface and interior/indoor sample collection.	Sections 6.3.4 and 6.3.6	
The portions addressing background contamination have been updated. EPA also updated with more specific methodologies for evaluating and/or decision-making and managing background contamination.	Sections 6.3.5, 7.4 and 7.6	*Background Indoor Air Concentrations of Volatile Organic Compounds in North American Residences (1990-2005): A Compilation of Statistics for Assessing Vapor Intrusion* (EPA 2011a)
The portion of this Technical Guide focusing on testing indoor air has been updated to allow more flexibility in the duration of sampling to take advantage of other sampling durations and methods.	Section 6.4.1	
The Draft VI Guidance allows site-specific decisions to be made based on indoor air concentrations in a relatively few representative buildings. This portion of this Technical Guide has been updated to increase the confidence that the approach fully addresses building-by-building variability.	Sections 6.2.2 and 7.8	
Updated and expanded the community involvement information to be more specific to vapor intrusion sites, including guidelines for effective risk communication and available resources, outreach products and tools for outreach.	Section 9	

1.6 Public Involvement in Developing this Vapor Intrusion Technical Guide

On November 29, 2002, EPA published a notice in the *Federal Register* (67 FR 71169) announcing and soliciting comment on its Draft VI Guidance. Since that time, EPA continued to gather information and learn more about vapor intrusion, in part by convening periodic forums where practitioners, regulated parties, and regulators could discuss the emerging science and engineering pertaining to vapor intrusion assessment and mitigation. In addition, on March 17, 2011, EPA published a notice in the *Federal Register* (76 FR 14660) re-opening the docket and soliciting additional comment on its development efforts for this Technical Guide. The docket was re-opened again in March 2012 to receive comments about specific technical documents that were prepared to support development of this Technical Guide; these technical documents are listed in Section 1.4. Finally, another review draft was released on April 16, 2013 for public comment. In developing and refining this Technical Guide, EPA considered all public comments and input received since 2002.

EPA also proactively engaged communities beyond the traditional outreach practices, especially environmental justice communities and communities subject to multiple stressors.[43] Aspects of this engagement have included:

- Conducting public listening sessions in communities impacted by vapor intrusion to solicit input on developing this Technical Guide.

- Using Internet sites and other communication tools to update stakeholders on the progress of developing this Technical Guide.

Table 1-3 identifies specific vapor intrusion topics that have received substantive public comment as a result of EPA's outreach efforts.

1.7 Organization

The next nine sections of this Technical Guide are as follows:

- Section 2.0 Conceptual Model of Vapor Intrusion further describes vapor intrusion and identifies many of the variables that influence vapor migration in the vadose zone and soil gas entry into buildings.

- Section 3.0 Overview of this Vapor Intrusion Technical Guide provides an overview of this Technical Guide and the general recommended framework for vapor intrusion assessment and response action.

- Section 4.0 Considerations for Nonresidential Buildings provides information regarding EPA roles, responsibilities, and risk management decision-making in nonresidential settings, including those (e.g., manufacturing facilities) where workers handle volatile hazardous chemicals similar to or different from those contaminating the subsurface.

[43] For more information about the Community Engagement Initiative visit: http://www.epa.gov/oswer/engagementinitiative/

TABLE 1-3
VAPOR INTRUSION TOPICS RECEIVING SUBSTANTIVE PUBLIC COMMENT

Topics	Location Within This Technical Guide	Companion Document(s)
Applicability to petroleum hydrocarbons	Sections 1.3.1, 6.3.2 and 7.3	*Technical Guide for Addressing Petroleum Vapor Intrusion at Leaking Underground Storage Tank Sites* (EPA 2015b)
Applicability to nonresidential buildings	Sections 1.3.2, 4.0 and 7.4.3	
Conditions warranting prompt response action	Sections 5.2, 7.5 and 8.2.1	
Planning investigations and applying data quality objectives	Section 6.2 and Appendix B	
Sampling and monitoring methods for indoor air	Section 6.4.1	
Attenuation factors and risk-based screening	Section 6.5 and Appendix A	*U.S. EPA's Vapor Intrusion Database: Evaluation of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings* (EPA 2012a)
Semi-site-specific screening and application of mathematical models	Sections 6.5 and 6.6	
Use of conceptual site models and multiple lines of evidence in evaluating risks posed by vapor intrusion	Sections 2, 3.2, 5.4, 6.3 and 7	
Risk management benchmarks and decision-making	Section 7	
Use of institutional controls for building mitigation	Section 8.6	
Monitoring and termination of mitigation systems	Sections 8.4 and 8.7	
Risk communication	Section 7.4 and 9	

- Section 5.0 Preliminary Analysis of Vapor Intrusion provides technical information for situations where only limited site-specific data may be available (e.g., initial site assessment).

- Section 6.0 Detailed Investigation of Vapor Intrusion provides technical information for conducting site-specific vapor intrusion assessments emphasizing multiple lines of evidence, including consideration of background concentrations.

- Section 7.0 Risk Assessment and Management Framework provides general recommendations about data evaluations and risk-informed decision-making pertaining to vapor intrusion, including consideration of background concentrations.

- Section 8.0 Building Mitigation and Subsurface Remediation provides technical information for mitigating vapor intrusion and describes how subsurface vapor source remediation and other final cleanup actions are combined with engineered and non-engineered exposure controls to ensure protection of human health.

- Section 9.0 Planning for Community Involvement provides information and describes available resources for engaging affected communities and communicating risk-related information.

- Section 10.0 Glossary provides definitions and descriptions of key terms used in this document.

This Technical Guide concludes with Section 11.0, Citations and References, and three supporting appendices:

- Appendix A: Recommended Subsurface-to-Indoor-Air Attenuation Factors.

- Appendix B: Data Quality Assurance Considerations.

- Appendix C: Calculating Vapor Source Concentration from Groundwater Sampling Data.

2.0 CONCEPTUAL MODEL OF VAPOR INTRUSION

This section presents a general (i.e., not site-specific) conceptual model of vapor intrusion, borrowing from published depictions (EPA 2008a; EPA 2012b; ITRC 2007a; McAlary et al. 2011; DoD 2009). It identifies and describes the 'what', 'where', 'how' and 'why' of vapor intrusion, to provide insights about the many of the lines of evidence pertinent to evaluating vapor intrusion on a site-specific basis, which are discussed further in Sections 5, 6, and 7 of this Technical Guide.[44] It concludes with several general observations that may assist practitioners when planning and conducting detailed vapor intrusion investigations at specific sites, which is the subject of Section 6 of this Technical Guide.

Vapor intrusion is a potential human exposure pathway — a way that people may come into contact with hazardous vapors while performing day-to-day indoor activities. Figure 2-1 summarizes the vapor intrusion pathway for soil gas entry. For purposes of this Technical Guide, the vapor intrusion pathway is referred to as "complete" [45] for a specific building or collection of buildings when the following five conditions are met under current conditions:

1. A subsurface source of vapor-forming chemicals is present (e.g., in the soil or in groundwater) underneath or near the building(s);

2. Vapors form and have a route along which to migrate (be transported) toward the building(s);

3. The building(s) is(are) susceptible to soil gas entry, which means openings exist for the vapors to enter the building and driving 'forces' exist to draw the vapors from the subsurface through the openings into the building(s);

4. One or more vapor-forming chemicals comprising the subsurface vapor source(s) is (or are) also present in the indoor environment; and

5. The building(s) is (or are) occupied by one or more individuals when the vapor-forming chemical(s) is (or are) present indoors.[46]

If one (or more) of these conditions is currently absent and is reasonably expected to be absent in the future (e.g., vapor migration is significantly and persistently impeded by natural geologic, hydrologic, or biochemical (e.g., biodegradation) processes and conditions), the vapor intrusion pathway is referred to as "incomplete."

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[44] In general, a conceptual site model integrates all lines of site-specific evidence into a three-dimensional conceptualization of site conditions that includes contaminant sources, release mechanisms, vapor migration route(s), and potential receptors. Section 5.4 provides additional information about developing conceptual site models.

[45] A complete vapor intrusion pathway indicates that there is an opportunity for human exposure in the subject building(s), whereas an incomplete pathway would not provide an opportunity for human exposure,

[46] The exposure route of general interest for vapor intrusion is inhalation of toxic vapors present in indoor air. Because breathing is not avoidable for prolonged periods, individuals in occupied buildings are presumed to be exposed by the inhalation route to any hazardous vapors present in indoor air. Hence, the presence of a human exposure route is implied in the fifth condition.

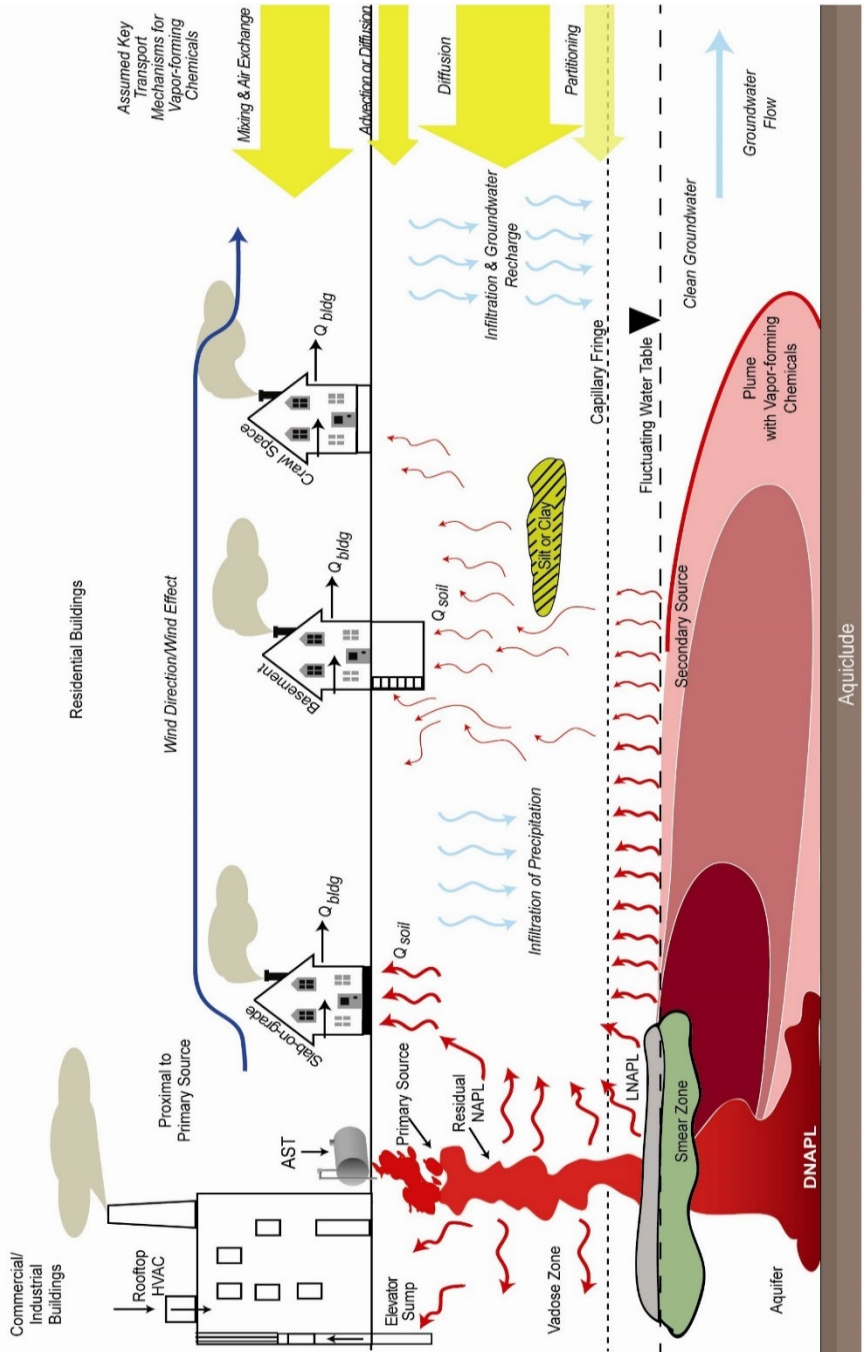

Figure 2-1 Illustration of Key Elements of the Conceptual Model of Soil Vapor Intrusion
Note: Q_{soil} represents soil gas entry; Q_{bldg} represents air exchange.

The first three of these five conditions are further discussed in the next three subsections. Knowledge of potential vapor sources and vapor fate and transport mechanisms is essential for interpreting the data collected during a site-specific investigation of vapor intrusion. Knowledge of the factors that influence the vapor intrusion pathway is also invaluable for identifying, prioritizing, and sequencing data collection activities, which allows a phased and efficient overall investigation plan to be developed. Practitioners are encouraged to refer to quantitative discussions of these subjects, which are provided in *Conceptual Model Scenarios for the Vapor Intrusion Pathway* (EPA 2012b).

The human population of primary interest is comprised of individuals living in, working in, or otherwise occupying a building subject to vapor intrusion. All types of buildings have openings and conduits that render them potentially vulnerable to vapor intrusion. This includes residential buildings (e.g., single-family homes, trailer or 'mobile' homes, multi-unit apartments and condominiums), commercial workplaces (e.g., office buildings, retail establishments), industrial facilities (e.g., manufacturing plants), and educational and recreational buildings (e.g., schools and gyms). Vapor intrusion can occur in buildings with any foundation type (e.g., basement, crawl space, slab-on-grade).

As noted previously, methane and certain other vapor-forming chemicals can also pose explosion hazards in buildings and unoccupied structures,[47] depending upon building-, structure-, and site-specific circumstances. The discussion in the next three sections pertains also to methane and other vapor-forming chemicals that can pose explosion hazards, because similar processes and conditions are involved in explosive vapors migrating towards the interior of buildings or non-occupied structures from the subsurface environment; i.e.,

1) A subsurface source of vapor-forming chemicals is present (i.e., in the soil or in groundwater) underneath or near the structure(s) or building(s).

2) Vapors form and have a route along which to migrate (be transported) toward the structure(s) or building(s).

3) The structure(s) or building(s) is (or are) susceptible to soil gas entry, which means openings exist for the vapors to enter the structure(s) or building(s) and driving 'forces' exist to draw the vapors from the subsurface through the openings into the structure(s) or building(s).

[47] For purposes of evaluating potential explosion hazards, non-occupied structures, in addition to buildings, are relevant structures for intrusion and accumulation of vapors.

2.1 Subsurface Vapor Sources

The originating (i.e., primary) source(s) of subsurface contamination may include, but are not limited to, leaking tanks (above or below ground), discharges to sewer lines[48], septic tanks, and floor drains, landfills and other land disposal management units, fire-training areas, spills, discharge areas, and vapor leaks from pressurized tanks and pipelines. The resulting subsurface contamination may be comprised of non-aqueous-phase liquids (NAPLs) [49] (e.g., solvents; petroleum-related products, such as gasoline) and contaminated soil. These are often referred to as the source zone(s). Groundwater and sewer lines[50] flowing through or underneath[51] the source zone(s) can become contaminated and in turn become a (secondary or derivative) subsurface vapor source of contaminant vapors at locations distant from the source zone.

Contaminants in soil, NAPLs, and groundwater can become sources for vapor intrusion if they are likely to volatilize under normal temperature and pressure conditions. Water solubility is also a factor for chemicals in source zones that come into contact with migrating groundwater. Common classes of chemicals of concern for vapor intrusion that exhibit the foregoing characteristics are VOCs, such as tetrachloroethylene (PCE), trichloroethylene (TCE), vinyl chloride, carbon tetrachloride, and benzene, toluene, ethylbenzene and xylenes (collectively, BTEX). Other compounds that are not as volatile as these VOCs (e.g., so-called semi-volatile organic compounds), but that may be cause for concern, include some polycyclic aromatic hydrocarbons (PAHs) (e.g., naphthalene), some polychlorinated biphenyl (PCB) congeners, and elemental mercury, a dense NAPL (DNAPL).[52]

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[48] Historically, sanitary sewers and septic tanks have been common disposal points for aqueous and chemical wastes from commercial and industrial operations. Contaminated water, non-aqueous phase liquid (NAPL), and VOC vapors can leak from sewer lines through cracks, joints, or breaks. A study of solvent contamination in California arising from dry cleaning operations concluded that discharges to and leakage from sewer lines is an important source of PCE contamination of soil and groundwater: "Where a source investigation has been done in connection with PCE contamination, the … data strongly indicate that leakage through the sewer lines is the major avenue through which PCE is introduced to the subsurface." (Izzo 1992). In the South Weber neighborhood near the Hill Air Force Base in Utah, sewer lines carrying discharged contaminated groundwater to the municipal treatment system were identified as a source of vapor intrusion in homes [Source: *EnviroNews* - Updating environmental issues and activities at Hill Air Force Base, Utah (March 2011); Currently available on-line at: http://www.hillrab.org/news.aspx]

[49] EPA's Contaminated Site Cleanup Information website (http://www.clu-in.org/) provides information describing NAPLs that are denser than water (DNAPLs) or less dense than water (LNAPLs), and methods for their detection and remediation in the subsurface environment.

[50] In addition to receiving direct discharges, sewers can be indirect receptacles of subsurface contamination via infiltration of NAPL, soil gas, or contaminated groundwater through cracks in piping and manholes. For example, Vroblesky et al (2011) found that infiltration of contaminated groundwater into sewers and its transport via and exfiltration from sewers caused complex and unanticipated patterns of groundwater contamination at a site in South Carolina.

[51] Figure 2-1 illustrates a NAPL release/source (near the commercial/industrial building on the left) that fully penetrates the vadose zone. A partially penetrating NAPL release/source may also cause groundwater contamination, however, as infiltrating water passes through the source zone and migrates to the groundwater table.

[52] Once volatilized into soil or sewer gas from a subsurface vapor source(s), these less volatile chemicals will migrate under the influence of diffusion and advection (see Section 2.2) as do more volatile chemicals, although there may be chemical-specific differences in their susceptibility to biodegradation in the vadose zone.

Landfill gases, such as methane and hydrogen sulfide, also can be associated with the vapor intrusion pathway for buildings located near current or former landfills or other degrading wastes. These gases are actively produced as a result of anaerobic biodegradation processes. Methane can also be associated with the vapor intrusion pathway for buildings located near degrading petroleum hydrocarbons or fuel-grade ethanol released into the subsurface environment (Ma et al. 2014, 2012; Sihota et al. 2013).

Properties with potential contamination by vapor-forming chemicals can be found in many industrial and commercial areas. These properties include current and former manufacturing and chemical processing plants, warehouses, landfills and other land disposal units, coal gasification plants, chemical handling or transfer facilities and areas (e.g., train yards), dry cleaners, and retail fueling outlets (also known as gas stations). Use, storage, or transport of chemicals at these facilities may have resulted in a release of vapor-forming chemicals to the environment creating the potential for future vapor intrusion issues. In addition to industrial and commercial activities, roadside dumping, pesticide spraying, or even disposal of household chemicals via a septic field may also release volatile chemicals that may eventually migrate to the subsurface environment.

The primary contamination source need not, however, be on the property of interest to pose a vapor intrusion problem.[53] As illustrated in Figure 2-1, the primary source(s) of vapor intrusion (e.g., contaminated soil, or leaked tanks) may be present on a neighboring property or on a property some distance away. Even "greenspace" properties that have not previously been occupied or developed may contain contamination by vapor-forming chemicals due to migrating plumes of contaminated groundwater or migrating soil gases.[54]

In the case of groundwater as a subsurface vapor source for vapor intrusion, the source strength will be influenced by the vertical distribution of contaminant concentrations in the upper reaches (e.g., top foot) of the water table and by seasonal fluctuations in the groundwater table groundmass flux of vapors. If vapor-forming chemicals are not present in the upper reaches (e.g., within the uppermost foot) of the groundwater table (e.g., due to the presence of an overlying zone of clean water from recharge; i.e., "fresh water lens"),[55] vapor transport to the overlying vadose zone will be impeded due to the slower diffusion of volatile chemicals in water

[53] Depending on the geology and amount and form of contamination in the source zone(s), contaminated groundwater plumes can be long and narrow and can flow beneath a property located a mile or more away from the primary source. Soil gas plumes tend to extend in both lateral directions and can be larger in lateral extent relative to groundwater plumes.

[54] See Section 6.2.1 for further discussion on which buildings and non-occupied structures are considered "near" for purposes of a preliminary analysis.

[55] Infiltrating precipitation is important in recharging aquifers with fresh water, as well as in wetting vadose zone soils. At locations distant from "source zones," infiltrated water that reaches the upper surface of a plume of contaminated groundwater (i.e., recharges groundwater) in an unconfined aquifer will tend to dilute concentrations of vapor-forming chemicals and may form a lens of relatively "clean" water at the groundwater table, which overlies the plume. Because diffusion of dissolved-phase volatile chemicals will tend to control the mass transfer of vapors into the soil gas at the groundwater table, the presence of a lens of clean water as little as a foot in thickness overlying a plume may be sufficient to impede vapor flux to the vadose zone (McAlary et al. 2011). This condition is less likely to occur where fluctuations of the groundwater table are large, relative to local recharge, and would not generally be expected in arid climates.

than in soil gas. For this reason, Figure 2-1 does not show vapors emanating from the leading (i.e., right-most) edge of the plume.

If the vapor-forming chemicals are present in the upper reaches of the groundwater table (i.e., volatile chemicals are in the uppermost reaches of an unconfined – "water table" – aquifer), fluctuations in the water table will tend to transport the volatile chemicals upward (during periods of rising water table) or expose impacted water above the water table to soil gas (during periods of falling water table). The latter will facilitate the episodic formation of vapors in the vadose zone. Rising water tables also will bring the vapor source closer to the building(s).

2.2 Subsurface Vapor Migration

At many sites, the subsurface vapor source (e.g., in soil or groundwater) is not in contact with the bottom of the subject building. Under these circumstances, vapors emanating from the source medium enter the pore space around and between the subsurface soil particles in the soil column above the groundwater table, which is called the unsaturated soil zone or vadose zone. If the subsurface vapor source is in the vadose zone, the vapors have the potential to migrate radially in all directions from the source via diffusion (i.e., upward toward the atmosphere, laterally outward, and downward toward the water table; downward migration may eventually lead to groundwater contamination). If the subsurface vapor source is in the upper-most zone of groundwater, the vapors have the potential to migrate upwards toward the atmosphere via diffusion. Figure 2-1 illustrates these conditions and this process.

Regardless of source type, soil gas concentrations emanating from a subsurface vapor source generally attenuate, or decrease, as the volatile chemicals move from the source through the soil and into indoor air. If and when soil vapor monitoring data at a given site are not consistent with this trend, the conceptual site model may be incomplete (e.g., additional, unrecognized sources or a preferential migration route(s) may exist at the site) and/or bias or error may have been imparted by the sampling and analysis techniques.

Diffusion, which is caused by the random motion of molecules, affects the distribution of soil vapors when there are spatial differences in chemical concentrations in the soil gas. The net direction of diffusive transport is toward the direction of lower concentrations.

Advection occurs in the vadose zone when there is bulk movement of soil gas induced by spatial differences in soil gas pressure. The direction of advective vapor transport is always toward the direction of lower air pressure. Advection is generally expected to occur in the vicinity of buildings, because differences in temperature between the building interior and the subsurface environment or the operation of combustion units or fans within the building can create driving forces for soil gas entry (See Section 2.3). Advection of soil gas may also occur:

- near the ground surface due to fluctuations in barometric (atmospheric) pressure, which can either release soil gas into the atmosphere (Clements and Wilkening 1974) or

introduce ambient air into the subsurface environment (the latter process may be important in oxygenating surface soil horizons);[56]

- wherever methane generation from anaerobic degradation is sufficiently high (e.g., near some landfills, some locations with degrading fuels).

Advection may be hindered where extensive surface barriers, such as asphalt, concrete, or frozen soil are present.

Vapors also can migrate via advection (and diffusion) along a preferential subsurface pathway, such as a utility corridor or more porous zones of soil or rock, or beneath surface barriers that limit the direction(s) of vapor migration, such as frozen ground or asphalt.[57]

Vapor migration in the vadose zone can be impeded by several factors, including high soil moisture, low-permeability (generally fine-grained) soil, and biodegradation:

- High moisture levels in the vadose zone can significantly reduce the effective rate of diffusive transport, owing to the substantially smaller diffusion coefficient of vapor-forming chemicals in water compared to air. Where ground covers, such as asphalt or concrete, are absent, soil cores taken external to building structures can reasonably be expected to show greater soil moisture than underneath buildings (Tillman and Weaver 2007), particularly after episodes of precipitation and infiltration. Fluctuations in the elevation of the groundwater table can also contribute to temporal changes in soil moisture profiles, in addition to changing the thickness of the vadose zone.

- A low-permeability layer in the vadose zone, particularly one with high moisture content or perched water, may impede or prevent upward migration of vapors from deeper sources in the vadose zone. Figure 2-1 illustrates partial impedance due to a silty or clay layer of limited lateral extent.[58] In some cases, soil or rock can impose sufficient resistance to vapor migration to make the vapor intrusion pathway insignificant, because low-permeability layers are laterally extensive over distances that are large compared to the size of the building(s) or the extent of subsurface contamination with vapor-forming chemicals.

[56] Under certain conditions, such as periods during which indoor–outdoor pressure differences are small, atmospheric pressure fluctuations may contribute to the vapor flux into a building (Robinson and Sextro, 1997).

[57] Whether the subsurface vapor source is contaminated soil or groundwater, soil gas concentrations emanating from a subsurface source generally attenuate, or decrease, as the vapors move from the source through the soil and into indoor air due to diffusion and advection and are subject to any degradation. If and when soil vapor monitoring data at a given site are not consistent with this trend, the possible existence of a preferential migration route(s) warrants consideration. Sewer lines also warrant consideration as potential sources of vapors, as well as conduits for preferential (e.g., unattenuated) transport of vapors towards buildings. Preferential migration routes are discussed further throughout this Technical Guide, including in Sections 5.4, 6.3.2, and 6.5.2.

[58] Low-permeability layer(s) overlying contaminated groundwater (i.e., "aquicludes") can, likewise, impede the flux of vapors from the contaminated plume to the vadose zone. The aquiclude shown at the base of Figure 2-1 would not impede the flux of vapors from the contaminated plume to the vadose zone, however, because the aquiclude is below both. The aquiclude would impede vapor flux from any additional contaminated plume located below it.

- Some chemicals (e.g., benzene, methane, and other petroleum hydrocarbons; vinyl chloride (Patterson et al. 2013) and some other chlorinated hydrocarbons) may experience reductions in their soil gas concentrations due to biodegradation in the vadose zone under certain conditions. Depending upon the potential for oxygen to migrate into the subsurface and underneath buildings from the ambient air, biodegradation may be anaerobic or aerobic. The rate of biodegradation *in situ* will be chemical-specific (i.e., chemicals have different degradation rates even within a similar microbial environment), will be site-specific (i.e., the microbial environment will depend upon soil moisture, nutrient and oxygen levels, and the chemical mixture,[59] among other factors (Holden and Fierer 2005)), and may be location-specific (i.e., the microbial environment can change over time and space due to variations in soil moisture,[60] nutrient and oxygen[61] levels). In some cases, biodegradation in the vadose zone can impede vapor migration significantly.

Demonstrating the extent, if any, to which these processes act as a barrier to vapor transport at specific sites may entail intensive testing or investigative methods that are very different from the sampling and analysis techniques for indoor air and soil gas (see, for example, Sections 6.3.2 and 6.4). Where and when it occurs, biodegradation may result in the formation of by-products that are potentially hazardous (e.g., methane from ethanol, vinyl chloride from PCE or TCE).

The distribution and magnitude of soil gas concentrations immediately beneath a building are expected to reflect the interplay between vapor transport toward the building (via diffusion and advection) in the vadose zone and vapor withdrawal due to soil gas entry into the building (in the case where the building is under-pressurized), which may be spatially and temporally variable (Section 2.3). Likewise, soil vapor may become contaminated as a result of over-pressurized buildings forcing contaminated indoor air through openings in the foundation into nearby soil.

2.3 Openings and Driving Forces for Soil Gas Entry into Buildings

Hazardous vapors in the vadose zone may eventually enter buildings as a component of a gas by migrating through cracks, seams, interstices, and gaps in basement floors, walls, or foundations ("adventitious openings") or through intentional openings, such as perforations due to utility conduits and sump pits. Figure 2-2 illustrates some of these types of openings. Buildings can be expected to vary, even within a single community, in the amount of opening

[59] For example, aerobic biodegradation of benzene may be impeded by the presence of methane, due to competition for oxygen by methane-oxidizing ("methanotrophic") bacteria, depending upon site-specific conditions (Ma et al. 2012).

[60] Moisture plays a particularly important role for microorganisms in the vadose zone. Microbial growth and activity can decrease rapidly with depth, coincident with the soil moisture profile, and increase again in the capillary fringe (Holden and Fierer 2005).

[61] Site-specific infrastructure and soil conditions, climate, and other factors will determine the extent to which oxygen levels underneath a building will be different compared to locations outside the building footprint. In addition to buildings, surface covers, such as asphalt or concrete, can impede oxygenation of the vadose zone, relative to the case where the ground surface is in contact with the atmosphere, all other factors being equal.

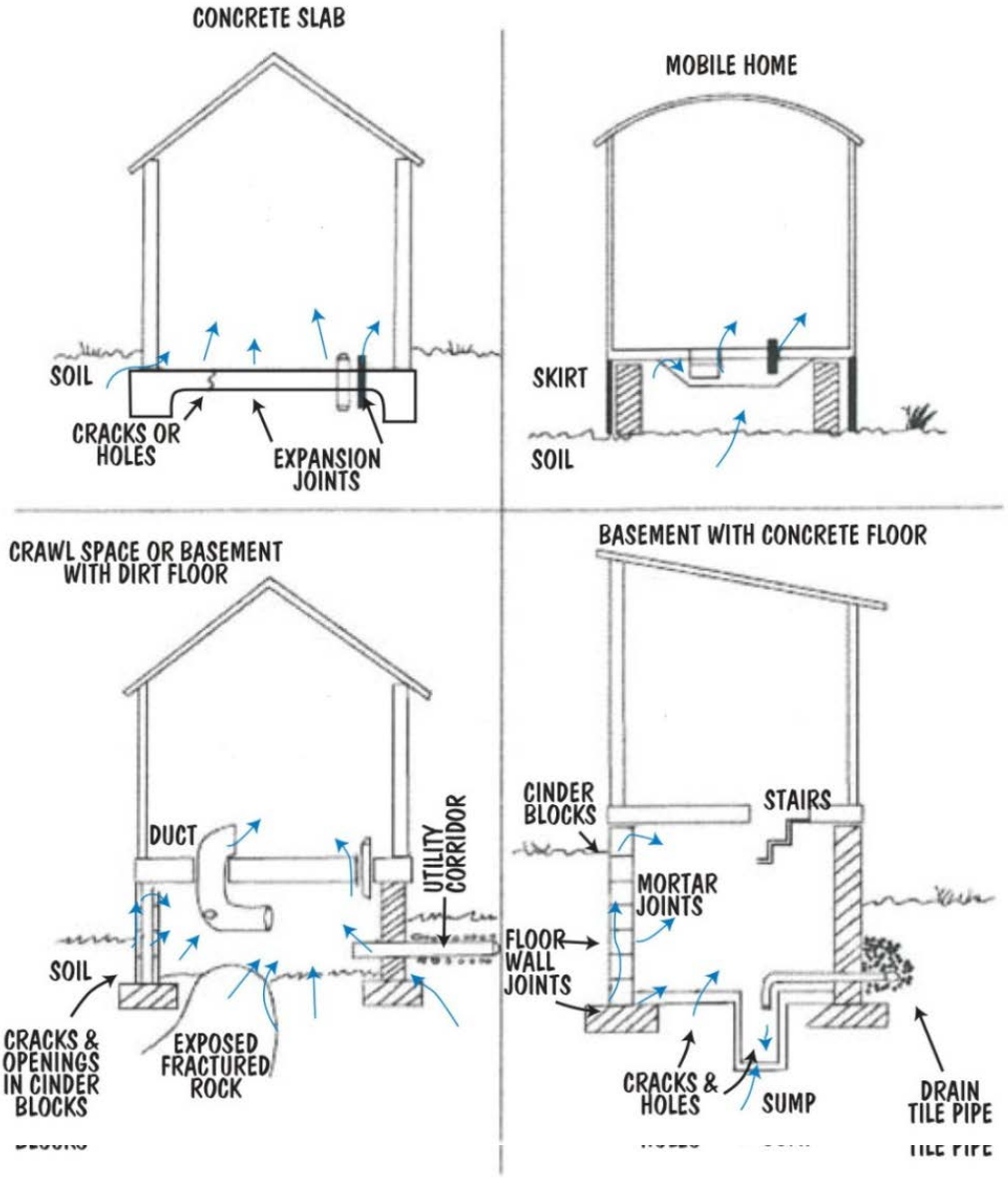

Figure 2-2 Illustration of Potential Openings in Various Building Types
Note: Blue arrows represent soil gas migration or entry. Source: EPA (2008)

area available for soil gas entry; for example, buildings with deteriorating basements and foundations or dirt floors are more susceptible to soil gas entry.

As mentioned in Section 2.2, advection in the vadose zone can arise in the vicinity of buildings whenever there is a difference between the air pressure within a building and the subsurface environment. The air pressure within a building can be lower than in the subsurface due to:

- Temperature differences between indoor and subsurface locations (e.g., the winter-time "stack effect," when buildings are commonly heated, leading to convection cells driven by heated air that rises to upper levels and leaks through roofs and upper-floor windows).

- The operation of mechanical devices, such as exhaust fans for ventilation, air conditioners, and clothes dryers, with vents to the outdoors.

- The operation of fireplaces that vent combustion (exhaust) gases to the outdoors.

- The operation of furnaces in basements of centrally heated buildings, which can incrementally depressurize the basement (EPA 1993a).

- Wind load on the building walls.[62]

Even small pressure differences may cause advective flow of soil gas into or out of the building through pores, cracks, or openings in the building floor or basement walls[63] or gas present in drain lines, sumps, and sewer lines that do not have adequate vapor traps.[64]

[62] The wind effect is caused by differences in building pressure on a building's surfaces. The outdoor air pressure will be higher on the windward side of the building, than on the leeward side, as ambient air flows around the building. The net effect of this pressure difference will vary from building to building, depending upon the location of the primary openings for soil gas entry (and the primary opening for air infiltration through the building envelope –see Section 2.4) (EPA 1993a, Section 2.3 therein).

[63] As a result of the construction of foundation walls and floor slabs, a perimeter crack (i.e., space between the floor slab and walls) may be created and serve as an entry location for soil vapors. This perimeter crack is often obscured by wall coverings, and may not be accessible for inspection or direct testing. Vapors have been observed to migrate through what appears to be intact concrete floors and walls, which may, in fact, have small unobserved fractures or porous areas from improper curing. In addition, conduits may be present that facilitate soil gas entry into buildings. These conduits may include utility (e.g., sewer, water, or electrical) penetrations and floor drains

[64] Where sewers or other conduits contain volatile contaminants, lateral lines connecting buildings to these conduits may facilitate vapor intrusion into indoor air. Although floor drains are designed to allow water to drain away from the building, they are usually not designed or constructed to eliminate gas entry. At a test house in Indianapolis, elevated levels of PCE and chloroform were found in gas in a laundry drain line, which was suspected of serving as a source of vapors found in indoor air (EPA 2012f). Although building construction codes and toilet designs are intended to prevent sewer gas from entering homes, inadequate maintenance (e.g., plumbing fixture seals) can result in loss of the intended protection. Pennell et al (2013), for example, found sewer gas entry to be a significant source of PCE in indoor air at a home in Massachusetts. In addition, sewer gas was a suspected source of benzene in indoor air in many buildings near a gasoline spill site in Hazleton, Pennsylvania (www.epa.gov/reg3hwmd/npl/PA0001409671.htm), where sewer vent traps were subsequently installed to mitigate intrusion of gasoline vapors into homes.

To date, most analytical and computational models of vapor intrusion have been predicated on the assumption that residences and other small buildings experience a constant under-pressurization (i.e., lower pressure in the building than in the subsurface), which fosters vapor intrusion. Whereas this assumption facilitates analyses and may be reasonable for some purposes (see, for example, Section 2.5), it is highly idealized. To illustrate: fluctuations in subslab-to-building pressure difference (and, hence, soil gas entry rates) over time can be reasonably expected due to:

- diurnal (daily) and seasonal changes in the temperature of ambient air, whereas indoor temperatures may be more stable, particularly during periods when mechanical heating and cooling systems are in use;
- changes in ambient air pressure;
- non-instantaneous response (i.e., lag or delay in response) of subsurface soil gas to changes in ambient air pressure (EPA 1993a, Section 2.3 therein), particularly where low-permeability soil is in direct contact with a building foundation (e.g., basement) below the ground surface;[65]
- changes in wind direction and speed; and
- intermittent operation of mechanical ventilation systems and combustion devices that vent exhaust gases to the outside.

Theoretically, these processes and variables suggest that soil gas entry rates can be expected:

- to vary over different time scales (e.g., within an day, and between seasons);
- to differ geographically due to differences in ambient air temperature, pressure, wind, and building conditions (e.g., leakage area and its distribution over the building envelope); and
- to be discontinuous over some time periods.

[65] On the other hand, where granular fill is present underneath a building, there is potential for preferential soil gas flow through the fill, especially in locations where the gas permeability of the surrounding soil is low. Where granular materials have differentially settled, air voids (also highly permeable to soil gas flow) may form beneath the foundation. Utility penetrations and other conduits may be connected to the granular fill, accentuating the potential pathway for soil gas entry into a building. Adding to the complexity, pressure differentials caused by wind flows conceivably could create a cross-flow through granular fill underneath the foundation, which may episodically dilute vapor concentrations (and oxygenate soil gas) in the building vicinity.

2.4 Air Exchange and Mixing

Air exchange refers to the flows into and out of a building, which are generally in balance, and is composed of three processes:

1) infiltration—air leakage through random cracks, interstices, and other unintentional openings in the building envelope;

2) natural ventilation—airflows through open windows, doors, and other designed (intentional) openings in the building envelope; and

3) mechanical ventilation—air movement controlled and driven by fans.

For the vapor intrusion exposure scenario, air exchange by each of these processes will generally tend to mitigate the effects of vapor intrusion (i.e., reduce indoor air concentrations) via dilution, while air inflows will also transport indoors any vapor-forming chemicals in ambient air (see Section 2.7).[66]

The air exchange rate is conventionally defined as the ratio of the airflow rate (e.g., cubic meters per second) to the building volume (e.g., cubic meters) and is generally expressed in terms of exchanges per hour (i.e., overall units of $hour^{-1}$). Values for residential air exchange rates are typically on the order of approximately 0.18 to 1.26 air changes per hour (ACH) (EPA 2011b, see Table 19-24 therein, 10^{th} and 90^{th} percentiles).[67,68] Values for non-residential buildings are highly-dependent upon building use and can range widely (on the order of approximately 0.3 to 4.1 ACH) (EPA 2011b, see Table 19-27 therein, 10^{th} and 90^{th} percentiles).

[66] The potential diluting effect of air exchange arises when ambient air has negligible presence of the volatile chemicals found in site-related contamination in the subsurface environment. In some situations, site-related contamination has the potential to impact ambient air with the same vapor-forming chemicals that pose a threat from vapor intrusion. For example, contamination of shallow soil or groundwater may release site-related vapor-forming chemicals to ambient air. In such situations, air exchange would contribute to the presence of site-related contamination in indoor air, rather than only dilute any impacts from vapor intrusion.

[67] EPA's Office of Research and Development evaluated eight studies of air exchange rate for residential buildings and selected a 1995 EPA study as the basis for recommending values for risk assessment (EPA 2011b, Table 19-24). The key study analyzed almost 3,000 time-averaged measurements of exchange rate in occupied homes in the United States, which were generally obtained using a tracer-release method. Median values ranged from 0.35 $hour^{-1}$ in the mid-western region to 0.49 $hour^{-1}$ in the northeast and southern regions. Tenth percentile values ranged from 0.16 $hour^{-1}$ in the mid-western and southern regions of the U.S. to 0.23 $hour^{-1}$ in the northeast region. Regional differences in exchange rate reflect differences in weather (e.g., temperature and wind speed), prevailing building conditions (e.g., house 'leakiness'), and the time periods (e.g., season) in which measurements were made.

[68] EPA's Office of Research and Development (EPA 2011b, Section 19.5.1.2.7) also summarized a study that conducted approximately 500 indoor-outdoor air exchange rate (AER) calculations based on residences in three urban locations (metropolitan Elizabeth, NJ; Houston, TX; and Los Angeles, CA). This study highlights how climate and season can influence air exchange rate. In Texas, the measured AERs were lower in the summer cooling season (median = 0.37 ACH) than in the winter heating season (median = 0.63 ACH), likely because windows were closed while air conditioners were in use. The measured AERs in California were higher in summer (median = 1.13 ACH) than in winter (median = 0.61 ACH), because summers in Los Angeles County are less humid than NJ or TX and residents are more likely to utilize natural ventilation through open windows and screened doors. In New Jersey, air exchange rates in the heating and cooling seasons were similar.

To date, most analytical and computational models of vapor intrusion have been predicated on the assumption that residences and other small buildings are well mixed spaces throughout which concentrations of vapor-forming chemicals are uniform. Whereas this assumption facilitates analyses and may be reasonable for some purposes (see Section 2.5), it is highly idealized. To illustrate: airflow within a building (i.e., inter-zonal airflow) can be impeded by doors, walls, and other partitions that separate rooms and other building areas. Whereas airflows within a building can be facilitated by mechanical means, spatial variation of temperature and humidity suggest that air mixing is not necessarily complete even in buildings that benefit from centralized systems for heating, air condition, and ventilation. Furthermore, many residences do not have such mechanical systems. Therefore, buildings subject to vapor intrusion may exhibit differences in concentration of vapor-forming chemicals among building areas (e.g., rooms) as a result of the differential proximity to openings for soil gas entry (see Section 2.3) and openings for air leakage and ventilation and the magnitude and balance of inter-zonal airflows. For example, rooms with perforations through the foundation (e.g., bathrooms or utility rooms) may have greater concentrations of vapor-forming chemicals in air compared to rooms that do not. Generally, basements can reasonably be expected to exhibit greater concentrations of vapor-forming chemicals than upper occupied levels.

Buildings constructed over a crawl space with a dirt floor may benefit from the dilution of soil gas by any ventilation of crawl space air, but would not have the impedance to vapor intrusion that concrete slabs can provide. Trailers enclosed at the bottom by a skirt are expected to have greater potential for vapor intrusion than would non-enclosed trailers. Wind movement between the ground surface and the bottom of the non-enclosed trailer would tend to minimize vapor buildup and associated potential for vapor flux into the building. Similarly, the existence of underground parking for a multi-story building (or other modifications to the foundation that enhance subsurface ventilation) would tend to minimize the potential for vapor intrusion.

2.5 Conceptual Model Scenarios

Based upon the foregoing conceptual model, numerous factors can influence the potential indoor air concentration arising from vapor intrusion. Some of these significant factors are illustrated in Figure 2-3.

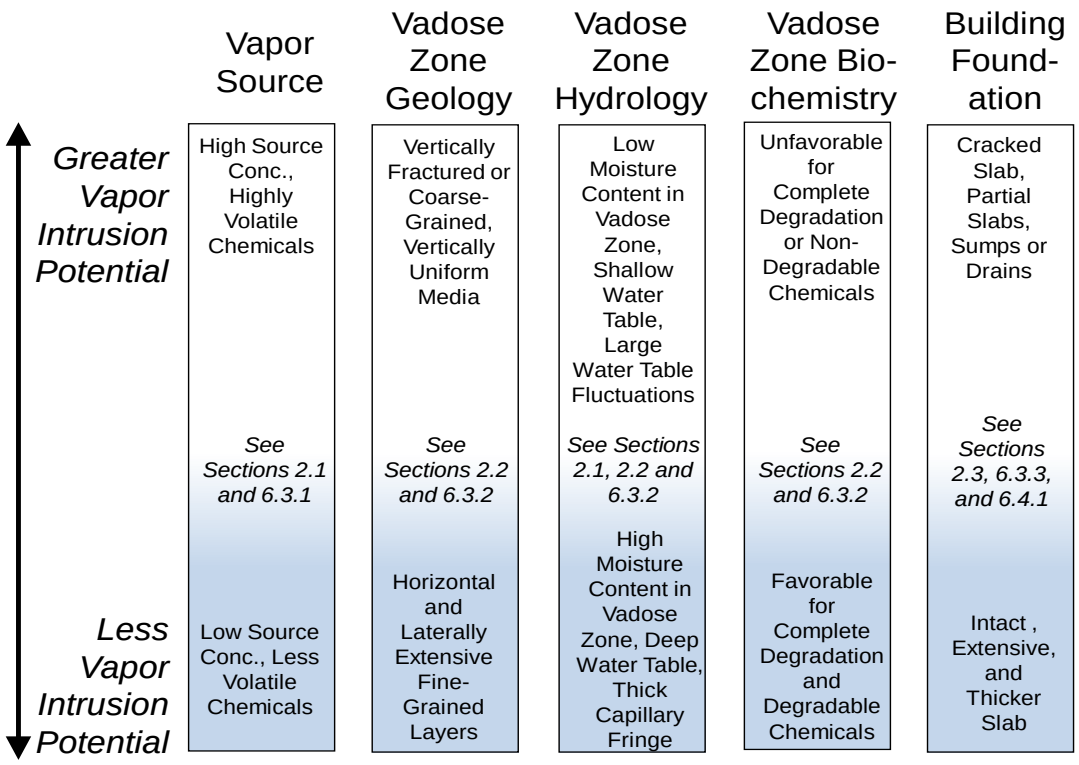

Figure 2-3 Some Factors That Affect Vapor Intrusion

The document *Conceptual Model Scenarios for the Vapor Intrusion Pathway* (EPA 2012b) provides simplified simulation examples[69] to illustrate graphically how several of the subsurface and building-specific factors work together to determine the distribution of volatile contaminants in the subsurface and the indoor air concentration relative to a source concentration. The conceptual model scenarios document offers insights into the factors influencing the vapor intrusion pathway. It provides a theoretical framework with which to draw inferences about and better understand the complex vapor fate and transport conditions typically encountered at actual, non-idealized contaminated sites. The following general observations can be made from these simplified simulation examples, and may be useful when considering the vapor intrusion pathway at a particular site:

- The horizontal and vertical distance over which vapors may migrate in the subsurface depends on the source concentration, source depth, soil matrix properties (e.g., porosity and moisture content), and time since the contaminant release to the environment occurred. Months or years of volatilization and vapor migration may be required to fully develop vapor distributions in the vadose zone at sites with deep vapor sources or with impedances to vapor migration arising from hydrologic or geologic conditions.

- Vapor concentrations, including oxygen, in the vadose zone (i.e., soil gas concentrations) may not be uniform in sub-slab soil gas or in soil gas at similar depths exterior to the building of interest. Therefore, soil gas concentrations at exterior locations (i.e., outside a building's footprint) may be substantially different from the concentration underneath the building (e.g., the sub-slab concentration), depending on site-specific conditions and the location and depth of the exterior soil gas sample.

- Simulations assuming an idealized, constructed ground cover suggest that shallow soil gas concentrations can be greater under low-permeability ground covers (e.g., asphalt) than under soil open to the atmosphere.

- The soil gas distribution beneath a building is not the only factor that determines the indoor air concentration. The indoor air concentration is also influenced by building conditions, including the presence of openings (e.g., cracks, utility penetrations) in the foundation, building pressurization, and the air exchange rate.

- Advective flow into buildings, which is presumed to occur predominantly near cracks and openings in the foundation slab, may affect the distribution of vapor-forming chemicals directly beneath the structure. Heterogeneities in the permeability of geologic materials and backfill, along with wind effects and building and atmospheric pressure temporal variation, may also contribute to the spatial and temporal variability of vapor concentrations in sub-slab soil gas and indoor air.

[69] Two important simplifications are the assumptions of constant values for the driving force for vapor intrusion (i.e., subslab to indoor air pressure difference) and air exchange rate, whereas time-variable values are reasonably expected as a result of changing weather and other conditions (as summarized in Sections 2.3 and 2.4, respectively).

- Subsurface heterogeneities in site geology, such as layering and moisture content, can influence the extent and rate of vapor migration from a contaminant source towards overlying or adjacent buildings.

- The soil gas distribution of aerobically biodegradable chemicals (e.g., BTEX) can be significantly different than that of other chemicals that are not biodegradable (i.e., are recalcitrant) in similar settings. Specifically, the soil gas concentrations of aerobically biodegradable chemicals exhibit greater attenuation than those of recalcitrant chemicals when the subsurface availability of oxygen is adequate.

2.6 Variability in Exposure Levels

Given the foregoing conceptual model of vapor intrusion and summary of modeled scenarios (EPA 2012b), the degree to which vapor intrusion is a pathway of concern can vary widely from site to site and from building to building within a site. Adding to the complexity, theoretical considerations (i.e., soil gas entry rates, air exchange rates, interior compartmentalization and inter-zonal airflows) suggest that indoor air concentrations arising from vapor intrusion can be expected to vary over time and within a building. Field observations and measurements demonstrate that indoor air concentrations can exhibit significant temporal variation within a day and between days and seasons in an individual residential building (EPA 2012a; Holton et al. 2013ab).

2.7 Consideration of Indoor and Outdoor Sources of VOCs

Indoor air in many buildings will contain detectable levels of a number of vapor-forming chemicals whether or not the building overlies a subsurface source of vapors (EPA 2011a), because indoor air can be impacted by a variety of indoor and outdoor sources. Indoor sources of volatile contaminants include the use and storage of consumer products (e.g., cleaners, air fresheners, aerosols, mothballs, scented candles, insect repellants, or other household products), combustion processes (e.g., smoking, cooking, and home heating), occupant activities (e.g., craft hobbies, home improvements, automotive repairs), and releases from interior building materials (e.g., carpets, insulation, paint, and wood-finishing products). Outdoor sources of volatile chemicals may arise due to releases from nearby sources such as industrial facilities, vehicles, yard maintenance equipment, fuel storage tanks, and paint or pesticide applications; regional sources such as air emissions from regional industry, vehicle exhaust, agricultural activities, and fires; or global sources, such as distant air emissions. The outdoor air surrounding a building is referred to as “ambient air” throughout this Technical Guide.

The contribution of indoor and outdoor sources of vapors (or both) to indoor air concentrations, which do not arise from site-related contamination,[70] is referred to as “background” throughout this Technical Guide (see, for example, Sections 2.7, 6.3.5, and 7.4.2 and the Glossary). In

[70] In some situations, site-related contamination has the potential to impact indoor or ambient air (EPA 1993c) with the same vapor-forming chemicals that pose a threat from vapor intrusion. For example, contaminated groundwater in building sumps or intruding into the building via groundwater seepage could provide an indoor source of site-related contamination. Contamination of shallow soil or groundwater may also release site-related vapor-forming chemicals to ambient air. In such situations, neither of these sources of indoor air contamination would be considered ‘background.’

some buildings, “background” sources by themselves can cause building occupants and visitors to experience significant exposures to vapor-forming chemicals.

In contrast to “background” concentrations in soil arising from naturally occurring minerals, “background” concentrations in indoor air often are not uniform in time. For example, concentrations of vapor-forming chemicals in ambient air may exhibit temporal variation over several time scales (e.g., daily, seasonal, longer term) and spatial differences across urban, suburban, and rural land use areas, reflecting differences in emission sources and rates and environmental factors that transport, disperse, and remove these pollutants (Jia et al. 2012 and citations therein). Concentrations of vapor-forming chemicals arising in indoor air in residential buildings due to indoor sources have been observed to depend upon season and other factors. Available studies suggest complex (e.g., patchy) spatial patterns in exposure concentration, which has led some researchers to refer to “microplumes” in the indoor air environment (McBride et al., 1999 and citations therein).

3.0 OVERVIEW OF THIS VAPOR INTRUSION TECHNICAL GUIDE

This section provides an overview of this Technical Guide and the general recommended framework for vapor intrusion assessment and response action, which is illustrated in Figure 3-1. This section opens with a description of subsurface contaminants that have the greatest potential to pose a health concern via vapor intrusion, based upon their volatility and potential hazards.

3.1 Contaminants of Potential Concern

Several physicochemical criteria may be considered for defining and screening for volatility.[71] For purposes of this Technical Guide, a chemical generally is considered to be "volatile" if:

1) Vapor pressure is greater than 1 millimeter of mercury (mm Hg), or

2) Henry's law constant (ratio of a chemical's vapor pressure in air to its solubility in water) is greater than 10^{-5} atmosphere-meter cubed per mole (atm m^3 mol^{-1}) (EPA 1991b, Section 3.1.1; EPA 2002c, Appendix D).

Various other criteria may be considered for identifying when volatile chemicals are present at levels of potential health concern. For purposes of this Technical Guide, a volatile chemical generally is considered to be "potentially toxic" via vapor intrusion if:

1) the vapor concentration of the pure component exceeds the indoor air target risk level, when the subsurface vapor source is in soil, or

2) the saturated vapor concentration exceeds the target indoor air risk level, when the subsurface vapor source is in groundwater.

Each of the chemicals with one or more toxicity values used to derive Regional Screening Levels (http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/Generic_Tables/index.htm) were evaluated for volatility and toxicity, according to the foregoing recommended criteria. These criteria do not include a consideration of whether these chemicals are regulated pursuant to CERCLA, as amended, or RCRA, as amended. The universe of chemicals evaluated and the results of the evaluation are provided in EPA's on-line VISL Calculator (EPA 2015a), which is described further in Sections 1.4.1 and 6.5.2 of this Technical Guide.

Chemicals which satisfy the foregoing screening criteria for volatility and toxicity are designated as "vapor-forming chemicals" for purposes of this Technical Guide. In addition:

[71] In chemistry and physics, volatility refers to the tendency of a substance to form vapors, which are molecules in a gaseous state, and escape from a liquid or solid. Volatility is directly related to a substance's vapor pressure and Henry's law constant. EPA (1991b) also cites molecular weight as a necessary criterion for assessing volatility. Molecular weight is not retained for this Technical Guide as a volatility criterion, because it is a relatively weak predictor of volatility.

- cis-1,2-dichloroethylene, a volatile chemical that lacks sufficient toxicity information (to apply the toxicity criteria above), is identified as a vapor-forming chemical due to its potential use as an indicator of vapor intrusion when it is present as a subsurface contaminant;[72]

- methane is identified as a vapor-forming chemical due to its potential to pose an explosion hazard and to be formed via anaerobic biodegradation processes in the subsurface environment;[73] and

- radon is identified as a vapor-forming chemical when it arises from uranium- or radium-bearing solid wastes in the subsurface.[74]

Chemicals that meet these recommended screening criteria are referred hereafter in this Technical Guide as "vapor-forming chemicals." EPA recommends that these chemicals be evaluated during vapor intrusion assessments, when they are present as subsurface contaminants due to a site-related release(s). EPA recommends that chemical analyses be limited to those vapor-forming chemicals known or reasonably expected to be present in the subsurface environment due to a site-related release(s). The list of vapor-forming substances warranting consideration for potential vapor intrusion may be modified in the future.[75]

3.2 Vapor Intrusion Assessment

The approach for assessing vapor intrusion will vary from site to site, due to site-specific factors. For example, the information available for evaluating vapor intrusion potential will vary depending upon when vapor intrusion is first considered during a site's investigation-and-cleanup life cycle. Many sites can be evaluated for potential vapor intrusion during the normal course of an initial site assessment. Examples include brownfield sites that are intended for redevelopment and buildings where chemical odors have been reported. The data available for evaluating vapor intrusion may be very limited at the outset for these situations. At the other end of the investigation and cleanup life cycle, certain sites with long- term cleanups underway for contaminated groundwater may be evaluated for vapor intrusion during periodic reviews, if any,

[72] EPA (2011a) and DoN (2011a) report that cis-1,2-dichloroethylene (cis-1,2-DCE) is "rarely detected in background indoor air." When they are subsurface contaminants, volatile chemicals, such as cis-1,2-DCE, that are rarely or never present in indoor sources can be inferred to arise in indoor air via vapor intrusion "without further explanation" (DoN 2011a). Brenner (2010), for example, employed this principle to identify buildings susceptible to vapor intrusion and to diagnose the relative contributions of vapor intrusion and infiltration to indoor air concentrations.

[73] As noted previously, methane in soil gas may produce two other undesirable consequences: (1) it can exacerbate migration and intrusion of other vapors if it is generated at rates sufficient to foster advective flow of soil gas (see Section 2.3); and (2) its biodegradation in the vadose zone can reduce the oxygen available for biodegradation of other hydrocarbons (Ma et al. 2012).

[74] Radon emanating from natural geological materials may also affect indoor air quality in occupied buildings, but is not a subject of this Technical Guide. For more information about radon emanating from natural geological materials, see: http://www.epa.gov/radon/index.html.

[75] For example, inhalation toxicity values for additional volatile chemicals may become available in the future.

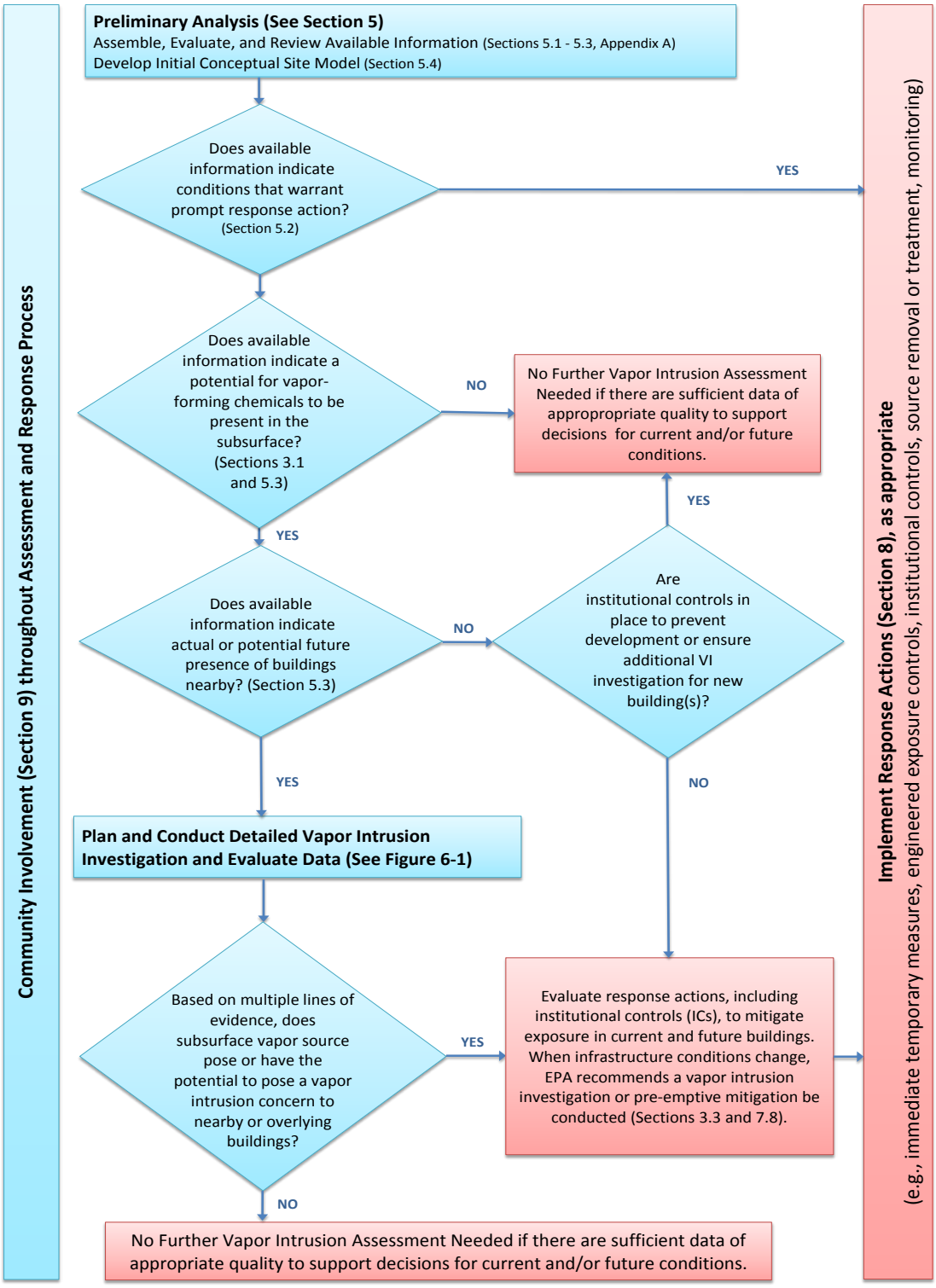

Figure 3-1 Overview of Recommended Framework for Vapor Intrusion Assessment and Response Action

of remedy performance and groundwater monitoring data.[76] In such situations, detailed information about the nature and extent of subsurface contamination and the relevant hydrogeologic conditions may already exist. In addition, there are different scenarios for vapor intrusion (EPA 2012b), depending on characteristics of the source (e.g., types, chemicals of concern, mass, distribution, and distance from building(s)), subsurface conditions and vapor migration routes (e.g., soil types and layering, existence of preferential migration routes due to geology or infrastructure, and existence of any impediments to vapor migration), building susceptibility (e.g., age, design, construction, condition), lifestyle factors (e.g., keeping windows open or closed), and regional climate. For these reasons, every site (and every building) will not warrant the same approach to or intensity of assessment for vapor intrusion. This Technical Guide, therefore, recommends a framework for planning and conducting vapor intrusion investigations, rather than a prescriptive step-by-step approach to be applied at each and every site.

Broadly speaking, two general levels of vapor intrusion assessments can be distinguished:

1) A preliminary analysis utilizes available and readily ascertainable information to develop an *initial* understanding of the potential for human health risk that are or may be posed by vapor intrusion, which would typically be performed as part of an initial site assessment. The recommended information, approaches, and practices for conducting a preliminary analysis and its potential outcomes are described in Section 5.0.

2) A detailed investigation is generally recommended when the preliminary analysis indicates that subsurface contamination with vapor-forming chemicals may be present underlying or near buildings. A detailed investigation of the vapor intrusion pathway is typically performed as part of the site investigation stage. The recommended approaches and practices for conducting detailed vapor intrusion investigations are described in Section 6.0.

Considerable information, primarily empirical, has been generated regarding evaluation of the vapor intrusion pathway since the pathway emerged as a national issue in the late 1990s and especially in the past ten years. Broadly speaking, this information demonstrates that the vapor intrusion pathway can be complex. (The conceptual model of vapor intrusion provided in Section 2.0 identifies many of the factors, variables, and conditions that warrant consideration on a site-specific basis.) As a result, current practice suggests that the vapor intrusion pathway generally be assessed using multiple lines of evidence.[77]

Specific conclusions that EPA recommends be based upon multiple lines of evidence include:

[76] These situations can arise, for example, if the groundwater remedy was selected in the 1980s (long before vapor intrusion became recognized as a potentially significant exposure pathway), or if supplemental groundwater data indicate that the plume is migrating toward new inhabited areas.

[77] As discussed further in Section 7.2, confidence in the assessment and risk management decisions is expected to be higher when multiple independent lines of appropriate site- or building-specific evidence from, for example, multiple types samples of environmental media (e.g., groundwater, soil-gas, sub-slab vapor, crawlspace, and indoor air) and/or other data come together to provide mutually supporting evidence for a common understanding of the site conditions/scenarios and the potential for vapor intrusion (EPA 2010b) (i.e., the various lines of evidence are in agreement with each other).

- The subsurface vapor source(s) at a specific site has (or, alternatively, does not have) the potential to pose an unacceptable vapor intrusion exposure under current or reasonably expected future conditions, due to its strength (e.g., concentration and mass of vapor-forming chemicals) and proximity relative to one or more existing buildings or a building that may be constructed in the future.

- The vapor intrusion pathway is complete for one or more buildings under current conditions or is potentially complete under reasonably expected future conditions.

- The vapor intrusion pathway is incomplete for one or more buildings near a subsurface source of vapor-forming chemicals, due to geologic, hydrologic, and/or biochemical (e.g., biodegradation) processes that provide substantial and persistent attenuation of vapors extending laterally over large distances relative to the footprint of the building(s) and the extent of the vapor source.

- Indoor air concentrations attributable to vapor intrusion pose (or, alternatively, are unlikely to pose) an unacceptable human health risk in one or more existing buildings under current or reasonably expected future conditions.

- Indoor air concentrations measured in one or more buildings can (or alternatively, cannot) be reasonably attributed to indoor or ambient air sources (i.e., background).

Multiple lines of evidence are particularly important for supporting "no-further-action" decisions regarding the vapor intrusion pathway (e.g., pathway incomplete determinations) to reduce the chance of reaching a false-negative conclusion (i.e., concluding vapor intrusion does not pose unacceptable human health risk, when it actually poses an unacceptable human health risk). Collecting and weighing multiple lines of evidence can also help avoid reaching a false-positive conclusion (i.e., concluding vapor intrusion poses an unacceptable human health risk, when it does not.

In summary, EPA recommends that site assessors generally collect and weigh multiple lines of evidence, including qualitative information, to support decision-making regarding the vapor intrusion pathway. Lines of appropriate evidence to evaluate the vapor intrusion pathway were identified in Section 2 and are discussed further in Sections 5 through 7.

As noted in Section 1.3, Figure 3-1, and the preceding discussion of lines of evidence, EPA recommends that site assessors consider reasonably expected future conditions, in addition to current conditions, when reaching conclusions about the vapor intrusion pathway.[78] For this reason, this Technical Guide includes recommendations for evaluating whether subsurface vapor sources that remain have the potential to pose unacceptable human health risks in the future if current conditions were to change. For example:

- Section 6.3.3 recommends that site assessors consider investigating vapor intrusion in non-residential buildings under conditions when the heating, ventilation, and air-conditioning system is not operating; and

[78] "Both current and reasonably likely future risks need to be considered in order to demonstrate that a site does not present an unacceptable risk to human health and the environment." (EPA 1991a).

- Section 7.3 identifies some factors and processes that can make the characteristics of the vadose zone (e.g., soil moisture) transitory.

EPA also recommends that vapor intrusion be evaluated for reasonably expected future land use conditions, including new building construction and new uses and occupants for any uninhabited buildings.

3.3 Building Mitigation and Subsurface Remediation

The NCP expresses the preference for response actions that eliminate or substantially reduce the level of contamination in the source medium to acceptable levels, thereby achieving a permanent remedy. In the case of vapor intrusion, such a response action would generally entail eliminating or substantially reducing the level of vapor-forming chemicals in the subsurface (e.g., in contaminated groundwater, soil, and/or sewer lines) via treatment or removal (i.e., "remediation"). Section 8 discusses source remediation to achieve a permanent remedy and associated institutional controls (ICs) and monitoring for vapor intrusion mitigation, including criteria for their termination.

Comprehensive remediation[79] of the subsurface environment often occurs over a prolonged period (e.g., several years) to attain cleanup levels. In the interim, problems of unacceptable vapor intrusion are often addressed by also installing engineered exposure controls to reduce or eliminate vapor intrusion in buildings (i.e., "mitigate" vapor intrusion) or reduce indoor air exposure levels. Engineered exposure controls can generally be deployed and generally become effective relatively quickly. They can be considered as "interim" or "early" response actions, which are also authorized by the NCP (Section 1.2), as necessary and appropriate to promptly reduce threats to human health. Section 8 summarizes technical information about specific exposure controls and provides information about their operation, maintenance and monitoring and associated ICs, including criteria for their termination.

Functionally, engineered exposure controls can be categorized into two basic strategies:

- Those that seek to prevent or reduce vapor entry into a building (e.g., active depressurization technologies). These methods are more commonly implemented when response actions are needed.[80]

- Those that seek to reduce or eliminate vapors that have entered into a building (e.g., indoor air treatment, ventilation).

[79] For purposes of this Technical Guide, "remediation" is intended to apply to interim and final cleanups, whether conducted pursuant to RCRA corrective action, the CERCLA removal or remedial programs, or using EPA brownfield grant funds with oversight by state and tribal response programs. In addition to permanent remedies for subsurface vapor sources, site remediation may also entail implementation of ICs and construction and operation of engineered systems to reduce risks to human health and the environment posed by environmental pathways other than vapor intrusion. Although this Technical Guide is intended for use at any site subject to federal statutes, regulations, and rules, it is not intended to alter existing requirements, guidance, or practices in OSWER's programs about development, selection, or documentation of final "remediation" plans (addressing subsurface vapor sources, for example) – see, for example, Sections 7.6 and 7.7.

[80] Mitigation methods that prevent or reduce vapor entry into a building from subsurface vapor sources would generally also be expected to reduce radon entry.

Neither strategy entails reducing the level of vapor-forming contamination in the subsurface source medium.[81]

As reflected in the foregoing conceptual model of vapor intrusion (Section 2.0), entry of the vapors into a building may be prevented or reduced by any of several techniques, which have the following objectives:

- Remove or reverse the driving forces for vapor intrusion into the building (e.g., install and operate an active depressurization technology to mitigate vapor intrusion from contaminated soil or groundwater; establish over-pressurization within and throughout the footprint of a nonresidential building).

- Eliminate or minimize identified openings for vapor entry into the building (e.g., caulking, grouting, or otherwise sealing all holes, cracks, sumps and other foundational openings or creating a barrier between the soil and the building that blocks openings for entry of soil gas into the building; install, repair, and/or maintain vapor traps in sewer and drain lines).

Engineered exposure controls that entail mechanical systems and forces (e.g., sub-slab depressurization or ventilation systems; building over-pressurization) are often referred to as "active." Engineered exposure controls that do not involve mechanical operations (e.g., installing a sub-slab barrier to chemical vapor entry) are often referred to as "passive." Many building mitigation systems rely on both active and passive strategies.

Engineered exposure controls that seek to reduce or eliminate vapors that have entered into a building can also be effective. In some instances, they can be implemented more readily than engineered exposure controls that reduce or eliminate entry of the vapors into a building. Typically, the simplest approach to limiting the concentration levels in occupied indoor spaces is to increase building ventilation (i.e., increase the rate at which indoor air is replaced with outdoor air), thereby diluting indoor air concentrations (see Section 2.4).[82] Alternatively, vapor-forming chemicals are removed from indoor air using an adsorbing material (such as activated carbon) that can be either properly disposed of or recycled. Building mitigation methods that act upon vapor-forming chemicals in indoor air (i.e., rely upon enhanced ventilation or treatment) are generally capable of reducing background levels of chemicals, in addition to reducing indoor levels of vapor-forming chemicals that intrude from subsurface sources.

[81] Even when operated for prolonged periods, engineered exposure controls are considered 'interim' remedies for purposes of this Technical Guide, because their implementation does not substitute for remediation of the subsurface source(s) of vapor-forming chemicals. Engineered exposure controls may, nevertheless, become part of a final cleanup plan.

[82] It can be difficult to establish a ventilation rate that mitigates vapor intrusion and yields an environment conducive to human occupancy (e.g., considering air temperature or moisture). In addition, ventilation may affect the driving forces for vapor intrusion. For example, mechanically exhausting air from the building will generally contribute to building under-pressurization (see Section 2.3), which may result in increased intrusion of soil gas into the building, which may offset the intended dilution effect of ventilation. On the other hand, introducing outdoor air at a rate slightly greater than the exhaust rate can create over-pressurization, which opposes the primary driving force for vapor intrusion.

Selection of an interim response action from these options may depend upon building- and site-specific factors (EPA 2008). For example, building-specific factors may include:

- Use (e.g., single-family residential, multi-family residential, commercial, educational, recreational, governmental, religious, industrial)
- Type of foundation/basement (e.g., basements with concrete slab floors or dirt floors, slab on grade, slab below grade) and other construction features
- Type of heating/cooling/ventilation systems (e.g., some systems will tend to increase pressure, whereas others will tend to decrease pressure, inside the building).

Each of these characteristics can influence the choice of mitigation methodology and, therefore, they are commonly identified during building surveys during a site-specific vapor intrusion investigation. Site-specific considerations may include the degree of risk or hazard being addressed and whether the subsurface vapor source(s) is stable in extent and concentration or is undergoing remediation.

Temporary relocation may warrant consideration in instances where explosion hazards are present (see Section 7.5.1), which may pose an imminent and substantial danger to human health and public welfare. Prompt response action may also be warranted where short-term or acute exposures may pose unacceptable human health risk (see Section 7.5.2) that cannot be addressed timely or feasibly by implementing engineered exposure controls. Section 8.2 discusses various prompt response actions for such situations, which may include temporary relocation.

There may be situations where a party may wish to implement mitigation or control measures for vapor intrusion, even though only limited lines of evidence or measurements may be available to characterize the overall vapor intrusion pathway. For example, a party may be aware that vapor intrusion has been documented at neighboring structures, where measures are being implemented to mitigate the vapor intrusion pathway. A party may conclude there is a reasonable basis to take action, but each building presents a fact-specific situation that calls for its own individual judgment. Likewise, it may be appropriate and cost-effective to design, install, operate, and monitor engineered exposure controls for individual buildings to mitigate vapor intrusion in newly constructed buildings, or in buildings to be constructed in the future, that are located in areas of vapor-forming subsurface contamination, rather than potentially allow vapor intrusion to occur later and assess vapor intrusion after the fact. The term “preemptive mitigation/early action” is used in this Technical Guide to describe these situations.[83]

The decision for preemptive mitigation/early action arises from precaution and from recognizing that:

- Installing engineered exposure controls in buildings is typically a cost-effective means of protecting human health and normally can be implemented relatively quickly in many buildings while subsurface contamination is being delineated or remediated.

[83] The term ‘preemptive’ has been used to describe the use of various types of controls that can prevent vapor intrusion from occurring prior to having fully demonstrated that unacceptable vapor intrusion currently exists in specific buildings being considered (EPA 2010a).

- Conventional vapor intrusion investigations can be disruptive for building occupants (residents, workers, etc.) and owners.

- Comprehensive subsurface characterization and investigation of vapor intrusion can entail prolonged study periods, during which time building occupants and owners and others may have questions and concerns about human health risk that are or may be posed via vapor intrusion.

Early action and interim action are allowed by federal environmental protection statutes, regulations, and guidance, including CERCLA, as amended, and RCRA, as amended – see Section 1.2 of this Technical Guide, for example. Other aspects of preemptive mitigation/early action are also discussed in Section 7.8, including situations and criteria for decision-makers to consider.

As noted in Figure 3-1, EPA recommends that risk managers consider reasonably expected future conditions, in addition to current conditions, when making risk management decisions about the vapor intrusion pathway. For this reason, this Technical Guide includes recommendations for response actions at sites where subsurface vapor sources remain into the future, but do not pose unacceptable human health risk under current conditions (e.g., no building is present nearby). For example, institutional control s are generally recommended to restrict land use and/or alert parties (e.g., prospective developers, owners, and municipalities) of the presence of subsurface sources of vapor-forming chemicals at levels that pose a continuing threat via vapor intrusion (see Sections 7.3, 7.4, and 8.6). When infrastructure conditions change above or near an area of known contamination with vapor-forming chemicals, EPA recommends a vapor intrusion investigation or pre-emptive mitigation be conducted, particularly if a building is constructed for human occupancy (see Section 8.2.3).

3.4 Community Outreach and Involvement

EPA is committed to transparency and upfront collaboration with community stakeholders regarding land cleanup, emergency preparedness and response, and management of hazardous chemicals and wastes. OSWER's Community Engagement Initiative (CEI), in particular, is designed to enhance OSWER's and the Regional offices' engagement with local communities and stakeholders (e.g., state and local governments, tribes, academia, private industry, other federal agencies, and nonprofit organizations) to help them participate meaningfully in government decisions regarding OSWER's nationwide programs.

Meaningful and sustained community outreach and engagement efforts are critical to the implementation of work plans for site-specific vapor intrusion assessment and mitigation. Because assessing the vapor intrusion pathway may involve sampling in a home or workplace, as well as other temporary inconveniences (e.g., assisting in reducing indoor sources of contaminants), individual, one-on-one communication with each property owner or renter generally warrants consideration. Building-by-building contact and communication are recommended as the most effective means of educating the community and obtaining access needed to assess, mitigate, and monitor the vapor intrusion pathway. Personal contact is further recommended to establish a good working relationship with each building owner or occupant and to build trust. In many instances, local religious and cultural organizations, and other community groups can be sought for assistance in reaching out to affected community members.

Vapor intrusion education and training are important components of meaningful community outreach and engagement efforts. Informing stakeholders about the vapor intrusion pathway and the cleanup process can help to build trust and can foster community participation in the overall assessment and risk management process.

Recognizing the importance of community outreach and engagement efforts, EPA staff are highly encouraged to consult with colleagues experienced in community outreach and utilize available EPA planning resources, including those discussed in Section 9, which provides OSWER's community involvement planning guide for vapor intrusion projects. Like EPA, the ITRC also recommends implementing a community outreach program that provides timely information to concerned community members and property owners.

4.0 CONSIDERATIONS FOR NONRESIDENTIAL BUILDINGS

The approach for investigating and, if necessary, mitigating vapor intrusion can vary from site to site, and from building to building, due to site- and building-specific factors and circumstances, including: the nature (e.g., mixture of vapor-forming chemicals and form), locations, and extent of subsurface contamination; geologic, hydrologic, and biochemical factors in the vadose zone; and the size, structural conditions and uses of buildings and background levels of vapor-forming chemicals in the building. Information on 'background' contributions of site-related, vapor-forming chemicals in indoor air is important to risk managers because generally EPA does not clean up to concentrations below natural or anthropogenic background levels (EPA 2003e). These statements hold true for residential and non-residential buildings.

Section 6.3.5 of this Technical Guide provides specific recommendations about how to evaluate background concentrations. Section 7.4 of this Technical Guide provides clarifications and recommendations about applying the methods in Section 6.3.5 to informing risk management decisions and recommendations. The Glossary in this Technical Guide defines various terms and types of vapor sources to foster a common understanding of EPA's approach and recommendations.

This section summarizes EPA's general recommendations to consider in making decisions about evaluating and addressing potential vapor intrusion for nonresidential buildings[84] pursuant to CERCLA and RCRA, including decisions that a response action or corrective action is not currently warranted.

When evaluating nonresidential buildings at sites that have subsurface contamination with vapor-forming chemicals, EPA generally recommends that building owners or operators (e.g., lessees) be contacted for information about vapor-forming chemicals used or stored or otherwise present in the building, the types of building occupants potentially exposed to subsurface vapor intrusion, as well as any training, equipment, or engineering controls to mitigate inhalation exposures. EPA recommends that information be provided to building owners concerning the potential for vapor intrusion so that this information can be communicated to building employees, tenants, and other occupants. Building occupants include, but are not limited to, facility employees, visitors, customers, suppliers, and building maintenance personnel.

Generally, EPA recommends the following factors be considered when making decisions pertaining to vapor intrusion at nonresidential buildings, including as to whether indoor air sampling, soil gas sampling underneath the building, or interim measures to mitigate vapor intrusion to reduce associated indoor air exposures for a nonresidential building may be warranted:

[84] As used in this Technical Guide, the phrase "nonresidential buildings" may include, but is not limited to, institutional buildings (e.g., schools, libraries, hospitals, community centers and other enclosed structures for gathering, gyms and other enclosed structures for recreation), commercial buildings (e.g., hotels, office buildings, many (but not all) day care facilities, and retail establishments); and industrial buildings where vapor-forming substances may or may not be routinely used or stored.

1) The types of populations potentially exposed to vapor-forming chemicals in the indoor air of the nonresidential building, including, for example, whether:

   a) Individuals are or may be present under current or reasonably expected future conditions who would not likely anticipate any chemical exposures (e.g., office workers, visitors, customers, suppliers, and other members of the general public) and may not benefit fully from hazard communication programs and other work practices in place to foster protection of workers who use chemicals, if any.

   b) Sensitive populations are or may be present under current or reasonably expected future conditions, who may have increased susceptibility or vulnerability.

2) The potential for vapor intrusion versus background vapor sources (See Glossary) to contribute to indoor air concentrations of vapor-forming chemicals found in the subsurface. Questions to consider include, for example:

   a) Can subsurface vapor intrusion be identified as a potential cause of unacceptable human health risk to building occupants (see Section 5 for further discussion about the preliminary analysis stage and Section 7 for further discussion and definition of acceptable versus unacceptable human health risk)? [85]

   b) Can subsurface remediation (e.g., excavation of contaminated soil or soil vapor extraction beneath the subject building) that is planned or underway reduce human health risk from vapor intrusion within a time frame that is protective for any potential current or near-term exposures in the building?

   c) Is there a known source(s) of one or more vapor-forming chemical(s) – see Section 3.1 – in indoor air in the nonresidential building other than vapor intrusion (e.g., indoor use and storage of chemicals, which would constitute a 'background' vapor source(s) and contribute to indoor air exposure concentrations; see Sections 2.7 and 6.3.5 for further discussion and recommendations about background sources and concentrations)? If such a vapor-forming chemical(s) is (or are) present:

      i. Is(are) it the same as the vapor-forming chemical(s) found in the subsurface?

      ii. How does the indoor air exposure concentration(s) arising from the indoor vapor source(s) compare to the indoor air concentration(s) estimated or reasonably expected to arise from vapor intrusion? [86]

   Information on 'background' contributions of site-related, vapor-forming chemicals in indoor air is important to risk managers because generally EPA does not clean up to concentrations below natural or anthropogenic background levels (EPA 2002e).

[85] EPA's recommended approaches to human health risk assessment are provided in Sections 7.4 and 7.5 of this Technical Guide.

[86] EPA's recommended approaches to distinguishing and considering 'background' are provided in Sections 6.3.5 and 7.4.2 of this Technical Guide.

3) Any existing or planned engineering or institutional control(s) in the building or any industrial hygiene/occupational health program that addresses workplace inhalation exposures and its scope. Questions to consider include, for example:

    a) Do work practices and engineering controls currently in place ensure protection[87] of all building occupants who may be exposed via the vapor intrusion pathway?

    b) Are enforceable institutional controls (ICs) or other control mechanisms in place to ensure that current land use and workplace practices will be sustained and will remain protective regarding indoor air exposures from vapor intrusion to all building occupants? Have these ICs and control mechanisms been communicated to all appropriate parties and documented to EPA? Can they be readily monitored and, if necessary, be enforced?

EPA recommends documenting any decision not to undertake investigation or mitigation for vapor intrusion in a nonresidential building, as well as any decision to pursue such activities. EPA may consider reviewing these decisions, as appropriate and consistent with applicable statutes and regulations and considering EPA guidance,[88] if the land use changes or new information becomes available that suggests circumstances supporting past risk management decisions have changed and prompt the need to revisit those decisions. It is recommended that EPA request from property owners and building tenants/operators timely notification of significant changes in building ownership, uses, access by the general public, or building construction (e.g., renovations), which may affect exposure of occupants and related risk management decisions pertaining to potential vapor intrusion assessment and mitigation, subsurface remediation, or ICs.

Regardless of decisions about indoor air sampling, soil gas sampling underneath the building, or interim measures to mitigate vapor intrusion, EPA[89] may proceed, consistent with applicable federal statutes and regulations (see Section 1.2) and considering EPA guidance, with activities such as the following, where appropriate:

- Subsurface investigation to delineate the areal extent of a subsurface vapor plume.
- Subsurface remediation to reduce or eliminate subsurface sources of vapors-forming chemicals to protect human health and the environment.

[87] EPA's recommended approaches to risk management are provided in Sections 7.4 and 7.5 of this Technical Guide.

[88] For the Superfund five-year review process, OSWER Directive 9200.2-84 (EPA 2012c) provides a recommended framework for considering vapor intrusion while evaluating remedy protectiveness.

[89] On January 23, 1987, the President of the United States signed Executive Order 12580 entitled, "Superfund Implementation," which delegates to a number of Federal departments and agencies the authority and responsibility to implement certain provisions of CERCLA. The policies and procedures for implementing these provisions (e.g., carrying out response actions) are spelled out in the NCP. The provisions of Executive Order 12580 appear at 52 *Federal Register* 2923. At federal facilities on the NPL, EPA may not be the lead agency, but does have oversight responsibilities pursuant to CERCLA Section 120.

5.0 PRELIMINARY ANALYSIS OF VAPOR INTRUSION

When a site is first identified and evaluated for vapor intrusion,[90] the amount, utility, and reliability of available information may be limited. A preliminary analysis utilizes available and readily ascertainable information to develop an *initial* understanding of the potential for human health risk to be posed by vapor intrusion, which would typically be performed as part of an initial site assessment.

This section describes EPA's recommended information, approaches, and practices for conducting preliminary analyses for vapor intrusion using pre-existing and readily ascertainable information to develop an initial understanding of the vapor intrusion potential at a site. This section:

- Explains the recommended types of information that generally can be obtained when a site is first considered for vapor intrusion (see Sections 5.1, 5.3, 5.4, and 5.5).
- Identifies some of the site conditions for which prompt action is generally warranted (see Section 5.2).
- Illustrates some of the site conditions for which further evaluation of the vapor intrusion pathway might be warranted (see Sections 5.3, 5.4, and 5.5).
- Describes the recommended approaches to evaluating the reliability of pre-existing information, including any sampling data (see Sections 5.1 and 5.5).

Depending upon the nature and reliability of the available information, it may be possible to determine whether a vapor intrusion investigation (see Section 6) or a response action (see Sections 7 and 8) is warranted. If the available information is not reliable or adequate for these purposes, however, additional data collection generally is recommended.

5.1 Assemble, Evaluate, and Review Available Information

The recommended first step in a preliminary analysis generally entails assembling and reviewing relevant information that is available at the time for the site. At a minimum, EPA recommends that information about potential subsurface sources of vapors and the presence and current use(s) of nearby buildings be developed and evaluated. For some sites, such as sites being evaluated for redevelopment (EPA 2008a), information about contiguous or nearby facilities also may be relevant, because vapors can encroach from nearby facilities due to migration of contaminated groundwater or soil gas, even though vapor-forming chemicals may not have been used at the subject site.

The following recommended types of information are often available through documents (e.g., federal, state, tribal and local government records) or through interviews with individuals

[90] A site may be identified, for example, based on reports to the National Response Center, citizen complaints or inquiries, state agency referrals, or other information (e.g., site history, land use, site inspections) obtained by EPA. At a brownfield site subject to an EPA grant, subsurface contamination may be discovered as a result of pre-acquisition investigation by prospective purchasers, during site redevelopment, or at other project stages.

knowledgeable about the facility or site and surrounding area (e.g., past and present owners, operators and occupants; area residents or workers):

- History and descriptions of the types of operations and activities that occurred on or near the site and nearby properties.
- Information or records about the types of chemicals that may have been used or disposed of at the site and nearby properties or are currently used and disposed at the site.
- Information about the site and nearby properties, such as the occurrence of odors, reports of dumping liquids, observations of unreported waste disposal practices, or other indications of chemical presence and release.
- Adverse physiological effects reported by building occupants (e.g., dizziness, nausea, vomiting, confusion).
- Evidence of subsurface intrusion of groundwater (e.g., wet basements) reported by building owners or occupants.

Such information usually can be reviewed and weighed together to assess whether vapor-forming chemicals (see Section 3.1) were or are being used, stored, or handled at or near the site and were or may have been released to the subsurface environment.

In addition, the following types of information may be available through documents, interviews with individuals knowledgeable about the facility or site, or reconnaissance and site inspection:

- Locations, ownership, occupancy, and intended and actual use(s) of buildings on or near the site.
- Current and reasonably anticipated future land use on and near the site.
- Location of subsurface utility corridors.

Evaluation of such information usually can help determine whether humans are present currently or are reasonably expected to be present in the future, and who may become exposed to any intrusion of vapors from the subsurface into a building(s). Zoning, land use planning, and related information may also need to be consulted to identify reasonably anticipated future land use and building types in areas where buildings do not exist or to ascertain whether reasonably anticipated uses of existing buildings are likely to change (EPA 2010c).

EPA recommends evaluating the available data to identify any data gaps for purposes of the preliminary analysis. For example, has the history of operations and primary activities been established for the site and all contiguous properties, including currently vacant land? To the extent that there are significant data gaps, EPA recommends that additional data gathering (e.g., interviews, records review) generally be planned and conducted.

EPA also recommends evaluating the available data to assess its reliability and internal consistency. For example, if the available information about operations and activities at a specific property comes only from area residents, EPA recommends additional efforts to

identify, contact, and interview current and past owners to obtain and corroborate this information. Also, if anecdotal information about current activities at a specific property is in conflict with common knowledge about local zoning, EPA recommends that additional data gathering and evaluation be identified (e.g., contact property owner), planned, and conducted to resolve the inconsistency.

Section 5.5.1 describes additional considerations for evaluating the reliability of sampling data that may be available for some sites at the preliminary analysis stage.

5.2 Identify and Respond to Conditions that Warrant Prompt Action

The following conditions may indicate a need for prompt action, including follow-up evaluations to determine whether urgent intervention is warranted to eliminate, avoid, reduce, or otherwise address a human health hazard:

- Odors reported by occupants, particularly if described as "chemical," "solvent," or "gasoline." The presence of odors does not necessarily correspond to an unacceptable human health risk due to vapor intrusion, and the odors could be the exclusive result of indoor vapor sources; however, it is generally prudent to investigate any reports of odors as the odor threshold for some vapor-forming chemicals exceeds their respective lower explosive limit (LEL) or health-protective concentrations for short-term or acute exposure.

- Physiological effects reported by occupants (e.g., dizziness, nausea, vomiting, confusion, etc.). These effects may or may not be due to subsurface vapor intrusion (or even indoor vapor sources); however, it is generally prudent to investigate any such reports.

- Wet basements in areas where groundwater is known to contain vapor-forming chemicals (see Section 3.1) and the associated water table is shallow enough that the basements are prone to groundwater intrusion or flooding. This condition is particularly important where there is evidence of light NAPL (LNAPL) on the water table directly below the building or direct evidence of intrusion of liquid-phase contamination (i.e., liquid chemical or dissolved in water) inside the building.

EPA generally recommends testing of indoor air (see Sections 6.4.1 and 6.3.4) as soon as practical in buildings where:

- chemical odors or physiologic effects are reported and there is a credible information to suggest that a release to the subsurface environment may be a contributing factor, or

- intruding contaminated groundwater is reported and observed.

Likewise, EPA generally recommends testing of unoccupied structures for explosive gases as soon as practical where chemical odors are reported and there is a credible information to suggest that a release to the subsurface environment may be a contributing factor.

Section 7.4 provides EPA's approach and recommendations for identifying when human health risks are "unacceptable." Section 7.5.2 describes EPA's recommended approaches to identifying concentration levels indicating a potential need for prompt response action. Section

8.2.1 identifies potential response actions to reduce or avoid these threats promptly, when the results of testing reveal threats or potential threats warranting prompt response action.

EPA recommends health and safety planning for all building- or site-specific actions, as discussed further in Section 6.2, which considers expected work conditions and anticipated hazards.

5.3 Determine Presence of Structures and Vapor-forming Chemicals

For purposes of this Technical Guide and as reflected in the conceptual model of vapor intrusion (Section 2), the vapor intrusion pathway is referred to as "complete" for a specific building or collection of buildings when the following five conditions are met under current conditions:

1) A subsurface source of vapor-forming chemicals is present underneath or near the building(s) (see Sections 2.1, 6.2.1, and 6.3.1);

2) Vapors form and have a route along which to migrate (be transported) toward the building(s) (see Sections 2.2 and 6.3.2);

3) The building(s) is (or are) susceptible to soil gas entry, which means openings exist for the vapors to enter the building(s) and driving 'forces' exist to draw the vapors from the subsurface through the openings into the building(s) (see Sections 2.3 and 6.3.3);

4) One or more vapor-forming chemicals comprising the subsurface vapor source(s) is (or are) present in the indoor environment (see Sections 6.3.4 and 6.4.1); and

5) The building(s) is (or are) occupied by one or more individuals when the vapor forming chemical(s) is (or are) present indoors.

EPA recommends that site managers also evaluate whether subsurface vapor sources that remain have the potential to pose a complete vapor intrusion pathway in the future if site conditions were to change (e.g., reasonably expected occupancy or construction in the future of a building above or near a subsurface vapor source). A complete vapor intrusion pathway indicates that there is an opportunity for human exposure, which warrants further analysis (see Section 7.4) to determine whether there is a basis for undertaking a response action(s) (see Section 7.7).

At the preliminary assessment stage, the available information may not be sufficient to evaluate whether all five conditions are present under current or reasonably expected future conditions. EPA recommends, however, that readily ascertainable information be reviewed for purposes of assessing whether the first and fifth conditions are present; that is:

- A subsurface source of vapor-forming chemicals is present or is reasonably expected to be present (e.g., in contaminated groundwater, soil, or sewer lines or from a primary

vapor release).[91] Section 3.1 describes chemicals that have the potential to pose an unacceptable human health risk through the vapor intrusion pathway. In the absence of environmental sampling data, the potential presence of vapor-forming chemicals in the subsurface may be inferred from site information, as identified in Section 5.1 (e.g., site history).

- At least one building is present or is reasonably expected to be constructed in the future above or "near" the subsurface vapor source(s), which is or could be occupied by humans. For purposes of this Technical Guide and its recommendations for evaluating human health risk posed by vapor-forming chemicals, "building" refers to a structure that is intended for occupancy and use by humans. This would include, for instance, homes, offices, stores, commercial and industrial buildings, etc., but would not normally include sheds, carports, pump houses, or other structures that are not intended for human occupancy. However, where the assessment identifies the potential for methane or other potentially explosive vapors to be present in the subsurface, EPA recommends reviewing readily ascertainable information for purposes of assessing whether non-occupied structures (including, but not limited to, sewers, pits, and subsurface drains) are present, which may also accumulate vapors, in addition to occupied and non-occupied buildings. Existing buildings (and non-occupied structures) can be identified during inspections of the land areas overlying and near subsurface vapor sources. The potential presence of buildings in the future may be inferred from site information, such as identified in Section 5.1. See Section 6.2.1 for further discussion on which buildings and non-occupied structures are considered "near" for purposes of a preliminary analysis.

If the available information is deemed reliable, well documented, and sufficient (see Section 5.1) and indicates that neither of these conditions is met, then further vapor intrusion assessments are not generally warranted.[92]

Example: From 1920 to 1931, the ABC Mining Company obtained and shipped iron ore from a local deposit. Ore from the mine was shipped by rail to a different location where it was milled and processed to extract the metal. Although no company records are available for the mine, a review of mining techniques indicates that solvents and other vapor-forming chemicals were not used in the mining process during the 1920s and 1930s. Former mining structures have been removed, and the site is currently vacant. The city has proposed redeveloping the site with bike and hiking trails but no buildings or other structures for storage or site maintenance support. Based on the information and

[91] As noted in Section 2.1, the primary contamination source need not be on the property of interest to pose a vapor intrusion problem. The primary source(s) of vapor-forming chemicals (e.g., contaminated soil, leaking tanks) may be present on a neighboring property or on a property some distance away. Even "greenspace" properties that have not previously been occupied or developed may contain subsurface contamination by vapor-forming chemicals due to migrating plumes of contaminated groundwater or migrating soil gases. Therefore, EPA recommends that the potential for vapor intrusion be considered at all properties being considered for redevelopment (EPA 2008a) or proximate to industrial and commercial use areas.

[92] Consistent with federal environmental protection statutes, regulations, and OSWER guidance, a subsurface investigation may still be warranted for non-volatile substances or for other potential exposure pathways such as those identified in Section 1.3.

findings, the need for further assessment of the vapor intrusion pathway due to mining-related contamination is not indicated.

If, on the other hand, there is reliable evidence to indicate that a release of vapor-forming chemicals to the subsurface has occurred (e.g., environmental sampling data indicate detectable levels of a vapor-forming chemical(s) in potential source media)[93] or may have occurred underneath or near a property, then EPA recommends further vapor intrusion assessment in areas where buildings are present or future buildings could be constructed, including development of a conceptual site model (see Section 5.4) and investigation of site-specific conditions (see Section 6).

Example: The XYZ Recycling Center site was used from 1963 to 1984 for the collection and recycling of industrial solvents and other fluids. The site was repeatedly cited by the state and city for improper handling and disposal of solvents, and was closed in 1985. Groundwater data indicate the presence of multiple chlorinated hydrocarbons. Buildings overlying the contaminated groundwater are currently used mainly for storage of non-chemical goods, but the site has been proposed for future residential or commercial redevelopment. Based on the foregoing information and findings, further assessment of the potential for vapor intrusion is warranted, possibly including risk-based screening of the groundwater data (see Section 6.5).

If a release of vapor-forming chemicals to the subsurface is known or suspected to have occurred at or near the site, but buildings are not present and none are reasonably anticipated in the future (e.g., the contaminated source underlies an open space, recreational area, or wildlife refuge), then further vapor intrusion assessments may not be appropriate under current conditions. It may be appropriate, however, to establish an institutional control (IC) requiring a vapor intrusion investigation or building mitigation[94] in the future, in case land use changes. ICs for building mitigation and subsurface vapor source remediation are discussed further in Sections 3.3 and 8.6 of this Technical Guide.

Existing guidance and practice pursuant to CERCLA and RCRA corrective action (CA) recognize and entail various phases of subsurface or site characterization, including a site investigation to determine the full nature and extent of contamination at a site, quantify risks posed to human health and the environment, and gather information to support the selection and implementation of appropriate remedies. On this basis, a subsurface investigation may be warranted at some point to characterize subsurface contamination and assess the need for subsurface remediation to protect the environment and human health for potential exposure pathways other than vapor intrusion (such as those identified in Section 1.3). For example, site investigations to characterize the nature and extent of groundwater contamination and support assessments of risk to human health through the ingestion pathway are typically conducted, consistent with federal statutes and regulations (e.g., CERCLA and RCRA) and considering EPA guidance.

[93] Section 6.5 provides information on how such data may be used in a quantitative fashion to screen the site further.

[94] If, for example, a developer is considering acquiring and building on land that contains subsurface contamination with vapor-forming chemicals, the developer could retrofit existing buildings or build new buildings with vapor mitigation systems without first conducting an extensive vapor intrusion investigation (see Sections 3.3 and 7.8). Section 8.2.3 identifies additional approaches and considerations for new buildings.

5.4 Develop Initial Conceptual Site Model

EPA recommends that the planning and data review team develop an initial conceptual site model (CSM) for vapor intrusion when the preliminary analysis indicates the presence of subsurface contamination with vapor-forming chemicals underlying or near buildings. The initial CSM (and any subsequent refined CSM) can be used to support evaluations of the adequacy of the available site-specific information, to guide any vapor intrusion investigations (see Sections 6.2 and 6.3), and to support data selection for risk-based screening (see Section 6.5). The CSM can also provide useful information for supporting prompt development of a strategy for early/interim response actions (see Sections 7.8 and 8.2).

The remainder of this section discusses recommended information that can be useful for developing a CSM. Note that some of the recommended information may not be readily available when a site is first considered for vapor intrusion. Although the CSM may be updated iteratively (and interim mitigation measures may be undertaken) as the vapor intrusion investigation unfolds, EPA recommends completing the CSM before making final risk management decisions for a given site (see Section 7).

As discussed in Section 5.3, the available information may not be sufficient at the preliminary analysis stage to evaluate whether the vapor intrusion pathway is complete under current or future conditions. Therefore, the initial CSM for vapor intrusion is likely to be incomplete. EPA recommends, however, that the initial CSM for vapor intrusion portray the current understanding of site-specific conditions pertaining to the vapor intrusion pathway. Ideally, at a minimum, the initial CSM will address:

- Nature (i.e., type, chemical composition), location, and spatial extent of the source(s) of vapor-forming chemicals in the subsurface (see Sections 2.1 and 6.3.1, for example). For example, it is useful to know which vapor-forming chemical(s) primarily comprise the subsurface vapor source[95] and whether it is also capable of posing explosion hazards. It is also useful to know whether vapor-forming chemicals are present in groundwater, vadose zone soils, sewer lines, and/or some other source underneath or near buildings.

- Location, use, occupancy, and basic construction (e.g., foundation type) of existing buildings.

The CSM can be updated as additional information is obtained through investigation (Section 6) and building surveys (Section 6.4.1).

EPA recommends the CSM also portray the current understanding of the hydrologic and geologic setting in and around the subsurface vapor source(s) and the buildings, which is expected to influence vapor migration and attenuation in the vadose zone (see Sections 2.2 and 6.3.2, for example). When these conditions are not well established from existing information, and the preliminary analysis indicates the presence of subsurface contamination with vapor-

[95] EPA also recommends that the CSM identify any site-specific chemicals of concern that may be biodegradable and identify and summarize information and data pertaining to the possible role of biodegradation *in situ* in limiting vapor migration in the vadose zone (see Section 6.3.2) or generating hazardous, volatile degradation products (e.g., methane from anaerobic biodegradation, vinyl chloride as a byproduct of PCE or TCE biodegradation).

forming chemicals underlying or near buildings, EPA recommends that a detailed vapor intrusion investigation be scoped and conducted to address these data gaps (see Section 6.3).

Furthermore, EPA recommends the CSM identify known or suspected preferential migration routes that could facilitate vapor migration to greater distances and at higher concentrations than otherwise expected. EPA recommends that buildings with significant preferential migration routes be evaluated closely. For the purposes of this Technical Guide, a preferential migration route is a naturally occurring subsurface feature or anthropogenic (human-made) subsurface conduit that is expected to exhibit little resistance to vapor flow in the vadose zone (i.e., exhibits a relatively high gas permeability) or groundwater flow (i.e., exhibits a relatively high hydraulic conductivity), depending upon its location and orientation relative to the water table and ground surface, thereby facilitating the migration of vapor-forming chemicals in the subsurface and/or into buildings.[96] Naturally occurring examples include fractures and macropores, which may facilitate a preferential route for either the vertical or horizontal migration of source materials and/or vapors. Anthropogenic examples include sewer lines and manholes,[97] utility vaults and corridors, elevator shafts, subsurface drains, permeable fill, and underground mine workings that intersect subsurface vapor sources or vapor migration routes. In highly developed residential areas, extensive networks of subsurface utility corridors may be present, which can significantly influence the migration of contaminants. A preferential migration route can be a "significant" influence on vapor intrusion when it is of sufficient volume and proximity to a building that it may be reasonably anticipated to influence vapor migration towards or vapor intrusion into the building. Significant vertical routes of preferential migration may result in higher than anticipated concentrations in the overlying near-surface soils, whereas significant horizontal routes of preferential migration may result in elevated concentrations in areas on the periphery of subsurface contamination (see Section 6.2.1).

CSMs for vapor intrusion assessments often need to consider two distinct exposure situations:

1) At some sites and contaminated locations, there are concerns as to whether vapor intrusion may pose a human health risk to current occupants of an existing building(s). For this situation, EPA recommends that building-specific information be available to support the CSM, which may be obtained through a building survey (see Section 6.4.1, for example) .

2) At other sites and contaminated locations, buildings are not present, but are expected to be constructed, and building-specific information may not be available to support the CSM. For this situation, the CSM may need to consider a hypothetical building constructed anywhere over (or near) the subsurface vapor source.

[96] For purposes of this Technical Guide, preferential migration routes are distinguished from adventitious and intentional openings in a building that may also facilitate vapor entry from the subsurface (see Section 2.3), but which are expected to typically be present in all buildings (e.g., cracks, seams, interstices, and gaps in basement floors and walls or foundations; perforations due to utility conduits).

[97] In addition to receiving direct discharges of aqueous and chemical wastes from commercial and industrial operations, sewers can be indirect receptacles of subsurface contamination via infiltration of NAPL, soil gas, or contaminated groundwater through cracks in piping and manholes (see Section 2 of this Technical Guide, for example, for further discussion).

In general, CSMs identify the potentially exposed populations, potential exposure routes, and potential adverse health effects (i.e., toxicity) arising from these exposures. As such, EPA recommends the CSM also identify and consider sensitive populations, including but not limited to:

- Elderly,
- Women of child-bearing age,
- Infants and children,
- People suffering from chronic illness, or
- Disadvantaged populations (i.e., an environmental justice situation).

By definition and as noted in Section 2, the exposure route of general interest for vapor intrusion is inhalation of vapors in indoor air and the human population of primary interest is comprised of individuals living or working in or otherwise occupying a building subject to vapor intrusion. However, EPA also recommends that the CSM identify any site-specific chemicals of concern that have potential for explosion hazards (e.g., methane) or for posing other routes of exposure (e.g., dermal exposure to shallow contaminated groundwater seeping into a basement).

EPA recommends that the CSM also identify and characterize suspected sources of site-related, vapor-forming chemicals that are also found in ambient air in the site vicinity. In some situations, site-related contamination has the potential to impact ambient air with the same vapor-forming chemicals that pose a threat from vapor intrusion. For example, contamination of shallow soil or groundwater may release site-related vapor-forming chemicals to ambient air. EPA recommends the CSM identify any such conditions, which have implications for the scope and objectives of the overall site investigation, as well as for data evaluation and the human health risk assessment.

To document current site conditions, EPA recommends that a CSM be supported by maps, cross sections, and site diagrams, to the extent practical, and that the narrative description clearly distinguish what aspects are known or determined and what assumptions have been made in its development.

EPA generally recommends that developing a CSM be incorporated into the first step in EPA's data quality objective (DQO) process (EPA 2006a). It is rare for a site to have readily available sources of sufficient information to develop a complete CSM when the vapor intrusion potential is first considered. For example, a detailed site-specific investigation may be necessary to characterize the full extent of subsurface vapor sources and geologic conditions underlying nearby buildings (see Sections 6.3.1 and 6.3.2) and to demonstrate the absence of preferential routes for vapor migration and intrusion. The CSM normally warrants updating as new information is developed and new questions are framed and answered. A well-defined, detailed CSM may also facilitate the identification of additional data needs and development of appropriate detection limits for laboratory and field analyses, which can support planning of the detailed vapor intrusion investigation (see Section 6.2) and site-specific human health risk assessment, if any (see Section 7.4). Sections 6.3, 6.4, 7.1, and 7.2 provide additional information about data collection and evaluation for purposes of supporting the CSM.

5.5 Evaluating Pre-Existing and Readily Ascertainable Sampling Data

Sites and adjacent facilities that have been the subject of previous environmental investigations or regulatory actions may already have data on contaminant concentrations in site media (i.e., sampling data) when the vapor intrusion pathway is first considered and evaluated. Some of these sites and facilities may be undergoing remediation but warrant a vapor intrusion assessment as a result, for example, of changing toxicity information for vapor-forming chemicals, as part of a periodic review of remediation effectiveness and protectiveness (if any), or for other reasons.

If the pre-existing environmental data are deemed reliable and other conditions are met (as described in the remainder of this subsection and in Section 6.5.2), the sampling data may be compared to recommended generic vapor intrusion screening criteria (see Section 6.5) for purposes of developing some preliminary insights about the potential level of exposure and risk posed by vapor intrusion. Such a screening can, for example, help focus a subsequent vapor intrusion investigation (see Section 6) or provide support for considering building mitigation as an early action (see Section 7.8.2), depending upon building- and site-specific circumstances. Note that some of the site-specific information generally recommended for supporting a risk-based screening (see Section 6.5.2) may not be available when a site is first considered for vapor intrusion.

5.5.1 Evaluate Sampling Data Reliability and Quality

To the extent that environmental sampling data are identified for the site or nearby properties, EPA recommends that these data be evaluated to determine whether they are of sufficient quality and reliability to support a comparison to recommended generic vapor intrusion screening criteria (see Section 6.5). Some questions that could be considered when reviewing historical sampling data include:

- How were the samples collected and analyzed? EPA recommends using pre-existing data when they have been collected and analyzed by methods considered reliable by today's standards.

- How old are the data? Were analyses conducted for all vapor-forming chemicals known or suspected to be present and reasonably expected degradation products? EPA recommends using pre-existing data when they can be considered representative of current conditions.

- Were the reporting limits sufficiently low for comparison with vapor intrusion screening criteria? EPA recommends use of pre-existing data with non-detect results only when they can be considered reliable on this basis.

- Were multiple locations sampled to assess spatial variability of the results? Were multiple sampling events conducted to assess temporal variability of the results? EPA recommends characterizing spatial and temporal variability to increase confidence in

data evaluation and decision-making and ensure consideration of a reasonable maximum vapor intrusion condition.[98]

EPA also recommends that the reliability of any historical sampling data be assessed by considering the principles for collecting subsurface and indoor air samples that are described in Sections 6.3.1 and 6.4 of this Technical Guide. In addition, the EPA's *Guidance for Data Usability in Risk Assessment, Part A* (EPA 1992a) outlines a recommended approach for evaluating whether the data are useable for the human health risk assessment. As such, its recommended approach is also worthwhile and complementary for evaluating the quality and usefulness of historical data collected at a site.

5.5.2 Evaluate Applicability of the VISLs and Adequacy of the Initial CSM

Before performing any comparison of existing sampling data to recommended generic vapor intrusion screening levels (VISLs) (see Section 6.5), it is important to verify that site-specific conditions reflect the conditions and assumptions of the generic model underlying the VISLs, which are summarized in Section 6.5.2. To verify that the generic vapor intrusion model applies, there is a need for basic knowledge of the subsurface source of vapors (e.g., location, form, and extent of site-specific vapor-forming chemicals) and subsurface conditions (e.g., soil type in the vadose zone, depth to groundwater for groundwater sources), which are important elements of the CSM (see Section 5.4). When these subsurface data are not available, EPA recommends they be collected (i.e., initiate a vapor intrusion investigation; see Section 6.3.2, for example) before relying upon risk-based screening using pre-existing sampling data.

5.5.3 Preliminary Risk-based Screening

If reliable pre-existing sampling data are available and an adequate CSM has been developed (i.e., sufficient subsurface characterization information exists to adequately characterize the locations, forms, and extent of site-specific vapor-forming chemicals and general subsurface conditions (e.g., hydrologic and geologic setting in and around the source(s) and the buildings)), then a risk-based screening may be useful to obtain some preliminary insights about the potential level of exposure and risk posed by vapor intrusion.

Example: A prospective developer of a vacant lot with no history of onsite chemical use is interested in evaluating the potential for vapor intrusion in the future due to potential migration onto the lot of a plume of contaminated groundwater emanating from another property. The extent and nature of this off-property plume have been adequately and recently characterized and geologic conditions near (but not on) the lot have been characterized, as documented in a publicly available report(s). In this circumstance, it may be possible to support a preliminary screening and obtain some useful insights. For example, if the maximum concentration of each chemical of concern in the off-property plume of contaminated groundwater currently and in the future is less than the generic chemical-specific screening level for groundwater, then vapor intrusion may not be a future

[98] EPA recommends basing the decision about whether to undertake response action for vapor intrusion (i.e., a component of risk management; see Section 7.4) on a consideration of a reasonable maximum exposure (e.g., EPA 1989, 1991a), which is intended to be a semi-quantitative phrase, referring to the lower portion of the high end of the exposure distribution (see Glossary).

concern on the vacant lot, provided there are sufficient data to document that conditions on the vacant lot are consistent with the generic model behind the vapor intrusion screening levels, as described in Section 6.5.2.

Depending upon lot-specific circumstances, additional data collection or evaluation, possibly including on-lot site characterization, may be warranted (i.e., proceed to a detailed vapor intrusion investigation) to verify that the expected conditions hold true (e.g., hydrogeologic conditions on the vacant lot are consistent with the generic model behind the vapor intrusion screening levels). EPA generally also recommends consideration of the vapor intrusion pathway during the development planning or initial post-construction stage (e.g., pre-emptive mitigation – Sections 3.3 and 7.8; mathematical modeling, where parameters are chosen to represent conditions that give a high-impact case – Section 6.6; indoor air testing – Section 6.4.1 -- to confirm the screening results based upon the groundwater source data) before making final risk management decisions.

This example reinforces the following general recommended guidelines:

- EPA generally recommends that site-specific data be collected and evaluated to verify that the subject property reflects the conditions and assumptions of the generic model underlying the VISLs (see Section 6.5.2).

- EPA generally recommends that multiple lines of evidence (e.g., hydrogeologic information in addition to sampling data) be collected and weighed together in supporting assessments of the vapor intrusion pathway (see Sections 7.1, 7.2, and 7.3 for further information).

- Multiple rounds of groundwater (or soil gas) sampling results can be useful in supporting conclusions that a specific vapor source is stable or shrinking and/or is not expected to pose a vapor intrusion concern (see Sections 6.3.1 and 6.4.5) under reasonably expected future, as well as current, conditions.

Similar recommended guidelines may be appropriate in situations where vapor intrusion potential is being evaluated as part of a periodic review of an existing remedy (prompted, for example, by recent construction of a new building over a contaminated plume that is undergoing remediation) (EPA 2002b, 2012c).

6.0 DETAILED INVESTIGATION OF VAPOR INTRUSION

EPA recommends that the planning and data review team plan and conduct a site investigation for vapor intrusion when the preliminary analysis (Section 5.3) indicates the presence of subsurface contamination with vapor-forming chemicals underlying or near buildings.

This section describes EPA's generally recommended approaches and practices for conducting detailed vapor intrusion investigations, which typically entail collecting and weighing multiple lines of evidence to characterize the vapor intrusion pathway. Specifically, this section:

- Identifies that a wide variety of scenarios may be encountered among sites investigated for potential vapor intrusion, which necessitates site-specific approaches to scoping investigations and sequencing investigation phases and objectives (Section 6.1);
- Provides EPA's recommendations for planning, scoping, and conducting vapor intrusion investigations (Sections 6.2, 6.3, and 6.4);
- Presents EPA's recommended screening levels for vapor intrusion and describes EPA's recommended uses of risk-based screening and suggested interpretation of the results (Section 6.5); and
- Provides recommendations for developing and using mathematical models in vapor intrusion assessments (Section 6.6).

Section 7 describes EPA's generally recommended approaches and practices for determining, on the basis of the investigation results, whether the vapor intrusion pathway poses a potential human health risk to building occupants under current and reasonably expected future conditions and whether response actions are warranted for vapor intrusion mitigation at individual facilities, buildings, or sites.

6.1 Common Vapor Intrusion Scenarios

Vapor intrusion scenarios can be quite varied, owing to the possible combinations of:

- Multiple hazardous chemicals that can form vapors.
- Multiple forms in which these chemicals may be released to or present as contaminants in the subsurface, for example:
    - Residual NAPL and adsorbed-phase chemicals, including LNAPLs that are less dense than water and DNAPLs that are denser than water.
    - Dissolved-phase chemicals in groundwater or soil moisture.
    - Primary vapor releases (e.g., from chemical vapor transmission lines).
- The variety of geologic and hydrologic characteristics and conditions in the subsurface environment in which this contamination may occur.

- The variety of buildings (in terms of size, age, condition, and use) and current or expected land use settings (e.g., residential, commercial, industrial) that may be subject to vapor intrusion from such subsurface contamination.

- Circumstances under which subsurface contamination is found or suspected and investigated (e.g., brownfield redevelopment, citizen reports/complaints, reported release)

- The variety of sources that may contribute to vapor concentrations in ambient air and may serve as indoor vapor sources unrelated to vapor intrusion.

A few of the possible scenarios are illustrated in Figure 2-1. Many more can be inferred from the conceptual model of vapor intrusion discussed in Section 2. Some of the common scenarios where vapor intrusion has been documented to occur include:

- Groundwater contaminant plumes in shallow aquifers underlying residential and nonresidential buildings. Many well-known vapor intrusion sites are in this category, in part because there is generally a greater opportunity to have multiple buildings overlying the vapor source. Specific sites and buildings normally can be prioritized and distinguished based upon their potential for vapor intrusion, which generally would depend upon a number of site-specific factors, such as:

    - strength, proximity, and extent of the vapor source emanating from shallow groundwater (see Sections 2.1 and 5.4);

    - the potential for significant attenuation of vapor migration due to geologic, hydrologic, or biochemical conditions in the vadose zone (see Sections 2.2 and 5.4);

    - the potential for significant attenuation of the contaminant plume due to geologic, hydrologic, or biochemical conditions in the saturated zone; and

    - type(s), characteristics and structural condition of the overlying building(s) (see Sections 2.3, 2.4, and 5.4).

- Soil contamination in the vadose zone underlying commercial or industrial buildings. Typically, one or a few buildings may be threatened by potential vapor intrusion. Specific buildings and sites normally can be prioritized and distinguished based upon their potential for vapor intrusion, which generally would depend upon a number of site-specific factors, such as:

    - strength, proximity, and extent of the vadose zone source (see Sections 2.1 and 5.4);

    - the potential for attenuation of vapor migration due to geologic, hydrologic, or biochemical conditions in the vadose zone (see Sections 2.2 and 5.4); and

    - type(s), characteristics and structural condition of the overlying building(s) (see Sections 2.3, 2.4, and 5.4).

- Sites with residual wastes (e.g., landfills, former manufactured gas plants, former oil production fields) underlying or near buildings. The potential for methane formation may more frequently warrant additional consideration for sites with residual wastes than for contaminated groundwater plumes.

EPA's recommended approaches and practices for vapor intrusion investigations aim to be flexible and adaptable to a wide range of reasonably expected scenarios and are not intended to be prescriptive or exhaustive for any specific scenario.

6.2 Planning and Scoping

Before information or data are collected, EPA generally recommends conducting systematic and thorough planning during which performance or acceptance criteria are developed for the collection, evaluation, or use of these data (EPA 2006a).[99] EPA recommends the data quality objective (DQO) process as the appropriate systematic planning process for its decision-making and has issued guidance for its application to hazardous waste site investigations pursuant to CERCLA and RCRA (EPA 2000a).[100] When appropriately conducted, planning provides greater assurance that the data collected will fulfill specific project needs and that mitigation and subsurface remediation options will be considered early in the process.[101] A clear and logical plan will often facilitate communication with building owners, occupants, and other stakeholders.

Given these considerations, a thorough planning process, guided by a CSM, is usually advisable for detailed vapor intrusion investigations. Figure 6-1 provides a diagram to illustrate such planning and scoping. The initial stages of planning would typically entail gathering readily available existing information and formulating an initial CSM, as described in Section 5.4. The CSM portrays the current understanding of site-specific conditions, including the nature and extent of contamination, contaminant fate and transport routes, potential "receptors" and contaminant exposure pathways. The term "conceptual" merely reflects that the model need not be entirely quantitative and mathematical; it does not, however, denote a simplistic or incomplete understanding of site conditions. The CSM normally warrants updating as new information is developed and new investigatory questions are framed and answered.

Subsequent to formulating an initial CSM based on readily available information, the scope for an initial phase of vapor intrusion investigation would be developed, preferably along with a logical plan for future directions in response to the reasonably expected outcomes of the initial investigatory phases and in coordination with the objectives and phasing of the broader site

[99] In situations where imminent threats (see Section 5.2) are known or reasonably expected, the initial planning process may be more truncated and focused, but careful and thoughtful planning is still recommended.

[100] Appendix B provides additional information about EPA's quality system and DQO process.

[101] *Science and Decisions: Advancing Risk Assessment* was prepared by the National Academy of Sciences (NAS) Committee on Improving Risk Analysis Approaches Used by the U.S. EPA (NRC 2009) and is commonly referred to as the "Silver Book." Among other recommendations, the NAS Committee encouraged EPA to focus greater attention on design in the formative stages of risk assessment, specifically on planning and scoping and problem formulation, and to view risk assessments as a method for evaluating the relative merits of various options for managing risk, rather than as an end in itself. Consistent with these recommendations, plausible mitigation and subsurface remediation options (see Section 8) may warrant consideration during development of vapor intrusion investigation plans.

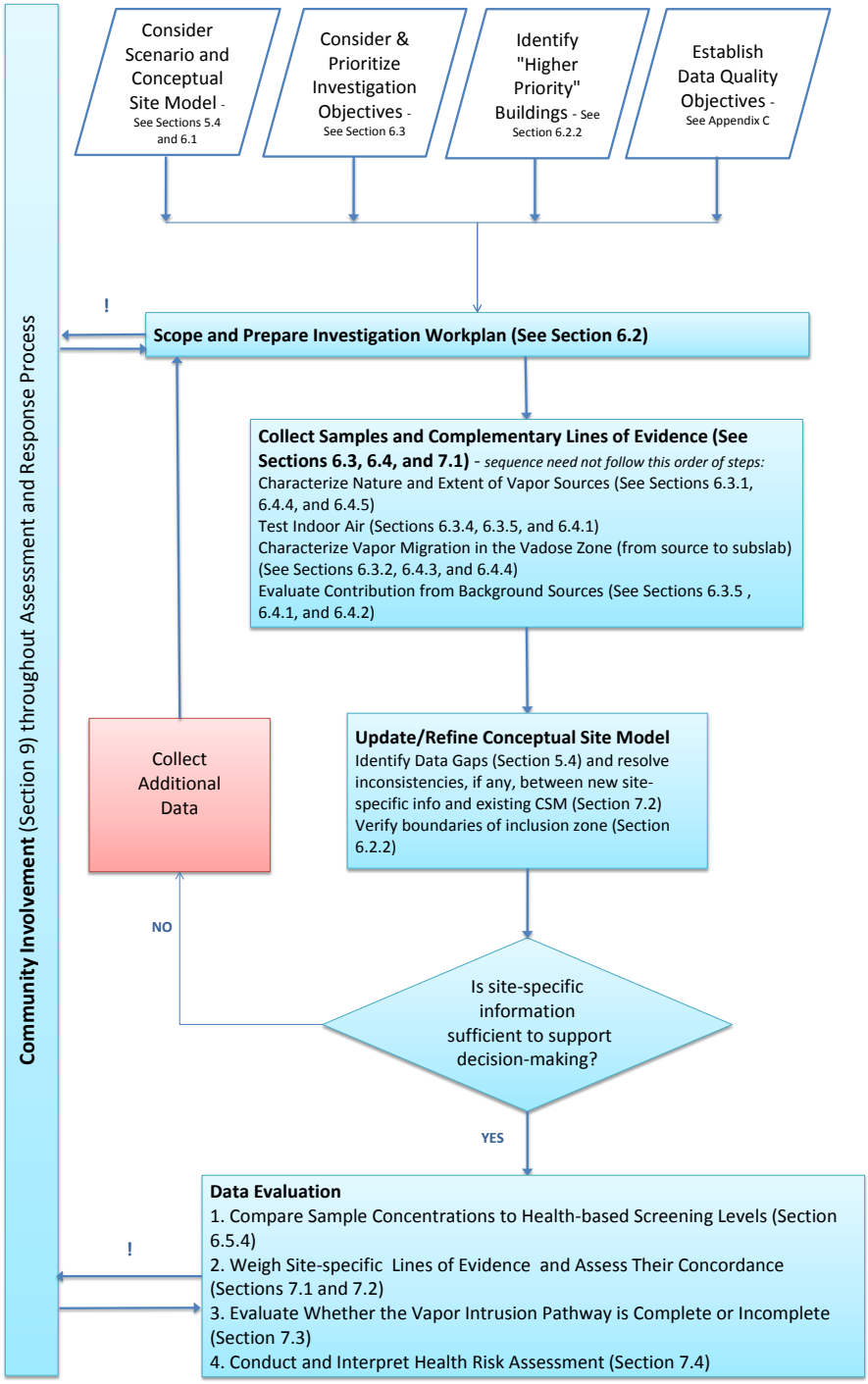

Figure 6-1 Overview of Planning, Scoping, and Conducting Vapor Intrusion Investigations

characterization. Initial plans may warrant periodic updates and refinements, particularly when data outcomes are unexpected and prompt the need to reevaluate the CSM. In each case, EPA recommends that the investigation work plan include the identification of and basis for the indoor air screening levels (such as the vapor intrusion screening levels (VISLs)) and/or indoor air action levels (i.e., level of each vapor-forming chemical of potential concern that would trigger a response action if exceeded), which would dictate the DQOs for the sampling and analysis methods. In general, EPA recommends the plan also include a rationale or logic for where and how the data will be collected and over what duration(s), how the data will be interpreted (e.g., weighed with other lines of evidence, compared to risk-based benchmarks), whether confirmatory sampling will be needed if all sample concentrations are less than the action levels, whether response action(s) would be triggered if sample concentrations exceed the target levels, and similar considerations. EPA recommends considering potential health effects and relevant exposure periods (e.g., chronic versus short-term effects and exposure durations and scenarios; see Section 7.4) for site-related, vapor-forming chemicals when developing DQOs and sampling plans for indoor air (see Section 6.4.1, for example). Sections 6.3 through 6.6 below provide additional information for planning and scoping site-specific investigations for vapor intrusion assessment.

EPA's fundamental approach to evaluating contaminated sites calls for proceeding in a stepwise fashion with early data collection efforts usually limited to developing a basic understanding of the site, as reflected in the CSM.[102] Subsequent data collection efforts focus on filling gaps in the understanding of the CSM and gathering information necessary to evaluate the relative merits of various options for managing risk. Therefore, EPA generally recommends developing and implementing an overall vapor intrusion investigation plan in multiple stages or phases. Such a phased approach encourages the identification of key data needs early in the process to better ensure that data collection provides information relevant to decision-making (e.g., interim action to mitigate vapor intrusion and selection of a cleanup plan for subsurface contamination). In this way, the overall site characterization effort can be scoped to prioritize data collection and minimize the collection of unnecessary data and maximize data quality.

EPA recommends that the objectives and methods of the investigation be documented, preferably in a vapor intrusion work plan. An individual work plan may address a single phase or stage or may address the overall investigation. The vapor intrusion work plan(s) may be

[102] Investigations under CERCLA and RCRA corrective action (CA) explicitly recognize phasing. In these cleanup programs, the first investigatory phase is an *initial site assessment.* The purpose of this activity is to gather information on site conditions (current and historical), releases, potential releases, and exposure pathways. Investigators use this information to determine whether a response action (e.g., removal action or interim cleanup measure) may be needed or to identify areas of concern for further study. Information collected during this phase usually forms the basis for determining whether the next stage, site investigation, is warranted. In the RCRA CA program, the initial site assessment is called the RCRA facility assessment. Under CERCLA, this phase is called the preliminary assessment/site inspection. The purpose of the second phase, site investigation, is to determine the nature and extent of contamination at a site, quantify risks posed to human health and the environment, and gather information to support the selection and implementation of appropriate remedies. In the RCRA CA program, this phase is known as the RCRA facility investigation. Under the CERCLA remedial program, this phase is referred to as the remedial investigation. In addition, the site investigation may itself be conducted in multiple stages (or phases).

incorporated as part of a comprehensive site investigation work plan or as a stand-alone document, depending upon site-specific circumstances.[103]

At a minimum, EPA recommends that the components of the work plan(s) include or reference:

- Narrative description of the rationale, objective(s), and scope of the investigation.
- Summary of the CSM, based upon the current understanding of site conditions.
- Scaled map(s) illustrating known extent of subsurface contamination and readily identifiable landmarks (e.g., streets and buildings).
- Media to be sampled.
- Number, type, and location of and rationale for proposed sampling locations.
- Sampling methods and procedures for each medium.
- Analytic method(s) to be used to obtain chemical concentrations and a statement about whether a stationary or mobile laboratory will be used.
- Standard operating procedures of the laboratory and for field instruments.
- Quality assurance project plan (QAPP).
- Health and safety plan.[104]

EPA recommends that planning for vapor intrusion investigations also consider site and building access agreements, equipment security, and locations of underground utilities.

EPA recommends that the planning, data collection, and data review team(s) for vapor intrusion investigations generally include:

- Individuals with expertise in characterizing subsurface environmental conditions and interpreting and communicating environmental data.
- On-site (field) personnel with appropriate training and experience in hazard identification, workplace practices to foster health and safety, and recommended sampling protocols.

[103] EPA recommends that monitoring programs (see Section 8.4) that assess the performance and effectiveness of remediation and mitigation systems (see Sections 8.1 and 8.2, respectively) also be documented, preferably in work plans similar to those recommended herein for characterizing and assessing the vapor intrusion pathway.

[104] All governmental agencies and private employers are directly responsible for the health and safety of their employees. This general rule applies to many parties involved in the assessment and cleanup of Superfund sites, RCRA corrective action sites, and brownfield redevelopment sites. Standards established pursuant to the Occupational Safety and Health Act are found in Title 29 of the Code of Federal Regulations (29 CFR), which include standards for training, hazard communication, and site-specific health and safety plans.

- Individuals with expertise in human health risk assessment to characterize risks posed by the vapor intrusion pathway.

- Individuals with expertise in community involvement and outreach.

Depending upon the complexity of the CSM (see Section 5.4) and site-specific data evaluations, decision-makers may also find valuable input from individuals with expertise in hydrogeology, inferential statistics, laboratory analysis methods, and building construction, ventilation, and operations and individuals knowledgeable about land use planning, zoning, and land development.

EPA recommends that the scope of investigations within buildings and on individual properties be contemplated, planned, and implemented with the goal of limiting, to the extent practical, return visits, which can cause disruption and inconvenience for building occupants and owners. For example, it may be preferable to collect a comprehensive set of data (e.g., indoor air, sub-slab soil gas, and ambient air samples; pressure readings; see Section 6.4) and confirm information about building occupancy, building usage, heating, cooling, and ventilation (see Section 6.4.1) in a single mobilization, rather than over separate visits, when the investigation objectives include indoor air sampling (see Section 6.3.4) or evaluating contributions of 'background' sources on levels of vapor-forming chemicals in indoor air (see Section 6.3.5).

6.2.1 Vapor Intrusion Inclusion Zones

Soil gas concentrations generally decrease with increasing distance from a subsurface vapor source, and eventually at some distance the concentrations become negligible. The distance at which soil gas concentrations become negligible is a function of the strength and dimensions of the vapor source, the type of vapor source, the soil types and layering in the vadose zone, the presence of physical barriers (e.g., asphalt covers or ice) at the ground surface, and the presence of preferential migration routes, among other factors (see, for example, EPA 2012b). The extent of the site-specific "inclusion zone" for vapor intrusion may also expand in the future, depending upon:

- The age of the chemical release and whether sufficient time has elapsed to allow soil gas to migrate from the source to its maximum potential extent.[105]

- Whether the subsurface vapor source is expanding (i.e., is migrating) or rising in concentration, including hazardous byproducts of any biodegradation.

Because these factors vary among sites, the distance beyond which structures will not be affected by vapor intrusion should be a site-specific determination.

Recommended Distance for Initial Evaluation. There are limited published empirical data relating observed indoor air concentrations of subsurface contaminants to distance from a well-

[105] EPA (2012b, Section 6.1) presents some information about transient vapor migration after a subsurface vapor source is released. Sites with shallow vapor sources (e.g., less than one meter deep) may take only a few hours to a few days for soil gas to migrate to its maximum potential extent. Sites with deeper vapor sources (e.g., greater than 10 meters deep) may take months or years for soil gas to migrate to its maximum potential extent.

defined source boundary. However, a buffer zone of approximately 100 feet (laterally or vertically from the "boundary" of subsurface vapor concentrations of potential concern) generally has been used in determining which buildings to include in vapor intrusion investigations (i.e., which buildings are 'near' a subsurface vapor source for purposes of a preliminary analysis) when significant surface covers are not present, under the assumption that preferential vapor migration routes are absent.[106] Specifically, a buffer zone of 100 feet (or approximately two houses wide) has been suggested by several states for initial evaluation and is supported, in general, by:

- theoretical analyses that assume the absence of a preferential vapor migration route(s) and that diffusion is the predominant mechanism of vapor migration in the vadose zone (Lowell and Eklund 2004); and

- reports that vapor intrusion impacts generally have not been observed "at distances greater than one or two houses beyond the estimated extent of the groundwater plume", at sites where contaminated groundwater is the subsurface vapor source (Folkes et al. 2009).

However, we would note that vapor source types for which use of a 100-foot buffer would typically be inappropriate include:

- Landfills where methane is generated in sufficient quantities to induce advective transport in the vadose zone.[107]

- Commercial or industrial settings where a vapor-forming chemical(s) has been released within an enclosed space at a density that may result in significant advective transport of the vapor(s) downward through cracks or openings in floors and into the vadose zone.

- Leaking vapors from pressurized gas transmission lines.

In each of these cases, the diffusive transport of vapors may be overridden by advective transport and the vapors may be transported in the vadose zone several hundred feet from the source of contamination.[108]

Moreover, we would also note that anecdotal evidence indicates that in some settings buildings greater than 100 feet from a plume "boundary" are affected by vapor intrusion, even when

[106] Preferential migration routes are defined and discussed in Section 5.4. When present, they may facilitate subsurface vapor migration over distances greater than 100 feet.

[107] EPA has also published *Guidance for Evaluating Landfill Gas Emissions from Closed or Abandoned Facilities* (EPA 2005), which provides procedures and a set of tools for evaluating landfill gas emissions to ambient air and soil gas migration due to pressure gradients.

[108] For example, Little et al (1992) describe a landfill in southern California, where methane was detected in enclosed spaces in nearby homes at concentrations approaching 1% by volume and chlorinated hydrocarbons had migrated into a house 180 meters from the landfill.

diffusion is the presumed mechanism of vapor migration.[109] Furthermore, the presence of conduits (e.g., sewer and drain lines that intercept and carry subsurface contamination (Vroblesky et al. 2011), as well as permeable bedding for sewer lines or other utilities) or preferential hydrogeologic pathways that facilitate unattenuated vapor migration in the vadose zone, and other factors (e.g., presence of extensive surface covers, uncertainties in delineating the boundaries) may extend the recommended inclusion distance for a vapor intrusion investigation. For these reasons, EPA recommends investigating soil vapor migration distance on a site-specific basis. That is, larger or smaller distances may need to be considered when developing objectives for detailed vapor intrusion investigations and interpreting the resulting data. Data from sub-slab and exterior soil gas sampling (see, for example, Sections 6.4.3, and 6.4.4, respectively)[110] and indoor air testing (see, for example, Sections 6.3.4 and 6.4.1) can be collected and evaluated to delineate or confirm areas at specific sites within which buildings are potentially subject to vapor intrusion.

Criteria for Establishing "Boundaries" of the Plumes that Contain Vapor-forming Chemicals. This Technical Guide is intended to be applied to existing groundwater plumes as they are currently defined (e.g., Maximum Contaminant Levels, state standards, or risk-based concentrations). However, it is important to recognize that some non-potable aquifers may have plumes that have been defined by threshold concentrations significantly higher than drinking-water concentrations. In these cases, contamination that is not technically considered part of the plume may still have the potential to pose unacceptable human health risk via the vapor intrusion pathway. Consequently, the plume definition may need to be expanded for purposes of defining an inclusion zone for a vapor intrusion investigation. When groundwater is the subsurface vapor source, EPA generally recommends comparing groundwater concentrations to the VISLs to estimate the boundaries of the plume, when contaminated groundwater is a subsurface vapor source, for purposes of establishing the boundaries of the vapor intrusion inclusion zone.

Criteria for Establishing "Boundaries" of NAPL Plumes that Contain Vapor-forming Chemicals. EPA generally recommends comparing soil gas concentrations to the respective VISLs to estimate the boundaries of the vapor plume, when residual or free-phase NAPL is a subsurface vapor source, for purposes of establishing the boundaries of the vapor intrusion inclusion zone.

6.2.2 Prioritizing Investigations with Multiple Buildings

At sites where numerous buildings are potentially subject to vapor intrusion (e.g., developed areas with an extensive plume of contaminated groundwater), it may not be feasible or practical at the outset to sample indoor air in each building or soil gas underneath or near each building. In such circumstances, EPA generally recommends a "worst first" approach to prioritize

[109] Among other possibilities, vapor intrusion impacts observed to occur at distances greater than 100 feet in the absence of a preferential migration route(s) may reflect imprecision in the interpolated edge of a plume, based upon sampling data from sparse monitoring wells, and/or use of screening levels for drinking water, rather than for vapor intrusion (i.e., VISLs), to delineate a plume's extent.

[110] For assessing the extent of soil gas migration from the subsurface vapor source, EPA generally recommends measuring soil gas concentrations, either sub-slab soil gas (preferably) or exterior soil gas, with a sufficient density to characterize and understand spatial variability (Section 6.3.2).

buildings for investigation. Factors that, if known, may warrant consideration in prioritizing buildings for investigation include:

- Source strength and proximity. Buildings overlying and near a source of vapors in the vadose zone would generally be expected to have a greater potential for vapor intrusion than buildings that do not overlie this same vapor source. Where the subsurface vapor source is groundwater, buildings located over higher concentrations or shallower water levels would generally be expected to have a greater potential for vapor intrusion than buildings located over lower concentrations and deeper groundwater plumes.

- Building types and conditions. Buildings that are continuously occupied may pose a more immediate concern than buildings that are not currently occupied, if all other factors (e.g., source strength and proximity) are equivalent. Nonresidential buildings with bay-style doors that are routinely open may be better ventilated than other types of nonresidential buildings, providing greater potential for dilution of vapor-forming chemicals that enter the building via vapor intrusion.

- Vapor migration ease. Buildings overlying vadose zones comprised of coarse geological materials (e.g., gravel, boulders) generally would be expected to have a greater potential for vapor intrusion than buildings overlying vadose zones comprised of fine-grained materials (e.g., silts, clays), provided significant preferential migration routes (e.g., geologic fractures, utility corridors) are not present in the fine-grained layers.

Interviews and building surveys during development of the investigation work plan (or during the preliminary analysis – see Section 5) also can provide useful information for prioritizing buildings, when phased testing is chosen or indicated. Sections 6.3 and 6.4 provide additional examples of survey information that can support planning, in addition to supporting data interpretation.

In situations where "higher-priority" buildings and locations are investigated initially, investigation of locations of other buildings may still be warranted, for example, to ensure that the CSM is complete and accurate and that variability in the subsurface conditions and building conditions is understood. There usually is substantial spatial variability in the concentrations of subsurface vapors, caused by heterogeneities in the subsurface materials and other factors, that can result in variability among buildings in vapor flux and indoor air concentrations arising from vapor intrusion. Additionally, building construction, building age and maintenance, and occupants' activities that affect soil gas entry and air exchange rate will vary from building to building, further adding to the variability in indoor air concentrations between buildings. Therefore, it may be difficult to identify *a priori* either a "representative" or "reasonable worst case"[111] building or group of buildings, when it is determined that sampling all buildings is not practical.

[111] For purposes of this Technical Guide, "reasonable worst case" is intended to be a semi-quantitative phrase, referring to the upper portion of the high end of the exposure distribution, but less than the absolute maximum exposure (see Glossary). Because EPA generally recommends a "worst first" approach to prioritize buildings for investigation of the vapor intrusion pathway, "reasonable worst case" buildings would warrant a "higher priority" than "representative" or typical buildings.

When sampling all buildings is not practical, but other lines of evidence suggest that vapor intrusion may be occurring, the site management team may wish to consider installing engineered exposure controls for vapor intrusion mitigation in buildings without baseline indoor air data (i.e., building mitigation as an early action – see Sections 3.3 and 7.8).

6.2.3 Planning for Community Involvement

Community involvement is an important component of any vapor intrusion investigation. EPA recommends that a community involvement or public participation plan (see Section 9.1) be developed or refined while planning a vapor intrusion investigation. Proper and sustained community outreach and engagement efforts are critical to effectively implementing work plans for vapor intrusion investigations, particularly when they involve sampling in a home or workplace or on private property. Resuming and conducting community involvement at legacy sites (i.e., sites that have a past history of agency involvement; see Section 9.6) can be particularly complex. The site planning team is encouraged to consult with appropriate EPA colleagues experienced in community outreach and involvement efforts and utilize available EPA planning resources, including those discussed in Section 9.

6.3 Characterize the Vapor Intrusion Pathway

As discussed in Section 2, the vapor intrusion pathway entails emanation of volatile chemicals from a subsurface source(s) in a vapor form that migrates in the vadose zone, gradually increases in amount underneath buildings as time passes, and enters buildings through openings and conduits. As a result, detailed vapor intrusion investigations designed to develop or enhance the CSM for a specific site will typically address one or more of the following objectives, often in phases:[112]

- Characterize the nature and extent of subsurface sources of vapors.
- Characterize the subsurface migration paths between vapor sources and buildings (potential “receptors”).
- Assess building(s) for their susceptibility to soil gas entry.
- Evaluate the presence and concentration of a site-related subsurface contaminant(s) in indoor air.
- Identify and evaluate contributions of indoor and ambient air sources to concentrations of hazardous vapors in indoor air.

[112] The order of presentation is not intended to convey a suggested sequencing of objectives; rather, it follows the presentation of the conceptual model of vapor intrusion in Section 2.

These objectives are described in the following subsections for purposes of identifying the primary lines of evidence typically developed and evaluated for each objective and describing how the objectives fit together in developing and enhancing the CSM for a specific site an characterizing vapor intrusion potential. This information is provided to assist the site planning team in selecting and sequencing objectives for vapor intrusion investigations.

6.3.1 Characterize Nature and Extent of Subsurface Vapor Sources

Where the preliminary analysis indicates that subsurface contamination with vapor-forming chemicals may be underlying or near buildings, EPA recommends that the nature and extent of such contamination be well characterized. Source characterization data are critical to developing a sound CSM and supporting confident, final decisions about the vapor intrusion pathway.

Investigations to characterize the nature and delineate the extent of potential sources of vapors may rely upon the results of groundwater sampling, soil sampling, or soil gas sampling, as dictated by the site-specific source(s) and subsurface conditions.

Groundwater Sources:

Where contaminated groundwater is a vapor source located near buildings, EPA recommends that groundwater observation wells (i.e., monitoring wells) be installed at strategic locations and used to assess groundwater flow and contaminant concentrations; i.e., verify the nature and extent of groundwater contamination through groundwater sampling and analysis.[113] Groundwater samples obtained from the uppermost portion of the aquifer[114] that underlies the study area of interest (i.e., where buildings are located) are recommended for characterizing representative vapor source concentrations for vapor intrusion assessment. For this purpose, wells (or multi-level samplers) that are screened across the water table interface are preferred and EPA recommends samples be collected as close as possible to the top of the water table using approved sampling methods designed to minimize loss of volatiles while sampling (EPA 2002a, EPA-ERT 2001a).[115] Ideally, the plume can be shown as stable or shrinking (i.e., is not migrating or rising in concentration, including hazardous byproducts of any biodegradation), through multiple rounds of sampling, so that vapor source concentrations can be confidently evaluated under reasonably expected future, as well as current, conditions. Otherwise, the inclusion zone for vapor intrusion (see Section 6.2.1) may expand over time and/or current sample concentrations in or beneath a given building may under-estimate the reasonable maximum vapor intrusion condition in the future.

For purposes of assessing vapor intrusion for specific buildings, groundwater samples from wells nearer to buildings are generally recommended over those from more distant wells. Interpolation of the results obtained from two or more wells in the uppermost portion of the aquifer may be warranted for these purposes when the spatial pattern suggests significant lateral gradients in contaminant concentrations within the area of interest. However, for purposes of determining whether contaminated groundwater poses acceptable human health risk from vapor intrusion on an area-wide basis, it may be more appropriate to utilize sampling results for the most greatly impacted well within the area of interest.

In addition, EPA generally recommends that a soil gas sample be collected immediately above the groundwater table (and above the capillary fringe) (i.e., "near-source" soil gas sample)[116] to help characterize the subsurface vapor source. The results of such "near

[113] Although a soil gas survey can also be employed as a screening tool to assist with the delineation of a plume of contaminated groundwater, EPA recommends that plume delineation ultimately be supported by the collection and analysis of confirmatory groundwater samples at appropriate locations.

[114] EPA recommends that, to the extent practical, groundwater samples be collected over a narrow interval (e.g., a few feet or less) just below the water table when the data are to be used for assessing the potential for vapor intrusion. Of course, the broader objectives of a site characterization will generally necessitate installation and sampling of additional wells, from other depth intervals, to accurately characterize the full nature and extent of groundwater contamination. Such wells and the broader topic of site characterization are not discussed in this Technical Guide, which is focused instead on recommended guidelines that are pertinent specifically to vapor intrusion.

[115] If available groundwater data do not meet these criteria, the site data review team may consider whether they are nevertheless representative of potential vapor source concentrations emanating from groundwater.

[116] In this context and for purposes of this Technical Guide, "near" means "within a practically short distance." Site- and location-specific circumstances and project-specific objectives typically will influence the quantitative definition of "near" for purposes of collecting "near-source" soil gas samples.

source" soil gas samples can be compared to calculations of the vapor concentration expected when the soil gas is in equilibrium with the concentrations measured in shallow groundwater (see Appendix C). A favorable comparison (i.e., the two concentrations are equivalent for each vapor-forming chemical in groundwater) would help to support the results of the groundwater characterization. On the other hand, a "fresh water lens" (or other site-specific conditions; see, for example, Section 6.3.2) could account for measured soil gas concentration(s) being significantly lower than the calculated equilibrium concentration(s).

Because fluctuations in water table elevation can lead to elevated vapor concentrations in the vadose zone, EPA also recommends that "near source" soil gas sampling (and possibly a soil gas survey) be considered in different seasons that coincide with groundwater fluctuations.

Vadose Zone Sources:

Where contaminated soil or non-aqueous-phase liquid (NAPL) in the vadose zone is a subsurface vapor source, soil sampling using coring techniques for sample retrieval or using sensors, such as a membrane interface probe, can be used to characterize the chemical composition and general location of contamination; that is, bulk soil concentration data can be used in a qualitative sense for this purpose. For example, high soil concentrations generally would indicate impacted soil. Unfortunately, the converse is not always true. Non-detect results for soil samples cannot be interpreted to indicate the absence of a subsurface vapor source, because of the potential for vapor loss due to volatilization during soil sampling, preservation, and chemical analysis.

Alternatively or in addition, a soil gas survey can be used to locate the primary source zone and delineate the areal and vertical extent of the vapor-affected area. Generally, EPA recommends that the soil gas survey include a soil gas sample collected immediately above each contaminant source in the vadose zone (i.e., "near-source" soil gas samples) to help characterize the vapor source.

Although a soil gas survey can generally be used to characterize many other subsurface vapor sources (e.g., sewer and drain lines; landfills and other land-based disposal units; impoundments and other land-based storage and/or treatment units, pressurized tanks and pipelines), additional approaches tailored to the specific source type may also warrant consideration.

These sampling options are generally coupled with an understanding of the site-specific subsurface conditions that control the location and extent of contamination (e.g., geologic properties, including stratigraphy and level of heterogeneity; hydrogeologic conditions; sewers, drains, and other conduits that lie underneath or intersect areas of groundwater and soil contamination). Such understanding is generally developed by interpreting the data obtained through borehole logging (i.e., visually inspecting soil cores and determining soil texture) or geophysical tools.

EPA generally recommends sample locations be of sufficient density to adequately account for spatial variability and heterogeneity in subsurface conditions. EPA generally recommends consulting with individuals who have expertise in characterizing subsurface environmental conditions (e.g., a geologist) when determining appropriate sampling locations and spacing.

When combined with the data demonstrating that the property reflects the conditions and assumptions of the generic model invoked in the VISLs (see Section 6.5.2), groundwater and "near-source" soil gas samples can be compared to medium-specific screening levels to develop an initial quantitative perspective about the potential level of exposure and human health risk posed by vapor intrusion. Section 6.5 provides additional information about risk-based screening of vapor source concentrations.

6.3.2 Characterize Vapor Migration in the Vadose Zone

As described in Section 2, geologic, hydrologic, biochemical factors in the vadose zone, as well as elapsed time since the environmental release, can influence vapor migration and attenuation in soil gas concentrations between subsurface vapor sources and nearby building(s).[117] As noted in Section 5.4, EPA recommends the CSM portray the current understanding of these vadose zone conditions in and around the subsurface vapor source(s) and nearby building(s). Furthermore, EPA recommends the CSM identify known or suspected preferential migration routes that could facilitate vapor migration to greater distances and at higher concentrations than otherwise expected. When these conditions are not well established from existing information, EPA recommends that a detailed investigation be scoped to address these data gaps.

When combined with other data, as discussed further in Section 7.3, information about subsurface vapor migration can support determinations that the vapor intrusion pathway is complete under current conditions or may be complete under future conditions. In some cases, vadose zone conditions may impose sufficient resistance to vapor migration to make the vapor intrusion pathway insignificant. In these circumstances, information about subsurface vapor migration, combined with other lines of evidence, can support determinations that the vapor intrusion pathway is incomplete under current conditions, as discussed further in Section 7.3.

Investigations seeking to characterize vapor migration in the vadose zone generally entail, at a minimum, a soil gas survey. Because soil gas concentrations can exhibit considerable spatial variability, due to a variety of factors,[118] EPA generally recommends that soil gas surveys collect soil gas samples at multiple locations and depth intervals between the vapor source and building(s) (potential "receptors"). As a result, the soil gas survey may include samples collected immediately outside the building ("exterior soil gas") at various depths or several depth intervals,

[117] The horizontal and vertical distance over which vapors may migrate in the subsurface depends on the source concentration, source depth, soil matrix properties (e.g., porosity and moisture content), and time since the release occurred. For example, months or years of volatilization and vapor migration may be required to fully develop vapor distributions in the vadose zone at sites with deep vapor sources or with impedances to vapor migration arising from hydrologic or geologic conditions (Section 2.5; EPA 2012b). Under such circumstances, soil gas surveys conducted soon after an environmental release may not yield data indicating the maximum extent of vapor migration.

[118] Modeling of idealized scenarios provides additional demonstrations about spatial variability of soil gas concentrations. For example, vertical profiles of soil gas concentration(s) can be very different underneath buildings compared to locations exterior to the building and soil gas concentrations may not be uniform laterally, particularly in the vicinity of the building, even when the vapor source is a laterally extensive plume of contaminated groundwater (EPA 2012b). These simulation results indicate why EPA recommends that soil gas generally be sampled in multiple sampling locations, when assessing subsurface vapor migration routes.

as well as immediately beneath it (e.g., sub-slab soil gas sampling).[119] If any shallow soil gas samples are collected, EPA recommends they be collected as close as possible to the building and at depths below the respective building foundation and no less than five feet below ground surface, depending on site-specific conditions. Where crawl spaces are present, crawl space air sampling may also be conducted.

Generally, EPA recommends that the soil gas survey include a "near-source" soil gas sample collected immediately above each source of contamination to help characterize the subsurface vapor source (see Section 6.3.1). The results of such "near source" soil gas samples can be compared to calculations of the vapor concentration expected when the soil gas is in equilibrium with the concentrations measured in shallow groundwater (see Appendix C), when the subsurface vapor source is in the groundwater. Geologic, hydrologic, or biologic impedances to vapor migration may be indicated if the measured "near source" soil gas concentrations are significantly lower than the calculated equilibrium concentrations.

To characterize subsurface migration in the vadose zone, soil gas survey data are generally coupled with an understanding of the site-specific subsurface conditions that influence vapor migration and attenuation (e.g., geologic properties, including stratigraphy and level of heterogeneity; hydrologic conditions, including groundwater elevation and soil moisture;[120] and biological properties, including availability of oxygen to support aerobic biodegradation).[121] Such geologic understanding is generally developed by interpreting the data obtained through borehole logging and geophysical tools. Soil permeability to air flow can be measured in the field (McHugh et al. 2013) and would be used to corroborate inferences based upon borehole logging data. Hydrologic conditions can be characterized by analyzing soil samples for porosity and moisture content and by hydrologic modeling. For potentially biodegradable contaminants, an intensive soil gas survey to establish current vertical profiles for contaminant vapors and oxygen (and, in some cases, biodegradation products, such as carbon dioxide or methane)[122] may be able to demonstrate that biodegradation is responsible for attenuating vapor migration

[119] EPA recommends that spacing of soil gas sampling locations generally consider the extent and location of the subsurface vapor source, distance between the building and the source, and other site-specific factors.

[120] Tillman and Weaver (2007) conducted hydrologic modeling and collected field data, which showed that moisture content determined from soil cores taken external to a building may over-estimate soil moisture underneath the building. They inferred that vapor intrusion assessments based upon moisture content in soil from open areas between buildings may under-estimate vapor intrusion potential.

[121] As noted in Section 2, vapor migration in the vadose zone can be impeded by several factors, including soil moisture, low-permeability (generally fine-grained) soils, and biodegradation. Significant characterization of the vadose zone may be needed to demonstrate that such geologic, hydrologic, and biologic features are laterally extensive over distances that are large compared to the footprint of the building and the extent of the subsurface vapor source at a specific site.

[122] Interpretation of profiles for carbon dioxide and methane can be challenging, due to the presence of natural sources unrelated to contaminant biodegradation (Holden and Fierer 2005).

to a greater extent than can be attributed to advection and diffusion in the vadose zone.[123, 124] For both purposes, samples collected directly underneath the building will tend to be more representative of conditions influencing vapor intrusion potential than samples collected outside the building footprint, all else being equal.

When conducted contemporaneously for multiple buildings, a soil gas survey and characterization of the vadose zone can help identify distances from subsurface vapor sources beyond which threats from vapor intrusion are not reasonably expected, as mentioned in Section 6.2.1. At sites with a limited number of potentially affected buildings, it may be feasible to characterize the subsurface vapor migration near and surrounding all of them. However, at sites where a large number of buildings may be affected, this approach is not likely to be feasible; in these cases, EPA generally recommends that the site manager seek the advice of an individual familiar with the site-specific subsurface conditions (typically a geologist) to help guide selection of appropriate sampling locations and assess whether "representative" or "reasonable worst case" locations can be identified, as appropriate to the objectives of the investigation. Because there usually is substantial spatial variability in the concentrations of subsurface vapors, caused partially by heterogeneities in the subsurface materials, it may be difficult to identify *a priori* locations that are either "representative" or are "reasonable worst case" subsurface conditions.

Subsurface investigations of vapor intrusion also generally warrant an evaluation of utility corridors, which can facilitate unattenuated vapor transport over longer-than-anticipated distances and/or vapor migration towards and into buildings that are serviced by the utility. EPA also recommends subsurface investigations of vapor intrusion consider whether sewers and other man-made conduits have the potential to transport NAPLs, contaminated groundwater, and/or vapors (through soil) towards and/or directly into buildings. Public and facility records may be useful sources of information about utility and sewer locations, which may provide maps, "as built diagrams," or construction specifications. Depending upon the CSM, sampling of vapors within the utility corridor (or within a sewer, if present) may be warranted to characterize vapor migration in the subsurface (or characterize a secondary source of vapors – see Sections 6.3.1 and Section 2.1).

Reasonably expected future risks posed by the subsurface vapor source(s) warrant consideration, in addition to risks posed under current conditions, "in order to demonstrate that a site does not present an unacceptable risk to human health and the environment" (EPA 1991a). For example, when evaluating subsurface vapor migration and attenuation in locations where buildings do not exist, it is important to recognize that the conditions in the vadose zone and soil

[123] At sites where aerobic biodegradation is limiting the upward migration of petroleum hydrocarbon vapors, for example, the vertical concentration profile will typically show higher concentrations of petroleum hydrocarbons and lower (or non-detect) concentrations of oxygen in deeper soil gas samples. At these same sites, the vertical concentration profile will typically show lower (or non-detect) concentrations of petroleum hydrocarbons and higher concentrations of oxygen in shallower soil gas samples. Because weather events can affect rates of oxygen replenishment in the vadose zone (Lundegard et al. 2008), multiple rounds of such sampling are recommended to demonstrate that biodegradation consistently poses a significant impedance to upward vapor migration. This recommendation is particularly apt where the subsurface vapor source is strong (e.g., unweathered NAPL in the vadose zone) relative to time-variable processes supplying oxygen to the vadose zone.

[124] In this context, mathematical modeling (see Section 6.6) can be employed to characterize vapor migration attributable to advection and diffusion in the vadose zone.

gas concentrations may be changed as a result of constructing a new building and/or supporting infrastructure. The moisture content may decrease and the moisture profile change in the vadose zone as a result of reduced infiltration of rainwater below a building footprint (Tilman and Weaver 2007). The permeability to vapor flow in the vadose zone may be altered in the foundation vicinity due to construction. Finally, the future presence of extensive surface covers and/or utility corridors may also modify the vertical and horizontal profile of soil gas concentrations in the subsurface (EPA 2012b). As a result, EPA recommends that appropriate lines of evidence in addition to a soil gas survey (e.g., mathematical modeling, where parameters are chosen to represent conditions that give a high-impact case – Section 6.6) be developed and considered to support any determination that a future building will not be subject to vapor intrusion or will not pose unacceptable human health risk for occupants. Owing to the potentially unpredictable plans for building construction and site redevelopment, as well as potentially unpredictable changes in the transitory soil characteristics (e.g., soil moisture) and soil gas concentrations, institutional controls may be warranted (e.g., to inform the need for a confirmatory evaluation of the vapor intrusion pathway) when new buildings are constructed in areas where the subsurface vapor source(s) has(have) significant potential to pose a vapor intrusion threat.

6.3.3 Assess Building Susceptibility to Soil Gas Entry

When elevated concentrations of vapor-forming chemicals accumulate in the soil gas immediately underneath the foundation, surrounding the basement, or within the crawl space of a vulnerable building, then soil gas entry (i.e., vapor intrusion) can lead to unacceptable levels of subsurface contaminants in indoor air, depending upon building- and site-specific circumstances. As discussed in Section 2.3, soil gas can enter a building when openings are present and driving ‘forces’ exist to draw the vapors from the subsurface through the openings into the indoor environment.

Single-family detached homes can generally be presumed to have openings for soil gas entry; as such, they will generally be susceptible to soil gas entry unless a mitigation system (e.g., radon mitigation system) is present and operating as intended. Some buildings are more susceptible to soil gas entry than others. For example, buildings with significant openings, such as:

- buildings with deteriorating basements or dirt floors, which generally provide poor barriers to vapor (soil gas) entry; and
- buildings with sumps (or other openings to the subsurface) that can facilitate transport of vapors via soil gas entry.

EPA recommends that appropriate lines of evidence be employed to assess susceptibility to soil gas entry, when this objective is selected as part of a site-specific investigation plan for vapor intrusion assessment. Vulnerability to soil gas entry can be assessed for a specific building by using any of several methods, including:

- Concurrently monitoring indoor air samples for presence of radon and finding radon in indoor air at levels greater than in ambient air.[125]

- Concurrently monitoring indoor air and ambient air (see Section 6.3.5) and finding cis-1,2-dichloroethylene, vinyl chloride, 1,1-dichloroethylene, or 1,1-dichloroethane in indoor air at levels greater than in ambient air, when and where they are present in the subsurface vapor source(s), but are not used indoors.[126]

- Employing a photoionization detector (PID) or other real-time in-field device, capable of detecting parts per billion by volume (ppbv) levels, to directly survey suspected locations of soil gas entry (e.g., utility penetrations, sumps) and finding elevated readings of vapors.

- Conducting a visual inspection for cracks and holes in concrete foundation slabs, basement walls, or any floor drain(s). (Openings for soil gas entry will not necessarily be visible or accessible for inspection, so the absence of visible openings, by itself, is insufficient to demonstrate that a building is not susceptible to soil gas entry.)

- Monitoring pressure differences between the building and subsurface environment to characterize the 'driving force' for soil gas entry and the effects of the heating, ventilation, and air-conditioning (HVAC) systems.

- Injecting tracers into the subsurface at selected concentrations and subsequently finding it in indoor air samples.

Certain complementary information obtained for the building, as identified in Section 6.4.1, can also support such assessments. Relevant information includes the operating characteristics of HVAC systems.

In many commercial buildings, the HVAC system brings outdoor air into the building, potentially creating building over-pressurization relative to the outdoor environment. When the building is

[125] Because vapor intrusion and radon intrusion entail similar mechanisms for subsurface vapor migration and gas entry into buildings and structures (Section 2.3), naturally occurring radon may serve as a tracer to help identify those buildings that are more susceptible to soil gas entry than others. Buildings with radon concentrations greater than levels in ambient air are likely susceptible to soil gas intrusion and would likely be susceptible to intrusion of any chemical vapors in the subsurface. On the other hand, the radon concentration in a building is not generally expected to be a good quantitative indicator of indoor air exposure concentrations of vapor-forming chemicals arising from sub-surface contamination. Hence, radon measurement is not generally recommended as a proxy for directly measuring vapor-forming chemicals in indoor air. Among other factors, the distribution of radon-emanating rock and soil and the spatial and temporal variability of their source strength are generally expected to be very different (e.g., tending to be broader and more uniform) than the distribution and source strength variability for subsurface sources of chemical vapors.

[126] EPA (2011a) reports that "vinyl chloride, 1,1-dichoroethylene, cis-1,2-dichloroethylene, and 1,1-dichloroethane are rarely detected in background indoor air." DoN (2011a) also reports that vinyl chloride and cis-1,2-dichloroethylene "are rarely detected in background indoor air." When they are subsurface contaminants, volatile chemicals that are rarely or never present in indoor sources can be inferred to arise in indoor air via vapor intrusion "without further explanation" (DoN 2011a). Brenner (2010), for example, employed this principle (and cis-1,2-dichloroethylene) to identify buildings susceptible to vapor intrusion and to diagnose the relative contributions of vapor intrusion and infiltration to indoor air concentrations.

over-pressurized sufficiently to eliminate the driving force for soil gas entry over at least a portion of the building foundation, vapor intrusion potential is diminished.[127]

Reasonably expected future risks posed by subsurface contamination warrant consideration, in addition to risks posed under current conditions, "in order to demonstrate that a site does not present an unacceptable risk to human health and the environment" (EPA 1991a). For example, current building use and HVAC systems might not be sustained perpetually. Therefore, when the subsurface vapor source(s) underneath or near a building with an over-pressurizing HVAC system has(have) significant potential to pose a vapor intrusion threat, it may be useful to assess susceptibility to soil gas entry and diagnose vapor intrusion (also see Sections 6.3.4 and 6.4.1) in such buildings under conditions when the HVAC system is not operating. (In addition, indoor air testing could be conducted during periods when the HVAC system operates with diminished flows, such as weekends or evenings.) The results of such testing can be used to support determinations about whether the vapor intrusion pathway is "potentially complete" and is reasonably expected to pose unacceptable human health risk (see Section 7.4) in the future,[128] in which case a response action(s) may be warranted (see Section 7.7). For example, if the results indicate susceptibility to soil gas entry when the HVAC system is not in operation and vapor intrusion under these conditions has the potential to pose a health concern, then the building may warrant future monitoring (e.g., continuous monitoring of the pressure gradient across the foundation or indoor air testing) and/or engineered exposure controls, which may be enforceable through an institutional control (IC) (see Section 8.6).

Likewise, well-designed and operated radon mitigation systems generally should diminish vapor intrusion via soil gas entry under current conditions. Therefore, buildings with pre-existing radon mitigation systems, which overlie or are near subsurface vapor sources, could be tested under conditions where the radon mitigation system is temporarily not operated to support decisions about monitoring and ICs as part of a vapor intrusion remedy.[129]

6.3.4 Evaluate Presence and Concentration of Subsurface Contaminants in Indoor Air

Indoor air sampling (see Section 6.4.1) using time-integrated sampling methods or grab samples can confirm the presence, if any, of a site-related vapor-forming chemical (i.e., one comprising the subsurface vapor source(s)) in the indoor environment. When combined with data characterizing subsurface vapor migration and demonstrating the building is (or is not) susceptible to soil gas entry, indoor air sampling data can support determinations that the vapor intrusion pathway is (or is not) complete for a given building, as discussed further in Section 7.3. When conducted contemporaneously in multiple buildings, indoor air sampling can, in concert with soil gas survey data and data delineating subsurface vapor sources, help identify the boundaries of the land area(s) within which buildings are known or suspected to have indoor air concentrations of subsurface contaminants arising from vapor intrusion (also see Section 6.2.1).

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[127] Over-pressurization may not be uniform throughout a building, particularly in large buildings. Over-pressurization in portions of a building will not necessarily mitigate all openings for soil gas entry.

[128] "Both current and reasonably likely future risks need to be considered in order to demonstrate that a site does not present an unacceptable risk to human health and the environment." (EPA 1991a).

[129] EPA recommends that state and local laws be researched before any such testing is conducted. Some areas have local ordinances governing operation and maintenance of radon mitigation systems.

Indoor air sampling is most commonly conducted using time-integrated sampling methods, when characterizing exposure concentrations for building occupants (see Section 6.4.1), which may include contributions from "indoor" or ambient air sources of these chemicals (see Section 2.7). For example, time-integrated concentrations of hazardous vapors in samples of indoor air can be compared to appropriate, risk-based screening criteria (see Section 6.5) to obtain some preliminary insights about the potential level of exposure and risk posed by vapor intrusion or can be used to support a human health risk assessment (Section 7.4) about vapor-forming chemicals found in the subsurface environment.[130]

When sampling indoor air (or sub-slab soil gas) to characterize exposure concentrations arising from vapor intrusion, EPA recommends removing potential indoor sources of vapor-forming chemicals (see Section 2.7 and 6.4.1) from the building to strive to ensure that the concentrations measured in the indoor air samples are attributable to the vapor intrusion pathway. However, even after removing indoor sources, their effects may linger depending on source strength, relative humidity in the building, the extent to which the contaminants have been absorbed by carpets and other fabrics or "sinks," and air exchange rate. In addition, field experience suggests that it may not be possible to remove all indoor sources. It may be particularly impractical to do so in industrial settings where vapor-forming materials are used or stored.

6.3.5 Identify and Evaluate Contributions from Indoor and Ambient Air Sources

As noted in Section 2.7 herein, indoor air is likely to contain detectable levels of a number of vapor-forming chemicals regardless of whether the building overlies a subsurface vapor source, because indoor air can be impacted by a variety of indoor and outdoor vapor sources unrelated to site contamination. The contribution of indoor and outdoor vapor sources (or both) to indoor air concentrations is referred to as "background" throughout this Technical Guide, when they do not arise from site-related contamination (see Glossary). Information on 'background' contributions of site-related, vapor-forming chemicals in indoor air is important to risk managers because generally EPA does not clean up to concentrations below natural or anthropogenic background levels (EPA 2002e).

To determine if a subsurface vapor source(s) is (or are) responsible for indoor air contamination, EPA recommends that such background sources of site-specific analytes be identified and distinguished from vapor-forming chemicals arising from vapor intrusion. A comprehensive investigation of all background substances found in the environment is usually not recommended. For example, sub-slab soil gas and ambient air samples typically would not be analyzed for radon for purposes of characterizing 'background' exposures *per se*, whereas EPA would recommend analyzing for radon if its precursor was part of a regulated release to the subsurface environment (EPA 2002e).[131] Generally, EPA recommends the site planning and

[130] In certain cases, depending in part on the results (e.g., concentrations exceed risk-based screening levels), indoor air sampling data may be a sufficient basis for supporting decisions to undertake pre-emptive mitigation/early action (see Sections 3.3 and 7.8) in lieu of additional rounds of sampling and analysis or an evaluation of the contribution of background sources to indoor air concentrations.

[131] Sub-slab soil gas and indoor air samples might also be analyzed for radon, where its precursor was not part of a release to the subsurface environment, for purposes of diagnosing vulnerability to soil gas entry (see, for example, Section 6.3.3), depending upon the objectives of the vapor intrusion investigation.

data evaluation team limit chemical analyses to those vapor-forming chemicals known (based upon subsurface contaminant characterization) or reasonably expected (based upon site history) to be present as a result of a release to the subsurface environment.

To support evaluations of sources of indoor air concentrations, EPA recommends conducting a building survey (see Section 6.4.1) that identifies in individual buildings known or suspected indoor sources of the vapor-forming chemicals also found in the subsurface (see Section 2.7) and characterizing ambient air quality (see Section 6.4.2) in the site vicinity for these same chemicals. Key supporting information includes: (1) the locations and types of known or potential indoor vapor sources; (2) information about outdoor vapor sources related to the site (e.g., locations of chemical storage, use, and/or release to the environment); (3) information about outdoor vapor sources un-related to the site, such as nearby commercial or industrial facilities and mobile sources (e.g., cars, trucks, and other equipment); and (4) data on the local ambient air quality.

Interviews of building occupants and inspections of buildings can be helpful initial sources of information about indoor uses and storage of vapor-forming consumer and commercial products.[132] In addition, vapor-detecting field instruments and in-field gas chromatographs[133] can be used to locate indoor vapor sources. Grab (essentially short-duration) samples of indoor air, as described in Section 6.4.1, can be useful for identifying specific vapor-forming chemicals emanating from indoor vapor sources of consumer or commercial products. When the objective is to quantitatively distinguish contributions to indoor air concentrations from vapor intrusion versus contributions from indoor and ambient air sources, as described below, EPA recommends obtaining indoor air concentrations using time-integrated sampling methods (see Section 6.4.1) instead of grab samples.

If the subsurface vapor source(s) is (or are) comprised of multiple vapor-forming chemicals and the subsurface source medium (e.g., soil, groundwater) and location are identical for these chemicals, then contemporaneous samples of sub-slab soil gas (see Section 6.4.3) and indoor air (see Section 6.4.1) can be compared, potentially supporting one of the following conclusions:

> Results indicating vapor intrusion as solely responsible for vapor concentrations in indoor air. The predominant vapor-forming chemicals in the sub-slab soil gas and their relative proportions in indoor air and sub-slab vapor samples would be expected to be similar, whereas their concentrations in sub-slab soil gas would be expected to be substantially higher than in indoor air,[134] if vapor intrusion is solely responsible for indoor air

[132] Information about the chemical composition of commonly encountered products is provided by the U.S. Navy (DoN 2011a, Appendix A) in its guidance for background analysis for the vapor intrusion pathway.

[133] Gorder and Dettenmaier (2011) reported on the use of a field-portable gas chromatograph and mass spectrometer to identify specific sources of vapor-forming chemicals and estimate their mass emission rate(s). EPA's Environmental Response Team has employed the Trace Atmospheric Gas Analyzer (TAGA) mobile laboratory for similar purposes.

[134] Based upon the generic sub-slab attenuation factor identified in Section 6.5.3 herein, sub-slab soil gas concentrations can be expected to typically exceed indoor air concentrations by 33 times or more in residences that are impacted by vapor intrusion (i.e., 33 is the inverse of an attenuation factor of 0.03), when background sources are negligible and the building is under-pressurized relative to the subsurface during indoor air sampling.

concentrations.[135] If recalcitrant (i.e., not subject to biodegradation in the vadose zone), the predominant vapor-forming chemicals and their relative proportions in the subsurface vapor source would likewise tend to be similar to those in indoor air if vapor intrusion is solely responsible for indoor air concentrations.[136]

Results indicating indoor vapor sources as primarily responsible for indoor air concentrations. If a vapor-forming chemical is present with an elevated concentration in indoor air, but is not present or is negligibly present in sub-slab soil gas samples (or representative samples of the subsurface vapor source), then the presence of this contaminant in indoor air may not arise from the vapor intrusion pathway, but rather from indoor sources or other background sources (e.g., ambient air). In these circumstances, EPA recommends considering additional attempts to identify and temporarily eliminate indoor sources, where practical, and re-sample indoor air and sub-slab soil gas after doing so.

Likewise, outdoor (ambient) air samples can be collected (see Section 6.4.2) contemporaneously with indoor air (see Section 6.4.1) and sub-slab soil gas (see Section 6.4.3) samples, as recommended in Section 6.4.

Results indicating outdoor vapor sources as primarily responsible for indoor air concentrations. If a vapor-forming chemical(s) is(are) detected in outdoor air and indoor air at similar concentrations, but is(are) not present in sub-slab soil gas samples (or representative samples of the subsurface vapor source) or is present in the subsurface samples at concentration(s) similar to indoor air),[137] then the presence of this contaminant(s) in indoor air may not arise from the vapor intrusion pathway, but rather from outdoor sources (i.e., ambient air).

Concentrations of vapor-forming chemicals in indoor air, sub-slab soil gas, and ambient air can be compared, as described above, using an individual time-integrated sample for each medium. Recognizing that weather conditions and building operations can lead to variable contributions from vapor intrusion and ambient air infiltration over time, EPA recommends, however, that such

[135] Conversely, if there is an interior source of a vapor-forming chemical in indoor air samples, the relative proportion of this chemical in indoor air will be greater than its respective proportion in the sub-slab soil gas, even where vapor intrusion is occurring, assuming that the other vapor-forming chemicals in the sub-slab soil gas do not have 'background' sources.

[136] Conversely, if there is an interior source of a vapor-forming chemical in indoor air samples, the relative proportion of this chemical in indoor air will be greater than its respective proportion in the subsurface vapor source or in "near-source" soil gas samples (see Section 6.3.1), even where vapor intrusion is occurring, assuming that the other vapor-forming chemicals in the sub-surface do not have 'background' sources.

[137] Sample concentrations of vapor-forming chemicals in indoor air and sub-slab soil gas can be compared to conservative, risk-based screening levels to provide a complementary line of evidence. Generally, vapor-forming chemicals with concentrations that consistently fall below screening levels (see Section 6.5) through multiple sampling events (see Section 6.4) warrant no further action or study, so long as the exposure assumptions match those taken into account by the calculations and the site fulfills the conditions and assumptions of the generic conceptual model underlying the screening levels (see Section 6.5.2).

comparisons be made for multiple sets of paired samples, collected in different seasons,[138] to support any conclusion that vapor intrusion is not a significant contributor to indoor air concentrations, which can instead be attributed to indoor and outdoor sources unrelated to the subject site. Even with a few sets of such samples, rigorous statistical tests may not be feasible. Nevertheless, comparing contemporaneously measured concentrations and proportions of vapor-forming chemicals in indoor air, subsurface media, and ambient air can be effective for this investigation objective, particularly when one (or more) of the analytes is known to be present only in the subsurface or in ambient air.

The following hypothetical example illustrates how site-specific sampling data might inform conclusions about the relative contributions of indoor versus subsurface vapor sources in a building overlying contaminated groundwater:

Example: Time-integrated samples of indoor air, outdoor air, and subslab soil gas were collected contemporaneously for a building that overlies shallow groundwater that is contaminated with a suite of vapor-forming chemicals (designated as VFCA, VFCB, VFCC, and VFCD). The sampling results are summarized as follows:

Vapor-forming Chemical in Groundwater	Time-weighted Sample Concentrations ($\mu g/m^3$)			Ratio of Subslab Concentration to Indoor Air Concentration
	Subslab Soil Gas	Indoor Air	Outdoor Air	
VFCA	*1*	*0.65*	*0.75*	*3*
VFCB	*33,000*	*26*	*0.18*	*1,300*
VFCC	*5,200*	*5.8*	*0.14*	*900*
VFCD	*15,000*	*15*	*0.51*	*1,000*

Based upon the conceptual site model, the presence of these vapor-forming chemicals in outdoor (ambient) air is believed to be due to anthropogenic sources that are not associated with the environmental release responsible for the subsurface contamination. The building is presumed to be susceptible to vapor intrusion, as indicated by pressure monitoring data that indicate building under-pressurization, relative to the subsurface environment, during the sampling event (as discussed further in Section 6.4.1).

Based upon these findings, the presence of VFCB, VFCC, and VFCD in indoor air appears to be solely or primarily attributable to vapor intrusion. The relative proportions

[138] A goal of collecting multiple samples is to observe and characterize a reasonable maximum vapor intrusion condition for the respective building. Because weather conditions and building operations can lead to time-variable contributions from vapor intrusion (e.g., driving forces for vapor intrusion; see Section 2.3) and ambient air infiltration (see Sections 2.4), indoor air concentrations of vapor-forming chemicals can be expected to vary over time. An individual sample, collected at a randomly chosen time, may under-estimate or over-estimate average and reasonable maximum exposure conditions (see Section 6.4.1) to different degrees, depending upon the season of sample collection and other factors.

of these subsurface contaminants in indoor air and sub-slab vapor samples are similar, as indicated by a similar ratio of subslab to indoor air concentration, considering analytical uncertainty. In addition, their indoor air concentrations exceed those found in the paired sample of ambient air.

By contrast, the presence of VFCA in indoor air may be entirely attributable to infiltration of ambient air, as the sample concentrations in indoor air and outdoor are similar, considering analytical uncertainty.

Recommended next steps in the investigation might include a human health risk assessment (see Section 7.4) and a review of the conceptual site model (see Section 5.4) to evaluate whether the different conclusion for VFCA can be reasonably explained (e.g., by vapor attenuation in the vadose zone that is expected to be substantially greater than for VFCB, VFCC, and VFCD).

EPA has compiled and published an evaluation of studies pertaining to indoor air concentrations of volatile organic compounds in North American residences in 1990-2005 (EPA 2011a), which can be employed to identify whether measured indoor air concentrations in residences exceed the historical range of background concentrations. Specifically, if measured indoor air concentrations are found to greatly exceed the historical range of background levels, there is a greater likelihood that the indoor air concentrations are the result of vapor intrusion. This conclusion is supported by the expectation that current levels of vapor-forming chemicals in ambient air and in indoor air due to indoor and ambient air sources are likely to be lower than those observed historically,[139] due to regulations and business practices fostering less use of toxic chemicals in consumer products and industrial processes and reduced emissions from mobile and stationary sources. As a result of this expectation, EPA does not recommend the use of generic values of historical background concentrations, even those cited in peer-reviewed publications or available from databases maintained by regulatory agencies, to characterize current levels in any building, for purposes of supporting conclusions that indoor air concentrations are due to 'background' sources. Rather, EPA recommends that site-specific data (e.g., sub-slab, indoor air and ambient air sampling data) be obtained (as described in Sections 6.4.1, 6.4.2, and 6.4.3), and evaluated, as described above, when the investigation objectives include determining whether indoor air concentrations arise from indoor or ambient air sources.

The following additional approaches for identifying and characterizing 'background' sources may warrant consideration in special situations:

- McHugh et al. (2012) have demonstrated the principle that building over-pressurization can be employed temporarily to minimize vapor intrusion and facilitate measuring indoor

[139] McCarthy et al. (2007), for example, analyzed ambient air data for 25 toxic substances collected in the United States from 1990 through 2005 and found that concentrations of many halogenated volatile organic compounds were declining at most sites and evaluation periods (i.e., 1990-2005, 1995-2005, and 2000-2005). They found that concentrations of petroleum hydrocarbons, such as benzene, associated with mobile sources were all consistently decreasing over the three evaluation periods at most sites.

air concentrations under conditions where only indoor sources may be contributing.[140] At this time, however, there are no standard practices for using over-pressurization to assess 'background' contributions, which is a research and development need (SERDP-ESTCP 2014).

- Forensic and multi-variate statistical methods have been described and illustrated by the U.S. Navy (DoN 2011a) in its guidance for background analysis for the vapor intrusion pathway.

6.3.6 Select, Prioritize, and Sequence Investigation Objectives

Site-specific investigations of potential vapor intrusion frequently begin with pursuing one or more of the objectives presented in Sections 6.3.1 through 6.3.5. Criteria potentially warranting consideration by the site planning team when making decisions about prioritizing and sequencing investigation objectives include, but are not limited to: site scenario (see Section 6.1); building occupants who may be particularly sensitive to the potentially toxic effects of vapors; buildings that are more susceptible to soil gas entry (e.g., buildings with deteriorating basements or dirt floors; whether there are any significant data gaps in the CSM (see Section 5.4); and relationships with and perspectives of the owners and occupants of potentially impacted buildings.

Characterizing subsurface vapor sources (Section 6.3.1), characterizing subsurface vapor migration (Section 6.3.2), and evaluating the presence of subsurface contaminants in indoor air (Section 6.3.4) – are frequently candidates for an initial objective and each can be pursued separately. For example, characterizing subsurface vapor sources (Section 6.3.1) may be a useful initial choice when responding to an initial report about a release of hazardous, vapor-forming chemicals to the subsurface from a commercial or industrial operation or when buildings do not exist currently, but are expected in the future. Characterizing subsurface vapor sources may also be a useful initial choice when building owners or occupants are reluctant to grant access for indoor air testing. In this situation, the site planning team may need to pursue subsurface investigations more intensely to characterize vapor intrusion potential before being granted building access. On the other hand, testing indoor air is recommended as an initial objective when responding to reports of odors in buildings or clusters of inhalation-related symptoms and there is credible information to suggest that a subsurface environmental release may be a contributing factor (see Section 5.2).

In a different scenario, characterizing subsurface vapor migration (Section 6.3.2) may be a useful starting point when addressing sources that are comprised of potentially biodegradable chemicals or that are suspected to occur below an extensive geologic layer that might impede upward diffusive migration. For large buildings with HVAC systems that may over-pressurize the interior relative to the subsurface environment, EPA generally recommends: a building assessment early in the investigation, which obtains and weighs the complementary information

[140] Indoor air concentrations measured after sufficient periods of over-pressurization may be indicative of 'background' levels, whereas indoor air concentrations detected before and after a sufficient period of "rebound" from temporary over-pressurization may be indicative of joint contributions from 'background' sources and any vapor intrusion from the subsurface.

identified in Section 6.4.1, to support investigation planning; and an evaluation of susceptibility to soil gas entry under conditions when the HVAC system is not operating (see Section 6.3.3).

Each of the investigation objectives described in Sections 6.3.1 through 6.3.5 may, in some cases, be conducted iteratively with increasing complexity as the investigation proceeds and the CSM is refined. For example, field instruments can be useful for locating potential background sources (e.g., household or commercial cleaning products) (see Section 6.3.5) and grab (essentially short-duration) samples of indoor air, as described in Section 6.4.1, can be useful for characterizing the chemical composition of identified indoor sources of vapors during an initial building reconnaissance while potential background sources are surveyed. These activities might be followed by indoor air and sub-slab soil gas sampling, using time-integrated sampling methods as described in Section 6.4.1 and 6.4.2, to distinguish subsurface contributions from indoor sources. More advanced methods of distinguishing the various potential contributions to indoor air might be utilized, if warranted, in intermediate phases of the investigation under such an iterative approach.

6.4 General Principles and Recommendations for Sampling

Sampling of indoor air, outdoor air, soil gas, and groundwater and analysis for vapor-forming chemicals can play an important role in vapor intrusion investigations for one or more of the objectives identified in Section 6.3. This subsection summarizes for indoor air, outdoor air, sub-slab soil gas, exterior soil gas, and groundwater the following:

- Principal methods for collecting samples.
- Potential uses of the resulting sampling data.
- Recommended practices for sample collection.
- Unique or frequently encountered logistical issues.

We would note that soil and NAPL sampling has been and may be used to characterize the nature (e.g., chemical composition) and general location of subsurface vapor sources (see Section 6.3.1). Information about soil sampling can be found in *Standard Operating Procedures, Soil Sampling* (EPA-ERT 2001b). However, bulk soil (as opposed to soil gas) sampling and analysis is not currently recommended for estimating the potential for vapor intrusion to pose unacceptable human health risk in indoor air, because of the potential for vapor loss due to volatilization during soil sampling, preservation, and chemical analysis. In addition, there are uncertainties associated with soil partitioning calculations.

To ensure that the sampling data will meet the site-specific data quality needs, EPA recommends that the sampling and analytical methods selected by the site planning team be capable of obtaining reliable analytical detections of concentrations less than project-appropriate, risk-based screening levels (e.g., VISLs). Towards that end, EPA recommends that, as part of establishing site-specific data quality objectives (DQOs), the planning and data collection team(s) consult with a laboratory skilled in the analysis of air and soil gas samples and choose sampling and analytical methods capable of routinely attaining the desired detection sensitivity for each medium.

EPA also recommends that the site planning team identify and utilize appropriate sampling locations and durations and address spatial and temporal variability to fulfill the specific objectives of the investigation, which may include obtaining data to characterize the potential human exposure in a building(s). EPA recommends the CSM, the objective(s) of the investigation, and other site-specific information be considered in determining the number and types of samples used at a specific site.

The sampling duration depends on the type of medium being sampled (for example, soil gas, sub-slab soil gas, and indoor or outdoor air) and analytical methods (for example, Method TO-15). Some of the key recommended considerations are provided in the following subsections. Several rounds of sampling are recommended to develop an understanding of temporal variability[141] to ensure that final risk management decisions are based upon a consideration of a reasonable maximum vapor intrusion condition.[142]

6.4.1 Indoor Air Sampling

Indoor air sampling results are used to assess the presence of and level of human health risk posed by vapor-forming chemicals in indoor air (see Sections 6.3.4 and 7.4), and to diagnose whether vapor intrusion is occurring (see Sections 6.3.3, 6.3.5, and 7.3). These two uses of indoor air sampling in vapor intrusion investigations are discussed further below with recommended methods for each. As discussed further in Sections 8.4 and 8.7, indoor air sampling may also be useful for supporting performance evaluations of vapor intrusion mitigation systems and verifying the health protectiveness of subsurface remediation systems.

EPA recommends that the decision to collect indoor air data be supported by lines of site- or building-specific evidence (e.g., characterization of subsurface vapor source(s) strength and proximity to building(s), vadose zone conditions, and building conditions) that demonstrate that vapor intrusion has the potential to pose a significant human exposure. Confidence in the assessment is expected to be higher when multiple lines of site- or building-specific evidence, in addition to indoor air data, come together to provide mutually supporting evidence for a common understanding of the site conditions/scenarios and the potential for vapor intrusion (i.e., the various lines of evidence are in agreement with each other).

A potential shortcoming of indoor air testing is that indoor sources and outdoor sources unrelated to subsurface contamination and to releases from the subject site – “background” (see Glossary) – may contribute to the presence of volatile chemicals in occupied buildings (see Section 2.7), particularly if these sources cannot be removed from the building prior to and throughout the duration of sampling indoors. This shortcoming of indoor air testing is

[141] Seasonally variable conditions (e.g., moisture levels, depth to groundwater) can lead to seasonally variable concentrations and distributions of vapors in the vadose zone. Likewise, weather conditions and building operations can lead to time-variable contributions from vapor intrusion (e.g., driving forces for vapor intrusion; see Section 2.3) and ambient air infiltration (see Sections 2.4). Collectively, these processes cause indoor air concentrations of vapor-forming chemicals to vary over time (see Section 2.6). An individual sample (or single round of sampling) would be insufficient to characterize seasonal variability, or variability at any other time scale.

[142] EPA recommends basing the decision about whether to undertake response action for vapor intrusion (i.e., a component of risk management; see Section 7.4) on a consideration of a reasonable maximum exposure (e.g., EPA 1989, 1991a), which is intended to be a semi-quantitative phrase, referring to the lower portion of the high end of the exposure distribution (see Glossary).

unavoidable when the subsurface environment contains the very same volatile chemicals that contemporaneously arise in indoor air due to background sources, which is common for some chemicals and relatively rare for others (EPA 2011a). In this circumstance, additional lines of evidence, possibly including special procedures and analyses, may warrant evaluation to distinguish background contributions from those originating from vapor intrusion (see Section 6.3.5).

After discussing recommended sampling methods and practices for the primary uses of indoor air sampling data, this sub-section concludes by discussing:

- Recommended measures to reduce the impact of indoor sources of vapor-forming chemicals.
- Recommended approach to establishing analyte lists for indoor air samples.
- Complementary, building-specific data (i.e., additional lines of evidence) that can be collected contemporaneously while indoors.

Characterize Human Exposure Levels. Indoor air sampling and analysis provide a direct approach to obtaining concentrations of vapor-forming chemicals in indoor air to which building occupants can be exposed. For this purpose, EPA generally recommends time-integrated sampling methods, since indoor air concentrations can be temporally variable[143] and time-integrated exposure estimates over appropriate exposure durations (e.g., chronic typically; less-than-chronic in some cases) are generally most useful for assessing human exposure and human health risk (see Section 7.4).

Because of variability, a single indoor air sample, collected at a randomly chosen time, is insufficient information to estimate an average exposure. On the other hand, it is impractical to collect indoor air samples continuously over a chronic exposure period (i.e., up to 30 years for a reasonable maximum exposure duration in a residence (EPA 2014a)), which would also entail deferring risk management decisions for a prolonged period while human exposures from vapor intrusion could occur unabated. Hence, current and past practice has generally relied upon collecting multiple indoor air samples for purposes of estimating long-term average (i.e., chronic) exposures and assessing human health risk (see Section 7.4). All else being equal, a longer collection period for each individual sample would be expected to yield a more reliable basis for estimating long-term, time-average exposure than would a one-day sample collection period.

When investigating short-term exposure conditions that might warrant prompt response action to protect human health (see, for example, Sections 5.2 and 7.5.2), time-integrated indoor air samples can provide useful estimates of exposure for the location and time period of sample collection. (A short-term exposure is defined as a “repeated exposure for more than 24 hours,

[143] Because weather conditions and building operations can lead to time-variable contributions from vapor intrusion (e.g., driving forces for vapor intrusion; see Section 2.3) and ambient air infiltration (see Sections 2.4), indoor air concentrations of vapor-forming chemicals can be expected to vary over time (see Section 2.6). Field observations indicate that indoor air concentrations arising from vapor intrusion can be temporally variable within a day and between days and seasons in an individual residential building (EPA 2012f; Holton et al., 2013ab).

up to 30 days" – see Glossary.) All else being equal, a longer collection period for an individual sample would be expected to yield a more reliable basis for estimating time-average short-term exposure than a one-day sample.

As noted above, EPA also recommends considering potential health effects and relevant exposure periods for site-related, vapor-forming chemicals when developing DQOs and sampling plans for indoor air.

Variability in laboratory analyses can be considered when evaluating these data in support of risk management decisions.[144]

Time-integrated samples provide a direct measurement of the average chemical concentration over a fixed period of time (e.g., ranging from 8 hours to several weeks, depending upon the sampling method, its capabilities, and its deployment). Time-integrated samples can be collected using either evacuated canisters, which collect gas in a container, or sorbent samplers, which collect vapor-forming chemicals on a sorbent material.

Evacuated canisters

Evacuated canisters are spherical- or cylindrical-shaped stainless steel or silica-lined containers that are prepared to be under negative pressure relative to the environment and certified by the laboratory to be clean and leak-free.[145] As described in EPA Method TO-14A (EPA 1999c), evacuated canisters can be used as passive (sub-atmospheric pressure sampling) or active (pressurized sampling) samplers. In both cases, the canister is initially evacuated to a standard vacuum in preparation for sampling. For sub-atmospheric sampling, when the canister is opened for sample collection, the differential pressure causes air to flow into the canister without use of a pump. In this case, sampling must end before the vacuum is fully dissipated, else the sample collection period will be unknown. For pressurized sampling, a pump is used to pass air into the canister until a specified pressure (up to two atmospheres) is reached. In both cases, a flow-control device is used to maintain a constant flow into the canister over the desired sample period. To ensure that the canisters are filling at the proper rate, EPA recommends checking the flow rate periodically during sample collection. EPA Methods TO-14A and TO-15 provide further information on measuring and controlling flow rates into canister-type samplers.

[144] For a recently published study, EPA's ORD determined "The acceptance criterion to demonstrate equivalency is ±30% … based on what is defined as acceptable reproducibility in vapor intrusion field studies" (EPA 2012f).

[145] Canisters are cleaned and re-used because they are too expensive to dispose routinely. The certification process entails cleaning the interior of the container using a combination of dilution, heat, and high vacuum. Canisters are then analyzed for a large suite of vapor-forming chemicals to establish that they are free of detectable chemicals at a suitably low (sensitive) detection level. The cleanliness of canisters can be certified individually (i.e., direct testing of each canister, or 100% certification), which is generally desirable in instances where the data are to be used for exposure/risk assessment purposes. Alternatively, canisters can be certified by batch (or lot), in which a subset of the canisters are tested directly (e.g., 10%) and results are extrapolated to the remainder of the batch. Batch-certified canisters may be sufficient when concentrations of target analytes are expected to be high, relative to potential levels of residual contamination in the canister after cleaning. EPA recommends that flow controllers also be cleaned between uses to avoid artificial contamination.

Typically, for vapor intrusion investigations, indoor air samples are collected using six-liter canisters using sub-atmospheric pressure sampling over a 24-hour period in residences or over an 8-hour period (or workday equivalent) in commercial and industrial settings, when using these devices. Larger canisters (i.e., 15-liter) allow higher flow rates and may be preferable for longer sampling events or to collect a larger volume of sample.[146] A capillary flow controller has been developed and demonstrated for use in industrial hygiene applications (Rossner et al. 2002; Rossner and Wick 2005), which may hold promise for extending sampling time periods for indoor air with standard-sized canisters.

Details for selecting and utilizing sampling canisters are provided in EPA Methods TO-14A (EPA 1999c) and TO-15 (EPA 1999d). EPA's Environmental Response Team has developed a standard operating procedure for sampling air with evacuated canisters (EPA-ERT 1995).

An advantage of using evacuated canisters for sample collection is the capability of analyzing multiple sub-samples from the same canister (because these canisters obtain a "whole air" sample). They are also reasonably easy to deploy and retrieve. However, sample recovery and representativeness can be affected by ambient conditions; for example, low humidity conditions in the sample may lead to losses of certain volatile compounds on the canister walls (EPA 1999c).

Fourteen days is the most commonly cited hold time for air samples in canisters. Some analytes, however, may be stable in canisters for up to 30 days.

Sorbent Samplers

Sorbent sampling devices are hollow containers that hold one or more adsorbent media that can bind vapor-forming chemicals. They have been developed and tested over several decades for industrial hygiene monitoring and have more recently been employed for other purposes, including vapor intrusion investigations. Sorbent samplers can be used in an active or passive mode.

In the active mode, a pump is used to draw air at a known rate through the device. The flow rate and sampling volume are determined based on the type of sorbent used, the target constituent(s), and the amount of sorbent contained in the device. Care must be taken to ensure that the volume of air drawn through the tube does not exceed the "breakthrough" volume[147] (i.e., the volume of air which may be passed through the sorbent tube before a detectable level of the analyte concentration elutes from the non-sampling end), else the time-weighted average concentration will be biased low by an unknown amount.

In the passive mode, no pump is used, and vapor-forming chemicals enter the device due to diffusion. Consequently, passive (diffusion) samplers may be placed in locations of interest without consideration of power availability.

[146] Alternatively, two (or more) large canisters can be connected together to allow collection of time-integrated samples over longer durations, which is generally desirable for characterizing long-term average exposure levels.

[147] For this reason, sample volumes in the one- to four-liter range are generally recommended for this method (EPA 1999e).

Although passive (diffusion) samplers have been less commonly used to quantify indoor air concentrations, their use may grow as a result of recent demonstrations that they can yield results comparable to those obtained using evacuated canisters (EPA-Region 9 2010; EPA 2012f; Odencrantz et al. 2009; Odencrantz et al. 2008),[148] and a recognition that they may be less intrusive for some building owners and occupants and more convenient for field staff (EPA-Region 9 2010). Passive samplers are also capable of being deployed for longer durations than evacuated canisters, thereby providing a more economic means of obtaining average indoor air concentrations over longer periods of exposure. Time-integrated samples of indoor air over longer periods than one day are also indicated by field observations demonstrating that indoor air concentrations arising from vapor intrusion can be temporally variable within a day and between days and seasons (EPA 2012f; Holton et al., 2013a).

The basic configuration of a passive sampler is a solid, typically granular, sorbent contained in a metal, glass of plastic container with openings of known dimensions. Several different containers and a wide range of adsorptive media are commercially available, which function similarly. After sample collection, adsorbed mass is measured in a laboratory for each analyte; the two most common analytical methods involve thermal desorption or solvent extraction combined with gas chromatography/mass spectrometry. The air concentration for each analyte is calculated from the adsorbed mass, the duration of sampling, and the uptake rate.

The uptake rate is dependent upon the geometry of the sampling device and the diffusion coefficient of the analyte. The uptake rate is the most critical variable for accurately measuring air concentrations with passive samplers, since the sampling duration and adsorbed mass can generally be measured very accurately. Fortunately, most commercially available passive samplers have published uptake rates for several compounds, which collectively address many of the vapor-forming chemicals described in Section 3.1.[149] Once the target analyte(s) and uptake rate(s) are known, the sample duration needed to attain data quality objectives (i.e., reporting limit equal to or lower than the risk-based screening level or risk-based action level) can be calculated for each analyte.

Uptake rates of deployed samplers can be affected by ambient conditions (e.g., temperature, because chemical-specific diffusion rates are temperature-dependent; and humidity, which influences the uptake of water vapor, which may interfere with retention and stability of the analyte and/or with laboratory analysis). EPA, therefore, recommends that ambient conditions be recorded during deployment of passive samplers.

One potential advantage of passive samplers is that they can be left unattended for relatively longer durations, thereby conveniently providing estimates of longer-term time-

[148] For example, EPA's National Exposure Research Laboratory found that Radiello™ charcoal passive samplers performed well for sampling periods up to 28 days for TCE (EPA 2012f). In that study, one-week (7-day) Radiello™ passive samplers were utilized as a primary measurement tool and the resulting data were used as a basis of comparison to longer-duration samples (e.g., two-week, four-week (monthly), and 13-week (quarterly) samples).

[149] Standard methods for determining uptake rates have been published by a few organizations. Ideally, the selected passive sampling device will have vendor-supplied uptake rates supported by controlled chamber tests or a considerable body of field-calibrated uptake rates for most, if not all, of the target compounds.

weighted average concentrations. However, similar to active sorbent sampling, the duration of passive sampling must be such that the adsorptive capacity of the media is not approached or exceeded, else the time-weighted average concentration will be biased low by an unknown amount.

One potential disadvantage of sorbent sampling, compared to canister sampling, is that only one analysis is possible from an individual device, because it does not collect a "whole air" sample. Thus, if an error occurs in laboratory handling or there is an instrument malfunction, the sample is lost. Such errors generally are not common. Therefore, this potential disadvantage will not generally offset the benefits of sorbent sampling, the foremost of which is the ability to obtain time-integrated samples over longer periods (i.e., up to a few months for some compounds) than with evacuated canisters.

For a typical-size residential building or a commercial building less than 1,500 square feet, EPA recommends that the site teams generally collect one time-integrated sample in the area directly above the foundation floor (basement or crawl space) and one from the first floor living or occupied area, at least for the initial sampling round.[150] In general, EPA recommends samples be collected at the breathing zone level for the most sensitive exposed population.[151]

EPA recommends the site planning and data evaluation team discuss the number of sample locations per building for atypical situations, which include: (1) very large homes or buildings;[152] (2) multi-use buildings, particularly ones with segmented areas that are occupied by different populations (e.g., day care with young children versus office with adult workers) or have different occupancy patterns over time. Additional samples may also be warranted, depending on internal building partitions, HVAC layout, contaminant distribution in the subsurface, and occurrence of observable locations of potential soil gas entry (e.g., basement sumps or drains, relatively large holes or spaces in the foundation floor, entry points for utilities). Closed rooms located below ground may have appreciably higher contaminant concentrations originating from vapor intrusion. Closed rooms may warrant sampling to characterize the reasonably maximum exposure levels, if occupied, or to diagnose vapor intrusion (e.g., see below), even if not occupied.

[150] Placement of indoor air sampling devices may entail compromises. Whereas the ideal location may be a central location that is unobstructed and representative of the actual used area of a room, placement at breathing zone height in a heavily used area well away from any wall is likely to interfere with normal occupant activities.

[151] The "most sensitive" exposed population may be identifiable by combining information about the types of human occupants in a given building and the types of potential toxic effects for vapor-forming chemicals found in the subsurface environment. For example, the 'most sensitive' exposed population could be children, pregnant women, or elderly adults, depending upon building- and chemical-specific characteristics.

[152] Larger commercial and residential buildings (e.g., multi-family residences) may warrant additional discussion with the site planning team and perhaps a statistician to select the appropriate number and placement of indoor air samples to meet DQOs.

Indoor air concentrations vary over time, due to time-dependent changes in soil gas entry rates, exchange rates, intra-building mixing, among other factors (see Section 2).[153] Therefore, multiple rounds (and often several rounds) of indoor air sampling is generally recommended in order to reduce the chance of reaching a false-negative conclusion (i.e., concluding exposure is at an acceptable risk level when it is not) or reaching a false-positive conclusion (i.e., concluding exposure is at an unacceptable risk level when it is not).[154] Also, multiple sampling events generally are considered necessary to account for seasonal variations in climate and the habits of building occupants and ensure that related risk management decisions are based upon a consideration of a reasonable maximum vapor intrusion condition.[155] In many geographic areas in the continental United States, indoor air sampling during the heating season may yield higher indoor air concentrations than at other periods, because stack effects are generally more significant and, therefore, higher rates of soil gas entry are reasonably expected. Another scenario that may yield higher indoor air concentrations is when a building is sealed and the ventilation system is not operating.

When sampling indoor air (or sub-slab soil gas), EPA generally recommends removing potential indoor sources of vapor-forming chemicals (see Section 2.7) from the building to strive to ensure that the concentrations measured in the indoor air samples are attributable to the vapor intrusion pathway.[156] After removal of indoor sources, their effects may linger longer depending on source strength, relative humidity inside the building, the extent to which the contaminants have been absorbed by carpets and other fabrics or "sinks," and air exchange rate of the building. In residential settings, EPA generally recommends that potential indoor sources be removed from the structure and stored in a secure location at least 24 to 72 hours prior to the start of sampling, based on an approximate air exchange rate of 0.25 to 1.0 per hour in

[153] Because weather conditions and building operations can lead to time-variable contributions from vapor intrusion (e.g., driving forces for vapor intrusion; see Section 2.3) and ambient air infiltration (see Sections 2.4), indoor air concentrations of vapor-forming chemicals can be expected to vary over time. Holton et al. (2013ab) obtained and reported a set of long-term, high-frequency, indoor air data for an unoccupied house (except for periodic visits by researchers) in Utah overlying a plume of chlorinated hydrocarbons. TCE concentrations in indoor air varied by approximately two to three orders of magnitude, exceeding variations in measured air exchange rate.

[154] An individual sample, collected at a randomly chosen time, may under-estimate average and reasonable maximum exposure conditions. From their high-frequency, measured data, Holton et al. formulated a synthetic data set (simulating one-day-average concentrations), which they used to estimate that a single, randomly drawn, one-day sample had a forty percent chance of being less than the true mean (Holton et al. 2013b; see Table 1 therein). When the true mean was assumed to exceed the risk-based action level ("target concentration" in their parlance) by two or five times, they estimated that a single, randomly drawn, one-day sample had a twenty percent or six percent chance, respectively, of not detecting the exceedance. These data support EPA's recommendation to collect multiple rounds of indoor air sampling to reduce the chance of reaching a false-negative conclusion. Collecting multiple rounds of indoor air sampling can also reduce the chance of reaching a false-positive conclusion (i.e., concluding that vapor intrusion poses unacceptable human health risk when it does not), because an individual sample, collected at a randomly chosen time, may over-estimate the average exposure condition.

[155] Given EPA's over-arching duty to protect human health and recognizing the disruption to building owners and occupants caused by indoor air sampling, risk managers may choose to pursue pre-emptive mitigation (i.e., early action) at some buildings (see Sections 3.3 and 7.8) rather than, for example, conduct multiple rounds of sampling over a few years to establish an estimate of long-term average exposure concentration and characterize temporal variability.

[156] Vapor-detecting field instruments and in-field gas chromatographs can be used to locate indoor sources of vapors. For example, Gorder and Dettenmaier (2011) reported on the use of a field-portable gas chromatograph and mass spectrometer to identify specific sources of vapor-forming chemicals. EPA's Environmental Response Team has employed the Trace Atmospheric Gas Analyzer (TAGA) mobile laboratory for similar purposes.

residential buildings. In residences with attached garages, keeping the door(s) between the garage and the living space closed prior to and during indoor air sampling may also be warranted, in situations where the site-specific chemicals of potential concern include petroleum hydrocarbons or are components of products stored in the garage.

Diagnose Vapor Intrusion and Background Sources. When access is granted for indoor air sampling, EPA generally recommends concurrently collecting samples of sub-slab soil gas (see Section 6.4.3) and outdoor (ambient) air (see Section 6.4.4) over similar durations using the same methods. Comparing these results to each other and to results for subsurface vapor sources can foster insights and support findings about the relative contribution of vapor intrusion and background sources to indoor air concentrations (as described in Section 6.3.5). In this case, time-integrated sampling methods are recommended for indoor air, because concentrations of vapor-forming chemicals can vary significantly over time (see Section 2.6).

Grab (essentially short-duration) samples can, however, be useful for:

- confirming the presence of a subsurface contaminant in indoor air[157] (see Section 6.3.4) or in gas in a drain line or sewer lateral that enters a building,
- identifying specific vapor-forming chemicals emanating from indoor sources of consumer or commercial products[158] (see Section 6.3.5), and
- identifying specific vapor-forming chemicals emanating from suspected openings for soil gas entry into buildings (see Section 6.3.3).

Grab samples can provide a convenient and less intrusive means of confirming the presence, if any, of a site-related subsurface contaminant(s) in the indoor environment. However, an individual grab sample is not reliable for purposes of demonstrating that vapor intrusion is not occurring in a specific building; among other considerations, vapor intrusion and indoor air concentrations can exhibit significant temporal variability (EPA 2012f, Holton et al., 2013ab). Consequently, EPA recommends collecting multiple time-integrated samples to support any such building-specific determination.

Indoor air samples can also be concurrently collected for radon testing, which may be useful in evaluating building susceptibility to soil gas entry (see Section 6.3.3).

Evaluate and Develop Analyte Lists. EPA recommends the site planning and data evaluation team generally limit chemical analyses to those vapor-forming chemicals known (based upon subsurface contaminant characterization) or reasonably expected (based upon site history) to be present in the subsurface environment. For example, if the site history and reliable subsurface sampling data do not identify benzene as a subsurface contaminant, it would be appropriate for site managers to exclude benzene as a target analyte for indoor air samples. Benzene could originate indoors as a result of a car, lawnmower, or snow blower in a garage. In

[157] For this purpose, EPA generally recommends collecting one sample directly above the foundation floor (e.g., basement or crawlspace) and one from the first floor living or occupied area.

[158] For characterizing indoor sources or openings for soil gas entry, one round of grab sampling of indoor air may be sufficient.

this hypothetical case, benzene would not typically be amenable to reduction by vapor mitigation systems or subsurface remediation efforts. In fact, requesting an extensive list of analytes that are not related to subsurface contamination may unnecessarily complicate risk communication if indoor air testing reveals volatile chemicals unrelated to vapor intrusion.

Collect Complementary Data While Indoors. A variety of useful information can be gathered during a building survey conducted in advance of or during indoor air sampling. EPA recommends that the following complementary data be gathered by observation, interviews, or reports (e.g., mechanical test-and-balance reports) when buildings are to be sampled to analyze indoor air:

- Building Occupancy
    - Characteristics and locations of building occupants (e.g., residents, including children or other sensitive populations; expectations for presence of general public in commercial or industrial settings; presence of multiple exposure units – due to different uses or activities and occupants – within a building other than a single-family residence).
    - Hours of building occupancy under current conditions (and reasonably expected future conditions, as appropriate), particularly for a nonresidential setting. Because this information is pertinent to the human health risk assessment and data evaluation, EPA recommends considering hours of building occupancy when establishing the sampling duration for characterizing indoor air exposure levels.
- Susceptibility to Soil Gas Entry Under Current Conditions
    - EPA recommends that the pressure difference between the indoors and the subsurface be measured whenever indoor air samples are collected. Ideally, differential pressure data would be collected continuously starting several days before sampling and throughout the sample collection period.[159] The magnitude and direction of the pressure difference during sampling can support insights about whether a 'driving force' for vapor intrusion is present during indoor air sampling; if not, then the resulting sampling data are unlikely to characterize a reasonable maximum vapor intrusion exposure condition. Differences in driving forces (direction or magnitude) among indoor air sampling events may help to explain any significant differences in observed indoor air concentrations over time.[160] Measuring pressure difference between the indoors and the subsurface

[159] These data can be collected using portable pressure monitors installed in a dedicated sub-slab probe at one or more locations. Pressure transducers were employed for this purpose during high-frequency sampling as part of a research study in Indianapolis (EPA 2012f, see Section 3.6.6 therein); readings were recorded every 15 minutes. Technical information about pressure-measuring instruments (e.g., description, operation, and calibration) can be found in Section 4 of *Technical Guidance Document: Compliance Assurance Monitoring* (EPA 1998).

[160] Pre-mitigation measurements of the pressure difference between indoors and the subsurface may also be useful for supporting design of active depressurization technologies to reduce vapor intrusion (EPA 1993a, see Section 3 therein).

is a more direct means of assessing building under-pressurization than is monitoring weather/climate factors (e.g., air temperature, wind speed). Pressure difference monitoring in large buildings can help identify any areas with significant under-pressurization.

- Presence and operation of a mitigation system, which would generally be expected to mitigate intrusion of vapor-forming chemicals even if designed for radon.

- Physical conditions that indicate potential openings to soil gas entry (e.g., potential conduits, such as cracks or floor drains; presence of structures such as utility pits, sumps, and elevators; basements or crawl spaces; modifications to the original foundation).

- Building Heating, Ventilation, and Cooling

  - Building ventilation, including zones of mechanical influence and stagnation. As noted in Section 2.4, greater ventilation is intended to result in smaller vapor concentrations in indoor air. Any non-ventilated or passively ventilated rooms (such as mechanical rooms) may be subject to greater accumulation of vapors. For commercial and industrial buildings, each distinct zone of influence may warrant sampling, when indoor air testing is selected as part of a site-specific investigation plan for vapor intrusion assessment.

  - Operating characteristics of HVAC systems. In many commercial buildings, the HVAC system brings outdoor air into the building, potentially creating building over-pressurization relative to the outdoor environment. EPA recommends noting any areas with significant over-pressurization, relative to the outdoors.

- Indoor and Outdoor Sources of Vapor-Forming Chemicals

  - Chemicals and consumer products used or stored within the building that can act as potential sources of toxic vapors. Vapor-forming chemicals are used in many commercial and most industrial buildings.[161] As noted in Section 2.7, consumer products that can emit vapors may be common in residential buildings. In some circumstances, a photoionization detector (PID) can be used to directly screen the building for locations with vapor-forming chemicals and materials; however, the PID may not be sensitive enough for very low concentration sources. More sensitive options include use of the HAPSITE gas chromatograph/mass spectrometer (Gorder and Dettenmaier 2011) or the TAGA Mobile Laboratory (EPA-ERT 2012).

  - HVAC systems that bring outdoor air into the building potentially bring contaminated outdoor air into the building, depending on the location of the vent and exhaust with regard to other spaces. For example, HVAC intakes adjacent to

[161] Depending upon it history of uses and operations, buildings undergoing renovation, redevelopment or reuse may have lingering presence of vapor-forming chemicals due to a past release(s) also.

or near a dry-cleaning facility may introduce vapors of the dry-cleaning solvent into the building.

- In some cases, contaminated groundwater seeps into or actively collects in the building (for example, in sumps), possibly serving as a direct source of vapors. It may be appropriate to collect water samples concurrently with indoor air (and any sub-slab) samples in these circumstances.

- Presence and operation of any indoor air treatment system (e.g., in-line carbon adsorption) that can reduce indoor exposure levels of vapor-forming chemicals.

In general, EPA recommends that the foregoing complementary information be collected during investigation planning and scoping to help determine where to sample and prioritize or sequence buildings for testing. Then, the information can be confirmed during indoor sampling.

Field experience in residential settings suggests that it may not be possible to remove all indoor sources of vapor-forming chemicals. It may be particularly impractical to do so in industrial settings where vapor-forming materials are used or stored. It may also be impractical when deploying passive samplers, owing to their longer deployment period. Therefore, EPA recommends asking building occupants to document indoor sources (and relevant building operations) during indoor air sampling, using an activity log or questionnaire.

6.4.2 Outdoor Air Sampling

Outdoor air concentration data can be useful in identifying potential contributions to indoor air concentrations from ambient air sources (see Section 6.3.5). Therefore, EPA generally recommends collecting ambient air samples using similar sampling and analysis methods, whenever indoor air samples are collected. Normally, EPA recommends one or two outdoor air sample locations to characterize the conditions surrounding a single or a few buildings.[162] Additional outdoor air samples may be warranted if the investigation is assessing multiple buildings over a wide area. EPA also recommends that sample locations be designed to characterize representative conditions in the absence of site-related subsurface contamination (e.g., avoid collecting ambient air samples near locations of known or suspected chemical release(s), including any atmospheric releases from remediation equipment). It also is suggested that observable potential outdoor sources of pollutants (e.g., air emissions from nearby commercial or industrial facilities) be recorded during all building surveys.

Because concentrations of vapor-forming chemicals in ambient air can vary with time, EPA recommends that ambient air samples generally be collected over the same sampling period as indoor air, which will facilitate data evaluations when contaminant concentrations are compared between media. For residential buildings, EPA generally recommends beginning ambient air sampling at least one hour, but preferably two hours, before indoor air monitoring begins and continuing to sample until at least 30 minutes before indoor monitoring is complete. EPA recommends this practice because most residential buildings have an hourly air exchange rate in the range of 0.25 to 1.0, causing air that enters the building before indoor air sampling to

[162] For buildings where outdoor air is mechanically brought into the building, an outdoor sample may be co-located near the HVAC intake.

remain in the building for a long time (for example, see Section D.10, ITRC 2007a). Recommended lag times may warrant adjusting for nonresidential buildings.

Evaluate and Develop Analyte Lists. To characterize potential concentrations entering a building via ambient air, EPA generally recommends that chemical analyses for ambient air samples be limited to those vapor-forming chemicals known (based upon subsurface testing) or suspected (based upon site history) to be present in the subsurface environment. Requesting an extensive list of analytes that are not related to subsurface contamination, as discussed previously, may unnecessarily complicate risk communication.

Consider Collecting Complementary Data. Monitoring air exchange during ambient air sampling events can provide useful complementary data. Ideally, these data would be collected continuously starting before sampling and throughout the sample collection period. Information about air exchange can support insights about the amount of ambient air infiltration during sampling.

6.4.3 Sub-slab Soil Gas Sampling

Sub-slab sampling is intended to draw soil gas from the air space immediately below the floor slab of a building. Depending upon building construction and condition, this air space may be an air gap that forms beneath a concrete foundation due to differential settlement over time or a pore space within a granular layer that may have been placed below the concrete slab. Access to this air space is generally provided by drilling or coring through the concrete and inserting a probe, which is sealed into the floor. EPA's Environmental Response Team has developed a standard operating procedure for constructing and installing sub-slab soil gas sampling probes (EPA-ERT 2007).

Sub-slab soil gas samples can provide useful data for characterizing the levels of hazardous, vapor-forming chemicals that can enter a building via soil gas intrusion. When combined with other soil gas data, sub-slab soil gas data can be used to assess whether the subsurface vapor migration route is complete (i.e., subsurface vapor migration is capable of transporting hazardous vapors from the source to building; see Section 6.3.2). When combined with an appropriate attenuation factor (e.g., a conservative generic value – see Section 6.5.3), sub-slab soil gas data can be used to estimate a potential upper-bound indoor air concentration[163] that may arise from vapor intrusion. In this way, sub-slab data can be used to assess the potential for the vapor intrusion pathway to pose a health concern.[164]

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[163] For purposes of this Technical Guide, the term "upper bound indoor air concentration" is intended to be a semi-quantitative phrase, referring to the high end of the exposure distribution. EPA recommends basing the decision about whether to undertake response action for vapor intrusion (i.e., a component of risk management) on a consideration of a "reasonable maximum exposure" (e.g., EPA 1989, 1991a), which is intended to be a semi-quantitative phrase, referring to the lower portion of the high end of the exposure distribution (see Glossary). Alternatively, a "worst case" or "reasonable worst case" (see Glossary) indoor air concentration would refer to the upper portion of the exposure distribution. Section 6.6, which discusses mathematical modeling of vapor intrusion, notes that consideration of a "worst case" exposure condition may be particularly useful where the predicted "worst case" indoor air concentrations can be shown to pose acceptable human health risk.

[164] The sub-slab soil gas concentration provides only half of the information for estimating vapor flux into a building. The other information needed is the soil gas flow rate (Q_{soil}), which is embodied in the attenuation factor. The soil gas flow rate can also be explicitly calculated using a model.

Field experience indicates there may be substantial spatial variability in sub-slab soil gas concentrations even over an average-sized footprint of a residential building. EPA, therefore, recommends site planning and data review teams consider collecting multiple samples per building when sub-slab soil gas sampling is conducted.[165] Three sub-slab samples have been collected in a number of EPA investigations of a typical size residential building or commercial building less than 1,500 square feet in area. EPA recommends the site planning and data evaluation team discuss the number of sample locations per building for atypical situations, which include: (1) very large or small homes or buildings;[166] (2) buildings with more than one foundation floor type;[167] (3) subsurface structures or conditions that might facilitate or mitigate vapor intrusion; and 4) multi-use buildings with distinct segmented areas that differ significantly by occupying population or exposure frequency. In addition, EPA recommends multi-point sub-slab samples be considered to support data interpretation and resolve uncertainties that may arise when:

- There are fewer surrounding buildings that are being sampled (that could have helped the understanding of typical sub-slab values and variability).[168]

- The indoor and sub-slab concentrations for a specific building(s) are out of line with expectations based on data from neighboring homes and other information.

EPA generally recommends that sub-slab sampling include centrally located sub-slab samples in buildings identified for testing when the subsurface vapor source is laterally extensive relative to the building footprint (e.g., a broad plume of contaminated groundwater).[169] In addition, EPA recommends that site teams consider internal building partitions, HVAC layout, contaminant distribution, utility conduits, and openings for preferential soil gas entry in selecting any additional locations for collecting sub-slab samples.

Several rounds of sampling are generally recommended to develop an understanding of temporal variability of sub-slab soil gas concentrations, particularly when these data are used with the recommended attenuation factor (see Section 6.5.3) to estimate a potential upper-bound indoor air concentration that may arise from vapor intrusion.

[165] An individual sample, collected at a randomly chosen time, may under-estimate or over-estimate average subslab conditions. Collecting multiple subslab soil gas samples can, therefore, reduce the chance of reaching a false-negative conclusion (i.e., concluding subsurface vapor source strength is limited, when vapor intrusion actually poses an unacceptable human health risk) or a false-positive conclusion (i.e., concluding subsurface vapor source strength is unacceptably elevated, when vapor intrusion actually poses an acceptable human health risk).

[166] For larger structures, a statistician may assist in identifying the number and placement of sampling ports to meet the desired DQOs.

[167] In basements with a partial slab, but one large enough to allow vapors to accumulate (for example, if the slab covers more than 50 percent of the building footprint), EPA generally recommends that one sub-slab port be installed on the slab portion and an indoor air sample be collected directly over the dirt portion.

[168] In these cases, EPA recommends multiple ports be installed in a specific percentage (e.g., more than 10 percent) of the buildings sampled to provide a check for variability in the study area.

[169] Based on work conducted in New York as of the spring of 2010, it appears that the sub-slab concentrations beneath the central area of a home are usually (75 percent of the time) higher than (or as high as) the concentrations closer to the perimeter of the home. This field observation is supported by modeling results for idealized scenarios, which show greater sub-slab soil gas concentrations near foundation centers in under-pressurized residential buildings when the vapor source is laterally extensive relative to the building footprint (EPA 2012b).

If a site team decides to proceed with sub-slab sampling, EPA recommends that leak-testing be performed to ensure the hole is properly sealed, for example through the use of a helium tracer gas shroud. Because installing soil gas probes can disturb subsurface conditions, EPA recommends that the site team allow some time after the sampling probe has been installed for the subsurface to return to equilibrium conditions. An EPA study of the time needed for the subsurface conditions to come back to equilibrium (equilibration rate) after they have been disturbed by installation of the soil gas probes found that an equilibration time of two hours generally was sufficient because most sub-slab material consists of sand or a sand-gravel mixture—even for buildings built directly on clay (Section 5.0, EPA 2006b).

There also may be special considerations for sub-slab soil gas samples because of either a unique construction (for example, pretension concrete slab) or environmental situation. Key EPA recommendations include, but are not limited to:

- Identify the location of cables in post-tensioned concrete (e.g., using ground-penetrating radar) before sub-slab sampling, as drilling through a cable poses a significant health and safety concern and may damage the slab.

- Avoid locating sub-slab samples in areas where groundwater might intersect the slab.

- Identify and avoid the location(s) of underground utilities and structures (for example, electric, gas, water, or sewer lines) to prevent damage to these lines; however, sample collection in close proximity to these lines may be warranted as building penetrations for these lines may pose openings for soil gas entry.

- Consider whether to augment sub-slab samples with samples through the basement walls, as the primary entry points for vapors in basements might be through the sidewalls rather than from below the floor slab.

Evaluate and Develop Analyte Lists. To characterize potential concentrations entering a building via soil gas, EPA generally recommends that chemical analyses for sub-slab soil gas samples be limited to those vapor-forming chemicals known (based upon subsurface testing) or suspected (based upon site history) to be present in the subsurface environment. Requesting an extensive list of analytes that are not related to subsurface contamination, as discussed previously, may unnecessarily complicate risk communication.

Collect Complementary Data While Indoors. When sub-slab soil gas samples are collected, EPA recommends that the following complementary information be gathered by observation or interviews:

- Physical conditions and characteristics that are pertinent to assessing the building's susceptibility to soil gas entry, if any (e.g., potential conduits, such as cracks or floor drains; presence of structures, such as utility pits and elevators; basements or crawl spaces). Such information may help interpret spatial differences in sub-slab or indoor air concentrations within a building.

- Areas with potentially significant over- or under-pressurization relative to the outdoors. Such information may assist in interpreting spatial differences in sub-slab or indoor air concentrations within a building.

- Where outdoor air is mechanically brought into the building by the HVAC system and building(s) interiors are over-pressurized, it may be helpful to also collect ambient air samples to support interpretations of the sub-slab sampling results. If the predominant vapor-forming substances and their respective concentrations in sub-slab soil gas and outdoor air samples are similar, then ambient air may be influencing sub-slab soil gas conditions.

EPA recommends that the pressure difference between the indoors and the subsurface be measured whenever sub-slab soil gas samples are collected. Ideally, differential pressure data would be collected continuously starting several days before sampling and throughout the sample collection period.[170] EPA recommends measuring pressure at locations away from where sub-slab sampling probes are installed to avoid any pressure artifacts caused during purging and sampling. The magnitude and direction of the pressure difference during sampling can support insights about whether a driving force for vapor intrusion is present during sampling.

When any sub-slab soil gas sample is collected, EPA recommends that relevant meteorological data that can influence soil gas concentration patterns at the time of sampling, such as wind speed, snow or ice cover, significant recent precipitation, and changes in barometric pressure, be recorded, using direct observation (e.g., for snow or ice cover) or readily available data sources (e.g., regional weather stations). These data may be helpful qualitatively in data interpretation; for example, in reconciling soil gas data collected on multiple occasions.

A potential shortcoming of sub-slab soil gas testing is that gaining access may be difficult (or, in some cases, infeasible). This difficulty can often be overcome by implementing a program of community outreach and engagement that fosters trust and good relationships (see Section 9.0).

When access is granted for indoor sampling, EPA recommends collecting sub-slab and indoor air samples contemporaneously using similar sampling and analysis methods and sampling durations to allow for data comparison. The sub-slab sampling ports can be installed after the indoor air sample is deployed and collected (8 - 24 hours later) to avoid biasing the indoor air concentrations with potentially higher sub-slab gas infiltration rates during port installation. Alternatively, the sub-slab ports may be installed prior to indoor air sampling and sampled concurrently with the indoor air samples, provided sufficient time is allowed for the indoor air concentrations to return to “normal” after installation of the sub-slab port.[171]

[170] These data can be collected using portable pressure monitors installed in a dedicated sub-slab probe at one or more locations. Pressure transducers were employed for this purpose during high-frequency sampling as part of a research study in Indianapolis (EPA 2012f, see Section 3.6.6 therein); readings were recorded every 15 minutes. Technical information about pressure-measuring instruments (e.g., description, operation, and calibration) can be found in Section 4 of *Technical Guidance Document: Compliance Assurance Monitoring* (EPA 1998).

[171] EPA generally recommends delaying indoor air testing for at least 24 to 72 hours based on an approximate air exchange rate of 0.25 to 1.0 per hour. Note that the effects of any ‘spike’ in indoor air concentration may linger depending on source strength, relative humidity inside the building, and the extent to which the contaminants have been absorbed by carpets and other fabrics or “sinks.”

6.4.4 Soil Gas Sampling

Data obtained from a soil gas survey can be used to identify, locate, and characterize subsurface vapor sources (see Section 6.3.1) and characterize subsurface vapor migration routes, including any impedances from geologic, hydrologic, or biochemical conditions (see Section 6.3.2). Soil gas survey data can also be useful in supporting the design of soil vapor extraction systems and other subsurface remediation systems and the performance assessment of these systems (see Section 8.1). For each of these purposes, EPA recommends that soil gas survey data be supported by site-specific geologic information (i.e., site geology and subsurface lithology).

Soil gas sampling generally consists of installing a probe into the ground, drawing gas out of the probe, and collecting the gas for transport to a location for analysis. Inert materials (e.g., stainless steel, copper, brass, polyvinyl chloride, high-density polyethylene) are recommended for constructing soil gas probes. To ensure that data collected are representative of conditions *in situ* (e.g., are not adversely impacted by artificial infiltration of ambient air), a reliable seal of the annulus between the probe and the probe housing and leak testing for the seal are generally recommended. In addition, purging of the probe before collecting the soil gas sample is recommended, analogous to purging of monitoring wells before collecting groundwater samples. EPA's Environmental Response Team has developed a standard operating procedure for soil gas sampling, including constructing and installing sampling probes (EPA-ERT 2001c).

Typically, grab (rather than time-integrated) samples are collected when sampling soil gas. EPA recommends that the site team allow some time after the sampler has been installed for the subsurface to return to equilibrium conditions because installing temporary or permanent soil gas probes can disturb subsurface conditions. The equilibration time may depend on the degree of soil disturbance during installation, which is influenced by the type of drilling techniques used to install the soil gas probes (e.g., with more time needed for auger drilling compared with hand drilling). For example, the California Environmental Protection Agency recommends an equilibration time of two hours for temporary driven probes and 48 hours for probes installed using augered borings (CalEPA 2012).

EPA recommends documenting wind direction, precipitation information, temperature, and other site-specific information that can influence soil gas concentration patterns at the time of sampling, using readily available data sources. These data may be helpful qualitatively in data interpretation; for example, in reconciling soil gas data collected on multiple occasions or assessing concordance of sampling data from various media, when not collected contemporaneously.

EPA recommends that soil gas samples be taken as close to the areas of interest as possible and preferably from directly beneath the building structure. As vapors are likely to migrate upward through the coarsest or driest material in the vadose zone, EPA recommends that soil gas samples be collected from these materials.

Using vertical boring or drilling techniques, it is generally practical to collect soil gas samples only in locations exterior or adjacent to a building's footprint ("exterior" soil gas samples). Modeling results for idealized scenarios show that, in homogeneous soil, soil gas concentrations tend to be greater beneath the building than at the same depth in adjacent open areas when the vapor source is underneath the building, even if the source is laterally extensive relative to the building footprint (e.g., broad plume of contaminated groundwater) (EPA 2012b). Given these

predictions and supporting field evidence (EPA 2012a, see Figure 6; Luo et al. 2009; Patterson and Davis 2009, see Figure 1), individual exterior soil gas samples cannot generally be expected to accurately estimate sub-slab or indoor air concentrations. This potential limitation may be particularly valid for shallow soil gas samples collected exterior or adjacent to a building footprint. On the other hand, when the subsurface vapor source is not underneath the building, "exterior" soil gas samples collected from depths below a building's foundation and along the side of the building closest to the source may be useful for characterizing a reasonable worst case condition underneath the building in the absence of routes for preferential vapor migration or soil gas entry.

Deeper soil gas samples collected in the vadose zone immediately above the source of vapor contamination (i.e., "near-source" soil gas samples; see Section 6.3.1) can reasonably be expected to be less susceptible to the diluting effects of ambient air, compared to shallow soil gas samples. On this basis, deeper soil gas samples collected in the vadose zone immediately above the source of vapor contamination will tend to be more suitable than will be shallow soil gas samples for assessing vapor concentrations that may be in contact with the building's sub-slab.[172] Several rounds of sampling are generally recommended to develop an understanding of temporal variability of "near-source" soil gas concentrations, particularly when these data are used with the recommended attenuation factor (e.g., a conservative generic value – see Section 6.5.3) to estimate a potential upper-bound indoor air concentration that may arise from vapor intrusion.[173]

6.4.5 Groundwater Sampling

Groundwater sampling and analysis also feature prominently in many vapor intrusion investigations, for example, to help characterize plumes that can serve as vapor sources. Groundwater sampling methods are not discussed here because practitioners typically are relatively experienced and trained to collect samples that meet site-specific data quality needs (see, for example, EPA-ERT 2001a). However, Section 6.3.1 provides a few recommended guidelines for groundwater sampling that are pertinent for characterizing representative vapor source concentrations for vapor intrusion assessment. One key consideration in sampling groundwater for vapor intrusion investigations is focusing on characterizing water table

[172] Luo et al. (2009) also point to the shortcomings of relying on exterior sampling data, citing significant differences in vapor concentrations and soil gas composition between interior and exterior sampling locations at a maintenance warehouse located at a former refinery. They also observed that the spatial variability in the soil-gas distribution was smaller for soil-gas samples drawn from the source zone, suggesting greater confidence in the assessment of source zone or "near source" vapor concentrations.

[173] For purposes of this Technical Guide, the term "upper bound indoor air concentration" is intended to be a semi-quantitative phrase, referring to the high end of the exposure distribution. EPA recommends basing decisions about whether to undertake response action for vapor intrusion (i.e., a component of risk management) on a consideration of a reasonable maximum exposure (e.g., EPA 1989, 1991a), which is intended to be a semi-quantitative phrase, referring to the lower portion of the high end of the exposure distribution (see Glossary). Alternatively, a "worst case" or "reasonable worst case" (see Glossary) indoor air concentration would refer to the upper portion of the exposure distribution. Section 6.6, which discusses mathematical modeling of vapor intrusion, notes that consideration of a "worst case" exposure condition may be particularly useful where the predicted "worst case" indoor air concentrations can be shown to pose acceptable human health risk.

concentrations. EPA recommends that groundwater samples be taken from wells screened (preferably over short intervals) across the top of the water table.[174]

Groundwater data can be compared to the groundwater VISLs (see Section 6.5).[175] When combined with an appropriate attenuation factor (see Section 6.5.3), groundwater data can be used to estimate a potential upper-bound indoor air concentration that may arise from vapor intrusion.[176] In these ways, groundwater data can be used to assess the potential for vapor intrusion from groundwater sources to pose a health concern.

6.4.6 Planning for Building and Property Access

Vapor intrusion investigations generally entail gaining legal access to buildings and properties to conduct sampling. To address this practical and logistical concern during the planning stage, EPA recommends that an access agreement be executed between the property owner, any occupants, and the investigating entity. Section 9.3 provides additional information for addressing building and property access for sampling.

Obtaining and scheduling access to a property and building can be difficult, whether the structure is a commercial or institutional building or a private residence. This potential difficulty can often be overcome by implementing a program of community outreach and engagement that fosters trust and good relationships. EPA recommends conducting public outreach and communication for this purpose considering the site-specific community involvement plan (See Section 9.1).

6.5 Overview of Risk-Based Screening

Risk screening for vapor intrusion generally is performed using site-specific data collected via appropriate methods, as described in Section 6.4. In some cases, pre-existing data identified during a preliminary analysis can be deemed reliable and adequate for use in risk-based screening (see Section 5.5).

6.5.1 Objectives of Screening

The primary objective of risk-based screening is to identify sites or buildings unlikely to pose a health concern through the vapor intrusion pathway. Generally, at properties where subsurface concentrations of vapor-forming chemicals (e.g., groundwater or "near source" soil gas concentrations) fall below screening levels (i.e., VISLs), no further action or study is warranted, so long as the exposure assumptions match those taken into account by the calculations and the site fulfills the conditions and assumptions of the generic conceptual model underlying the

[174] EPA recommends that, to the extent practical, groundwater samples be collected over a narrow interval (e.g., a few feet or less) just below the water table when the data are to be used for assessing the potential for vapor intrusion.

[175] If available groundwater data do not meet the criteria set forth in Section 6.4.5, the site data review team may judge whether they are nevertheless representative of potential vapor source concentrations emanating from groundwater.

[176] EPA recommends basing decisions about whether to undertake response action for vapor intrusion (i.e., a component of risk management) on a consideration of a reasonable maximum exposure (e.g., EPA 1989, 1991a).

screening levels. In a similar fashion, the results of risk-based screening can help the data review team identify areas, buildings, and/or chemicals that can be eliminated from further assessment.

Subsurface concentrations of vapor-forming chemicals that exceed the VISL for the respective medium (e.g., groundwater, soil gas, subslab soil gas) would not automatically trigger mitigation or subsurface remediation (i.e., they are not offered as response action levels or cleanup levels). Exceeding a subsurface screening level generally suggests, however, that further evaluation of the vapor intrusion pathway is appropriate. In this way, risk-based screening, along with other lines of evidence, can help focus a subsequent site-specific investigation, the results of which would provide support for considering building mitigation and other risk management options (see Section 8.0). For example, the results of vapor source strength screening can help identify and prioritize buildings for indoor testing.

Finally, risk-based screening can also support:

- a preliminary evaluation of human health risk using individual building data (e.g., indoor air concentrations), which would consider the magnitude of the concentration exceedance of the indoor air screening level and site-specific risk management benchmarks (see Section 7.4.1); and

- identification of buildings and structures that may warrant prompt action due to potential explosion threats (see Section 7.5.1).

6.5.2 Scope and Basis for Health-based, Vapor Intrusion Screening Levels

EPA developed VISLs for human health protection that are generally recommended, medium-specific, risk-based screening-level concentrations intended for use in identifying areas or buildings that may warrant further investigation of the vapor intrusion pathway. These VISLs are calculated and documented in the VISL Calculator and are based on:

- Current toxicity values selected considering OSWER's hierarchy of sources for toxicity values (EPA 2003).

- Physical-chemical parameters for vapor-forming chemicals.

- EPA-recommended approaches for human health risk assessment (e.g., EPA 2009c, 2014a).

The VISLs for human health protection include indoor air screening levels for long-term (i.e., chronic) exposures, which consider the potential for cancer and noncancer effects of vapor-forming chemicals.[177] The VISLs for human health protection also include subsurface screening levels for comparison to sub-slab soil gas, "near-source" soil gas, and groundwater sampling

[177] The VISL Calculator does not include information about radon. Information about characterizing the human health risk posed by radon can be found on-line at: http://epa-prgs.ornl.gov/radionuclides/

results. These screening levels are derived from the indoor air screening levels for chronic exposures using medium-specific, generic attenuation factors described further in Section 6.5.3 and Appendix A. The user's guide for the VISL Calculator provides additional information about derivation of the indoor air and subsurface screening levels (EPA 2015a).

The medium-specific VISLs for human health protection are intended to be compared to:

- Building-specific data, such as results from sub-slab soil gas samples, crawl space samples, or indoor air samples; or
- Site- or building-specific data that characterize subsurface vapor sources (e.g., groundwater samples, "near-source" soil gas concentrations)

to determine if there is a potential for the vapor intrusion pathway to pose a health concern to building occupants.

The medium-specific VISLs for health protection are developed considering a generic conceptual model for vapor intrusion consisting of:

- A source of vapors underneath the building(s) either in the vadose zone or in the uppermost, continuous zone of groundwater.
- Vapor migration via diffusion upwards through unsaturated soils from these sources toward the ground surface and overlying buildings.
- Buildings with poured concrete foundations (e.g., basement or slab-on-grade foundations) that are susceptible to soil gas entry.

A critical assumption for this generic model is that site-specific subsurface characteristics will tend to reduce or attenuate soil gas concentrations as vapors migrate upward from the source and into overlying structures. Specific factors that may result in relatively unattenuated or enhanced transport of vapors into a building include the following:

- Significant openings to the subsurface that facilitate soil gas entry into the building (e.g., sumps, unlined crawl spaces, earthen floors) other than typical utility penetrations. [178]
- Very shallow groundwater sources (e.g., depths to water less than five feet below foundation level) (see, for example, EPA (2012a), Section 5.2).
- Significant routes for preferential, subsurface vapor migration whether naturally-occurring (e.g., fractured bedrock) or anthropogenic (see Sections 5.4 and 6.3.2).

[178] For purposes of this Technical Guide, the term "significant openings" is intended to refer to forms and amounts of openings, other than adventitious and intentional openings in a building that are expected to typically be present in all buildings (e.g., cracks, seams, interstices, and gaps in basement floors and walls or foundations; perforations due to utility conduits). Such an atypical opening would be "significant" when it is of sufficient volume and proximity to a building that it may be reasonably anticipated to influence vapor migration towards or soil gas entry into the building.

These specific factors are likely to render inappropriate the use of the recommended attenuation factors and the sub-slab, groundwater, and soil gas VISLs for purposes of identifying sites or buildings unlikely to pose a health concern through the vapor intrusion pathway. On the other hand, further evaluation of the vapor intrusion pathway is still appropriate when the sub-slab, groundwater, and soil gas VISLs are exceeded for samples from a building or site where these specific factors are present.

Vapor source types that typically make the use of the recommended attenuation factors and health-based VISLs for groundwater and soil gas inappropriate include:

- Those originating in landfills where methane is generated in sufficient quantities to induce advective transport in the vadose zone.

- Those originating in commercial or industrial settings where vapor-forming chemicals can be released within an enclosed space and the density of the chemicals' vapor may result in significant advective transport of the vapors downward through cracks and openings in floors and into the vadose zone.

- Leaking vapors from pressurized gas transmission lines.

In each case, the diffusive transport of vapors may be overridden by advective transport, and the vapors may be transported in the vadose zone several hundred feet from the source of contamination with little attenuation in concentration.

In general, EPA recommends considering whether the assumptions underlying the generic conceptual model are attained at a given site. If they are not attained, then EPA recommends that the medium-specific VISLs not be relied upon as a line of evidence for identifying sites or buildings unlikely to pose a health concern through the vapor intrusion pathway. Where the assumptions regarding the subsurface attenuation factors do not or may not apply, EPA generally recommends collecting indoor air samples.

As noted in Section 6.5.1, these VISLs are not automatically response action levels, although EPA recommends that similar calculation algorithms be employed to derive cleanup levels (see Section 7.6)**.** Comparison of sample concentrations to the VISLs is only one factor recommended for use in determining the need for a response action at a site. As discussed further in Section 6.5.4, an individual subsurface sampling result that exceeds the respective, chronic screening level does not establish that vapor intrusion will pose an unacceptable human health risk to building occupants. Conversely, these generic, single-chemical VISLs do not account for the cumulative effect of all vapor-forming chemicals that may be present. Thus, if multiple chemicals that have a common, non-cancer toxic effect are present, a significant health threat may exist at a specific building or site even if none of the individual substances exceeds its VISL (see discussion of non-cancer hazard index in Section 7.4.1).

6.5.3 Recommended Attenuation Factors for Health-based Screening

Vapor attenuation refers to the reduction in volatile chemical concentrations that occurs during vapor migration in the subsurface, coupled with the dilution that can occur when the vapors enter a building and mix with indoor air (Johnson and Ettinger 1991). The aggregate effect of these physical and chemical attenuation mechanisms can be quantified through the use of a vapor intrusion attenuation factor, which is defined as the ratio of the indoor air concentration

arising from vapor intrusion to the soil gas concentration at the source or a depth of interest in the vapor migration route (EPA 2012a).[179]

EPA compiled a database of empirical attenuation factors for chlorinated VOCs and residential buildings through review of data from 913 buildings at 41 sites with indoor air concentrations paired with sub-slab soil gas, groundwater, exterior soil gas, or crawl space concentrations (EPA 2012a). After removing data that do not meet quality criteria and data likely to be influenced by background sources, the distributions of the remaining attenuation factors were analyzed graphically and statistically.[180] Based upon these analyses, the attenuation factors in Table 6-1 are recommended by EPA to derive the VISLs for health protection.

With the exception of the "near-source" exterior soil gas attenuation factor, the recommended values for residential buildings are the estimated 95th percentile values, rounded to one significant figure.[181] The rationale for these recommendations and related analyses are provided in Appendix A. These recommended values are proposed to apply to all vapor-forming chemicals for use in estimating potential upper-bound concentrations in indoor air that may arise from vapor intrusion.[182] The recommended groundwater and "near-source" soil gas attenuation factors do not, however, include the effects of biodegradation.[183] On the other hand, because biodegradation is not expected to occur indoors (i.e., in indoor air in the absence of an air treatment system), the sub-slab soil gas and crawl space attenuation factors are expected to apply equally to vapor-forming chemicals that biodegrade in the vadose zone and those that do not.

As with the medium-specific VISLs, EPA recommends considering whether there are site- or building-specific factors that may result in unattenuated or enhanced transport of vapors toward and into a building, such as the presence of preferential migration route(s) as described in Sections 5.4 and 6.3.2. The presence of such factors is likely to render inappropriate the use of any of these generic attenuation factors.

[179] As defined here, the vapor attenuation factor is an inverse measurement of the overall dilution that occurs as vapors migrate from a subsurface vapor source into a building; i.e., lower attenuation factor values indicate lower vapor intrusion impacts and greater dilution; higher values indicate greater vapor intrusion impacts and less dilution (EPA 2012a, b). Johnson and Ettinger (1991) utilized the symbol α for the vapor intrusion attenuation factor. For example, the subslab soil gas attenuation factor is intended to account for concentration dilution arising during migration through openings in the foundation and from mixing of subsurface contaminants inside the building. The groundwater attenuation factor is intended to account for concentration dilution arising during vapor migration from the groundwater table through the vadose zone, in addition to concentration dilution arising during migration through openings in the foundation and from mixing of subsurface contaminants inside the building.

[180] A summary of the resulting distributions is provided in Appendix A of this document.

[181] The recommended "near-source" exterior soil gas attenuation factor corresponds to approximately the estimated 75th percentile value.

[182] EPA recommends basing decisions about whether to undertake response action for vapor intrusion (i.e., a component of risk management) on a consideration of a reasonable maximum exposure (e.g., EPA 1989, 1991a).

[183] Appropriate data can be collected and evaluated, as described in Section 6.3.2, to characterize and document the occurrence of biodegradation in the vadose zone and its effects in attenuating vapor concentrations of biodegradable vapor-forming chemicals.

TABLE 6-1
RECOMMENDED VAPOR ATTENUATION FACTORS FOR RISK-BASED SCREENING OF THE VAPOR INTRUSION PATHWAY[184]

Sampling Medium	Medium-specific Attenuation Factor for Residential Buildings
Groundwater, generic value, except for shallow water tables (less than five feet below foundation) or presence of preferential vapor migration routes in vadose zone soils	1E-03 (0.001)
Groundwater, specific value for fine-grained vadose zone soils, when laterally extensive layers are present[185]	5E-04 (0.0005)
Sub-slab soil gas, generic value	3E-02 (0.03)
"Near-source" exterior soil gas, generic value except for sources in the vadose zone (less than five feet below foundation) or presence of routes for preferential vapor migration in vadose zone soils	3E-02 (0.03)
Crawl space air, generic value	1E-00 (1.0)

The VISL Calculator (http://www.epa.gov/oswer/vaporintrusion/guidance.html) also facilitates calculation of groundwater screening levels based on the recommended attenuation factor for fine-grained soil. EPA recommends that any use and application of this semi-site-specific groundwater attenuation factor be supported by site-specific geologic information (i.e., site geology and subsurface lithology). Significant characterization of the vadose zone may be needed to demonstrate that fine-grained layers are laterally extensive over distances that are large compared to the size of the building(s) or the extent of vapor contamination at a specific site, which is the recommended support for using the semi-site-specific attenuation factor for

[184] Use of these attenuation factors for estimating indoor air concentrations is contingent upon site conditions fitting the generic model of vapor intrusion described in Section 6.5.2 and subsurface conditions being characterized considering the recommendations in Sections 6.3 and 6.4.

[185] The Draft VI Guidance allowed for the modification of VISLs for groundwater by incorporating a lower attenuation factor, based upon "some site-specific inputs", which estimates a greater reduction in vapor concentrations in the vadose zone than the generic value (EPA 2002c, 2010b). In the Draft VI Guidance, graphs were provided from which such "semi-site-specific" attenuation factors could be selected and justified based upon site-specific soil type and depth to the water table. Based upon analysis of EPA's expanded database, a single groundwater attenuation factor is provided in this Technical Guide for fine-grained soils.

fine-grained soil.[186] For purposes of applying the groundwater attenuation factors, EPA recommends the depth to groundwater be estimated relative to the bottom of the building foundation and be based upon the seasonal high groundwater table.

6.5.4 Comparing Sample Concentrations to Health-based Screening Levels

When evaluating environmental sampling results to assess the vapor intrusion pathway, it is important to first determine that the samples were collected appropriately. Section 6.4 provides information about recommended sampling locations and procedures for vapor intrusion investigations. In addition, EPA recommends collecting and evaluating appropriate site-specific information to demonstrate that the property fulfills the conditions and assumptions of the generic conceptual model underlying the VISLs, as described in Section 6.5.2.

After verifying that the CSM justifies the use of the VISLs, the individual sample concentrations may be compared to the appropriate medium-specific screening levels. In order to select the appropriate target media concentrations for comparison, it generally is important to identify whether a source of vapors for a building or a developed area occurs in the unsaturated zone, which is an important aspect of the CSM. This allows the site data to be segregated into two categories:

- Data representing areas where contaminated groundwater is the only source of contaminant vapors.

  In this first case, groundwater VISLs are generally appropriate to use to evaluate groundwater concentrations (also see sampling recommendations in Sections 6.3.1 and 6.4.5). Under these circumstances, EPA recommends that the plume be shown to be stable or shrinking (i.e., is not migrating or rising in concentration, including hazardous byproducts of any biodegradation) to establish that the potential for vapor intrusion to pose a human health risk from vapor intrusion will not increase in the future. "Near-source" soil gas data (i.e., soil gas samples collected immediately above the water table) could also be compared to the soil gas VISLs to obtain a corroborating line of evidence (see recommendations in Section 6.3.1).

  When the anticipated outcome of the screening is a finding that groundwater poses acceptable human health risk from vapor intrusion on an area-wide basis, it may be appropriate to compare sampling results for the most greatly impacted well within the area of interest and show that these results are less than the groundwater VISLs.

- Data representing areas where the underlying vadose zone soil contains a source of vapors (e.g., residual NAPL).

  In this second case, EPA recommends that only soil gas VISLs be used and compared to results from "near-source" soil gas samples collected near the vapor source zone

[186] The general soil type assigned to paired vapor intrusion data in the EPA's database "generally represents the coarsest soil described in the vadose zone near the sample location" unless "sufficient stratigraphic information was available to indicate finer sediments are laterally continuous" (EPA 2012a). EPA recommends that similar criteria be applied to justifying the use of the semi-site-specific attenuation factor for groundwater (or selection of soil-related parameters for modeling); see Section 6.6. For these purposes, soil classified as clay, silty clay, silty clay loam, or silt consistent with the U.S. Soil Conservation Service classification system can be considered to be "fine-grained."

(also see sampling recommendations in Sections 6.3.1 and 6.4.4). In this situation, the groundwater VISLs (and vapor attenuation factors for groundwater) are not recommended for estimating potential upper-bound indoor air concentrations, because they have been derived assuming no other vapor sources exist between the water table and the building foundation.

In both cases, because of the complexity of the vapor intrusion pathway, EPA recommends that professional judgment be used when applying the VISLs.

Generally, if all subsurface sample concentrations for a given building or area are less than the respective medium-specific screening level, then vapor intrusion is less likely to pose an unacceptable human health risk to building occupants. On the other hand, when individual sample concentrations exceed the respective screening level, additional assessments may be warranted. So, for example, if a groundwater or "near-source" soil gas concentration exceeds the respective screening level, it is recommended that sub-slab soil gas testing and indoor air testing be conducted.

However, we would note that any individual subsurface sampling result that exceeds the respective, chronic screening level does not establish that vapor intrusion will pose an unacceptable human health risk to building occupants. For one, the subsurface screening levels are expected to be conservative (i.e., are likely to over-estimate the contribution to indoor air levels arising from vapor intrusion) for many buildings due to the use of a high-end attenuation factor (see Section 6.5.3). In many cases, indoor air concentrations arising from vapor intrusion would be expected to be lower than those estimated using the recommended generic attenuation factors. For carcinogens, the screening levels are set using a one-per-million lifetime cancer risk (i.e., 10^{-6}), whereas EPA recommends consideration of a cancer risk range when making risk management decisions (see Section 7.4.1). Finally, sampling results can be expected to be variable spatially and temporally and these screening levels assume a long period of exposure at the stated concentration.

Owing to the temporal variability in building-specific data and the potential temporal and spatial variability in soil gas vapor concentrations, EPA generally recommends multiple samples be collected (see Section 6.4) and compared to the respective medium-specific screening level. In addition, the results of risk-based screening are generally most useful when they can be evaluated for indoor air and subsurface vapor sources concurrently and in the context of the CSM. EPA, therefore, generally recommends that multiple lines of evidence be developed and their results weighed together when evaluating and making risk-informed decisions pertaining to vapor intrusion. EPA generally recommends that concordance among the multiple lines of evidence be obtained, particularly when considering a determination that the vapor intrusion pathway is incomplete or does not pose an unacceptable human health risk. Sections 7.1, 7.2, and 7.3 provide additional information and recommendations about developing and using multiple lines of evidence and risk management decision-making.

6.5.5 Planning for Communication of Sampling Results

EPA recommends the community involvement or public participation plan (See Section 9.1) describe and address community questions, concerns, and preferences for participation regarding sampling results. Generally, EPA recommends that the site planning team provide validated results to property owners and occupants. These results can be transmitted to relevant parties in a letter, along with a description of what future actions, if any, may be

warranted. In addition, the site planning team may choose to hold a community meeting to discuss the sampling results in general terms and EPA's plans, if any, for response actions. Section 9.4 provides additional information for communicating sampling results.

6.6 General Principles and Recommendations for Mathematical Modeling

When suitably constructed, documented, and verified, mathematical models can provide an acceptable line of evidence supporting risk management decisions pertaining to vapor intrusion. In certain situations (e.g., for future construction on vacant properties), it is particularly useful to employ mathematical modeling to predict reasonable maximum indoor air concentrations, because indoor air testing is not possible.

Mathematical modeling is most appropriately used in conjunction with other lines of evidence. For example, in the brownfield development case (i.e., yet-to-be-constructed building), EPA generally recommends these additional lines of evidence include, at a minimum, data that characterize potential subsurface vapor sources and associated geologic and hydrologic conditions in the vadose zone (see Sections 6.3.1 and 6.3.2).

Generally, mathematical models transform empirical values of input parameters into predictions of chemical concentrations in environmental media. The model input parameters are equally as important to the results as the mathematical components of the model (i.e., governing equations and solution algorithms). As a consequence, the results critically depend on the choices for the inputs.

Historically, to assure confidence in predictions of mathematical models, they have been compared to measured, site-specific values. When measured and predicted values do not reasonably match, model input parameters are adjusted through calibration. For example, calibration is commonly used in groundwater flow modeling, in which model-predicted groundwater levels are matched to measured groundwater levels for a baseline condition to gain insight into hydrogeologic properties. The calibrated input parameters must reasonably represent the underlying phenomena and the characteristics of the model must reasonably match the field situation. Calibration of mathematical models is known to be non-unique, so that different sets of parameters can be used to fit the same observed data. This means that calibration does not produce a theoretically correct set of parameters. Because various values of input parameters could be used in the calibrated model, there will always be uncertainty as to the actual values.

Three approaches exist for applying mathematical models in these circumstances:

1) Calibrating the mathematical model to the measured indoor air concentration (and, possibly, the sub-slab soil gas concentration) considered to be representative of vapor intrusion (i.e., background vapor sources have been identified and removed prior to sampling and data evaluation indicates that the concentration is reasonably attributable to vapor intrusion). Calibration entails adjusting the input parameters within plausible and realistic ranges so that the predicted indoor air concentrations (or sub-slab soil gas concentrations) are similar to the measured vapor concentrations. The adjusted input parameters can then be compared to site-specific conditions and data to verify that the CSM and calibrated model are coherent and sound.

2) Conducting an uncertainty analysis (perhaps using an automated uncertainty analysis (see http://www.epa.gov/athens/learn2model/part-two/onsite/uncertainty-vi.html as only one example)) to understand where, within the probability distribution of results, model results with pre-selected default parameters lie. This approach may be particularly useful where indoor air concentrations have not been measured or non-site-specific inputs have been used.

3) Using a bounding case analysis, where parameters are chosen to represent conditions that give a high-impact (e.g., "reasonable worst") case – see Glossary – or "worst" (maximum plausible)[187] case. This approach may be particularly useful where the predicted indoor air concentrations for the bounding case can be shown to pose acceptable human health risk.[188] The range of predicted indoor air concentrations can be established if the analysis also includes a low-impact ("best") case.

Unless site-specific parameter values are obtained for input parameters and the mathematical model is calibrated to field data, use of default input parameter values will generate model results that lie at an unknown point within an uncertainty band of the model outcomes. Because the combined effect of parameter uncertainty is large, a one- or two-order of magnitude error might be made unknowingly. To reduce these errors, sub-slab vapor sampling could be used to characterize the vapor concentration(s) beneath a building. Model results (i.e., predicted sub-slab soil gas concentrations) that match measured values would have increased confidence. Alternately, using bounding estimates of parameter values could provide a conservative model result that would be expected to represent the reasonable worst case of potential exposure.

Three examples follow where differing applications of mathematical models would be useful in vapor intrusion assessment:

- Verify General Magnitude. Modeling using site-specific inputs can be useful for verifying the general magnitude of measured indoor air sample concentrations, which may allow risk managers to reach supportable conclusions not to conduct additional indoor air testing. In this situation, the model could be calibrated to indoor air measurements and the plausibility of the calibrated input parameters evaluated. If the calibrated model input parameters are plausible, then they can be considered an additional line of evidence supporting risk management decisions.

- Explore Range of Outcomes through Uncertainty Analysis. In certain situations, indoor air testing is not possible (e.g., for future construction on vacant properties) or feasible.

[187] For purposes of this Technical Guide, the phrase "worst case indoor air concentration" is intended to be a semi-quantitative phrase, referring to the high end of the exposure distribution. "No-further-action" decisions can normally be supported more confidently when the "worst case indoor air concentration" can be shown to pose acceptable health risks. Under these conditions, the "reasonable maximum exposure" (see Glossary) typically would also pose acceptable health risks.

[188] "Bounding estimates" purposely overestimate the exposure or dose in an actual population for the purpose of developing a statement that the risk is "not greater than..." (EPA 1992c).

Here the range of possible outcomes could be explored with the model through an uncertainty analysis. For example, model input parameters, including building and vadose zone soil properties, could be varied within plausible ranges to determine the parameters to which the model is most sensitive to guide field investigations. Uncertainty analyses can also be used to ascertain whether the subsurface vapor source concentrations are such that indoor air samples would not be expected to contain detectable levels of vapor-forming chemicals arising from vapor intrusion.

- Generate Bounding Estimates. If the range of parameter values is known with confidence for the site, then parameters can be chosen to represent the bounding case of maximum plausible vapor intrusion (i.e., worst case).

In each of these examples, model parameters might vary in space and time because of subsurface heterogeneity, transient hydrologic conditions, or variation in building operation. Thus, there is a need for characterizing spatial and temporal variability.

Mathematical models provide opportunities to predict conditions that cannot be observed directly, but the reliability of the results need to be confirmed, especially when limited site-specific data are available and the model is not calibrated to observed indoor air concentrations. Use of a generic, conservative attenuation factor (see Section 6.5.3) to predict potential, upper-bound indoor air concentrations (based upon soil gas concentrations – see Sections 6.4.3 and 6.4.4) implicitly represents use of a mathematical model, even when the attenuation factor is selected from an empirical data set. Whether the mathematical model is implicit (e.g., generic, conservative attenuation factor) or explicit (e.g., mathematical model that generates a bounding estimate), both analytic approaches make the assumption that site-specific attenuation is likely to be greater and the indoor air concentration(s) is (are) likely to be lower than predicted value(s).

The use of extreme and non-representative assumptions or parameter values is the most common weakness of mathematical modeling for environmental assessments. Mathematical modeling typically yields more reliable results when used with high-quality, site-specific data inputs (that is, representative groundwater or soil gas concentrations, depth to groundwater, soil type and moisture content underneath the building, and the building conditions (e.g., air exchange rate, building mixing height), for example); in these cases, the site-specific data inputs and CSM provide additional lines of evidence supporting the use of mathematical modeling as a line of evidence.

Whenever mathematical modeling is used to make predictions pertaining to vapor intrusion, EPA recommends that the site planning and data team:

- Identify the underlying mathematical model and include appropriate references to document that it has been peer-reviewed.
- Verify that the selected model fits the CSM and is appropriate for the chosen purpose.
- Document all inputs and outputs in a readily recognizable and understandable format.
- Identify the critical parameters and conduct a sensitivity analysis for the most critical parameters.

- Determine and document the appropriate modeling approach (e.g., calibration, uncertainty analysis, bounding case analysis).

- Perform new individual measurements (i.e., field sampling) to confirm one or more results of the modeling.

A critical assumption underlying almost all mathematical models of vapor intrusion is that site-specific subsurface characteristics will tend to reduce or attenuate soil gas concentrations as vapors migrate upward from the source and into overlying structures. Mathematical modeling of vapor intrusion is, therefore, not generally recommended for sites and buildings where unattenuated or enhanced transport of vapors toward and into a building is reasonably expected. Sections 5.4, 6.3.2, and 6.5.2 identify several factors that may result in unattenuated or enhanced transport of vapors toward and into a building.

7.0 RISK ASSESSMENT AND MANAGEMENT FRAMEWORK

This section provides general recommendations about risk-informed decision-making pertaining to vapor intrusion. The risk management information described herein presumes that a sound CSM has been developed (see Sections 5.4 and 6.3), which is supported by multiple lines of evidence, and that subsurface vapor sources have been characterized (see Section 6.3.1) sufficiently to support the risk management decisions for the site. EPA also notes that temporal and spatial variability of sampling data can span at least an order of magnitude and often more.

Site-specific decisions potentially supported by the information described in this section include:

- Whether to install engineered exposure controls to prevent or reduce the impacts of vapor intrusion in specific buildings.
- Whether to remediate subsurface vapor sources for the site to reduce risks posed by vapor intrusion.
- Whether the vapor intrusion pathway is incomplete and there is no potential for unacceptable human exposure under current or future conditions.
- Whether to collect additional information as part of the detailed vapor intrusion investigation or monitor indoor air as part of an overall vapor intrusion remedy.

As conditions warrant and resources allow, EPA generally recommends that officials responsible for overseeing cleanups pursuant to RCRA and CERCLA ensure that past decisions pertaining to vapor intrusion continue to be supported by current conditions (EPA 2002b).

Finally, EPA encourages systematic approaches to decision-making, which can foster scientific rigor, consistency, and transparency.

7.1 Collect Site-specific Lines of Evidence

Current practice suggests that the vapor intrusion pathway generally be assessed using multiple lines of evidence. As discussed in Sections 5.1, 5.4, 5.5.2, 6.3, 6.4, and 6.5, appropriate lines of evidence to support development of the CSM and evaluate the vapor intrusion pathway may include, but are not limited to:

Subsurface Vapor Sources

- Site history and source of the contaminants to demonstrate that vapor-forming chemicals have been or may have been released to the underlying and surrounding subsurface environment and identify the type of vapor source (e.g., vapor-forming chemicals dissolved in groundwater or present in a NAPL).
- Groundwater data (generally recommended from more than one sampling event), as appropriate, to confirm the presence of a water-table aquifer, if present, as a source of vapors and establish its chemical and hydrogeologic characteristics.

- Soil gas data, bulk soil sampling data,[189] and/or NAPL sampling data to confirm the presence of contamination in the vadose zone, if present, as a source of vapors and establish its chemical and physical characteristics.

- Sub-slab (or crawl space) soil gas data to assess concentrations potentially available for entry with any intruding soil gas (generally recommended from multiple sampling events and in multiple locations to reduce the chance of reaching a false-negative conclusion (i.e., concluding subsurface vapor source strength is limited when vapor intrusion actually poses an unacceptable human health risk) or a false-positive conclusion.

- Comparison of groundwater and/or soil gas concentrations to VISLs to evaluate source strength and potential for a health concern if the vapor intrusion pathway is complete.

Vapor Migration and Attenuation in the Vadose Zone

- Soil gas survey data, including some level of vertical and spatial profiling, as appropriate, to confirm soil gas migration and attenuation along anticipated routes in the vadose zone between sources and buildings.

- Data on site geology and hydrology (e.g., soil moisture and porosity) to support the interpretation of soil gas profiles, the characterization of gas permeability, and the identification of anticipated soil gas migration routes in the vadose zone or the identification and characterization of impeded migration.

- Vertical profiles of chemical vapors, electron acceptors for microbial transformations (e.g., oxygen), and degradation products (e.g., methane, vinyl chloride) to characterize attenuation due to biochemical (e.g., biodegradation) processes.

- Utility corridor assessment to identify preferential migration routes, if any, that facilitate subsurface vapor migration between sources and towards and into buildings

Building Foundation Assessment, Including Susceptibility to Soil Gas Entry

- Building construction and current conditions, including utility conduits or other preferential routes or openings for soil gas entry, heating and cooling systems in use, and any segmentation of ventilation and air handling.

- Instrumental (e.g., PID) readings to locate and identify potential openings for soil gas entry into buildings.

[189] As noted in Section 6.4, bulk soil sampling and analysis can be used to characterize the chemical composition and general location of contamination; for example, high soil concentrations generally would indicate impacted soil. On the other hand, non-detect results for soil samples cannot be interpreted to indicate the absence of a subsurface vapor source, because of the potential for vapor loss due to volatilization during soil sampling, preservation, and chemical analysis. Therefore, bulk soil (as opposed to soil gas) sampling and analysis is not currently recommended for estimating the potential for vapor intrusion to pose unacceptable human health risk in indoor air.

- Grab samples of soil gas or indoor air near openings to characterize the composition of presumptive soil gas entering buildings.

- Pressure data to assess the driving force for soil gas entry into building(s) via advection.

- Tracer-release data to verify openings in building foundations for soil gas entry or assess fresh air exchange within buildings.

Interior Assessment

- Indoor air sampling data (Section 6.4.1) to assess the presence of subsurface contaminants in indoor air (Section 6.3.4), estimate potential exposure levels to building occupants to support site-specific human exposure and human health risk assessments (see Section 7.4), and otherwise diagnose vapor intrusion and characterize background concentrations (Section 6.3.5).[190]

Indoor and Outdoor Sources of Vapor-forming Chemicals Found in the Subsurface

- Building-specific indoor sources of volatile chemicals (Section 2.7).

- Concurrent outdoor air data to assess potential contributions of ambient air to indoor air concentrations (Sections 6.3.5 and 6.4.2).

- Comparative evaluations of indoor air and sub-slab soil gas data (e.g., Section 6.3.5), including calculation and comparison of building-specific, empirical attenuation factors (EPA 2012a, Section 3.0) (e.g., to assess their consistency among subsurface contaminants to assist in identifying indoor vapors arising from vapor intrusion).

Additional Supporting Lines

- Results of statistical analyses (e.g., data trends, contaminant ratios) to support data interpretation.

- Results of mathematical modeling that rely upon site-specific inputs (Section 6.6).

The relative utility of these and other individual lines of evidence will depend on site-specific factors, as described and documented in the CSM (Section 5.4), and the objectives of the investigation (Section 6.3). For example:

- When the primary subsurface vapor source is residual NAPL in the vadose zone, bulk soil data would typically be collected to characterize the chemical composition and general location of contamination; for example, high soil concentrations generally would

[190] In certain cases, depending in part on the results (e.g., concentrations exceed risk-based screening levels), indoor air sampling data may be a sufficient basis for supporting decisions and recommendations to undertake pre-emptive mitigation (see Sections 3.3 and 7.8) in lieu of additional rounds of sampling and analysis or an evaluation of the contribution of background sources to indoor air concentrations.

indicate impacted soil in the vadose zone, as discussed in Sections 6.3.1 and 6.4.[191] In this situation, "near source" soil gas data, rather than groundwater data, would be recommended for assessing the potential for vapor intrusion to pose an unacceptable human health risk to occupants of any building overlying the NAPL zone. On the other hand, when the subsurface vapor source underneath a building is shallow groundwater, groundwater sampling data from the uppermost hydrogeologic unit would be an appropriate line of evidence for purposes of assessing the potential for vapor intrusion to pose an unacceptable human health risk, unlike the previous example.

- In both of the preceding cases, information about the soil conditions (e.g., soil type and moisture) *underlying the buildings* would be useful for characterizing the subsurface vapor migration route between the subsurface vapor source and the building. Sub-slab soil gas samples and indoor air samples (if background sources are removed or accounted for), in concert with other lines of evidence, can provide a strong line of evidence regarding whether the vapor intrusion pathway is complete.

- For an industrial building, indoor air testing while the HVAC system is not operating (see Section 6.3.3) could be useful for diagnosing vapor intrusion. On the other hand, single-family detached homes can generally be presumed susceptible to soil gas entry when heating or cooling systems are operating.

7.2 Weigh and Assess Concordance Among the Lines of Evidence

To the risk manager, the ideal outcome from collecting multiple lines of appropriate evidence is a concordant set of site-specific information that unambiguously supports decisions that can be made confidently. However, based upon observations at many buildings and sites, the vapor intrusion site where all available information is in agreement and is unambiguous may be the exception rather than the rule. Some lines of evidence may not be definitive (e.g., indoor air and subsurface concentrations can be greatly variable temporally and spatially). At worse, some individual lines of evidence may be inconsistent with other lines of evidence. In general, when lines of evidence are not concordant and the weight of evidence does not support a confident decision, EPA recommends re-evaluating the CSM, which may warrant adjusting the CSM to better represent the weight of the available evidence.

For example, a building overlying contaminated shallow groundwater may have high concentrations of vapor-forming chemicals in the sub-slab soil gas samples, but lower concentrations in soil gas samples collected exterior to the building at intermediate depths. In this example, the exterior soil gas data suggest there may not be a connected vapor migration path between the groundwater source and the building that exhibits continuous attenuation along the path. Nevertheless, the data review team may conclude that vapor migration is capable of transporting hazardous vapors from the source to building(s) if the groundwater and sub-slab soil gas samples share common contaminants that are known or suspected to have been released at the site (for example, samples of both groundwater and

[191] Because of the large uncertainties associated with measuring concentrations of volatile contaminants introduced during soil sampling, preservation, and chemical analysis, bulk soil (as opposed to soil gas) sampling and analysis is not currently recommended for estimating the potential for vapor intrusion to pose unacceptable human health risk in indoor air. In addition, there are uncertainties associated with soil partitioning calculations.

the sub-slab soil gas contain TCE). In this circumstance, the data review team may wish to consider whether the occurrence of a higher TCE concentration in the sub-slab soil gas than in the exterior soil gas sample(s) can be explained by: (1) a previously unknown or unrecognized utility corridor or other preferential migration route that provides relatively unattenuated vapor transport between the groundwater and the building; (2) a previously unknown or unrecognized source of TCE in the vadose zone; or (3) the possibility that the exterior soil gas samples were not well located for purposes of characterizing subsurface vapor migration. This example also underscores the importance of developing an adequate CSM (e.g., identify all sources and preferential routes of subsurface vapor migration) and illustrates why EPA generally recommends that the vapor intrusion pathway not be deemed incomplete based upon any single line of evidence (EPA 2010b), such as exterior soil gas in this example.

When lines of evidence are not concordant and the weight of evidence does not support a confident decision, it may also be appropriate to collect additional lines of evidence, possibly including additional samples, depending upon the CSM. For example:

- Appropriate site-specific testing (see Section 6.3.5) can be conducted to assess the contribution of background sources of vapor-forming chemicals, including comparisons among chemicals of their relative concentrations in indoor air, outdoor air, and soil gas. Background sources of vapor-forming chemicals may help to explain situations where the indoor air concentration is higher than can be accounted for by the subsurface vapor source or the sub-slab soil gas data.

- Diagnostic testing of indoor air (see Section 6.4.1), building condition assessments or utility surveys, or supplemental hydrogeologic characterization (see Section 6.3.2) can be used to investigate the suspected presence of preferential migration routes, such as those described in Sections 5.4 and 6.3.2. Such investigations may help to explain situations where the sub-slab or indoor air concentration appears to reflect unattenuated vapor transport from the subsurface vapor source.

- Building susceptibility to vapor intrusion can be tested (see Section 6.3.3), which may help to explain situations where the indoor air concentration is significantly lower than expected based upon the sub-slab soil gas data.

- Vapor migration in the vadose zone can be further characterized to identify impedances to vapor migration (see Section 6.3.2), appropriate semi-site specific attenuation factors can be considered (see Section 6.5.3), and appropriate modeling can be conducted (see Section 6.6) to investigate site-specific vapor attenuation. Such data and analyses may help to explain situations where the sub-slab soil gas concentration is significantly lower than expected based upon groundwater source or “near-source” soil gas concentrations and the respective medium-specific attenuation factor (Section 6.5.2 and Appendix A). In some of these situations, the vapor intrusion pathway may be impeded, or perhaps even incomplete, due to geologic, hydrologic, or microbial characteristics in the vadose zone (see Sections 6.3.2 and 7.3).

Recognizing the temporal and spatial variability of indoor air and subsurface concentrations and the potentially episodic nature of vapor intrusion at some sites (Section 2), EPA generally recommends collecting multiple rounds of sampling in the respective media from multiple locations (see Section 6.4) to reduce the chance of reaching a false-negative or false-positive

conclusion. Considerable judgment may be necessary when evaluating multiple data sets from individual sampling events to support decision-making.

In summary, EPA recommends the appropriate use and evaluation ("weighing") of multiple lines of evidence for determining whether the vapor intrusion pathway is complete or not, whether any elevated levels of contaminants in indoor air are likely caused by subsurface vapor intrusion versus an indoor source or an ambient (outdoor) air source, whether concentrations of subsurface contaminants in indoor air may pose a health concern, and whether interim response measures to mitigate vapor intrusion are warranted.

7.3 Evaluate Whether the Vapor Intrusion Pathway is Complete or Incomplete

For purposes of this Technical Guide, and as reflected in the conceptual model of vapor intrusion (see Section 2), the vapor intrusion pathway is referred to as "complete" for a specific building or collection of buildings when the following five conditions are met under current conditions:

1) A subsurface source of vapor-forming chemicals is present underneath or near the building(s) (see Sections 2.1, 5.3, 6.2.1, and 6.3.1);

2) Vapors form and have a route along which to migrate (be transported) toward the building(s) (see Sections 2.2 and 6.3.2);

3) The buildings are susceptible to soil gas entry, which means openings exist for the vapors to enter the building and driving 'forces' exist to draw the vapors from the subsurface through the openings into the building(s) (see Sections 2.3 and 6.3.3);

4) One or more vapor-forming chemicals comprising the subsurface vapor source(s) is (or are) present in the indoor environment (see Sections 6.3.4 and 6.4.1); and

5) The building is occupied by one or more individuals when the vapor-forming chemical(s) is (or are) present indoors.

Considerable scientific and professional judgment will likely be needed when weighing lines of evidence to determine whether the vapor intrusion pathway is complete or incomplete. Each of the first four conditions generally entails obtaining and weighing multiple lines of evidence, whereas the fifth condition generally can be confidently determined by direct observation. EPA recommends considering and evaluating together the various lines of evidence in determining completeness of the vapor intrusion pathway under current conditions.

As noted previously (e.g., Section 3.2), EPA recommends that risk management decisions also consider whether the vapor intrusion pathway is 'potentially complete' under reasonably expected future conditions. The vapor intrusion pathway is referred to as 'potentially complete' for a building when:

- a subsurface source of vapor-forming chemicals is present underneath or near an existing building or a building that is reasonably expected to be constructed in the future;

- vapors can form from this source(s) and have a route along which to migrate (be transported) toward the building; and

- three additional conditions are reasonably expected to all be met in the future, which may not all be met currently; i.e.,

    - the building is susceptible to soil gas entry, which means openings exist for the vapors to enter the building and driving forces exist to draw the vapors from the subsurface through the openings into the building;

    - one or more vapor-forming chemicals comprising the subsurface vapor source(s) is (or will be) present in the indoor environment (see Sections 6.3.4 and 6.4.1); and

    - the building is or will be occupied by one or more individuals when the vapor-forming chemical(s) is (or are) present indoors.

This determination also generally entails obtaining and weighing multiple lines of evidence.

A complete pathway indicates that there is an opportunity for human exposure, which warrants further analysis to determine whether there is a basis for undertaking a response action(s). Specifically, a complete exposure pathway does not necessarily mean that an unacceptable human health risk exists due to vapor intrusion. Rather, specific exposure conditions, such as the magnitude, frequency, and duration of exposures, and the contribution from background concentrations warrant examination; hence, EPA recommends additional analyses be conducted to assess and characterize human health risk to building occupants where the vapor intrusion pathway is determined to be complete (see, for example, Sections 7.4 and 6.3.5). On the other hand, human exposure, and hence human health risk, from the vapor intrusion pathway would not exist if the pathway is incomplete.

The conceptual model described in Section 2 identifies the characteristics of the vadose zone that could render the vapor intrusion pathway incomplete under current and future conditions. These individual characteristics include, but are not limited to:

- Soil layers that significantly and persistently impede vapor transport due to geologic or hydrologic conditions (e.g., fine-grained soil, soil with high moisture content) and are laterally extensive over distances that are large compared to the size of the building(s) or the extent of subsurface contamination with vapor-forming chemicals; and

- A biologically active vadose zone that can significantly and persistently attenuate soil gas concentrations due to biodegradation, in which all appropriate conditions (e.g., nutrients, moisture, and electron acceptors, such as dissolved oxygen in the case of aerobic biodegradation) are readily available over a laterally extensive area.

EPA recommends demonstrating these characteristics, when present, by collecting, evaluating, and documenting multiple lines of evidence, as identified in Section 6.3.2. In addition, EPA recommends that any determination that the vapor intrusion pathway is incomplete be supported by site-specific evidence to demonstrate that:

- The nature and extent of vapor-forming chemical contamination in the subsurface has been well characterized, as discussed in Sections 6.3.1 and 6.4. Ideally, where groundwater is the source of vapors, the plume has been shown to be stable or

shrinking to establish that the potential for vapor intrusion to pose a health concern will not increase in the future.

- The types of vapor sources and the conditions of the vadose zone and surrounding infrastructure do not present opportunities for unattenuated or enhanced transport of vapors toward and into any building (e.g., via a preferential migration route(s)), as discussed in Sections 5.4, 6.2.1, 6.3.2, and 6.5.2.

When the vapor intrusion pathway is determined to be incomplete, then vapor intrusion mitigation is not generally warranted under current conditions. EPA recommends that site managers also evaluate whether subsurface vapor sources that remain have the potential to pose a complete vapor intrusion pathway and unacceptable human health risk due to vapor intrusion in the future if site conditions were to change. For example, potentially unpredictable changes in the transitory soil characteristics (e.g., soil moisture) and soil gas concentrations may occur as a result of constructing a new building or supporting infrastructure. Either type of change could result in the potential for unacceptable human health risk due to vapor intrusion in the future.

Response actions may, therefore, be warranted to protect human health wherever and as long as subsurface vapor sources remain that have the potential to pose unacceptable human health risk in the future due to vapor intrusion. These response actions (see Section 7.7) may include institutional controls (see Section 8.6) (e.g., to record and alert parties about the presence of subsurface vapor sources and/or to inform the need for a confirmatory vapor intrusion investigation in case infrastructure or geologic conditions are modified in the future). In addition, subsurface remediation may be warranted to protect human health or the environment via other exposure pathways (e.g., groundwater discharge to surface water bodies), consistent with applicable statutes and considering EPA guidance.

7.4 Conduct and Interpret Human Health Risk Assessment

EPA generally recommends that a human health risk assessment be conducted to determine whether the potential human health risk posed to building occupants by a complete or potentially complete vapor intrusion pathway are within or exceed acceptable levels, consistent with applicable statutes[192] and considering EPA guidance (EPA 1991a, 2009c). The primary purpose of this risk assessment is to provide risk managers with an understanding of the actual and potential risks to human health posed by vapor intrusion under current and reasonably expected future conditions. This information may be useful in determining whether a current or potential future threat to human health exists, as described in Sections 7.4.1, 7.4.2, and 7.5.2,[193] which warrants response action(s), as described in Sections 7.7 and 8.

[192] In the RCRA corrective action program, any human health risk assessment would typically be conducted during the RCRA facility investigation, if a release to the environment is identified. Under the CERCLA remedial program, a human health risk assessment would typically be conducted during the remedial investigation and is generally referred to as a baseline (i.e., pre-cleanup) risk assessment.

[193] In appropriate circumstances (e.g., where time is of the essence to ensure protection of human health; see, for example, Section 7.5.2), a formal human health risk assessment need not be completed and documented before taking a response action, but a preliminary evaluation of human health risk using individual building data or aggregated community data is generally recommended (also see Section 7.8).

The human health risk posed to building occupants by intrusion of a given vapor-forming chemical will depend upon its toxicity, its concentration in indoor air, the amount of time the occupants spend in the building, and other variables (e.g., human life stage (e.g., child) can matter for some chemicals (e.g., those with a mutagenic mode of action for carcinogenicity)). EPA recommends that its risk assessment guidance (e.g., EPA 2009c, EPA 2003) be used to identify, develop, and combine information about these variables and characterize human health risk due to vapor intrusion from subsurface contaminant sources.

For the vapor intrusion pathway, the inhalation route is the primary means of human exposure. Therefore, the human health risk assessment uses estimates of indoor air exposure concentrations, exposure duration and frequency for building occupants, and the potential toxicity of the vapor-forming chemicals found in the subsurface (e.g., inhalation unit risk and noncancer reference concentration) to characterize risks of cancer and noncancer effects (EPA 2009c). Generally, exposure concentrations in existing buildings can be estimated using direct measurements of indoor air (see Sections 6.3.4 and 6.4.1). EPA recommends that time-integrated measurements from multiple sampling events be used to estimate exposure concentrations appropriate for the exposure (occupancy) scenario being evaluated (e.g., residential versus commercial), when the risk assessment for an existing building would support a conclusion that the human health risk is acceptable (see Section 7.4.1).[194,195] Generally, modeling would be used to conservatively estimate exposure concentrations under future conditions in buildings yet to be constructed in areas with subsurface contamination by vapor-forming chemicals (see Section 6.6). EPA recommends the noncancer assessment consider the potential for adverse health effects from short-duration inhalation exposures (i.e., acute, short-term, or subchronic exposure durations),[196] as well as longer term inhalation exposure (i.e., chronic exposure) conditions. EPA recommends that inhalation toxicity values be selected

[194] An individual sample, collected at a randomly chosen time, may under-estimate (or over-estimate) average and reasonable maximum exposure conditions. From their high-frequency, measured data, Holton et al. formulated a synthetic data set (simulating one-day-average concentrations), which they used to estimate that a single, randomly drawn, one-day sample had a forty percent chance of being less than the true mean (Holton et al. 2013b; see Table 1 therein). When the true mean was assumed to exceed the risk-based action level ("target concentration" in their parlance) by two or five times, they estimated that a single, randomly drawn, one-day sample had a twenty percent or six percent chance, respectively, of not detecting the exceedance. These data support EPA's recommendation to collect multiple rounds of indoor air sampling data to reduce the chance of reaching a false-negative conclusion (i.e., concluding exposure is at an acceptable risk level when it is not). Collecting multiple rounds of indoor air sampling can also reduce the chance of reaching a false-positive conclusion (i.e., concluding that vapor intrusion poses unacceptable human health risk when it does not), because an individual sample, collected at a randomly chosen time, may over-estimate the average and reasonable maximum exposure conditions.

[195] Given EPA's assigned mission to protect human health from environmental contamination and recognizing the disruption to building owners and occupants caused by indoor air sampling, risk managers may choose to pursue pre-emptive mitigation (i.e., early action) at some buildings (see Sections 3.3 and 7.8) rather than, for example, conduct multiple rounds of sampling over a few years to establish an estimate of long-term average exposure concentration and characterize temporal variability.

[196] The inhalation reference concentration (RfC) (expressed in units of mass concentration in air) is defined as an estimate (with uncertainty spanning perhaps an order of magnitude) of a continuous inhalation exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. Reference values may be derived for acute (≤24 hours), short-term (>24 hours, up to 30 days), subchronic (>30 days, up to approximately 10% of the life span), and chronic (greater than 10% of the life span) exposure durations, all of which are derived based on an assumption of continuous exposure throughout the duration specified. See http://www.epa.gov/ncea/iris/help_ques.htm#whatiris

considering OSWER's hierarchy of sources (EPA 2003) and that relevant existing guidance (e.g., EPA 2009c) be followed in situations where a desired toxicity value is not available.

When a single vapor-forming chemical is present in the subsurface and intrudes as a vapor into occupied building spaces, the noncancer human health risk can be characterized by calculating the noncancer hazard quotient (HQ) (EPA 2009c,Chapter 8). When multiple vapor-forming chemicals are present in the subsurface and intrude as vapors into occupied building spaces, the HQ estimates for each chemical are aggregated (as a simple sum, which is the Hazard Index (HI)), based upon the assumption that each chemical acts independently (i.e., there are no synergistic or antagonistic toxicity interactions among the chemicals). If the HI exceeds one, there may be concern for potential adverse non-cancer effects and risk assessors should consider segregating the chemicals by target organ or toxic effect to derive separate hazard index (HI) values for each (EPA 2009c, Chapter 8). EPA recommends that noncancer HQ and HI values be estimated for each type of exposure period identified in the conceptual site model or indicated by measurements of indoor air levels of vapor-forming chemicals (e.g., chronic, subchronic, short-term, acute), evaluating inhalation reference concentrations that "match the characterization of the exposure scenario" (EPA 2009c, Chapter 4).[197]

The carcinogenic risks can be characterized by calculating the excess cancer risk over a lifetime (LCR) and, if multiple vapor-forming chemicals are present, aggregating the LCR estimates for each carcinogen (as a simple sum), based upon the assumption that each chemical acts independently (EPA 2009c, Chapter 8).

A well-crafted risk characterization section (EPA 1992c, 1995ab, 2000b, 2009c) puts risk calculations into context for risk managers, so that they may effectively weigh and interpret risk assessment results and recognize key uncertainties (e.g., in the exposure and dose-response assessments and risk estimation).[198] Additional recommendations for promoting and increasing the utility and transparency of human health risk assessments can be found in *Framework for Human Health Risk Assessment to Inform Decision Making* (EPA-RAF, 2014).

[197] For example, when evaluating situations in which vapor concentrations in indoor air exceed the chronic reference concentration (see Section 7.4.1), and there are shorter periods of significantly higher vapor intrusion exposure, EPA recommends that noncancer risks for the shorter periods also be characterized using toxicity values appropriate for the respective period(s). On the other hand, if vapor concentrations in indoor air are consistently less than benchmarks for acceptable chronic exposure, then exposures for less-than-chronic scenarios are unlikely to pose unacceptable human health risk.

[198] For example, EPA recommends that the risk characterization for existing buildings describe the uncertainty in the exposure assessment arising from: (i) inherent variability of indoor air exposures over time and space; (ii) the match between the sampling data [e.g., sampling frequency (i.e., number of samples and time intervals between samples); and time period over which each sample was collected] and the exposure period represented by the selected toxicity value (e.g., chronic); and (iii) the ability to distinguish and apportion the contribution to indoor air concentrations arising from vapor intrusion versus background sources. EPA recommends that the risk characterization for future buildings describe the principal uncertainties in the exposure assessment, which may be associated with the type(s) of building use, building construction and operations (e.g., HVAC system), frequency and duration of occupancy, vapor concentrations in indoor air, or other factors.

EPA recommends that any human health risk assessment be documented; a summary in a decision document is also generally warranted.[199] EPA also recommends that human health risk information for individual buildings be communicated to building occupant(s) and owners. Section 9.4 provides additional information for communicating sampling results.

7.4.1 Risk Management Benchmarks

EPA recommends that OSWER programs make the risk management determination to take response action consistent with their statutes and regulations and considering existing program guidance.[200] The carcinogenic risk and non-cancer HI values used in this determination generally are the "cumulative risks" that include all exposure pathways that a given population may consistently face.[201] In making such risk management determinations, EPA generally recommends reporting the HQ and HI to one significant figure.

EPA generally uses a cancer risk range of 10^{-6} to 10^{-4} as a "target range" within which to manage human health risk as part of site cleanup. For judging whether indoor air exposures may pose acceptable health risk based upon potential non-cancer effects, EPA generally recommends that the target HQ or HI not exceed 1.

Once a decision has been made to undertake a response action, EPA has expressed a preference for cleanups that are at the more protective end of the cancer risk range. Thus, EPA recommends using an individual lifetime cancer risk of 10^{-6} as a point of departure for establishing cleanup levels based upon potential cancer effects (see Section 7.6).[202] The EPA risk manager may determine that a response action achieving reductions in human health risk

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[199] Devices that have been found to improve comprehension and retention of textual materials include a table of contents, clear section headings, and a summary (Morgan et al. 1992). It is most helpful to provide a summary that translates the risk assessment into relatively simple language that non-expert risk managers, stakeholders, and wider audiences can understand (Lundgren and McMakin, 2013). Hazards and risks posed by vapor intrusion are more likely to be misunderstood or misinterpreted if they are not explained in simple terms.

[200] See, for example: *The Role of the Baseline Risk Assessment in Superfund Remedy Selection Decisions*, OSWER Directive 9355.0-30, April 22, 1991 (EPA 1991a); *Rules of Thumb for Superfund Remedy Selection,* OSWER Directive 9355.0-69, August 1997 (EPA 1997); and Advanced Notice of Proposed Rulemaking: Corrective Action for Solid Waste Management Units at Hazardous Waste Management Facilities (61 *Federal Register* 19432, May 1, 1996). So, for example, EPA cited OSWER Directive 9355.0-30 (EPA 1991a) in its *Compilation of Information Relating to Early/Interim Actions at Superfund Sites and the TCE IRIS Assessment* (EPA 2014b).

[201] In some site-specific situations, a population might be exposed to a substance or combination of substances through several exposure pathways (i.e., not only the vapor intrusion pathway). For example, individuals might be exposed to substance(s) from a contaminated site by consuming contaminated drinking water from a groundwater supply, as well as from vapor intrusion. Once reasonably expected exposure pathways have been identified, EPA recommends examining whether it is likely that the same individuals would consistently face the reasonable maximum exposure for each pathway or a combination of some of these pathways. Under such circumstances, the total exposure to each chemical would equal the sum of the exposures by all consistently faced pathways (EPA 1989, Section 8.3) and EPA recommends that the risk assessor clearly identify those exposure pathway combinations for which a total risk estimate or hazard index is being developed. When characterizing human health risk arising from multiple pathways and posed by a vapor-forming chemical(s) with potential adverse noncancer effects, EPA recommends that the toxicity values for each pathway "match the characterization of the exposure scenario" (EPA 2009c, Chapter 4).

[202] See: National Oil and Hazardous Substances Pollution Contingency Plan (55 *Federal Register* 8717); and Advanced Notice of Proposed Rulemaking: Corrective Action for Solid Waste Management Units at Hazardous Waste Management Facilities (61 *Federal Register* 19432, May 1, 1996).

within the 10^{-6} to 10^{-4} cancer risk range is acceptable, however, depending on site-specific conditions or remedial factors.

For establishing cleanup levels based upon potential non-cancer effects, EPA generally recommends that the target HI not exceed 1 (see Section 7.6).

7.4.2 Accounting for Background Contributions

As noted previously, EPA recommends including in the human health risk assessment vapor-forming chemicals that are related to releases to the subsurface environment. Some of these vapor-forming chemicals may be present in indoor air due to 'background' sources (see Section 2.7). If data are available, EPA recommends that the contribution of 'background' to total exposure concentration(s) be distinguished in the human health risk assessment (EPA 2002e). If background vapor sources (see Glossary) are found to be primarily responsible for indoor air concentrations (see Section 6.3.5), then response actions for vapor intrusion would generally not be warranted for current conditions. In any event, EPA recommends that the risk characterization include a discussion of 'background' contributions to indoor air exposure and associated human health risk. With such information, EPA can help advise affected individuals about the environmental and public health risks they face that are within their control (e.g., indoor sources of vapor-forming chemicals in residences).[203] Other parties, including building owners and operators, may help with risk communication.

If 'background' contributions are unknown and such data are sought to support risk management decisions, EPA recommends that additional data be collected (see, for example, Section 6.3.5). Information on 'background' contributions of site-related, vapor-forming chemicals in indoor air is also important to risk managers because generally EPA does not clean up to concentrations below natural or anthropogenic background levels (EPA 2002e).

7.4.3 Occupational Exposure Limits

Permissible exposure limits (PELs) are enforceable occupational exposure standards developed by the Occupational Safety and Health Administration (OSHA) in the U.S. Department of Labor. Most of OSHA's PELs were adopted in 1971 from then-existing secondary guidance levels, such as Threshold Limit Values (TLVs) developed by the American Conference of Governmental Industrial Hygienists (ACGIH) to protect workers from adverse effects of occupational exposure to airborne chemicals. They were intended to protect workers against catastrophic effects (such as cardiovascular, liver, kidney, and lung damage), as well as more subtle effects (such as narcosis, central liver system damage, and sensory irritation).

PELs (and TLVs), however, are not intended to protect sensitive workers, may not incorporate the most recent toxicological data, and may differ from EPA derivations of toxicity values with respect to weight-of-evidence considerations and use of uncertainty factors. For these and other

[203] In cases where 'background' contamination (e.g., due to indoor use of a consumer product or household chemical in a residence) may pose a human health risk, but its remediation is beyond the authority of the applicable statute, risk communication to the public may be most effective when coordinated with public health agencies (EPA 2002e).

reasons, [204] EPA does not recommend using OSHA's PELs (or TLVs) for purposes of assessing human health risk posed to workers (EPA 1991c, Appendix C) by the vapor intrusion pathway or supporting final "no-further-action" determinations for vapor intrusion arising in nonresidential buildings. Rather, EPA's recommendations for assessing human health risk posed by vapor intrusion are set forth herein in Sections 7.4.1 and 7.4.2.

7.5 Concentration Levels Indicating Potential Need for Prompt Response Action

In some circumstances, human health risk arises from vapor intrusion, which warrants prompt response action. This Section provides some recommendations for identifying such circumstances.

7.5.1 Potential Explosion Hazards

EPA recommends using the chemical-specific LELs[205] to identify potential explosion hazards (e.g., for methane and other petroleum hydrocarbons). Whenever building-specific data (such as results from sub-slab soil gas samples and crawl space samples for any building type, indoor air samples from sheds or pump houses, or gas samples from confined or semi-confined spaces (e.g., sewers)) exceed one-tenth (10%) of the LEL for any chemical, a hazard is indicated that generally warrants prompt action.[206,207] EPA recommends to building owners and occupants the evacuation of buildings with potential explosion and fire hazards, along with immediate notification to the local fire department about the threat. Construction and operation of engineered systems that can reduce or eliminate intrusion of explosive vapors into existing buildings or unoccupied structures may also warrant consideration to reduce the potential for future explosion hazards.

7.5.2 Considering Short-term and Acute Exposures

EPA may identify health-protective concentration levels for vapor-forming chemicals based upon potential noncancer health effects that can be posed by air exposures over short-term or acute exposure durations, considering EPA guidance for human health risk assessment (e.g., EPA

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[204] OSHA's website (May 2015) currently states: "OSHA recognizes that many of its permissible exposure limits (PELs) are outdated and inadequate for ensuring protection of worker health. Most of OSHA's PELs were issued shortly after adoption of the Occupational Safety and Health (OSH) Act in 1970, and have not been updated since that time. Since 1970, OSHA promulgated … new PELs for 16 agents, and standards without PELs for 13 carcinogens. Industrial experience, new developments in technology, and scientific data clearly indicate that in many instances these adopted limits are [also] not sufficiently protective of worker health. This has been demonstrated by the reduction in allowable exposure limits recommended by many technical, professional, industrial, and government organizations, both inside and outside the United States." [On-line source: https://www.osha.gov/dsg/annotated-pels/] On October 10, 2014, OSHA issued a Chemical Management Request for Information (79 FR 61384), in which it acknowledges many of its PELs are not sufficiently protective and seeks comment on strategies to address this problem; available on-line at: https://www.osha.gov/FedReg_osha_pdf/FED20141010.pdf

[205] The Vapor Intrusion Screening Level Calculator (EPA 2015a) provides LELs for vapor-forming chemicals to facilitate identification of potential explosion hazards.

[206] NIOSH has designated such concentrations as immediately dangerous to life or health (IDLH).

[207] Although the building-specific data may vary temporally, any short-term exceedance of one-tenth of the LEL indicates vapor concentrations that, given an ignition source and available oxygen, may be capable of causing an explosion.

2009c) and using sources of toxicity information considering OSWER's hierarchy (EPA 2003). For example, subchronic reference concentrations, developed by the EPA Office of Research and Development/National Center for Environmental Assessment/ Superfund Health Risk Technical Support Center (STSC), are currently available for some vapor-forming chemicals as Provisional Peer Reviewed Toxicity Values (PPRTVs), which are designated as a Tier 2 source of toxicity values by OSWER (EPA 2003). Acute and intermediate Minimal Risk Levels (MRLs)[208] adopted by the Agency for Toxic Substances and Disease Registry (ATSDR) are currently available for some vapor-forming chemicals and are designated as a Tier 3 source of toxicity values by OSWER (EPA 2003). PPRTVs and ATSDR MRLs are peer reviewed and are publicly available (see, http://hhpprtv.ornl.gov/ and http://www.atsdr.cdc.gov/mrls.html).

Historically, toxicity values for short-term or acute exposure durations have not been derived or published in EPA's IRIS, which otherwise is EPA's preferred source of toxicity values (EPA 2003). EPA, under its authority, will work to develop expanded science policy direction to address short-term exposures and develop and identify appropriate toxicity values for additional chemicals for consideration for vapor intrusion assessment and related OSWER regulatory frameworks. EPA recommends that relevant existing guidance (e.g., EPA 2009c) be followed in situations where a desired toxicity value is not available, using sources of toxicity information considering OSWER's hierarchy (EPA 2003).

Although the indoor air concentrations may vary temporally, an appropriate exposure concentration estimate (e.g., time-integrated or time-averaged indoor air concentration measurement in an occupied space – see Section 6.4.1) that exceeds the health-protective concentration levels for acute or short-term exposure (i.e., generally considered to be a hazard quotient (HQ) greater than one for an acute or short-term exposure period)[209] indicates vapor concentrations that are generally considered to pose an unacceptable human health risk.[210]

As noted in Section 7.4 of this Technical Guide, a well-crafted risk characterization section (EPA 1992c, 1995ab, 2000b, 2009c) puts risk calculations into context for risk managers, so that they may effectively weigh and interpret risk assessment results and recognize key uncertainties (e.g., in the exposure and dose-response assessments and risk estimation). Uncertainties include the derivation of an RfC, which is defined as "…an estimate (with uncertainty spanning perhaps an order of magnitude)…" (See http://www.epa.gov/ncea/iris/help_ques.htm#whatiris). Sections 3.3 and 7.7 identify other EPA-recommended considerations for risk managers.

When indoor air concentrations in an occupied space exceed health-protective concentration levels for short-term or acute inhalation exposures arising from a complete vapor intrusion

[208] Minimal Risk Levels (MRLs) published by ATSDR are estimates of the daily human exposure to a hazardous substance that is likely to be without appreciable risk of adverse non-cancer health effects over a specified duration of exposure. The ATSDR MRLs are peer reviewed and are publicly available (http://www.atsdr.cdc.gov/mrls.html).

[209] See Glossary for definitions of "acute" and "short-term" exposure durations.

[210] See, for example: *The Role of the Baseline Risk Assessment in Superfund Remedy Selection Decisions*, OSWER Directive 9355.0-30, April 22, 1991 (EPA 1991a); and *Rules of Thumb for Superfund Remedy Selection,* OSWER Directive 9355.0-69, August 1997 (EPA 1997). In addition, the NCP states "For systemic toxicants, acceptable exposure levels shall represent concentration levels to which the human population, including sensitive subgroups, may be exposed without adverse effect during a lifetime or part of a lifetime, incorporating an adequate margin of safety" [40 *CFR* 300.430(e)(2)(i)(1)].

pathway, ventilation, indoor air treatment, temporary relocation, and other response actions may be implemented to reduce or avoid these threats promptly (see Section 8.2.1). Construction and operation of engineered systems that can reduce or eliminate vapor intrusion into existing buildings (see Section 8.2) may also warrant consideration after urgent threats to human health have been addressed.

7.6 Risk-based Cleanup Levels

When response action is determined to be warranted to reduce or eliminate indoor air exposures from vapor intrusion (see Sections 7.4 and 7.5), EPA recommends that cleanup levels be established and documented consistent with statutes and regulations and considering guidance for the respective OSWER program.[211] These cleanup levels would be used to evaluate when building mitigation measures, subsurface remediation, and associated monitoring can be terminated and to assess cleanup progress in the meantime (see Section 8.7).

Candidate risk-based cleanup levels can be calculated using information from the risk assessment (Section 7.4). Results of the human health risk assessment indicate, for example, which site-related vapor-forming chemicals warrant building mitigation and subsurface remediation. The exposure factors and toxicity values used in the human health risk assessment can be used to calculate chemical-specific cleanup levels, considering EPA risk assessment methods (e.g., EPA 2009c, EPA 2003). Candidate cleanup levels are usually developed for potential cancer and non-cancer effects. The lower (or lowest if there are multiple potential non-cancer effects) of the candidate values, based upon cancer risk and non-cancer HQ/HI targets, is generally recommended for selection as the cleanup level (EPA 1991c, Section 3.4 therein).[212] The VISL Calculator (http://www.epa.gov/oswer/vaporintrusion/guidance.html) can be used to support these calculations, including input of alternative attenuation factor(s) based upon site- or building-specific information.

Calculating candidate cleanup levels based upon potential cancer effects entails selecting a target cancer risk. As noted above (Section 7.4.1), once a decision has been made to undertake a response action, EPA has expressed a preference for cleanups achieving the lower end of the cancer risk range (i.e., 10^{-6}) (EPA 1991a). Response actions achieving reductions in human health risk anywhere within the cancer risk range may be deemed acceptable by the EPA risk manager, however.

To protect human health from potential noncancer effects, EPA generally recommends using a target value of one for the non-cancer HQ (if there is a single vapor-forming chemical of health concern for vapor intrusion) or for the non-cancer HI (if there are multiple vapor-forming chemicals of health concern for vapor intrusion acting by a common effect).

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[211] See, for example: *RCRA Corrective Action Plan (Final),* OSWER Directive 9902.3-2A (EPA 1994); and *A Guide to Preparing Superfund Proposed Plans, Records of Decision, and Other Remedy Selection Decision Documents,* OSWER Directive 9200.1-23P (EPA 1999b).

[212] An exception arises when 'background' sources pose elevated exposures, because generally EPA does not clean up to concentrations below natural or anthropogenic background levels (EPA 2002e).

Cleanup levels for indoor air can be readily calculated, as described above, without additional assumptions or modeling about vapor intrusion processes. On the other hand, cleanup levels for groundwater and/or soil gas in the vadose zone will entail developing a medium-specific vapor attenuation factor, which EPA recommends be conservatively estimated based upon site-specific information. The cleanup level for soil gas can be calculated by dividing the chemical-specific indoor air cleanup level by the site-specific soil gas vapor attenuation factor. The cleanup level for groundwater can be calculated by dividing the chemical-specific indoor air cleanup level by the site-specific vapor attenuation factor for groundwater vapors and assuming equilibrium between the aqueous and vapor phases at the groundwater table. EPA recommends that site-specific attenuation factors intended to be protective of chronic exposure conditions: be conservatively estimated when based upon mathematical models; and be based upon multiple measurements of indoor air concentration in different seasons, which have negligible influences from 'background' sources, when based upon site-specific measurements.

EPA recommends that cleanup levels be documented with at most two significant figures, even though some of the input values may carry additional significant figures (EPA 1991b, see page 19).

7.7 Options for Response Action

When response action is determined to be warranted to reduce or eliminate indoor air exposures from vapor intrusion (see Sections 7.4 and 7.5), EPA recommends that OSWER programs select, recommend, and document response action(s) consistent with statutes and regulations and considering their existing program guidance.[213]

The selection of a health-protective interim response action(s) for existing buildings will generally depend on site-specific considerations, which can include: nature of subsurface vapor source (e.g., groundwater, vadose zone soils, sewer lines), magnitude of the exposure above cleanup levels; the severity of the potential adverse health effects or health hazard; building features and conditions (e.g., construction; heating, ventilation, and air conditioning equipment); climate and season (which influence the feasibility of ventilation, for example); the quality of ambient air in the vicinity; and the feasibility of implementing a given option quickly.[214] In general, EPA recommends that response actions limit the amount of time individuals are exposed to concentrations that correspond to unacceptable human health risk, as described in Sections 7.4 and 7.5.

[213] See, for example: *RCRA Corrective Action Plan (Final),* OSWER Directive 9902.3-2A (EPA 1994); and *A Guide to Preparing Superfund Proposed Plans, Records of Decision, and Other Remedy Selection Decision Documents,* OSWER Directive 9200.1-23P (EPA 1999b).

[214] Most response actions cannot be implemented immediately upon determining that a response is warranted. For example, engineered exposure controls ordinarily entail from two to four weeks of lead time (at a minimum) for planning, design, any permit acquisition, material acquisition and construction. In many circumstances, ventilation measures to reduce exposure can be implemented more quickly, but local climate or air quality may render this option less attractive during some seasons.

TABLE 7-1
MATRIX OF OPTIONS TO RESPOND TO HUMAN HEALTH RISK POSED BY THE VAPOR INTRUSION PATHWAY

Option for Response Action	Applicability of Response Action for Common Sources of Sub-surface Vapors		
	Groundwater	Vadose Zone Soil	Sewer & Drain Lines
Remediation of Source*	•	•	•
Removal of contaminated soil via excavation	#	•	
Treatment of contaminated soil *in situ*	#	•	
Treatment of contaminated groundwater *in situ*	•		
Removal of contaminated groundwater (e.g., pump-and-treat)	•		
Decontaminating and/or rehabilitating sewer and drain lines			•
Interim Measures to Reduce or Eliminate Vapor Intrusion*	•	•	•
Subslab de-pressurization and ventilation systems	•	•	
Sealing major openings for soil gas entry, where known and identified+	•	•	
Building over-pressurization	•	•	
Installing, repairing, or maintaining vapor traps			•
Interim Measures to Reduce or Avoid Exposure to Vapors	•	•	•
Notification to local fire department about potential explosion hazards+	•	•	•
Notification and risk communication to building occupants and owners, including institutional controls (e.g., deed notices)	•	•	•
Increasing building ventilation*	•	•	•
Treating indoor air*	•	•	•
Temporary relocation+	•	•	•
Monitoring Indoor Air to Characterize Human Exposure	•	•	•

KEY: • designates potentially appropriate response action for indicated vapor source

FOOTNOTES:

* includes: associated institutional controls to maintain operations and provide public notification of residual contamination; and associated monitoring to assess effectiveness and protectiveness of the response action

\# remediation of soil may also be warranted for purposes of protecting groundwater from further contamination, even if contaminated soil in the vadose zone is not a source for vapor intrusion directly (e.g., due to the absence of an existing building near the contaminated soil)

\+ response option primarily applies to existing buildings

Table 7-1 presents an overview of key candidate response options for the vapor intrusion pathway, which are discussed further in Section 8. Response actions that may be recommended for and implemented in existing buildings include:

- Interim measures that can be implemented relatively quickly (see Section 8.2.1), if prompt action is warranted to reduce or eliminate exposures to vapor-forming chemicals (see Sections 5.2 and 7.5.2) or to mitigate explosion hazards (see Section 7.5.1);
- Engineered exposure controls (see Section 8.2.2) with associated monitoring and institutional controls (see Section 8.6), as an interim (but potentially long-term) measure to reduce or eliminate vapor intrusion into buildings; and
- Remediation of the subsurface vapor source (see Section 8.1) with associated monitoring and institutional controls (see Section 8.6).

Response actions that may be warranted in buildings that may be constructed in the future include:

- Remediation of the subsurface vapor source (see Section 8.1) with associated monitoring and institutional controls (see Section 8.6); and
- Institutional controls (see Section 8.6) to inform the need for building mitigation (see Section 8.2.2) and/or a confirmatory vapor intrusion investigation before the building is occupied, in case the building is to be or may be constructed before subsurface vapor sources are remediated to cleanup levels.

Indoor air monitoring has frequently been selected as a response action in circumstances where subsurface vapor sources are present and the vapor intrusion pathway has not been shown to be incomplete. Indoor air monitoring may be deemed warranted, for example:

- To better characterize spatial or temporal variability;
- To address uncertainty in the characterization of the vapor intrusion pathway when subsurface vapor sources have the potential to pose a health concern in overlying or nearby buildings (e.g., incomplete pathway characterization, concern about the potential for changes in building conditions, discordant lines of evidence); or
- For other site-specific or situation-specific reasons.

EPA generally prefers to obtain building access and undertake response actions through consent and cooperation from building owners, tenants, and other stakeholders (see Section 1.2).

7.8 Pre-emptive Mitigation/Early Action

It may be appropriate to implement mitigation of the vapor intrusion pathway as an early action, even though all pertinent lines of evidence have not yet been completely developed to characterize the vapor intrusion pathway for the subject building(s), when sufficient site-specific data indicate that vapor intrusion: (1) is occurring or may occur due to subsurface contamination that is being addressed by federal statutes, regulations, or guidance for environmental protection; and (2) is posing or may pose a health concern to occupants of an existing

building(s). Likewise, it may be appropriate and cost-effective to design, install, operate, and monitor mitigation systems (including passive barrier systems) in newly constructed buildings (or buildings planned for future construction) that are located in areas of vapor-forming subsurface contamination, rather than allow vapor intrusion (if any) to occur and address vapor intrusion after the fact. As described in Section 3.3, preemptive mitigation/early action is the term used to describe both situations.

Preemptive mitigation (PEM) is recognized as an early action that is intended to ensure protectiveness of human health. In this context and as described further in Section 8.2, mitigation refers to methods that seek to:

- Prevent or reduce vapor entry into a building.
- Reduce or eliminate vapors that have entered a building.

Note that the selection and implementation of PEM, when it occurs, is not necessarily intended to pre-judge final decisions about remediation of subsurface vapor sources; however, EPA generally recommends that decision-making about PEM include a consideration of the O&M and monitoring obligations. In addition, EPA recommends that the selection of PEM be based upon data and information in the administrative record and be documented in the administrative record, consistent with statutes and regulations and considering EPA guidance for the respective land restoration program (e.g., CERCLA, RCRA corrective action, brownfields, etc.), in order to provide an adequate basis for actions undertaken.

7.8.1 Rationale

In ensuring protectiveness of human health, PEM generally may be an appropriate approach to consider for buildings with potential vapor intrusion for a number of reasons, including:

- Building mitigation typically is an effective means of protecting human health and is cost effective for many buildings.
- The potential exposure scenario (e.g., inhalation of potentially toxic vapors) cannot generally be readily avoided by building occupants.
- Involuntary and unavoidable exposures and hazards are generally sources of anxiety and concern for affected building occupants and the general public, particularly when they occur in homes and in the workplace.
- Comprehensive subsurface characterization and investigations of vapor intrusion (to conclusively characterize unacceptable, but variable, levels of vapor-forming chemicals in soil, groundwater, and indoor air, as described in Section 6) can entail prolonged study periods, during which building occupants may be exposed and owners and environmental stewardship groups may remain anxious and concerned about potential indoor air exposures to subsurface vapors in the absence of mitigation.
- Conventional vapor intrusion investigations in and of themselves can be disruptive, particularly when indoor access is sought to acquire interior samples and assess interior building conditions.

- Mitigation can typically be implemented relatively quickly, while subsurface contamination is being more fully delineated or remediated.

- EPA's experience with residential communities suggests that many affected residents seek and prefer that mitigation systems be installed when vapor intrusion is suspected.

- Mitigation can be a cost-effective approach to help ensure protectiveness of human health during ongoing vapor intrusion investigations to acquire multiple lines of evidence and characterize spatial and temporal variability in subsurface and indoor air concentrations, as well as while subsurface remediation is being planned and conducted to reduce or eliminate subsurface vapor sources.

In summary, PEM, based on limited but credible subsurface and building data, can be an appropriate approach to begin to implement response actions quickly and ensure protectiveness of current building occupants. In such circumstances, resources can be used appropriately to focus first on mitigation of buildings and subsurface remediation, rather than site and building characterization efforts, which may be prolonged. Although PEM may be an effective tool to reduce the human exposure and human health risk, building mitigation is not generally intended to address the subsurface vapor source; as such, EPA recommends that it typically be used in conjunction with remediation of the subsurface source of vapor-forming chemicals (e.g., source removal or treatment), as discussed in Section 8.1.

7.8.2 General Decision Framework

To consider PEM, EPA recommends that reliable data supporting a preliminary analysis, as described in Section 5.0, and risk-based screening, as described in Section 6.5, be obtained and documented in the administrative record. In appropriate circumstances (e.g., where time is of the essence to ensure protection of human health; see, for example, Section 7.5.2), a formal human health risk assessment need not be conducted and documented before selecting PEM, but a preliminary evaluation of human health risk using individual building data or aggregated community data is generally recommended. If there are insufficient data to perform a preliminary risk analysis, but subsurface vapor sources are known to be present near buildings (see Section 5.3), EPA recommends that an appropriate vapor intrusion investigation (see Section 6) be conducted to obtain sufficient data.

EPA generally recommends that the decision to undertake building mitigation be supported by appropriate lines of site- or building-specific evidence (e.g., characterization of subsurface vapor source(s) strength and proximity to building(s); building conditions) that demonstrate that vapor intrusion has the potential to pose an unacceptable human health risk. Sections 5, 6, and 7 herein provide information about the types of evidence obtained and relied upon in assessing vapor intrusion potential and the types of analyses that can support determinations of whether the vapor intrusion pathway is complete for a specific building or collection of buildings and poses or has the potential to pose a health concern to building occupants. This information is equally pertinent for supporting final remediation and mitigation decisions and for supporting PEM consistent with applicable statutes and regulations. The premise of PEM, however, is to protect human health first without necessarily waiting to collect all lines of pertinent evidence or multiple rounds of sampling data.

Certain types of subsurface conditions may have greater potential to facilitate vapor intrusion when subsurface sources of vapors are present. These conditions include, but are not limited to:

- Shallow aquifers (for example, five feet or less from the building foundation to the seasonal high water table).

- High-permeability (e.g., gravelly) vadose zone soils that are fairly dry, which are favorable to upward migration of gases.

- Preferential migration routes, such as fractured sediments or bedrock, buried streambeds, subsurface drains, and utility conduits, as they can facilitate vertical or lateral migration of vapor with limited attenuation of chemical concentrations.

Under these conditions, it may be easier to determine that PEM may be warranted if a structure is located near a subsurface vapor source that has the potential to pose an unacceptable human health risk. Other factors to consider include the following:

- Susceptibility to soil gas entry. Some buildings have greater potential for vapor intrusion (i.e., are more susceptible to soil gas entry; see Section 2.3) than others. For example, buildings with deteriorating basements or dirt floors generally provide poor barriers to vapor (soil gas) entry. Buildings with sumps or other openings to the subsurface that can facilitate soil gas entry are also more susceptible to vapor intrusion.

- Actions undertaken or planned to address the subsurface source of vapors. For example, if the source of vapors (e.g., contaminated soil in the vadose zone) is being removed (e.g., excavation of contaminated soil or soil vapor extraction underneath the building) or is to be removed within a time frame that is protective for any potential current or near-term exposures in the overlying or nearby building, then PEM may not be warranted.

7.8.3 Some General Scenarios Where Pre-emptive Mitigation May be Warranted

Three general scenarios where PEM may be warranted are summarized below. The first two scenarios address situations where building(s) currently exist, while the third scenario addresses a situation where building(s) may be constructed in the future.

Site with High Potential to Facilitate Vapor Intrusion. In this scenario, indoor air concentration data have not been collected, but other lines of evidence support a conclusion that the vapor intrusion pathway is likely complete and may pose an unacceptable human health risk. Figure 7-1 shows a hypothetical residential area located near a shopping center that contains an active dry-cleaning facility. In this hypothetical example, a sufficient number of appropriately screened monitoring wells have been installed throughout the neighborhood to characterize a historical groundwater plume emanating from the dry cleaner that has migrated under eight homes and continues to migrate. Groundwater is encountered at approximately five feet below ground surface, and site geology consists of dry gravel and sands. “Near-source” soil gas samples have also been collected from several locations throughout the neighborhood and found to corroborate a high-strength vapor source near the buildings. All homes have crawl spaces with dirt floors. In this hypothetical example, PEM may be warranted for the eight buildings located above, near, or downgradient of the groundwater plume, based on the groundwater concentration and soil gas data available (i.e., PCE concentrations significantly exceeding

screening levels in this example),[215] and the likelihood that the proximity of the groundwater table, characteristics of the vadose zone, and building conditions will collectively facilitate vapor migration and intrusion.

Note that if a groundwater restoration system is constructed and operated and plume migration is thereby controlled, additional buildings downgradient of the plume may not warrant PEM in the future. In the meantime, an IC may be appropriate for the undeveloped parcel hydraulically down-gradient of the current leading edge of the plume.

Site with Indoor Air Data for Some Buildings but Not for All Buildings. Depending on individual owners and occupants in the affected community, it may be difficult to obtain adequate data for all buildings within a specified area. Challenges include gaining timely access into each building and other practical considerations. In such circumstances, it may be appropriate to characterize a limited number of buildings under a reasonable maximum vapor intrusion condition,[216] by collecting and weighing multiple lines of evidence, and then extrapolating those findings to similar buildings nearby. The following hypothetical scenario describes one such situation, which is represented in Figure 7-2. In this hypothetical example, a sufficient number of appropriately screened monitoring wells have been installed throughout the neighborhood to characterize a historical groundwater plume. "Near-source" soil gas samples have also been collected from several locations throughout the neighborhood and found to corroborate the measured groundwater concentrations. Indoor air has been sampled and analyzed for a few homes and found to exhibit concentrations that pose an unacceptable human health risk. In this scenario, the assumption can be made that buildings with similar construction and built about the same time may have similar susceptibility to soil gas entry. As a result, it may be determined to use a PEM approach to offer mitigation systems to all buildings within a specified area of subsurface contamination.

[215] Several site-specific factors render inappropriate the use of the recommended attenuation factors and groundwater and soil gas VISLs for purposes of identifying sites or buildings unlikely to pose a health concern through the vapor intrusion pathway, as discussed in Section 6.5.2. Nevertheless, response actions for vapor intrusion can be supported when the groundwater and soil gas VISLs are exceeded for samples from a building or site where these specific factors are present.

[216] EPA recommends basing decisions about whether to undertake response action for vapor intrusion (i.e., a component of risk management) on a consideration of a reasonable maximum exposure (e.g., EPA 1989, 1991a), which is intended to be a semi-quantitative phrase, referring to the lower portion of the high end of the exposure distribution (see Glossary).

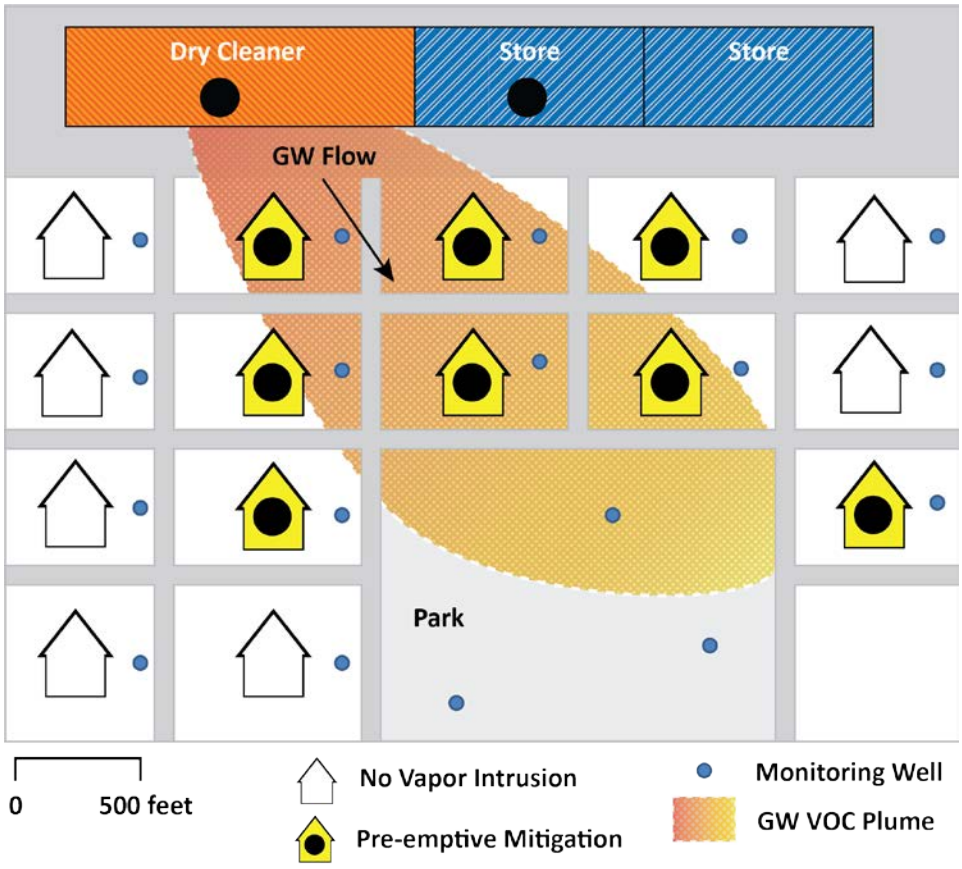

Figure 7-1 Sample Depiction of Subsurface Vapor Source and Data to Support Pre-emptive Mitigation/Early Action for Multiple Buildings, Each with Limited Data

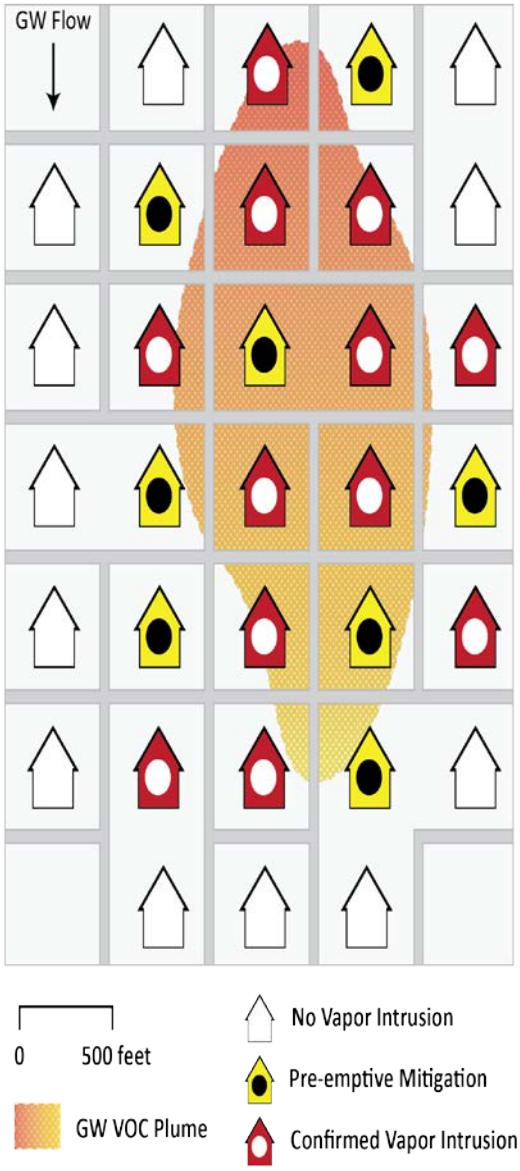

Figure 7-2 Sample Depiction of Subsurface Vapor Source and Data to Support Pre-emptive Mitigation/Early Action for Multiple Buildings, Some with Only Limited or No Data

Future Construction and Development. If current data (e.g., "near-source" soil gas) indicate that there is potential for unacceptable human health risk arising from vapor intrusion in an area where a building(s) is expected to be constructed in the future, EPA recommends that the remediation decision document record the known facts and data analyses and clearly state that vapor intrusion mitigation or site re-evaluation may be needed when the property is developed or occupied. EPA generally recommends appropriate ICs to ensure enforcement of such remediation decisions.[217]

Prior site use (see Section 5) can be particularly relevant where residential development is planned or occurring on property formerly used for commercial or industrial purposes. In these situations, it is not uncommon for residual NAPLs or shallow plumes to remain. Under this circumstance, PEM may be warranted for new construction as a precautionary measure without direct evidence of a vapor intrusion pathway. Incorporating mitigation systems into newly constructed buildings is generally easier to implement and incurs lower cost when compared with retrofitting existing structures.

On the other hand, if response actions to treat or remove the subsurface vapor source(s) are being conducted or will be conducted before a building is constructed and occupied, then building mitigation for the vapor intrusion pathway may not be warranted in the future.

7.8.4 Additional Considerations

EPA recommends that the following factors also be considered in evaluating PEM and determining whether to implement it.

Weighing Relative Costs of Characterization versus Engineered Exposure Controls. EPA recommends that cost not be the primary criterion for deciding whether or how to mitigate vapor intrusion because protection of human health could be compromised. On the other hand, cost effectiveness is addressed by CERCLA and the NCP and can be an important consideration when evaluating response alternatives. Cost can be a factor in deciding when and whether to pursue PEM, in relation to continuing to investigate and assess actual or potential vapor intrusion, and in ensuring effective human health protection through installing and operating a vapor intrusion mitigation system. At PRP-lead sites, for example, PEM may be viewed favorably where the costs associated with a complete site characterization or continued monitoring are estimated to easily exceed the cost of installing a mitigation system (and associated system monitoring). The number of buildings that would need to be characterized, or the order of priority, may be a factor in considering whether to implement PEM.

Institutional Controls. For existing vapor intrusion mitigation systems, ICs may be warranted to ensure that the system is operated, maintained, and monitored. Maintenance and monitoring of the mitigation system, which are discussed in Sections 8.3 and 8.4 of this document, are generally appropriate to ensure that the system is performing as intended. In addition, ICs may facilitate access to property to conduct routine maintenance and monitoring activities, although

[217] At undeveloped sites, or at sites where land use may change in the future, ICs may be important to ensure that the vapor intrusion pathway is effectively addressed in the future. ICs at undeveloped sites could include mechanisms to inform the need for PEM in new buildings. Selecting and implementing PEM for new buildings avoids some of the difficulties associated with attempting to predict the potential for vapor intrusion prior to building construction.

separate access agreements also warrant consideration. Additional information regarding ICs is provided in Section 8.6 of this document.

Community Input and Preferences. Community acceptance of early action may vary widely, depending on the human health risk to building occupants and past experiences at the site, including interaction with site stakeholders and regulators and perceptions of the site. Some owners and occupants may view PEM as a precautionary measure and be willing to have mitigation systems installed; some may even request them before characterization is completed. On the other hand, some home owners may not agree to have a mitigation system installed unless the pathway is demonstrated to be complete.

Others may be reluctant to install mitigation systems because of the operation costs or the inconvenience associated with the installation and subsequent monitoring. Although some owners may view mitigation systems as an advantage when they sell a property, others may be concerned with the possible negative effect on property values.

Issues and concerns about equity and fairness can also arise when some homes within a neighborhood receive mitigation systems and others do not. In some situations, it may be easier to persuade property owners to install vapor intrusion mitigation systems if the entire street, block, or neighborhood is found to warrant early action.

Public meetings and one-on-one meetings provide opportunities to discuss PEM with affected property owners and building occupants and obtain information and input. Section 9.0 of this document provides additional information about community involvement and engagement.

Refined Conceptual Site Model

Decisions to undertake pre-emptive mitigation may warrant re-evaluation as additional monitoring and/or site and/or building characterization data become available and are evaluated in the context of the conceptual site model. If and when such data shift the weight of evidence towards a conclusion that the vapor intrusion pathway is incomplete or otherwise does not pose unacceptable health risk, then EPA recommends re-considering whether continued operation, maintenance, and monitoring of the interim response action (Section 8.2) is warranted.

8.0 BUILDING MITIGATION AND SUBSURFACE REMEDIATION

This section summarizes information and recommendations on potential response options to mitigate and manage vapor intrusion. It is organized as follows:

- Section 8.1 summarizes the role of subsurface remediation in mitigating vapor intrusion.
- Section 8.2 provides an overview of engineered exposure controls (i.e., building mitigation technologies) for existing and new buildings.
- Sections 8.3 and 8.4 summarize information about operating and monitoring building mitigation systems, respectively.
- Section 8.5 summarizes information about documenting building mitigation systems.
- Section 8.6 describes and provides information about institutional controls (ICs).
- Section 8.7 provides information about exit strategies (e.g., termination of: subsurface remediation for vapor source control; building mitigation system operation; and associated ICs).

Sections 5.2, 7, and 9 discuss potential bases for deciding to implement response options for vapor intrusion. Sections 3.3 and 7.7 introduced some of the response options and policies discussed in the remainder of this Section regarding components and development of cleanup plans.

8.1 Subsurface Remediation for Vapor Source Control

The preferred long-term response to the intrusion of vapors into buildings is to eliminate or substantially reduce the level of contamination in the subsurface vapor source (e.g., groundwater, subsurface soil, sewer lines) by vapor-forming chemicals to acceptable-risk levels, thereby achieving a permanent remedy. Remediation of the groundwater plume or a source of vapor-forming chemicals in the vadose zone will eventually eliminate potential exposure pathways and can include the following actions, among others:

- Removal of contaminated soil via excavation;
- Removal of contaminated groundwater with pump-and-treat approaches;
- Decontaminating and/or rehabilitating sewer lines that harbor vapor-forming chemicals; and
- Treatment of contaminated soil and groundwater *in situ*, using technologies such as soil vapor extraction, multiphase extraction, and bioremediation, or natural attenuation.

Because there is a substantial body of EPA and other guidance on selection, design, construction, and operation of technologies for remediation of subsurface vapor sources (e.g., EPA 1993b, 2006c; NRC 2004), these topics are not discussed further here.

When monitoring to assess the performance and effectiveness of remediation technologies for subsurface vapors, EPA recommends employing the methods, approaches, and recommendations described in Sections 5.4, 6.2, 6.4 and 7.0 of this Technical Guide.

ICs may be necessary to help ensure the continued integrity of the cleanup. In some cases, therefore, ICs such as zoning or deed restrictions, may accompany implementation of vapor source remediation methods. Section 8.6 provides information about ICs and their application to the vapor intrusion pathway.

8.2 Building Mitigation for Vapor Intrusion

In cases where subsurface vapor sources cannot be remediated quickly, it may be appropriate to also undertake (interim) measures in individual occupied buildings (i.e., building mitigation for vapor intrusion) to reduce threats to human health more quickly. EPA recommends that building mitigation for vapor intrusion be regarded as an interim action that can provide effective human health protection, which may become part of a final cleanup plan. Mitigation of vapor intrusion in specific buildings generally is not a substitute for remediation of subsurface vapor sources. Thus, EPA recommends that building mitigation generally be conducted in conjunction with vapor source remediation where at all possible.

The purpose of this section is to provide an overview of vapor intrusion mitigation for new and existing buildings where response action is determined to be warranted. Section 8.2.1 summarizes response options that generally can be implemented relatively quickly to reduce indoor air concentrations. Section 8.2.2 identifies and summarizes the most commonly implemented engineered control methods for reducing vapor intrusion into existing buildings. Section 8.2.3 identifies and describes some approaches and considerations for addressing vapor intrusion for new buildings. Additional detailed information about technologies for reducing vapor intrusion into buildings and their selection, design, operation, and monitoring is provided in other EPA documents (EPA 1993a, 2008c). Building owners and occupants may find EPA's *Consumer's Guide to Radon Reduction* (EPA 2013b) a useful source of additional information, in light of similarities in technologies for reducing vapor intrusion and radon intrusion.

ICs may be necessary to help ensure the continued integrity of building mitigation systems. In many cases, therefore, ICs may accompany implementation of engineered exposure controls, for example to ensure that an active system remains operational and passive membranes are not disturbed (EPA 2008c). Additional information about ICs is provided in Section 8.6.

8.2.1 Prompt Response Options for Existing Buildings

For buildings with potential explosion and fire hazards, EPA recommends evacuation, along with notification of the local fire department about the threat. If, on the other hand, prompt action is warranted to reduce or eliminate vapor intrusion exposures in an existing building (e.g., measured indoor air concentrations pose an unacceptable human health risk for an acute or short-term exposure scenario (see Section 7.5.2)), it may be appropriate to implement response options such as the following:

- Sealing major openings for soil gas entry, where known and identified;
- Over-pressurizing nonresidential buildings by adjusting the HVAC system;

- Installing, repairing, or maintaining vapor traps for sewer or drain lines that are sources of vapor intrusion;

- Increasing building ventilation, for example using fans or natural ventilation;

- Treating indoor air (e.g., adsorption using activated carbon); and

- Temporary relocation

The fore-going response actions may take several days to a few weeks to plan (e.g., arrange, design) and implement, which generally is quicker than other interim response actions (e.g., active depressurization technologies). The first three options seek to reduce or eliminate vapor entry into the building. The last three options seek to reduce, eliminate, or avoid vapors that have entered the building by vapor intrusion. Specifically:

- Vapor intrusion into the building via soil gas entry from vadose zones soils can be reduced by sealing foundational openings using products such as synthetic rubbers, acrylics, oil-based sealants, asphalt/bituminous products, swelling cement, silicon, epoxy or elastomeric polymers. EPA recommends screening the selected sealant(s) (e.g., checking the composition, relying upon manufacturer's data) to ensure they do not contain or emit vapor-forming chemicals that might pose a human health risk to building occupants. This interim mitigation approach is among the easiest and least expensive to implement; however, its effectiveness relies upon being able to identify and access openings for soil gas entry. EPA recommends appropriate monitoring of indoor air concentrations be conducted to ensure that sealing attains and sustains sufficient reduction in vapor intrusion. In some cases, however, sealing openings may not be capable of reducing indoor air concentrations to acceptable levels and/or some openings may not be visible and accessible. EPA recommends that this response option generally be supplemented by installing, operating, and maintaining an engineered exposure control (e.g., an active depressurization technology) that reduces or eliminates vapor entry into the building until remediation of subsurface vapor sources is complete and terminated.

- For commercial and industrial buildings where HVAC units blow air into the building and are well maintained, it may be advantageous to increase pressurization in the building to prevent or reduce vapor intrusion. In some cases (e.g., buildings with few doors and other openings), relatively small increases in building pressure may be sufficient, which may be accomplished by increasing the air flow rate and using specialized equipment to monitor and balance air flow rates. EPA recommends appropriate monitoring of pressure and other indicators (e.g., indoor air monitoring) be conducted to ensure that adequate pressurization is sustained throughout areas of the building that could be subject to vapor intrusion. In some climates and for some buildings, this response option may be impractical or prohibitively expensive.

- Vapor intrusion into the building via gas entry from sewer and drain lines can be reduced or eliminated by installing, repairing, and maintaining vapor traps.

- Increasing building ventilation (i.e., increasing the rate at which indoor air is replaced with outdoor air) can reduce the buildup of indoor air contaminants within a structure. Natural ventilation may be accomplished by opening windows, doors, and vents. Forced

or mechanical ventilation may be accomplished by using a fan to blow air into or out of the building. Increased ventilation is easiest and least costly to implement in locations where the air is not conditioned (heated or cooled). If indoor air is conditioned, increased ventilation can be a costly option because the conditioned air is ventilated to the outdoors. This drawback can be partly overcome by use of heat exchangers, but they are also costly. Another concern is that exhausting air from the building will generally contribute to under-pressurization of the building, relative to the subsurface, thereby potentially resulting in an increased rate of soil gas entry (i.e., vapor intrusion) unless ambient air entry into the building is increased equivalently. EPA recommends appropriate monitoring of indoor air concentrations be conducted to ensure that ventilation attains and sustains sufficient reduction in exposures to vapor-forming chemicals. In some cases, ventilation may not be capable of reducing indoor air concentrations to acceptable levels. In addition, building occupants may find it uncomfortable to increase the air exchange rate by more than a factor of three or four. EPA generally recommends that this response option be supplanted, when feasible, by installing, operating, and maintaining an engineered exposure control that reduces or eliminates vapor entry into the building until remediation of subsurface vapor sources is complete and terminated.

- Commercially available indoor air cleaners, which include both in-duct models and portable air cleaners, is another response option. These devices operate on various principles, including zeolite and carbon sorption and photocatalytic oxidation. Methods that rely on adsorption generate a waste that must be disposed of appropriately or regenerated and warrant periodic replacement of the adsorption medium. EPA recommends appropriate monitoring of indoor air concentrations be conducted to ensure that adequate treatment is sustained throughout the building. EPA generally recommends that this response option be supplanted, when feasible, by installing, operating, and maintaining an engineered exposure control that reduces or eliminates vapor entry into the building until remediation of subsurface vapor sources is complete and terminated.

- Temporary relocation may be implemented for buildings where conditions warranting prompt response action (see Section 7.5) and cannot be adequately addressed by other means.[218]

None of these options entails reducing the level of vapor-forming contamination in the subsurface medium (see Section 8.1). EPA generally recommends that these response options be supplanted, when feasible, by installing, operating, and maintaining an engineered exposure

[218] For response actions carried out under Sections 104(a) and 106(a) of CERCLA, OSWER Directive 9230.0-97 (*Superfund Response Actions: Temporary Relocations Implementation Guidance* (EPA 2002d)) states: "Temporary relocation should not be selected if health and safety risks or circumstances that pose an unreasonable inconvenience can be adequately addressed by other means without significantly increasing the overall cost or duration of the response action." Similarly, OSWER Directive 9355.0-71P (*Interim Policy on the Use of Permanent Relocations as Part of Superfund Remedial Actions* (EPA 1999f)) states: "EPA's preference is to address the risks posed by the contamination by using well-designed methods of cleanup which allow people to remain safely in their homes and business." OSWER Directive 9230.0-97 provides recommended procedures and other policies for temporarily relocating residents when this response action is selected and implemented under Sections 104(a) and 106(a) of CERCLA.

control that reduces or eliminates vapor entry into the building (see Section 8.2.2), until remediation of subsurface vapor sources is complete and terminated.

8.2.2 Active Depressurization Technologies for Existing Buildings

This section provides a brief overview of engineered systems that can be used to reduce or eliminate soil vapor intrusion in existing buildings, along with a summary of steps and considerations for selecting an appropriate technology for a given building. The focus is on active depressurization technologies most commonly employed for reducing soil vapor intrusion into buildings. This focus does not mean, however, that active depressurization technologies are always preferred over other mitigation methods or that they will be the best option for every site. More detailed information on vapor intrusion mitigation systems for existing buildings, including sub-membrane ventilation systems and passive technologies,[219] can be found in several EPA publications (e.g., EPA 2008c).

Active depressurization technologies (ADT) have been used successfully to mitigate the intrusion of radon into buildings and have also been successfully installed and operated in residential, commercial, and school buildings to control vapor intrusion from subsurface vapor-forming chemicals. ADT systems are widely considered the most practical vapor intrusion mitigation strategy for most existing buildings, including those with basement slabs or slab-on-grade foundations. ADT systems are generally recommended for consideration for vapor intrusion mitigation because of their demonstrated capability to achieve significant concentration reductions in a wide variety of buildings[220] and their moderate cost.

Sub-slab depressurization (SSD) systems, a common type of ADT system, function by creating a pressure difference across the building slab to prevent soil gas entry into the building (i.e., overcoming the building's natural under-pressurization, which is the 'driving force' for vapor intrusion; see Section 2.3). Creating this pressure difference is accomplished by extracting soil gas from beneath the slab and venting it to the atmosphere.[221] For the system to be effective by this mechanism,[222] this soil depressurization must be established and maintained at least near the primary openings for soil gas entry (EPA 1993a). Construction of SSD systems entails opening one or more holes in the existing slab, removing soil from beneath the slab to create a "suction pit" (6–18 inch radius), placing vertical suction pipes into the holes, and sealing the

[219] As noted in Section 3.3, engineered exposure controls that do not involve mechanical operations (e.g., creating a barrier between the soil and the building that blocks openings from soil gas entry into the building) are referred to as "passive."

[220] Folkes and Kurz (2002) describe a case study of a vapor intrusion mitigation program in Denver, Colorado. Sub-slab depressurization systems and/or sub-membrane depressurization systems were installed in 337 residential homes to control indoor air concentrations of 1,1-dichloroethylene (DCE) resulting from migration of vapors from groundwater with elevated 1,1-DCE concentrations. Over three years of monitoring data for 301 homes have shown that these systems are capable of achieving the very substantial reductions in concentrations in indoor air. Approximately one quarter of the systems warranted minor adjustment or upgrading after initial installation in order to achieve the state standards established for indoor air exposure.

[221] Depending, in part, upon location and prevailing statutes and regulations, governmental permits or authorizations may be required for venting systems that exhaust to the atmosphere.

[222] A second mechanism by which ADT systems can function is diluting the vapor concentrations beneath the slab and foundation (EPA 1993a, 2008c). Engineered controls designed and operated to use this mechanism predominately are often referred to as sub-slab ventilation systems.

openings around the pipes. These pipes are then connected together to a fan, which draws soil gas from the sub-slab area through the piping and vents it to the outdoors.[223] Sealing known and accessible openings in the slab and foundation can reduce the flow rate of conditioned indoor air that can be pulled into the sub-slab region by the suction wells and the sub-slab depressurization (EPA 2008).

SSD systems were first developed for radon reduction (EPA 1993a) and operate under similar design principles as radon mitigation methods. Figure 8-1 illustrates such an SSD system.

When sumps and associated drain tile systems are present, they may also be depressurized to prevent soil gas entry into the building (again, overcoming the building's natural under-pressurization). This variation on active depressurization is often referred to as drain-tile depressurization (DTD). Depressurization of drain tiles located near a foundation wall can help control soil gas entry at the joint between the foundation wall and slab. Figure 8-2 illustrates such a DTD system.

If the building has hollow block walls, the usual sub-slab suction point may not adequately mitigate the wall cavities, which may be particularly important if the outside surfaces are in contact with the soil. In these situations, the void network within the wall may be depressurized by drawing air from inside the wall and venting it to the outside. This method, called "block-wall depressurization" (BWD) is often used in combination with SSD. Because uniform depressurization of block walls can be difficult, BWD is generally recommended only when sub-slab or DTD prove inadequate to control vapor intrusion. Figure 8-3 illustrates such a BWD system.

In buildings with a crawl space foundation or a basement with a dirt floor, a flexible membrane may be installed over the floor to facilitate depressurization of the soil gas beneath the membrane, which prevents vapors from intruding into the crawl space or basement air. To maximize the effectiveness of a sub-membrane depressurization (SMD) system, EPA recommends the membrane cover the entire floor area and be sealed at all seams and penetrations. Figure 8-4 illustrates such an SMD system.

Extensive guidance is available for the design, sizing, installation, and testing of ADT systems for radon control in existing and new homes and large institutional (e.g., school) and commercial buildings. EPA recommends that ADT systems be designed and installed by qualified persons, typically environmental professionals and licensed radon contractors. EPA guidance for design of ADT systems can be found in several publications (e.g., EPA 1993a, 2008c). EPA recommends documenting each constructed ADT system via a system manual, as described further in Section 8.5.

The Vapor Intrusion Mitigation Quick Guide provided in Table 8-1 summarizes a list of steps for selecting and implementing a vapor intrusion mitigation system in existing buildings.

[223] A central issue that determines the design and effectiveness of ADT systems is the ease with which suction at one location can extend to other subsurface areas underneath the building. Where a good and uniform layer of aggregate (e.g., gravel or crushed rock) was placed underneath a slab foundation during construction, for example, such hydraulic control and communication can generally be expected to be good (EPA 1993a). Where the layer of aggregate under a slab is interrupted or uneven to a significant degree, additional suction pipes will generally be needed and their location will be increasingly important.

TABLE 8-1
VAPOR INTRUSION MITIGATION QUICK GUIDE FOR EXISTING BUILDINGS

Step 1: Consider Prompt Response Actions

It may be appropriate to implement certain interim measures before engineered controls are constructed and operated, as warranted and feasible. For example, building ventilation can be increased, cracks and other openings in the floor or foundation (that otherwise allow soil gas entry) can be sealed, or indoor air treatment can be conducted (refer to Section 8.2.1).

Step 2: Select a Building Mitigation System

The initial step in selecting the appropriate vapor intrusion mitigation technology is to conduct a visual inspection of an existing building. The selection of a vapor intrusion mitigation system primarily depends on building characteristics and contaminant concentrations. In the majority of cases, a type of active depressurization technology (ADT) can be an efficient, reliable, and cost-effective vapor intrusion mitigation technique. In some cases, however, other approaches may be preferable.

Factors that may prompt consideration of vapor intrusion mitigation approaches other than ADT include foundation conditions that prevent development and extension of a suction field below the building.

If there are no factors that would rule out an ADT technology, appropriate systems that can be considered include:

- Sub-slab depressurization (SSD) systems, particularly in houses having slabs (basements and slabs on grade) where drain tiles are not present.
- Drain-tile depressurization (sump/DTD or remote discharge/DTD) when drain tiles are present.
- Sub-membrane depressurization (SMD) in buildings with a crawlspace foundation or a basement with a dirt floor,
- Block-wall depressurization (BWD), usually used only as a supplement to SSD, DTD, or SMD to better mitigate vapors found to be migrating through the wall.

Step 3: Design Building Mitigation System

EPA recommends the final detailed design of the selected vapor intrusion mitigation technology specify the number and location of suction points, location and size of piping, suction fan, piping network and exhaust system, and sealing options to be used in conjunction with the ADT technology. Pre-mitigation diagnostic testing can provide information about the suction field underneath a building and pressure differences that will need to be overcome (EPA 1993a) if the ADT system is to be effective. Diagnostic testing during installation can also help verify the adequacy of the design.

Step 4: Install Building Mitigation System

EPA recommends that the vapor intrusion mitigation system be installed consistent with design specifications by equipment manufacturers, local permit conditions and regulations, and relevant industry standards.

Step 5: Confirm the Installed System is Operating Properly

EPA recommends a visual inspection of the installed system as a routine quality assurance step to confirm that all construction details have been completed. Post-construction monitoring is recommended (refer to Section 8.4) to demonstrate the ADT system is operating appropriately and effectively. Where a vapor intrusion mitigation system is not performing adequately, post-construction diagnostic tests can be helpful in trouble-shooting (EPA 1993a).

Step 6: Ensure Proper Operation and Maintenance of Vapor Intrusion Mitigation System (refer to Sections 8.3 and 8.4)

EPA recommends proper system maintenance and periodic inspections and monitoring to ensure the system is operating as designed and is effective at reducing indoor air concentrations to (or below) target levels. EPA recommends that site managers provide the building owner/occupant with information to help ensure proper operation and maintenance of the system.

EPA recommends that periodic inspections include periodic measurements to confirm that the building mitigation system is continuing to perform adequately.

The U.S. Navy has issued a concise fact sheet that contains useful technical information (DoN 2011b).

8.2.3 Approaches and Considerations for New Buildings

The ADT systems described above are generally available for new buildings also. However, a wider array of approaches and technical options is typically available to mitigate or avoid vapor intrusion for new buildings, compared to existing buildings. These options potentially include the choice of building location and opportunities to modify the building design and construction, which are not available for existing buildings. For example:

- At some sites, contaminated areas most likely to produce unacceptable vapor intrusion exposures can be avoided and designated for another purpose, such as recreational space or undeveloped landscape.

- Mitigation needs can also be considered in the selection of heating and cooling systems, which are normally selected based only on economics, aesthetics, preference, and custom. A system design that avoids creating under-pressurization inside the structure and maintains over-pressurization inside the structure may be effective in mitigating vapor intrusion.

- Passive barriers, such as a low-permeability membrane, can be more readily installed between the soil and the building during new building construction. Passive barriers are intended to reduce vapor intrusion by limiting openings for soil gas entry. However, passive barriers as stand-alone technologies may not adequately reduce vapor intrusion owing to difficulties in their installation and the potential for perforations of the barrier during or after installation. They are commonly combined with ADT systems or with sub-membrane ventilation systems to help improve their efficiency.

- Venting layers can be more readily installed between the soil and the building during new building construction.[224]

- New buildings may be designed to include a highly ventilated, low-occupancy area at ground level, such as an open parking garage.

Steps 2-6 of the Vapor Intrusion Mitigation Quick Guide provided in Table 8-1 are also pertinent to newly constructed buildings. EPA guidance for selecting, designing, and installing vapor intrusion mitigation systems for new buildings can be found in several publications (e.g., EPA 2008c). The U.S. Navy has issued a concise fact sheet that contains useful technical information (DoN 2011c).

[224] Constructed sub-slab ventilation systems typically consist of: a venting layer (e.g., filled with porous media such as sand or pea gravel; or suitably fabricated with continuous voids) below a floor slab to allow soil gas to move laterally to a collection piping system for discharge to the atmosphere; and a sub-slab liner that is installed on top of the venting layer to reduce entry points for vapor intrusion. These and other sub-slab ventilation systems function by drawing outside air into and through the sub-slab area, which dilutes and reduces concentrations of vapor-forming chemicals, and provides a route for soil gas to vent to the atmosphere or migrate outside the building footprint, rather than into a building.

8.2.4 Owner/Occupant Preferences and Building Access

Building owners and occupants can initially be notified in various ways that their home or building warrants construction and operation of a building mitigation system. Section 9.5 provides information regarding such notifications and other messages pertaining to building mitigation.

Whereas EPA managers and mitigation system designers may be primarily concerned with the performance, cost-effectiveness, and reliability of any mitigation system, the building owners and occupants may have additional perspectives and opinions that warrant consideration during technology selection, design, construction, and operation. For example, owners and tenants will often have strong opinions about where fans and piping are located, what level of fan noise is acceptable, and what quality of construction craftsmanship is satisfactory. When there are multiple mitigation options (for example, at a large commercial building), EPA recommends these options be presented fairly to the building owner and tenants, explaining the advantages and disadvantages associated with each and describing the rationale for the preferred alternative.

In some cases, obtaining and scheduling access to a building can be difficult, whether the structure is a commercial or institutional building or a private residence. Commercial building tenants may not want construction activities disrupting business operations. Some homeowners/tenants may resist granting access to their home. Other homeowners/tenants may prefer to schedule tests before or after their work-day. To address these practical and logistical concerns, EPA recommends that an access agreement(s) be executed between the property owner, any tenants, and the mitigating entity to ensure appropriate access as needed to operate, maintain, and monitor the engineered exposure controls in each impacted building.

8.3 Operation and Maintenance of Vapor Intrusion Mitigation Systems

For purposes of this Technical Guide, operation and maintenance (O&M) is used generically to refer to periodic inspections, component maintenance or replacements, repairs, and related activities that are generally necessary to ensure continued operation and effectiveness of engineered exposure controls to mitigate vapor intrusion. EPA generally recommends that such O&M activities be conducted routinely, be documented in an O&M plan (as described further in Section 8.5), and consider recommendations of equipment manufacturers, if any, and site-specific factors. Additional information about ensuring continued effectiveness of systems is available in EPA (2009b).

Design specifications for vapor migration systems may include (1) a maintenance frequency that varies over the operating period of the mitigation system and/or (2) a provision to evaluate and modify the frequency based on data or information obtained during monitoring and maintenance. For example, it may be acceptable to reduce inspection or maintenance frequency once efficient system operation has been demonstrated for at least an initial year, with triggers for additional, unscheduled inspections following alarms (from warning devices) and floods, earthquakes, and building modifications, if any.

Typical O&M activities for either passive or active systems may include, but are not limited to:

- Routine inspection of all visible components of the vapor intrusion mitigation system, including fans, piping, seals, membranes and collection points, to ensure there are no

signs of degradation or blockage. EPA recommends that the as-built drawing for the vapor intrusion mitigation system be examined to verify the system configuration has not been modified.

- Visual inspection of the building to evaluate whether any significant changes were made (such as remodeled basement, new furnace) that would affect the design of the vapor intrusion mitigation system or the general environment in which it is operated. A crawl space SMD membrane, for example, may warrant repair or replacement if its integrity is compromised.

- Visual inspection of the area of concern (including basement floor and wall seals, sumps, floor drains and utility penetrations) to ensure there are no significant changes in conditions that would warrant modification of the system design.

- Routine monitoring of vent risers for flow rates and pressures generated by the fan to confirm the system is working and moisture is draining correctly.

- Routine maintenance, calibration and testing of functioning components of the venting system consistent with the manufacturers' specifications.

    - Pressure readings for both active and passive depressurization systems as well as positive pressurization systems (e.g., periodic verification of measurable pressure differences across the slab).

    - Confirmation that the extraction fan is operating.

    - SSD system fans generally can function well for prolonged periods without maintenance; however, EPA recommends fans be replaced periodically throughout the operating life of the system (e.g., every 4 to 10 years) to avoid breakdowns and associated problems.

- Inspection of external electrical components to identify undesirable conditions, such as excessive noise, vibration, moisture, or corrosion, and to verify that the fan cut-off switch is operable.

    - Inspection of the fan(s) is important throughout the operating period but may be particularly important near the end of its expected lifespan. Noisy fans typically indicate problems with ball bearings and warrant replacement on that basis.

    - Confirmation of adequate operation of the warning device or indicator.

- Confirmation that building owner/occupants are knowledgeable about how to maintain system operation. Confirmation that a copy of the O&M manual is present in the building and has been updated as necessary.

EPA also recommends that the site team determine if there has been any change in ownership/occupant. If such a change has occurred, EPA recommends the site manager work with the new owner/occupant to ensure continued integrity and operation of the vapor intrusion mitigation system.

8.4 Monitoring of Vapor Intrusion Mitigation Systems

Regardless of the type of system selected for mitigating vapor intrusion in a given building, EPA recommends monitoring to demonstrate that performance standards are achieved at the time of installation and that those performance standards continue to be met throughout the operating period of the mitigation system. EPA recommends that any monitoring program developed for a building mitigation system be based upon site-specific considerations, including the degree of risk or hazard being mitigated, the building use, the technology used to mitigate vapor intrusion, whether the subsurface vapor source(s) is stable in extent and concentration, and coordination with site remediation efforts. For example:

- An older building with highly volatile chemicals at high concentrations may need a more intense level of monitoring than a new building with lower concentrations of less volatile chemicals.

- Passive systems are generally less predictable and less efficient at preventing vapor intrusion than active systems and, therefore, typically warrant more intensive monitoring, all else being equal.

- When contaminated groundwater plumes are migrating to new areas (i.e., expanding) or concentrations in shallow groundwater are increasing, increased frequency and intensity of mitigation monitoring may be warranted.

- During start-up, some remediation methods have the potential to alter soil gas conditions in ways and to a degree that may be difficult to predict. Increased frequency and intensity of mitigation monitoring may be warranted when such remediation methods are implemented near buildings undergoing mitigation.

Mitigation monitoring will generally entail two phases: (i) an initial post-construction phase, which is generally more intensive; and (ii) a subsequent phase, which may be comprised of fewer diagnostic tests to be conducted periodically. As with radon mitigation systems (EPA 1993a, Section 11.1.2), results of indoor air sampling during initial post-construction monitoring may be used to demonstrate that the occupant's exposure to vapor-forming subsurface contaminants has been reduced as anticipated. In addition, pressure field measurements in the subslab region can be used to demonstrate that the system has attained hydraulic control and communication (e.g., depressurization in the case of an ADT system) over the footprint of the building (or portion of a large building, as appropriate, considering the extent of subsurface contamination). Adjustments to the mitigation system and/or additional diagnostic testing (EPA 1993a, 1993c) may be warranted if the results of such testing do not clearly demonstrate that the system is achieving its intended performance and effectiveness. Once an adequate demonstration of effectiveness has been made for the vapor intrusion mitigation system, periodic monitoring is recommended to verify that this performance is sustained; for this purpose, monitoring may be comprised of fewer types of tests than during the immediate post-construction (i.e., start-up) phase at the discretion of EPA when the subsurface vapor source(s) is stable. Examples of various monitoring scenarios for these two phases are provided in Table 4 of CalEPA (2011), Table 6-2 of NJDEP (2012), and Table 3-1 of MADEP (2011). Additional information about ensuring continued effectiveness is available in the *Operational and Functional Determination and the Transfer of Fund-lead Vapor Intrusion Mitigation Systems to the State* (EPA 2009b).

When monitoring to assess the performance and effectiveness of building mitigation technologies, EPA recommends employing the methods, approaches described in Sections 5.4, 6.2, 6.4 and 7.0 of this Technical Guide. EPA also recommends that monitoring programs that assess the performance and effectiveness of remediation and mitigation systems be documented, preferably in work plans similar to those recommended herein for characterizing and assessing the vapor intrusion pathway (see Section 6.2). Such vapor intrusion monitoring plans may be incorporated as part of a comprehensive remedial design and operations manual or as a stand-alone document, depending upon site-specific circumstances. In addition, EPA recommends that data and other results obtained through such monitoring programs be documented (e.g., in the administrative record), as they become available.

The remainder of this section identifies and further discusses some elements commonly incorporated in monitoring programs for active depressurization technologies.

Pressure Measurements

Sub-slab probes can be used to monitor differential pressures for a direct indication of the hydraulic performance of ADT systems (i.e., the pressure difference across the slab prevents soil gas entry); see Section 2.3. For basements, the walls that are underground become part of the critical building envelope that must prevent soil gas entry. For subsurface depressurization systems, EPA recommends that the pressure gauge be monitored quarterly to verify the system is operating efficiently. A reduced monitoring frequency may be appropriate after one year of successful operation of the remedial system.

Tracer Testing

Openings within the building or leaks in the mitigation system can affect system performance. Tracers can be used either for leak detection through barriers, building materials or system components (piping, for example) or to measure the air exchange rate in the building.

Smoke testing is a qualitative form of tracer testing used to detect leaks (e.g., at seams and seals of membranes in SMD systems or at potential leakage points (openings) through floors above sealed crawl space systems or through conduits that facilitate preferential vapor migration), or to test airflow patterns. A limitation of smoke testing in existing structures is that non-noxious smokes can be expensive, and cheaper high-volume smoke sources can leave undesirable residues. The efficacy of smoke testing in some applications has been questioned on the grounds that many leaks are too small for visual detection using this method (Maupins and Hitchins 1998, Rydock 2001), and that leaks large enough to detect using smoke could be detected other ways. More quantitative methods have been recommended, such as tracer testing with instrumentation for quantitative results.

Air Sampling

Once an adequate demonstration of vapor intrusion mitigation system effectiveness has been made, indoor air quality generally will be acceptable as long as an adequate pressure difference is maintained throughout the footprint of the building. Periodic or intermittent sampling of indoor air, nevertheless, warrants consideration, since indoor air data can provide direct confirmation that the system is reducing exposure levels of vapor-forming chemicals and because depressurization technologies can be expected to alter the distribution of vapors in the vadose zone and available for soil gas entry, if any.

Weather-Related Considerations

EPA recommends that weather conditions be noted during monitoring activities (EPA 1993a). Weather conditions, such as temperature and precipitation, can affect the performance of a vapor intrusion mitigation system. For example, cold temperatures may increase the building depressurization created by the thermal stack effect and thus increase the driving force for soil gas entry, depending upon the height of the house and the temperature difference between indoors and outdoors (see Section 2.3). As a result, the ADT system may need to overcome more building depressurization than originally considered when designed. Precipitation may also increase moisture in the fill under the slab, which may affect the performance of the system, and is a factor to consider in developing a monitoring program.

Alarms

Alarms generally are used as part of a monitoring program to ensure that malfunctions of vapor intrusion mitigation systems are timely and readily detected and addressed. According to ASTM (2003), "All active radon mitigation systems shall include a mechanism to monitor system performance (air flow or pressure) and provide a visual or audible indication of system degradation and failure" (i.e., an 'alarm'). ASTM goes on to say, "The mechanism shall be simple to read or interpret and be located where it is easily seen or heard. The monitoring device shall be capable of having its calibration quickly verified on site." Such devices may indicate operational parameters (such as on/off or pressure indicators) or hazardous gas buildup (such as percent LEL indicators). EPA concurs with the cited advice from ASTM and recommends it be considered when monitoring and maintaining mitigation systems for vapor-forming chemicals and sites addressed by this Technical Guide.

In particular, EPA recommends that system failure alarms be installed on active depressurization systems, and appropriate responses to alarms be communicated by the building owner/occupants. EPA also recommends that alarms be placed in readily visible, frequently trafficked locations within the respective building and their proper operation be confirmed on installation and monitored periodically.

Placards

EPA also recommends that permanent placards be placed on the system to describe the system's purpose and operational requirements (e.g., power source) and instructions on what to do if the system does not operate as designed (for example, a phone number to call for corrective action). EPA recommends the placard provide information about how to read and interpret the monitoring instruments or warning devices provided. EPA also recommends that these placards be placed as close to the monitoring/alarm part of the system as possible, as well as close to the fan or other active parts of the system.

8.5 Documentation of Engineered Exposure Controls for Vapor Intrusion Mitigation

EPA recommends that documentation be provided to building owners and occupants and appropriate regulatory agencies[225] describing the vapor intrusion mitigation system (i.e., a 'system manual') and its associated O&M (i.e., an 'O&M plan'). The system manual provides a detailed record about the mitigation system, including as-built drawings, permits (if any), copies of agreements, and construction/layout plans, whereas the O&M manual describes the O&M activities to be conducted routinely and identifies which party is responsible for these O&M activities. Additional information about ensuring continued effectiveness is available in *Operational and Functional Determination and the Transfer of Fund-lead Vapor Intrusion Mitigation Systems to the State* (EPA 2009b).

O&M Plan

O&M plans generally are prepared on a site-specific basis, and they often are particularly useful at sites where:

- Monitoring is needed to verify remedial effectiveness.
- The remedial system warrants periodic adjustments and maintenance.
- Human health risk would result if the system fails or if site conditions change.
- Conditions that would trigger specific contingent response may occur sporadically or episodically.

Some site remedial systems may also warrant the use of a regulatory agency-approved contingency plan or similar corrective response document approved by the regulatory agency to identify conditions that may trigger the need for additional maintenance, collection of additional data, modifications of monitoring frequency, or other responses to ensure the remedy remains effective.

Communication with building owners and occupants about vapor intrusion and the O&M of a vapor intrusion mitigation system is critically important. For example, building owners may be concerned about some aspect of system operation and decide to turn it off. It is important to communicate that turning off the system may result in harmful indoor air concentrations inside the building.

System Manual

The specific contents of the system manual will depend on the type of system. EPA recommends, however, that the system manual generally include at least the following information or items:

- Cover/transmittal letter;

[225] For example, EPA recommends the potentially responsible party (PRP) provide a system manual and O&M plan to EPA at PRP-lead Superfund sites.

- Description and diagram of final as-built system layout with components labeled;
- Building permits for a vapor intrusion mitigation system;
- Pre- and post-mitigation air and gas sampling data;
- Pre- and post-mitigation diagnostic test data;
- Copies of contracts and warranties;
- Proper operating procedures of the system;
- Contact information of the contractor or installer;
- Copy of signed access agreement;
- Copy of vapor mitigation system O&M agreement;
- Copy of pre-mitigation sample result letter (see Section 9.4);
- Copy of post-construction sample result letter;
- Contact information in case of future questions; and
- Inspection and maintenance guidelines.

User's Guide

Documentation typically is also provided to the property owner and occupant in the form of a user's guide suitable to keep lay persons informed about the system and to provide a summary reference in case questions or issues arise pertaining to the system.

A user's guide is a brief summary of why a vapor intrusion mitigation system was installed at a property and how the system works, and may include the following: (1) a brief description of the system and its proper range of operation; (2) contact information for the party responsible for responding to malfunctions and ensuring the system performs properly; and (3) information about routine maintenance to be conducted by the owner/occupant, if any. EPA recommends that a user's guide be placed near the system for quick access and easy reference (e.g., into a clear protective sleeve and attached to the main extraction pipe of the ADT system). An easy-to-read user's guide may be especially helpful at rental properties because the guide informs each new tenant about what the system is and why it was installed.

8.6 Use of Institutional Controls

ICs may be used to restrict certain land uses, buildings, or activities that could otherwise pose an unacceptable human exposure via the vapor intrusion pathway.

Response actions for vapor intrusion may include ICs to restrict land use for protection of human health regardless of whether a vapor intrusion mitigation system provides interim measures to control (i.e., reduce, limit) human exposures. ICs can be used as either an interim

response until site cleanup goals are reached or as part of a long-term response where vapor-forming waste remains in place.

General EPA guidance on ICs is provided in *Institutional Controls: A Guide to Planning, Implementing, Maintaining, and Enforcing Institutional Controls at Contaminated Sites* ("PIME IC Guidance") (EPA 2012d). As discussed in the PIME IC Guidance, ICs are non-engineered instruments, such as administrative or legal controls, that help to minimize the potential for human exposure to contamination and protect the integrity of a response action. ICs typically operate by imposing land or resource use restrictions at a given site or by conveying notice to stakeholders regarding subsurface contamination or the possible need to refrain from certain actions that may result in human exposure to hazardous chemicals. For example, ICs may be used to restrict the development and use of properties for certain land uses (e.g., prohibiting residential housing, hospitals, schools, and day care facilities).

In some situations, ICs can be used to restrict access to a property, facilitate response activities conducted by a responsible party or EPA, such as the installation or maintenance of vapor intrusion mitigation systems, or help ensure the integrity of vapor mitigation systems. ICs may also be used to help inform the need for vapor intrusion mitigation for future construction where vapor-forming waste remains in place and may pose unacceptable human health risk due to vapor intrusion.

As described further in Section 2.2 of the PIME IC Guidance, ICs can be described in four general categories:

- Proprietary controls.
- Governmental controls.
- Enforcement and permit tools with IC components.
- Informational devices.

The first three categories (i.e., proprietary controls, governmental controls, and enforcement and permit tools with IC components) typically memorialize and prescribe substantive use restrictions concerning the land or resource use, while informational devices generally operate to provide notice of contamination and any remedial activities to parties. Depending on the nature of the site and the particular jurisdiction in which it is located, certain instruments may not be available or feasible for a particular site. Certain ICs may help facilitate how interim response actions and subsurface remediation are carried out, such as provisions addressing access, O&M of vapor intrusion mitigation systems, and design specifications for buildings (see Example #3 box below).

8.6.1 Evaluating ICs in the Overall Context of Response Selection

As a site moves through a program's response selection process (for example, a Superfund remedial investigation/feasibility study [RI/FS] or RCRA facility investigation/corrective measures study [RFI/CMS]), EPA recommends that site managers develop information about reasonably anticipated future land uses and infer reasonably expected exposure pathways related to land use. This information may be incorporated in the conceptual site model and often can be used to evaluate whether ICs will be needed to ensure protectiveness of current and

reasonably anticipated future land uses over time. EPA's land use guidance (EPA 1995a, 2010c) recommends that the site manager discuss reasonably anticipated future land uses of the site with local land use planning authorities, local officials, property owners, and the public, as appropriate, as early as possible during the scoping phase of the RI/FS, RFI/CMS, or equivalent phase under other cleanup programs.

EPA recommends that the Region's decisions to implement ICs be documented in proposed cleanup plans and in final cleanup decision documents. For example, for CERCLA cleanups, the proposed restriction, and need for ICs would normally be identified in the Proposed Plan for notice and opportunity to comment by potentially affected landowners and the public. Such use restrictions or notices typically are then selected and memorialized in the Record of Decision (ROD).

In some cases, unanticipated changes in land use may occur after the response action is implemented, which may impact the protectiveness of a completed response action and raise questions concerning the effectiveness of the ICs. As a result, vapor intrusion may be identified as a potential human exposure pathway in a subsequent periodic review. In this case, EPA recommends that site managers evaluate options for modifying the original response decision, including the need for new or additional ICs consistent with existing and reasonably anticipated future land uses and other response selection considerations.

8.6.2 Common Considerations and Scenarios Involving ICs

The evaluation of whether an IC is needed at a contaminated site, including one where the vapor intrusion pathway poses a current or potential threat to human health, is a site-specific determination. When evaluating whether an IC will be needed, EPA recommends that EPA Regional staff consider whether the site meets unlimited use and unrestricted exposure (UU/UE), among other factors. UU/UE is generally the level of cleanup at which all exposure pathways present an acceptable level of human health risk for all land uses, including reasonably anticipated future land use scenarios that are considered during response selection.

Common scenarios where ICs may be a useful instrument for fostering protectiveness at a site involving vapor intrusion threats include, but are not limited to, the following:

1. Existing buildings overlie soil or groundwater contamination, or a migrating groundwater plume that is moving toward existing buildings potentially poses a future vapor intrusion threat;

2. Future construction is planned or is reasonably anticipated on a site that overlies subsurface contamination with vapor-forming chemicals;

3. Changes to building construction/design (such as remodeling or ventilation changes) or building use (such as commercial building converted for residential use) potentially affect exposure to the vapor intrusion pathway;

4. Vapor intrusion mitigation systems are needed in buildings, or existing ventilation systems are being utilized for vapor intrusion mitigation, and continued access is sought to facilitate their O&M;

5. Response actions to reduce source contamination will not immediately meet response objectives; and

6. Response actions to reduce or eliminate source contamination will not be taken (for example, where it is technically impracticable to treat groundwater that is the source of vapor intrusion).

Informational ICs may also serve to provide notice to parties, including prospective purchasers, about what land or building uses are compatible with human health risk that may be posed by vapor intrusion at the site. For example, modifications to a building's ventilation or air conditioning system may affect building under-pressurization in a way that fosters a greater potential vapor intrusion threat. Various ICs can be tailored to address construction and design specifications of both existing and future buildings—a local ordinance, for example, may require parties to submit a building design to its building department that incorporates mitigation measures as determined appropriate by a Professional Engineer (P.E.) (see IC Example #1).

In addition to restricting land, building, or resource use, some types of ICs may provide an effective means for addressing O&M at vapor intrusion sites consistent with decision documents and enforcement documents. This could happen, for instance, when an IC specifies that mitigation systems be installed and maintained in future construction or if the use of an existing building changes (e.g., industrial building use changes to mixed commercial or residential uses). Provisions regarding access to and periodic maintenance and testing of the mitigation systems, and other site-specific obligations may be incorporated into the IC (see IC Example #2).

IC EXAMPLE 1:

City of Mandan, North Dakota Ordinance No. 1002 (City of Mandan 2006)

In 2006, the City of Mandan, North Dakota, enacted an ordinance that created an Environmental Institutional Control Zoning District to define an area of downtown Mandan impacted by petroleum contaminated soil and groundwater and to establish ICs for the protection of human health and the environment. Among other provisions, the ordinance requires any person proposing redevelopment, demolition, excavation, grading, or construction activities at properties within the District to submit to the city administrator or their appointee a contingency plan, approved by the North Dakota Department of Health, to evaluate and manage any petroleum contaminated soils or groundwater and any potential petroleum vapor impacts. The contingency plan must be prepared by a P.E. with experience in the environmental field, and the plan must consider and protect against, among other things, the vapor intrusion pathway. In addition, the ordinance also provides for restrictions on construction of new structures within the District. In pertinent part, the ordinance provides:

"Any person proposing to construct a new structure within the District shall submit a design for that structure that incorporates engineered controls to mitigate the effects of the potential presence of petroleum in the subsurface to the city administrator or their appointee. The design must be prepared by a P.E. and the design must be approved by the North Dakota Department of Health and must meet additional applicable codes and standards relative to the presence of petroleum. The design shall protect the public health and the environment by considering, at a minimum a) historic water/product intrusion; b) historic petroleum vapor/odor issues; c) potential future water/product intrusion; and d) potential future petroleum vapor/intrusion. The design shall incorporate vapor barriers, venting system, groundwater suppression/collection, and specialized HVAC as determined appropriate by a P.E."

IC EXAMPLE 2: State IC Legislation

Some states have enacted statutes that directly authorize proprietary controls for the purpose of preventing use in conflict with environmental contamination or remedies. These state statutes divide into ones modeled after the Uniform Environmental Covenants Act (UECA)[226] and other non-UECA statutes.[227] These UECA and non-UECA state statutes tend to provide advantages over traditional common law proprietary controls by reducing certain legal and management complications associated with their use. The Model UECA, for instance, contemplates that the grantee or "holder" of the "environmental covenant" may be given specific rights or obligations with respect to future implementation of the environmental covenant.[228] This ability to oblige parties to undertake affirmative actions at a site, such as long-term maintenance of a cap or O&M of a vapor intrusion mitigation system, through a UECA environmental covenant, is different from traditional common law proprietary controls.

Proprietary controls that bind current and subsequent landowners (that is, the proprietary control "runs with the land") to use restrictions at properties, as well as oblige them to undertake affirmative obligations, may have utility at vapor intrusion sites. For instance, at a contaminated site in Bucks County, Pennsylvania, an environmental covenant executed pursuant to the Pennsylvania Uniform Environmental Covenants Act contained provisions to address vapor intrusion threats. In addition to provisions for access, annual inspections, compliance reporting, and other specifications related to cleanup activities, parties to the environmental covenant agreed to construct slab-on-grade buildings without basements and install vapor barriers as an engineered control to mitigate the potential for vapor intrusion as part of the eventual development of the property. Further, the environmental covenant provided that engineering plans for the vapor barriers first be submitted to and approved by EPA prior to construction. For examples of environmental covenants executed pursuant to the Pennsylvania Uniform Environmental Covenants Act, Act No. 68 of 2007, 27 Pa. C.S. §§ 6501-6517: http://www.depweb.state.pa.us/portal/server.pt/community/land_recycling_program/20541/uniform_environmental_covenants_act/1034860

[226] UECA was developed by the National Conference of Commissioners on Uniform State Laws. See: www.uniformlaws.org.

[227] See, for example, Colo. Rev. Stat. § 25-15-320 (2011); Cal. Civ. Code § 1471 (2011).

[228] "Grantee" is a traditional property law term describing a person to whom property is conveyed. States that have passed legislation based on UECA have created different legal concepts specific to those jurisdictions. For example, UECA jurisdictions typically define "holder" and "environmental covenant" to reflect, respectively, the grantee and the servitude that imposes the land or resource use restrictions. The model UECA provides that "[h]older means the grantee of an environmental covenant…" See definition 6 in Section 2.0 of the model UECA.

8.6.3 Selecting the Right Instrument(s)

When evaluating potential IC instruments, EPA recommends that site managers and site attorneys balance the relative advantages and limitations of IC instruments under consideration—for example, consider legal implementation issues, jurisdictional questions, permanence and enforceability concerns—and select those that best achieve the response objectives. (IC Example #3 describes how these factors were considered at the Middlefield-Ellis-Whisman Study Area.)

EPA guidance on ICs provides detailed considerations regarding the selection of ICs and the relative strengths of the different categories of IC instruments.[229] Ultimately, the selection of ICs is a site-specific evaluation based on the characteristics of the site (for example, the nature and extent of the vapor intrusion threat) and the particular jurisdiction in which it is located. There are times when multiple IC instruments can be "layered" to best ensure protectiveness of the response action while meeting the response objectives outlined in the decision documents.[230]

Because many ICs are created pursuant to state and other non-federal laws, the authority to implement and otherwise oversee these ICs resides with government entities other than EPA. Units of local governments, for instance, typically have jurisdiction to implement, maintain, enforce, and terminate certain governmental controls, such as zoning ordinances and building permit conditions. Therefore, it is important to evaluate the capacity (financial, technical, etc.) and willingness of the entity ultimately responsible for taking over IC responsibilities prior to IC selection.[231] Site managers and site attorneys are encouraged to coordinate early with IC stakeholders so that adequate assurances may be acquired and then subsequently maintained as necessary over time.

Given the potential role of non-EPA entities, it may be appropriate for EPA to facilitate or recommend a process by which IC stakeholders provide similar assurances or otherwise reach a common understanding[232] regarding their respective IC responsibilities to ensure that selected ICs are effectively implemented, maintained, and enforced. At a vapor intrusion site, for example, a zoning ordinance may be effective in preventing or ensuring responsible future development of properties overlying a contaminated groundwater plume that presents a vapor intrusion pathway threat. Such zoning ordinances generally are designed and enacted by the local government. Once enacted, the ordinance must be followed and enforced for it to serve as an effective IC over its lifespan. One inherent limitation of governmental controls, however, is that their implementation, modification, and termination generally follow a legislative process

[229] See Site Manager's IC Guide and Section 3.2 of the PIME IC Guide for a framework to consider when deciding among available ICs.

[230] See Section 3.2 of the PIME IC Guide for more discussion on layering ICs.

[231] See Section 3.8 of the PIME IC Guide on IC stakeholder capacity considerations.

[232] Parties may be able to provide assurances or otherwise reach a common understanding regarding their respective IC roles and responsibilities through various mechanisms that may be available under state law (for example, a Memorandum of Understanding, Memorandum of Agreement, Administrative Order on Consent, contract, City Resolution, or enforceable agreement, etc.). For additional discussion about obtaining or memorializing IC assurances, see Sections 3.3, 3.8, and 4.3 of the PIME IC Guide.

IC EXAMPLE 3: Efforts to Address VI at the Middlefield-Ellis-Whisman Study Area

The Middlefield-Ellis-Whisman (MEW) Study Area is composed of four separate CERCLA sites—Raytheon Corp., Intel Corp. (Mountain View Plant), Fairchild Semiconductor Corp. (Mountain View Plant), and portions of the former Naval Air Station Moffett Field Superfund site—and many distinct parcels with land uses including residential, commercial, and light industrial. In 2009, EPA finalized a Supplemental FS for the MEW Study Area that presented an evaluation of a variety of remedial alternatives that could be used to mitigate potential vapor intrusion into current and future buildings overlying the shallow plume of contaminated groundwater. The FS provided an analysis of ICs using the NCP evaluation criteria: overall protection of human health and the environment; long-term protectiveness and permanence; compliance with applicable or relevant and appropriate requirements; reduction of toxicity, mobility, or volume through treatment; short-term effectiveness; implementability; and cost. The other two NCP evaluation criteria, state acceptance and community acceptance, were evaluated in the ROD Amendment for the vapor intrusion pathway remedy at the MEW Study Area.

In 2009, EPA published the Proposed Plan for the MEW Study Area that identified EPA's preferred alternatives for the vapor intrusion remedy. The Proposed Plan identified the adoption of a municipal ordinance as EPA's preferred IC, but the City of Mountain View and concerned property owners raised concerns that this was not necessary. Instead, EPA worked with the City of Mountain View, California, to have the City formalize its permitting procedures that apply to future construction. These permitting procedures oblige those proposing new building construction within the MEW Study Area to obtain EPA approval of construction plans to ensure that, where necessary, the appropriate vapor intrusion control system is integrated into building construction. In a 2010 ROD Amendment, EPA presented its selected remedy for the vapor intrusion pathway for the MEW Study Area. The ROD Amendment identified a combination of ICs for use at the site. In place of a municipal ordinance as called for in the Proposed Plan, the ROD Amendment selected reliance upon the internally modified permitting procedures by the City of Mountain View's Building, Planning, and Permitting Departments. The City will also implement remedy requirements for projects subject to the California Environmental Quality Act through that law's procedures. With regard to existing commercial buildings where an active remedy is necessary, EPA selected the use of recorded agreements that will help provide notice to current and future owners and occupants, notice to EPA and the MEW Companies when there is a change in building ownership or configuration, and the necessary access to install, maintain and operate the vapor intrusion remedy. These agreements will be binding on and enforceable against future property owners. Additionally, EPA selected the use of a tracking service to provide notice when changes are made to properties within the MEW Study Area. Additional controls that will be implemented by the City of Mountain View include creation of a mapping database to help ensure that parties interested in properties within the MEW Study Area are informed of the appropriate construction specifications when making inquiries with the City.

For more information on the MEW Study Area, see the *Final Supplemental Feasibility Study for the Vapor Intrusion Pathway* (June 2009), *Proposed Plan for the Vapor Intrusion Pathway* (July 2009), and *Record of Decision Amendment for the Vapor Intrusion Pathway* (August 2010), available at: www.epa.gov/region9/mew

outside the authority of EPA that may raise questions regarding the reliability and continued sustainability of the IC. Obtaining early and continued assurances from a local government specifying its commitment to the governmental control is recommended to help address this limitation prior to its selection as part of a final cleanup plan.

Certain IC instruments may not be available for use at a site, depending on federal, state, local, tribal, or other applicable laws. Therefore, after determining the universe of ICs available for use at a particular site, the practical and legal limitations can be evaluated. For example, large sites with widespread contamination pose unique IC challenges. These challenges could arise, for instance, where a contaminated groundwater plume underlies many distinct parcels with multiple property owners/occupants and vapor intrusion is the exposure pathway of concern. Negotiating and implementing proprietary controls with many property owners, some of whom may not be PRPs, may present legal, administrative, and other challenges.[233]

8.6.4 Long-term Stewardship

Long-term stewardship (LTS) activities are intended to help ensure that cleanups remain protective of human health and the environment over time and that reuse activities remain compatible with residual site contamination and associated human health risk potentially posed by the vapor intrusion pathway. LTS procedures vary widely, but they generally are intended to help assure compliance with the response actions at the site, including IC compliance, by providing relevant information in a timely manner to stakeholders who may use the property (e.g., owners, excavators, developers, prospective purchasers or tenants) or to parties who otherwise have IC responsibilities (i.e., an entity with enforcement authority). LTS procedures, for example, may entail provisions to monitor and then inform those responsible for the response actions of potential changes in land use, ownership, tenancy, or building construction at a site. Also, LTS procedures may facilitate monitoring IC(s) so that they remain effective and reliable over time. EPA guidance on ICs generally speaks to LTS procedures in terms of IC maintenance[234] and enforcement activities.[235]

Periodic Reviews

A key part of IC maintenance is a periodic process over the IC life cycle to critically review and evaluate the IC instrument(s). Site managers and other stakeholders can evaluate the status of IC implementation, maintenance and enforcement activities at a site and address any potential IC deficiencies during the periodic review. The CERCLA FYR process,[236] for example, allows site managers to evaluate overall protectiveness of the remedy, including ICs.[237]

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[233] See Section 4.4 of the PIME IC Guide for strategies for implementing proprietary controls.

[234] The term "maintenance" generically refers to those activities, such as monitoring and reporting, that ensure ICs are implemented properly and functioning as intended.

[235] See Sections 8 and 9 of the PIME IC Guide discussing IC maintenance and enforcement activities.

[236] See CERCLA section 121(c).

[237] For general FYR guidance, see *Comprehensive Five-Year Review Guidance* (EPA 2001) at www.epa.gov/superfund/cleanup/postconstruction/5yr.htm. For a more detailed discussion on IC considerations during the CERCLA FYR process, see *Recommended Evaluation of Institutional Controls: Supplement to the "Comprehensive Five-Year Review Guidance,"* (EPA 2011c).

A list of possible IC-specific issues arising from any periodic review of a vapor intrusion site may include:

- ICs that are specified by the decision documents but are not yet in place;
- ICs that are in place but are not attaining compliance with the use restrictions specified by the decision documents (e.g., land use not compatible with IC-specified use restrictions);
- ICs are not identified in the decision documents but are necessary for the remedy to be protective of human health because of the vapor intrusion pathway; and
- Response selection assumptions change (e.g., toxicity values, potential exposure pathways, or land uses change) and warrant the need for new or different response actions, including additional IC(s).

IC Planning Documents

Responsibilities to monitor and report on IC compliance, among other obligations, may be documented in an Institutional Controls Implementation and Assurance Plan (ICIAP)[238] or other IC-related planning documents.[239] An ICIAP can serve to: (1) document the activities necessary to implement and ensure the long-term effectiveness and permanence of ICs (that is, the IC life cycle); and (2) identify the person(s) or organization(s) who, under state or local law, are responsible for conducting those activities. Some ICs generally fall within the jurisdiction of a particular category of stakeholders. Therefore, in addition to developing a comprehensive planning document, such as an ICIAP, it may be useful for parties who share IC responsibilities (e.g., a PRP and local government regarding the use of governmental controls, such as an ordinance or permitting system) to reach a common understanding and acknowledge various IC roles and responsibilities in a formalized manner. Where possible, EPA recommends that these types of arrangements among IC stakeholders be documented to describe commonly understood roles and responsibilities for proper and effective monitoring, reporting, and other IC maintenance and enforcement activities.

8.6.5 Community Involvement and ICs

EPA recommends that site managers and site attorneys provide adequate opportunities for public participation (including potentially affected landowners and communities) when considering appropriate use of ICs (EPA 2012e). Those opportunities may include providing appropriate notice and soliciting comments about cleanup plans. Community acceptance of the need for ICs to provide protection from residual contamination and public understanding of the legal and administrative steps for maintaining ICs often are important to the long-term effectiveness of ICs.

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[238] For further guidance on developing ICIAPs, EPA developed *Institutional Controls: A Guide to Preparing Institutional Control Implementation and Assurance Plans at Contaminated Sites* (EPA 2012e).

[239] For example, other types of documents may address IC-related activities and responsibilities at a site, such as a ROD, O&M plan, and land use control and implementation plan for federal facility sites.

8.7 Termination/Exit Strategy

This sub-section focuses on the termination/exit strategy for vapor mitigation response actions. Termination for vapor mitigation activities implemented under CERCLA, RCRA, Brownfields, and federal facilities cleanups can occur when the objectives of these cleanup activities have been met. For purposes of this sub-section, termination refers to the cessation of all activities related to building mitigation, control of subsurface vapor source(s), ICs, and monitoring.

When mitigating vapor intrusion through subsurface source remediation, building mitigation, and ICs, it is important to develop termination criteria, including the rationale for their selection, early in the remedy planning (e.g., alternatives development) process. (Termination criteria generally refer to numeric cleanup levels for each site-specific contaminant and narrative cleanup objectives that are to be attained by the response actions.) EPA recommends that these termination criteria be recorded in decision documents, in any other planning reports, and in monitoring reports. EPA generally recommends also developing and documenting an exit strategy, which clarifies how it will be determined that the termination criteria have been attained (e.g., monitoring data and associated statistics that will be used to demonstrate attainment). This document could be developed in conjunction with the O&M plan and monitoring program so that all stakeholders are provided with a clear and comprehensive set of termination criteria for the remediation and mitigation systems and ICs. If site conditions (e.g., building usage, vapor flux) change during the cleanup activities, it may become necessary to modify the termination criteria and/or strategy.

When reviewing vapor intrusion activities, considerations for evaluating termination activities may include:

- Termination of subsurface remediation activities;
- Termination of engineered exposure controls (building mitigation);
- Termination of the associated ICs; and
- Termination of monitoring.

8.7.1 Termination of Subsurface Remediation Activities

Where feasible, the preferred response to address vapor intrusion is to eliminate or substantially reduce the level of volatile chemical contamination in the source media (e.g., groundwater and subsurface soil) to levels that eliminate the need to mitigate or monitor vapor intrusion, as noted in Section 8.1 of this Technical Guide. If subsurface remediation activities are being conducted at the site, termination of these activities will be contingent on demonstrating that the chemical-specific cleanup levels for the subsurface media have been attained. EPA recommends that the termination criteria and exit strategy for these remediation activities be documented to foster collection and evaluation of appropriate data to support eventual termination of these subsurface activities.

EPA recommends that site-specific monitoring data be evaluated to determine if the termination criteria have been met. Typically, monitoring will continue until the source(s) are remediated to cleanup levels that eliminate the need to mitigate vapor intrusion at the point of exposure. As appropriate, the exit strategy may provide criteria for phased remediation, resulting in a

termination evaluation as source cleanup levels are achieved in parts of the contaminated area. If the subsurface vapor source(s) is not remediated, it is generally anticipated that remediation (and monitoring and any building mitigation) will continue.

Monitoring, in part, could be based on data similar to those that were used in a multiple-lines-of-evidence approach for characterizing the pathway and human health risk or for supporting the decision to undertake preemptive mitigation/early action (e.g., soil gas sampling, sub-slab sampling, or vapor sampling within potentially affected structures). EPA recommends identifying and documenting target concentration(s) that would allow for remediation termination, along with recommended monitoring/sampling frequencies.

If evaluation of the site-specific data indicates an increase in subsurface vapor concentrations during the monitoring period, it may be appropriate to evaluate whether the subsurface remediation plan and the CSM are adequate and appropriate.

Typically, once it is preliminarily determined that the subsurface remediation system(s) may be terminated, EPA recommends a period of attainment monitoring. During the attainment period, EPA recommends that the remediation system (e.g., reagent delivery equipment, soil vapor extraction wells) not be operated for a sufficient period to allow subsurface vapors reach equilibrium and indicate post-remediation conditions. The type and frequency of data collected during attainment monitoring entails a site-specific determination. Additionally, EPA recommends that criteria be described and documented, as part of exit strategy development, to determine when ending the attainment monitoring period is appropriate. To develop an exit termination strategy, site-specific fate and transport data may be used to identify an appropriate time period to allow the vapor concentrations to equilibrate. In addition, the termination of the attainment monitoring period may involve an evaluation of the contaminant attenuation in the vadose zone.

8.7.2 Termination of Building Mitigation

For purposes of this Technical Guide, “termination of building mitigation” refers to ending the use of an engineered exposure control(s) that reduces or eliminates human exposure via the vapor intrusion pathway. Typically, vapor mitigation is implemented when it is determined that (1) unacceptable human health risk to inhabitants is identified, or (2) the system(s) was(were) installed as part of an early action strategy (see Sections 3.3 and 7.8 for a discussion of building mitigation as an early action).

As described in Section 8.2, vapor intrusion can be mitigated in specific buildings using either an active or passive vapor mitigation system (or a combination thereof).

Active Building Mitigation

Generally, building mitigation systems are implemented in conjunction with the investigation and remediation of subsurface vapor source(s). Typically, building mitigation systems will be operated until the source(s) are remediated to attain the cleanup levels (e.g., for the subsurface vapor source(s)) that eliminate the need to mitigate vapor intrusion at the point of exposure. If subsurface vapor source(s) are not remediated, it is generally anticipated that mitigation activities will continue indefinitely. As appropriate, the termination strategy may provide criteria for phased evaluation of system cessation as source cleanup levels are achieved in parts of the contaminated area.

Generally, once the subsurface vapor source(s) is remediated to levels that meet the remedial objectives and protect human health from the vapor intrusion pathway, EPA recommends that the site-specific monitoring data be evaluated to determine if the termination criteria for the building mitigation system have been met. These monitoring data, in part, could be based on data similar to those that were used for characterizing human health risk or for supporting the decision to undertake preemptive mitigation/early action during the vapor intrusion investigation (e.g., sub-slab soil gas sampling and/or indoor air sampling). EPA recommends identifying and documenting target concentration(s) that would allow for system termination, along with recommended monitoring/sampling frequencies. In addition, certain site-specific performance assessment data (e.g., standpipe vapor sampling) may also warrant consideration to make this determination.

Typically, once it is determined that the building mitigation system may be terminated, EPA recommends a period of attainment monitoring. During the attainment period, EPA recommends that the mitigation system (e.g., subslab suction wells or ventilation fans) be offline for a sufficient period to allow vapors beneath the structure reach equilibrium and indicate post-remediation conditions. The type and frequency of data collected during attainment monitoring entails a site-specific determination. Additionally, EPA recommends that criteria be established in the exit strategy to determine when ending the attainment monitoring period is appropriate. To develop an exit termination strategy, site-specific fate and transport data may be used to identify an appropriate time period to allow the vapor concentrations to equilibrate. In addition, the termination of the attainment monitoring period may involve an evaluation of the contaminant attenuation in the vadose zone.

If the attainment criteria evaluation indicates that cleanup levels and objectives are not being met, it may be necessary to continue or resume subsurface remediation and mitigation activities. Once it is determined that the cleanup levels and objectives have been met, the active components of the system may be removed from the building; on the other hand, the building owner may elect to continue to operate the mitigation system under their own discretion and for their own purposes (e.g., radon reduction and moisture control). Once the cleanup levels and objectives have been met, all O&M and monitoring of active mitigation systems specified by EPA can cease.

Passive Building Mitigation

The termination of passive vapor mitigation systems will typically be similar to the criteria established for the termination of active mitigation systems. In summary:

- Like active mitigation systems, passive mitigation systems are typically implemented in conjunction with the investigation and remediation of subsurface vapor source(s).

- Generally, once the subsurface vapor source(s) is remediated to levels that meet the cleanup levels and objectives that will protect human health from the vapor intrusion pathway, EPA recommends that the site-specific monitoring data be evaluated to determine if the termination criteria have been met.

If the site-specific criteria evaluation indicates that cleanup levels and objectives are not being met, it may be appropriate to evaluate the current system's effectiveness or the possible application of an active mitigation system. Once it is determined that contaminant cleanup levels and objectives have been met, all O&M and monitoring specified by EPA can cease. EPA

generally does not have a need to seek removal of barriers or seals that comprise a passive mitigation system as part of termination activities.

8.7.3 Termination of ICs

"Termination of ICs," as used in this Technical Guide, refers to discontinuing any and all ICs specified by EPA because restrictions on land or resource use and/or notices and other informational devices are no longer necessary to help ensure protectiveness of human health (i.e., human health risk from exposures to vapor intrusion, if any, are expected to be acceptable in the absence of all IC(s)). Generally, ICs are implemented in conjunction with the investigation and remediation of source(s). It is anticipated that ICs selected and implemented will be needed until (1) subsurface vapor source(s) are adequately remediated, or (2) restrictions on land, resource, or building use are no longer necessary based on current and reasonably anticipated future exposure scenarios. Therefore, when developing a termination strategy for ICs that have been selected as part of a response action, the strategy is typically based on data collected from the affected media.

EPA recommends that the exit strategy consider and identify cleanup levels for the subsurface vapor source(s). As long as the subsurface vapor source exceeds such cleanup levels, it is generally anticipated that the associated ICs will continue. As appropriate, the termination/exit strategy may provide criteria for a phased IC termination evaluation as source cleanup levels are achieved in parts of the contaminated area.

If the site-specific criteria evaluation indicates that terminating the ICs is appropriate, EPA may conclude that site conditions no longer warrant ICs being used as part of the response action for the vapor intrusion pathway. At this point, EPA could notify the appropriate entity(s), such as local or state government, tribe, affected landowner, or responsible parties, in writing that EPA's response objectives have been met and that the IC need not be maintained. As such, EPA's oversight of the IC(s) can cease.

8.7.4 Termination of Monitoring

For purposes of this Technical Guide, monitoring includes activities conducted to verify that the vapor intrusion pathway does not pose a health concern to building inhabitants while remediation and mitigation activities are underway and in the event that the remediation and mitigation activities are terminated. "Termination of monitoring," for purposes of this Technical Guide, refers to ending any monitoring that was needed to verify that no further response action, including IC-related activity, is necessary to protect human health from indoor air exposures posed by vapor intrusion. When developing termination criteria for monitoring, the decision is generally based on data collected from all the affected media.

As noted above, monitoring is generally implemented in conjunction with the remediation of subsurface vapor sources(s). EPA recommends that the exit strategy consider cleanup levels for all contaminated media. Typically, monitoring will continue until the source(s) are remediated to cleanup levels that eliminate the need to mitigate vapor intrusion at the point of exposure (i.e., allow building mitigation systems to be terminated). If the subsurface vapor source is not remediated, it is generally anticipated that any associated monitoring will continue. As appropriate, the exit strategy may provide criteria for phased monitoring, resulting in a termination evaluation as source cleanup levels are achieved in parts of the contaminated area.

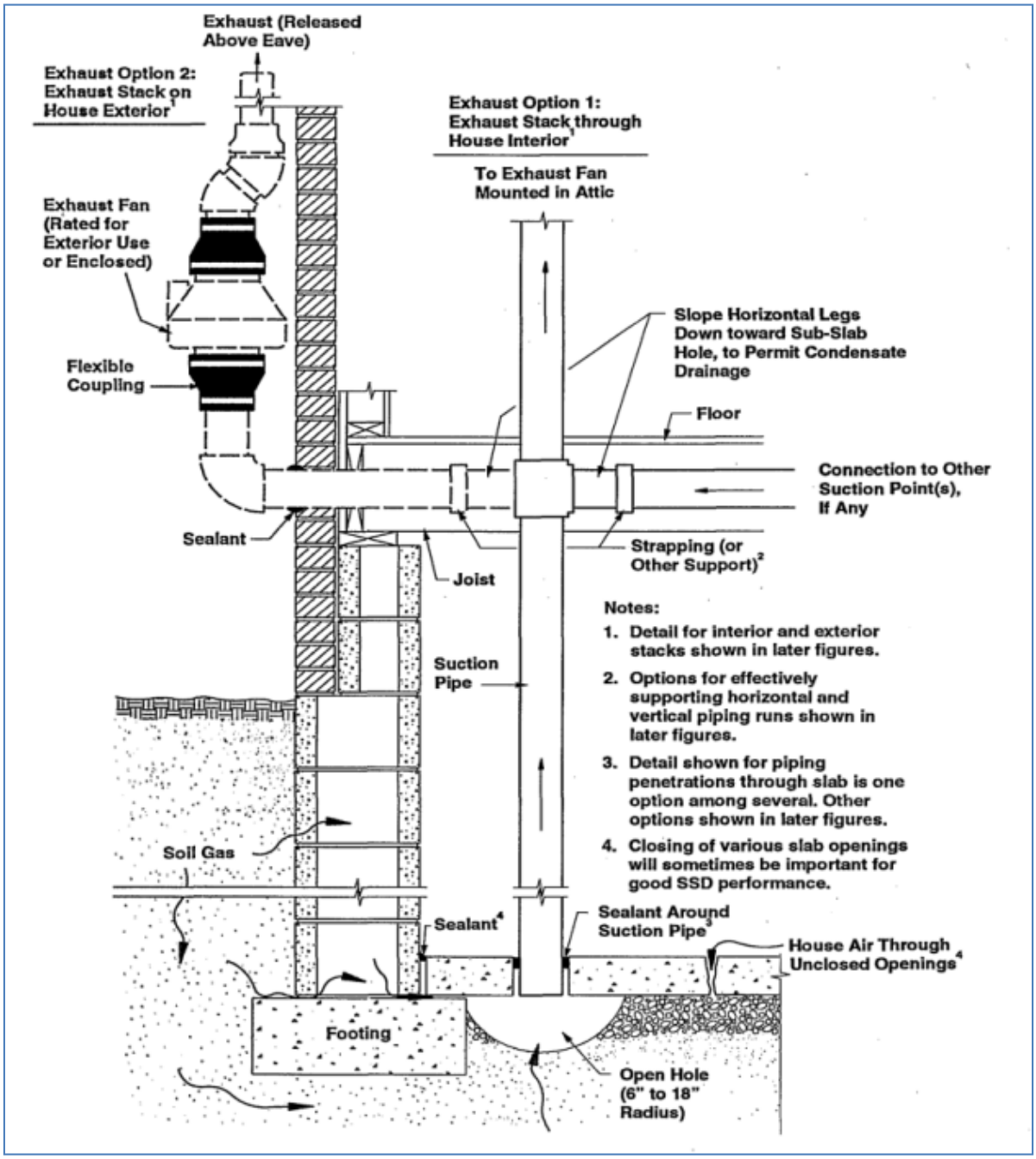

Figure 8-1 Illustration of Sub-slab Depressurization (SSD) System

Note: Shows one example of how a sub-slab depressurization system might be constructed. In this case, the example suction pipe has been inserted vertically downward through the slab from inside the house. Two options are indicated for location of the exhaust fan: one exterior to the building; and the other within an attic. In both of these cases, the exhaust gas stream is to be vented outside and above the building.

Source: EPA (1993a; Figure 1)

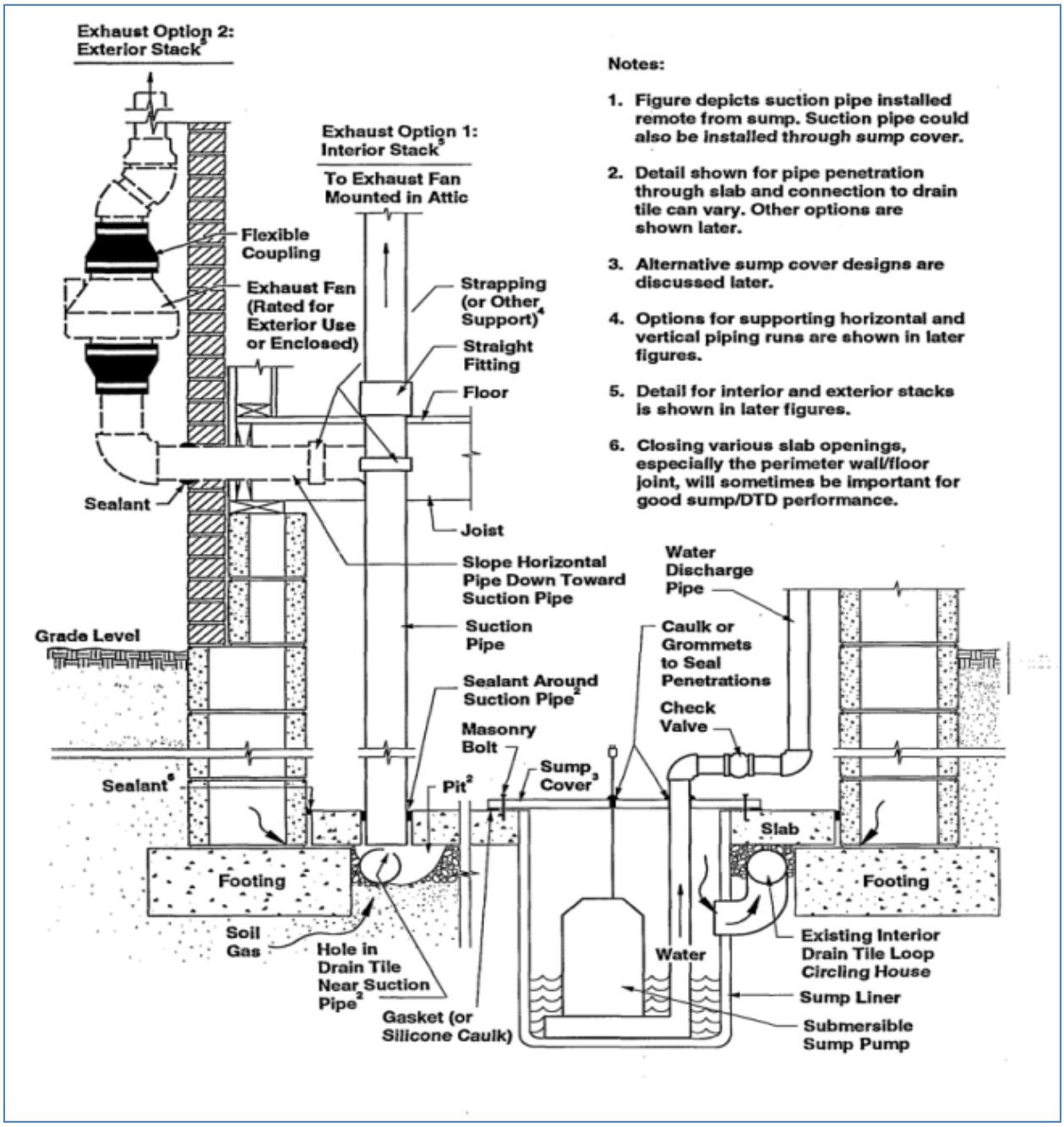

Figure 8-2 Illustration of Drain-tile Depressurization (DTD) System

Note: Shows one example of how a drain-tile depressurization system might be constructed. In this case, tiles are shown draining to a sump in the basement, to which an air-tight cover is sealed. The example suction pipe has been inserted vertically downward through the slab at a location remote from the sump. Two options are indicated for location of the exhaust fan: one exterior to the building; and the other within an attic. In both of these cases, the exhaust gas stream is to be vented outside and above the building.
Source: EPA (1993a; Figure 3)

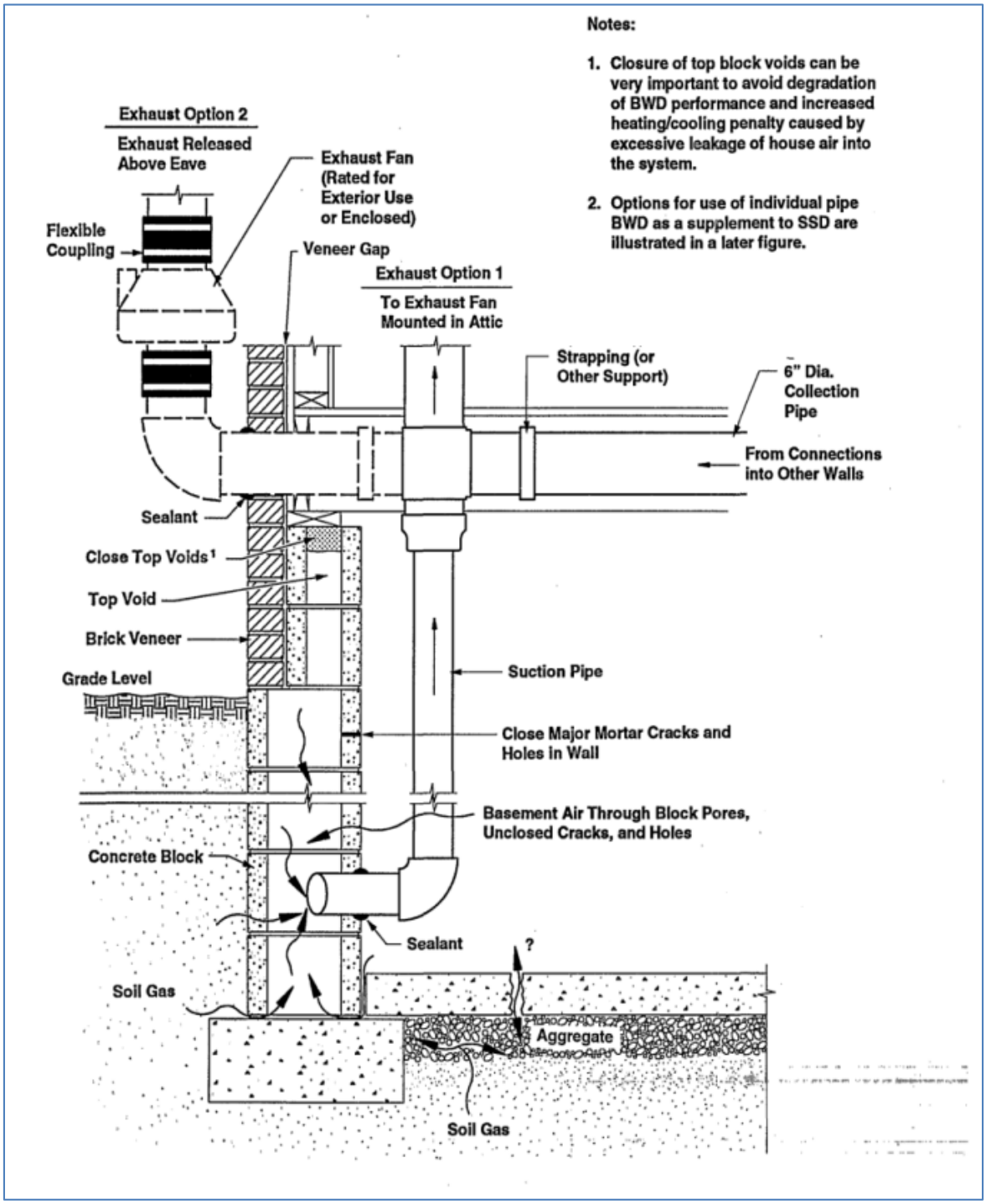

Figure 8-3 Illustration of Block-wall Depressurization (BWD) System

Note: Shows one example of how a block-wall depressurization system might be constructed. In this case, individual suction pipes are inserted into the void space in the basement wall, which are connected to one or more fans. Source: EPA (1993a; Figure 5)

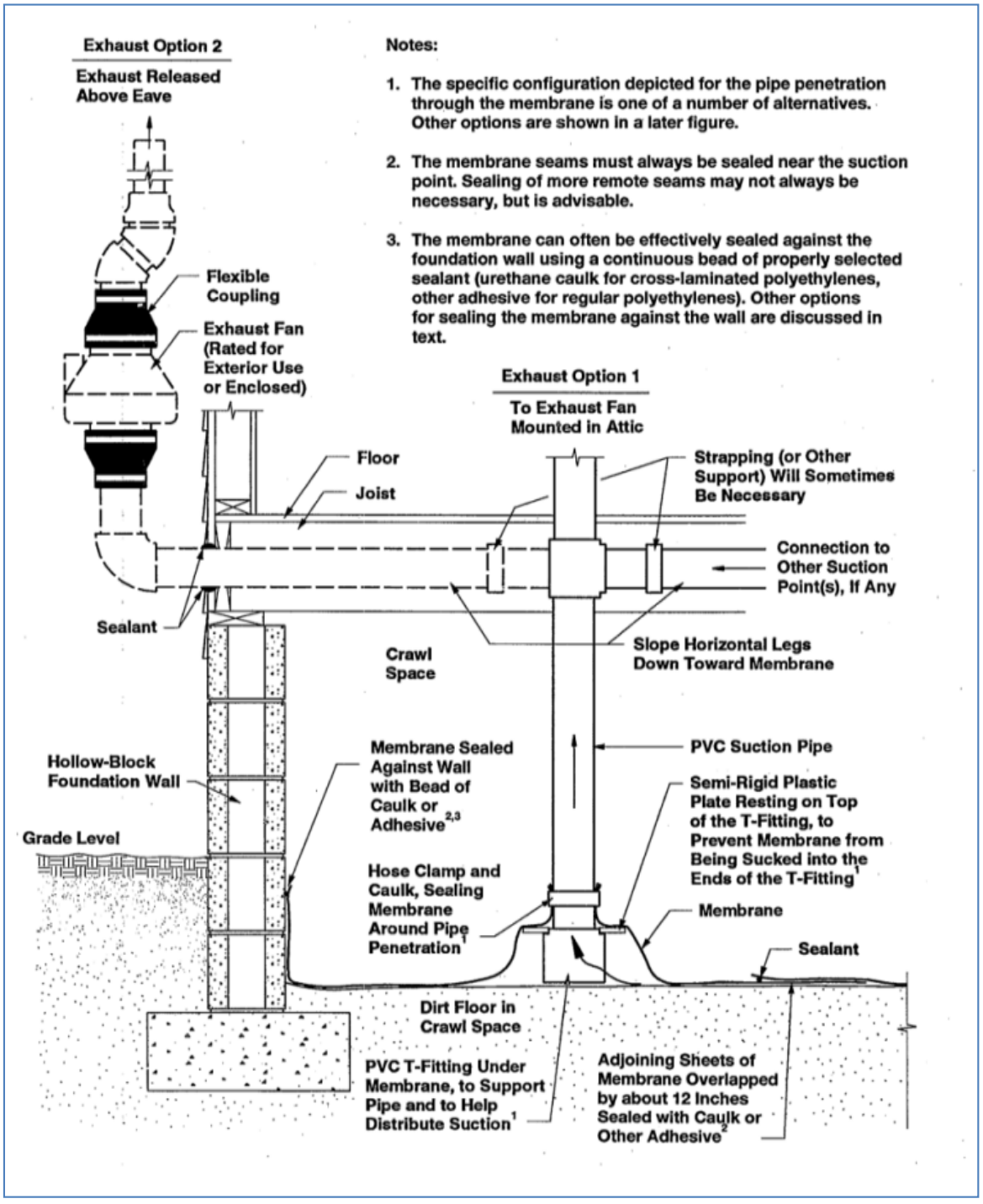

Figure 8-4 Illustration of Sub-membrane Depressurization (SMD) System

Note: Shows one example of how a sub-membrane depressurization system might be constructed. In this case, the example suction pipe penetrates the membrane overlying a dirt floor.

Source: EPA (1993a; Figure 6)

9.0 PLANNING FOR COMMUNITY INVOLVEMENT

Communicating information about environmental risk is one of the most important responsibilities of site managers and community decision-makers. Simply stated, risk communication, whether written, verbal, or visual statements concerning risk, is the process of informing people about potential and perceived hazards to their person, property, or community.

EPA recommends that human health risk be described in context, recognizing there are personal, cultural and societal dimensions of risk. EPA also recommends providing advice about risk-reduction behavior and encouraging a dialogue between the sender and receiver of the message. The best risk communication occurs in contexts in which the participants are informed about risks they are concerned about, the process is fair, and the participants are free and able to solve whatever communication difficulties arise. *Risk Communication in Action: The Risk Communication Workgroup* (EPA 2007) is one of several resources available that explain the elements of successful risk communication and describe communication tools and techniques.

Thus, community involvement is a key component of any site investigation or other EPA response action. Members of the public affected by environmental contamination can be made aware of what EPA is doing in their community and have a say in the decision-making process. Stakeholder and community involvement is particularly important for sites with vapor intrusion issues, in part because the exposure to toxic vapors may pose a significant human health risk that is unknown to inhabitants (in the absence of mitigation systems), as they potentially arise in homes, workplaces, schools, and places of commerce and gathering. Because of the potentially intrusive nature of assessment and mitigation for vapor intrusion, stakeholder involvement is important throughout the process.

EPA generally recommends that stakeholder and community involvement be conducted from the earliest stage of the site assessment and risk assessment process, with on-going education, two-way communication, and discussion throughout the entire process to create community trust and acceptance. For example, EPA recommends initiating community involvement activities as soon as possible after determining that vapor intrusion may exist at a particular site.

Informing the community about vapor intrusion concerns and plans to conduct an assessment, including sampling, can be resource intensive. Thus, EPA recommends evaluating each project, in coordination with appropriate state and tribal officials, to assess the level of stakeholder interest and need for community involvement during various stages of the decision-making process.

Public Participation and Risk Communication

A meaningful community involvement process is founded upon knowledge of effective public participation and risk communication practices. Public participation refers to the full range of activities that EPA uses to engage communities in the Agency's decision-making process. In 2003, EPA updated its Public Involvement Policy.[240] Its foundation includes seven basic steps to support effective public participation:

[240] EPA Public Involvement Policy (2003): http://www.epa.gov/publicinvolvement/policy2003/index.htm.

1) Plan and budget.

2) Identify those to involve.

3) Consider providing assistance.

4) Provide information.

5) Conduct involvement.

6) Review and use input and provide feedback to the public.

7) Evaluate involvement.

To help implement the steps, EPA developed a series of brochures[241] on effective public participation that outline how to budget for, plan, conduct, and evaluate public participation.

EPA Program-Specific Community Involvement Guidance and Recommendations

CERCLA and other EPA regulations[242] identify specific community involvement activities that are appropriate at certain points throughout the cleanup process. Specifically, in 2005, OSWER published the *Community Involvement Handbook*[243] (EPA 540-K-05-003). The handbook presents legal and policy motivations for Superfund community involvement and includes additional suggestions for involving the community in the Superfund process. In addition, EPA's *Proposed Guidelines for Brownfields Grants* encourages applicants to describe their plans for involving community-based organizations in site cleanup and reuse decisions.[244] The *Grant Funding Guidelines for State and Tribal Response Programs* for brownfields funding also encourage programs to establish, at a minimum, "mechanisms and resources to provide meaningful opportunities for public participation."[245] In addition, in 1995, EPA promulgated the *RCRA Expanded Public Participation* rule (60 FR 63417-34, December 11, 1995)[246] which created additional opportunities for public involvement in the permitting process and increased access to permitting information.[247]

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[241] EPA Public Involvement Brochures: http://www.epa.gov/publicinvolvement/brochures/index.htm

[242] 40 CFR §300.155 http://edocket.access.gpo.gov/cfr_2003/julqtr/pdf/40cfr300.155.pdf

[243] EPA *Superfund Community Involvement Handbook*: http://www.epa.gov/superfund/community/cag/pdfs/ci_handbook.pdf

[244] EPA Brownfields Grants website: http://www.epa.gov/brownfields/cleanup_grants.htm

[245] EPA Brownfields State and Tribal Response Program Grants website: http://www.epa.gov/brownfields/state_tribal/fund_guide.htm

[246] Section 7004(b) of the Resource Conservation and Recovery Act provides EPA broad authority to encourage and assist public participation in the development, revision, implementation, and enforcement of any regulation, guideline, or program under RCRA.

[247] EPA *RCRA Public Participation Manual*: http://www.epa.gov/osw/hazard/tsd/permit/pubpart/manual.htm

At sites with vapor intrusion issues, EPA recommends that the site planning team (i.e., the remedial project manager (RPM) or on-scene coordinator (OSC); community involvement coordinator (CIC); risk assessor; the enforcement case team; EPA contractor; state, tribal, or local agency staff; federal agency staff relevant to the site; or others) to consider the following:

- Develop a community involvement plan (CIP) or update the existing CIP.
- Learn about the site and the community to foster development of a CIP that highlights key community needs, concerns and expectations.
- Commit to ongoing, sustained communication activities throughout vapor mitigation and site cleanup efforts.
- Develop a communication strategy[248] and conduct outreach to inform stakeholders about the facts and findings pertaining to the site.
- Obtain written permission, if appropriate and necessary, for building/property access, and involve the property owner/occupant in identifying or removing potential indoor air contamination sources, including inspection of residence and completing an occupant survey.
- Fully communicate and interpret sampling results, and evaluate mitigation options, if any are warranted.
- Recognize preference of owners and occupants for confidentiality with regards to property-specific data.

When considering the most effective community involvement strategies, EPA recommends that its previous involvement be considered, as well as the existence of community or neighborhood groups and the phase of the regulatory process in which vapor intrusion is being addressed. Additional resources for planning and implementing effective community involvement activities are discussed in Section 9.2: Communication Strategies and Conducting Community Outreach.

9.1 Developing a Community Involvement or Public Participation Plan

A CIP is a site-specific strategy to enable meaningful community involvement throughout the cleanup process.[249] CIPs specify EPA-planned community involvement to address community needs, concerns, and expectations that are identified through community interviews and other means. A CIP will enable community members to understand the ways in which they can participate in decision-making throughout the cleanup process. That is, the CIP is a way for EPA to plan for informing and involving the community in the cleanup process and can be a powerful

[248] A communication strategy can be one component of a CIP, but it addresses a specific event, issue, or concern, such as an emergency response to a release, or communicating risk at a site. The CIP, on the other hand, describes an overall strategy for conveying information throughout the cleanup process at a site.

[249] Community involvement plans available at: http://www.epa.gov/superfund/community/pdfs/toolkit/ciplans.pdf

way to communicate EPA's commitment to listening and responding to community concerns, and provide timely information and opportunities for community involvement.

The CIP is intended to be a "living" document and is most effective when it is updated or revised as site conditions change. When developing the CIP document, EPA recommends that the site planning team consider the following steps:

Describe the Environmental Setting and Cleanup Process

Describe the release and affected areas (the site). This includes information about the site, its history, the key issues related to site contamination, and how vapor intrusion fits into EPA's overall cleanup effort at the site.

Describe and Learn about the Community

Describe the community. The community profile is a description of the affected community that summarizes demographic information and identifies significant subgroups in the population, languages spoken, and other important characteristics of the affected community, such as whether the site is located in an area with environmental justice concerns or includes sensitive populations. EPA recommends that the community profile also document information sources and describe how the profile was developed.

Learn about community needs, concerns and expectations: Issues of concern to residents and business owners can be identified through community interviews, informal discussions and interactions, local media reports, and other insights about the affected community. Questions may include:

- What are public perceptions and opinions of EPA and the cleanup process?
- How do people want to be kept informed (i.e., mechanisms to deliver information)?
- How do people want to be included in the decision-making process?
- What are the perceived barriers to effective public participation?
- Are there other sources of pollution that affect the community?
- Have there been past experiences of mistrust or any unique concerns?

This information can be used to recommend any special services to be provided, including technical assistance, formation of a Community Advisory Group, facilitation/conflict resolution, or translation services.

Write and Compile the CIP

Once the site planning team has learned about the community, it is time to put the information together in a way that will be useful to EPA and the community. In addition to the site description, community description, and community needs and concerns, the CIP also may include a reference listing of contacts (name, address, phone, email) useful for the

community or the site planning team. EPA recommends that the contact list generally include contact information for:

- The site planning team.
- Community groups and community leaders.
- Local elected officials.
- Local, state, tribal, and federal agency staff relevant to the site.
- Media contacts (including social media outlets and community journalists).
- Others, as appropriate.

To ensure that the CIP is indeed informed by the community, EPA recommends that a draft of the CIP be shared with the community, and their input and feedback be invited as it evolves. Again, the CIP is intended to be a "living" document and is most effective when it is updated or revised as site conditions change. In some cases, particularly when the CIP is updated or revised for a FYR or where community interest is minimal, a short CIP outlining EPA's plan for community involvement may be all that is needed. For most sites, EPA recommends that the CIP be written to address the community directly, and their active involvement be invited at each stage of the cleanup process.

9.2 Communication Strategies and Conducting Community Outreach

EPA recommends that community outreach activities be initiated as soon as possible after determining that vapor intrusion may exist at a particular site. Informing and educating the community includes distributing information and providing opportunities for EPA to listen to community concerns. EPA recommends community outreach activities be tailored to the community based on information gleaned from community interviews and other methods used in developing the CIP. Public health officials from state, tribal, or local agencies may be helpful in communicating risk information and answering questions from the community.

Communication Strategies

Communication strategies are plans for communicating information related to a specific issue, event, situation, or audience. They serve as the blueprints for communicating with the public, stakeholders, or even colleagues. EPA recommends that communication strategies:

- Outline the objective and goals of the communication.
- Identify stakeholders.
- Define key messages.
- Pinpoint potential communication methods and vehicles for communicating information and obtaining information from the community for a specific purpose.

When developing a communication strategy, the first step is to determine why the communication is necessary and define its desired objectives, and then to focus on defining the audiences and how to reach them. Keep in mind that the demographics, knowledge, and concerns of the audiences play an important role in defining the key messages. Once the key messages are defined, the outreach vehicle can be determined.

Conducting Community Outreach

The site planning team likely will use several different outreach techniques during the course of the cleanup process. When planning community outreach, EPA generally recommends that the site planning team collaborate with internal and external partners, such as local, state, and tribal officials and departments of health; faith-based organizations; and community groups. It is important to accommodate hearing-impaired or limited English proficiency (LEP)[250] persons in all outreach efforts by providing spoken or sign language interpreters at meetings and translating printed outreach materials. It also is important to ensure that the community understands the concept of vapor intrusion.

Examples of community outreach techniques to consider are described below.

Public Meetings/Gatherings

Public meetings are a useful opportunity to explain environmental conditions at the site, potential health impacts, intended indoor air sampling, and remediation strategies. It may be helpful to hold meetings prior to and following key sampling events to describe sampling strategies and consequent results, respectively. EPA recommends that the meeting include a period to address specific questions from the public regarding sampling results or any other specific concerns, as well as visual aids and maps and spoken or sign language interpreters to facilitate communication and discussion. The use of a CSM, for example, is useful in public meetings to graphically reinforce the messages. It may be helpful to follow up with meeting participants to inquire about the effectiveness of the meeting and whether it met their needs. Other meeting follow-up activities could include responding to requests for information, distributing meeting notes, and creating a mailing list.

Additional opportunities for the site planning team to communicate with the community in a group setting include public availability sessions and public forums or poster sessions at community group meetings or neighborhood board meetings. These options are a more informal way of interacting with community members and they allow a casual “question and answer” or discussion format as compared to the more formal presentation at a public meeting.

Mass Media

The media can be the best means of reaching a large audience quickly. Extending invitations to the media for important meetings, providing opportunities for media questions

[250] Executive Order 13166, *Improving Access to Services for Persons with Limited English Proficiency*, directs federal agencies to examine the services they provide, identify any need for services to those with LEP, and develop and implement a system to provide those services so LEP persons can have meaningful access to them.

to be addressed in a timely manner, and recognizing that the media control the content of their publications all are important considerations when working with the media. The site planning team can work with the Agency's regional site press officer to foster a relationship with the media by sharing the Agency's rationale for its plans and actions. It is appropriate to use the media to publicize a site-related decision, an upcoming meeting, changes in schedule, or changes in activities or expectations. Press releases can be used to inform the media of major site-related milestones.

Fact Sheets

Communities appreciate concise, easy-to-understand, and technically accurate fact sheets on the history of the contamination, chemicals of concern, human health risk, planned cleanup activities, and the vapor intrusion assessment and response actions. Be sure to include who to contact for more information.

Because sites involving vapor intrusion can be complex, it may be useful to include additional information in the fact sheets for home owners and renters, including information about household products that may be potential sources of indoor air contamination, as well as steps that can be taken to minimize these sources. EPA recommends preparing and distributing periodic status updates and fact sheets to concerned community members throughout the cleanup process.

Letters

Whenever there are plans to conduct indoor air sampling, EPA recommends sending a letter to each building owner and renter explaining plans to conduct indoor air sampling and requesting written permission for voluntary access to do so. In addition, a one-on-one meeting with the building owner or renter is generally recommended to discuss sampling efforts and access agreements in detail (see Section 9.3).

EPA also recommends that letters be sent to each building owner and renter to report sampling results in a timely manner (see Section 9.4). These letters and meetings often are part of a larger effort that also includes use of other communication strategies, such as community meetings and in-person visits.

In-person Visits

EPA recommends individual, one-on-one communication with each property owner and renter whenever possible.

- Try to schedule in-person visits with individual property owners and renters. These visits also may include owners and renters of properties located outside the planned investigation area. The initial visit can be used to explain sampling plans in more detail, answer questions, and obtain written permission to sample.

- During the visit, the property owner or renter can be briefed about any instructions to follow during sampling activities (for example, keep doors and windows closed during sampling). A general survey of the building could be conducted to determine likely sources of indoor air contaminants.

- EPA recommends the site planning team also describe to owners and renters the sampling devices that will be used, what they look like, where they will be located, and any restrictions or impediments to daily activities that may arise from the ongoing sampling activities.

Information Repository

An information repository can be established and maintained prior to, during, and following site activities, which is generally required for sites where remedial action or removal actions (where on-site action is expected to exceed 120 days) are undertaken pursuant to CERCLA. The information repository is intended to include the administrative record, fact sheets, question-and-answer sheets, and other site-related documents and be located reasonably near the site. However, given the tremendous change in information technology, it may also be appropriate to set up an Internet-based or digital repository (webpages) to share key information. This depends on the community's ability to access and utilize this technology. EPA recommends that community members be made aware of the information repository through the other public outreach mechanisms described above (e.g., local media, newsletters, and public meetings).

Electronic Notification

It also may be useful to establish a registration capability that allows interested community members to sign up for automatic alerts to updates posted on the site website or email listserv.

9.3 Addressing Building Access for Sampling and Mitigation

EPA recommends that all requests for access, as well as provision of access, be in writing in order to document EPA's due diligence to protect human health at the site. EPA recommends that the site planning team provide building owners and occupants with information about the sampling device(s)) being used, including what they look like, where they will be located and any restrictions or impediments to daily activities that may arise due to ongoing sampling.

In the case of an initial refusal to provide access, additional attempts for access are generally recommended, although regional practices may vary. EPA recommends documenting all attempts to gain access, for example using telephone conversation records, emails, or letters sent to home or building owners.

Gaining access to owner-occupied residences for vapor intrusion sampling and mitigation may be handled differently than for commercial buildings or rental properties.

Owner-Occupied Residences: Allowing EPA to sample or install mitigation systems in an owner-occupied residence is a voluntary action. EPA generally encourages owners to take advantage of an offer for an assessment and mitigation system, if necessary.

Rental Properties: Access may be voluntary or involuntary. Site planning teams often deal with both owners and renters when there is a need to sample on, in, or under a rental property. There are different legal and communication issues for owners and renters. For example, the owner is responsible for granting access for sampling and for installation of mitigation measures, if they are necessary; however, if the owner grants access, logistics normally are

arranged with the renter. EPA recommends apprising both the owner and the renter of human health risk that may be posed by vapor intrusion, which includes providing building-specific sampling results to both parties when available. If the owner of a rental property refuses access, EPA may, nevertheless, pursue access, in the interest of protecting the occupants, for determining the need for response, choosing a response action, taking a response action, or otherwise enforcing CERCLA or RCRA (EPA 1986, 1987, 2010a). Notifying the owner of a rental property of this statutory authority may help to avoid the need for legal action.

Nonresidential Buildings: Site managers also may need to sample on, in, or under nonresidential buildings, such as schools, libraries, hospitals, hotels, and stores. In these situations, broader outreach to the public may be appropriate in addition to maintaining direct contact with the property owner. Similar to rental properties, access for sampling and for implementation of mitigation methods, if they are necessary, may be voluntary or involuntary. If the owner of a nonresidential building refuses access, EPA may, nevertheless, pursue access, in the interest of protecting the occupants, for determining the need for response, choosing a response action, taking a response action, or otherwise enforcing CERCLA or RCRA (EPA 1986, 1987, 2010a).

Property Ownership Changes: For owners of homes or buildings who did not provide access for assessment sampling or installation of a mitigation system, EPA recommends that the site planning team make reasonable attempts to track ownership changes, although the appropriate state, tribal, or local agency or PRP may be in a better position to track this information. For example, reasonable attempts to make contact can be done by annually conducting drive-bys or inspections and noting homes or buildings for sale, periodically checking on-line real estate sales or title insurance listings, or using other mechanisms. Homes that were initially targeted but not sampled can be reconsidered during the review or if there are major changes to the toxicity values for the site contaminants of concern. Annually mailing notifications to buildings not previously sampled is a means to foster reconsideration of testing with a change in ownership. If ownership changes are noted, appropriate follow-up can be conducted with the new home owner or building owner.

Federal statutory authority to access private property to conduct investigations, studies and cleanups pursuant to CERCLA and RCRA is discussed in Section 1.2 of this Technical Guide.

9.4 Communication of Indoor Sampling Efforts and Results

The community involvement plan or public participation plan is intended to address community concerns and participation regarding indoor air and sub-slab sampling. In addition to the general community involvement activities occurring throughout the cleanup process (see Section 9.2), the site planning team may choose to hold a community meeting to discuss indoor sampling efforts and results. EPA recommends sending a letter to each home or building owner and renter explaining plans to conduct sampling or providing sampling results. EPA recommends that this letter be in addition to a one-on-one meeting with the building or home owner to discuss access agreements, sampling efforts, and sampling results. Prompt communication of sampling results to building or home owners is important as some people may choose to make precautionary decisions prior to regulatory decisions on remediation or mitigation measures.

EPA recommends the site planning team inquire about stakeholder preferences for confidentiality with regards to property-specific data. It may be appropriate to segregate data for private residential properties versus community properties (e.g., schools, daycare centers,

commercial buildings) or provide different types of property identifiers for these respective building types in reports and maps and tables displayed at public meetings or otherwise made available to the community.

Letters Transmitting Sampling Results[251]

EPA recommends that the site planning team provide validated sampling results and interpretations (e.g., chemicals of concern, associated risk assessment implications) in plain English (and translations, if necessary) to property owners and renters in a timely manner (e.g., within approximately 30 days of receiving the results). EPA also recommends the transmittal letter indicate what future actions (e.g., mitigation options), if any, are contemplated,[252] based on the sampling results, and contain additional site-specific and possibly building-specific information, including, but not limited to:

- Site and Home/Building Information.
  - Site name and location of contamination.
  - Date of sampling.
  - Address of sampled home or building.
  - Locations sampled (both indoor and outdoor).

- Sampling Results
  - Sampling results for site-related, vapor-forming chemical(s) and for any other chemicals, if detected, including an explanation of results believed to be attributable to background sources, if known.[253]
  - Risk-based screening levels (for example, VISLs described in Section 6.5) or other risk-based benchmarks used to explain and interpret the sampling results.
  - Explanation and interpretation of sampling results, if known, which may include a summary of the human health risk assessment, if available (see Section 7.4).[254]

[251] Within the community of risk professionals, the phrase 'risk communication' has come to mean communication that supplies lay people with the information they need to make informed independent judgments about human health risk or public safety (Morgan et al. 1992). In this case about vapor intrusion, the ultimate goal of risk communication is to assist stakeholders and the general public in understanding the investigation data and the rationale behind any risk-informed decision, so they may arrive at a balanced judgement that reflects the factual evidence in relation to their own interests and values.

[252] This section may include an explanation of mitigation process and responsibilities and a timeline for further contact regarding system installation and options. If a building mitigation system is recommended on the basis of a human health risk assessment, EPA recommends that the site planning team explain that the risk calculation reflects conservative, health-protective factors.

[253] With such information, EPA can help advise citizens about the environmental and public health threats they face that are within their control (e.g., from indoor sources). In cases where 'background' contamination may pose a human health risk, but its remediation is beyond the authority of the applicable statute, risk communication to the public may be most effective when coordinated with public health agencies (EPA 2002e). The public may also be advised about the scope and limits of EPA's statutory authorities.

[254] Assessment uncertainty is generally an important factor in deciding how to act (Frewer 2004); i.e., whether to reduce risk through response action or reduce uncertainty (e.g., through additional monitoring and data collection). Risk professionals, therefore, generally recommend that risk communication to stakeholders and the general public characterize the sources of uncertainty, as well as the magnitude of uncertainty associated with a particular hazard (see, for example, Frewer (2004) and Markon and Lemyre 92013)).

  - Simple tabulated and color-coded results (representing exceedances of human health risk levels or no exceedance).

- Diagrams/Illustrations
  - Diagrams and illustrations of sampling devices.
  - Diagrams and illustrations of sampling locations
  - Diagrams of specific mitigation systems (e.g., how a SSD system works and looks).

- Next Steps
  - Actions that property owners and occupants can take to reduce vapor intrusion exposure until mitigation systems are in place.

- Information Sources
  - Contact information for a person who can answer questions or supply further explanations.
  - The location of the site information repository or site website can be included as a resource for public access to more detailed information and site documents.

9.5 Transmitting Messages Regarding Mitigation Systems

The initial notification to residents or building owners about mitigating vapor intrusion can be delivered in various ways. A primary mechanism is a face-to-face meeting with the building owner or occupant to explain the sampling results and discuss next steps, including installation of a vapor intrusion mitigation system. EPA recommends that this meeting include a member of the site planning team (RPM or OSC and risk assessor, for example), a representative from the local health department or the Agency for Toxic Substances and Disease Registry (ATSDR), and the mitigation contractor scheduler. This meeting could discuss topics such as:

- Sampling Results: Describe where samples were taken and the chemicals of concern, and explain the results as related to site action levels. Any questions related to human health risk can be answered by the risk assessor or public health representative at this time. For questions or concerns regarding personal health, EPA recommends that residents and building owners contact their medical professional.

- Mitigation System Details: Describe the need for a mitigation contractor to visit the residence to identify potential locations for the mitigation system. The property owner will need to be present for the visit and will have input about where the system is installed, if they agree to install such a system. Photos of a mitigation system (piping, system fan, number of holes drilled in the slab, height of the vent on the outside of the residence, etc.) may be helpful. EPA recommends that plans and schedules for periodic inspection, maintenance, and monitoring also be described.

- Access: EPA recommends advance planning to ensure building access to install, monitor and maintain any mitigation system. Arrangements could be made at this meeting to sign an additional access agreement for these activities, if needed.

- Cost of the Mitigation System: Identify which party will pay for installation of the mitigation system and anticipated property-owner costs. For example, EPA or a PRP may pay for the

system installation, and the property owner or PRP may take responsibility to pay for the monthly costs associated with the mitigation system.

- Project Schedule and Next Steps: The meeting may be concluded by giving an overview of the overall project timeline, including the appointment for the mitigation contractor visit and system installation.

Notification also can be provided through the data transmittal letter. In many cases, however, the decision to install mitigation systems will not have been made prior to the transmittal of sampling results. In these situations, data transmittal letters can convey that EPA is reviewing all data results for the affected area and considering appropriate next steps. Once the decision document is signed, the site planning team can develop and mail a fact sheet to all community members in the affected area, followed by a community meeting.

In addition, if a vapor intrusion mitigation system is installed, EPA recommends that the property owner or renter be informed that the system normally is designed to protect the home or building only against vapor-forming chemicals coming from the subsurface. A vapor intrusion mitigation system generally will not protect the home against continuing indoor sources because vapor intrusion mitigation systems typically are not indoor air filtration systems.

EPA recommends that current owner-occupants be advised that if they decline or waive an offer to install a vapor mitigation system, they might be responsible for the costs of installing and maintaining their own system if they decide to do so at a later time. EPA also recommends documenting any declination or waiver.

9.6 Addressing Community Involvement at Legacy Sites

Ongoing site activities with assessment components, such as remedial investigations and monitoring, allow EPA to continually evaluate site conditions and adjust cleanup actions as warranted. During periodic reviews or conducting other site activities, such as the FYR pursuant to CERCLA, EPA has evaluated vapor intrusion where appropriate. In some instances, EPA has newly identified vapor intrusion as an exposure pathway. These mature or “legacy” sites present a unique challenge to site planning teams.

Conducting community involvement at legacy sites may be complicated by several factors including:

- A remedy for the control of exposure to volatile chemicals already has been installed, proposed, or is under construction as part of the cleanup plan.

- Ownership of properties previously exposed to VOCs has changed hands through resale, foreclosure, or assumption of the property by second-generation homeowners. These owners were not part of any original resolution of exposure issues and in many cases may not be aware that a remediation or treatment was put in place.

- Property owners and other community members who participated in prior cleanup efforts may be reluctant to fully engage with efforts to reopen lines of investigation at their properties.

In these and similar circumstances, the challenge for Agency representatives is to resume contact with communities who have put past difficulties behind them. In many cases, mailing lists are outdated, previous reliable contacts no longer are available, and elected officials may not have institutional memory of the events that prompted the remediation.

Strategies for Revitalizing Community Involvement at Legacy Sites

Every legacy re-entry will be a site-specific situation. Therefore, EPA recommends that events and activities be planned to acknowledge and accommodate the inevitable changes in the makeup of a community. In addition to the communication strategies and community involvement techniques described in Sections 9.1 through 9.5, additional suggestions to ease re-entry and revitalize community involvement at a legacy site include:

- Reassess the community and the site by revisiting the site and the surrounding areas and taking note of new construction.
- Reintroduce yourself and the Agency to current municipal staff and check previously used public venues for viability. Determine if new venues may be closer or more accessible to the community.
- If contacts within the community are still extant, reconnect; ask for updates on the growth and stability of the community. If no viable contacts exist, attempt to cultivate new ones.
- Revise and update mailing lists and fact sheets.

As with all sites affected by vapor intrusion issues, be prepared to meet with property owners door to door and to hold public meetings or forums to explain the current investigation and its importance to protecting human health.

9.7 Property Value Concerns for Current and Prospective Property Owners

EPA recognizes that vapor intrusion impacts may have implications for property values. In some instances, mitigation systems and other clean-up measures may help to restore property values.

Nevertheless, property value issues are outside the scope of Agency authority. In general, if asked, EPA recommends that regional staff suggest that prospective buyers and sellers contact real estate professionals and lenders from the local area with questions about property values. If a home owner or renter has questions about vapor intrusion mitigation systems, EPA regions can provide information that explains how vapor intrusion systems are designed to reduce exposure to chemicals found in indoor air and to avert human health-related problems.

9.8 Additional Community Involvement Resources

EPA's Superfund Community Involvement Program:

EPA's Superfund Community Involvement website contains many resources that may be helpful for planning community involvement activities for other cleanup programs. This resource includes a list of regional Superfund community involvement points of contact, a list of technical

assistance and training resources, and descriptions and links to community involvement policies, guidance and publications (see http://www.epa.gov/superfund/community/).

EPA's Superfund Community Involvement Toolkit (CI Toolkit):

While targeted to a Superfund Program audience, the CI toolkit may be helpful to a wide variety of users because it is a practical, easy-to-use aid for designing and enhancing community involvement activities and contains tips on how to avoid some of the pitfalls common to the community involvement process. The toolkit enables users to quickly review and adapt a variety of community involvement tools to engage the community during all stages of the cleanup process. Relevant tools include tips for conducting public availability and poster sessions and public meetings, developing fact sheets, working with the media, planning communication strategies, developing a Community Involvement Plan, and establishing an information repository (see http://www.epa.gov/superfund/community/toolkit.htm).

EPA's Community Engagement Initiative:

The OSWER CEI is designed to enhance OSWER and regional offices' engagement with local communities and stakeholders to help them participate meaningfully in government decisions on land cleanup, emergency preparedness and response, and the management of hazardous substances and waste (see http://www.epa.gov/oswer/engagementinitiative/).

10.0 GLOSSARY

The following definitions are provided for purposes of this Technical Guide:

accumulate ..... Increase gradually in amount as time passes. Note that there will be a finite maximum amount, which will be determined by site- and building-specific conditions and will reflect a balance among physical processes (e.g., soil gas entry, air exchange).

active ..... Involving mechanical operations; Compare with *passive*.

active depressurization technology..... Vapor intrusion mitigation method that creates a driving force for air flow from the building into the subsurface by lowering the pressure below the slab, thereby reducing vapor intrusion (soil gas entry into a building).

acute ..... Refers to repeated or single exposure for 24 hours duration or less. Compare with *short-term* and *subchronic*.

advection ..... As it pertains to soil gas, refers to bulk movement in the vadose zone induced by spatial differences in soil gas pressure. The direction of advective vapor transport is always toward the direction of lower air pressure.

aerobic ..... Describes a process or activity requiring oxygen. Compare with *anaerobic*.

air exchange rate ..... Rate of air infiltration into a building through windows, doorways, intakes and exhausts, 'adventitious openings' (e.g., cracks and seams that combine to form the building envelope), plus natural and mechanical ventilation.

ambient air ..... The outdoor air surrounding a building or site.

anaerobic ..... Describes a process or activity requiring the absence of oxygen. Compare with *aerobic*.

analyte..... A substance for which identification (of presence) and/or quantification (of amount, such as concentration) is/are sought by instrumental measurement.

attenuation ..... Decrease in vapor concentration in soil gas emanating from a subsurface vapor source along the migration route towards and into a building (indoor air)

attenuation factor..... The ratio of the indoor air concentration arising from vapor intrusion to the soil gas concentration at the source or a depth of interest in the vapor migration route.

background ..... Refers to a vapor-forming chemical(s) or location(s) that is(are) not influenced by the releases from a site, and is usually described (EPA 1989, 1995c, 2002e) as naturally occurring or anthropogenic: 1) *Anthropogenic* – natural

	and human-made substances present in the environment as a result of human activities and not specifically related to the site-related release in question; and, 2) *Naturally occurring* – substances present in the environment in forms that have not been influenced by human activity. Background may include a vapor-forming chemical(s) present in indoor air due to human activities that is(are) not related to vapor intrusion or site-related contamination.
background vapor concentration	This term may include the concentration of a vapor-forming chemical in indoor air that fits within the definition of "background" above. Information on background concentrations of vapor-forming chemicals in indoor air "is important to risk managers because generally EPA does not clean up to concentrations below natural or anthropogenic background levels" (EPA 2002e).[255]
background vapor source.....	The origin(s) and location(s) of a vapor-forming chemical(s), other than vapor intrusion, and not associated with or emanating from a site-related release(s) to the environment. Background vapor sources may include indoor or outdoor sources. See also *indoor vapor source, outdoor vapor source,* and *background vapor concentration;* compare to *subsurface vapor source*.
biodegradation.....	Decomposition or breakdown of a substance through the action of microorganisms (such as bacteria or fungi).
brownfield	A parcel of real estate that is abandoned or inactive or may not be operated at its fully beneficial use and on which expansion or redevelopment is contemplated or reasonably expected; distinguished from "greenfield" because expansion or redevelopment may be complicated by the presence of vapor-forming chemicals in the subsurface environment.
building.....	a structure that is intended for human occupancy and use. This would include, for instance, homes, offices, stores, commercial and industrial buildings, etc., but would not normally include sheds, carports, pump houses, or other structures that are not intended for human occupancy.
building survey.....	Refers generically to gathering -- by observation, interviews, reviewing documents and records or other means -- information about existing buildings, including,

[255] It should, however, be noted that some EPA regulations (e.g., indoor radon standards under 40 CFR 192.12) are inclusive of background.

	but not limited to, location, use, occupancy, basic construction (e.g., foundation type), heating ventilation and cooling systems, potential indoor sources of vapor-forming chemicals, and anticipated susceptibility to soil gas entry (e.g., presence of radon mitigation system).
capillary fringe	The porous material just above the ground water table which may hold water by capillarity (a property of surface tension that draws water upwards) in the smaller void spaces.
chlorinated hydrocarbon (CHC)	Compound comprised solely of the elements chlorine, hydrogen and carbon. Includes dry-cleaning solvents such as tetrachloroethylene (PCE) and degreasing solvents such as trichloroethylene (TCE) and 1,1,1-trichloroethane (TCA).
chronic	Refers to repeated exposure for more than approximately 10% of the life span (approximately seven years) in humans. Compare with *subchronic*.
concentration	Amount (mass) of a vapor-forming chemical contained in a unit quantity (e.g., volume) of a specific medium (e.g., air, soil gas).
conceptual site model (CSM)	Narrative description of the current understanding of the site-specific conditions, which, in the case of vapor intrusion, include the nature, location, and spatial extent of the source(s) of vapor-forming chemicals in the subsurface and the location, use, occupancy, and basic construction of existing buildings. A CSM represents an adaptation of a general *conceptual model* to account for and reflect site- and/or building-specific conditions. See also *model*.
crawl space	A type of basement in which one cannot stand up — the height may be as little as one foot, and the bottom surface is often bare soil.
complete (vapor intrusion) pathway	The vapor intrusion pathway is referred to as “complete” for a building or collection of buildings when five conditions are met under current conditions: (1) a subsurface source of vapor-forming chemicals is present underneath or near the building(s); (2) vapors form and have a route along which to migrate (be transported) toward the building(s); (3) the building(s) is (or are) susceptible to soil gas entry, which means openings exist for the vapors to enter the building(s) and driving forces exist to draw the vapors from the subsurface into the building(s); (4) one or more vapor-forming chemicals comprising the subsurface vapor source(s) is (or are) present in the indoor environment; and (5) the building(s)

	is (or are) occupied by one or more individuals when the vapor-forming chemical(s) is (or are) present indoors.
data objectivity	Refers to the accuracy, reliability, and absence of bias in the information; scientific information will generally attain this criterion when the original or supporting data are generated using sound research, investigatory, or statistical methods.
data quality objective (DQO)	Performance and acceptance criteria that clarify study objectives, define the appropriate type of data, and specify tolerable levels of potential decision errors that will be used as the basis for establishing the quality and quantity of data needed to support decisions.
data utility	Refers to the usefulness (e.g., relevance, importance) of the information to reaching a conclusion or judgment (e.g., is the vapor intrusion pathway complete or incomplete? Does the vapor-forming chemical in indoor air arise from background sources or vapor intrusion? Does vapor intrusion pose an unacceptable human health risk in a specific building?)
diffusion	Random motion that affects the distribution of molecules when there are spatial differences in chemical concentrations in the fluid (e.g., soil gas, indoor air, groundwater). The net direction of diffusive transport is toward the direction of lower concentrations.
driving force	refers to the combination of: (i) pressure differences between a building interior and the subsurface or ambient air, which foster vapor intrusion and infiltration, respectively, via advection; and (ii) concentration differences between a building interior and the subsurface or ambient air, which foster vapor transport via diffusion.
early action	Refers to a response action undertaken early in the cleanup process to achieve prompt risk reduction. Also see *response action* and *pre-emptive mitigation.*
evidence	A fact or other information (i.e., datum) ascertainable by direct observation, interviews, review of records and documents, instrumental analysis in a lab or field setting, research and testing, sampling of environmental media (e.g., indoor air, soil gas, groundwater), statistical analysis, or other means, which is useful for forming a conclusion or judgment; each distinguishable datum is referred to as a line of evidence, which may be categorized into scientific realms (e.g., geology, biology, physics) or investigatory objectives (e.g., characterization of subsurface vapor source, accounting for background sources)

exposure	Opportunity to come into contact with vapor-forming chemicals (via inhalation, in the case of vapor intrusion).
exposure assessment	Process of characterizing the magnitude, frequency, and duration of exposure to a vapor-forming chemical, along with the characteristics of the population exposed.
exposure control	Modification of a property or building intended to reduce or eliminate human exposure to hazardous vapors in buildings or explosive vapors in structures, which arise from the vapor intrusion; such controls may include engineered methods (e.g., active depressurization technologies, mechanical ventilation, indoor air treatment) or non-engineered methods (e.g., institutional controls, such as deed notices and land use restrictions)
exposure pathway	The physical course a vapor-forming chemical takes from its source (e.g., groundwater) to the individual (in a building in the case of vapor intrusion).
exposure route	The way in which a vapor-forming chemical enters a human body (i.e., inhalation in the case of vapor intrusion).
flux	The rate of movement of mass through a unit cross-sectional area per unit time in response to a concentration gradient or a driving force for advection.
gas	A fluid (as air) that has neither independent shape nor volume but tends to expand indefinitely; a state of matter in which the matter concerned occupies the whole of its container irrespective of its quantity.
grab sample	A sample of air collected over a short (practically instantaneous) duration. Compare with *time-integrated sample*.
hazard index (HI)	The sum of hazard quotients for substances that affect the same target organ or organ system. Because different pollutants can cause similar adverse health effects, it is often appropriate to combine hazard quotients associated with different substances.
hazard quotient (HQ)	The ratio of the potential exposure to the substance and the level at which no adverse effects are expected. If the HQ is calculated to be equal to or less than 1, then no adverse health effects are expected as a result of exposure. If the HQ is greater than 1, then adverse health effects are possible.
hazardous	Involving or exposing one to threat of adverse health effects (due to toxicity) or loss of loss of life or welfare (due to explosiveness).

Henry's Law Coefficient or Constant	Ratio of a chemical's vapor pressure in air to its solubility in water. Generally reported for standard reference temperature, such as 25 °C.
human exposure pathway	A way that people may come into contact with environmental contaminants while performing their day-to-day indoor activities.
human health risk assessment	The evaluation of scientific information on the hazardous properties of vapor-forming chemicals (hazard assessment and characterization), the dose-response relationship, and the extent of human exposure to those agents. The product of the risk assessment is a statement regarding the probability that populations or individuals so exposed will be harmed and to what degree and describing the principal technical uncertainties (i.e., risk characterization).
hydrocarbon	Compound comprised solely of the elements hydrogen and carbon. See also *chlorinated hydrocarbon* and *petroleum hydrocarbon*.
inclusion zone	Land area within which EPA recommends assessing the vapor intrusion pathway, which extends beyond the aggregate boundaries of the site-specific source(s) of vapor-forming chemicals.
indoor vapor source	Refers to a vapor-forming chemical(s) in indoor air which originates within a building. Indoor sources of vapor-forming chemicals may include, but are not limited to, use and storage of consumer or household products, use or storage of industrial materials or products, combustion processes, activities or operations within a building, and releases from interior building materials (e.g., off-gases from furniture or clothing); for example, operational use or storage of chemicals in an industrial building may represent an indoor vapor source separate from a site-related release. Also see *background vapor source;* compare to *subsurface vapor source*.
infiltration	Air leakage into a building through random cracks, interstices, and other unintentional openings in the building envelope.
institutional control (IC)	Non-engineering measures intended to affect human activities in such a way as to prevent or reduce exposure to hazardous substances. For example, ICs may be used to restrict certain land uses, buildings, or activities that could otherwise result in unacceptable exposure to the vapor intrusion pathway. Generally, four categories of ICs are recognized: governmental controls; proprietary controls; enforcement tools; and informational devices. They are almost always used in conjunction with, or as a

	supplement to, other cleanup measures such as treatment or containment.
interim action	Refers to a response action that is undertaken to protect human health, but is limited in scope and objective (e.g., does not accomplish complete or final remediation of subsurface vapor sources). Also see *response action.*
interzonal air flow	Movement or transport of air through doorways, ductwork, and service chaseways that interconnect rooms or zones within a building.
lines of evidence	Data collected and weighed together in supporting assessments of the vapor intrusion pathway, which are identified and described throughout Sections 2 through 7 inclusive. See also *evidence*.
lower explosive limit (LEL)	The lowest concentration at which a gas or vapor is flammable or explosive at ambient conditions.
mitigation	Interim actions taken to reduce or eliminate human exposure to vapor-forming chemicals in a specific building arising from the vapor intrusion pathway; compare with *remediation.*
model	Refers to a description of a system. In the case of vapor intrusion the 'system' will generally consist of a subsurface source of vapors, one or more buildings potentially subject to soil gas entry, and the soil underlying the building(s). *Conceptual models* (i.e., models that are conceptual) are comprised of narrative descriptions that identify the primary physical elements and processes of the system and the interactions between and relationships among them; for example, Section 2 of this document provides a general conceptual model of how vapor intrusion can arise and why it may be variable over time and in space. A *mathematical model* is an expression of a conceptual model, which uses mathematical symbols and language to identify key elements (e.g., variables) and processes. Generally, mathematical models are highly idealized or simplified descriptions, compared to the complex systems they represent. For example, Johnson and Ettinger (1991) formulated an idealized mathematical model of vapor intrusion. In the case of a *physical model,* the description is provided using physical objects, which may or may not have full functionality; for example, a physical model of a construction project might differ from a planned system in its scale, but would necessarily show significant elements in relationship to each other.

near-source	Refers to a soil gas sample collected within a practically short distance from subsurface vapor source
nonresidential building	Refers to a building other than a home; includes, but is not limited to, institutional buildings (e.g., schools, libraries, hospitals, community centers and other enclosed structures for gathering, gyms and other enclosed structures for recreation); commercial buildings (e.g., hotels, office buildings, many (but not all) day care centers, and retail establishments); and industrial buildings where vapor-forming chemicals may or may not be routinely used or stored. Compare with *residential building*; see also *building*.
outdoor vapor source	Refers to a vapor-forming chemical(s) present in outdoor (ambient) air. Sources of vapor-forming chemicals in outdoor air may include, but are not limited to, releases from industrial facilities, vehicle exhaust, yard maintenance equipment, fuel storage tanks, paint or pesticide applications, agricultural activities, and fires, as well as site-related contamination, activities, and operations (e.g., emissions from remediation equipment). Also see *background vapor source;* compare to *subsurface vapor source*.
passive	Not involving mechanical operations; Compare with *active*.
petroleum hydrocarbon (PHC)	Hydrocarbons derived from petroleum and present in various refined products of petroleum (such as automotive gasoline, diesel fuel, lubricating oils). See also *hydrocarbon*.
potentially complete (vapor intrusion pathway)	The vapor intrusion pathway is referred to as 'potentially complete' for a building when: a subsurface source of vapor-forming chemicals is present underneath or near an existing building or a building that is reasonably expected to be constructed in the future; vapors can form from this source(s) and have a route along which to migrate (be transported) toward the building; and three additional conditions are reasonably expected to all be met in the future, which may not all be met currently (i.e., the building is susceptible to soil gas entry, which means openings exist for the vapors to enter the building and driving forces exist to draw the vapors from the subsurface through the openings into the building; one or more vapor-forming chemicals comprising the subsurface vapor source(s) is (or will be) present in the indoor environment; and the building is or will be occupied by one or more individuals when the vapor-forming chemical(s) is (or are) present indoors.

preemptive mitigation (PEM)	Implementation of systems or control measures to mitigate the vapor intrusion pathway as an early action, even though all pertinent lines of evidence have not yet been completely developed to characterize the vapor intrusion pathway for the subject building(s). Also see *early action* and *response action.*
preferential migration route	Naturally occurring subsurface feature (e.g., gravel lens, fractured rock) or anthropogenic (human-made) subsurface conduit (e.g., utility corridor or vault, subsurface drain) that is expected to exhibit little resistance to vapor flow in the vadose zone (i.e., exhibits a relatively high gas permeability) or groundwater flow (i.e., effectively exhibits a relatively high hydraulic conductivity), depending upon its location and orientation relative to the water table and ground surface, thereby facilitating the migration of vapor-forming chemicals in the subsurface and towards or into buildings
pressure difference/differential pressure	Difference between the air pressure within a building and the subsurface environment or ambient air. Can promote advective flow of gas into or out of a building through pores, cracks, or openings in the building foundation or envelope.
radon	A radioactive gas formed during the radioactive decay of radium, which occurs naturally in many geologic settings.
reasonable maximum exposure (RME)	A semi-quantitative term, referring to the lower portion of the high end of the exposure distribution; conceptually, above the 90th percentile exposure but less than the 98th percentile exposure.
reasonable worst case	A semi-quantitative term, referring to the upper portion of the high end of the exposure distribution, but less than the absolute maximum exposure.
reference concentration (RfC)	An estimate of the continuous inhalation exposure to the human population (including sensitive subgroups) that is likely to be without appreciable risk of deleterious effects during a lifetime.
remediation	Refers to interim and final cleanups, whether conducted pursuant to RCRA corrective action, the CERCLA removal or remedial programs, or using EPA brownfield grant funds with oversight by state and tribal response programs. In addition to permanent remedies for subsurface vapor sources, site remediation may also entail implementation of institutional controls and construction and operation of engineered systems.

residential building	refers to a building used as or intended for use as a home; includes, but is not limited to, single-family detached homes with foundations, trailer homes, multi-unit apartments and condominiums. Compare with *non-residential building;* see also *building*.
response action	any action taken to reduce or eliminate human exposure to or risk posed by hazardous vapors in buildings and structures, which arise from the vapor intrusion pathway; these actions may include engineered exposure controls in a specific building(s), non-engineered exposure controls, remediation of subsurface vapor sources, and associated monitoring to assess effectiveness and protectiveness. Also see *remediation* and *mitigation.*
risk	Probability of an adverse human health effect (due to toxicity) or physical hazard (e.g., due to potential for explosion) caused under specific circumstances by a vapor-forming chemical.
risk communication	The process of exchanging information about health threats and levels or significance of human health risk.
risk management	The process of determining whether response action(s) is(are) warranted to protect human health and, if so, selecting response actions to implement.
screening	Process of comparing concentrations of vapor-forming chemicals in a specific medium (e.g., indoor air, soil gas, crawl space air, groundwater) to screening levels to identify sites, buildings, or chemicals unlikely to pose a health concern through the vapor intrusion pathway versus those warranting further investigation or analysis.
screening level	Risk-based concentrations derived from standardized equations combining exposure information and assumptions with toxicity values.
short-term	Refers to repeated exposure for more than 24 hours, up to 30 days. Compare with *acute* and *subchronic*.
significant opening	Refers to refer to an atypical form and amount of an opening in a building (e.g., a sump, an unlined crawl space, an earthen floor), which could facilitate greater amounts of soil gas entry, all else being equal. Forms of openings typically expected to be present in all buildings include cracks, seams, interstices, and gaps in basement floors and walls or foundations and perforations due to utility conduits.
site	The geographical area where investigation and evaluation of the presence of vapor-forming chemicals is desired; in many situations, it includes areas surrounding

	a facility where a release to the subsurface environment is known or suspected to have originated.
soil gas	The gas present underground in the pore spaces between soil particles.
soil gas concentration	Vapor concentration in a soil gas sample. Sub-slab soil gas is found immediately beneath a building. Near-source or exterior soil gas samples are collected at other depths and typically outside the building footprint.
source strength	Vapor concentration(s) of vapor-forming chemical(s) arising from a subsurface vapor source.
stakeholder	A person, group, community, or corporate entity with an interest in activities at a site with subsurface contamination.
subchronic	Refers to repeated exposure for more than 30 days, up to approximately 10% of the life span (approximately seven years) in humans. Compare with *short-term* and *chronic*.
subsurface remediation	Response action that eliminates or substantially reduces the level of vapor-forming chemicals in the subsurface vapor source via treatment or physical removal. Compare with *mitigation.*
subsurface vapor source	Refers to a vapor-forming chemical(s) present in the subsurface environment arising from a release(s) to the environment. A subsurface vapor source may occur as a non-aqueous-phase liquid (NAPL), adsorbed-phase contamination, or dissolved-phase contamination, which may be present in the vadose zone, in groundwater, or within sewers and other conduits. Information on subsurface vapor sources is important to risk managers because response actions are generally warranted when vapor intrusion is determined to pose unacceptable human health risks. Compare with *background vapor source* and *background vapor concentration*.
termination criteria	Refers to numeric cleanup levels for each site-specific contaminant and narrative cleanup objectives that are to be attained by the response actions.
time-integrated sample	Sample collected over an extended period of time to account for temporal variations in vapor concentrations. Compare with *grab sample*.
toxicity value	Refers to an inhalation unit risk (IUR) for potential cancer effects or an inhalation reference concentration (RfC) for potential non-cancer effects of a vapor-forming chemical.

vadose zone	The soil zone between land surface and the groundwater table within which the moisture content is less than saturation (except in the capillary fringe). Soil pore spaces not occupied by moisture contain (soil) gas. Also referred to as the "unsaturated zone."
vapor	A substance in the gaseous state as distinguished from the liquid or solid state.
vapor intrusion	The migration of potentially hazardous vapors from any subsurface contaminant source, such as contaminated soil or groundwater, through the vadose zone and into a building or structure.
vapor source	The place and form of origin of chemical vapors. Also see *background vapor source*, *indoor vapor source*, *outdoor vapor source*, and *subsurface vapor source*.
vapor-forming chemical	A volatile chemical that EPA recommends be routinely evaluated during a site-specific vapor intrusion assessment, when it is present as a subsurface contaminant.
volatile chemical	Chemical with a vapor pressure greater than 1 milliliter of mercury (mm Hg), or Henry's law constant greater than 10^{-5} atmosphere-meter cubed per mole.
volatility	The tendency of a substance to form vapors, which are molecules in a gaseous state, and escape from a liquid or solid source. This tendency is directly related to a substance's vapor pressure and Henry's law constant and is indirectly related to a substance's molecular weight (i.e., substances with lower molecular weights tend to volatilize more readily than substances with similar molecular structures that have higher molecular weights).
water table	The water surface in an unconfined aquifer at which the fluid pressure in the pore spaces is at soil gas pressure.
weight of evidence	Refers to a conceptual approach to data evaluation, in which each of several lines of evidence is critically appraised for its quality (e.g., utility, objectivity) and systematically assessed for its logical support for a particular conclusion, as well as alternative conclusions; the appraisals consider lines of evidence individually and in light of other lines of reliable evidence for purposes of determining whether a particular conclusion is supported by the preponderance of the evidence and is consistent with the conceptual site model; this 'weighing' concept does not entail a quantitative (*a priori*) scheme to score or rank the individual lines of evidence. See also *evidence*.

work plan	A site-specific document that includes a project description, project objective(s), historical information about the site.
worst case	A semi-quantitative term, referring to the absolute maximum plausible exposure (i.e., a bounding – high-impact – case).

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APPENDIX A
RECOMMENDED SUBSURFACE-TO-INDOOR AIR ATTENUATION FACTORS

A.1 INTRODUCTION

This Technical Guide includes recommended medium-specific (groundwater, soil gas, and indoor air) Vapor Intrusion Screening Levels (VISLs) that are intended to help identify those sites unlikely to pose a health concern from vapor intrusion and identify areas or buildings that may warrant further investigation of the vapor intrusion pathway. These VISLs are recommended for use in evaluating the concentrations of vapor-forming chemicals measured in groundwater, "near-source" exterior soil gas, and sub-slab soil gas in residential and nonresidential settings where the potential for vapor intrusion is under investigation.

The subsurface VISLs are developed considering a generic conceptual model for vapor intrusion consisting of a groundwater or vadose zone source of vapor-forming chemicals that diffuse upwards through unsaturated soils towards the surface and enter buildings. The underlying assumption for this generic model is that subsurface characteristics will tend to reduce or attenuate soil gas concentrations as vapors migrate upward from the source and into structures. Section 6.5.2 describes this conceptual model further. In general, EPA recommends considering whether the assumptions underlying the generic conceptual model are attained at each site. The *Vapor Intrusion Screening Level (VISL) Calculator User's Guide* (EPA 2015a) provides additional information about the technical basis for deriving the VISLs.

Comparison of sampling results to medium-specific VISLs (see Section 6.5.4) comprises one line of evidence in the multiple-lines-of-evidence approach described in this Technical Guide (see, for example, Sections 7.1 and 7.2). The subsurface (groundwater and soil gas) VISLs (C_{VISL}) are calculated using risk-based, screening levels for indoor air ($C_{target,ia}$) and a medium-specific, subsurface-to-indoor air attenuation factor (α_{VI}), as follows:

$$C_{VISL} = \frac{C_{target,ia}}{\alpha_{VI}} \qquad \text{Equation A.1}$$

The risk-based, indoor air screening levels ($C_{target,ia}$) are calculated according to the guidance provided in *Risk Assessment Guidance for Superfund (RAGS) Part F* (EPA 2009) as implemented in EPA's Regional Screening Levels (RSLs) for Chemical Contaminants at Superfund Sites (http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/). The medium-specific, attenuation factors (α_{VI}) recommended for calculating the subsurface VISLs are derived from information in *EPA's Vapor Intrusion Database: Evaluation and Characterization of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings* (EPA 2012a).

This appendix describes the technical basis for the selection of the subsurface-to-indoor air attenuation factors (α_{VI}) that are recommended for use in calculating the VISLs for groundwater, sub-slab soil gas, "near-source" exterior soil gas, and crawl space air, according to Equation A.1.

A.2 DEFINITION AND DESCRIPTION OF ATTENUATION FACTOR

Vapor attenuation refers to the reduction in concentration of vapor-forming chemicals that occurs during vapor migration in the subsurface, coupled with the dilution that can occur when the vapors enter a building and mix with indoor air (Johnson and Ettinger 1991). The aggregate effect of these physical and chemical attenuation mechanisms can be quantified through the use of a subsurface-to-indoor air vapor intrusion attenuation factor (α_{VI}), which is defined as the ratio of the indoor air concentration arising from vapor intrusion ($C_{IA\text{-}VI}$) to the subsurface vapor concentration (C_{sv}) at the source or a depth of interest in the vapor migration route (EPA 2012a):

$$\alpha_{VI} = \frac{C_{IA-VI}}{C_{SV}} \alpha_{VI} = \frac{C_{IA-VI}}{C_{SV}} \qquad \text{Equation A.2}$$

As defined here, the vapor attenuation factor is an inverse measurement of the overall dilution that occurs as vapors migrate from a point of measurement in the subsurface into a building; i.e., attenuation factor values decrease with increasing dilution of vapor concentration.

Subsurface vapor concentrations (C_{SV}) may be measured directly under a building (often called sub-slab soil gas or just sub-slab), measured exterior to a building at any depth in the unsaturated zone (often called exterior soil gas), or derived from groundwater concentrations by converting the dissolved concentration to a vapor concentration assuming equilibrium conditions (i.e., by multiplying the groundwater concentration by the chemical's dimensionless Henry's law constant for the groundwater temperature *in situ*) (EPA 2001); also see Appendix C of this Technical Guide.

Subfloor vapor concentrations may also be measured in building crawl spaces. Although crawl space samples are not strictly subsurface samples, they represent the vapor concentration underlying a building's living space. Thus, crawl space samples may be evaluated in a manner similar to subsurface vapor samples.

A.3 RECOMMENDED ATTENUATION FACTORS

This section summarizes the technical basis and rationale for EPA's recommended attenuation factors for groundwater, sub-slab soil gas, exterior soil gas, and crawl space air, as follows:

- Section A.3.1 summarizes EPA's database of empirical attenuation factor values and the results of analyzing that database.
- Section A.3.2 identifies the recommended empirically based attenuation factors for groundwater.
- Section A.3.3 identifies the recommended attenuation factor for sub-slab soil gas and presents a theoretical analysis that supports the selection of the recommended empirically based value.
- Section A.3.4 recommends a generic attenuation factor for exterior soil gas and discusses its basis, justification, and limited applications.

- Section A.3.5 identifies the recommended attenuation factor for crawlspace vapor.
- Section A.3.6 presents a reliability analysis of the recommended generic attenuation factors.

A.3.1 EPA'S VAPOR INTRUSION DATABASE (EPA 2012A)

The information in *EPA's Vapor Intrusion Database: Evaluation and Characterization of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings* (EPA 2012a) is used to derive recommended attenuation factor values for use in evaluating subsurface sample concentrations collected as part of vapor intrusion investigations. EPA's vapor intrusion database consists of numerous pairings of concentrations in indoor air and subsurface samples (groundwater, sub-slab soil gas, exterior soil gas, and crawlspace vapor) from actual sites. It represents the most comprehensive compilation of vapor intrusion data for chlorinated hydrocarbons (CHCs) available at this time.

EPA's vapor intrusion database was analyzed and screened to reduce the impacts of background sources to indoor air concentrations. The resulting data distributions are considered representative of vapor intrusion of CHCs from subsurface vapor sources into residential buildings for most conditions. These distributions serve as the basis for identifying the high-end (conservative) attenuation factors for those media.

Table A-1 and Figure A-1 (Table 19 and Figure 34, respectively, in EPA (2012a)) present and compare the distributions of the attenuation factors (groundwater, exterior soil gas, sub-slab soil gas, and crawl space) that remain after applying the respective source strength and indoor air screens considered most effective at reducing the influence of background contributions to indoor air concentrations. These data demonstrate that the attenuation factor distributions obtained for groundwater, sub-slab soil gas, and crawl spaces for multiple buildings and sites are consistent with the conceptual model for vapor intrusion, which predicts that greater attenuation is expected with greater depths to the vapor sources or vapor samples. As shown in Table A-1 and Figure A-1, the paired groundwater–indoor air data generally exhibit greater attenuation (lower attenuation factors) than the paired sub-slab soil gas–indoor air data, which in turn exhibit greater attenuation than the paired crawl space-indoor air data.

A.3.2 RECOMMENDED ATTENUATION FACTORS FOR GROUNDWATER

To account for the inherent temporal and spatial variability in indoor air and subsurface vapor concentrations, the 95th percentile value of the "source-screened" groundwater data subset in EPA 2012a is recommended as a reasonably conservative generic attenuation factor, after considering a range of values. **Thus, for groundwater, the recommended generic attenuation factor (α_{gw}) is 0.001.** This value is considered to apply for any soil type in the vadose zone (excepting where preferential vapor pathways are present; see Section 5.4) in cases where the groundwater is greater than five feet below the ground surface. If the depth to groundwater is less than five feet below the building foundation, investigation of the indoor space is recommended, as there is potential for contaminated groundwater to contact the building foundation, either because the capillary fringe intersects the building foundation or groundwater fluctuations results in groundwater wetting the foundation.

Table A-2 (Table 13 in EPA (2012a)) provides statistics and Figure A-2 (Figure 28 in EPA (2012a)) shows box-and-whisker plots for individual sites compared with the statistics for the combined set of screened groundwater attenuation factors. This table and figure show that the 95th percentile value of the combined groundwater-indoor air measurements is considered appropriate for estimating reasonable maximum indoor air concentrations that might be observed at a site due to vapor intrusion. The majority of sites and buildings would be expected to exhibit lower indoor air concentrations.

A factor that commonly results in greater attenuation (lower attenuation factors) is the presence of laterally extensive, unfractured fine-grained sediment in the vadose zone. Table A-3 (Table 14 in EPA (2012a)) provides selected statistics and Figure A-3 (Figure 29 in EPA (2012a)) shows the box-and-whisker plots for the groundwater attenuation factors for three soil types. Comparing each descriptive statistic (except for the 25th percentile values) indicates that the attenuation factor values for residences overlying soils classified as "very coarse" generally are larger than those for residences overlying soils classified as "coarse," which are larger than those for soils classified as "fine." This pattern is consistent with the conceptual model for vapor intrusion; smaller attenuation factors, which indicate greater reduction in vapor concentration, would be expected in vadose zones with finer-grained soils, when all other factors (e.g., depth to groundwater, biodegradability of the volatile chemicals) are the same. The 95th percentile value of the coarse-grained soil is equal to the generic value, as expected, since coarse-grained soil provide low resistance to vapor transport and thus would be expected to yield high-valued attenuation factors. Where fine-grained sediments underlay buildings, however, more attenuation is expected and observed in the database. **Thus, a semi-site-specific attenuation factor of 0.0005 may be used at sites where laterally extensive fine-grained sediment has been demonstrated through site-specific sampling to underlay buildings being investigated for vapor intrusion**.

A.3.3 RECOMMENDED GENERIC ATTENUATION FACTOR FOR SUB-SLAB SOIL GAS

To account for the inherent temporal and spatial variability in indoor air and subsurface vapor concentrations, the 95th percentile value of the "source-screened" sub-slab data subset in EPA (2012a) is recommended as a reasonably conservative generic attenuation factor, after considering a range of values. Thus, **for sub-slab soil gas, the recommended generic attenuation factor (α_{ss}) is 0.03.**

The selection of this value can be supported by theoretical analysis. Specifically, a simple mass balance analysis, assuming a well-mixed interior volume and steady-state conditions, indicates that the theoretical (true) sub-slab soil gas attenuation factor can be expressed as the ratio of the soil gas entry rate to the building ventilation rate (Song et al., 2011; EPA 2012a) for cases where there is no background contribution to the indoor air concentration. Using median values for residential building volume and air exchange rate (395 m^3 and 0.45 ACH, respectively) provided in the *Exposure Factors Handbook 2011 Edition* (EPA, 2011) and a mid-range value of 5 L/min for soil gas entry rate in sandy materials (EPA 2002, Appendix G), the central tendency value of the sub-slab soil gas attenuation factor (according to Equation 4a therein), is expected to be approximately 0.002. Using upper-end (10th percentile) values for residential building volume and air exchange rate (154 m^3 and 0.18 ACH, respectively (EPA 2011)) and soil gas entry rate (10 L/min), an upper-end value of 0.02 for the sub-slab soil gas attenuation factor is obtained. These values agree well with the 95th percentile and 50th percentile (median) values

(0.03 and 0.003, respectively) obtained from the source-screened data. These calculations buttress the conclusion that the sub-slab attenuation factor distributions summarized in EPA's vapor intrusion database report can be considered representative of vapor intrusion of CHCs into residential buildings for most conditions.

Table A-4 (Table 10 in EPA (2012a)) provides statistics and Figure A-4 (Figure 25 in EPA (2012a)) shows box-and-whisker plots for individual sites compared with the statistics for the combined set of screened sub-slab attenuation factors. This table and figure show that the 95th percentile value of the combined sub-slab-indoor air measurements is considered appropriate for estimating reasonable maximum indoor air concentrations that might be observed at a site due to vapor intrusion. The majority of sites and buildings would be expected to exhibit lower indoor air concentrations.

A.3.4 RECOMMENDED ATTENUATION FACTOR FOR "NEAR-SOURCE" EXTERIOR SOIL GAS

Based upon the conceptual model for vapor intrusion, the attenuation factors for exterior soil gas data would be expected to be less than those for sub-slab soil gas, because the former includes an additional contribution from attenuation through the vadose zone, and greater than those for groundwater vapors for a given building at a site where groundwater is the primary subsurface source of vapors. The distributions of exterior soil gas attenuation factors shown in Table A-1 and Figure A-1 do not exhibit this expected relationship. In addition, a comparison of exterior soil gas to sub-slab soil gas concentrations for buildings where both types of samples were collected, shown in Figure A-5 (see Figure 6 in EPA (2012a)), suggests that a substantial proportion of the exterior soil gas data in the database, particularly shallow soil gas data, may not be representative of soil gas concentrations directly underneath a building. On this basis, shallow exterior soil gas sampling data generally are not recommended for purposes of estimating indoor air concentrations and the exterior soil gas attenuation factors in Table A-1 are not recommended for use in deriving generic attenuation factors.

Based upon the data in Figure A-5, "deep" exterior soil gas data appear to more reliably reflect sub-slab concentrations beneath buildings. On this basis, "near-source" soil gas sampling data (i.e., collected in the vadose zone immediately above each vapor source) generally are allowed for purposes of assessing vapor concentrations that may be in contact with the building's sub-slab, as discussed further in Section 6.4.4. However, the same conservative attenuation factor value for sub-slab soil gas is recommended for use with "near-source" exterior soil gas data for this purpose. **Thus, for "near-source" exterior soil gas, the recommended generic attenuation factor is 0.03**.

A.3.5 RECOMMENDED ATTENUATION FACTOR FOR CRAWLSPACE VAPOR

The distribution of attenuation factors presented in Figure A-1 show that attenuation between building crawlspaces and living spaces is limited. To account for the inherent temporal and spatial variability in indoor air and crawlspace vapor concentrations, the 95th percentile value of the "indoor air-screened" crawlspace data subset in EPA (2012a) is recommended as a reasonably conservative generic attenuation factor, after considering a range of values. **Thus, for crawl space vapor the recommended generic attenuation factor is 1.0** (0.9 rounded up to 1.0).

A.3.6 RELIABILITY ANALYSIS OF THE RECOMMENDED SUBSURFACE-TO-INDOOR AIR GENERIC ATTENUATION FACTORS

An analysis was performed to determine the reliability of these recommended attenuation factors for screening in residences in EPA's vapor intrusion data base with measured indoor air concentrations exceeding target levels corresponding to a cancer risk of 10^{-6} and a hazard quotient of 1. The reliability analysis was performed separately for each medium by determining the number of correct assessments and the number of false negatives for a range of attenuation factors. The potential incidence of false negatives is a critical criterion, because the primary objective of risk-based screening is to identify sites or buildings unlikely to pose a health concern through the vapor intrusion pathway (see Section 6.5.1).

For the purposes of this analysis:

- A correct assessment is deemed to occur either: (1) when a chemical's measured indoor air concentration exceeds the target level and the measured subsurface vapor concentration also exceeds the appropriate medium-specific VISL calculated using the specified generic attenuation factor, or (2) when a chemical's measured indoor air concentration is below the target level and the measured subsurface vapor concentration also is below the appropriate medium-specific VISL calculated using the recommended generic attenuation factor. Correct assessments in this analysis represent a correct decision based on subsurface concentration data regarding the potential for vapor intrusion to pose indoor air concentrations that exceed target risk-based concentrations in affected buildings.

- A false negative is deemed to occur when a chemical's measured indoor air concentration exceeds the target level, but the measured subsurface vapor concentration does not exceed the appropriate medium-specific VISL calculated using the specified generic attenuation factor. False negatives in this analysis represent the potential for making an incorrect decision based on subsurface concentration data regarding the potential for vapor intrusion to pose indoor air concentrations that exceed target risk-based concentrations in affected buildings.

This assessment uses the Data Consistency Subset of the EPA's vapor intrusion database for residential buildings (i.e., before screening to minimize the impacts of background contributions to indoor air as described in EPA (2012a)). This subset was chosen to allow for the possibility that background indoor air contributions were incorrectly identified and removed from further analysis in the "source-screened" data subsets presented in EPA (2012a). Thus, false negatives may appear if indoor or ambient (outdoor) sources of VOCs are present and they exceed the

indoor air target level. This choice of datasets provides a conservative estimate of the frequency of false negatives identified by this reliability analysis. Even lower rates of false negatives would be obtained when considering the "source-screened" data subsets, described in EPA (2012a), in which the impacts of background contributions to indoor air are minimized.

The results of this assessment are shown in Figures A-6 through A-8 for sub-slab soil gas, groundwater, and exterior soil gas.[256] The essential results are as follows:

- The recommended generic attenuation factors yield low rates of false negatives (< 2%) for all three media when individual pairs of samples are evaluated together.

- The recommended generic attenuation factors for groundwater, exterior soil gas, and sub-slab soil gas provide generally high rates of correct assessments when individual pairs of samples are evaluated together: 78% for groundwater; 76% for exterior soil gas; and 87% for sub-slab soil gas. Higher rates of correct assessments are expected for sub-slab soil gas than for the other subsurface media, likely due to the closer spatial correspondence of building sub-slab soil gas and indoor air samples.

- The rates of correct assessments appear to level off in Figure A-6 through A-8 at about the point on the x-axis where the recommended generic attenuation factors occur.

- The rates of false positives using the Data Consistency Subset can be inferred from Figure A-6 through A-8. This analysis indicates that use of ground water data or exterior soil gas data is more likely to incorrectly identify a site or building as warranting further investigation than is use of sub-slab soil gas data.

Compared to the values estimated in Figures A-6 through A-8, significantly higher rates of a correct assessment (and, hence, lower rates of false negatives and false positives) are reasonably anticipated to be realized by following this Technical Guide. Specifically, collecting multiple samples to characterize spatial and temporal variability (see, for example, Section 6.4), collecting multiple lines of additional evidence (see, for example, Section 6.3 and 7.1), and weighing this information together (see, for example, Sections 6.3 and 7) are reasonably expected to significantly reduce the "error rates" estimated in this reliability analysis, which are based upon comparison of individual pairs of indoor air and subsurface sample concentrations.

As previously stated, this Technical Guide includes subsurface VISLs that are intended to help identify those sites with the potential to pose a vapor intrusion concern. The reliability analysis described above suggests the recommended attenuation factors, on which the recommended VISLs are based, can reasonably be expected to provide an acceptably small probability of 'screening out' sites that pose a vapor intrusion concern and a high probability of correctly identifying sites or buildings that may pose a vapor intrusion concern.

[256] The reliability assessment was not conducted for crawlspace data, because the distribution of attenuation factors presented in Figure A-1 show that attenuation between building crawlspaces and living spaces is limited.

A.4 CONSIDERATIONS FOR NONRESIDENTIAL BUILDINGS

The recommended attenuation factors (see Sections B.3.2 through B.3.5) are proposed for use for nonresidential buildings as well as residential buildings. The rationale is that, in many geographic locations, some commercial enterprises have been established in converted residential buildings. Although used for commercial purposes, such buildings can reasonably be expected to exhibit similar susceptibility to vapor intrusion and similar interior mixing and dilution (and, hence, similar attenuation factors) as residential buildings represented in EPA's vapor intrusion database. In addition, McDonald and Wertz (2007) found that sub-slab attenuation factors for commercial and institutional buildings in Endicott, New York, which were not "extraordinarily large", were not substantially different than those for residential buildings in the same area.

There are theoretical considerations to support expectations that larger nonresidential buildings that are constructed on thick slabs will have lower attenuation factors than residential buildings. These considerations include:

- Given that the size (e.g., interior height and footprint area) and air exchange rate tend to be larger for many nonresidential buildings (see, for example, Table A-5), it is expected that building ventilation rates for many nonresidential buildings would be higher than those for residential buildings. A higher ventilation rate is expected to result in greater overall vapor dilution as vapors migrate from a subsurface vapor source into a building. On this basis, many nonresidential buildings would be expected to have lower attenuation factors than those for residential buildings, all else being equal.

- Comparing buildings with slab-on-grade construction, nonresidential buildings tend to have thicker slabs than residential buildings. With thicker slabs, a given amount of differential settling would be expected to lead to less cracking in the slab and would be less likely to create cracks that extend across the entire slab thickness. Buildings with thicker slabs would, therefore, be expected to exhibit lower soil gas entry rates, all else being equal.

Where appropriate, EPA may consider appropriate building-specific data, information, and analysis when evaluating vapor intrusion into large nonresidential buildings.

A.5 CITATIONS (APPENDIX A)

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TABLE A-1.
DESCRIPTIVE STATISTICS SUMMARIZING ATTENUATION FACTOR DISTRIBUTIONS FOR GROUNDWATER, EXTERIOR SOIL GAS, SUB-SLAB SOIL GAS, AND CRAWL SPACE VAPOR AFTER APPLICATION OF THE DATABASE SCREENS CONSIDERED MOST EFFECTIVE AT MINIMIZING THE INFLUENCE OF BACKGROUND SOURCES ON INDOOR AIR CONCENTRATIONS.

Statistic	Groundwater (GW > 1,000X Bkgd)	Exterior Soil Gas (SG > 50X Bkgd)	Sub-slab Soil Gas (SS > 50X Bkgd)	Crawl Space (IA > Bkgd)
Min	1.0E-07	5.0E-06	2.5E-05	5.7E-02
5%	3.6E-06	7.6E-05	3.2E-04	1.0E-01
25%	2.3E-05	6.0E-04	1.5E-03	2.2E-01
50%	7.4E-05	3.8E-03	2.7E-03	3.9E-01
75%	2.0E-04	2.7E-02	6.8E-03	6.9E-01
95%	1.2E-03	2.5E-01	2.6E-02	9.0E-01
Max	2.1E-02	1.3E+00	9.4E-01	9.2E-01
Mean	2.8E-04	5.0E-02	9.2E-03	4.6E-01
StdDev	1.0E-03	1.7E-01	5.0E-02	2.8E-01
95UCL	3.4E-04	7.8E-02	1.3E-02	5.3E-01
Count All	774	106	431	41
Count >RL	743	106	411	41
Count <RL	31	0	20	0
No. of sites	24	11	12	4

Note: The applied database screens are groundwater (vapor) concentrations > 1,000X "background," exterior soil gas > 50X "background," sub-slab soil gas > 50X "background," and for crawl space, indoor air concentrations > 1X "background." SOURCE: Table 19 in EPA (2012a).

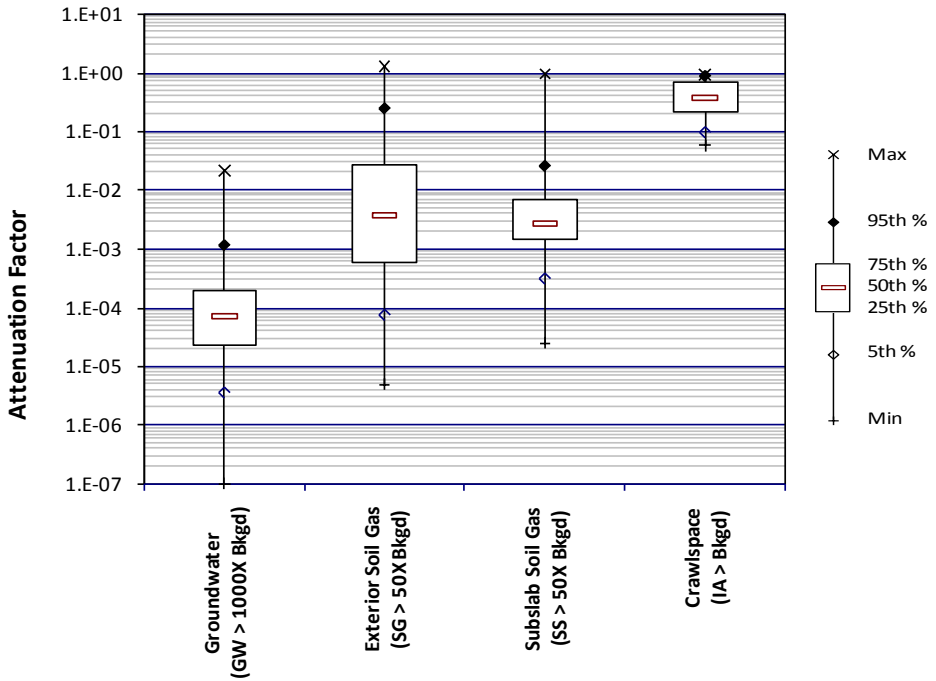

Figure A-1. Box-and-whisker plots summarizing attenuation factor distributions for groundwater, exterior soil gas, sub-slab soil gas, and crawl space vapor after application of the database screens considered most effective at minimizing the influence of background sources on indoor air concentrations. SOURCE: Figure 34 in EPA (2012a).

TABLE A-2.
DESCRIPTIVE STATISTICS SUMMARIZING GROUNDWATER ATTENUATION FACTOR DISTRIBUTIONS FOR INDIVIDUAL SITES COMPARED WITH THE COMBINED DATA SET AFTER SOURCE STRENGTH SCREEN (GROUNDWATER VAPOR CONCENTRATIONS > 1,000 TIMES "BACKGROUND").

Statistic	GW > 1,000 X Bkgd	Allepo	Alliant	BillingsPCE	CDOT	Davis	Eau Claire	Endicott	Grants	Hamilton-Sundstrand	Harcros/Tri State	Hopewell Precision	Jackson	LAFB	Lockwood	MADEP 1	MADEP 2	Moffet	Mountain View	Rapid City	Redfield	SCM - Cortlandville	Uncasville	Wall	West Side Corp.
Min	1.0E-07	9.1E-06	2.5E-06	1.0E-06	1.8E-06	4.7E-05	3.6E-06	1.9E-05	1.0E-07	9.6E-06	1.2E-06	2.5E-05		2.9E-06	8.6E-07	1.6E-04		1.3E-06	4.8E-07	9.9E-06	1.7E-06	5.9E-05	3.3E-05	1.4E-06	2.1E-06
5%	3.6E-06			1.1E-05	3.4E-06			2.8E-05	9.7E-07	1.2E-05		1.7E-04		4.0E-06	2.9E-06						7.6E-06	5.9E-05		1.7E-05	1.3E-05
25%	2.3E-05			2.1E-05	9.9E-06			2.8E-05	2.7E-06	5.8E-05		2.9E-04		1.7E-05	1.9E-05						2.8E-05	5.9E-05	3.5E-04	2.9E-05	1.5E-05
50%	7.4E-05		3.7E-06	3.9E-05	2.2E-05		2.5E-04	1.7E-04	1.2E-05	1.0E-04	2.5E-04	5.6E-04	4.7E-04	3.4E-05	8.8E-05		4.0E-05	4.0E-06	3.3E-06	3.1E-05	7.3E-05	3.1E-04	4.8E-04	8.2E-05	3.7E-05
75%	2.0E-04			8.9E-05	1.5E-04			7.0E-04	8.7E-05	1.5E-04		1.2E-03		1.4E-04	2.7E-04						1.5E-04	1.7E-03	6.5E-04	3.2E-04	2.7E-04
95%	1.2E-03			6.8E-04	5.4E-04			1.4E-03	2.9E-04	2.9E-04		7.7E-03		6.8E-04	1.3E-03						4.8E-04	4.2E-03		1.4E-03	4.3E-03
Max	2.1E-02	1.4E-05	1.1E-03	8.0E-04	5.4E-04	4.3E-04	1.9E-03	1.5E-03	2.9E-04	5.2E-04	3.7E-03	7.7E-03		2.3E-03	2.4E-03	1.0E-03		1.9E-05	3.3E-05	4.0E-05	1.8E-03	6.6E-03	1.8E-03	1.1E-02	2.1E-02
Mean	2.8E-04		1.1E-04	1.2E-04	1.1E-04	2.4E-04	7.7E-04	4.3E-04	7.5E-05	1.2E-04	7.1E-04	1.2E-03		1.6E-04	2.6E-04	6.0E-04		7.9E-06	9.7E-06	2.7E-05	1.3E-04	1.1E-03	6.0E-04	4.9E-04	1.1E-03
StdDev	1.0E-03		3.4E-04	2.1E-04	1.7E-04		8.1E-04	4.8E-04	1.1E-04	9.8E-05	1.3E-03	1.8E-03		3.6E-04	4.5E-04			9.3E-06	1.4E-05	1.6E-05	1.9E-04	1.6E-03	5.1E-04	1.7E-03	4.0E-03
95UCL	3.4E-04		2.8E-04	1.9E-04	1.8E-04		1.4E-03	5.7E-04	1.2E-04	1.5E-04	1.7E-03	2.0E-03		2.2E-04	3.5E-04			2.4E-05	2.3E-05	5.4E-05	1.5E-04	1.6E-03	9.2E-04	9.2E-04	2.3E-03
Count All	774	2	12	25	17	2	6	32	14	32	7	17	1	93	63	2	1	3	5	3	329	28	9	43	28
Count >RL	743	1	5	25	17	2	6	22	14	32	7	17	1	93	63	2	1	3	5	3	329	21	9	43	22
Count <RL	31	1	7	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	6

SOURCE: Table 13 in EPA (2012a).

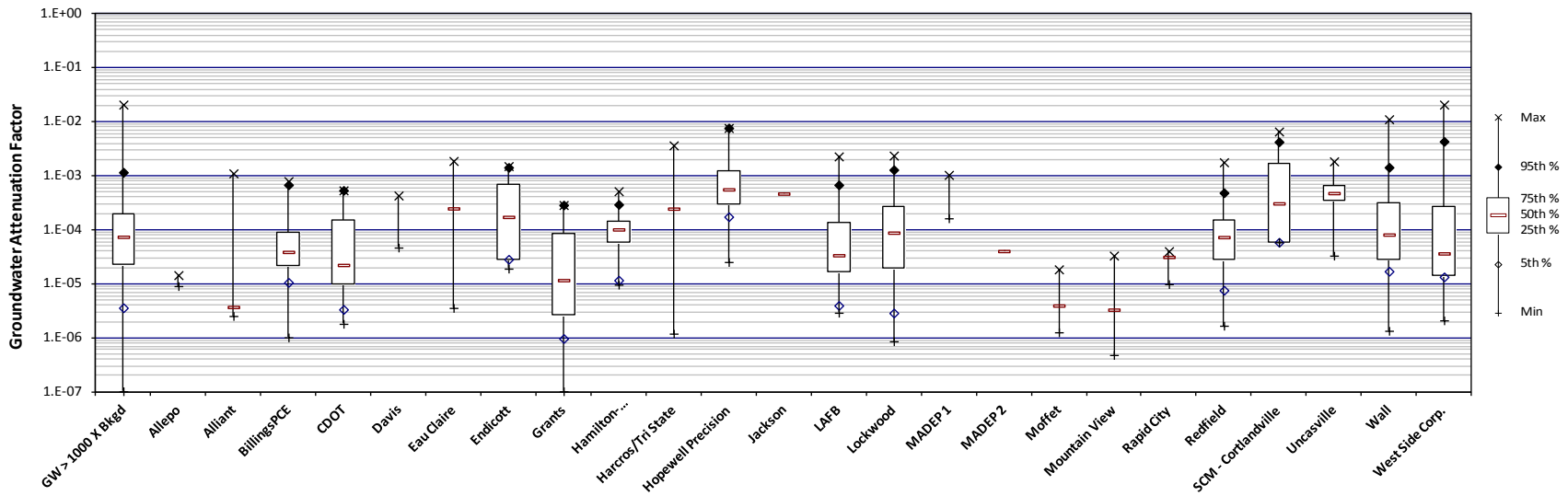

Figure A-2. Box-and-whisker plots summarizing groundwater attenuation factor distributions for individual sites compared with the combined data set after Source Strength Screen (groundwater vapor concentrations > 1,000 times "background"). SOURCE: Figure 28 in EPA (2012a).

TABLE A-3.
DESCRIPTIVE STATISTICS SUMMARIZING GROUNDWATER ATTENUATION FACTOR DISTRIBUTIONS FOR SPECIFIC SOIL TYPES AFTER SOURCE STRENGTH SCREEN.

	Soil Type Below Foundation		
Statistic	**Fine**	**Coarse**	**V.Coarse**
Min	1.0E-07	4.8E-07	2.1E-06
5%	2.3E-06	7.6E-06	1.3E-05
25%	1.9E-05	3.1E-05	2.0E-05
50%	4.6E-05	1.0E-04	1.5E-04
75%	1.4E-04	2.5E-04	6.8E-04
95%	4.5E-04	1.4E-03	4.2E-03
Max	2.4E-03	1.1E-02	2.1E-02
Mean	1.3E-04	3.3E-04	9.7E-04
StdDev	2.4E-04	8.9E-04	3.0E-03
95UCL	1.5E-04	4.1E-04	1.7E-03
Count All	353	369	52
Count >RL	344	359	40
Count <RL	9	10	12
No. of sites	10	15	3

SOURCE: Table 14 in EPA (2012a).

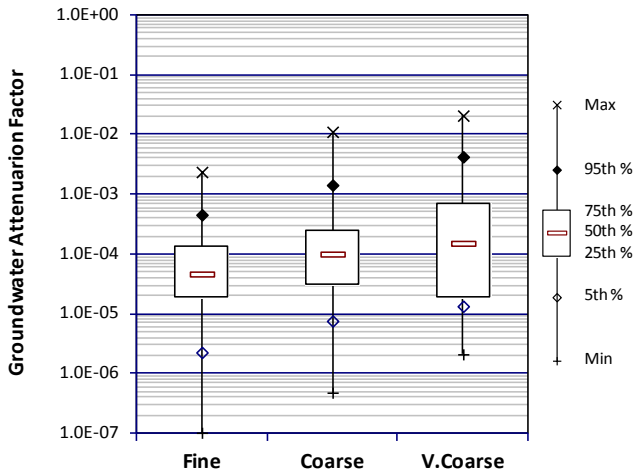

Figure A-3.Box-and-whisker plots summarizing groundwater attenuation factor distributions for specific soil types after Source Strength Screen. SOURCE: Figure 29 in EPA (2012a).

TABLE A-4.
DESCRIPTIVE STATISTICS SUMMARIZING SUB-SLAB ATTENUATION FACTOR DISTRIBUTIONS FOR INDIVIDUAL SITES COMPARED WITH THE COMBINED DATA SET AFTER SOURCE STRENGTH SCREEN (SUB-SLAB SOIL GAS CONCENTRATIONS > 50 TIMES "BACKGROUND").

Statistic	SS > 50X Bkgd	BillingsPCE	DenverPCEBB	Endicott	Georgetown	Harcros/Tri State	Hopewell Precision	Jackson	LAFB	Orion Park	Raymark	SCM-Cortlandville	West Side Corporation
Min	2.5E-05	2.5E-05	1.1E-03	2.6E-04	1.3E-03	3.8E-04	1.5E-03		3.5E-05	5.0E-04	2.5E-04	3.4E-03	2.0E-04
5%	3.2E-04	9.6E-05		6.9E-04			1.9E-03		1.4E-04		1.2E-03	3.6E-03	
25%	1.5E-03	4.6E-04		1.7E-03			5.0E-03		4.1E-04	1.8E-03	2.0E-03	7.1E-03	5.9E-04
50%	2.7E-03	7.0E-04	6.4E-03	2.6E-03	1.9E-03	4.5E-04	1.0E-02	8.4E-03	1.9E-03	2.8E-03	5.5E-03	1.8E-02	1.5E-03
75%	6.8E-03	1.5E-03		5.0E-03			1.8E-02		5.3E-03	8.8E-03	8.3E-03	4.1E-02	9.7E-03
95%	2.6E-02	2.6E-03		1.1E-02			3.4E-02		3.2E-02		2.1E-02	1.5E-01	
Max	9.4E-01	2.7E-03	4.1E-02	9.4E-01	2.9E-03	2.7E-03	3.4E-02		4.2E-02	3.3E-02	7.9E-02	1.5E-01	3.5E-01
Mean	9.2E-03	9.5E-04	1.7E-02	8.5E-03	2.0E-03	1.0E-03	1.3E-02	8.4E-03	5.0E-03	7.6E-03	7.4E-03	4.1E-02	4.3E-02
StdDev	5.0E-02	7.7E-04	1.9E-02	6.5E-02	8.4E-04	1.1E-03	1.0E-02		9.0E-03	1.1E-02	1.0E-02	5.0E-02	1.2E-01
95UCL	1.3E-02	1.2E-03	3.5E-02	1.6E-02	3.5E-03	2.3E-03	1.7E-02		7.1E-03	1.4E-02	9.2E-03	6.8E-02	1.2E-01
No. of AFs	431	27	5	207	3	4	19	1	52	9	83	12	9
No. of AFs > RL	411	27	5	188	3	4	19	1	52	9	83	12	8
No. of AFs < RL	20	0	0	19	0	0	0	0	0	0	0	0	1

SOURCE: Table 10 in EPA (2012a).

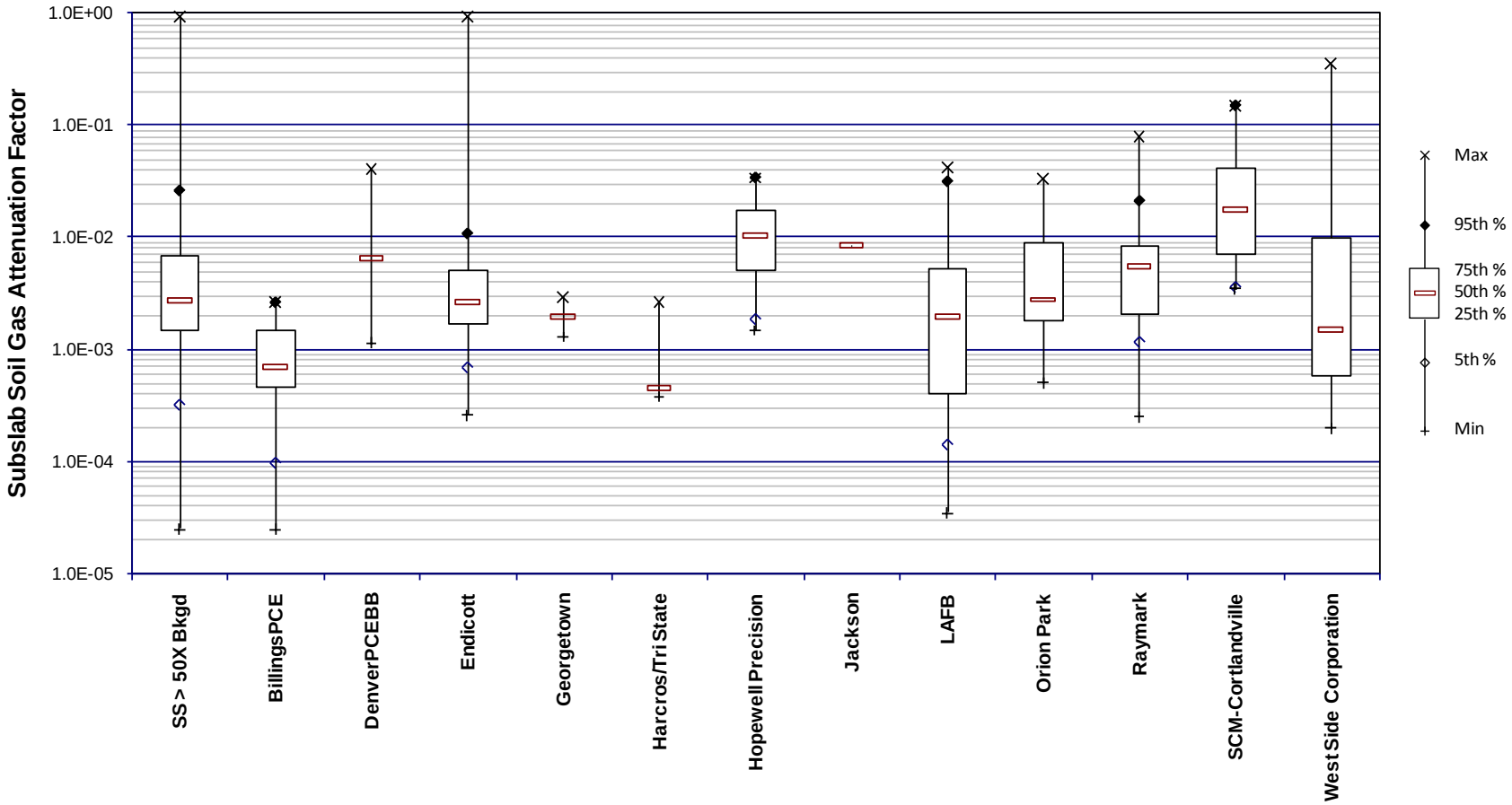

Figure A-4. Box-and-whisker plots summarizing sub-slab soil gas attenuation factor distributions for individual sites after Source Strength Screen (sub-slab soil gas concentrations > 50 times "background"). SOURCE: Figure 25 in EPA (2012a).

TABLE A-5

COMPARISON OF SIZE CHARACTERISTICS FOR RESIDENTIAL AND SOME COMMERCIAL BUILDINGS

Building Parameter and Units	Value and Source for Residential Building	Value and Source for Commercial Buildings, Other Than Warehouses and Enclosed Malls
ACH_{Bldg} (1/hr), 10th percentile	0.18 (EPA 2011, Table 19-1)	0.6 (EPA 2011, Table 19-27)
H_{Bldg} (feet)	8-feet ceiling height (EPA 2011, assumed value)	12-feet ceiling height (EPA 2011, assumed value)

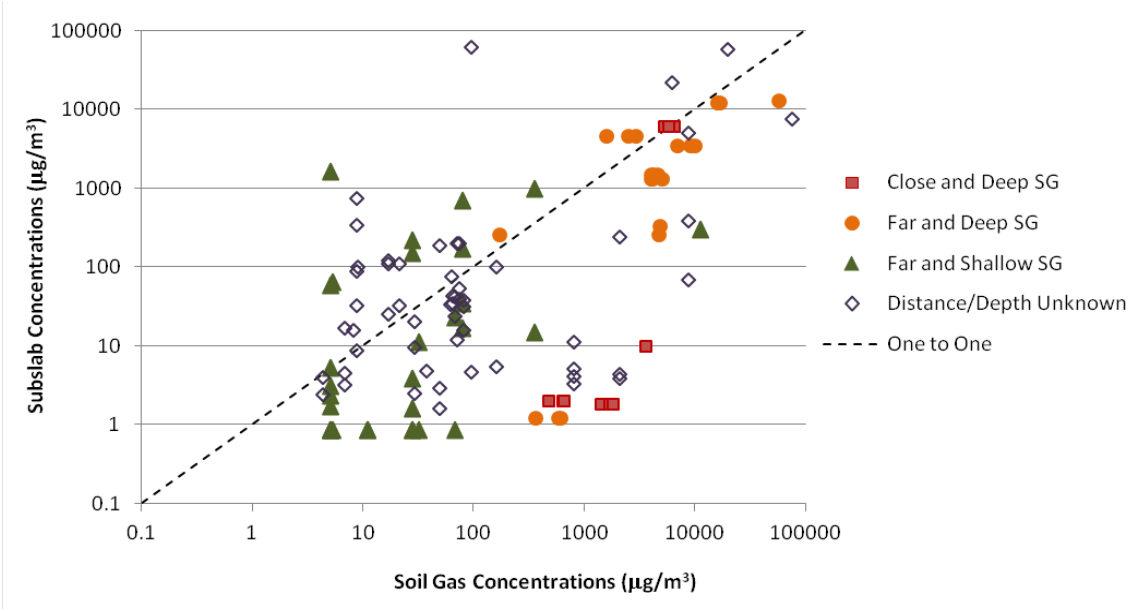

Figure A-5. Exterior soil gas versus sub-slab soil gas concentrations for buildings with both types of data in EPA's vapor intrusion database differentiated qualitatively by horizontal distance to building and depth to the exterior soil gas sample. SOURCE: Figure 6 in EPA (2012a).

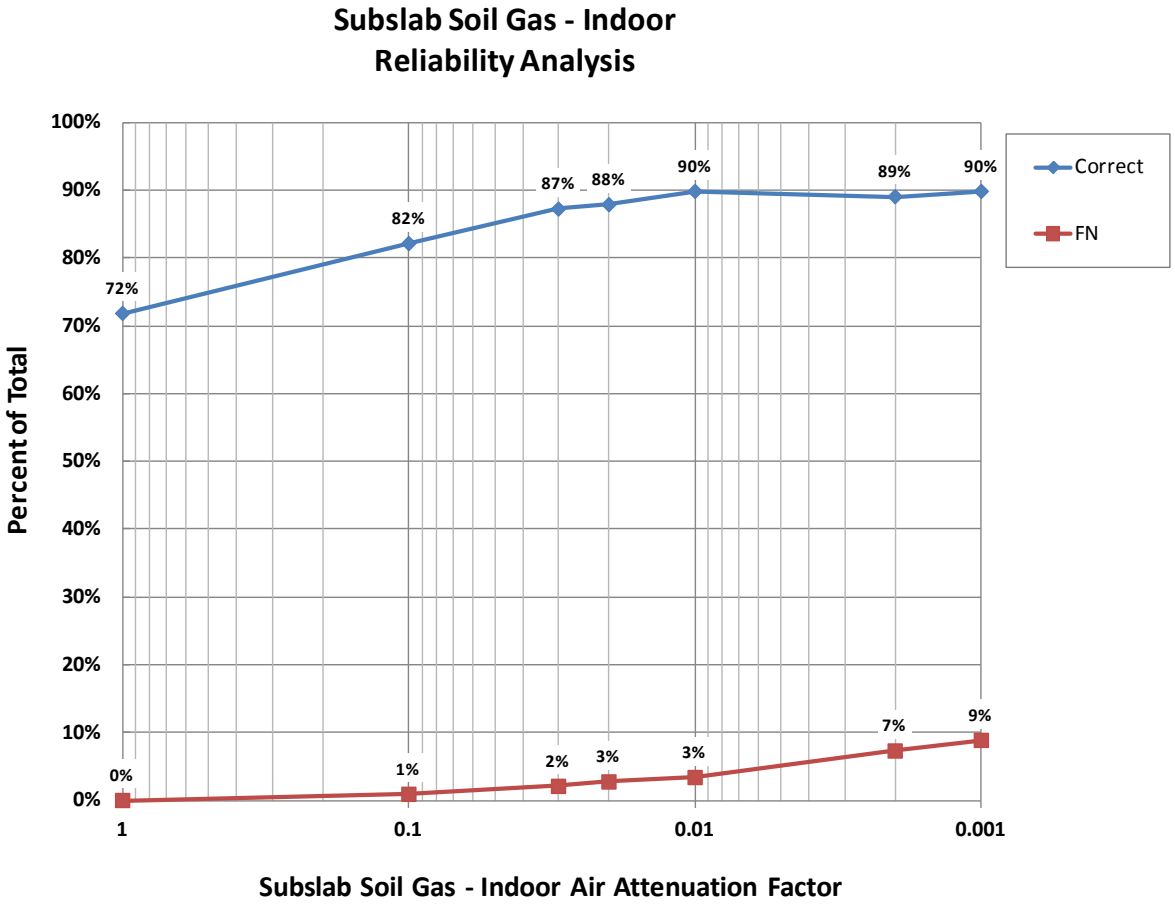

Figure A-6. Reliability Predictions for Alternative Choices of the Sub-slab Attenuation Factor Based on a Comparison of Paired Data in the Data Consistency Screen Dataset
[tabulated values shown below]

Reliability Analysis: Subslab Soil Gas - Indoor Air

Classification	SS AF = 1	SS AF = 0.1	SS AF = 0.03	SS AF = 0.02	SS AF = 0.01	SS AF = 0.002	SS AF = 0.001
Correct	551	630	669	674	689	683	689
FN	0	7	16	21	26	56	68
Total	767	767	767	767	767	767	767
SS AF	1	0.1	0.03	0.02	0.01	0.002	0.001
Correct	72%	82%	87%	88%	90%	89%	90%
FN	0%	1%	2%	3%	3%	7%	9%

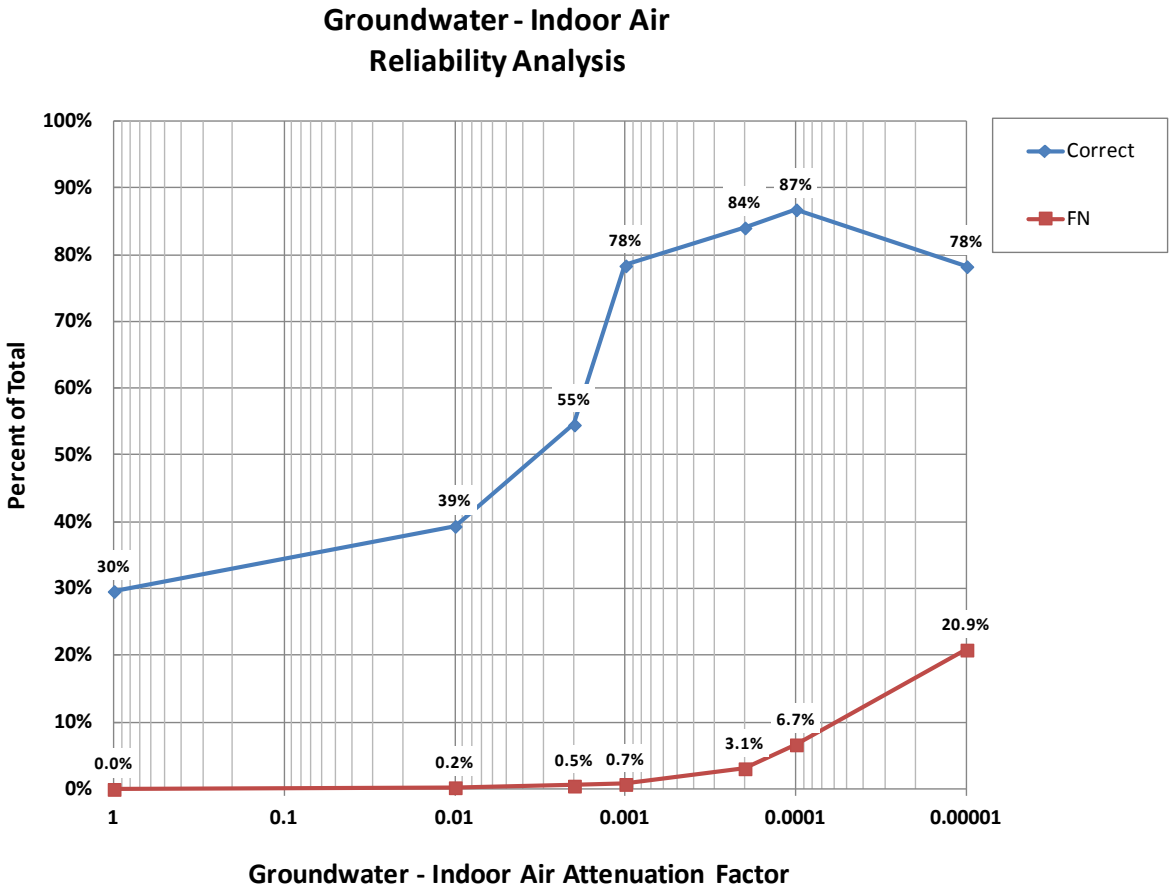

Figure A-7. Reliability Predictions for Alternative Choices of the Groundwater Attenuation Factor Based on a Comparison of Paired Data in the Data Consistency Screen Dataset
[tabulated values shown below]

Reliability Analysis: Groundwater -Indoor Air

Classification	GW AF = 1	GW AF = 0.01	GW AF = 0.002	GW AF = 0.001	GW AF = 0.0002	GW AF = 0.0001	GW AF = 0.00001
Correct	240	319	442	635	681	703	634
FN	0	2	4	6	25	54	169
Total	810	810	810	810	810	810	810
GW AF	1	0.01	0.002	0.001	0.0002	0.0001	0.00001
Correct	30%	39%	55%	78%	84%	87%	78%
FN	0.0%	0.2%	0.5%	0.7%	3.1%	6.7%	20.9%

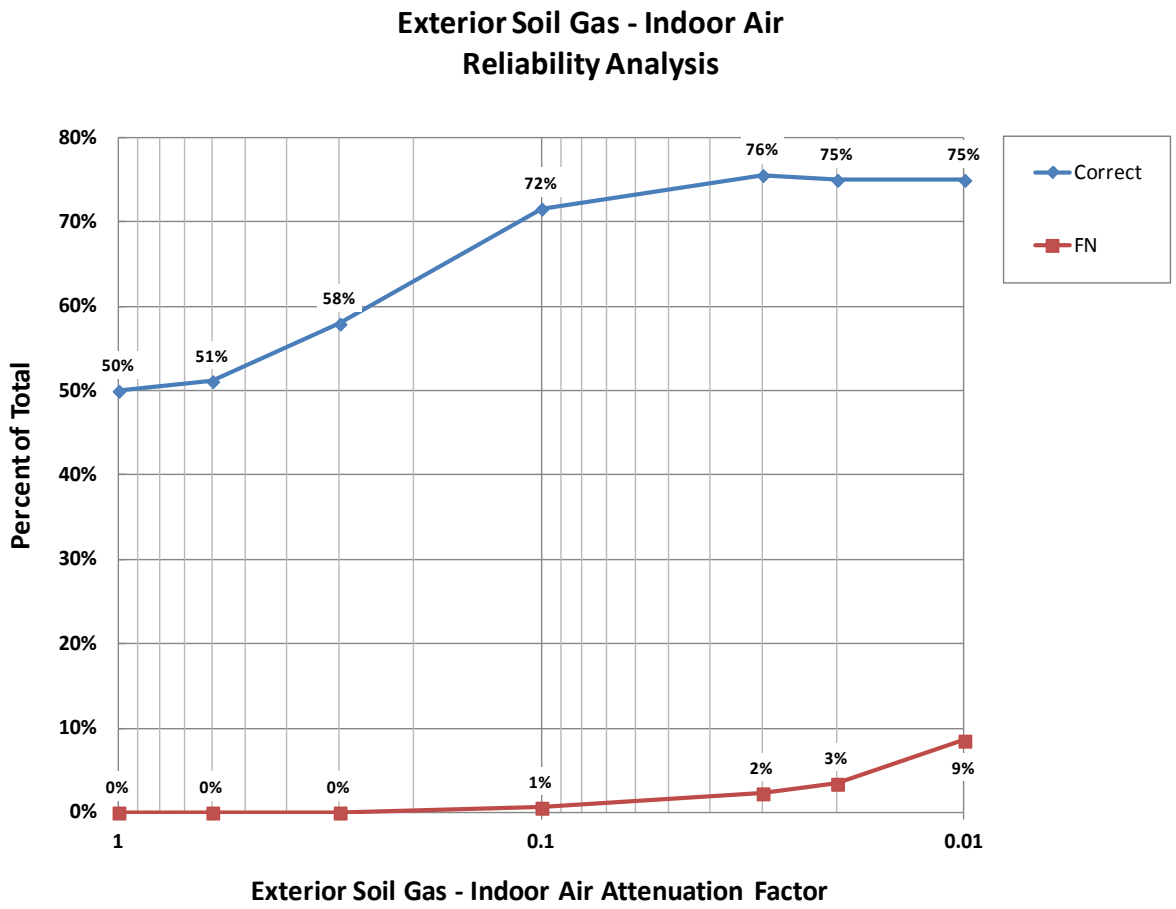

Figure A-8. Reliability Predictions for Alternative Choices of the Exterior Soil Gas Attenuation Factor Based on a Comparison of Paired Data in the Data Consistency Screen Dataset
[tabulated values shown below]

Reliability Analysis: Exterior Soil Gas - Indoor Air							
Classification	SG AF = 1	SG AF = 0.6	SG AF = 0.3	SG AF = 0.1	SG AF = 0.03	SG AF = 0.02	SG AF = 0.01
Correct	88	90	102	126	133	132	132
FN	0	0	0	1	4	6	15
Total	176	176	176	176	176	176	176
SG AF	1	0.6	0.3	0.1	0.03	0.02	0.01
Correct	50%	51%	58%	72%	76%	75%	75%
FN	0%	0%	0%	1%	2%	3%	9%

APPENDIX B
DATA QUALITY ASSURANCE CONSIDERATIONS

B.1 INTRODUCTION

Site-specific investigations of the vapor intrusion pathway will generally entail the collection and evaluation of environmental data and possibly the use of modeling. As noted in Exhibit B-1, EPA generally recommends the use of a quality assurance project plan (QAPP) for the collection of primary (and existing or secondary) data. A QAPP is a tool for project managers and planners to document the type and quality of data needed to make environmental decisions and to describe the methods for collecting and assessing the quality and integrity of those data. A QAPP is a plan or roadmap intended to help a project team document how they plan, implement, and evaluate a project. It applies the systematic planning process and the graded approach for collecting environmental data for a specific intended use. EPA standards governing the collection of data are outlined in Exhibit B-1.

Exhibit B-1. EPA Data Standards

CIO 2105 (formerly EPA Order 5360; *Policy and Program Requirements for the Agency-wide Quality System*, May 2000) is intended to promote the organization collecting or using the data to (1) establish a Quality System and prepare and approve a QAPP for each project.

For clarity, CIO 2105 will be replaced by the following two standards:

- CIO 2106-S-01 is the *Quality Standard for Environmental Data Collection, Production, and Use by EPA Organizations*, also called "Internal Standard" (EPA 2013a); and
- CIO 2106-S-02 is the *Quality Standard for Environmental Data Collection, Production, and Use by Non-EPA (External) Organizations*, also called "External Standard" (EPA 2013b).

These standards conform to *EPA Quality Policy*, CIO 2106.0, "Quality Policy" (EPA 2008a), *Procedure for Quality Policy,* CIO 2106-P-01.0, "Quality Procedure" (EPA 2008b), and the American National Standards Institute (ANSI) consensus standard, *Quality Systems for Environmental Data and Technology Programs – Requirements with Guidance for Use* (ANSI/ASQ 2004).

Two guidance documents accompany these standards:

- *EPA Guidance on Quality Management Plans* (EPA 2012b, CIO 2106-G02-QMP), documents the quality system of the organization conducting environmental data collection or using the data for EPA.
- *EPA Guidance on Quality Assurance Project Plans* (EPA 2012a, CIO 2106-G-05) focuses on projects requiring the collection of new data, projects using existing data, and projects involving modeling.

EPA also encourages the use of the *Uniform Federal Policy for Quality Assurance Project Plans (UFP-QAPP)* (EPA/DoD 2005) as a collaborative approach to fulfill the purposes of a QAPP, especially for Federal Facilities. OSWER Directive 9272.0-17, *Implementation of the Uniform Federal Policy for Quality Assurance Project Plans (UFP-QAPP) at Federal Facility Hazardous Waste Sites* (EPA 2005a) and OSWER Directive 9272.0-20 (EPA 2005b) state that QAPPs prepared and approved under the UFP conform to EPA's quality standards and are consistent with EPA Standards CIO 2106-S-0 and CIO 2106-S-02, EPA's Quality Policy (EPA 2008a), and ANSI/ASQ 2004.

B.2 RECOMMENDATIONS

This appendix provides two recommendations concerning the key components of QAPP development. These recommendations are not exhaustive, but are included as a starting point as considerations before studying or applying EPA or UFP QAPP guidance.

Recommendation 1: Using the conceptual site model (CSM), develop the project plan and QAPP through a process that involves all key players and share these materials with interested parties in draft form so that potential study weaknesses can be addressed early. The CSM is developed to portray the current understanding of site conditions, the nature and extent of contamination, routes of contaminant transport, potential contaminant pathways, and potentially exposed human population. Developing the CSM is the first step in EPA's DQO process.

Recommendation 2: Use systematic planning in developing project documents, including the QAPP. Systematic planning is a science-based, common-sense approach designed to ensure that the level of documentation and rigor of effort in planning is commensurate with the intended use of the information and available resources. DQOs are a key component of systematic planning and play a central role in the systematic planning process. DQOs generally are addressed within the QAPP and typically are a critical element in the planning for environmental investigations. *Guidance on Systematic Planning Using the Data Quality Objectives Process (QA/G-4)* (EPA 2006) provides guidance addressing implementation of DQOs and application of systematic planning to generate performance and acceptance criteria for collecting environmental data.

Table B-1 summarizes the steps in the DQO process, the purpose of each step, and provides some examples of how plans could be structured.

TABLE B-1. EXAMPLE OF STEPS IN THE DQO PROCESS

DQO Step	Purpose of the DQO Step	Example Application for Vapor Intrusion
1. State the Problem	Summarize the problem (e.g., the monitoring hypothesis, the investigation objective(s)) for which new environmental data will be collected or modeling or analysis will be performed.	Indoor air in one or more buildings overlying a shallow plume of PCE-contaminated groundwater is (are) to be sampled to determine whether PCE is present. The original PCE release occurred at an industrial site approximately 1,000 feet away from the closest building.
2. Identify the Decision	Identify the decision that will be supported by the new data, modeling or analysis.	The data will be used to support decisions about whether additional indoor air sampling or preemptive vapor intrusion mitigation will be pursued in one or more buildings.
3. Identify the Inputs to the Decision	Identify the information needed to support the decision, including data gaps that warrant collection of new information.	Indoor air sampling data for one or more buildings, in conjunction with information about measured or interpolated concentrations in groundwater near or underneath the building(s).
4. Define the Boundaries of the Study	Specify the spatial and temporal aspects of the environmental media or endpoints that the data are to represent to support the decision.	The boundaries of this initial study area extend a prescribed distance outside the lateral extent of the plume. Eventually, the boundaries of a vapor intrusion impact zone will be defined by the extent to which indoor air contamination can be associated with site-related contamination.
5. Develop a Decision Rule	Develop a logical "if…then" statement that defines the conditions that will inform the decision-maker to choose among alternative decisions.	Buildings with detectable concentrations of PCE in indoor air samples will be considered for additional indoor air sampling or preemptive vapor intrusion mitigation.
6. Specify Tolerable Limits on Decision Errors	Specify acceptable limits on decision errors, which are used to establish performance goals for limiting uncertainty in the analysis.	EPA recommends analytical limits of detection be less than risk-based screening levels for PCE to ensure that a building's indoor air concentration is not misidentified.
7. Optimize the Design for Obtaining Data	Identify the most resource-effective sampling and analysis design for generating the information needed to satisfy the DQOs.	Time-integrated samples will be collected in basements and in the first above-ground level of each building. The sampling and analysis plan and approach will be documented in a QAPP.

B.3 CITATIONS AND REFERENCES (APPENDIX B)

ANSI/ASQ. 2004. *Quality Systems for Environmental Data and Technology Programs – Requirements with Guidance for Use.* E4-2004. Currently available for purchase online at http://webstore.ansi.org/FindStandards.aspx?SearchString=ansi+e4&SearchOption=0&PageNum=0&SearchTermsArray=null|ansi+e4|null

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U.S. Environmental Protection Agency (EPA). 2012a. *U.S. Environmental Protection Agency Guidance on Quality Assurance Project Plans.* CIO 2106-G-05 QAPP. January 17.

U.S. Environmental Protection Agency (EPA), 2012b. *EPA Draft Final Guidance on Quality Management Plans.* CIO 2106-G02-QMP. January 17. Currently available online at http://www.epa.gov/oeitribalcoordination/2106-G-05%20QAPP%20Final%20Draft%2001-17-12.pdf

U.S. Environmental Protection Agency (EPA). 2013a. *Quality Standard for Environmental Data Collection, Production, and Use by EPA Organizations.* CIO 2106-S-01.

U.S. Environmental Protection Agency (EPA). 2013b. *Draft Final Quality Standard for Environmental Data Collection, Production, and Use by Non-EPA (External) Organizations.* "External Standard." CIO 2106-S-02. February 22. Currently available online at http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OEI-2012-0774-0002

U.S. Environmental Protection Agency and U.S. Department of Defense (EPA/DoD). 2005. *Uniform Federal Policy for Quality Assurance Project Plans (UFP-QAPP). Part 1: UFP-QAPP Manual.* EPA-505-B-04-900A, DTIC ADA 427785. March. Currently available online at http://www2.epa.gov/fedfac/uniform-federal-policy-quality-assurance-project-plans-evaluating-assessing-and-documenting

APPENDIX C
CALCULATING VAPOR SOURCE CONCENTRATION FROM GROUNDWATER SAMPLING DATA

Correcting the Henry's Law Constant for Groundwater Temperature

In the case of groundwater as the vapor source, the subsurface source concentration (C_{sv}) is estimated assuming that the vapor and aqueous phases are in local equilibrium according to Henry's law such that:

$$C_{sv} = H'_{TS} \times C_w \qquad \text{Equation C.1}$$

where:

C_{sv} = vapor concentration at the source of contamination (g/cm^3-v),

H'_{TS} = Henry's law constant at the system (groundwater) temperature (dimensionless), and

C_w = concentration of volatile chemical in groundwater (g/cm^3-w).

The Henry's law constants generally are reported for a temperature of 25 degrees Celsius (^{o}C). **Table C-1** provides these values for the chlorinated hydrocarbons (CHCs) in the vapor intrusion database. Average groundwater temperatures, however, are typically less than 25^{o}C. In such cases, use of the Henry's law constant at 25^{o}C may over-predict the volatility of the contaminant in water.

As described in EPA's *Soil Screening Guidance* (EPA 1996), the dimensionless form of the Henry's law constant at the average groundwater temperature (H'_{gw}) may be estimated using the Clapeyron equation:

$$H'_{gw} = \frac{\exp\left[-\frac{\Delta H_{v,gw}}{R_c} \times \left(\frac{1}{T_{gw}} - \frac{1}{T_R}\right)\right] H_R}{R \times T_{gw}} \qquad \text{Equation C.2}$$

where:

$\Delta H_{v,gw}$ = enthalpy of vaporization of the specific chemical at the groundwater temperature (cal/mol),

T_{gw} = groundwater temperature (^{o}K = ^{o}C + 273.15),

T_R = reference temperature for the Henry's law constant (298.15^{o}K),

R_C = gas constant (= 1.9872 cal/mol-^{o}K),

H_R = Henry's law constant for the specific substance at the reference temperature (atm-m^3/mol), and

R = gas constant (= 8.205 E-05 atm-m^3/mol-^{o}K).

The enthalpy of vaporization at the groundwater temperature can be approximated from the enthalpy of vaporization at the normal boiling point, as follows:

$$\Delta H_{v,gw} = \Delta H_{v,b}\left[\frac{\left(1-T_{gw}/T_C\right)}{\left(1-T_B/T_C\right)}\right]^{\eta} \qquad \text{Equation C.3}$$

where:

$\Delta H_{v,gw}$ = enthalpy of vaporization at the groundwater temperature (cal/mol),

$\Delta H_{v,b}$ = enthalpy of vaporization at the normal boiling point (cal/mol),

T_C = critical temperature for specific chemical (^oK),

T_B = normal boiling point for specific chemical (^oK),

η = exponent (unitless), and

all other symbols are as defined previously. **Table C-1** provides the chemical-specific property values used for temperature corrections to the Henry's law constant. **Table C-2** provides the value of η as a function of the ratio T_B/T_C. If site-specific data are not readily available for the groundwater temperature, then Figure 1 of the EPA fact sheet, *Correcting the Henry's Law Constant for Soil Temperature* (EPA 2001) can be used to generate an estimate.

Citations (Appendix C)

U.S. Environmental Protection Agency (EPA). 1996. *Soil Screening Guidance: Technical Background Document*. Office of Solid Waste and Emergency Response, Washington, D.C. EPA-540-R-95-128. Currently available online at: http://www.epa.gov/superfund/health/conmedia/soil/introtbd.htm

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U.S. Environmental Protection Agency (EPA). Regions 3, 6, and 9. 2011. *Regional Screening Levels for Chemical Contaminants at Superfund Sites*. Region 3, Philadelphia, PA. November. Currently available online at http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/index.htm

Lide, D.R. (Ed.). 1998. *CRC Handbook of Chemistry and Physics, 79th Ed*. Boca Raton, FL. CRC Press.

Mallard, W.G. and P.J. Linstrom (Eds.). 1998. *NIST Chemistry WebBook: NIST Standard Reference Database Number 69.* Gaithersburg, MD. National Institute of Standards and Technology. November. Currently available online at http://webbook.nist.gov/chemistry/

Table C-1. Chemical-Specific Parameters for Adjusting Henry's Law Coefficients for Groundwater Temperature

Chemical Abstracts Service Registry Number (CASRN)	Alphabetized List of Compounds	Henry's Law Constant @25°C		Henry's Law Constant @25°C[g]	Normal Boiling Point		Critical Temperature		Enthalpy of vaporization at the normal boiling point	
		H_R		H'_R	T_b		T_c		$\Delta H_{v,b}$	
		(atm-m^3/mol)	source	(unitless)	(^oK)	source	(^oK)	source	(cal/mol)	source
56-23-5	Carbon tetrachloride	2.76E-02	a	1.13E+00	3.50E+02	b	5.57E+02	h	7.13E+03	h
75-00-3	Chloroethane (ethyl chloride)	1.11E-02	a	4.54E-01	2.85E+02	b	4.60E+02	f	5.88E+03	f
67-66-3	Chloroform	3.67E-03	a	1.50E-01	3.34E+02	b	5.36E+02	h	6.99E+03	h
75-34-3	Dichloroethane,1,1-	5.62E-03	a	2.30E-01	3.30E+02	b	5.23E+02	h	6.90E+03	h
75-35-4	Dichloroethene, 1,1-	2.61E-02	a	1.07E+00	3.05E+02	b	5.76E+02	h	6.25E+03	h
156-59-2	Dichloroethene,cis-1,2-	4.08E-03	a	1.67E-01	3.28E+02	b	5.44E+02	h	7.19E+03	h
156-60-5	Dichloroethene,trans-1,2-	4.08E-03	a	1.67E-01	3.28E+02	b	5.17E+02	h	6.72E+03	h
75-09-2	Methylene chloride	3.25E-03	a	1.33E-01	3.13E+02	b	5.10E+02	h	6.71E+03	h
127-18-4	Tetrachloroethylene	1.77E-02	a	7.23E-01	3.94E+02	b	6.20E+02	h	8.29E+03	h
76-13-1	Trichloro-1,2,2-trifluoroethane,1,1,2-	5.26E-01	a	2.15E+01	3.21E+02	b	4.87E+02	f	6.46E+03	f
71-55-6	Trichloroethane, 1,1,1-	1.72E-02	a	7.03E-01	3.47E+02	b	5.45E+02	h	7.14E+03	h
79-01-6	Trichloroethylene	9.85E-03	a	4.03E-01	3.60E+02	b	5.44E+02	h	7.51E+03	h
75-01-4	Vinyl chloride (chloroethylene)	2.78E-02	a	1.14E+00	2.60E+02	b	4.32E+02	h	5.25E+03	h

Sources and Footnotes:

a Based on values reported in the U.S. EPA Regional Screening Tables. November 2011. Available online at: http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/Generic_Tables/xls/params_sl_table_run_NOV2011.xls

b Experimental values. EPA 2009. *Estimation Programs Interface Suite™ for Microsoft® Windows, v 4.00*. U.S EPA, Washington, DC, USA. Available online at: http://www.epa.gov/opptintr/exposure/pubs/episuite.htm

f *CRC Handbook of Chemistry and Physics, 76th Edition*

h EPA (2001). FACT SHEET *Correcting the Henry's Law Constant for Soil Temperature*. Attachment.

g National Institute of Standards and Technology (NIST). *Chemistry WebBook*. Available online at http://webbook.nist.gov/chemistry/

Table C-2. Values of Exponent η as a Function of T_B/T_C

Chemical-specific ratio T_B/T_C	H
< 0.57	0.30
0.57 - 0.71	0.74 (T_B/T_C) - 0.116
> 0.71	0.41

Document 17

U.S. EPA, Office of Solid Waste and Emergency Response, OSWER Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor in Indoor Air, June 2015.

United States
Environmental Protection
Agency

Office of Solid Waste
and Emergency Response
Washington, DC 20460

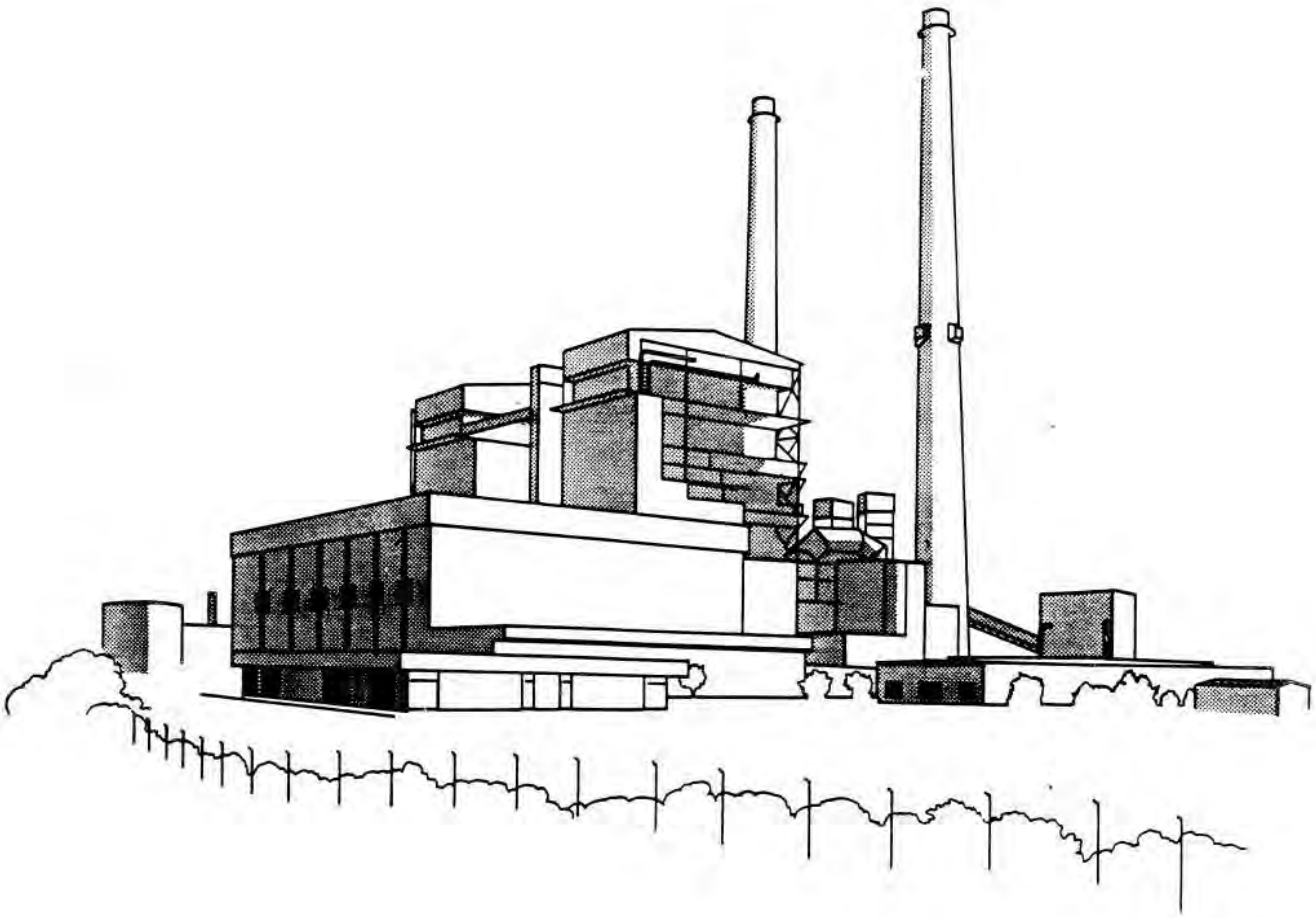
EPA/530-SW-88-002
February 1988

Solid Waste

EPA

Report to Congress

Wastes from the Combustion of Coal by Electric Utility Power Plants



UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C 20460

MAR 8 1988

THE ADMINISTRATOR

Honorable George Bush
President of the Senate
Washington, D.C. 20510

Dear Mr. President:

I am pleased to transmit the Report to Congress on Wastes from the Combustion of Coal by Electric Utility Power Plants. The report presents the results of studies carried out pursuant to Section 8002(n) of the Resource Conservation and Recovery Act of 1976 as amended (42 U.S.C. Section 6982(n)).

The report provides a comprehensive assessment of the management of solid wastes generated by the combustion of coal from electric utility power plants. These wastes account for approximately 90 percent of all wastes generated from the combustion of fossil fuels. The principal waste categories covered include fly ash, bottom ash, boiler slag and flue gas emission control waste.

The report and appendices are transmitted in two separate volumes.

Sincerely,

Lee M. Thomas

Enclosure

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

MAR 8 1988

THE ADMINISTRATOR

Honorable James C. Wright
Speaker of the House
of Representatives
Washington, D.C. 20515

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Lee M. Thomas

Enclosure

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EXECUTIVE SUMMARY

The Environmental Protection Agency (EPA) has prepared this report on fossil fuel combustion wastes pursuant to the requirements of Section 8002(n) of the Resource Conservation and Recovery Act (RCRA), as amended in 1980. These amendments to the Act added Section 8002(n), which directed the Administrator of EPA to

> conduct a detailed and comprehensive study and submit a report on the adverse effects on human health and the environment, if any, of the disposal and utilization of fly ash waste, bottom ash waste, slag waste, flue gas emission control waste, and other by-product materials generated primarily from the combustion of coal or other fossil fuels.

Pending the completion of this study, fossil fuel combustion wastes were exempted from the hazardous waste requirements established under RCRA. Under Section 3001(b)(3)(A), EPA is prohibited from regulating these wastes until at least six months after this report is submitted to Congress.

If EPA determines that fossil fuel combustion wastes are hazardous under RCRA, and therefore subject to regulation under Subtitle C, EPA has some flexibility to promulgate regulations that take into account the unique characteristics of these wastes. Section 3004(x) states ...

> If ... fly ash waste, bottom ash waste, slag waste and flue gas emission control waste generated primarily from the combustion of coal or other fossil fuels ... is subject to regulation under this subtitle, the Administrator is authorized to modify the requirements of subsections (c), (d), (e), (f), (g), (o) and (u) and section 3005(j) ... to take into account the special characteristics of such wastes, the practical difficulties associated with implementation of such requirements, and site-specific characteristics ... so long as such modified requirements assure protection of human health and the environment.

This report examines only those wastes generated from the combustion of coal by the electric utility industry. These wastes account for approximately 90 percent of all wastes generated from the combustion of fossil fuels. EPA has deferred study of the disposal of wastes generated by the combustion of other fossil fuels and from coal combustion in industries other than the electric utility industry until a later date.

Coal-fired power plants produce substantial quantities of wastes. In 1984 about 69 million tons of ash and 16 million tons of flue gas desulfurization wastes were generated. Because of increasing reliance on coal for producing electricity, by the year 2000 the amount of ash waste is expected to increase by about 75 percent to about 120 million tons annually; production of FGD wastes is expected to triple to about 50 million tons annually.[1] In addition to the high-volume ash and flue gas desulfurization wastes, coal-fired power plants also generate several lower-volume waste streams as a result of equipment maintenance and cleaning activities.

About one-fifth of all waste generated at coal-fired electric utility power plants is currently reused; the remaining four-fifths are typically disposed in surface impoundments or landfills. The recycled wastes, usually fly ash, bottom ash, or boiler slag, have been used primarily as cement additives, high-volume road construction material, and blasting grit. There is some potential for increased use of these wastes in such applications. However, barring the

---

[1] It is possible that advances in coal combustion technology will alter the amount and types of coal-combustion wastes produced in the future. An analysis of these technological advances is beyond the scope of this report.

development of new utilization techniques, or major changes in combustion and environmental control technologies, the proportion of coal combustion wastes that are reused is unlikely to change significantly.

While utility waste management sites are currently exempt from RCRA hazardous waste requirements, they are subject to state and local level solid waste laws and regulations. There is substantial variation in the state-mandated disposal requirements.

Most utility waste management facilities were not designed to provide a high level of protection against leaching. Only about 25 percent of all facilities have liners to reduce off-site migration of leachate, although 40 percent of the generating units built since 1975 have liners. Additionally, only about 15 percent have leachate collection systems; about one-third of all facilities have ground-water monitoring systems to detect potential leachate problems. Both leachate collection and ground-water monitoring systems are more common at newer facilities.

The primary concern regarding the disposal of wastes from coal-fired power plants is the potential for waste leachate to cause ground-water contamination. Although most of the materials found in these wastes do not cause much concern (for example, over 95 percent of ash is composed of oxides of silicon, aluminum, iron, and calcium), small quantities of other constituents that could potentially damage human health and the environment may also be present. These constituents include arsenic, barium, cadmium, chromium, lead, mercury, and selenium. At certain concentrations, these elements have toxic effects.

To assess the potential threat to health and the environment posed by these wastes and to document any specific damage cases, EPA, other agencies, and various private organizations sponsored several studies. The main research efforts cited in this Report to Congress are a 1985 study by Arthur D. Little, Inc. for EPA, which characterized the environmental effects of waste disposal at several utility disposal sites, and a series of reports submitted to the Agency in 1982 by the Utility Solid Waste Activities Group, the Edison Electric Institute, and the National Rural Electric Cooperative Association.

The findings of these various research efforts indicate that most coal combustion wastes do not exhibit any of the four hazardous characteristics defined in RCRA Subpart C. The results of a substantial number of extraction procedure tests were examined; these tests indicated that metals do not generally leach out of coal combustion wastes at levels classified as hazardous under RCRA. The only metals which were found in any ash or sludge samples at "hazardous" levels were cadmium and arsenic. For boiler cleaning wastes, chromium and lead were sometimes found at levels classified as hazardous under RCRA. This waste stream was also found to be corrosive in a number of samples. Results of EP Tests performed on co-disposed high and low volume wastes indicate, however, that boiler cleaning wastes do not exhibit hazardous characteristics when co-disposed with ash.

While most of the laboratory results indicated that coal combustion wastes do not possess RCRA hazardous characteristics, in some instances, data on actual field observations indicate that migration of potentially hazardous constituents from utility waste disposal sites has occurred. For example, observed

concentrations of contaminants found in ground water downgradient from the sites exceed the Primary Drinking Water Standards about 5 percent of the time. Although the magnitude of the PDWS exceedances are typically not many times greater than the standard, a large number of disposal facilities report at least one PDWS exceedance at some time.

While a causal connection cannot always be made between the utility waste disposal site and the presence of contaminants at concentrations in excess of these standards, the available information indicates that some ground-water contamination from utility disposal sites is indeed occurring. The actual potential for exposure of human and ecological populations is likely to be limited, however, since ground water in the vicinity of utility waste disposal sites is not typically used for drinking water; the concentrations of contaminants in the ground water also tend to be diluted in nearby surface water bodies. These surface water bodies are typically used by electric utilities in the power plants for cooling and other purposes.

The electric utility industry currently spends about $800 million annually to dispose of its coal-fired combustion wastes. Under current practices, costs for waste management at most basic facilities range from as little as $2 per ton to as much as $31 per ton. Mitigative measures to control potential leaching include installation of liners, leachate collection systems, and ground-water monitoring systems and corrective action to clean up ground-water contamination. These mitigative measures, which are currently used at some utility waste disposal sites, may reduce the likelihood of ground-water contamination, but may also substantially increase disposal costs. For example,

the incremental cost of new waste disposal practices, excluding corrective action costs or higher recycling costs, could range up to $70 per ton, or $3.7 billion annually if all wastes were listed as hazardous. While substantial on a total cost basis, these increases would be unlikely to significantly affect the rate at which existing power plants consume coal. Due to the competitiveness of alternative fuels for electricity generation at future power plants, however, any increase in disposal costs could potentially slow the growth in electric utility coal consumption in future years. Moreover, if new disposal standards require corrective action measures as set forth in 40 CFR 264.100, the costs to utilities could be extremely high and could have a substantial effect on the utility industry.

Based on the findings from this Report to Congress, the Agency presents three preliminary recommendations for those wastes included in the scope of this study. The recommendations are subject to change based on continuing consultations with other government agencies and new information submitted through the public hearings and comments on this report. Pursuant to the process outlined in RCRA 3001(b)(3)(C), EPA will announce its regulatory determination within six months after submitting this report to Congress.

First, EPA has concluded that coal combustion waste streams generally do not exhibit hazardous characteristics under current RCRA regulations. EPA does not intend to regulate under Subtitle C fly ash, bottom ash, boiler slag, and flue gas desulfurization wastes. EPA's tentative conclusion is that current waste management practices appear to be adequate for protecting human health and the environment. The Agency prefers that these wastes remain under Subtitle D

authority. EPA will use section 7003 of RCRA and sections 104 and 106 of CERCLA to seek relief in any cases where wastes from coal combustion waste disposal sites pose substantial threats or imminent hazards to human health and the environment. Coal combustion waste problems can also be addressed under RCRA Section 7002, which authorizes citizen lawsuits for violations of Subtitle D requirements in 40 CFR Part 257.

Second, EPA is concerned that several other wastes from coal-fired utilities may exhibit the hazardous characteristics of corrosivity or EP toxicity and merit regulation under Subtitle C. EPA intends to consider whether these waste streams should be regulated under Subtitle C of RCRA based on further study and information obtained during the public comment period. The waste streams of most concern appear to be those produced during equipment maintenance and water purification, such as metal and boiler cleaning wastes. The information available to the Agency at this time does not allow EPA to determine the exact quantity of coal combustion wastes that may exhibit RCRA Subtitle C characteristics. However, sufficient information does exist to indicate that some equipment maintenance and water purification wastes do occasionally exhibit RCRA hazardous characteristics, and therefore, may pose a danger to human health and the environment. These wastes are similar to wastes produced by other industries that are subject to Subtitle C regulation, and waste management practices for coal combustion wastes are often similar to waste management practices employed by other industries. EPA is considering removing the exemption for all coal-fired utility wastes other than those identified in the first recommendation. The effect would be to apply Subtitle C regulation to any of those wastes that are hazardous by the RCRA characteristic tests. EPA

believes there are various treatment options available for these wastes that would render them nonhazardous without major costs or disruptions to the utilities.

Third, EPA encourages the utilization of coal combustion wastes as one method for reducing the amount of these wastes that need to be disposed to the extent such utilization can be done in an environmentally safe manner. From the information available to the Agency at this time, current waste utilization practices appear to be done in an environmentally safe manner. The Agency supports voluntary efforts by industry to investigate additional possibilities for utilizing coal combustion wastes.

Through its own analysis, evaluation of public comments, and consultation with other agencies, the Agency will reach a regulatory determination within six months of submission of this Report to Congress. In so doing, it will consider and evaluate a broad range of management control options consistent with protecting human health and the environment. Moreover, if the Agency determines that Subtitle C regulation is warranted, in accordance with Section 3004(x) EPA will take into account the "special characteristics of such waste, the practical difficulties associated with implementation of such requirements, and site-specific characteristics . . .," and will comply with the requirements of Executive Orders 12291 and 12498 and the Regulatory Flexibility Act.

CHAPTER ONE

INTRODUCTION

This is the Environmental Protection Agency's Report to Congress on wastes from fossil fuel combustion, as required by section 8002(n) of the Resource Conservation and Recovery Act. It describes sources and quantities of utility waste, current utilization and disposal practices and alternatives to these practices, potential dangers to human health and the environment, and the costs of current and alternative waste management practices. This report is based on numerous literature reviews and contractor studies; EPA's RCRA Docket contains copies of the source materials that the Agency used in preparing this report.

1.1 Legislative History

Because Congress has amended the Resource Conservation and Recovery Act several times and EPA's regulatory program continues to evolve in response to these Congressional mandates and other additional information, a brief legislative and regulatory history is provided below.

The Resource Conservation and Recovery Act (RCRA, or the Act) of 1976 (Public Law 94-580) substantially amended the Solid Waste Disposal Act of 1965 and authorized the U.S. Environmental Protection Agency (EPA) to establish and enforce regulations concerning the identification, generation, transportation, and management of hazardous waste. These regulations would accomplish the Act's objectives of "...promote[ing] the protection of health and the environment ... and conserve[ing] valuable material and energy resources...."[1] RCRA comprises several subtitles, including Subtitle C-- Hazardous Waste

Management, and Subtitle D-- State or Regional Solid Waste Plans. The intent of the regulations promulgated under Subtitle C of the Act is that wastes identified as hazardous be properly managed from "cradle to grave," that is, from the time they are generated, during transport, throughout their use in various applications, and during disposal. As provided under RCRA Subtitle D, other wastes not considered hazardous as defined under Subtitle C are subject to State regulations.

On December 18, 1978, EPA proposed the first regulations to implement Subtitle C. In the course of preparing these regulations, EPA recognized that certain very large-volume wastes (e.g., wastes generated by utility power plants) could require special treatment:

> ... The Agency has very little information on the composition, characteristics, and the degree of hazard posed by these wastes, nor does the Agency yet have data on the effectiveness of current or potential waste management technologies or the technical or economic practicability of imposing the Subpart D standards [current RCRA section 3004--Standards applicable to owners and operators of hazardous waste treatment, storage, and disposal facilities] on facilities managing such waste.
>
> The limited information the Agency does have indicates that such waste occurs in very large volumes, that the potential hazards posed by the waste are relatively low, and that the waste generally is not amenable to the control techniques developed in Subpart D.[2]

Thus, the Agency proposed a limited set of regulations for managing large-volume wastes, pending an additional rulemaking. Until that rulemaking was completed, EPA proposed exempting utility wastes from storage and disposal regulations.

On May 19, 1980, EPA promulgated the first regulations implementing Subtitle C of RCRA. By then, Congress was debating RCRA reauthorization, and both Houses had passed bills restricting EPA's ability to regulate utility wastes. Anticipating the enactment of legislation amending RCRA Section 3001, EPA excluded utility wastes from the promulgated regulations, writing in the preamble:

> The United States Senate and House of Representatives have each recently passed a bill to reauthorize and amend RCRA (S.1156 and H.R.3994). Both bills contain amendments to Section 3001 which, if enacted, would repeal or temporarily suspend EPA's authority to regulate certain utility and energy development wastes as hazardous wastes under Subtitle C. These bills are now awaiting action by a conference committee. Because it appears likely that Congress will act before November 19, 1980 [the end of the six month comment period on the promulgated interim final regulations and the date on which they would take effect] to exempt these wastes, EPA has temporarily excluded them from this regulation (see section 261.4(b)). This exclusion will be revised, if necessary, to conform to the legislation which is ultimately enacted.[3]

In fact, Congress did act before November 19, 1980; the Solid Waste Disposal Act Amendments (Public Law 96-482) were passed in October 1980.

As anticipated, the amendments temporarily exempted from regulation fly ash waste, bottom ash waste, boiler slag waste, and flue gas emission control waste generated primarily from the combustion of coal or other fossil fuels. In section 8002(n), Congress directed EPA to produce a report on the kinds of waste generated by the combustion of coal and other fossil fuels, which would include an analysis of eight topics:

1. the source and volumes of such material generated per year;

2. present disposal and utilization practices;

3. potential danger, if any, to human health and the environment from the disposal and reuse of such material;

4. documented cases in which danger to human health or the environment from surface runoff or leachate has been proved;

5. alternatives to current disposal methods;

6. the costs of such alternatives;

7. the impact of those alternatives on the use of coal and other natural resources; and

8. the current and potential utilization of such materials.[4]

Finally, in section 3001(b)(3)(C), Congress directed that within six months after submitting this report, EPA must conduct public hearings and decide whether regulating the management of coal combustion wastes under Subtitle C is warranted. Once the decision is made, the Administrator must publish the Agency's regulatory determination in the Federal Register.

In a January 1981 letter,[5] Gary Dietrich, then Associate Deputy Assistant Administrator for Solid Waste, provided an interpretation of RCRA regulations concerning the exemption from regulation of fossil fuel combustion waste.[6] (This letter, as well as a February 18, 1981 memorandum that enclosed it as part of a mailing to EPA Regional Directors, is included as Appendix A.) The letter noted that the beneficial use of hazardous waste as a fuel was not subject to regulation, though it might well be subject to regulation in the future. This meant that utilities could burn as fuel a combination of

hazardous waste and coal, as long as more than 50 percent of the mixture was comprised of coal. The letter also addressed disposal, noting that wastes produced in conjunction with the burning of fossil fuels (e.g., cleaning and other maintenance-related wastes) may be exempt from Subtitle C regulations provided they are mixed and co-disposed or co-treated with fossil fuel wastes and provided "there is no evidence of any substantial environmental danger from these mixtures."[7] The letter concluded:

> ...Pending the completion of [further study on the hazards posed by waste from coal-fired utility plants and the collection of relevant data from the utility industry], EPA will interpret 40 CFR 261.4(b)(4) to mean that the following solid wastes are not hazardous wastes:
>
> (a) Fly ash, bottom ash, boiler slag, and flue gas emission control wastes resulting from (1) the combustion solely of coal, oil, or natural gas, (2) the combustion of any mixture of these fossil fuels, or (3) the combustion of any mixture of coal and other fuels, where coal makes up more than 50 percent of the mixture.
>
> (b) Wastes produced in conjunction with the combustion of fossil fuels, which are necessarily associated with the production of energy, and which traditionally have been, and which actually are, mixed with and co-disposed or co-treated with fly ash, bottom ash, boiler slag, or flue gas emission control wastes from coal combustion.

This provision includes, but is not limited to, boiler cleaning solutions, boiler blowdown, demineralizer reagent, pyrites, and cooling tower blowdown.

In November 1984, Congress reauthorized RCRA by passing the Hazardous and Solid Waste Amendments (HSWA). These amendments restricted the land disposal

of certain hazardous wastes without treatment, established minimum technology requirements for landfills and surface impoundments, issued corrective action requirements for continuing releases at permitted facilities, and established interim status requirements for surface impoundments. Under this new legislation, EPA was granted some flexibility to promulgate regulations that take into consideration the unique characteristics of several types of large-volume wastes, including wastes generated by utility power plants. Specifically, if EPA determined that some or all of the wastes from fossil fuel combustion were subject to regulation under Subtitle C, EPA was empowered to modify the standards imposed by HSWA "...to take into account the special characteristics of such wastes, the practical difficulties associated with implementation of such requirements, and site-specific characteristics ... so long as such modified requirements assure protection of human health and the environment."[8]

The HSWA Conference Report accompanying H.R. 2867 (which in its final amended form was passed by both Houses of Congress as Public Law 98-616) provides clarification:

> This Amendment recognizes that even if some of the special study wastes [which include utility wastes as specified in Section 8002(n)] are determined to be hazardous it may not be necessary or appropriate because of their special characteristics and other factors, to subject such waste to the same requirements that are applicable to other hazardous wastes, and that protection of human health and the environment does not necessarily imply the uniform application of requirements developed for disposal of other hazardous wastes. The authority delegated to the Administrator under this section is both waste-specific and requirement-specific. The Administrator could also exercise the authority to modify requirements for different classes of wastes. Should these wastes become subject to the requirements of Section 3005(j), relating to the retrofit of surface impoundments, the Administrator could

> modify such requirements so that they are not identical to the requirements that are applied to new surface impoundments containing such wastes. It is expected that before any of these wastes become subject to regulation under Subtitle C, the Administrator will determine whether the requirements of Section 3004(c), (d), (e), (f), (g), (o), and (u), and Section 3005(j) should be modified.[9]

1.2. Scope and Sources

This report addresses only the wastes generated by coal-fired electric utility power plants. Because this industry generates the vast majority of all fossil fuel combustion waste (nearly 90 percent),[10] EPA decided to focus its study in this area. This study does not address oil- and gas-fired electric utility power plants or coal, oil and gas-fired industrial boilers.

A number of research projects were undertaken to provide data for this report. EPA sponsored a major study of current coal ash and flue gas desulfurization waste management practices at coal-fired electric utility power plants.[11] In this study comprehensive environmental monitoring was conducted, which included characterizing the wastes, soils, ground water, and surface water at six disposal sites. The contractor (Arthur D. Little, Inc.) evaluated the environmental effects of the disposal practices used at these six sites and, by inference, what effects may be present at other utility waste disposal sites. They also performed extensive engineering and cost evaluations of disposal practices at the six sites.

EPA also sponsored a separate study effort to develop information on the incidences of ground water contamination resulting from utility waste management practices.[12] In this study, contamination was defined as the presence of hazardous constituents at levels above primary drinking water

standards. The main source of information for this phase of the research was a review of case files at the state offices having responsibility for such matters.

In addition, the Agency also reviewed reports submitted by the Utility Solid Waste Activities Group (USWAG), the Edison Electric Institute (EEI), and the National Rural Electric Cooperative Association (NRECA).[13] The reports present information on the sources, volumes, and physical and chemical characteristics of waste streams; ground-water monitoring results assembled from various utility plants; damage case information from various sources; costs of complying with hazardous waste regulations; and resource recovery opportunities using utility wastes.

EPA also has incorporated findings from several documents prepared by the Department of Energy (DOE) and the Electric Power Research Institute (EPRI).[14] These reports examined the chemical composition of utility wastes, technologies for disposal and the costs associated with disposal, as well as results of leaching tests performed on utility wastes.

Finally, EPA gathered information from the Utility Data Institute's Power Statistics Database.[15] This database contains information concerning the size of utility power plants, location of power plants, the types of disposal technologies employed by each power plant, and the amount of waste produced by site and by region. The information on location of power plants was combined with hydrogeologic, population, and ecological profiles of these locations to analyze the potential for exposure to coal combustion wastes.

1.3 Organization

The following chapters of this report address the eight issues (enumerated earlier in this chapter) as required by Section 8002(n) as they apply to coal-fired combustion wastes generated by electric utilities. Chapter Two of this report provides an overview of the U.S. electric utility industry. Chapter Three examines the amount and types of wastes that are generated. Chapter Four discusses current waste management and disposal practices used by the electric utility industry, as well as alternatives to these practices; a review of applicable State regulations is included in this chapter. Chapter Five reviews the potential and documented impact of these wastes on human health and the environment, and Chapter Six evaluates costs associated with current waste disposal practices and additional costs that could be incurred under a variety of alternative waste management practices. Finally, Chapter Seven summarizes the conclusions contained in the previous chapters and presents recommendations.

CHAPTER ONE

NOTES

[1] Resource Conservation and Recovery Act of 1976 (RCRA), Section 1003(a).

[2] Federal Register, Volume 43, No. 243, December 18, 1978, pp. 58991-58992.

[3] Federal Register, Volume 45, No. 98, May 19, 1980, p. 33089.

[4] RCRA, Section 8002(n).

[5] Letter of January 13, 1981, from Gary N. Dietrich, Associate Deputy Assistant Administrator for Solid Waste, to Paul Elmer, Jr., Chairman of the Utility Solid Waste Activities Group.

[6] See 40 CFR 261.4.

[7] Gary N. Dietrich, January 13, 1981, op. cit.; for further information, see Congressional Record, February 20, 1980, p. H 1102, remarks of Congressman Bevill; also see remarks of Congressional Record, February 20, 1980, p. H 1104, remarks of Congressman Rahall.

[8] RCRA, Section 3004(x)

[9] H.R. Report 98-1133, pp. 93-94, October 3, 1984.

[10] Most fossil fuel combustion wastes are generated from coal. For example, as indicated in Physical-Chemical Characteristics of Utility Solid Wastes (by Tetratech, Inc. for EPRI, September 1983), only about one percent of utility wastes are generated from oil; the remaining 99 percent is largely attributable to coal-fired electricity production. Of the coal consumed in the U.S., electric utilities burn nearly 90 percent (excluding metallurgical coal, which is not burned but is instead converted into coke primarily for making steel).

[11] Arthur D. Little, Inc., Full-Scale Field Evaluation of Waste Disposal From Coal-Fired Electric Generating Plants. Prepared for EPA's Office of Research and Development, EPA Contract #68-02-3167; June 1985.

[12] Franklin Associates, Ltd., Survey of Groundwater Contamination Cases at Coal Combustion Waste Disposal Sites, prepared for U.S. Environmental Protection Agency, March 1984.

[13] USWAG is an informal consortium of approximately 65 electric utility operating companies, EEI, and NRECA. The primary source used in the preparation of this report was Report and Technical Studies On The Disposal and Utilization of Fossil-Fuel Combustion By-Products, USWAG, EEI, and NRECA, October 26, 1982.

[14] For example, see Impacts of Proposed RCRA Regulations and Other Related Federal Environmental Regulations on Utility Fossil Fuel-Fired Facilities; Prepared by Engineering-Science for DOE, DOE Contract Number DE-AC-01-79ET-13543, May 1983; Physical-Chemical Characteristics of Utility Solid Wastes, EPRI, September 1983; Analytical Aspects of the Fossil Energy Waste Sampling and Characterization Project, Prepared by Western Research Institute, DOE Order Number DE-AP20-84LC00022, March 1984; and Environmental Settings and Solid Residues Disposal in the Electric Utility Industry, EPRI, July 1984. More sources are included in the Bibliography.

[15] Utility Data Institute's Power Statistics Database was developed under the auspices of the Edison Electric Institute to assist in their analysis of issues affecting the electric utility industry.

CHAPTER TWO

OVERVIEW OF THE ELECTRIC UTILITY INDUSTRY

This chapter provides a general overview of the U.S. electric utility industry. Section 2.1 summarizes electricity demand and discusses the overall structure of the electric utility industry. Section 2.2 focuses the discussion on the role that coal plays in generating electricity. Section 2.3 provides details of coal-fired electric generating technologies and the regional characteristics of coal-fired plants. The chapter concludes with a discussion in Section 2.4 of the waste streams that are produced during coal combustion.

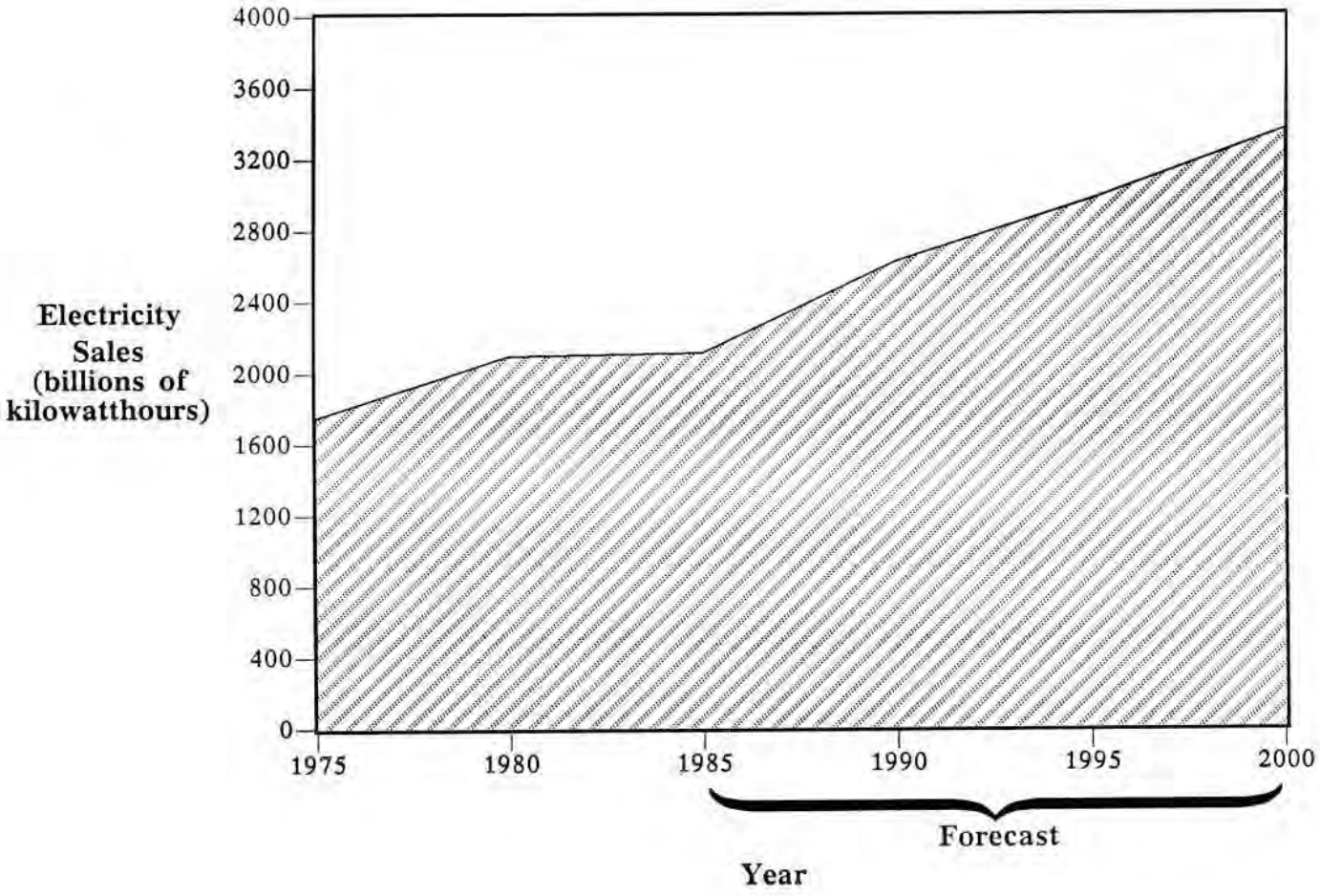
2.1 THE DEMAND FOR ELECTRICITY

The generation, transmission, and distribution of electricity is one of our nation's largest industries. With annual revenues in excess of $140 billion and assets of about $500 billion, the electric utility industry provides vital services to nearly every person in the U.S.[1]

Total demand for electricity in the U.S. has increased substantially in recent decades and will likely continue to grow in coming years (see Exhibit 2-1). From the 1940's through the early 1970's, electricity demand grew at about 7 percent per year, doubling approximately every ten years. This growth slowed beginning with the 1973 OPEC oil embargo and subsequent changes in the energy markets such as fuel price increases, shifts in the economy to markets that require less electricity to meet their power needs, and energy conservation measures. Since 1973, growth in electricity demand has averaged

EXHIBIT 2-1

GROWTH IN ELECTRICITY DEMAND - 1975-2000



Sources: 1975-1985: Energy Information Administration, Electric Power Monthly, DOE/EIA-0226 (85/12), December 1985, p. 39.

1985-2000: ICF Incorporated, Analysis of 6 and 8 Million ton and 30 Year/NSPS and 30 Year/1.2 lb. Sulfur Dioxide Emission Reduction Cases, Prepared for Environmental Protection Agency, February 1986.

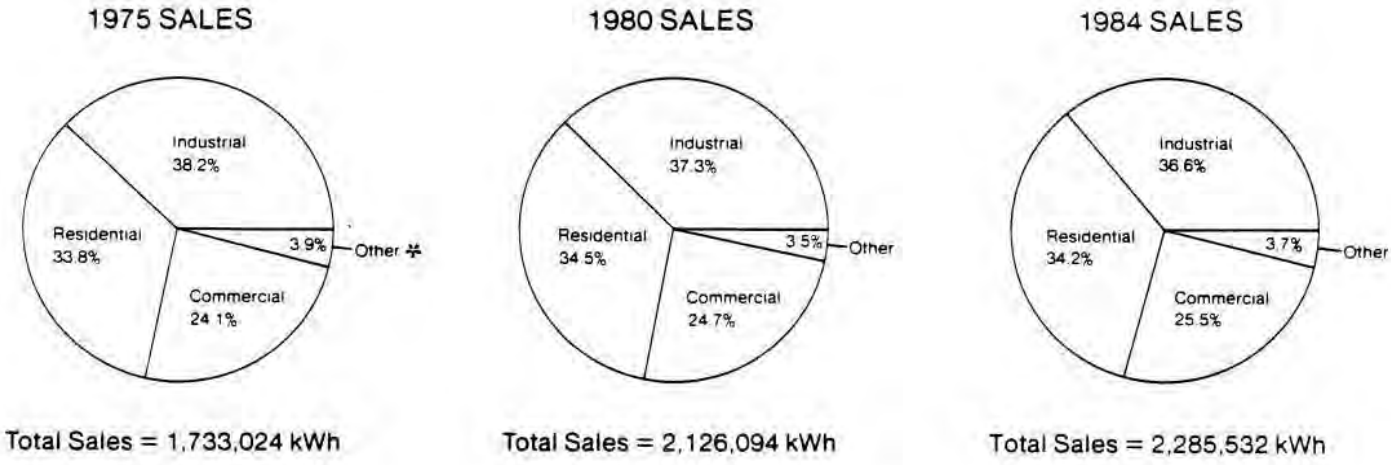
about three percent per year. Expectations are that electricity demand will continue to grow at an average rate of about 2 to 3 percent per year over the next several years.[2]

Every major segment of the U.S. economy relies on electricity to meet a portion of its energy needs. As shown in Exhibit 2-2, the demand for electricity is divided almost evenly between the industrial, commercial, and residential sectors. This demand for electricity has continued to increase over the last decade with total sales increasing from 1.7 million gigawatt-hours (Gwh) in 1975 to 2.3 million Gwh in 1985.[3] As demand has increased, electricity sales patterns have remained relatively consistent. Industry continues to be the largest consuming sector, although industry's fraction of total sales has decreased by about 2.7 percent from 1975 to 1985, primarily due to an increased market share for the commercial sector (i.e., stores, office buildings, restaurants, etc.). Residential customers consume about one-third of all electricity for basic necessities such as lighting, heating, and electrical appliances.

Virtually every geographic area in the U.S. relies on electricity supplied by the electric utility industry. As shown in Exhibit 2-3, electricity demand is highest in the eastern half of the U.S., particularly in EPA Regions 3-6 (see Exhibit 2-4 for a map of these EPA Regions). This level of demand is not surprising considering that these areas are the most heavily industrialized and densely populated areas of the country.

EXHIBIT 2-2

ELECTRICITY SALES BY YEAR AND CLASS OF SERVICE
(gigawatt-hours)



Total Sales = 1,733,024 kWh

Total Sales = 2,126,094 kWh

Total Sales = 2,285,532 kWh

Source: Edison Electric Institute, Statistical Yearbook of the Electric Utility Industry/1985, December 1986.

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*Includes street lighting, other public authorities, railroads and interdepartmental transfers within utilities (i.e., use of electricity by the utility itself).

EXHIBIT 2-3

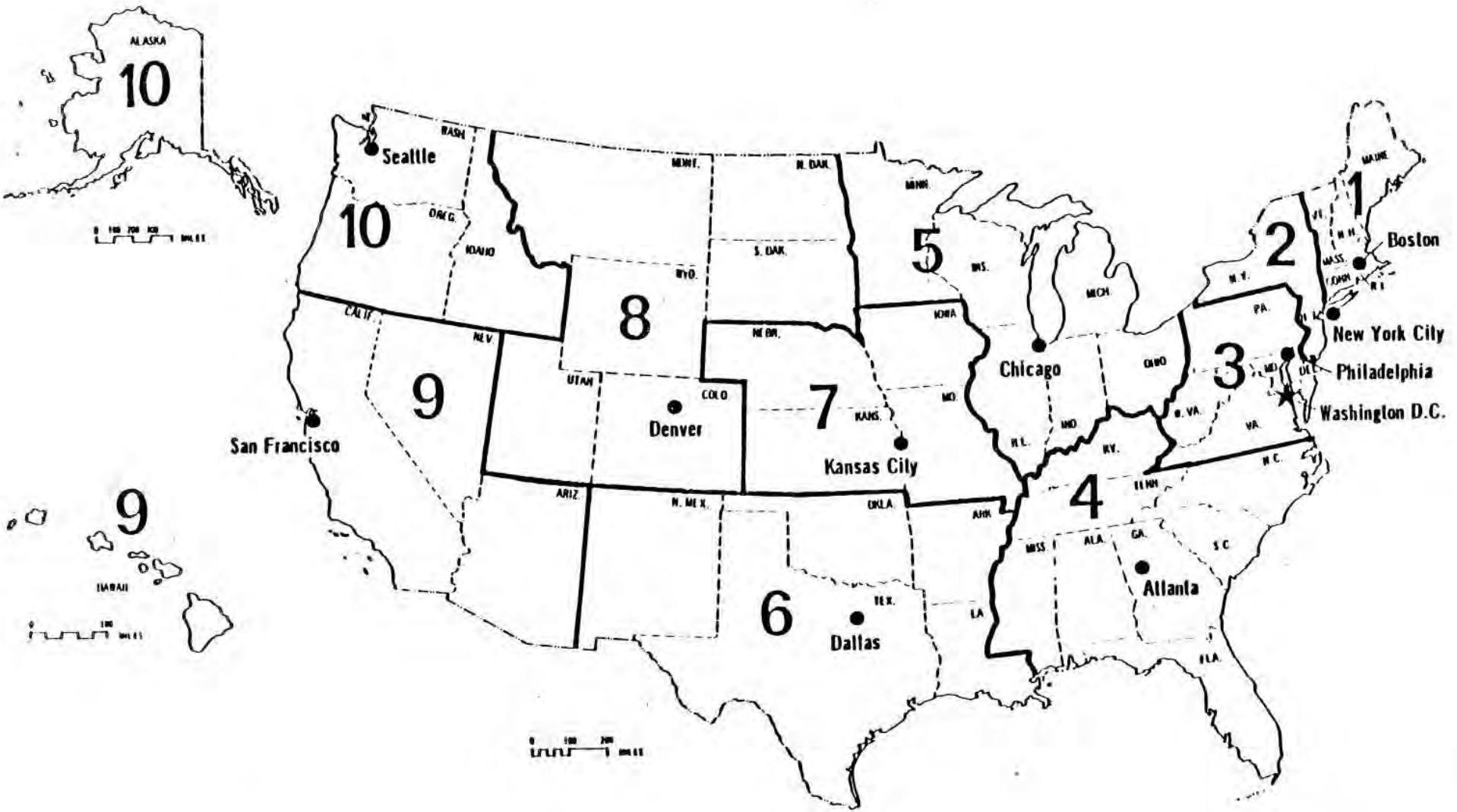
ELECTRICITY DEMAND by EPA REGION
1985

EPA Region	Millions of Kilowatt Hours	Percent of Total
1	86,397	3.8
2	164,780	7.2
3	230,055	10.1
4	483,248	21.2
5	428,873	18.8
6	340,198	14.8
7	112,076	4.9
8	72,458	3.2
9	227,006	10.0
10	135,716	6.0
Total U.S.	2,280,585	100.0

Source: Edison Electric Institute, Statistical Yearbook of the Electric Utility Industry/1985, December 1986.

EXHIBIT 2-4

EPA FEDERAL REGIONS



2.1.1 Structure of the U.S. Electric Utility Industry

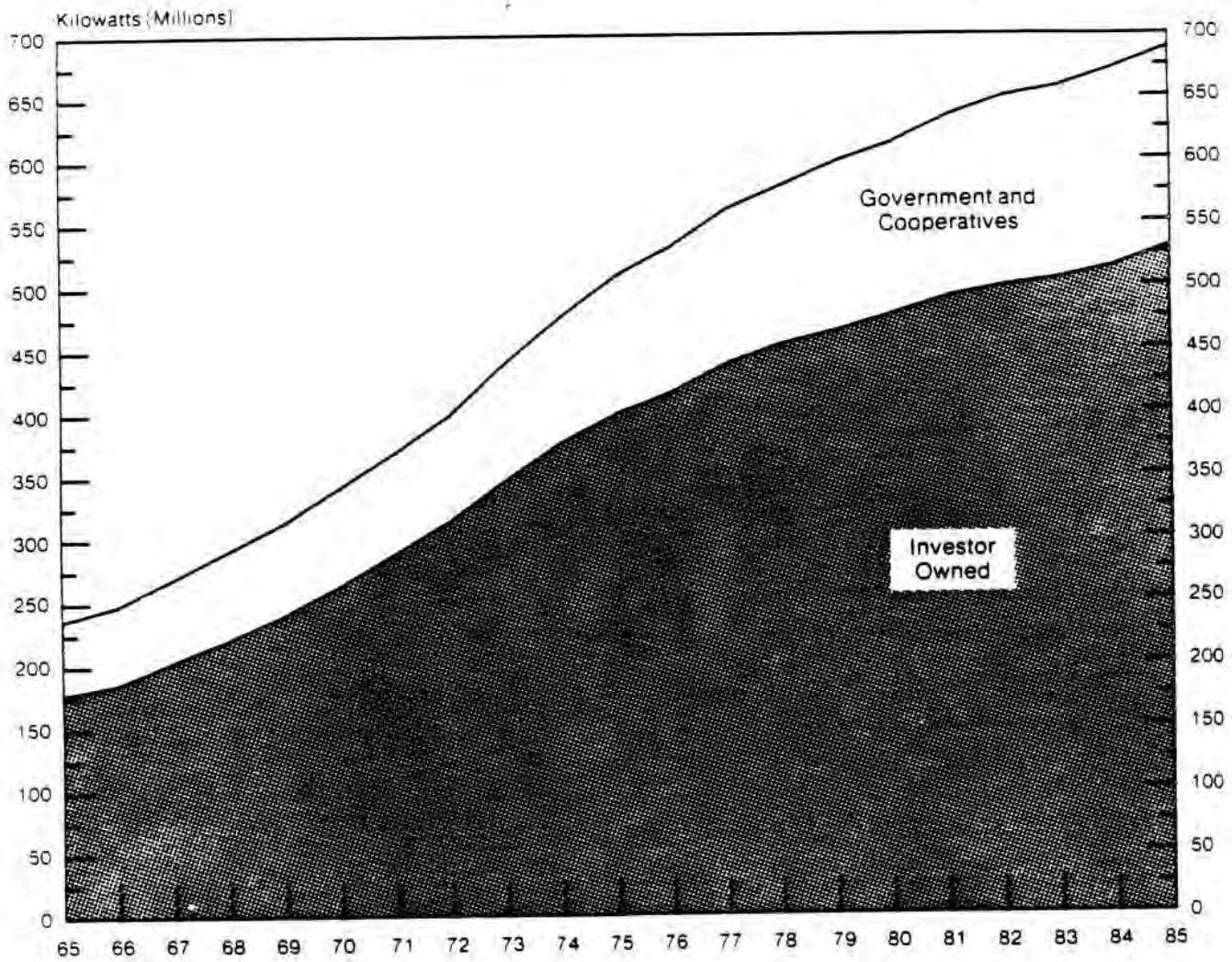
The U.S. electric power industry is a combination of private, Federal, and public nonprofit organizations. The distribution of capacity, generation, revenue, and sales differs widely among these ownership groups since each group has different objectives, organizational characteristics, and financing methods. Private investor-owned utilities dominate the U.S. electric utility industry as shown in Exhibit 2-5. Investor-owned utilities have historically served large consolidated markets to take advantage of economies of scale. Federal, municipal, cooperative, and other publicly-owned utilities have generally served smaller markets where local governments or nonprofit organizations have had access to limited supplies of less expensive Federal power or to government-supplied capital for power plant construction. These circumstances have allowed municipal, cooperative, or other publicly-owned utilities to predominate in areas not traditionally served by investor-owned utilities.[4] A brief discussion of each type of organization is provided below.

2.1.1.1 Investor-Owned Utilities

Investor-owned utilities account for about three-quarters of all U.S. electric utility generating capacity, generation, sales, and revenue. Investor-owned utilities are privately owned, profit-oriented businesses granted service monopolies in certain geographic areas. As franchised monopolies, they are obligated to provide service to all customers within their geographic area. In providing this service, investor-owned utilities are required to charge reasonable prices, to charge similar prices to similar

EXHIBIT 2-5

GENERATING CAPACITY IN THE UNITED STATES



Source: Edison Electric Institute, Statistical Yearbook for the Electric Utility Industry/1985, December 1986.

customers, and to give customers access to services under similar conditions.[5] Investor-owned utilities operate in all states except Nebraska (which depends primarily on public power districts and rural electric cooperatives for electricity). In 1984, consumers paid an average of 6.5 cents per kilowatt-hour (kwh) for privately-produced power compared to the industry average from all ownership groups of 6.3 cents per kilowatt-hour (an average customer consumed 23,150 kwh in 1984).[6]

2.1.1.2 Federal Power

The U.S. Government is the second largest producer of electricity in the United States with roughly 10 percent of total U.S. generation and generating capacity. Consumers of Federal power paid the lowest rate among the different ownership groups -- only 3.5 cents per kwh on average in 1984, (compared to an industry average of 6.3 cents per kwh).[7] Federal power production is designed to provide power at the lowest possible rate, with preference in the sale of electricity given to public entities and cooperatives.[8] In this role the Federal Government is primarily a generator and wholesaler of electricity to other organizations, rather than a direct distributor to electricity consumers.[9]

2.1.1.3 Municipal Utilities

Municipal utilities are nonprofit local government agencies designed to serve their customers at the lowest possible cost. Most municipal utilities simply distribute power obtained from one of the other ownership groups (e.g., Federal facilities), although some larger ones also generate and transmit

power. Municipally-owned electric utilities rank third in the amount of installed capacity (5.5 percent of total generating capacity), but comprise the single most numerous ownership group (1,811 utilities in 1984).[10] Average revenue per kwh sold in 1984 was 5.69 cents compared to an industry average of 6.3 cents per kwh. Municipal utilities are exempt from local, state, and Federal taxes and have access to less expensive capital via public financing and less expensive Federal power. As a result, municipal utilities can generally afford to charge less than investor-owned utilities for the power they produce.[11]

2.1.1.4 Cooperatives

Rural electric cooperatives are owned by and provide electricity to their members and currently operate in 46 states. They have the lowest amount of installed capacity among all ownership categories (24.7 gigawatts in 1984 or less than 4 percent of all capacity).[12]

In 1984, average revenue for cooperatives from sales to consumers was 6.7 cents per kwh, the highest of all ownership types (the industry average was 6.3 cents per kwh). Large construction programs in the 1970's usually account for the high rates.[13]

2.1.1.5 Other Public Entities

There are a variety of other public organizations that provide electric power, including public power districts, state authorities, irrigation districts, and various other State organizations. These other public entities

operated a combined total of 32.8 gigawatts in 1984, or about 5 percent of all generating capacity in the U.S.[14] The public power districts are concentrated in five states -- Nebraska, Washington, Oregon, Arizona, and California. The average price paid for electricity from all of these entities was 4.37 cents per kwh in 1984, compared to an industry average of 6.3 cents per kwh.[15]

2.1.2 Economic and Environmental Regulation of the Electric Utility Industry[16]

The electric utility industry is regulated by several different regulatory bodies at both the Federal and State levels. According to the U.S. Department of Energy: "The basic purpose of public utility regulation is to assure adequate service to all public utility patrons, without discrimination and at the lowest reasonable rates consistent with the interests both of the public and the electric utilities."[17] This regulation involves both economic and environmental objectives. As natural monopolies, electric utilities are regulated to ensure that adequate, reliable supplies of electric power are available to the public at a reasonable cost. Additionally, since the operations of electric utilities can affect environmental quality, they are regulated to ensure the protection of the nation's air and water resources. This section briefly reviews the main regulatory bodies that affect the electric utility industry.

2.1.2.1 Federal Regulation

There are five major organizations at the Federal level that regulate some aspect of the electric utility industry -- the Federal Energy Regulatory Commission (FERC), the Economic Regulatory Administration (ERA), the

Securities and Exchange Commission (SEC), the Nuclear Regulatory Commission (NRC), and the Environmental Protection Agency (EPA).

- The Federal Energy Regulatory Commission (FERC) oversees various aspects of the electric utility, natural gas, hydroelectric, and oil pipeline industries. FERC approves the rates and standards for wholesale interstate electricity sales between investor-owned utilities and other investor-owned utilities, municipals, or cooperatives (these sales are about 15 percent of total U.S. electricity sales).[18] It determines whether these rates are reasonable and non-discriminatory. FERC also oversees utility mergers and the issuance of certain stock and debt securities, approves the rates of Federal Power Marketing Administrations, and administers agreements between utilities concerning electricity transmission.

- The Economic Regulatory Administration (ERA) has several responsibilities, including administering a program to ensure that all future power plants have the potential to burn coal, regulating international electricity transmission connections, and licensing exports of power.

- The Securities and Exchange Commission (SEC) is an independent regulatory agency established to regulate interstate transactions in corporate securities and stock exchanges. With respect to the electric utility industry, the SEC regulates the purchase and sale of securities, utility properties, and other assets.

- The Nuclear Regulatory Commission (NRC) is involved only in the regulation of nuclear facilities owned and operated by the utility industry. Its main responsibilities include licensing the construction and operation of nuclear facilities, licensing the possession, use, transportation, handling, and disposal of nuclear materials, licensing the export of nuclear reactors and the import and export of uranium and plutonium, and regulating activities affecting the protection of nuclear facilities and materials.

In addition to these regulatory bodies, the Environmental Protection Agency (EPA) is the main Federal regulatory authority for protecting the nation's air and water quality. As part of its overall authority, EPA sets limits on the level of air pollutants emitted from electric power plants and develops regulations to control discharges of specific water pollutants.

Throughout this Report to Congress key regulations that affect the electric utility industry are discussed. While EPA often takes the Federal lead when these regulations are developed, the Agency also works closely with the States since they often retain primary authority for implementing and enforcing standards (for example, see Section 4.1 on state regulation of coal combustion wastes).

2.1.2.2 State Regulation

States are also involved in the environmental and economic regulation of the electric utility industry. As mentioned above, the States often share regulatory authority with the various Federal organizations. For environmental regulation the States often have their own environmental protection agencies to implement and enforce State and Federal environmental regulations. For example, they are responsible for drafting State Implementation Plans (SIP) that must be approved by the U.S. EPA to attain National Ambient Air Quality Standards (NAAQS). Similarly, as will be discussed in greater detail in Chapter Four, the States have authority for implementing and enforcing regulations concerning the disposal of solid wastes under Subtitle D of RCRA. Environmental regulations for which the States exercise regulatory authority are discussed throughout this Report to Congress.

States are also very involved in the economic regulation of the electric utility industry. The primary goals of state economic regulation is usually to provide adequate nondiscriminatory service to electricity consumers at reasonable prices.[19] This is usually accomplished by state regulatory

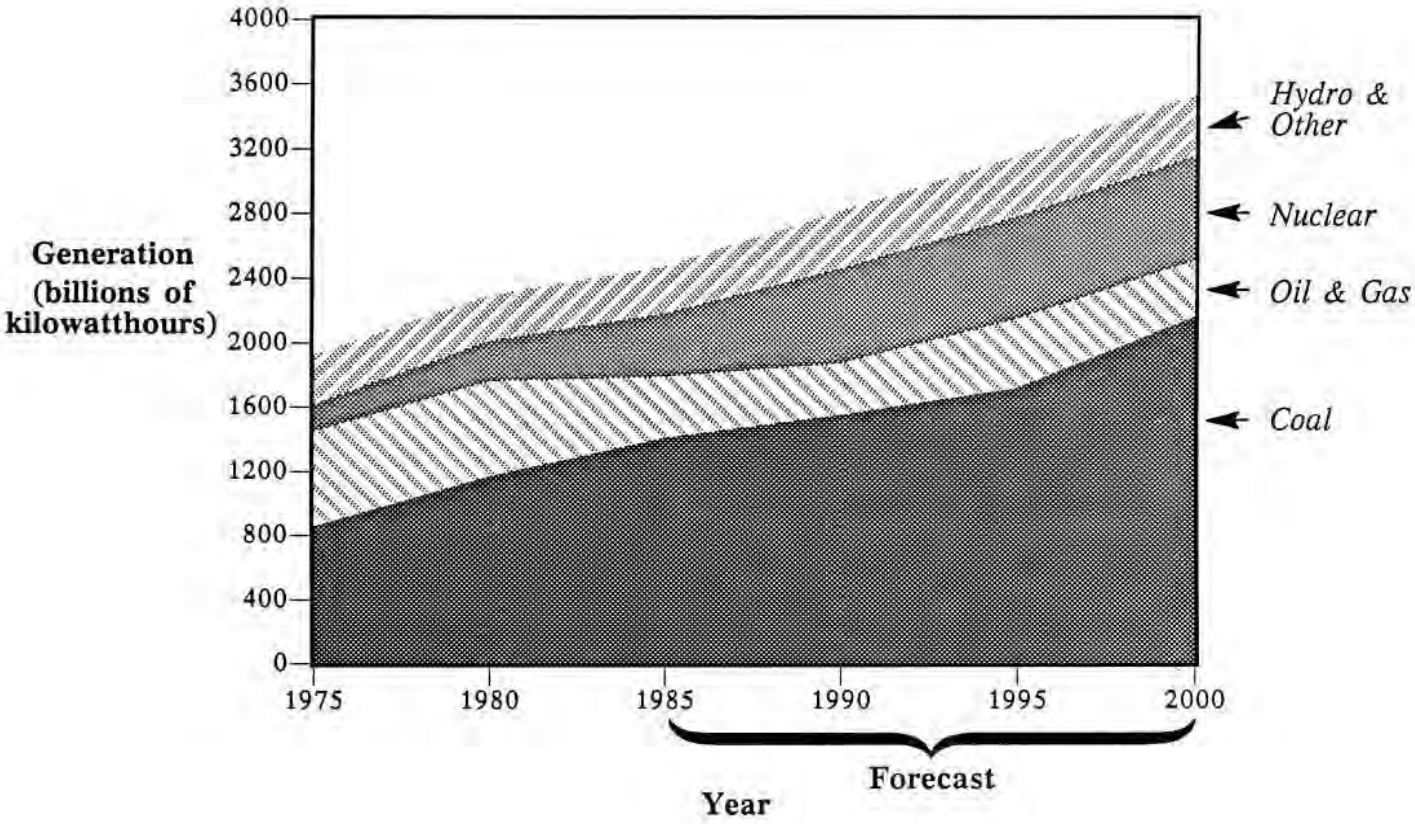
agencies such as public utility commissions. The amount of authority these state regulatory agencies have can differ widely from state to state. However, these agencies usually have the authority to approve electricity price levels and the rates of return allowed for utility stockholders. State regulators also approve the franchise under which the utility operates. Licensing for construction and operation and approval of the sites at which power plants will be built are also important functions of some state regulatory commissions. Other areas into which some commissions have entered to ensure that utility activities protect the public interest include setting rules about when competitive bids are required, promulgating company performance standards, deriving methods for allocating power during shortages, establishing billing and safety rules, and promoting conservation.[20]

2.2 IMPORTANCE OF COAL TO ELECTRIC UTILITIES

Electric utilities use many different technologies and energy sources to generate electricity. At present, as shown in Exhibit 2-6, over 70 percent of electricity in the U.S. is generated by the combustion of fossil fuels (coal, oil and natural gas); most of the remaining 30 percent is generated by hydroelectric plants and nuclear power plants. A small portion of electricity demand is satisfied by alternative sources such as geothermal energy, renewable resource technologies (e.g., wood, solar energy, wind), purchased power from industrial and commercial cogeneration (cogeneration is the simultaneous production of electricity and process steam; the electricity is typically used by the cogenerator or sold to another industry while the steam is used for various production processes), and power imports (primarily from Canada).

EXHIBIT 2-6

ELECTRICITY GENERATION BY PRIMARY ENERGY SOURCE
1975-2000



Source: 1975-1985: Energy Information Administration, Electric Power Monthly DOE/EIA-0226 (85/12), December 1985, p. 10.

1985-2000: ICF Incorporated, Analysis of 6 and 8 million Ton and 30 Year/NSPS and 30 Year/1.2 lb. Sulfur Dioxide Emission Reduction Cases, Prepared for Environmental Protection Agency, February 1986.

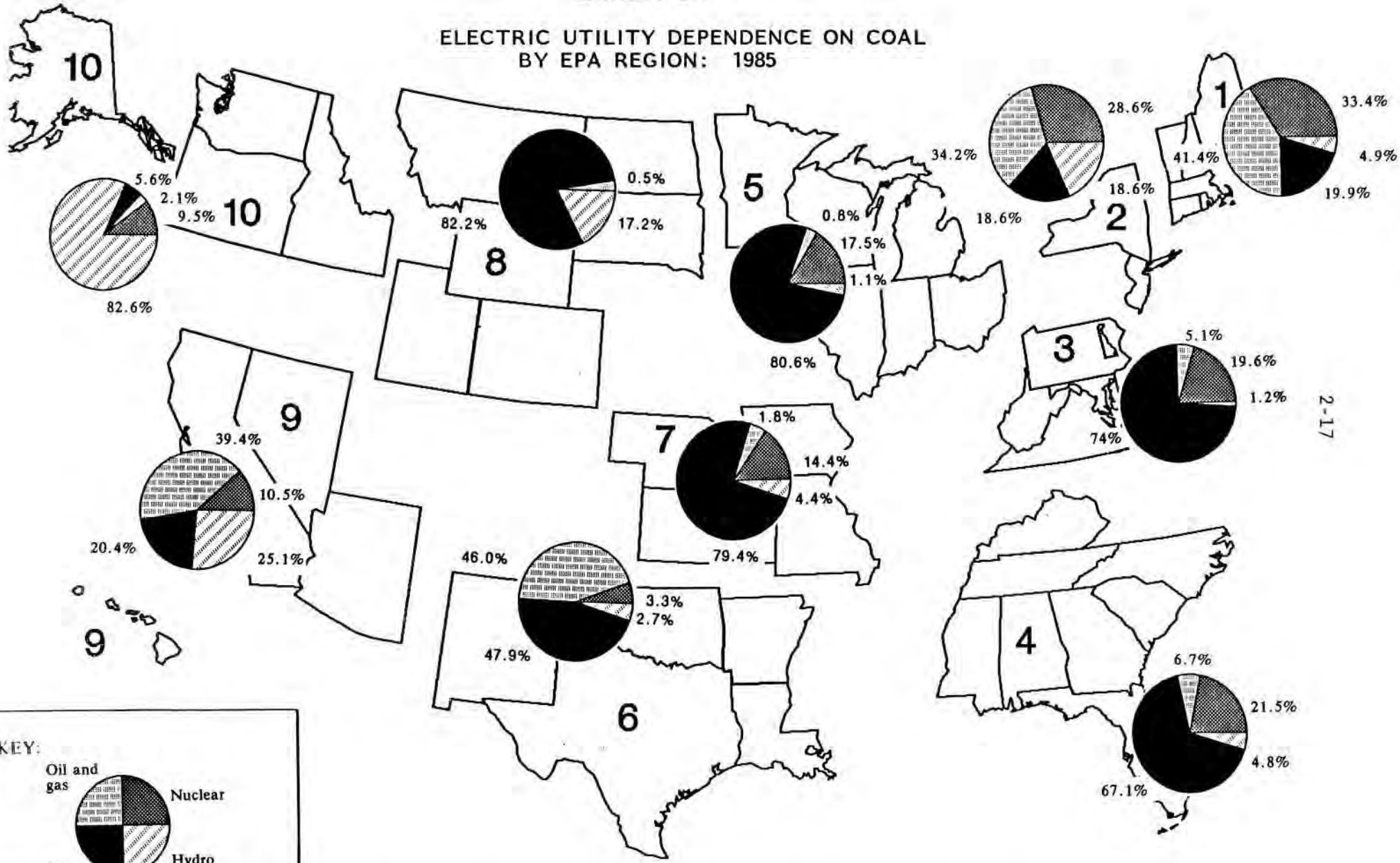
In 1984, coal accounted for more than half of all the electricity generated in the U.S.[21] The portion of electricity generated from coal is expected to remain at about this level throughout the rest of the century since coal-fired generation is expected to remain economically attractive. The relative contribution to total generation made by other fossil fuels and by hydroelectric power will likely continue to decline, while the contribution made by nuclear power plants will likely increase for the next few years as several new units come on-line. However, the addition of nuclear plants beyond those now under construction will be minimal, leading to an eventual decline in nuclear's relative contribution. Cogeneration, power imports, and emerging technologies are expected to continue to grow, but their share of total generation will remain small. As a result, coal will continue to be the major fuel source for electricity generation.

The extent of the electric utility industry's dependence on coal varies geographically. Exhibit 2-7 shows that coal accounts for over three-quarters of electricity generation in some regions, but less than half in others. For example, in the far West and southern Plains states, the local availability of oil, gas, and hydroelectric power has limited regional dependence on coal. In many of the eastern regions, where coal is relatively more accessible and less costly than oil or gas, coal is significantly more dominant. Despite these regional variations, however, coal-fired electricity generation is an important source of electricity in most regions of the United States.

The use of coal by electric utilities has also made the coal and electric utility industries highly interdependent; not only does coal-fired electricity generation account for over half of the electricity produced in the U.S., but

EXHIBIT 2-7

ELECTRIC UTILITY DEPENDENCE ON COAL
BY EPA REGION: 1985



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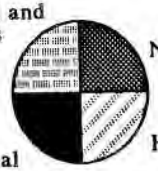


Percentages represent the proportion of the total electricity generated in the region by each type of fuel.

Source: Energy Information Administration, Electric Power Annual 1985, DOE/EIA-0348(85), pp.17-30.

the electric utility industry is the largest customer of the coal industry, purchasing approximately three-quarters of all coal mined, as shown in Exhibit 2-8. This interdependence has increased as electric utility coal consumption has grown from 406 million tons in 1975 to over 600 million tons in 1985.[22] Moreover, electric utility coal consumption is expected to continue to increase to about 1 billion tons by the year 2000.

2.3 OVERVIEW OF COAL-FIRED POWER PLANTS

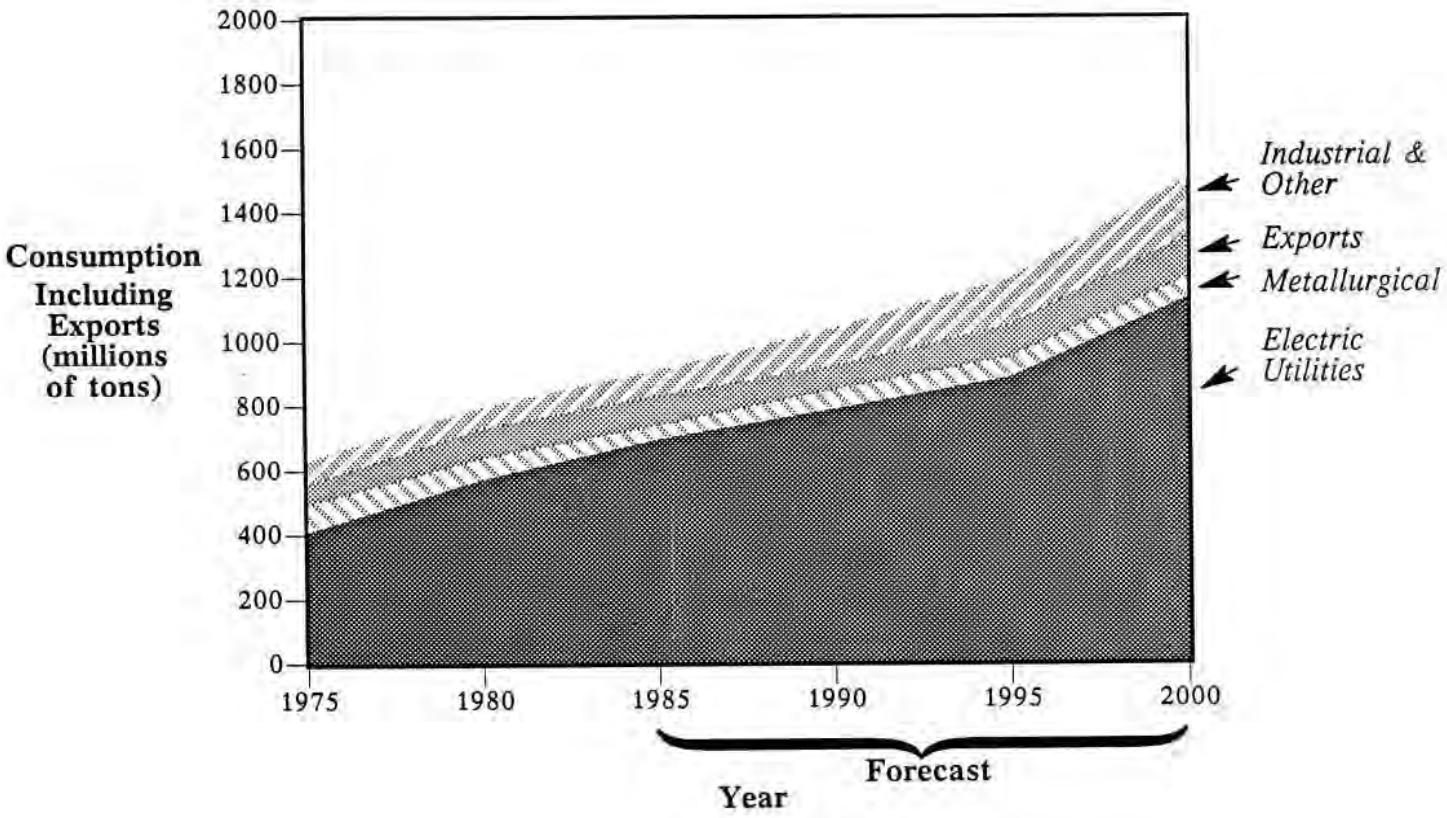
Coal-fired power plants can vary greatly in terms of their generating capacity and the type of boiler technology they employ which, in turn, can affect the amount and type of combustion wastes produced. This section discusses the geographic differences in the size of plants and generating units and describes the three main boiler types along with the regional importance of each.

2.3.1 Regional Characteristics of Coal-Fired Electric Generating Plants

Coal-fired power plants can range in size from less than 50 MW to larger than 3000 MW. In many cases, particularly at the larger power plants, one power plant site may be the location for more than one generating unit (a generating unit is usually one combination of a boiler, turbine, and generator for producing electricity). Exhibit 2-9 shows the number of coal-fired power plants and number of units in each EPA region and their average size in megawatts. On average, each power plant site is comprised of about three generating units. The average generating capacity of coal-fired power plants in the U.S. is approximately 584 MW, with an average unit size of 257 MW.

EXHIBIT 2-8

U.S COAL CONSUMPTION BY SECTOR
1975-2000



Sources: 1975-1985: Energy Information Administration, Annual Energy Review 1985, DOE/EIA-0384 (85), April 1985, pp. 167, 169.

1985-2000: ICF Incorporated, Analysis of 6 and 8 Million Ton and 30 Year/NSPS and 30 Year/1.2 lb. Sulfur Dioxide Emission Reduction Cases, Prepared for Environmental Protection Agency, February 1986.

EXHIBIT 2-9

TOTAL NUMBER AND AVERAGE SIZE OF COAL-FIRED PLANTS AND UNITS

EPA Region	Number of Plants	Average Size (MW)	Number of Units a/	Average Size a/ (MW)
1	6	374	18	158
2	17	297	39	138
3	57	753	144	308
4	93	799	295	301
5	171	492	492	185
6	39	852	87	580
7	66	400	149	186
8	48	454	109	250
9	13	603	34	383
10	4	479	11	382
U.S. Total	514	584	1378	257

Source: Utility Data Institute Power Statistics Database.

a/ The total amount of generating capacity indicated by multiplying the number of units by their average size (e.g., 1378 units X 257 Mw = 354,146 Mw) is greater than the amount indicated by multiplying the number of power plants by their average (e.g., 514 plants X 584 Mw = 300,176 Mw) because the information in the UDI Power Statistics Database by generating units includes units planned, currently under construction, etc. while the information by power plants refers only to power plants currently operating.

Regional averages for power plant size range from 297 MW in Region 2 to 852 MW in Region 6. Unit sizes range from an average of 138 Mw in Region 2 to 580 Mw in Region 6. Individual power plants and units can be larger or smaller than these averages indicate.

The majority of coal-fired plants (60%) are smaller than 500 MW, while only about 4 percent of U.S. coal-fired power plants have a generating capacity exceeding 2000 MW. Exhibit 2-10 shows the distribution of coal-fired plant sizes across EPA regions.

2.3.2 Electricity Generating Technologies

The basic process by which electricity is produced with coal is shown in Exhibit 2-11. When coal is burned to produce electricity, there are three key components that are critical to the operation of the power plant: the boiler, turbine, and generator. As coal is fed into the boiler, it is burned in the boiler's furnace. In the boiler there are a series of water-filled pipes. As heat is released during combustion, the water is converted to steam until it reaches temperatures that can exceed 1000°F and pressures that approach 4000 pounds per square inch. This high pressure, high temperature steam is then injected into a turbine, causing the turbine blades to rotate. The turbine, in turn, is connected to a generator, so the mechanical energy available from the rotating turbine blades is transformed into electrical energy. The electricity produced by this process is distributed via transmission lines to residential, commercial, and industrial end-users who rely on the power to meet their electrical requirements. Although each step of this process is critical to the production of electricity, this study focuses on boilers only

EXHIBIT 2-10

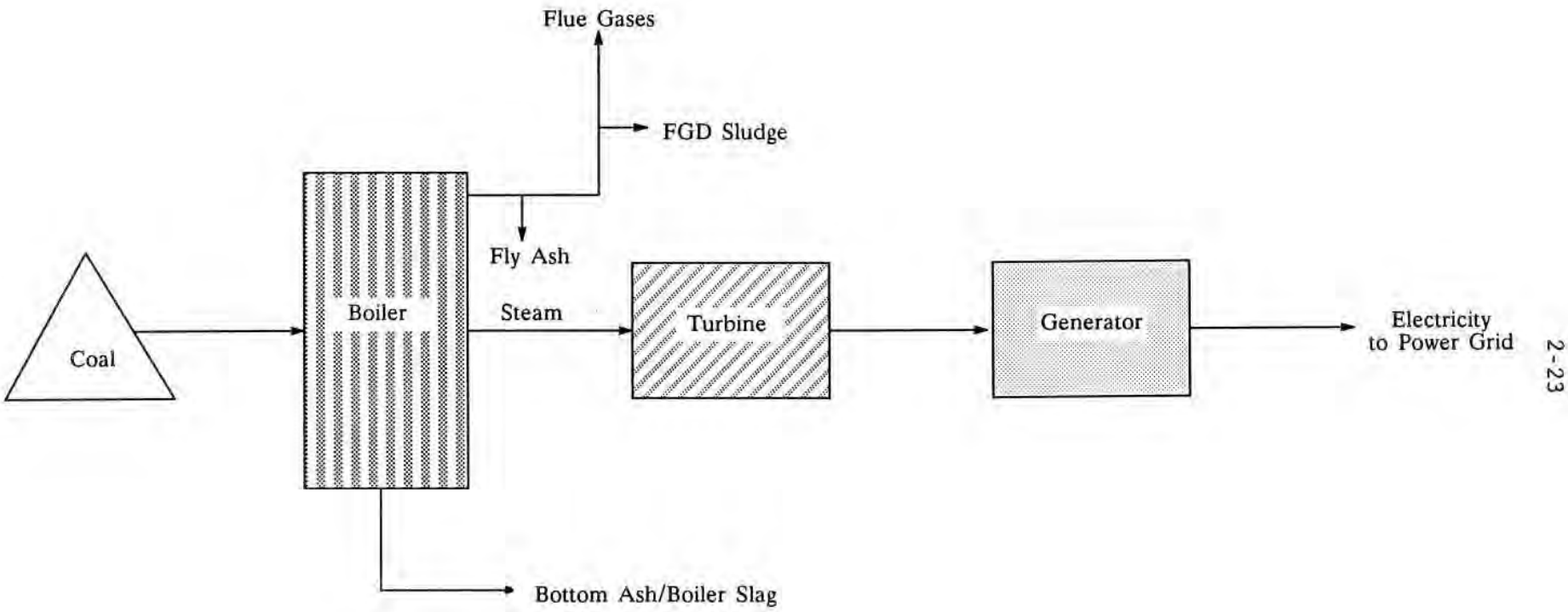
RANGE OF COAL-FIRED POWER PLANT SIZES
(number of plants)

	Power Plant Size					
EPA Region	<100 MW	101-500 MW	501-1000 MW	1001-2000 MW	≥2000 MW	Total
1	1	4	0	1	0	6
2	6	6	5	0	0	17
3	6	23	11	14	3	57
4	15	31	17	23	7	93
5	63	51	23	29	5	171
6	10	4	10	12	3	39
7	25	24	8	7	2	66
8	18	14	10	4	2	48
9	5	2	4	1	1	13
10	2	0	1	1	0	4
U.S. Total	151	159	89	92	23	514

Source: Utility Data Institute Power Statistics Database.

EXHIBIT 2-11

PROCESS FOR GENERATING ELECTRICITY
AT COAL-FIRED POWER PLANTS



Source: ICF Incorporated

since it is in the boiler where the combustion wastes are produced as the coal is burned.

There are three main types of boilers: (1) pulverizers, (2) cyclones, and (3) stokers. As discussed below in greater detail, the key differences between these boiler types are operating size and the procedures used for handling and burning the coal. Pulverized coal boilers are so-named because the coal is finely pulverized prior to combustion; most utility boilers are this type. Cyclones have been used in past utility applications, but have not been built recently. They are called cyclones because of the cyclone-like vortex created by the coal particles in the furnace during combustion. Stoker boilers are usually used when smaller capacities are required (e.g., 20-30 MW) and burn coal in a variety of sizes.

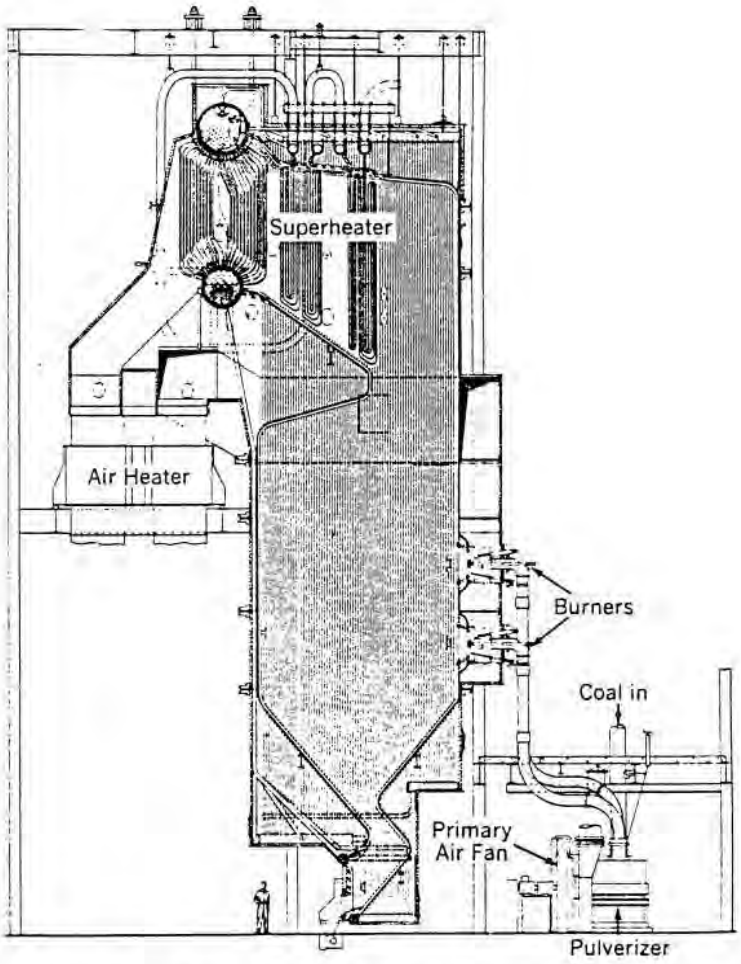
A brief description of each of these coal combustion technologies follows.[23]

2.3.2.1 Pulverized-Coal Boiler

Exhibit 2-12 shows a typical pulverized-coal boiler setup. In a pulverized coal boiler, coal is ground to a fine size (about 200 mesh, which is powder-like) in a pulverizer or mill. The pulverized fuel is then carried to the burners by forced air injection and blown into the furnace, where it is burned in suspension. Much of the ash remaining after combustion remains airborne and is carried from the furnace by the flue gas stream (i.e., it becomes fly ash; see Chapter Three for a more detailed discussion of types of waste and how they are produced). Some ash is deposited on the furnace walls,

EXHIBIT 2-12

DIAGRAM OF A PULVERIZED COAL BOILER



Two-drum boiler direct-fired with pulverized coal.

Source: Babcock and Wilcox Co., Steam: Its Generation and Use, New York, NY 1978.

where it agglomerates and may sinter or fuse. Ash that falls to the bottom of the furnace is removed via an ash hopper. Ash deposits and slagging are more of a problem in pulverized coal boilers than in stoker boilers.

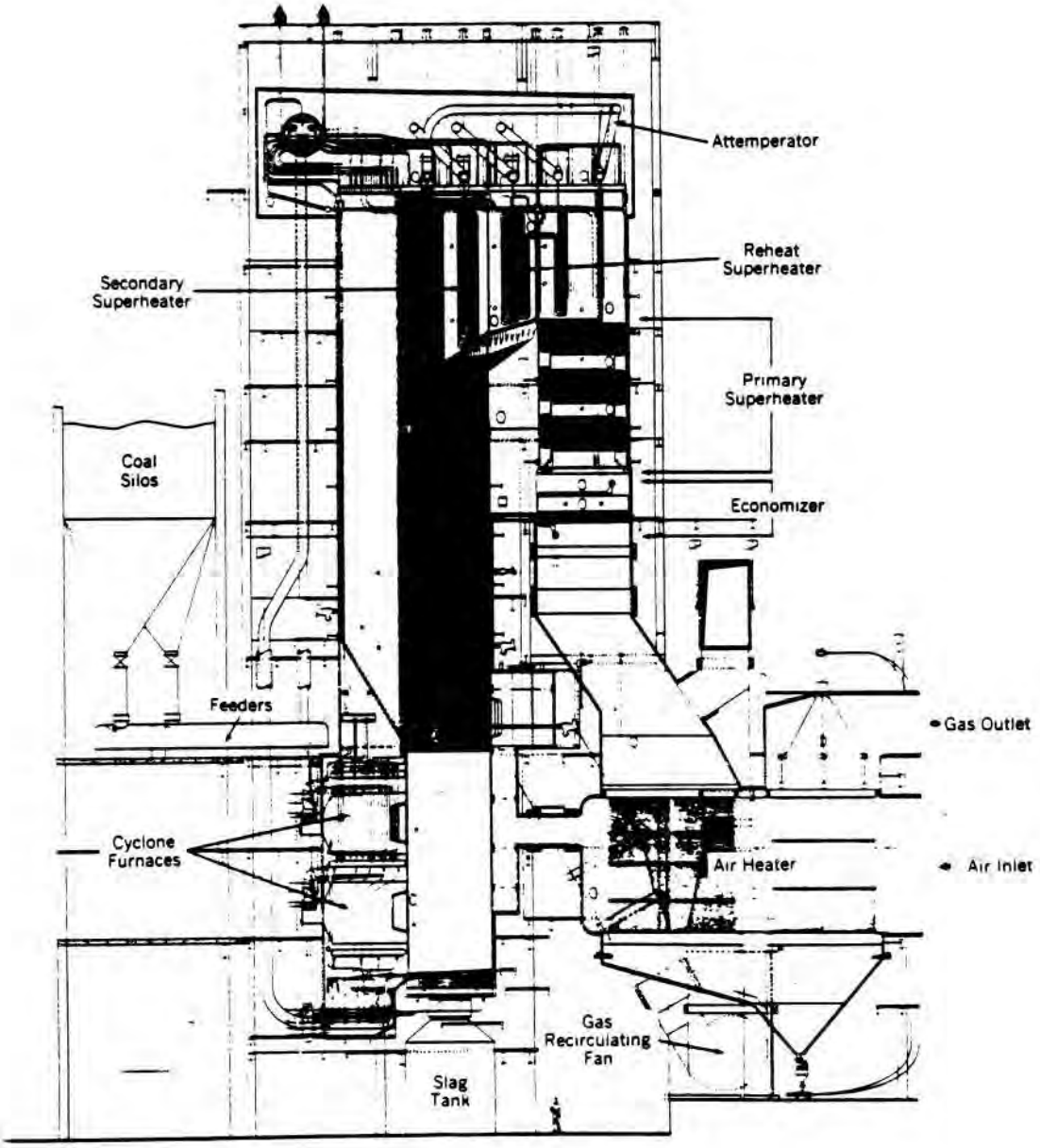
Most modern pulverized-coal boilers have dry-bottom furnaces; that is, the ash is intended to be removed as a dry solid before complete melting occurs. As a result, for dry-bottom boilers, the ash-fusion temperature (the melting point) of the coal must be high enough to prevent the ash from becoming a running slag (i.e., a liquid form). Wet-bottom, or slag-tap, pulverized-coal boilers are designed to remove the ash as a flowing slag. These boilers depend on lower ash-fusion temperature coals so that the ash will melt to form slag for easier removal.

2.3.2.2 Cyclones

The cyclone furnace consists of a water-cooled horizontal furnace in which crushed coal is fired and heat is released at high rates, as shown in Exhibit 2-13. The temperature inside the furnace may reach 3000°F, which is sufficient to melt the ash into a liquid slag that forms on the walls of the furnace. Air circulation within the furnace typically creates a cyclone-like vortex that not only helps the coal to burn in suspension but also causes many coal particles to impinge upon the slag-covered walls of the furnace. This tendency for coal particles to adhere to the walls of the cyclone boiler aids the combustion process because the coal particles will burn more thoroughly before reaching the bottom of the boiler. Most of the ash is retained in the slag layer, thus minimizing the amount of fly ash that is carried out of the boiler. The slag,

EXHIBIT 2-13

DIAGRAM OF A CYCLONE BOILER



Source: Babcock and Wilcox Co., Steam: Its Generation and Use, New York, NY, 1978.

or melted ash particles, is typically removed at the bottom of the furnace.

The cyclone offers the advantage of being able to burn low ash-fusion coals that create problems when burned in most conventional pulverized-coal burners. The cyclone design also helps to minimize erosion and fouling problems in the boiler. The smaller amounts of fly ash created compared to other boiler types reduces the costs associated with particulate collection.

2.3.2.3 Stokers

Stokers are designed to mechanically feed coal uniformly onto a grate within a furnace. Because most of the combustion takes place in the fuel bed, not in suspension within the furnace, the heat release rate of this type of boiler is lower than it is for pulverizers or cyclones. As a result, stokers are generally designed for smaller-sized applications. In fact, this boiler type is used by many manufacturing industries, but has seen only limited use by electric utilities.

Stokers are classified by the method of feeding fuel to the furnace and by the type of grate. The three most important stoker types include:

1) the spreader stoker, the most popular type of overfeed stoker,

2) other overfeed stokers, such as the chain-grate, travelling-grate stoker, or the vibrating-grate stoker, and

3) the underfeed stoker.

The major features of each are summarized in Exhibit 2-14. An illustration of a spreader stoker is provided in Exhibit 2-15.

Use of the different boiler types varies by geographic region. As shown in Exhibit 2-16, about three-fourths of all boiler capacity in the U.S. uses pulverizers, with most of these dry-bottom pulverizers. Cyclones are the next most prevalent boiler type, representing only about 8 percent of all boilers. Stokers represent less than one-half of one percent of the total; due to their size limitations stokers are used primarily in other industrial applications for the production of steam.

Exhibit 2-17 shows the distribution of average capacity for each boiler type by EPA region. The range in average sizes is most pronounced in dry bottom boilers (127.8-610.0 MW), which reflects their substantial flexibility in terms of size and dominance in electric utility applications. Stokers tend to have the smallest capacities (an average of 14 MW nationwide), limiting their usefulness in utility applications compared to all of the other boiler types.

2.4 COAL CONSTITUENTS AND BY-PRODUCTS

Despite its attractiveness as a power plant fuel, coal has its drawbacks. As a solid fuel, coal is often more difficult and more costly to transport, store, and burn than oil or gas. Also, coal's many impurities require environmental control at various stages of the fuel cycle.

EXHIBIT 2-14

CHARACTERISTICS OF VARIOUS TYPES OF STOKERS

Stoker Type & Subclass	Typical Maximum Capacity Range (pph steam) a/	Burning Rate (Btu/hr/ft^2) b/	Characteristics
1. Spreader			Capable of burning a wide range of coals, best ability to follow fluctuating loads, high fly ash carry over, low load smoke.
- Stationary and dumping grate	20,000-80,000	450,000	
- Travelling grate	100,000-400,000	750,000	
- Vibrating grate	20,000-100,000	400,000	
2. Overfeed			Characteristics similar to vibrating-grate stokers except these stokers experience difficulty in burning strongly caking coals
- Chain grate and travelling grate	20,000-100,000	600,000	
- Vibrating grate	30,000-150,000	400,000	Low maintenance, low fly ash carry over, capable of burning wide variety of weakly caking coals, smokeless operation over entire range.
3. Underfeed			Capable of burning caking coals and a wide range of coals (including anthracite), high maintenance, low fly ash carry over, suitable for continuous-load operation.
- Single or double retort	20,000-30,000	400,000	
- Multiple retort			

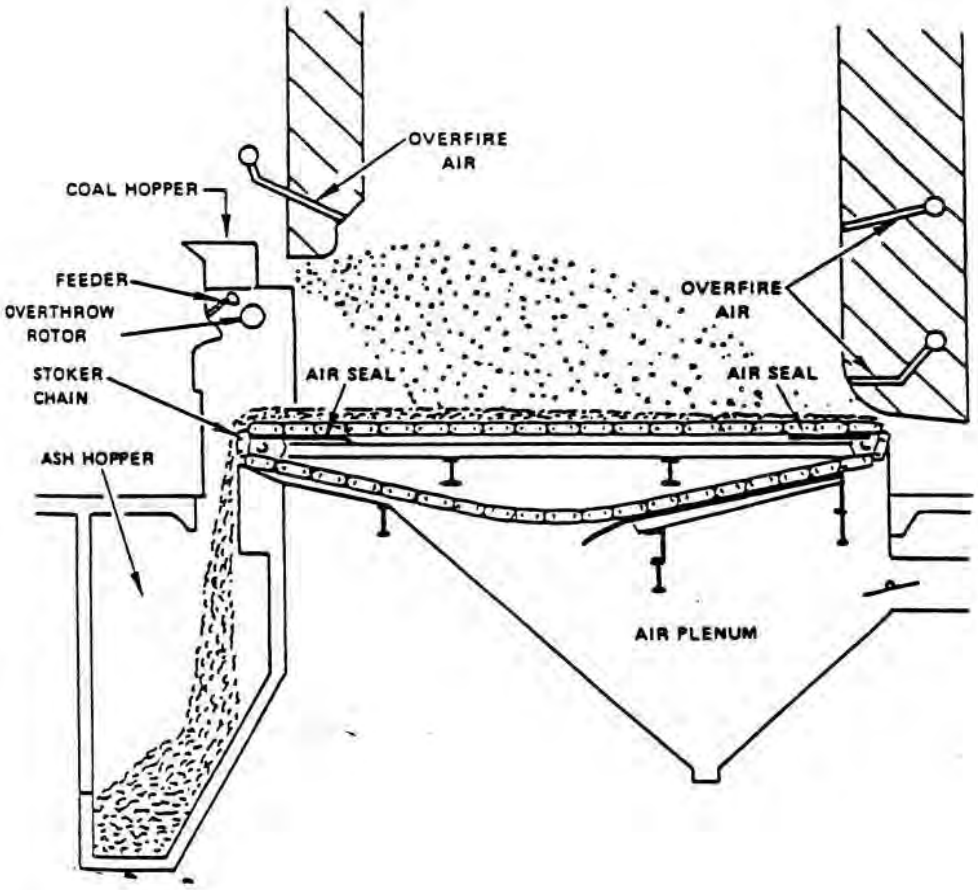
a/ pph = pounds steam/hr; 1 pph = 1000 Btu/hr.

b/ Maximum amount of Btus consumed per hour for each square foot of grate in the stoker.

Source: Meyers, Robert A. (Ed.), Coal Handbook, Marcel Dekker, Inc., New York, NY, 1981.

EXHIBIT 2-15

DIAGRAM OF A SPREADER STOKER



Source: Meyers, Robert A. (Ed.), Coal Handbook, Marcel Dekker, Inc., New York, NY, 1981.

EXHIBIT 2-16

TOTAL COAL BOILER CAPACITY BY EPA REGION
(%)

EPA Region	Pulverizers		Cyclone	Stoker	Other a/	Total
	Dry Bottom	Wet Bottom				
1	69.2	11.3	16.7	0.0	2.8	100.0
2	60.6	19.4	5.0	2.7	12.2	100.0
3	87.6	0.3	2.8	0.0	9.2	100.0
4	71.6	5.3	5.2	0.1	17.7	100.0
5	70.4	4.9	14.0	0.5	10.1	100.0
6	48.6	12.5	0.0	0.0	38.9	100.0
7	58.3	3.5	19.2	1.0	18.0	100.0
8	60.3	5.4	10.6	1.1	22.5	100.0
9	77.5	0.0	0.0	0.0	22.5	100.0
10	100.0	0.0	0.0	0.0	0.0	100.0
U.S. Total	69.3	5.3	8.3	0.4	16.7	100.0

a/ Includes unknown, or other boiler types.

Source: ICF Coal and Utilities Information System Database.

EXHIBIT 2-17

AVERAGE COAL BOILER SIZE BY TYPE OF BOILER AND BY EPA REGION (MW)

EPA Region	Pulverizers		Cyclone	Stoker
	Dry Bottom	Wet Bottom		
1	210.2	102.7	228.0	N/A
2	127.8	137.7	143.5	39.0
3	297.6	136.0	195.3	N/A
4	249.3	147.4	342.6	14.6
5	185.0	117.0	222.6	11.2
6	522.7	489.0	N/A	N/A
7	162.5	148.3	243.2	12.3
8	234.2	141.7	322.8	17.9
9	388.3	N/A	N/A	N/A
10	610.0	N/A	N/A	N/A
U.S. Total	231.8	162.9	243.2	14.0

N/A = Not applicable.

Source: ICF Coal and Utilities Information System Database.

These impurities are typically referred to as "ash", whether the reference is to some of the constituents that compose the coal itself prior to combustion or the waste products that result from its combustion. Some coal ash is inherent to the coal seam, while other ash comes from non-coal strata near the coal seam which are intermixed during mining. The coal consumed by electric utilities is generally over 10 percent ash.[24] At current rates of coal consumption, about 70 million tons of ash pass through coal-fired power plants each year.[25]

The ash generated at utility power plants is produced inside the boiler furnace from the inorganic components as the organic components of the coal combust. The types of ash produced can vary -- some ash is swept through the furnace with the hot flue gases to form fly ash, while some settles to the bottom of the boiler as bottom ash or slag. The amount of each type of ash produced depends upon the boiler configuration as described in Section 2.3 and the characteristics of the coal (see Chapter Three for further discussion of ash types).

Air quality regulations have long restricted the amount of fly ash that may be released through a power plant's stacks. Primarily through the use of electrostatic precipitators or bag houses, power plants collect fly ash particles, leaving the flue gases nearly particulate-free as they are emitted from the stack. As a result, the fly ash, bottom ash, and slag that is collected during and after combustion is approximately equal to the amount of ash in the coal prior to combustion.

For many power plants constructed since the 1970's, additional environmental controls also require that a portion of the sulfur oxides be removed from the flue gases. The dominant technology for removing sulfur oxides is known as flue gas desulfurization (FGD), in which alkaline agents, usually in liquid slurry form, are mixed with the flue gases to convert the sulfur into non-gaseous compounds. The resulting waste product is generally referred to as FGD sludge and can amount to 25 percent or more of the volume of coal consumed at a given plant.[26] In total, U.S. coal-fired power plants produce about 85 million tons of ash and FGD sludge per year. By the end of the century, this volume is expected to approximately double.

Exhibit 2-18 shows the number of coal-fired utility power plants and units that produce FGD wastes in each EPA region as of 1985. Regions 6, 8, and 9 have the highest proportion of both plants and units producing FGD wastes. For example, more than half of the coal-fired units in region 9 produce FGD wastes. The high proportion of FGD-producing plants in these regions is in part attributable to the fact that many of the coal-fired plants in these regions are relatively new and were required to incorporate scrubbers to meet air emission regulations.

Plants and units producing FGD waste represent a smaller percentage in other regions, primarily because these regions relied on coal-fired capacity for a major portion of their generation before units with FGD technology were installed. For example, the absolute number of both plants and units producing FGD waste is greatest in Region 4, reflecting this area's reliance on coal for generating electricity.

EXHIBIT 2-18

ELECTRIC UTILITY PRODUCTION OF FGD WASTES: 1985

EPA Region	# of Plants Producing FGD waste	Percent of Plants Producing FGD Wastes	# of Units Producing FGD Wastes	Percent of Units Producing FGD Wastes
1	0	0.0	0	0.0
2	3	17.6	3	7.9
3	5	8.8	13	9.4
4	11	12.0	26	9.8
5	10	5.8	16	3.6
6	8	20.5	23	35.9
7	6	9.1	11	7.9
8	9	18.8	25	29.4
9	3	23.1	12	57.1
10	0	0.0	0	0.0
Total U.S.	55	12.0	129	14.4

Source: Utility Data Institute Power Statistics Database.

Regions 1 and 10, at the other extreme, have no plants or units producing FGD wastes. These regions (New England and the Pacific Northwest) are not highly dependent upon coal and consequently, have relatively few coal-fired plants.

Numerous other types of wastes are produced during normal operation and maintenance at coal-fired power plants. These include, among others, boiler blowdown, coal pile runoff, cooling tower blowdown, demineralizer regenerants and rinses, metal and boiler cleaning wastes, pyrites, and sump effluents. These wastes are usually small in volume relative to ash and FGD sludge, but because they may have higher concentrations of certain constituents that may cause environmental concern, they also require care in handling and disposal. All of these wastes are discussed in greater detail in Chapter Three.

CHAPTER TWO

NOTES

[1] Edison Electric Institute, 1985 Statistical Yearbook.

[2] Energy Information Administration, Annual Energy Outlook 1985, DOE/EIA-0383(85), p. 50.

[3] A gigwatt-hour (Gwh) is one million kilowatt-hours; a kilowatt-hour is the amount of electricity generated by 1 kilowatt of electric generating capacity operating for one hour.

[4] Energy Information Administration, Annual Outlook for U.S. Electric Power, DOE/EIA-0474(86), 1986.

[5] Ibid.

[6] Ibid.

[7] Ibid.

[8] Ibid.

[9] Ibid.

[10] Ibid.

[11] Ibid.

[12] Ibid.

[13] Ibid.

[14] Ibid.

[15] Ibid.

[16] The major portion of this discussion is taken from Annual Outlook for U.S. Electric Power, DOE/EIA, 1986. See this document for further information.

[17] Ibid., page 5.

[18] Ibid.

[19] Ibid.

[20] Ibid.

[21] Energy Information Administration, Electric Power Annual 1984, DOE/EIA-0348(84), p. 24.

[22] Energy Information Administration, Electric Power Monthly, DOE/EIA-0226(85/12), December 1985, p. 21.

[23] For more detail, see Meyers, Robert A. (Ed.), Coal Handbook, Marcel Dekker, Inc., New York, New York, 1981, pp. 378-431.

[24] Energy Information Administration, Cost and Quality of Fuels for Electric Utility Plants 1984, DOE/EIA-0191(84), July 1985, p. 6.

[25] American Coal Ash Association.

[26] For example, a coal with 2 percent sulfur would produce approximately 80 pounds sulfur dioxide per ton of coal consumed. A limestone scrubber capturing 90 percent of the sulfur dioxide, assuming a stoichiometric ratio of 1.4 and a sludge moisture content of 50 percent, would product almost 500 pounds of FGD sludge per ton of coal consumed. See Appendix B for a detailed discussion of the methodologies used to determine this calculation.

CHAPTER THREE

WASTES GENERATED FROM COAL-FIRED ELECTRIC UTILITY POWER PLANTS

As part of EPA's responsibility under Section 8002(n) of RCRA, Congress directed that the study of wastes from the combustion of fossil fuels should include an analysis of "the source and volumes of such material generated per year." In response to this directive, this chapter examines the physical and chemical characteristics of the types and quantities of wastes that are generated currently and likely to be generated in the future.

3.1 OVERVIEW OF ELECTRIC UTILITY WASTES

As discussed initially in Chapter Two, the noncombustible material that remains after coal is burned is called ash. The proportion of noncombustible material in coal is referred to as the ash content. There are four basic types of wastes that can be produced directly from coal combustion: fly ash, bottom ash, boiler slag, and flue gas desulfurization (FGD) sludge. The smaller ash particles entrained by the flue (exhaust) gas are referred to as fly ash and are produced in varying degrees by all plants. Larger ash particles that settle on the bottom of the boiler will form either bottom ash (if the particles have never completely melted) or boiler slag (if the ash particles have melted), depending on the furnace design. Another waste product, called FGD sludge, is generated when some of the sulfur dioxide (formed when the sulfur present in the coal combines with oxygen during combustion) is removed from other flue gases. This removal process is required by the Clean Air Act Amendments of 1979, which revised the New Source

Performance Standards for any electric utility boiler constructed after September 1978. These plants are required to remove 90 percent of the sulfur dioxide, which is usually accomplished with a flue gas desulfurization (FGD, or scrubber) system. Because they are generated in very large quantities, these four waste materials -- fly ash, bottom ash, boiler slag, and FGD sludge -- are referred to by the industry as high-volume wastes. This term will be used throughout this study to be consistent with the terminology that is commonly used for these wastes.

Electric utility power plants also generate waste streams that the industry typically calls low-volume wastes, which are formed during equipment maintenance and water purification processes. Types of low-volume wastes generated by coal-fired power plants include boiler blowdown, coal pile runoff, cooling tower blowdown, demineralizer regenerants and rinses, metal and boiler cleaning wastes, pyrites, and sump effluents. Because it is common industry terminology, the term "low-volume wastes" will be used throughout this report; however, some of these wastes (such as cooling tower blowdown) can be generated in substantial quantities, although generally in smaller quantities than high-volume wastes.

The remainder of this chapter describes each type of high-volume and low-volume waste stream, the various methods of collection used for each, the volumes produced, and the physical and chemical characteristics that determine the waste's behavior during disposal and its potential to leach.

3.2 HIGH-VOLUME WASTES

High-volume coal combustion utility wastes are those waste streams generated in the boiler furnace -- fly ash, bottom ash, and boiler slag -- and in the cleaning of coal combustion flue gas. The following sections describe the volumes and the physical and chemical characteristics of these high-volume waste streams.

3.2.1 Ash

The noncombustible waste material that remains after coal is burned is referred to as ash. Some noncombustible materials are characteristic of the coal itself, originating from the chemical elements in the plants from which the coal was formed. These materials generally account for no more than two percent of the ash content of the coal. Other noncombustible materials extraneous to the coal, such as minerals lodged in the coal seam during or after its geologic formation and rocks near the coal seam that are carried away with the coal during mining, are burned during the fuel combustion process along with the coal itself. These materials account for most of the ash content.

3.2.1.1 How Ash is Generated

The type of ash produced from a boiler is determined by the type of coal that is burned and the design of the boiler furnace. As discussed in Chapter Two, the major types of boilers used by electric utilities are wet-bottom pulverizers, dry-bottom pulverizers, cyclone-fired boilers, and stokers.

Pulverizers are the most widely used boilers in the electric utility industry because they can burn many different types of coal. Due to the very fine consistency of the coal after it is pulverized, the ash particles are easily carried out of the boiler along with the flue gases, resulting in a relatively large proportion of fly ash.

The amount of fly ash that accumulates in a pulverizer depends on whether it is dry-bottom or wet-bottom.[1] In dry-bottom pulverizers, which constitute the majority of electric utility boilers, ash particles in the coal generally do not melt during the combustion process because the ash fusion temperature (i.e., the melting point) is higher than the operating temperature in the boiler. In dry-bottom pulverizers, therefore, about 80 percent of the fine ash remains in the flue gas as fly ash. The remaining ash settles to the bottom of the boiler (hence the term bottom ash) where it is collected at a later time. In wet-bottom pulverizers, about 50 percent of the ash exits the boiler as fly ash, while the other 50 percent remains in the furnace. However, ash particles that remain in wet-bottom pulverizers become molten; this boiler slag remains in a molten state until it is drained from the boiler bottom.

Cyclone-fired boilers burn larger-sized coal particles than do pulverizers, since partial crushing is the only preparation required prior to injection into the furnace. The amount of fly ash that is generated in a cyclone boiler is less than that generated in a pulverizer because of the larger-sized coal particles and the design of the cyclone boiler. Because the air circulation within the boiler furnace is designed to create a cyclone-like

vortex, the coal particles have a tendency to contact the boiler walls. The operating temperature is high enough to melt the ash so that it adheres to the furnace walls as liquid slag. Excess slag continually drains to the bottom of the furnace, where it is removed for disposal. Only 20 to 30 percent of the ash formed in a cyclone boiler leaves the boiler as fly ash.

A few older and smaller power plants have stoker-type boilers, in which coal is burned on or immediately over a grate in the furnace. Stokers are designed to burn coals that do not contain too many small particles (fines), which can tend to smother the fire. Because there are fewer small particles, the amount of fly ash is reduced. For example, in a spreader stoker, the most common type of stoker boiler, the coal is uniformly fed over the fire in a manner that enables suspension burning of the finer pieces, while heavier pieces of coal fall onto the grate for further combustion. The large amount of coal that is burned on the grate reduces the amount of fly ash; the ash produced in a spreader stoker is generally about 50 percent fly ash and 50 percent bottom ash.

3.2.1.2 Methods of Ash Collection

As the flue gas leaves the boiler, it is passed through a mechanical ash collector to remove some of the fly ash particles. A mechanical ash collector operates by exerting centrifugal force on the fly ash particles, throwing them to the outside wall of the collector where they can be removed. These collectors are effective mainly for capturing the larger fly ash particles. To remove the smaller particles, the flue gas must then pass through some

other type of particulate control device, such as an electrostatic precipitator, a baghouse, or a wet scrubber.

The electrostatic precipitator (ESP) is the most common device for fine ash collection. ESPs operate by applying an electrical charge to the fly ash particles. In the presence of an intense electrical field, the charged particles are attracted to a grounded collection electrode. The collected dust is then discharged to a storage hopper by a process called rapping that dislodges the collected particles. ESPs are most efficient when coal with high sulfur content is used because the sulfur dioxide in the flue gas helps retain the electrical charge. When properly designed and maintained, an ESP is capable of collecting over 99 percent of the ash present in the flue gas.[2]

When coal with lower sulfur content is burned, baghouses (also called fabric filters) are often more appropriate to use as fly ash collection devices. If operated efficiently, they also can remove over 99 percent of the ash from the flue gas.[3] In this system, the flue gas passes through a filter that traps the ash particles. The ash builds up on the filter, forming a filter cake. As this process continues, the ash collection efficiency tends to increase as it becomes more difficult for particles to pass through the filter material. Periodically, the cake is dislodged from the filters, which reduces efficiency until buildup occurs again.

Some power plants remove fly ash by the wet scrubbing method, in which liquids are used to collect the ash. In one method, the ash particles are removed from the flue gas stream by contacting them with a scrubbing liquid in a spray tower. This process forms an ash slurry, which is then discharged.

Alternatively, fly ash particles may be dislodged from the walls of the scrubber by a liquid flushing of the scrubber. Because the operation of a scrubber is very plant-specific, the collection efficiency of wet scrubbers varies, though wet scrubbers are generally not as efficient as ESPs and baghouses. The advantage of wet scrubbers, however, is that they can also be used simultaneously to collect sulfur oxides from the flue gas system.

Ash particles that do not escape as fly ash become bottom ash or boiler slag. In dry-bottom pulverizers and stokers, the temperatures are low enough to allow the molten ash to cool and reform into dry, solid ash particles, or bottom ash. In smaller boilers of this type, the ash falls onto a grate, which then is opened, allowing the ash to drop into a flat-bottom hopper. The large quantities of bottom ash produced in larger boilers often require hoppers with sloped sides for self-feeding. Some hoppers may contain water to quench the ash and to facilitate disposal.

In cyclone-fired boilers and wet-bottom pulverizers, the liquified ash particles that fall to the bottom of the boiler during combustion remain in a molten state and coalesce into large masses (called slag), which then drop onto the boiler floor. The slag is tapped into a water-filled hopper, or slag tank, which is periodically emptied and the slag disposed. Slag tanks for cyclone-fired boilers are similar to those used for pulverizers but have a higher relative capacity because a greater percentage of the ash in cyclones becomes boiler slag.

3.2.1.3 Quantities of Ash Generated

Nearly all of the noncombustible material in coal ends up as fly ash, bottom ash, or boiler slag. As mentioned earlier, the coal industry and the electric utility industry refer to this material as a coal's ash content. As a result, the volume of ash generated is directly related to the amount of coal consumed and the ash content of the coal. The ash content of coal will vary according to several factors, including coal-producing region, coal rank (i.e., bituminous, subbituminous, anthracite, or lignite), mine, seam, and production method. Although the proportion of ash in coal may range from 3 to 30 percent, the industry-wide average for electric utility power plants is 10.1 percent.[4] Exhibit 3-1 shows the average ash content of coal that was delivered to coal-fired power plants in 1985 for some of the major coal-producing regions.

In 1984, electric utilities generated about 69 million tons of coal ash. Ash generation is expected to increase considerably, to about 120 million tons in the year 2000, an increase of about 72 percent over 1984 levels. This increase can primarily be attributed to the increase in the demand for coal by electric utilities. While there is some uncertainty over the amount of coal that will be consumed by electric utility power plants, coal-fired electricity generation is likely to increase significantly. For example, one estimate indicates that by the year 2000 electric utility power plants will burn over one billion tons of coal to meet 61 percent of total electricity demand,[5] an increase of 70 percent over the 664 million tons consumed in 1984.[6] Exhibit 3-2 shows historical and forecasted future ash generation by coal-fired electric power plants.

EXHIBIT 3-1

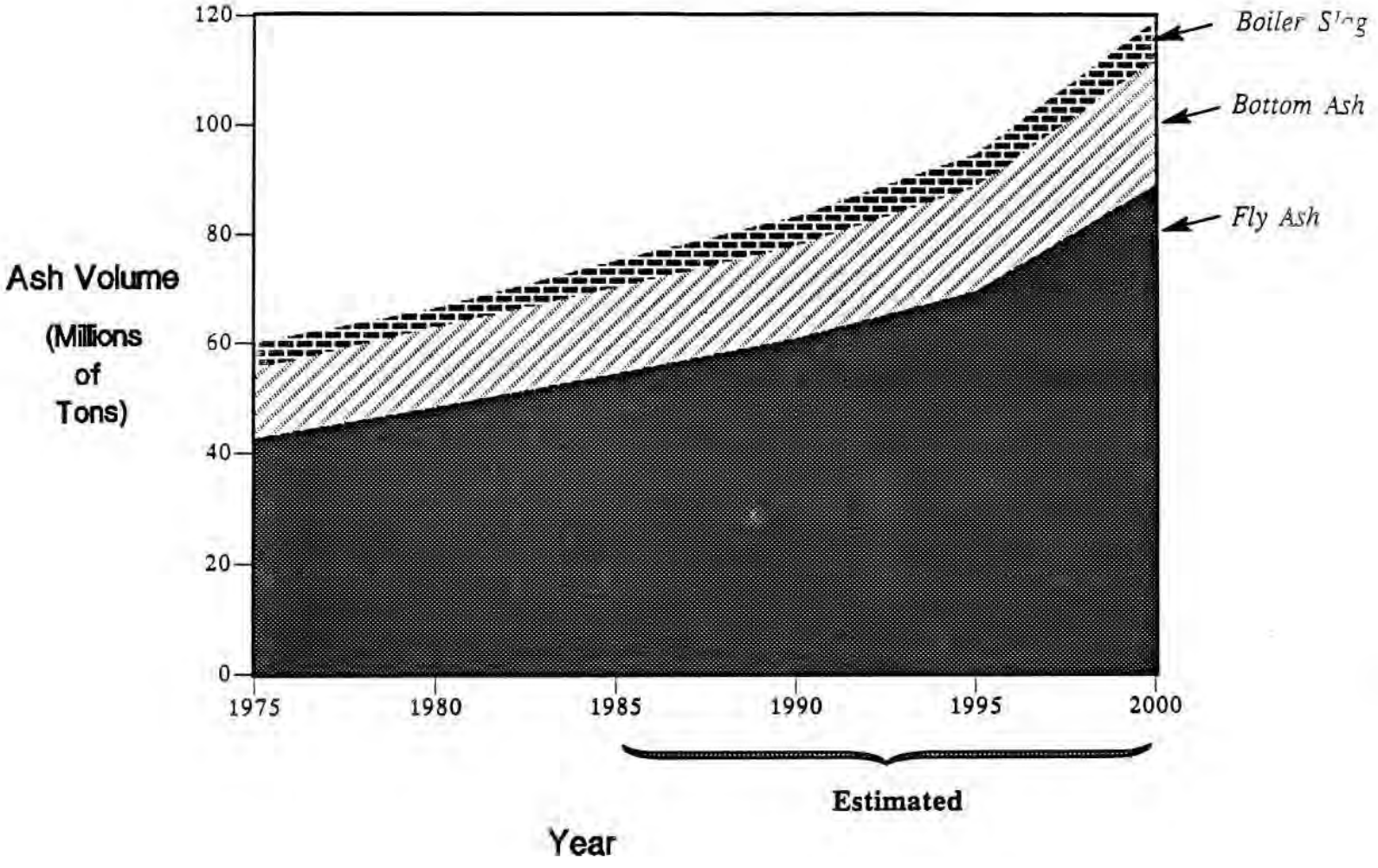
REPRESENTATIVE ASH CONTENTS BY PRODUCING REGION AND COAL RANK: 1985

Coal Rank and Region	Percent Ash
Anthracite	
Northeastern Pennsylvania	29.4
Bituminous	
Western Pennsylvania	10.9
Northern West Virginia	10.4
Ohio	11.3
Eastern Kentucky	9.9
Alabama	12.2
Illinois	9.7
Colorado	6.2
Utah	9.4
Arizona	8.9
Subbituminous	
Wyoming	5.9
New Mexico	18.8
Lignite	
Texas	15.8
North Dakota	9.0
U.S. Average	10.1

Source: Energy Information Administration, Cost and Quality of Fuels for Electric Utility Plants 1985, DOE/EIA-0191(85), July 1986.

EXHIBIT 3-2

VOLUME OF ASH GENERATED BY COAL-FIRED
ELECTRIC UTILITY POWER PLANTS
1975 - 2000



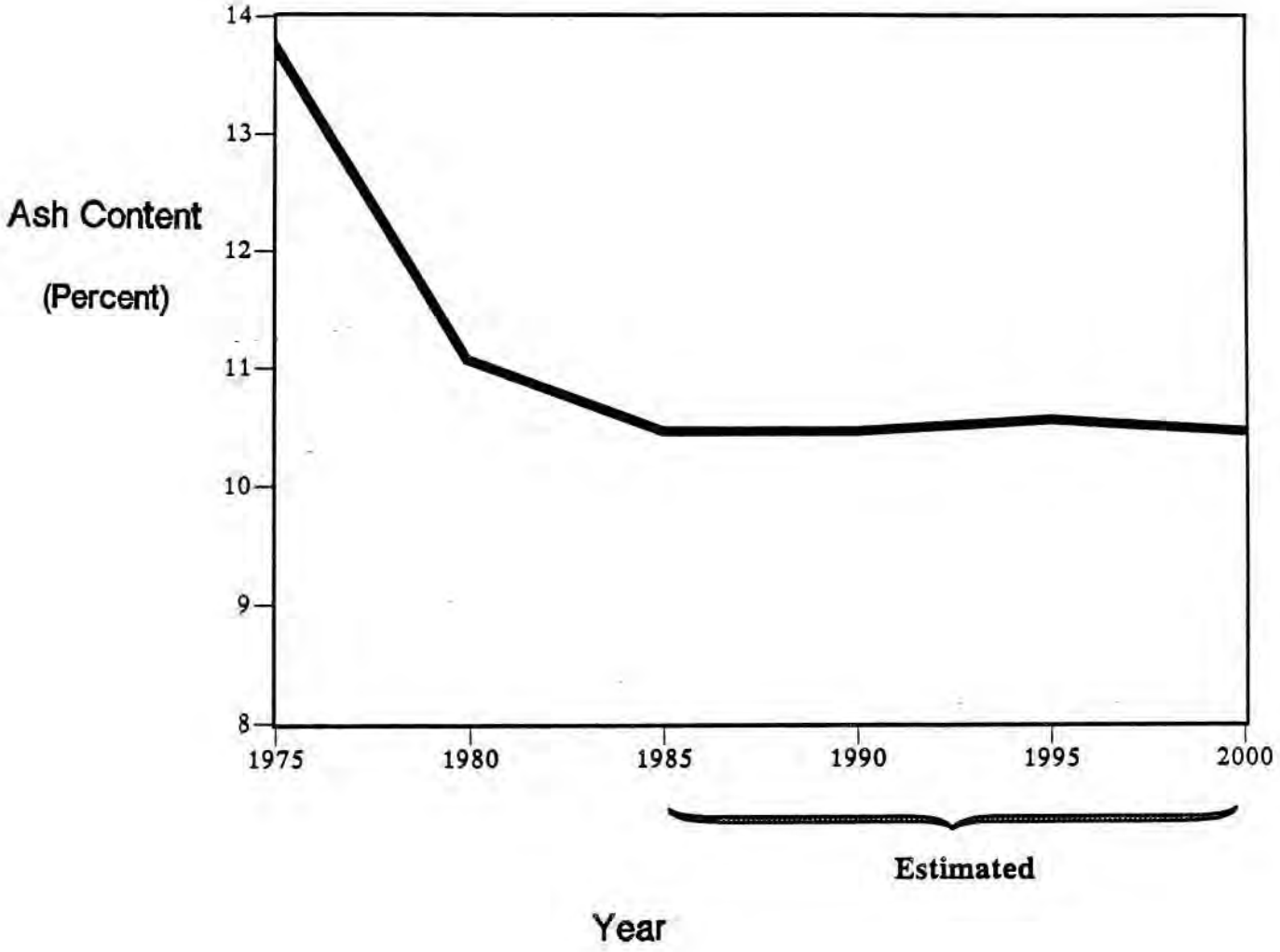
Sources: 1975-1984: American Coal Ash Association.
1985-2000: ICF Incorporated. See Appendix B for in-depth discussion of the methodologies used to develop these estimates.

The average ash content of coal burned by electric utilities has declined from about 14 percent to slightly more than 10 percent over the past decade (see Exhibit 3-3). To meet particulate emission standards and to lower certain operating and maintenance costs, more electric utilities are now choosing to burn coal with lower ash contents. Although some coals are naturally low in ash, producers and/or utilities can also reduce ash content by cleaning the coal.[7] In some cases, cleaning can reduce ash content by as much as 50 to 70 percent. At present, utilities clean about 35 percent of all the coal they consume; most of the coal that is cleaned comes from eastern and midwestern underground bituminous coal-mining operations. Another reason for the increased use of coal with lower average ash content is the growth in Western coal production, particularly in the Powder River Basin area of Montana and Wyoming. These coals are naturally low in ash content, and little ash is extracted during the mining process.

The quantity of fly ash and bottom ash produced is likely to increase faster over time than the quantity of boiler slag because most new coal-fired plants will employ dry-bottom pulverizer boilers, which generate fly ash and bottom ash rather than boiler slag. Because dry-bottom pulverizers are capable of burning coal with a wide range of ash fusion temperatures,[8] they are able to burn a greater variety of coals compared with cyclone boilers and wet-bottom pulverizers. Another advantage of dry-bottom pulverizers is that they produce less nitrogen oxide emissions than do other boiler types, which enables electric utilities to meet requirements for nitrogen oxide emissions control more easily.

EXHIBIT 3-3

AVERAGE ASH CONTENT OF COAL BURNED BY ELECTRIC UTILITY POWER PLANTS IN THE U.S. 1975 - 2000



Source: 1975-1984: Energy Information Administration, Cost and Quality of Fuels for Electric Utility Plants.

1985-2000: ICF Incorporated. See Appendix B for in-depth discussion of the methodologies used to develop these estimates.

3.2.1.4 Physical Characteristics of Ash

The physical characteristics of coal combustion ash of interest are particle size and distribution, compaction behavior, permeability, and shear strength. Exhibit 3-4 provides representative ranges of values for these characteristics of fly ash, bottom ash, and boiler slag.

The greater the assortment of particle sizes in the material, the more it can be compacted to achieve greater density and shear strength and lower permeability. Generally, fly ash is similar in size to silt. Most fly ash particles are between 5 and 100 microns in diameter; within a single sample, the largest particles may be 200 times larger than the smallest particles.[9] The size of bottom ash and boiler slag particles can range from that of fine sand to fine gravel, or about 0.1 to 10 millimeters.[10]

Compaction behavior refers to the amount of settling that takes place after disposal and the rate at which such settling occurs. Compressibility, density, and moisture content are factors affecting compaction behavior.[11] When compacted and dry, most fly ash and bottom ash behave very similarly to cohesive soil.

Permeability reflects the rate at which water will seep through the waste material in a given period of time and provides a good first estimate of the rate and quantity of leachate migration. A number of factors can influence the degree of permeability, such as the size and shape of the waste particles, the degree of compaction, and the viscosity of the water. Properly compacted fly ash often has low permeability, similar to that of clay, while the

EXHIBIT 3-4

REPRESENTATIVE RANGES OF VALUES FOR THE PHYSICAL CHARACTERISTICS OF FLY ASH, BOTTOM ASH, AND BOILER SLAG

	Fly Ash	Bottom Ash/ Boiler Slag
Particle Size (mm)	0.001-0.1	0.1-10
Compaction Behavior:		
Compressibility (%)	1.8	1.4
Dry Density (lbs/ft^3)	80-90	80-90
Permeability (cm/sec)	10^{-6}-10^{-4}	10^{-3}-10^{-1}
Shear Strength		
Cohesion (psi)	0-170	0
Angle of Internal Friction (^{o})	25-45	25-45

Sources: For compressibility values, Arthur D. Little, Full-Scale Field Evaluation of Waste Disposal from Coal-Fired Electric Generating Plants, Volume I, Prepared for U.S. Environmental Protection Agency, June 1985, p. 3-29. For other values, Tetra Tech Inc., Physical-Chemical Characteristics of Utility Solid Wastes, Prepared for Electric Power Research Institute, EPRI EA-3236, September 1983, p. 3-3 - 3-8.

permeability of bottom ash is usually slightly higher. Boiler slag is higher still, having a permeability comparable to that of fine gravel.

Shear strength is an important determinant of the shape and structural stability of wastes disposed in landfills; a strong material (i.e., one with high shear strength) can form steep slopes and support heavy loads from above. Two indicators of shear strength are cohesion, a measure of the attraction between particles due to electrostatic forces, and the angle of internal friction, an indicator of the friction between particles. Dry, nonalkaline ash has no cohesion. Dry ash that is alkaline demonstrates some cohesion and, when compacted, increases in strength over time. The angle of internal friction associated with ash varies with the degree of compaction, although it is similar to that for clean, graded sand.

3.2.1.5 Chemical Characteristics of Ash

The chemical composition of ash is a function of the type of coal that is burned, the extent to which the coal is prepared before it is burned, and the operating conditions of the boiler. These factors are very plant- and coal-specific.

In general, over 95 percent of ash is made up of silicon, aluminum, iron, and calcium in their oxide forms. Magnesium, potassium, sodium, and titanium are also present to a lesser degree. Exhibit 3-5 shows the concentration of these major elements typically found in fly ash, bottom ash, and boiler slag.

Ash also contains many other elements in much smaller quantities. The types and proportions of these trace elements are highly variable and not

EXHIBIT 3-5

LOW AND HIGH CONCENTRATIONS OF MAJOR CHEMICAL CONSTITUENTS FOUND IN ASH GENERATED BY COAL-FIRED POWER PLANTS (parts per million)

	Fly Ash		Bottom Ash/Boiler Slag	
	Low	High	Low	High
Aluminum	11,500	144,000	88,000	135,000
Calcium	5,400	177,100	8,400	50,600
Iron	7,800	289,000	27,000	203,000
Magnesium	4,900	60,800	4,500	32,500
Potassium	1,534	34,700	7,300	15,800
Silicon	196,000	271,000	180,000	273,000
Sodium	1,180	20,300	1,800	13,100
Titanium	400	15,900	3,300	7,210

Source: Utility Solid Waste Activities Group, Report and Technical Studies on the Disposal and Utilization of Fossil-Fuel Combustion By-Products, Appendix A, Submitted to the U.S. Environmental Protection Agency, October 26, 1982, p. 31.

readily categorized. Concentrations for various trace elements in coal ash are shown in Exhibit 3-6, which indicates the potential range of values and median concentration for such trace elements for coals from different regions of the U.S. A summary of how the concentration of elements in ash varies according to coal source is shown in Exhibit 3-7. For example, Eastern and Midwestern coal ashes usually contain greater amounts of arsenic, selenium, chromium, and vanadium than do Western coal ashes, while Western coals have larger proportions of barium and strontium. Coal mining and cleaning techniques can reduce the amount of trace elements that are ultimately found in the ash after combustion. For example, in some cases, coal cleaning can remove more than half of the sulfur, arsenic, lead, manganese, mercury, and selenium that is contained in the coal prior to combustion.

The proportions of elements contained in fly ash, bottom ash, and boiler slag can vary. Exhibit 3-8 provides ranges and median values for element concentrations in different types of ash -- bottom ash and/or boiler slag, and fly ash. The concentrations of elements formed in fly ash are shown for two types -- the larger particles removed from the flue gas by mechanical collection and the smaller particles removed with an electrostatic precipitator or a baghouse (see Section 3.2.1.2 for more detail on methods of ash collection). For example, much higher quantities of arsenic, copper, and selenium are found in fly ash than are found in bottom ash or boiler slag. The distribution of elements among the different types of ash is largely determined by the firing temperature of the boiler relative to the coal's ash fusion temperature, which in turn affects the proportions of volatile elements that end up in fly ash and bottom ash. Some elements, such as sulfur, mercury, and chlorine, are almost completely volatilized and leave the boiler

EXHIBIT 3-6

ELEMENT CONCENTRATIONS IN ASH FROM THREE GEOGRAPHIC SOURCES
(milligrams per kilogram)*

Element	Eastern Coal		Midwestern Coal		Western Coal	
	Range	Median	Range	Median	Range	Median
Arsenic	2.0-279	75	0.50-179	54	1.3-129	18
Barium	52-2200	892	300-4300	905	300-5789	2700
Boron	10.0-580	121	10-1300	870	41.9-1040	311
Cadmium	0.10-8.24	1.59	0.50-18	2.6	0.10-14.3	1.01
Chromium	34-437	165	70-395	172	3.4-265	45
Cobalt	6.22-79	40.6	19-70	35.7	4.9-69	13.0
Copper	3.7-349	136	20-330	125	29-340	74.8
Fluorine	0.40-89	8.8	3.2-300	75	0.40-320	50.1
Lead	1.3-222	18.0	3.0-252	149	0.40-250	26.1
Manganese	79-430	190	194-700	410	56.7-769	194
Mercury	0.02-4.2	0.192	0.005-0.30	0.044	0.005-2.5	0.067
Molybdenum	0.84-51	15.0	7.0-70	43	1.4-100	12.0
Nickel	6.6-258	78	26-253	121	1.8-229	38.0
Selenium	0.36-19.0	8.05	0.08-19	7.0	0.13-19.0	4.1
Silver	0.25-8.0	0.695	0.10-1.20	0.39	0.040-6.0	0.26
Strontium	59-2901	801	30-2240	423	931-3855	2300
Thallium	7.0-28.0	25.0	2.0-42	16.0	0.10-3.50	1.06
Vanadium	110-551	269	100-570	270	11.9-340	94
Zinc	16-1420	163	20-2300	600	4.0-854	71

* Values shown are for all types of ash combined.

Source: Tetra Tech Inc., Physical-Chemical Characteristics of Utility Solid Wastes, EPRI EA-3236, September 1983.

EXHIBIT 3-7

EFFECT OF GEOGRAPHIC COAL SOURCE ON ASH ELEMENT CONCENTRATION

Element	Concentration Pattern
Arsenic	low in western coal ash; eastern and midwestern coal ashes indistinguishable
Barium	highest in western coal ash
Cadmium	most concentrated in midwestern coal ash
Chromium	low in western coal ash; eastern and midwestern coal ashes indistinguishable
Mercury	highest in eastern coal ash; all distributions highly skewed toward high concentrations
Lead	highest in midwestern coal ash
Selenium	similar in eastern and midwestern coal ash; lower in western coal ash
Strontium	greater in eastern than in midwestern coal ash; greater still in western coal ash
Vanadium	similar in eastern and midwestern coal ash; lower in western coal ash
Zinc	greater in eastern than in western coal ash; greater still in midwestern coal ash

Source: Tetra Tech, Inc., Physical-Chemical Characteristics of Utility Solid Wastes, EPRI EA-3236, September 1983, p. 3-30.

EXHIBIT 3-8

ELEMENT CONCENTRATIONS IN THREE TYPES OF ASH
(milligrams per kilogram)

Element	Bottom Ash/Boiler Slag		Fly Ash			
			Mechanical Hopper Ash		Fine Fly Ash	
	Range	Median	Range	Median	Range	Median
Silver	0.1-.51	0.20	0.08-4.0	0.70	0.04-8.0	0.501
Arsenic	.50-168	4.45	3.3-160	25.2	2.3-279	56.7
Boron	41.9-513	161	205-714	258	10.0-1300	371
Barium	300-5789	1600	52-1152	872	110-5400	991
Cadmium	0.1-4.7	0.86	0.40-14.3	4.27	0.10-18.0	1.60
Cobalt	7.1-60.4	24	6.22-76.9	48.3	4.90-79.0	35.9
Chromium	3.4-350	120	83.3-305	172	3.6-437	136
Copper	3.7-250	68.1	42.0-326	130	33.0-349	116
Fluorine	2.5-104	50.0	2.50-83.3	41.8	0.40-320	29.0
Mercury	0.005-4.2	0.023	0.008-3.00	0.073	0.005-2.50	0.10
Manganese	56.7-769	297	123-430	191	24.5-750	250
Lead	0.4-90.6	7.1	5.2-101	13.0	3.10-252	66.5
Selenium	.08-14	0.601	0.13-11.8	5.52	0.60-19.0	9.97
Strontium	170-1800	800	396-2430	931	30.0-3855	775
Vanadium	12.0-377	141	100-377	251	11.9-570	248
Zinc	4.0-798	99.6	56.7-215	155	14.0-2300	210

Source: Tetra Tech, Inc., Physical-Chemical Characteristics of Utility Solid Wastes, EPRI EA-3236, September 1983, p. 3-24.

in the flue gas rather than remaining in the bottom ash or boiler slag. Some of these more volatile elements may condense on the surface of the fly ash particles as the flue gas cools.

3.2.2 FGD Sludge

Another waste stream often generated in large volumes by coal-fired utility power plants is FGD sludge, which is created when utilities remove sulfur oxides from the flue gases. Emissions of sulfur oxides in the flue gases are due to the oxidation of sulfur during coal combustion. State and Federal regulations require power plants to control the amount of sulfur oxides released through the stack. To meet the applicable requirements most power plants use coals whose inherent sulfur content is low. If the sulfur content is so low that additional sulfur dioxide removal is not needed, then FGD sludge is not produced.

Present requirements for all new coal-fired plants, however, not only limit the amount of sulfur oxides that can be emitted, but also mandate a percentage reduction in the amount of sulfur dioxide emissions.[12] This requirement will substantially increase the number of sulfur dioxide control systems in use. The primary method of sulfur dioxide control currently available is a flue gas desulfurization (FGD) system through which the flue gases pass before being emitted from the stack. The wastes produced by this system are called FGD (scrubber) sludge. Other methods of control include newer technologies such as fluidized bed combustion (FBC) and limestone injection multistage burners (LIMB).[13] The technical and economic feasibility of the latter two technologies are currently under evaluation by private industry and the U.S.

Department of Energy. If these technologies do become more widely available, they also will produce substantial volumes of wastes.

3.2.2.1 Methods of FGD Sludge Collection

There are two major types of FGD (scrubber) systems. Non-recovery systems produce a waste material for disposal. Recovery systems produce recyclable by-products. Exhibit 3-9 illustrates the different types of FGD systems currently in use. Non-recovery systems, which account for 95 percent of the scrubber systems now in use by electric utilities, are further classified as wet or dry systems. In wet non-recovery scrubber systems, the flue gas contacts an aqueous solution of absorbents, thereby producing waste in a slurry form. The wastes generated by dry non-recovery systems contain no liquids.

Direct lime and limestone FGD systems are the most common wet non-recovery processes. With these systems, flue gases pass through a fly ash collection device and into a contact chamber where they react with a solution of lime or crushed limestone in the form of a slurry. The slurry circulates between the contact chamber and a separate reaction tank, where the reagents are added. From the reaction tank, the slurry is fed to a thickening and dewatering device to be prepared for disposal. After dewatering, the resulting liquid is recycled back to the reaction tank and the sludge solids are removed for disposal. Under certain conditions, direct lime and limestone scrubbers have been able to remove over 95 percent of the sulfur dioxide in the flue gas.[14]

EXHIBIT 3-9

MAJOR TYPES OF FLUE GAS DESULFURIZATION SYSTEMS

Non-Recovery		Recovery	
Wet	Dry	Wet	Dry
Direct Lime	Spray Drying	Wellman-Lord	Alumina/Copper* Sorbent
Direct Limestone	Dry Sorbent Injection*	Magnesium Oxide	Activated Carbon* Sorbent
Alkaline Fly Ash			
Dual-Alkali			

*Systems are currently in development and testing phases, and are not as yet being used commercially.

Source: Tetra Tech Inc., Physical-Chemical Characteristics of Utility Solid Wastes, Prepared for Electric Power Research Institute, EPRI EA-3236, September 1983, pp. 4-1 - 4-4.

A variation on the direct lime and limestone systems is the alkaline fly ash scrubber. Several western power plants that burn coal containing high-alkaline ash use these systems, which can improve sulfur dioxide removal. Rather than being collected by a separate upstream device (such as an ESP or baghouse), fly ash particles remain in the gas stream as it passes through the scrubber. In the scrubber, the alkaline fly ash, augmented with an alkaline lime/limestone slurry, acts to remove sulfur oxides. Alkaline fly ash scrubbers are not as efficient as direct lime and limestone systems, removing on average only about 40 percent of the sulfur dioxide.[15]

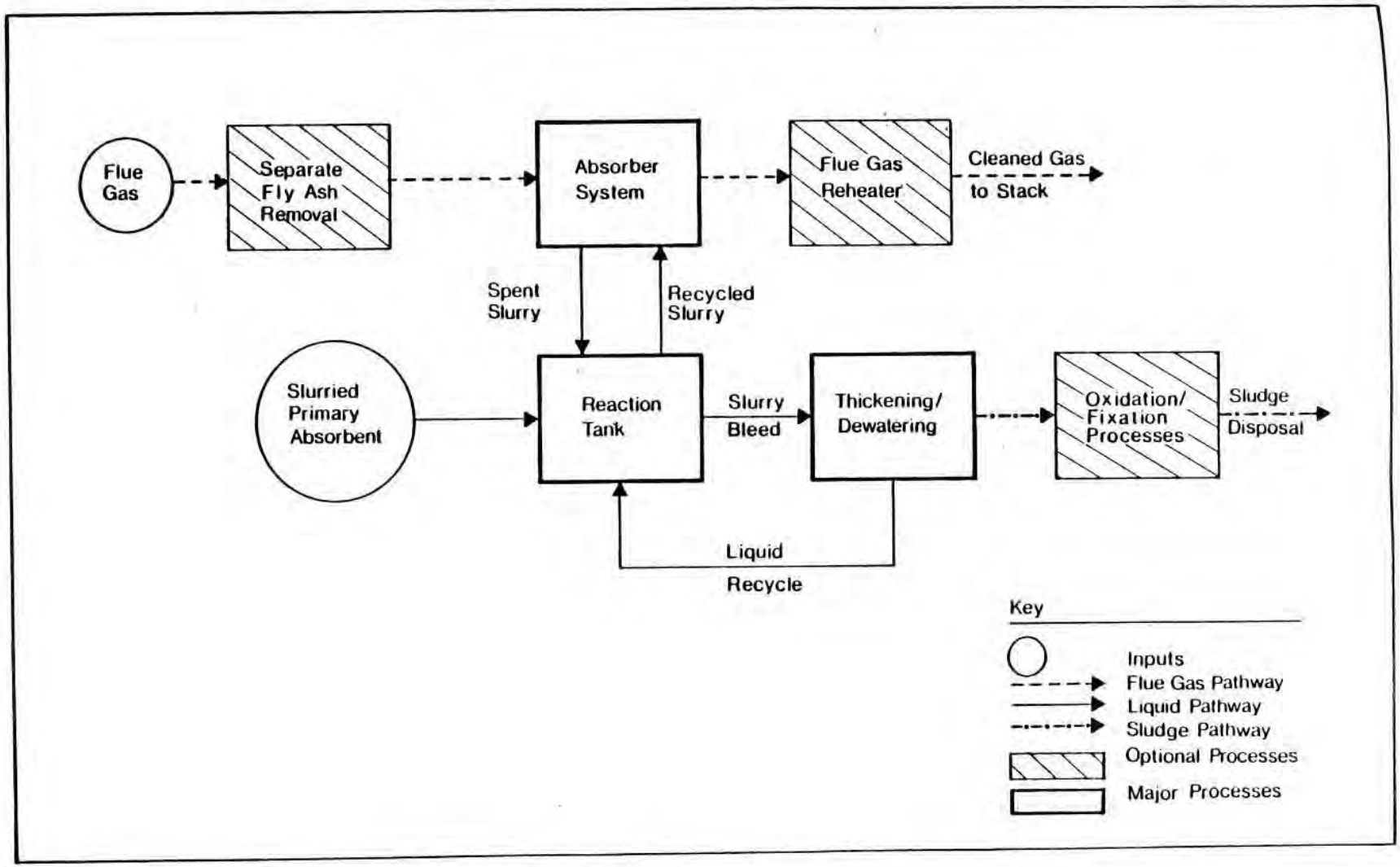
Another wet non-recovery system is the dual-alkali process. These scrubbers operate in much the same manner as the direct lime and limestone scrubbers. However, dual-alkali systems use a solution of sodium salts as the primary reagent to which lime is added for additional absorption. The soluble sodium salts are then recycled to the scrubber system and the insoluble portion of the slurry is left to settle so that it can be collected and disposed. Like direct lime and limestone systems, dual-alkali scrubbers remove up to 95 percent of the sulfur dioxide.[16]

Exhibit 3-10 presents a diagram of the operations of a wet FGD system. The flows shown for the flue gas, absorbent, slurry, and sludge are essentially the same for direct lime, direct limestone, alkaline fly ash, and dual-alkali systems.

At present, the two most popular methods of dry scrubbing under investigation are spray-drying and dry sorbent injection, although only the spray-drying process is now in commercial use at electric utility power plants.

EXHIBIT 3-10

FLOW DIAGRAM OF WET FLUE GAS DESULFURIZATION SYSTEM



Source: Tetra Tech Inc., Physical-Chemical Characteristics of Utility Solid Wastes, Prepared for Electric Power Research Institute, September 1983, p. 4-3.

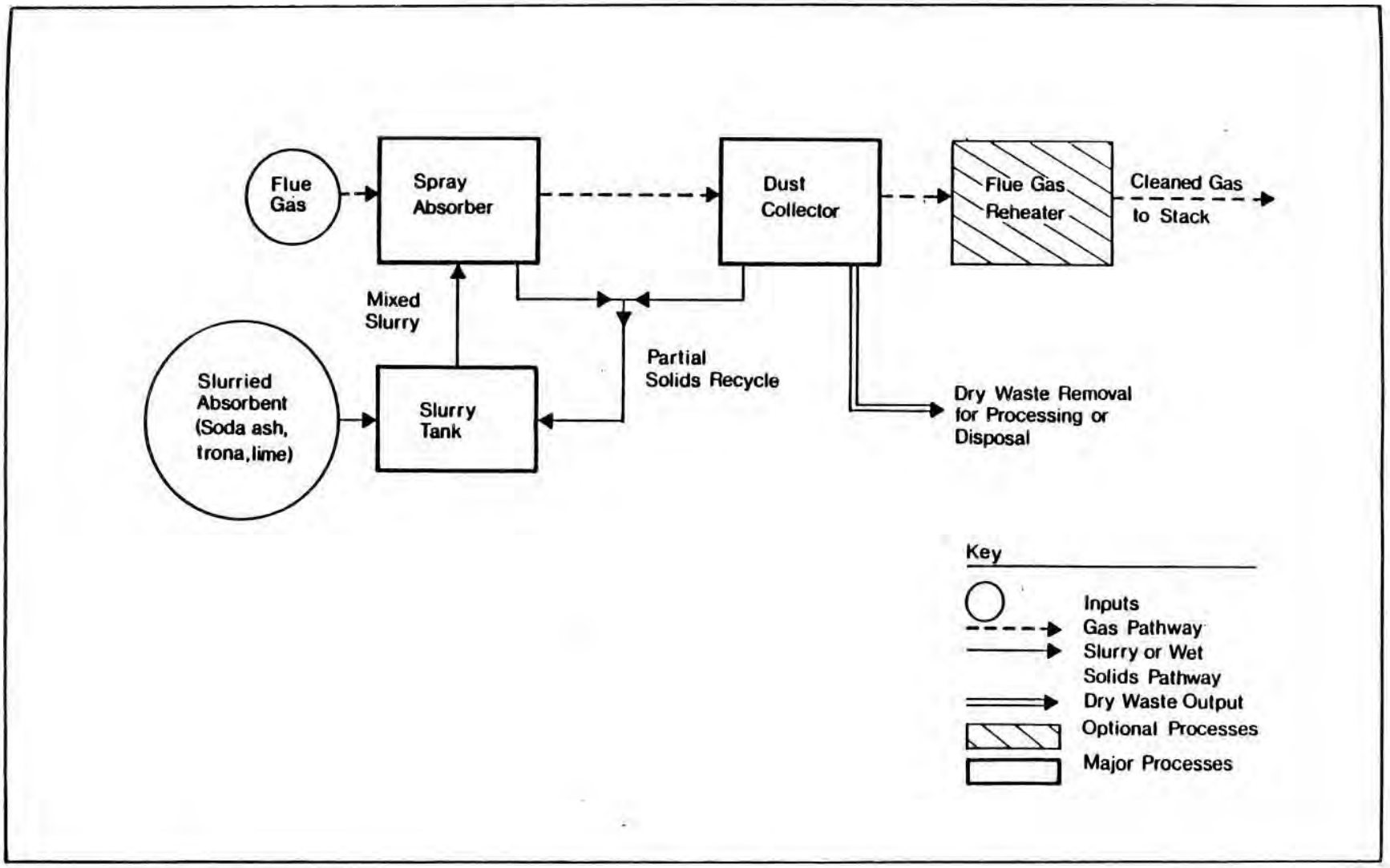
A flow diagram of a spray-drying system is presented in Exhibit 3-11. With this system, a fine spray of an alkaline solution is injected into the flue gas as it passes through a contact chamber, where the reaction with the sulfur oxides occurs. The heat of the flue gas evaporates the water from the absorbent solution, leaving a dry powder. This powder is then collected downstream of the contact chamber by a particulate collector, usually a baghouse. Spray-drying typically removes about 70 percent of the sulfur dioxide from the flue gas.[17] Because of the relatively low percentage reduction in sulfur dioxide achieved by spray-drying scrubbers compared with other scrubber technologies, this dry-scrubbing method is most commonly used for furnaces that burn lower sulfur coals.

Dry sorbent injection, illustrated schematically in Exhibit 3-12, is not yet used commercially by electric utilities, although one utility is designing a generating unit that will use this type of scrubber and which is due to begin operation by 1990.[18] This system involves the injection of a powdered sorbent, either nacholite or trona, into the flue gas upstream of a baghouse. Sulfur dioxide reacts with the reagent in the flue gas and on the surface of the filter in the baghouse. The dry wastes, which form a filter cake, are then removed during normal filter cleaning.

Dry injection offers several advantages over traditional wet scrubbing and spray-drying techniques: the required equipment is smaller and less expensive, no water is needed, flue gas reheating is not necessary, and sulfur dioxide and fly ash are removed simultaneously. Potential drawbacks of this process are the limited geographic availability of the sorbents and problems associated with waste disposal. For example, the waste tends to be very water soluble,

EXHIBIT 3-11

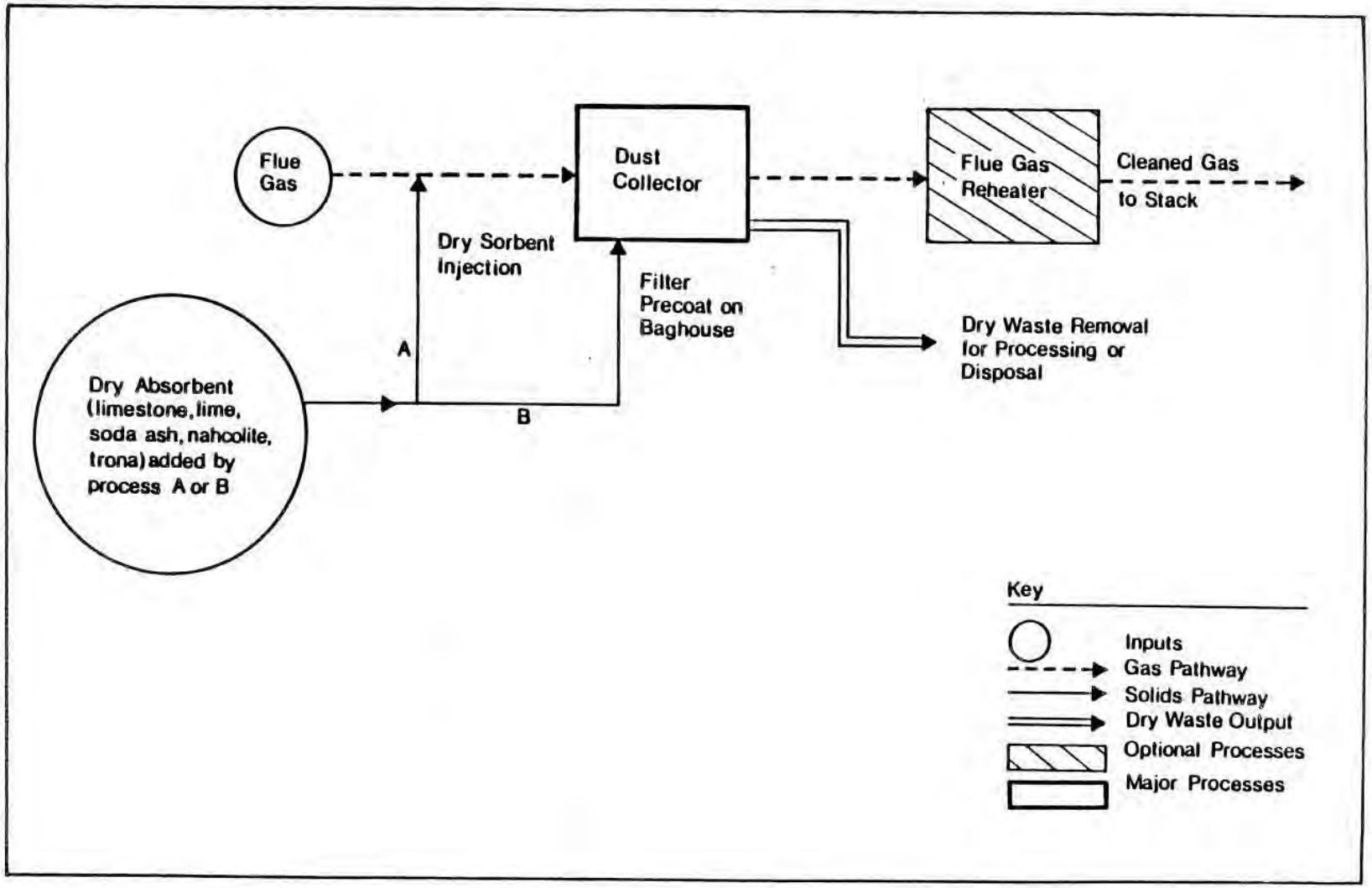
FLOW DIAGRAM OF SPRAY-DRYING FLUE GAS DESULFURIZATION SYSTEM



Source: Tetra Tech Inc., Physical-Chemical Characteristics of Utility Solid Wastes, Prepared for Electric Power Research Institute, September 1983, p. 4-5.

EXHIBIT 3-12

FLOW DIAGRAM OF DRY INJECTION FLUE GAS DESULFURIZATION SYSTEM



Source: Tetra Tech Inc., Physical-Chemical Characteristics of Utility Solid Wastes, Prepared for Electric Power Research Institute, September 1983, p. 4-6.

and could potentially affect ground-water quality. Also, dry injection is most effective when used for low-sulfur coals, achieving only 70 to 80 percent sulfur dioxide removal in most cases, compared with up to 95 percent removal by wet scrubbing systems.[19]

Recovery systems are designed to produce a salable by-product such as sulfur, sulfuric acid, or liquid sulfur dioxide; however, small amounts of waste are still produced. A prescrubber is usually required upstream of the main scrubber to filter out such contaminants as fly ash and chlorides. Secondary waste streams formed by the oxidation of the absorbent are sometimes present and, along with the prescrubber by-products, are the materials that need to be disposed. Two recovery FGD systems presently used commercially, the Wellman-Lord and Magnesium Oxide processes, are both based on wet scrubbing. Diagrams of these systems are shown in Exhibit 3-13. Other recovery systems, both wet and dry, have been developed, but are still in the testing phase.

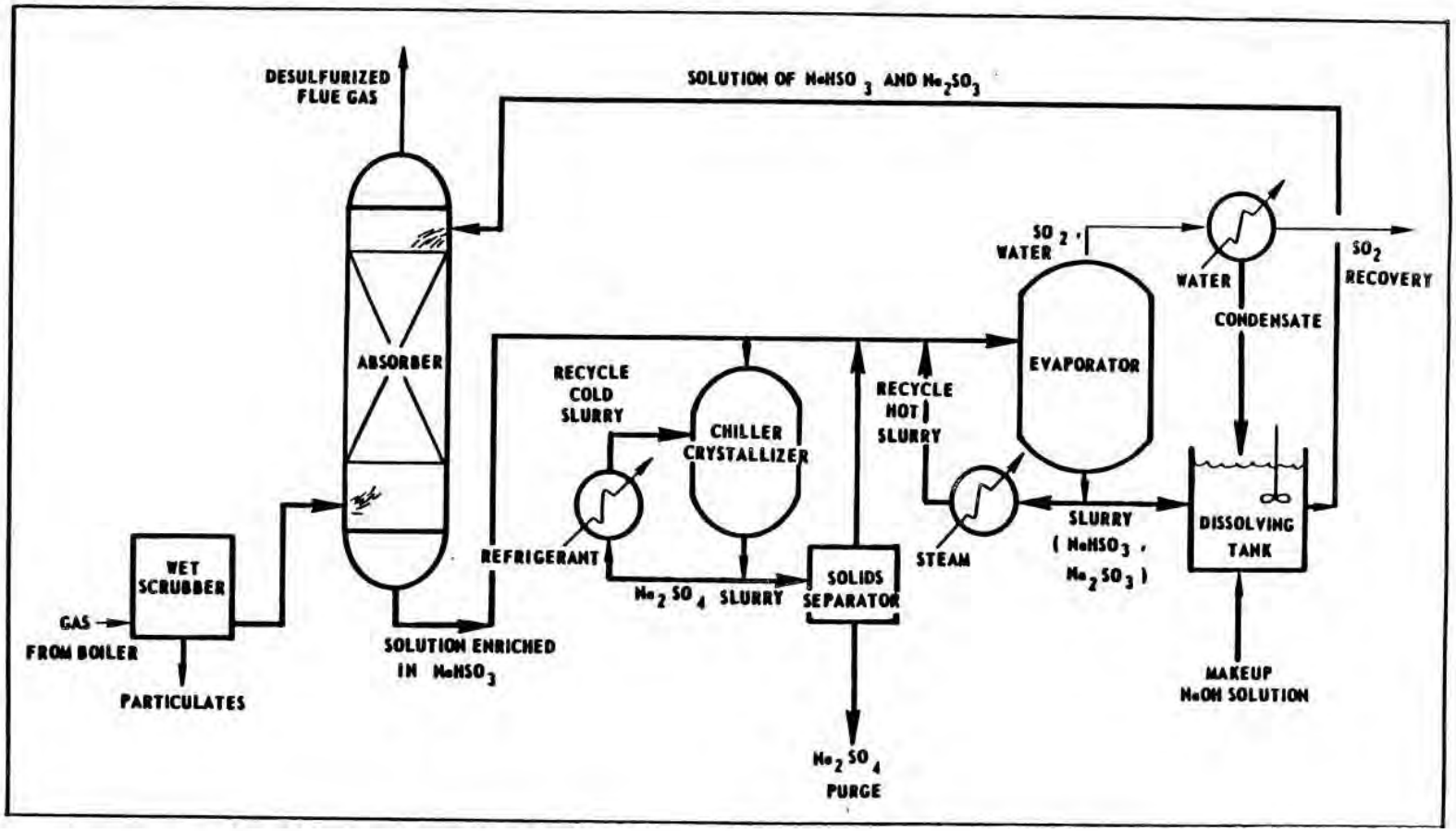
3.2.2.2 Quantities of FGD Sludge Generated

There has been a large increase in the quantity of FGD sludge generated over the past decade, as shown in Exhibit 3-14. This increase is due to the more widespread use of scrubbers brought about by tightened state limits on sulfur dioxide emissions, the Federal New Source Performance Standards (NSPS) of the Clean Air Act of 1971, and the revisions to the NSPS in 1979. This trend will continue as new power plants are equipped with scrubbers as required under the NSPS. By the year 2000, scrubber capacity is likely to be several times greater than at present.

EXHIBIT 3-13

FLOW DIAGRAMS OF RECOVERY FLUE GAS DESULFURIZATION SYSTEMS

WELLMAN-LORD PROCESS

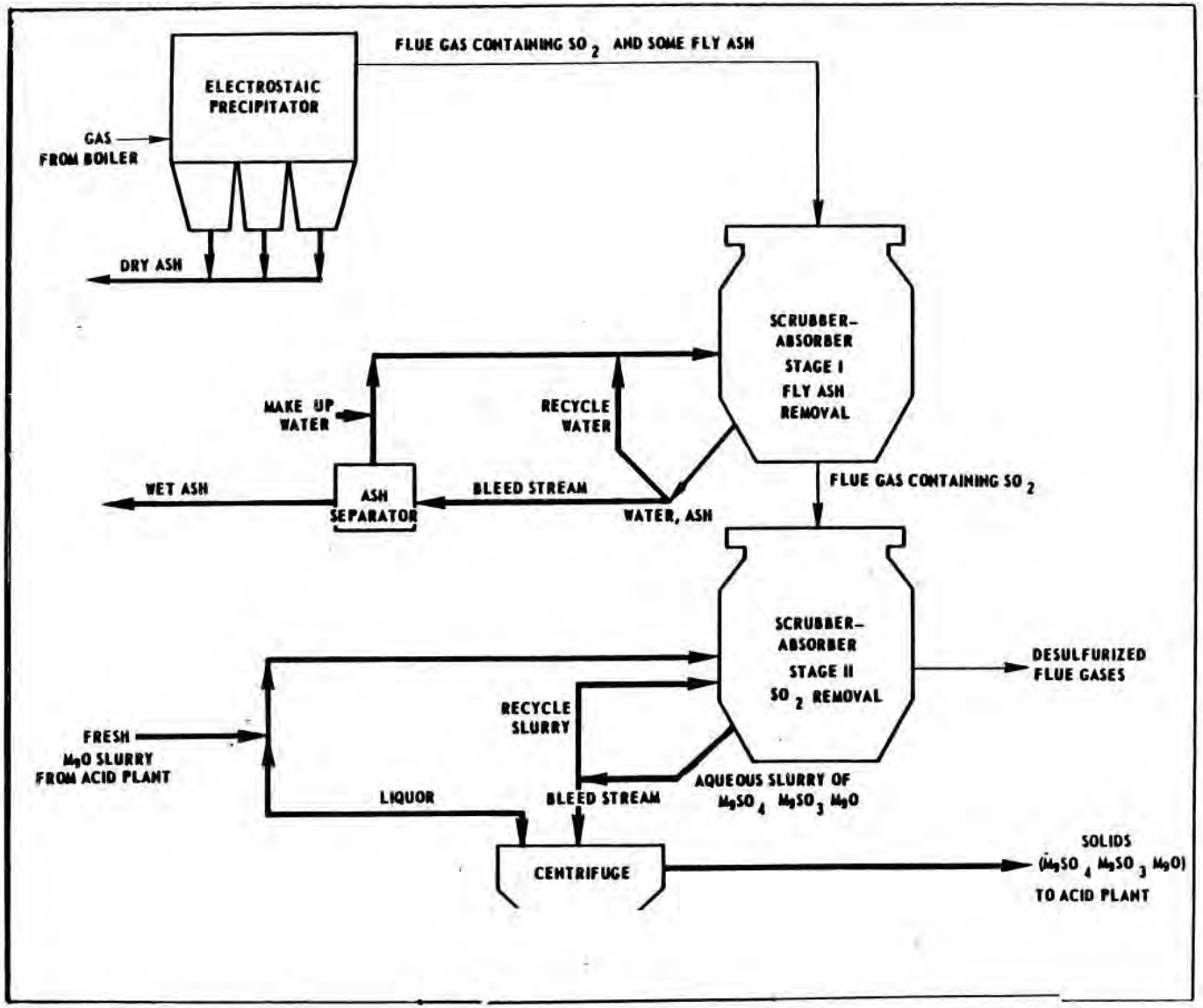


Source: Federal Power Commission, The Status of Flue Gas Desulfurization Applications in the United States: A Technological Assessment, July 1977, pp. VII-27, VII-30.

EXHIBIT 3-13 (Continued)

FLOW DIAGRAMS OF RECOVERY FLUE GAS DESULFURIZATION SYSTEMS

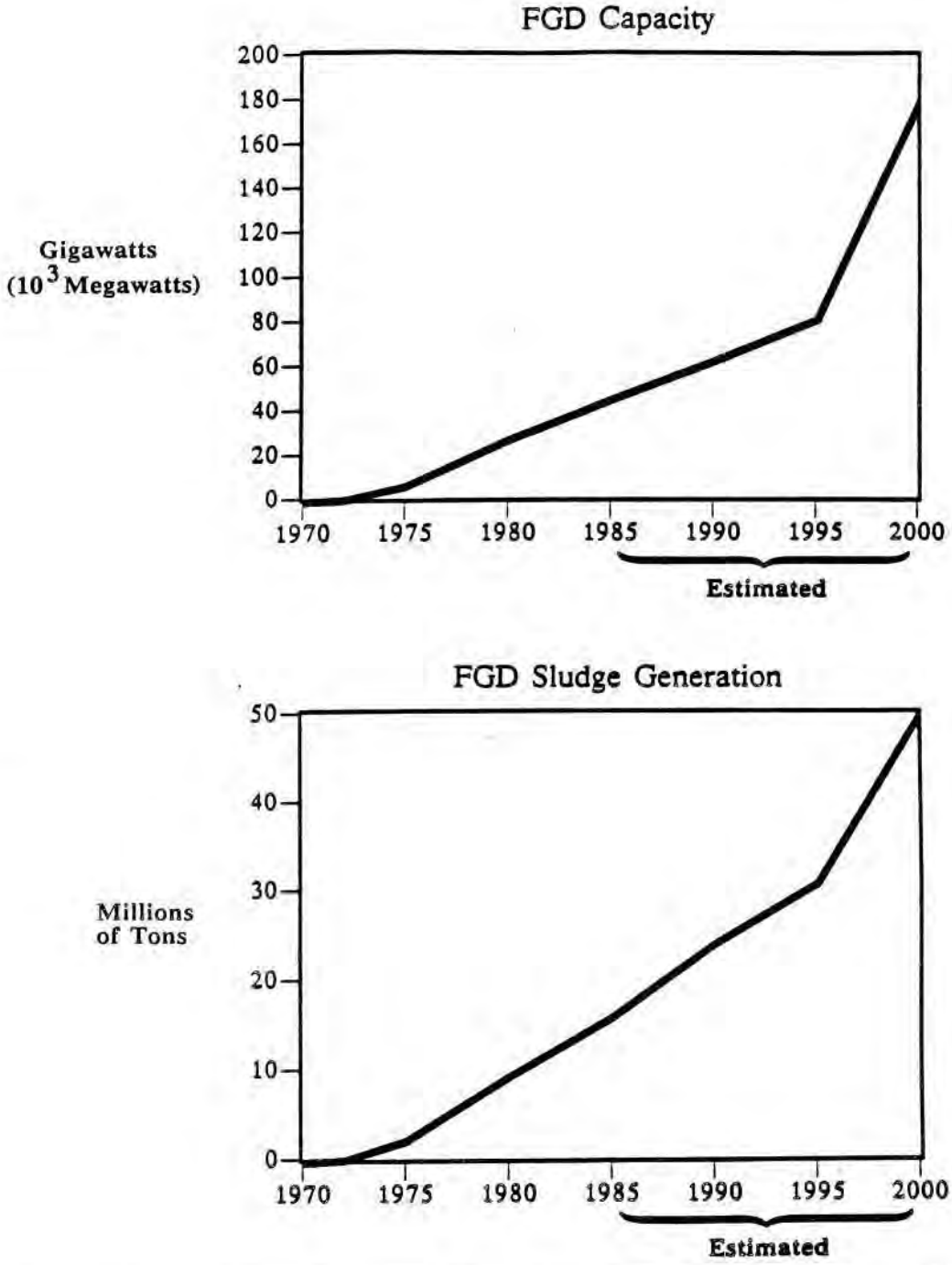
MAGNESIUM OXIDE PROCESS



Source: Federal Power Commission, The Status of Flue Gas Desulfurization Applications in the United States: A Technological Assessment, July 1977, pp. VII-27, VII-30.

EXHIBIT 3-14

FGD CAPACITY AND FGD SLUDGE GENERATION
1970-2000



Source: 1970-1984: Energy Information Administration, Cost and Quality of Fuels for Electric Utility Plants, and Arthur D. Little, Inc., Full Scale Field Evaluation of Waste Disposal from Coal-Fired Electric Generating Plants, Vol. 1, June 1985.

1985-2000: ICF Incorporated. See Appendix B for in-depth discussion of the methodologies used to develop these estimates.

The dramatic increase in scrubber capacity has a direct effect on the amount of scrubber sludge produced. In 1984, about 16 million tons of scrubber sludge were generated. By 2000, the annual amount of sludge produced is estimated to be about 50 million tons, over three times the sludge generated at present.[20]

All FGD sludge is comprised of spent reagent, which is made up of the chemicals that result from the reaction of the absorbent with the sulfur oxides in the flue gas, plus any unreacted portion of the absorbent. The sludge may also contain water and fly ash. Several factors determine how much spent reagent, water, and ash are present in the FGD sludge. These factors include the type of scrubber system used, the characteristics of the coal, and the sulfur dioxide emission limit that the power plant is required to meet by state or Federal law.

The type of FGD system is an important determinant of the amount of spent reagent, amount of water, and amount of ash present in the sludge. Reagents used in different systems vary as to their absorbent utilization, or "stoichiometry," which is the percentage of the reagent that reacts with the sulfur oxides. A lower percentage implies more reagent is needed to remove a given percentage of sulfur dioxide. Direct limestone systems have an average absorbent utilization of 80 percent, while the direct lime and dual-alkali processes both achieve higher utilization of 90 and 95 percent, respectively. This results in the generation of about six percent more sludge by direct limestone scrubbers compared to direct lime and dual-alkali processes.[21]

Wet systems, both non-recovery and recovery, employ aqueous solutions to remove the sulfur oxides from the flue gas. Dry FGD systems use no water for sulfur oxide removal, although dry FGD wastes may be mixed with water prior to disposal, which increases the volume of sludge. Because of their dependency on water, wet FGD systems generally produce larger volumes of wastes than do dry systems.

Wet FGD systems can also be used as fly ash removal devices. The amount of ash in the sludge depends on how much fly ash is generated by the boiler and whether any other particulate control device is upstream of the scrubber. In particular, alkaline fly ash scrubbers rely on the entrapment of ash to act as their primary absorbent, and therefore their sludge contains large amounts of ash. The collection of fly ash and wastes in a spray-drying system occurs simultaneously by a baghouse; therefore, the wastes from these systems also contain large proportions of ash. Recovery FGD systems often require prescrubbers to remove fly ash. Although recovery systems produce only about half the wastes of non-recovery systems, these wastes are predominantly made up of ash.

Specific characteristics of the coal can have a large effect on the quantity of sludge generated. For example, the higher the sulfur content, the more reagent that must be used to achieve a certain level of sulfur dioxide removal and, consequently, the more spent reagent in the sludge. The ash content of the coal affects the amount of ash caught up in the sludge. Just as using low-sulfur coal will reduce the amount of spent reagent, reducing the ash content prior to combustion will greatly reduce the amount of fly ash that is absorbed by wet scrubbers and thus the amount of sludge that must be disposed.

The amount by which a power plant must reduce sulfur dioxide emissions also affects the volume of sludge produced. To achieve a higher reduction, the amount of reagent used in the scrubber needs to be increased, which will, in turn, produce greater quantities of sludge.

3.2.2.3 Physical Characteristics of FGD Sludge

In general, the same physical properties important in determining the disposal behavior of ash are also important determinants of the disposal characteristics of FGD sludge. These physical characteristics -- particle size, compaction behavior, permeability, and shear strength -- vary considerably depending on the type of scrubber system and what (if any) preparation is done prior to disposal. Exhibit 3-15 presents representative ranges of values for these characteristics of FGD sludge.

Depending on the type of FGD system used, the particle size distribution of FGD sludge can vary substantially. For example, sludge from wet scrubbers tends to have a narrow range of particle sizes. The particles produced by dual-alkali systems are finer than those produced by direct lime or limestone scrubbers, while dry scrubbers generally produce sludge containing larger particles.

The density of FGD sludge depends directly on the method of handling. Wet sludge mixed with ash will have a higher density than untreated sludge, while chemical fixation increases the density even more.[22] The density of the particles in dry sludge varies widely.

EXHIBIT 3-15

REPRESENTATIVE RANGES OF VALUES FOR THE PHYSICAL CHARACTERISTICS OF FGD SLUDGE

	Wet	Dry
Particle Size (mm)	.001-.05	.002-.074
Density (g/cm3)	0.9-1.7	Variable
Optimum Moisture Content (%)	16-43	0
Permeability (cm/sec)	10^{-6}-10^{-4}	10^{-7}-10^{-6}
Unconfined Compressive Strength (psi)	0-1600	41-2250

Source: Tetra Tech Inc., Physical-Chemical Characteristics of Utility Solid Wastes, prepared for Electric Power Research Institute, EPRI EA-3236, September 1983, pp. 4-8 - 4-15.

The solids content of scrubber sludge is a function of many things, including whether the sludge is treated prior to disposal, the size of the particles in the sludge, the sulfur content of the coal, the amount of ash present in the sludge, and the desulfurization process used. The percentage of solids in untreated sludges usually ranges from 20 to 40 percent, although it can be as high as 60 percent.[23] Depending on the method of treatment used before disposal (if any), the percentage of solids could be much higher. In fact, some chemical fixation processes are designed to transform the sludge into a cement-like product.

The permeabilities of untreated FGD sludges from wet scrubber systems generally are very similar. Mixing the sludge with fly ash does not necessarily change the degree of permeability, although if fly ash acts as a fixative when added to the sludge, the mixed waste product will have a reduced permeability. Chemical fixation also can decrease permeability. Sludge from dry scrubber systems has low permeability relative to sludge from wet systems.

The shear strength of FGD sludge is referred to as "unconfined compressive strength," which reflects the load-bearing capacity of the sludge. The unconfined compressive strength of sludge is sensitive to the moisture content and age of the sludge. Untreated wet sludge has no compressive strength and is similar to toothpaste in this respect. Mixing with ash or lime increases compressive strength, as does chemical fixation. Also, as the treated sludge ages, its compressive strength becomes greater.

3.2.2.4 Chemical Characteristics of FGD Sludge

The major constituents found in wet FGD sludge are determined by the absorbent reagent used, the quantity of fly ash present, the sulfur content of the coal, and whether or not forced oxidation is used.

Most wet FGD systems operate by causing the sulfur dioxide in the flue gas to react with an absorbent reagent, such as lime or limestone, to form a calcium compound, such as calcium sulfite (CaSO3), calcium sulfate or gypsum (CaSO4), or calcium sulfite-sulfate (CaSO3·CaSO4), which can then be removed from the system in the sludge. The ratio of calcium sulfate to calcium sulfite is generally greater in sludge generated by direct limestone scrubber systems than in that produced by direct lime systems.

Dual-alkali scrubber systems differ slightly in that they use absorbent solutions containing sodium hydroxide (NaOH) or sodium sulfite (Na2SO3) as well as lime; sludges from these processes tend to have high levels of calcium sulfite and sodium salts. Because these compounds are highly soluble and apt to leach, they may pose problems as major components in a landfilled sludge.[24]

Spray-drying scrubber systems produce particulates containing either sodium sulfate (Na2SO4) and sodium sulfite (Na2SO3) or calcium sulfate (CaSO4) and calcium sulfite (CaSO3), depending on whether the reagents are sodium- or calcium-based.

Exhibits 3-16 and 3-17 show the major chemical constituents found in sludge solids and sludge liquors. Oxides of calcium, silicon, magnesium, aluminum, iron, sodium, and potassium can be found in most FGD sludge. The presence of

EXHIBIT 3-16

CONCENTRATION OF MAJOR CHEMICAL CONSTITUENTS OF WET FGD SLUDGE SOLIDS BY SCRUBBER SYSTEM AND SOURCE OF COAL * (percent of total)

	Direct Lime		Direct Limestone		Dual-Alkali		Alkaline Fly Ash
	East	West	East	West	East	West	West
Calcium Sulfate ($CaSO_4$)	15-19	17-95	5-23	85	15-68	82	20
$CaSO_3 \cdot 1/2\ H_2O$	13-69	2-11	17-50	8	13-68	1	15
Calcium Sulfite ($CaSO_3$)	1-22	0-3	15-74	6	8-10	11	--
Sodium Sulfate ($Na_2SO_4 \cdot 7H_2O$)	--	--	--	--	4-7	4	--
Fly Ash	16-60	3-59	1-45	3	0-7	8	65

---

* Source of coal is categorized by Eastern producing regions (Northern Appalachia, Central Appalachia, Southern Appalachia, Midwest, Central West, and Gulf; i.e., Bureau of Mine (BOM) Districts #1-15, 24) and Western producing regions (Eastern Northern Great Plains, Western Northern Great Plains, Rockies, Southwest, and Northwest; i.e., BOM Districts #16-23).

Source: Tetra Tech Inc., Physical-Chemical Characteristics of Utility Solid Wastes, prepared for Electric Power Research Institute, EPRI EA-3236, September 1983, p. 4-18.

EXHIBIT 3-17

CONCENTRATION OF MAJOR CHEMICAL CONSTITUENTS OF WET FGD SLUDGE LIQUORS BY SCRUBBER SYSTEM AND SOURCE OF COAL a/

Constituent b/	Direct Lime	Direct Limestone		Dual-Alkali
	East	East	West	East
pH (units)	8-9.4	5.5-8.4	6.6-6.8	12.1
Total Dissolved Solids	2,800 - 10,260	5400	3300- 14,000	155,700
Chloride	1050-4900	1000	620-4200	4900-5600
Potassium	11-28	24	8-28	320-380
Sodium	36-137	12	370-2250	53,600-55,300
Calcium	660-2520	1600	390-770	7-12
Magnesium	24-420	53	3-9	0.1
Sulfate	800-4500	2500	1360-4000	80,000-84,000
Sulfite	0.9-2.7	160	1-3900	--

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a/ Source of coal is categorized by Eastern producing regions (Northern Appalachia, Central Appalachia, Southern Appalachia, Midwest, Central West, and Gulf; i.e., BOM Districts #1-15, 24) and Western producing regions (Eastern Northern Great Plains, Western Northern Great Plains, Rockies, Southwest, and Northwest; i.e., BOM Districts #16-23).

b/ All constituent concentrations, unless noted, in milligrams per liter.

Source: Tetra Tech Inc., Physical-Chemical Characteristics of Utility Solid Wastes, prepared for Electric Power Research Institute, EPRI EA-3226, September 1983, p. 4-20.

these compounds results from the presence of fly ash in the sludge, and they are unreactive in FGD systems. In wet scrubbers that also serve as fly ash collection devices, more than 50 percent of the sludge solids may be ash. However, when an ESP or baghouse precedes the scrubber, ash may make up less than 10 percent of the sludge solids.[25]

The calcium sulfate/calcium sulfite ratio of the sludge solids is important because sludge containing a greater proportion of sulfates has better disposal properties due to its lower solubility. This ratio is usually higher in systems scrubbing lower sulfur coals and in direct limestone systems. Many scrubber systems add a forced oxidation step to lower the calcium sulfite content of the sludge, thereby lowering its solubility.

The concentration of trace elements in FGD sludge reflects the levels of trace elements in the ash, the efficiency of the scrubber in capturing trace elements in the flue gas, and the trace elements present in the reagent and in the process makeup waters. Fly ash is the primary source of most of the trace elements found in scrubber sludge. Some elements, such as mercury and selenium, may be scrubbed directly from the flue gases and then captured in the scrubber sludge. Exhibit 3-18 illustrates the concentrations at which major trace elements are found in sludge from wet scrubber systems.

3.3 LOW-VOLUME WASTES

Low-volume utility wastes are those waste streams generated in the routine cleaning of plant equipment and in purifying of water used in the combustion process. The types and volumes of low-volume wastes vary among different power

EXHIBIT 3-18

CONCENTRATION OF TRACE ELEMENTS FOUND IN WET-FGD SLUDGES (Solids and Liquors)

	Sludge Solids a/			Sludge Liquors b/		
	Range			Range		
	Low	High	Median	Low	High	Median
Arsenic	0.8	52.0	12	0.0004	0.1	0.03
Boron	42.0	530.0	14.0	2.1	76.0	14.9
Cadmium	0.1	25.0	10.6	0.002	0.1	0.02
Chromium	1.6	180.0	15.0	0.0002	0.3	0.02
Copper	6.0	340.0	17.5	0.0045	0.5	0.03
Fluoride	266.0	1017.0	625.0	0.2	63.0	2.3
Mercury	0.01	6.0	0.4	0.00006	0.1	0.005
Lead	0.2	290.0	2.4	0.005	0.5	0.03
Selenium	2.0	60.0	5.0	0.003	1.9	0.18

a/ Sludge solid concentrations in milligrams per kilogram.

b/ Sludge liquor concentrations in milligrams per liter.

Source: Tetra Tech Inc., Physical-Chemical Characteristics of Utility Solid Wastes, prepared for Electric Power Research Institute, EPRI EA-3226, September 1983, p. 4-24.

plants, depending on plant-specific factors such as the size of the plant, the type of equipment, and the age of the equipment. Some low-volume wastes commonly produced are:

- boiler blowdown,
- coal pile runoff,
- cooling tower blowdown,
- demineralizer regenerants and rinses,
- metal and boiler cleaning wastes,
- pyrites, and
- sump effluents.

Estimates of the total amount of low-volume wastes generated each year by coal-fired power plants are not available. The frequency of generation and the quantities generated vary widely from power plant to power plant, depending on the maintenance requirements of the plant and operating conditions. Variations also occur within the same power plant, according to its maintenance schedule and operations. Exhibit 3-19 gives representative annual production figures for low-volume wastes generated by a typical power plant.

This section presents for each type of low-volume waste a brief description of how the waste is generated, typical quantities produced, and the physical and chemical composition of the waste.

3.3.1 Boiler Blowdown

Boiler systems can be either a once-through (supercritical) type or a

EXHIBIT 3-19

ANNUAL LOW-VOLUME WASTE GENERATION AT A REPRESENTATIVE COAL-FIRED POWER PLANT *

Type of Waste	Average Annual Production
Boiler Blowdown	11 million gallons/year
Coal Pile Runoff	20 inches/year
Cooling Tower Blowdown	2.6 billion gallons/year
Demineralizer Regenerant	5 million gallons/year
Gas-side Boiler Cleaning	700,000 gallons/year
Water-Side Boiler Cleaning	180,000 gallons/year
Pyrites	65,000 tons/year

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* Assuming a 500 megawatt power plant, operating at 70 percent capacity.

Sources: Envirosphere Company, Information Responding to EPA's Request Regarding Burning and Co-Treatment/Co-Disposal of Low Volume Wastes Generated at Fossil Fuel Fired Electric Generating Stations, prepared for Utility Solid Waste Activities Group and Edison Electric Institute, August 1981.

U.S. Environmental Protection Agency, Waste and Water Management for Conventional Coal Combustion Assessment Report - 1979: Volume II: Water Management, EPA-600/7-80-012b, March 1980.

drum-type. In drum-type boiler systems, after steam passes through the turbines, it is converted back to water in the condenser and is recirculated through the boiler to produce steam again. In this process, impurities that become concentrated in the feedwater periodically must be purged from the system. This waste stream is known as boiler blowdown. A once-through system, however, maintains pressurized steam throughout the cycle, and thus does not require the recirculation of water. These boiler types, therefore, do not generate boiler blowdown.

Boiler blowdown is produced either in a continuous stream or intermittently during the day. The flow is adjusted in order to maintain the desired water quality in the boiler and is dependent on the quality of the feedwater and the size and condition of the boiler. The average blowdown rate for a 500 megawatt unit can range from 20 to 60 gallons per minute, or about 2 to 7 gallons per megawatt-hour.[26]

Boiler blowdown is generally fairly alkaline with a low level of total dissolved solids. The waste stream usually contains certain chemical additives used to control scale and corrosion. Trace elements commonly found in boiler blowdown are copper, iron, and nickel. The components and characteristics of boiler blowdown are presented in Exhibit 3-20.

3.3.2 Coal Pile Runoff

Power plants typically maintain two types of coal storage piles in their coal yards: an active pile to supply their immediate needs and an inactive or long-term pile, which generally stores a 60- to 90-day supply of coal. Coal

EXHIBIT 3-20

CHARACTERISTICS OF BOILER BLOWDOWN

Parameter	Range a/ Low	Range a/ High
pH (units)	8.3	12.0
Total Solids	125.0	1,407.0
Total Suspended Solids	2.7	31.0
Total Dissolved Solids	11.0	1,405.0
BOD5	10.8	11.7
COD	2.0	157.0
Hydroxide Alkalinity	10.0	100.0
Oil and Grease	1.0	14.8
Phosphate (total)	1.5	50.0
Ammonia	0.0	2.0
Cyanide (total)	0.005	0.014
Chromium (total)	0.02	b/
Chromium (Hexavalent)	0.005	0.009
Copper	0.02	0.2
Iron	0.03	1.4
Nickel	0.03	b/
Zinc	0.01	0.05

a/ All concentrations, unless noted, in milligrams per liter.

b/ Data on these elements were limited.

Source: Envirosphere Company, Information Responding to EPA's Request Regarding Burning and Co-Treatment/Co-Disposal of Low Volume Wastes Generated at Fossil Fuel Fired Electric Generating Stations, prepared for Utility Solid Waste Activities Group and Edison Electric Institute, August 1981.

piles are usually 25-40 feet high and can cover an area of up to 75 acres, depending on the size and demands of the power plant.[27] Inactive coal piles are generally sealed with a tar spray to protect the coal against the weather; active piles are usually open and exposed. Coal pile runoff is formed when water comes into contact with the piles, whether from rainfall or snowfall, during spraying for dust control, or from underground streams that surface under the piles.

The quantity of coal pile runoff depends primarily on rainfall and, to a lesser extent, the permeability of the soil. It has been estimated that, on average, 73 percent of the total rainfall on coal piles becomes coal pile runoff.[28]

The composition of coal pile runoff is influenced by the composition of the coal, the drainage patterns of the coal pile, and the amount of water that has seeped through. Bituminous coals generate runoff that is usually acidic, with the level of acidity depending on the availability of neutralizing materials in the coal, while subbituminous coals tend to produce neutral to alkaline runoff. Elements commonly found in high concentrations in coal pile runoff are copper, zinc, magnesium, aluminum, chloride, iron, sodium, and sulfate. Exhibit 3-21 displays ranges of concentrations for these and other characteristics.

3.3.3 Cooling Tower Blowdown

Power plants need cooling systems to dissipate the heat energy that remains after the production of electricity.[29] The two major types of cooling systems are once-through and recirculating. Cooling tower blowdown generally refers to

EXHIBIT 3-21

CHARACTERISTICS OF COAL PILE RUNOFF

Parameter	Range a/ Low	Range a/ High
pH (units)	2.1	9.3 b/
Acidity (as CACO3)	300.0	7,100.0
Total Dissolved Solids	270.0	28,970.0
Total Suspended Solids	8.0	2,500.0
Aluminum	20.0	1,200.0
Ammonia	0.0	1.8
Arsenic	0.005	0.6
Beryllium	0.01	0.07
Cadmium	0.001	0.003
Chloride	3.6	481.0
Chromium	0.005	16.0
Cobalt	0.025	--
Copper	0.01	6.1
Iron	0.1	5,250.0
Magnesium	0.0	174.0
Manganese	0.9	180.0
Mercury	0.0002	0.007
Nickel	0.1	4.5
Nitrate	0.3	1.9
Phosphorus	0.2	1.2
Selenium	0.001	0.03
Sodium	160.0	1,260.0
Sulfate	130.0	20,000.0
Zinc	0.006	26.0

a/ All concentrations, unless noted, in milligrams per liter.

b/ Electric Power Research Institute, Manual For Management of Low-Volume Wastes From Fossil-Fuel-Fired Power Plants, prepared by Radian Corporation, Austin, Texas, July 1987.

Source: All information, unless noted otherwise, is from Envirosphere Company, Information Responding to EPA's Request Regarding Burning and Co-Treatment/Co-Disposal of Low Volume Wastes Generated at Fossil Fuel Fired Electric Generating Stations, prepared for Utility Solid Waste Activities Group and Edison Electric Institute, August 1981.

the water withdrawn from a recirculating cooling system to control the concentration of impurities in the cooling water; although once-through systems also discharge water from the cooling system, this discharge is not typically referred to as cooling tower blowdown. At present, about two-thirds of electric utility power plants use a once-through cooling system. This percentage may decrease, however, due to concern over water availability and potential environmental concern over thermal discharges; consequently, future plants may be built with recirculating systems that use cooling towers or cooling ponds.[30]

Once-through cooling systems are primarily used by power plants located next to large bodies of water. After passing through the condenser, the cooling water is discharged, usually into a river, lake, or pond. The quantity discharged ranges from 26,000 to 93,000 gallons per megawatt-hour. For a 500 megawatt plant, this roughly equals 70-300 billion gallons per year.[31] In most instances, the chemical composition of the water remains the same after passing through the condenser, but some changes may occur as the result of the formation of corrosion products or the addition of biocides.

Recirculating cooling systems can use either cooling ponds or cooling towers. In a cooling pond system, water is drawn from a large body of water, such as a pond or canal. After it passes through the condenser to absorb waste heat, the water is recycled back into the pond or canal. Cooling tower systems operate by spraying the water through a cooling tower. About 80 percent of the waste heat contained in the water is then released through evaporation. The remainder of the water is recycled back through the cooling tower system. Cooling tower blowdown is a waste stream bled off to control the concentrations

of impurities and contaminants in the cooling system that could lead to scale formation in the condenser.[32]

The cooling tower blowdown rate is adjusted to maintain water quality in the recirculating cooling system in order to prevent scale formation in the condenser. The quantity of blowdown generated is a function of the quality of the makeup water (the water added to the system to replace that which is lost by evaporation and blowdown), the condition of the cooling system, and the amount of water evaporated by the cooling tower. For a representative 500 megawatt unit, the blowdown rate varies between 2 and 30 cubic feet (15 to 225 gallons) per second.[33]

The composition and quantity of cooling tower blowdown varies greatly from plant to plant. It generally reflects the characteristics of the makeup waters (e.g., fresh water versus brackish or saline water) and the chemicals added to prevent the growth of fungi, algae, and bacteria in the cooling towers and to prevent corrosion in the condensers. Some of these chemical additives are chlorine, chromate, zinc, phosphate, and silicate. Ranges of concentration for some of the characteristics and components of cooling tower blowdown are shown in Exhibit 3-22.

3.3.4 Demineralizer Regenerant and Rinses

A power plant must treat water prior to its use as makeup water. The use of demineralizers is the most common method of purification. During the demineralization process, which may entail several rinses, high-purity process water is provided for the boiler through an ion exchange process. The wastes

EXHIBIT 3-22

CHARACTERISTICS OF COOLING TOWER BLOWDOWN

Parameter	Range a/ Low	Range a/ High
Alkalinity (as CaCO3)	8.0	556.0
BOD	--	94.0
COD	--	436.0
Total Solids	750.0	32,678.0
Total Dissolved Solids	4.1	32,676.0
Total Suspended Solids	0.2	220.0
Ammonia (as N)	0.01	11.6
Nitrate (as N)	0.1	711.0
Phosphorus (as P)	0.1	17.7
Total Hardness (as CaCO3)	84.0	2,580.0
Sulfate	7.2	20,658.0
Chloride	5.0	16,300.0
Fluoride b/	0.3	33.0
Aluminum b/	1,100.0	1,700.0
Boron b/	0.5	1.0
Chromium (ug/l)	0.02	120.0
Copper (ug/l)	0.01	1,740.0
Iron (ug/l))	0.1	1,160.0
Lead (ug/l) b/	4.0	--
Magnesium (ug/l)	0.1	1,580.0
Manganese (ug/l) b/	24.0	220.0
Mercury (ug/l) b/	1.5	--
Nickel (ug/l)	0.03	150.0
Zinc (ug/l)	0.02	3,000.0
Oil & Grease	1.0	7.4
Phenols (ug/l)	--	72.0
Surfactants	0.2	--
Sodium	3.4	11,578.0

a/ All concentrations, unless noted, in milligrams per liter.

b/ Data on these elements were limited.

Source: Envirosphere Company, Information Responding to EPA's Request Regarding Burning and Co-Treatment/Co-Disposal of Low Volume Wastes Generated at Fossil Fuel Fired Electric Generating Stations, prepared for Utility Solid Waste Activities Group and Edison Electric Institute, August 1981.

produced in this process can be either acidic or alkaline. When sulfuric acid is employed as the regenerant, calcium sulfate is precipitated in the waste stream. Exhibit 3-23 presents ranges for the components of demineralizer regenerants and rinses.

Regeneration of boiler makeup water by demineralizers is done on a batch basis. The frequency with which the process occurs depends on the quality of the incoming water, although for a 500 megawatt unit, regeneration usually occurs every one to four days. A single regeneration requires approximately 30,000 gallons of water, which amounts to about 3-10 million gallons per year.[34]

3.3.5 Metal and Boiler Cleaning Wastes

This category of low-volume waste streams can be divided into two basic types: gas-side cleaning wastes and water-side cleaning wastes. Gas-side wastes are produced during maintenance of the gas-side of the boiler, which includes the air preheater, economizer, superheater, stack, and ancillary equipment. Residues from coal combustion (such as soot and fly ash), which build up on these surfaces, must be removed periodically -- usually with plain water containing no chemical additives.

Water-side wastes are produced during cleaning of the boiler tubes, the superheater, and the condenser, which are located on the water-side or steam-side of the boiler. The scale and corrosion products that build up on these boiler parts must be removed with cleaning solutions containing chemical additives.

EXHIBIT 3-23

CHARACTERISTICS OF SPENT DEMINERALIZER REGENERANTS

Parameter	Range a/ Low	High
Alkalinity (as CaCO3)	0.0	3,831.0
BOD	0.0	344.0
COD	0.0	440.0
Total Solids	284.0	36,237.0
Total Dissolved Solids	283.0	25,235.0
Total Suspended Solids	0.0	300.0 c/
Ammonia (as N)	0.0	435.0
Phosphorus (as P)	0.0	87.2
Turbidity (JTU)	2.5	100.0
Total Hardness (as CaCO3)	0.0	8,000.0
Sulfate	4.5	9,947.0
Chloride	0.0	20,500.0
Boron	0.0	0.1
Chromium	0.0	2,168.0
Copper (ug/l)	0.0	3,091.0
Iron (ug/l)	0.0	2,250.0
Lead (ug/l) b/	160.0	37,500.0
Magnesium (ug/l)	0.0	753.0
Manganese (ug/l)	0.0	3,100.0
Mercury (ug/l)	0.05	--
Nickel (ug/l)	0.0	560.0
Zinc (ug/l)	0.0	4,500.0
Oil & Grease b/	0.0	24.5
Phenols (ug/l)	0.0	303,000.0
Surfactants b/	1.7	--
Nitrate as N	0.0	118.0
Algicides b/	0.003	--
Sodium	4.9	30,000.0

a/ All concentrations, unless noted, in milligrams per liter.

b/ Data on these components were limited.

c/ Electric Power Research Institute, Manual For Management of Low-Volume Wastes From Fossil-Fuel-Fired Power Plants, prepared by Radian Corporation, Austin, Texas, July 1987.

Source: All data, unless noted otherwise, are from Envirosphere Company, Information Responding to EPA's Request Regarding Burning and Co-Treatment/Co-Disposal of Low Volume Wastes Generated at Fossil Fuel Fired Electric Generating Stations, prepared for Utility Solid Waste Activities Group and Edison Electric Institute, August 1981.

The boiler and auxiliary equipment are cleaned intermittently, creating large quantities of wastes in a short time. Gas-side boiler cleaning is done approximately twice a year. The volume of the waste stream produced depends on the size of the boiler and the number of rinses. For a typical plant, gas-side cleanings can produce between 24,000 and 700,000 gallons of wastes. Water-side equipment is cleaned less frequently, approximately once every three years. As is true of gas-side cleaning, the volume of waste produced varies with the number of rinses. A representative 500 megawatt unit generates about 120,000-240,000 gallons of wastewater per treatment.[35]

Because no chemicals are used, the composition of the waste streams associated with gas-side cleaning directly reflects the composition of the soot and fly ash residues and, therefore, of the coal that is burned. Exhibit 3-24 shows two reported values for components and characteristics of gas-side cleaning waste streams.

The particular solution used for the cleaning of the water-side of the boiler varies depending on the equipment being cleaned and the type of scale that needs to be removed. When the scale contains high levels of metallic copper, an alkaline solution that contains ammonium salts, an oxidizing agent such as potassium or sodium bromate or chlorate, and nitrates or nitrites is used. Exhibit 3-25 presents some of the major characteristics associated with these types of solutions and representative ranges of concentrations in which they are found.

For the removal of scale caused by water hardness, iron oxides, and copper oxide, an acid cleaning solution is needed. Usually hydrochloric acid acts as

EXHIBIT 3-24

REPORTED CHARACTERISTICS OF GAS-SIDE CLEANING WASTES

Parameter	Quantities Produced per Cleaning (in lbs. except as noted) a/	
	Source A	Source B
Cleaning Frequency (cycles/yr)	2.0	8.0
Batch Volume (1000 gallons)	720.0	24.0
Alkalinity	0.0	6.0
COD	1,134.0	19.0
Total Solids	40,861.0	4,002.0
Total Dissolved Solids	35,127.0	3,002.0
Total Suspended Solids	3,823.0	119.1
Turbidity (JTU)	476.0	98.0
Hardness	35,409.0	791.4
Ammonia	1.5	0.4
Chloride	0.0	18.0
Chromium (total)	0.03	1.0
Copper	--	0.3
Iron	900.0	30.0
Lead	--	--
Magnesium	11,949.0	190.3
Nickel	30.0	--
Nitrate	14.7	0.7
Phosphorus	11.1	0.3
Sodium	0.0	9.0
Sulfate	11,949.0	299.4
Vanadium	--	--
Zinc	28.7	2.0

a/ Quantities produced are shown for two different reported values.

Source: Envirosphere Company, Information Responding to EPA's Request Regarding Burning and Co-Treatment/Co-Disposal of Low Volume Wastes Generated at Fossil Fuel Fired Electric Generating Stations, prepared for Utility Solid Waste Activities Group and Edison Electric Institute, August 1981.

EXHIBIT 3-25

CHARACTERISTICS OF SPENT WATER-SIDE ALKALINE CLEANING WASTES

Parameter	Range a/ Low	High
Alkalinity (as CaCO3)	20,200.0	25,700.0
NH3-N	4,280.0	6,360.0
Kjeldahl-N	5,190.0	7,850.0
Nitrate-N	1.0	193.0
Oil & Grease	7.9	10.3
BOD5	5,820.0	8,060.0
COD	14,600.0	20,900.0
Total Suspended Solids	5,580.0	6,720.0
Total Dissolved Solids	10.0	400.0
TDS	22,100.0	32,300.0
Total Iron	180.0	10,800.0
Silica	1.0	40.0
Chromium	0.2	7.7 b/
Copper	8.0	1,912.0
Lead	0.004 b/	23.0 b/
Manganese	0.1	14.3
Nickel	2.5	130.0
Tin	2.0	20.7
Zinc	3.1	390.0
pH (units)	8.4 b/	10.3 b/

a/ All concentrations, unless noted, in milligrams per liter.

b/ Electric Power Research Institute, Manual For Management of Low-Volume Wastes From Fossil-Fuel-Fired Power Plants, prepared by Radian Corporation, Austin, Texas, July 1987.

Source: All data, unless noted otherwise, are from Envirosphere Company, Information Responding to EPA's Request Regarding Burning and Co-Treatment/Co-Disposal of Low Volume Wastes Generated at Fossil Fuel Fired Electric Generating Stations, prepared for Utility Solid Waste Activities Group and Edison Electric Institute, August 1981.

the solvent in these solutions, although sulfuric, phosphoric, and nitric acids can also be used. Organic acids have been used increasingly as substitutes for hydrochloric acid because of their lower toxicity. For the removal of silica deposits, hydrofluoric acid or fluoride salts are added to the cleaning solution. Exhibit 3-26 presents the various characteristics of acid boiler cleaning solutions.

Alkaline chelating rinses and alkaline passivating rinses are often used to remove iron and copper compounds and silica and to neutralize any residual acidity left over from acid cleaning. These solutions may contain phosphates, chromates, nitrates, nitrites, ammonia, EDTA, citrates, gluconates, caustic soda, or soda ash. Exhibit 3-27 gives representative ranges for these components and others present in these rinses.

3.3.6 Pyrites

Pyrites are the solid mineral compounds, such as iron sulfides or other rock-like substances, present in raw coal. Most pyrites are generally separated out before coal is burned, usually at a preparation plant prior to shipment to the power plant. Smaller quantities of pyrites are often removed at the power plant just before the coal is pulverized. The size of the deposits depends on the method by which they are separated from the coal.

The volume of pyrites collected at a power plant depends on the amount and quality of the coal that is burned, which is determined by the source of the coal and the preparation process, as well as by the coal pulverization process.

EXHIBIT 3-26

CHARACTERISTICS OF SPENT WATER-SIDE HYDROCHLORIC ACID CLEANING WASTES

Parameter	Range a/ Low	High
pH (units)	0.5	3.3
Total Suspended Solids	8.0	2375.0
Silica	19.0	280.0
NH3-N	80.0	325.0
Nitrogen	1.0	870.0
Phosphorus	1.0	300.0
Sulfate	1.0	10.0
Aluminum	6.5	8.2
Arsenic	0.01	0.1
Barium	0.1	0.4
Beryllium	0.0	0.1
Cadmium	0.001	0.13 b/
Calcium	16.0	980.0
Chromium	0.005	16.8
Copper	2.2	960.0
Iron	1125.0	6470.0
Lead	0.01	5.2
Magnesium	5.7	8.8
Manganese	6.9	29.0
Mercury	0.0	0.002
Nickel	3.0	500.0
Potassium	1.4	2.3
Selenium	0.002	0.004
Silver	0.02	0.2 b/
Sodium	9.2	74.0
Tin	1.0	7.3
Zinc	0.9	840.0

a/ All concentrations, unless noted, in milligrams per liter.

b/ Electric Power Research Institute, Manual For Management of Low-Volume Wastes From Fossil-Fuel-Fired Power Plants, prepared by Radian Corporation, Austin, Texas, July 1987.

Source: All data, unless noted otherwise, are from Envirosphere Company, Information Responding to EPA's Request Regarding Burning and Co-Treatment/Co-Disposal of Low Volume Wastes Generated at Fossil Fuel Fired Electric Generating Stations, prepared for Utility Solid Waste Activities Group and Edison Electric Institute, August 1981.

EXHIBIT 3-27

CHARACTERISTICS OF SPENT WATER-SIDE ALKALINE PASSIVATING WASTES

Parameter	Range* Low	High
pH (units)	9.2	10.0
Total Suspended Solids	13.0	45.0
NH3-N	15.0	232.0
Kjeldahl-N	97.0	351.0
Nitrite-N	7.0	12.9
BOD5	40.0	127.0
COD	98.0	543.0
TOC	16.0	23.0
Iron	7.5	28.0
Chromium	0.0	0.4
Copper	0.1	1.2

* All concentrations, unless noted, in milligrams per liter.

Source: Envirosphere Company, Information Responding to EPA's Request Regarding Burning and Co-Treatment/Co-Disposal of Low Volume Wastes Generated at Fossil Fuel Fired Electric Generating Stations, prepared for Utility Solid Waste Activities Group and Edison Electric Institute, August 1981.

The amount of pyrites to be disposed at a power plant can vary considerably, although coal typically contains up to 5 percent pyrites.[36] A 500 megawatt plant, depending on how often it operates and the quality of its coal, will generate, on average, between 30,000 and 100,000 tons of pyrites per year. The characteristics of pyrites and pyrite slurry transport water are shown in Exhibit 3-28.

3.3.7 Sump Effluents

Floor and yard drains collect waste streams from a variety of sources at power plants, such as rainfall, seepage from ground-water sources, leakage, small equipment cleaning operations, and process spills and leaks. As a result, the composition of drain effluents is highly variable. Depending on the particular circumstances at the power plant, these waste streams may contain coal dust, fly ash, oil, and detergents.

The frequency of sump effluent generation and quantities generated are very plant-specific. The more efficient a plant's operating procedures, the smaller this waste stream will be. Also, power plants located in dry areas of the country will have relatively small amounts of wastes collected in yard drains.

3.4 SUMMARY

In the process of generating electricity, coal-fired utility power plants produce a number of waste products. These wastes are produced in large quantities and have widely varying physical and chemical characteristics.

EXHIBIT 3-28

CHARACTERISTICS OF PYRITES AND PYRITE TRANSPORT WATER

Parameter	Pyrite Slurry Water a/	Pyrites Solid Form b/
Total Suspended Solids	1,700.0	--
Total Aluminum	93.3	--
Total Calcium	134.0	--
Total Iron	220.0	--
Total Magnesium	13.6	--
Sulfate	177.0	--
pH (units)	7.7	--
Arsenic	--	500-5000
Chromium	0.1	--
Copper	0.1	10-10,000
Lead	0.1	200-1000
Zinc	0.3	500-10,000
Manganese	--	10-5000
Selenium	--	10-100
Silica	212.0	--
Silver	--	10-50
Cobalt	--	100-5000
Nickel	--	10-1000
Vanadium	--	100-200

a/ All concentrations, unless noted, in milligrams per liter.

b/ All concentrations in parts per million.

Source: Envirosphere Company, Information Responding to EPA's Request Regarding Burning and Co-Treatment/Co-Disposal of Low Volume Wastes Generated at Fossil Fuel Fired Electric Generating Stations, prepared for Utility Solid Waste Activities Group and Edison Electric Institute, August 1981.

- Coal-fired electric utility power plants produce three major forms of wastes:

  1) Ash, formed from the noncombustible material present in coal. There are three types of ash -- fly ash, bottom ash, and boiler slag;

  2) FGD sludge, produced by flue gas desulfurization systems designed to remove sulfur oxides from flue gas; and

  3) Low-volume wastes, generated primarily from equipment maintenance and cleaning operations.

- In 1984, about 69 million tons of ash and about 16 million tons of FGD sludge were produced by coal-fired electric utilities. By the year 2000, these wastes are expected to increase to about 120 million and 50 million tons, respectively.

- Several physical characteristics of utility waste determine the waste's behavior during disposal and the potential for leachate problems. These characteristics vary a great deal among the different types of ash and FGD sludge.

- The chemical constituents of ash and FGD sludge largely depend on the chemical components in the coal. Other chemical compounds present in FGD sludge, primarily calcium and sodium salts, are the result of the reactions between the absorbent reagent used and the sulfur oxides in the flue gas.

- Compared with ash and FGD sludge, low-volume wastes are generally produced in much smaller quantities. Many of these wastes contain various chemicals from the cleaning solutions used for power plant operations and maintenance; potentially-hazardous elements in these chemicals may be found at high concentrations in the low-volume waste.

CHAPTER THREE

NOTES

[1] See Appendix B for a more in-depth discussion of boiler types and how the type of boiler affects the types of waste that are generated.

[2] Babcock & Wilcox, Steam: Its Generation and Use, New York: The Babcock & Wilcox Company, 1978, p. 18-3.

[3] Ibid.

[4] Energy Information Administration, Cost and Quality of Fuels for Electric Utility Plants-1985, DOE/EIA-0191(85), July 1986.

[5] ICF Incorporated, Analysis of 6 and 8 Million Ton and 30 Year/NSPS and 30 Year/1.2 Pound Sulfur Dioxide Emission Reduction Cases, prepared for EPA, February 1986. There are many factors that can affect the amount of coal consumed, including electricity growth rates, oil and gas prices, types of technology available, etc. Nevertheless, utilities will continue to burn substantial amounts of coal in the foreseeable future.

[6] Energy Information Administration, Electric Power Annual 1984, DOE/EIA-0348(84), p. 45.

[7] There are presently over 500 coal cleaning plants in the U.S., the majority of which are operated by coal companies and located at the mouth of the mine. The type of cleaning method employed depends upon the size of the coal pieces to be cleaned, a factor that can be controlled at the cleaning plant.

The most widely used methods of coal cleaning are those that use specific gravity, relying on the principle that heavier particles (i.e., impurities) separate from lighter ones (i.e., coal) when settling in fluid. A common method of cleaning coarse coal pieces is to pulse currents of water through a bed of coal in a jig; impurities, such as shale and pyrite, sink, while the coal floats on top. The heavy, or dense, media process is used for cleaning coarse and intermediate-sized pieces. A mixture of water and ground magnetite, having a specific gravity between that of coal and its impurities, acts as a separating fluid. An inclined vibrating platform with diagonal grooves, known as a concentrating table, also is used to clean intermediate-sized coal pieces. Raw coal slurry is fed onto the high end of the table. As the slurry flows down, the vibrations separate the coal from the refuse, allowing the lighter coal to be carried along in the water, while the heavier impurities are trapped in the grooves.

Because of their small size, fine coal particles are very difficult to clean. Their recovery is important, however, because these particles can provide up to 25 percent of the energy derived from raw coal. A popular method of fine coal cleaning is froth flotation. The coal pieces are coated with oil and then agitated in a controlled mixture of water, air, and reagents until froth is formed on the surface. Bubbles tend to attach to the coal pieces, keeping them buoyant, while heavier particles such as pyrite, shale, and slate remain dispersed in the water. The coal can then be removed from the

surface. For more information, see Coal Preparation, 4th edition, Joseph Leonard, editor, American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., 1979.

[8] Ash melts when heated to a sufficiently high temperature. The temperatures at which the ash changes forms -- e.g., melting from a cone shape to a spherical shape to a hemispherical shape to a flat layer -- are referred to as ash fusion temperatures.

[9] Tetra Tech, Inc., Physical-Chemical Characteristics of Utility Solid Wastes, EPRI EA-3236, prepared for Electric Power Research Institute, September 1983, p. 3-4. A micron is 0.001 millimeters.

[10] Ibid.

[11] The compressibility of a material is measured as the ratio of its height at 50 psi to its original height at atmospheric pressure. The dry density, the ratio of weight to unit volume of the material containing no water, affects permeability and strength, which in turn determine the structural stability of a landfill and the extent of leachate mobility. The optimum moisture content is the moisture content, in percentage terms, at which the material attains its maximum density.

[12] In 1979 the New Source Performance Standards, part of the Clean Air Act of 1971, were revised. The new regulations required that all coal-fired electric utility units with capacity greater than 73 megawatts, whose construction commenced after September 18, 1978, would not only have to meet a 1.2 pound sulfur dioxide per million Btu emission limit, but would have to do so by a continuous system of emissions reduction. New power plants must reduce sulfur dioxide emissions between 70 and 90 percent, depending on the type of coal burned.

[13] During fluidized bed combustion the sulfur oxides react with limestone or dolomite to form calcium sulfate. In LIMB technology, limestone is injected into the boiler, also forming calcium compounds.

[14] Federal Power Commission, The Status of Flue Gas Desulfurization Applications in the United States: A Technological Assessment, July 1977, p. VII-15.

[15] Ibid., p. VII-18.

[16] Ibid., p. VII-23.

[17] Tetra Tech, Inc., Physical-Chemical Characteristics of Utility Solid Wastes, EPRI EA-3236, prepared for Electric Power Research Institute, September 1983, p. 4-4.

[18] "Dry Capture of SO2," EPRI Journal, March 1984, p. 21.

[19] Ibid., p. 15.

[20] ICF, op. cit. See Appendix B for a detailed explanation of how future FGD sludge estimates were derived.

[21] U.S. Environmental Protection Agency, Controlling SO2 Emissions from Coal-Fired Steam-Electric Generators: Solid Waste Impact, Volume I, EPA-600/7-78-044a, March 1978, p. 23.

[22] See Chapter Four for a detailed discussion of the methods of sludge fixation.

[23] Michael Baker, Jr., Inc., State-of-the-Art of FGD Sludge Fixation, prepared for Electric Power Research Institute, January 1978, p. 2-25.

[24] Tetra Tech, Inc., op. cit., p. 4-17.

[25] Ibid.

[26] Envirosphere Company, Information Responding to EPA's Request Regarding Burning and Co-Treatment/Co-Disposal of Low Volume Wastes Generated at Fossil Fuel Fired Electric Generating Stations, prepared for Utility Solid Waste Activities Group and Edison Electric Institute, August 1981, p. 26.

[27] U.S. Environmental Protection Agency, Waste and Water Management for Conventional Coal Combustion Assessment Report - 1979; Volume II: Water Management, EPA-600/7-80-012b, March 1980, p. 3-146.

[28] Ibid., p. 3-147.

[29] Ibid., p. 3-16. About 35 to 40 percent of the total heat input of a power plant is converted to electricity, about 5 percent is lost in the stack gases, and the remaining 55 to 60 percent is rejected in the condenser.

[30] Ibid., p. 3-17.

[31] Ibid.

[32] The term "cooling tower blowdown" refers to the waste waters produced by all recirculating cooling systems, whether they use a cooling pond or a cooling tower.

[33] U.S. EPA, Waste and Water Management, p. 3-19.

[34] Envirosphere Company, Information Responding to EPA's Request Regarding Burning and Co-Treatment/Co-Disposal of Low Volume Wastes Generated at Fossil Fuel Fired Electric Generating Stations, prepared for Utility Solid Waste Activities Group and Edison Electric Institute, August 1981, p. 27.

[35] Ibid., p. 27.

[36] Ibid., p. 28. The term "pyrites" is used to refer to a variety of rock-like substances that may be found in raw coal; it does not just refer to pyritic sulfur that is found in all raw coal, although pyritic sulfur is typically part of the pyrites generated at a power plant.

CHAPTER FOUR

COAL COMBUSTION WASTE MANAGEMENT PRACTICES

Under Section 8002(n) of RCRA, EPA is to analyze "present disposal and utilization practices" and "alternatives to current disposal methods." This chapter addresses these issues by first examining the various state regulations that affect coal combustion disposal since these regulations set the context for current practices. The following section describes coal combustion waste management practices. First, three commonly employed types of land management practices are described in detail. Next, this chapter describes additional measures currently employed by some utilities; more widespread use of these technologies could be employed as an alternative to current practices. Ocean disposal, an alternative that is in the research and development stage, is also addressed in this chapter. Finally, the extent of coal combustion waste recycling as an alternative to disposal is described.

4.1 STATE REGULATION OF COAL COMBUSTION WASTE DISPOSAL

Since coal combustion wastes are currently exempt from Federal hazardous waste regulation under RCRA, their regulation is primarily carried out under the authority of state hazardous and solid waste laws. State solid waste laws establish programs to provide for the safe management of non-hazardous solid wastes. If solid wastes are considered hazardous, state hazardous waste laws establish programs to provide for their safe management. To implement these laws, state health or environmental protection agencies promulgate solid and hazardous waste regulations. A 1983 report for the Utility Solid Waste Activities Group (USWAG) surveyed these regulations; the USWAG report provided

summaries of state regulations based on applicable state laws, regulations, and interviews with state environmental officials.[1] EPA updated the information provided in the USWAG summaries for the purposes of this report.

Exhibit 4-1 lists the disposal requirements promulgated under each state's solid waste (non-hazardous) regulations. (As will be discussed below, it is very rare for coal combustion wastes to be regulated as hazardous under state regulations.) The list of states is arranged in descending order according to each state's share of national coal-fired generating capacity (Column 1 of Exhibit 4-1). The information shown in the Exhibit is discussed in detail in Sections 4.1.1 and 4.1.2.

4.1.1 State Classification of Coal Combustion Wastes

Forty-three states have exempted coal combustion wastes from hazardous waste regulation.[2] As a result, in these states the state solid waste laws, which apply to non-hazardous wastes, regulate the disposal of these coal combustion wastes. Column 2 of Exhibit 4-1 shows that: (1) in seven states, coal combustion wastes are not exempt from hazardous waste regulation (indicated by an entry of CH), which means that they are tested to determine whether they will be regulated as solid or hazardous wastes; (2) in all but one of the remaining states wastes are regulated by solid waste regulations (indicated by an entry of SW); and (3) in the one remaining state, wastes are exempt from both the hazardous waste and solid waste regulations (indicated by an entry of EX).

EXHIBIT 4-1

STATE REGULATIONS GOVERNING COAL COMBUSTION WASTE DISPOSAL

STATE	(1) % NATIONAL COAL-FIRED CAPACITY	(2) CLASSIFICATION	(3) PERMITS	(4) SITE RESTRICTIONS	(5) LINER	(6) LEACHATE CONTROL	(7) GROUND-WATER MONITORING	(8) CLOSURE CONDITIONS	(9) FINANCIAL ASSURANCE
Texas	8.40%	SW	OFF SITE	NO	NO	NO	MAY	YES	YES
Indiana	6.44%	SW	ON & OFF SITE	NO	NO	NO	MAY	NO	NO
Kentucky	6.43%	CH	ON & OFF SITE	YES	MAY	YES	MAY	YES	NO
Ohio	6.02%	EX							
Pennsylvania	5.71%	SW	ON & OFF SITE	YES	NO	NO	MAY	YES	YES
Illinois	5.46%	SW	ON & OFF SITE	NO	NO	NO	NO	YES	YES
West Virginia	3.87%	SW	ON & OFF SITE	NO	NO	NO	NO	NO	NO
North Carolina	3.41%	SW	ON & OFF SITE	YES	NO	NO	YES	YES	NO
Michigan	3.37%	SW	ON & OFF SITE	YES	NO	NO	YES	NO	NO
Georgia	3.35%	SW	ON & OFF SITE	NO	NO	NO	NO	NO	NO
Florida	3.26%	SW	OFF SITE	YES	YES	YES	YES	YES	YES
Missouri	3.16%	SW	ON & OFF SITE	YES	NO	MAY	NO	YES	NO
Alabama	3.08%	SW	ON & OFF SITE	YES	MAY	NO	YES	YES	NO
Tennessee	2.54%	CH	ON & OFF SITE	YES	MAY	NO	MAY	YES	NO
Nevada	2.49%	SW	ON & OFF SITE	YES	NO	NO	NO	NO	NO
South Carolina	2.24%	SW	ON & OFF SITE	YES	NO	YES	NO	YES	NO
Wisconsin	2.19%	SW	ON & OFF SITE	YES	MAY	MAY	MAY	YES	YES
Louisiana	1.98%	SW	ON & OFF SITE	YES	YES	YES	YES	YES	YES
Colorado	1.97%	SW	OFF SITE	YES	YES	YES	YES	NO	NO
Iowa	1.83%	SW	OFF SITE	NO	NO	MAY	NO	NO	NO
Wyoming	1.82%	SW	ON & OFF SITE	YES	NO	NO	NO	NO	NO
Kansas	1.69%	SW	ON & OFF SITE	YES	NO	NO	MAY	YES	YES
Arizona	1.67%	SW	ON & OFF SITE	NO	NO	NO	NO	NO	NO
New Mexico	1.58%	SW	ON & OFF SITE	NO	NO	NO	NO	NO	NO
Utah	1.57%	SW	ON & OFF SITE	NO	NO	NO	NO	NO	NO
Minnesota	1.54%	SW	ON & OFF SITE	YES	NO	MAY	YES	YES	NO
Arkansas	1.48%	SW	ON & OFF SITE	YES	NO	NO	NO	YES	YES
Maryland	1.48%	SW	OFF SITE	NO	NO	YES	YES	NO	NO
North Dakota	1.39%	SW	ON & OFF SITE	NO	NO	MAY	YES	YES	YES
Oklahoma	1.34%	CH	ON & OFF SITE	YES	NO	NO	YES	YES	YES
New York	1.24%	SW	ON & OFF SITE	YES	MAY	MAY	YES	YES	NO
Virginia	0.94%	SW	ON & OFF SITE	NO	NO	NO	NO	NO	NO
Washington	0.93%	CH	OFF SITE	YES	YES	YES	YES	YES	NO
Nebraska	0.85%	SW	ON & OFF SITE	NO	NO	MAY	NO	NO	NO
Montana	0.74%	SW	OFF SITE	YES	NO	NO	NO	NO	NO
Mississippi	0.62%	SW	OFF SITE	NO	MAY	NO	NO	YES	NO
New Jersey	0.51%	CH	ON & OFF SITE	YES	NO	NO	YES	YES	YES
Massachusetts	0.41%	SW	ON & OFF SITE	YES	NO	NO	NO	NO	NO
Oregon	0.31%	SW	ON & OFF SITE	YES	NO	NO	MAY	NO	YES
Delaware	0.27%	SW	ON & OFF SITE	YES	NO	YES	YES	YES	NO
Maine	0.15%	CH	ON & OFF SITE	YES	YES	YES	MAY	YES	NO
South Dakota	0.13%	SW	ON & OFF SITE	NO	NO	NO	NO	YES	NO

EXHIBIT 4-1 (continued)
STATE REGULATIONS GOVERNING COAL COMBUSTION WASTE DISPOSAL

STATE	(1) % NATIONAL COAL-FIRED CAPACITY	(2) CLASSIFICATION	(3) PERMITS	(4) SITE RESTRICTIONS	(5) LINER	(6) LEACHATE CONTROL	(7) GROUND-WATER MONITORING	(8) CLOSURE CONDITIONS	(9) FINANCIAL ASSURANCE
New Hampshire	0.12%	SW	ON & OFF SITE	NO	NO	NO	YES	NO	NO
Alaska	0.01%	SW	ON & OFF SITE	YES	NO	NO	MAY	NO	NO
California	0.00%	CH	ON & OFF SITE	YES	NO	YES	MAY	YES	YES
Connecticut	0.00%	SW	ON & OFF SITE	YES	NO	YES	YES	YES	NO
Vermont	0.00%	SW	ON & OFF SITE	NO	NO	NO	NO	NO	NO
Rhode Island	0.00%	SW	ON & OFF SITE	YES	NO	YES	YES	NO	NO
Hawaii	0.00%	SW	ON & OFF SITE	NO	NO	NO	NO	NO	NO
Idaho	0.00%	SW	ON & OFF SITE	NO	NO	MAY	NO	NO	NO

NOTES

Column (1) Percent national coal-fired capacity: i.e., each state's share of total U.S. coal-fired generating capacity.

Column (2) Classification: SW - coal combustion waste is exempted from hazardous waste regulation and regulated as a solid waste.

CH - coal combustion waste is not exempted from hazardous waste regulation and is tested for hazardous characteristics (In practice, coal combustion wastes are rarely considered hazardous, therefore columns 3-8 reflect solid, not hazardous, waste regulations).

EX - coal combustion waste is exempted from both solid and hazardous waste regulation.

Column (3) Permits: Permits are required for off-site facilities only, or for both on-site and off-site facilities.

Columns (4), (5), (6), (7), (8), (9): YES - the disposal standard is imposed by state regulations.

NO - the disposal standard is not imposed by state regulations.

MAY - the regulation states that a case-by-case investigation will determine whether the disposal standard will be imposed.

Source: Wald, Harkrader & Ross, Survey of State Laws and Regulations Governing Disposal of Utility Coal-Combustion Byproducts, prepared for the Utility Solid Waste Activities Group, September, 1983.

Of the seven states that do not exempt coal combustion wastes from hazardous waste regulation (indicated by a CH classification in Exhibit 4-1), California burns little coal to produce electricity. The hazardous waste regulations of the six remaining states -- Kentucky, Tennessee, New Jersey, Oklahoma, Maine, and Washington -- regard coal combustion wastes as "characteristic" waste; that is, the wastes are tested for Extraction Procedure (EP) toxicity (see Chapter Five for further discussion), and if the waste proves to be toxic, some or all sections of state hazardous waste regulations apply. In Kentucky, for example, hazardous waste standards concerning lining and leachate control are enforced for coal combustion wastes that are found to be toxic, but utilities are not required to participate in the hazardous waste management fund established to ensure the long-term viability of disposal facilities. Similarly, according to the hazardous waste regulations of Tennessee and Oklahoma, if a waste is determined to be toxic, strict analysis and monitoring requirements must be followed, but compliance with state hazardous waste design and operating standards is not required. Officials from these five states have indicated that it is very rare for a coal-burning utility's waste to be classified as hazardous.[3] Therefore, state solid waste regulations, with only isolated exceptions, establish the standards applicable to most coal combustion waste disposal activities.

Although solid waste regulations in most states do not differentiate between coal combustion wastes and other solid wastes, solid waste regulations in three states make specific reference to coal combustion waste disposal:

- Ohio's solid waste regulations list "non-toxic fly ash ... and slag ... that are not harmful or inimical to public health" as wastes that are exempt from solid waste regulation. Ash is typically determined to be non-toxic, according to the USWAG report.

- Maine's solid waste regulations provide a separate, more stringent set of design and operating requirements for the disposal of coal combustion wastes. The requirements call for lining, leachate control, and ground-water monitoring at coal combustion waste sites. These standards do not apply to other solid waste disposal facilities.[4]

- Pennsylvania has established industry-specific waste disposal standards. Pennsylvania's regulations for coal combustion waste disposal exclude the leachate control systems and liner requirements that apply to general solid waste disposal facilities.

4.1.2 Requirements for Coal Combustion Waste Disposal

The solid waste regulations of every state require that off-site solid waste disposal facilities be permitted or have some form of official approval. In order to obtain a permit, the operator of a facility must meet the requirements that are outlined in the regulations. These regulations are listed in Exhibit 4-1 and described below:

- The regulations in 41 states require permits for both on-site and off-site facilities. Eight states' regulations explicitly exempt on-site disposal from the permit requirement (Ohio, which exempts coal combustion wastes from solid waste regulation, is not included among the eight states). Column 3 of Exhibit 4-1 shows whether a permit is required for the operation of on-site and off-site solid waste disposal facilities.[5]

- Site restrictions are included in the solid waste regulations of 30 states. Examples of site restrictions are prohibiting solid waste disposal facilities from violating local zoning laws, banning placement of a new facility in a 100-year floodplain, and prohibiting waste placement unless there is a minimum depth to ground water. Column 4, "site restrictions," shows whether a state's regulations include restrictions on a disposal facility's location.

- Five states' regulations (Florida, Louisiana, Colorado, Washington, and Maine) call for all solid waste facilities to have a clay or synthetic liner. In addition, six states' regulations (Kentucky, Alabama, Tennessee, Wisconsin, New York, and Mississippi) call for the state permitting authority to determine, on a case-by-case basis, whether a liner is required. Column 5, "liners," shows whether the state's regulations include a requirement for liners at solid waste disposal facilities.

- Leachate control systems are collection devices placed under wastes in landfills or impoundments to collect waste leachate. Regulations in 12 states call for leachate control systems in all solid waste disposal facilities; the regulations of an additional 8 states allow leachate control systems to be required on a case-by-case basis. Column 6, "leachate control systems," shows whether a state's regulations include a requirement for leachate control systems at solid waste disposal facilities.

- The solid waste regulations of 17 states call for ground-water monitoring systems at all solid waste disposal facilities. The regulations of an additional 11 states specify that ground-water monitoring may be required on a case-by-case basis. Column 7, "ground-water monitoring," shows whether a state's regulations include requirements for ground-water monitoring wells at solid waste disposal facilities.

- Twenty-six states have solid waste regulations that call for closure and post-closure care. Column 8, "closure conditions," shows whether a state's regulations include requirements for closure and post-closure care for disposal facilities that have ceased operating.

- Thirteen states have solid waste regulations that include a financial assurance requirement. Column 9, "financial assurance," shows whether a state's regulations include a requirement that a solid waste facility operator post a bond or participate in a waste management fund to ensure the long-term viability of safe disposal facilities.

The management of waste in surface impoundments, a common practice for coal-burning utility plants, is often only indirectly addressed by state solid waste regulations. Only six states -- Louisiana, Colorado, New York, Washington, Oregon, and New Hampshire -- have solid waste regulations that include requirements exclusively for surface impoundments. The solid waste regulations of Indiana, Tennessee, Kentucky, North Carolina, Georgia, and Missouri exclude surface impoundments and defer to state water laws for regulatory authority. The water regulations in these states do not include any design and operating requirements for surface impoundments. However, according to the USWAG report, the water agencies in Missouri do regulate the design and operation of impoundments -- requiring lining and ground-water monitoring. According to the same report, state water agencies in Pennsylvania also regulate the design and operation of surface impoundments.

The regulatory requirements discussed above refer to regulations explicitly promulgated by the states for waste disposal facilities. However, state solid and hazardous waste regulations generally allow state authorities a large degree of discretion in designing site-by-site disposal standards that are more strict than those specified in the solid waste regulations. Many states' regulations allow local governments to design their own waste disposal regulations, provided that the standards set forth in the state solid waste regulations are enforced. Interviews with several state environmental

officials and the summaries in the USWAG report indicate that in some states coal combustion utility wastes are regulated more stringently than what is required by the solid waste regulations. For example, the solid waste regulations in Texas have few design and operating requirements and exempt on-site disposal from the permit requirement. It is, however, the policy of the state environmental agency to provide guidelines for on-site facilities as well as off-site facilities, and to require ground-water monitoring. (For more information on individual state regulations, see Appendix C.)

4.1.3 Summary

The regulation of coal combustion waste is generally carried out under state solid, not hazardous, waste regulations. These solid waste regulations vary from state to state. Based on the requirements included under each state's solid waste regulations (as shown in Exhibit 4-1), it is difficult to generalize about the extent of state regulation of coal combustion wastes; some states have very stringent regulations and/or policies, such as those that impose design and operating standards and on-site and off-site permit requirements, whereas other states have few requirements or exempt on-site disposal from regulation. For a number of states, requirements are determined on a case-by-case basis. This allows the states to take climatic, geologic, and other site-specific characteristics into account for each waste management facility.

4.2 AVAILABLE WASTE MANAGEMENT METHODS AND CURRENT PRACTICES

There are a variety of methods available for managing coal combustion wastes. Wastes may be land managed in impoundments, landfills, mines, and quarries or may be reused for various purposes. This section describes types of land management of coal combustion wastes and their prevalence within the ten EPA-designated regions of the United States. The second part of the section reviews available waste management technology alternatives (such as lining, leachate collection, and pre-disposal treatment), and explores how these different technologies are currently used in different parts of the U.S. and how these technologies have changed over time. The third part of this section describes the potential for ocean disposal to be used to manage coal combustion wastes. The final section describes coal combustion waste recycling. The waste management methods discussed in this section apply to high-volume and low-volume utility waste streams since these wastes are often co-disposed in the same facility.[6]

4.2.1 Land Management of Coal Combustion Wastes

80 percent of coal combustion waste is treated, stored, and/or disposed by means of land management, with the remaining 20 percent recycled (see Section 4.2.4). This section describes three common methods of land management currently used for coal combustion wastes. It also presents data on use of these management methods geographically and how land management practices have changed over time.

4.2.1.1 Types of Coal Combustion Waste Land Management

Three types of utility waste land management facilities are commonly used today:[7]

- **Surface Impoundments** -- often called wet ponds, in which coal combustion wastes are disposed as a slurry or sludge, allowing solids to settle and accumulate at the bottom of the pond.
- **Landfills** -- facilities used for disposing of dry or dewatered coal combustion wastes; landfills are typically managed like an earth-moving operation in which the wastes are disposed in the excavated area.
- **Mines and Quarries** -- abandoned pits in which wet or dry wastes are disposed.

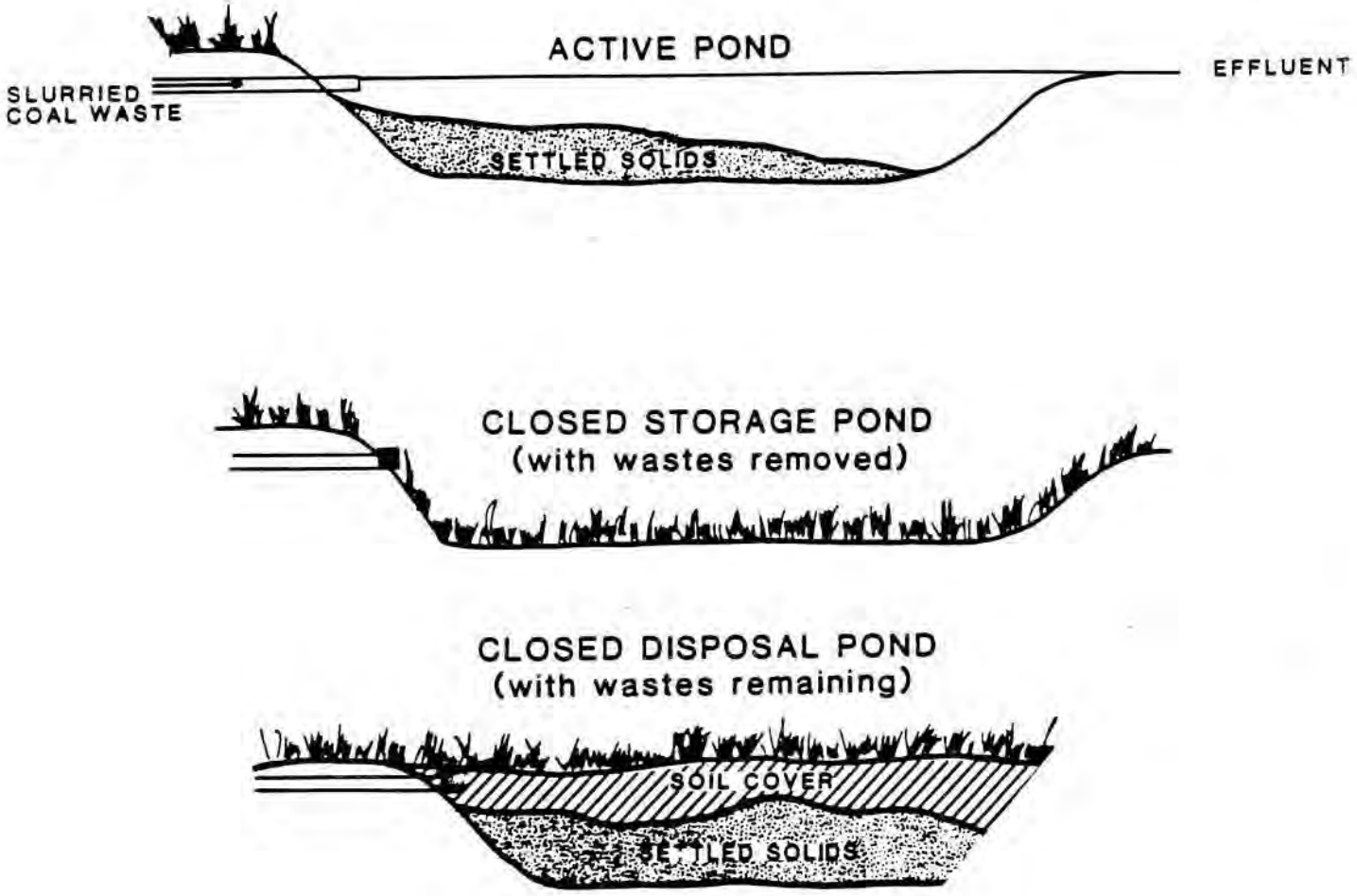
Surface Impoundments

Surface impoundments are used to treat, store, and dispose of coal combustion wastes. Slurried coal ash and other wastes are introduced into the impoundment; the solids settle out and gradually accumulate at the bottom of the pond, leaving relatively clear water at the surface, which is often discharged to surface water. By using this method, certain types of waste treatment, such as neutralization of acids, can be accomplished concurrently with disposal. Exhibit 4-2 illustrates the different stages in the life of a typical impoundment.

Historically, wet ponding has been one of the most widely used disposal methods for coal ash and FGD wastes because it is simple and easily implemented. In 1983, about 80 percent of the waste management facilities used

EXHIBIT 4-2

TYPICAL SURFACE IMPOUNDMENT (POND) STAGES



by utilities employed some type of sedimentation treatment pond; most of these treatment ponds were used directly as final disposal impoundments (about 45 percent of all facilities; see section 4.2.1.2). The remainder of the impoundments were used only for treatment and temporary storage of waste, in part to comply with the National Pollutant Discharge Elimination System established in Section 402 of the Clean Water Act.[8] In recent years, some state and local regulations concerning wet ponds have become more restrictive, requiring liners and ground-water monitoring at these facilities. These types of restrictions will tend to increase wet ponding costs, making it less attractive as a disposal option.[9]

Utilities may use a single pond or a series of ponds to facilitate the settling of solids. Chemicals or different wastes can be added at different points in the ponding system to produce desired chemical reactions, such as metals precipitation or neutralization. Fly ash, bottom ash, and FGD wastes are usually sluiced with water to the impoundments. The ash solids may be allowed to accumulate in a pond until it is full, or the pond may be drained and the solids dredged periodically and taken to an alternative disposal site, such as a landfill.

Pond designs vary widely depending upon local site conditions, the regulations that govern design of the impoundment, and whether bottom ash, fly ash, FGD wastes, or a combination of wastes are to be disposed and/or treated in the ponds. Because utility wastes are generated in large volumes, a pond's total surface area may cover up to several hundred acres, and the initial depth of a pond may be anywhere between 10 and 100 feet.[10] The total

volume of an impoundment system depends on several factors, including the total quantity of ash to be disposed (both dry and slurried volumes), the liquid and solid retention times, the type and degree of treatment performed, and the desired quality of the discharge or effluent. The number of ponds in a system and the specific uses to which each is put can also influence the total volume required for wet ponding.

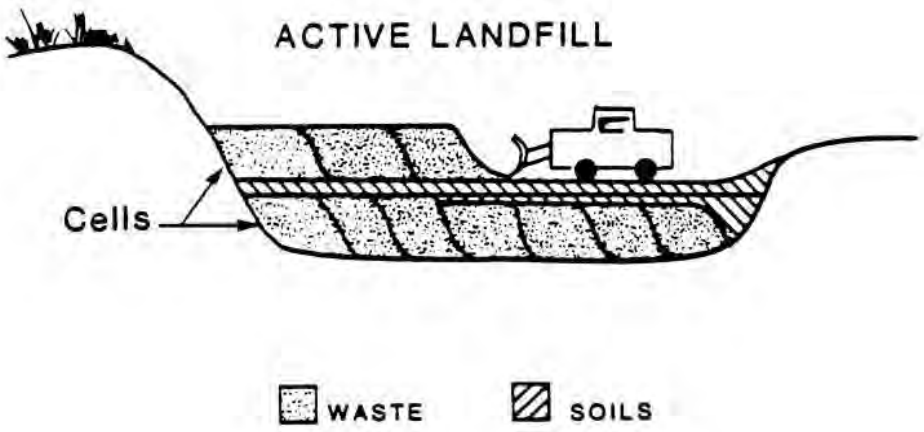
Landfills

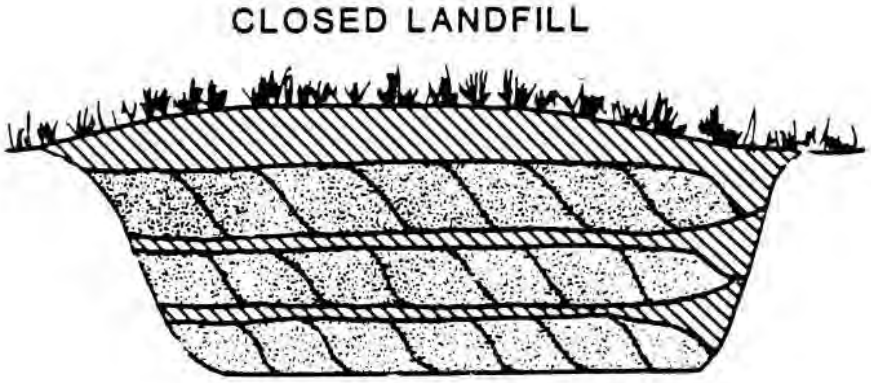
Landfills are used to dispose of coal combustion wastes such as fly ash, bottom ash, and FGD sludges when they are produced or after they are dredged from surface impoundments that are used as interim treatment facilities. The typical design of a landfill during its active stage and after closure is depicted in Exhibit 4-3.

Landfills are constructed in a somewhat similar fashion to surface impoundments. Excavation is required in both cases, but may be ongoing throughout a landfill's active life because most large landfills are divided into sections, or cells, of which only one or two may be active at any given time. A landfill cell is defined as the area (up to several hundred square feet) over which waste is placed to a depth ranging from one to ten feet (industry practice refers to each layer of cells as a lift). Several lifts may be stacked atop one another in the landfill. A cell may be open for periods ranging from a day to a few weeks, after which it is usually covered with six inches to several feet of soil. The waste and soils are often sprinkled with water throughout the fill operation to mitigate potential dust problems.

EXHIBIT 4-3

DIAGRAMS OF ACTIVE AND CLOSED LANDFILLS





Excavation may be initiated in phases; for example, as one cell is filled, another is prepared for waste placement, while yet another is being excavated. Roads are built in to provide access for waste-hauling equipment as well as for the earth-moving and earth-compacting equipment that prepares the waste after it has been placed in the landfill cell. After a cell is filled, the access road frequently becomes part of the containment system as a wall separating one cell from the next.

Landfilling of coal ash and FGD sludges has increased over the past few years as the costs of wet ponding have increased (see section 4.2.1.2). Most electric utilities that use landfills currently dispose their high-volume wastes in Subtitle D (non-hazardous waste) landfills. Landfills in compliance with RCRA Subtitle C standards may be used occasionally for disposal of small quantities of hazardous waste.[11]

Mine and Quarry Disposal

Some utilities use abandoned mines or quarries as ash and FGD sludge disposal sites. Abandoned mine disposal includes the use of mine shafts as well as strip-mined areas. Wastes disposed to abandoned mine shafts can be dumped into the shaft or carefully placed within the mine to fill the areas remaining after the coal or other material has been removed. Strip-mined areas may be filled like a landfill. Regulatory agencies may consider wastes disposed in this manner to pose less of a threat than the runoff and potential contamination from the abandoned mine itself.[12] In some cases, a chemical reaction between the waste and the mine runoff and leachate might actually

reduce the toxicity of the runoff (for example, an alkaline sludge could neutralize acid mine drainage). However, the likelihood of such a mitigative effect is very site-specific and would not necessarily occur uniformly throughout any given mine disposal site.

In a few cases, utility wastes, particularly acidic wastes, have been disposed in quarries. Limestone quarries are considered the best setting for this type of disposal because they provide a natural acid buffering capacity and the capacity for the metals present in the waste to be attenuated by chemically combining with materials in the quarry.[13] Quarry disposal of wastes works well for lime or limestone slurry wastes, which harden to form a concrete-type floor at the bottom of the quarry, thereby plugging any potential leakage paths. The probability of achieving success with this method must be evaluated on a case-by-case basis prior to its use.

4.2.1.2 Prevalence of Various Land Management Methods

Use of the waste management methods described above can vary from plant to plant and, in some cases, among individual generating units at a single power plant. This section presents information on how these utility waste management methods are employed nationwide and within EPA regions. It also discusses how these utility waste management methods have changed over time. The emphasis is on surface impoundments and landfills because these two waste management methods are the most commonly-used utility waste management practices in the United States.

The information presented in this section was derived from the Edison Electric Institute Power Statistics Database, currently maintained by the Utility Data Institute. This database contains information on power plant characteristics for all electric utility generating plants in the U.S. These data include number of power plants, number of generating units at each power plant site, type of fuel, plant capacity, as well as other information. It also contains information on the type of waste management methods currently used by power plants throughout the country, including type of disposal facility and whether the wastes were disposed at the power plant or in off-site facilities. Because each generating unit at a power plant may have its own waste management practice, the database gives waste disposal information for all generating units.

Data were not available for all generating units in the database. When information is not available, the extent of data coverage is indicated. In some instances the number of generating units on which no information was available was quite high. Although EPA recognizes the possibility of some statistical bias due to lack of data on some generating units, this database is the most comprehensive source available on utility waste management practices. EPA has no reason to believe that such bias is serious enough to call into question conclusions drawn in this analysis.

Exhibit 4-4 displays, for each of the ten EPA regions of the U.S. (see Exhibit 2-4 for a map of these regions), the number of generating units whose waste is managed in surface impoundments, in landfills, or mines. The most

EXHIBIT 4-4

UTILITY WASTE MANAGEMENT FACILITIES BY EPA REGION
(number of generating units) a/

EPA Region	Surface Impoundments	Landfills	Minefills	Other/ Unknown	Total
1	1	10	0	7	18
2	0	22	0	17	39
3	33	103	1	7	144
4	195	55	0	45	295
5	160	198	4	130	492
6	19	48	2	18	87
7	55	61	1	32	149
8	9	56	23	21	109
9	11	16	0	7	34
10	0	9	2	0	11
U.S. Total	483	578	33	284	1378

Source: Utility Data Institute Power Statistics Database

a/ The data are provided by generating unit because each generating unit at a power plant may have its own management facility. A generating unit typically refers to a single boiler, turbine, and generator set at a power plant. A power plant may have more than one generating unit at the site. For the database used here, data were available for 1,378 generating units located at 514 power plants.

common types of facilities used by the electric utility industry are surface impoundments and landfills:

- Landfills are the most common type of disposal facility used. Of the 1,094 generating units for which data were available (for 284 units, type of waste disposal method was unknown), 578 units (about 53 percent) used landfills for waste disposal. Landfills are used throughout the United States, with the largest number (over one-half of all landfills) located in the high coal-consuming, industrialized areas of the East and Midwest (Regions 3 and 5).

- Surface impoundments are also commonly used; approximately 44 percent of the generating units (483 out of 1,094) used this type of management facility. Of the 483 generating units that place wastes in surface impoundments, nearly 75 percent are located in Regions 4 and 5. (In the past, access to abundant, inexpensive supplies of water in these Regions often made it economical to use this management option.)

- Mine disposal is used for about three percent of all generating units (33 units out of 1,094). This disposal technique is used most frequently in the western U.S., particularly Region 8. Power plants in this area are often located at or near the coal mine that is supplying the plant. Since the coal mine is located nearby, disposal of waste in the mine is often economic.

When managing coal combustion wastes, electric utilities may treat, store, or dispose of the wastes at the power plant or at facilities located off-site. EPA could not determine from the data available how far the wastes are transported when managed off-site, although the cost of transporting the wastes would tend to encourage disposal near the power plant. A summary of industry practices is provided in Exhibit 4-5, which shows for each EPA region, by type of facility, whether the wastes are managed on-site or off-site.

EXHIBIT 4-5

**LOCATION OF UTILITY WASTE MANAGEMENT FACILITIES:
ON-SITE VERSUS OFF-SITE
(number of generating units)***

EPA Region	On-Site	Off-Site	Unknown	Total
1				
Surface Impoundments	1	0	0	1
Landfills	0	8	2	10
Other/Unknown	0	0	7	7
Total	1	8	9	18
2				
Surface Impoundments	0	0	0	0
Landfills	3	18	1	22
Other/Unknown	0	0	17	17
Total	3	18	18	39
3				
Surface Impoundments	25	3	5	33
Landfills	62	37	4	103
Other/Unknown	0	1	7	8
Total	87	41	16	144
4				
Surface Impoundments	186	4	5	195
Landfills	26	8	21	55
Other/Unknown	0	0	45	45
Total	212	12	71	295
5				
Surface Impoundments	141	5	14	160
Landfills	41	140	17	198
Other/Unknown	0	6	128	134
Total	182	151	159	492
6				
Surface Impoundments	18	0	1	19
Landfills	36	3	9	48
Other/Unknown	0	6	14	20
Total	54	9	24	87

EXHIBIT 4-5 (continued)

**LOCATION OF UTILITY WASTE MANAGEMENT FACILITIES:
ON-SITE VERSUS OFF-SITE
(number of generating units)***

EPA Region	On-Site	Off-Site	Unknown	Total
7				
Surface Impoundments	42	0	13	55
Landfills	20	26	15	61
Other/Unknown	7	1	25	33
Total	69	27	53	149
8				
Surface Impoundments	6	2	1	9
Landfills	28	11	17	56
Other/Unknown	2	23	19	44
Total	36	36	37	109
9				
Surface Impoundments	9	2	0	11
Landfills	16	0	0	16
Other/Unknown	0	0	7	7
Total	25	2	7	34
10				
Surface Impoundments	0	0	0	0
Landfills	5	4	0	9
Other/Unknown	0	2	0	2
Total	5	6	0	11
Total U.S.				
Surface Impoundments	428	16	39	483
Landfills	237	255	86	578
Other/Unknown	9	39	269	317
Total	674	310	394	1378

* The data are provided by generating unit because each generating unit at a power plant may have its own management facility. A generating unit typically refers to a single boiler, turbine, and generator set at a power plant. A power plant may have more than one generating unit at the site. For the database used here, data were available for 1,378 generating units located at 514 power plants.

- Nearly 70 percent of all generating units in the U.S. manage their coal combustion wastes on-site (based on information for 984 units, 674 units dispose on-site). About two-thirds of the on-site facilities are surface impoundments; most of the other on-site facilities are landfills.

- Landfills are used for about 95 percent of all off-site disposal in the U.S. This is not surprising considering that surface impoundments are typically used when wastes are transported as a wet slurry; the cost of disposal could become prohibitive if a utility transported the slurry off-site.

- Coal combustion waste management practices also differ by region:

  -- In the Northeast (Regions 1 and 2), where few coal-fired generating units are located, management tends to occur off-site in landfills.

  -- The highest percentage of on-site management is found in the South (Region 4), where about 95 percent of all units manage their waste on-site (212 units, based on information from 224 units). On-site management is common because utilities in this region often use surface impoundments, which are typically located at the power plant.

  -- In the Rockies and northern Great Plains area (Region 8), most of the off-site disposal (23 of 36 units) occurs in mines that are generally adjacent to the power plant.

These trends in utility waste management methods have been changing in recent years, with a shift towards greater use of disposal in landfills located on-site. For example, for generating units built since 1975, nearly 65 percent currently dispose of coal combustion wastes in landfills, compared with just over 50 percent for units constructed before 1975. Similarly, over 80 percent of all units built since 1975 use

on-site management facilities, compared with just under 65 percent of all units built before 1975 that manage wastes on-site.

4.2.2 Alternative Waste Management Technologies

Section 4.2.1 described the types of land management facilities used by utilities and patterns of use. This section describes the additional technologies that utilities may employ at the facilities described above in order to reduce potential environmental risk associated with waste management. For example, some utilities use liner systems for impoundments and landfills, leachate collection systems, and ground-water monitoring systems to control and monitor waste constituent migration. Pre-treatment technologies, by altering physical and chemical properties, can also render wastes more amenable for certain disposal methods. This section also presents data on the prevalence of these various technologies. The alternative technologies discussed in this section, although not necessarily the same as technologies required for RCRA Subtitle C facilities, may be required by current state regulations (described in Section 4.1) and could be more widely used in the future to further mitigate potential environmental impacts at utility waste disposal sites not currently employing these technologies.

4.2.2.1 Installation of Liners

Until recently, most surface impoundments and landfills used for utility waste management have been simple, unlined systems. Lining is

becoming a more common practice, however, as concern over potential ground-water contamination from "leaky ponds" and, to a lesser extent, from landfills has increased. Some waste management facilities use one or more impermeable synthetic liners; some are lined with one or more layers of low-permeable clay[14]; and some use a combination of clay and synthetic liners.

Synthetic Liners

Several dozen manufacturers and distributors supply impermeable synthetic liners. The most common materials of construction for these liners include polyvinyl chloride (PVC) and high-density polyethylene (HDPE), although several other impermeable synthetics have also been used. Liners may be reinforced with fibers to increase strength and decrease the likelihood of punctures. The liners can be purchased in standard thicknesses that range from 10 mils to 100 mils,[15] or can be made to order. Most liner installations will include protective geotextile fabric above and/or below the impermeable synthetic liner to minimize further the potential for puncture.

Preparation of the site prior to installation of a synthetic liner is similar to that which occurs before clay liner construction. However, more care must be taken to smooth out the surfaces to eliminate any peaks and cavities on the disposal facility floor that could cause a puncture of the liner material. Consequently, surface preparation costs are greater than those for clay liners. Excavation costs are usually less, however,

because the thinner synthetic liners allow shallower excavation (i.e., the additional excavation required to install a clay liner that is several feet thick can be avoided if a much thinner synthetic liner is installed).

The liner itself, which comes rolled or folded in large pieces, is laid in the field and sealed along the seams by heat or solvent fusion techniques; the seams may be field tested at spot checkpoints. The liner is usually covered with a foot or more of soil to protect it from puncture and to keep it in place during construction of the disposal facility. The edges of the liner at the tops of the dikes or landfill cell walls must be well secured to prevent the liner from pulling out and shifting due to the mass of the wastes placed in the impoundment or landfill. Some facilities are double lined and often contain a leachate collection system located in a soil or sand layer between the two liners.

Among the limitations to the use of synthetic liners is their susceptibility to tear and puncture. This is of particular concern in a single-lined impoundment because of the opportunity for liquids to seep through a single tear. Synthetic liners are also susceptible to degradation by certain waste materials. Acidic wastes, for example, can degrade some synthetic liner materials. As with clay liners, waste/liner compatibility testing should be performed to ensure that the disposed wastes will not weaken or permeate the liner. Additionally, because the seams of a synthetic liner are frequently weaker than the liner itself, they may pull apart under stress (e.g., large mass loadings or wave

action). Finally, dredging of synthetically-lined impoundments must be done cautiously, sometimes at very significant expense.

Synthetic liners, unlike clay liners (described below), are impermeable. Another advantage is the ease of repairing an exposed, damaged impoundment liner. A tear or puncture can be patched and seamed, and an impoundment put back into service, relatively quickly. (To repair subsurface damage, however, the impoundment must be wholly or partially drained.) Another advantage to using synthetic liners is that because of manufacturer quality control, a facility owner can be fairly certain that each liner sheet is as impermeable as the next. Clay is expensive to transport and in areas of the country where clay soils are scarce, a synthetic liner system may prove to be the less expensive option.

Clay Liners

The installation of a clay liner in a surface impoundment or landfill entails several steps. First, the site must be excavated or graded to a level below the design elevation of the facility floor. Many facilities take advantage of natural low areas or abandoned ponds to minimize excavation costs. The excavated earth can be used to build up the dike walls for the impoundment or to build containing berms within the landfill. Occasionally, soil must be brought to the construction site to raise the dikes to the design height.

Once the floor and dikes or berms have been prepared, the clay liner is laid in 6- to 9-inch lifts; its final thickness will be between 1 foot and 8 feet. Each lift is individually compacted before the next one is laid, thereby providing effective compaction and minimizing leakage potential. Field testing of the clay for permeability and other pertinent characteristics is sometimes performed during construction to provide quality assurance. Before the impoundment or landfill can be used, the liner is visually inspected for flaws; non-contaminated water may also be piped to the pond to assure that the liner is sufficiently impermeable.

One of the primary concerns about the use of clay liners is whether the entire clay liner meets thickness and permeability requirements. If weather conditions during liner construction are arid and hot, the liner may dry out and crack, causing localized areas of leakage. If conditions are wet or the clay is too moist, clay compaction may never be sufficient to achieve the necessary low permeability. The clays used as liner materials vary in the degree to which they are compatible with the wastes placed in the facility. Laboratory tests, in which the proposed liner material is exposed to the wastes intended for management, should be conducted for each facility to ensure that components of the waste material will not unduly alter the permeability of the clay used as liner material. If the chemical characteristics of the generated waste were to change over time, then the tests would need to be repeated to determine what effect the altered waste stream would have on the clay liner.

An advantage of clay liners is their potential for chemical, particularly cation, attenuation. The chemical structure of clay allows its use as an exchange site for metallic cations and other ions that might gradually seep out of the facility. Such exchange further reduces the opportunities for migration of waste constituents to the ground water. For facilities with fairly ready access to clays, the capital and construction costs associated with the use of a clay liner, even one that is several feet thick, may be substantially lower than those associated with the use of a synthetic liner.

Composite Liners

Many waste management facilities in industries currently subject to RCRA Subtitle C requirements are installing liner systems that combine both clay liner and synthetic liner technologies. Most commonly, an impoundment or landfill will be lined with 2-4 feet of impermeable clay, which is then prepared for placement of a synthetic liner. The synthetic liner may be covered with 1-2 feet of sand to serve as drainage for a leak detection system. Some facilities may then add another 1- to 2-foot layer of clay, which is again prepared for placement of the upper synthetic liner. In landfills, another leachate collection system is usually placed above this upper liner.

The composite synthetic/clay liner system offers a combination of advantages over single-material liners. A composite liner has some of the advantages provided by synthetic liners, such as factory quality control

and ease of repair (for the upper liner), as well as the advantage of clay's propensity for attenuating escaped ions. Furthermore, use of multiple-liner materials reduces the likelihood that waste material will leak into the ground water because of chemical incompatibility between a waste and a single liner material. In general, the more layers of impermeable liner material that are used, the more efficient containment of liquids will be, thus reducing the likelihood of a release of waste material.

The biggest drawback of the composite synthetic/clay liner system is the cost of installation. Utility waste landfills are very large (up to 100 acres or more), and a liner large enough to cover such a area could be very expensive. In areas where labor costs are high and clay is unavailable locally and must be transported long distances, these costs would be magnified.

Frequency of Liner Use

Some electric utilities have installed liners to retard the flow of leachate from the waste disposal facility to the surrounding area. Exhibit 4-6 shows the extent to which electric utilities are currently using this technology.

- About 25 percent of all generating units in the U.S. for which data were available (139 of 580 units) have installed some type of liner. There are no available data on the material used to construct these liners or if more than one liner has been installed at the disposal facility.

EXHIBIT 4-6

INSTALLATION OF LINERS FOR LEACHATE CONTROL AT UTILITY WASTE MANAGEMENT FACILITIES (number of generating units)*

EPA Region	Unlined	Lined	Unknown	Total
1				
Surface Impoundments	0	0	1	1
Landfills	0	0	10	10
Other/Unknown	0	0	7	7
Total	0	0	18	18
2				
Surface Impoundments	0	0	0	0
Landfills	1	14	7	22
Other/Unknown	0	0	17	17
Total	1	14	24	39
3				
Surface Impoundments	17	2	14	33
Landfills	17	7	79	103
Other/Unknown	0	0	8	8
Total	34	9	101	144
4				
Surface Impoundments	153	3	39	195
Landfills	14	7	34	55
Other/Unknown	0	0	45	45
Total	167	10	118	295
5				
Surface Impoundments	90	20	50	160
Landfills	64	31	103	198
Other/Unknown	0	4	130	134
Total	154	55	283	492
6				
Surface Impoundments	7	7	5	19
Landfills	11	17	20	48
Other/Unknown	0	0	20	20
Total	18	24	45	87

EXHIBIT 4-6 (continued)

INSTALLATION OF LINERS FOR LEACHATE CONTROL AT UTILITY WASTE MANAGEMENT FACILITIES (number of generating units)*

EPA Region	Unlined	Lined	Unknown	Total
7				
Surface Impoundments	30	4	21	55
Landfills	7	4	50	61
Other/Unknown	6	0	27	33
Total	43	8	98	149
8				
Surface Impoundments	4	0	5	9
Landfills	12	6	38	56
Other/Unknown	0	0	44	44
Total	16	6	87	109
9				
Surface Impoundments	2	9	0	11
Landfills	2	4	10	16
Other/Unknown	0	0	7	7
Total	4	13	17	34
10				
Surface Impoundments	0	0	0	0
Landfills	4	0	5	9
Other/Unknown	0	0	2	2
Total	4	0	7	11
Total U.S.				
Surface Impoundments	303	45	135	483
Landfills	132	90	356	578
Other/Unknown	6	4	307	317
Total	441	139	798	1378

* The data are provided by generating unit because each generating unit at a power plant may have its own waste management facility. A generating unit typically refers to a single boiler, turbine, and generator set at a power plant. A power plant may have more than one generating unit at the site. For the database used here, data were available for 1378 generating units located at 514 power plants.

- Based on the information available, landfills are more likely to be lined than surface impoundments. Of the 222 generating units that use landfills and that indicated whether the disposal facility was lined or not, about 40 percent (90 units) have lined disposal facilities. Only 13 percent of surface impoundments have liners installed (based on information from 348 of the 483 units).

The information in Exhibit 4-6 should be interpreted cautiously since data were available for only 42 percent of the population (580 units of 1,378 units). One of the reasons this information is unavailable is due to the number of electric utilities that dispose of coal combustion wastes off-site. In many of these cases, the utility does not know whether the off-site disposal facility is lined or not since the utility does not run the disposal operation.

Liner use has been increasing in recent years. Before 1975, less than 20 percent of all generating units managed their coal combustion wastes in lined facilities. For units constructed since 1975, however, this percentage has increased to over 40 percent. The proportion of lined management facilities is particularly high at generating units that produce FGD sludge; since 1975 about 60 percent of management facilities containing these wastes have been lined.

4.2.2.2 Leachate Collection and Ground-Water Monitoring

Any lined management facility may have a leachate collection system and any facility (lined or unlined) may be equipped with a ground-water monitoring system. Leachate collection systems are used to prevent the

migration of contamination from a landfill or impoundment. Both systems can be used to monitor the rate and extent of contaminant migration. The design and placement of ground-water monitoring and leachate collection systems should take into account the manner in which a landfill or impoundment might potentially interfere with natural ground-water flow and usage patterns.

In surface impoundments, the leachate collection system(s) can be placed below the entire liner system or it can be placed between any two liners. Leachate collection systems typically consist of a drainage media (coarse sand and/or gravel) and perforated pipes (called riser pipes) that slope toward a collection sump. The collected leachate is pumped out via these riser pipes to the surface for treatment and/or disposal. If the riser pipes through which the leachate is pumped perforate the synthetic or clay liner, tight seals are necessary to ensure that the leachate does not escape through the perforation.

In landfills, leachate control systems can be installed below all liners (this is usually called a pressure relief system), between liners (the inter-liner leachate control system), and/or above the upper liner. The floors of a landfill cell are designed to slope to the leachate collection sumps and are usually covered with a drainage media such as sand or gravel. Each leachate control system has its own collection sump, which is emptied through riser pipes so that the leachate can be treated or disposed appropriately. As with impoundment liner systems, riser pipes, if they pierce the liners, must be sealed to prevent leakage.

Ground-water monitoring wells are placed at strategic locations to facilitate early detection of any contaminants that escape the facility and migrate to the ground water. The design and placement of the monitoring wells is based on site-specific hydrogeological assessments, soil chemistry, specific regulatory directives, and other physical and chemical factors. Downgradient wells typically are used to monitor the extent of contamination arising from a facility, and upgradient "background" wells are installed to serve as controls.

Most newer utility waste management facilities have ground-water monitoring systems, and many also have leachate collection systems. In other industries, permitted facilities subject to Subtitle C regulations are required by law to have both ground-water monitoring and leachate collection systems.[16] For utility waste disposal sites, it is estimated that about 15 percent of all facilities have leachate collection systems and about 35 percent have ground-water monitoring systems.[17]

4.2.2.3 Pre-disposal Treatment

Facilities employ a variety of waste treatment processes to alter the physical or chemical characteristics of wastes so that they will be compatible with the disposal method used. Treatment methods may also be employed to comply with the effluent limitations established under the Clean Water Act.

Sludge Dewatering

The most commonly used pre-disposal treatment process is sludge dewatering. This process is often necessary so that the sludge can be more easily handled and of a consistency suitable for landfill disposal. This procedure can also be used for any wet coal ash or combined coal ash/FGD sludge wastes. Most frequently, sludge dewatering is accomplished by sedimentation of the suspended solids in surface impoundments or, in some cases, in clarification tanks. This type of dewatering is carried out at 80 percent of the utilities.[18]

After the waste solids have had sufficient time to settle, the water layer is drawn off the tank or impoundment and is either discharged subject to National Pollutant Discharge Elimination System (NPDES) permits or recycled back to the plant as sluice or cooling water. The sludge layer containing the solid ash and other particles is allowed to accumulate for several months (or longer), and is finally dredged after the pond is drained. With this process, the solids content (initially between 5 and 15 percent by weight) can be increased to between 30 and 60 percent. The final solids content in the sludge is affected by the sedimentation impoundment or tank design, the initial solids content, the liquid and solids retention times, and the physical and chemical characteristics of the solid particles.

Even after dewatering, the settled sludges often have a mud-like consistency and still contain so much free liquid that they are

inappropriate for landfill disposal. In this case, the sludge may be further dewatered by natural or mechanical processes. In arid and semi-arid areas, the sludges may be retained in the impoundments until natural evaporation removes still more water. Sludges may also be placed on drying beds made of screens, sand, or other drainage media designed to allow water to percolate out by gravity, while the solids are retained. In mechanical sludge dewatering, belt or vacuum filters, filter presses, thermal dryers, or other processes are used. Ten percent of the utilities use some sort of filtration to dewater sludges.[19] For high-volume sludges, however, mechanical dewatering equipment may be expensive and inconvenient to operate.

Reagent Addition

Most FGD sludges and some other wet sludges can be rendered less chemically reactive and/or more structurally stable by adding solidification, stabilization, or fixation reagents. This practice is not widespread; less than 10 percent of the utilities report using these processes.[20] Solidification agents, such as sawdust or soil, absorb the liquid in a sludge but do not chemically react with the sludge. Stabilization and fixation reagents chemically react with some portion of the sludge -- either the water, the dissolved solids, the particulate solids, or some combination of the three-- and, in some cases, may render potentially hazardous material non-hazardous as a result. All of these processes result in an increased volume of waste that contains less free water and is easier to handle than the original waste stream. An

additional benefit is an increase in the structural integrity (shear stress and load-bearing potential; see Chapter Three for discussion of these characteristics) of the waste material so that it may be placed in deeper disposal facilities and covered with more material.

Low-volume Waste Treatment

The major methods available for low-volume waste management and treatment include:

- co-disposal;
- contract disposal;
- evaporation;
- incineration;
- neutralization;
- physical/chemical treatment; and
- recycle/reuse.

The type of waste management method used most often depends on the type of low-volume waste stream. Exhibit 4-7 shows the treatment process commonly used for each low volume waste stream. Each of these treatment processes is discussed briefly below.

EXHIBIT 4-7

SUMMARY OF CURRENT HANDLING, TREATMENT AND DISPOSAL OF LOW VOLUME WASTES

Low Volume Waste	Treatment	Predominant Disposal Method
Waterside Cleaning Waste	If organic chelating agents are used, this stream can be incinerated. If acids are used, the stream is often neutralized and precipitated with lime and flocculants.	1. Co-disposal with high volume wastes in pond or landfill following treatment. 2. Disposal by paid contractor.
Fireside Cleaning Waste	Sometimes neutralized and precipitated. For coal-fired plants most often diverted to ash ponds without treatment. If metals content is high, chemical coagulation and settling is used.	1. Co-disposal with high volume wastes in pond without treatment. 2. Ponding following treatment.
Air Preheater Cleaning Waste	Settling in ash pond; neutralized and coagulated if combined with other streams before treatment.	1. Co-disposal in pond without treatment. 2. Ponding with treatment.
Coal Pile Runoff	Neutralized by diverting to alkaline ash pond. Fine coal material caught in perimeter ditch is often diverted back to coal pile.	1. Co-disposal of sludge in landfill after treatment. 2. Co-disposal in ash pond.
Wastewater Treatment	Usually ponded with ash or as a separate waste. Sometimes solids co-disposed with bottom ash.	1. Ponding 2. Landfilling
Make-up Water Treatment	usually co-disposed in ash pond.	1. Co-disposal in pond.
Cooling Tower Basin Sludge	Very little survey or literature information; infrequent stream. Sludge comingled with wastewater treatment sludge.	1. Landfilling

EXHIBIT 4-7 (Continued)

SUMMARY OF CURRENT HANDLING, TREATMENT AND DISPOSAL OF LOW VOLUME WASTES

Low Volume Waste	Treatment	Predominant Disposal Method
Demineralizer Regenerants	Equalized in tanks, then comingled into ash ponds.	1. Ponding
Pyrite Wastes	Disposed in landfills with bottom ash or diverted to ash pond	1. Ponding 2. Landfilling

Source: EPRI, Characterization of Utility Low-Volume Wastes, prepared by Radian Corporation, Austin, Texas, May 1985.

-- Co-Disposal

Co-disposal of low-volume wastes with high-volume wastes into landfills and surface impoundments is commonly used in the utility industry. A January 1981 EPA letter (the Dietrich memorandum) currently allows co-disposal of low-volume wastes with high-volume wastes in landfills and surface impoundments.[21] In a 1985 EPRI study on low-volume waste management, about three-fourths of the power plants interviewed co-disposed some low-volume wastes in a surface impoundment or landfill.[22] The amount of treatment necessary before co-disposal varies with the waste stream. Solid wastes are typically disposed directly into the waste management facility. Liquid wastes are often routed to an interim treatment surface impoundment. Once in the surface impoundment, evaporation occurs and the remaining sludge is landfilled. If the liquid waste is chemically treated before ponding, heavy metals are often removed in a treatment facility; the treated liquid may then be reused or diverted to a surface impoundment while the residue from the treatment process is disposed in a landfill.

-- Contract Disposal

Many utilities hire outside contractors to treat and dispose of low-volume wastes. Contract disposal is most common for low-volume waste streams produced intermittently that are difficult to treat on-site. For example, hydrochloric acid boiler cleaning waste typically requires neutralization with high dosages of a caustic material. Construction of an on-site treatment system for this waste stream requires a large capital investment, although boiler cleaning wastes are produced only over a few hours once every two to five years. As a result, some

utilities (7 of 22 power plants surveyed in EPRI's 1985 study) employ outside contractors when boiler cleaning is required.[23] The treated boiler cleaning waste is then co-disposed on-site or disposed of off-site.

Contract disposal is also a common waste management practice for spent ion exchange resin. In EPRI's 1985 study, of five power plants responding, four plants hauled these wastes off-site while one power plant co-disposed the waste on-site.[24]

-- Evaporation

Evaporation ponds are used to dispose of high concentration, low-volume liquid wastes. Prior to final disposal, liquid wastes are diverted to an evaporation pond, generally shallow ponds with a large surface area. The sludge remaining after most of the water evaporates is then dredged and disposed of in a landfill.

-- Incineration

Incineration of low-volume wastes includes injection into the boiler or mechanical evaporation. This method of disposal is most common with organic cleaning wastes (Ethylenediamide tetracedic acid (EDTA) or citrate waste). A 1987 EPRI study[25] examined the effect of incinerating EDTA and citrate wastes in a utility boiler. The findings showed that the additional metals contributed were minimal compared to the amount contributed by the coal.

Two of the twenty-two power plants interviewed in EPRI's 1985 study use this method of waste disposal.[26]

-- Neutralization

Acidic or alkaline wastes can be treated with either strong bases or acids, respectively, to produce a near neutral stream. For example, wastewaters, demineralizer regenerant, and coal pile runoff must typically be within a pH range of 6.0 to 9.0 to meet Clean Water Act (CWA) and National Pollutant Discharge Elimination System (NPDES) limits. Neutralization can be used to achieve these levels. Similarly, hydrochloric acid boiler cleaning waste, which may have a ph below 2.0, can undergo neutralization to raise the ph above RCRA corrosivity guidelines (ph values between 2.0 and 12.5 are not considered corrosive under RCRA).[27]

-- Other Physical/Chemical Treatment

Physical and/or chemical treatment systems can be used for reducing and removing dissolved and suspended contaminants from aqueous streams. The most prevalent treatments incorporate pH adjustment (i.e., addition of basic or acidic materials), precipitation (i.e., separating solids from solution or suspension), flocculation (i.e., aggregation of fine suspended particles), clarification (i.e., separating liquid and suspended solids) and filtration (i.e., trapping suspended solids). The continuous waste streams are treated to allowable levels. Boiler chemical cleaning and fireside cleaning wastes require higher reagent doses and occasionally additional

processing to meet Clean Water Act (CWA) and National Pollutant Discharge Elimination System (NPDES) discharge limits for metals. Ten of the 15 power plants questioned in EPRI's 1985 study route boiler cleaning wastes through physical and/or chemical treatment systems prior to discharge.[28]

-- Reuse

Reuse is a common practice for many water-based low volume wastes, especially in water-limited regions of the country. For example, less contaminated streams (boiler blowdown, yard drains) can be used without treatment in cooling towers, ash handling systems, and flue gas desulfurization systems. Other wastes, such as boiler cleaning wastes and coal pile runoff, cannot easily be reused because they require extensive treatment prior to reuse. If a power plant does decide to treat these waste streams, the liquid portion of treated waste may be reused while the sludges produced during treatment are typically landfilled.

4.2.3 Ocean Disposal

Many different types of wastes, including industrial and municipal wastes, have been disposed at sea in the past, although the use of this method for disposing coal combustion wastes is only in the research and development phase. Typically, industrial and municipal wastes are shipped out to sea and disposed at any of several regulated dump sites, which are located anywhere from 20 miles to over 100 miles off the shore line. Another method of ocean disposal (seldom used, however) involves pumping or

gravity feeding wastes through a pipeline that feeds directly from the land-based waste generating site or dump site into the ocean. When the wastes reach the final oceanic disposal site, they either dissolve and disperse or form a manmade reef.

The 1972 Marine Protection Research and Sanctuaries Act (MPRSA), EPA regulations regarding ocean disposal,[29] and the London Dumping Convention currently regulate ocean dumping with respect to the solids content, metals content, and toxicity of wastes considered for this method of disposal.

4.2.4 Waste Utilization and Recovery of Various Waste By-Products

Although the majority of the waste generated by coal-fired electric utilities is land disposed, a substantial percentage is recovered and reused. From 1970 to 1980, an average of 18 percent of all coal ash generated annually was utilized;[30] from 1980 to 1985, the average coal ash utilization rate exceeded 22 percent, with utilization in 1985 over 27 percent of all coal ash produced.[31] The amount of FGD sludge waste utilized is less than one percent of the total volume of FGD waste generated, although more efficient FGD sludge recovery and utilization processes currently being developed by the utility industry may increase this use. The combined utilization rate for all high-volume coal combustion wastes, i.e., fly ash, bottom ash, boiler slag, and FGD sludge, was about 21 percent in 1985.

The recovery processes are usually performed at the power plant. Use of the recycled waste may occur on-site or the recycled product may be sold for off-site use. Like any industrial product, the wastes to be recycled may be accumulated on-site prior to sale and delivery.

The recovery processes and the uses for waste by-products are numerous and quite varied:

- Bottom ash currently has the highest rate of utilization at 33 percent. It is used as blasting grit, road and construction fill material, for roofing granules, and has other miscellaneous uses.[32]

- Fly ash utilization is substantial. About 17 percent of fly ash production is used for concrete admixture, cement additives, grouting, road and construction fill material, and for miscellaneous other uses.[33]

- FGD wastes are not heavily utilized in the industry (less than 1 percent), but some utilities have the capacity to recover sulfur, sulfuric acid, or other sulfur products from the waste.[34]

- Some low-volume wastes (particularly solvents) that are segregated from the high-volume waste streams are potentially recoverable or available for other uses.

- Numerous other recovery processes and utilization techniques are currently in the research and development phase. At this time, however, the Agency is unaware of any advances in recovery processes that will significantly change the proportion of coal combustion wastes that are disposed.

Coal Ash

There are a variety of different options currently available for the utilization of fly ash, bottom ash, and boiler slag from coal-fired electric

utilities. All types of coal ash are appropriate for use as construction materials, as cement additives, and for several other uses. Coal ash utilization is primarily centered in the southeast and north central United States.[35]

Most fly ash and some bottom ash exhibit pozzolanic (bonding) properties -- that is, the dried materials are cohesive and exhibit high shear strength and compressive load-bearing characteristics. These properties make ash an appropriate substitute for portland cement for many applications, including concrete production, standard cement production, and for special uses such as for the production of road base cement or even grouting.

Cement made with fly ash may be preferable to regular portland cement for some applications. One of the key benefits is the absence of heat release while the concrete or cement mixture cures; this absence of heat generation means that the design structural strength is more likely to be achieved. However, the use of fly ash and bottom ash as cement substitutes is limited because of the wide variability in ash composition, even in ash originating from the same coal supply or utility. The presence of metals in the ash can reduce the structural integrity of the final concrete by preventing the necessary chemical bonding. The presence of large quantities of sulfates or nitrates will also interfere with the pozzolanic properties. Because of this bonding interference, fly ash and bottom ash are thought to be able to replace no more than 20 percent of the cement used (or about 15 million tons of ash annually).[36] Improvements in utilization techniques may reduce the bonding interference and increase the reutilization potential of

fly ash; however, the Agency is unaware of technical advances at this time that will allow substantially greater utilization in cement applications.

Fly ash and bottom ash are also commonly used as high-volume fill for various construction materials. The pozzolanic properties of these materials facilitate soil stabilization, making them desirable as fill additives. Coal ash has been used as fill in asphalt, road bases, parking lots, housing developments, embankments, and to line on-site disposal facilities at the utilities. In the future, numerous other construction applications may use coal ash as fill, particularly if the ash is available at lower cost than standard fill materials. However, the use of ash as fill is limited somewhat because of the variability of the ash composition.

Bottom ash and boiler slag have been used as substitutes for sand in sand-blasting operations and road de-icing. Ash and slag particles are similar in size and density to sand particles. In areas where sand is costly to transport, these wastes can be economical substitutes. Ash is less corrosive than salt and could therefore be a preferable de-icing material, although in some municipalities the use of ash for de-icing has been prohibited due to public concern over aesthetics (e.g., ash residue on cars).

A variety of minor uses for fly ash and bottom ash have been considered, some of which have already been implemented at a small number of utilities. For example, bottom ash has been used for granular roofing material. Fly ash has been used by some facilities as a stabilization reagent for acidic

aqueous or semi-solid hazardous wastes: the high-pH fly ash reacts with other, low-pH waste to generate a neutral solution and to simultaneously precipitate dissolved metals as oxides and hydroxides. Because the fly ash exhibits pozzolanic properties, the ultimate waste product, when dried, often resembles concrete. The metals from the original waste stream are usually so strongly bound within the chemical structure of the final waste product that they will not leach out, even under acidic conditions.

Because fly ash has some of the same physical characteristics as a silty clay, fly ash may be used as an additive to clay liners for waste management facilities, particularly for impoundments. Fly ash is cohesive and fairly impermeable when properly compacted, and mixes well with some of the clays used in impoundment liners. However, because chemical composition of fly ash is variable, its utilization as liner material may be limited. If methods are improved to be sure that minimum permeability and shear strength requirements could be maintained over time, then the use of fly ash as an impoundment liner material may increase.

Fly ash has been used occasionally as a soil conditioner to increase the pH of acidic soils, thereby enhancing crop growth. Fly ash can also contribute minerals to the soil. However, soil conditioners in common use today, mostly agricultural limestones, are so inexpensive and easy to obtain that it would be difficult to penetrate this market with a fly ash product.

There are few processes currently available for recovery of materials from coal ash. One facility has had some commercial success at producing

magnetite from fly ash.[37] Magnetite recovered from fly ash actually contains a higher percentage of magnetics than does natural magnetite, making it a more efficient coal cleaning agent. This particular technology shows some promise of expanding; other processes, mostly for metals recovery, are in the development stage. Recovery processes for alumina and titanium are at an advanced stage of development. However, while both these technologies have been proven feasible, neither is currently economically competitive with ore-processing technologies. Another potential metal recovery process, dubbed the DAL process and still in the research stage, involves a series of relatively simple operations that can be performed with commercially available process equipment to recover various metals from fly ash. Theoretically, this process could show a substantial return on investment soon after the recovery facility began operating.[38]

There is little information available to the Agency on the environmental effects of utilization of coal combustion wastes. For many applications, such as the use of coal ash in cement and concrete products, it would appear that any adverse environmental impacts would be minimal. To the extent that coal combustion wastes can be recycled in an environmentally acceptable manner, utilization would help to reduce the amount of waste disposed. The Agency is very interested in reducing the amount of waste that needs to be disposed by the utility industry; however, barring major breakthroughs in recycling techniques, it appears the potential for significantly increasing the amount of waste utilization may be limited.[39] Given current utilization techniques, the Agency expects that the major portion of coal combustion wastes will continue to be land disposed.

FGD Wastes

The prospects for utilization of FGD sludge are less promising than those for ash utilization. FGD sludge is not structurally stable or strong enough to serve as a construction material, nor does it show the pozzolanic properties required for a cement substitute. Current research in the field of FGD sludge utilization is focusing on a dry scrubber method in which reagents will be used to precipitate the FGD waste streams as dry gypsum powder. Gypsum is sold for use in wallboard; however, there is currently a glut on the market, and in any case, other sources of gypsum may be preferred because the gypsum produced from FGD is often of lesser quality. Some researchers are making an effort to find a reagent that will precipitate a dry powder which, when mixed with water, will exhibit pozzolanic properties and will harden to a concrete-like material. No testing has been done, however, as the research is still in the conceptual stage.

Although by-product utilization of FGD sludges comprises less than one percent of total sludge production, a much greater percentage of FGD by-products may be recoverable in the very near future since two full-scale recovery processes and one test-scale recovery process for FGD by-products are currently under development. Of the two full-scale processes, the Wellman-Lord process recovers both sulfuric acid and elemental sulfur from the waste stream, while the magnesium oxide scrubber process recovers only sulfuric acid.[40] The citrate scrubbing process, currently in the testing phase, recovers elemental sulfur. FGD recovery processes currently in the

research stage will be used to recover elemental sulfur, sulfuric acid, and gypsum from the FGD process, and should be available for full-scale use within the next decade.[41] All recovery processes for FGD wastes generate both a by-product stream and a waste stream that must be disposed.

Low-Volume Utility Wastes

EPA currently assumes that most low-volume utility wastes are co-disposed with the high-volume wastes or, in some instances, burned in the boiler at the power plant, although little data exist that accurately describe industry-wide practices on low-volume waste disposal.[42] Since co-disposal is a common industry practice, low-volume wastes do not have specific processes associated with their recovery or utilization. Although this practice of co-disposal (or burning) may continue into the future, certain waste streams, such as spent cleaning solvents, might be recovered by distilling and collecting the solvents at high temperature, which would leave a low-volume residue to be disposed. The recovered solvent could then be reused on-site as a cleaning solvent or sold to another facility. If an organic solvent were contaminated in such a way that contaminant removal were difficult or impossible, the contaminated solvent could be burned. For low-volume waste streams burned in the boiler, these wastes could be transported to an off-site facility that would burn them as fuel. If low-volume wastes were considered hazardous, regulations might restrict the burning of these wastes, potentially making this option infeasible.[43]

Other recovery schemes for individual low-volume waste streams may be developed if these streams are segregated from the high-volume wastes. At this time, however, few recovery processes and utilization techniques have been considered separately for low-volume utility wastes.

Recycled Effluent

Approximately 25 percent of the utilities that utilize surface impoundments recycle some of their pond effluent back to the plant.[44] If the recycled effluent is used as sluice water, the system pH may increase to values well above 10. The recycled effluent may also be used as cooling water prior to ultimate discharge. Although effluent recycling is not a waste recovery or utilization technique, it can affect the chemical characteristics of the solid wastes that may come into contact with the recycled water.

4.3 SUMMARY

Coal combustion waste management practices by electric utilities vary widely across the industry. State regulation, regional factors such as land availability and water availability, and age of the power plant all have an effect on the type of waste management practices that are employed. Alternative practices, such as ground-water monitoring and leachate collection, are used by some utilities, and in some states are mandated by regulation. A significant portion of coal combustion by-products are recovered and utilized for various purposes.

- All but one state regulates the disposal of coal combustion wastes under their hazardous or solid waste disposal regulations. One state exempts these wastes from regulation.

- State solid waste regulations applicable to coal combustion wastes vary widely across the country. Generally, solid waste regulations require that disposal facilities have permits; location restrictions and standards related to liners, leachate control, and ground-water monitoring are applied on a case-by-case basis.

- Currently, about 80 percent of all coal-fired power plant wastes are land managed; the remaining 20 percent are recycled or recovered. The most common types of disposal facilities used by utilities generating coal-fired wastes are surface impoundments, landfills, and abandoned mines.

- Currently, about 25 percent of utility treatment, storage, and disposal facilities that receive combustion waste are lined. About 15 percent of all facilities have leachate collection systems, and 35 percent have ground-water monitoring.

- Newer facilities are more likely to be lined, have leachate collection systems, and ground-water monitoring systems. More than 40 percent of all generating units constructed since 1975 use lined disposal facilities.

- About 20 percent of all high-volume combustion wastes, particularly fly ash and bottom ash, are recycled, primarily as cement additives, high-volume road construction material, or blasting grit.

- About 99 percent of FGD wastes are currently disposed; however, recovery of sulfur and sulfur products from FGD wastes is a developing and promising technology.

CHAPTER 4

NOTES

[1] Wald, Harkrader & Ross, Survey of State Laws and Regulations Governing Disposal of Utility Coal-Combustion Byproducts, for the Utility Solid Waste Activities Group (USWAG), 1983.

[2] States have probably followed U.S. EPA's lead in exempting coal combusting wastes. Many states' regulations explicitly refer to 40 CFR 261.4, or use the clause's exact wording.

[3] The following State officials were interviewed: Brett Bettes, Solid Waste Division, Washington Department of Ecology, January 6, 1987; Ken Raymond, Industrial and Solid Waste Division, Oklahoma Department of Health, December 31, 1986; Dwight Hinch, Division of Waste Management, Tennessee Department of Health, December 31, 1986; Shelby Jett, Division of Waste Management, Kentucky Department of Environmental Protection, January 6, 1987; Vincent Nikle, Assistant Liaison's Office, New Jersey Department of Environmental Protection, December 17, 1986.

[4] According to Maine's Solid Waste Management Regulations: "More Stringent Criteria for Large-Scale Disposal of Oil, Coal and Incinerator Ash: Because of the concentration of heavy metals in residues from the combustion of municipal solid waste or the combustion of oil or coal, including bottom ash and fly ash, disposal of such ashes when they occur in amounts that exceed a total accumulation of 20 cubic yards of coal ash ... per week over any one-month period shall be confined to a secure landfill. For the purposes of these rules, a secure landfill shall mean a landfill with a liner and a leachate management system." (Maine's Solid Waste Management Regulations, Chapter 401.2.3.).

[5] The exhibit assumes that both on-site and off-site permits are required unless the regulations explicitly state otherwise.

[6] See Chapter One for discussion of the regulation of low-volume utility waste streams.

[7] Waste piling, a method occasionally employed by utilities, is not discussed in this report. Waste piles are mounds of ash placed on the ground and covered with soil.

[8] U.S. Department of Energy, Impacts of Proposed RCRA Regulations and Other Related Federal Environmental Regulations on Utility Fossil Fuel-Fired Facilities, Volume II. 1983.

[9] See Chapter 6 for a discussion of disposal costs.

[10] Haller, W.A., J.E. Harwood, S.T. Mayne, and A. Gnilka, "Ash Basin Equivalency Demonstration (for treatment of boiler cleaning wastes containing heavy metals)," Duke Power Company, 1976.

[11] Envirosphere Company, Environmental Settings and Solid Residues Disposal in the Electric Utility Industry, EPRI Report EA-3681, 1982.

[12] Ibid.

[13] Ibid.

[14] A low-permeable clay is one that has been determined in laboratory testing to have a permeability coefficient, K, of 10^{-7} cm/sec or less.

[15] There are one thousand mils per inch.

[16] See 40 CFR 264.

[17] Engineering-Science, Background Data on Utility Fossil Fuel-fired Facilities, prepared for USDOE, Office of Fossil Energy, 1983.

[18] Ibid.

[19] Ibid.

[20] EPRI Journal, 1985, op. cit.

[21] EPRI, Manual for Low-Volume Wastes From Fossil-Fuel-Fired Power Plants, prepared by Radian Corporation, Austin, Texas, July 1987.

[22] EPRI, Characterization of Utility Low-Volume Wastes, prepared by Radian Corporation, Austin, Texas, May 1985.

[23] Ibid.

[24] Ibid.

[25] EPRI, 1987.

[26] EPRI, 1985.

[27] EPRI, 1987.

[28] EPRI, 1985.

[29] 40 CFR 228, Criteria for the Management of Ocean Disposal Sites for Ocean Dumping.

[30] Envirosphere Company, "Economic Analysis of Impact of RCRA on Coal Combustion By-Products Utilization" in Report and Technical Studies on the Disposal and Utilization of Fossil-Fuel Combustion By-Products, Appendix G, prepared for Utility Solid Waste Activities Group (USWAG), October 1982.

[31] Information compiled by the American Coal Ash Association on 1985 ash utilization, August 1, 1986.

[32] EPRI Journal. 1985. op. cit.

[33] Ibid.

[34] Ibid.

[35] USWAG, 1982.

[36] EPRI Journal. 1985. op. cit.

[37] USWAG. 1982. op. cit.

[38] Ibid.

[39] For example, see comments by Garry Jablonski, section manager of ash utilization for the American Electric Power Company, "Coal Ash Market Report," Vol. 1, No. 9, July 15, 1987.

[40] EPRI, State-of-the-Art of FGD Sludge Fixation, 1978.

[41] Ibid.

[42] Envirosphere Company, Information Responding to EPA's Request Regarding Burning and Co-Treatment/Co-Disposal of Low Volume Wastes Generated At Fossil Fuel Electric Generating Stations, prepared for USWAG and Edison Electric Institute, August 1981.

[43] The economics of burning these wastes would depend on the applicable regulations. Regulations concerning the burning of hazardous wastes are currently being developed and are scheduled for final promulgation in mid-1987.

[44] U.S. Department of Energy. 1983. Op. cit.

GLOSSARY

acidity - the amount of free carbon dioxide, mineral acids and salts (especially sulfates or iron and aluminum) which hydrolyze to give hydrogen ions in water and is reported as milli-equivalents per liter of acid, or ppm acidity as calcium carbonate, or pH the measure of hydrogen ions concentration. Indicated by a pH of less than 7.

administrator - the Administrator of the United States Environmental Protection Agency, or his/her designee.

alkaline cleaning solution wastes - water-side cleaning waste resulting from the removal of high copper content scale from the utility boiler.

alkaline passivating waste - water-side cleaning waste resulting from the removal of iron and copper compounds and silica to neutralize acidity after acid cleaning.

alkalinity - the amount of carbonates, bicarbonates, hydroxides and silicates or phosphates in the water and is reported as grains per gallon, pH, or ppm of carbonate. Indicated by a pH of greater than 7.

alkaline fly ash scrubber - a flue gas desulfurization system in which flue gas reacts with alkaline fly ash that is augmented with a lime/limestone slurry.

anthracite - a high ASTM ranked coal with dry fixed carbon 92% or more and less than 98%; and dry volatile matter 8% or less and more than 2% on a mineral-matter-free basis.

aquifer - a water-bearing bed or structure of permeable rock, sand, or gravel capable of yielding quantities of water to wells or springs.

ash - the incombustible solid matter in fuel.

ash fusion - the temperatures at which a cone of coal or coke ash exhibits certain melting characteristics.

attenuation - a process that slows the migration of constituents through the ground.

baghouse - an air pollution abatement device used to trap particulates by filtering gas streams through large fabric bags usually made of glass fibers.

base load - base load is the term applied to that portion of a station or boiler load that is practically constant for long periods.

batch test - a laboratory leachate test in which the waste sample is placed in, rather than washed with, leachate solution.

bituminous coal - ASTM coal classification by rank on a mineral/matter-free basis and with bed moisture only.

> low volatile: dry fixed carbon 78% or more and less than 86%; and dry volatile matter 22% or more and less than 14%.
> medium volatile: dry fixed carbon 69% or more and less than 78%; and dry volatile matter 22% or more and less than 31%.
> high volatile (A): dry fixed carbon less than 69% and dry volatile matter more than 31% - Btu value equal to or greater than 14,000 moist, mineral-matter-free basis.
> high volatile (B): Btu value 13,000 or more and less than 14,000 moist, mineral-matter-free basis.
> high volatile (C): Btu value 11,000 or more and less than 13,000 moist, mineral-matter-free basis commonly agglomerating, or 8,300 to 11,500 Btu agglomerating.

blower - the fan used to force air through a pulverizer or to force primary air through an oil or gas burner register.

boiler - a closed vessel in which water is heated, steam is generated, steam is superheated, or any combination thereof, under pressure or vacuum by the application of heat.

boiler blowdown - removal of a portion of boiler water for the purpose of reducing solid concentration or discharging sludge.

boiler cleaning waste - waste resulting from the cleaning of coal combustion utility boilers. Boiler cleaning wastes are either water/side or gas-side cleaning wastes.

boiler slag - melted and fused particles of ash that collect on the bottom of the boiler.

boiler water - a term used to define a representative sample of the boiler circulating water. The sample is obtained after the generated steam has been separated and before the incoming feedwater or added chemical becomes mixed with it so that its composition is affected.

bottom ash - large ash particles that settle on the bottom of the boiler.

British Thermal Unit (Btu) - the mean British Thermal Unit is 1/180 of the heat required to raise the temperature of 1 pound of water from 32°F to 212°F at a constant atmospheric pressure. It is about equal to the quantity of heat required to raise 1 pound of water 1 degree F.

capacity factor - the total output over a period of time divided by the product of the boiler capacity and the time period.

CERCLA - The Comprehensive Environmental Response, Compensation, and Liability Act, commonly referred to as Superfund.

cell - a section of a landfill, or the size of that section. Usually only a few cells of a landfill are open to accept waste at a time.

chain grate stoker - a stoker which has a moving endless chain as a grate surface, onto which coal is fed directly from a hopper.

coal pile runoff - surface runoff from a plant's coal pile.

cogeneration - the production of steam (or hot water) and electricity for use by multiple users generated from a single source.

column test - a leachate extraction procedure that involves passing a solution through the waste material to remove soluble constituents.

contingency plan - a document setting out an organized, planned, and coordinated course of action to be followed in case of a fire or explosion or a release of hazardous waste constituents into the environment.

cooling tower blowdown - water withdrawn from the cooling system in order to control the concentration of impurities in the cooling water.

cyclone furnace - specialty furnace for high intensity heat release. So named because of its swirling gas and fuel flows.

demineralizer regeneration and rinses waste - a low volume wastewater generated from the treatment of water to be used at the plant.

direct lime flue gas desulfurization - see lime/limestone FGD process.

direct limestone flue gas desulfurization - see lime/limestone FGD process.

disposal - the discharge, deposit, injection, dumping, spilling, leaking, or placing of any solid waste or hazardous waste into or on any land or water such that any constituent thereof may enter the environment or be emitted into the air or discharged into any waters, including ground waters.

dry-bottom furnace - a pulverized-fuel furnace in which ash particles are deposited on the furnace bottom in a dry, non-adherent condition.

dry scrubber - an FGD system for which sulfur dioxide is collected by a solid medium; the final product is totally dry, typically a fine powder.

dry sorbent injection - an FGD system in the research and development stage for which a powdered sorbent is injected into the flue gas before it enters the baghouse. Sulfur dioxide reacts with the reagent in the flue gas and on the surface of the filter in the baghouse.

dual alkali fly ash scrubber - a flue gas desulfurization system similar to the lime/limestone process, except that the primary reagent is a solution of sodium salts and lime.

effluent - a waste liquid in its natural state or partially or completely treated that discharges in to the environment from a manufacturing or treatment process.

electrostatic precipitator - an air pollution control device that imparts an electrical charge to particles in a gas stream causing them to collect on an electrode.

evapotranspiration - the combined process of evaporation and transpiration.

fabric filter - a cloth device that catches dust and particles from industrial or utility emissions.

flash point - the lowest temperature at which vapors above a volatile combustible substance ignite in air when exposed to flame.

flue gas - the gaseous products of combustion in the flue to the stack.

flue gas desulfurization (FGD) sludge - waste that is generated by the removal of some of the sulfur compounds from the flue gas after combustion.

fly ash - suspended ash particles carried in the flue gas.

furnace - the combustion chamber of a boiler.

gas-side cleaning waste - waste produced during the removal of residues (usually fly ash and soot) from the gas-side of the boiler (air preheater, economizer, superheater, stack, and ancillary equipment).

ground water - water found underground in porous rock strata and soils.

ground water monitoring well - a well used to obtain ground-water samples for water-quality analysis.

hazardous waste - a solid waste, or combination of solid wastes, which, because of its quantity, concentration, or physical, chemical, or infectious characteristics, may (1) cause, or significantly contribute to, an increase in serious irreversible, or incapacitating reversible illness; or (2) pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, disposed of, or otherwise managed.

hard water - Water that contains sufficient dissolved calcium and magnesium to cause a carbonate scale to form when the water is boiled or to prevent the sudsing of soap in the water.

high volume waste - fly ash, bottom ash, boiler slag, and flue gas desulfurization sludge.

hydraulic conductivity - the quantity of water that will flow through a unit cross-sectional area of a porous material per unit of time.

hydrochloric acid cleaning waste - wastes from the cleaning of scale caused by water hardness, iron oxides, and copper.

land disposal - the placement of wastes in a landfill, surface impoundment, waste pile, injection well, land treatment facility, salt dome formation, salt bed formation, or underground mine or cave.

landfill - a disposal facility or part of a facility where hazardous waste is placed in or on land and which is not a land treatment facility, a surface impoundment or injection well.

leachate - the liquid resulting from water percolating through, and dissolving materials in, waste.

leachate extraction test - a laboratory procedure used to predict the type and concentration of constituents that will leach out of waste material.

leachate collection, removal, and treatment systems - mitigative measures used to prevent the leachate from building up above the liner.

lift - the depth of a cell in a landfill.

lignite - a coal of lowest ASTM ranking with calorific value limits on a moist, mineral-matter-free basis less than 8,300 Btu.

lime - calcium oxide (CaCO3), a chemical used in some FGD systems.

limestone - calcium carbonate (CaOH2), a chemical used in some FGD systems.

lime/limestone FGD process - form of wet non-recovery flue gas desulfurization system in which flue gases pass through a fly ash collection device and into a contact chamber where they react with a solution of lime or crushed limestone to form a slurry which is dewatered and disposed.

liner - a mitigative measure used to prevent ground-water contamination in which synthetic, natural clay, or bentonite materials that are compatible with the wastes are used to seal the bottom or surface impoundments and landfills.

low volume waste - wastes generated during equipment maintenance and water purification processes. Low volume wastes include boiler cleaning solutions, boiler blowdown, demineralizer regenerant, pyrites, cooling tower blowdown.

mechanical stoker - a device consisting of mechanically operated fuel feeding mechanism and a grate, and is used for the propose of feeding solid fuel into a furnace, and to distribute it over a grate, admitting air to the fuel for the purpose of combustion, and providing a means for removal or discharge of refuse.

net recharge - the amount of precipitation absorbed annually into the soil.

off-site - geographically noncontiguous property, or contiguous property that is not owned by the same person. The opposite of on-site.

on-site - the same or geographically contiguous property which may be divided by public or private right(s)-of-ways, provided the entrance and exit between the properties is at across-roads, intersection, and access is by crossing as opposed to going along the right(s)-of-way. Noncontiguous properties owned by the same person but connected by a right-of-way which the person controls and to which the public does not have access, is also considered on-site property.

Part A - the first part of the two part application that must be submitted by a TSD facility to receive a permit. It contains general facility information.

Part B - the second part of the two part application that includes detailed and highly technical information concerning the TSD in question. There is no standard form for the Part B, instead the facility must submit information based on the regulatory requirements.

particulates - fine liquid or solid particles such as dust, smoke, mist, fumes, or smog, found in the air or emissions.

permeability (1) - the ability of a geologic formation to transmit ground water or other fluids through pores and cracks.

permeability (2) - the rate at which water will seep through waste material.

petroleum coke - solid carbaceous residue remaining in oil refining stills after distillation process.

pH - a measure of the acidity or alkalinity of a material, liquid or solid. pH is represented on a scales of 0 to 14 with 7 being neutral state, 0 most acidic and 14 most alkaline.

plume - a body of ground water originating from a specific source and influenced by such factors as the local ground-water flow pattern and character of the aquifer.

pond liquors - waste fluid extracted from a surface impoundment or landfill.

pozzolanic - forming strong, slow-hardening cement-like substance when mixed with lime or other hardening material.

PDWS - Primary Drinking Water Standards established by the Safe Drinking Water Act.

pulverizer - a machine which reduces a solid fuel to a fineness suitable for burning in suspension.

pyrites - solid mineral deposits of raw coal that are separated from the coal before burning.

reagent - a substance that takes part in one or more chemical reactions or biological processes and is used to detect other substances.

recharge - the replenishment of ground water by infiltration of precipitation through the soil.

RCRA - Resource Conservation and Recovery Act, as amended (Pub. L. 94-580). The legislation under which EPA regulates solid and hazardous waste.

RCRA Subtitle C Characteristics - criteria used to determine if an unlisted waste is a hazardous waste under Subtitle C of RCRA.

- corrosivity - a solid waste is considered corrosive if it is aqueous and has a pH less than or equal to 2 or greater than or equal to 12.5 or if it is a liquid and corrodes steel at a rate greater than 6.35 mm per year at a test temperature of 55°C.

- EP toxicity - a solid waste exhibits the characteristic of EP (extraction procedure) toxicity if, after extraction by a prescribed EPA method, it yields a metal concen- tration 100 times the acceptable concentration limits set forth in EPA's primary drinking water standards.

- ignitability - a solid waste exhibits the characteristic of ignitability if it is a liquid with a flashpoint below 60°C or a non-liquid capable or causing fires at standard temperature and pressure.

- reactivity - a waste is considered reactive if it reacts violently, forms potentially explosive mixtures, or generates toxic fumes when mixed with water, or if it is normally unstable and undergoes violent change without deteriorating.

SDWS - Secondary Drinking Water Standards established by the Safe Drinking Water Act.

settling lagoon - surface impoundment.

shear strength - the resistance offered by a material subjected to a compressive stress created when two contiguous parts of the material are forced in opposite parallel directions.

slag - molten or fused solid matter.

sludge - a soft water-formed sedimentary deposit that is mud-like in its consistency.

slurry - a mixture of insoluble mater in a fluid.

solid waste - As defined by RCRA, the term "solid waste" means any garbage, refuse, sludge from a waste treatment plant, water supply treatment plant, or air pollution control facility and other discarded material, including solid, liquid, semisolid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from community activities,

but does not include solid or dissolved material in domestic sewage, or solid or dissolved materials in irrigation return flows or industrial discharges which are point sources subject to permits under the Clean Water Act, or special nuclear or byproduct material as defined by the Atomic Energy Act of 1954.

spray drying process - a flue gas desulfurization system in which a fine spray of alkaline solution is injected into the flue gas as it passes through a contact chamber, where the reaction with the sulfur oxides occurs. The heat of the flue gas evaporates the water in the solution, leaving a dry powder, which is collected by a particulate collector.

stabilization - making resistant to physical or chemical changes by treatment.

steady state - an adjective that implies that a system is in a stable dynamic state in which inputs balance outputs.

stoker - see mechanical stoker.

storage - the holding of waste for a temporary period, at the end of which the hazardous waste is treated, disposed of, or stored elsewhere.

subbituminous coal - An intermediate rank coal between lignite and bituminous with more carbon and less moisture than lignite.

sump effluent - waste from sumps that collect floor and equipment drains.

surface impoundment - a facility which is a natural topographic depression, artificial excavation, or diked area formed primarily of earthen materials (although it may be lined with artificial materials), which is designed to hold an accumulation of liquid wastes or wastes containing free liquids.

surface water - water that rests on the surface of the rocky crust of the earth.

traveling grate stoker - a stoker similar to a chain grate stoker except that the grate is separate from but is supported on and driven by chains.

trace element - An element that appears in a naturally-occurring concentration of less than 1 percent.

treatment - any method, technique, or process, including neutralization, designed to change the physical, chemical, or biological character or composition of a waste so as to neutralize it, recover it, make it safer to transport, store or dispose of, or amenable for recovery, storage, or volume reduction.

TSD facility - waste treatment, storage, or disposal facility.

utility boiler - a boiler which produces steam primarily for the production of electricity in the utility industry.

volatile - A volatile substance is one which tends to vaporize at a relatively low temperature.

water-side cleaning waste - waste produced during the removal of scale and corrosion products from the water side of the boiler (i.e., the piping systems containing the steam or hot water).

wet bottom furnace - a pulverized fuel fired furnace in which the ash particles are deposited and retained on the floor thereof and molten ash is removed by tapping either continuously or intermittently. (also called a slag tap furnace)

wet scrubber - a device utilizing a liquid, designed to separate particulate matter or gaseous contaminants from a gas stream by one or more mechanisms such as absorption, condensation, diffusion, inertial impaction.

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CHAPTER FIVE

POTENTIAL DANGERS TO HUMAN HEALTH AND THE ENVIRONMENT

Under Section 8002(n) of RCRA, EPA is to analyze the "potential danger, if any, to human health and the environment from the disposal and reuse" of coal combustion wastes and "documented cases in which danger to human health or the environment from surface runoff or leachate has been proved." This chapter examines potential and documented dangers to human health and the environment caused by wastes generated from the combustion of coal at electric utility power plants.

As described in Chapter One, special large volume wastes, including coal combustion wastes, are to be treated differently under RCRA than other industrial wastes. Due to the extremely large volume of coal combustion waste and the expectation of relatively low risk from its disposal, Congress directed EPA to evaluate all the factors in 8002(n) of RCRA in determining whether Subtitle C regulation is warranted. The danger from coal combustion waste management is only one of the factors EPA must consider. In order to provide a starting point for evaluating the potential danger from coal combustion waste management, this chapter begins by providing the reader with background information on the characteristics that an industrial solid waste must exhibit to be considered hazardous under RCRA, and then looks at which of these characteristics apply to coal combustion wastes. The next section analyzes several studies that monitored ground-water and surface-water concentrations in and around coal combustion waste disposal sites and documented the number of times that drinking water standards were exceeded. The third section of this

chapter reviews studies that compiled and evaluated reported incidences of contamination to ground water and surface water due to the disposal of coal combustion wastes. Finally, the fourth section analyzes the factors affecting the exposure of humans, animals, and plants to contaminants from coal combustion waste by examining environmental setting and population data for a random sample of 100 coal-fired utility power plants.

5.1 RCRA SUBTITLE C HAZARDOUS WASTE CHARACTERISTICS AND LISTING CRITERIA

Under RCRA, solid wastes are classified as hazardous if they exhibit characteristics of ignitibility, corrosivity, reactivity, and/or EP toxicity as defined by RCRA or if they are listed as hazardous by the Administrator.

- Ignitibility refers to the tendency of a substance to catch fire. A liquid waste is ignitable if it has a flash point less than 60°C, as determined by EPA-specified test protocols. A non-liquid waste is ignitable if, under standard temperature and pressure, it is capable of causing a persistent, hazardous fire through friction, absorption of moisture, or spontaneous chemical change.[1]

- Corrosivity of waste is determined by measuring the waste's pH, the value used to express relative acidity or alkalinity. A pH value of 7.0 is neutral; substances with a pH less than 7.0 are acidic, while those with a pH greater than 7.0 are alkaline. A waste is corrosive, and therefore hazardous, if it is aqueous and has a pH less than or equal to 2.0 or greater than or equal to 12.5.[2] A waste is also corrosive if it is liquid and corrodes steel at a rate greater than 6.35 mm per year. The pH measurements and the corrosion rate must be determined using EPA-approved methods.[3]

- Reactivity refers to the stability of a substance. Wastes that are highly reactive and extremely unstable tend to react violently or explode. A waste is reactive if it undergoes violent physical change without detonating, if it reacts violently with water, if it forms a potentially explosive or toxic mixture with

water, or if it is capable of detonating or exploding at standard temperature and pressure.[4]

- Extraction Procedure (EP) Toxicity is determined from a laboratory procedure designed to simulate leaching from a disposal site under actual disposal conditions.[5] Concentrations in the effluent from this test are compared with the Primary Drinking Water Standards (PDWS) of eight constituent metals to determine whether a waste is hazardous. A waste is EP toxic if it produces a leachate using an EPA-approved procedure that has concentrations of contaminants that are 100 times the PDWS.[6]

Wastes are also regulated as hazardous wastes under Subtitle C if the Administrator lists them in 40 CFR 261.31-261.33. The Administrator may list wastes using several criteria:

- if they are ignitable, corrosive, reactive, or EP toxic as described above.
- if they have been found to be fatal to humans in low doses, or, in the absence of data on human toxicity, fatal to animals in laboratory tests (these wastes are designated Acute Hazardous Wastes).[7]
- if they contain any of the toxic constituents listed in Appendix VIII of 40 CFR 261, unless the Administrator, after considering the factors contained in 40 CFR 261.11(a)(3), concludes that "the waste is not capable of posing a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported or disposed of, or otherwise managed." The factors that the Administrator may consider include the toxicity of the constituent, the concentration of the constituent in the waste, the potential for degradation, the degree of bioaccumulation to be expected from the constituent, and the quantities of the waste generated. These wastes are designated Toxic Wastes.[8]

Determining whether coal combustion wastes show any of the hazardous characteristics is important in analyzing potential danger to human health and the environment. In general, most coal combustion wastes, such as ash and FGD sludge, are not ignitable. Reactivity is also generally not a characteristic

of concern for coal combustion wastes. The chemical and physical characteristics of most coal combustion wastes identified in Chapter Three indicate that these wastes are very stable and will likely not react with other substances in their disposal area. The remainder of this section will analyze data on coal combustion wastes to see if these wastes exhibit the characteristics of corrosivity and/or EP toxicity.

5.1.1 Corrosivity of Coal Combustion Wastes

Under current RCRA regulations, only liquid wastes can be considered corrosive. Coal combustion ash, therefore, could not by itself be considered corrosive, even if it generates a corrosive leachate.

For wastes that are aqueous, a waste is corrosive if its pH is less than or equal to 2.0 or greater than or equal to 12.5. Available data indicate that the pH values of most waste streams of coal-fired power plants do not fall within these ranges; in fact, the only wastes that may be classified as corrosive according to the above definition are water-side, hydrochloric acid-based cleaning wastes, which have had measured pH as low as 0.5 (see Exhibit 3-26). In an EPRI report on low volume wastes (see section 5.1.2) three samples of hydrochloric acid-based boiler cleaning waste all had pH levels less than 2. However, these wastes are often neutralized before disposal. Several other waste streams have pH levels which fall very near the corrosive ranges. Most of these are also low volume wastes. Boiler blowdown has measured pH as high as 12, with a range of 8.3-12 (see Exhibit 3-20), and coal pile runoff has measured pH as low as 2.1, with a range of 2.1-6.6 (see Exhibit 3-21). Sludge from dual-alkali FGD processes using eastern coal is a high volume waste with

measured pH of approximately 12.1 (see Exhibit 3-17). Chapter Three contains a complete description of these wastes.

Several studies of coal combustion waste streams surveyed in this chapter indicate that the alkalinity or acidity of coal combustion wastes, while not necessarily falling in the RCRA corrosive ranges, may occasionally reach levels of potential concern. For example, pH readings of waste fluids taken during a study by Arthur D. Little were as high as 11.4 (see Section 5.2.1). Three case studies described in Appendix D (a study of 12 Tennessee Valley Authority power plants, an individual study at the Bull Run Power Plant, and a study of the Savannah River Project) showed pH readings of waste fluids at 2.0, 3.5, and 2.9, respectively. Section 5.3.1 describes a documented case in which highly alkaline coal combustion waste (pH 12.0) caused substantial harm to aquatic life after it accidentally spilled into Virginia's Clinch River in 1967.

5.1.2 Extraction Procedure (EP) Toxicity of Coal Combustion Wastes

Current RCRA regulations (40 CFR 261.24) specify that if a leachate extracted using an EPA-approved extraction procedure contains any of the metals shown in Exhibit 5-1 at concentrations equal to or greater than the given limit, the waste is classified as EP toxic and, unless otherwise exempted, will be subject to Subtitle C regulation.[9] The concentrations shown in Exhibit 5-1 are 100 times the current Primary Drinking Water Standards (PDWS) established by the Safe Drinking Water Act for those constituents.

Waste extraction tests are used to predict the type and concentration of constituents that may leach from a waste disposal site under field conditions.

EXHIBIT 5-1

MAXIMUM CONCENTRATION OF CONTAMINANTS FOR CHARACTERISTIC OF EP TOXICITY

Contaminant	Level	
Arsenic	5.0	mg/l
Barium	100.0	mg/l
Cadmium	1.0	mg/l
Chromium	5.0	mg/l
Lead	5.0	mg/l
Mercury	0.2	mg/l
Selenium	1.0	mg/l
Silver	5.0	mg/l

Source: 40 CFR 261.24, January 16, 1987.

Most extraction tests are conducted by mixing or washing a waste sample with a water-based solution of a specified composition for a specified length of time. The resulting leachate solution is then separated from the solids and tested for constituent concentrations.

5.1.2.1 Types of Extraction Procedures

Several different types of waste extraction procedures are described in detail below. Although under current regulations only the Extraction Procedure (EP) toxicity test is used to determine whether a waste is EP toxic, EPA has recently proposed a new procedure, the Toxic Characteristic Leaching Procedure (TCLP), to replace the EP test (see Federal Register, Volume 51. No. 114, June 13, 1986, p. 21648). Furthermore, in the period since EPA has promulgated the Extraction Procedure (EP) toxicity test, many people have alleged that the EP provides an inappropriate measure of leaching under field conditions. For these reasons, EPA has reviewed the results of other extraction procedure tests as well as the EP. To the extent that the results of these other procedures on coal combustion wastes are generally consistent with the EP results, the debate over whether the EP test is appropriate or not is moot. Three of the extraction tests described below (EP, TCLP, and ASTM) are batch leaching tests. Batch tests are conducted by placing a waste sample in a water-based solution for a specified period of time. The fourth procedure, the column test, passes a solution through the waste.

- The procedure for the standard EPA extraction test, the Extraction Procedure (EP) toxicity test,[10] requires obtaining a waste sample of at least 100 grams and then separating the liquids from the solids. The solid portion is placed in a container along with 16 times its weight in deionized water, and continually agitated at 20-40°C. Throughout the test, the pH of the batch

mixture is monitored. If the solution remains above pH 5.0, acetic acid is added to maintain a pH of 5.0. If the solution is less than pH 5.0, no acetic acid is added. If the pH of the batch solution is not below 5.2 after the initial 24-hour agitation period, the pH is adjusted to 5.0 $\pm$ 0.2 at the beginning of each hour during an additional 4 hour agitation period. After agitation, the leachate solution is then separated from the solid portion, and the liquid extracted from the original waste sample is added to the leachate solution. These combined liquids are then tested for constituent concentrations.

- Toxic Characteristic Leaching Procedure (TCLP), which EPA has proposed as a replacement for the EP,[11] uses a different leaching solution depending on the nature of the waste being tested. For wastes of low alkalinity, a pH 5.0 acetic acid/sodium acetate buffer is used for extraction. If the waste is more alkaline, a normal acetic acid solution is used. Unlike the EP toxicity test, the TCLP can be used for volatile waste constituents.

- The American Society for Testing and Materials (ASTM) developed the ASTM A procedure, which requires 48-hour agitation of a 1:4 mixture of waste to distilled deionized water. Another test, ASTM B, involves the extraction of waste constituents in a buffered acetic acid solution of pH 4.5.[12] ASTM D, similar to ASTM A, involves the 48-hour agitation of a 350-gram sample with 1400 milliliters of deionized distilled water, and the filtering of the aqueous phase, after agitation, with a 0.45 micron filter.

- Unlike the batch testing methods described above, the column test is conducted by passing a solution through the waste. This test process simulates the migration of leachate and ground water through waste, but still cannot duplicate field conditions perfectly. Because there is no standard column test procedure, column tests are described individually in the studies reviewed in the next section of this chapter.

The results of various studies (conducted with the above-mentioned extraction tests) on the leaching of constituents from coal combustion wastes are discussed below.

5.1.2.2 Results of Extraction Tests

Tetra Tech Study

In 1983 Tetra Tech conducted a literature review for the Electric Power Research Institute (EPRI) and reported results from a number of leachate extraction studies.[13] An examination of the results of various leaching tests (EP toxicity test, ASTM A, and ASTM B) on coal ash and flue gas desulfurization (FGD) sludge revealed that results differed by waste type and were ultimately dependent upon the source of the fuel (see Exhibit 5-2) and the mechanics of combustion. The study results were presented separately for ash and FGD sludge.

Results of the batch leaching tests (EP, ASTM A, and ASTM B) reported in the studies reviewed by Tetra Tech were presented as averages of the element concentrations found in numerous runs of one type of extraction test. Ranges of the concentrations were sometimes presented as well. Depending on the laboratory that ran the test, EP, ASTM A, and ASTM B batch leaching tests were run on as few as 3 and as many as 62 samples.

Tetra Tech reviewed 457 EP tests on various types of ash. Results from these EP tests show a geometric mean concentration for selenium equal to its PDWS. Geometric mean concentrations for the other 7 metals were below their respective PDWS. The maximum concentrations were 4 times the PDWS for silver, 29 times for arsenic, 8 times for barium, 140 times for cadmium, 14 times for chromium, 4 times for mercury, 5 times for lead, and 17 times for selenium.

Tetra Tech also reported results from 202 ASTM A tests on ash. Selenium was

EXHIBIT 5-2

EFFECT OF GEOGRAPHIC COAL SOURCE ON ELEMENT CONCENTRATION IN ASH

Element	Geographic Variation
Arsenic	low in western coal ash; difference in concentration between eastern coal and midwestern coal ashes indistinguishable
Barium	highest in western coal ash
Cadmium	most concentrated in midwestern coal ash
Chromium	low in western coal ash; difference in concentration between eastern and midwestern coal ashes indistinguishable
Mercury	highest in eastern coal ash; all distributions highly skewed toward high concentrations
Lead	highest in midwestern coal ash
Selenium	similar in eastern and midwestern coal ash; lower in western coal ash
Strontium	highest in western ash; lowest in midwestern ash
Vanadium	similar in eastern and midwestern coal ash; lower in western coal ash
Zinc	highest in midwestern ash; lowest in western ash

Source: Tetra Tech, Inc., Physical-Chemical Characteristics of Utility Solid Wastes, prepared for Electric Power Research Institute, EA-3236, September 1983.

the only constituent with a geometric mean concentration greater than the PDWS, at a level approximately 2 times the PDWS. The maximum concentrations were less than the PDWS for silver and mercury. For the other elements, the maximum concentrations from the ASTM-A procedure were 7 times PDWS for arsenic, 4 times for barium, 1.3 times for cadmium, 10 times for chromium, 5 times for lead, and 48 times for selenium.

Cadmium was the only constituent in fly ash leachate extracted using the EP for which there was a maximum concentration over 100 times the PDWS (and therefore above the EP toxicity level). The EP produced a leachate that had a maximum cadmium concentration 140 times the PDWS. However, the average cadmium concentration for the 62 EP samples was only half the PDWS. Tetra Tech did not report the percentage of samples whose cadmium concentration exceeded 100 times the PDWS. In general, the more acidic or alkaline the leaching solution, the higher the concentrations of leached constituents. Tetra Tech concluded that the geometric mean concentrations from the EP and ASTM-A tests were similar. The results of the EP and ASTM-A tests are presented in Exhibit 5-3.

Tetra Tech also reviewed data from a number of column tests on coal ash. The test results did not show any concentrations greater than 100 times the PDWS for any element tested. One test was conducted during a two-year period using a continuous-flow method to produce leachate from fly ash. In another test, fly ash and bottom ash were packed separately in glass columns, each of which was leached for 27 days with 200 milliliters per day of either distilled water, dilute base, or dilute acid. For a third test, fly ash and bottom ash were packed in water-saturated glass columns. At one-week intervals, the columns were flushed from below at a moderate rate for two hours. This test was

EXHIBIT 5-3

RESULTS OF TETRA TECH EXTRACTION TESTS ON COAL COMBUSTION ASH

		EP Test Results			ASTM A Test Results		
Constituent	Primary Drinking Water Standard (mg/l)	Range	Geometric Mean	Maximum Exceedance	Range	Geometric Mean	Maximum Exceedance
Arsenic	.05	<.004- 1.46 mg/l	.012 mg/l	29 X PDWS	<.0005-0.37 mg/l	.0072 mg/l	7 X PDWS
Barium	1.0	.003- 7.6 mg/l	0.222 mg/l	8 X PDWS	.0004-3.8 mg/l	0.208 mg/l	4 X PDWS
Cadmium	.01	.0001- 1.4 mg/l	.0047 mg/l	140 X PDWS	.0001-.013 mg/l	.00039 mg/l	1.3 X PDWS
Chromium	.05	.001- 0.68 mg/l	.036 mg/l	14 X PDWS	.0005-0.5 mg/l	.047 mg/l	10 X PDWS
Lead	.05	<.0001-0.25 mg/l	.005 mg/l	5 X PDWS	<.0001-0.25 mg/l	.0025 mg/l	5 X PDWS
Mercury	.002	<.0001- .007 mg/l	.00042 mg/l	4 X PDWS	<.0001-.0012 mg/l	.00027 mg/l	0.6 X PDWS
Selenium	.01	<.0001-0.17 mg/l	.01 mg/l	17 X PDWS	.0005-0.48 mg/l	.019 mg/l	48 X PDWS
Silver	.05	<.0001-0.20 mg/l	.00064 mg/l	4 X PDWS	<.0001-.03 mg/l	.0007 mg/l	0.6 X PDWS

Source: Tetra Tech, Inc., Physical-Chemical Characteristics of Utility Solid Wastes, prepared for Electric Power Research Institute, EA-3236, September 1983.

intended to simulate the intermittent wetting to which some ash disposal sites are subject.

Partly because flue gas desulfurization (FGD) technologies have only achieved widespread commercial usage in recent years, FGD sludge has not been as thoroughly characterized as coal ash. However, the Tetra Tech study reported the results of tests performed on sludges from a number of scrubber processes, including the lime/limestone/alkaline fly ash process, the dual alkali/sodium carbonate process (both these processes produce "lime sludge" and are the main technologies currently in use), and the spray drying process (this process produces calcium-based dry scrubber sludge and may be used more extensively in the future).

Results from EP tests on calcium-based dry scrubber sludge showed a maximum concentration of cadmium that was 150 times the PDWS, above the EP toxic level. Arsenic and selenium were also analyzed using the EP test; the maximum arsenic concentration was 32 times the PDWS and the maximum for selenium was 1.8 times the PDWS. No other constituents were tested for this waste stream. (Results from the EP studies on calcium-based dry scrubber sludge were not averaged but reported as ranges - the number of tests performed was not given).

Tetra Tech also presented results of EP tests on lime sludge. These tests measured concentrations of all EP toxicity constituents, and none were found to be at EP toxic levels.

Tetra Tech also reported on column tests performed on FGD sludge. In one column test, calcium-based dry scrubber sludge was leached with deionized water

for 11 months. In another, various proportions of fly ash, wet calcium sulfate (i.e., gypsum), calcium sulfite precipitate, and calcium oxide (lime) were mixed, cured for 500 days, and leached with deionized water that was forced through the waste columns. The leaching test results (reported in a manner similar to that for reporting results of coal ash leaching studies) indicated, on the basis of an unreported number of tests, that PDWS constituents in lime sludge and calcium-based dry scrubber sludge leached at concentrations that exceeded their PDWS by multiples of less than 5 for silver, 32 for arsenic, 2 for barium, 30 for chromium, 10 for lead, and 15 for selenium; the concentration of mercury found in sludge leachate matched its PDWS. No constituents were at concentrations above 100 times the PDWS.

In summary, none of the coal ash or FGD sludge leaching studies reviewed by Tetra Tech showed constituent concentrations greater than 100 times the PDWS, with the exception of cadmium from calcium-based dry scrubber FGD sludge and from coal ash. Both results were from EP toxicity procedure tests. The behavior of these wastes primarily depended on the source of the fuel and the mechanics of combustion. Tetra Tech concluded that there were gaps in the characterization of these wastes that made definitive conclusions difficult to reach.

Department of Energy Study

The Department of Energy (DOE) conducted a compilation study of leaching test results, Analytical Aspects of the Fossil Energy Waste Sampling and Characterization Project,[14] for the purpose of generating a data base on the

leaching characteristics of coals and their combustion wastes. The EP test was compared to a water leach test developed by ASTM (this test later became ASTM D) and evaluated to determine the precision of the EP toxicity method when applied to coal wastes. In their summary of the collected data, DOE reported that for six of the analyzed constituents there were no significant differences between the testing results derived from the two methods. The results of 2492 separate extraction tests for the eight PDWS constituent metals (arsenic, barium, cadmium, chromium, lead, mercury, selenium and silver) indicated that none of the metals leached at concentrations that exceeded the PDWS by 50 times, and most leached at concentrations less than 10 times the PDWS. This was true for both the EP test and the ASTM test.

Arthur D. Little Study

EPA sponsored a study by Arthur D. Little, Inc. (see Section 5.2.1) which included EP Toxicity tests on 20 fly ash samples from 16 power plants and 3 FGD waste samples from 3 power plants.[15] The names of the plants from which the samples were taken were not revealed because Arthur D. Little did not consider the single "grab" samples obtained for testing to be representative. The EP test results showed no EP toxic levels in the extracted leachates of any samples. Silver and mercury concentrations were below the reported detection limits of .001 mg/l and .002 mg/l, respectively, for all samples. Lead was detected in only three out of seventeen samples. Other PDWS constituents (arsenic, cadmium, chromium, selenium, and barium) were detected, but all were found at concentrations less than 100 times the PDWS. In contrast to the Tetra Tech study reported above, leachates extracted from FGD samples had concentrations of PDWS constituents that tended to be lower than the

concentrations in leachates extracted from fly ash samples, whereas the Tetra Tech report indicated that, in general, higher concentrations of PDWS constituents were leached from FGD sludges than from coal ash. This discrepancy may be due to variations in the wastes themselves, which, in turn, are due to differences among coals derived from different sources. Results of the Arthur D. Little study are presented in Exhibit 5-4.

Battelle Pacific Northwest Study

In another study for the Electric Power Research Institute (EPRI), Battelle Pacific Northwest reviewed data developed during a round-robin study that compared results from three laboratories performing both the EP and TCLP tests.[16] Battelle Northwest compared the two extraction procedures by looking at the ratio of the mean TCLP concentrations to the mean EP concentrations for each element. These ratios fell within the range of 0.8 to 1.2 about 60 percent of the time. Only 15 percent of the ratios exceeded 2.0. In 83 percent of the comparisons, the TCLP test leachate contained greater concentrations of the PDWS constituents than the EP test leachate.[17]

Battelle compared the maximum mean concentration of each compound (taken from the pool of averaged results for each constituent from both EP and TCLP testing of all the waste samples) with the corresponding PDWS. This comparison indicated that for both the EP and the TCLP procedures, concentrations of silver, barium, and mercury were less than the established PDWS for those metals, whereas the concentration of arsenic was 21 times the PDWS; cadmium, 25 times; chromium, 13 times; lead, 4 times; and selenium, 14 times.

EXHIBIT 5-4

RESULTS OF ARTHUR D. LITTLE TESTING SHOWING THE
RANGE OF CONCENTRATION OF METALS IN EP EXTRACTS a/

Metal	Average Values		(A) Overall Range Observed (mg/l)		(B) Primary Drinking	Ratio of Observed Range to PDWS (A/B)	
	Fly Ash	FGD Waste	Fly Ash	FGD Waste	Water Standards	Fly Ash	FGD Waste
Arsenic	.08	0.20	0.002-.410	0.002-0.065	.05 mg/1	0.04-8.2	0.04-1.30
Barium	.34	.18	0.1-0.7	0.15-0.23	1.0 mg/1	0.1-0.7	0.15-0.23
Cadmium	.03	.01	0.002-0.193	0.002-0.020	0.01 mg/1	0.2-19.3	0.2-2
Chromium (CrVI) b/	.16	.02	0.008-0.930	.011-0.026	0.05 mg/1	0.16-18.6 c/	0.22-0.52
Lead	.01	.01	0.003-0.036	0.005	0.05 mg/1	0.06 to 0.72	0.1
Mercury	<.002	<.002	<0.002	<0.002	0.002 mg/1	<1	<1
Selenium	.05	.020	.002-0.340	0.008-0.049	0.01 mg/1	0.2 to 34	0.8-4.9
Silver	<.001	<.001	<0.001	<0.001	0.05 mg/1	<0.02	<0.02

a/ Ranges are shown for fly ash and FGD samples; comparisons are made to the Primary Drinking Water Standards.

b/ The Arthur D. Little study tested the concentration of Cr(VI), an ion of chromium.

c/ Since total chromium values are measured by the graphite furnace atomic absorption analysis method, these are upper limits for the Cr(VI) values.

Source: Arthur D. Little, Inc., Full-Scale Evaluation of Waste Disposal from Coal-fired Electric Generation Plants, prepared for the Air and Energy Research Laboratory of the U.S. Environmental Protection Agency, for the Office of Solid Waste, EPA-600-7-85-028, June 1985.

University of Alberta Study

The University of Alberta conducted a study for EPRI that involved passing a water-based solution through a series of columns with increasing ash concentrations.[18] The study results indicate that while some constituent metals were initially released or mobilized from the wastes using this method, these same constituents were attenuated in columns further along in the series. Boron, selenium, and arsenic were initially mobilized, but only boron remained mobilized to a significant extent. Arsenic and selenium interacted in successive columns such that the movement of arsenic and selenium through the system was retarded.

In addition to studying the test leachates, the University of Alberta researchers studied the fly ash itself to determine the processes that affect the migration of metal constituents. The study results indicated that some constituents are not uniformly distributed within the fly ash particles. The fly ash particles typically consist of an interior "glass" matrix covered by a relatively reactive and soluble exterior coating. The study found that arsenic and selenium were concentrated almost exclusively in the coating of the fly ash particles and thus were readily leached; the barium concentration was split evenly between the interior and exterior of the particles; about 75 percent of the cadmium and chromium were concentrated in the interior glass matrix; and almost all the lead was concentrated in the interior glass matrix and was, therefore, not readily mobilized.

The study attributed the uneven concentration of constituents in the fly ash particles to the vaporization of relatively volatile constituents during

combustion, followed by the condensation of these constituents on the exterior of fly ash particles entrained in the flue gas. However, this study reported that lead was contained within the interior glass matrix of the fly ash particles, while the Tetra Tech study discussed earlier reported that lead was volatile and thus likely to be found on the surface of fly ash particles. Both studies reported that arsenic and selenium were found on the surface of the fly ash particles. The University of Alberta concluded that the physical and chemical characteristics of the fly ash were determined by both the chemical composition of the coal from which it came and the mechanics of fly ash formation during combustion.

The difference between the University of Alberta study and the standard leaching test studies is that the mobility of constituents was observed under a variety of conditions. A number of waste concentrations could be tested in the columns to imitate specific field conditions. (Single column extractions also possess such flexibility, but to a lesser degree.) The University of Alberta study simulated landfill conditions by allowing the laboratory leachate solution to continually change as it migrated through multiple waste columns, whereas in batch extraction tests the laboratory leachate solution is allowed to come into contact with only one ash sample.

Battelle Chemical Characterization Study

Battelle Pacific Northwest Laboratories recently completed a study for EPRI on chemical characteristics of fly ash, bottom ash, and FGD sludge.[19] As part of this study, Battelle performed a comparison of the EP Toxicity Test and the TCLP test. While most of the results of the two procedures were consistent,

differences were observed with acidic samples. One acidic fly ash EP sample had both arsenic and chromium above RCRA limits. Another acidic fly ash sample also exhibited elevated levels of arsenic and chromium, but not at levels exceeding RCRA limits. The study found, however, that the two samples showed considerably less leachability for arsenic and chromium with the TCLP, while other elements tested showed similar results from the two testing procedures. The study concluded that the difference between the two types of tests resulted from the acidic character of the samples.

Radian Corporation Study

The Radian Corporation conducted two studies for EPRI that involved testing various low-volume waste streams. In the first of these studies (published in May 1985),[20] Radian Corporation collected thirty-two samples on eight types of low volume wastes. These samples were tested using the EP toxicity test as well as some other testing procedures. The results of the EP toxicity test showed that the only waste stream Radian tested that exceeded the EP toxicity limits in the 1985 Radian study was untreated boiler chemical cleaning waste. Exhibit 5-5 presents the results for three samples of untreated boiler cleaning wastes. All three samples had elevated levels of chromium and cadmium, including exceedances of EP toxicity limits, and two samples of boiler cleaning wastes had elevated concentrations of lead, including an exceedance of EP limits. This study also performed EP tests on boiler cleaning wastes after neutralization in a plant treatment system. As shown in Exhibit 5-5, the two samples of treated boiler cleaning waste did not exceed EP toxicity limits for any metals.

EXHIBIT 5-5

EP TOXICITY ANALYSIS FOR UNTREATED AND TREATED BOILER CHEMICAL CLEANING WASTES a/ (concentrations in mg/l)

Untreated Boiler Cleaning Waste Type

Metals	Maximum Allowable EP Toxicity Limits	Ammoniated EDTA with Inhibitor	Oxidizer	Hydrochloric Acid
Silver	5.0	0.002 b/	0.002 b/	0.007
Barium	100.0	0.76	0.67	0.91
Cadmium	1.0	3.0	3.0	0.64
Chromium	5.0	4.7	4.7	20.0
Arsenic	5.0	0.006	0.002 b/	0.051
Mercury	0.2	0.0002 b/	0.0002 b/	0.0042
Lead	5.0	3.6	5.6	0.002 b/
Selenium	1.0	0.002 b/	0.002 b/	0.003 b/

Treated Boiler Cleaning Waste Type

Metals	Maximum Allowable EP Toxicity Limits	HCl+ Inhibitor, Chelant	Hydrochloric Acid
Silver	5.0	0.042	0.033
Barium	100.0	0.40	0.25
Cadmium	1.0	0.002 b/	0.012
Chromium	5.0	0.001 b/	0.099
Arsenic	5.0	0.002 b/	0.002 b/
Mercury	0.2	0.0002 b/	0.0002 b/
Lead	5.0	0.002 b/	0.002 b/
Selenium	1.0	0.002 b/	0.002 b/

a/ All underlined values exceed maximum allowable limits under current RCRA regulations for hazardous wastes.

b/ Values shown are detection limits. Actual values could be less than, but no greater than, the indicated value.

Source: Electric Power Research Institute, Characterization of Utility Low-Volume Wastes, Radian Corporation, May 1985.

In Radian Corporation's second study of low-volume wastes (published in July 1987),[21] they collected additional data on certain low-volume waste streams that the first study indicated might have high concentrations of metals. As shown in Exhibit 5-6, eight of twenty-one samples of low-volume liquid wastes from coal-fired plants were found to exceed EP toxicity limits. For boiler chemical cleaning wastes, 7 of 10 samples exceeded EP toxicity limits for at least one constituent. Six of the boiler chemical cleaning waste exceedances were for chromium and the remaining exceedance was for lead. One wastewater brine sample out of five tested samples exceeded the EP limits for selenium. There were no reported EP exceedances for waterside rinses or coal pile runoff.

Radian Corporation also conducted EP Toxicity tests on low-volume waste sludges. None of the three samples from coal-fired power plants were considered EP Toxic, including a boiler chemical cleaning waste sludge. For the two wastewater pond sludges, the study compared the EP and TCLP testing procedures. Results of the EP and TCLP tests are shown in Exhibit 5-7. The two extraction procedures produced nearly identical concentrations of metals in their extracts.

As in their first study, the Radian Corporation also sampled low-volume wastes that had been treated. This study found significant reductions in concentrations of chromium, copper, iron, nickel and zinc after hydrochloric acid boiler cleaning waste was neutralized.

The study also examined the treatment effectiveness of co-disposal of low-volume wastes with high-volume wastes. Results of EP toxicity tests on co-disposal mixtures found that co-disposal significantly reduced concentrations of contaminants in the co-disposed mixture. Results of the EP tests are

EXHIBIT 5-6

EP TOXICITY TEST RESULTS FOR LIQUID LOW-VOLUME WASTES

(mg/l)

		Boiler Cleaning Waste			Waterside Rinses			Coal Pile Runoff			Wastewater Brines		
ELEMENT	EP Toxicity Limit	# of Tests	Range	Mean	# of Tests	Range	Mean	# of Tests	Range	Mean	# of Tests	Range	Mean
Arsenic	5.0	10	.002-0.36	0.112	3	0.01-0.018	0.014	3	0.002-0.006	0.003	5	0.019-0.52	0.194
Barium	100.0	10	0.022-2.6	0.629	3	0.005-0.097	0.064	3	0.04-0.078	0.054	5	0.1-0.18	0.134
Cadmium	1.0	10	0.002-0.21	0.181	3	0.002-0.04	0.015	3	0.001-0.004	0.002	5	0.002-0.04	0.019
Chromium	5.0	10	0.02-35	8.467 1/	3	0.028-0.77	0.303	3	0.005-0.005	0.005	5	0.005-0.31	0.148
Lead	5.0	10	0.008-23	2.603 2/	3	0.002-0.46	0.181	3	0.002-0.08	0.032	5	0.002-0.002	0.002
Mercury	0.2	10	.0002-0.0039	0.001	3	0.0002-0.0002	0.0002	3	0.0002-0.0003	0.0003	5	0.0002-0.025	0.005
Selenium	1.0	10	.002-.002	0.002	3	0.002-0.002	0.002	3	0.002-0.002	0.002	5	0.002-1.5	0.314 4/
Silver	5.0	10	.001-0.2	0.065	3	0.002-0.02	0.011	3	0.012-0.0023	0.002	5	0.002-0.03	0.013
ph (units)	2≤ph≤12.5	8	1.01-10.8	5.6 3/	2	9.3-9.4	9.35	3	3.1-9.3	6.9	4	4.6-4.9	4.75

1/ 6 of 10 tests exceeded RCRA limits; all underlined values indicate a measurement in excess of the allowable RCRA limits.

2/ 1 of 10 tests exceeded RCRA limits; all underlined values indicate a measurement in excess of the allowable RCRA limits.

3/ 3 of 8 tests were outside RCRA limits; all underlined values indicate a measurement in excess of the allowable RCRA limits.

4/ 1 of the 5 tests exceeded RCRA limits; all underlined values indicate a measurement in excess of the allowable RCRA limits.

NOTE: Boiler Cleaning Wastes include EDTA, Hydrochloric Acid, Bromate, Citric Acid, and Hydroxyacetic/formic acid..
Waterside Rinses are wastes resulting from washing the boiler and other plant equipment.
Wastewater Brines are produced during treatment of water-based low volume wastes.

Source: Manual for Management of Low-Volume Wastes From Fossil-Fuel-Fired Power Plants, Electric Power Research Institute, prepared by Radian Corporation, Austin, Texas, July 1987.

EXHIBIT 5-7

COMPARISON OF EP AND TCLP EXTRACTIONS FOR LOW-VOLUME SLUDGE DREDGED FROM WASTEWATER PONDS (mg/l)

ELEMENT	RCRA Limit	# of Tests	EP Test Range	EP Test Mean	TCLP Test Range	TCLP Test Mean
Arsenic	5.0	2	0.002-0.015	0.0085	0.004-0.016	0.010
Barium	100.0	2	0.045-0.12	0.0825	0.07-0.089	0.080
Cadmium	1.0	2	0.002-0.002	0.002	0.002-0.002	0.002
Chromium	5.0	2	0.01-0.011	0.0105	0.018-0.023	0.021
Lead	5.0	2	0.002-0.006	0.004	0.002-0.16	0.081
Mercury	0.2	2	.0002-0.0002	0.0002	0.0002-0.0002	0.0002
Selenium	1.0	2	.003-0.0003	0.003	0.003-0.03	0.017
Silver	5.0	2	0.002-0.004	0.003	0.009-0.012	0.011

Source: Manual for Management of Low-Volume Wastes From Fossil-Fuel-Fired Power Plants, Electric Power Research Institute, prepared by Radian Corporation, Austin, Texas, July 1987.

presented in Exhibit 5-8 for co-disposal with fly ash from three geographic areas.

5.1.2.3 Summary of Extraction Test Results

In conclusion, the results of these studies indicate that coal combustion utility wastes may leach several elements, including PDWS constituents. While a variety of extraction procedures were used in these studies, and questions have been raised about the applicability of certain testing methods to coal combustion wastes (which are generally disposed on-site in monofills), all of the extraction procedures used in the studies (EP, TCLP, ASTM, and column) produced average concentrations of constituents that were below the EP toxic level for all waste streams except untreated boiler cleaning waste. In the 1987 Radian Corporation study, untreated boiler cleaning wastes had a mean concentration 169 times the PDWS for chromium using the EP Toxicity test.

For the high-volume waste streams, cadmium, arsenic, and chromium were the only elements for which a maximum concentration was found that was over 100 times the PDWS. Arsenic and chromium were above EP toxicity limits based on EP tests for one acidic fly ash sample in the Battelle chemical characterization study. These were the only exceedances based on 23 samples. Cadmium was found at a concentration 150 times the PDWS in calcium-based dry scrubber sludge leachate and at a concentration 140 times the PDWS in some coal ash leachate as reported in the Tetra Tech study; these leachates were extracted using the EP test method. For both types of waste, however, the exceedances represented the maximum concentrations; all averages of cadmium concentration levels were below 100 times the PDWS. In fact, the geometric mean of cadmium in coal ash

EXHIBIT 5-8

EP TOXICITY TEST RESULTS OF LOW VOLUME WASTES BEFORE AND AFTER CO-DISPOSAL*
(mg/L)

Midwestern Bituminous Coal Fly Ash

ELEMENT	RCRA Limit	Fly Ash Waste	EDTA Waste	EDTA Waste Co-disposed With Ash	Citrate Waste	Citrate Waste Co-disposed With Ash	General Wastewater	Wastewater Co-disposed With Ash
Arsenic	5.0	0.006	0.006	0.026	0.21	0.037	0.003	0.031
Barium	100.0	0.006	0.76	0.23	1.6	0.006	1.2	0.17
Cadmium	1.0	0.02	3	0.02	0.64	0.02	0.008	0.02
Chromium	5.0	0.01	4.7	0.01	3.9	0.01	0.11	0.01
Lead	5.0	0.002	3.6	0.008	0.002	0.002	0.002	0.002
Mercury	0.2	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
Selenium	1.0	0.028	0.002	0.006	0.003	0.002	0.003	0.002
Silver	5.0	0.02	0.002	0.02	0.006	0.02	0.009	0.02

Southeastern Bituminous Coal Fly Ash

ELEMENT	RCRA Limit	Fly Ash Waste	EDTA Waste	EDTA Waste Co-disposed With Ash	Citrate Waste	Citrate Waste Co-disposed With Ash	General Wastewater	Wastewater Co-disposed With Ash
Arsenic	5.0	0.037	0.006	0.036	0.21	N/A	0.003	0.042
Barium	100.0	N/A	0.76	0.33	1.6	0.006	1.2	0.47
Cadmium	1.0	0.02	3	0.02	0.64	0.02	0.008	0.085
Chromium	5.0	0.036	4.7	0.01	3.9	0.15	0.11	0.01
Lead	5.0	0.002	3.6	0.002	0.002	0.004	0.002	0.023
Mercury	0.2	0.0002	0.0002	0.0003	0.0002	0.0002	0.0002	0.0002
Selenium	1.0	0.003	0.002	0.015	0.003	0.082	0.003	0.003
Silver	5.0	0.02	0.002	0.02	0.006	0.02	0.009	0.02

EXHIBIT 5-8 (Continued)

EP TOXICITY TEST RESULTS OF LOW VOLUME WASTES BEFORE AND AFTER CODISPOSAL (mg/L)

Western Subbituminous Coal Fly Ash

ELEMENT	RCRA Limit	Fly Ash Waste	EDTA Waste	EDTA Waste Co-disposed With Ash	Citrate Waste	Citrate Waste Co-disposed With Ash	General Wastewater	Wastewater Co-disposed With Ash
Arsenic	5.0	0.006	0.006	0.08	0.21	0.45	0.003	0.005
Barium	100.0	0.94	0.76	0.7	1.6	0.43	1.2	0.8
Cadmium	1.0	0.02	3	0.02	0.64	0.02	0.008	0.02
Chromium	5.0	0.01	4.7	0.01	3.9	0.01	0.11	0.01
Lead	5.0	0.002	3.6	0.041	0.002	0.002	0.002	0.002
Mercury	0.2	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
Selenium	1.0	0.034	0.002	0.026	0.003	0.031	0.003	0.003
Silver	5.0	0.02	0.002	0.02	0.006	0.02	0.009	0.02

*All underlined values indicate an exceedance of the current RCRA limit for hazardous wastes.

Source: Manual for Management of Low-Volume Wastes From Fossil-Fuel-Fired Power Plants, Electric Power Research Institute, prepared by Radian Corporation, Austin, Texas, July 1987.

leachates in the Tetra Tech study was just under 0.5 of the PDWS.

For the low-volume waste streams, the only exceedance of EP toxicity limits for wastes other than boiler cleaning waste was one wastewater brine sample that had selenium at 150 times the PDWS. The mean concentration of selenium in the wastewater brine samples was below EP toxicity limits. While untreated boiler cleaning wastes had exceedances of EP toxicity limits for chromium and lead, as noted above, EP toxicity tests on neutralized boiler cleaning wastes and on boiler cleaning wastes co-disposed with fly ash showed no exceedances of EP limits.

5.2 EFFECTIVENESS OF WASTE CONTAINMENT AT UTILITY DISPOSAL SITES

Coal combustion wastes contain trace elements that at certain levels could pose a potential danger to human health and the environment if they migrate from the disposal area. The extraction procedure tests described in Section 5.1.2 indicate that these trace elements may leach out of disposed wastes, although rarely at concentrations greater than 100 times the PDWS. This section of the report analyzes studies of ground-water and surface-water quality at and around utility disposal sites to ascertain whether potentially hazardous constituents that leach out of the waste migrate into surrounding ground water or surface water. The studies discussed in this section use as a measure of water quality the concentration of Primary Drinking Water Standards (PDWS) and Secondary Drinking Water Standards (SDWS) constituents in the water around utility waste disposal sites. Primary and Secondary Drinking Water Standards were established in the Safe Drinking Water Act. Primary Drinking Water Standards establish concentration limits for toxic constituents. Secondary Drinking Water Standards

are based on aesthetic characteristics such as taste, color, and odor. Exhibit 5-9 shows the current PDWS and SDWS. If ground water and surface water downgradient from waste disposal sites have concentrations of constituents in excess of PDWS or SDWS, and upgradient concentrations are below the standards or are lower than the downgradient concentrations, the coal combustion waste could be one of the sources contributing to ground water or surface water contamination.

EPA has conducted a number of studies on the quality of ground water in the immediate vicinity of utility disposal sites. Arthur D. Little performed extensive ground-water monitoring at six utility disposal sites. In a second study, Franklin Associates compiled data from state records on ground-water quality in the vicinity of 66 utility disposal sites. This section also reviews and evaluates a study conducted by Envirosphere for USWAG on available data on ground-water quality at 23 electric utility sites to evaluate whether and to what extent occurrences of ground-water contamination have resulted from the disposal of coal combustion wastes.

5.2.1 ADL Study of Waste Disposal at Coal-Fired Power Plants

Arthur D. Little, Inc. (ADL), conducted a three-year study for EPA's Office of Research and Development to assess the environmental effects and engineering costs associated with coal ash and flue gas desulfurization waste disposal practices at six coal-fired power plants.[22] Appendix E contains a detailed discussion of the study, including how the six sampled sites were selected, the study approach, and results for each site. A summary of the six sites is presented below:

EXHIBIT 5-9

PRIMARY DRINKING WATER STANDARDS

Contaminant	Concentration (mg/l)
Arsenic	0.05
Barium	1.0
Cadmium	0.01
Chromium	0.05
Fluoride	4.0
Lead	0.05
Mercury	0.002
Nitrate (as N)	10.0
Selenium	0.01
Silver	0.05

SECONDARY DRINKING WATER STANDARDS

Contaminant	Level
Chloride	250 mg/1
Color	15 color units
Copper	1.0 mg/1
Corrosivity	Noncorrosive
Foaming Agents	0.5 mg/1
Iron	0.3 mg/1
Manganese	0.05 mg/1
Odor	3 Threshold odor number
pH	6.5 - 8.5
Sulfate	250 mg/1
Total Dissolved Solids	500 mg/1
Zinc	5.0 mg/1

Source: 40 CFR 141 and 143, September 1, 1986.

- The Allen Plant in North Carolina disposed of a mixture of fly ash and bottom ash in two unlined disposal ponds, one closed and one in active use. Intermittent waste streams, such as boiler wastes and coal pile runoff, were also disposed in the ponds. While concentrations of trace elements in downgradient ground water were higher than upgradient concentrations, exceedances of the Primary Drinking Water Standards were not found. Elevated concentrations of arsenic (up to 31 times the PDWS) were found in fluids within the active ash pond. Attenuation tests indicated that the arsenic concentrations would be chemically attenuated by iron and manganese in the soils beneath and surrounding the site. Ground-water contamination, particularly from arsenic, could have resulted if these attenuative soils had not been present. Secondary Drinking Water Standards were exceeded in both the upgradient and downgradient ground water for manganese and in the downgradient ground water for iron. This was attributed to high concentrations of these elements present in the soils of the site. Steady-state conditions have probably not been achieved at the Allen site; increases in downgradient ground-water concentrations of non-attenuated contaminants may be expected in the future.

- The Elrama Plant in western Pennsylvania disposed a fixated FGD sludge-fly ash mixture, along with small volumes of bottom ash and sludge from coal pile runoff treatment ponds, in an abandoned coal-mining area 12 miles from the plant. Part of the landfill is underlain by acid-producing spoils from the strip mining of coal. Cadmium was found in concentrations exceeding the Primary Drinking Water Standard by as much as 20 times in downgradient ground water; the highest concentration was found in the well closest to the landfill. There were no upgradient exceedances for cadmium. Steady-state conditions did not appear to have been achieved at the site, so that effects of leachate from the landfill may be expected to increase with time. Secondary Drinking Water Standards (for pH, manganese, sulfate, and iron) were exceeded at the site in both upgradient and downgradient ground water. These exceedances probably occurred because of characteristics of the disposal area and because ground water was already contaminated from acid mine drainage. Test results indicated that any constituent migration from the landfill did not measurably affect the water quality of the nearby Youghiogheny River.

  Arsenic was repeatedly detected at levels three to five times the Primary Drinking Water Standard in pond liquors, but appeared to be attenuated by soils at the site. This suggests the possibility that similar wastes

at other sites could leach arsenic at higher levels if arsenic were not attenuated by surrounding soils or diluted before reaching drinking water.

The results discussed above indicate that the fixated FGD/fly ash wastes have been, and will continue to be, a source of contamination at the site. Because exceedances for many contaminants were probably due to concurrent contamination from acid mine drainage, leachate from coal combustion waste may have only a small incremental impact on water quality.

- The Dave Johnston plant in Wyoming is located in an arid region with little ground-water recharge. The plant is the oldest of the six sites, and burns low-sulfur western coal. There are a number of disposal areas at the site; the ADL study investigated two unlined fly ash landfills, one active and one closed. Exceedances of the Primary Drinking Water Standards for cadmium (up to 3 times the PDWS) were found in ground water upgradient and downgradient of the site. Cadmium was found at elevated concentrations in pond liquors and ground water beneath the wastes. Exceedances of Secondary Drinking Water Standards for manganese and sulfate were also observed in downgradient and upgradient ground water. These two contaminants and boron were found in elevated concentrations in ground water beneath the waste and in pond liquors. No samples were analyzed for the presence of arsenic in the pond liquors. Chemical attenuation by soils at the site was found to be low for trace metals such as arsenic.Interpretations of the sampling results were difficult to make because other potential contamination sources exist, such as other waste disposal areas at the site (the location and ages of which are uncertain) and contaminants naturally occurring in the soil, which is highly mineralized around the Johnston site; and uncertainties with regard to what degree leachate from the two landfills had reached the downgradient wells. Contamination from the site could possibly increase until steady-state concentrations are reached.

- The Sherburne County Plant in central Minnesota disposed of fly ash and FGD waste in one clay-lined pond and bottom ash in an adjacent clay-lined pond. Exceedances of the Primary Drinking Water Standards were observed in both upgradient and downgradient ground water for cadmium (up to 2 times the PDWS for both) and for nitrate, and in downgradient ground water for chromium (up to 1.2 times the PDWS). Pond liquors were found to exhibit high concentrations of several constituents, including cadmium (up to 30 times the PDWS), chromium (up to 16 times the PDWS), fluoride, nitrate, lead (up to 28 times the PDWS), and selenium (up to 25 times the PDWS). While the pond

liquors exhibited high concentrations of contaminants, leachate from these wastes did not appear to have migrated into and mixed with ground water to a great extent. Ground-water samples collected at the site seemed to indicate that a few constituents (sulfate and boron) had migrated from the wastes, but not at levels exceeding SDWS. The clay liner appeared to have significantly reduced the rate of release of leachate from the disposal ponds, precluding the development of elevated trace metal concentrations at downgradient wells. Over time, downgradient wells will likely show increased levels of contamination, since steady-state conditions had not been achieved between leachate from the landfill and the ground water. Without the clay liner, the leachate seepage rate would probably have been much greater. Since the surrounding soils may not chemically attenuate selenium, this contaminant might cause PDWS exceedances once steady-state concentrations in ground water are reached.

- The Powerton Plant disposed fly ash, bottom ash, and slag in an older landfill approximately one mile south of the site. In a newer portion of the landfill, disposal operations consisted of disposing intermixed fly ash and slag. The newer landfill and part of the older one are underlain by a liner consisting of ash and lime. The downgradient ground-water wells exhibited levels of cadmium up to three times the Primary Drinking Water Standard and, in one sample, lead at four times the PDWS. An upgradient well, located on the border of the landfill wastes, exhibited a concentration of cadmium at the level of the Primary Drinking Water Standard. Secondary Drinking Water Standards for iron, manganese, and sulfate were exceeded in downgradient wells, and for manganese in an upgradient well (but at a level of exceedance lower than the downgradient measurements). These results indicate that leaching and migration of ash wastes had occurred at the site, but it was difficult to determine the effect the leachate had, or will have, on ground-water quality. Dilution and chemical attenuation may have prevented the buildup at downgradient locations of significant concentrations of trace metals such as arsenic and selenium. The degree to which Lost Creek, a nearby downgradient stream, was diluting waste constituents that reach it may be significant.

- The Lansing Smith plant in southern Florida disposed a mixture of fly ash and bottom ash in an unlined disposal pond located in a coastal area. Concentrations greater than the Primary Drinking Water Standards were observed for cadmium (up to five times the PDWS), chromium (up to four times the PDWS), and fluoride in the downgradient ground water at the site and, with the possible exception

of fluoride, appeared to be due largely to the leaching of the ponded ash wastes. Exceedances of Secondary Drinking Water Standards for sulfate, chloride, manganese, and iron were also observed in downgradient ground water. However, most of these contaminants are seawater-related and their reported concentrations appeared to be influenced by the use of seawater in plant operations and infiltration of estuarine (saline) water at the site. The leachate generated migrates to a shallow, unused, tidal aquifer. These results indicate that ash disposal at this site appears to have had a measurable impact on ground-water quality. Health risks at this particular site, however, were probably minimal since the ground water and surface water were not used as a source of drinking water.

5.2.1.1 Ground-water Sampling

Exhibits 5-10 and 5-11 summarize the results of the ADL ground-water quality data at the six disposal sites for constituents with established Primary and Secondary Drinking Water Standards, respectively. As can be seen from Exhibit 5-10:

- One site had no exceedances of PDWS constituents, either upgradient or downgradient.
- One site had PDWS exceedances for cadmium only, with the same maximum PDWS exceedance upgradient and downgradient.
- One site had downgradient PDWS exceedances for cadmium, chromium, and nitrate, but for cadmium and nitrate the upgradient exceedances were at least as large as the downgradient exceedances. There were no upgradient exceedances of chromium; the one downgradient exceedance was 1.2 times PDWS.
- The three remaining sites had downgradient PDWS exceedances for cadmium that were more frequent and larger than upgradient exceedances. The largest downgradient exceedance for cadmium at any of the six sites was 20 times the PDWS.
- There were no upgradient chromium exceedances and only three exceedances out of 94 downgradient observations. Two of the downgradient exceedances were 1.2 times the PDWS and one was 4 times the PDWS. These three exceedances were at three different sites.

EXHIBIT 5-10

SUMMARY OF ARTHUR D. LITTLE'S GROUND-WATER QUALITY DATA ON PRIMARY DRINKING WATER EXCEEDANCES

Units = ppm		Allen Site				New Elrama Site				Dave Johnston Site			
PDWS		1/ Downgradient (11 wells)		1/ Upgradient (1 well)		1/ Downgradient (5 wells)		1/ Upgradient (1 well)		1/ Downgradient (3 wells)		1/ Upgradient (2 wells)	
Contam.	2/ Drinking Water Standard	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.
Arsenic (liq.)	0.05	0/12		0/2		0/1		0/2		0/2		0/3	
Barium	1	0/31		0/3		0/19		0/4		0/9		0/6	
Cadmium	0.01	0/31		0/3		3/19	20	0/4		6/9	3	3/6	3
Chromium (Cr VI)	0.05	0/31		0/3		1/19	1.2	0/4		0/9		0/6	
Fluoride	4.0	0/34		0/4		0/21		0/4		0/12		0/8	
Lead	0.05	0/31		0/3		0/19		0/4		0/9		0/6	
Mercury	0.002	0/0		0/0		0/0		0/0		0/0		0/0	
Nitrate 5/	45	0/34		0/4		0/20		0/4		0/12		0/8	
Selenium (liq.)	0.1	0/5		0/2		0/1		0/2		0/2		0/3	
Silver	0.05	0/31		0/3		0/19		0/4		0/9		0/9	

1/ For specific site descriptions, including lists and maps of wells used for data, see Appendix E.

2/ Where the reported detection limit for a contaminant was greater than the drinking water standard and the sample contained less contaminant than the reported detection limit, the sample is tabulated as being below the drinking water standard. For a more detailed explanation, see Appendix E.

3/ The number of samples with reported concentrations above the drinking water standard (slash) the total number of samples.

4/ Max. Exceed. is the concentration of the greatest reported exceedance divided by the drinking water standard for that particular contaminant.

5/ The PDWS for nitrate measured as N is 10 ppm.

EXHIBIT 5-10 (Continued)

SUMMARY OF ARTHUR D. LITTLE'S GROUND-WATER QUALITY DATA ON PRIMARY DRINKING WATER EXCEEDANCES

Units = ppm		Sherburne County Site				Powerton Station Site				Lansing Smith Steam Plant			
PDWS		1/ Downgradient (3 wells)		1/ Upgradient (2 wells)		1/ Downgradient (3 wells)		1/ Upgradient (1 well)		1/ Downgradient (5 wells)		1/ Upgradient (3 wells)	
Contam.	2/ Drinking Water Standard	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.
Arsenic (liq.)	0.05	0/3		0/3		0/8		0/2		0/5		0/4	
Barium	1	0/12		0/8		0/9		0/4		0/14		0/6	
Cadmium	0.01	2/12	2	2/8	2	8/9	3	2/4	1	10/14	5	2/6	2
Chromium (Cr VI)	0.05	1/12	1.2	0/8		0/9		0/4		1/14	4	0/6	
Fluoride	4.0	0/12		0/8		0/9		0/4		5/14	13.5	0/6	
Lead	0.05	0/12		0/8		1/9	4	0/4		0/14		0/6	
Mercury	0.002	0/0		0/0		0/0		0/0		0/0		0/0	
Nitrate 5/	45	2/12	1.1	2/8	27	0/9		2/4	1.1	0/0		0/0	
Selenium (liq.)	0.1	0/3		0/3		0/8		0/2		0/5		0/4	
Silver	0.05	0/12		0/8		0/9		0/4		0/14		0/6	

1/ For specific site descriptions, including lists and maps of wells used for data, see Appendix E.

2/ Where the reported detection limit for a contaminant was greater than the drinking water standard and the sample contained less contaminant than the reported detection limit, the sample is tabulated as being below the drinking water standard. For a more detailed explanation, see Appendix E.

3/ The number of samples with reported concentrations above the drinking water standard (slash) the total number of samples.

4/ Max. Exceed. is the concentration of the greatest reported exceedance divided by the drinking water standard for that particular contaminant.

5/ The PDWS for nitrate measured as N is 10 ppm.

EXHIBIT 5-11

SUMMARY OF ARTHUR D. LITTLE'S GROUND-WATER QUALITY DATA ON SECONDARY DRINKING WATER EXCEEDANCES

Units = ppm		Allen Site				New Elrama Site				Dave Johnston Site			
SDWS		1/ Downgradient (11 wells)		1/ Upgradient (1 well)		1/ Downgradient (5 wells)		1/ Upgradient (1 well)		1/ Downgradient (3 wells)		1/ Upgradient (2 wells)	
Contam.	2/ Drinking Water Standard	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.
Chloride	250	0/34		0/4		0/21		0/4		0/12		0/8	
Copper	1	0/31		0/3		0/19		0/4		0/9		0/6	
Iron	0.3	7/31	82	0/3		0/19		1/4	1.8	0/9		0/6	
Manganese	0.05	19/31	102	1/3	1.4	19/19	456	4/4	197	1/9	3.2	1/6	4.6
Sulfate	250	0/34		0/3		9/19	4.7	3/4	1.5	12/12	5.8	4/8	5.1
Zinc	5	0/31		0/3		0/19		0/4		0/9		0/6	
pH Lab 5/	<=6.5	10/10	4.7	1/1	5.9	0/0		0/0		0/0		0/0	
	>=8.5	0/10		0/1		0/0		0/0		0/0		0/0	
pH Field 5/	<=6.5	21/28	4.4	2/3	6.2	9/14	5.2	2/2	4.5	0/9		0/6	
	>=8.5	0/28		0/3		0/14		0/2		0/9		0/6	

1/ For specific site descriptions, including lists and maps of the wells used for data, see Appendix E.

2/ Where the reported detection limit for a contaminant was greater than the drinking water standard and the sample contained less contaminant than the reported detection limit, the sample is tabulated as being below the drinking water standard. For a more detailed explanation, see Appendix E.

3/ The number of samples with reported concentrations above the drinking water standard (slash) the total number of samples.

4/ Max. Exceed. is the concentration of the greatest reported exceedance divided by the drinking water standard for that particular contaminant. The only exception is for pH, where Max. Exceed. is the actual measurement.

5/ As indicated in footnote 15, the Max. Exceed column for the reported pH measurements is a tabulation of the actual measurements, not the maximum exceedance divided by the drinking water standard.

EXHIBIT 5-11 (Continued)

SUMMARY OF ARTHUR D. LITTLE'S GROUND-WATER QUALITY DATA ON SECONDARY DRINKING WATER EXCEEDANCES

Units = ppm		Sherburne County Site				Powerton Station Site				Lansing Smith Steam Plant			
SDWS		1/ Downgradient (3 wells)		1/ Upgradient (2 wells)		1/ Downgradient (3 wells)		1/ Upgradient (1 well)		1/ Downgradient (5 wells)		1/ Upgradient (3 wells)	
Contam.	2/ Drinking Water Standard	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.
Chloride	250	0/12		0/8		0/9		0/4		14/14	22.4	0/6	
Copper	1	0/12		0/8		0/9		0/4		0/14		0/6	
Iron	0.3	0/12		1/8	1.9	4/9	42	0/4		14/14	118	6/6	37
Manganese	0.05	2/12	22	1/8	1.4	9/9	194	2/4	11	13/14	17.2	2/6	1.4
Sulfate	250	0/12		0/8		6/9	2.7	0/4		8/14	8.4	0/6	
Zinc	5	0/12		0/8		0/9		0/4		0/14		0/6	
pH Lab 5/	<=6.5	0/0		0/0		0/0		0/0		4/6	4.4	1/2	6.5
	>=8.5	0/0		0/0		0/0		0/0		0/6		0/2	
pH Field 5/	<=6.5	0/8		0/6		1/9	6	0/3		10/13	2.9	4/6	6
	>=8.5	0/8		0/6		0/9		0/3		0/13		0/6	

1/ For specific site descriptions, including lists and maps of the wells used for data, see Appendix E.

2/ Where the reported detection limit for a contaminant was greater than the drinking water standard and the sample contained less contaminant than the reported detection limit, the sample is tabulated as being below the drinking water standard. For a more detailed explanation, see Appendix E.

3/ The number of samples with reported concentrations above the drinking water standard (slash) the total number of samples.

4/ Max. Exceed. is the concentration of the greatest reported exceedance divided by the drinking water standard for that particular contaminant. The only exception is for pH, where Max. Exceed. is the actual measurement.

5/ As indicated in footnote 15, the Max. Exceed column for the reported pH measurements is a tabulation of the actual measurements, not the maximum exceedance divided by the drinking water standard.

- One site had downgradient PDWS exceedances for fluoride in 5 of 14 samples. The maximum exceedance was 13.5 times the PDWS. There were no upgradient PDWS exceedances for fluoride at any of the six sites.

- There were no lead exceedances upgradient and only one PDWS exceedance out of 94 downgradient observations at 4 times the PDWS.

- The contaminants of most concern at the six sites appear to be cadmium and, to a lesser extent, chromium. For both of these contaminants, three sites had exceedances of the PDWS in downgradient ground water at levels higher than were found in upgradient ground water.

For constituents for which there are Secondary Drinking Water Standards, exceedances in downgradient ground water generally were higher than levels observed in upgradient wells. Results are shown in Exhibit 5-11.

5.2.1.2 Surface Water Sampling

Exhibit 5-12 summarizes the results of surface-water quality data obtained by ADL at background, peripheral, and downstream locations at three of the study sites -- Elrama, Powerton, and Lansing Smith -- for constituents with established Primary and Secondary Drinking Water Standards. Examination of these results for PDWS constituents indicates that:

- At the Lansing Smith site, downgradient and peripheral surface water samples showed cadmium concentrations up to 5 times the PDWS, chromium concentrations up to 1.2 times the PDWS, and fluoride concentrations up to 20 times the PDWS. No upgradient samples were collected at the Lansing Smith site.

- Exceedances were found for cadmium (up to 2 times the PDWS) and nitrate (up to 1.2 times the PDWS) in both upgradient and downgradient surface water at the Powerton site. The exceedances were similar in upgradient and downgradient samples both in terms of the proportion of samples in which exceedances were found and the magnitude of the exceedances.

EXHIBIT 5-12

SUMMARY OF ARTHUR D. LITTLE'S SURFACE-WATER QUALITY DATA ON PRIMARY AND SECONDARY DRINKING WATER EXCEEDANCES

Units = ppm	New Elrama Site				Powerton Station Site				Lansing Smith Steam Plant					
														1/
PDWS	1/		1/		1/		1/		1/		1/		Downgradient	
	Downgradient (4 stations)		Upgradient (1 station)		Downgradient (1 station)		Upgradient (3 stations)		Downgradient (6 stations)		Peripheral (3 stations)		Saline (2 stations)	
2/ Drinking Contam. Water Standard	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.
Arsenic (liq.) 0.05	0/1		0/1		0/1		0/2		0/2		0/1		0/3	
Barium 1	0/7		0/3		0/3		0/8		0/13		0/8		0/5	
Cadmium 0.01	0/7		0/3		2/3	2	5/8	2	10/13	5	4/8	4	5/5	4
Chromium (Cr VI) 0.05	0/7		0/3		0/3		0/8		0/13		0/8		1/5	1.2
Fluoride 4.0	0/7		0/3		0/3		0/8		5/13	6.5	2/8	2	2/5	20
Lead 0.05	0/7		0/3		0/3		0/8		0/13		0/8		0/5	
Mercury 0.002	0/0		0/0		0/0		0/0		0/0		0/0		0/0	
Nitrate 5/ 45	0/7		0/3		1/3	1.1	3/7	1.2	0/0		0/0		0/0	
Selenium (liq.) 0.1	0/1		0/1		0/1		0/2		0/2		0/1		0/3	
Silver 0.05	0/7		0/3		0/3		0/8		0/13		0/8		0/5	

1/ For specific site descriptions, including lists and maps of the stations used for data, see Appendix E. Peripheral stations are neither upgradient nor downgradient of the site. These stations are located across the gradient from the site, and may become contaminated by lateral dispersion of waste constituents.

2/ Where the reported detection limit for a contaminant was greater than the drinking water standard and the sample contained less contaminant than the reported detection limit, the sample is tabulated as being below the drinking water standard. For a more detailed explanation, see Appendix E.

3/ The number of samples with reported concentrations above the drinking water standard (slash) the total number of samples.

4/ Max. Exceed. is the concentration of the greatest reported exceedance divided by the drinking water standard for that particular contaminant.

5/ The PDWS for nitrate measured as N is 10 ppm.

EXHIBIT 5-12 (Continued)

SUMMARY OF ARTHUR D. LITTLE'S SURFACE-WATER QUALITY DATA ON PRIMARY AND SECONDARY DRINKING WATER EXCEEDANCES

Units = ppm		New Elrama Site				Powerton Station Site				Lansing Smith Steam Plant					
		1/		1/		1/		1/		1/		1/		1/	
SDWS		Downgradient (4 stations)		Upgradient (1 station)		Downgradient (1 station)		Upgradient (3 stations)		Downgradient (6 stations)		Peripheral (3 stations)		Downgradient Saline (2 stations)	
Contam.	2/ Drinking Water Standard	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.	3/ Exceed./ Total	4/ Max. Exceed.
Chloride	250	0/7		0/3		0/3		0/8		13/13	11.9	5/8	10	5/5	58
Copper	1	0/7		0/3		0/3		0/8		0/13		0/8		0/5	
Iron	0.3	0/7		0/3		0/3		0/8		11/13	370	6/8	34	0/5	
Manganese	0.05	7/7	7.4	3/3	4.2	2/3	2.2	2/8	1	11/13	64	6/8	4.8	0/5	
Sulfate	250	0/7		0/3		0/3		0/8		12/13	7.5	4/8	3.4	5/5	9.9
Zinc	5	0/7		0/3		0/3		0/8		0/13		0/8		0/5	
pH Lab 5/	<=6.5	0/0		0/0		0/0		0/0		5/6	3.3	2/3	3.8	0/1	
	>=8.5	0/0		0/0		0/0		0/0		0/6		0/3		0/1	
pH Field 5/	<=6.5	4/7	6.1	2/3	6	0/3		0/8		5/10	4.1	4/7	3.4	0/5	
	>=8.5	0/7		0/3		1/3	8.5	2/8	8.5	0/10		0/7		0/5	

1/ For specific site descriptions, including lists and maps of the stations used for data, see Appendix E. Peripheral stations are neither upgradient nor downgradient of the site. These stations are located across the gradient from the site, and may becom contaminated by lateral dispersion of waste constituents.

2/ Where the reported detection limit for a contaminant was greater than the drinking water standard and the sample contained less contaminant than the reported detection limit, the sample is tabulated as being below the drinking water standard. For a more detailed explanation, see Appendix E.

3/ The number of samples with reported concentrations above the drinking water standard (slash) the total number of samples.

4/ Max. Exceed. is the concentration of the greatest reported exceedance divided by the drinking water standard for that particular contaminant. The only exception is for pH, where Max. Exceed. is the actual measurement.

5/ As indicated in footnote 10, the Max. Exceed. column for reported pH measurements is a tabulation of the actual measurements, not the maximum exceedance divided by the drinking water standard.

- No exceedances of PDWS were found upgradient or downgradient at the Elrama site, although there had been downgradient exceedances at Elrama in ground water for cadmium and chromium.

5.2.1.3 Waste Fluid Sampling

In addition to ground-water monitoring, waste fluid samples were collected from the waste ponds at the Allen, Sherburne County, and Lansing Smith sites, and from dry fly ash landfills at the Dave Johnston site. Water from within and beneath FGD sludge and fly ash waste mixtures were collected from the Elrama landfill. No waste fluid samples were obtained at the Powerton site. Key observations are presented below.

- Arsenic was present in the waste fluids at elevated concentrations (up to 31 times the Primary Drinking Water Standard) at two of the five sites sampled. At these sites (Allen and Elrama), arsenic may be attenuated by soils at the site; attenuation tests indicate the soils had a moderate to high attenuation capacity, and no exceedances for arsenic were observed in ground water at the sites. The Dave Johnston site was the only disposal area where soils were found to have low attenuation capacities for arsenic; however, there are no data pertaining to waste fluids at this site, and exceedances for arsenic in the ground water were not observed. These results indicate that, depending on the coal source, arsenic may occur at elevated concentrations in waste fluids, but can be attenuated by soils within and surrounding a coal combustion waste disposal site. If the soils at a disposal site have low attenuation capacities for arsenic, this element may be of concern with regard to ground water and surface water contamination.

- Cadmium is present at elevated concentrations (up to 30 times the Primary Drinking Water Standard) in the waste fluids at all five sites. At Powerton, although no waste fluid samples were taken, ground-water samples obtained from directly beneath the wastes also exhibited elevated concentrations of cadmium. These results support the conclusion that elevated concentrations of cadmium observed in downgradient ground water may be attributable to coal combustion wastes.

- Chromium is present at elevated concentrations (up to 21 times the Primary Drinking Water Standard) in the waste fluids at two of the five sites. At these sites, higher chromium concentrations were found in downgradient ground water than were found in upgradient ground water. These observations suggest that ground-water contamination by chromium at these two study sites may be attributable to the coal combustion wastes. At a third site at which downgradient exceedances of chromium in ground water were observed, waste fluid samples were mixed with ground water occurring beneath the wastes during collection, which may account for lower waste fluid concentrations at this site.

- Other constituents that were found at elevated concentrations within the waste fluids include fluoride at all five sites (up to 10 times the PDWS); lead at one of five sites (up to 28 times the PDWS); nitrate at one of five sites (up to 7 times the PDWS); and selenium at one of four sites (up to 25 times the PDWS).

- Constituents for which Secondary Drinking Water Standards are established were found at the following elevated concentrations: chloride at three of five sites (up to 61 times the SDWS); iron at two of five sites (up to 221 times the SDWS); manganese at four of five sites (up to 466 times the SDWS); and sulfate at four of five sites (up to 42 times the SDWS). Exceedances of pH standards were found in the waste fluids at two of three sites tested. At these two sites, both acidic (as low as pH 5.9) and alkaline (as high as pH 11) conditions were found to exist. Average pH values measured in these waste fluids indicated that they were generally alkaline.

- Results of waste fluid sampling at the Sherburne County site showed exceedances of Primary Drinking Water Standards for cadmium (up to 30 times PDWS); chromium (up to 16 times the PDWS); fluoride (up to 13 times the PDWS); lead (up to 28 times the PDWS); nitrates (up to 6.9 times the PDWS); and selenium (up to 25 times the PDWS). Measurements also showed maximum exceedances of Secondary Drinking Water Standards for chloride (up to 1.9 times the SDWS); iron (up to 6.1 times the SDWS); manganese (up to 316 times the SDWS); and sulfate (up to 42 times the SDWS). This was the only site where disposal areas or ponds were completely lined. The clay liner appeared to have reduced the release of leachate, thereby concentrating waste constituents.

Results from waste fluid studies conducted by other organizations are described in Appendix D.

5.2.1.4 Summary

Results from the Arthur D. Little study suggest that under the waste management procedures used by the facilities studied, some coal combustion waste leachate was migrating into ground water beneath and downgradient from disposal sites. Five sites had concentrations of cadmium in downgradient ground water that exceeded the PDWS. Two of these five had maximum upgradient exceedances at the same level as the maximum downgradient exceedance, and two of the sites had upgradient concentrations that were equal to or above the PDWS, although the maximum concentration was less than the downgradient concentrations. One of the five sites had upgradient measurements of cadmium that were below the PDWS. Exceedances of chromium were detected in a few ground-water samples downgradient of three sites; there were no chromium concentrations above the PDWS in the upgradient ground water of any site. There were no detected exceedances of arsenic, barium, mercury, selenium, or silver in the ground water or surface water at any of the six sites. In total, approximately 5 percent of the downgradient observations exceeded the PDWS.

5.2.2 Franklin Associates Survey of State Ground-Water Data

EPA commissioned Franklin Associates to gather data from state regulatory agencies on the quality of ground water at or near coal-fired electric utility fly ash disposal sites.[23] The objective of this survey was to determine the level of ground-water contamination in the vicinity of disposal sites. However,

according to the Franklin Associates report: "No attempt was made to determine what monitoring wells might be up gradient, or what wells might be down gradient, or even as to whether specific ash disposal sites were in fact contributing specific pollutants."

Franklin Associates contacted 44 states in which coal-fired facilities were located; of these 44 states, 13 provided data. The data base that was developed included data from more than 4700 well samples taken from 66 sites.

Analysis of these samples revealed 1129 exceedances of the PDWS out of more than 15,000 observations, as shown in Exhibit 5-13. Ninety-two percent of the exceedances were less than ten times the PDWS; eight of the exceedances were 100 times greater than the PDWS.

There were 5952 exceedances of the SDWS out of nearly 20,000 observations as shown in Exhibit 5-14. These secondary standards were exceeded more frequently than the primary standards, and exceedances were usually greater. For example, about 77 percent of the SDWS exceedances were less than 10 times the standard (compared with 92 percent for PDWS exceedances), whereas 4 percent of the exceedances were greater than 100 times the SDWS (compared with less than one percent for PDWS exceedances).

Since this study did not compare upgradient and downgradient concentrations, it is not possible to determine whether occurrences of contamination at particular sites are the result of utility waste disposal practices or background levels of contaminants.

EXHIBIT 5-13

SUMMARY OF PDWS EXCEEDANCES IN THE FRANKLIN ASSOCIATES SURVEY

Constituent	Total Observations	Number of Observations Exceeding PDWS By 1 X	10 X	100 X	Highest Exceedance (X PDWS)
Arsenic	1995	94	0	0	9.8
Barium	1353	108	9	0	44.0
Cadmium	1733	126	16	1	531.0
Chromium	1863	92	5	0	50.2
Fluoride	995	28	3	0	19.3
Lead	1722	243	20	1	182.0
Mercury	1282	30	8	5	500.0
Nitrate	1432	204	0	0	7.3
Selenium	2453	196	30	1	100.0
Silver	530	8	0	0	8.0
TOTAL	15,358	1129	81	8	

Source: Franklin Associates, Ltd., Summary of Ground-water Contamination Cases at Coal Combustion Waste Disposal Sites, prepared for the U.S. Environmental Protection Agency, March 1984.

EXHIBIT 5-14

SUMMARY OF SDWS EXCEEDANCES IN THE FRANKLIN ASSOCIATES SURVEY

Constituent	Total Observations	Number of Observations Exceeding SDWS By 1 X	10 X	100 X	Highest Exceedance (X SDWS)
Chloride	2921	109	14	0	42.0
Copper	650	1	0	0	1.2
Iron	3140	1942	862	149	4,000.0
Manganese	1673	1050	467	80	2,400.0
pH	4107	843	-	-	-
Sulfate	4378	1059	13	0	23.2
TDS	1925	920	24	0	28.7
Zinc	1175	28	4	0	46.0
TOTAL	19,969	5952	1384	229	

Source: Franklin Associates, Ltd., Summary of Ground-water Contamination Cases at Coal Combustion Waste Disposal Sites, prepared for the U.S. Environmental Protection Agency, March 1984.

5.2.3 Envirosphere Ground-Water Survey

In response to the temporary exemption of utility wastes from regulation under Subtitle C of RCRA, the Utility Solid Waste Activities Group (USWAG) commissioned Envirosphere, Inc., to review information available from electric utilities on the quality of ground water at utility waste disposal sites.[24] Envirosphere solicited information from 98 utilities on the number and type of constituents they monitored, the frequency with which measurements were taken, and the period of time for which they had collected ground-water monitoring data. Ninety-six of the contacted utilities responded to the request for information. From these 96 utilities, Envirosphere selected for further study those that appeared to have adequate data on ground-water quality. These utilities were contacted and asked to provide their available data for use in Envirosphere's study. The participating utilities (the exact number of utilities was not provided) forwarded the requested information to Envirosphere on the 28 disposal facilities they operated. The utilities chose to withdraw three of the 28 disposal sites from the study subsequent to the analysis of the data, leaving 25 disposal sites in the data pool.

In order to analyze the data, Envirosphere paired the measurements taken at upgradient and downgradient wells at approximately the same time and in the same aquifer.[25] These data were then compared to the applicable drinking water standards to determine whether the standards had been exceeded. Two disposal sites were then eliminated from further consideration because no upgradient wells could be identified. The remaining 23 disposal sites produced a total of 9,528 paired measurements of upgradient and downgradient ground-water concentrations.

Exhibit 5-15 summarizes the information from the Envirosphere data base for those cases where the Primary Drinking Water Standards (PDWS) were exceeded by the downgradient measurement. The most obvious indication that a waste facility is contributing to a PDWS exceedance is a measurement indicating downgradient values higher than the PDWS and upgradient values lower than the PDWS. According to Envirosphere's report, about 1.7 percent of the data fell into this category.[26] For those cases in which both the upgradient and downgradient values were exceeded, Envirosphere argued that it was difficult to attribute the exceedances to the disposal facility without further site-specific analysis. About 5 percent of the measurements fell into this category, with 60 percent of these indicating upgradient values equal to or greater than the downgradient values.

Maximum concentrations of several substances significantly exceeded the PDWS in downgradient wells: arsenic, 560 times the PDWS; lead, 480 times the PDWS; mercury, 235 times the PDWS, and selenium, 100 times the PDWS. These values must be compared to the maximum upgradient reading since some of the contamination may be unrelated to the disposal facility. As shown in Exhibit 5-15, the downgradient concentration was sometimes higher than the upgradient value even when the upgradient value exceeded the PDWS. However, exceedances of the magnitudes shown in Exhibit 5-15 comprised a small fraction of the total measurements in the Envirosphere data base.

The Envirosphere data also included information regarding exceedances of the Secondary Drinking Water Standards (SDWS). A summary of these data is shown in Exhibit 5-16. The data indicate that in 8.2 percent of the cases the

EXHIBIT 5-15

SUMMARY OF PDWS EXCEEDANCES IN ENVIROSPHERE'S GROUND-WATER DATA

Constituent	Total Observations	Downgradient Observations a/ Exceeding PDWS When: Upgradient Does Not Exceed — Number	%	Upgradient Exceeds — Number	%	Maximum Downgradient Observation (X PDWS) b	
Arsenic	588	7	1	0	0	560	(192)
Barium	298	0	0	0	0	1	(3)
Cadmium	571	59	10	9	2	6	(1)
Chromium	658	20	3	10	2	20	(76)
Lead	639	29	5	67	10	480	(220)
Mercury	575	8	1	2	c/	235	(9)
Selenium	489	5	1	34	7	100	(100)
Silver	261	0	0	0	0	1	(0.2)
TOTAL	4079	128	3 d/	122	3 d/		

a/ Envirosphere classified measurements by comparing downgradient values with upgradient values. When the downgradient value exceeded the PDWS, classification depended on whether the upgradient value also exceeded the PDWS. Both categories of measurements are shown here, although Envirosphere focused primarily on pairs of measurements in which the downgradient value exceeded the PDWS but the upgradient value did not.

b/ Maximum downgradient value observed in the Envirosphere data base. The corresponding paired upgradient concentrations are not available. The maximum upgradient value of all measurements at the same facility is shown in parentheses.

c/ Less than 0.5 percent.

d/ These percentages apply to the total number of observations. Envirosphere "normalized" the data to correct for sites that had a high proportion of data points so that one site would not be overly represented; these normalized values are noted in the text of the report.

Source: Envirosphere Company, "Report on the Ground-water Data Base Assembled by the Utility Solid Waste Activities Group," in USWAG, Report and Technical Studies on the Disposal and Utilization of Fossil-Fuel Combustion By-Products, October 26, 1982, Appendix C.

EXHIBIT 5-16

SUMMARY OF SDWS EXCEEDANCES IN ENVIROSPHERE'S GROUND-WATER DATA

Constituent	Total Observations	Downgradient Observations a/ Exceeding SDWS When: Upgradient Does Not Exceed — Number	%	Upgradient Exceeds — Number	%	Maximum Downgradient Observation (X SDWS) b/	
Chloride	502	4	1	7	1	22	(5)
Copper	452	9	2	0	0	2	(0.02)
Iron	964	60	6	376	39	3458	(2)
Manganese	487	157	32	143	29	474	(5)
Sulfate	1028	289	28	57	6	32	(8)
Total Dissolved Solids	908	159	18	292	32	31	(2)
Zinc	387	3	1	3	1	1	(0.1)
TOTAL	4728	681	14 c/	875	19 c/		

a/ Envirosphere classified measurements by comparing downgradient values with upgradient values. When the downgradient value exceeded the SDWS, classification depended on whether the upgradient value also exceeded the SDWS. Both categories of measurements are shown here, although Envirosphere focused primarily on pairs of measurements in which the downgradient value exceeded the SDWS but the upgradient value did not.

b/ Maximum downgradient value observed in the Envirosphere data base. The corresponding (paired) upgradient concentrations are not available. The maximum upgradient value of all measurements at the same facility is shown in parentheses.

c/ These percentages apply to the total number of observations. Envirosphere "normalized" the data to correct for sites that had a high proportion of data points so that one site would not be overly represented; these normalized values are noted in the text of the report.

Source: Envirosphere Company, "Report on the Ground-water Data Base Assembled by the Utility Solid Waste Activities Group," in USWAG, Report and Technical Studies on the Disposal and Utilization of Fossil-Fuel Combustion By-Products, October 26, 1982, Appendix C.

downgradient value exceeded the SDWS while the upgradient value did not. In some cases the exceedances were substantially greater than the SDWS; e.g., the maximum observation for iron was 3458 times greater than the SDWS and manganese was 474 times greater.

In summary, the Envirosphere ground-water data show that Primary and Secondary Drinking Water Standards were exceeded in ground water downgradient from utility waste disposal facilities. However, the percentage of cases in which constituent concentrations in downgradient wells exceeded the standards when those in upgradient wells did not was small. There are limitations in the data, due in part to the way in which they were collected (e.g., only data from those utilities that voluntarily submitted data are included in the report). There is also a limited amount of information regarding the extent to which site-specific factors, such as environmental setting characteristics or other possible sources of contamination, could have had an effect on ground-water contamination.

5.2.4 Summary

The studies described in this section demonstrate that downgradient ground-water and surface-water concentrations exceeded the PDWS and SDWS for a few constituents. In some of these downgradient exceedances, corresponding upgradient exceedances also occurred, suggesting that the contamination was not necessarily caused by the waste disposal sites. For cases in which the downgradient ground water had constituent concentrations higher than the corresponding upgradient concentrations, the PDWS exceeded most often were those for cadmium, chromium, lead, and to a lesser extent, arsenic.

Some PDWS exceedances were quite high, e.g., up to 560 times for arsenic and 480 times for lead (see Exhibit 5-15). However, the frequency of PDWS exceedances for downgradient ground water and surface water is rather low. For example, 3.7 percent of the Envirosphere data had downgradient ground-water concentrations of PDWS higher than those measured in upgradient wells. Three of the six Arthur D. Little sites had downgradient ground water with concentrations of constituents that were both above the PDWS and above corresponding upgradient concentrations. Although the Arthur D. Little pond liquor data show high concentrations of PDWS and SDWS constituents, in most cases the constituents appeared to be contained within the disposal area or attenuated in the surrounding soils. This is particularly true for the case of arsenic, which was detected in the waste fluids at a level 31 times the PDWS, but was not found at elevated levels in ground water or surface water. There were no exceedances of arsenic, barium, mercury, selenium, or silver in downgradient ground water at any of the six Arthur D. Little sites. The Envirosphere study detected no exceedances of barium or silver.

5.3 EVIDENCE OF DAMAGE

This section examines documented cases in which danger to human health or the environment from surface runoff or leachate from the disposal of coal combustion wastes has been proved. The first part of this section reviews two major studies conducted for the Utility Solid Waste Activities Group (USWAG): a 1979 Envirosphere, Inc., study and a 1982 Dames and Moore study. To supplement these two major studies, in 1987 EPA conducted a literature review of all readily-available sources, which revealed only two additional case studies on proven damages occurring in 1980 and 1981. The Agency has not identified any

proven damage cases in the last seven years; however, no attempt was made to compile a complete census of current damage cases by conducting extensive field studies.

As with all damage cases, it is not always clear whether damages could occur under current management practices or whether they are attributable to practices no longer used. As described in Chapter Four, there has been an increased tendency in recent years for utilities to utilize mitigative technologies, including a shift to greater use of landfills rather than surface impoundments and an increased use of liners.

5.3.1 Envirosphere Case Study Analysis

The Utility Solid Waste Activities Group (USWAG) and the Edison Electric Institute (EEI) commissioned the Envirosphere Company in 1979 to investigate and document available information on the nature and extent of the impact of utility solid waste disposal on public health, welfare, and the environment.[27] To conduct this analysis, Envirosphere reviewed various reports, including EPA's damage incident files, environmental monitoring studies at utility disposal sites, and other research and studies as available; they contacted state regulatory agencies to determine what information was available in state files.

From its review of the available data, Envirosphere found few documented cases where utility solid waste disposal had potentially adverse environmental effects. They identified nine cases from EPA's damage incident files that appeared to show damage to the environment. Envirosphere reviewed data from environmental monitoring studies at the utility disposal sites and other

available research, and noted that the information available on the potential impacts of utility waste disposal was inconclusive. Some data indicated "... that elevated levels of some chemical parameters have occurred at locations downgradient of some utility solid waste disposal sites." Envirosphere concluded, however, that it was not clear to what extent these impacts could be attributed to utility solid waste disposal practices.

Some of the specific cases from Envirosphere's sources are summarized below:

- Texas, 1977. A clay liner was improperly installed in a 14.3 acre disposal pond for metal cleaning solutions. The liner dried and cracked before wastes were introduced into the facility. After the pond was put in service, ground-water monitoring wells detected contaminant migration. Levels of selenium and chromium occasionally exceeded the PDWS for these elements, and several SDWS were exceeded. The pond was taken out of service, the liner was saturated with water, and the pond was put back into operation.

- Indiana, 1977. Envirosphere found that leaching from two large, unlined ash disposal ponds was contributing to ground-water contamination. Arsenic and lead were found in downgradient ground water at concentrations about two times the PDWS, while concentrations of selenium were about four times the PDWS.

- Pennsylvania, 1975. A private waste handler illegally disposed fly ash in a marsh located in a tidal wetland area. Visual inspections by the state indicated marsh contamination due to fly ash leachate. When ordered to stop the dumping and clean up the site, the handler declared bankruptcy, and the ash remained in the marsh. Detailed analysis of any potential impacts has not been conducted.

- Connecticut, 1971. A municipal landfill, which was located in a marsh, accepted many substances, including large quantities of fly ash. Surveys revealed numerous SDWS contaminants, some of which appeared to be related to the ash. The site, considered unsuitable for disposal of solid waste, was closed and turned into a state park.

- Virginia, 1967. A dike surrounding a fly ash settling lagoon collapsed, and 130 million gallons of caustic solution (pH 12.0) were released into the Clinch River.

> Large numbers of fish were killed over a distance extending 90 miles from the spill site. Surveys conducted 10 days after the spill showed dramatic reductions in bottom dwelling fish food organisms for 77 miles below the release site. Virtually all such organisms were eliminated for a distance of 3 to 4 miles. The waste was eventually diluted, dispersed, and neutralized by natural physical/chemical processes. Two years after the spill, however, the river had not fully recovered.

5.3.2 Dames & Moore Study of Environmental Impacts

Dames & Moore, in a study for USWAG, conducted a survey of existing data and literature to document instances in which danger to human health and the environment was found to have occurred because of the disposal of coal combustion wastes.[28] Dames & Moore established criteria by which to evaluate whether a given record of a contamination incident could be considered "documented" evidence proving danger to health or the environment: 1) the report must exist in the public record; 2) the case must involve high-volume (utility) wastes; 3) information must exist to permit determination of possible health or environmental risks; and 4) the possible risks may have been caused by leachate migration or runoff from utility disposal sites.

The danger to health and the environment was examined by accounting for the types, concentrations, and locations of constituents shown to be present that could have harmful effects. In addition, Dames & Moore considered both the potential for public access to utility waste constituents and any observed effects on the population or environment. The three major data sources providing information reviewed in this study were computer data bases used to search for publicly available references; Federal Government agencies such as

EPA, U.S. Geological Survey, and the Tennessee Valley Authority; and 12 state environmental, natural resource, health or geological agencies.

Using information from these sources, Dames & Moore identified seven cases that presented a potential danger to human health and the environment. Six of the seven cases involved potential impacts from ground water and one case involved surface water. Dames & Moore concluded that none of these cases represented a "documented" case of such danger. However, Dames & Moore eliminated several sites from the documented category because they believed sufficient data from the sites were unavailable or did not meet the selection criteria described above. Dames & Moore evaluated in detail the seven sites at which there existed a potential for adverse environmental and health effects. Their findings are summarized below.

- Chisman Creek Disposal Site, York County, Virginia. The Chisman Creek disposal area was an inactive site with four separate fly ash disposal pits on both sides of Chisman Creek. An electric utility hired a private contractor to transport and dispose of fly ash and bottom ash from petroleum coke (a residual product of the oil distillation process) and coal combustion. The site was active from the late 1950's to 1974. In 1980, nearby residential drinking water wells became green from contamination of vanadium and selenium and could no longer be used. The site is currently on the CERCLA (Superfund) National Priorities List. A minimum of 38 domestic wells and 7 monitoring wells near the four disposal sites were sampled over time. Two off-site domestic wells located 200 feet from the disposal area had elevated concentrations of vanadium, selenium, and sulfate. One of these two wells was sampled four times. Three of the four measurements exceeded the PDWS for selenium up to 2 times. Another domestic well contained 0.11 mg/l of vanadium. (EPA has not established concentration limits for vanadium.) At both wells, sulfate concentrations exceeded the SDWS. In addition, samples from six of the seven monitoring wells exhibited increased concentrations of sulfates. The highest concentrations of selenium and vanadium that were observed in monitoring well samples were 0.03 (3 times

the PDWS) and 30 mg/l, respectively. The high concentrations of selenium and vanadium were noticed in monitoring wells that were drilled directly through the disposal pits.

The Virginia State Water Control Board (SWCB) conducted the initial study at this site. The SWCB concluded that the quality of ground water immediately beneath and down-gradient from the site had been affected. Moreover, the SWCB stated that the water in the two domestic wells had elevated concentrations of selenium and vanadium because of the disposal of the fly ash. Dames & Moore was critical of the conclusions reached by the SWCB because of what they termed "significant data gaps." Dames & Moore cited a lack of background water quality information and a general lack of information on the well installation, sample collection procedures, and other possible sources of contamination, such as the York County landfill which is adjacent to one of the ash disposal areas. The two contaminated off-site domestic wells identified by the SWCB, however, were over 2,000 feet from the county landfill but within a couple of hundred feet from the ash disposal areas. Additionally, monitoring wells located between the landfill and the affected domestic wells did not register the same elevated concentrations of selenium. Residents in the area no longer rely on ground water for their drinking water.

- Pierce Site, Wallingford, Connecticut. Coal fly ash had been deposited at the Pierce Site since 1953. In 1978, the United States Geological Survey (U.S.G.S.) collected ground-water quality data from three on-site wells - one upgradient and two downgradient. The U.S.G.S. took samples from the wells on three days over a period of two months. One sample from one downgradient well showed a concentration of chromium that exceeded the PDWS by a multiple of 1.6. Concentrations of cadmium, manganese, zinc, and sulfate were higher in the downgradient wells than in the upgradient well.

  According to Dames & Moore, there were not enough data at this site to state conclusively whether or not the ground water had been adversely affected by the fly ash pit. To determine potential damage to ground water quality, Dames & Moore stated that EPA recommends a minimum of three downgradient wells and one upgradient well. In this case, there were only two downgradient wells. Three samples over a period of two months were not considered sufficient because naturally occurring temporal changes in the area were believed to render comparisons invalid.

  The Pierce disposal site is situated on a deposit of thick, stratified sediments composed of particles that

range in size from clay to coarse sand. The disposal site is located within a few hundred feet of the Quinnipiac River, and the ground water flows from the site to the river, which diluted contaminants in the ground water. Although there are residences within a few blocks of the power plant, they do not use local ground water for drinking supplies.

- Michigan City Site, Michigan City, Indiana. The Michigan City site, situated on the shore of Lake Michigan, contained two fly ash disposal ponds. Ground-water flow at the site was towards Lake Michigan, facilitated by the porous sand that underlies the site. Twenty-one monitoring wells were installed at this site. Two of these were placed upgradient from the site outside the site boundaries; the remaining 19 wells were established within the boundaries of the facility and downgradient from the disposal areas.

  Monitoring of the wells (which took place periodically over a one-year period) indicated that trace metals migrated from the disposal sites and that certain constituents had elevated ground-water concentrations. Arsenic and lead were observed in concentrations that exceeded their PDWS. Seven samples collected from three downgradient monitoring wells had arsenic concentrations that exceeded the standard -- up to 100 times the PDWS. All of the samples taken from the upgradient off-site monitoring wells contained arsenic at concentrations below the PDWS. Five of the downgradient monitoring wells contained lead concentrations which exceeded the PDWS, with the highest exceedance 7 times the PDWS. Three samples from the two upgradient monitoring wells also had lead concentrations in excess of the standard, with the highest exceedance 3 times the PDWS.

  Dames & Moore concluded that effects on ground water appeared to be limited to areas within the facility boundaries because of attenuation mechanisms operative at the site -- absorption, dilution, precipitation, and a steel slurry wall installed between the disposal site and Lake Michigan. However, no downgradient monitoring wells were situated off-site. Based on the locations of the waste disposal sites and the monitoring wells, it appears that the ash ponds are responsible for arsenic concentration above the PDWS in the ground water within the site boundaries. Because high lead concentrations were observed in some of the upgradient background wells, it is impossible to state with certainty that the high lead concentrations in the ground water are attributable to the disposal sites. Dames and Moore noted that nearby residents do not use the ground water for their water supply.

- Bailly Site, Dune Acres, Indiana. The Bailly site is located near the Indiana National Lakeshore on Lake Michigan in a highly industrialized area. Fly ash at this site has been slurried to interim settling ponds, which are periodically drained. The drained ash is then disposed in an on-site pit. Two aquifer units, designated Unit 1 and Unit 3, underlie the site. Unit 1 contains fine-to-medium sand and some gravel, while Unit 3 is composed of sand with overlying layers of varying amounts of sand, clay and gravel.

  Ground-water samples from Unit 1 were collected from an upgradient well and from several wells downgradient from the ash settling ponds. Samples from Unit 3 were collected upgradient and from one well downgradient from the ash ponds. These wells were sampled at five-week intervals between September 1976 and May 1978.

  In samples from Unit 1, arsenic, cadmium, fluoride, and lead occasionally exceeded the PDWS. Upgradient concentrations of arsenic never exceeded the PDWS, whereas the maximum downgradient concentration for arsenic was 4.6 times the PDWS. Downgradient on-site concentrations of cadmium exceeded the PDWS at one well by 25 times, while the maximum upgradient concentration of cadmium exceeded the PDWS by 22 times. One downgradient well measurement indicated lead concentrations that exceeded PDWS by 1.26 times.

  All of the above-mentioned exceedances were observed in Unit 1. None of the samples from Unit 3 contained constituents at concentrations that exceeded the PDWS.

  Aluminum, boron, iron, manganese, molybdenum, nickel, strontium, and zinc all increased in concentration downgradient from the disposal areas, though not in levels exceeding the SDWS.

  Leachate from the ash disposal ponds is the most probable contributor to the increased concentrations of arsenic and lead observed in the aquifer samples taken from the on-site wells. Cadmium was the only constituent whose downgradient off-site concentration was observed to exceed the PDWS. However, because elevated cadmium concentrations were also found in samples taken from the background well, the elevated concentrations of cadmium may not have been caused by the leachate from the coal ash. Dames and Moore noted that ground water at this site flows away from the nearest residential area.

- Zullinger Quarry Fly Ash Disposal Site, Franklin County, Pennsylvania. The Zullinger quarry was situated in a limestone formation in south-central Pennsylvania. The

quarry was excavated to 40 feet below the water table. Fly ash was deposited in the quarry from 1973 to 1980 with no attempt to dewater the quarry prior to placement of the fly ash.

The site operator, consultants, and the Pennsylvania Department of Environmental Resources (DER) have been independently involved in water quality investigations at the site. Initially, six monitoring wells were established onsite. Later, several existing off-site domestic wells were added to the sampling program. Two of the monitoring wells were installed upgradient to provide background constituent concentrations. The other monitoring wells, and the domestic wells in the sampling program, were downgradient from the fly ash deposited in the quarry.

Lead was found to exceed its PDWS by up to eight times in eight out of over 100 samples. Six of these eight exceedances occurred in two on-site monitoring wells, while the seventh (2.6 times PDWS) was found in an off-site domestic well. Another exceedance (1.5 times PDWS) was found in the background well.

Several constituents for which there are secondary drinking water standards were found in elevated concentrations downgradient from the ash disposal site. Sulfate concentrations increased dramatically during the first few years of quarry filling, then began to sharply decline in 1976 when the fly ash had filled the quarry. From 1976 until deactivation of the disposal site in 1980, the fly ash was deposited above the water table. Zinc and iron were also found in elevated concentrations. Elevated levels of sulfate, zinc, and iron are probably attributable to leachate from the fly ash, as are the lead levels in excess of the PDWS. Most of the trace metals appear to be attenuated onsite by the limestone formation.

- Conesville Site, Conesville, Ohio. Various types of coal combustion waste had been deposited at the Conesville site in central Ohio. The monitoring program at the Conesville site was established to determine the ability of an FGD sludge fixation process (Poz-O-Tec, a solid material produced by mixing FGD sludge with fly ash and lime) to stabilize and thus immobilize potential contaminants. The stabilized FGD sludge has been deposited next to a fly ash pond. Permeable sand and gravel underlie the Muskingum River flood plain on which the Conesville site is located.

  A total of 34 monitoring wells were installed at the Conesville site. Two of the wells were situated upgradient from the disposal area to provide the

necessary background water quality data. Two sets of water quality data were taken, the first between February 27 and April 12, 1979, and the second between December 4, 1979, and July 10, 1980.

Some samples from the first set of data contained constituents at concentrations that exceeded the PDWS. Lead concentrations exceeded the PDWS in two on-site wells by up to 3 times and three off-site wells by up to 2 times. The concentration of mercury found in one sample from an on-site well exceeded the PDWS by 1.4 times; however, this exceedance could not be attributed to the fly ash. One of the fourteen background measurements had the highest observed concentration of selenium, 6 times the PDWS. Thus, selenium appears to be leaching from indigenous sediments rather than from the FGD waste and fly ash deposited at the site. The first set of data also showed the SDWS constituents of calcium, magnesium, total dissolved solids, sulfate, and iron, had increased in those wells located on the site property and just across the property boundaries.

Measurements taken between December 1979 and July 1980 showed increases in calcium, magnesium, total dissolved solids, and sulfate relative to those measurements taken in the first data collection period. Concentrations in excess of the PDWS were found for selenium (several wells), arsenic (one sample), cadmium (four samples), and chromium (five samples). Two of the chromium exceedances were found in on-site wells, while three occurred in off-site wells, with concentrations ranging up to 16 times the PDWS on-site and 2 times the PDWS off-site. Background wells also had elevated levels of selenium. The single arsenic exceedance (2.4 times the PDWS) and all of the cadmium exceedances (up to 12 times the PDWS) were detected in on-site wells. In contrast to the first round of sampling, lead was not detected in concentrations greater than the PDWS. The only constituents that appear to be migrating offsite are lead and chromium. Based on the data collected, it appears there may be a temporal variation in the water quality at this site. Dames and Moore noted that the town of Conesville is downgradient from the site but on the other side of the river, which would tend to mitigate potential adverse impacts.

- Hunts Brook Watershed, Montville-Waterford, Connecticut
  The electric utility hired a private contractor to transport and dispose of fly ash in three separate sites (Chesterfield-Oakdale, Moxley Hill, and Linda Sites) along three different tributaries to Hunts Brook. Disposal of fly ash in this area began in the mid 1960's and ended in 1969. The surface-water quality studies that took place in this area focused on pH, iron,

sulfate, and total dissolved solids (TDS). No analyses were performed for any of the PDWS constituents. Upstream surface water samples were compared to downstream samples to determine if the surface water quality had been degraded at any of the sites.

At the Chesterfield-Oakdale site, concentrations of iron in the surface water increased from less than the SDWS to more than 100 times the SDWS between the upstream and downstream sampling points. Sulfate concentrations increased by over an order of magnitude, from 20 to 299 mg/l, (at 299 mg/l, still only 1.2 times the SDWS) between the upstream and downstream sampling positions, while TDS increased from less than the SDWS to 44 times the SDWS. At another sampling point approximately 1.2 miles downstream from the site, the measured parameters had all returned to levels close to the upstream values.

At the Moxley Hill Site, the pH and iron concentrations remained relatively constant between the upstream and downstream sampling points; median sulfate values increased, although not to levels exceeding the SDWS. The elevated concentrations of sulfate and TDS had been significantly attenuated at another point three-quarters of a mile downstream.

At the Linda Site, no upstream data were collected. It is therefore impossible to quantify the potential effects of fly ash deposition on the water quality.

5.3.3 Other Case Studies of the Environmental Impact of Coal Combustion By-Product Waste Disposal

This section presents a review of two independent case studies of ground-water contamination at utility disposal sites.

Cedarsauk Site, Southeastern Wisconsin

The Cedarsauk site is a fly ash landfill in southeastern Wisconsin. At the time of this study,[29] fly ash had been deposited at the site into an abandoned sand and gravel pit over a period of eight years. Part of the pit is in direct contact with an aquifer composed mainly of sand and gravel with some clay. This upper aquifer is approximately 15 to 20 meters thick with a permeability of 10^{-3}

to 10^{-2} cm/sec. Soluble carbon aqueous material comprises about 35 percent of the aquifer. The upper sandy aquifer overlies another aquifer consisting of fractured dolomite-bedrock.

A water quality study of the area was undertaken in 1975. This study eventually included 35 monitoring wells and seven surface-water sampling sites. Twenty of the wells were placed upgradient of the site to provide background water quality information, while the remaining wells were positioned downgradient. Sampling was performed on a monthly basis. Most of the ground-water flow beneath the site surfaced in a marsh directly east of the ash disposal area.

The monitoring results showed that downgradient ground water had SDWS exceedances. Background levels of total dissolved solids (TDS) were below 500 mg/l, while the levels in the ground water downgradient from the disposal site exceeded 800 mg/l, or 1.6 times the SDWS. After eight years of disposal, the contaminant plume appeared to stabilize approximately 200 meters downgradient from the ash disposal site. The stabilization of the constituent plume appeared to be due to dilution and the ability of the materials in the aquifer to attenuate contaminants. Only iron, manganese, and zinc were found in detectable quantities in the downgradient off-site wells.

The maximum detected iron concentration was more than 33 times the SDWS, while the maximum manganese concentration reached 30 times the SDWS. Neither iron nor zinc could be detected 200 meters downgradient from the disposal site. Another contributor to ground-water contamination at this site was sulfate. Background concentrations of sulfate varied between 20 and 30 mg/l (well below

the SDWS), while the concentrations of sulfate in the contaminant plume achieved levels approximately 3.4 times the SDWS. Other trace metals for which analyses were performed, such as copper, molybdenum, nickel, lead, and titanium, were not detected.

As the leachate contacted the sediments in the aquifer, it was neutralized from an initial pH value of 4.5 to around neutral pH levels (i.e., about 7.0). This change in pH probably caused the precipitation of many of the trace metals and other constituents in the leachate. In addition, adsorption reactions between the clay in the sediments and the constituents probably attenuated the leachate concentrations of many of the potential contaminants observed in the leachate.

Center Mine, Center, North Dakota

Fly ash at this site had been deposited in a mine pit and between mine ash piles. A study was conducted to determine the potential effects of FGD and fly ash disposal on ground water quality at the surface mining site.[30] This investigation used field monitoring and laboratory column leaching experiments in conjunction with geochemical computations. By collecting both field and laboratory data, the investigators hoped to test the applicability of laboratory column experiments to field situations. Roughly 150 wells were placed both in the vicinity of the waste disposal sites and in unaffected areas.

Ground-water concentrations were generally within drinking water standards in the background wells. However, selected constituents were higher than the drinking water standards. For instance, sulfate concentrations tended to exceed

the SDWS by a factor of 2 to 4. The maximum iron concentration was 4.3 times the SDWS. Manganese concentrations were all above the SDWS, varying from 0.06 to 2.75 mg/l, or 1.2 to 55 times the SDWS.

Samples collected from wells located adjacent to the FGD waste site indicated that none of the PDWS constituents exceeded the standards. For the SDWS constituents, molybdenum concentrations fluctuated between 0.070 and 4.850 mg/l, and sulfate concentrations reached a high of 9,521 mg/l, or 38 times the SDWS. (EPA has not established maximum concentration levels for molybdenum.)

Ground water in areas that appear to be affected by leachate from the fly ash disposal sites had sulfate concentrations ranging from 21.7 to 211 times the SDWS. Higher values were obtained immediately below recent deposits of fly ash, while lower values were observed at older sites or at greater distances from the disposal area. Arsenic and selenium concentrations in the ground water were as high as 0.613 mg/l (12 times the PDWS) and 0.8 mg/l (80 times the PDWS), respectively. The highest arsenic and selenium concentrations were associated with higher pH values. Ground-water pH values for samples in the area of the fly ash ranged from 6.95 to 12.1. (The Secondary Drinking Water Standard for pH is 6.5 to 8.5). Iron and manganese concentrations were also high in samples taken from around the fly ash disposal site. The maximum concentration of iron was 8.6 times the SDWS; the maximum concentration of manganese was 130 times the SDWS.

Leachates from the fly ash of western coals are often characterized by a high pH that tends to cause many potentially harmful constituents to be released. The pH-dependent solubility of many trace elements, as apparently

observed at this site, demonstrates the importance of neutral pH values that are conducive to contaminant attenuation.

5.3.4 Summary

The studies reviewed in this section indicate that constituents from coal-combustion waste disposal sites have been detected in both on-site and off-site ground and surface water. However, those constituents that did exceed the drinking water standards seldom exceeded these standards by more than ten times. Moreover, the total number of exceedances is quite small compared to the total number of monitoring wells and samples gathered. The contaminant exceedances that do occur appear to be correlated to some extent with acidic or alkaline pH levels. At fly ash disposal sites, pH values between 2 and 12 have been measured. High and low pH values can contribute to metal solubility in ground water.

There are two documented cases of coal combustion waste disposal sites causing significant harm to the environment. Drinking water wells around the Chisman Creek fly ash disposal site in Virginia (which was closed in 1974) were contaminated with high concentrations of vanadium and selenium. Concentrations of these elements at this site were also due to petroleum coke waste (a product of oil combustion, not coal combustion). The site has been placed on the CERCLA National Priority List. In 1967, a dike failed at a utility waste disposal site on the banks of the Clinch River in Virginia, causing waste to spill into the river. This accident caused substantial damage to the biotic life in the river.

5.4. FACTORS AFFECTING EXPOSURE AND RISK AT COAL COMBUSTION WASTE SITES

The previous sections analyzed the constituents of coal combustion waste leachates and the quality of the ground water and surface water surrounding disposal sites. However, this is only part of determining the potential dangers that the wastes pose to human health and the environment. Exposure potential, the degree to which populations could be expected to be exposed to potentially harmful constituents, must also be analyzed. Exposure potential is determined by a variety of factors. Hydrogeologic characteristics of a site will affect the migration potential of waste constituents. Proximity of sites to drinking water sources and to surface-water bodies will determine potential for exposure to populations using the water sources.

In order to address this issue of exposure, EPA collected a wide variety of data on a random sample of 100 coal-fired utility plants around the country. The sample was taken from the Utility Data Institute Power Statistics Database, which contains information on every coal-fired electric utility plant in the country. Most plants dispose of their waste on-site, and in these cases information was collected on the plant location given by the data base. If the plant disposed off-site, data were collected on that off-site location. EPA assumed that off-site disposal took place at the nearest municipal landfill, unless additional information indicated otherwise. Characteristics such as depth to ground water, hydraulic conductivity, distance to surface water, location of private and public drinking water systems, type of surrounding natural ecosystems, and location of human population were obtained from a wide variety of sources. This simple aggregation of the individual factors affecting exposure at coal combustion waste sites provides a qualitative perspective on

the potential risk that coal combustion waste sites pose, and is presented in Sections 5.4.1-5.4.3. Appendix F displays the data for each coal combustion waste site in the random sample.

5.4.1 Environmental Characteristics of Coal Combustion Waste Sites

Environmental characteristics of coal combustion utility waste sites will have a significant effect on the potential for the waste constituents to travel and reach receptor populations. Key environmental characteristics are:

- Distance to surface water - The distance between a coal combustion waste disposal site and the nearest surface water body. Proximity to surface water would decrease the possible health effects of ground-water contamination due to the fact that there would be fewer opportunities for drinking water intakes before the ground water reached the surface water body; once the plume reached the surface water, contamination would be diluted. However, proximity to surface water would possibly increase danger to aquatic life because less dilution of the contaminant plume would occur before the plume reached the surface water body.

- Flow of surface water - A high surface water flow will increase the dilution rate of coal combustion constituents that may enter the surface water, thereby reducing concentrations in the surface water.

- Depth to ground water - The distance from ground level to the water table. A larger depth to ground water will increase the time it takes for waste leachates to reach the aquifer; it also allows more dispersion of the leachate before it reaches the aquifer so that once the leachate reached the aquifer, concentrations of metals would be decreased.

- Hydraulic conductivity - This factor is an indication of the rate at which water travels through the aquifer. A high hydraulic conductivity indicates that constituents will travel quickly through the ground water and possibly more readily reach drinking water wells, although high conductivity also indicates a more rapid dilution of constituent concentration.

- Net recharge - This factor is a measure of net precipitation of a site after evapotranspiration and estimated runoff is subtracted. Recharge is calculated in order to determine the amount of rainfall annually absorbed by the soil. A high net recharge indicates a short period of time for contaminants to travel through the ground to the aquifer, but will also indicate a higher potential for dilution.

- Ground-water hardness - This factor is a measure of the parts per million (ppm) of calcium carbonate (CaCO3) in the aquifer. Ground water with over 240 ppm of CaCO3 is typically treated when used as a public drinking water supply. This treatment of the hard ground water has an indirect mitigative effect on exposure because treatment of the ground water will tend to remove contamination from other sources.

To conduct this exposure analysis, environmental data on the 100 randomly selected coal combustion waste sites were gathered using a number of sources. These data were then aggregated in order to present an overview of the environmental characteristics that contribute to exposure. The data collected on the sample of coal combustion waste sites were compared to information presented in a study by Envirosphere for the Electric Power Research Institute.[31] The Envirosphere report gave detailed information on the hydrogeologic settings of 450 operating utility plants. The information provided by the exposure analysis on the sample of 100 plants corresponded fairly closely with the settings described in the Envirosphere report.

The following sections summarize the data that were collected and the relationship of the various characteristics to potential exposure.

5.4.1.1 Distance to Surface Water and Surface-Water Flow

The proximity of a waste site to surface water affects exposure potential in several ways. If the site is very near a surface-water body, there is less

opportunity for humans to use contaminated ground water as a source of drinking water. However, sites that are close to surface water can more easily contaminate the surface-water body, although waste constituents will be more quickly diluted if the flow of the surface water is high.

Distance to the nearest surface-water body, e.g., creek, river, lake, or swamp, was determined from measurements obtained using United States Geologic Survey (U.S.G.S.) maps. The sample of coal combustion waste sites was located on 7-1/2 or 15 minute maps, and the distance between the site and nearest surface water body was calculated.

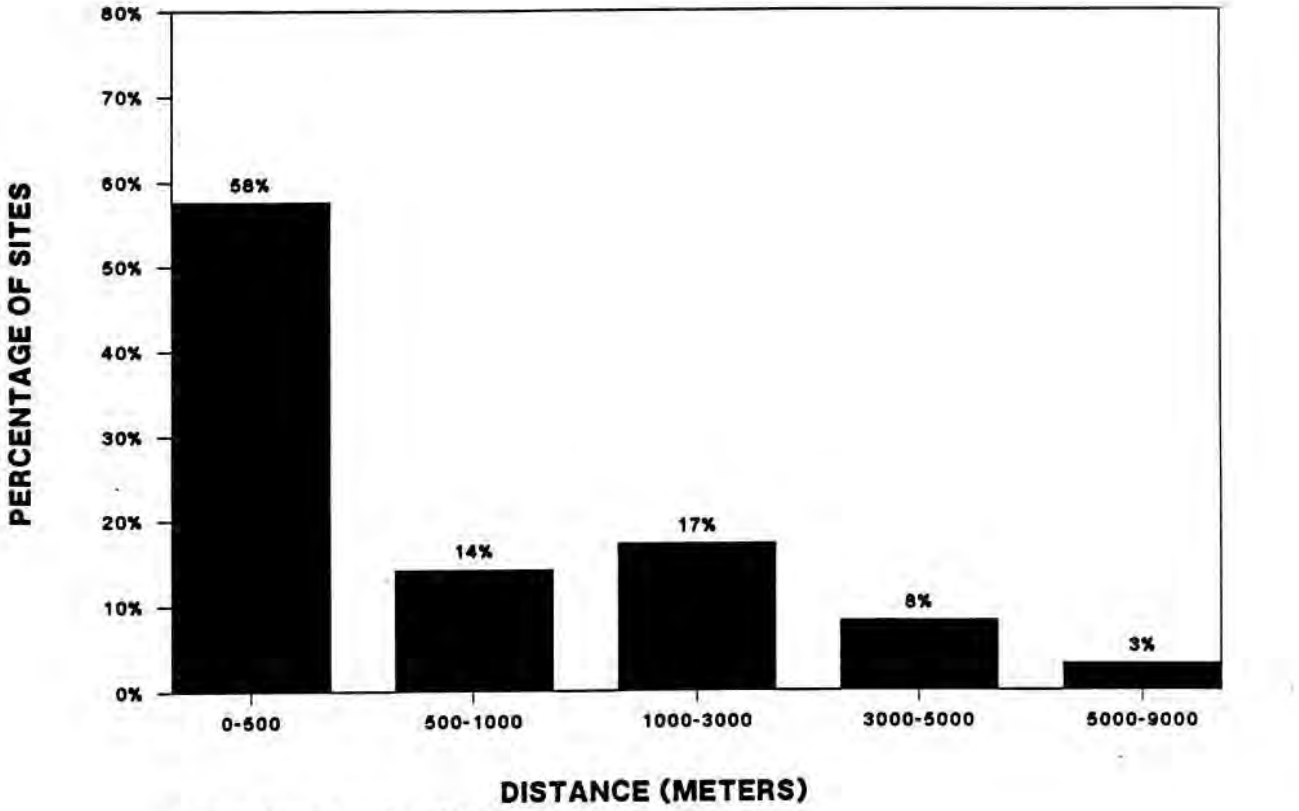
When the boundaries of the plant or waste site were marked on the maps, the reference point was the downgradient boundary of the site. If the boundaries were not marked, the latitude and longitude points for the sites provided by the Utility Data Institute Power Statistics Database were used.

The average distance from the sample of coal-burning waste sites to surface-water body is 1279 meters. Distances range from 10 to 18,000 meters. Over 50 percent of the disposal sites are within 500 meters of surface water; more than 70 percent are within 1,000 meters of surface water. Exhibit 5-17 provides the number and percentage of sites within specified distances of surface water.

Since most sites are located somewhat near surface-water bodies, the potential for human exposure to contaminated ground water seems to be low. The proximity of the sites to surface water could, however, pose a threat to aquatic life and to humans using the surface water if contaminants are entering

EXHIBIT 5-17

DISTANCE OF COAL COMBUSTION WASTE SITES TO SURFACE WATER



SOURCE: ICF Inc, based on USGS data

the surface water. The concentration in surface water will be less, however, if the surface-water body close to the site has a high flow.

Flow data on surface-water bodies near the sample of 100 sites were obtained from U.S.G.S. data. Flow is expressed in terms of cubic feet per second (cfs), and given for minimum and maximum average flow for one-month periods. In order to obtain a conservative estimate of exposure (i.e., one that does not understate exposure) this report used estimates for the month with the minimum monthly flow. The results are presented in Exhibit 5-18.

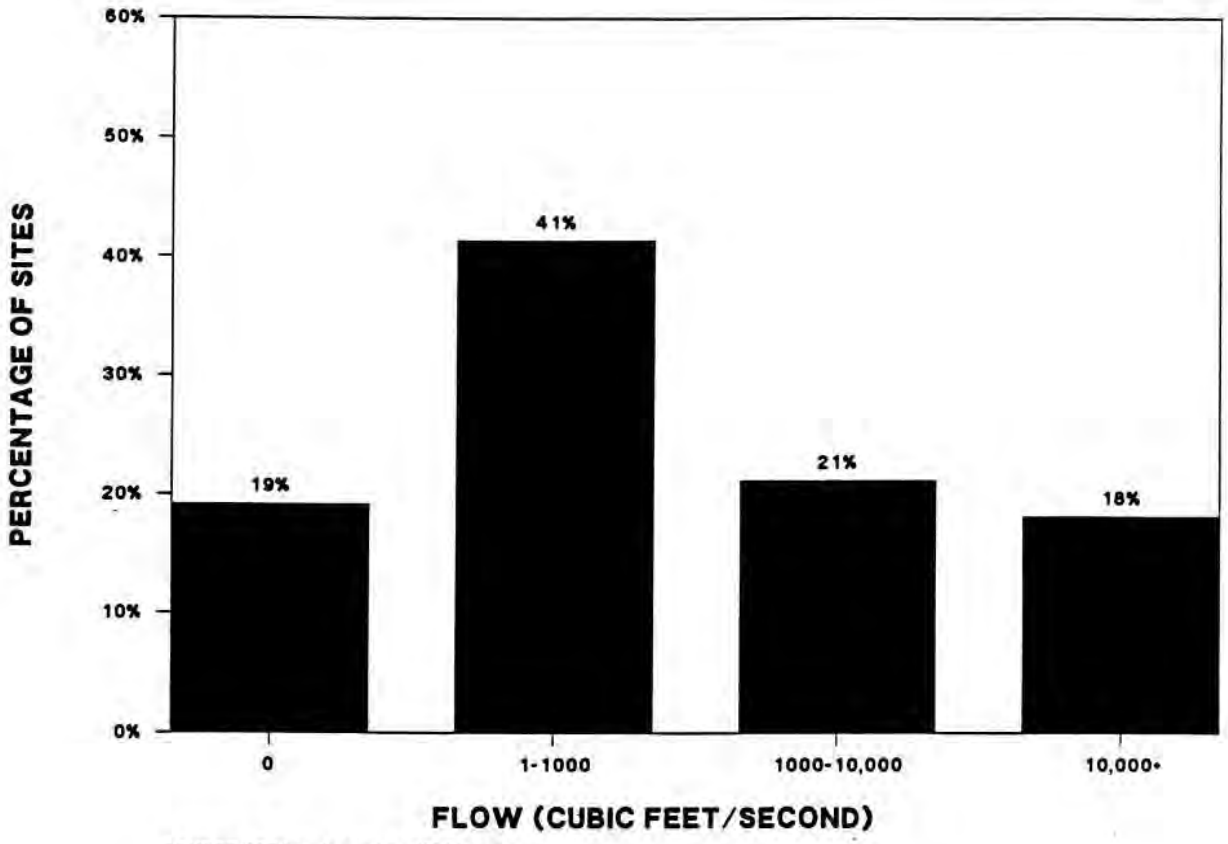
Exhibit 5-18 shows that 19 percent of the sites have a flow of zero. A zero flow generally indicates that the body of water is a lake, swamp, or marsh that does not have any continual flow of water, although this category could include a seasonal stream. For surface-water bodies with zero flow, dilution of potential contamination would occur because of the volume of water in the surface-water body, but there would not be any additional dilution as water flowed away from the source of contamination. Forty-one percent of the surface-water bodies have a flow of 1-1000 cubic feet per second, 21 percent have a flow of 1,000-10,000 cfs, and 18 percent have a flow of over 10,000 cfs.

5.4.1.2 Hydrogeologic Measurements

The hydrogeologic measurements of depth to ground water, hydraulic conductivity, and net recharge were determined through the use of information provided by the DRASTIC system. The DRASTIC system, developed by the National Well Water Association, categorizes aquifers on the basis of geographic region and subregion. Each site was located on a 7 1/2 or 15 minute U.S.G.S. map that

EXHIBIT 5-18

FLOW OF NEAREST SURFACE-WATER BODY



SOURCE: ICF Inc, based on USGS data

was then compared with a map on which the 11 major DRASTIC regions had been outlined. The topography and geology of the sites, which were determined from looking at the U.S.G.S. maps, were assessed in order to further classify thesites into DRASTIC subregions. Subregions are defined by hydrogeologic characteristics and vary in size from a few acres to hundreds of square miles. Measurements for depth to ground water, hydraulic conductivity, and net recharge of the sites were taken largely from A Standardized System for Evaluating Ground-water Pollution Potential Using Hydrogeologic Settings, by the National Well Water Association, which presents a range of values for each of these hydrogeologic properties for each subregion.[32] The ranges were compared with characteristics that could be observed by studying U.S.G.S. maps, and, when necessary, they were modified accordingly.

Depth to Ground Water

A small depth to ground water indicates a higher potential for waste constituents to reach the ground water at harmful concentrations than if the distance to ground water were greater, thereby increasing the chance of ground-water contamination. Depth to ground water was generally based on DRASTIC region and subregion, but was modified when the topography or site characteristics indicated a depth different from that provided by the DRASTIC system. For example, if the DRASTIC subregion indicated that there was a high depth to ground water range, but a particular site was located very near a surface-water body, the Agency used a smaller depth to ground water than the DRASTIC range indicated.

Exhibit 5-19 provides the number and percentage of sites within each range of depth to ground water. Depth to ground water is calculated in feet and based on 10 ranges. In over 80 percent of the sites depth to ground water is less than 30 feet, indicating a reasonably high potential that leachate from the disposal site would reach the ground water.

Hydraulic Conductivity

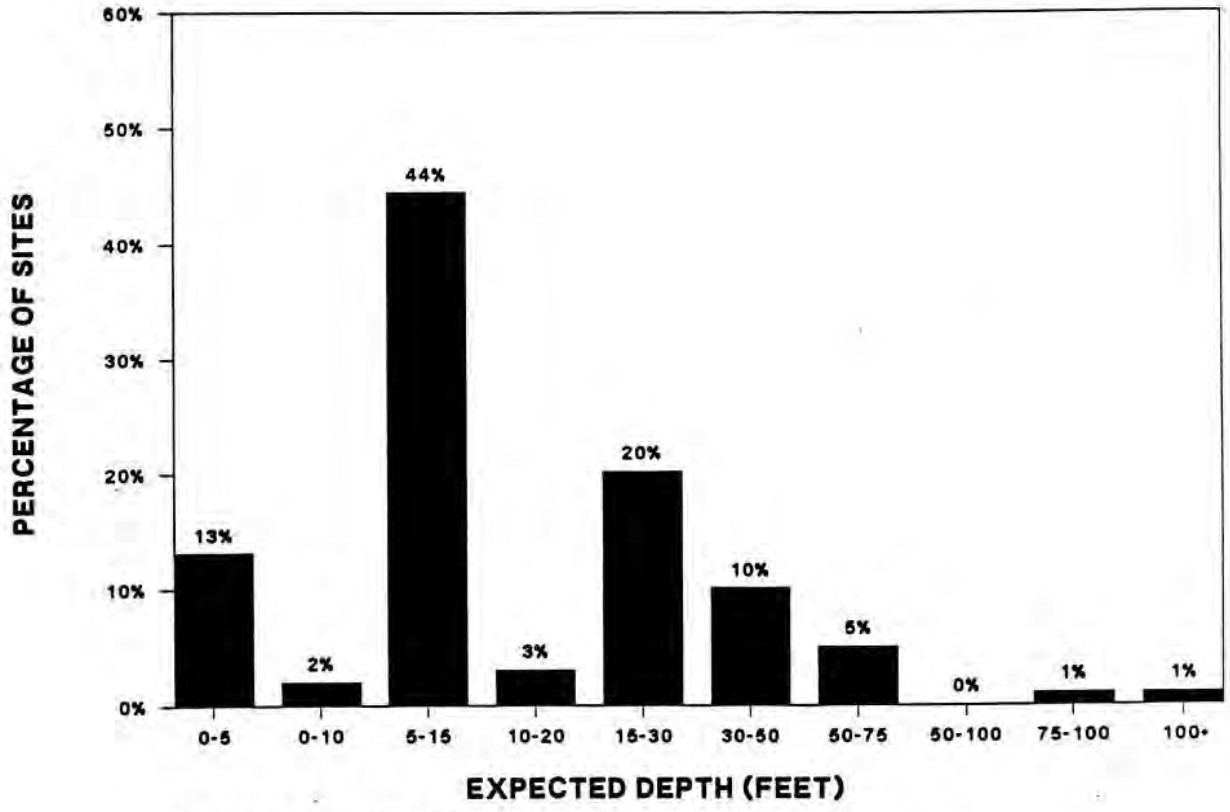
Hydraulic conductivity is an indication of the ease with which a constituent may be transported through the ground water. Conductivity is also based on the site's DRASTIC region and subregion, and is measured in gallons per day per square foot and grouped into six ranges.

Hydraulic conductivity is one of the factors used to calculate ground-water velocity, or volumetric flow of the water table. Velocity has a direct bearing on the degree to which leachate constituents are diluted once they reach the ground water and travel to a point of exposure (i.e., human drinking water source). High ground-water conductivity signifies high velocity and therefore a high dilution potential.

Exhibit 5-20 provides the number and percentage of sites falling into each hydraulic conductivity range. Thirty-three percent of the sites show a hydraulic conductivity of 700-1,000 gallons per day per square foot; 27 percent have a conductivity of 1,000-2,000 gallons per day per square foot. There is a wide spread of conductivity values -- indicating hydrogeologic diversity among sites.

EXHIBIT 5-19

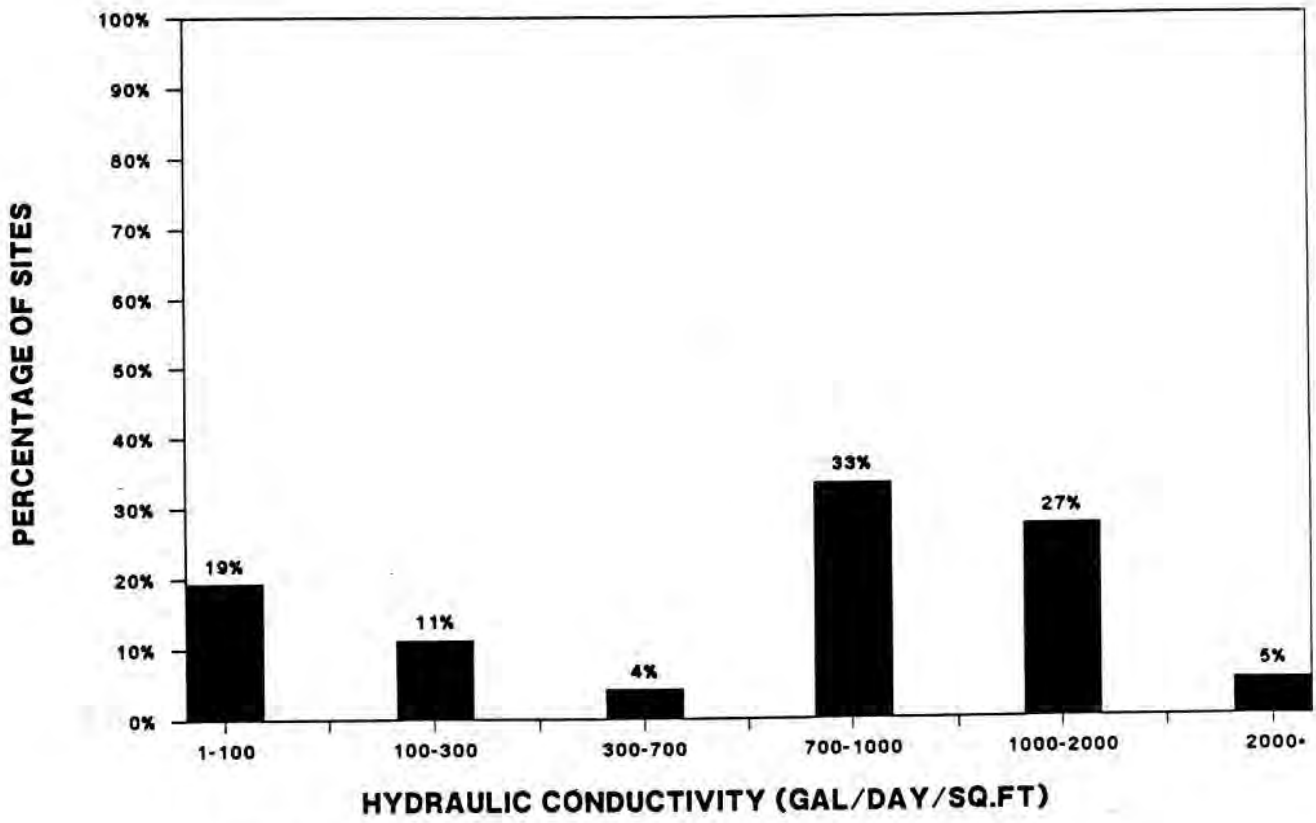
DEPTH TO GROUND WATER
AT COAL COMBUSTION WASTE SITES



SOURCE: ICF Inc, based on DRASTIC

EXHIBIT 5-20

HYDRAULIC CONDUCTIVITY
AT COAL COMBUSTION WASTE SITES



SOURCE: ICF Inc, based on DRASTIC data

While ground-water velocity gives an indication of how fast contamination may travel in the ground water, contaminants do not move at the same velocity as the ground water. This is because of basic interactions between contaminants and soil that retard the movement of the contaminants. There are three different mechanisms that affect the retardation of contaminant movement -- exchange on soil particle sites (ion exchange), adsorption onto soil particle surfaces, and precipitation. The exchange and adsorption mechanisms will retard the movement of contaminants but will not eliminate the movement of all contaminants due to limited soil attenuation capacity.

As with the diversity among sites in terms of hydraulic conductivity and ground-water velocity, the various attenuation mechanisms differ among sites. To determine the attenuation potential at a site requires detailed data inputs on water chemistry on a site-specific basis.

Net Recharge

Net recharge indicates how much water is annually absorbed into the ground. It is measured by subtracting evapotranspiration (the amount of rainfall that evaporates and transpires from plant surfaces) and estimated runoff from total precipitation at a site. It affects exposure potential in a number of ways. Low recharge will result in smaller volumes of more concentrated leachate, but if the aquifer is deep and/or has a high velocity, it will quickly dilute the leachate. High recharge produces more leachate, but may also indicate that the area has higher ground-water flow.

Exhibit 5-21 shows the number and percentage of sites that fall into each range. Recharge is measured in inches and is grouped into five ranges. Although a wide variety of net recharge ranges is represented by the sample, the recharge of sites generally falls into the higher ranges of 4-7 inches, 7-10 inches, and over 10 inches. For example, more than 80 percent of the sites have a net recharge of over 4 inches and over 50 percent have a recharge of over 7 inches. This implies that leachate constituents will be more quickly carried to the water table but the higher recharge rate will also result in greater dilution of the leachate.

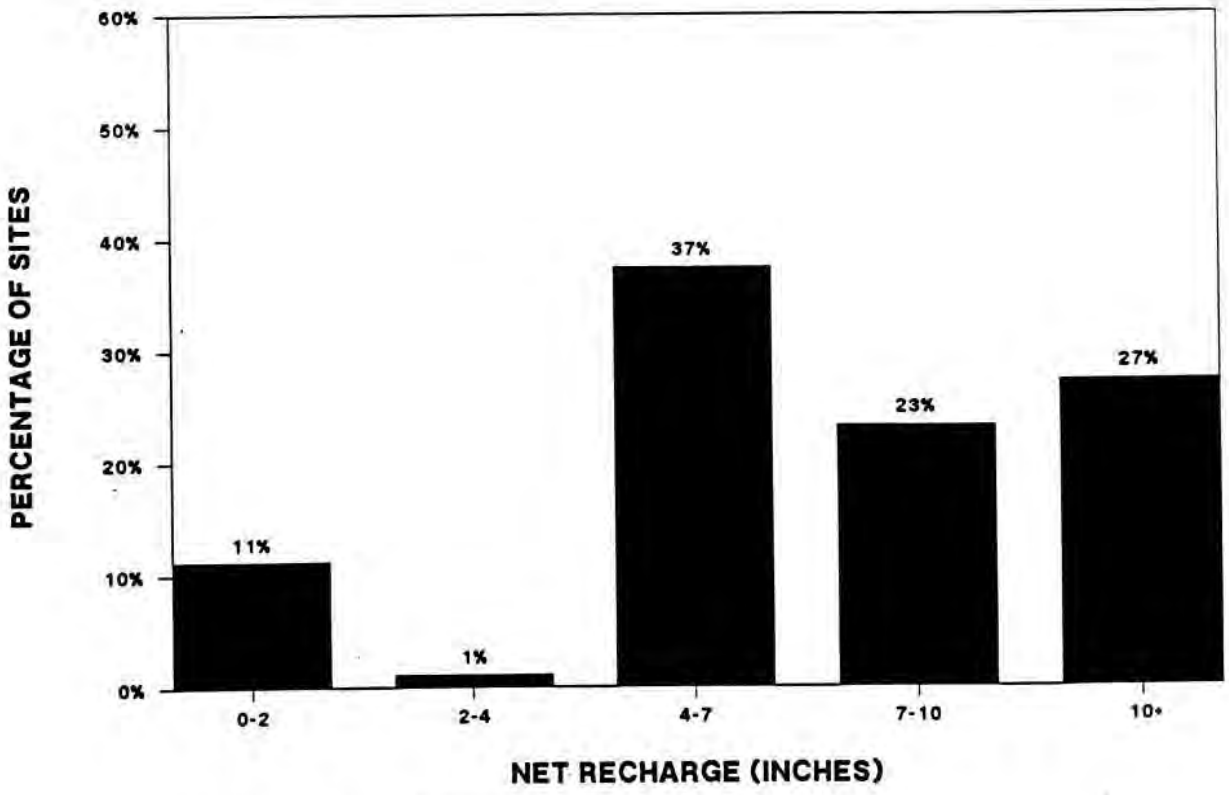
Ground-water Hardness

The hardness of the ground water near coal combustion waste sites will have an effect on potential exposure through drinking water since excessive hardness is typically treated in a public drinking water system. Treatment would lessen the exposure potential to humans from contaminants in the ground water from other sources (such as coal combustion wastes). Measurements for ground-water hardness were obtained by locating the sites on maps provided in Ground-water Contamination in the United States (Pye, Patrick, and Quarles).[33]

As shown in Exhibit 5-22, ground-water hardness is measured in parts per million (ppm) of calcium carbonate (CaCO3) and grouped into five ranges. Ground water with a hardness of over 240 ppm of calcium carbonate is typically treated if used in a public drinking water system. In this sample, 45 percent of the sites show ground-water hardness in this range. Ground water with a hardness of 180-240 ppm of calcium carbonate may also be treated, although

EXHIBIT 5-21

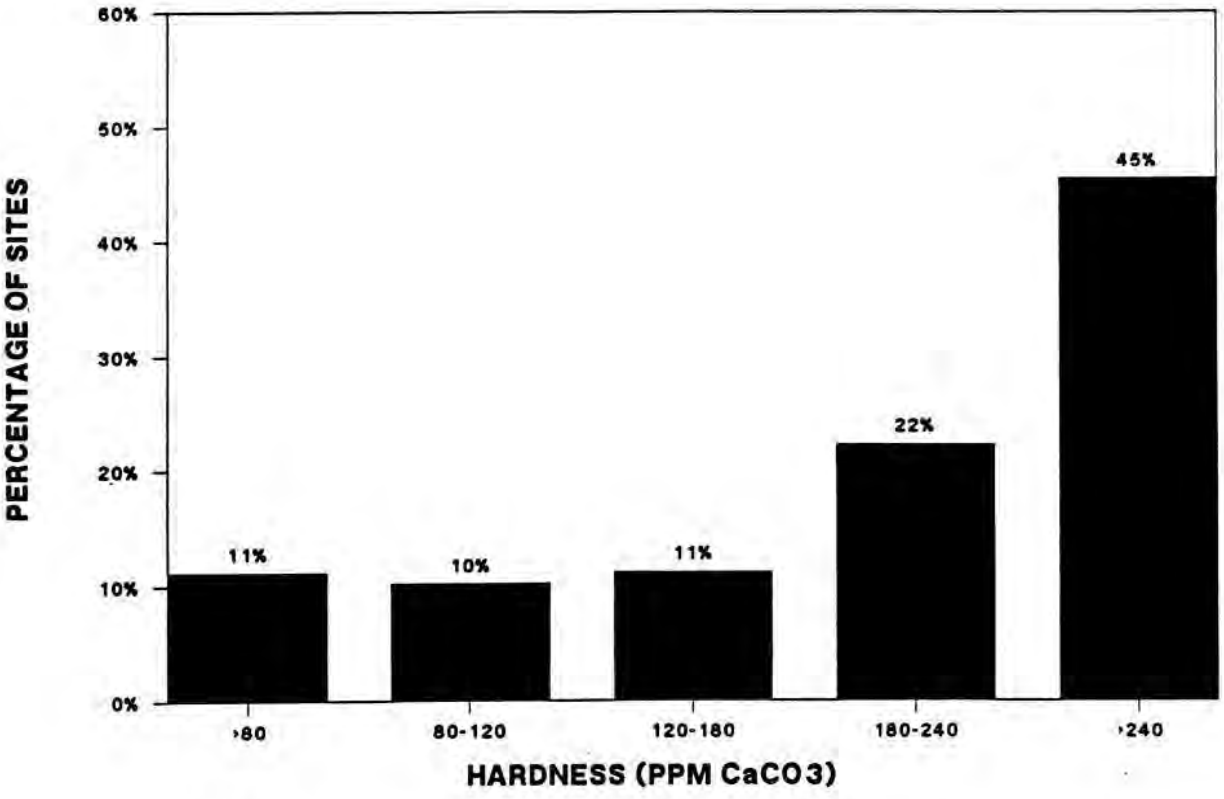
NET RECHARGE
AT COAL COMBUSTION WASTE SITES



SOURCE: ICF Inc, based on DRASTIC

EXHIBIT 5-22

GROUND-WATER HARDNESS
AT COAL COMBUSTION WASTE SITES



SOURCE: ICF Inc, based on Pye, et al, Groundwater Contamination in U.S.

treatment is much less likely. An additional 22 percent fall in the 180-240 ppm range.

The high levels of calcium carbonate found in the ground water near coal combustion waste disposal sites suggest that if a drinking water supply is in the vicinity, the water would often require treatment before being used. Therefore, contamination that might exist in the drinking water from other sources would be mitigated due to the treatment process since trace constituents tend to be removed during the treatment process.

5.4.2 Population Characteristics of Coal Combustion Waste Sites

Environmental characteristics, such as distance and flow of surface water and hydrogeologic measurements, are only one part of the analysis of exposure potential. Opportunities for human exposure to coal combustion waste constituents depend in part on the proximity of coal combustion waste disposal sites to human populations and to human drinking water supplies. Census data (1980) provide information about the number of people living within specified distances from the coal combustion waste sites. This information is obtained through the CENBAT program, part of the Graphic Exposure Modeling System developed by EPA's Office of Solid Waste. The Federal Reporting Data System (FRDS) data base, developed by EPA's Office of Drinking Water, provides estimates of the number of public water supply systems and the size of the populations using them.

5.4.2.1 Proximity of Sites to Human Populations

CENBAT provides information on the number of people living within specified distances around designated locations. The sites were defined by latitude and longitude coordinates. Populations were analyzed for areas within 1-, 2-, 3-, 4-, and 5-kilometer radii of the waste disposal sites.

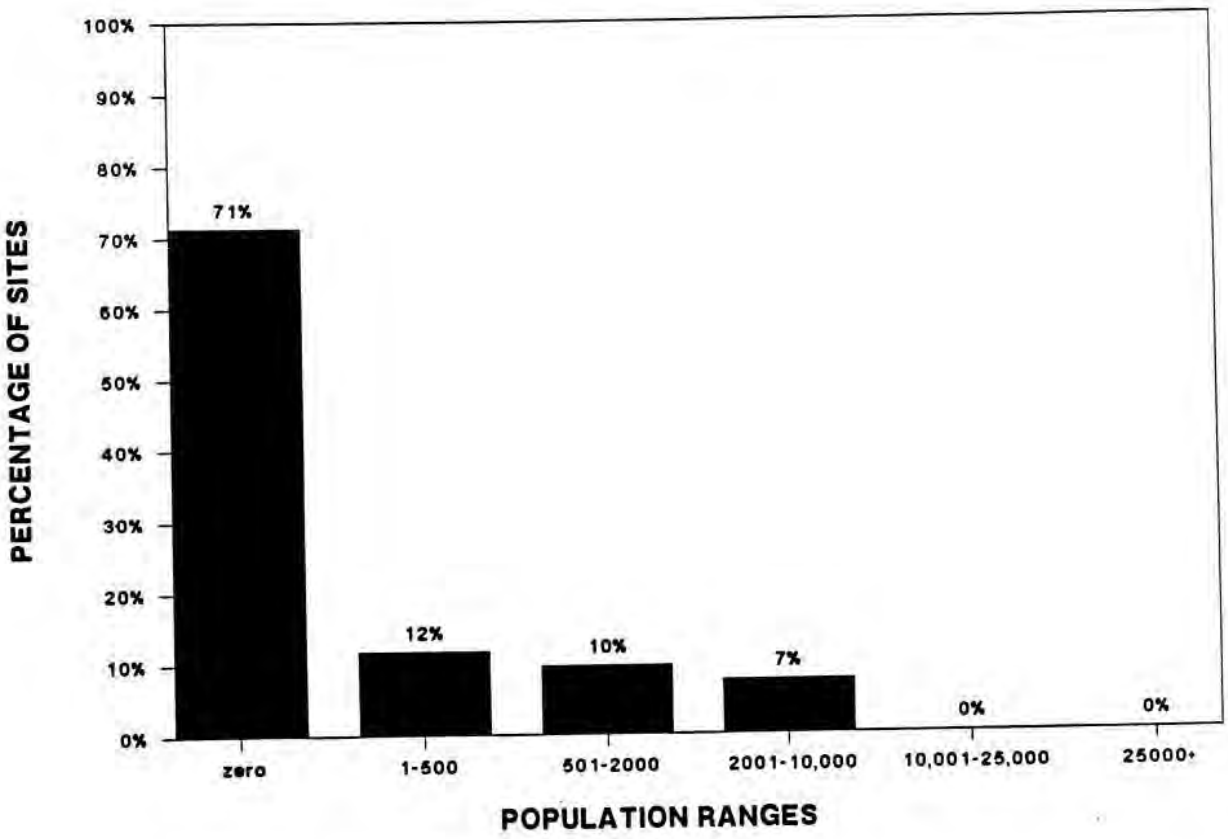
Exhibit 5-23 shows the distribution of population within one kilometer of the waste disposal sites. The CENBAT results show that most sites, 71 percent, do not have any population within a one-kilometer radius. Overall, the population range within a one-kilometer radius is 0 - 3708 people, with an average of 359 people.

Exhibit 5-24 shows the population characteristics for the sample of coal combustion waste sites at a three-kilometer radius. When the search distance is increased to three kilometers, the percentage of sites that have no people within a three-kilometer radius decreases to 32 percent. Average population within three kilometers is 3,737, and the range is 0 - 35,633 people. There is a large degree of diversity of populations at this distance. For example, while 32 percent of the sites have zero population, the same percentage has populations over 2,000.

Exhibit 5-25 shows the distribution of populations within a five-kilometer radius. Only 10 percent of the sites do not have any population living within this distance. The average population is 12,128 people, with a range from 0 to 123,160. The diversity among coal combustion waste disposal sites is even more apparent at this distance. While 20 percent of the sites have populations

EXHIBIT 5-23

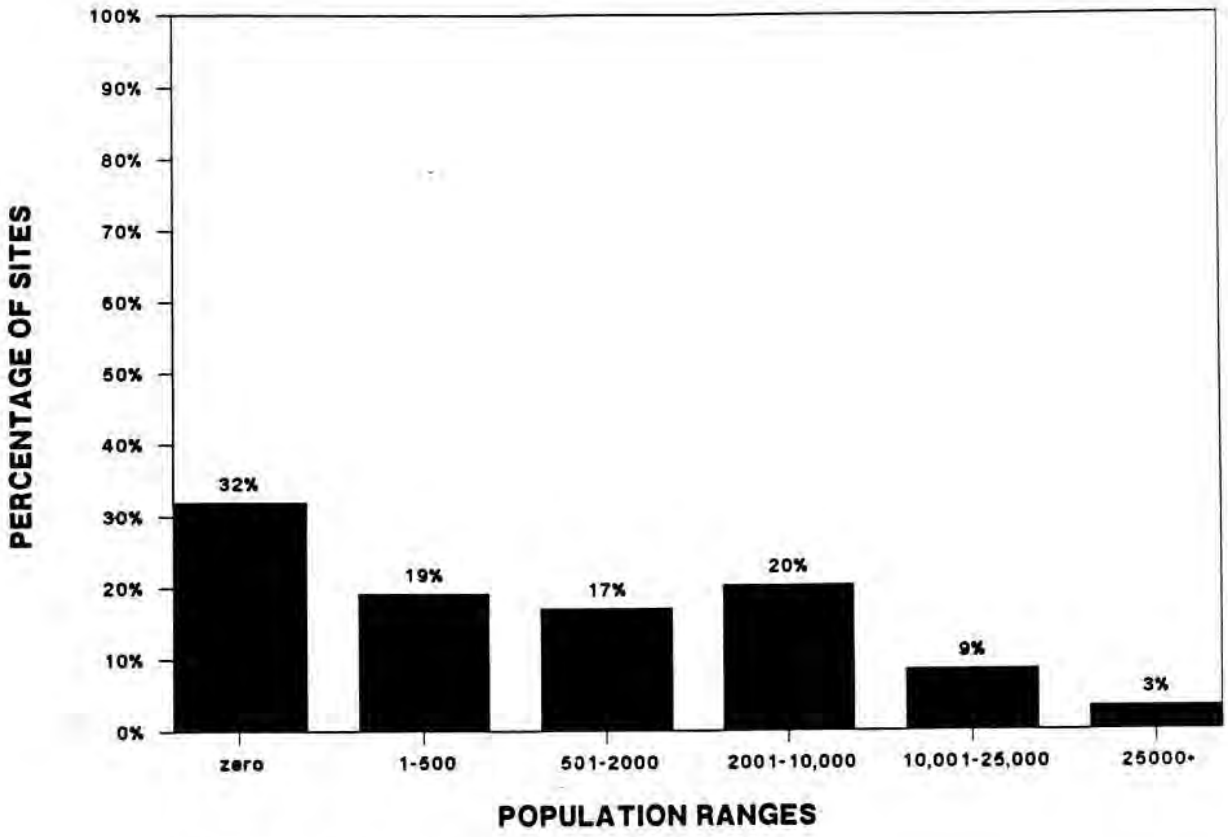
POPULATIONS WITHIN ONE KILOMETER OF WASTE SITES



SOURCE: ICF Inc, based on CENBAT data

EXHIBIT 5-24

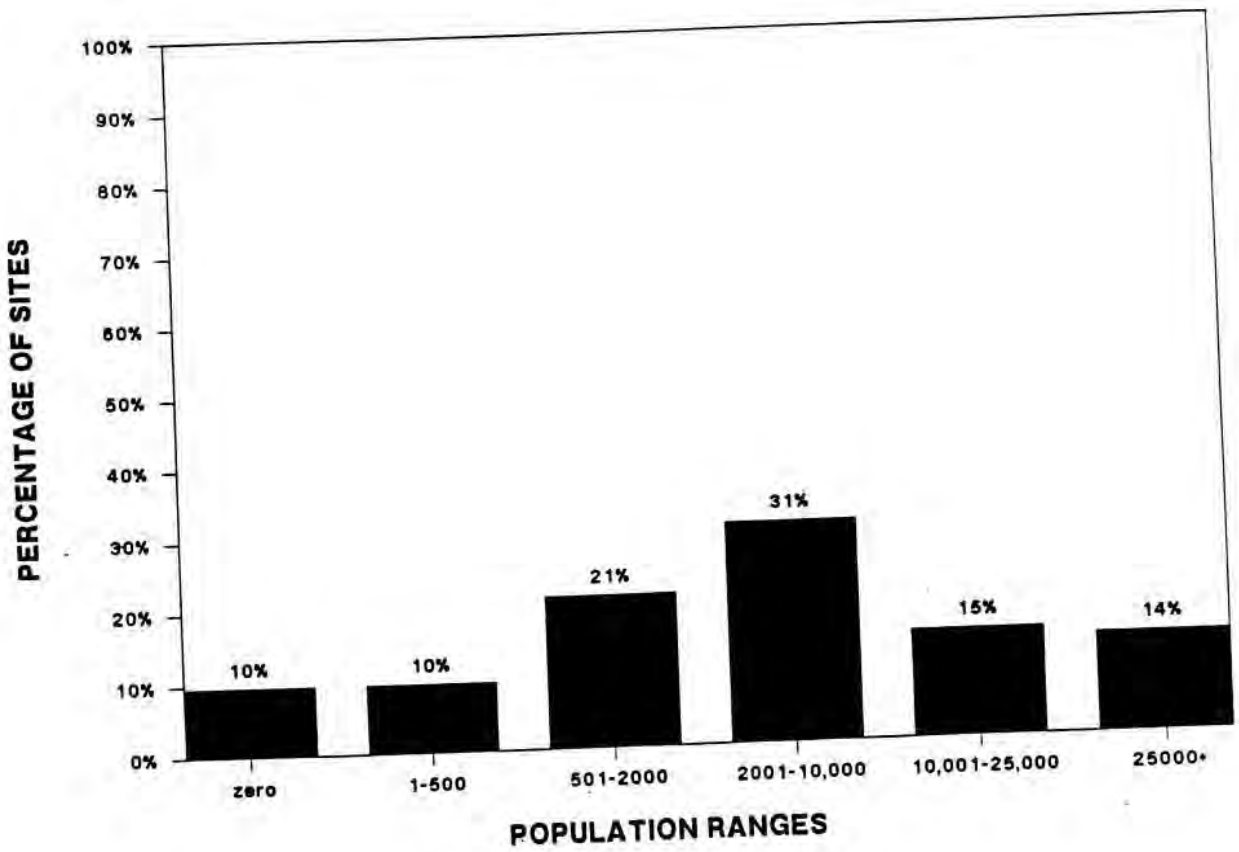
POPULATIONS WITHIN THREE KILOMETERS OF WASTE SITES



SOURCE: ICF Inc., based on CENBAT data

EXHIBIT 5-25

POPULATIONS WITHIN FIVE KILOMETERS OF WASTE SITES



SOURCE: ICF Inc., based on CENBAT

within a five-kilometer radius of fewer than 500 persons, 29 percent have populations over 10,000.

The CENBAT results indicate that density increases on average with distance from the disposal site. Many waste sites appear to be located on the outskirts of populated areas, with fairly low population immediately adjacent to the site, but with significant populations within a five-kilometer radius.

5.4.2.2 Proximity of Sites to Public Drinking Water Systems

If coal combustion waste sites are close to public drinking water systems, there may be potential for human exposure through drinking water supplies. The location of public water supplies was determined through the use of the Federal Reporting Data System (FRDS), developed by EPA's Office of Drinking Water.

The FRDS data base provides the number of public water supply systems located within specified distances from a site and the populations using the systems. It should be noted that the FRDS data base locates water systems based on the centroid of the zip code of the mailing address of each utility and that the actual location of the intake or well may be different. This can cause some inaccuracy in the calculation of the distance and location of public drinking water supplies in relation to the waste site. In order to remedy potential inaccuracies and omissions, the locations of public water systems that appeared on topographical maps but were not reported by FRDS are also recorded.

Exhibit 5-26 shows the population served by public water systems located in the downgradient plume from the sites and within a five-kilometer radius. The exhibit also shows how many sites have no public water systems within a five-kilometer radius. Sixty-six percent of the sites have no public water systems within a five-kilometer radius. Fifteen percent of coal combustion sites have public water systems located within a five-kilometer distance and had systems which served over 5,000 people, and 19 percent have public water systems that serve fewer than 5,000 people.

The population data indicate that while there are often quite large populations in the vicinity of coal combustion waste sites, only 34 percent of the sites have public drinking water systems downgradient from the site.

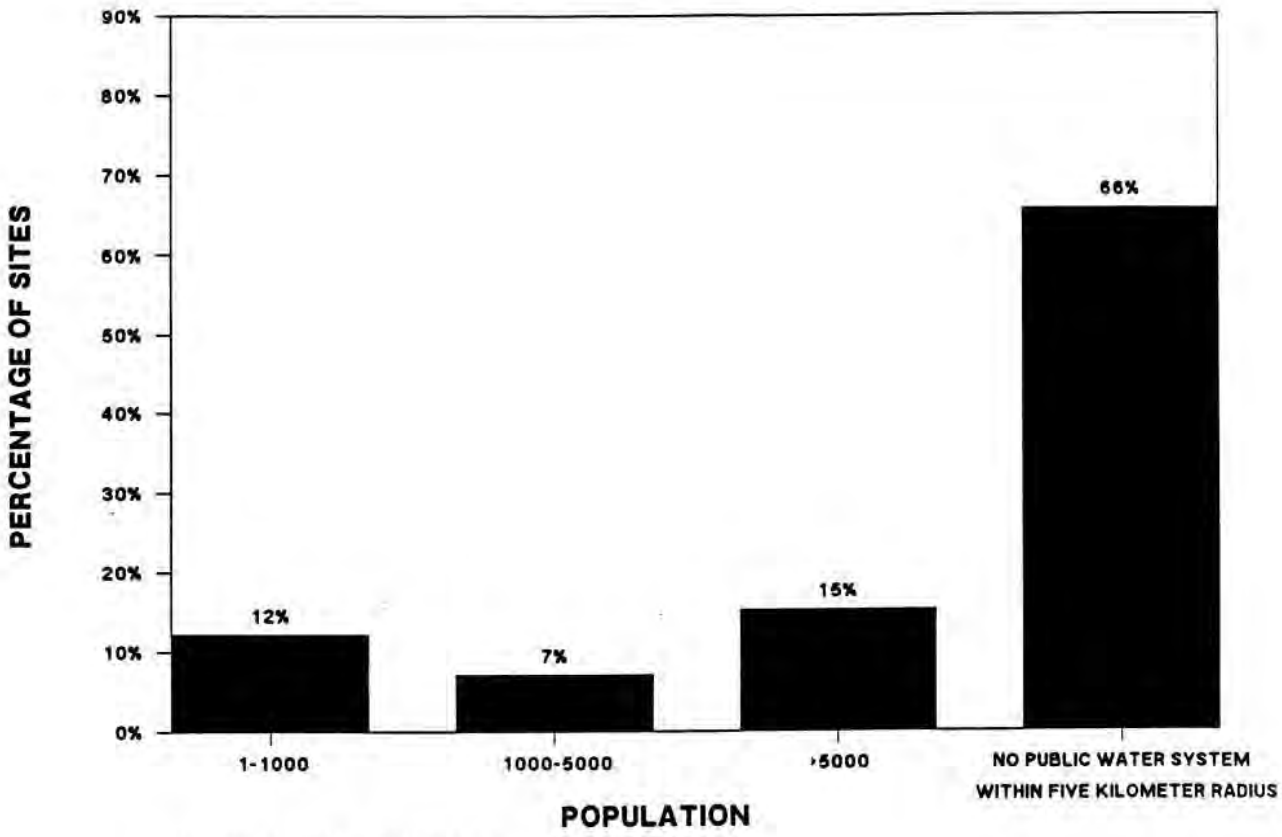
5.4.3 Ecologic Characteristics of Coal Combustion Waste Sites

Ecological data on endangered, threatened, or unique plants and animals is available through state Heritage Programs. The Nature Conservancy established the Heritage Programs, which now usually function as offices of state governments. The Heritage Programs develop and maintain data bases that describe jeopardized species and rare ecosystems within each state. It should be noted that there can be substantial variation in the completeness of data available from different states; some state Heritage Programs are fairly new, and basic data collection is still in its preliminary stages.

While it may not currently be possible to quantitatively model risk to ecosystems from coal combustion waste, the information provided by the Heritage Programs can indicate whether there are any jeopardized species near a specific

EXHIBIT 5-26

POPULATIONS SERVED BY PUBLIC WATER SYSTEMS NEAR WASTE SITES



SOURCE: ICF, based on FRDS data

waste site. If potentially hazardous constituents of coal combustion waste do migrate and produce environmental contamination, it could affect species and natural communities that are particularly vulnerable, thereby lessening ecosystem diversity.

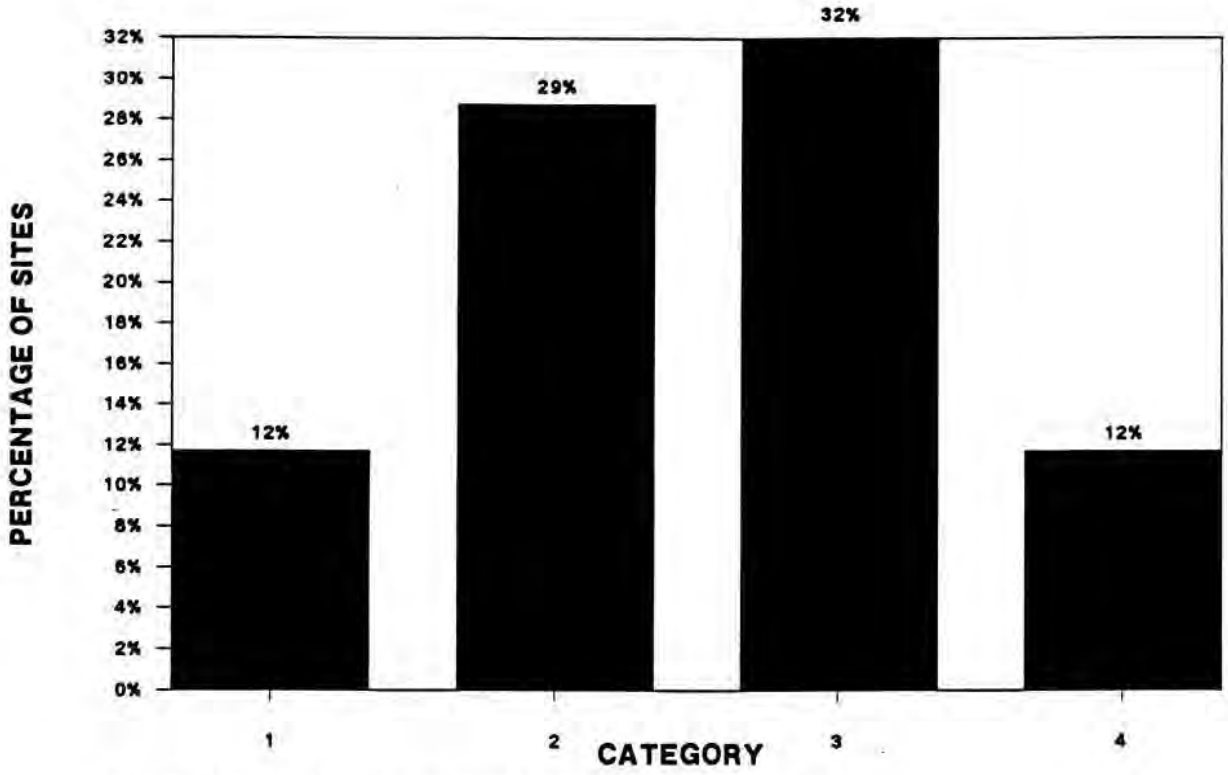
EPA provided Heritage Program staff with latitudes and longitudes for the sampled sites in states that had such programs. Using these coordinates, the Heritage Program staff performed a search of their data bases for rare or endangered species within a five-kilometer radius from the site.

The sample sites were grouped into four categories based on the results obtained from the Heritage Program. Category 1 includes sites having Federally designated threatened or endangered species within the five-kilometer radius. Category 2 includes sites that have no Federally designated threatened or endangered species within the five-kilometer distance, but which do contain species or natural communities designated by state Heritage Offices as critically endangered in that state. Category 3 contains sites for which there are species or natural communities of concern in the area. For sites in Category 4, there is no record of the existence of species of concern in the five-kilometer area.

Information was available on 85 of the 100 coal combustion waste sites in the sample. Exhibit 5-27 presents the breakdown of sites according to the categories described above. Twelve percent of the sites fall into Category 1, 29 percent in Category 2; 32 percent in Category 3; and 12 percent in Category 4 (no information was available for 15 percent).

EXHIBIT 5-27

ECOLOGICAL STATUS OF WASTE SITES



Category 1 : Federally designated plants or animals within a five km. radius
Category 2: Species of priority state concern within five km. radius
Category 3: species of concern to state environmental offices
Category 4: no data on ecosystem surrounding the site

SOURCE: ICF Inc., based on State Heritage Data

Given the high percentage of sites that have rare plant and animal communities within a five-kilometer radius supplies, and the proximity discussed earlier of waste disposal sites to surface-water bodies (which provide animals with drinking water), there could be a high potential for species exposure to coal combustion constituents.

5.4.4 Multivariate Analysis

The previous sections of this exposure analysis presented independent analyses of the population, environmental, and ecological characteristics of coal combustion waste sites. This section examines a number of these factors simultaneously in order to determine interactions that affect the overall potential for exposure from coal combustion waste sites.

As mentioned previously, only 34 percent of coal combustion waste sites (based on a random sample of 100 sites) have public drinking water systems in the downgradient plume within 5 kilometers of the waste site. Some of these public drinking water systems may use ground water that is currently treated before it is used as drinking water, indicating that human populations are unlikely to be directly exposed to any water that may be contaminated from coal combustion waste constituents. As discussed earlier, one reason for treating the water is ground-water hardness. Ground water that has a hardness greater than 240 ppm CaCO3 is likely to be treated if it is used as a drinking water source. Of the 34 percent of the sites in the sample that have public water systems in the downgradient plume within 5 kilometers of the waste site, just under one-half of these sites have ground water with a hardness over 240 ppm CaCO3. These results show that the potential for human exposure through

drinking water is likely to be less than the proximity to public drinking water systems (FRDS data) indicates. Of all the sites sampled, only 18 percent have public drinking water systems within 5 kilometers and ground water under 240 ppm $CaCO_3$.[34]

The potential for human exposure through drinking water can be further evaluated by comparing the FRDS and ground-water quality characteristics with the hydrogeologic factors of net recharge and depth to ground water. Sites with a net recharge greater than 7 inches and a depth to ground water of fifteen feet or less are more likely to develop ground-water contamination due to waste leaching since water has a greater likelihood of contacting the coal combustion wastes. Of the 18 percent of the sites that have public water supplies and ground-water hardness below 240 ppm $CaCO_3$, two-thirds have a net recharge greater than 7 inches as well as a depth to ground water of 15 feet or less. Therefore, only 12 percent of the sites in the sample (18 percent x 2/3) have ground water that is likely to be used without treatment and hydrogeologic characteristics that indicate high potential for leachate migration.

This multivariate analysis of the factors affecting exposure at coal combustion waste sites illustrates the limited potential for human health risk through drinking water. Only 34 percent of the sites have public water systems within five kilometers and many of these public water systems are likely to treat the ground water due to hardness.

5.5 SUMMARY

This chapter has reviewed available information on the potential for coal-fired combustion wastes from electric utility power plants to affect human health and the environment. First, data on the potential corrosivity and EP toxicity of utility wastes was reviewed. After determining that coal combustion leachate sometimes contains hazardous constituents at levels above drinking water standards, the potential for this leachate to migrate from waste disposal sites was examined. Results of ground-water monitoring in several studies were interpreted and a number of compilations of "documented" damage cases were evaluated. After describing instances in which trace elements in coal combustion leachate have migrated from waste disposal sites, the potential effect of these migrations was examined. A sample of 100 utility waste disposal sites was selected, and these sites were evaluated in terms of population, environmental, and ecological characteristics to assess the potential for leachate migration and exposure of human and ecological populations.

Based on these data and analyses, several observations relating to potential dangers to human health and the environment can be made:

- If the current exemption from Subtitle C regulation were lifted for coal combustion wastes and these wastes were required to be tested for corrosivity or EP toxicity, most current waste volumes and waste streams would not be subject to hazardous waste regulation. The only waste stream which has had corrosive results is boiler cleaning waste. (Since coal ash is not aqueous, it cannot be corrosive.) For the other waste streams, available data indicate that while some of these waste streams could have high or low pH levels, they are not likely to fall under the RCRA definition of corrosive waste.

Similarly, while a few high-volume waste samples did exceed the EP toxicity limits for cadmium, chromium, and arsenic, this was limited to a few waste streams and represented only a small fraction of the samples for these waste streams (the chromium and arsenic exceedances were from only one fly ash sample). Available data on low-volume wastes showed that the only waste stream with significant RCRA exceedances was boiler cleaning waste, which had exceedances for chromium and lead. Wastewater brines were shown to exceed the RCRA standard for selenium in one sample. Results of EP tests on co-disposed wastes indicate that boiler cleaning wastes may not possess hazardous characteristics when co-disposed with ash. Results for all other waste streams and all other constituents were below EP toxicity limits.

- Results available from ground-water monitoring studies and documented cases of ground-water or surface-water contamination show some migration of PDWS constituents from utility waste disposal sites. In the most comprehensive and systematic of these studies, the Arthur D. Little survey of six utility sites, evidence of constituent migration downstream from the waste sites was conclusive only for cadmium. The Envirosphere ground-water study showed that only 3.7 percent of the samples showed downgradient concentrations of PDWS constituents that were higher than the concentrations of upgradient constituents (indicating that some contaminants are migrating from the site). This tends to support the results of the waste extraction tests. For the one utility disposal site on the National Priorities List, a site currently inactive since it was closed in 1974, the major ground-water contaminants were vanadium and selenium. However, this site differs from some other sites for which ground-water quality data are available in that wastes are from both coal and petroleum coke combustion.

- Although coal combustion waste leachate has the potential to migrate from the disposal area, the actual potential for exposure of human and ecological populations is likely to be limited. Because utility plants need a source of water to operate, most of the disposal sites are located quite close to surface water. Fifty eight percent of the 100 sample sites were within 500 meters of surface water. It is not common for drinking water wells to be located between the disposal site and the nearest downgradient surface water body. The effect of this proximity to surface water is that only 34 percent of the sampled sites had drinking

water intakes within five kilometers. Furthermore, the flow of the surface water will tend to dilute the concentrations of trace metals to levels that satisfy drinking water standards.

- Simultaneously examining the environmental and population characteristics of coal combustion waste sites shows even less potential for exposure to human populations. 12 percent of the sites in the sample have public water systems within five kilometers of the site where the ground water may not be treated (i.e., ground-water hardness below 240 ppm $CaCO_3$) and hydrogeologic characteristics that indicate high potential for leachate migration.

CHAPTER 5

NOTES

1 See 40 CFR 261.21.

2 See 40 CFR 261.22. In using pH to determine corrosivity, EPA explained that "wastes exhibiting low or high pH can cause harm to human tissue, promote the migration of toxic contaminants from other wastes, and harm aquatic life."

3 These methods are set forth in 40 CFR 260.21 and 260.22.

4 See 40 CFR 261.23.

5 See 40 CFR 261.24.

6 See 40 CFR Part 261, Appendix II. These procedures for testing and the limits allowed for determining whether a waste is hazardous or not are currently under review.

7 A waste would be considered hazardous if it has been shown to have an oral LD 50 toxicity to rats of less than 50 mg/kg, an inhalation LC toxicity to rats of less than 2 mg/1, or a dermal LD 50 toxicity to rabbits of less than 2000 mg/kg.

8 See 40 CFR 261.11.

9 See CFR 40 Section 261.24. RCRA also establishes EP toxicity limits for six pesticides.

10 See CFR 40 Section 261, Appendix II.

11 Federal Register, Volume 51, No. 114, Friday, June 13, 1986, p. 21648.

12 Since the completion of the ASTM B tests discussed in this section, ASTM has dropped this extraction test (EPRI 1983).

13 Tetra Tech, Inc., Physical-Chemical Characteristics of Utility Solid Wastes, prepared for Electric Power Research Institute, EA-3236, September 1983.

14 Jackson, L. and Moore, F., Analytical Aspects of the Fossil Energy Waste Sampling and Characterization Project, prepared for the U.S. Department of Energy, Office of Fossil Energy, DOE/LC/00022-1599 (DE84009266), March 1984.

15 Arthur D. Little, Inc., Full-Scale Field Evaluation of Waste Disposal from Coal-fired Electric Generation Plants, prepared for the Air and Energy Engineering Research Laboratory of the U.S. Environmental Protection Agency for the Office of Solid Waste, EPA-600-7-85-028, June 1985.

16 Mason, B.J., and Carlile, D.W., draft report of Round Robin Evaluation for Selected Elements and Anionic Species from TCLP and EP Extractions, prepared by Battelle Pacific Northwest Laboratories, for the Electric Power Research Institute, EPRI EA-4740, April 25, 1986.

17 Battelle's test varied from standard TCLP procedure by allowing 14 days, rather than the normal 7, for the completion of the test.

18 Electric Power Research Institute, "Mobilization and Attenuation of Trace Elements in an Artificially Weathered Fly Ash," prepared by the University of Alberta, Edmonton, Canada, EPRI EA-4747, August 1986.

19 Battelle Pacific Northwest Laboratories, Chemical Characterization of Fossil Fuel Combustion Wastes, prepared for the Electric Power Research Institute, September 1987.

20 Radian Corporation, Characterization of Utility Low-Volume Wastes, prepared for the Electric Power Research Institute, May 1985.

21 Radian Corporation, Manual For Management of Low-Volume Wastes From Fossil-Fuel-Fired Power Plants, prepared for the Electric Power Research Institute, July 1987.

22 Arthur D. Little, Inc., Full-Scale Field Evaluation of Waste Disposal from Coal-fired Electric Generation Plants, prepared by the Air and Energy Engineering Research Laboratory of the U.S. Environmental Protection Agency, for the Office of Solid Waste, EPA-600-7-85-028, June 1985.

23 Franklin Associates, Ltd., Survey of Ground-water Contamination Cases at Coal Combustion Waste Disposal Sites, prepared for U.S. Environmental Protection Agency, March 1984.

24 Envirosphere Company, "Report on the Ground Water Data Base Assembled by the Utility Solid Waste Activities Group," in Utility Solid Waste Activities Group (USWAG), Report and Technical Studies on the Disposal and Utilization of Fossil Fuel By-Products, October 26, 1982, Appendix C.

25 It is not necessarily true that measurements taken from upgradient and downgradient wells at approximately the same time yield comparable measurements. In fact, due to migration time, there will be a lag between the time of comparable upgradient and downgradient measurements.

26 Envirosphere Company, Op. cit., p. 38. These percentage numbers do not correspond precisely to the data in Exhibit 5-11 because Envirosphere normalized the data it received from the utilities so that each facility would be weighted evenly (i.e.,, a facility with many more measurements would not be weighted excessively). Envirosphere reports that 1.7 percent of the normalized data had upgradient measurements lower than the PDWS and the downgradient higher than the PDWS; 5 percent of the data indicated that both values exceeded the standard.

27 Envirosphere Company, Environmental Effects of Utility Solid Waste Disposal, prepared for Utility Solid Waste Activities Group and Edison Electric Institute, July 1979.

28 Dames & Moore, "Review of Existing Literature & Published Data to Determine if Proven Documented Cases of Danger to Human Health and the Environment Exist as a Result of Disposal of Fossil Fuel Combustion Wastes", in Utility Solid Waste Activities Group (USWAG), Report and Technical Studies on the Disposal and Utilization of Fossil-Fuel Combustion By-Products, October 26, 1982, Appendix B.

29 Cherkauer, D. S. "The Effect of Fly Ash Disposal on a Shallow Ground-Water System." Ground Water, Vol. 18, No. 6, pp. 544-550, 1980.

30 Groenewold, G. H., and B. W. Rehm. "Applicability of Column Leaching Data to the Design of Fly Ash and FGD Waste Disposal Sites in Surface- Mined Areas." In Proceedings of the Low-Rank Coal Technology Development Workshop, comp. Energy Resources Company, Inc., DOE/ET/17086-1932, CONF-8106235; Washington, D.C., U.S. Department of Energy, Technical Information Center, pp. 3-79 - 3-95, 1981.

31 Envirosphere Company, Environmental Settings and Solid-Residues Disposal in the Electric Utility Industry; prepared for the Electric Power Research Institute, August 1984.

32 Linda Aller, Truman Bennet, Jay H. Laher, Rebecca J. Betty, A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrologic Settings, prepared by the National Well Water Association for U.S. EPA Office of Research and Development, Ada, OK, May 1985. EPA 600-285-018.

33 Veronica T. Pye, Ruth Patrick, John Quarles, Ground Water Contamination in the United States, Philadelphia: University of Pennsylvania Press, 1983.

34 Ground water over 180 ppm CaCO3 may also be treated. Of the 34 percent of the sites in the sample that have public water systems in the plume downgradient from the site within 5 kilometers, 73 percent have ground water with a hardness over 180 ppm CaCO3. Therefore, only 9 percent of the sites in the sample have both public water systems within 5 kilometers and ground water under 180 ppm CaCO3. Since many public water systems may not treat water in the range of 180-240 ppm CaCO3, the discussion in the report focuses only on ground water in excess of 240 ppm CaCO3. This is a conservative assumption since the water may be treated, either by the public authority or the private homeowner. In all cases, the extent of exposure through private wells would have to be evaluated on a site-by-site basis.

CHAPTER SIX

ECONOMIC COSTS AND IMPACTS

Section 8002(n) of RCRA requires that EPA's study of coal combustion wastes examine "alternatives to current disposal methods," "the costs of such alternatives," "the impact of those alternatives on the use of coal and other natural resources" and "the current and potential utilization of such materials." In response to these directives this chapter examines the potential costs to electric utilities if coal-fired combustion waste disposal practices are regulated differently than they are currently.

The first section of this chapter (Section 6.1) examines the costs incurred by electric utilities using current disposal methods for coal combustion wastes.[1] Section 6.2 follows with a discussion of the costs that could be incurred if coal combustion wastes were regulated differently than they are today. These costs include the costs of implementing alternative waste management practices and the costs of additional administrative responsibilities that would be incurred. Section 6.3 examines how new regulations might affect the cost of utilizing coal combustion wastes in various by-product applications. The last section of this chapter (Section 6.4) considers how energy use patterns in the electric utility industry might change if alternative waste management practices that significantly affect the cost of generating electricity with coal were imposed.

6.1 WASTE DISPOSAL COSTS ASSOCIATED WITH CURRENT DISPOSAL METHODS

The management of utility wastes comprises a series of activities -- from initial waste collection to disposal. These current waste management activities can be classified into five basic components:[2]

1. **Waste Handling and Processing.** This is the initial phase of the disposal process, involving collection of the various waste products after they have been generated and initial treatment of the wastes to prepare them for final disposal.

2. **Interim Waste Storage at the Plant.** Some waste products that are dry when produced, such as fly ash or flue gas desulfurization (FGD) wastes from dry scrubbers, often require interim storage prior to final disposal.

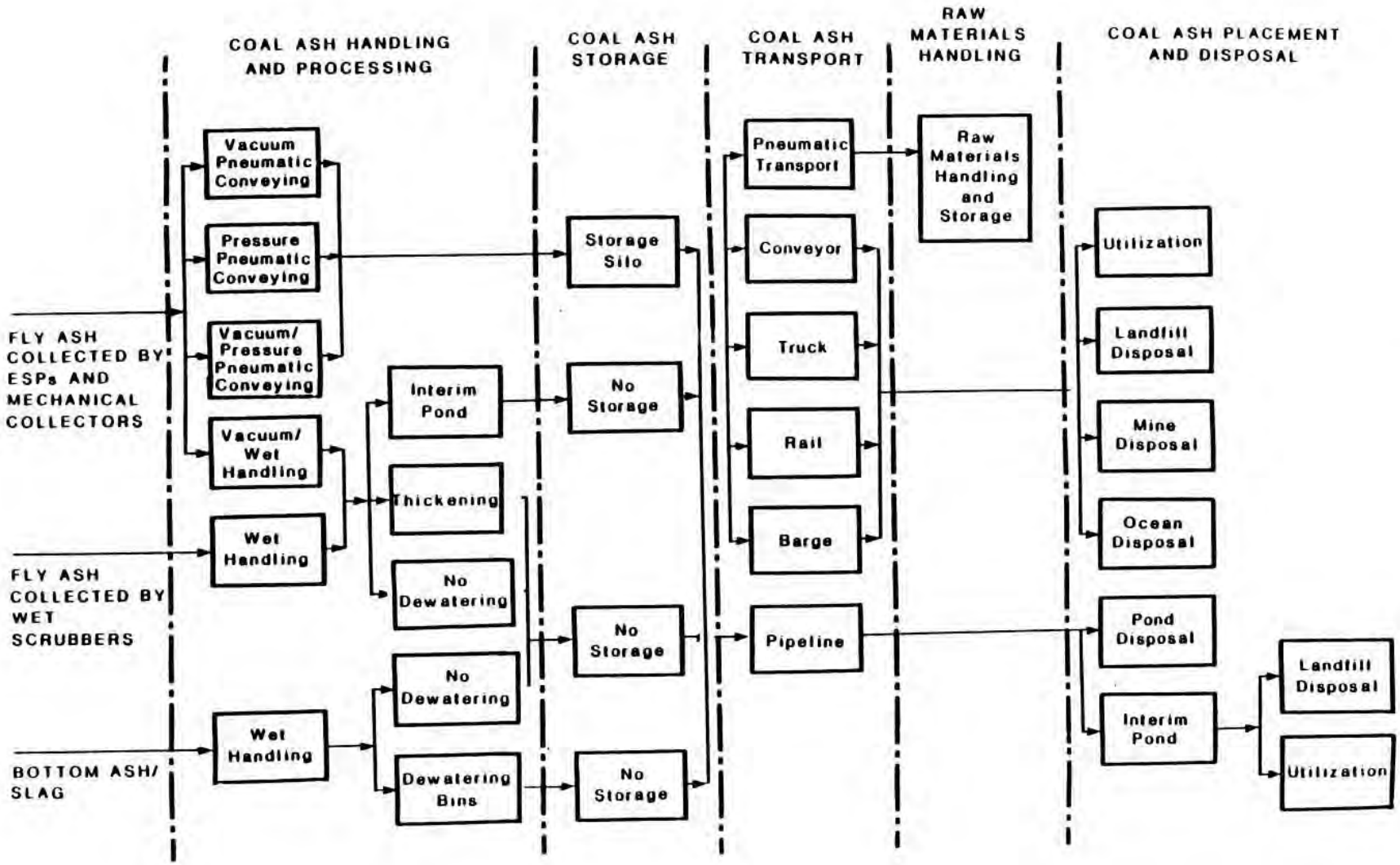
3. **Raw Materials Handling and Storage.** Some disposal processes involve stabilization or chemical fixation of the waste to prepare it for disposal. The raw materials used for this phase, including additives such as lime, Calcilox, and basic fly ash, often require special handling and storage facilities.

4. **Waste Transport to a Disposal Facility.** Environmentally sound disposal requires careful transportation of the waste to the disposal site. Many modes of transportation can be used, including trucks, railroads, barges, pipelines, and conveyor systems.

5. **Waste Placement and Disposal.** This is the final stage of the waste disposal chain. It involves placing the waste in a suitable waste management facility (usually a surface impoundment or landfill) and all activities required after the facility is closed. Alternatively, the final disposition of a waste product may entail utilization of the waste in various applications (such as cement production or sandblasting operations).

Exhibit 6-1 presents a schematic illustration of the current waste management and disposal options for coal ash; Exhibit 6-2 illustrates the options available for FGD wastes. The waste management costs discussed in this

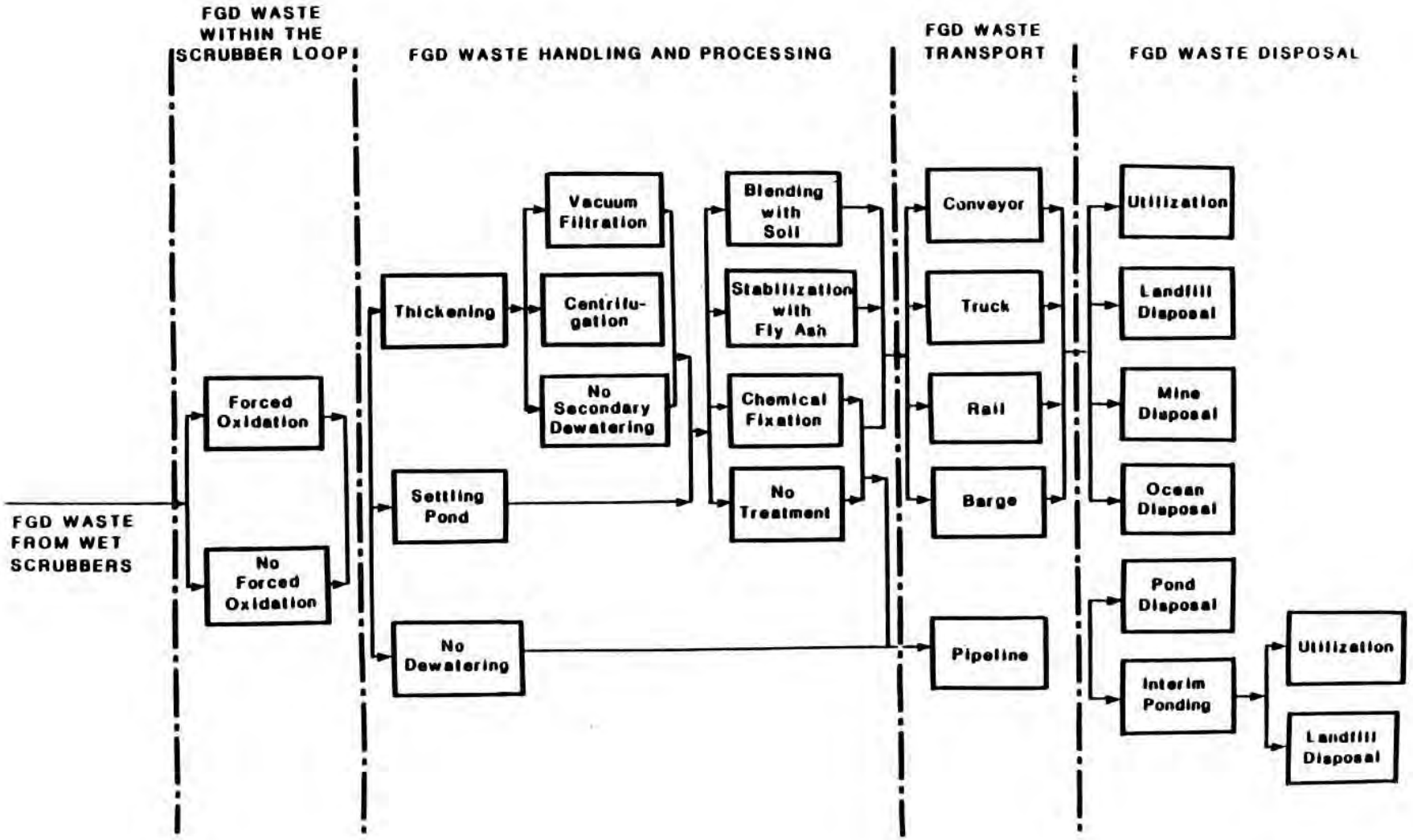
Exhibit 6-1
Overview of Waste Handling and Disposal Options for Coal Ash



Source: Arthur D. Little, Inc., *Full-Scale Field Evaluation of Waste Disposal From Coal-Fired Electric Generating Plants*, June 1985.

Exhibit 6-2

Overview of Waste Handling and Disposal Options for FGD Waste



Source: Arthur D. Little, Inc., *Full-Scale Field Evaluation of Waste Disposal From Coal-Fired Electric Generating Plants*, June 1985.

chapter are those associated with the last component of waste management (i.e., waste placement and disposal). These are the costs associated with actual construction of the waste management facility and placement of the wastes into the facility. If current practices for managing coal-fired wastes from electric utilities are altered, it is this final stage in waste management that would probably be most affected. However, as will be explored later in this chapter, some regulatory alternatives may affect other aspects of waste management.

6.1.1 Costs of Waste Placement and Disposal

The wastes from coal-fired combustion at electric utility power plants are often mixed together in the same waste management facility, typically a surface impoundment or landfill. Although surface impoundments were once the preferred method, and are still widely used, landfilling has become the more common practice because less land is required, and it is usually more environmentally sound (because of the lower water requirements, reduced leaching problems, etc.).

The costs of waste disposal can vary substantially. Exhibit 6-3 shows representative capital costs associated with constructing surface impoundments and landfills for coal-fired electric utility wastes. Exhibit 6-4 shows total costs (i.e., annualized capital costs plus operation and maintenance expenses).[3] Costs are shown for power plants that range in size from 100 to 3000 megawatts (Mw); power plants that fall outside of this range may incur

EXHIBIT 6-3

RANGES OF AVERAGE CAPITAL COSTS ASSOCIATED WITH COAL-FIRED ELECTRIC UTILITY WASTE DISPOSAL (4th quarter 1986 dollars per kilowatt)

Type of Waste	Size of Power Plant			
	100 MW	500 MW	1000 MW	3000 MW
Landfills				
Fly Ash	9-14	4-7	3-5	2-3
Bottom Ash	2- 5	2-3	1-2	1-1.3
FGD Waste	6-13	4-7	3-6	2-4
Surface Impoundments				
Fly Ash	27-50	15-27	13-23	10-18
Bottom Ash	10-20	6-11	5- 9	3- 6
FGD Waste	14-30	10-19	9-17	7-14

Source: Arthur D. Little, Inc., Full-Scale Field Evaluation of Waste Disposal From Coal-Fired Electric Generating Plants, EPA 600/7-85-028, June 1985.

EXHIBIT 6-4

RANGES OF AVERAGE TOTAL COSTS FOR COAL-FIRED ELECTRIC UTILITY WASTE DISPOSAL (4th quarter 1986 dollars per ton)*

Type of Waste	Size of Power Plant			
	100 MW	500 MW	1000 MW	3000 MW
Landfills				
Fly Ash	9-18	6-11	5-9	2-6
Bottom Ash	10-16	5-9	4-8	2-6
FGD Waste	4-10	4-7	3-6	2-4
Surface Impoundments				
Fly Ash	17-31	9-17	8-14	5-8
Bottom Ash	11-26	8-15	7-13	5-8
FGD Waste	8-17	7-13	6-10	5-7

* Dollar per ton estimates are based on the amount of waste produced each year. For purposes of this illustration, a power plant is assumed to generate annually 308 tons of fly ash per megawatt (MW), 77 tons of bottom ash per MW, and 264 tons of FGD waste per MW. Amounts will vary depending on coal quality, FGD technology, and boiler type, among other factors.

Source: Arthur D. Little, Inc., Full-Scale Field Evaluation of Waste Disposal From Coal-Fired Electric Generating Plants, EPA 600/7-85-028, June 1985.

different waste management costs. Both capital costs and total costs are shown for unlined facilities without ground-water monitoring or leachate control systems. The major factors affecting the cost of waste management are discussed below.

The amount of capital costs for a waste management facility can be attributed primarily to three factors: site preparation, excavation, and construction of containment structures.[4] Capital costs can be substantially reduced if the amount of earthwork can be minimized. Capital costs for surface impoundments, for example, increase significantly if dike construction or excavation is required. However, if existing site features can be used, such as valleys or abandoned pits, capital costs will be lower. Similarly, capital costs for landfills that require little excavation are lower than for those sites requiring extensive earthwork.

As Exhibit 6-3 illustrates, landfills are far less capital intensive than surface impoundments. For example, capital costs for fly ash placement in a surface impoundment at a 500 MW power plant would range from approximately $15 to $27 per kilowatt.[5] In contrast, capital costs for landfills range from about $4 to $7 per kilowatt. Landfills tend to cost less than impoundments primarily because the area required for a given amount of waste is less, and neither dikes nor piping and pumping systems are necessary.

Annual costs for landfills (see Exhibit 6-4) also tend to be less than those for surface impoundments primarily because landfills tend to be far less capital intensive. For example, costs for fly ash management at a 500 MW power plant range from about $9 to $17 per ton when the wastes are placed in surface

impoundments, while the comparable range at a landfill is about $6 to $11 per ton. Similarly, the cost for bottom ash disposal at an impoundment for a 500 MW power plant ranges from $8 to $15 per ton, while the costs to dispose in a landfill range from about $5 to $9 per ton.

Other factors that affect the cost of utility waste disposal include

- **Size of the Power Plant.** Because larger power plants consume more coal than smaller facilities, they generate more waste material. However, more efficient operating procedures allow a larger disposal site to realize economies of scale not available at smaller sites; thus, the cost per ton of waste disposed is typically less.
- **Rate of Operation.** The number of hours that a coal-fired power plant operates varies from plant to plant, ranging from fewer than 3,500 hours per year to more than 6,500 hours. As operating levels increase, the amount of waste generated will increase as more coal is burned to meet the higher generation load.
- **Type of Coal.** The quantity of ash produced is proportional to the ash content of the coal, which ranges from 5 to 20 percent on average. Also, the grade of coal and boiler design will affect the relative proportions of fly ash and bottom ash (see Chapter Three for a discussion of the impact of boiler design on types and amount of wastes generated).
- **FGD Equipment.** Because of the additional materials used in flue gas desulfurization, a power plant that uses this process to remove sulfur dioxide generates substantially more waste than does a power plant with no sulfur dioxide controls. The amount of waste generated also varies from one FGD operation to the next, primarily because of differences in sulfur content among the various coals and, to a lesser extent, because of the type of FGD process employed.

For the few power plants currently disposing their waste in mines or quarries, this disposal method has been economic because of convenient access to the disposal site. Since much of the excavation normally required at a disposal

site has already been performed as a result of the mining or quarrying operation, waste disposal costs can be quite competitive with costs associated with more traditional methods of disposal. The cost of disposing in mines or quarries for power plants that do not have easy access to the mine or quarry could quickly become prohibitive due to the costs of arranging for disposal at a remote site and of transporting the waste. Costs are also affected by whether or not the mine or quarry is still operating, whether the mining was surface or underground, and the amount of additional preparation required to dispose of the wastes, among other factors.

The costs of ocean disposal are not well known because there has been limited experience with this disposal method. Ocean disposal has been considered for unconsolidated waste (i.e., waste material that has not been physically or chemically altered prior to disposal)[6] and for more stabilized forms of waste, such as blocks for artificial reef construction;[7] however, this method has been attempted only for projects such as artificial reef construction, and then only on a trial basis. The most critical factors that would affect the magnitude of costs for ocean disposal are the availability of ash-handling facilities to load ocean-going vessels, the ability to gain easy access to the necessary waterways, and the physical characteristics of the wastes intended for disposal.

Because neither ocean disposal nor mine or quarry disposal is likely to be used on a widespread basis, they have been discussed here only briefly; see Chapter Four for a more detailed discussion of these two disposal options.

6.1.2 Costs Associated with Lined Disposal Facilities

The waste management costs presented above for surface impoundments and landfills do not include the cost of natural or synthetic liners to control the flow of leachate from the disposal area. Traditionally, most waste management sites, both surface impoundments and landfills, have not been lined to retard leaching, although this practice has become more widespread in recent years (see Chapter Four for a detailed discussion of liners). Currently, about 25 percent of all coal combustion waste management sites employ some type of liner system. Most liners are made of clay, synthetic materials, or stabilized utility waste.

Clay is used as a liner material because it is not very permeable, although its permeability will vary depending on the nature of the clay and the degree of compaction. Because clay is expensive to transport, the costs of the various clays used for liner material are directly related to the local availability of the clay. The installed cost of clay liners can range from $4.45 to $15.75 per cubic yard.[8] For a liner 36-inches thick, (liner thicknesses do vary), this results in a cost range of $21,000 to $75,000 per acre, or about $0.70 to $2.55 per ton of waste disposed in a landfill and $2.25 to $8.20 per ton for waste placed in an impoundment for a 500 MW power plant.[9]

Synthetic liner materials come in two basic varieties--exposable and unexposable. The membranes of exposable liners are resistant to degradation from exposure to the elements even if the liner is left uncovered. The membranes of unexposable liners will not function properly if the liner is exposed. Costs for installing exposable liners range from $43,000 to $113,000 per acre, or $1.45 to $3.85 per ton of waste disposed in landfills and from

$4.70 to $12.35 per ton of waste placed in surface impoundments.[10] Costs to install unexposable liners range from $59,000 to $123,000 per acre, or $2.00 to $4.15 per ton of waste disposed in landfills and $6.45 to $13.45 per ton placed in impoundments.[11] The ranges of costs are due primarily to differences in the cost of the material, differences in liner thickness, and allowances for various site-specific costs.

Stabilized utility waste, made from combinations of various ash wastes (such as fly ash or bottom ash), FGD waste, and lime, may be used as liner material when the required materials are available at the plant site. At an installed cost of about $13.70 per cubic yard, liners ranging from 3 feet to 5 feet in thickness can be constructed for $66,000 to $110,000 per acre,[12] which corresponds to total capital costs of $3.0-$5.0 million at a landfill, or about $2.25 to $3.75 per ton of disposed waste from a 500 Mw power plant. Total capital costs at impoundments would be $9.6-$16.0 million, or $7.20-$12.00 per ton of waste managed.[13]

6.2 COSTS OF ALTERNATIVE DISPOSAL OPTIONS

As described above, coal-fired utility wastes are currently exempt from RCRA Subtitle C waste management requirements. In the interim, coal combustion wastes are regulated under state statutes and regulations (see Chapter Four). If these wastes are subject to Subtitle C regulation, the incremental costs will depend on the regulatory option(s) ultimately selected. Section 6.2.1 outlines the major regulatory alternatives and discusses the flexibility allowed EPA under RCRA to promulgate regulations that account for the special nature of coal combustion wastes. Section 6.2.2 presents cost estimates for individual

Subtitle C disposal requirements, and Section 6.2.3 presents cost estimates for three regulatory scenarios if coal combustion wastes are regulated under Subtitle C.

6.2.1 Regulatory Alternatives under Subtitle C

As described in Chapter Five, there are two ways in which coal combustion wastes could be identified as hazardous and thus subject to requirements outlined in Part 264 of RCRA: the characteristic procedure and the listing procedure.

- **Regulation As Characteristic Waste.** Unless otherwise exempted, solid wastes are hazardous under RCRA if they display any of four characteristics: ignitibility, corrosivity, reactivity, or EP toxicity. Coal combustion wastes are unlikely to be ignitable or reactive, but could be corrosive (for aqueous wastes) or EP toxic. Subtitle C regulations would apply only to those waste streams that exhibited any of the hazardous characteristics. As discussed in Chapter Five, it is likely that only a small percentage of all waste generated would be hazardous. However, since some low volume wastes may be corrosive, this could have an impact on utilities that currently co-dispose high- and low-volume wastes. In these cases, the utility could either stop co-disposing or the landfill would have to conform to Subtitle C standards. In the case of surface impoundments, it might still be possible to co-dispose high- and low-volume wastes if the disposal impoundment met the requirements for a neutralization surface impoundment as set forth in 47 FR 1254, January 11, 1982.

- **Regulation as Listed Waste.** In addition to regulation under Subtitle C as characteristic waste, the Administrator may list a waste as hazardous under RCRA if it meets any of the three criteria contained in 40 CFR 261.11: (1) the waste exhibits any of the four characteristics described above; (2) it has been found to be fatal to humans in low doses or is otherwise measured as acutely hazardous; or (3) it contains any of the toxic constituents listed in Appendix VIII of Part 261. The Administrator does not have to list a

waste that contains any of the toxic constituents listed in Appendix VIII if the Agency concludes that "the waste is not capable of posing a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported or disposed of, or otherwise managed". The Administrator could decide to list as hazardous all coal combustion waste streams or only selected ones.

If Subtitle C regulation is warranted for coal combustion wastes, all the requirements for hazardous waste treatment, storage, disposal, and recycling facilities in 40 CFR 264 could be applied to the wastes from coal-fired power plants. Since coal combustion waste is mainly managed in surface impoundments and landfills, the requirements of Subparts A-H, K, and N would apply. In general, the required activities include the following:

- **General Facility Standards.** Facilities must apply for an identification number, prepare required notices when necessary, perform general waste analysis, secure the disposal facility to prevent unauthorized entry, comply with general inspection requirements, provide personnel training, and observe location standards (these include a provision that facilities located in a 100-year flood plain must be designed, constructed, operated, and maintained to prevent washout of any hazardous waste by a 100-year flood). (40 CFR 264 Subpart B)

- **Preparedness and Prevention.** Hazardous waste facility operators must design and operate facilities to minimize the possibility of fire or explosion, equip the facility with emergency equipment, test and maintain the equipment, and provide EPA and other government officials access to communications or alarm systems. (40 CFR 264 Subpart C)

- **Contingency Plan and Emergency Procedures.** The facility operators must have a contingency plan to minimize hazards to human health or the environment in the event of fire or explosion. (40 CFR 264 Subpart D)

- **Manifest System, Recordkeeping, and Reporting.** Hazardous waste facility operators must maintain a manifest system, keep a written operating record, and prepare a biennial report. (40 CFR 264 Subpart E)

- **Ground-water Protection.** Unless a waste management facility meets certain standards,[14] a Subtitle C facility is required to comply with requirements to detect, characterize, and respond to releases from solid waste management units at the facility. These requirements include ground-water monitoring and corrective action as necessary to protect human health and the environment. (40 CFR 264 Subpart F)

- **Closure and Post-closure.** Subtitle C facilities must comply with closure and post-closure performance standards to minimize the risk of hazardous constituents escaping into the environment. (40 CFR 264 Subpart G)

- **Financial Requirements.** Subtitle C facilities must establish a financial assurance plan for closure of the facility and for post-closure care. Possible methods of financial assurance include a closure trust fund, surety bonds, closure letter of credit, closure insurance, or financial test and corporate guarantee.[15] (40 CFR 264 Subpart H)

- **Design and Operating Requirements.** Unless granted an exemption, new surface impoundments or landfills or new units at existing impoundments or landfills must install two or more liners and a leachate collection system between the liners. (40 CFR 264 Subparts K and H)

In recognition of the special nature of coal combustion wastes, Congress afforded EPA some flexibility in designing regulations for coal combustion wastes if they are subject to regulation under Subtitle C. This flexibility allows EPA to exempt electric utilities from some regulations imposed on owners and operators of hazardous waste treatment, storage, and disposal facilities by the Hazardous and Solid Waste Amendments of 1984. Specifically, section 3004(x) of RCRA allows the Administrator to modify the following requirements when promulgating regulations for utility waste.

- Section 3004 (c) prohibits the placement of uncontained liquids in landfills;
- Section 3004 (d) prohibits the land disposal of specified wastes;[16]
- Section 3004 (e) prohibits the land disposal of solvents and dioxins;
- Section 3004 (f) mandates a determination regarding disposal of specified wastes into deep injection wells;
- Section 3004 (g) mandates determinations on continued land disposal of all listed hazardous wastes;
- Section 3004 (o) lists minimum technical requirements for design and operation of landfills and surface impoundments, which specify the installation of two or more liners, a leachate collection system, and ground-water monitoring;
- Section 3004 (u) requires the Administrator to promulgate standards for facilities that burn hazardous waste as fuel; and
- Section 3005 (j) provides that interim-status surface impoundments must also meet minimum technical requirements specified in section 3004 (o).

In addition to the flexibility afforded by 3004 (x), it is possible for EPA to modify any of the standards applicable to waste treatment and disposal facilities if lesser standards are protective of human health and the environment. Section 3004 (a) states "... The Administrator shall promulgate regulations establishing such performance standards, applicable to owners and operators of facilities for the treatment, storage, or disposal of hazardous waste identified or listed under this subtitle, as may be necessary to protect human health and the environment."

There remains substantial uncertainty, however, about the extent to which, in practice, the statutory language of Subtitle C would provide sufficient flexibility to design a waste management program appropriate for high-volume,

low-toxicity coal combustion wastes. EPA may also consider waste management requirements, as needed, under the current Subtitle D provisions for solid wastes, or may seek appropriate additional authorities.

6.2.2 Cost Estimates for Individual RCRA Subtitle C Disposal Standards

If EPA determines that Subtitle C regulation is warranted for coal combustion wastes, there is a wide range of regulatory options that could be undertaken. Required activities could consist of some, all, or variations of the requirements listed in 40 CFR Subparts B-H (and described briefly in Section 6.2.1). This section presents estimates for the costs that would be associated with compliance with individual Subtitle C requirements.

6.2.2.1 General Facility Standards; Preparedness and Prevention; Contingency Plan and Emergency Procedures; and Manifest System

Subparts B through E in Part 264 of the RCRA regulations list general requirements for such activities as preparing written notices and plans for submission to EPA; conducting waste analyses; providing security at the disposal site; and recordkeeping and reporting. Many of these activities would be undertaken during the permitting process, which is set forth in Part 270 of RCRA.

The Part B application must contain the technical information listed in Part 264 B through E. The cost to the electric utility industry to prepare a Part B permit application was estimated in a study done for the Utility Solid Waste Activities Group (USWAG), which calculated that the total cost of submitting

Part B permit analyses would be $721,000 per plant, or about $0.55 per ton of waste disposed.[17] The industry cost, if all power plants filed Part B applications, would be about $370 million, or about $54 million in annualized costs.

Location standards are also specified under Subpart B of Part 264 of RCRA. One such standard is for facilities located in a 100-year flood plain. Part 246.16(b) requires protective measures to prevent washout from flooding.

USWAG estimated the costs for protecting waste disposal facilities located within a 100-year flood plain to be about $740 per acre for surface impoundments and about $1,100 per acre for landfills on an annualized basis.[18] This corresponds to waste management costs of approximately $0.55 per ton of waste at surface impoundments and $0.25 per ton at landfills.[19] Industry-wide costs for flood protection at all impoundments are estimated to be about $92 million for capital expenditures (about $13 million in annualized costs); costs for flood protection at all landfills would be about $146 million for capital expenditures (about $20 million in annualized costs).[20]

6.2.2.2 Ground-water Protection

Subpart F of 40 CFR Part 264 lists requirements for ground-water monitoring systems. The costs of installing and maintaining an acceptable ground-water monitoring program are dependent on the number of monitoring wells required and the frequency of testing. The study conducted by Arthur D. Little for EPA estimated that capital costs for installing six monitoring wells at a facility would range from $18,000 to $25,000.[21] At a sampling frequency of four times

per year, annual operating and maintenance costs would be $10,000 to $14,500. Total ground-water monitoring costs would range from $0.06 to $0.10 per ton of managed waste. In another study conducted for USWAG by Envirosphere, which used different well configurations and cost parameters, somewhat higher costs ($0.10-$0.12 per ton of waste managed) were estimated.[22]

It is not known how many coal-fired power plants currently have adequate ground-water monitoring systems in place. To estimate industry-wide costs, EPA has conservatively assumed that all power plants would be required to install new ground-water monitoring systems. Using the costs developed in the Arthur D. Little study, EPA calculated that total capital costs would be about $9.3 to $12.8 million. Total annualized costs would range from $6.5 to $9.3 million.

6.2.2.3 Corrective Action

Subpart F of 40 CFR Part 264 also lists requirements for corrective action. A variety of actions may be undertaken to correct ground-water contamination problems caused by a hazardous waste disposal facility. The facility owner or operator would need to conduct a site-specific investigation to ascertain the potential degree of contamination and the appropriate response that would be most effective in remedying the situation. Types of remedial responses that might be required would be placing a cap (made of either a clay or synthetic material) on the disposal unit, counter-pumping the ground water to retard contaminant migration, excavating the disposal area and removing the wastes to a Subtitle C landfill, or installing an impermeable curtain around the disposal area to prevent ground-water flow into or out of the disposal area. As one example of the potential magnitude of corrective action costs, this section

evaluates the cost to excavate the existing disposal areas and transfer the wastes to RCRA Subtitle C-approved facilities.

EPA developed the following formula to calculate total excavation costs for Subtitle C units, (including closure of the existing site and removal of the wastes to a Subtitle C facility):

$$\text{Cost} = [(\text{Surface Area} \times \$45) + (\text{Volume} \times \$187)] \times 2.16$$

where the surface area is measured in square meters, and volume is measured in cubic meters.[23]

For a power plant of average size (500 MW), it has been assumed that a 45-acre landfill would be required, or about 182,000 square meters, with a capacity of approximately 5 million cubic meters. Based on the cost equation listed above, costs for excavation and waste transfer for a landfill site would be about $2.0 billion.[24] For surface impoundments, the appropriate parameters are 145 acres, or about 587,000 square meters, and a volume of about 5 million cubic meters, which works out to about $2.1 billion for the same type of corrective action. If this type of corrective action were required at all power plants, compliance costs for the industry would be enormous. At a cost of about $2 billion per plant, industry-wide costs would exceed one trillion dollars.

6.2.2.4 Closure and Post-closure

Subpart G of 40 CFR 264 specifies general closure and post-closure requirements for Subtitle C facilities and 40 CFR 264(K) and (N) list specific

requirements for closure and post-closure care of surface impoundments and landfills, respectively. These requirements, as applied to coal combustion wastes, would require the dewatering of ash ponds, installation of a suitable cover liner made of synthetic materials, application of topsoil to support vegetation, seeding and fertilizing, installation of security fencing, and long-term ground-water monitoring. USWAG estimates that capital costs for closing a waste management facility range from $39,000 to $128,000 per acre for surface impoundments and from $55,000 to $137,000 per acre for landfills.[25] Once the facility is closed, additional costs would be incurred for post-closure care -- about $1,050 per acre annually.[26] Total annual costs for closure of a surface impoundment would range from about $1.0 to $2.8 million for a typical 500 Mw power plant, or $5.00 to $14.75 per ton of waste managed. For a landfill, total annual costs would range from $0.4 to $0.9 million, or $2.10 to $4.90 per ton.[27].

An owner or operator that chooses to close a facility in the event that coal combustion wastes are brought under Subtitle C regulation would not necessarily have to follow the closure and post-closure requirements for hazardous waste facilities listed in 40 CFR Part 264. If regulations are proposed, there would be some period of time before final regulations take effect.[28] If the disposal facility is closed during this interim period, the closure standards that would apply would be those required under state regulations, not Subtitle C regulations.

A facility that closes after the new regulations take effect, however, is subject to Subtitle C closure and post-closure requirements. The USWAG study provides an estimate of the total costs of closing all existing coal combustion

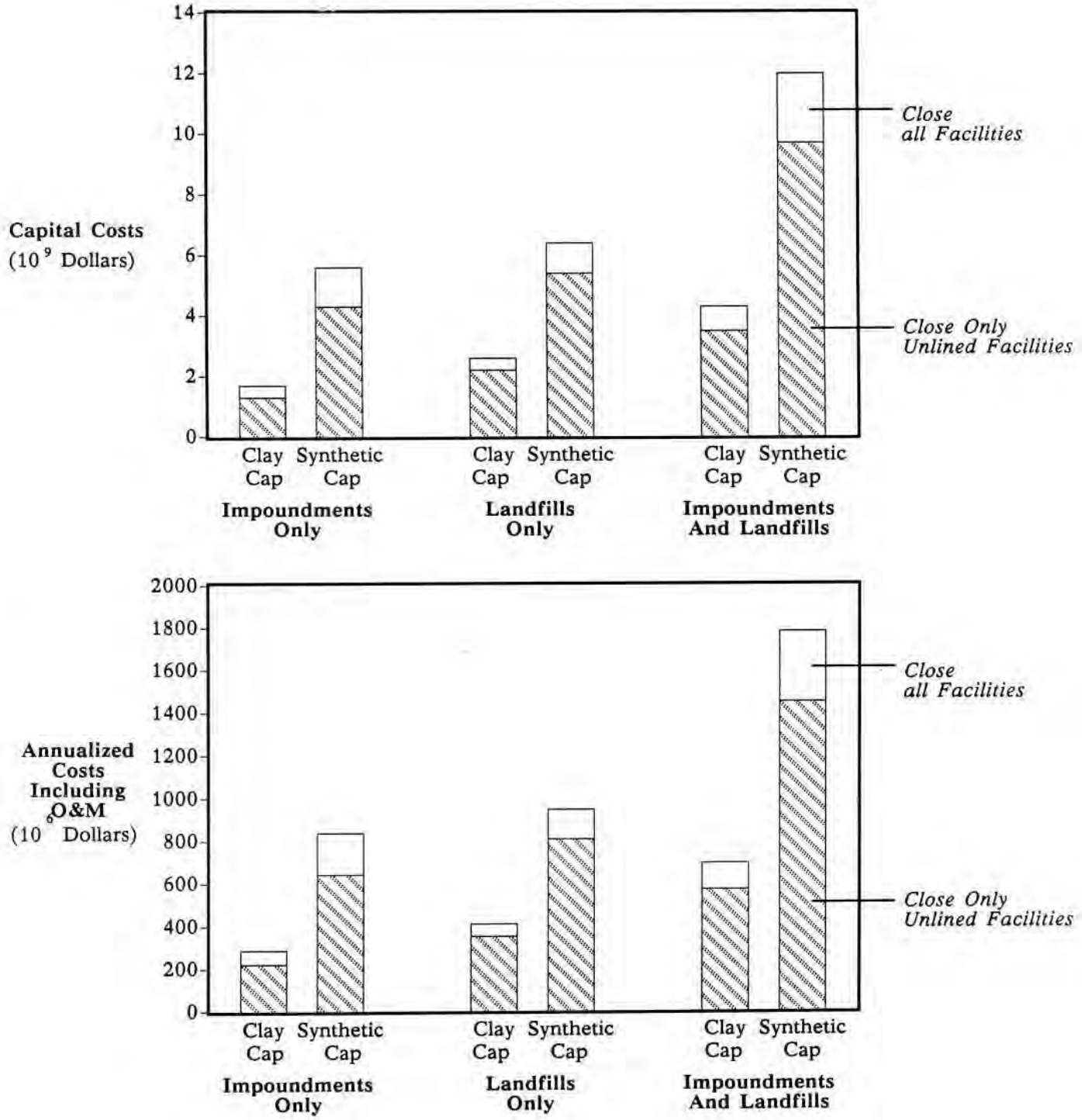
waste disposal facilities and of the costs of closing only unlined facilities (See Exhibit 6-5). Total capital costs required to close all unlined landfills and impoundments would range from $3.5 billion for clay-capped facilities to $9.7 billion for synthetic-capped facilities. If all facilities closed under Subtitle C regulation, total capital costs would be about $4.3 billion for clay-capped closure and $12.0 billion for synthetic-capped closure.[29] Total annualized costs to close only unlined facilities would range from about $575 million for closure with clay caps to about $1.5 billion for synthetic caps. If all current waste management facilities were closed, annualized costs would be about $700 million for clay caps to $1.8 billion for synthetic caps.

6.2.2.5 Financial Responsibility

Subpart H of 40 CFR 264 sets forth requirements for financial responsibility for closure and post-closure care of hazardous waste facilities. A facility owner may use several different financial mechanisms to demonstrate financial responsibility, including purchasing a letter of credit, posting a surety bond, establishing a trust fund, purchasing an insurance policy, providing a corporate guarantee, or passing a financial test. Financial responsibility could be required for closure/post-closure costs or corrective action costs. The magnitude of the costs can vary considerably depending on the financial mechanism that is used and the type of activity for which financial assurance is required. For example, costs to provide a corporate guarantee or pass a financial test may be on the order of a few hundred dollars per facility; on the other hand, annual costs to obtain a letter of credit or to establish a trust fund are often based on some percentage (e.g., one to two percent) of the total

EXHIBIT 6-5

SUMMARY OF COSTS TO CLOSE EXISTING WASTE DISPOSAL FACILITIES



Source: Envirosphere Company, "Report on the Costs of Utility Ash and FGD Waste Disposal," in USWAG, *Report on the Costs of Utility Ash and FGD Waste Disposal*, Appendix F Part 2, October 19, 1982.

costs of the closure/post-closure or corrective action activity to be undertaken.[30]

6.2.2.6 Design and Operating Requirements for Landfills and Surface Impoundments

The level of effort required to come into compliance with Subtitle C design and operating requirements will depend on many site-specific considerations. In some cases, it may be possible to seal off the portion of the existing disposal site that has been in use and upgrade the remaining portion by installing a liner. In other situations the required changes may be sufficiently different from existing disposal practices that the most cost-effective action may be to open an entirely new disposal facility.

Given the variety of site-specific situations that may arise, and given the regulatory flexibility EPA has in designing coal combustion waste management standards, it is not feasible to estimate how many utility waste management facilities may be affected or what type of waste management measures may be required without conducting site-specific investigations. Nevertheless, to indicate the approximate magnitude of costs that may be involved for different waste management practices, the costs for three management options -- single-lined landfills, single-lined surface impoundments, and double-lined surface impoundments -- are presented below.

Landfills

As noted earlier, single clay liners can be installed in a landfill for

about $0.70 to $2.55 per ton of disposed waste and single synthetic liners for about $1.45 to $4.15 per ton of disposed waste. The costs presented in Exhibit 6-4 indicate that waste disposal costs at a representative 500 Mw power plant with no flue gas desulfurization equipment would average about $5 to $11 per ton of disposed waste for a landfill operation. Adding a single clay liner to the landfill would increase total costs to $5.70 to $13.55 per ton of disposed waste; adding a single synthetic liner would increase costs to $6.45 to $15.15 per ton of disposed waste.

These estimates appear to be similar in magnitude, although somewhat lower than costs estimated in another study of utility waste disposal costs conducted for the Utility Solid Waste Activities Group (USWAG) by Econometric Research, Inc. That study estimated that total costs for complying with requirements related to the construction, operation, and maintenance of a single-lined landfill would range from about $15 to $24 per ton of waste, depending on the type of liner.[31]

The study for USWAG also analyzed the total costs to the electric utility industry if all power plants currently using landfills were required to construct new landfills with single liners. For this scenario, USWAG assumed that existing facilities, even if lined, would have to be replaced to comply with new requirements. Total capital costs for this alternative would range from $2.6 billion for landfills with one synthetic liner to $4.0 billion for landfills with a single clay liner.[32] Estimated annualized costs were about $400 million for installing a single synthetic liner at all landfills and about $600 million for installing a single clay liner.[33]

Surface Impoundments

The costs presented in Exhibit 6-4 for unlined surface impoundments indicated that waste managed at a representative 500 Mw power plant with no FGD waste production would cost about $8 to $17 per ton of waste. Using the cost estimates for liners noted earlier (see Section 6.1.2), adding a single clay liner would increase total management costs to about $10.25-$25.20 per ton of waste, and adding a synthetic liner would increase costs to $12.70-$30.45 per ton of waste.

These cost estimates for single-lined impoundments appear to be reasonably consistent with other estimates. Studies for USWAG indicated that management costs for impoundments with a single synthetic liner were about $19 per ton of waste and $30 per ton of waste for impoundments with a single clay liner.[34]

The USWAG report also estimated the total costs to the electric utility industry to construct new impoundments with single liners (i.e., all power plants currently using surface impoundments would be required to construct new facilities to meet disposal requirements even if the current impoundment is already lined). For this alternative total capital costs would range from $5.8 billion for impoundments with single synthetic liners to $9.5 billion for impoundments with single clay liners.[35] Annualized costs would range from $850 million for single synthetic liners at all impoundments to $1.4 billion for single clay liners.[36]

The study for USWAG also estimated management costs for surface impoundments with two different types of double liners -- a double synthetic liner (each with

a 30 mil thickness) and a double liner system consisting of one synthetic liner (30 mil) and a clay liner (36 inches). Total management costs for double-lined surface impoundments would range from about $29 per ton of waste for a site with two synthetic liners to $36 per ton of waste for a site with one synthetic liner and one clay liner.[37]

Industry-wide costs were also estimated for the installation of new double-lined surface impoundments at all power plants currently using surface impoundments. Total capital costs for installing a double-lined impoundment ranged from $9.3 billion for a double synthetic liner to $11.6 billion for one clay and one synthetic liner.[38] Total annualized costs were estimated at $1.4 billion for all impoundments with a double synthetic liner and $1.7 billion for all impoundments with one clay liner and one synthetic liner. A summary of the costs for the various types of lined disposal facilities discussed herein is presented in Exhibit 6-6.

6.2.2.7 Summary of Costs for Various Waste Management Alternatives

Exhibit 6-7 summarizes the costs to the electric utility industry of each of the waste management options previously discussed. The exhibit presents cost estimates for the total amount of capital required for each waste management standard and for the total amount of annualized costs (i.e., annual capital, operation, and maintenance costs) that would be incurred in order to comply with each requirement if coal-fired combustion wastes were regulated as hazardous wastes.

EXHIBIT 6-6

SUMMARY OF COSTS FOR DIFFERENT TYPES OF LINED WASTE MANAGEMENT FACILITIES

	Cost per ton	Total Annual Costs for the industry a/ (millions of dollars)
Landfills		
Basic Practice--Unlined	$ 5.00-$11.00	N.A.
Single Clay Liner	$ 5.70-$13.55	600
Single Synthetic Liner	$ 6.45-$15.15	400
Surface Impoundments		
Basic Practice--Unlined	$ 8.00-$17.00	N.A.
Single Clay Liner	$10.25-$25.20	1,380
Single Synthetic Liner	$12.70-$30.45	865
Double Synthetic Liners	$29.00	1,360
Double Liners: 1 Synthetic and 1 Clay	$36.00	1,680

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a/ Total annual costs refer to annualized costs that capture capital, operation, and maintenance expenses. Since these costs were calculated by assuming that the utility industry would have to construct new facilities to comply with hypothetical alternative regulations, these costs are in addition to the current management costs incurred by the industry.

Source: Envirosphere Company, "Report on the Costs of Utility Ash and FGD Waste Disposal." In USWAG, Report and Technical Studies on the Disposal and Utilization of Fossil-Fuel Combustion By-Products, October 19, 1982.

EXHIBIT 6-7

COSTS TO THE ELECTRIC UTILITY INDUSTRY FOR HYPOTHETICAL RCRA COMPLIANCE STRATEGIES

	Total Capital Costs (billions of dollars)	Total Annual Costs (millions of dollars)
Preparation of Part B Permit	0.37 a/	54
Construction of New Disposal Facilities		
Landfills		
- Single clay liner	4.0	600
- Single synthetic liner	2.6	400
Surface Impoundments		
- Single clay liner	9.5	1400
- Single synthetic liner	5.8	850
- Double liner		
- clay/synthetic	11.6	1700
- two synthetic	9.3	1400
Closure of Existing Disposal Facilities		
Only Unlined Facilities Close		
- Clay cap	3.5	575
- Synthetic cap	9.7	1500
All Facilities Close		
- Clay cap	4.3	700
- Synthetic cap	12.0	1800
Installation of Leachate Collection Systems	1.2	460
Provisions for Flood Protection		
Landfills	0.15	20
Impoundments	0.09	13
Ground-water Monitoring Systems	0.009-0.013	6-9
Excavate Existing Facilities, Removing Waste to Subtitle C Facilities	1028.0 a/	NA

a/ Costs shown are for capital, operation, and maintenance costs for the entire industry since the amount of capital required was not readily available.

A combination of compliance alternatives could occur (e.g., closing existing disposal facilities and constructing new facilities with leachate collection and ground-water monitoring systems). The actual cost to the electric utility industry for complying with RCRA Subtitle C requirements would depend on the regulatory actions taken by the Agency if the temporary exemption under Section 3001 of RCRA is removed. Three possible regulatory scenarios are discussed in the following section.

6.2.3 Potential Costs to the Industry of RCRA Subtitle C Waste Management

Section 6.2.2 presented cost estimates for individual regulatory requirements that could be imposed on utilities if EPA determines that Subtitle C regulation is warranted for coal combustion wastes. In this section, three possible regulatory scenarios are examined to quantify the range of incremental costs that could result from various regulatory options. In the first scenario, the incremental costs of regulating a portion of low volume wastes under Subtitle C are presented. The second scenario assumes that all coal combustion waste would be subject to Subtitle C requirements. The third scenario assumes that high volume coal combustion wastes would be tested for RCRA hazardous characteristics and that a small portion of the waste would be classified as Subtitle C characteristic waste. For all three regulatory scenarios, costs are shown only for bringing all existing power plants into compliance with the assumed RCRA Subtitle C management regulations.

Low Volume Waste Scenario

This scenario evaluates the costs to the utility industry if some low volume waste streams are classified as hazardous wastes under Subtitle C. As discussed in Chapter Three, some of these wastes can exhibit hazardous characteristics such as corrosivity. The information available to EPA at this time does not permit the Agency to quantify the amount of low volume wastes that may exhibit hazardous characteristics. In this scenario, EPA has assumed that all water-side boiler cleaning wastes are regulated as hazardous wastes since these waste streams may exhibit corrosive characteristics. These waste streams are assumed to be hazardous to provide an approximate estimate of the costs to the industry if some low volume wastes display RCRA hazardous characteristics. That is, both high-volume and low-volume wastes could be tested for RCRA hazardous characteristics, but only a small portion of the low-volume wastes (as represented by all water-side boiler cleaning wastes) would need to be treated as hazardous.

As shown in Exhibit 3-19, a representative power plant generates about 180,000 gallons per year of water-side boiler cleaning wastes. The cost to dispose of these wastes as hazardous liquids can vary depending on waste stream variability, regional differences in disposal costs, and quantity to be disposed, among other factors.[39] For purposes of this analysis, an incremental cost of $2 per gallon (including transportation) has been assumed based on a 1985 survey of hazardous waste management prices.[40] With 180,000 gallons generated per year at a representative power plant, annual disposal costs would be about $360,000 per power plant. Since there are 514 power plants in the U.S., annual disposal costs to the utility industry would be about $185 million.

Full Subtitle C Regulation Scenario

If EPA lists high volume coal combustion waste streams in 40 CFR 261.31-261.33, all utilities will be affected. Utilities would be required to manage all coal combustion wastes in Subtitle C permitted facilities. To estimate the incremental costs to the industry of this regulatory scenario, the Agency assumed that all utilities would close existing facilities and open new waste management facilities that complied with Subtitle C standards. This scenario assumes that the costs of managing wastes off-site will equal the costs of managing wastes on-site and that existing facilities would be closed in the six months before Subtitle C regulation took effect, thereby avoiding Subtitle C closure and post-closure requirements.

Under existing state regulations, a clay cap is assumed to be adequate to close existing waste management facilities. The total annual costs of closing all existing facilities with a clay cap would be $700 million. For the new facilities, EPA assumed utilities would prepare a Part B permit application, construct new landfills and surface impoundments with clay/synthetic double liners, install leachate collection systems, make provisions for flood protection, and install ground-water monitoring systems. To determine incremental costs for the industry, EPA assumed that the current proportions of waste management facilities that were landfills and surface impoundments would remain unchanged under Subtitle C regulation. As summarized in Exhibit 6-7, total annual costs of the new Subtitle C facilities would be $54 million for Part B permit applications, $725 million for new double lined landfills,[41] $1700 million for new double lined surface impoundments, $460 million for leachate

collection systems, $33 million for flood protection, and $9 million for ground-water monitoring. Total incremental costs for this regulatory scenario would be $3.7 billion annually.[42]

High Volume Characteristic Waste Scenario

If coal combustion wastes were not exempt from RCRA Subtitle C regulation, utilities would have to test high-volume and low-volume coal combustion wastes for RCRA hazardous characteristics. Based on the RCRA characteristic results in Chapter Five, it appears that only a small portion of coal combustion wastes possess the hazardous characteristics of EP Toxicity or corrosivity. For purposes of this scenario, the Agency assumed that five percent of the wastes generated by utilities would need to be disposed in Subtitle C permitted facilities. The Agency does not have sufficient information to know exactly the amount of coal combustion waste that would exhibit RCRA hazardous characteristics. EPA believes that coal combustion wastes generally would not fail the RCRA hazardous characteristic tests. Based on limited information presented in Chapter Five that indicate about five percent of all ground-water observations at utility sites exceed the Primary Drinking Water Standards, the Agency assumed that five percent of all wastes would require Subtitle C treatment. The total annual cost to the industry if utilities close existing facilities and construct new double lined facilities for five percent of all coal combustion wastes would be $185 million.

6.3 IMPACT OF REGULATORY ALTERNATIVES ON UTILIZATION OF COAL COMBUSTION WASTES

As discussed in Chapter Four, coal-fired utility wastes have been used in a

variety of applications by electric utilities and other industries to replace other types of material. The use of utility wastes as a replacement for other materials has reduced the amount of wastes utilities have had to dispose, while correspondingly reducing the resource requirements of other industries that have managed to find a productive use for the waste material.

In the event that some or all of these wastes were declared hazardous, it is possible that the amount of by-product utilization of coal-fired utility wastes would decline as a result of increased costs for their use and the potential for outright prohibition of their use in some applications. On the other hand, it is possible that certain forms of utilization (e.g., the use of fly ash in cement) may be deemed environmentally acceptable practices if the wastes would be unlikely to pose an environmental threat when used for such purposes. Since costs for other forms of disposal may increase, utilization may also increase. However, for discussion purposes, this section assumes that designation as a hazardous waste would tend to discourage by-product utilization.

The costs that would be incurred as a result of environmental concerns over the utilization of coal-fired utility wastes would depend on the regulatory requirements that would have to be followed to use the wastes. The more stringent the additional regulatory burden imposed, the greater the impact on by-product utilization due to the higher costs of using the wastes.

In the USWAG study referenced above, the potential range of costs associated with reduced use of coal combustion by-products was also evaluated. Three different regulatory scenarios were analyzed.[43]

- The transportation of coal-fired utility wastes is regulated as hazardous waste transportation under Subtitle C of RCRA; use or disposal of the wastes would not be regulated.
- All activities associated with reuse of coal combustion by-products is regulated, and the regulations affect both the transporter and owner/operator of a Subtitle C hazardous waste management facility.
- Reuse of coal combustion by-products is prohibited.

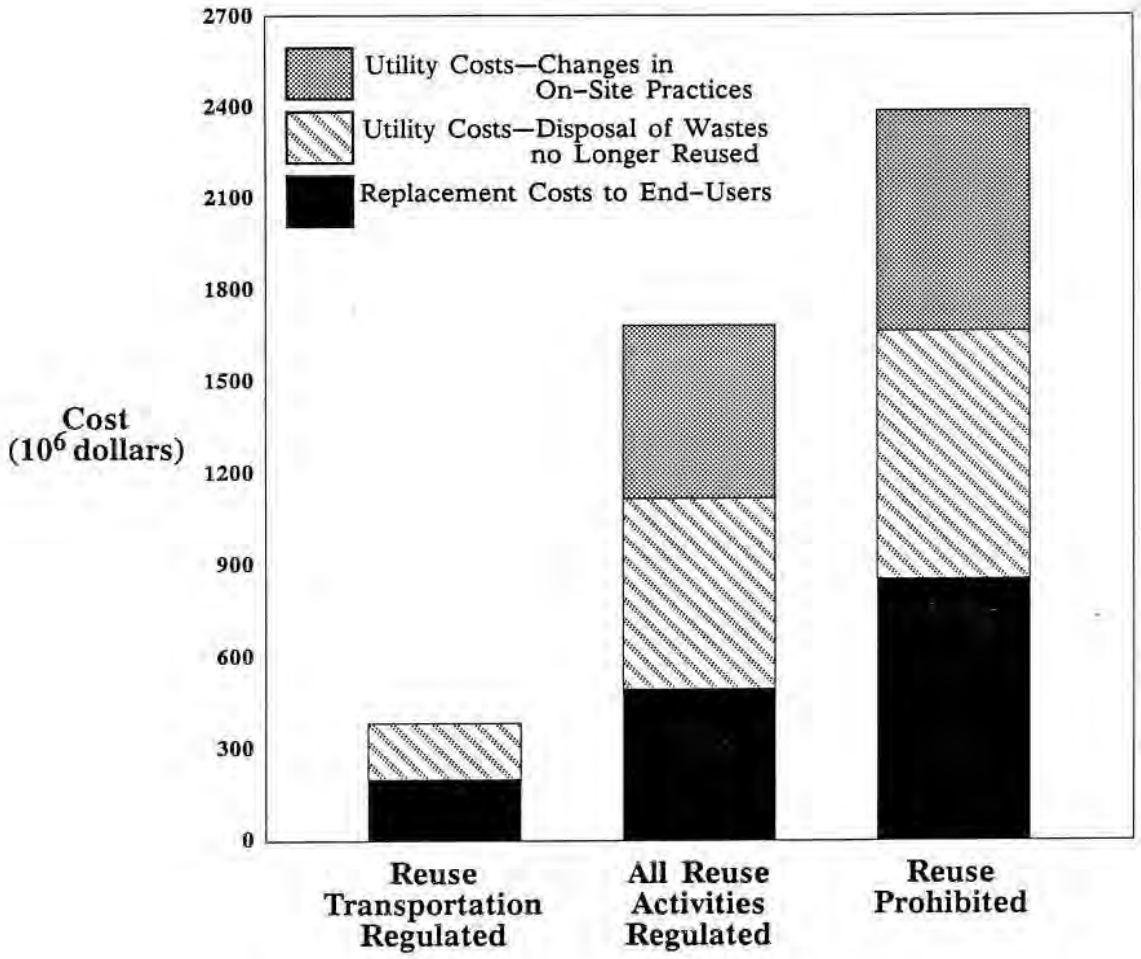
There would be three types of costs incurred under these regulatory scenarios: (1) replacement costs to the end-users who would no longer find it economic to utilize the coal combustion by-products, (2) costs to utilities to dispose of wastes no longer reused by other industries, and (3) additional costs to the utility industry for replacement and disposal of wastes that could no longer be used on-site. A summary of the costs associated with each scenario is provided in Exhibit 6-8.[44]

If the transportation of coal combustion by-products were subject to increased regulation under Subtitle C, the USWAG report estimated that the use of these by-products would decline by nearly 40 percent, increasing overall disposal volumes by about 8 percent.[45] The industries that would be affected the most would be the roofing granules industry (conventional roofing granules would replace bottom ash and boiler slag at a cost of about $115 million in annual costs) and the concrete industry (portland cement would replace fly ash at a cost of about $40 million in annual costs).[46]

If all activities pertaining to reuse of coal combustion wastes were subject to Subtitle C regulations, utilization of coal combustion

EXHIBIT 6-8

Summary of Economic Impacts on By-Product Utilization under Different RCRA Regulatory Scenarios*



*All costs are annualized based on impacts estimated from 1984-2000.

Source: *USWAG, Report and Technical Studies on the Disposal and Utilization of Fossil-Fuel Combustion By-Products, Appendix G, October 26, 1982*

by-products was estimated to decline by about 75 percent, increasing overall disposal volumes by about 14 percent.[47] The greatest impact would be on the concrete industry, which would spend about $270 million annually to replace fly ash with portland cement.[48]

If all reuse of coal combustion by-products were prohibited, industries using these by-products would have to find suitable replacements; total disposal volumes would increase by nearly 20 percent.[49] The largest impacts would be on the asphalt industry, which would be forced to replace ash with asphalt at a cost of approximately $250 million annually, and the concrete industry, which would replace fly ash with portland cement at a cost of about $270 million annually.[50]

6.4 ECONOMIC IMPACTS OF ALTERNATIVE WASTE DISPOSAL OPTIONS

Since many alternative disposal practices discussed in this chapter could impose additional costs on the electric utility industry, this section evaluates the effect that these increased costs might have on electricity generation costs and U.S. coal consumption. This study employs three measures to determine the potential economic impact of alternative disposal practices:

1. Average increase in electricity generation costs at existing coal-fired power plants,

2. Average increase in electricity generation costs at coal-fired power plants yet to be constructed, and

3. Impact on the electric utility industry's consumption of coal.

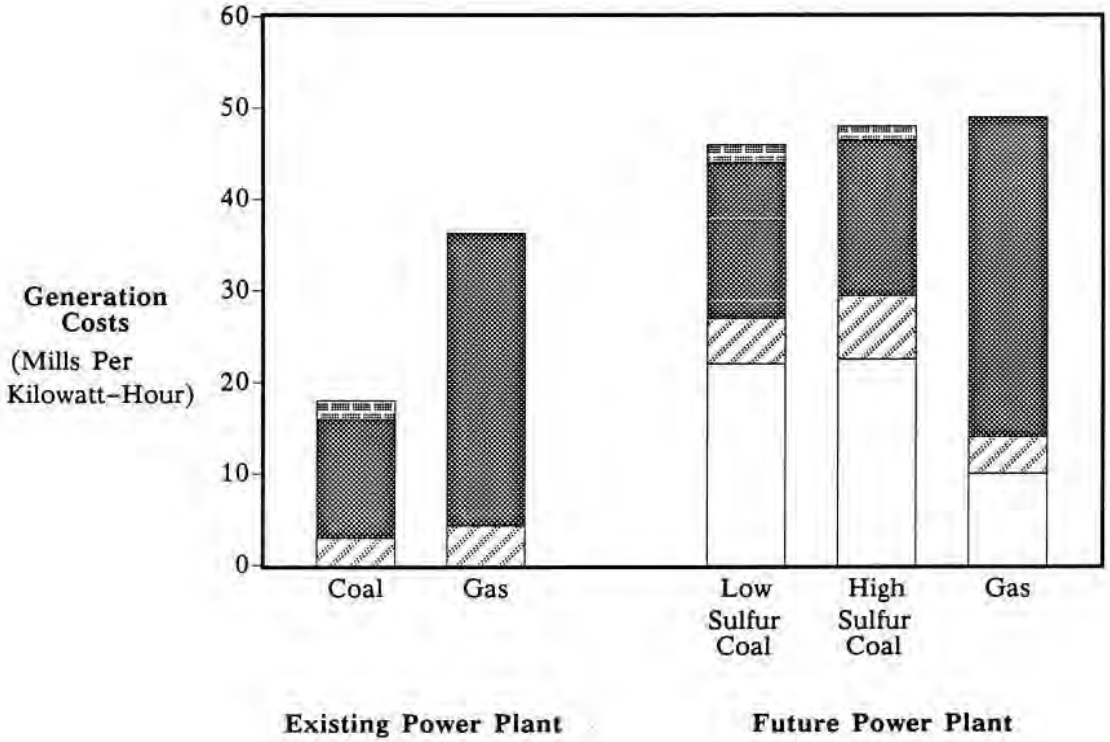
Exhibit 6-9 summarizes the cost of generating electricity at both existing and yet-to-be-constructed power plants (see Appendix G for a detailed discussion of the assumptions used to determine these generation costs).[51] Disposal costs average about 3-5 percent of total generation costs at existing coal-fired power plants, but only about 1-3 percent at future power plants. Although the actual costs of disposal at existing and future power plants are similar, the percentages are different because total generation costs at future power plants are higher than generation costs at existing power plants (resulting in a lower overall percentage for disposal costs at future power plants). Total generation costs are higher at future power plants because they include capital, operation and maintenance, and fuel costs, while the generation costs for existing power plants include operation and maintenance and fuel costs only.[52] Based on the cost assumptions used to develop Exhibit 6-9, coal-fired electricity generation at both new and future baseload[53] power plants is less expensive than generation with natural gas.[54]

The economic impacts likely to result from the use of alternative coal-fired utility waste disposal practices will depend upon several factors, including which disposal options are required, how much the cost of coal-fired electricity generation changes, and whether these changes affect the relative competitiveness between coal and other fuels. To indicate the potential magnitude of these impacts, Exhibit 6-10 summarizes the potential cost impacts on electricity generation rates due to the alternative waste disposal options discussed earlier in this chapter.

As indicated in Exhibit 6-10, some alternative disposal options could

EXHIBIT 6-9

IMPACT OF CURRENT WASTE DISPOSAL COSTS ON TOTAL ELECTRICITY GENERATION COSTS*



* Generation costs are based on typical 500 Mw power plant in the midwest operating at 70 percent utilization rate. Regional costs will vary depending on fuel price and availability, among other factors.

Source: Generation cost estimates are from ICF Incorporated. Waste disposal costs are taken from Arthur D. Little, Inc., *Full-Scale Field Evaluation of Waste Disposal From Coal-Fired Electric Generating Plants*. June 1985.

EXHIBIT 6-10

IMPACT OF ALTERNATIVE DISPOSAL OPTIONS ON ELECTRICITY GENERATION COSTS

Option	Incremental Cost ($/ton of disposed waste)	Impact On Generation Costs: mills/kilowatt-hour a/	Impact On Generation Costs: % of Total Generation Costs, Existing Plant	Impact On Generation Costs: % of Total Generation Costs, Future Plant
Part B Permit	$0.55	0.03	0.2	0.1
Existing Landfills b/				
Single Clay Liner	$0.70-$2.55	0.04-0.16	0.2-0.9	0.1-0.3
Single Synthetic Liner	$1.45-$4.15	0.09-0.26	0.5-1.4	0.2-0.6
Existing Surface Impoundments				
Single Clay Liner	$2.25-$8.20	0.14-0.51	0.8-2.8	0.3-1.1
Single Synthetic Liner	$4.70-$13.45	0.30-0.84	1.7-4.7	0.6-1.8
New Landfills				
Single Clay Liner	$ 5.70-$12.55	0.36-0.79	2.0-4.4	0.8-1.7
Single Synthetic Liner	$ 6.45-$15.15	0.40-0.95	2.2-5.3	0.9-2.0
New Surface Impoundments				
Single Clay Liner	$10.25-$25.20	0.64-1.58	3.6-8.8	1.4-3.4
Single Synthetic Liner	$12.70-$30.45	0.80-1.91	4.4-10.6	1.7-4.1
Double Synthetic Liner	$29.00	1.82	10.1	3.9
Double Synthetic/ Clay Liner	$36.00	2.26	12.6	4.8
Site Closure	$2.10-$14.75	0.13-0.93	0.7-5.2	0.3-2.0
Leachate Control	$4.70	0.30	1.7	0.6
Flood Protection	$0.25-$0.55	0.02-0.03	0.1-0.2	c/
Ground-water Monitoring	$0.06-$0.10	0.004-0.006	c/	c/
Utilization				
Transportation Regulated	$3.00	0.19	1.1	0.4
All Activities Regulated	$13.20	0.83	4.6	1.8
Reuse Prohibited	$18.75	1.18	6.6	2.5

a/ Based on a representative 500 Mw plant operating at a 70 percent utilization rate. Costs are incremental costs only; that is, cost impact of new disposal facilities is only that portion of costs in excess of current disposal costs (see Exhibit 6-4 for these costs). A mill is one-tenth of a cent ($0.001).

b/ Costs for existing waste disposal facilities refer only to the cost of liner installation. Costs for new waste disposal facilities refer to all the costs for site construction and liner installation.

c/ Less than 0.1 percent.

increase electricity generation costs at existing power plants by several percent. In some cases the cost impact could be substantial if several options were combined as part of an integrated waste management strategy. For example, if new waste management regulations led to closure of the current disposal site and the construction of a new lined facility with a leachate control system, flood protection, and ground-water monitoring system, coal-fired generation costs at existing coal-fired power plants could increase by nearly 20 percent (roughly 3.5 mills/kilowatt-hour).

Generation cost increases of this magnitude have the potential to reduce coal consumption at existing coal-fired power plants if these cost increases make it more expensive to generate electricity with coal than with other fuels. A utility decides how much electricity to generate at any existing power plant primarily by comparing the operation and maintenance costs (including fuel) associated with generating electricity at all of its power plants. Power plants with the lowest generation costs will be operated first. Generally, it is less expensive to generate electricity with coal than with other fuels such as oil or gas, but oil-fired electricity generation can be competitive with coal when the price of oil is approximately $10-$15 per barrel.[55] However, whether and to what degree electric utilities would shift away from the use of coal would depend on several factors, including the relative price of coal compared with the price of other fuels, the magnitude of the increase in generation costs if disposal practices were altered, and the overall efficiency of competing power plants.

For power plants yet to be constructed, the impact of higher disposal costs on coal consumption could be more substantial, with possible generation cost

increases approaching 8-10 percent if several options are combined. Generation cost increases of this magnitude could have a substantial effect on the amount of coal consumed at future power plants since many utilities may decide not to build coal-fired power plants. Although currently coal-fired electricity generation may be a more economic option than oil-fired or gas-fired generation at plants yet to be constructed, this situation could change if more expensive disposal practices were required for coal combustion wastes. This is because the higher capital costs of coal-fired electricity generation, compared with oil- or gas-fired generation, reduces the overall cost differential between the use of coal and the use of oil or gas at future power plants (compared to the cost differential between coal and oil or gas at existing power plants). As a result, coal is more likely to be replaced by alternative fuels at future power plants than it is at existing power plants.

In fact, since oil prices dropped below $20 per barrel in early 1986, many utilities have been seriously evaluating the feasibility of building oil- or gas-fired generating capacity in lieu of coal-fired units. As a result, in some instances even an increase of a few percent in coal-fired generation costs could be sufficient to tip the balance in favor of using natural gas or oil to fuel power plants that have not yet been constructed. If increased disposal costs do promote such competition, growth in future U.S. consumption of coal would probably decline. The exact magnitude of this decrease in future coal consumption would depend on many factors, including the type of new waste disposal practices adopted and the price of alternative fuels in different regions of the country. An in-depth analysis of the potential impact of alternative waste management scenarios on electric utility generation practices and investment decisions and, as a result, the level of coal consumption, is

beyond the scope of this Report to Congress. However, EPA intends to seek more information and analysis on the issue of economic impacts through the public hearing process and through its own additional investigations. As required by law EPA will conduct the appropriate regulatory impact analyses, including the economic impact analysis, during the six month public review period following submission of this report to Congress if it is determined that current utility waste management practices for coal-fired combustion wastes are inadequate and additional regulations are warranted.

6.5 SUMMARY

The cost to manage coal combustion waste in basic waste management facilities currently ranges from as little as $2 to as much as $31 per ton. The wide range in management costs is primarily due to differences in (1) the type of facility, (2) the size of the facility and (3) the characteristics of the waste.

- Some facilities currently incur additional costs because they have undertaken additional safeguards against leaching, including liner installation, leachate collection and treatment, and ground-water monitoring.
- Management costs at surface impoundments tend to be greater than those at landfills because of the higher costs of site preparation at impoundments.
- The size of larger waste disposal facilities allows them to operate more efficiently, which tends to reduce the cost per ton of waste management.
- Fly ash is typically more expensive to manage than bottom ash or FGD waste because of additional requirements for collection, handling, and treatment prior to disposal.

- If additional regulations are promulgated requiring electric utilities to alter the current methods by which they manage coal-fired wastes, additional costs may be incurred by the industry as it complies with the new requirements.

- The most common practice for controlling leaching at a waste management site is installation of a liner prior to placement of the waste. Liners are usually made of low permeable clay or a synthetic material and can be installed in one or more layers. The cost of installing a liner ranges from $0.70 to $8.20 per ton of waste for clay liners and $1.45 to $13.45 per ton for synthetic liners. Total disposal costs for single-lined landfills range from about $6 to $15 per ton of waste, while costs for single-lined surface impoundments range from $10 to $30 per ton. Industry-wide costs to construct and install lined management facilities could range from $0.4 to $1.7 billion on an annualized basis, depending on type of facility, type of liner material, and number of liners installed.

- Installation of leachate collection systems to control potential environmental problems that might result from substances leaching from a waste management site could cost about $4 to $5 per ton of waste. Total costs to the utility industry to install leachate collection systems could be $1.2 billion in capital costs, or about $460 million in annualized costs.

- The cost of installing a ground-water monitoring system to detect the presence and concentration of various waste constituents in the ground water surrounding a waste management facility is generally less than $0.25 per ton of waste. Total capital requirements to the industry would likely range from $9 to $13 million, with annual costs of $6 to $9 million.

- If coal combustion wastes were regulated under Subtitle C of RCRA, costs to the utility industry could approach $3.7 billion annually if all wastes were listed as hazardous. Costs would be substantially lower than $3.7 billion annually if coal combustion wastes were tested for hazardous characteristics since only a small portion of coal combustion wastes would be likely to fail the RCRA hazardous characteristic tests. These costs to comply with Subtitle C do not include corrective action costs or the higher costs that may be associated with recycling coal combustion wastes; these costs to the utility industry could be very high.

- New waste management practices could increase the cost of generating electricity at existing coal-fired power plants by nearly 20 percent in some cases. Although coal is generally the preferred boiler fuel at existing power plants, an increase of this magnitude could cause a decline in the amount of coal consumed at these power plants if alternative fuel prices were reasonably competitive.

- If new management practices are required at future power plants, the increase in generation costs is unlikely to exceed 10 percent. Although on a percentage basis this increase would be less than the percentage increase possible at existing power plants, the choice of fuels at future power plants is much more competitive (due to the capital costs that must be included in the costs of a future power plant). In some instances this could lead to a decrease in coal consumption if the use of alternative fuels is found to be more cost effective since many utilities may decide not to build coal-fired power plants.

CHAPTER SIX

NOTES

[1] The disposal costs in this chapter are assumed to apply to high-volume and low-volume wastes since these wastes are often co-disposed in the same disposal facility.

[2] Arthur D. Little, Inc., Full-Scale Field Evaluation of Waste Disposal from Coal-Fired Electric Generating Plants, Final Report, EPA-600/7-85-0286, June 1985, p. 6-1.

[3] The methodology used to develop the cost estimates presented in this chapter is detailed in Appendix G. All costs in this report are presented in fourth quarter 1986 dollars. Costs were escalated to this level based on the GNP price deflator index reported by the U.S. Department of Commerce. The value of this index for fourth quarter 1986 was 115.2 (1982 = 100). Capital charges not already annualized in the various studies cited in this report were annualized by using a 14.5 percent capital recovery factor. This capital recovery factor was chosen to approximate the factors used in the two primary studies cited throughout this chapter -- the ADL study (which used a capital recovery factor of 14.7 percent) and the USWAG study (14.1 percent).

[4] Arthur D. Little, Inc., p. 6-112.

[5] Many of the cost estimates presented throughout this chapter are based on a 500 Mw power plant in order to approximate representative costs for a "typical" size power plant. Capital costs are often expressed on a "per kilowatt" basis to reflect the amount of capital required for each kilowatt of a power plant's capacity. Total disposal costs are often expressed on a "per ton" basis, which refers to each ton that must be disposed over the life of the facility. The amount of waste generated each year from a 500 Mw plant is assumed to be 154,000 tons of fly ash, (308 tons/Mw), 38,500 tons of bottom ash (77 tons/Mw), and 132,000 tons of FGD waste (264 tons/Mw). These estimates are based on average values reported in Full-Scale Field Evaluation of Waste Disposal From Coal-Fired Electric Generating Plants, Arthur D. Little, Inc., June 1985. The actual amount of waste generated at a plant will vary depending on plant size, coal quality, FGD technology, and boiler type, among other factors.

[6] In one study for Consolidated Edison of New York, analyses were conducted on the feasibility of ocean disposal of coal-fired utility wastes from the Arthur Kill and Ravenswood oil-to-coal conversions. Capital costs for this 612,500 tons per year operation were estimated at $36 million. Annual operation and maintenance costs were approximately $2.7 million, for total costs of about $13 per ton of waste disposed. See Energy Resources, Inc., Demonstration of Compliance of Coal-Ash Disposal at the 106-Mile Ocean Waste Disposal Site with Subpart C of the Ocean Dumping Regulations, Attachment I, May 1981, p. I-26.) Capital costs would be about $5.2 million on an annualized basis, resulting in total annualized costs of about $7.9 million.

[7] In one study, the cost of building and operating an artificial reef construction system was estimated to be about $50 per ton, roughly double the amount estimated by the study authors for more conventional waste disposal. In those situations where space constraints or other factors would substantially increase the costs for conventional disposal, ocean disposal through reef construction was seen as an economically viable option. See J.H. Parker, P.M.J. Woodhead, and I.W. Dued all, "A Constructive Disposal Option for Coal Wastes -- Artificial Reefs," in Proceedings of the Second Conference on Management of Municipal, Hazardous, and Coal Wastes, S. Sengupta (Ed.), September 1984, p. 134.

[8] Arthur D. Little, p. 6-132. "Installed cost" of a liner (expressed in terms of cost per ton of disposed waste) refers to the increase in the cost of disposing of one ton of waste as a result of adding a liner to an unlined landfill or surface impoundment.

[9] Ibid. The costs in the Arthur D. Little report were presented for an 18-inch clay liner. Costs were doubled to approximate the costs for installing a 36-inch clay liner, which is currently a more common practice. The dollar per ton estimate was derived by multiplying total capital costs by a 14.5 percent capital recovery factor to determine annual capital charges. Assuming that a 500 Mw power plant has a 45 acre landfill disposal site, total capital charges would range from $945,000 to $3.4 million, or about $140,000 to $490,000 in annualized charges. Assuming that a 500 Mw power plant would need a 145-acre wet surface impoundment, total costs would range from $3.0 to $10.9 million, or $440,000 to $1.6 million in annualized costs. These annualized charges were then divided by the amount of waste produced annually by a 500 Mw power plant with no FGD process, (i.e., 192,500 tons) to determine the dollar per ton cost. This approach is used throughout the report to calculate dollar per ton estimates. See Appendix G for more detail on this methodology.

[10] Ibid. For landfills, total installed costs would range from $1.9 to $5.1 million per plant, assuming a 45-acre disposal site. Annual costs would range from about $280,000 to $740,000. Based on 192,500 tons of waste, the cost is $1.45-$3.85 per ton. For ponds (i.e., impoundments), total installed costs would be $6.2-$16.4 million, or $900,000-$2.4 million annualized. On a dollar per ton basis, this range is $4.70-$12.35.

[11] Ibid. For landfills total installed costs would range from $2.7-$5.5 million, or about $385,000-$800,000 in annual costs per ton. This corresponds to $2.00-$4.15 per ton. Total installed costs for ponding operations are $8.6-$17.8 million, or $1.2-$2.6 million annualized. This corresponds to $6.45-$13.45 per ton.

[12] Ibid.

[13] Total capital costs for landfills of $3.0 to $5.0 million correspond to annual charges of about $430,000 to $720,000. Assuming 192,500 tons of waste, the per ton cost is $2.25 to $3.75. Using the same approach to derive disposal costs at a 145-acre lined impoundment yields $7.20 to $12.00 per ton.

[14] A waste management unit is not subject to regulation under Section 264.1 if the Regional Administrator finds that the unit (1) is an engineered structure, (2) does not receive or contain liquid waste or waste containing free liquids, (3) was designed and is operated in such a way to exclude liquids, precipitation, and other run-on and run-off (4) has both inner and outer layers of containment enclosing the waste, (5) has a leak detection system built into each containment layer, (6) will have continuing operation and maintenance of these leak detection systems during its active life and throughout the closure and post-closure care periods, and (7) is constructed in such a way that, to a reasonable degree of certainty, hazardous constituents will not migrate beyond the outer containment layer prior to the end of the post-closure care period. (40 CFR 264.90(b)(vii).

[15] See 40 CFR 246.143.

[16] These specified wastes are liquid hazardous wastes that have a pH less than or equal to 2.0 and/or (1) free cyanides at concentrations greater than or equal to 1,000 mg/1, (2) arsenic and/or arsenical compounds at concentrations greater than or equal to 500 mg/1, (3) cadmium and/or cadmium compounds at concentrations greater than or equal to 100 mg/1, (4) chromium and/or chromium compounds at concentrations greater than or equal to 500 mg/1 (5) lead and/or lead compounds at concentrations greater than or equal to 500 mg/1, (6) nickel and/or nickel compounds at concentrations greater than or equal to 134 mg/1, (7) mercury and/or mercury compounds at concentrations greater than or equal to 20 mg/1, (8) selenium and/or selenium compounds at concentrations greater than or equal to 100 mg/1, (9) thallium and/or thallium compounds at concentrations greater than or equal to 130 mg/1, (10) polychlorinated biphenyls at concentrations greater than or equal to 50 mg/1, (11) halogenated organic compounds at concentrations greater than or equal to 1,000 mg/kg.

[17] Envirosphere Company, "Report on the Costs of Utility Ash and FGD Waste Disposal", in USWAG, Report and Technical Studies on the Disposal and Utilization of Fossil-Fuel Combustion By-Products, October 19, 1982, p. 21, Appendix F, part 2. Dollar per ton estimates were determined by calculating annual costs ($721,000 x 14.5 percent capital recovery factor = $104,500). The capital recovery factor was applied to all costs since a breakdown of different types of costs required for a Part B permit was not available.

[18] Ibid, p. 18.

[19] Assuming a 145-acre impoundment site, costs would be about $107,000. On a per ton basis, this corresponds to about $0.55. For a 45-acre landfill with costs of $1100 per acre, total costs would be about $50,000, for a per ton cost of $0.25.

[20] Envirosphere, in USWAG, Appendix F, Part 2, p. 27, 32.

[21] Arthur D. Little, p. 6-133. On an annualized basis, capital costs would range from about $2,650 to $3,550.

[22] Envirosphere Company, in USWAG, Appendix F, Part 2, p. 37. Envirosphere estimated that about four wells, one upgradient from the site and three downgradient, would be required for each 100 acre disposal site (or about six wells for a site of 145 acres) at a capital cost of approximately $6,000 per well. Total capital costs for six wells would be $36,000, which is about $5,200 on an annualized basis. It was assumed that the wells would be sampled quarterly the first year, then semi-annually thereafter. The operation and maintenance costs would average about $2,500 to $3,000 per well, for facility costs (assuming six wells) of $15,000 to $18,000 per year. Total annualized costs, therefore, would range from $20,200 to $23,200, or $0.10 to $0.12 per ton of waste disposed.

[23] For a more complete discussion, see ICF Incorporated, Liner Location Risk and Cost Analysis Model, Draft Phase II Report, Appendix F-2, Office of Solid Waste, U.S. Environmental Protection Agency, March 1987.

[24] The cost equation on which this cost estimate is based was developed for typical RCRA Subtitle C landfills. Since these facilities tend to be much smaller than the size of utility disposal areas, extrapolating the cost equation for larger sizes may introduce some errors. Nevertheless, these cost estimates do indicate the approximate magnitude of corrective action costs that would likely be incurred.

[25] Econometric Research, "The Economic Costs of Potential RCRA Regulations Applied to Existing Coal-Fired Electric Utility Boilers," in USWAG, Report and Technical Studies on the Disposal and Utilization of Fossil-Fuel Combustion By-Products, October 26, 1982, p. 15, Appendix F, part 1.

[26] Ibid, p. 15.

[27] Ibid, p. 18. On a per acre basis, total annual costs range from $6,700 to $19,600 for surface impoundments and $9,000 to $21,000 for landfills. For a 145-acre impoundment, this corresponds to $1.0 to $2.8 million in total annual costs, or $5.00 to $14.75 per ton of waste. For landfills the per ton cost would be $2.10 to $4.90 based on total annual costs of $0.4 to $0.9 million.

[28] See Administrative Procedure Act, U.S. Code 5 Sec. part 551.

[29] Ibid, see pages 26 and 31 of the Econometric report for all closure costs.

[30] For further discussion of the potential magnitude of these costs, see ICF Incorporated, Flexible Regulatory and Enforcement Policies for Corrective Action, prepared for U.S. Environmental Protection Agency, September 12, 1985.

[31] Econometric Research, in USWAG, Appendix F, Part 1, p. 15. Econometric Research used capital costs for disposal of about $5.20 per ton of waste produced over a 20-year life of the facility for synthetic liners and about $8.10 per ton for clay liners, plus about $0.06 per ton per year for operation and maintenance costs. Total initial capital outlays would then be $104 per ton ($5.20 per ton times 20 years) for synthetic liners, or about $15.08 per ton on an annualized basis, and $162 per ton ($8.10 per ton times 20 years) for clay liners, or $23.49 per ton on an annualized basis. With the addition of

the $0.06 per ton for operation and maintenance costs, total costs would range from $15.14 per ton for synthetic liners and $23.55 per ton for clay liners for each ton of waste produced annually.

[32] Ibid., p. 27. Total capital costs for existing power plants were assumed to be $2.1 billion for single synthetic liners and $3.2 billion for single clay liners. Since these cost estimates were based on a universe of 412 power plants, costs were adjusted upward by 514/412 to approximate total industry costs for the number of power plants estimated at the time of this study -- 514 power plants. This adjustment was made for all industry-wide costs cited from the USWAG report.

[33] Ibid., p. 32.

[34] Ibid., p. 18. Econometric Research, Inc., calculated that disposal costs for an impoundment with a single synthetic liner were about $0.95 per ton of waste over the life of the facility and about $1.50 per ton of waste for clay-lined impoundments. For a plant generating 192,500 tons each year for 20 years (or 3.85 million tons), that corresponds to 3.85 million tons x $0.95 per ton = $3.7 million for an impoundment with a single synthetic liner (or about $19 per ton based on $3.7 million divided by 192,500 tons of waste annually) and 3.85 million tons x $1.50 per ton = $5.8 million for an impoundment with a single clay liner (or about $30 for each ton of waste disposed in a year).

[35] Ibid, p. 26. The costs in the USWAG report were adjusted by 514/412 to account for the 514 power plants estimated at the time of this study compared to the 412 power plants assumed in the USWAG report.

[36] Ibid. p. 31.

[37] Ibid, p. 18. The double synthetic liner disposal system averages about $1.45 per ton over the life of the facility and a system with one synthetic liner and one clay liner costs about $1.80 per ton. At 3.85 million tons of waste over a 20 year facility life, that is $5.6 million for a double synthetic liner (or about $29 for each ton disposed in a year). For a combination synthetic/clay liner system, 3.85 million tons x $1.80 per ton = $6.9 million (or about $36 per ton).

[38] Ibid, p. 26.

[39] ICF Incorporated, 1985 Survey of Selected Firms In The Commercial Hazardous Waste Management Industry, Prepared for U.S. Environmental Protection Agency, November 6, 1986.

[40] Ibid.

[41] To develop a cost estimate for landfills constructed with clay/synthetic double liners, the ratio of the cost of single clay and synthetic liners at landfills in Exhibit 6-7 to the cost of single clay and synthetic liners at surface impoundments was multiplied by the cost of clay/synthetic liners at surface impoundments.

[42] The costs to close and cap existing facilities have been included in this estimate, while corrective action costs have not been included. Although closure costs will be incurred eventually by the industry, in most cases they would not be incurred for many years to come. To be conservative, EPA has included closure costs as part of potential RCRA Subtitle C compliance costs.

[43] Envirosphere Company, "Economic Analysis of Impact of RCRA On Coal Combustion By-Products Utilization." In USWAG, Report and Technical Studies On the Disposal and Utilization of Fossil-Fuel Combustion By-Products, October 26, 1982, Appendix G.

[44] Envirosphere Company, in USWAG, Appendix G. The costs in Exhibit 6-8 are based on estimated impacts between 1984 and 2000 and adjusted by a capital recovery factor of 14.5 percent to annualize the costs (total capital requirements were not identified). It was estimated that about 203 million tons of coal combustion by-products would be used over this period, with a similar amount used on-site by the utilities. That is, the costs assume that the amount of by-products utilized would have increased over time.

[45] Ibid., p. 89. Total ash generation in 2000 was assumed to be 169.5 million tons, with about 27.3 million tons utilized and therefore, 142.2 million tons destined for disposal areas. Utilization was estimated to decline about 11.5 million tons, so the total amount of waste to be disposed would increase to 153.7 million tons.

[46] Ibid.

[47] Ibid., p. 91. Total utilization was assumed to decline by about 20.3 million tons in 2000. Therefore, the total amount of waste disposed would increase from 142.2 million tons to 162.5 million tons.

[48] Ibid.

[49] Total utilization was assumed to be 27.3 million tons in 2000, thereby increasing total disposal volume from 142.2 million tons to 169.5 million tons.

[50] Envirosphere Company, in USWAG, Appendix G, p. 93.

[51] To estimate the potential impact of alternative disposal practices on electricity generation costs, the first step was to calculate the approximate portion of generation costs due to current basic disposal practices. Current basic disposal practices for coal-fired utility wastes were assumed to be disposal in either an unlined pond or landfill, although other practices are sometimes followed. Generation costs for a typical coal- and gas-fired power plant are shown to indicate the relative competitiveness of these two fuels when current disposal practices for coal-fired utility wastes are followed. See Appendix G for a detailed discussion of the assumptions used to determine these generation costs.

[52] Capital costs are not included in the cost estimates for existing power plants because these are "sunk" costs, i.e., they have already been spent. As a result, the percentage impact on total generation costs at existing power plants is larger because the cost base is smaller compared to future power plants.

[53] Baseload refers to power plants that are operated as much as possible to maximize the amount of electricity these plants can generate. For this analysis a baseload power plant is assumed to operate 70 percent of the time.

[54] The generation costs in Exhibit 6-9 are intended to be representative of typical power plants. However, the actual cost of generation and the relative competitiveness between coal and gas depends on many factors, including plant size, utilization rate, and delivered fuel cost.

[55] This price range is only intended to illustrate the approximate range at which oil becomes competitive with coal at existing power plants. The actual level at which coal might begin to lose market share depends on many factors, including relative price differentials, fuel availability, gas prices vis-a-vis oil prices, types of power plants (i.e., overall plant efficiency), etc.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

This chapter concludes the Environmental Protection Agency's Report to Congress on fossil fuel combustion wastes. Pursuant to the requirements of Section 8002(n) of the Resource Conservation and Recovery Act (RCRA), the Report addresses the nature and volumes of coal combustion wastes, the environmental and human health effects of the disposal of coal combustion wastes, present disposal and utilization practices, and the costs and economic impacts of employing alternative disposal and utilization techniques. A statement of the scope of the report and a summary of the report's findings are presented below, followed by the Agency's recommendations.

7.1 SCOPE OF REPORT

As discussed in Chapter One, this Report to Congress covers the generation of coal-fired combustion wastes by the electric utility industry. Other fossil fuel combustion wastes not discussed in this report include coal, oil and gas combustion wastes from other industries and oil and gas combustion wastes from electric utilities. Overall, coal combustion by electric utilities accounts for approximately 90 percent of all fossil fuel combustion wastes that are produced. Moreover, this percentage is likely to increase in the future since coal consumption by the electric utility industry is expected to increase substantially while coal use by other sectors remains relatively constant. Electric utility coal consumption will grow as new coal-fired power

plants are constructed to meet increasing electricity requirements in the United States.

7.2 SUMMARY OF REPORT

The Agency's conclusions from the information presented in this report are summarized under seven major groupings paralleling the organization of the report: 1) Location and Characteristics of Coal-Fired Power Plants, 2) Waste Quantities and Characteristics, 3) Waste Management Practices, 4) Potential Hazardous Characteristics, 5) Evidence of Environmental Transport of Potentially Hazardous Constituents, 6) Evidence of Damage, and 7) Potential Costs of Regulation.

7.2.1 Location and Characteristics of Coal-Fired Power Plants

1. There are about 500 power plant sites in the United States that consume coal to generate electricity. Each power plant may be the location for more than one generating unit; at these 500 power plants there are nearly 1400 generating units.

2. The size of coal-fired power plants can vary greatly. The size of a power plant is typically measured by the number of megawatts (Mw) of generating capacity. Coal-fired power plants can range in size from less than 50 Mw to larger than 3000 Mw.

3. Coal-fired power plants are located throughout the United States. Coal is used to generate electricity in every EPA region; almost every state has some coal-fired generating capacity.

4. More coal-fired power plants will be built as the demand for electricity increases. Coal is a fuel often used by the electric utility industry to generate power. This reliance on coal is unlikely to change for many years to come in the absence of greatly increased costs for coal-fired electricity.

5. Coal-fired power plants are located in areas of widely-varying population density. Some power plants are located in remote rural areas, whereas others are located in urban environments. They are usually, although not always, located at least a couple of kilometers from major population concentrations. In general they are located near a major body of surface water such as a lake, river, or stream.

7.2.2. Waste Quantities and Characteristics

1. The amount of wastes generated annually by coal-fired power plants is large by any standard. About 84 million tons of high-volume wastes -- fly ash, bottom ash, boiler slag, and FGD sludge -- are generated annually. The total amount of low-volume wastes generated from equipment maintenance and cleaning operations is not known precisely, but is also substantial.

2. Quantities of waste produced will increase significantly as more electricity is generated by coal. The amount of high-volume wastes produced annually could double by the year 2000. In particular, the amount of FGD sludge produced will triple (to about 50 million tons) as newly-constructed power plants install FGD equipment to remove sulfur dioxide from the flue gases.

3. Coal combustion wastes are a common by-product from the generation of electricity. The noncombustible materials are present in the coal as a result of geologic processes and mining techniques. Given current technologies for generating electricity, wastes from coal combustion will continue to be produced in significant quantities.

4. High-volume coal combustion wastes do contain elements that in sufficient concentrations can pose a potential danger to human health and the environment. Most elements in coal are not hazardous. However, trace elements typically found in coal become concentrated as a result of the combustion process. Certain elements known to pose health risks can be found in the wastes at hazardous levels.

5. Although most low-volume wastes do not appear to be hazardous, there are some waste streams from cleaning that could potentially be hazardous. The waste streams of most concern are water-side boiler cleaning solutions, which may be corrosive or toxic. Because the amount and type of low-volume wastes produced can vary substantially from one power plant to the next, not as much is known about low-volume wastes compared to high-volume wastes.

7.2.3 Waste Management Practices

1. Most coal combustion wastes are typically disposed in landfills or surface impoundments, with recent trends toward increased reliance on landfills. Although some disposal does occur off-site, most wastes are disposed on-site; it is likely that most power plants built in the future will dispose on-site in a landfill.

2. Typical industry practice is to co-dispose low-volume wastes with high-volume wastes or, in some instances, to burn the low-volume wastes in the utility boiler. There are many other types of waste management practices that are also used to alter the physical and chemical characteristics of low-volume wastes prior to disposal. These practices vary widely from plant to plant. There are no reliable data sources that accurately describe the types of low-volume disposal practices used at each power plant.

3. The potential for increased waste utilization as a solution to waste management in the utility industry appears to be limited. About 21 percent of all high-volume wastes are currently recycled; some opportunities appear to exist to increase utilization, but not in a major way.

4. Coal combustion wastes are typically regulated under state solid waste laws, which treat these wastes as non-hazardous materials. The

extent of state regulation can vary significantly from one state to another.

5. Many waste management practices applied to hazardous waste in other industries, such as liners, have only seen limited use for coal combustion waste management. In recent years, some of these practices, including liners and leachate collection systems, have become more common. There is an increasing tendency to manage coal combustion wastes by disposing on-site (at the power plant) in landfills.

6. There are few major innovations under development that would lead to major changes in waste management practices.

7.2.4 Potential Hazardous Characteristics

1. The RCRA hazardous characteristics of most concern are corrosivity and EP toxicity. Coal combustion wastes are generally not ignitable or reactive.

2. Most waste streams would not be considered corrosive under RCRA definitions. Only aqueous wastes, which most coal combustion wastes are not, are considered corrosive under RCRA. There are some aqueous coal combustion waste streams that are very near corrosive levels, particularly low volume wastes such as boiler blowdown or coal pile runoff. In some instances, boiler cleaning wastes may be corrosive, particularly those that are hydrochloric acid-based.

3. Coal combustion wastes generally are not EP toxic, although there are some exceptions. It is rare for coal combustion wastes to fail the EP test (or the TCLP test developed more recently). Extract concentrations in excess of 100 times the Primary Drinking Water Standards have been found only for the elements cadmium, chromium, and arsenic from some FGD sludges and coal ash samples, although these levels are quite rare -- average levels are substantially below 100 times the PDWS.

4. There are insufficient data to determine a priori which waste streams at a power plant will exhibit RCRA hazardous characteristics. Accurate determinations could only be made if site-specific analyses were conducted.

7.2.5 Evidence of Environmental Transport of Potentially Hazardous Constituents.

1. Migration of potentially hazardous constituents has occurred from coal combustion waste sites. From the limited data available, exceedances of the Primary Drinking Water Standards have been observed in the ground water for several elements, including cadmium, chromium, lead, selenium, and arsenic.

2. Ground-water contamination does not appear to be widespread. Only a few percent of all ground-water quality observations indicate that a PDWS exceedance has occurred, although many utility waste management

sites at which ground-water monitoring has been done have had at least one exceedance. However, the observed contamination may not necessarily be chronic since sites at which exceedances have been noted do not consistently register in excess of the PDWS.

3. When ground-water contamination does occur, the magnitude of the exceedance is generally not large. Most PDWS exceedances tend to be no more than 10 or 20 times the PDWS, although a few observations greater than 100 times the PDWS have been noted.

4. Human populations are generally not directly exposed to the groundwater in the vicinity of utility coal combustion waste management sites. Public drinking water intakes are usually at least a few kilometers away. Also, most power plants are located near surface water bodies that dilute the concentration of any elements found in the ground water.

5. Because high-volume and low-volume waste streams are often co-disposed, it cannot be determined if one specific waste stream was the source of contamination.

6. The ground-water quality information on which this evidence is based is limited. Data were only available from a small number of utility waste management sites; no comprehensive database on ground-water contamination potentially attributable to coal combustion wastes exists.

7.2.6 Evidence of Damage

1. There are few cases considered to be documented evidence of damage from coal combustion wastes. Among these cases there is some dispute whether any observed damage can be attributed to the utility waste management facility.

2. Damage cases are dominated by chronic incidents (seepage, periodic runoff) as opposed to catastrophic incidents (sudden releases, spills), although one documented damage case was due to structural failure of a surface impoundment.

3. Documented damage typically involves physical or chemical degradation of ground water or surface water, including fish kills or reduction in biota, but seldom involves direct effects on human health because the water is not consumed for drinking water purposes. Much of the damage has occurred in the immediate vicinity of the waste management site; drinking water intakes are generally far enough away such that any contaminated water is not being directly used for human consumption.

7.2.7 Potential Costs of Regulation

1. If additional regulations are promulgated for utility waste management, the total costs incurred by the industry could vary considerably depending on the extent of the additional regulations.

For example, total annual costs to install and operate ground-water monitoring systems would be unlikely to exceed $10 million. On the other hand, total annual costs for the industry could approach $5 billion if all existing facilities were capped and closed and new facilities were constructed with liners, leachate collection systems, flood protection, and ground-water monitoring. (Corrective action costs, such as excavating all existing facilities for removal of the wastes to RCRA Subtitle C facilities, are not included in this estimate; such costs would be extremely high.)

2. Regulation of utility coal combustion wastes under full RCRA Subtitle C requirements could halt all recycling of coal combustion wastes if recycling was also subject to Subtitle C requirements. Total costs to the industry could approach $2.4 billion annually. If recycled wastes were not subject to Subtitle C disposal requirements, it is possible the amount of recycling could increase as the utility industry increased waste utilization to avoid full Subtitle C disposal costs.

3. The costs to the utility industry for full RCRA Subtitle C compliance could decrease the amount of coal consumed in coal-fired power plants. The costs of generating electricity with coal could increase by several percent (depending on the extent of additional regulations), making it economic to generate electricity with other fuels. These impacts could be felt in two ways: 1) lower coal consumption at existing power plants and 2) construction of fewer coal-fired power plants in the future.

7.3 RECOMMENDATIONS

Based on the findings from this Report to Congress, this section presents the Agency's preliminary recommendations for those wastes included in the scope of this study. The recommendations are subject to change based on continuing consultations with other government agencies and new information submitted through the public hearings and comments on this report. Pursuant to the process outlined in RCRA 3001(b)(3)(C), EPA will announce its regulatory determination within six months after submitting this report to Congress.

First, EPA has concluded that coal combustion waste streams generally do not exhibit hazardous characteristics under current RCRA regulations. EPA does not intend to regulate under Subtitle C fly ash, bottom ash, boiler slag, and flue gas desulfurization wastes. EPA's tentative conclusion is that current waste management practices appear to be adequate for protecting human health and the environment. The Agency prefers that these wastes remain under Subtitle D authority. EPA will use section 7003 of RCRA and sections 104 and 106 of CERCLA to seek relief in any cases where wastes from coal combustion waste disposal sites pose substantial threats or imminent hazards to human health and the environment. Coal combustion waste problems can also be addressed under RCRA Section 7002, which authorizes citizen lawsuits for violations of Subtitle D requirements in 40 CFR Part 257.

Second, EPA is concerned that several other wastes from coal-fired utilities may exhibit the hazardous characteristics of corrosivity or EP toxicity and merit regulation under Subtitle C. EPA intends to consider

whether these waste streams should be regulated under Subtitle C of RCRA based on further study and information obtained during the public comment period. The waste streams of most concern appear to be those produced during equipment maintenance and water purification, such as metal and boiler cleaning wastes. The information available to the Agency at this time does not allow EPA to determine the exact quantity of coal combustion wastes that may exhibit RCRA Subtitle C characteristics. However, sufficient information does exist to indicate that some equipment maintenance and water purification wastes do occasionally exhibit RCRA hazardous characteristics, and therefore, may pose a danger to human health and the environment. These wastes are similar to wastes produced by other industries that are subject to Subtitle C regulation, and waste management practices for coal combustion wastes are often similar to waste management practices employed by other industries. EPA is considering removing the exemption for all coal-fired utility wastes other than those identified in the first recommendation. The effect would be to apply Subtitle C regulation to any of those wastes that are hazardous by the RCRA characteristic tests. EPA believes there are various treatment options available for these wastes that would render them nonhazardous without major costs or disruptions to the utilities.

Third, EPA encourages the utilization of coal combustion wastes as one method for reducing the amount of these wastes that need to be disposed to the extent such utilization can be done in an environmentally safe manner. From the information available to the Agency at this time, current waste utilization practices appear to be done in an environmentally safe manner. The Agency supports voluntary efforts by industry to investigate additional possibilities for utilizing coal combustion wastes.

Through its own analysis, evaluation of public comments, and consultation with other agencies, the Agency will reach a regulatory determination within six months of submission of this Report to Congress. In so doing, it will consider and evaluate a broad range of management control options consistent with protecting human health and the environment. Moreover, if the Agency determines that Subtitle C regulation is warranted, in accordance with Section 3004(x) EPA will take into account the "special characteristics of such waste, the practical difficulties associated with implementation of such requirements, and site-specific characteristics . . .," and will comply with the requirements of Executive Orders 12291 and 12498 and the Regulatory Flexibility Act.

Document 18

U.S. EPA, Report to Congress: Wastes. from the Combustion of Fossil Fuels, Vol. 1 – Executive Summary, EPA 530-S-99-010, March 1999.

United States
Environmental
Protection Agency

Office of Solid Waste and
Emergency Response
Washington, DC 20460

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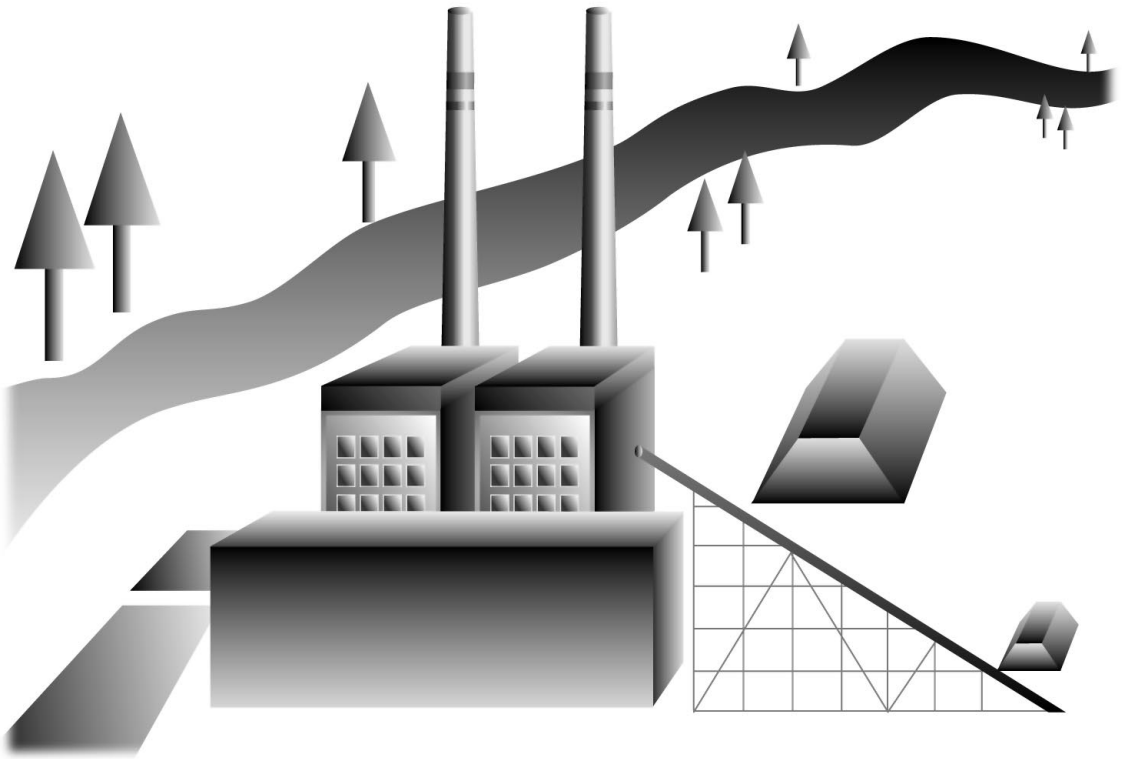
March 1999

Solid Waste

Report to Congress

Wastes from the Combustion of Fossil Fuels

Volume 1 – Executive Summary



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EXECUTIVE SUMMARY

1.0 INTRODUCTION

1.1 BACKGROUND

Section 3001(b)(3)(A)(i) of the Resource Conservation and Recovery Act (RCRA) excludes certain large-volume wastes generated primarily from the combustion of coal or other fossil fuels from being regulated as hazardous waste under Subtitle C of RCRA, pending completion of a Report to Congress required by Section 8002(n) and a determination by the U.S. Environmental Protection Agency (EPA) Administrator either to promulgate regulations under Subtitle C or to deem such regulations as being unwarranted.

In 1988, EPA published the *Report to Congress on Wastes from the Combustion of Coal by Electric Utility Power Plants* (EPA, 1988). The report, however, did not address comanaged utility coal combustion wastes, other fossil fuel wastes that are generated by utilities, and wastes from non-utility boilers burning any type of fossil fuel. Further, because of other priorities, EPA did not complete a regulatory determination on fossil fuel combustion (FFC) wastes at that time.

In 1991, a suit was filed against EPA for failure to complete a regulatory determination on FFC wastes (Gearhart v. Reilly Civil No. 91-2345 (D.D.C.). On June 30, 1992, the Agency entered into a Consent Decree that established a schedule for EPA to complete the regulatory determinations for all FFC wastes. FFC wastes were divided into two categories: (1) fly ash, bottom ash, boiler slag, and flue gas emission control waste from the combustion of coal by electric utilities and independent commercial power producers, and (2) all remaining wastes subject to RCRA Sections 3001(b)(3)(A)(i) and 8002(n). On August 9, 1993, EPA published a determination for the first category of wastes, concluding that regulation under Subtitle C for these wastes was not warranted. To make an appropriate determination for the second category or "remaining wastes," EPA decided that additional study was necessary. Under the current court-ordered deadlines, the Agency must complete this Report to Congress by March 31, 1999, and issue a regulatory determination by October 1, 1999.

In keeping with its court-ordered schedule, and pursuant to the requirements of Section 3001(b)(3)(A)(i) and Section 8002(n) of RCRA, the EPA has prepared this report on remaining FFC wastes. In addition to complying with the Congressional mandate, this report will serve to establish a factual basis for EPA decision-making regarding the appropriate regulatory status, under RCRA, of remaining FFC wastes. The report addresses the following eight study factors required by Section 8002(n) of RCRA for FFC wastes:

1. The source and volumes of such materials generated per year
2. Present disposal practices
3. Potential danger, if any, to human health and the environment from the disposal of such materials
4. Documented cases in which danger to human health or the environment has been proved
5. Alternatives to current disposal methods
6. The costs of such alternatives

7. The impact of those alternatives on the use of natural resources

8. The current and potential utilization of such materials.

In addition, the report includes a review of applicable state and federal regulations so that regulatory decisions that derive from the report will avoid duplication of existing requirements.

1.2 SCOPE AND ORGANIZATION OF THE REPORT TO CONGRESS

This report addresses the remaining wastes from FFC. As defined in the 1992 Consent Decree, remaining wastes comprise the following:

- Fly ash, bottom ash, boiler slag, and flue gas emission control wastes from the combustion of coal by electric utility power plants, when such wastes are mixed with, codisposed, cotreated, or otherwise comanaged with other wastes generated in conjunction with the combustion of coal or other fossil fuels

- Any other wastes subject to Section 8002(n) of RCRA, except fly ash, bottom ash, boiler slag, and flue gas emission wastes from coal combustion by electric utilities.

For the purposes of this report, EPA is addressing the following FFC wastes:

- Comanaged coal combustion wastes, wastes from the combustion of petroleum coke, and wastes from mixtures of coal and other fuels ("coburning") generated by utilities.

- Wastes from the combustion of coal, petroleum coke, and mixtures of coal and other fuels (coburning) generated by non-utilities.

- Wastes from the combustion of coal, petroleum coke, and mixtures of coal and other fuels (coburning) by facilities that employ fluidized bed combustion technology.

- Wastes from the combustion of oil by utilities and non-utilities.

- Wastes from the combustion of natural gas by utilities and non-utilities.

The report is organized into seven chapters that address the study factors required under Section 8002(n) of RCRA. Chapter 2 provides an overview of FFC in the United States, including a brief description of the utility and non-utility sectors and a discussion of projected trends for the industry. Chapters 3 through 7 parallel the categories of remaining wastes listed above in Section 1.2. Chapter 3 focuses on comanaged utility coal combustion waste and also covers coburning by utilities. Chapter 4 examines non-utility coal combustion waste. Chapters 5 and 6 discuss fluidized bed combustion wastes and oil combustion wastes, respectively. Chapter 7 focuses on natural gas combustion wastes. Chapters 3 through 6 each provide overviews of their relevant sectors; describe the wastes generated, their characteristics, and volumes; and examine current waste management practices, potential and documented dangers to human health and the environment, existing regulatory controls, waste management alternatives, and costs and economic impacts. Chapter 7 presents a brief overview of natural gas combustion technology (additional discussion of natural gas combustion wastes is not warranted because of minimal waste generation). Finally, each of the chapters presents the Agency's findings and recommendations.

2.0 INFORMATION SOURCES AND METHODS

In conducting this study, EPA gathered publicly available information from a broad range of sources, including federal and state agencies, industry trade groups, environmental organizations, and open literature. EPA reviewed information on each of the Section 8002(n) study factors for each of the FFC waste sectors. For many study factors, very limited information existed prior to this study. Accordingly, EPA worked closely with the Edison Electric Institute's (EEI) Utility Solid Waste Activities Group (USWAG), the Electric Power Research Institute (EPRI), and the Council of Industrial Boiler Owners (CIBO) as those organizations developed new information in support of EPA's decision process. Because other ongoing EPA projects currently focus on portions of the FFC waste generator universe, EPA also leveraged data collection efforts conducted for air, industrial waste, and hazardous waste programs. In addition, EPA maintained contact with a number of environmental organizations to share information and ideas regarding beneficial uses of some FFC wastes and methods of characterizing the risks associated with FFC wastes.

In the Agency's part 1 fossil fuel combustion regulatory determination (58 FR 42466, 8/9/93), the Agency applied a three-step decision-making process. Under this procedure, the Agency first considers the potential impacts of the wastes in question on human health and the environment. If EPA finds there may be significant impact, the Agency next considers whether there is a need for regulation under RCRA Subtitle C in light of existing waste management practices and existing regulatory controls imposed by states under authorities other than Subtitle C. The Agency also considers whether Subtitle C would effectively address problems associated with the waste without imposing significant unnecessary controls. Finally, if the Agency concludes that additional regulation under Subtitle C is warranted, EPA considers the potential economic impacts and affects on operations and beneficial uses of the wastes from such regulation on the industry.

In this report, EPA has continued to consider the factors previously utilized in the three-step decision-making process, since the Agency believes that these factors appropriately reflect the statutory criteria in Section 8002 of RCRA that EPA must consider in issuing this report. The Agency has modified somewhat, however, how those factors are considered in formulating its recommendations. Rather than apply the statutory criteria in rigid, stepwise fashion, EPA has considered the totality of the relevant factors (i.e., the potential environmental and human health impacts, the need, if any, for additional regulation and, finally, the potential impacts of imposing regulation under subtitle C in developing the report's recommendations). The step-wise approach to making regulatory determinations assumes that it is possible to reach readily discernable, yes-or-no decisions regarding each step in the decision-making process. As we gain experience in evaluating Bevill wastes, however, we have learned that such clear-cut answers may not be possible for each individual decision-making criterion, and that it may be necessary to balance all the relevant factors to reach the appropriate recommendation. For example, where a particular waste poses some potential risk, but existing controls are wholly inadequate and regulation under subtitle C would not cause severe economic dislocation, a determination to regulate the waste may be appropriate. Conversely, where a waste poses more substantial risks but existing controls are generally adequate and the costs of subtitle C controls would be substantial, continuing the exemption might be the appropriate outcome. In both cases, each individual decision criterion may not yield a definitive regulatory determination. Instead, considering the totality of the relevant factors would be most likely to yield a rational conclusion consistent with our statutory mandate. Thus, EPA will take this approach in this report and the regulatory determination to follow, which the Agency believes is consistent with the broad decision-making discretion that Congress intended EPA to exercise in making regulatory determinations for Bevill wastes.

To support each of these analytical steps, and to address data limitations, EPA performed a variety of specific analyses. These included human health and ecological risk assessment, analyses of existing federal and state regulatory programs, and economic impact analyses.

3.0 SUMMARY OF FINDINGS: COAL-FIRED UTILITY COMANAGED WASTES

Coal-fired utilities represent the largest single category of fossil fuel combustion, and likewise generate the greatest proportion of FFC wastes. Each year, utilities burn roughly 900-million tons of coal using a variety of conventional combustion technologies. Utility coal usage results in the generation of roughly 100-million tons of large-volume FFC wastes: fly ash, bottom, ash, boiler slag, and flue gas desulfurization (FGD) sludge. These wastes may be managed in landfills and surface impoundments, or, increasingly, may be applied to a variety of beneficial uses.

In addition to large volume wastes, utilities generate a variety of low-volume wastes that result from supporting processes (see Section 3.1.4) that are ancillary to the combustion and power generation processes. Low-volume wastes include the following:

- Coal pile runoff
- Coal mill rejects/pyrites
- Boiler blowdown
- Cooling tower blowdown and sludge
- Water treatment sludge
- Regeneration waste streams
- Air heater and precipitator washwater
- Boiler chemical cleaning waste
- Floor and yard drains and sumps
- Laboratory wastes
- Wastewater treatment sludge.

In 1993, EPA completed its regulatory determination on large-volume wastes from coal-fired electric utilities and independent power producers (IPPs). The regulatory determination permanently exempts large-volume FFC wastes from utilities and IPPs from hazardous waste regulation. However, the exemption only extends to large-volume wastes that are managed alone. Recent studies conducted by EPRI demonstrate that most utility operators comanage some or all of their large-volume wastes with low-volume wastes. Accordingly, remaining wastes include most utility large-volume wastes as they are actually managed.

EPA estimates that there are roughly 600 FFC waste management units operated at approximately 450 coal-fired utility power plants. These units include equal proportions of landfills and surface impoundments, with recent trends suggesting increasing preference for landfills. Nearly all of the surface impoundments are located onsite, while landfills may be onsite or offsite. Based on utility survey data, EPA estimates that more than 80 percent of these operations comanage large- and low-volume wastes.

Individual surface impoundments and landfills may comanage as many as 15 different low-volume waste streams. Surface impoundments typically comanage more different waste types (a median of eight) than do landfills (a median of four). Coal mill rejects are among the most common wastes to be comanaged in landfill and impoundments, while floor drain wastes, coal pile runoff, and water treatment wastes are also commonly disposed in comanaged waste impoundments. The total quantity of low-volume wastes managed in landfills will generally be small compared with the large-volume wastes. In surface impoundments, however, the low-volume wastes may be very large compared with the quantity

of ash disposed. This relative measure largely reflects the volume of water and not the solids content of the low-volume waste.

The size of comanaged waste units ranges from modest to very large, with some surface impoundments covering 1,500 acres or more. Median landfill and surface impoundment capacities are 3.8- and 3.4-million cubic yards, respectively.

Nearly all comanagement units operate under some sort of regulatory permit. Additionally, more than half of landfills and roughly one quarter of impoundments are lined with compacted clay, asphalt, synthetic, or other type of liner. Significantly, the newer the management unit the more likely it will possess modern environmental controls, such as liners, monitoring requirements, cover requirements, and other features.

In addition to traditional waste management in landfills and surface impoundments, utility coal combustion wastes can be used in a variety of applications. Categories of beneficial use include cement and concrete products, construction fills (including structural fill, flowable fill, and road base), agricultural uses, waste management applications, mining applications, and incorporation into other products. Overall, these uses reportedly account for nearly 30 percent of annual waste generation nationwide. Given the prevalence of comanagement, EPA believes that much of these wastes may be comanaged wastes.

In the 1988 Report to Congress and 1993 Regulatory Determination, EPA evaluated whether large-volume wastes exhibited any of the four characteristics of hazardous waste: corrosivity, reactivity, ignitability, and toxicity. EPA determined that large-volume utility coal combustion wastes are unlikely to be corrosive, reactive, or ignitable. EPA also found that metals generally are not found in leachate above the toxicity characteristic (TC) levels.

Based on limited available data, EPA concludes that comanaged wastes also generally are not corrosive, reactive, ignitable, or toxic. Available data on low-volume waste characteristics show that some low-volume wastes occasionally exhibit RCRA corrosivity (regeneration wastes, boiler chemical cleaning wastes) and RCRA toxicity (coal pile runoff, regeneration wastes, boiler chemical cleaning wastes). However, most comanaged waste units predominantly contain large-volume wastes and/or dilute low-volume waste waters, reducing the likelihood that the combined wastes will exhibit hazardous characteristics. Further, waste characterization data collected from comanaged waste landfills and impoundments show no exceedences of TC levels in any TCLP sample of comanaged wastes, and exhibit only infrequent exceedences of TC levels in *in situ* pore water samples from some impoundments.

EPA also found that coal mill rejects containing pyritic sulfur may result in the generation of acidic leachate from comanaged wastes that exceeed TC levels. In fact, most of the exceedences of TC levels observed in *in situ* pore water samples from comanaged waste impoundments appear to be associated with oxidation of pyrites contained in coal mill rejects.

EPA examined the risks associated with comanaged wastes and focused on metals as constituents of concern. The Agency used the *Composite Model for Leachate Migration with Transformation Products v1.2* (EPACMTP) to evaluate the potential risks associated with human ingestion of contaminated ground water. Additionally, EPA used an integrated, multi pathway exposure model to examine human health and ecological risks from inhalation, ingestion, and direct contact to contaminated media above ground.

EPA selected the EPACMTP to model the movement in ground water of metals of concern released from waste landfills and surface impoundments. Waste management scenarios were developed for use with EPACMTP using site-specific, industry-wide, and general nationwide information to estimate values for parameters describing waste and management unit properties (e.g., unit size, waste density), unit environmental settings (e.g., recharge rate, soil properties, ground-water velocity), and contaminant properties (e.g., retardation factors). Each scenario was used to predict the peak metals concentrations expected to occur in a nearby drinking water well during a 10,000-year study period. Comparing the predicted peak concentration with health-based benchmarks, EPA estimated the risk to an individual receptor exposed through ingestion of contaminated drinking water.

EPA calculated estimated risks for each scenario by selecting combinations of variables most likely to produce high-end (to include the 95th percentile of all possible risks) results. EPA then performed probabilistic modeling to determine where the deterministic results fell within a distribution of estimated risks. Finally, EPA performed sensitivity analyses to improve its confidence in the overall estimate of risks.

Overall, EPA found that the ground-water pathway risks associated with all modeled constituents of concern, except for arsenic, fell below a hazard quotient of 1 or a lifetime cancer risk of 1×10^{-6}. Potential risks associated with arsenic in the landfill and the surface impoundment high-end deterministic scenarios were 3×10^{-4} and 5×10^{-4}, respectively. Monte Carlo probabilistic risks for the landfill and impoundment were 4×10^{-5} and 2×10^{-5}, respectively. For arsenic, the risk for young children increased roughly 25 percent compared to the adult receptors.

EPA also considered the time at which risks were predicted to result from the release of constituents of concern in each of the scenarios. EPA found that the concentration of arsenic in ground water at the receptor well would not reach the health-based level for arsenic (e.g., achieve a risk level of 1×10^{-6}) for roughly 500 years. For the landfill, the predicted time to reach a risk of 1×10^{-6} or more was found to exceed 3,500 years.

As in the case for the ground-water risk assessment, EPA conducted a broad above-ground risk assessment to estimate potential risks associated with direct and indirect exposure to wastes and waste contaminated media. Using the Indirect Exposure Methodology (IEM), EPA estimated the concentration of constituents of concern in air, soils, and plant and animal tissues resulting from airborne and waterborne releases of comanaged wastes. EPA then estimated the human health risks associated with exposure to the contaminated media for a wide range of exposure scenarios. To provide confidence in its model results, EPA conducted sensitivity analyses for each scenario, constituent, and receptor, focusing in particular on those driving parameters for which only limited information was available.

EPA found no risks from the ingestion exposure route in excess of 10^{-6} (cancer), or with hazard quotients in excess of 1, except for arsenic in the case of agricultural applications and when managed in an onsite active landfill. For both the landfill and the impoundment, for arsenic, ingestion risks were found at the 10^{-6} level for both the farmer and the child of the farmer. In the agricultural use scenario, EPA found arsenic risks from this composite and complex pathway to be 5×10^{-5}.

EPA examined potential ecological risks from comanaged waste landfills and impoundments using the modeling results generated for the above-ground human health risk assessment. EPA compared the predicted media concentrations of metals of concern with calculated benchmark values for a wide range of ecological receptors, including mammals, birds, and amphibians, as well as collections of soil, sediment, and surface water organisms. The risk estimates for landfills and land application units suggest that ecological risks associated with the release and surface transport of chemicals of concern are not

likely to be significant for these management/use practices. The risk estimates for comanaged coal ash surface impoundments and associated drainage systems indicate that this scenario is of special concern. In particular, EPA found that the concentrations of some metals of concern (e.g., aluminum, boron, selenium) may be present in surface impoundment waters at levels well in excess of the benchmark values for amphibians, birds, and/or mammals.

EPA reviewed a range of information sources to identify possible cases of documented damages to human health or the environment arising from comanaged waste practices. EPA identified a total of six sites at which comanagement of coal combustion wastes has occurred and which meet one or more "tests of proof" for damage cases. Five of these sites were previously identified in the 1988 Report to Congress and the 1993 Regulatory Determination (58 FR 42473, 8/9/93). A sixth site was more recently identified by EPA. Detrimental effects from these sites included the presence of contaminants in drinking water wells above maximum contaminant levels (MCLs) and vegetative damage in wetlands or streams.

EPA reviewed current state regulations governing management of FFC wastes and found that states currently have more authority to impose controls on utility coal combustion waste management units than in previous years. In addition to regulatory permits, the majority of states are now able to require siting controls, liners, leachate collection systems, ground-water monitoring, closure controls, daily (or other operational) cover, and fugitive dust controls. EPA believes that the use of such controls has the potential to mitigate risks, particularly ground-water pathway risks, from comanaged waste disposal.

The utility sector in recent years has increasingly installed more environmental controls for comanaged waste facilities. Today more than one-half of the landfills and one quarter of the impoundments are lined. Other examples of in-place controls include leachate collection, ground-water monitoring, and operation under regulatory permits, each of which has a high rate of implementation at landfill management units, and significant implementation at surface impoundment management units.

EPA analyzed the costs and economic impacts of a risk mitigation alternative that would require comanaged wastes to be managed in units compliant with RCRA Subtitle D requirements. This alternative was designed to mitigate the potential ground-water human health risks found for unlined management units. The Agency also considered alternatives to mitigate the potential risk from agricultural use of these wastes, including a standard limiting the arsenic concentration in wastes intended for this use.

The alternative technology selected to target the identified risks for landfills and surface impoundments at coal-fired utilities is construction of new, composite-lined units. EPA's estimate of annualized incremental compliance cost for this alternative for the whole industry is from $800 million per year to $900 million per year, with a most likely estimate of $860 million per year. At the individual plant level, incremental compliance costs would reduce net income as a percentage of revenues by 1.5 to 2.1 percent, depending on the plant size. While this incremental cost should not affect the financial viability of coal-fired plants, EPA recognizes that such profit margin reductions may be considered significant by the individual utility. At the industry level, the total incremental cost represents 0.4 percent of the value of sales. Individual operators would likely take this effect into consideration, along with several other factors, in assessing how soon to close marginal coal plants and what type of new plants to build. This implies that a possible effect of the alternative would be a shift to alternative energy sources.

Recommendations: Coal-Fired Utility Comanaged Wastes

Following are the Agency's recommendations for the wastes covered in this chapter. The recommendations are based on EPA's analysis of the eight Congressionally mandated study factors (Section 1.2). These conclusions are subject to change based on continuing information collection, continuing consultations with other government agencies and the Congress, and comments and new information submitted to EPA during the comment period and any public hearings on this report. The final Agency decision on the appropriate regulatory status for these wastes will be issued after receipt and consideration of comments as part of the Regulatory Determination, which will be issued within 6 months.

1. *The Agency has tentatively concluded that disposal of these wastes should remain exempt from RCRA Subtitle C.*

The Agency has tentatively concluded that the comanaged wastes generated at coal-fired utilities, including petroleum coke combustion wastes as well as wastes from other fuels co-fired with coal, generally present a low inherent toxicity, are seldom characteristically hazardous, and generally do not present a risk to human health and the environment. Current management practices and trends and existing state and federal authorities appear adequate for protection of human health and the environment. State programs increasingly require more sophisticated environmental controls, and tend to focus on utility waste management due to the high waste volumes. For example, the frequency of environmental inspections at utilities is among the highest of all the major industry sectors in the United States. Most of the landfills and 40 percent of the impoundments implement ground-water monitoring, reflecting the states' focus on this industry sector. In addition, the Agency has identified relatively few damages cases. Although one damage case identified arsenic as a constituent of concern, none of the damage cases affected human receptors. These types of facilities are typically located in areas of low population and thus present infrequent opportunity for human exposure. The industry trend, as detailed in this chapter, is to line waste disposal units and to use dry ash handling techniques at new facilities; dry ash handling eliminates the use of impoundments for waste management. Currently, more than one-half of the active landfills are lined. Although one-quarter of all existing active impoundments are lined, about 45 percent of the impoundments constructed since 1975 have been lined.

If these wastes were listed as hazardous, and therefore regulated under Subtitle C, coal combustion units would be required to obtain a Subtitle C permit, which would unnecessarily duplicate existing State requirements, and would establish a series of waste unit design and operating requirements for these wastes that would most often be in excess of requirements to protect human health and the environment. The estimated total annual cost to mitigate the potential arsenic risk identified in this study exceeds $800 million. This cost does not represent implementation of full Subtitle C controls, but rather Subtitle C requirements modified by RCRA 3004(x) factors to target the identified risks. The Agency estimates that the total cost of full Subtitle C controls would be several times this amount. Full Subtitle C controls include location restrictions, manifesting, liners, leachate collection, ground-water monitoring, covers, dust control, closure controls, financial assurance, and corrective action.

For these reasons, EPA tentatively concludes that Subtitle C is inappropriate to address any problems associated with disposal of these wastes and that the continued use of site and region specific approaches by the states is more appropriate for addressing the limited human health and environmental risks that may be associated with disposal of these wastes. For the issues discussed below involving agricultural use and management of these wastes in mines (minefill), the Agency is still considering whether some regulation under RCRA Subtitle C may be warranted.

The Agency identified several situations where pyrite materials (sulfur-bearing components of mill rejects) comanaged with coal combustion wastes might have been of concern. The pyritic waste materials had turned acidic and may have caused localized environmental damage. One such situation is considered to be a damage case. While mismanagement of these pyritic wastes can theoretically cause problems because of their inherent chemical properties, such evidence is rare, and the Agency has no means of systematically evaluating the extent to which they would cause or contribute to risks. To address the problem management situations, the Agency has engaged the utility industry in a program to ensure that these particular wastes are appropriately managed, as reflected in the industry's development of technical guidance and an industry education program concerning proper management of pyritic materials. The Agency is encouraged by the industry program, and has tentatively concluded that additional regulation of pyrite disposal is not necessary. EPA, however, will follow-up with oversight on the industry's progress with management of these wastes, and will revisit this issue if necessary.

The Agency identified potential ecological risks from selenium (mammals), although potential risks were also found from arsenic (birds), aluminum (amphibians), and boron (amphibians) for coal combustion wastes that are comanaged in surface impoundments. While the waters in surface impoundments can theoretically pose risks to birds, mammals, and amphibians exposed to them, the Agency has no actual information about the scale and frequency at which receptors are actually exposed, and therefore cannot quantify the magnitude of the actual ecological impacts at these facilities. No documented or anecdotal ecological impact information was available with which to compare with the risk modeling results. Moreover, the Agency was unable to identify any feasible risk mitigation practices for these very large impoundments other than to continue to rely on the Clean Water Act new source standards to move the industry toward dry handling of the coal combustion wastes. (Dry handling methods do not involve surface impoundments and therefore do not present the ecological risks identified for impoundments.) Outright elimination of the large impoundments would impose extremely high costs on the operators. The benefits to be derived from elimination of impoundments are uncertain due to unavailability of information on actual receptor exposure rates and impacts as described above. The Agency solicits information on the practices and techniques that may be effective in mitigating the potential ecological risks, considering the large surface areas involved at these facilities.

2. *The Agency has tentatively concluded that most beneficial uses of these wastes should remain exempt from RCRA Subtitle C.*

No significant risks to human health and the environment were identified or believed to exist for any beneficial uses of these wastes, with the possible exception of minefill and agricultural use as discussed below. This is based on one or more of the following reasons for each use or resulting product: absence of identifiable damage cases, fixation of the waste in finished products which immobilizes the material, and/or low probability of human exposure to the material.

3. *The Agency is tentatively considering the option of subjecting practices involving the use of these wastes for agricultural purposes (i.e., as a soil nutrient supplement or other amendment) to some form of regulation under Subtitle C.*

As mentioned above, the Agency identified potential risk from exposure to arsenic in these wastes when they are used for agricultural purposes. The risks identified with this practice are of sufficient concern to consider whether some form of control under Subtitle C is appropriate, given the increasing trend for use of these materials as agricultural amendments. An example of such controls could include regulation of the content of these materials such that arsenic concentrations could be no higher than that found in agricultural lime. On the other hand, imposition of controls under Subtitle C may not be warranted if sufficient protection may be afforded by the Agency engaging the industry to

establish voluntary controls on this practice. An example of such voluntary controls could consist of an agreement to limit the level of arsenic in these materials. The Agency solicits comment on its tentative conclusion and specific approaches that could be pursued to address the concern. While the part 1 regulatory determination exempted all beneficial uses for the large-volume coal combustion wastes, the tentative conclusion for the comanaged wastes would also affect the status of the part 1 wastes for agricultural use. This is because the source of the identified risk is the metal content of the coal combustion wastes. The Agency has no information indicating that any of the comanaged low-volume wastes significantly affect the identified potential risks and, therefore, the risks should be comparable for the wastes subject to the part 1 regulatory determination. Additionally, the Agency considers its current risk analysis for this practice to be more thorough than that conducted for the part 1 wastes, and accordingly believes it proper to reconsider the part 1 wastes in this respect.

As indicated in the summary above, although the practice of minefilling these wastes is within the scope of this study, the Agency currently lacks sufficient information with which to adequately assess risk associated with this practice. Several factors make the practice of minefilling difficult to assess. First, minefill is occurring in areas where there are often pre-existing environmental concerns, such as acid mine drainage. With its existing data the Agency is unable to determine if elevated contaminants in ground water are due to minefill practices, or rather are associated with pre-existing problems or conditions. Second, although minefill in a surface pit has similarities to landfill situations we have modeled, both surface and subsurface minefill raises complexities beyond the landfill model. Third, these operations, with their pre-existing concerns, may require very site-specific determinations that do not lend themselves to national standards.

The Agency solicits comment on whether there are some minefill practices that are universally poor and warrant specific attention. For example, the Agency has found several situations where cement kiln dust placed in direct contact with the ground-water table has created problems. EPA specifically seeks comment on whether coal or other fossil fuel combustion wastes used as minefill and placed in direct contact with the water table would create other environmental concerns, and if that specific practice should be regulated. Last, with a few exceptions, use of these wastes as minefill is generally a recent practice and therefore long-term practices and environmental data cannot be assessed. The potential for risks associated with this practice may be of sufficient concern to consider whether some form of control under Subtitle C is appropriate, given the increasing trend for use of these materials as minefill. The Agency's focus is on potential risks that may be posed via the ground-water and surface pathways from use of these wastes as minefill. The Agency solicits additional information in the form of additional case studies of actual minefill situations, with the following types of information: minefill project design including areal extent, volumes, depth, environmental controls, mine spoils mixing ratio; characterization of combustion wastes that are involved; the background, pre-existing conditions in ground water at the mine location; and the depth to ground water at the mine location. The Agency is also interested in obtaining information on analytical modeling tools that can simulate fractured flow conditions and facilitate prediction of alkalinity consumption by acid mine drainage intrusion into the combustion wastes. The Agency will consider such comments and information in the formulation of the Regulatory Determination.

4.0 SUMMARY OF FINDINGS: NON-UTILITY COAL COMBUSTION WASTES

Coal-fired non-utilities use the same combustion technologies and fuels as coal-fired utilities. As a result, they generate the same large-volume and low-volume combustion wastes as utilities. In addition, non-utilities have the potential to generate a wide range of process wastes unrelated to the combustion of fossil fuels. These process wastes may be disposed along with combustion wastes.

Coal-fired non-utilities include a larger number of facilities than utilities. Non-utility boilers, however, are smaller in size than utility boilers and include a larger percentage of stoker (as opposed to pulverized coal) boilers. As a result, these facilities use less fuel than utilities. Non-utilities also less frequently use particulate control and flue gas desulfurization (FGD) technologies. As a result of these factors, non-utilities as a population generate much lower quantities of coal combustion waste than do utilities; large-volume coal combustion wastes at non-utilities represent about 6 percent of the amount of similar wastes generated by utilities.

EPA believes that non-utility coal combustion waste characteristics are similar to those of utility coal combustion wastes and that metals are the class of constituents of concern. A comparison of leachate concentrations of metals from the available data representing non-utility wastes suggests that differences are not significant for the purpose of evaluating risk to human health and the environment. Based on the observed similarity of non-utility and utility coal combustion wastes, EPA relied on data for comanaged utility coal combustion wastes to characterize non-utility coal combustion wastes. Comanaged waste data were chosen, rather than data representing large-volume non-utility coal combustion wastes alone, because of the high rate of comanagement at non-utilities and because the comanaged waste data are more extensive.

The predominant management practice for non-utility coal combustion waste is landfilling. Few facilities operate surface impoundments. The available data also suggest a larger proportion of offsite landfills (including commercial facilities) for non-utilities than for utilities. Comingling of large-volume coal combustion wastes and other wastes at non-utilities appears to be as common as at utilities. Low-volume combustion wastes comanaged include the same types reported for utilities, although coal mill rejects in particular are comanaged less frequently at non-utilities. Non-utilities also comingle combustion wastes with a wide variety of noncombustion wastes.

Based on the lower waste generation rates at non-utilities, non-utility landfills are expected to be much smaller than those for utility coal combustion wastes. The available data for onsite landfills suggest these units may less frequently employ environmental controls (particularly liners) than do utility landfills. No data are available on the offsite landfills that manage non-utility coal combustion wastes. Many of these units, however, are expected to be commercial industrial or municipal waste landfills that accept a variety of other wastes and are subject to state solid waste management requirements.

The available data indicate that non-utilities sometimes apply their coal combustion wastes in beneficial uses, including agricultural use and minefilling. EPA believes that nearly all of the beneficial uses applied by utilities also are applicable to non-utility wastes.

EPA modeled potential risks to human health and the environment from non-utility coal combustion wastes managed in small unlined, onsite landfills and applied to agricultural use. In assessing ground-water risks, EPA found that potential high-end risks associated with all modeled constituents of concern, except for arsenic, fell below a hazard quotient of 1 or a lifetime cancer risk of

1×10^{-6}. Potential high-end risks associated with arsenic exceeded 1×10^{-4}. EPA found, however, that the concentration of arsenic in ground water at a receptor well would not achieve a risk level of 1×10^{-6} for 1,400 years. In assessing above-ground multi-pathway risks, EPA found no plausible risks except in agricultural applications, where risks would be similar to those for utility coal combustion wastes.

EPA identified four Superfund Records of Decision involving non-utility coal combustion wastes (codisposed with other wastes). Two of these cases met the "test of proof" for a damage case. In both of these cases, noncombustion wastes are codisposed with coal combustion wastes and the source of the coal combustion waste (utility or non-utility) is unspecified. In one of these cases, the available information does not implicate, or rule out, contributing influences from coal combustion wastes. In the second case, an area used as a fly ash waste pile is identified as a potential source of risk. EPA also reviewed information for about 50 additional sites collected from conversations with state personnel and the review of facility-specific files at state offices. At these latter sites, although releases of waste have been documented and ground-water monitoring results show exceedences of standards in some cases, documentation was not available that would satisfy the "test of proof" for damage cases.

Currently 44 states (representing 87 percent of non-utility coal-fired electrical generating capacity) duplicate the federal policy exempting coal combustion wastes from hazardous waste regulation. Therefore, the majority of non-utility coal combustion wastes would be subject to state solid (non-hazardous) waste requirements because they do not fail the hazardous waste tests and/or are generated in the 44 states that duplicate the federal exemption. These requirements are expected to be essentially the same as those applicable to utility coal combustion wastes—the majority of states have the authority to require permits and to impose physical controls and monitoring requirements on non-utility landfills, at least on a case-by-case basis. The available data on waste management practices suggest that states have exercised their authority to impose controls, although perhaps to a lesser extent at non-utilities than at utilities.

EPA examined in greater detail state requirements in five states (Indiana, Pennsylvania, Wisconsin, North Carolina, and Virginia) accounting for more than 20 percent of coal-fired non-utility electrical generating capacity. EPA found that state requirements have become more stringent over time. States, however, vary in their approaches to regulating landfills that may manage non-utility coal combustion wastes. For example, programs in Indiana and Pennsylvania impose requirements tailored to the characteristics of the waste. North Carolina may impose requirements based on site-specific modeling. In Virginia, requirements apply generically to all industrial wastes. Wisconsin may modify its requirements specifically for landfills designed to receive coal combustion ash. In several of the states studied, coal combustion wastes may be disposed of in landfills that are "grandfathered" out of liner and other requirements.

EPA analyzed the costs and economic impacts of a risk mitigation alternative that would require non-utility coal combustion wastes to be managed in units compliant with RCRA Subtitle D requirements. The Agency also considered alternatives to mitigate the potential risk from agricultural use of these wastes, including a standard limiting the arsenic concentration in wastes intended for this use. EPA has not estimated the costs for such an approach, but believes they would be minimal because of the small quantity of waste that would be affected.

The risk mitigation alternative would require non-utility coal combustors that currently operate unlined landfills to construct new, composite-lined landfills or transport waste to an offsite commercial Subtitle D landfill. EPA's estimate of annualized incremental compliance cost for this alternative for all coal-fired non-utilities is $103 million per year. Facilities in the food processing, pulp and paper, chemical manufacturing, primary metals, and transportation equipment sectors would bear the majority

of these costs. The costs would affect only a small percentage of facilities in each of these sectors (i.e., those that operate coal-fired boilers) At average-sized facilities in these industries, incremental compliance costs would represent 0.2 percent to 0.5 percent of facility sales, depending on the industry. At large facilities in each sector, which are more likely those that operate coal-fired boilers, incremental compliance costs would represent 0.1 percent or less of facility sales. This should not affect the financial viability of individual plants. At the industry level, the total incremental cost represents an even smaller percentage of sales because of the small number of facilities affected compared to the total number in each industry sector.

Recommendations: Non-Utility Coal Combustion Wastes

Following are the Agency's recommendations for the wastes covered in this chapter. The recommendations are based on EPA's analysis of the eight Congressionally mandated study factors (Section 1.2). These conclusions are subject to change based on continuing information collection, continuing consultations with other government agencies and the Congress, and comments and new information submitted to EPA during the comment period and any public hearings on this report. The final Agency decision on the appropriate regulatory status for these wastes will be issued after receipt and consideration of comments as part of the Regulatory Determination, which will be issued within 6 months.

1. *The Agency has tentatively concluded that disposal of these wastes should remain exempt from RCRA Subtitle C.*

As with the utility coal combustion wastes addressed in Chapter 3, the Agency has tentatively concluded that the non-utility CCWs, including wastes from petroleum coke combustion and from other fuels that are co-fired with coal, and also low-volume wastes where they are managed with the combustion wastes, generally present a low inherent toxicity, are seldom characteristically hazardous, and generally do not present a risk to human health and the environment. State programs increasingly require more sophisticated environmental controls at these types of facilities. There are few damage cases and none of the identified damage cases exclusively involved these wastes or affected human receptors. These types of facilities are typically located in areas of low population and thus present infrequent opportunity for human exposure. The Agency believes that no significant ecological risks are posed by disposal of these wastes. The predominant practice is to manage these wastes in landfills, with a much lower frequency of using impoundments. Environmental controls are common at the landfills. For example, nearly all implement ground-water monitoring and runoff controls, and two-thirds have leachate collection. Overall, the Agency believes that when these wastes are disposed, regulation under Subtitle C authority is not warranted. For the issues discussed below involving agricultural use and management of these wastes in mines (minefill), the Agency is still considering whether some regulation under RCRA Subtitle C may be warranted.

There is a very small segment of non-utility coal burners that generates mill rejects, a low-volume waste, that may be comanaged with the CCWs. The Agency has the same concerns about the potential for problem management situations involving pyritic materials as described for utilities in Chapter 3. Although the Agency did not identify any of these situations at non-utility facilities during this study, it is engaging the non-utility sector in a program to ensure that these particular wastes are appropriately managed. This effort parallels the pyrites management program described for utilities in Chapter 3. EPA will follow-up with oversight on the industry's management of these wastes, and will revisit this issue if necessary.

2. *The Agency has tentatively concluded that most beneficial uses of these wastes should remain exempt from Subtitle C.*

No significant risks to human health and the environment were identified or believed to exist for any beneficial uses of these wastes, with the possible exception of minefill and agricultural use as discussed below. This is based on one or more of the following reasons for each use or resulting product: absence of identifiable damage cases, fixation of the waste in finished products which immobilizes the material, and/or low probability of human exposure to the material.

3. The Agency is tentatively considering the option of subjecting practices involving the use of these wastes for agricultural purposes (i.e., as a soil nutrient supplement or other amendment) to some form of regulation under Subtitle C.

As mentioned above, the Agency identified potential risk from exposure to arsenic in these wastes when they are used for agricultural purposes. The risks identified with this practice may be of sufficient concern to consider whether some form of control under Subtitle C is appropriate, given the increasing trend for use of these materials as agricultural amendments. An example of such controls could include regulation of the content of these materials such that arsenic concentrations could be no higher than that found in agricultural lime. On the other hand, imposition of controls under Subtitle C may not be warranted if sufficient protection may be afforded by the Agency engaging the industry to establish voluntary controls on this practice. An example of such voluntary controls could consist of an agreement to limit the level of arsenic in these materials. The Agency solicits comment on its tentative conclusion and specific approaches that could be pursued to address the concern.

Non-utility burners of coal, particularly those that generate significant quantities of combustion wastes, may have opportunities for their wastes to be minefilled, that is, permanently placed in mine voids similar to the practice with some utility combustion wastes. As discussed in Chapter 3, the Agency currently lacks sufficient information with which to adequately assess risk associated with this practice and, therefore, to decide whether this practice should remain exempt from Subtitle C. For the same reasons discussed in Chapter 3's recommendations, the Agency solicits comment on whether there are some minefill practices that are universally poor and warrant specific attention. EPA also seeks comment on whether coal or other fossil fuel combustion wastes used as minefill and placed in direct contact with the water table would create environmental concerns, and if that specific practice should be regulated. The Agency's focus is on potential risks that may be posed via the ground-water and surface pathways from use of these wastes as minefill.

5.0 SUMMARY OF FINDINGS: FLUIDIZED BED COMBUSTION WASTES

Fluidized bed combustion (FBC) is an emerging technology for the combustion of fossil and other fuels. In FBC processes, fuel is burned on a bed of incombustible material (e.g., sand and limestone) while combustion air is forced upward at high velocities, making the particles flow as a fluid. Coal is the most common fossil fuel burned by FBC facilities, although some facilities burn waste coal, petroleum coke, or other fuels. The bed material often includes a sorbent, such as limestone, that allows the capture of sulfur oxides without the end-of-stack scrubbers often required for conventional coal combustion processes.

FBC makes up only a small portion of the fossil fuel combustion universe—approximately 1 percent of fossil fuel-fired capacity. As of December 1996, there were 84 facilities with 123 FBC boilers representing 4,951 megawatts of equivalent electrical generating capacity (CIBO, 1997). Together, these facilities generated more than 9-million short tons of FBC wastes, or roughly 10 percent of the volume of FFC wastes generated by conventional coal-fired utilities.

Like conventional coal boilers, FBC boilers generate fly ash and bottom ash (called bed ash). FBC fly ash and bed ash contain noncombustible mineral matter, sorbent material, and unburned carbon. The major constituents of FBC waste are calcium, sulfur, silicon, iron, aluminum, magnesium, and potassium. As with conventional coal combustion waste, most of these constituents are present in the form of oxides. Due to the presence of sorbent material, however, FBC wastes have a higher content of calcium and sulfate and a lower content of silica and alumina than conventional coal combustion wastes (CIBO, 1997).

Based on the TCLP and EP data, FBC wastes rarely exhibit RCRA characteristic toxicity. Only one FBC site of 24 (4 percent) for which data are available had any samples of waste for which TCLP or EP analyses exceeded the regulatory threshold any metal. At that site, a facility that burns waste coal, one sample of fly ash exceeded the threshold for mercury. Similarly, no sample from seven sites analyzed for organics exceeded a threshold value.

The Council of Industrial Boiler Owners (CIBO) report that landfilling is the most common FBC waste disposal practice. While four FBC waste surface impoundments have been identified, EPA believes the impoundments represent unusual cases. FBC waste landfills are smaller than conventional utility landfills, with a median fill capacity of 1.5-million cubic yards. Nearly all of the landfills for which data are available are permitted disposal units, and roughly half of the landfills are lined.

Like conventional coal combustion wastes, FBC wastes may be applied to useful purposes as an alternative to traditional waste management. In fact, according to CIBO survey statistics, the majority of FBC wastes currently are beneficially used. The most dominant use of these wastes is in minefills (61 percent), followed by waste stabilization (6 percent), construction fills (5 percent), and agricultural uses (1 percent). Overall, roughly 75 percent of all FBC wastes may be beneficially reused.

As with coal-fired utility comanaged wastes, EPA examined the potential human health and ecological risks associated with the disposal of FBC wastes. For the ground-water exposure pathway, EPA modeled the risks associated with landfills. Overall, EPA found that the risks associated with all modeled constituents of concern, except for antimony, arsenic, beryllium, and chromium, fell below a hazard quotient of 1 or a lifetime cancer risk of 1×10^{-6}. Potential risks associated with arsenic in the

high-end deterministic scenario exceeded 1×10^{-4}. Probabilistic results for all of these metals were more than 1 order of magnitude lower than the deterministic results at the same confidence level.

EPA also considered the time at which risks were predicted to result from the release of constituents of concern. EPA found that the concentration of arsenic in ground water at the receptor well would not reach the health-based level for arsenic (i.e., achieve a risk level of 1×10^{-6}) for more than 3,000 years. The times to reach the antimony health-based level and the beryllium MCL in ground water were predicted to be nearly 6,000 years and greater than 6,500 years, respectively.

EPA found no ingestion risks in the above-ground human health risk assessment except for the FBC agricultural use scenario. In the agricultural use scenario, EPA found arsenic risks from this composite and complex pathway to be at five times the 10^{-5} level, for both the farmer and the child of farmer receptors.

EPA found no ecological risks associated with FBC wastes. In addition, EPA found no documented cases of damage associated with FBC waste management.

EPA reviewed current state regulations governing management of FFC wastes and found that states currently have more authority to impose controls on UCCW management units than in previous years. In addition to regulatory permits, the majority of states are now able to require siting controls, liners, leachate collection systems, ground-water monitoring, closure controls, daily (or other operational) cover, and fugitive dust controls. EPA believes that the use of such controls has the potential to mitigate risks, particularly ground-water pathway risks, from comanaged waste disposal.

States increasingly have begun to impose controls on FBC waste management units. In addition to regulatory permit programs, the majority of states now have the authority to require siting controls, liners, leachate collection systems, ground-water monitoring, closure controls, daily or other operational cover, and fugitive dust controls for management of these wastes.

EPA analyzed the costs and economic impacts of a risk mitigation alternative that would require FBC wastes that are currently disposed of to be managed in units compliant with RCRA Subtitle D requirements. The Agency also analyzed the cost of a ban on minefilling and agricultural use for FBC wastes, requiring wastes currently destined for these uses also to be managed in Subtitle D units.

The risk mitigation alternative would require FBC facilities that currently operate unlined landfills to construct new composite-lined landfills or transport waste to an offsite commercial Subtitle D landfill. EPA's estimate of annualized incremental compliance cost for this alternative for all FBC facilities is $32 million per year for currently disposed quantities of waste. If the quantities of FBC waste currently used in minefilling and agricultural applications also were subject to the Subtitle D-based alternative, the additional incremental compliance cost would be an estimated $52 million per year (for a total of some $84 million per year). Other approaches, such as a limit on the arsenic concentration in FBC wastes destined for agricultural use, would substantially reduce this latter cost.

EPA analyzed economic impacts *excluding* costs for quantities currently used in minefilling and agriculture. Half of the potentially affected FBC facilities are in the electric service industry (i.e., independent power producers and utilities). At individual facilities in this sector, incremental compliance costs would reduce net income as a percentage of revenues by 1.4 percent to 1.7 percent, depending on the plant size. While this incremental cost should not affect the financial viability of coal-fired plants, EPA recognizes that such profit margin reductions may be considered significant by the individual firm. At the industry level in the electric service sector, the total incremental cost represents

0.3 percent of the value of sales. In other industrial/institutional sectors, FBC facilities represent an even smaller share of their industries than do conventional non-utility combustors. Thus, individual facility impacts and industry level impacts in these sectors would be similar to or less than those discussed for coal-fired non-utilities.

Recommendations: Fluidized Bed Combustion Wastes

Following are the Agency's recommendations for the wastes covered in this chapter. The recommendations are based on EPA's analysis of the eight Congressionally mandated study factors (Section 1.2). These conclusions are subject to change based on continuing information collection, continuing consultations with other government agencies and the Congress, and comments and new information submitted to EPA during the comment period and any public hearings on this report. The final Agency decision on the appropriate regulatory status for these wastes will be issued after receipt and consideration of comments as part of the Regulatory Determination, which will be issued within 6 months.

1. *The Agency has tentatively concluded that disposal of these wastes should remain exempt from RCRA Subtitle C.*

As with the utility and non-utility coal combustion wastes addressed in Chapters 3 and 4, the Agency has tentatively concluded that FBC wastes, including wastes from petroleum coke combustion and from other fuels that are co-fired with coal, and also low-volume wastes where they are managed with the combustion wastes, generally present a low inherent toxicity, are seldom characteristically hazardous, and generally do not present a risk to human health and the environment. State programs increasingly require more sophisticated environmental controls at these types of facilities. For example, most all of the FBC landfills are subject to regulatory permits and ground-water monitoring requirements; nearly all implement dust suppression and runon/runoff controls. No documented damage cases were identified and no significant ecological risks were identified. These types of facilities are typically located in areas of low population and thus present infrequent opportunity for human exposure. Although arsenic was identified from EPA modeling to pose a potential risk at unlined landfills, there were no documented problem or damage cases identified with arsenic as a constituent of concern. The predominant practice is to manage these wastes in landfills, with a much lower frequency of using impoundments. Nearly half of the landfills are lined and more than half have leachate collection systems and covers. Overall, the Agency believes that regulation under Subtitle C authority is not warranted when these wastes are disposed. For the issues discussed below involving agricultural use and management of these wastes in mines (minefill), the Agency is still considering whether some regulation under RCRA Subtitle C may be warranted.

2. *The Agency has tentatively concluded that most beneficial uses of these wastes should remain exempt from Subtitle C.*

No significant risks to human health and the environment were identified or believed to exist for any beneficial uses of these wastes, with the possible exception of minefill and agricultural use as discussed below. This is based on one or more of the following reasons for each use or resulting product: absence of identifiable damage cases, fixation of the waste in finished products which immobilizes the material, and/or low probability of human exposure to the material.

3. The Agency is tentatively considering the option of subjecting practices involving the use of these wastes for agricultural purposes (i.e., as a soil nutrient supplement or other amendment) to some form of regulation under Subtitle C.

As mentioned above, the Agency identified potential risk from exposure to arsenic in these wastes when they are used for agricultural purposes. The risks identified with this practice may be of sufficient concern to consider whether some form of control under Subtitle C is appropriate, given the increasing trend for use of these materials as agricultural amendments. An example of such controls could include regulation of the content of these materials such that arsenic concentrations could be no higher than that found in agricultural lime. On the other hand, imposition of controls under Subtitle C may not be warranted if sufficient protection may be afforded by the Agency engaging the industry to establish voluntary controls on this practice. An example of such voluntary controls could consist of an agreement to limit the level of arsenic in these materials. The Agency solicits comment on its tentative conclusion and specific approaches that could be pursued to address the concern..

A significant amount of FBC waste, about 60 percent, is used for minefill. Of this amount, large quantities are used specifically for reclamation of old surface coal mine working. EPA recognizes that mine reclamation practices with the highly alkaline FBC wastes can have some significant, positive environmental benefits. For example, the FBC wastes contribute to neutralizing acid mine drainage at the old mine workings, and when mine reclamation activities are completed, new productive uses may be made of the land. The Agency also realizes that there are a number of well-managed state mine reclamation programs that oversee the application of FBC wastes. RCRA, however, does require the Agency to review the management of these wastes. As discussed in Chapter 3's recommendations, the potential for risks associated with this practice may be of sufficient concern to consider whether some form of control under Subtitle C is appropriate, given the increasing trend for use of these materials as minefill. The Agency, however, currently lacks sufficient information with which to adequately assess risk associated with this practice and therefore to decide whether this practice should remain exempt from Subtitle C. The Agency solicits comment on whether there are some minefill practices that are universally poor and warrant specific attention. For example, the Agency has found several situations in which cement kiln dust placed in direct contact with the ground-water table has created problems. EPA also seeks comment on whether coal or other fossil fuel combustion wastes used as minefill and placed in direct contact with the water table would create environmental concerns, and if that specific practice should be regulated. The Agency's focus is on potential risks that may be posed via the ground-water and surface pathways from use of these wastes as minefill.

6.0 SUMMARY OF FINDINGS: OIL COMBUSTION WASTES

Oil combustion wastes (which include fly ash and bottom ash) are generated in significant quantities only when residual fuel oil is burned in oil-fired steam electric boilers. Other technologies (e.g., combustion turbines) and fuels (e.g., distillate oil) generate little or no wastes. Overall, oil combustion wastes are generated in much smaller quantities than other large-volume fossil fuel combustion wastes. Oil-fired utilities, as opposed to non-utilities, generate the majority (more than 80 percent) of these wastes. The majority of oil combustion waste generation and management also takes place in the Northeast, mid-Atlantic, and Florida, consistent with the use of oil by utilities to provide baseload power supplies in these regions.

Metals are the class of constituents of concern in oil combustion wastes. These wastes can contain high levels of vanadium and nickel, and varying levels of other metals. Oil combustion wastes, however, only infrequently exhibit the RCRA characteristic of toxicity (6 percent of available samples). Exceedences for arsenic, cadmium, chromium, lead, and/or selenium were observed in at least one sample from seven (or 18 percent) of the 40 sites for which data were available.

The common management practices at oil-fired utilities include onsite settling basins and offsite landfills, with a few onsite landfills (monofills managing only oil combustion wastes) represented. The most common practice for oil bottom ash is to collect it dry and transport it to an offsite landfill. Fly ash, on the other hand, typically is sluiced wet to an onsite solids settling basin (SSB) where it is managed along with low-volume liquid wastes such as equipment washwaters and boiler chemical cleaning wastes. Solids from these basins are typically dredged on an "as-needed" basis and transported to an offsite landfill. Oil combustion wastes have not been used extensively for beneficial use applications similar to those reported for other fossil fuel combustion wastes. Several oil-fired utilities, however, have reported sending their waste offsite for vanadium recovery as an alternative to offsite landfilling, when economically viable.

Oil combustion waste management units typically are much smaller than those for utility coal combustion wastes. About two-thirds of the SSBs for which data were available are lined. The unlined SSBs are percolation basins permitted under state regulations to discharge to ground water. Limited data for SSBs suggest a trend toward the increasing use of liners. The few onsite landfills observed are lined or partially lined. No data are available on the offsite landfills that manage oil combustion wastes. Because of the small quantities of oil combustion waste generated, however, these units are expected to be commercial industrial or municipal waste landfills that accept a variety of other wastes and are subject to state solid waste management requirements.

EPA modeled potential risks to human health and the environment from oil combustion wastes managed in small, unlined landfills and surface impoundments (solid settling basins). In assessing ground-water risks, EPA found that potential high-end risks associated with arsenic exceeded 1×10^{-5}. For nickel and vanadium, potential high-end hazard quotients exceeded 1. In assessing above-ground multi-pathway risks, EPA found a potential risk at the low 10^{-6} level for arsenic ingestion for a child living near an onsite landfill. No non-groundwater risks were found for the solid settling basins.

EPA identified a total of nine sites managing oil combustion wastes that have ground-water contamination. Only one of these sites, however, met the test of proof for a damage case. The level of contamination at these sites was not always above MCLs or other state standards. In no case was there evidence that the contaminated ground-water is used as drinking water.

Only 26 states extend the federal exemption from hazardous waste requirements to oil combustion wastes. These 26 states, however, represent more than 80 percent of oil-fired utility capacity and, therefore, the majority of waste generation. These states vary in their application of solid (non-hazardous) waste management requirements to oil combustion waste management units. EPA examined state requirements in the states accounting for the greatest share of oil-fired utility capacity (Florida, New York, Massachusetts, and Pennsylvania). EPA found that, in two of these states, oil combustion wastes may be disposed of in landfills that are "grandfathered" out of liner and other requirements. Three of the four states do not impose specific design requirements on the solids settling basins typically used to store oil combustion wastes. Two of these states permit discharges to ground water from these units.

EPA analyzed the costs and economic impacts of a risk mitigation alternative that would require oil combustion wastes to be managed in units compliant with RCRA Subtitle D requirements. Most significantly, this alternative would require oil-fired utilities that currently operate unlined solids settling basins to construct new, composite-lined basins. EPA's estimate of annualized incremental compliance cost for this alternative for the whole industry is from $1.0 million per year to $3.5 million per year, with a most likely estimate of $1.7 million per year. At the individual plant level, incremental compliance costs would reduce net income as a percentage of revenues by 0.1 percent to 0.4 percent, depending on the plant size. This reduction should not affect the financial viability of individual oil-fired plants. At the industry level, the total incremental cost represents less than one-tenth of 1 percent of the value of sales. Thus, the cost of compliance would be a very small percentage of revenues.

Recommendations: Oil Combustion Wastes

Following are the Agency's recommendations for the wastes covered in this chapter. The recommendations are based on EPA's analysis of the eight Congressionally mandated study factors (Section 1.2). These conclusions are subject to change based on continuing information collection, continuing consultations with other government agencies and the Congress, and comments and new information submitted to EPA during the comment period and any public hearings on this report. The final Agency decision on the appropriate regulatory status for these wastes will be issued after receipt and consideration of comments as part of the Regulatory Determination, which will be issued within 6 months.

1. *The Agency is considering two approaches to address the potential risks that may be posed by disposal of these wastes. One approach would be regulatory using Subtitle C authority and the other would be to encourage voluntary changes in industry practices.*

The Agency found in many cases that OCWs, whether managed alone or comanaged with low-volume wastes, are seldom characteristically hazardous and may not present a significant risk to human health and the environment. These cases include situations in which the wastes are managed in lined units with adequate cover. The Agency believes that no significant ecological risks are posed by disposal of these wastes. Only one damage case was identified and it did not affect human receptors.

In light of the results of EPA's risk assessment, however, the Agency is concerned about situations in which the wastes are managed in unlined units, particularly comanagement in settling basins and impoundments that are designed and operated to discharge to ground water. As discussed in this chapter, the Agency's risk analysis suggests that three metals may pose potential ground-water pathway risks at such facilities: arsenic, nickel, and vanadium. While there is a trend in recent years to line new units and the Agency has anecdotal information that some facilities are preparing to either line or close their unlined units, the Agency has particular concerns with the high levels of nickel and vanadium in the wastes and in the leachate that is being discharged to ground water. The Agency's risk analysis

identified high hazard quotients and short time periods to exceedence of health-based risk criteria at potential ground-water receptor locations for nickel and vanadium. The risks identified with these practices may be of sufficient concern to consider whether tailored regulations are necessary to target the potential risks. On the other hand, since the recent industry and state regulatory trends have been toward liners and ground-water monitoring for these waste disposal units, sufficient protection may be obtained by facilitating this trend and engaging the industry to voluntarily establish the appropriate controls. An example would be to line the existing unlined units and, where appropriate, to implement ground-water monitoring. The Agency solicits comment on its tentative conclusion, specific approaches that could be pursued to address these concerns, and the identification of only one damage case.

2. *The Agency has tentatively concluded that the existing beneficial uses of these wastes should remain exempt from Subtitle C.*

There are few existing beneficial uses of these wastes, which include components of cement, concrete, and construction fill as discussed in this chapter. No significant risks to human health exist for the identified beneficial uses of these wastes. This is based on one or more of the following reasons for each use: absence of identifiable damage cases, fixation of the waste in finished products which immobilized the material, and/or low probability of human exposure to the material. In the case of vanadium recovery operations, a valuable product is being produced; however, if the wastes resulting from the metal recovery processes are hazardous, they will be subject to the existing hazardous waste requirements.

Unlike coal combustion wastes, these wastes are not known to be used in minefill or agricultural applications. These wastes are not generated at rates high enough to justify their transport and use for filling mine voids. There are no known benefits to using these wastes for agricultural purposes.

7.0 SUMMARY OF FINDINGS: NATURAL GAS COMBUSTION WASTES

Natural gas is the second most significant fossil fuel used by utilities in the United States. In 1996, gas-fired units accounted for approximately 20 percent of utility generating capacity, but only 9 percent of utility electricity generated. This generation rate represents a decline of 15 percent from the level reported in 1995 due in part to a substantial increase in the cost of gas in 1996. (Use of hydroelectric, oil-fired, and geothermal sources increased in 1996 to make up for the decrease in use of gas) (EIA, 1998). Many gas-fired units are used to generate power during periods of peak demand.

Gas-fired units generate virtually no solid waste. Thus, although a significant portion of capacity is represented by gas combustors, this study does not include extensive analysis of natural gas combustors. The Agency intends to continue the exemption from Resource Conservation and Recovery Act (RCRA) Subtitle C for gas combustors.

Natural gas combustion accounts for a substantial fraction of both utility and non-utility generating capacity. Natural gas combustion technologies are similar to those used for oil combustion. In gas-fired steam electric boilers, gas is injected into the furnace in the presence of excess air. The same burner designs used for oil also are used to inject and combust natural gas. In fact, many combustion units can utilize either oil or gas. Unlike oil, natural gas does not require preparation (atomization) for mixing with combustion air (Stultz and Kitto, 1992). Because of its negligible ash content, combustion of natural gas generates virtually no solid waste; therefore, this study focuses primarily on coal-fired and oil-fired combustors.

Recommendations: Natural Gas Combustion Wastes

Following are the Agency's recommendations for the wastes covered in this chapter. The recommendations are based on EPA's analysis of the eight Congressionally mandated study factors (Section 1.2). These conclusions are subject to change based on continuing information collection, continuing consultations with other government agencies and the Congress, and comments and new information submitted to EPA during the comment period and any public hearings on this report. The final Agency decision on the appropriate regulatory status for these wastes will be issued after receipt and consideration of comments as part of the Regulatory Determination, which will be issued within 6 months.

1. *The Agency has tentatively concluded that it will retain the Subtitle C exemption for natural gas combustors.*

The Agency has tentatively concluded that it will retain the Subtitle C exemption for natural gas combustors. The Agency solicits comment on whether it is appropriate to retain or remove the Subtitle C exemption for natural gas combustion since there are no solid wastes generated by the process.

REFERENCES

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GLOSSARY*

ACAA – American Coal Ash Association.

air heater or **air preheater** – device that uses flue gases to preheat combustion input air.

air heater and precipitator washwater – wastes resulting from the periodic cleaning of the fireside (i.e., the side exposed to hot combustion products) of heat exchanging surfaces.

air monitoring system – periodic collection and analysis of air samples near a waste management unit.

alkalinity – the amount of carbonates, bicarbonates, hydroxides, and silicates or phosphates in a liquid. Reported as grains per gallon, pH, or parts per million of carbonate. Indicated by a pH of greater than 7.

anthracite – a hard black lustrous rank of coal (see coal rank).

APC – air pollution control.

ash – incombustible material in fuel that can become waste after combustion.

ash fusion temperature – the temperature at which a cone of coal or coke ash exhibits certain melting characteristics.

ASTM – American Society for Testing and Materials.

ASTSWMO – Association of State and Territorial Solid Waste Management Officials.

backfill – a project in which an excavation area is refilled with earth or other materials.

BACT – Best Available Control Technology under the Clean Air Act.

baghouse – an air pollution abatement device used to trap particulates by filtering gas streams through large fabric bags usually made of glass fibers.

baseload – that portion of electricity demand from a station or boiler that is practically constant for long periods.

baseload unit – an electrical generating unit that is used to supply baseload, and thus is operated continuously at an essentially constant rate.

BAT – Best Available Technology Economically Achievable under the Clean Water Act.

bed ash – spent bed material and fuel ash (bottom ash) that settle on the bottom of an FBC boiler.

bituminous coal – A common dense black rank of coal (see coal rank).

* References for this glossary include EIA, 1997d; EPA, 1988; CIBO, 1997c, and Stultz and Kitto, 1992.

BMP – best management practice under the Clean Water Act.

boiler – a closed vessel in which heat from an external combustion source (such as a fossil fuel) is transferred to produce hot water or generate steam.

boiler blowdown – waste generated by removal of a portion of boiler water for the purpose of reducing solid concentration or discharging sludge.

boiler chemical cleaning waste – waste resulting from the cleaning of boiler surfaces using chemical solutions.

boiler slag – melted and fused particles of ash that collect on the bottom of the boiler. Slag forms when operating temperatures exceed ash fusion temperature.

bottom ash – large ash particles that settle on the bottom of a boiler. Bottom ash does not melt and therefore remains in the form of unconsolidated ash.

BPT – Best Practicable Control Technology Currently Available under the Clean Water Act.

Btu – British Thermal Unit, a unit of heat energy.

bubbling fluidized bed system – a fluidized bed combustion system in which excess air passes through the bed in the form of bubbles. These systems have air velocities of 5 to 12 feet per second and larger bed particle size than circulating fluidized bed systems. These conditions result in a dense bed (45 pounds per cubic foot) with a well-defined surface.

Bunker C fuel oil – a residual fuel oil, also characterized as No. 6 fuel oil, which is used for commercial and industrial heating, electricity generation, and to power ships.

CAA – Clean Air Act.

CCW – coal combustion waste.

CERCLA – the Comprehensive Environmental Response, Compensation, and Liability Act, commonly referred to as Superfund.

CIBO – Council of Industrial Boiler Owners.

circulating fluidized bed system – a fluidized bed system that has high air velocities (as high as 30 feet per second) and fine particle sizes. As a result, the fluid bed is less dense (35 pounds per cubic foot) and has no well-defined top surface. Large quantities of bed material are recaptured from the gas stream and recirculated back to the furnace to maintain bed inventory.

CMTP – Composite Model for Leachate Migration with Transformation Products.

coal cleaning – the act of processing coal prior to combustion to change its characteristics (e.g., size, ash content, and/or sulfur content).

coal pile runoff – surface water runoff produced by precipitation falling on coal storage areas.

coal mill rejects – solid waste produced by onsite processing of coal in a mill prior to use.

coal rank – a system of classifying coal corresponding to its degree of metamorphism, geologic age, and heating value. Ranks include anthracite, bituminous, subbituminous, and lignite, with anthracite being the oldest and lignite being the youngest.

cogeneration – the production of electricity and another form of useful thermal energy (steam or hot water) from a single source.

combustion turbine (CT) – a system that uses exhaust from combustion (typically of oil or natural gas) directly to drive turbines.

compaction – the act of compacting waste after placement to reduce or prevent wind and water erosion of the waste and subsequent release to the environment.

condenser – a device that converts low-pressure steam back to water by transferring heat to a cooling water system.

cooling tower/cooling pond – recirculating cooling water system used to transfer heat picked up in the condenser to the atmosphere by evaporative cooling.

cooling tower basin sludge – solids that collect in the bottom of cooling towers and must be removed periodically and disposed.

cooling tower blowdown – water withdrawn from the cooling system in order to control the concentration of impurities in the cooling water.

corrosivity – see RCRA Subtitle C characteristics.

cover – a barrier placed on top of a waste management unit.

culm – refuse from the cleaning of anthracite coal.

CWA – Clean Water Act.

cyclone furnace – A combustion technology that creates a cyclone-like air circulation pattern causing smaller particles to burn in suspension, while larger particles adhere to a molten layer of slag that forms on the barrel walls.

demineralizer regenerant and rinses – see regeneration waste streams.

dioxin – general term for polychlorinated dibenzo-p-dioxins (PCDDs), a class of toxic chemicals.

distillate fuel oil – one of the petroleum fractions produced in conventional distillation operations. Included are products known as No. 1, No. 2, and No. 4 fuel oils.

dry scrubber – a flue gas desulfurization system in which the resulting byproduct is a dry, typically fine, powder.

dust suppression/control – conditioning waste with water or other liquid before and during transport and placement to prevent airborne transport of the waste and to reduce inhalation exposure to site workers.

economizer – a device for transferring heat from combustion exhaust to boiler input water.

EEI – Edison Electric Institute.

EEI database – 1994 EEI Power Statistics Database.

EIA – The U.S. Department of Energy's Energy Information Association.

electrostatic precipitator (ESP) – an air pollution control device that imparts an electrical charge to particulates in a gas stream, causing them to collect on an electrode.

EP – Extraction Procedure.

EPACMTP – EPA's Composite Model for Leachate Migration with Transformation Products.

EPRI – Electric Power Research Institute.

fabric filter – see baghouse.

FGD – flue gas desulfurization.

flue gas – the gaseous products of combustion that exit a boiler through a flue or stack.

flue gas desulfurization (FGD) technology – device that is used to remove sulfur oxides from flue gas after combustion.

flue gas desulfurization (FGD) waste – waste that is generated during the process of removing sulfur oxide gas from the flue gas after combustion.

fluidized bed combustion (FBC) – a combustion process in which fuel is burned on a bed of incombustible material (e.g., sand and limestone) while combustion air is forced upward at high velocities, making the particles flow as a fluid.

fly ash – suspended, uncombusted ash particles carried out of the boiler along with flue gases.

fossil fuel – a naturally occuring organic fuel, including coal, oil, and natural gas.

Furan – general term for polychlorinated dibenzofurans (PCDFs), a class of toxic chemicals.

generating unit – a combination of one or more boilers operated together to produce electricity or other useable thermal energy. May include one or more turbines, fuel processing systems, and/or air pollution control devices.

gigawatt (GW) – one billion watts.

gob – refuse from the cleaning of bituminous coal.

ground water monitoring system – one or several wells from which samples of ground water are periodically collected and analyzed.

HAP – Hazardous Air Pollutant under the Clean Air Act.

HDPE – high density polyethylene.

ignitability – see RCRA Subtitle C characteristics.

kilowatt (kW) – one thousand watts.

landfill – a facility or part of a facility in which wastes are placed for disposal in or on land.

leachate – the liquid resulting from water percolating through waste.

leachate collection system – a series of drains and tubing placed beneath a waste management unit, typically a landfill, that collect leachate for treatment or disposal.

lift – the depth of a cell in a landfill.

lignite – a brownish-black rank of coal (see coal rank).

lime – calcium oxide (CaO).

limestone – calcium carbonate ($CaCO_3$).

liner – a barrier placed underneath a landfill or on the bottom and/or sides of a surface impoundment.

MCL – maximum contaminant level.

mechanical collector – an air pollution control device that forces a cyclonic flow of the exit gas. This flow causes ash particles to be thrown against the walls of the collector and drop out of the gas.

megawatt (MW) – one million watts.

minefill – a project involving placement of fossil fuel combustion wastes in mine voids, whether for purposes of disposal or for beneficial uses such as mine reclamation.

monofill – a landfill that contains only one type of waste.

NAAQS – National Ambient Air Quality Standards under the Clean Air Act.

natural gas – a fossil fuel consisting of a mixture of hydrocarbon and nonhydrocarbon gases found beneath the Earth's surface.

NESHAP – National Emissions Standards for Hazardous Air Pollutants under the Clean Air Act.

No. 1 fuel oil – A light distillate fuel oil intended for use in vaporizing pot-type burners.

No. 2 fuel oil – A distillate fuel oil for use in atomizing-type burners for domestic heating or for moderate capacity commercial-industrial burner units.

No. 4 fuel oil – a fuel oil for commercial burner installations not equipped with preheating facilities. It is used extensively in industrial plants. This grade is a blend of distillate fuel oil and residual fuel oil stocks.

No. 5 fuel oil – a residual fuel oil of medium viscosity.

No. 6 fuel oil – a residual fuel oil used for commercial and industrial heating, electricity generation, and to power ships. Includes Bunker C fuel oil.

non-utility – for purposes of this study, an entity that combusts fossil fuel and whose primary commercial activity is not the production of electricity (see utility).

NPDES – National Pollution Discharge Elimination System under the Clean Water Act.

NSPS – New Source Performance Standards under either the Clean Water Act or Clean Air Act.

OCW – oil combustion waste.

particulates – fine liquid or solid particles such as dust, smoke, mist, fumes, or smog, found in the air or emissions.

PCB – polychlorinated biphenyls, a class of toxic chemicals.

PCDD – polychlorinated dibenzo-p-dioxin.

PCDF – polychlorinated dibenzofuran.

PDWS – Primary Drinking Water Standards established by the Safe Drinking Water Act.

peakload – the maximum electricity demand from a facility or boiler that occurs during a specified period of time.

peakload unit or peaking unit – an electrical generating unit that is used to supply peakload, and thus is used intermittently during periods of high demand.

percolation basin – a surface impoundment in which liquids are allowed to discharge (percolate) into the ground.

petroleum coke – solid carbaceous residue remaining in oil refining stills after the distillation process.

PM – particulate matter.

pore water – interstitial water from borings of waste managed in surface impoundments.

POTW – Publicly Owned Treatment Works.

pozzolanic – forming a strong, slow-hardening cement-like substance when mixed with lime or other hardening material.

PSD – prevention of significant deterioration under the Clean Air Act.

PSES – Pretreatment Standards for Existing Sources under the Clean Water Act.

pulverized coal (PC) boiler or pulverizer – a combustion technology that burns finely ground coal in suspension.

PVC – polyvinyl chloride.

pyrites – iron sulfide (FeS_2) minerals that may oxidize during the combustion process to generate sulfur oxide gases. Pyrites may be a component of coal mill rejects.

RCRA – Resource Conservation and Recovery Act, as amended (Pub. L. 94-580). The legislation under which EPA regulates solid and hazardous waste.

RCRA Subtitle C characteristics – criteria used to determine if an unlisted waste is a hazardous waste under Subtitle C of RCRA.

> corrosivity – a solid waste is considered corrosive if it is aqueous and has a pH less than or equal to 2 or greater than or equal to 12.5, or if it is a liquid and corrodes steel at a rate greater than 6.35 millimeters per year at a test temperature of 55°C.
>
> toxicity – a solid waste exhibits the characteristic of toxicity if, after extraction by a prescribed EPA method, it yields a metal concentration 100 times the acceptable concentration limits set forth in EPA's primary drinking water standards.
>
> ignitability – a solid waste exhibits the characteristic of ignitability if it is a liquid with a flashpoint below 60°C or a non-liquid capable of causing fires at standard temperature and pressure.
>
> reactivity – a waste is considered reactive if it reacts violently, forms potentially explosive mixtures, or generates toxic fumes when mixed with water, or if it is normally unstable and undergoes violent change without deteriorating.

reactivity – see RCRA Subtitle C characteristics.

regeneration waste streams – wastes resulting from periodic cleaning of ion exchange beds used to remove mineral salts from boiler makeup water.

reinjection – the act of returning fly ash to a boiler to use any residual carbon content as fuel.

residual fuel oil – the heavier oils that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations. Included are No. 5 fuel oil, Navy Special, and No. 6 fuel oil (which includes Bunker C fuel oil).

RIA – Regulatory Impact Analysis.

run-on and runoff control and collection system – Run-on controls prevent precipitation runoff from other parts of a site from reaching waste management areas. Runoff controls and collection systems prevent precipitation runoff from the waste management unit from being transported offsite.

scrubber – an air pollution control device used to remove particulates or contaminant gases from flue gas (see wet scrubber and dry scrubber).

SDWS – Secondary Drinking Water Standards established by the Safe Drinking Water Act.

SIC – Standard Industrial Classification.

SIP – State Implementation Plan under the Clean Air Act.

slag – molten or fused solid matter.

sluice water – liquid used to transport combustion waste or other material.

sluiced ash – combustion waste that has been transported using liquid.

slurry – a mixture of insoluble matter in a fluid.

SPLP – Synthetic Precipitation Leaching Procedure.

spray canal – recirculating cooling water system used to transfer heat picked up in the condenser to the atmosphere by evaporative cooling.

SSB – solids settling basin.

Standard Industrial Classification (SIC) code – a code developed by the U.S. government that categorizes businesses into groups with similar economic activities.

steam electric boiler – a system that combusts fuel in a boiler to produce steam, which in turn is used to provide heat or steam or drive turbines.

stoker – a combustion technology using a mechanically operated fuel feeding mechanism to distribute solid fuel over a grate for combustion.

subbituminous coal – an intermediate ranked coal between lignite and bituminous with more carbon and less moisture than lignite (see coal rank).

superheater – a device that follows a boiler and uses exhaust gases from combustion to raise the temperature of steam generated in the boiler.

surface impoundment – a facility that is a natural topographic depression, artificial excavation, or diked area formed primarily of earthen materials (although it may be lined with artificial materials), which is designed to hold an accumulation of liquid wastes containing free liquids.

surface water monitoring system – periodic collection and analysis of surface water samples near a waste management unit.

TCLP – Toxicity Characteristic Leaching Procedure.

toxicity – see RCRA Subtitle C characteristics.

TSS – total suspended solids.

UCCW – utility coal combustion waste.

unit – see generating unit or waste management unit.

USWAG – Utility Solid Waste Activities Group.

utility – a private or public organization that generates, transmits, distributes, or sells electricity. For purposes of this study, includes independent power producers regulated under the Public Utility Regulatory Policies Act (PURPA).

waste management unit – a structure, typically a landfill or surface impoundment, in which waste is placed for disposal or storage.

wastewater treatment sludge – waste generated from the treatment in settling basins or other treatment facilities of liquid waste streams.

water treatment sludge – waste resulting from treatment of makeup water for the steam cycle or for non-contact cooling.

watt – a unit of electrical power.

wet scrubber – a device utilizing a liquid, designed to separate particulate matter or gaseous contaminants from a gas stream by one or more mechanisms such as absorption, condensation, diffusion, or inertial impaction.

Document 19

U.S. EPA, Technical Support Center Issue, Fingerprint Analysis of Contaminant Data: A Forensic Tool for Evaluating Environmental Contamination, EPA/600/5-04/054, May 2004.

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Technical Support Center Issue

Fingerprint Analysis of Contaminant Data: A Forensic Tool for Evaluating Environmental Contamination

— Russell H. Plumb, Jr.*

1.0 Introduction

Several studies have been conducted on behalf of the U.S. Environmental Protection Agency (EPA) to identify detection monitoring parameters for specific industries.[1,2,3,4,5] One outcome of these studies was the evolution of an empirical multi-variant contaminant fingerprinting process. This process, Fingerprint Analysis of Leachate Contaminants (FALCON), was developed through the EPA's Technical Support Center (TSC) in response to the need for identifying the source of contaminant plumes. FALCON combines data for several contaminants to develop a distinctive graphical fingerprint or multi-parameter chemical signature. These fingerprint patterns can be used to characterize the source of a contaminant plume, differentiate the contaminant plume from background conditions at the source, and monitor the migration of leachate into the environment. It can be applied to both organic and inorganic contaminants and is effective over a wide range of contaminant concentrations. This data evaluation process is analogous to using fingerprints to identify individuals. However, rather than using the size and location of ridges and swirls on the fingertip, the relative abundance of selected constituents is used to develop distinctive chemical signatures.

The objective of this paper is to demonstrate that FALCON is a quantitative, defensible fingerprinting process. A description of the stepwise FALCON technique is provided in *Section 2.0*. Examples are presented to illustrate the range of situations in which fingerprinting can be applied to characterize the occurrence and distribution of environmental contaminants. These examples were developed using routine monitoring data obtained from a variety of ongoing site characterization and monitoring programs. Case studies of FALCON applications are presented in *Section 3.0*.

2.0 FALCON Procedure

The FALCON procedure is a multi-step process of combining data from two or more measurements to create a distinctive ratio or multi-parameter chemical signature that can be used to characterize a contaminant plume from a particular source. The following example, using data from a dioxin-furan contaminated sawmill site, illustrates the individual steps in this fingerprinting process.

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Step 1: Data Review

Data are subjected to an initial review to assess the type and quantity of information available. The data are examined to identify subsets that are representative of the designated source area, background areas, impacted areas, and other potential sources that may be differentiated by fingerprinting. The data are then examined to determine whether there are replicate data to assess the reproducibility of any fingerprint pattern that may be identified. This information may exist as either duplicate analyses, multiple samples from the same area, or samples from the same location over time. The data are also reviewed to ensure each individual set is complete and comparable (there are no missing values, results are expressed in the same concentration units, non-detect limits are specified). Finally, the data are examined for any obvious data quality issues.

Step 2. Data Tabulation

The individual data sets are entered into a spreadsheet to (1) select parameters to be used in the fingerprinting process, (2) prepare graphical plots of the fingerprint patterns, and (3) estimate the statistical reproducibility/comparability of identified fingerprint patterns. In this particular example, the laboratory had reported results for 17 specific dioxin-furan congeners and several "total" congener measurements (e.g., total hexachlorodibenzodioxin). The "total" measurements were excluded from the fingerprint process because the results were vague (specific congeners included in the total were not identified and could not be confirmed with the congener-specific data). Also, Octachlorodibenzodioxin was excluded from the fingerprint because the extremely high concentrations for this specific congener overwhelmed the concentrations for the remaining dioxin-furan congeners. After data review and tabulation, 16 dioxin-furan congeners were selected to develop the sawmill fingerprint. The data from seven soil samples at this site are presented in Table 1. These samples, with a calculated total dioxin-furan congener concentration ranging from 231 nanograms per kilogram (ng/kg) to 1,302,460 ng/kg, were specifically selected to demonstrate the capability of this fingerprinting technique to handle the highly variable contaminant concentrations that can be encountered in a site investigation.

Step 3. Data Normalization

Data used for contaminant fingerprinting are transformed in a multi-step process. First, individual results listed as "not detected" in the original data set are replaced with a numerical value. The convention used in this example is to replace the "ND" result with a value equal to one-half the reported detection limit. Second, a total concentration is calculated for the parameters used in the fingerprint (fingerprint mass). Finally, the reported concentration for each fingerprint constituent in that sample is normalized to the calculated fingerprint mass. Thus, the reported concentrations for the fingerprint constituents are converted to a decimal percentage of the calculated fingerprint mass. The transformed dioxin-furan data for this example are shown in Table 2. The substitution of a numeric value for non-detected constituents and the subsequent data transformation process performs two functions; it permits individual data sets to be plotted on a common y-axis scale for visual inspection of the fingerprint (Step 4) and it permits individual data sets to be statistically compared (Step 5).

Table 1. Dioxin-Furan Monitoring Results for Sawmill Soil Samples*

Dioxin-Furan Congener	Chemical Number	Soil Sampling Locations						
		SM20	SM34	SM41	SM44	SM40	SM46	SM51
2378-TCDD	1	**0.95**	**0.95**	180	1.4	170	16	8.4
12378-PeCDD	2	**2.4**	**2.35**	520	9.8	1800	130	31
123478-HxCDD	3	**2.4**	3.1	1700	12	4000	290	48
123678-HxCDD	4	5.4	13	4900	89	47000	2500	350
123789-HxCDD	5	4.8	11	1400	35	12000	630	100
1234678-HxDD	6	160	300	100000	1100	760000	34000	3900
2378-TCDF	7	**0.95**	0.3	13	3.4	190	140	21
12378-PeCDF	8	**2.4**	**2.35**	13	2.6	280	110	6.1
23478-PeCDF	9	**2.4**	**2.35**	16	**2.3**	540	120	**5.5**
123478-HxCDF	10	**2.4**	**2.35**	30	12	3300	240	45
123678-HxCDF	11	**2.4**	**2.35**	150	11	1600	200	24
123789-HxCDF	12	**2.4**	**2.35**	**2.35**	**2.4**	**280**	9	**7.5**
234678-HxCDF	13	**2.4**	**2.35**	85	8.8	1500	180	17
1234678-HpCDF	14	11	30	23000	210	110000	3300	600
1234789-HpCDF	15	**2.4**	**2.35**	2300	14	9800	290	62
OCDF	16	26	69	43000	450	350000	8400	1300
Sum 1-16		230.7	446.1	177309	1964	1302460	50555	6525.5

* Dioxin-Furan concentrations reported in ng/kg.

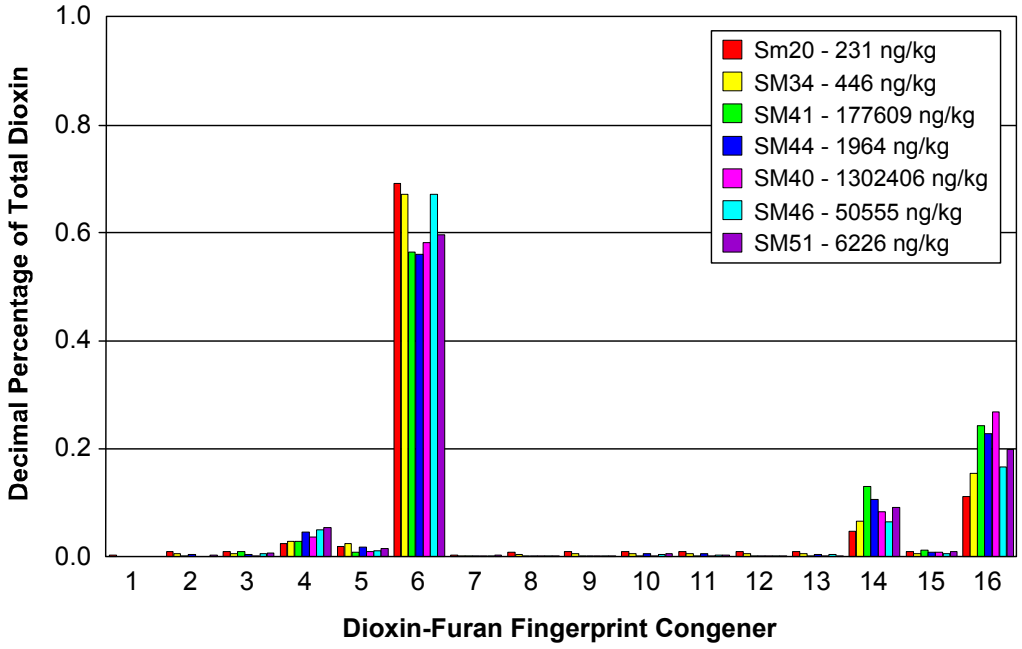
ND values have been replaced with a concentration equal to one-half the ND value (in **bold**).

Table 2. Normalized Dioxin-Furan Monitoring Results for Sawmill Soil Samples

Dioxin-Furan Congener	Chemical Number	Soil Sampling Locations						
		SM20	SM34	SM41	SM44	SM40	SM46	SM51
2378-TCDD	1	**0.0041**	**0.0021**	0.0010	0.0007	0.0001	0.0003	0.0013
12378-PeCDD	2	**0.0104**	**0.0053**	0.0029	0.0050	0.0014	0.0026	0.0048
123478-HxCDD	3	**0.0104**	0.0069	0.0096	0.0061	0.0031	0.0057	0.0074
123678-HxCDD	4	0.0234	0.0291	0.0276	0.0453	0.0361	0.0495	0.0536
123789-HxCDD	5	0.0208	0.0247	0.0079	0.0178	0.0092	0.0125	0.0153
1234678-HxDD	6	0.6935	0.6724	0.5640	0.5602	0.5835	0.6725	0.5977
2378-TCDF	7	**0.0041**	0.0007	0.0001	0.0017	0.0001	0.0028	0.0032
12378-PeCDF	8	**0.0104**	**0.0053**	0.0001	0.0013	0.0002	0.0022	0.0009
23478-PeCDF	9	**0.0104**	**0.0053**	0.0001	**0.0012**	0.0004	0.0024	**0.0008**
123478-HxCDF	10	**0.0104**	**0.0053**	0.0002	0.0061	0.0025	0.0047	0.0069
123678-HxCDF	11	**0.0104**	**0.0053**	0.0008	0.0056	0.0012	0.0040	0.0037
123789-HxCDF	12	**0.0104**	**0.0053**	**0.0000**	**0.0012**	**0.0002**	0.0002	**0.0011**
234678-HxCDF	13	**0.0104**	**0.0053**	0.0005	0.0045	0.0012	0.0036	0.0026
1234678-HpCDF	14	0.0477	0.0672	0.1297	0.1069	0.0845	0.0653	0.0919
1234789-HpCDF	15	**0.0104**	**0.0053**	0.0130	0.0071	0.0075	0.0057	0.0095
OCDF	16	0.1127	0.1547	0.2425	0.2292	0.2687	0.1662	0.1992

Step 4. Graphical Presentation of Fingerprint

The normalized data in Table 2 are plotted as a series of histograms. The x-axis in these plots is an ordered presentation of the individual fingerprint constituents. The actual order along the x-axis is not critical but it must be consistent in each of the histograms. The y-axis is a plot of the relative abundance of each constituent expressed as a decimal percentage of the calculated fingerprint mass. The data transformation process in Step 3 defines a common y-axis scale of 0.0 to 1.0 decimal percent for each data set since no constituent can be less than 0 percent of the fingerprint mass, no constituent can represent more than 100 percent of the fingerprint mass, and the sum of all constituents must be equal to 100 percent of the fingerprint mass. Therefore, each sample histogram can be plotted on the same scale even though the reported concentrations may vary by orders of magnitude. A visual inspection of Figure 1 demonstrates that the seven data sets presented in Table 1 define a single fingerprint pattern characterized by approximately 60 percent constituent 6, approximately 20 percent constituent 16, approximately 10 percent constituent 14, approximately 4 percent of constituent 4 and trace amounts of the remaining 12 constituents. The dioxin-furan congener number along the x-axis of Figure 1 corresponds to the chemical number listed in Tables 1 and 2.



Regression Analysis Comparison of Sawmill Fingerprint Pattern

	SM20	SM34	SM41	SM44	SM40	SM46	SM51
SM20		0.994	0.912	0.930	0.913	0.989	0.962
SM34			0.950	0.965	0.951	0.998	0.986
SM41				0.997	0.992	0.956	0.985
SM44					0.995	0.971	0.994
SM40						0.959	0.985
SM46							0.991
SM51							

Average regression analysis comparison = 0.970.

Figure 1. Graphical representation and regression analysis comparison of a dioxin-furan fingerprint pattern at a sawmill.

Step 5. Statistical Assessment of Pattern Reproducibility

A statistical estimate of the comparability of the individual histograms is calculated using regression analysis. Each histogram is individually compared with the remaining histograms to calculate an r^2 value (regression coefficient squared). The calculated r^2 values fall into the range of 0.00 (the two patterns are totally dissimilar) to 1.00 (the two patterns are identical) and provides a decimal estimate of the reproducibility or comparability of two patterns. This example produced 21 histogram comparisons (SM20 vs. SM34, SM20 vs. SM41, etc.) with calculated r^2 values ranging from 0.912 to 0.998 that are summarized in the Regression Analysis Table in Figure 1. The estimated reproducibility of the dioxin-furan fingerprint shown in Figure 1 is 0.970 ± 0.027 (97 ± 3 percent). Despite the highly variable dioxin-furan concentrations that spanned four orders of magnitude across the sawmill site and the variable number of non-detected congeners within each set, the FALCON process identified a single, reproducible chemical signature that characterizes the dioxin-furan contamination at this facility.

Step 6. Evaluate Remaining Data

Once a source fingerprint has been identified, regression analysis can be used to compare the dioxin-furan congener distribution at other monitoring locations with the source fingerprint.

These results can be used to:

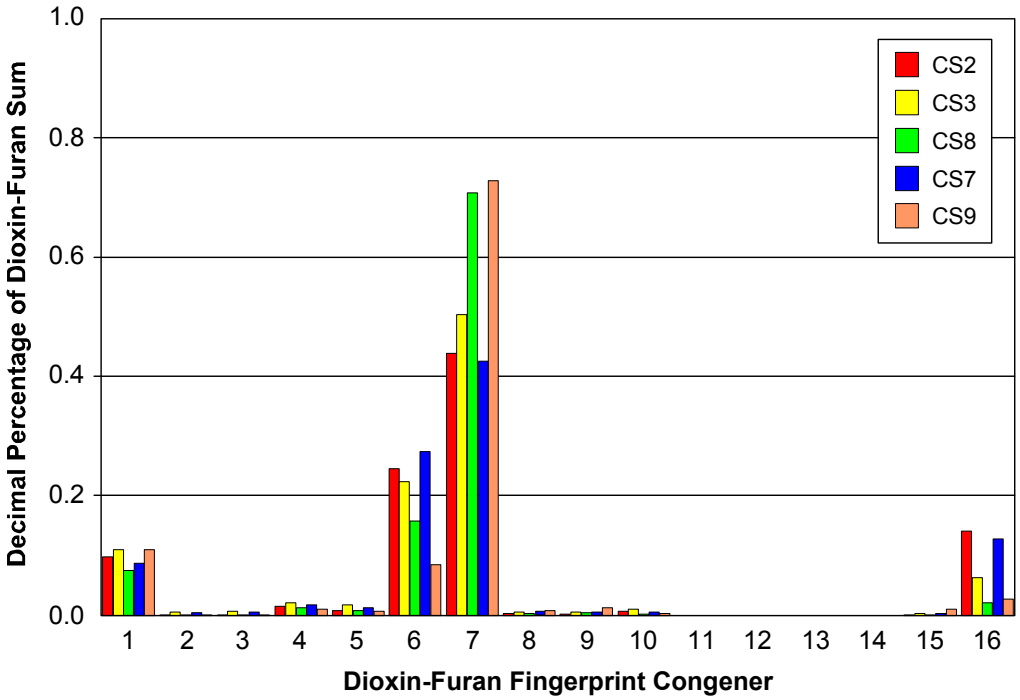
1. differentiate the source from background conditions,
2. demonstrate whether contamination detected at some distance from a site is related to the source,
3. map contaminant migration away from a source,
4. differentiate multiple sources of the same contaminant, and
5. estimate the mixing ratio of two plumes.

3.0 Contaminant Fingerprinting Case Studies

Case studies are presented to illustrate the versatility of FALCON in a variety of contamination scenarios. Data used in these case studies were generated using standard analytical techniques in ongoing site investigation, characterization, and monitoring programs. The intent of these case studies is not to provide detailed site investigation histories for each example, but simply to illustrate the variety of situations in which the FALCON fingerprinting process can be applied to characterize the occurrence and distribution of contaminants.

3.1 Source Characterization of Organic Contaminants - Pulp Mill Case Study

Fingerprinting was conducted to differentiate the impacts of a pulp mill from other potential dioxin-furan sources along the lower Roanoke River in eastern North Carolina. The waste stream from this mill passed through a baffled settling pond and discharged to a tributary of the Roanoke River. Samples were collected from the tributary sediments known to be impacted by the pulp mill. Data from these samples were carried through the FALCON process and produced the dioxin-furan fingerprint pattern shown in Figure 2 (the fingerprint constituents listed by number along the x-axis are identified in Table 1). The 16 dioxin-furan congeners used in this example defined a pattern characterized by 40 to 70 percent constituent 7 (2378-Tetrachlorodibenzofuran), 10 to 25 percent constituent 6 (1234678-Heptachlorodibenzodioxin), 10 percent constituent 1 (2378-Tetrachlorodibenzodioxin), and 2 to 17 percent constituent 16 (Octachlorodibenzofuran (OCDF)).



Regression Analysis for Pulp Mill Fingerprint

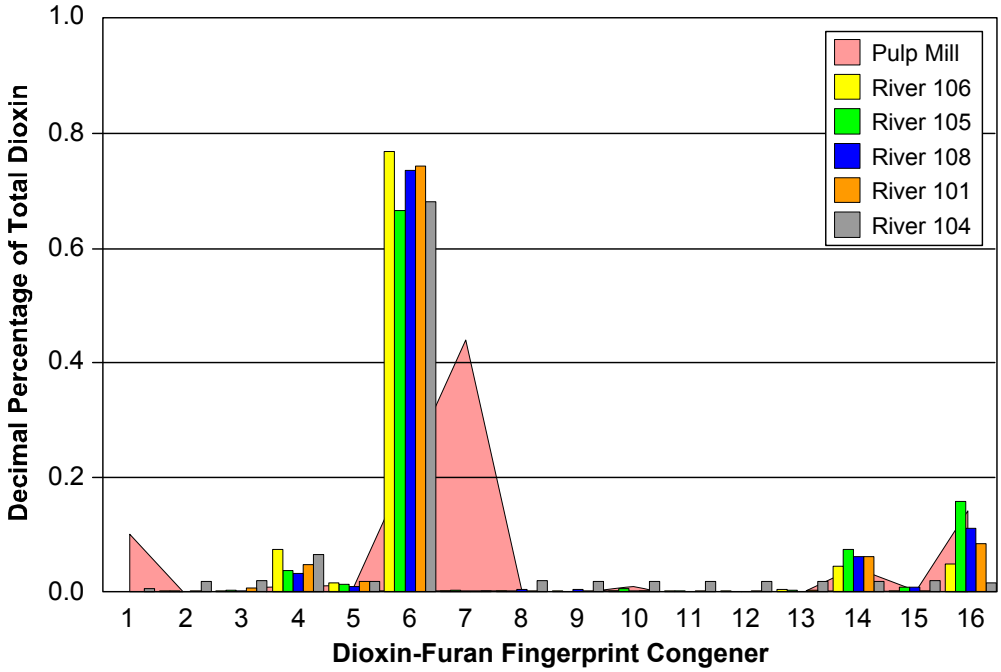
	CS2	CS3	CS8	CS7	CS9
CS2		0.958	0.849	0.993	0.791
CS3			0.948	0.951	0.902
CS8				0.826	0.985
CS7					0.754
CS9					

Average regression analysis comparison = 0.896.

Figure 2. Dioxin-furan fingerprint pattern for a pulp mill effluent.

There were several site-specific factors that influenced the variability of the individual peak heights and the fingerprint pattern for this source. First, the discharge practice to the tributary was terminated in 1987. Changing hydrologic conditions over time (spring runoff, storm events, and tidal cycles) and bioturbation could have affected the dioxin residuals in the sediments. Second, wood fiber accumulation in the sediments complicated the sample collection process. However, despite the possible influence of these factors, the graphical fingerprint for the pulp mill had an estimated reproducibility that ranged from 0.754 (75 percent) to 0.993 (99 percent) with an average value of 0.896 ± 0.08 (90 ± 8 percent).

Roanoke sediment samples were collected upriver from the confluence with the tributary that had been impacted by the pulp mill. These samples defined a second dioxin-furan fingerprint that is contrasted with the pulp mill fingerprint in Figure 3. The upriver sediment fingerprint is presented as a series of histograms and the pulp mill fingerprint is presented as an area plot that was calculated as the average of the tributary samples shown in Figure 2. The upriver sediment fingerprint is characterized by 67 to 78 percent constituent 6 (1234678-HpCDD), 1 to 17 percent constituent 16 (OCDF), 1 to 8 percent constituent 14 (1234678-Heptachlorodibenzofuran), 3 to 6 percent constituent 4, and trace amount of 12 other congeners. The reproducibility of the upriver fingerprint pattern ranged from 0.996 (99+ percent) to 0.999 (99^{+} percent) with an average value of 0.998 ± 0.005 (99+ ± 0.5 percent).



Regression Analysis of Dioxin-Furan Fingerprint Patterns

	River 106	River 105	River 108	River 101	River 104
Pulp Mill	0.063	0.062	0.062	0.061	0.061
River 106		1.000	0.998	0.999	0.998
River 105			0.996	0.998	0.997
River 108				1.000	0.999
River 101					0.999
River 104					

Comparison between mill and upriver sediments = 0.062.
Estimated reproducibility of upriver sediment pattern = 0.998.

Figure 3. Comparison of upriver sediment dioxin-furan fingerprint with the pulp mill dioxin-furan fingerprint.

The presentation in Figure 3 (histogram vs. area plot) permits a rapid visual comparison of the two identified fingerprint patterns at this site. The dioxin-furan fingerprint pattern for the pulp mill impacted tributary and the dioxin-furan fingerprint for the upriver Roanoke sediments can be differentiated both visually and statistically. The Roanoke upriver fingerprint is characterized by a single dominant peak for constituent 6 (1234678-HpCDD) and several minor peaks for constituent 4 (123678-HxCDD), constituent 14 (1234678-HpCDF), and constituent 16 (OCDF). The pulp mill fingerprint is characterized by a major peak for constituent 7 (2378-TCDF), and lesser peaks for constituent 1 (2378-TCDD), constituent 6 (1234678-HpCDD), and constituent 16 (OCDF). The upriver sediment pattern can be distinguished from the pulp mill pattern by the greater relative abundance of constituent 6 (67 to 78 percent versus 10 to 25 percent), the virtual absence of constituent 7 (<1 percent versus 42 to 73 percent), and the virtual absence of constituent 1 (< 1 percent versus 10 percent). For the purpose of this paper, an average pulp mill fingerprint was calculated based on the results presented in Figure 2. This "average" pulp mill fingerprint was compared with each of the Roanoke upriver sediment samples using regression analysis. As summarized in the regression table associated with Figure 3, the comparability of the upriver dioxin-furan fingerprint with the pulp mill dioxin fingerprint ranged from 0.061 (6 percent) to 0.063 (6 percent). A t-Test analysis of the set of r^2 values for the pulp mill and Roanoke sediments comparisons with the set of r^2 values for the Roanoke sediment

reproducibility comparisons demonstrates that the pulp mill dioxin has a significantly different fingerprint pattern at $p = 0.05$. In this case study, FALCON identified a reproducible (90 ± 8 percent) dioxin-furan fingerprint for the pulp mill source (Figure 2), a second highly reproducible (99 ± 0.5 percent) dioxin-furan fingerprint for the upriver source(s) (Figure 3), and the two fingerprint patterns could be easily differentiated both graphically and statistically.

Any dioxin-furan contamination washed out of the tributary will mix with dioxin-furan contamination from the upriver source(s). This will create an unknown mixture of upriver dioxin-furan with pulp mill dioxin-furan in sediments collected below the tributary confluence. Using the two identified FALCON fingerprints, it is possible to calculate the expected congener distribution pattern for possible mixtures of the two source fingerprints. The relative abundance of each congener is known for 100 percent upriver sediment (Figure 3), is known for 100 percent pulp mill waste (Figure 2), and the expected congener distribution was calculated for mixtures of 90 percent upriver sediment plus 10 percent pulp mill waste, 80 percent upriver sediment plus 20 percent pulp mill waste, continuing to 10 percent upriver sediment plus 90 percent pulp mill waste. These results are presented in Table 3 in which each vertical column represents the expected dioxin-furan congener distribution (fingerprint) for the indicated sediment-pulp mill mixture.

If there were no pulp mill dioxin-furan in the lower river sediments, each downriver station would be expected to have a congener distribution pattern similar to the upriver fingerprint (Table 3, 100 percent upriver and 0 percent pulp mill). Therefore, constituent 6 would have a relative abundance of 0.813 (81 percent), constituent 7 would have a relative abundance of 0.016 (2 percent), and the remaining congeners would have the relative abundance indicated. However, if contaminated tributary sediments were entering the river, there would be a characteristic shift in the relative abundance of each congener with increasing amounts of pulp mill dioxin-furan. Thus, the relative abundance of congener 6 would gradually decrease from 0.812 (81 percent) to 0.196 (20 percent) and the relative abundance of congener 7 would simultaneously increase from 0.016 (2 percent) to 0.546 (55 percent) as the mixture changes from 100 percent upriver sediment and 0 percent pulp mill waste to 0 percent upriver sediment and 100 percent pulp mill waste. The relative abundance of each remaining congener in the fingerprint would also be expected to change as indicated in Table 3.

The actual fingerprint pattern in each downriver sample can be compared to the calculated fingerprint patterns in Table 3 using regression analysis. This will produce a range of values for each sample as shown in Table 4. The fingerprint comparison with the best match (maximum r^2 value) provides an estimate of the dioxin-furan mixture at that location. The following examples from Table 4 illustrate the assessment process.

1. The sample from upriver Station R101 produced a match of 0.999 (99+ percent) with the upriver fingerprint. However, this sample only produced a match of 0.924 (92 percent) with the 70 percent upriver - 30 percent pulp mill mixture, a match of 0.437 (44 percent) with the 30 percent upriver - 70 percent pulp mill mixture, and a 0.061 (6 percent) match with the pulp mill fingerprint. Since the maximum fingerprint match for this sample occurred with the 100 percent - 0 percent pulp mill mixture, this location was considered to be 100 percent upriver dioxin-furan.
2. The sample from downriver Station R118 produced a match of 0.904 (90 percent) with the upriver fingerprint and also produced a match of 0.905 (90 percent) with the 90 percent upriver sediment - 10 percent tributary sediment mixture. This sample produced a match of 0.859 (86 percent) with the 70 percent upriver - 30 percent pulp mill mixture, 0.511 (51 percent) with the 30 percent upriver - 70 percent pulp mill mixture, and only 0.198 (20 percent) with the pulp mill fingerprint. Since the maximum fingerprint match for this sample occurred for both the 100 percent upriver sediment - 0 percent tributary sediment mixture and the 90 percent upriver sediment - 10 percent tributary sediment mixture, this location was considered to be 95 percent upriver dioxin-furan and 5 percent pulp mill dioxin-furan.
3. The sample from downriver Station R125 produced a match of 0.718 (72 percent) with the upriver fingerprint. The fingerprint match increased to 0.846 (85 percent) with the 80 percent upriver sediment -

20 percent pulp mill mixture and reached a maximum value of 0.966 (97 percent) with the 50 percent upriver - 50 percent pulp mill mixture. The fingerprint match decreased to 0.846 (85 percent) with the 20 percent upriver - 80 percent pulp mill mixture and 0.662 (66 percent) with the pulp mill fingerprint. This location was considered to have 50 percent upriver dioxin-furan and 50 percent pulp mill dioxin-furan.

4. The sample from downriver station R140 produced a match of only 0.052 (5 percent) with the upriver fingerprint. The fingerprint match increased to 0.231 (23 percent) with the 70 percent upriver - 30 percent pulp mill mixture, 0.696 (70 percent) with the 30 percent upriver - 70 percent pulp mill mixture, and reached a maximum of 0.944 (94 percent) with the pulp mill fingerprint. Since the maximum fingerprint match occurred with the pulp mill source fingerprint, this location was considered to be 100 percent pulp mill dioxin-furan.

The fingerprint analysis results for the lower Roanoke sediment samples are presented in Table 4.

Each of the samples produced a maximum fingerprint match (highlighted and bolded) of 0.832 (83 percent), or higher, with one of the calculated fingerprint patterns. An inspection of Table 4 shows that 90 to 100 percent of the dioxin-furan contamination upriver from the mill could be attributed to upriver sources. However, the influence of the mill is evident downriver from the facility. Samples from downriver stations R120, R127, R128, R143, and R144 have a fingerprint indicating 70 percent upriver dioxin-furan and 30 percent pulp mill dioxin furan. Samples from R133 and R145 have a fingerprint consistent with a 30 percent upriver - 70 percent pulp mill mixture, and samples from R121 and R140 produced a maximum match with the pulp mill source fingerprint (0 percent upriver and 100 percent pulp mill). The spatial variability of the pulp mill dioxin in the downriver samples was attributed to site-specific hydrologic factors such as storm events, channel scouring, tidal effects and eddying. Overall, fingerprinting results from more than 40 downriver locations (only a portion of which are presented in Table 4) indicate that approximately 35 to 40 percent of the dioxin-furan contamination downriver from the tributary confluence could be attributed to the pulp mill. This example demonstrates that the FALCON fingerprinting technique is able to (1) develop a characteristic, reproducible fingerprint for the dioxin-furan source (pulp mill), (2) differentiate pulp mill dioxin-furan from background and/or upriver sources of the same contaminants, (3) quantitatively estimate the mixing that has occurred between pulp mill dioxin-furan and upriver sources, and (4) track the migration of the pulp mill dioxin-furan several miles from the source.

Table 3. Calculated Dioxin-Furan Congener Distributions for Mixtures of Roanoke Sediments and Pulp Mill Effluent

Con-gener #	100% Upriver 0% pulp mill	90% Upriver 10% pulp mill	80% Upriver 20% pulp mill	70% Upriver 30% pulp mill	60% Upriver 40% pulp mill	50% Upriver 50% pulp mill	40% Upriver 60% pulp mill	30% Upriver 70% pulp mill	20% Upriver 80% pulp mill	10% Upriver 90% pulp mill	0% Upriver 100% pulp mill
1	0.003	0.011	0.019	0.028	0.036	0.044	0.052	0.060	0.068	0.076	0.085
2	0.005	0.005	0.004	0.004	0.004	0.003	0.003	0.003	0.002	0.002	0.002
3	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.003	0.003	0.003	0.002
4	0.018	0.017	0.016	0.016	0.015	0.015	0.014	0.014	0.013	0.012	0.012
5	0.022	0.021	0.019	0.018	0.017	0.016	0.014	0.013	0.012	0.011	0.009
6	0.813	0.751	0.690	0.628	0.566	0.504	0.443	0.381	0.319	0.258	0.196
7	0.017	0.069	0.122	0.175	0.228	0.281	0.334	0.387	0.440	0.493	0.546
8	0.007	0.006	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.004	0.003
9	0.007	0.007	0.007	0.007	0.006	0.006	0.006	0.006	0.006	0.005	0.005
10	0.008	0.007	0.007	0.007	0.006	0.006	0.006	0.005	0.005	0.004	0.004
11	0.008	0.007	0.007	0.006	0.005	0.005	0.004	0.003	0.003	0.002	0.002
12	0.009	0.008	0.007	0.006	0.006	0.005	0.004	0.004	0.003	0.002	0.001
13	0.008	0.007	0.006	0.006	0.005	0.004	0.004	0.003	0.003	0.002	0.001
14	0.048	0.047	0.046	0.044	0.043	0.042	0.040	0.039	0.037	0.036	0.035
15	0.008	0.007	0.006	0.006	0.005	0.005	0.004	0.003	0.003	0.002	0.001
16	0.034	0.040	0.046	0.053	0.059	0.065	0.071	0.077	0.084	0.090	0.096

Values represent the estimated abundance of each dioxin-furan congener as a decimal percentage of the fingerprint mass in the sediment-pulp mill mixture.

Table 4. Regression Analysis Comparison of Roanoke Sediment Samples with Calculated Dioxin-Furan Fingerprints Patterns

River Location	Station	Upriver Fingerprint	Calculated composition of upriver sediment - pulp mill mixtures									Pulp Mill Fingerprint
		100 URS to 0 TS	90 URS to 10 TS	80 URS to 20 TS	70 URS to 30 TS	60 URS to 40 TS	50 URS to 50 TS	40 URS to 60 TS	30 URS to 70 TS	20 URS to 80 TS	10 URS to 90 TS	0 URS to 100 TS
Upriver	R101	**0.999**	0.991	0.968	0.924	0.850	0.741	0.599	0.437	0.279	0.149	0.061
	R103	0.888	**0.892**	0.883	0.856	0.807	0.733	0.637	0.527	0.414	0.307	0.215
	R106	**0.859**	0.854	0.835	0.798	0.740	0.659	0.560	0.451	0.341	0.242	0.160
	R107	**0.863**	**0.857**	0.838	0.800	0.770	0.658	0.558	0.447	0.338	0.239	0.157
	R109	**0.904**	**0.897**	0.875	0.833	0.769	0.682	0.576	0.460	0.346	0.243	0.158
	R110	**0.900**	**0.894**	0.874	0.834	0.772	0.686	0.582	0.467	0.352	0.249	0.164
	R115	**0.998**	**0.994**	0.975	0.935	0.866	0.761	0.622	0.460	0.300	0.167	0.073
	Pulp Mill											
Downriver	R116	**0.911**	0.909	0.892	0.857	0.798	0.715	0.612	0.497	0.381	0.274	0.185
	R117	0.867	**0.883**	0.844	0.807	0.749	0.668	0.568	0.457	0.347	0.247	0.164
	R118	**0.904**	**0.905**	0.891	0.859	0.804	0.724	0.624	0.511	0.395	0.288	0.198
	R119	0.916	**0.927**	**0.924**	0.903	0.859	0.789	0.695	0.584	0.467	0.355	0.256
	R120	0.851	0.891	0.924	**0.942**	**0.940**	0.911	0.853	0.769	0.666	0.556	0.450
	R121	0.155	0.216	0.294	0.389	0.497	0.641	0.729	0.829	0.905	0.952	**0.972**
	R122	0.500	0.572	0.655	0.748	0.842	0.926	**0.982**	**0.993**	0.950	0.863	0.749
	R125	0.718	0.783	0.846	0.904	0.946	**0.966**	0.957	0.915	0.846	0.758	0.662
	R126	0.755	0.807	0.856	0.895	**0.917**	**0.914**	0.883	0.823	0.740	0.644	0.545
	R127	0.832	0.874	0.908	**0.929**	**0.931**	0.905	0.851	0.770	0.671	0.564	0.459
	R128	0.890	0.927	0.956	**0.969**	0.960	0.924	0.858	0.766	0.657	0.542	0.433
	R131	0.798	0.844	0.883	0.910	**0.919**	0.901	0.856	0.783	0.689	0.586	0.484
	R132	**0.839**	**0.837**	0.821	0.788	0.734	0.658	0.563	0.456	0.349	0.252	0.170
	R133	0.511	0.589	0.674	0.762	0.845	0.915	0.961	**0.977**	0.960	0.915	0.851
	R134	0.943	0.967	**0.979**	0.974	0.945	0.888	0.803	0.695	0.576	0.457	0.348
	R135	0.819	**0.832**	**0.834**	0.820	0.785	0.726	0.645	0.548	0.443	0.341	0.251
	R138	0.745	0.808	0.869	0.923	0.960	**0.974**	0.958	0.910	0.935	0.742	0.642
	R139	0.842	**0.851**	**0.849**	0.830	0.789	0.725	0.638	0.536	0.428	0.325	0.235
	R140	0.052	0.093	0.152	0.231	0.331	0.448	0.574	0.696	0.803	0.887	**0.944**
	R141	0.799	0.845	0.884	0.912	**0.920**	0.904	0.858	0.785	0.692	0.589	0.487
	R142	0.730	0.789	0.845	0.894	0.926	**0.936**	0.916	0.866	0.791	0.700	0.602
	R143	0.738	0.776	0.809	**0.829**	**0.832**	0.811	0.765	0.694	0.607	0.512	0.418
	R144	0.824	0.857	0.882	**0.909**	0.882	0.847	0.785	0.698	0.597	0.491	0.390
	R145	0.524	0.598	0.677	0.758	0.833	0.894	0.930	**0.937**	0.912	0.862	0.795
	R146	0.655	0.714	0.773	0.826	**0.965**	0.884	0.876	0.838	0.776	0.695	0.608

Tabulated results are regression analysis comparisons between actual sediment composition and calculated sediment-tributary mixtures.

URS = upriver sediments TS = tributary sediments **0.9305 = maximum fingerprint matches**

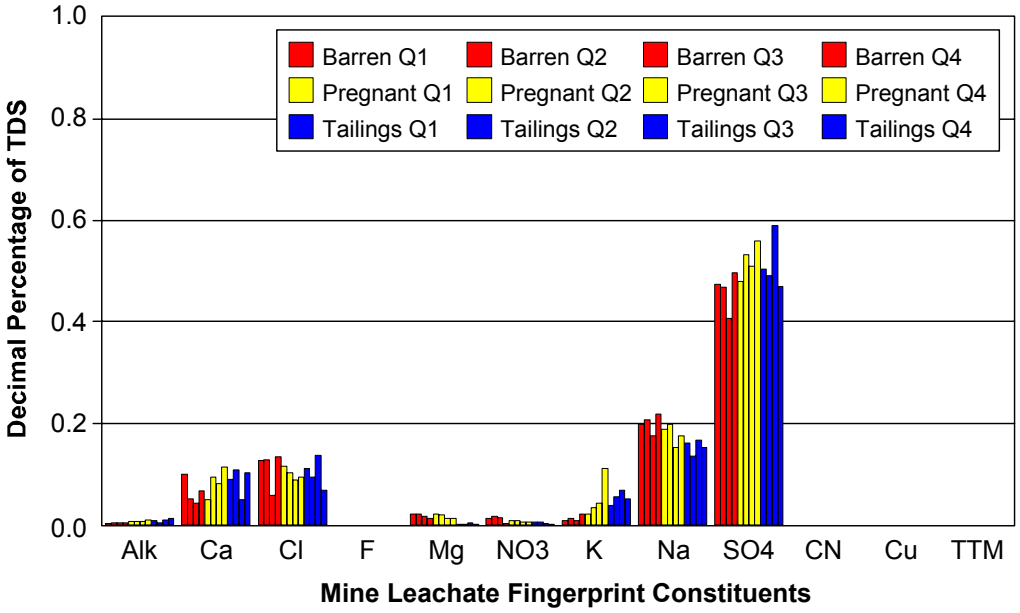
3.2 Inorganic Source Characterization and Leachate Migration Mapping - Gold Mine Case Study

An industry that displayed significant growth in the last quarter of the twentieth century was gold mining utilizing cyanide leaching technology. This process[1] uses a recirculating cyanide solution to extract gold, and other metals, from the ore being processed. An alkaline cyanide solution is prepared in an area referred to as a barren pond. This solution is sprayed on a crushed ore pile to extract gold by complexation as it percolates through the ore. The gold-rich leachate from this process is collected in a second pond referred to as the pregnant pond. Gold and other metals are recovered from the leachate and the cyanide solution is pumped back to the barren pond to repeat the process.

The State of Nevada currently requires heap leaching facilities to conduct quarterly monitoring for 12 geochemical parameters, 28 trace metals, and cyanide at several specified locations (barren pond, pregnant pond, tailings pond, and ground water monitoring wells).[1] Monitoring data from 35 heap leaching facilities were reviewed to develop a better understanding of the composition of mine leachates and to identify a shortened list of potential detection monitoring parameters for this industry.[1] This study demonstrated that nine geochemical parameters were always the most abundant constituents in mine leachates and their relative abundance (expressed as a percentage of total dissolved solids) was a constant at each mine despite the highly variable concentrations. These parameters were alkalinity, calcium, chloride, fluoride, magnesium, nitrate, potassium, sodium, and sulfate.

Data for the nine geochemical parameters specified above from the barren pond, the pregnant pond, and tailings reclaim water at a Nevada heap leaching facility were carried through the fingerprinting process described in *Section 2.0* and plotted as shown in Figure 4. Despite the variability displayed by the individual parameters (e.g., sulfate ranged from 969 to 1720 mg/L, and sodium ranged from 464 to 985 mg/L), the selected parameters define a distinctive chemical signature in which sulfate represents approximately 50 percent of the total dissolved solids concentration, sodium represents approximately 18 percent of the total dissolved solids concentration, chloride represents approximately 10 percent of the total dissolved solids concentration, and the remaining constituents are trace constituents of this pattern. Although cyanide (CN), copper (Cu), and total trace metals (the sum of all trace metal concentrations, TTM) are not significant components of the mine leachate fingerprint, they have been included in Figure 4 for comparison. A separate attempt at using trace metals for fingerprinting mine leachates did not define a distinctive fingerprint.[1]

The reproducibility of the mine leachate fingerprint at this facility is demonstrated in two ways. First, based on quarterly samples, the leachate fingerprint had a reproducibility over time of 0.980 (98 percent) at the barren pond, 0.986 (99 percent) at the pregnant pond, and 0.985 (99 percent) at the tailings reclaim pond. Second, the barren pond, the pregnant pond and the tailings reclaim area are all part of a recirculating system at the mine and a similar fingerprint pattern might be expected at each of these locations. As demonstrated by the regression analysis comparisons tabulated in Figure 4, the monitoring data from these different locations defined a consistent source fingerprint with an average reproducibility of 0.984 (98 percent). Therefore, data over time at a single location (quarterly monitoring data) and data from different locations within the leaching circuit define a reproducible geochemical fingerprint at this facility.



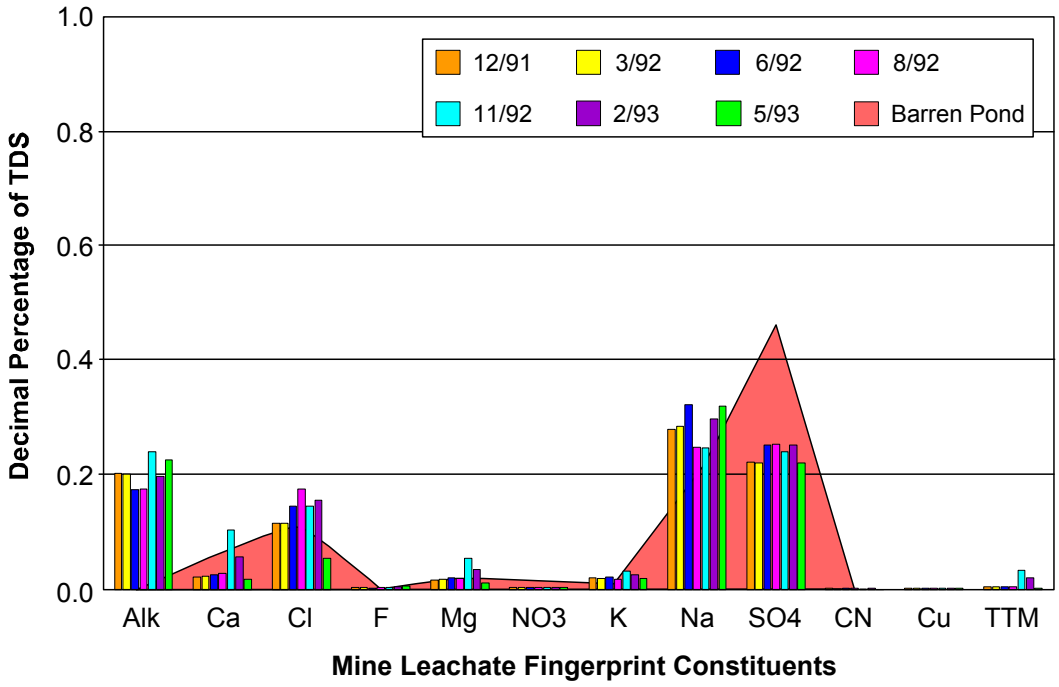
Regression Analysis of Gold Mine Tailings Leachate Fingerprint

	Barren Pond	Pregnant Pond	Tailings Reclaim
Background Ground Water	0.435	0.460	0.406
Barren Pond		0.983	0.972
Pregnant Solution			0.997
Tailings Reclaim			

Estimated reproducibility of mine leachate fingerprint = 0.984.
Comparison between mine leachate and ground water = 0.433.

Figure 4. Geochemical fingerprint at a gold mine using cyanide heap leaching.

A further evaluation of mine site monitoring records demonstrated that the same set of geochemical parameters used to fingerprint leachate at gold mines can also be used to fingerprint ground water in the vicinity of the mine.[1] The ground-water fingerprint developed from two years of quarterly monitoring at an upgradient location is contrasted with the heap leaching fingerprint in Figure 5. The quarterly upgradient ground water data are presented as a series of histograms and the mine leachate fingerprint is presented as an area plot. The first observation is that the ground water data define a single fingerprint pattern characterized by 25 to 30 percent sodium, 20 percent sulfate, 20 percent alkalinity (Alk in the figures), and 10 to 15 percent chloride. The estimated reproducibility of this chemical signature for ground water upgradient of the mine site is 0.941 (94 percent). The second observation is that the ground-water fingerprint developed with the FALCON procedure is visually distinct from the mine leachate fingerprint. Specifically, the mine leachate is enriched in sulfate and depleted in alkalinity when compared to the regional ground water. Despite the fact that the fingerprint constituents are naturally occurring substances and their concentrations are highly variable, the mine leachate and the regional ground water each have a distinctive, reproducible fingerprint that can be differentiated from each other visually and with regression analysis. In this example, there was only a 43 percent comparability between the two fingerprint patterns.



Regression Analysis Matrix for Gold Mine Upgradient Ground Water

	8/91	3/92	6/92	9/92	11/92	2/93	5/93
Barren Pond	0.493	0.489	0.566	0.609	0.475	0.558	0.414
8/91		0.999	0.978	0.948	0.924	0.980	0.963
3/92			0.982	0.944	0.919	0.980	0.966
6/92				0.960	0.882	0.984	0.922
9/92					0.908	0.975	0.835
11/92						0.948	0.857
2/93							0.908
5/93							

Average upgradient fingerprint comparison = 0.941.
Mine fingerprint comparison with upgradient ground water = 0.515.

Figure 5. Comparison of a ground-water fingerprint with the mine leachate fingerprint.

Once a source fingerprint pattern has been established for the mine, it can be used to monitor leachate migration into the environment. This is accomplished by comparing the geochemical pattern at each downgradient monitoring location with either the source fingerprint or the upgradient ground-water fingerprint. If the location was not impacted by fugitive mine leachate, it would be expected to have a geochemical fingerprint that more closely resembled the upgradient fingerprint rather than the mine leachate fingerprint. However, if fugitive leachate was impacting a location, the fingerprint would more closely resemble the mine leachate fingerprint rather than the upgradient fingerprint. Fingerprint analyses for several monitoring wells in the vicinity of a heap leaching facility are summarized in Table 5. An inspection of the results indicates that the wells fall into one of three categories. One category consists of upgradient wells that have a geochemical fingerprint that matches the upgradient fingerprint (80 to 99+ percent) but is different from the mine leachate fingerprint (36 to 63 percent). A second category consists of downgradient wells with a geochemical fingerprint similar to upgradient ground water (84 to 88 percent) and different from the mine leachate fingerprint (48 to 60 percent). The third category consists of wells with a geochemical fingerprint that has a poor match with the upgradient ground-water fingerprint (44 to 75 percent) and a stronger similarity to the mine leachate fingerprint (80 to 93 percent).

The compositional shift from alkalinity-rich and sulfate-poor to sulfate-rich and alkalinity-poor that has occurred in the category three wells is consistent with mine leachate migrating into that area. Once the impacted wells have been identified through the fingerprinting process, the results can be plotted and contoured to delineate specific areas impacted by fugitive mine leachate. This example demonstrates that the FALCON process develops reproducible fingerprints for mine leachate that can be visually and statistically differentiated from background ground-water conditions in the vicinity of the mine. Also, it demonstrates that the mine leachate fingerprint retains its distinctive chemical identity as it migrates through the ground water and can be used as an internal tracer to detect and map its presence some distance from the designated tailings disposal area.

Table 5. Comparison of Ground-water Fingerprints with a Mine Leachate Fingerprint

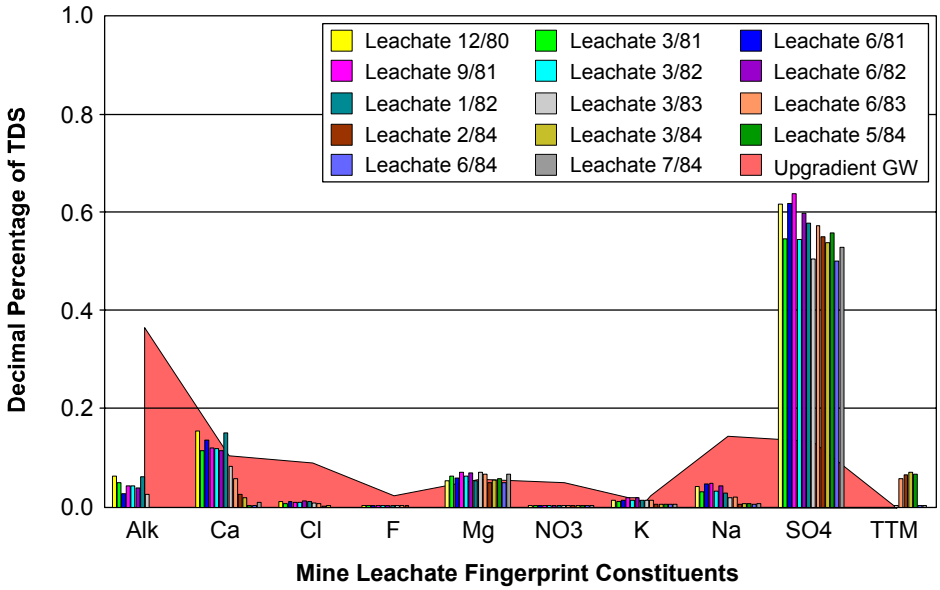
Classification	Sampling Location	Site Location	Fingerprint Comparison	
			Mine Source	Background GW
Category 1	Well 2	Upgradient	0.433	1.000
	Well 4	Upgradient	0.627	0.937
	Well 22	Upgradient	0.357	0.800
	Mine Site		1.000	0.429
Category 2	Well 37	Downgradient	0.480	0.885
	Well 42	Downgradient	0.492	0.844
	Well 38	Downgradient	0.602	0.880
	Well 45	Downgradient	0.531	0.882
Category 3	Well 1	Downgradient	0.835	0.463
	Well 9	Downgradient	0.898	0.492
	Well 12	Downgradient	0.844	0.747
	Well 15	Downgradient	0.874	0.621
	Well 39	Downgradient	0.866	0.584
	Well 44	Downgradient	0.932	0.441
	Well 40	Downgradient	0.801	0.592
	Well 61	Downgradient	0.885	0.610
	Well 66	Downgradient	0.897	0.381

Tabulated values are regression analysis comparisons between ground water and the indicated fingerprint pattern.

3.3 Early Detection of Leachate Migration - Copper Mine Case Study

A review of monitoring results from several copper mines demonstrated that the same set of geochemical parameters used at gold heap leaching facilities would also be useful for fingerprinting leachates at copper mines.[1] As indicated in Figure 6, tailings pond data over a period of 14 years produced a series of histograms that defined a single chemical fingerprint characterized by 55 to 60 percent sulfate, 15 percent calcium, 10 percent magnesium, 10 percent total trace metals (TTM), and 5 percent alkalinity. Despite variability in the ore being processed and the long period of record, the tailings pond at this facility had a single characteristic fingerprint with an estimated reproducibility of 0.970 (97 percent). In addition, this pattern was distinctively different from the alkalinity-rich, sulfate-poor background ground-water fingerprint in the vicinity of the mine (fingerprint comparison = 0.016 (2 percent)).[1] Fingerprint comparisons were used to identify several downgradient wells that had been impacted by mine leachate as demonstrated in the previous example. The monitoring results from one impacted well at this copper mine provided a set of data that illustrates another possible application of the FALCON procedure. Relative abundance (actual concentration divided by TDS) for the geochemical fingerprint parameters at well 1225 at this site are plotted as a function of time in Figure 7. Between 1970 and 1976, the dominant geochemical parameter in the ground water at this location was alkalinity while sulfate was almost

negligible. This alkalinity-rich, sulfate-poor pattern, that is typical of most unimpacted freshwater systems, had a 99 percent match with the ground water upgradient of the mining facility and less than a 5 percent match with the tailings pond leachate at the copper mine. However, the ground water composition at this location began to change around 1976. There was a gradual reduction in the relative abundance of alkalinity and a concurrent increase in the relative abundance of sulfate. This compositional shift, that is consistent with a sulfate-rich, alkalinity poor leachate entering the area, continued through 1984 when the Well 1225 fingerprint produced a 95 percent match with the tailings pond leachate. Even though sulfate and alkalinity are naturally occurring substances, fingerprint analysis clearly identifies mine leachate as the causative factor for the ground-water changes observed at this location. Thus, the fact that the geochemical fingerprint retains its distinctive identity as it migrates through the ground water could have been used to provide an early warning of mine leachate migration.



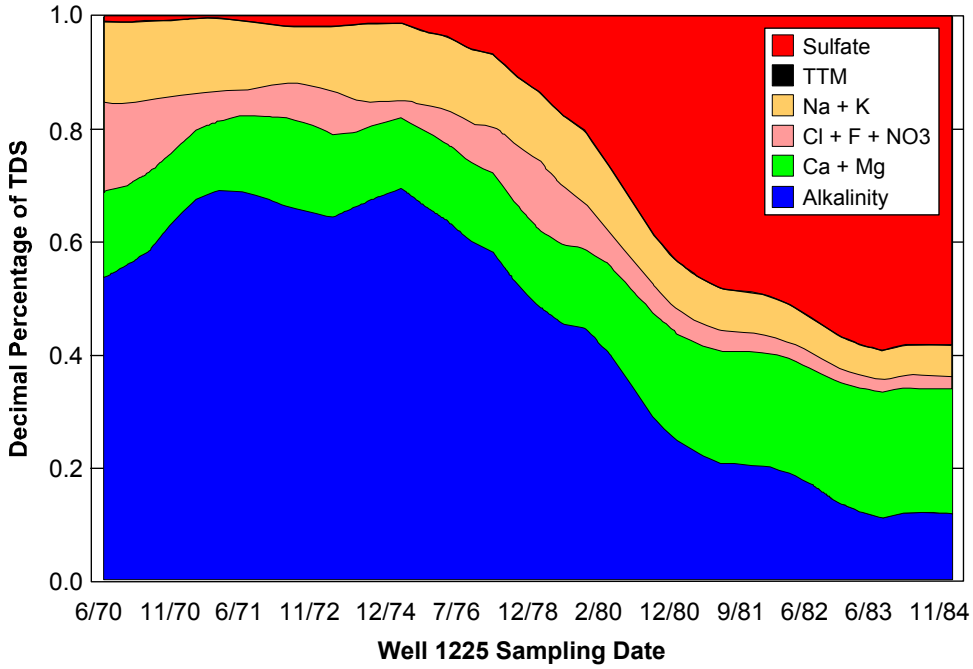
Regression Analysis Matrix for Copper Mine Tailings Pond Fingerprint

Tailings Pond Sampling Date

	12/80	3/81	6/81	9/81	3/82	6/82	12/82	3/83	6/83	2/84	3/84	5/84	6/84	7/84
12/80		0.997	0.995	0.994	0.997	0.994	0.999	0.985	0.952	0.929	0.919	0.911	0.936	0.937
3/81			0.996	0.998	1.000	0.998	0.996	0.995	0.967	0.947	0.939	0.933	0.957	0.959
6/81				0.998	0.998	0.998	0.984	0.992	0.968	0.946	0.936	0.929	0.953	0.954
9/81					0.999	1.000	0.992	0.996	0.973	0.954	0.946	0.941	0.965	0.967
3/82						0.999	0.996	0.995	0.967	0.947	0.938	0.932	0.956	0.958
6/82							0.992	0.997	0.974	0.954	0.946	0.941	0.965	0.968
12/82								0.984	0.949	0.926	0.916	0.908	0.933	0.935
3/83									0.981	0.964	0.958	0.954	0.976	0.980
6/83										0.996	0.994	0.991	0.986	0.986
2/84											0.999	0.998	0.986	0.984
3/8												0.999	0.983	0.982
5/84													0.986	0.985
6/84														0.999
7/84														

Average mine leachate fingerprint reproducibility = 0.970.

Figure 6. Comparison of a copper mine tailings pond fingerprint with the background ground-water fingerprint.



Ground-Water Conditions at Copper Mine Well 1225

Sampling Location	pH Standard Units	Total Metals (mg/L)	Fingerprint Match Decimal Percent
Tailings Pond Leachate	2.0	1963	1.000
Well 1225 10/70	nd*	0.291	0.033
Well 1225 3/71	nd*	0.372	0.027
Well 1225 11/72	nd*	0.467	0.031
Well 1225 6/73	nd*	0.410	0.037
Well 1225 12/74	nd*	0.296	0.017
Well 1225 10/75	nd*	0.341	0.043
Well 1225 7/76	nd*	0.357	0.038
Well 1225 5/78	nd*	0.697	0.018
Well 1225 12/78	nd*	0.383	0.075
Well 1225 11/79	nd*	0.354	0.026
Well 1225 2/80	nd*	0.350	0.375
Well 1225 5/80	nd*	0.342	0.576
Well 1225 8/80	nd*	0.322	0.755
Well 1225 12/80	nd*	0.354	0.717
Well 1225 3/81	nd*	0.295	0.898
Well 1225 6/81	nd*	0.302	0.805
Well 1225 9/81	7.4	0.110	0.731
Well 1225 3/82	7.0	0.030	0.890
Well 1225 6/82	6.7	0.150	0.890
Well 1225 12/82	7.2	1.190	0.946
Well 1225 6/83	7.4	1.110	0.867
Well 1225 12/83	7.4	0.000	0.950
Well 1225 5/84	7.7	0.470	0.920
Well 1225 11/84	7.1	1.570	0.945
Well 1225 5/85	6.9	1.550	0.949

* nd = no data

Figure 7. Geochemical fingerprint analysis of ground water downgradient of a copper mine tailings basin.

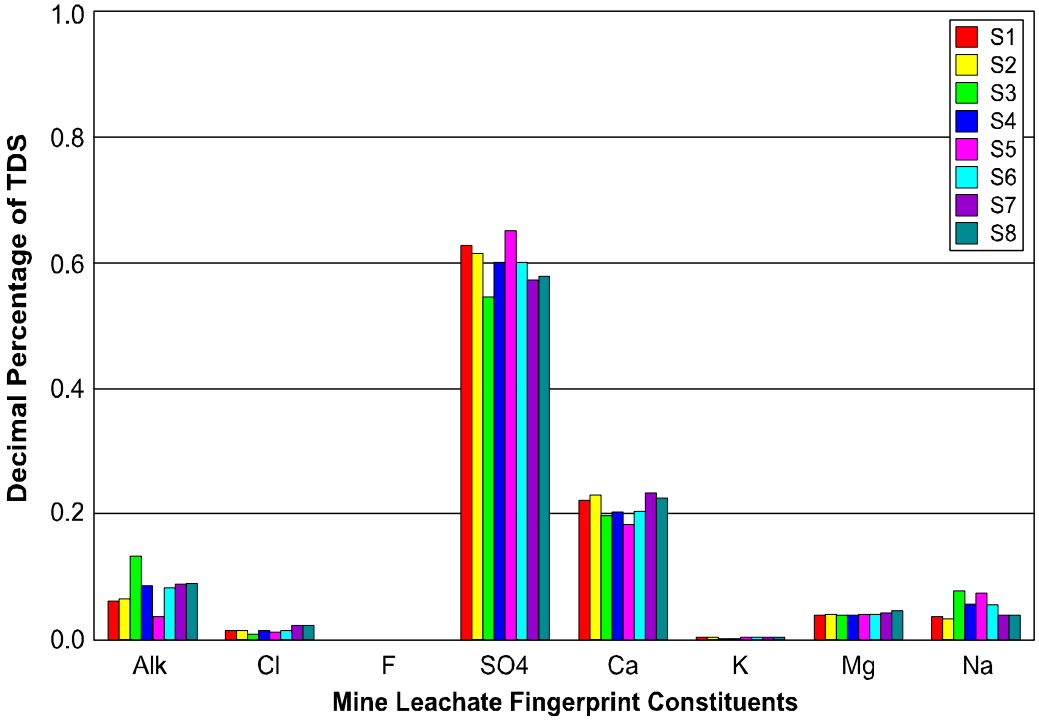
A review of additional monitoring data from this location (Figure 7) provides further insight into the capabilities of FALCON as a mechanism to provide early warning or early detection of leachate migration. The tailings pond at this facility has a total trace metals concentration (sum of 17 trace metals being routinely monitored) of 1963 mg/L and a pH of 2.0. Between 1970 and 1975, while the geochemical fingerprint was essentially identical to upgradient (background) conditions, the total trace metals concentration at this well was in the range of 0.291 to 0.467 mg/L. While the tailings pond fingerprint was being established at Well 1225 between 1976 and 1982, the total trace metals concentration remained in the range of 0.030 to 0.697 mg/L. After the tailing leachate fingerprint was fully established, the total trace metals concentration had only increased slightly to 0.470 to 1.570 mg/L. Also, the pH at this location was still in the range of 6.7 to 7.7 between 1981 and 1985. (The pH data from this set between 1970 and 1981 was missing. However, the pH at upgradient locations and other impacted downgradient locations was in the range of 6.7 to 7.7 between 1970 and 1985.) These field results, and an additional laboratory study[1], demonstrate that the geochemical fingerprint migrates faster through the ground water than other inorganic parameters of environmental concern that may be in mine leachate. Thus, in addition to providing a reliable characterization of mine leachates at their source and acting as an internal tracer, a geochemical fingerprint acts as a good indicator parameter because it migrates faster than mine leachate constituents of higher regulatory concern (pH and trace metals). Fingerprint analysis can provide an early warning so that remedial action can be initiated while a contaminant migration problem is smaller and more manageable.

This example demonstrates that the inorganic fingerprints can be used to characterize mine leachates at their source and to differentiate the leachate from background conditions. In addition, since the fingerprint retains its identity and migrates faster than other contaminants of higher regulatory concern, the fingerprint can function as an effective detection monitoring parameter.

3.4 Ground Water and Surface Water Mixing - Molybdenum Mine Case Study

This facility is located adjacent to the Red River in New Mexico and monitoring was conducted at the mine site, several ground water and seep locations, and the nearby river. The same set of geochemical parameters used in the gold mine and copper mine case studies were also useful at this site. Although the concentrations of the individual fingerprint parameters varied by a factor of 10 across the site, the monitoring results defined a single mine leachate pattern characterized by 60 percent sulfate, 20 percent calcium, 10 percent alkalinity, and small amounts of the remaining geochemical parameters (Figure 8). The regression analysis comparison of eight source samples produced r^2 values ranging from 0.9618 to 0.9999. The estimated reproducibility of this source fingerprint was 0.9894 (99 percent).

Monitoring was conducted at several ground water and surface seep locations between the mine operations and the river. Regression analysis of the geochemical pattern at these locations produced fingerprint comparisons of 94 to 99 percent with the source fingerprint. In addition, surface water data from several gulches that drain from the mine site towards the Red River also produced geochemical fingerprints with a strong similarity to the mine leachate (> 90 percent). Fingerprint analysis indicated that fugitive mine leachate was migrating through the ground water and may be entering the nearby river.



Regression Analysis of Molybdenum Mine Fingerprint

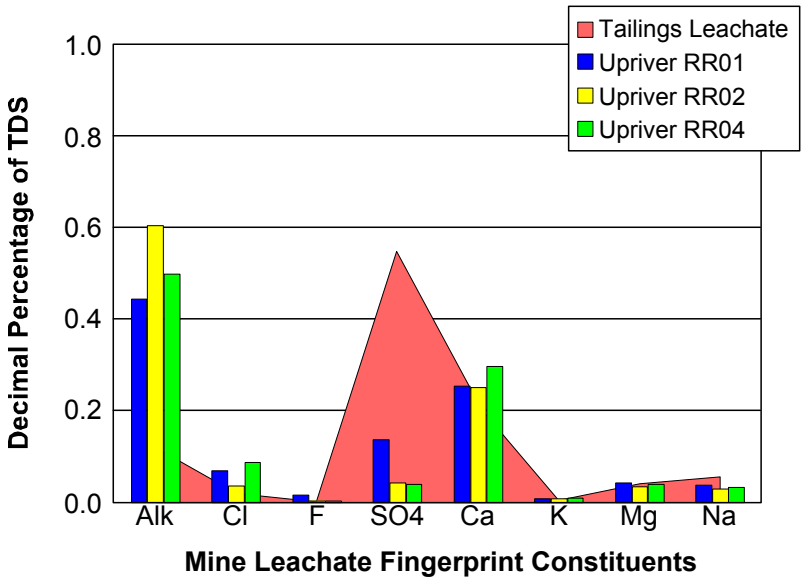
Molybdenum Mine Sampling Locations

	S1	S2	S3	S4	S5	S6	S7	S8
S1		1.000	0.997	0.977	0.996	0.984	0.998	0.997
S2			0.994	0.973	0.994	0.981	0.998	0.995
S3				0.990	1.000	0.987	0.996	0.997
S4					0.989	0.962	0.984	0.989
S5						0.988	0.995	0.996
S6							0.975	0.974
S7								1.000
S8								

Average fingerprint reproducibility = 0.989.

Figure 8. Geochemical fingerprint of molybdenum mine leachate.

The monitoring program at this mine site included 16 sampling stations in the nearby river. Data from three locations upriver from the mine site defined a geochemical fingerprint pattern that is contrasted with the mine leachate fingerprint in Figure 9. The river pattern, presented as a series of histograms, is characterized by 45 to 60 percent alkalinity, approximately 25 percent calcium, approximately 10 percent chloride, and 5 to 15 percent sulfate. This alkalinity-rich, sulfate-poor pattern upriver of the mine is typical of most fresh water systems and can be clearly differentiated from the sulfate-rich, alkalinity-poor mine fingerprint of the mine leachate that is presented as an area plot in Figure 9. The estimated reproducibility of the Red River fingerprint at these three upriver stations was 0.9804 (98 percent) and the comparability with the molybdenum mine fingerprint was only 0.0189 (2 percent). As in previous examples, the two inorganic fingerprint patterns can be readily distinguished from each other both visually and with regression analysis.



Fingerprint Analysis in Red River Near Molybdenum Mine

Station	Location	Background Fingerprint Match	Leachate Fingerprint Match	Percent Leachate in River
RR04	Upriver from mine	0.987	0.011	0
RR02	Upriver from mine	0.988	0.011	0
RR01	Upriver from mine	0.976	0.012	10
RR03	Adjacent to mine	0.906	0.063	20
RR05	Adjacent to mine	0.875	0.082	20
RR06	Adjacent to mine	0.767	0.192	30
RR09	Adjacent to mine	0.912	0.064	20
RR11	Adjacent to mine	0.969	0.015	10
RR08	Adjacent to mine	0.832	0.133	25
RR07	Adjacent to mine	0.856	0.111	20
RR10	Adjacent to mine	0.824	0.140	25
RR12	Adjacent to mine	0.458	0.496	40
RR13	Adjacent to mine	0.698	0.262	30
RR14	Downriver from mine	0.465	0.484	40
RR15	Downriver from mine	0.488	0.467	40
RR16	Downriver from mine	0.469	0.477	40

Figure 9. Comparison of mine leachate fingerprint with the background Red River fingerprint.

An evaluation of the data from the remaining river sampling locations adjacent to and downriver from the mine site demonstrated that the geochemical composition of the river was being altered. At stations adjacent to the mine site (RR03 to RR13), the comparability of the fingerprint with the upriver fingerprint ranged from 46 to 97 percent. At the three stations downriver from the mine site (RR14 to RR16), the comparability with the upriver fingerprint was reduced to 47 to 49 percent. These compositional changes were due to a reduced relative abundance of alkalinity and an increased relative abundance of sulfate as

the river flowed past the mining operation. This shift is consistent with a sulfate-rich, alkalinity-poor leachate characteristic of the mining operation (Figure 8) entering the river and is reflected by the increased comparability of the river fingerprint with the mine leachate fingerprint. The upriver stations only had a 1 percent match with the mine leachate fingerprint. However, as the river passed the site, the leachate fingerprint match increased to 6 to 50 percent at adjacent sampling locations and 47 to 48 percent at downriver sampling locations.

Fingerprint analysis indicated that mine leachate was migrating through the ground water and reaching the Red River in sufficient quantity to alter the geochemical composition. An additional capability of the FALCON technique is that the surface water to mine leachate dilution ratio can be estimated. As in the sediment dioxin case study (Section 3.1), the two source fingerprints can be used to calculate the expected composition for various mixtures of river water and mine leachate (i.e., 90 percent river + 10 percent mine leachate, 80 percent river water + 20 percent mine leachate, etc.). The actual inorganic composition at each river location can then be compared to each of the calculated mixtures to produce a range of fingerprint match values as shown in Table 6. For example:

1. The sample from station RR4 produced a fingerprint match of 0.987 (99 percent) with the upriver fingerprint. As the calculated amount of mine leachate in the mixture increased above 0 percent, the fingerprint match decreased. Since the best match (maximum r^2) occurred with the upriver fingerprint, this location was considered to be 100 percent upriver water.

2. The sample from station RR12 produced a fingerprint match of 0.458 (46 percent) with the upriver fingerprint. The fingerprint match increased to 0.772 (77 percent) for the 80 percent upriver + 20 percent mine leachate mixture and reached a maximum of 0.992 (99 percent) for the 60 percent upriver + 40 percent mine leachate mixture. As the calculated amount of mine leachate in the mixture increased above 40 percent, the fingerprint match decreased. This location was considered to be 60 percent upriver water and 40 percent mine leachate.

Each of the remaining samples was evaluated in a similar manner and the calculated fingerprint mixture that produced the best fingerprint match is highlighted and bolded in Table 6. It should be noted that the maximum fingerprint match for each river sample was 0.981 (98 percent), or higher.

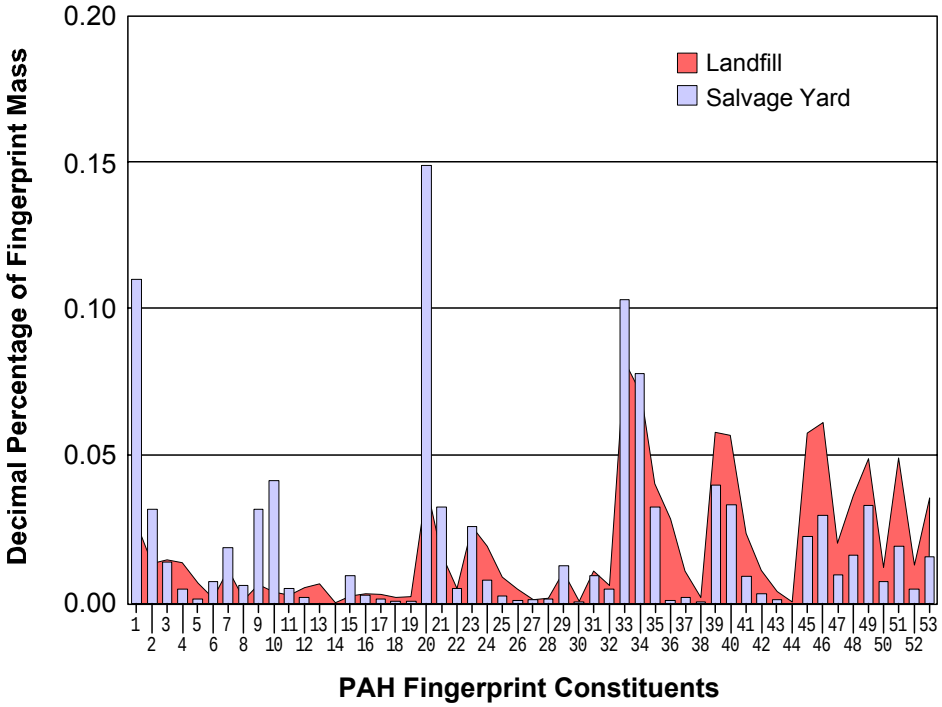
As shown in Table 6 and summarized in Figure 9, the three upriver stations produced a best fingerprint match for mixtures that contained 0 to 10 percent mine leachate. The stations adjacent to the mine site produced the best fingerprint match for mixtures that contained 10 to 40 percent mine leachate and the three downriver locations produced the best match for a mixture of 40 percent mine leachate and 60 percent river water. The fluctuations at the adjacent river stations listed in Table 6 (e.g., RR 11 has a lower percentage of leachate than RR6) are due to runoff entering the river from unimpacted tributaries. In this example, the FALCON technique was able to develop a characteristic fingerprint for the mine leachate and differentiate mine leachate from background ground water conditions and surface water. In addition, based on the properties of the fingerprint, it was possible to track the migration of mine leachate through the ground water, into a nearby river, and develop a quantitative estimate of the mixing that was occurring between river water and fugitive mine leachate.

Table 6. Comparison of Red River Geochemical Fingerprints with Secondary Mine Leachate Fingerprints

River Location	Station Number	Identified River Fingerprint	Calculated composition of surface water - mine leachate mixtures.									Identified Leachate Fingerprint
		100% UR 0% ML	90% UR 10% ML	80% UR 20% ML	70% UR 30% ML	60% UR 40% ML	50% UR 50% ML	40% UR 60% ML	30% UR 70% ML	20% UR 80% ML	10% UR 90% ML	0% UR 100% ML
Upriver	RR4	**0.987**	0.953	0.847	0.677	0.467	0.268	0.124	0.041	0.001	0.001	0.011
	RR2	**0.988**	0.954	0.848	0.679	0.468	0.269	0.124	0.042	0.006	0.001	0.011
	RR1	0.976	**0.999**	0.968	0.860	0.660	0.475	0.296	0.166	0.084	0.036	0.012
Adjacent	RR3	0.906	0.966	**0.991**	0.937	0.800	0.615	0.432	0.285	0.179	0.109	0.063
	RR5	0.875	0.943	**0.983**	0.945	0.822	0.646	0.466	0.317	0.208	0.132	0.082
	RR6	0.767	0.869	0.967	**0.994**	0.932	0.796	0.631	0.478	0.354	0.261	0.192
	RR9	0.912	0.972	**0.997**	0.943	0.806	0.619	0.435	0.287	0.180	0.109	0.064
	RR11	0.969	**0.995**	0.969	0.866	0.690	0.487	0.307	0.175	0.091	0.041	0.015
	RR8	0.832	0.918	**0.988**	**0.981**	0.887	0.727	0.551	0.397	0.279	0.193	0.133
	RR7	0.856	0.935	**0.993**	0.973	0.865	0.697	0.518	0.365	0.249	0.167	0.111
	RR10	0.824	0.913	**0.986**	**0.984**	0.894	0.737	0.562	0.408	0.288	0.201	0.140
	RR12	0.458	0.592	0.772	0.916	**0.992**	0.979	0.898	0.787	0.676	0.578	0.496
	RR13	0.698	0.813	0.937	**0.996**	0.969	0.859	0.710	0.561	0.435	0.336	0.262
Downriver	RR14	0.465	0.599	0.776	0.917	**0.989**	0.972	0.887	0.775	0.663	0.565	0.484
	RR15	0.488	0.622	0.797	0.933	**0.997**	0.971	0.880	0.762	0.648	0.549	0.467
	RR16	0.469	0.602	0.778	0.916	**0.986**	0.966	0.880	0.767	0.655	0.558	0.477

Tabulated results are regression analysis comparisons between river samples and the calculated surface water-mine leachate mixture.

UR = Upriver ML = Mine Leachate **0.9830 = maximum leachate matches**



PAH Fingerprint Analysis of Tributary Sediments

Station	Landfill Match Decimal Percent	Salvage Yard Match Decimal Percent	Total PAH (ng/kg)
T6	0.874	0.657	3951
T3	0.886	0.433	3075003
T4	0.900	0.429	99022
T5	0.901	0.508	91739
T17	0.930	0.203	4845764
T15	0.982	0.380	4135
S9	0.984	0.359	12256
T9	0.990	0.347	14671
T1	0.254	0.964	210573
T2	0.113	0.843	23743530
T10	0.247	0.781	1842
T14	0.154	0.850	58481394
S7	0.379	0.986	332628
S8	0.529	0.859	354305
S10	0.283	0.986	328377
S11	0.138	0.872	174072

Figure 10. Fingerprint analysis of PAH contaminated sediments.

3.5 Mixing of Similar Contaminant Plumes - PAH Case Study

Two potential sources of polycyclic aromatic hydrocarbon (PAH) are separated by a small tributary that drains into a river. One potential source is a landfill that included waste tar among its contents. The second potential source was a salvage yard that processed crude tar wastes to recover creosote, phenol, and other chemicals. Wastes from this salvage yard were disposed of on-site. Sediment sampling of the tributary that runs between these two operations produced total PAH concentrations ranging from less than 5 mg/kg to greater than 50,000 mg/kg.

The FALCON procedure was applied to a set of soil samples collected adjacent to the tributary. This effort identified two PAH fingerprint patterns as shown in Figure 10. For brevity, the 53 standard PAH compounds are not listed by name but simply referred to by compound number. One pattern was characterized by a relatively dominant peak for PAH compound 33, smaller peaks for PAH compounds 39, 40, 45, 46, and 20, and the low abundance of PAH compounds 1 to 19. The distinguishing characteristics of the second fingerprint pattern were the relatively large peaks for PAH compounds 1 and 20, several peaks for PAH compounds 2 to 10, and a relatively lower abundance of PAH compounds 39 to 53. The comparability of the two identified PAH fingerprints was only 0.329 (33 percent).

The PAH distribution in collected tributary sediment samples was compared to the two identified PAH fingerprints. One set of samples (T6, T3, T4, T5, T17, T15, S9 and T9) produced strong matches (0.874 to 0.990) with the fingerprint relatively enriched in compounds 33 to 53 and a poor match (0.203 to 0.657) with the fingerprint enriched in compounds 1 to 19. The second set of samples (T1, T2, T10, T14, S7, S8, S10, and S11) produced a strong match (0.781 to 0.986) with the fingerprint enriched in PAH compounds 1 to 20 and a poor match (0.113 to 0.529) with the fingerprint enriched in PAH compounds 33 to 53. Based on the fingerprint assessment, tributary sediments closest to the bank had a low total PAH concentration and a PAH fingerprint enriched with compounds 1 to 20. The mid-channel sediments had a very high total PAH concentration (two orders of magnitude greater than the sediments closest to the bank) and a PAH distribution relatively enriched in compounds 33 to 53.

4.0 FALCON Capabilities

FALCON is a flexible data analysis technique of combining data from two or more contaminants to develop a distinctive chemical signature. The resultant FALCON fingerprint, based on the relative abundance rather than actual concentrations of the individual contaminants, provides a mechanism to identify the source and monitor the environmental behavior of fugitive emissions and leachates. These source patterns provide a visual characterization of contaminants in liquid and solid matrices and generally have a reproducibility of 90 to 99 percent.

The FALCON process can assist in the evaluation and interpretation of site characterization and monitoring data in several ways:

1. The process produces a characteristic fingerprint that associates a contaminant with a particular source. The data normalization process permits a direct visual comparison of fingerprint patterns despite highly variable contaminant concentrations and the use of regression analysis provides a statistical estimate of the reproducibility or comparability of two patterns. Distinctive fingerprints can be developed to characterize organic and inorganic contamination due to spills, leaks, and landfill leaching. In addition to the dioxin-furan, mine site, and PAH examples illustrated in this report, the FALCON technique has also been used to characterize halogenated organic solvent spills, gasoline and diesel fuel spills, and landfill leachates.

2. The fingerprints can differentiate a source fingerprint from background conditions. As illustrated in the gold mine (Section 3.2), copper mine (Section 3.3), and the molybdenum mine (Section 3.4) examples, each source had a characteristic fingerprint that could be visually and statistically differentiated from background ground water and upriver surface water conditions in the vicinity of each facility.

3. FALCON fingerprints provide a mechanism to differentiate multiple sources of the same contaminants. As illustrated in the dioxin example (Section 3.1) and the PAH example (Section 3.5), distinctive fingerprints can be developed for each source.

4. FALCON fingerprints retain their chemical identity and act as an internal tracer as they migrate through the environment. Therefore, fingerprint patterns at established monitoring locations can be directly compared with the source fingerprint as demonstrated with the gold mine example (Section 3.2) to verify the source of detected contaminants and to map the areas that have been impacted by a specific potentially responsible party.

5. FALCON fingerprints can also be used as a tool to characterize the environmental behavior of contaminant plumes. Fingerprint analysis provided a quantitative estimate of the Roanoke sediment contamination that can be specifically attributed to a pulp mill even though there are multiple sources of dioxin-furan contamination to the river (Section 3.1). The molybdenum mine case study (Section 3.4) demonstrated that a source fingerprint could be tracked through the ground water and used to estimate the rate of mixing between mine leachate and surface water. Thus, in addition to source characterization, the fingerprints can be used to characterize the migration of contaminants between environmental phases (ground water, surface water, and sediments) and to quantify the extent of mixing or dilution that has occurred between two source fingerprints. This capability provides a mechanism to apportion responsibility for environmental degradation between potentially responsible parties.

6. Fingerprints also have a potential application as detection monitoring parameters to provide early warning of leachate migration. This capability is illustrated with the copper mine case study (Section 3.4) in which the tailings pond fingerprint was initially detected and then fully developed before the more hazardous constituents associated with mine leachate were detected downgradient from the mine site. Fingerprint analysis would have provided an early warning to implement a corrective action or remediation program while the developing problem was smaller and more manageable. The factors that would permit the FALCON process to be used in this capacity are (a) the fingerprint characterizes the source and differentiates it from background conditions, (b) the fingerprint retains its chemical identity as it migrates away from the source, and (c) the fingerprint migrates faster than the contaminants of higher regulatory concern.

7. Each of the case studies mentioned in this report were developed with routine monitoring data. It is not necessary to use special analytical techniques, that may not produce data compatible with historical site records, in order to use the FALCON technique.

The previous discussion focused on the use of contaminant fingerprinting to evaluate site-specific data. The FALCON process can also provide the technical basis for the development of industry-specific monitoring strategies. For example, a review of the gold mine (Section 3.2), copper mine (Section 3.3), and molybdenum mine (Section 3.4) case studies reveals that the same small set of geochemical parameters defined a characteristic, reproducible fingerprint at each mine as well as the ground water and surface water in the vicinity of the mine. This observation has been verified by evaluating data from more than 30 additional mines.[1] These results suggest the possibility of a uniform two-phased monitoring program at mining facilities based on the set of geochemical parameters that characterize mine leachates. The first phase would utilize the fingerprint parameters to characterize and detect the leachate. As long as

leachate is not detected, contaminants are not entering the ground water and the facility would remain at this monitoring level. However, once the leachate fingerprint is detected, the second phase would be triggered to more fully characterize the slower migrating contaminants that may be present. The factors that support consideration of this approach are that the fingerprint is a reliable indicator of the leachate, the fingerprint retains its identity as it migrates, and the fingerprint migrates faster than other leachate constituents (as illustrated in the copper mine case study, Section 3.3). This approach could reduce monitoring costs and provide a uniform monitoring strategy that would be easier to implement, evaluate, and enforce.

5.0 Summary

FALCON is an empirical data assessment and visualization tool that produces contaminant fingerprint patterns. This technique combines data from two or more parameters to produce visually distinctive and reproducible fingerprints. The resultant fingerprints can be used to:

1. Characterize contaminants at their source,

2. Compare and evaluate background levels of contaminants with anthropogenic sources,

3. Establish an internal tracer to monitor the migration of a contaminant plume through ground water, surface water, and sedimentary environments, and

4. Differentiate two sources of the same contaminant and estimate the relative mixing that has occurred between two contaminant plumes.

Additional information on the FALCON procedure can be obtained from Gareth Pearson, Director of the Technical Support Center, U.S. EPA National Environmental Research Laboratory, Las Vegas, Nevada (pearson.gareth@epa.gov).

6.0 References

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7.0 Notice

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Document 20

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December 2009

Characterization of Coal Combustion Residues from Electric Utilities – Leaching and Characterization Data

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Characterization of Coal Combustion Residues from Electric Utilities – Leaching and Characterization Data

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S. Thorneloe provided technical direction for this research. In addition, she was responsible for obtaining samples, communication, and report writing.

ABSTRACT

This report evaluates changes in composition and constituent release by leaching that may occur to fly ash and other coal combustion residues (CCRs) in response to changes in air pollution control technology at coal-fired power plants. The addition of flue-gas desulfurization (FGD) systems, selective catalytic reduction, and activated carbon injection to capture mercury and other pollutants will shift mercury and other pollutants from the stack gas to fly ash, FGD gypsum, and other air pollution control residues. The objective is to understand the fate of mercury and other constituents of potential concern (COPC) in air pollution control residues and support EPA's broader goal of ensuring that emissions being controlled in the flue gas at power plants are not later being released to other environmental media.

This report includes data on 73 CCRs [34 fly ashes, 20 flue gas desulfurization (FGD) gypsum, 7 "other" FGD residues (e.g., scrubbers without oxidation or with inhibited oxidation), and 8 blended CCRs "as managed" (e.g., scrubber sludge mixed with fly ash and lime prior to disposal)]. Each of the CCRs sampled has been analyzed for a range of physical properties, total elemental content, and leaching characteristics for mercury, aluminum, antimony, arsenic, barium, boron, cadmium, chromium, cobalt, lead, molybdenum, selenium and thallium.

The leach testing methods that were used in this research consider the impact on leaching of management conditions. These methods are intended to address concerns raised by the National Academy of Science and the EPA's Science Advisory Board with the use of single-point pH tests. Because of the range of field conditions that CCRs are managed during disposal or use as secondary (or alternative) materials, it is important to understand the leaching behavior of materials over the range of plausible field conditions that can include acid mine drainage and co-disposal of fly ash and other CCRs with pyrites or high-sulfur coal rejects. The methods have also been developed into draft protocols for inclusion in EPA's waste testing guidance document, SW-846, which would make them available for more routine use. (http://www.epa.gov/osw/hazard/testmethods/sw846/index.htm)

The major conclusions from this research include:

- There is great variability in both the range of total constituent concentration values and in leaching values (orders of magnitude). In comparing there results to health indicator values such as the maximum concentration limit or toxicity characteristic, there are multiple COPCs of potential concern.
- Distinctive patterns in leaching behavior have been identified over a range of pH values that would plausibly be encountered for CCR management.
- Total constituent content is not a good indicator of leaching which has been found to be a function of the characteristics of the material (pH) and field conditions in which the material is managed.
- The maximum eluate concentration from leaching test results varies over a wide range in pH and is different for different CCR types and elements. This indicates that there is not a single pH for which testing is likely to provide confidence in release estimates over a wide range of disposal and beneficial use options, emphasizing the benefit of multi-pH testing. Furthermore, for CCRs, the rate of constituent release to the environment is affected by leaching conditions (in some cases dramatically so), and that leaching

evaluation under a single set of conditions will, in many cases, lead to inaccurate conclusions about expected leaching in the field.

The intended use for the data in this report is to support future risk and environmental assessments of the CCRs studied. A follow-up report is planned which will use these data in conducting a probabilistic assessment of mercury and other COPCs release rates based on the range of plausible management scenarios for these materials in either disposal or beneficial use situations. The data summarized in this report will also be made available electronically through a leaching assessment tool (LeachXS Lite®) that can be used to develop source-term inputs needed for using groundwater transport and fate models. The leaching assessment tool will also provide means for data management in viewing data resulting from the of the improved leaching test methods.

GLOSSARY OF TERMS

ACI	Activated Carbon Injection
Al	Aluminum
AL	Action Level
APC	Air Pollution Control
APPCD	Air Pollution Prevention and Control Division
As	Arsenic
ASTM	American Society for Testing and Materials
B	Boron
Ba	Barium
BDL	Below Detection Limit
BET	Brunauer, Emmett and Teller (method for estimating surface area)
CAIR	Clean Air Interstate Rule
CAMR	Clean Air Mercury Rule
Cd	Cadmium
CCRs	Coal Combustion Residues
CCV	Continuing Calibration Verification
Co	Cobalt
COPCs	Constituents of Potential Concern
Cr	Chromium
CV	Coefficient of Variation
CVAA	Cold Vapor Atomic Adsorption
DIC	Dissolved Inorganic Carbon
DOC	Dissolved Organic Carbon
DOE	United States Department of Energy
DI	Deionized (i.e., deionized water)
DRC	Dynamic Reaction Chamber
dw	dry weight basis
DWEL	Drinking Water Equivalent Level
EPA	United States Environmental Protection Agency
EPRI	Electric Power Research Institute
ESP	Electrostatic Precipitator

GLOSSARY OF TERMS - CONTINUED

ESP-CS	Cold-side Electrostatic Precipitator
ESP-HS	Hot-side Electrostatic Precipitator
FF	Fabric Filter (baghouse)
FGD	Flue Gas Desulfurization
FID	Flame Ionization Detector
FO	Forced Oxidation
FSS	Fixated Scrubber Sludge
FSSL	Fixated Scrubber Sludge with Lime
Gyp-U	Unwashed Gypsum
Gyp-W	Washed Gypsum
Hg	Mercury
HHV	Higher Heating Value
Ho	Holmium
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometry
ICP-MS	Inductively Coupled Plasma-Mass Spectrometry
ICV	Initial Calibration Verification
In	Indium
IO	Inhibited Oxidation
IOx	Inhibited Oxidation (this abbreviation used in some figures to improve clarity)
LF	Landfill
LOI	Loss On Ignition
LS	Liquid-to-Solid Ratio (LS ratio)
M	Molar
Max	Maximum
MCL	Maximum Contaminant Level (for drinking water)
MDL	Method Detection Limit
Mg Lime	Magnesium Enriched Lime (often also referred to as “mag-lime”)
Min	Minimum
ML	Minimum Level of Quantification
Mo	Molybdenum

GLOSSARY OF TERMS - CONTINUED

NETL	National Energy Technology Laboratory (DOE)
NIOSH	National Institute of Occupational Safety and Health
NO	Natural Oxidation
NO_x	Nitrogen Oxides
NSPS	New Source Performance Standards
OC/EC	Organic Carbon/Elemental Carbon
ORD	Office of Research and Development (EPA)
OSWER	Office of Solid Waste and Emergency Response (EPA)
PAC	Powdered Activated Carbon
Pb	Lead
PJFF	Pulse-Jet Fabric Filter
PM	Particulate Matter
PRB	Sub-bituminous coal mined in Wyoming's Powder River Basin
PS	Particulate Scrubber
QA/QC	Quality Assurance/Quality Control
RCRA	Resource Conservation and Recovery Act
RFA	Reference Fly Ash
SAB	EPA Science Advisory Board
SCA	Specific Collection Area
Sb	Antimony
ScS	Scrubber Sludge
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
SDA	Spray Dryer Absorber
Se	Selenium
SI	Surface Impoundment
SO_2	Sulfur Dioxide
SOFA	Separated Overfire Air
SPLP	Synthetic Precipitation Leaching Procedure
SRM	Standard Reference Material
S/S	Stabilization/Solidification

GLOSSARY OF TERMS - CONTINUED

SWDA	Solid Waste Disposal Act
TC	Toxicity Characteristic
TCLP	Toxicity Characteristic Leaching Procedure
Tl	Thallium
XAFS	X-Ray Absorption Fine Structure
XRF	X-Ray Fluorescence

EXECUTIVE SUMMARY

This report is the third in a series to evaluate changes in composition and constituent release by leaching that may occur to fly ash and other coal combustion residues (CCRs) in response to changes in air pollution control technology at coal-fired power plants. The addition of flue-gas desulfurization (FGD) systems, selective catalytic reduction, and activated carbon injection to capture mercury and other pollutants will shift mercury and other pollutants from the stack gas to fly ash, FGD gypsum, and other air pollution control residues. The Air Pollution Prevention and Control Division (APPCD) of EPA's Office of Research and Development (ORD) is conducting research to evaluate potential leaching and other cross media transfers of mercury and other constituents of potential concern (COPCs) resulting from the management of CCRs resulting from wider use of state-of-the art air pollution control technology. This research was cited as a priority in EPA's Mercury Roadmap[1] to ensure that one environmental problem is not being traded for another. The objective is to understand the fate of mercury and other COPCs in air pollution control residues and support EPA's broader goal of ensuring that emissions being controlled in the flue gas at power plants are not later being released to other environmental media.

Approximately 40% of the 126 million tons of CCRs produced in the U.S. as of 2006 were utilized in agricultural, commercial, and engineering applications. The remainder (i.e., 75 million tons) was managed in either landfills or impoundments. The physical and chemical characteristics of CCRs make them potentially suitable as replacements for materials used in a wide range of products including cement, concrete, road base, and wallboard. Use of CCRs as an alternative to virgin materials helps conserve natural resources and energy, as well as decrease the amount of CCRs being land disposed.

In developing data to characterize the leaching potential of COPCs from the range of likely CCRs resulting from use of state-of-the-art air pollution control technology, improved leaching test methods have been used[2]. The principle advantage of these methods is that they consider the impact on leaching of management conditions. These methods address concerns raised by National Academy of Science and EPA's Science Advisory Board with the use of single-point pH tests. Because of the range of field conditions that CCRs are managed during disposal or use as secondary (or alternative) materials, it is important to understand the leaching behavior of materials over the range of plausible field conditions that can include acid mine drainage and co-disposal of fly ash and other CCRs with pyrites or high-sulfur coal rejects[3, 4]. The methods have

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[1] EPA (2006). EPA's Roadmap for Mercury, EPA-HQ-OPPT-2005-0013. U.S. Environmental Protection Agency, http://www.epa.gov/mercury/pdfs/FINAL-Mercury-Roadmap-6-29.pdf (accessed August 21, 2009).

[2] Improved leaching test methods described in (Kosson et al., 2002) have been developed as draft SW-846 protocols. These methods consider the effect of varying environmental conditions on waste constituent leaching.

[3] National Academy of Sciences (2006). Managing Coal Combustion Residues in Mines, Washington, D.C.

[4] Sanchez, F.; Keeney, R.; Kosson, D., and Delapp, R. Characterization of Mercury-Enriched Coal Combustion Residues from Electric Utilities Using Enhanced Sorbents for Mercury Control, EPA-600/R-06/008, Feb. 2006; http://www.epa.gov/ORD/NRMRL/pubs/600r06008/600r06008.pdf.

also been developed into draft protocols for inclusion in EPA's waste testing guidance document, SW-846, which would make them available for more routine use. (http://www.epa.gov/osw/hazard/testmethods/sw846/index.htm).

The selected testing approach was chosen for use because it evaluates leaching over a range of values for two key variables [pH and liquid-to-solid ratio (LS)] that both vary in the environment and affect the rate of constituent release from waste. The range of values used in the laboratory testing encompasses the range of values expected to be found in the environment for these parameters. Because the effect of these variables on leaching is evaluated in the laboratory, prediction of leaching from the waste in the field is expected to be done with much greater reliability.

The categories into which samples have been grouped are fly ash, flue gas desulfurization (FGD) gypsum, "other" FGD residues (such as from spray drier absorbers), blended CCRs "as managed" (mixtures of fly ash and scrubber residues with and without added lime or mixture of fly ash and gypsum), and wastewater filter cake. In the first report from this research[5], results of leaching from fly ash were reported for mercury, arsenic, and selenium. Report 2 provided leaching results for an expanded list of materials and COPCs to include mercury, aluminum, antimony, arsenic, barium, boron, cadmium, chromium, cobalt, lead, molybdenum, selenium and thallium[6]. In the current report (Report 3), analyses of eluates from CCR samples presented in Report 1 have been included for the expanded list of COPCs. Report 3 also includes the data previously reported in Report 2, and leach test results for an additional 38 CCRs. A total of 73 samples were evaluated, and all results are presented in the current report to facilitate comparisons (Table ES-1).

[5] Sanchez, F.; Keeney, R.; Kosson, D., and Delapp, R. Characterization of Mercury-Enriched Coal Combustion Residues from Electric Utilities Using Enhanced Sorbents for Mercury Control, EPA-600/R-06/008, Feb. 2006; http://www.epa.gov/ORD/NRMRL/pubs/600r06008/600r06008.pdf.

[6] Sanchez, F.; Kosson, D.; Keeney, R.; Delapp, R.; Turner, L.; Kariher, P.; Thorneloe, S. Characterization of Coal Combustion Residues from Electric Utilities Using Wet Scrubbers for Multi-Pollutant Control; EPA-600/R-08/077, July 2008; http://www.epa.gov/nrmrl/pubs/600r08077/600r08077.pdf.

Table ES-1. Identification of CCRs evaluated and included in this Report.

Samples Evaluated	Report 1*	Report 2**	Additional Samples Collected	Total in Report 3
Fly Ash	12	5	17	34
FGD Gypsum	-	6	14	20
"Other" FGD Residues	-	5	2	7
Blended CCRs "as managed"	-	7	1	8
Wastewater Treatment Filter Cake	-		4	4

* Sanchez, F.; Keeney, R.; Kosson, D., and Delapp, R. Characterization of Mercury-Enriched Coal Combustion Residues from Electric Utilities Using Enhanced Sorbents for Mercury Control, EPA-600/R-06/008, Feb. 2006; http://www.epa.gov/ORD/NRMRL/pubs/600r06008/600r06008.pdf.

**Sanchez, F.; Kosson, D.; Keeney, R.; Delapp, R.; Turner, L.; Kariher, P.; Thorneloe, S. Characterization of Coal Combustion Residues from Electric Utilities Using Wet Scrubbers for Multi-Pollutant Control; EPA-600/R-08/077, July 2008; http://www.epa.gov/nrmrl/pubs/600r08077/600r08077.pdf.

Each of the CCRs sampled has been analyzed for a range of physical properties, total elemental content, and leaching characteristics. Laboratory leach data are compared to field observations from industry and EPA data from sampling of impoundments and landfills. The laboratory leach results are also compared to reference indicators to provide context for the data including:

- The toxicity characteristic (TC), which is a threshold for hazardous waste determinations;
- The maximum concentration limit (MCL), which is used for protecting drinking water; and,
- The drinking water equivalent level (DWEL), which is used to be protective for non carcinogenic endpoints of toxicity over a lifetime of exposure[7].

These comparisons to reference indicators do not consider dilution and attenuation factors (collectively referred to in this report as attenuation factors) that arise as a consequence of disposal or beneficial use designs and transport from the point of release to the potential receptor. Minimum attenuation factors needed to reduce maximum leach concentrations (based on laboratory test results) to less than MCL or DWEL values are provided to illustrate the importance of consideration of attenuation factors during evaluation of management options.

The intended use for the data in this report is to support future risk and environmental assessments of the CCRs. A follow-up report is planned which will use these data in conducting a probabilistic assessment of mercury and other COPCs release rates based on the range of plausible management scenarios for these materials in either disposal or beneficial use situations.

The data summarized in this report will be made available electronically through a leaching assessment tool that can be used to develop source-term inputs needed for using groundwater

[7]DWEL was developed for chemicals that have a significant carcinogenic potential and provides risk managers with evaluation on non-cancer endpoints, but infers that carcinogenicity should be considered the toxic effect of greatest concern (http://www.epa.gov/safewater/pubs/gloss2.html#D).

transport and fate models[8]. The leaching assessment tool will provide easier access to the leach data for a range of CCRs and potential field conditions. The tool can be used to develop more detailed leach data as input to more refined assessments of CCRs and support environmental decision-making that will ensure protection of human health and the environment.

Summary of Conclusions

In Table ES-2 and Table ES-3, the total metals content of the fly ash and FGD gypsum samples evaluated is provided along with the leach test results. Reference indicators (i.e., TC, MCL, and DWEL) are also provided to provide some context in understanding the leach results. It is critical to bear in mind that the leach test results represent a distribution of potential constituent release concentrations from the material as disposed or used on the land. The data presented do not include any attempt to estimate the amount of constituent that may reach an aquifer or drinking water well. Leachate leaving a landfill is invariably diluted in ground water to some degree when it reaches the water table, or constituent concentrations are attenuated by sorption and other chemical reactions in groundwater and sediment. Also, groundwater pH may be different from the pH at the site of contaminant release, and so the solubility and mobility of leached contaminants may change when they reach groundwater. None of these dilution or attenuation processes is incorporated into the leaching values presented. Thus, comparisons with regulatory health values, particularly drinking water values, must be done with caution. Groundwater transport and fate modeling would be needed to generate an assessment of the likely risk that may result from the CCRs represented by these data.

In reviewing the data and keeping these caveats in mind, conclusions to date from the research include:

1. Review of the fly ash and FGD gypsum (Table ES-2 and Table ES-3) show a range of total constituent concentration values, but a much broader range (by orders of magnitude) of leaching values, in nearly all cases. This much greater range of leaching values only partially illustrates what more detailed review of the data shows: that for CCRs, the rate of constituent release to the environment is affected by leaching conditions (in some cases dramatically so), and that leaching evaluation under a single set of conditions may, to the degree that single point leach tests fail to consider actual management conditions, lead to inaccurate conclusions about expected leaching in the field.
2. Comparison of the ranges of totals values and leachate data from the complete data set supports earlier conclusions[9, 10, 11] that the rate of constituent leaching cannot be reliably estimated based on total constituent concentration.

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[8] The leaching assessment tool, LeachXS Lite®, will be available for inclusion in the CCR docket (December 2009).

[9] Senior, C; Thorneloe, S.; Khan, B.; Goss, D. Fate of Mercury Collected from Air Pollution Control Devices; Environmental Management, July 2009, 15-21.

[10] U.S. EPA, Characterization of Mercury-Enriched Coal Combustion Residuals from Electric Utilities Using Enhanced Sorbents for Mercury Control, EPA-600/R-06/008, Feb. 2006; http://www.epa.gov/ORD/NRMRL/pubs/600r06008/600r06008.pdf.

3. The maximum eluate concentration from leaching test results varies over a wide range in pH and is different for different CCR types and elements. This indicates that there is not a single pH for which testing is likely to provide confidence in release estimates over a wide range of disposal and beneficial use options, emphasizing the benefit of multi-pH testing.
4. From the more complete data in this report, distinctive patterns in leaching behavior have been identified over the range of pH values that would plausibly be encountered for CCR disposal, depending on the type of material sampled and the element. This reinforces the above conclusions based on the summary data.
5. Summary data in Table ES-2 on the leach results from evaluation of 34 fly ash samples across the plausible management pH domain of 5.4 to 12.4, indicates leaching concentration ranges over several orders of magnitude as a function of pH and ash source:
    - the leach results at the upper end of the concentration ranges exceeded the TC values for As, Ba, Cd, Cr, and Se.
    - the leach results at the upper end of the concentration ranges exceeded the MCL or DWEL for Sb, As, Ba, B, Cd, Cr, Pb, Mo, Se, and Tl.
6. Summary data in Table ES-3 on the leach results from evaluation of 20 FGD gypsum samples across the plausible management pH domain of 5.4 to 12.4, indicates leaching concentration ranges over several orders of magnitude as a function of pH and FGD gypsum source:
    - the leach results at the upper end of the concentration ranges exceeded the TC values for Cd and Se.
    - the leach results at the upper end of the concentration ranges exceeded the MCL or DWEL for Sb, As, B, Cd, Cr, Mo, Se, and Tl.
7. The variability in total content and the leaching of constituents within a material type (e.g., fly ash, gypsum) is such that, while leaching of many samples exceeds one or more of the available reference indicators, many of the other samples within the material type may be lower than the available regulatory or reference indicators. Additional or more refined assessment of the dataset may allow some distinctions regarding release potential to be made among particular sources of some CCRs, which may be particularly useful in evaluating CCRs in reuse applications.

Work is underway to develop a fourth report that presents such additional analysis of the leaching data to provide more insight into constituent release potential for a wider range of scenarios, including beneficial use applications. This will include calculating potential release

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[11]U.S. EPA, Characterization of Coal Combustion Residuals from Electric Utilities Using Wet Scrubbers for Multi-Pollutant Control; EPA-600/R-08/077, July 2008; http://www.epa.gov/nrmrl/pubs/600r08077/600r08077.pdf.

rates over a specified time for a range of management scenarios including use in engineering and commercial applications using probabilistic assessment modeling[12].

In interpreting the results provided in this report, please note that the CCRs analyzed in this report are not considered to be a representative sample of all CCRs produced in the U.S. For many of the observations, only a few data points were available. It is hoped that through broader use of the improved leach test methods (as used in this report), that additional data from CCR characterization will become available. That will help better define trends associated with changes in air pollution control at coal-fired power plants.

[12] Sanchez, F. and D. S. Kosson, 2005. Probabilistic approach for estimating the release of contaminants under field management scenarios. *Waste Management* 25(5), 643-472 (2005).

Table ES-2. Leach results for 5.4 ≤ pH ≤ 12.4 and at "own pH[13]" from evaluation of thirty-four fly ashes.

	Hg	Sb	As	Ba	B	Cd	Cr	Co	Pb	Mo	Se	TI
Total in Material (mg/kg)	0.01 – 1.5	3 – 14	17 – 510	590 – 7,000	NA	0.3 – 1.8	66 – 210	16 – 66	24 – 120	6.9 – 77	1.1 – 210	0.72 – 13
Leach results (µg/L)	<0.01 – 0.50	<0.3 – 11,000	0.32 – 18,000	50 – 670,000	210 – 270,000	<0.1 – 320	<0.3 – 7,300	<0.3 – 500	<0.2 – 35	<0.5 – 130,000	5.7 – 29,000	<0.3 – 790
TC (µg/L)	200	-	5,000	100,000	-	1,000	5,000	-	5,000	-	1,000	-
MCL (µg/L)	2	6	10	2,000	7,000 DWEL	5	100	-	15	200 DWEL	50	2

Note: The shade is used to indicate where there could be a potential concern for a metal when comparing the leach results to the MCL, DWEL, or TC. Note that MCL and DWEL values represent well concentrations; leachate dilution and attenuation processes that would occur in groundwater before leachate reaches a well are not accounted for, and so MCL and DWEL values are compared to leaching concentrations here to provide context for the test results and initial screening.

Table ES-3. Leach results for 5.4 ≤ pH ≤ 12.4 and at "own pH" from evaluation of twenty FGD gypsums.

	Hg	Sb	As	Ba	B	Cd	Cr	Co	Pb	Mo	Se	TI
Total in Material (mg/kg)	0.01 – 3.1	0.14 – 8.2	0.95 – 10	2.4 – 67	NA	0.11 – 0.61	1.2 – 20	0.77 – 4.4	0.51 – 12	1.1 – 12	2.3 – 46	0.24 – 2.3
Leach results (µg/L)	<0.01– 0.66	<0.3 – 330	0.32 – 1,200	30 – 560	12 – 270,000	<0.2 – 370	<0.3 – 240	<0.2 – 1,100	<0.2 – 12	0.36 – 1,900	3.6 – 16,000	<0.3 – 1,100
TC (µg/L)	200	-	5,000	100,000	-	1,000	5,000	-	5,000	-	1,000	-
MCL (µg/L)	2	6	10	2,000	7,000 DWEL	5	100	-	15	200 DWEL	50	2

Note: The shade is used to indicate where there could be a potential concern for a metal when comparing the leach results to the MCL, DWEL, or TC. Note that MCL and DWEL values represent well concentrations; leachate dilution and attenuation processes that would occur in groundwater before leachate reaches a well are not accounted for, and so MCL and DWEL values are compared to leaching concentrations here to provide context for the test results and initial screening.

[13] "Own pH" is defined as the end-point (equilibrium) eluate pH when a CCR is extracted with DI water at liquid to solid ratio of 10 mL/g, and is measured as part of leach testing as a function of pH.

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1. INTRODUCTION

More wide-spread implementation of multi-pollutant controls is occurring at U.S. coal-fired power plants. Although much research has occurred to characterize high-volume coal combustion residues [i.e., fly ash, bottom ash, boiler slag, and flue gas desulfurization (FGD) solids] extending back to the 1970s, previous research has not considered the wide range of field conditions that occur for coal combustion residues (CCRs) during land disposal and use in agricultural, commercial, and engineering applications. The objective of this research is to characterize the changes in total composition and constituent release potential occurring to CCRs resulting from wider use of multi-pollutant controls at U.S. coal-fired power plants. This characterization includes detailed analysis of the fly ash and other air pollution control residues in relationship to differences in air pollution control configurations and coal rank. The characterization also includes evaluating the leaching potential of constituents of potential concern (COPCs) across the range of plausible management conditions that CCRs are likely to encounter during land disposal or use in agricultural, commercial, and engineering applications. This research was cited as a priority in EPA's Mercury Roadmap (EPA, 2006b) to evaluate the potential for any cross-media transfers from the management of CCRs resulting from more stringent air pollution control at coal fired power plants. This report is part of a series of reports helping to document the findings of this research to provide more credible, up-to-date data on CCRs to identify any potential cross-media transfers.

The focus of this report is to present an evaluation of air pollution control residues that may result from the use of SO_2 scrubbers and other air pollution control technologies being used to control multiple pollutants at coal-fired power plants. The pathway of concern addressed in this report is the potential for transfer of pollutants to water resources or other environmental systems (e.g., soils, sediments). The residues studied for this report were fly ashes, unwashed and washed flue gas desulfurization (FGD) gypsum, scrubber sludge, blended CCR residues "as managed" (mixtures of fly ash and scrubber residues with and without added lime or mixture of fly ash and gypsum), and wastewater filter cake generated from power plants with a range of air pollution control configurations.

In particular, this report focuses on the potential for leaching of mercury and other COPCs during land disposal or beneficial use of the CCRs is the focus of this report. This research is part of an on-going effort by EPA to use an integrated, comprehensive approach to account for the fate of mercury and other metals in coal throughout the life-cycle stages of CCR management (Sanchez et al., 2006; Thorneloe et al., 2009; Thorneloe et al., 2008). Related research and assessment on environmental fate of constituents during CCR management includes conducting thermal stability studies, leach testing, and probabilistic assessment modeling to determine the fate of mercury and other metals that are in coal combustion residues resulting from implementation of multi-pollutant control technology (EPA, 2002; Kilgroe et al., 2001).

CCRs include bottom ash, boiler slag, fly ash, scrubber residues and other miscellaneous solids generated during the combustion of coal. Air pollution control can concentrate or partition metals to fly ash and scrubber residues. The boiler slag and bottom ash are not of interest in this study because air emission controls are not expected to change their composition. Use of multi-pollutant controls minimizes air emissions of mercury and other metals by the transfer of the metals to the fly ash and other CCRs. This research will help determine the fate of mercury and other COPCs from the management of CCRs through either disposal or reuse. Fly ash may

include unburned carbonaceous materials and inorganic materials in coal that do not burn, such as oxides of silicon, aluminum, iron, and calcium. Fly ash is light enough to be entrained in the flue gas stream and captured in the air pollution control equipment.

The type and characteristics of FGD scrubber residue produced is primarily a function of (i) the scrubber sorbent used (i.e., limestone, lime, magnesium enriched lime referred to as Mg lime, or alkaline fly ash), (ii) the extent of oxidation during scrubbing (i.e., forced oxidation, natural oxidation, or inhibited oxidation), (iii) post-scrubber processing, including possibly dewatering or thickening, drying, water rinsing, or blending with other materials, and (iv) coal rank combusted. The presence and leaching characteristics of the COPCs in air pollution control residues is a consequence of the coal combusted, process sequence employed, process conditions, process additives and use or disposal scenario.

Figure 1 illustrates the processes used in the production of materials that were sampled for this study, sample nomenclature, and the typical management pathways for each material. FGD gypsum is defined here as the by-product of the SO_2 wet scrubbing process when the scrubber residue is subjected to forced oxidation. In forced oxidation systems, nearly all of the by-product is calcium sulfate dihydrate ($CaSO_4 \bullet H_2O$). The resulting wet gypsum is partially dewatered and then either disposed in a landfill (unwashed gypsum; Gyp-U) or water rinsed (in some cases) and dried to produce washed gypsum (washed gypsum; Gyp-W) that then potentially can be used in wallboard manufacturing or agricultural applications. Scrubber sludge (ScS) is the by-product of the SO_2 wet scrubbing process resulting from neutralization of acid gases at facilities that use either inhibited oxidation or natural oxidation of scrubber residue. In inhibited oxidation systems, nearly all of the by-product is calcium sulfite hemihydrates ($CaSO_3 \bullet ½H_2O$). In natural oxidation systems, the by-product is a mixture of $CaSO_3 \bullet ½H_2O$ and $CaSO_4 \bullet H_2O$. Scrubber sludge typically will be either partially dewatered in a thickener and then disposed in a surface impoundment, or after thickening, further dewatered and mixed with fly ash to form blended CCRs "as managed[14]." In most cases, additional lime is also blended with the scrubber sludge and fly ash. The blend of fly ash and scrubber sludge is typically between 0.5 to 1.5 parts fly ash to 1 part scrubber sludge on a dry weight basis, with 0 or 2-4% additional lime added. Blended CCRs typically are either disposed in a landfill or supplied to a beneficial use (e.g., fill in mining applications). Facilities that have spray dryer absorbers (SDA) collect fly ash and FGD residues simultaneously as a sample residue stream.

This report evaluates the characteristics of fly ash, FGD gypsum, SDA, scrubber sludge, and blended CCRs "as managed" from thirty one (31) coal combustion facilities. In addition filter cake from waste water treatment was evaluated from four facilities.

[14] As managed is defined as how the material is managed by the coal-fired power plant either through disposal or reuse.

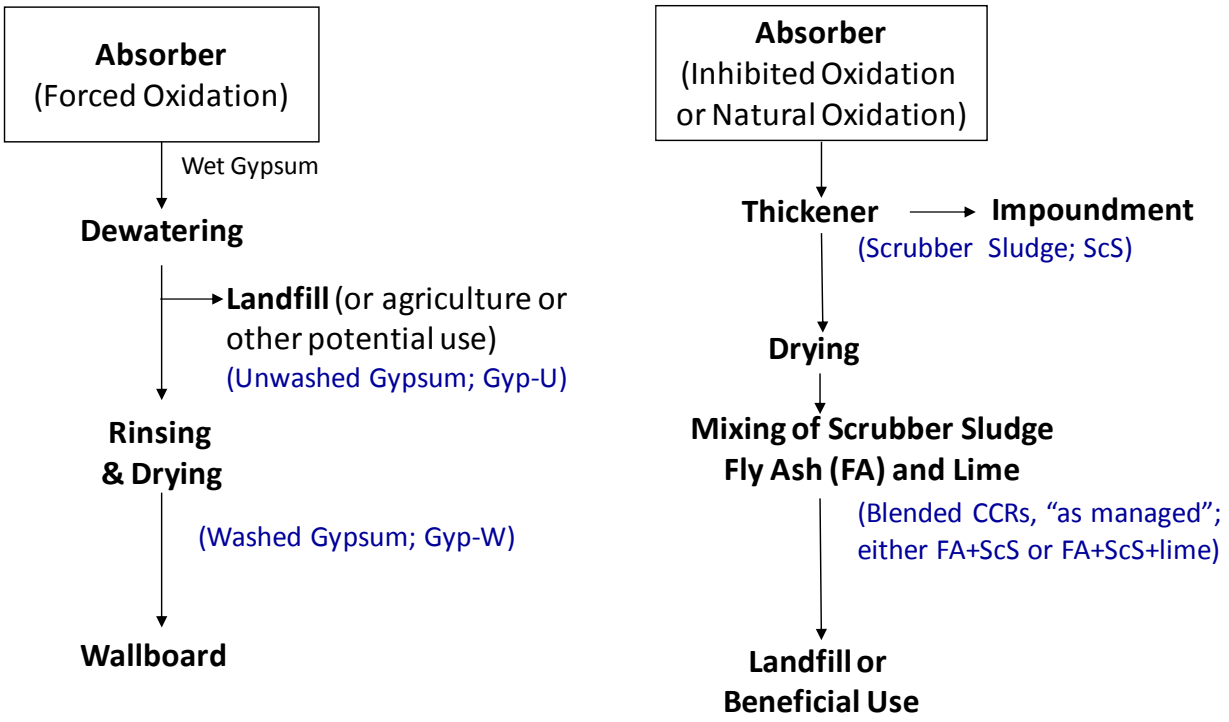


Figure 1. Flow diagram describing processing and nomenclature of FGD scrubber residues and samples included in this study.

When coal is burned in an electric utility boiler, the resulting high combustion temperatures vaporize the Hg in the coal to form gaseous elemental mercury (Hg^0). Subsequent cooling of the combustion gases and interaction of the gaseous Hg^0 with other combustion products may result in a portion of the Hg being converted to gaseous oxidized forms of mercury (Hg^{2+}) and particle-bound mercury (Hg_p). The specific chemical form–known as the speciation-as a strong impact on the capture of mercury and other metals by boiler air pollution control (APC) equipment (EPA, 2001).

Mercury and other elements partition between the combustion gas, fly ash and scrubber residues. Depending upon the gas conditioning, presence or absence of post-combustion NO_x control and other air pollution control technology in use, there may be changes occurring to the fly ash that can affect the stability and mobility of mercury and other metals in the CCRs. Similarly, NO_x control and SO_2 scrubber technology may affect the content, stability and mobility of mercury and other metals in scrubber residues.

The specific objectives of the research reported here are to:

1. Conduct analysis on range of air pollution control residues (i.e., fly ash, FGD residues and other CCRs) resulting from differences in coal rank and air pollution control configurations;
2. Evaluate the potential for leaching to groundwater of mercury and other COPCs (i.e., aluminum, antimony, arsenic, barium, boron, cadmium, chromium, cobalt, lead, molybdenum, selenium, and thallium) removed from the flue gas of coal-fired power plants using multi-pollutant controls to reduce air pollution; and

3. Provide the foundation for assessing the impact of enhanced mercury and multi-pollutant control technology on leaching of mercury and other COPCs from CCR management including storage, beneficial use, and disposal.

This is the third of a series of reports that addresses the potential for cross-media transfer of COPCs from CCRs. The first report focused on the use of sorbent injection (activated carbon and brominated activated carbon) for enhanced mercury control (Sanchez et al., 2006). The second report focused on facilities that use wet scrubbers for multi-pollutant control and includes results for 23 CCRs (fly ash, gypsum, scrubber sludge, fixated scrubber sludge) sampled from eight facilities (Sanchez et al., 2008). This report focuses on CCRs from coal-fired power plants that use air pollution control technologies, other than those evaluated in the first two reports, necessary to span the range of anticipated coal-types and air pollution control technology configurations. A subsequent report will address:

- Assessment of leaching of COPCs under additional management scenarios, including impoundments and beneficial use on the land (report 4); and,
- Broader correlation of CCR leaching characteristics to coal rank, combustion facility characteristics and geochemical speciation within CCRs supported by information and analysis on additional trace elements and primary constituents (report 4).

Sampled CCRs were subjected to multiple leaching conditions according to the designated leaching assessment approach, which is designed to examine leaching potential over a range of pH and LS ratios. Leaching conditions included batch equilibrium[15] extractions at acidic, neutral and alkaline conditions at an LS of 10 mL/g, and LS from 0.5 to 10 mL/g using distilled water as the leachant. In this report, the results of this testing are being used to evaluate the likely range of leaching characteristics during land disposal (i.e., landfill or surface impoundment) scenarios. Results of the laboratory leaching tests carried out in this study were compared to the range of observed constituent concentrations in field leachates reported in a U.S. EPA database (EPA, 2007b) and an Electric Power Research Institute (EPRI) database (EPRI, 2006). The testing results presented here will be used for evaluating disposal and beneficial use scenarios in a subsequent report.

The extensive nature of the results reported here necessitates detailed data presentation with only a broad assessment overview. Future reports will provide more detailed data evaluation and application of the data to evaluation of specific CCR management scenarios.

As part of this research program, a quality assurance/quality control (QA/QC) plan consistent with EPA requirements was developed for the leaching assessment approach (see Section 2.4). The QA/QC methodology included initial verification of acceptable mercury retention during laboratory testing through evaluation of a mass balance around testing procedures (Sanchez et al., 2006). Modifications to the QA/QC program to reduce the experimental and analytical burden while maintaining confidence in the resulting data, based on program results to date, are presented in Report 2 (Sanchez et al., 2008); further modifications are identified in this report.

[15] In the context of leaching tests, the term "equilibrium" is used to indicate that the test method result is a reasonable approximation of chemical equilibrium conditions even though thermodynamic equilibrium may not be approached for all constituents.

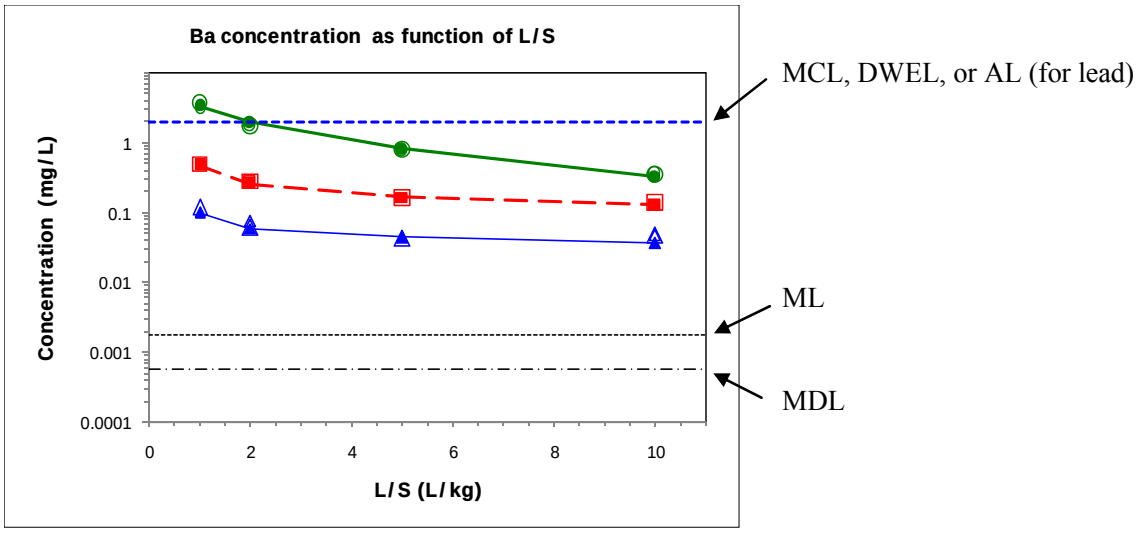


Figure 7. An example of eluate concentrations as a function of LS ratio from SR003.1.

2.5.2. Field pH Probability Distribution

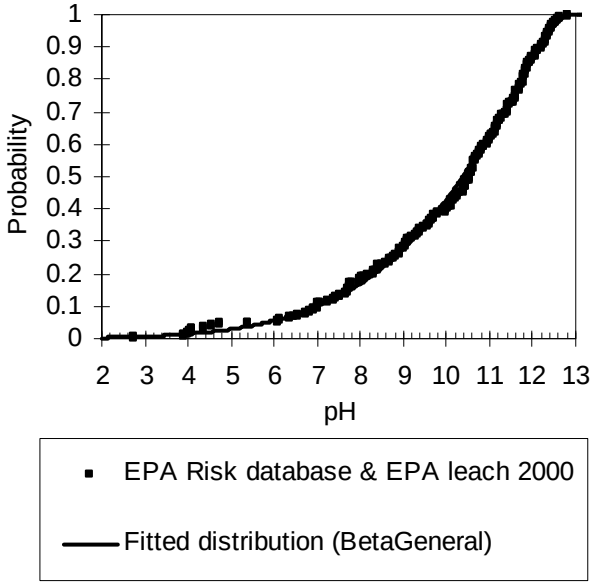
A probability distribution of field leachate pH values from coal combustion waste landfills was derived, as described below, from the set of field pH observations included in the EPA Risk Report (EPA, 2007b). The data set developed for the EPA Risk Report included (i) observations from the comprehensive database of landfill leachate characteristics developed by the EPA's Office of Solid Waste (EPA, 2000), (ii) field observations from literature, primarily from EPRI reports, (iii) additional data reported to EPA, and (vi) pH observations from laboratory leaching tests.

Only pH measurements from field samples (i.e., leachate, pore water) were selected for use in development of the resulting pH probability distribution. The resulting data set included 580 observations from 42 CCR landfill disposal facilities and was highly unbalanced, with some sites having only a few (e.g., less than five) observations and some sites having many observations (e.g., greater than 20). To prevent the unbalanced data from skewing the resulting probability distribution, the minimum, 25th, 50th, 75th percentile, and maximum values of observations for each individual facility were compiled into a single data set. For facilities with fewer than five observations, all observations for that facility were included. This data set then served as the basis for determining a balanced statistical distribution function of field leachate pH values from the disposal sites with reported values. Different distribution functions were used to fit the data and the one providing the best data fit based on the chi-square test was selected. The resulting field pH probability distribution was truncated and normalized to the pH range of the field data (Figure 8) (EPA, 2000; EPA, 2007b; EPRI, 2006).

Field pH observations were also evaluated for surface impoundments that receive CCRs from coal combustion facilities with FGD scrubbers in use. Pore water pH values measured in samples obtained from within the settled CCRs were extracted from the EPRI database. These pH observations were across the same range as the landfill field pH observations, but were insufficient to develop an independent pH probability distribution for surface impoundments.

Therefore, the same pH probability distribution was used for both landfill and surface impoundment facilities.

The resulting 5th and 95th percentiles of observed field pH values, equal to pH 5.4 and 12.4, respectively, are indicated on the figures of eluate concentrations as a function of pH (Figure 6).



pH	Field data	Fitted distribution	Simulated
Min	2.75	-7.42	2.76
5th percentile	5.40	5.84	5.85
50th percentile	10.53	10.38	10.24
90th percentile	12.20	12.18	11.94
95th percentile	12.40	12.43	12.43
Max	12.80	12.81	12.43

Distributions

BetaGeneral(9.0369, 1.5076, -7.4214, 12.814)

Figure 8. Probability distributions for field pH. Summary statistics for the field data and the probability distribution are provided to the right of the graph (EPA, 2000; EPA, 2007b; EPRI, 2006).

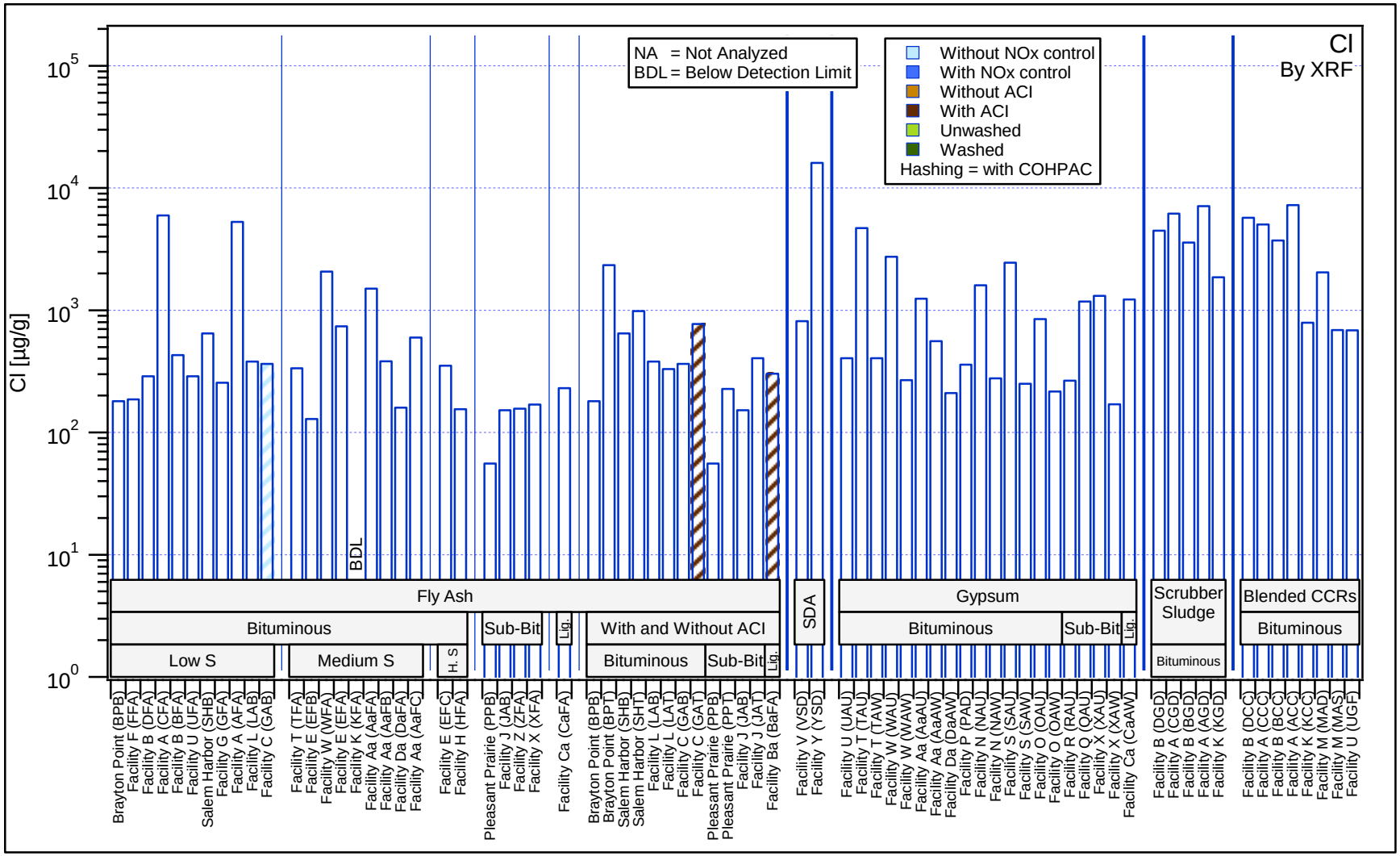


Figure 26. Chloride. Comparison of total elemental content by XRF.

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U.S. EPA, 75 FR 35128, June 21, 2010.

ENVIRONMENTAL PROTECTION AGENCY

40 CFR Parts 257, 261, 264, 265, 268, 271 and 302

[EPA–HQ–RCRA–2009–0640; FRL–9149–4]

RIN–2050–AE81

Hazardous and Solid Waste Management System; Identification and Listing of Special Wastes; Disposal of Coal Combustion Residuals From Electric Utilities

AGENCY: Environmental Protection Agency (EPA).

ACTION: Proposed rule.

SUMMARY: The Environmental Protection Agency (EPA or Agency) is proposing to regulate for the first time, coal combustion residuals (CCRs) under the Resource Conservation and Recovery Act (RCRA) to address the risks from the disposal of CCRs generated from the combustion of coal at electric utilities and independent power producers. However, the Agency is considering two options in this proposal and, thus, is proposing two alternative regulations. Under the first proposal, EPA would reverse its August 1993 and May 2000 Bevill Regulatory Determinations regarding coal combustion residuals (CCRs) and list these residuals as special wastes subject to regulation under subtitle C of RCRA, when they are destined for disposal in landfills or surface impoundments. Under the second proposal, EPA would leave the Bevill determination in place and regulate disposal of such materials under subtitle D of RCRA by issuing national minimum criteria. Under both alternatives EPA is proposing to establish dam safety requirements to address the structural integrity of surface impoundments to prevent catastrophic releases.

EPA is not proposing to change the May 2000 Regulatory Determination for beneficially used CCRs, which are currently exempt from the hazardous waste regulations under Section 3001(b)(3)(A) of RCRA. However, EPA is clarifying this determination and seeking comment on potential refinements for certain beneficial uses. EPA is also not proposing to address the placement of CCRs in mines, or non-minefill uses of CCRs at coal mine sites in this action.

DATES: Comments must be received on or before September 20, 2010. EPA will provide an opportunity for a public hearing on the rule upon request. Requests for a public meeting should be submitted to EPA's Office of Resource Conservation and Recovery by July 21, 2010. *See* the **FOR FURTHER INFORMATION CONTACT** section for contact information. Should EPA receive requests for public meetings within this timeframe, EPA will publish a document in the **Federal Register** providing the details of such meetings.

ADDRESSES: Submit your comments, identified by Docket ID No. EPA–HQ–RCRA–2009–0640, by one of the following methods:

- *http://www.regulations.gov:* Follow the on-line instructions for submitting comments.
- *E-mail:* Comments may be sent by electronic mail (e-mail) to *rcra-docket@epa.gov,* Attention Docket ID No. EPA–HQ–RCRA–2009–0640. In contrast to EPA's electronic public docket, EPA's e-mail system is not an "anonymous access" system. If you send an e-mail comment directly to the Docket without going through EPA's electronic public docket, EPA's e-mail system automatically captures your e-mail address. E-mail addresses that are automatically captured by EPA's e-mail system are included as part of the comment that is placed in the official public docket, and made available in EPA's electronic public docket.
- *Fax:* Comments may be faxed to 202–566–0272; Attention Docket ID No. EPA–HQ–RCRA–2009–0640.
- *Mail:* Send your comments to the Hazardous Waste Management System; Identification and Listing of Special Wastes; Disposal of Coal Combustion Residuals From Electric Utilities Docket, Attention Docket ID No., EPA–HQ–RCRA–2009–0640, Environmental Protection Agency, *Mailcode:* 5305T, 1200 Pennsylvania Ave., NW., Washington, DC 20460. Please include a total of two copies.
- *Hand Delivery:* Deliver two copies of your comments to the Hazardous Waste Management System; Identification and Listing of Special Wastes; Disposal of Coal Combustion Residuals From Electric Utilities Docket, Attention Docket ID No., EPA–HQ–RCRA–2009–0640, EPA/DC, EPA West, Room 3334, 1301 Constitution Ave., NW., Washington, DC 20460. Such deliveries are only accepted during the Docket's normal hours of operation, and special arrangements should be made for deliveries of boxed information.

Instructions: Direct your comments to Docket ID No. EPA–HQ–RCRA–2009–0640. EPA's policy is that all comments received will be included in the public docket without change and may be made available online at *http://www.regulations.gov,* including any personal information provided, unless the comment includes information claimed to be Confidential Business Information (CBI) or other information whose disclosure is restricted by statute. Do not submit information that you consider to be CBI or otherwise protected through *http://www.regulations.gov* or e-mail. The *http://www.regulations.gov* Web site is an "anonymous access" system, which means EPA will not know your identity or contact information unless you provide it in the body of your comment. If you send an e-mail comment directly to EPA without going through *http://www.regulations.gov,* your e-mail address will be automatically captured and included as part of the comment that is placed in the public docket and made available on the Internet. If you submit an electronic comment, EPA recommends that you include your name and other contact information in the body of your comment and with any disk or CD–ROM you submit. If EPA cannot read your comment due to technical difficulties and cannot contact you for clarification, EPA may not be able to consider your comment. Electronic files should avoid the use of special characters, any form of encryption, and be free of any defects or viruses. For additional information about EPA's public docket, visit the EPA Docket Center homepage at *http://www.epa.gov/epahome/dockets.htm.* For additional instructions on submitting comments, go to the **SUPPLEMENTARY INFORMATION** section of this document.

Docket: All documents in the docket are listed in the *http://www.regulations.gov* index. Although listed in the index, some information is not publicly available, *e.g.,* CBI or other information whose disclosure is restricted by statute. Certain other material, such as copyrighted material, will be publicly available only in hard copy. Publicly available docket materials are available either electronically in *http://www.regulations.gov* or in hard copy at the Hazardous Waste Management System; Identification and Listing of Special Wastes; Disposal of Coal Combustion Residuals From Electric Utilities Docket, EPA/DC, EPA West, Room 3334, 1301 Constitution Ave., NW., Washington, DC 20460. This Docket Facility is open from 8:30 a.m. to 4:30 p.m., Monday through Friday, excluding legal holidays. The Docket telephone number is (202) 566–0270. The Public Reading Room is open from 8:30 a.m. to 4:30 p.m., Monday through Friday, excluding legal holidays. The

producers, and (2) all remaining wastes subject to RCRA Sections 3001(b)(3)(A)(i) and 8002(n)—that is, large volume coal combustion wastes generated at electric utility and independent power producing facilities that are co-managed together with certain other coal combustion wastes; coal combustion wastes generated at non-utilities; coal combustion wastes generated at facilities with fluidized bed combustion technology; petroleum coke combustion wastes; wastes from the combustion of mixtures of coal and other fuels (*i.e.,* co-burning of coal with other fuels where coal is at least 50% of the total fuel); wastes from the combustion of oil; and wastes from the combustion of natural gas.

On August 9, 1993, EPA published its Regulatory Determination for the first category of wastes (58 FR 42466, *http://www.epa.gov/epawaste/nonhaz/industrial/special/mineral/080993.pdf*), concluding that regulation under subtitle C of RCRA for these wastes was not warranted. To make an appropriate determination for the second category, or "remaining wastes," EPA concluded that additional study was necessary. Under the court-ordered deadlines, the Agency was required to complete a Report to Congress by March 31, 1999, and issue a Regulatory Determination by October 1, 1999.

In keeping with its court-ordered schedule, and pursuant to the requirements of Section 3001(b)(3)(A)(i) and Section 8002(n) of RCRA, EPA prepared a Report to Congress on the remaining FFC wastes in March 1999 (*http://www.epa.gov/epaoswer/other/fossil/volume_2.pdf*). The report addresses the eight study factors required by Section 8002(n) of RCRA for FFC wastes (*see* discussion in section IV. B).

On May 22, 2000, EPA published its Regulatory Determination on wastes from the combustion of fossil fuels for the remaining wastes (65 FR 32214, *http://www.epa.gov/fedrgstr/EPA-WASTE/2000/May/Day-22/f11138.htm*). In its Regulatory Determination, EPA concluded that the remaining wastes were largely identical to the high-volume monofilled wastes, which remained exempt based on the 1993 Regulatory Determination. The high volume wastes simply dominate the waste characteristics even when co-managed with other wastes, and thus the May 2000 Regulatory Determination addressed not only the remaining wastes, but effectively reopened the decision on CCRs that went to monofills.

EPA concluded that these wastes could pose significant risks if not properly managed, although the risk information was limited. EPA identified and discussed a number of documented proven damage cases, as well as cases indicating at least a potential for damage to human health and the environment, but did not rely on its quantitative groundwater risk assessment, as EPA concluded that it was not sufficiently reliable. However, EPA concluded that significant improvements were being made in waste management practices due to increasing state oversight, although gaps remained in the current regulatory regime. On this basis, the Agency concluded to retain the Bevill exemption, and stated we would issue a regulation under subtitle D of RCRA, establishing minimum national standards. Those subtitle D standards have not yet been issued. (Today's proposal could result in the development of the subtitle D standards consistent with the May 2000 Regulatory Determination, or with a revision of the determination, or the issuance of subtitle C standards under RCRA.)

EPA also explicitly stated in the May 2000 Regulatory Determination that the Agency would continue to review the issues, and would reconsider its decision that subtitle C regulations were unwarranted based on a number of factors. EPA noted that its ongoing review would include (1) "the extent to which [the wastes] have caused damage to human health or the environment;" (2) the adequacy of existing regulation of the wastes; (3) the results of an NAS report regarding the adverse human health effects of mercury;[4] and (4) "risk posed by managing coal combustion solid wastes if levels of mercury or other hazardous constituents change due to any future Clean Air Act air pollution control requirements for coal burning utilities" and that these efforts could result in a subsequent revision to the Regulatory Determination. For a further discussion of the basis for the Agency's determination, *see* section IV below.

F. What are CCRs?

CCRs are residuals from the combustion of coal. For purposes of this proposal, CCRs are fly ash, bottom ash, boiler slag (all composed predominantly of silica and aluminosilicates), and flue gas desulfurization materials (predominantly Ca-SO_X compounds) that were generated from processes intended to generate power.

[4] Toxicological Effects of Methylmercury, National Academy of Sciences, July 2000 (*http://books.nap.edu/catalog.php?record_id=9899#toc*). EPA has not taken any actions regarding the May 2000 Regulatory Determination as a result of the NAS report.

Fly ash is a product of burning finely ground coal in a boiler to produce electricity. Fly ash is removed from the plant exhaust gases primarily by electrostatic precipitators or baghouses and secondarily by wet scrubber systems. Physically, fly ash is a very fine, powdery material, composed mostly of silica. Nearly all particles are spherical in shape.

Bottom ash is comprised of agglomerated coal ash particles that are too large to be carried in the flue gas. Bottom ash is formed in pulverized coal furnaces and is collected by impinging on the furnace walls or falling through open grates to an ash hopper at the bottom of the furnace. Physically, bottom ash is coarse, with grain sizes spanning from fine sand to fine gravel, typically grey to black in color, and is quite angular with a porous surface structure.

Boiler slag is the molten bottom ash collected at the base of slag tap and cyclone type furnaces that is quenched with water. When the molten slag comes in contact with the quenching water, it fractures, crystallizes, and forms pellets. This boiler slag material is made up of hard, black, angular particles that have a smooth, glassy appearance.

Flue Gas Desulfurization (FGD) material is produced through a process used to reduce sulfur dioxide (SO_2) emissions from the exhaust gas system of a coal-fired boiler. The physical nature of these materials varies from a wet sludge to a dry powdered material, depending on the process. The wet sludge generated from the wet scrubbing process using a lime-based reagent is predominantly calcium sulfite, while the wet sludge generated from the wet scrubbing process using a limestone-based reagent is predominantly calcium sulfate. The dry powdered material from dry scrubbers that is captured in a baghouse consists of a mixture of sulfites and sulfates.

CCRs are managed in either wet or dry disposal systems. In wet systems, materials are generally sluiced via pipe to a surface impoundment. The material can be generated wet, such as FGD, or generated dry and water added to facilitate transport (*i.e.* sluiced) through pipes. In dry systems, CCRs are transported in its dry form to landfills for disposal.

1. Chemical Constituents in CCRs

The chemical characteristics of CCRs depend on the type and source of coal, the combustion technology, and the pollution control technology employed. For the 1999 Report to Congress and the May 2000 Regulatory Determination, EPA developed an extensive database

Document 22

U.S. EPA, Human and Ecological Risk Assessment of Coal Combustion Wastes, August 2007.

Human and Ecological Risk Assessment of Coal Combustion Wastes

Draft

Prepared for:

U.S. Environmental Protection Agency
Office of Solid Waste
Research Triangle Park, NC 27709

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August 6, 2007

RTI INTERNATIONAL

Human and Ecological Risk Assessment of Coal Combustion Wastes

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Human and Ecological Risk Assessment of Coal Combustion Wastes – Executive Summary

The U.S. Environmental Protection Agency (EPA) is evaluating management options for solid wastes from coal combustion (e.g., fly ash, bottom ash, slag). As part of this effort, EPA is evaluating whether current management practices for coal combustion waste (CCW) pose risks to human health or ecological receptors. To inform this objective, EPA has conducted a nationwide assessment of the risks posed by CCW disposal practices across the country.

This report describes the results of the tiered, site-based, probabilistic (Monte Carlo) risk assessment of onsite CCW disposal practices at coal-fired power plants across the United States. These landfills and surface impoundments represent disposal practices for CCW reported in 1995. Although EPA acknowledges that management practices for CCW have improved since 1995, as documented in U.S. Department of Energy (DOE) (2006), EPA believes that characterizing risks from facilities observed in 1995 provides a snapshot of the potential risks from CCW disposal and can provide useful information as EPA evaluates CCW management options. In addition, the data available on these facilities' locations, environmental characteristics, and waste management units (WMUs) allow EPA to apply a site-based risk assessment approach that the agency believes characterizes the risks to human health and the environment from disposing CCW in landfills and surface impoundments.

In summary, this CCW risk assessment evaluates potential risk results at the 50th and 90th percentile exposure level, adopting a risk criteria of 10^{-5} for excess cancer risks. Potential noncancer and ecological risks are also evaluated at the 50th and 90th percentile levels, adopting a hazard quotient (HQ) risk criteria greater than 1 for noncancer effects to both human and ecological receptors. Overall, when all types of landfills and surface impoundments (as observed in 1995) are evaluated in aggregate, the risk at the 90th percentile exceeds the risk criteria for cancer and noncancer risks for certain constituents. There is no potential risk above the risk criteria (cancer and noncancer) found at the 50th percentile. The risk assessment also suggests that one of the most sensitive parameters in the risk assessment is infiltration rate. Infiltration rate is greatly influenced by whether and how a WMU is lined.

For humans exposed via the groundwater-to-drinking-water pathway, arsenic in CCW landfills poses a 90th percentile cancer risk of $5x10^{-4}$ for unlined units and $2x10^{-4}$ for clay-lined units. The 50th percentile risks are $1x10^{-5}$ (unlined units) and $3x10^{-6}$(clay-lined units). Risks are higher for surface impoundments, with an arsenic cancer risk of $9x10^{-3}$ for unlined units and $3x10^{-3}$ for clay-lined units at the 90th percentile. At the 50th percentile, risks for unlined surface impoundments are $3x10^{-4}$, and clay-lined units show a risk of $9x10^{-5}$. Five additional constituents have 90th percentile noncancer risks above the criteria (HQs ranging from greater than 1 to 4) for unlined surface impoundments, including boron and cadmium, which have been cited in CCW damage cases, referenced above. Boron and molybdenum show HQs of 2 and 3 for clay-lined surface impoundments. None of these noncarcinogens show HQs above 1 at the 50th percentile for any unit type.

Composite liners, which are used in the majority of new facilities constructed after 1995, effectively reduce risks from all pathways and constituents below the risk criteria (cancer and noncancer) for both landfills and surface impoundments[1].

Risks from clay-lined units, as modeled, are about one-third to one-half the risks of unlined

[1] These results suggest that with the higher prevalence of composite liners in new CCW disposal facilities, future national risks from onsite CCW disposal are likely to be lower than those presented in this risk assessment (which is based on 1995 CCW WMUs).

units, but are still above the risk criteria used for this analysis.

Arrival times of the peak concentrations at a receptor well are much longer for landfills (hundreds to thousands of years) than for surface impoundments (most less than 100 years).

For humans exposed via the groundwater-to-surface-water (fish consumption) pathway, selenium (HQ = 2) and arsenic (cancer risk = $2x10^{-5}$) pose risks slightly above the risk criteria for unlined surface impoundments at the 90th percentile. For both constituents, lined 90th percentile risks and all 50th percentile risks are below the risk criteria. No constituents pose risks above the risk criteria for landfills at the 90th or 50th percentile.

Waste type has little effect on landfill risk results, but in surface impoundments, risks are up to 1 order of magnitude higher for codisposed CCW and coal refuse than for conventional CCW.

The higher risks for surface impoundments than landfills are likely due to higher waste leachate concentrations, a lower proportion of lined units, and the higher hydraulic head from the impounded liquid waste. This is consistent with damage cases reporting wet handling as a factor that can increase risks from CCW management.

For ecological receptors exposed via surface water, risks for landfills exceed the risk criteria for boron and lead at the 90th percentile, but 50th percentile risks are well below the risk criteria. For surface impoundments, 90th percentile risks for several constituents exceed the risk criteria, with boron showing the highest risks (HQ = 2,000). Only boron exceeds the risk criteria at the 50th percentile (HQ = 4). Exceedances for boron and selenium are consistent with reported ecological damage cases, which include impacts to waterbodies through the groundwater-to-surface-water pathway.

For ecological receptors exposed via sediment, 90th percentile risks for lead, arsenic, and cadmium exceeded the risk criteria for both landfills and surface impoundments because these constituents strongly sorb to sediments in the waterbody. The 50th percentile risks are generally an order of magnitude or more below the risk criteria.

Background

EPA has conducted risk assessments to evaluate the environmental risks from CCW management practices,[2] including CCW disposal in landfills and surface impoundments. Although EPA determined (in April 2000) that certain CCWs were not subject to hazardous waste regulations and therefore would be subject to regulation as nonhazardous wastes, EPA did not specify regulatory options at that time. This risk assessment was conducted to identify and quantify human health and ecological risks that may be associated with current disposal practices for high-volume CCW, including fly ash, bottom ash, boiler slag, flue gas desulfurization (FGD) sludge, coal refuse waste, and wastes from fluidized-bed combustion (FBC) units. These risk estimates will help inform EPA's decisions about how to treat CCWs under Subtitle D of the Resource Conservation and Recovery Act.

Purpose and Scope of the Risk Assessment

The purpose of this risk assessment is to identify potential risks associated with CCW constituents, waste types, receptors, and exposure pathways, and to provide information about those scenarios that EPA can use to develop CCW management options.

The scope of this risk assessment is CCWs managed onsite at utility power plants. EPA's *Report to Congress: Wastes from the Combustion of Fossil Fuels* (U.S. EPA, 1999a) reports that there are 440 coal-fired utility power plants in the United States. Although these plants are concentrated in the East, they are found in nearly every state, with a broad variety of climate, geologic, and land use settings. The large volumes of waste generated by these plants

[2] Details on EPA's previous CCW work can be found at http://www.epa.gov/epaoswer/other/fossil/ index.htm.

are typically managed onsite in landfills and surface impoundments. This risk assessment was designed to develop national human and ecological risk estimates that are representative of onsite CCW management settings throughout the United States.

Risk Assessment Methodology

To estimate the risks posed by the onsite management of CCW, this risk assessment determined the release of CCW constituents from landfills and surface impoundments, estimated the concentrations of these constituents in environmental media surrounding coal-fired utility power plants, and estimated the risks that these concentrations pose to human and ecological receptors. To evaluate the significance of these risks, the risk criteria adopted for this assessment are:

- An estimate of the excess lifetime cancer risk for individuals exposed to carcinogenic (cancer-causing) contaminants of 1 chance in 100,000 (10^{-5} excess cancer risk)
- An HQ (the ratio of predicted intake levels to safe intake levels) greater than 1 for constituents that can produce noncancer human health effects
- An HQ greater than 1 for constituents with adverse effects to ecological receptors.

In support of this risk assessment, EPA assembled a constituent database that includes leachate and total waste analyses for 41 CCW constituents taken from more than 140 CCW disposal sites around the country. The CCW risk assessment subjected these waste and leachate constituent concentrations to a tiered risk assessment methodology (Figure ES-1) that implemented the following steps to assess the human and ecological risk of CCWs:

- **Hazard Identification**, which collected existing human health and ecological benchmarks for the 41 CCW constituents to identify the 26 chemicals with benchmarks for constituent screening
- **Constituent Screening**, which compared very conservative estimates of exposure concentrations (e.g., whole waste concentrations, leachate concentrations) to health-based concentration benchmarks to quickly and simply eliminate constituents and exposure pathways that do not require further analysis
- **Full-Scale Analysis**, which used a site-based Monte Carlo analysis to characterize at a national level the risks to human health and ecological receptors from onsite disposal (in landfills and surface impoundments) of CCW constituents that were not eliminated in the screening analysis.

The screening analysis looked at all probable exposure pathways from CCW management in landfills and surface impoundments and identified 21 CCW constituents and 3 exposure scenarios to evaluate in the full-scale analysis (Table ES-1). Exposure scenarios evaluated for people include contaminated groundwater being transported to drinking water wells from a CCW landfill or surface impoundment, and contaminated groundwater discharging into surface water and contaminating a nearby stream or lake where people catch and eat fish. The full-scale analysis also addressed ecological risk in the same waterbodies.

Constituents addressed in the full-scale analysis are listed in Table ES-2 along with the potential exposure pathways identified for full-scale modeling in the screening analysis.

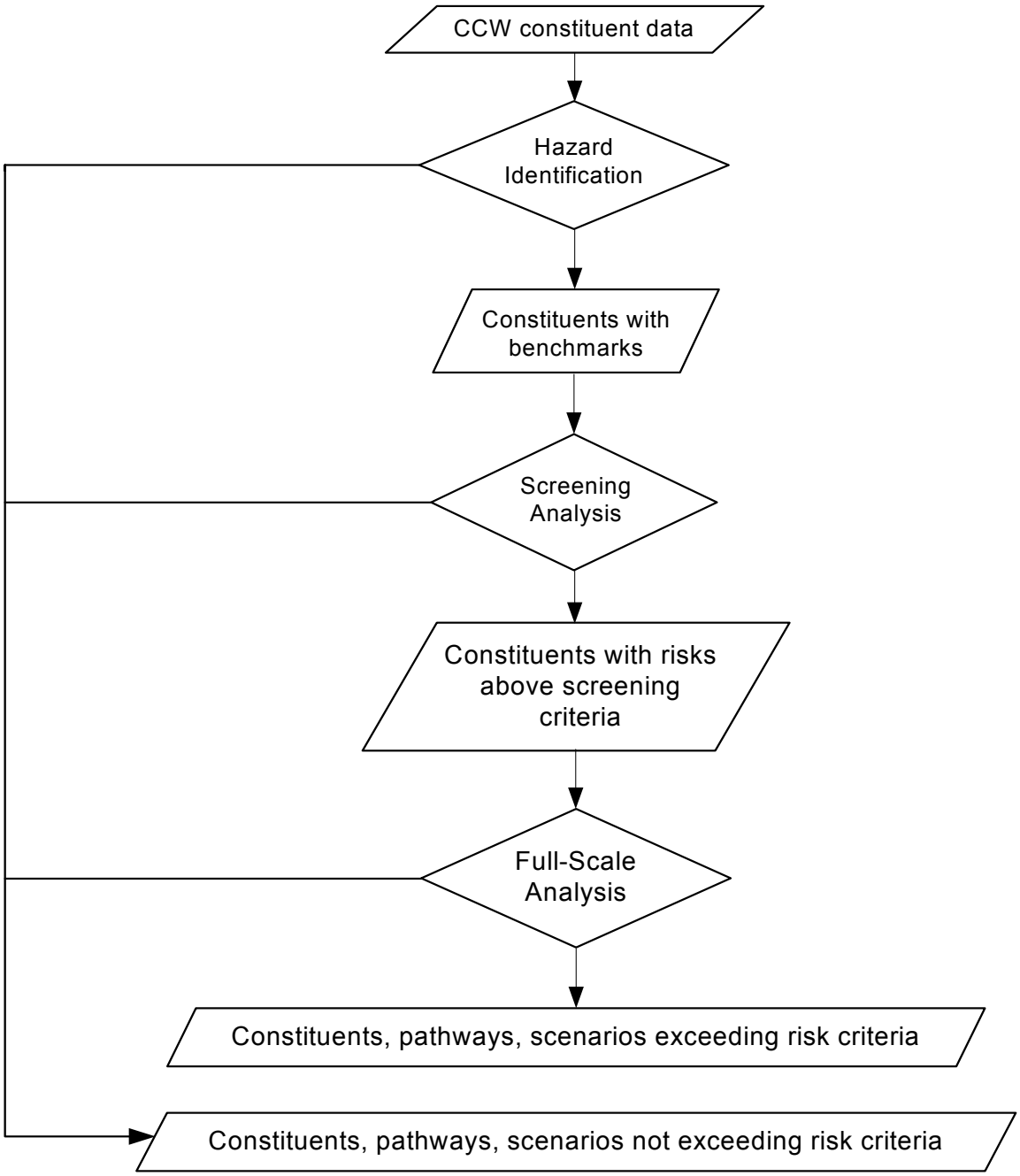


Figure ES-1. Overview of CCW risk assessment.

Table ES-1. Sources, Releases, Exposure Pathways, and Receptors Evaluated in the CCW Risk Assessment

Release Mechanism	Exposure Pathway	Exposure Mechanism	Receptor Type[a]	Screening Result
Landfills				
Leaching	Groundwater-to-drinking-water	Residential well	Resident	Full-scale analysis
	Groundwater-to-surface-water	Stream or lake, uptake by fish; contact with water, sediments	Recreational fisher; aquatic ecosystems	Full-scale analysis
Water erosion	Overland transport to surface water	Stream or lake, uptake by fish; contact with water, sediments	Recreational fisher; aquatic ecosystems	Below screening criteria
	Overland transport to soil	Soil ingestion; uptake from soil by plants, beef, dairy	Subsistence farmer; terrestrial ecosystems	Below screening criteria[b]
Wind erosion	Soil deposition	Soil ingestion; uptake from soil by plants, beef, dairy	Subsistence farmer; terrestrial ecosystems	Below screening criteria
	Fugitive dust	Inhalation	Resident	Below screening criteria
Surface impoundments				
Leaching	Groundwater-to-drinking water	Residential well	Resident	Full-scale analysis
	Groundwater-to-surface water	Stream or lake, uptake by fish; contact with water, sediments	Recreational fisher; ecological receptors	Full-scale analysis

[a] Human receptor types include adults and children.
[b] Except boron for plant toxicity. Also, damage cases indicate soil risks from selenium to terrestrial amphibians (Carlson and Adriano, 1993; Hopkins et al., 2006).

Table ES-2. Screening Analysis Results:
CCW Constituents Selected for Full-Scale Analysis[a]

Constituent	Human Health - Drinking Water		Human Health - Surface Water[b]		Ecological Risk - Surface Water	
	LF	SI	LF	SI	LF	SI
Arsenic	•	•	•	•	•	•
Boron	•	•			•	•
Cadmium	•	•	•	•	•	•
Lead	•	•			•	•
Selenium	•	•	•	•	•	•
Thallium	•	nd	•	nd	•	nd
Aluminum					•	•
Antimony	•	nd		nd		nd
Barium					•	•
Cobalt	na	•	na		na	•
Molybdenum	•	•				
Nitrate/Nitrite	•	•				
Chromium	•	•			•	•
Fluoride	•	•				
Manganese		•				
Vanadium	•	•			•	•
Beryllium					•	
Copper					•	•
Nickel		•				•
Silver					•	•
Zinc					•	

LF = landfill.
SI = surface impoundment
nd = nondetect—results are inconclusive because all analyses are nondetects.
na = not available—data were not available for cobalt in CCW landfill leachate.

[a] A mark in a cell indicates that the constituent was above the screening criteria for the indicated pathway and WMU type. Blank cells indicate that the constituent was below the screening criteria for a particular pathway/WMU combination. Risk screening was based on 90th percentile risk concentrations and no attenuation.

[b] Fish consumption pathway.

The full-scale analysis was designed to characterize waste management scenarios based on two waste management options (disposal of CCW onsite in landfills and in surface impoundments). The risk assessment was also used to characterize waste management scenarios based on three liner types (unlined units, clay-lined units, and composite-lined units) and three waste types, as follows:

- **Conventional CCW** (ash and FGD sludge), which includes fly ash, bottom ash, boiler slag, and FGD sludge
- **Codisposed CCWs and coal refuse,**[3] which are more acidic than conventional CCWs due to sulfide minerals in the coal refuse
- **FBC wastes**, which include fly ash and bed ash, and which tend to be more alkaline than conventional CCW because of the limestone mixed in during fluidized bed combustion.

These three waste types and the two waste management options provide a good representation of CCW disposal practices and waste chemistry conditions that affect the release of CCW constituents from WMUs.[4],[5]

The full-scale analysis was implemented using a site-based probabilistic approach that produces a distribution of risks or hazards for each receptor by allowing the values of some of the parameters in the analysis to vary. This approach is ideal for this risk assessment because there are many CCW facilities across the United States, and a site-based approach can capture both the variability in waste management practices at these facilities and the differences in their environmental settings (e.g., hydrogeology, climate, hydrology). This probabilistic approach was implemented through the following steps:

1. Characterize the CCW constituents and waste chemistry, along with the WMUs in which each waste stream may be managed (i.e., the size and liner status of CCW landfills and surface impoundments)
2. Characterize the environmental settings for the sites where CCW landfills and surface impoundments are located (i.e., locations of coal-fired power plants)
3. Identify how contaminants are released from a WMU (i.e., leaching) and transported to human and ecological receptors (i.e., via groundwater and surface water)
4. Predict the fate, transport, and concentration of constituents in groundwater and surface water once they are released to groundwater from the WMUs and travel to receptors at each site
5. Quantify the potential exposure of human and ecological receptors to the contaminant in the environment
6. Estimate the potential risk to each receptor from the exposure and characterize this risk in terms of exposure pathways and health effects.

Based on this approach, we characterized the potential risks associated with the waste disposal scenarios and exposure pathways, including the uncertainties associated with the analysis results.

Results and Conclusions

Risks from clay-lined units are lower than those from unlined units, but 90th percentile risks are still well above the risk criteria for arsenic and thallium for landfills and arsenic, boron, and molybdenum for surface impoundments. Composite liners, as modeled in this assessment, effectively reduce risks from all constituents to below the risk criteria for both landfills and surface impoundments. Although it is likely that today, most new landfills have some type of liner (based on more recent data that were not incorporated into this assessment),

[3] Coal refuse is the waste coal produced from coal handling and preparation operations.

[4] Conventional CCW and codisposed CCW and coal refuse were modeled in landfills and surface impoundments and are the focus of the overall analysis. FBC wastes were treated separately because of limited data on FBC waste management units.

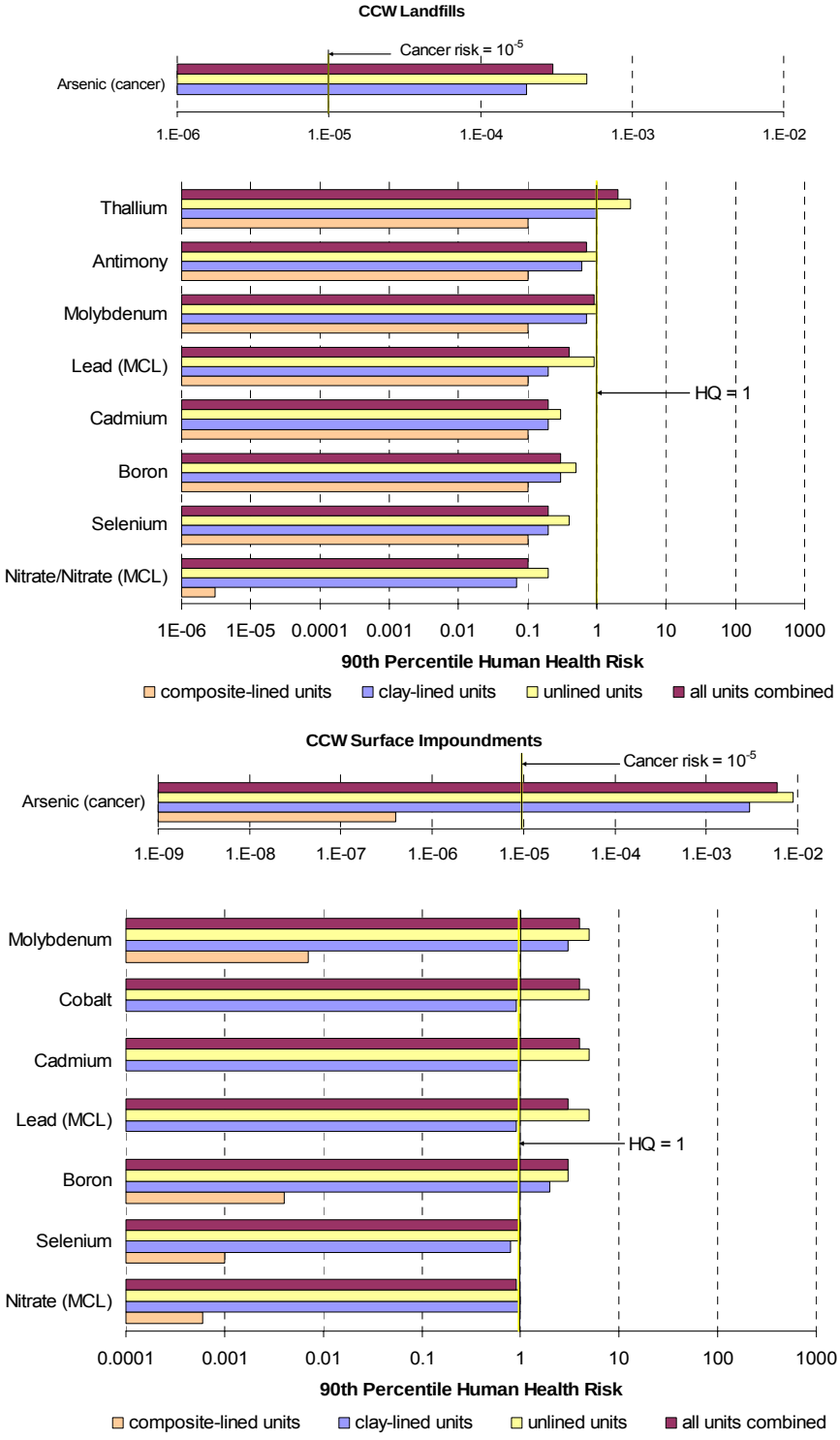
[5] Although different waste chemistries required the separate modeling of conventional CCW and CCW codisposed with coal refuse, the results were combined in this analysis to give an overall picture of the risks from CCW management,

it is not known how many unlined units continue to operate in the United States.

Recent data from a joint DOE/EPA survey suggests that more facilities are lined today than were in the 1995 data set on which this risk assessment is based. This suggests that the risks from CCW may be lower than the results presented in this report, although the older, unlined WMUs represented in this risk assessment may continue to pose potential risks to human health and the environment if they are closed with wastes in place.

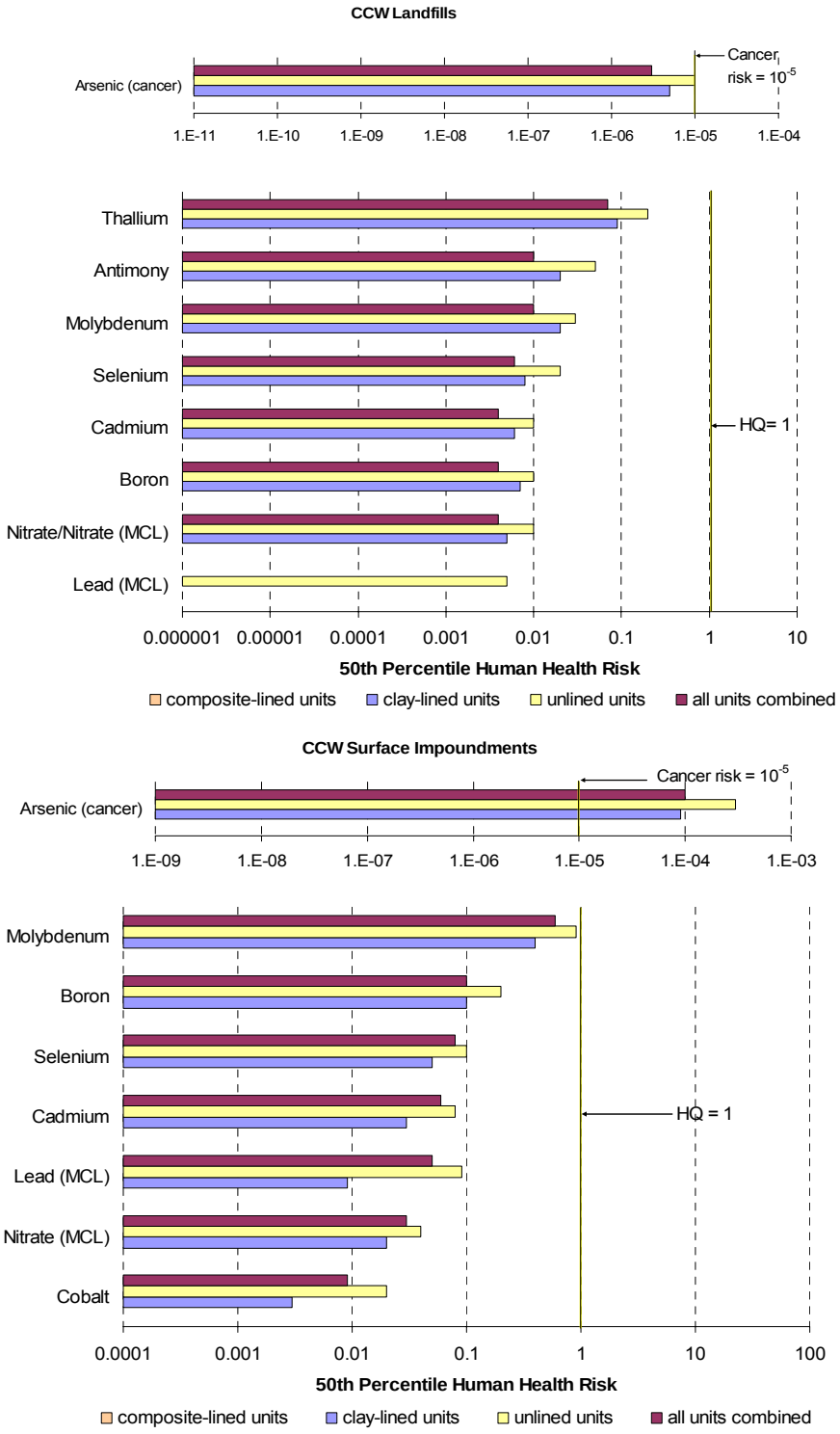
The CCW risk assessment results at the 90th percentile suggest that the management of CCW in landfills and surface impoundments as observed in 1995 for unlined and clay-lined units results in risks greater than the risk criteria of 10^{-5} for excess cancer risk to humans or an HQ greater than 1 for noncancer effects to both human and ecological receptors. Key risk findings include the following:

- 90th and 50th percentile risks for composite-lined units were consistently well below a cancer risk of 10^{-5} and an HQ of 1 for all constituents, waste management scenarios, and exposure pathways modeled in the CCW risk assessment.
- For humans exposed via the groundwater-to-drinking-water pathway (see Figures ES-2 and ES-3), arsenic and thallium show risks to human health above the risk criteria for unlined and clay-lined CCW landfills. Arsenic poses a 90th percentile cancer risk of $5x10^{-4}$ for unlined units and $2x10^{-4}$ for clay-lined units; thallium shows a 90th percentile HQ above 1 for unlined units only. As shown in Figure ES-3, 50th percentile results are at or below risk criteria for all constituents.
- Risks are higher for surface impoundments for the groundwater-to-drinking-water pathway, with a 90^{th}-percentile arsenic cancer risk of $9x10^{-3}$ for unlined units and $3x10^{-3}$ for clay-lined units. For unlined units, 5 additional constituents have noncancer HQs ranging from 3 to 4 for the 90th percentile, including boron, lead, cadmium, cobalt, and molybdenum. Two constituents (boron and molybdenum) have 90th percentile HQs greater than 1 (2 and 3, respectively) for clay-lined surface impoundments. The 50th percentile results are approximately 10-fold greater than the 10^{-5} cancer risk level for arsenic in unlined ($3x10^{-4}$) and clay-lined ($9x10^{-5}$) surface impoundments.
- For humans exposed via the groundwater-to-surface-water (fish consumption) pathway, selenium (HQ = 2) and arsenic (cancer risk = $2x10^{-5}$) show 90th percentile risks for unlined surface impoundments slightly above the risk criteria. All other waste management scenarios and all 50^{th} percentile results show risks at or below the risk criteria for the fish consumption pathway.
- Waste type has little effect on landfill risk results, but surface impoundment risks are higher for codisposed CCW and coal refuse than for conventional CCW.
- Higher risks for surface impoundments than landfills are likely due to a combination of higher waste leachate concentrations, a higher proportion of unlined units, and a higher hydraulic head from impounded liquid waste. This is consistent with damage cases reporting wet handling as a factor that can increase risks from CCW management.
- For ecological receptors exposed via surface water, the 90th percentile risks for landfills exceed an HQ of 1 for boron and lead. For surface impoundments, risks for the 90th percentile for 6 constituents (boron, lead, arsenic, selenium, cobalt, and barium) exceed an HQ of 1, with boron showing the highest risks (HQ over 2,000). The exceedances for boron and selenium are consistent with reported ecological damage cases, which include impacts to waterbodies through the groundwater-to-surface-water pathway (e.g., Carlson and Adriano, 1993; U.S. EPA, 2007). Only boron exceeds the ecological risk criterion for surface water at the 50th percentile, with an HQ of 4.



A cancer risk of 10^{-5} or an HQ of 1 are the risk criteria for this analysis.
Results for "all units combined" are results across all liner types (unlined, clay-lined, composite-lined).
Note: When the composite liner bar does not appear on the chart, the 90th percentile risk index is below the minimum shown on the x-axis.

Figure ES-2. Full-scale 90th percentile risk results for the groundwater-to-drinking-water pathway.



A cancer risk of 10^{-5} or an HQ of 1 are the risk criteria for this analysis.
Results for "all units combined" are results across all liner types (unlined, clay-lined, composite-lined).
Note: When the composite liner bar does not appear on the chart, the 50th percentile risk index is below the minimum shown on the x-axis.

Figure ES-3. Full-scale 50th percentile risk results for the groundwater-to-drinking-water pathway.

- For ecological receptors exposed via sediment, 90th percentile risks for lead, arsenic, and cadmium exceeded a HQ of 1 for both landfills (HQs from 2 to 20) and surface impoundments (HQs from 20 to200) probably because these constituents strongly sorb to sediments. No constituents exceed the ecological risk criterion for sediments at the 50th percentile.

Sensitivity analysis results indicate that for more than 75 percent of the scenarios evaluated, the risk assessment model was most sensitive to parameters related to groundwater flow and transport, including WMU infiltration rate, leachate concentration, and aquifer hydraulic conductivity and gradient. For the groundwater-to-surface water pathway, another sensitive parameter is the flowrate of the waterbody into which the contaminated groundwater is discharging. For strongly sorbing contaminants (such as lead and cadmium), variables related to sorption and travel time (adsorption coefficient, depth to groundwater, receptor well distance) are also important.

The multiple uncertainties associated with the CCW risk assessment include scenario uncertainty (i.e., uncertainty about the environmental setting around the plant), uncertainty in human exposure factors (such as exposure duration, body weight, and intake rates), uncertainty in human and ecological toxicity factors and potential cumulative risks, and uncertainty in estimates of fate and transport of waste constituents in the environment. Scenario uncertainty has been minimized by basing the risk assessment on conditions around existing coal-fired power plants around the United States, as observed in 1995. Uncertainty in environmental setting parameters has been incorporated into the risk assessment by varying these inputs within reasonable ranges when the exact value is not known. Uncertainty in human exposure factors has also been addressed through the use of national distributions.

Some uncertainties not addressed explicitly in the risk assessment have been addressed through comparisons with other studies and data sources, as described below:

- **Appropriateness of CCW leachate data.** Although porewater data were available and used for CCW surface impoundments, available data for landfills were mainly Toxicity Characteristic Leaching Procedure (TCLP) analyses, which may not be representative of actual CCW leachate. Comparisons with recent (2006) studies of coal ash leaching processes show very good agreement for arsenic. However, although the selenium CCW data are within the range of the 2006 data, some of the higher concentrations in the 2006 data are not represented by the TCLP data. This suggests that selenium risks may be underestimated, which is consistent with selenium as a cause for CCW damage cases.
- **Limited CCW leachate data.** Because of a high proportion of nondetect values[6] and a limited number of measurements, mercury could not be addressed in the CCW risk assessment for landfills or surface impoundments, and antimony and thallium could not be assessed in surface impoundments. Mercury levels in leachate were measured in EPA's 2006 leaching study and suggest a limited concern for mercury for the CCW leachates investigated, but additional work is needed to extend these results to all CCW disposal facilities.
- **Clean Air Interstate Rule (CAIR) and Clean Air Mercury Rule (CAMR) impacts.** While CAIR and CAMR will reduce air emissions of mercury and other metals from coal-fired power plants, mercury and other more volatile metals will be transferred from the flue gas to fly ash and other air pollution control residues, including the sludge from wet scrubbers. EPA is conducting research on how much total mercury will increase in CCW from the use of mercury controls, as well as how the leachability of mercury and other metals will be impacted. Preliminary results suggest that the impacts on mercury leaching will depend on the mercury control process.
- **Arsenic speciation.** The current model does not speciate metals during subsurface

[6] Nondetect values are measurements where the concentration of a constituent is below the level that the analytical instrument can detect. The actual level could range from zero to just below the detection limit. Nondetects for constituents other than mercury were modeled at one-half the detection limit for this risk analysis.

transport. Damage cases and other studies suggest that arsenic readily converts from arsenic III in CCW leachate to the less mobile arsenic V in soil and groundwater. However, model runs conducted for both species suggest that the difference in risk between the two species is only about a factor of 2 at the 90th percentile risk level, which is not enough to bring arsenic risks below the risk criteria.

Uncertainties that EPA does not have enough data at this time to evaluate with respect to CCW risk results include the following:

- **Well distance.** Nearest well distances were taken from a survey of municipal solid waste (MSW) landfills because data were not available from CCW sites. EPA believes that this is a protective assumption because MSW landfills generally tend to be in more populated areas, but there are little data available to test this hypothesis.
- **Liner performance.** Liner design and performance for CCW WMUs were based on data and assumptions EPA developed to be appropriate for municipal and nonhazardous industrial waste landfills. EPA believes that CCW landfills should have similar performance characteristics, but does not have quantitative data on CCW WMU liners to verify that.
- **Data gaps for ecological receptors.** Data were insufficient to develop screening levels and quantitative risk estimates for terrestrial amphibians, but EPA acknowledges that damage cases indicate risk to terrestrial amphibians through exposure to selenium (e.g., Hopkins et al., 2006).
- **Ecosystems and receptors at risk.** Certain critical assessment endpoints were not evaluated in this analysis, including impacts on managed lands, critical habitats, and threatened and endangered species. These would be addressed through more site-specific studies on the proximity of these areas and species to CCW disposal units.
- **Synergistic and additive risk.** The impact of exposures to multiple contaminants on human and ecological risks was not evaluated in this analysis. EPA recognizes that a single-constituent analysis may underestimate risks associated with multiple chemical exposures. The risk assessment also does not add risks across pathways (i.e., risks from drinking water and fish consumption), but EPA does not think that doing so would change the results markedly because the constituents of concern differ between pathways.

EPA recognizes that uncertainties in mercury levels in CCW leachate, both with and without the CAIR/CAMR mercury controls, represent a potentially significant gap in our knowledge of CCW risks.

1.0 Introduction

1.1 Background

The U.S. Environmental Protection Agency (EPA) has evaluated the human health and environmental risks associated with coal combustion waste (CCW) management practices, including disposal in landfills and surface impoundments. In May 2000, EPA determined that regulation as hazardous wastes under Subtitle C of the Resource Conservation and Recovery Act (RCRA) was not warranted for certain CCWs, but that regulation as nonhazardous wastes under RCRA Subtitle D was appropriate. However, EPA did not specify regulatory options at that time. This risk assessment was designed and implemented to help EPA identify and quantify human health and ecological risks that may be associated with current management practices for high-volume CCWs. These wastes are fly ash, bottom ash, boiler slag, and flue gas desulfurization (FGD) sludge, along with wastes from fluidized-bed combustion (FBC) units and CCWs codisposed with coal refuse. This risk assessment will help EPA develop CCW management options for these high-volume waste streams. Details on EPA's CCW work to date can be found at http://www.epa.gov/epaoswer/other/fossil/index.htm.

Note that the full-scale risk assessment described in this report was mostly conducted in 2003, meaning that the data collection efforts to support the risk assessment were based on the best information available to EPA at that time. As a result, more recent Agency efforts to characterize CCW wastes and management practices, such as the joint EPA and U.S. Department of Energy (DOE) survey of CCW waste management units (WMUs) (U.S. DOE, 2006) and EPA's recent study of CCW chemistries and leaching behavior (U.S. EPA, 2006), were not considered in the main analysis phase of this risk assessment. However, these more recent efforts are discussed as part of the risk characterization, and EPA is currently evaluating how to best incorporate and address the results and findings of these studies in future efforts to address CCW management practices.

The Agency is making the risk analysis document available in the Docket[1] to allow interested parties to submit comments on the analytical methodology, data, and assumptions used in the analysis and to submit additional information for the Agency to consider. In addition, the risk assessment will undergo independent scientific peer review by experts outside EPA following closure of the public comment period. Public comments will be made available to the peer reviewers for their consideration during the review process. The peer review will focus on technical aspects of the analysis, including the construction and implementation of the Monte Carlo analysis, the selection of models to estimate the release of constituents found in CCW from landfills and surface impoundments and their subsequent fate and transport in the environment, and the characterization of risks resulting from potential exposures to human and ecological receptors. As appropriate, EPA will update this analysis based on both public and peer-review comments.

[1] Available at http:www.regulations.gov; docket number EPA-HQ-RCRA-2006-0796.

1.2 Purpose and Scope of the Risk Assessment

The purpose of this risk assessment is to identify CCW constituents, waste types, exposure pathways, and receptors that may produce risks to human and ecological health, and to provide information about those scenarios that EPA can use to develop management options for CCW management.

The scope of this risk assessment is utility CCWs managed onsite at utility power plants. EPA's *Report to Congress: Wastes from the Combustion of Fossil Fuels* (U.S. EPA, 1999a) reports that there are 440 coal-fired utility power plants in the United States. Although these plants are concentrated in the East, they are found in nearly every state, with facility settings ranging from urban to rural. The large volumes of waste generated by these plants are typically managed onsite in landfills and surface impoundments. This risk assessment was designed to develop national human and ecological risk estimates that are representative of onsite CCW management settings throughout the United States.

1.3 Overview of Risk Assessment Methodology

To estimate the risks posed by the onsite management of CCW, this risk assessment estimated the release of CCW constituents from landfills and surface impoundments, the concentrations of these constituents in environmental media surrounding coal-fired utility power plants, and the risks that these concentrations pose to human and ecological receptors.

The size, design, and locations of the onsite CCW landfills and surface impoundments modeled in this risk assessment are based on data from a national survey of utility CCW disposal conducted by the Electric Power Research Institute (EPRI) in 1995 (EPRI, 1997). Data from this survey on facility area, volume, and liner characteristics were used in the CCW risk assessment because they were the most recent and complete data set available at the time the risk assessment was conducted (2003). However, as shown in Table 1-1, the EPA/DOE study conducted since then (U.S. DOE, 2006) shows a much higher proportion of lined facilities than do the 1995 EPRI data.

Table 1-1. Liner Prevalence in EPRI and DOE Surveys

Liner Type	Landfills	Surface Impoundments
1995 EPRI Survey[a] – 181 facilities		
Unlined	40%	68%
Lined (compacted clay or composite [clay and synthetic])	60%	32%
2004 DOE Survey[b] – 56 Facilities		
Unlined	3%	0%
Lined (compacted clay or composite [clay and synthetic])	97%	100%

[a] EPRI (1997)
[b] U.S. DOE (2006)

The releases, and hence media concentrations and risk estimates, are based on leaching to groundwater, wind and water erosion, and overland transport. This analysis does not address direct releases to surface water, which are permitted under the National Pollutant Discharge Elimination System (NPDES) of the Clean Water Act. Thus, the estimated media concentrations and risks do not take into account contributions from NPDES-permitted releases, including discharges due to flooding or heavy rainfall.

To evaluate the significance of the estimated risks, the risk criteria adopted for this assessment are

- An estimate of the excess lifetime cancer risk for individuals exposed to carcinogenic (cancer-causing) contaminants of 1 chance in 100,000 (10^{-5} excess cancer risk)[2]
- A measure of safe intake levels to predicted intake levels, a hazard quotient (HQ) greater than 1 for constituents that can produce noncancer human health effects (an HQ of 1 is defined as the ratio of a potential exposure to a constituent to the highest exposure level at which no adverse health effects are likely to occur)
- An HQ greater than 1 for constituents with adverse effects to ecological receptors.

In 1998, EPA conducted a risk assessment for fossil fuel combustion wastes (which include CCWs) to support the May 2000 RCRA regulatory determination (U.S. EPA, 1998a,b). Since then, EPA has added to the waste constituent database that was used in that effort, expanding the number of leachate and total waste analyses for 41 CCW constituents. The CCW risk assessment subjected these waste and leachate constituent concentrations to the tiered risk assessment methodology illustrated in Figure 1-1. This methodology implemented the following steps to assess the human and ecological risk of CCWs:

- **Hazard Identification**, which collected existing human health and ecological benchmarks for the CCW constituents. Only constituents with benchmarks move on to the next step, constituent screening.
- **Constituent Screening**, which compared very conservative estimates of exposure concentrations (e.g., whole waste concentrations, leaching concentrations) to health-based concentration benchmarks to quickly and simply identify constituents and exposure pathways with risks below the screening criteria.
- **Full-Scale Analysis**, which characterized at a national level the human health and ecological risks for constituents in CCW disposed onsite in landfills and surface impoundments using a site-based Monte Carlo risk analysis.

This document focuses on the full-scale Monte Carlo analysis. Constituent screening results are also presented as part of the problem formulation discussion, along with a summary of the screening methodology.[3]

[2] The typical cancer risk range used by the Office of Solid Waste and Emergency Response is 10^{-4} to 10^{-6}. In hazardous waste listings, the point of departure for listing a waste is 10^{-5}.

[3] Details on the CCW constituent screening analysis can be found in U.S. EPA (2002a).

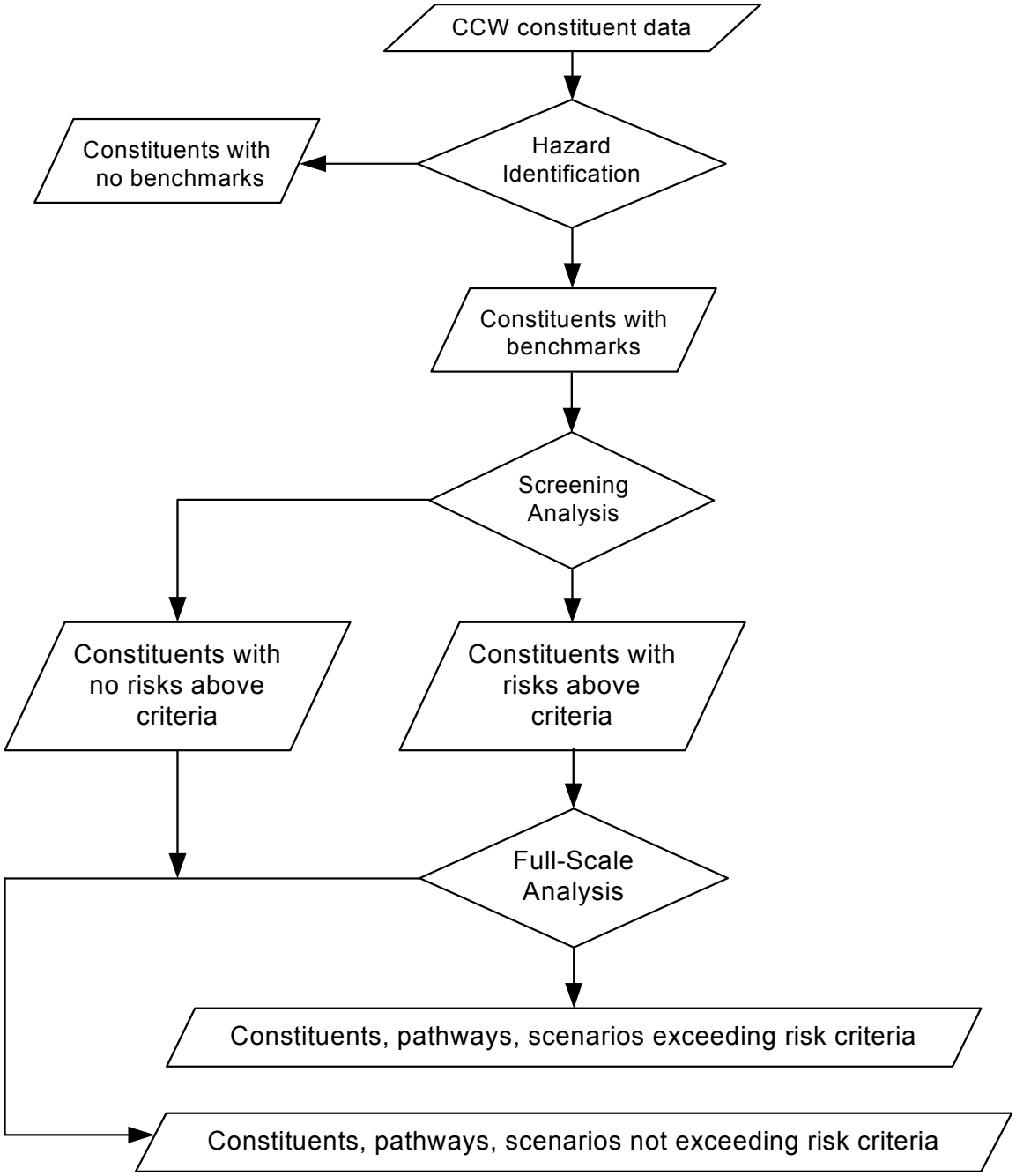


Figure 1-1. Overview of coal combustion waste risk assessment.

1.3.1 Waste Management Scenarios

The full-scale analysis was designed to characterize waste management scenarios based on two waste management options (disposal of CCW onsite in landfills and in surface impoundments) and three waste types, as follows:

- **Conventional CCW**, which includes fly ash, bottom ash, boiler slag, and FGD sludge
- **Codisposed CCWs and coal refuse,**[4] which are more acidic than conventional CCWs due to sulfide minerals in the mill rejects
- **FBC wastes**, which include fly ash and the fluidized bed ash, and which tend to be more alkaline than conventional CCW because of the limestone mixed in during fluidized bed combustion.

Conventional CCW and codisposed CCW and coal refuse are typically disposed of in landfills and surface impoundments that can be lined with clay or composite liners. FBC wastes are only disposed of in landfills in the United States; therefore, surface impoundment disposal was not modeled for FBC waste.

These three waste types, two waste management options, and three liner conditions (unlined, clay-lined, composite-lined) modeled in this analysis provide a good representation of CCW disposal practices and waste chemistry conditions that affect the release of CCW constituents from WMUs.

1.3.2 Approach

The full-scale analysis was implemented using a site-based probabilistic approach that produces a distribution of risks or hazard for each receptor by allowing the values of some of the parameters in the analysis to vary. This approach is ideal for this risk assessment because there are many CCW facilities across the United States, and a site-based approach can capture both the variability in waste management practices at these facilities and the differences in their environmental settings (e.g., hydrogeology, climate, hydrology). This probabilistic approach was implemented through seven primary steps:

Problem Formulation

1. Characterize the CCW constituents and waste chemistry, along with the size and liner status of the WMUs in which each waste stream may be managed
2. Characterize the environmental settings for the sites where CCW landfills and surface impoundments are located

[4] Coal refuse is the waste coal produced from coal handling, crushing, and sizing operations, and tends to have a high sulfur content and low pH from high amounts of sulfide minerals (like pyrite). In the CCW constituent database, codisposed coal refuse includes "combined ash and coal gob," "combined ash and coal refuse," and "combined bottom ash and pyrites."

3. Identify scenarios under which contaminants are released from a WMU and transported to a human receptor

Analysis

4. Predict the fate and transport of constituents in the environment once they are released from the WMUs at each site

5. Quantify the exposure of human and ecological receptors to the contaminant in the environment and the risk associated with this exposure

Risk Characterization

6. Estimate the risk to receptors from the exposure and characterize this risk in terms of exposure pathways, health effects, and uncertainties

7. Identify the waste disposal scenarios and environmental conditions that pose risks to human health or the environment that are above the risk criteria. Evaluate risks at the 50th and 90th percentiles.

1.4 Document Organization

This document is organized into the following sections:

- **Section 2, Problem Formulation,** describes how the framework for the full-scale analysis was developed, including identification of the waste constituents, exposure pathways, and receptors of concern; selection and characterization of waste management practices and sites to model; and development of the conceptual site models for the modeling effort.

- **Section 3, Analysis,** describes the probabilistic modeling framework and the models and methods used to (1) estimate constituent releases from CCW landfills and surface impoundments (source models), (2) model constituent concentrations in the environmental media of concern (groundwater and surface water), (3) calculate exposure, and (4) estimate risk to human and ecological receptors.

- **Section 4, Risk Characterization,** characterizes the human health and environmental risks posed by CCW, including (1) discussion of the methods used to account for variability and uncertainty and (2) identification of the scenarios and conditions that result in risks above the risk criteria. Results are presented as national estimates for CCW landfills and CCW surface impoundments, as well as by waste type and liner status. For risk exceedances, this section identifies the CCW constituents and pathways that exceed the risk criteria, along with any factors (such as liners or facility environmental setting) that might result in higher or lower risk levels. Finally, the risk characterization evaluates the risk results in light of more recent research on CCW waste management practices and the environmental behavior of CCW constituents.

The first three appendices provide detailed information on how wastes, WMUs, and settings were characterized for the risk assessment. Appendix A describes the chemical characteristics of the wastes disposed in the WMUs, including the CCW leachate concentration distributions used. Appendix B describes how EPA characterized the WMUs (landfills and surface impoundments), including surface area, capacities, geometry, and liner status. Appendix C presents the methodologies and data used to characterize the environmental setting at each CCW site, including delineating the site layout and determining the environmental setting (e.g., meteorology, climate, soils, aquifers, and waterbodies).

The remaining appendices provide detailed information on the specific models and data used to calculate risk, including the nonlinear sorption isotherms (Appendix D), the surface water fate and transport and intake equations (Appendix E), the exposure factors (Appendix F), and benchmarks for human health (Appendix G) and ecological risk (Appendix H).

2.0 Problem Formulation

The full-scale CCW risk assessment is intended to evaluate, at a national level, risk to individuals who live near WMUs used for CCW disposal. This section describes how the conceptual framework for the full-scale risk assessment was developed, including

- Constituent selection and screening to identify the CCW constituents, exposure pathways, and receptors to address in this analysis (Section 2.1.1)
- Location and characterization of the CCW landfills and surface impoundments to be modeled as the sources of CCW contaminants in the site-based analysis (Section 2.1.2)
- The conceptual site model used to represent CCW disposal facilities (Section 2.2)
- The general modeling approach and scope (Section 2.3), including data collection, fate and transport modeling to estimate exposure point concentrations, exposure assessment, and the calculation of risks to human and environmental receptors.

2.1 Source Characterization

The main technical aspects of the CCW risk assessment were completed in 2003, and the waste management scenarios modeled in this assessment are based on the best data on industry operations and waste management practices that were available at that time. These data sources include a 1995 industry survey on CCW management practices (the EPRI comanagement survey [EPRI, 1997]) and data collected from a variety of sources before the 2003 risk assessment (e.g., EPA's CCW constituent database). Since 2003, DOE and EPA have completed a survey to characterize CCW waste disposal practices from 1994 to 2004, with a focus on new facilities or facility expansions completed within that same time frame (U.S. DOE, 2006). Although these newer data were not available when this risk assessment was conducted, they are discussed in the risk characterization (Section 4) as an uncertainty with respect to how well the risk assessment represents current WMU liner conditions.

This risk assessment provides a national characterization of waste management scenarios for wastes generated by coal-fired utility power plants. The sources modeled in these scenarios are onsite landfills and surface impoundments, which are the primary means by which CCW is managed in the United States. The characterization of these sources, in terms of their physical dimensions, operating parameters, location, environmental settings, and waste characteristics, is fundamental to the construction of scenarios for modeling. This section describes how the coal combustion waste streams and management practices were characterized (based on the above data sources) and screened to develop the waste disposal scenarios modeled in the full-scale analysis.

2.1.1 Identification of Waste Types, Constituents, and Exposure Pathways

To identify the CCW constituents and exposure pathways to be addressed in this risk assessment, we relied on a database of CCW analyses that EPA had assembled over the past several years to characterize whole waste and waste leachate from CCW disposal sites across the country (see Appendix A). The 2003 CCW constituent database includes all of the CCW characterization data used by EPA in its previous risk assessments, supplemented with additional data collected from public comments, data from EPA Regions and state regulatory agencies, industry submittals, and literature searches up to 2003.

The CCW constituent database represents a significant improvement in the quantity and scope of waste characterization data available from the 1998 EPA risk assessment of CCWs (U.S. EPA, 1998a,b). For example, the constituent data set used for the previous risk assessments (U.S. EPA, 1999a) covered approximately 50 CCW generation and/or disposal sites. With the addition of the supplemental data, the 2003 CCW constituent database covers approximately 140 waste disposal sites.[1] The 2003 database also has broader coverage of the major ion concentrations of CCW leachate (e.g., calcium, sulfate, pH).

2.1.1.1 Waste Types

Comments received by EPA on the previous CCW risk assessment pointed out that the analysis did not adequately consider the impacts of CCW leachate on the geochemistry and mobility of metal constituents in the subsurface. Commenters stated that given the large size of the WMUs and the generally alkaline nature of CCW leachate, it is likely that the leachate affects the geochemistry of the soil and aquifers underlying CCW disposal facilities, which can impact the migration of metals in the subsurface.

To address this concern, EPA statistically evaluated major ion porewater data from the CCW constituent database for the waste streams shown in Table 2-1. Based on this analysis and prevalent comanagement practices, EPA grouped the waste streams into three statistically distinct categories: conventional CCW (ash and FGD sludge) (moderate to high pH); codisposed CCW and coal refuse (low pH); and FBC waste (high pH). As shown in Table 2-1, each of these waste types includes several waste streams that are usually codisposed in landfills or surface impoundments.

Along with the type of WMU (landfill or surface impoundment), the three waste types in Table 2-1 define the basic modeling scenarios to be addressed in the full-scale analysis. To characterize these waste types, the CCW constituent database was queried by waste type to develop the waste concentration data for the constituents and the major ion and pH conditions used to develop waste-type-specific metal sorption isotherms (see Appendix D for a more extensive discussion of the development of CCW waste chemistries and metal sorption isotherms).

[1] Although EPA believes that the 140 waste disposal sites do represent the national variability in CCW characteristics, they are not the same sites as in the EPRI survey. During full-scale modeling, data from the CCW constituent database were assigned to each EPRI site based on the waste types reported in the EPRI survey data.

Table 2-1. Waste Streams in CCW Constituent Database

Waste Type Waste Streams	Number of Sites by Waste Type[a]		
	Landfill Leachate	Surface Impoundment Porewater	Total Waste[b]
Conventional CCW	*97*	*13*	*62*
Ash (not otherwise specified)	43	0	30
Fly ash	61	2	33
Bottom ash and slag	24	3	23
Combined fly and bottom ash	7	4	4
FGD sludge	4	6	5
Codisposed Ash & Coal Refuse	9	5	1
FBC Waste	*58*	*0*	*54*
Ash (not otherwise specified)	18	0	10
Fly ash	33	0	32
Bottom and bed ash	26	0	25
Combined fly & bottom ash	20	0	22

[a] Number of sites by waste type from leachate, porewater, and whole waste data tables in the 2003 CCW constituent database.
[b] Whole waste concentration data.

2.1.1.2 Constituents and Pathways

The CCW constituent database contains data on more than 40 constituents. During the hazard identification step of the CCW risk assessment, constituents of potential concern were identified from this list of constituents by searching EPA and other established sources for human health and ecological benchmarks (e.g., Agency for Toxic Substances and Disease Registry [ATSDR]; see U.S. EPA, 2002a, for a full list of sources). Table 2-2 shows the results of that search for each constituent. Benchmarks were found for 26 chemicals in the constituent database. Constituents without human health or ecological benchmarks were not addressed further in the risk analysis.[2]

To further narrow down the list of constituents, a screening analysis (U.S. EPA, 2002a) was conducted that compared very conservative estimates of exposure concentrations (e.g., whole waste concentrations, leaching concentrations) to health-based concentration benchmarks to quickly, simply, and safely identify constituents and exposure pathways with risks that clearly do not exceed the risk criteria so that these could be eliminated from further analysis. For example, leachate concentrations were compared directly to drinking water standards, which is equivalent to assuming that human receptors are drinking leachate. The technical background document for the CCW screening analysis (U.S. EPA, 2002a) provides further detail on the

[2] The CCW constituents without benchmarks are limited to common elements, ions, and compounds (e.g., iron, magnesium, phosphate, silicon, sulfate, sulfide, calcium, pH, potassium, sodium, carbon, sulfur) that were used to determine overall CCW chemistries modeled in the risk assessment (see Section 3). Although some of these chemicals or parameters (e.g., pH, sulfate, phosphate, chloride) can pose an ecological hazard if concentrations are high enough, they were not addressed in this risk assessment.

Table 2-2. Toxicity Assessment of CCW Constituents

Constituent	CAS ID	HHB[a]	EcoB[b]	Constituent	CAS ID	HHB[a]	EcoB[b]
Metals				***Inorganic Anions***			
Aluminum	7429-90-5	✔	✔	Chloride	16887-00-6		
Antimony	7440-36-0	✔	✔	Cyanide	57-12-5	✔	
Arsenic	7440-38-2	✔[c]	✔	Fluoride	16984-48-8	✔	
Barium	7440-39-3	✔	✔	Nitrate	14797-55-8	✔	
Beryllium	7440-41-7	✔[d]	✔	Nitrite	14797-65-0	✔	
Boron	7440-42-8	✔	✔	Phosphate	14265-44-2		
Cadmium	7440-43-9	✔[d]	✔	Silicon	7631-86-9		
Chromium	7440-47-3	✔[c]	✔	Sulfate	14808-79-8		
Cobalt	7440-48-4	✔	✔	Sulfide	18496-25-8		
Copper	7440-50-8	✔[e]	✔	***Inorganic Cations***			
Iron	7439-89-6			Ammonia	7664-41-7	✔	
Lead	7439-92-1	✔[e]	✔	Calcium	7440-70-2		
Magnesium	7439-95-4			pH	12408-02-5		
Manganese	7439-96-5	✔		Potassium	7440-09-7		
Mercury	7439-97-6	✔	✔	Sodium	7440-23-5		
Molybdenum	7439-98-7	✔	✔	***Nonmetallic Elements***			
Nickel	7440-02-0	✔	✔	Carbon	7440-44-0		
Selenium	7782-49-2	✔	✔	Sulfur	7704-34-9		
Silver	7440-22-4	✔	✔	***Measurements***			
Strontium	7440-24-6	✔		Total Dissolved Solids	none		
Thallium	7440-28-0	✔	✔	Total Organic Carbon	none		
Vanadium	7440-62-2	✔	✔	Dissolved Organic Carbon	none		
Zinc	7440-66-6	✔	✔				

[a] HHB = human health effect benchmark
[b] EcoB = ecological benchmark
[c] Known carcinogen (for chromium VI, inhalation only); although arsenic can act as both a carcinogen and a noncarcinogen, the cancer risk exceeds the noncancer risk at any concentration, so we used the more protective cancer benchmark for human health throughout this assessment.
[d] Probable carcinogen
[e] Safe Drinking Water Act Action Level only

screening analysis. As detailed there, the risks for all above-ground pathways analyzed (soil ingestion, inhalation, gardening, beef and dairy, and erosion and overland transport) for human receptors did not exceed the screening criteria for any constituent, so they were not considered any further in the risk assessment. The above-ground pathway risks for ecological receptors also did not exceed the screening criteria except for boron and selenium. Boron, which showed risks above the risk criterion in above-ground pathways due to plant toxicity in the CCW screening analysis, has been shown to be toxic to plants (Carlson and Adriano, 1993). Selenium has shown toxicity to terrestrial amphibians via above-ground pathways (Carlson and Adriano, 1993; Hopkins et al., 2006). Because the risks posed by these CCW constituents to ecological communities via above-ground pathways is well documented in damage cases and field studies (see above references and U.S. EPA, 2007), we did not believe that a full-scale above-ground

pathway analysis was necessary to confirm this conclusion for two constituents. Thus, the full-scale risk assessment did not include any above-ground pathways, only groundwater pathways.

The groundwater-to-drinking-water and groundwater-to-surface-water pathways (human fish consumption and ecological risks) did show risks above the screening criteria for several CCW constituents in the screening analysis. Table 2-3 lists the 21 constituents that had 90th percentile screening analysis groundwater pathway risks greater than a cancer risk of 1 in 100,000 or a noncancer risk with an HQ greater than 1 for human health and 10 for ecological risk.[3] Note that mercury was not addressed in the screening or full-scale analysis because of a very high proportion of nondetects in the CCW constituent database. Similarly, a high number of nondetects (or a very low number of measurements) prevented screening or full-scale analysis for antimony, thallium, and cobalt in surface impoundments. The uncertainties associated with these limited analytical results are discussed in Section 4.4.3.1.

Resources did not allow full-scale modeling to be conducted for all 21 constituents that had 90th percentile risks above the screening criteria. To reduce the number of constituents to be modeled, those constituents were ranked and divided into two groups to focus the full-scale analysis on the CCW constituents that were likely to pose relatively higher risks to human and ecological receptors. The ranking was based on the magnitude of the HQs and the number of HQs exceeding the screening criteria, and was used to select chemicals for full-scale modeling. Constituents with at least one human health HQ greater than 6 or with ecological HQs greater than 100 for both landfills and surface impoundments were modeled. Arsenic, with cancer risks greater than 1 in 1,000, exceeded the cancer risk criterion by a factor of 100 and was also modeled in the full-scale analysis. Constituents with no human health HQs greater than 6 and only one or no ecological HQs greater than 100 were not modeled, but were addressed in a separate analysis using results from the modeled constituents.

Table 2-3 shows the 21 constituents and which of these constituents exceeded the screening criteria and thus were modeled in the full-scale analysis. As shown, 12 constituents were subjected to the full-scale probabilistic risk assessment described in this document. Nine constituents did not exceed the screening criteria and were addressed using risk factors developed from comparing the screening and full-scale results for the modeled constituents, as described in Section 4.1.5 of this document.

2.1.2 Waste Management Scenarios

The full-scale CCW risk assessment models landfills and surface impoundments managing wastes onsite at coal-fired utility power plants. Because EPA selected a site-based modeling approach for the full-scale analysis, it was necessary to locate these disposal sites across the country to provide the spatial foundation for this analysis. It was also necessary to characterize CCW WMUs to define the scope for source modeling.

[3] An HQ of 10 was used for screening ecological risks to account for conservatism of ecological benchmarks and exposure estimates used in the screening analysis (see Section 4.4.3.4).

Table 2-3. Screening Analysis Results: Selection and Prioritization of CCW Constituents for Further Analysis[a]

Constituent	Human Health – Drinking Water		Human Health – Surface Water[b]		Ecological Risk - Surface Water	
	LF HQ (*Cancer Risk*)	SI HQ (*Cancer Risk*)	LF HQ (*Cancer Risk*)	SI HQ (*Cancer Risk*)	LF HQ	SI HQ
Constituents Modeled in Full-scale Assessment						
Carcinogen						
Arsenic[c]	($1.4x10^{-3}$)	($1.8x10^{-2}$)	($2.2x10^{-4}$)	($1.7x10^{-5}$)	49	640
Noncarcinogens						
Boron	4.0	28	-	-	6,600	47,000
Cadmium	3.4	8.9	1.4	3.7	20	52
Lead	16	12	-	-	790	590
Selenium	1.2	2.4	4.7	9.5	35	71
Thallium	21	19	6.3	5.7	-	-
Aluminum	-	-	-	-	120	270
Antimony	22	5.5	-	-	-	-
Barium	-	-	-	-	400	75
Cobalt	-	11	-	-	-	270
Molybdenum	4.2	6.8	-	-	-	-
Nitrate/ Nitrite	- /1.2	60/1.2	-	-	-	-
Constituents Not Modeled in Full-scale Assessment[d]						
Noncarcinogens						
Chromium VI	2.3	4.2	-	-	18	33
Fluoride	1.8	5.2	-	-	-	-
Manganese	1	5.6	-	-	-	-
Vanadium	2.2	2.3	-	-	23	24
Beryllium	-	-	-	-	24	-
Copper	-	-	-	-	16	31
Nickel	-	1.3	-	-	-	14
Silver	-	-	-	-	110	14
Zinc	-	-	-	-	16	-

HQ = screening hazard quotient.
LF = landfill.
SI = surface impoundment.

[a] A dash in a cell indicates that the screening HQ was less than 1 (or 10 for ecological risk), so the risk did not exceed the screening criteria for the indicated pathway.

[b] Fish consumption pathway.

[c] Although arsenic can act as both a carcinogen and a noncarcinogen, the cancer risk exceeds the noncancer risk at any concentration, so we used the more protective cancer benchmark for human health throughout this assessment.

[d] These constituents were addressed using risk attenuation factors developed from full-scale results from modeled constituents (see Section 4.1.5).

Two primary sources of data on these were used to characterize this population:

- 1998 Energy Information Agency (EIA) data on coal-fired power plants, which identifies approximately 300 coal-fired power plants with onsite waste management
- The 1995 EPRI waste comanagement survey (EPRI, 1997), which contains detailed WMU data (i.e., area, capacity, liner status, and waste type) for 177 of those facilities.[4]

Because of the completeness of the WMU data from the EPRI survey, the EPRI data were used to establish the plant locations and WMU data for the full-scale modeling effort for conventional CCW[5] and CCW codisposed with coal refuse.

Although there is a good amount of FBC data in the constituent database (58 sites; see Table 2-1), there were only 3 FBC landfill sites in the EPRI database and 4 additional sites added by EPA for a total of 7 FBC sites with data on onsite WMUs. Because EPA believes that this small sample is not sufficient to represent the universe of FBC disposal units and, if included in the overall analysis, could bias the Monte Carlo results towards the environmental conditions around these few landfill units, FBC waste were addressed separately from the more conventional CCW types in the full-scale analysis and are not included with the conventional and codisposal CCW management scenarios in the overall results. Section 4.1.3 compares the risk results for each of these waste types, including FBC.

Table 2-4 shows how the plants are distributed across the waste type/WMU scenarios modeled in the full-scale analysis. The distribution across the waste type/WMU scenarios, the geographic distribution of these facilities, and the size and liner status of the WMUs were assumed to be representative of all onsite CCW landfills and surface impoundments in the continental United States as of 1995. As mentioned previously, DOE and EPA have conducted a newer survey on CCW disposal facilities (U.S. DOE, 2006), but the scope of this survey was not as comprehensive as the EPRI survey (e.g., WMU areas and capacity data were not collected). EPA does not believe that the number and locations of onsite CCW landfills and surface impoundments has changed significantly since 1995, although liners are more prevalent in the newer facilities (see further discussion in Section 4.4.1). The DOE/EPA report (U.S. DOE, 2006) supports this conclusion.

[4] Note that although there is overlap, the 140-site CCW constituent database described in Appendix A and the EPRI survey used to characterize CCW landfills and surface impoundments were assembled under separate efforts and represent different populations of disposal sites. As described in Section 3.1.3, these data sets were sampled independently during the Monte Carlo analysis, and constituent data were not assigned to particular sites except by waste type.

[5] Fly ash, bottom ash, boiler slag, and FGD sludge.

Table 2-4. Coal Combustion Plants with Onsite CCW WMUs Modeled in the Full-Scale Assessment

Waste Type and Liner Status	Number of Plants in 1995 EPRI Survey[a] with Onsite:		
	Landfills	Surface Impoundments	Either WMU Type[b]
Conventional CCW[c]	71	38	103
unlined	*38*	*24*	*60*
clay-lined	*28*	*10*	*38*
composite-lined	*10*	*5*	*15*
Codisposed CCW and coal refuse	38	65	100
unlined	*20*	*52*	*69*
clay-lined	*10*	*11*	*21*
composite-lined	*9*	*2*	*11*
FBC waste[d]	7	-	7
unlined	*3*		*3*
clay-lined	*3*		*3*
composite-lined	*1*		*1*
All waste types	108	96	181

[a] EPRI (1997); note that some coal combustion plants have one or more onsite WMUs.
[b] Number of coal combustion plants with onsite landfill(s), surface impoundment(s), or both.
[c] Fly ash, bottom ash, boiler slag, and FGD sludge.
[d] Includes 3 EPRI Survey FBC landfills plus 4 additional FBC landfills added by EPA. FBC was treated separately in the full-scale assessment because of the small number of FBC sites.

2.2 Conceptual Model

The waste stream/WMU combinations discussed above provide the waste management scenarios to be evaluated in the risk assessment. The full-scale assessment used the EPRI survey data to place these scenarios at actual onsite CCW disposal sites across the country. These sites were used as the basis for a national-scale site-based Monte Carlo assessment of risks posed by the onsite disposal of CCW at utility power plants across the United States.

2.2.1 Conceptual Site Model

Figure 2-1 depicts the conceptual site model for CCW disposal that was the basis for the national CCW risk assessment, including contaminant sources, exposure pathways, and receptors. The CCW conceptual site model includes the following exposure pathways:

Human Health

- Groundwater to drinking water (drinking water ingestion)
- Groundwater to surface water (fish consumption)
- Above-ground pathways, including soil ingestion, inhalation, and consumption of produce, beef, and milk.

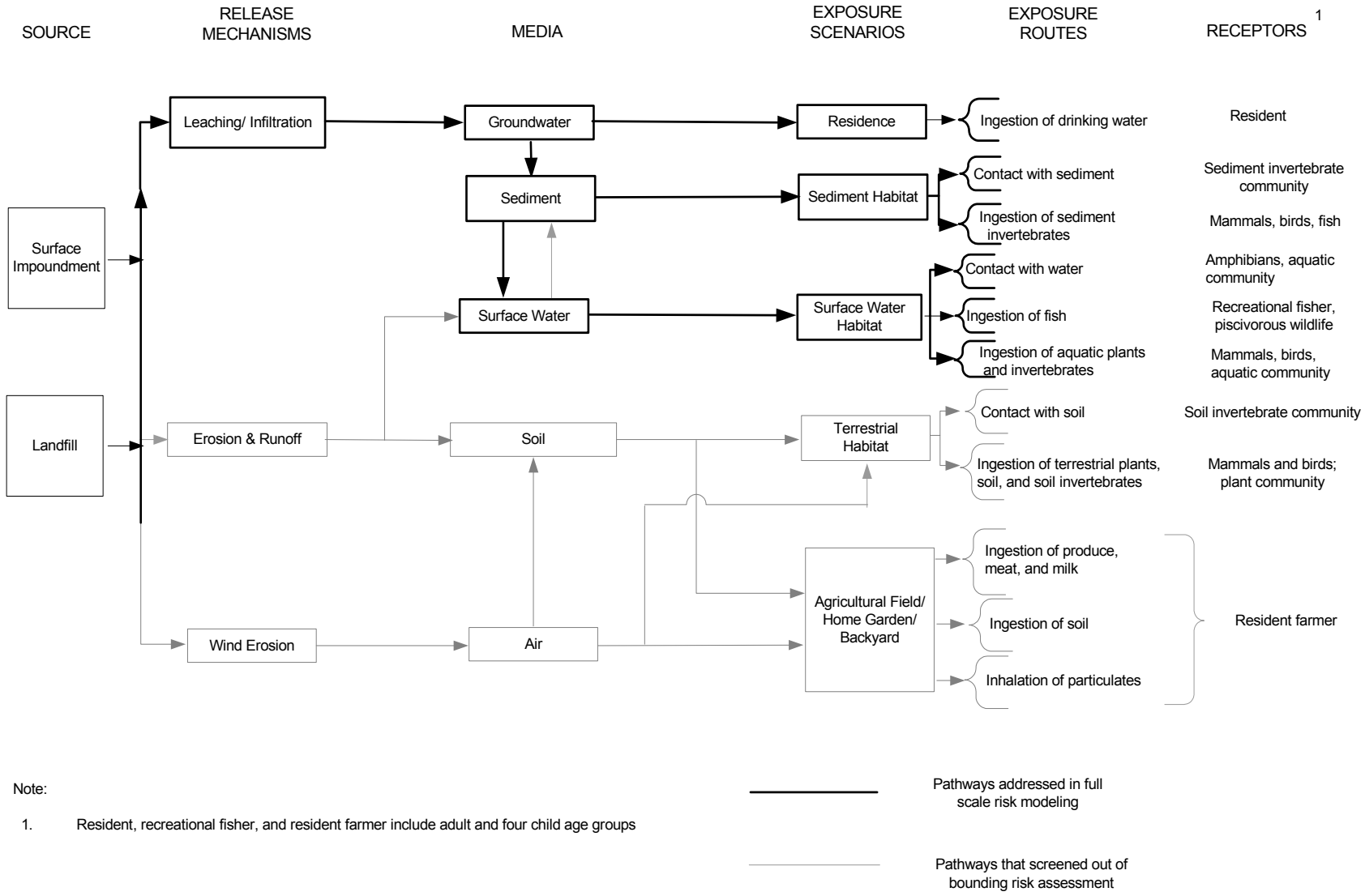


Figure 2-1. Conceptual site model of CCW risk assessment.

Ecological Risk

- Groundwater to surface water
- Above-ground soil
- Above-ground contamination of surface water and sediment.

As described in Section 2.1.1, the CCW screening analysis addressed all of these exposure pathways and receptors. Through that screening analysis, risks for all above-ground pathways (shown in gray instead of black in Figure 2-1) fell below the screening criteria and were not considered further in the full-scale risk assessment.[6] This enabled EPA to focus full-scale modeling on groundwater-to-drinking-water and groundwater-to-surface-water exposure pathways (shown in black in Figure 2-1). This groundwater pathway analysis evaluates exposures through drinking water ingestion and surface water contamination from groundwater discharge. For the groundwater-to-surface-water pathway, the analysis assumes that human exposure occurs through the consumption of contaminated fish and that ecological exposure occurs through direct contact with contaminated surface water and sediment or from the consumption of aquatic organisms.

2.2.2 Conceptual Site Layouts

This risk assessment was based on site layouts that are conceptual rather than site-specific. Although we had plant locations and some site-specific data on WMUs, we did not have the exact locations of each WMU or the residential wells surrounding each facility. Therefore, we had to develop conceptual layouts to place receptors around each WMU.

The conceptual site layouts capture possible relationships between a WMU and human and ecological receptors by locating, with respect to the WMU boundary, the geographic features (i.e., receptor wells, waterbodies) that are important for determining human and ecological exposures to chemicals released from CCW landfills and surface impoundments.

Two site layouts were used to model the land use scenarios of most concern for CCW disposal facilities:

- Residential groundwater ingestion scenario
- Recreational fisher and aquatic ecological risk scenario.

Figures 2-2 and 2-3 show these two conceptual site layouts, including WMU boundaries, waterbodies, and residential wells modeled in this analysis. In the conceptual site layouts, the WMU is represented as a square source. The size of the source is determined by the surface area of the WMU (CCW WMU areas were collected from the EPRI comanagement survey, as described in Appendix B). The WMU is assumed to be located at the property line of the facility to which it belongs.

[6] Although the risks from the aboveground screening analysis did exceed the risk criteria for boron and selenium in soil, to streamline the assessment, these compounds were not included in the full ecological assessment.

Adjacent to the WMU is a buffer area within which there is assumed to be no human activity that would present human risk (i.e., there are no residences or waterbodies in the buffer). The buffer area lies between the WMU boundary and the residential well or waterbody, and represents the distance to well or waterbody discharge point modeled by the groundwater model. Each site layout must also be oriented in terms of direction.

Residential Groundwater-to-Drinking-Water Scenario

The residential groundwater-to-drinking-water scenario calculates exposure through residential use of well water as drinking water. In the Monte Carlo analysis, the receptor well is randomly placed up to 1 mile downgradient from the edge of the WMU (this radial well distance is labeled R_{rw} in Figure 2-2), based on a nationwide distribution of nearest downgradient residential wells from Subtitle D municipal landfills (U.S. EPA, 1988a; this distribution is provided in Appendix C). EPA assumed that this distribution is relevant to onsite CCW landfills and surface impoundments at coal-fired utility power plants, but does not have data on typical distances (or the distributions of distances) of domestic drinking water wells from CCW disposal facilities. (The potential impact on the results of this assumption is discussed in Section 4.4.3.3).

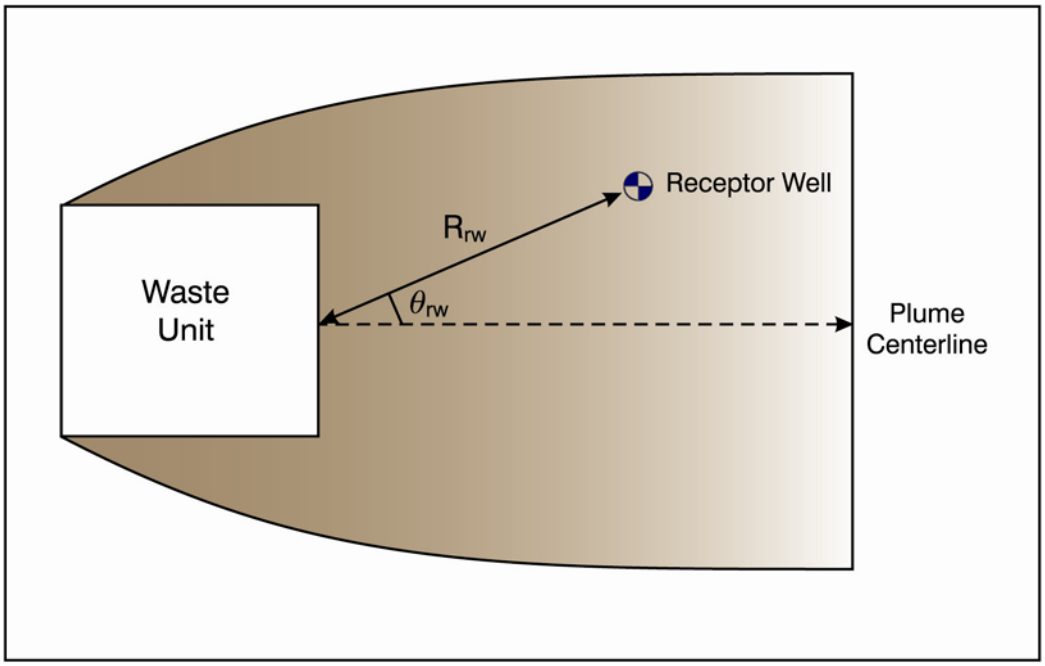


Figure 2-2. Conceptual site layout for residential groundwater ingestion scenario.

The angle off the contaminant plume centerline (θ_{rw} in Figure 2-2) was based on a uniform distribution ranging from 0 to 90°. The depth of the well below the water table was set within the groundwater model based on assumptions that are generally typical of average conditions for surficial aquifers across the United States. These limits are discussed in Section 3.4.3. In this assessment, receptors were always located within the lateral extent of the plume.

The soil and aquifer characteristics needed for the groundwater model were collected using a site-based approach, as described in Appendix C.

Recreational Fisher and Ecological Risk Scenario

The recreational fisher[7] scenario was used to estimate risks to recreational fishers (and their children) who live near the CCW landfills and surface impoundments and catch and consume fish from a waterbody located adjacent to the buffer. Note that the fisher's residence is not the same residence where the residential well is located, and therefore risks are not added across the drinking water and fish consumption pathways.

The waterbody was assumed to be a stream or lake located downgradient from the WMU, beginning where the buffer area ends (see Figure 2-3), and was also used as the most impacted aquatic system for the ecological risk assessment. Waterbody characteristics were determined based on site-specific, regional, or national data (as described in Appendix C), except for stream length, which was determined by the width of the plume as it intersects the waterbody.

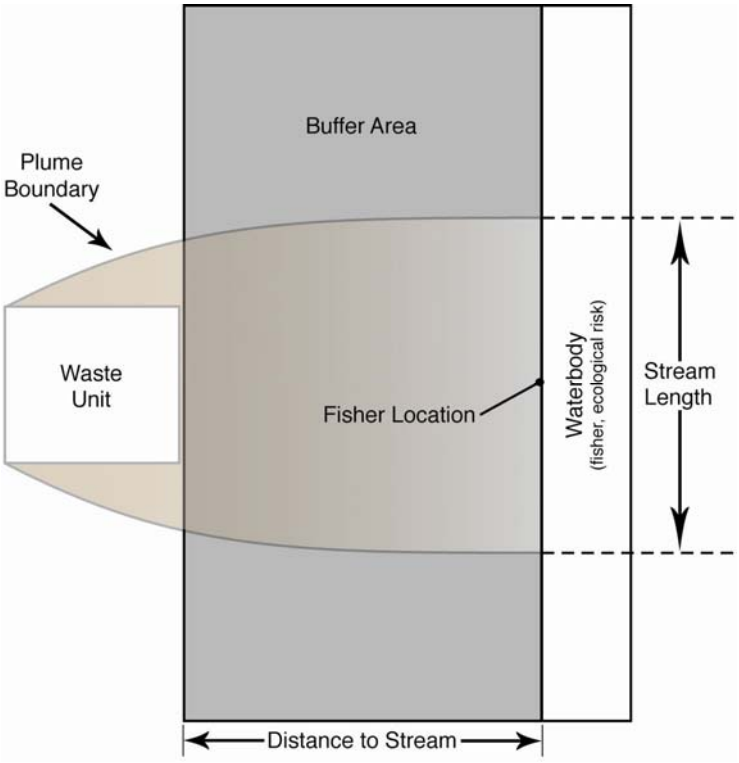


Figure 2-3. Conceptual site layout for residential fisher and aquatic ecological risk scenario.

[7] Only recreational fishers were considered because they represent the reasonable maximum exposed individuals and because the streams, lakes, or rivers that are near CCW plants are not likely to be used by commercial fishing operations.

The downgradient distance to the surface water body was determined from a national distribution developed by measuring this distance (using scaled U.S. Geological Survey [USGS] maps and aerial photographs obtained from the Terraserver Web site [http://terraserver.usa.com/geographic.aspx]) at 59 CCW landfill and surface impoundment sites randomly selected from a larger data set of 204 CCW WMUs, including those modeled in this risk assessment. Appendix C presents that distribution and further details on how the distribution was developed and the sample of 59 facilities used to develop the distribution.

2.3 Analysis Scope and Design

Although the screening analysis identified the potential for risk for a subset of the constituents reported in CCW, the conservative assumptions used precluded an accurate quantitative estimate of these risks. To gain a better understanding of the risks that may be posed by these constituents, EPA conducted a full-scale probabilistic (Monte Carlo) risk assessment to estimate the national distribution of the risks to human health and the environment posed by CCW disposal, and to provide the information needed to assess future management options for these wastes in the context of their risks to human health and the environment. The full-scale CCW Monte Carlo risk assessment was designed to characterize the national CCW risk profile in terms of WMU type, waste type, and constituent, and to use distributions in a probabilistic modeling framework to incorporate variability and uncertainty into the analysis.

The site-based approach used data about waste management practices and environmental conditions at 181 utility CCW disposal sites across the United States.[8] These sites were assumed to represent the universe of CCW onsite waste disposal sites at the time of the EPRI survey (1995) and defined the national framework for the risk assessment. As described in Appendices B and C, site-specific data for the following model inputs were collected for these sites and used in the risk assessment:

- WMU dimensions
- WMU liner status (unlined, clay liner, composite liner)
- Waste type (conventional CCW, CCW codisposed with coal refuse, and FBC wastes)
- Geology (aquifer type)
- Soil texture
- Climate (precipitation, infiltration)
- Surface water type and flow conditions.

One question related to this risk assessment is how CCW facilities may have changed in the decade since the 1995 EPRI survey. Although the DOE/EPA survey does not include all of

[8] These 181 sites include177 sites from the EPRI survey and 4 additional CCW sites added by EPA to better represent FBC waste disposal facilities; see Section 2.1.2.

the data needed to conduct a risk assessment (WMU area and capacity data were not collected), liner conditions were addressed, and by comparing the DOE/EPA survey results to the EPRI data one can assess how liner conditions changed as CCW facilities were built or expanded over the past decade. The 56 WMUs surveyed in the U.S. DOE (2006) study were commissioned between 1994 and 2004. Although the actual number of WMUs that were established in that timeframe cannot be verified, based on proxy data (i.e., CCW available for disposal in those states with identified new WMUs and coal-fired power plant generating capacity), the sample coverage is estimated to be at least between 61 to 63 percent of the total population of the newly commissioned WMUs.[9] With the exception of one landfill, the newly constructed facilities are all lined, with either clay, synthetic, or composite liners. The single unlined landfill identified in the recent DOE report receives bottom ash, which is characterized as an inert waste by the state, and therefore, a liner is not required. There is a marked trend away from unlined WMUs in favor of lined units, with a distinct preference for synthetic or composite liners. Comparison of the 26 coal combustion plants in both the EPRI survey and the DOE/EPA survey (U.S. DOE, 2006) shows that although most of those facilities (17 of 26) were using unlined WMUs in 1995, all 26 are now placing wastes in new or expanded landfills or surface impoundments that are lined with clay, synthetic, or composite liners. However, it is likely that the older unlined units were closed with wastes in place, and that these wastes therefore still pose a threat through groundwater pathways. In addition, the available data cannot be used to determine the number of unlined units that continue to operate in the United States.

Because site-specific data were not readily available for depth to groundwater or receptor location (i.e., distances to nearest drinking water well and surface waterbody), national distributions for those inputs taken from a national hydrogeologic database (Newell et al., 1989 and 1990) developed to support EPA's national groundwater risk assessments were used in the Monte Carlo analysis to characterize the national variability of receptor distances (see Appendix C). This enabled EPA to assess the importance of those variables for the national risk distribution for individuals with reasonable maximum exposure to CCW.

The full-scale assessment was conducted using several modeling components: (1) EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP; U.S. EPA, 1997a) groundwater model, (2) a simple steady-state surface water and aquatic food web model, and (3) a multipathway exposure and risk modeling system.

2.3.1 Data Collection

For the sites representing each WMU and waste type combination selected for analysis, the Monte Carlo analysis begins with input files that contain, for each Monte Carlo realization, the following site-based variables:

- WMU area, depth, and capacity
- WMU liner status

[9] For additional details as to how these estimates were derived, the reader is referred to the DOE study, pages S-2 to S-3 of the Summary Section and Section 3.1.2.

- Soil texture (for vadose zone properties and infiltration rates)
- Soil pH and organic carbon
- Aquifer type
- Groundwater temperature
- Climate center (for infiltration rates)
- USGS Hydrologic Region (for surface water quality data)
- Surface water flows.

CCW constituent data in the CCW constituent database were used as a national empirical distribution of the concentrations of the constituents of concern in CCW landfill leachate and surface impoundment porewater. Like the WMU database, the CCW constituent data include WMU type and waste type, which enabled constituent concentrations to be assigned to the 181 CCW sites by waste type and WMU type. The CCW constituent database was also used to assign (by waste type) the high, medium, and low leachate pH and ionic strength conditions needed to select the appropriate subsurface sorption isotherms for each model run (see Appendix D).

National distributions were used to populate the following variables by model run:

- Distance to nearest drinking water well
- Distance to nearest surface waterbody
- Aquifer depth, thickness, gradient, and hydraulic conductivity (based on site-specific hydrogeologic setting)
- Soil hydrologic properties (based on site-specific soil type).

The data sources used to develop national distributions for these variables are described in Appendix C. Human exposure factors, such as exposure duration and drinking water and fish consumption rates, were also based on national distributions, which are provided in Appendix F.

2.3.2 Model Implementation

As a first step in the modeling process, the groundwater model (EPACMTP) reads the site-based data files to estimate the following for each model run:

- Drinking water well peak concentration
- Time to drinking water peak concentration
- Peak surface water contaminant flux
- Time to peak surface water contaminant flux.

The groundwater model is run until contaminant concentrations at the receptor point return to zero after the concentration peak or for the maximum simulation time of 10,000 years, whichever comes first.

Groundwater model results are passed to the multimedia modeling system to estimate surface water and sediment concentrations and to calculate human and ecological exposure and risk. Additional inputs sent to the model at this stage include

- Site-based surface waterbody type, dimensions, flows, pH, and total suspended solids (TSS) concentration
- Chemical-specific fish bioconcentration factors (BCFs)
- Human exposure factors (from national distributions)
- Human and ecological health benchmarks.

For human health, the multimedia modeling system calculates risk from drinking water ingestion and fish consumption for each realization. For ecological risk, the model uses surface water and sediment concentrations along with ecological benchmarks to estimate the risks to ecological receptors.

2.3.3 Exposure Assessment

Table 2-5 lists the human and ecological receptors considered in the CCW risk assessment, along with the specific exposure pathways that apply to each receptor. All of the receptors that EPA considered were assumed to live offsite, at a location near the WMU.

Table 2-5. Receptors and Exposure Pathways Addressed in the Full-Scale CCW Assessment

Receptor	Ingestion of Drinking Water	Fish Consumption	Direct Contact with Surface Water and Sediment	Ingestion of Aquatic Organisms
Human Receptors				
Adult resident	✔			
Child resident	✔			
Adult recreational fisher		✔		
Child recreational fisher		✔		
Ecological Receptors				
Aquatic and sediment organisms			✔	
Mammals and birds				✔

For human receptors, the exposure assessment estimates the dose to an individual receptor by combining modeled CCW constituent concentrations in drinking water or fish with intake rates for adult and child receptors. The full-scale CCW risk assessment considered

exposures due to chemicals leaching from WMUs and contaminating groundwater. The groundwater exposures include drinking water ingestion and consumption of recreationally caught contaminated fish from surface waterbodies affected by contaminated groundwater. For the groundwater-to-drinking-water pathway, it was conservatively assumed that well water was the only source of drinking water (although some households may drink bottled or treated water or may drink water outside the home, e.g., at work or at school).

For ecological receptors, exposure assumptions are incorporated into the development of ecological benchmarks (see Appendix H), which are surface water and sediment concentrations corresponding to an HQ of 1.

The time period for the exposure assessment is defined by the peak concentration in the media of concern and the exposure duration. For human receptors, annual average media concentrations were averaged over the randomly selected exposure duration around the peak concentration for each run. To protect against chronic effects to ecological receptors, we consider the exposure duration over a significant portion of the receptor's lifetime, and we believe that one year is the appropriate period of time for that. To be protective, we use the highest (peak) annual average concentration to estimate ecological exposure and risk.

2.3.4 Risk Estimation

Risk was estimated using several risk endpoints as particular measures of human health risk or ecological hazard. A risk endpoint is a specific type of risk estimate (e.g., an individual's excess cancer risk) that is used as the metric for a given risk category. The CCW risk assessment evaluated cancer and noncancer endpoints for humans and noncancer endpoints for ecological receptors. For human risk, the availability of toxicological benchmarks for cancer and noncancer effects determined which endpoints were evaluated for each constituent.

EPA used two risk endpoints to characterize risk for the human receptors and a single risk endpoint, total HQ, to characterize risk for ecological receptors. These endpoints are discussed in Section 3.8; in addition, uncertainty related to these endpoints is discussed in Section 4.4.3.4.

From the distribution of risks for each risk endpoint generated by the Monte Carlo analysis, the 50th and 90th percentile risks were selected and compared to the risk criteria of 1 in 100,000 excess cancers and an HQ greater than 1 for noncarcinogens. An HQ greater than 1 for was also used for the ecological risk criterion in the full-scale risk assessment.

3.0 Analysis

The full-scale analysis evaluates risks from CCWs disposed of in landfills and surface impoundments located onsite at coal-fired utility power plants across the United States based primarily on data collected in 1995 by EPRI (1997).[1] Chemical constituents found in CCW can be released from these WMUs into the surrounding environment by various mechanisms. Releases to the atmosphere and by erosion and overland transport did not pose risks above the screening criteria in the screening analysis; therefore, these were not assessed in the full-scale analysis. Instead, the full-scale analysis focused on groundwater pathways, which exceeded the risk criteria for some constituents in the screening analysis. Leachate forms in both landfills and surface impoundments, migrates from the WMU through soil to groundwater, and is transported in groundwater to drinking water wells (groundwater-to-drinking-water pathway) and into surface waterbodies near the WMU (groundwater-to-surface-water pathway). These are the groundwater pathways evaluated in the full-scale CCW risk assessment.

For the full-scale analysis, EPA used computer-based models and sets of equations to estimate the risk to human health and the environment from current CCW disposal practices.[2] These models include

- **Source** models that simulate the release of CCW constituents in leachate from landfills and surface impoundments[3]
- **Fate and transport** models that estimate contaminant concentrations in groundwater and surface water
- **Exposure** models that estimate daily contaminant doses for humans and ecological receptors exposed to CCW constituents in groundwater and surface water
- **Risk** models that calculate risks to humans and ecological receptors.

This section describes the models and equations used to calculate exposure point concentrations and risk. Section 3.1 provides the overall structure for the analysis, including the spatial and temporal framework and the probabilistic (Monte Carlo) framework for the model runs. Sections 3.2 and 3.3 describe the landfill and surface impoundment source models used to predict environmental releases of constituents from CCW. Sections 3.4 and 3.5 describe the fate and transport modeling used to predict contaminant concentrations in groundwater and surface

[1] The selection and characterization of these CCW WMUs are described in more detail in Appendix B.

[2] As discussed in Section 2, the 1995 EPRI survey data is assumed to represent current CCW management practices. However, new data from a more recent DOE/EPA survey suggest that liners may be more prevalent in new and expanded units built since 1994. Section 4 discusses implications of this uncertainty on the risk assessment results.

[3] EPA used source-term models integrated into EPACMTP to estimate environmental releases of constituents in leachate from landfills and surface impoundments.

water. Section 3.6 describes the human exposure calculations. Section 3.7 describes the health benchmarks used to develop human and ecological risk estimates, and Section 3.8 describes how these risks were calculated for human and ecological receptors.

Supporting detail can be found in the following appendices:

- **Appendix A, Constituent Data**, provides the CCW constituent concentrations used and describes how they were collected and processed
- **Appendix B, Waste Management Unit Data**, describes the location and characteristics of each landfill and surface impoundment modeled and describes how the source model input parameter values were collected
- **Appendix C, Site Data**, describes how environmental data around each CCW waste disposal site were collected to provide inputs for the groundwater and surface water modeling
- **Appendix D, MINTEQA2 Nonlinear Sorption Isotherms**, describes the development and application of the CCW-specific MINTEQ metal sorption isotherms used to model fate and transport in soils and groundwater
- **Appendix E, Surface Water, Fish Concentration, and Contaminant Intake Equations**, documents the algorithms used to calculate surface water concentrations, fish concentrations, and drinking water and fish intake rates
- **Appendix F, Human Exposure Factors**, documents the human exposure parameters and equations
- **Appendix G, Human Health Benchmarks**, describes how the human toxicity benchmarks were selected and developed
- **Appendix H, Ecological Benchmarks**, describes how the ecological toxicity benchmarks were selected and developed.

3.1 General Modeling Approach

This section describes the framework, general assumptions, and constraints for the full-scale probabilistic analysis. Section 3.1.1 describes the temporal and spatial framework. Section 3.1.2 describes the probabilistic framework, and Section 3.1.3 describes how the assessment was implemented within the probabilistic framework.

3.1.1 Temporal and Spatial Framework

The spatial framework for the analysis was determined by the geographic distribution of CCW facilities modeled and by the site layout assumed as the conceptual site model for risk assessment. As described in Section 2.1.2, the geographic distribution of landfills and surface impoundments managing wastes onsite at coal-fired utility power plants was determined from

the 177 sites in the 1995 EPRI survey of the onsite management of CCW (EPRI, 1997). The assessment assumes that these 177 sites and their locations are representative of the approximately 300 coal-fired power plants identified by EIA data as having onsite waste management of conventional CCW and CCW codisposed with coal refuse throughout the United States. For FBC wastes, these 177 sites include only 3 FBC landfills. EPA was able to add 4 additional FBC landfill sites to better represent FBC waste management, for an overall total of 181 sites in this analysis.

The conceptual site layouts applied to each of the sites are described and pictured in Section 2.2.2. Two site layouts were used to define the relationship between a landfill or surface impoundment and (1) a drinking water well (for human risk via the groundwater-to-drinking-water pathway) and (2) a surface water body (for human and ecological risk via the groundwater-to-surface-water pathway). In each case, the receptor point (well or waterbody) was assumed to lie within the boundaries of the groundwater contaminant plume. The distance from the edge of the WMU to the well or waterbody was varied for each model run based on national distributions, with well distance taken from a national distribution for Subtitle D municipal landfills (U.S. EPA, 1988a) and distance to surface water taken from a set of measured distances for CCW landfills and surface impoundments developed for this assessment. Appendix C presents additional details on these distributions.

The temporal framework was mainly defined by the time of travel from the modeled WMU to the well or waterbody, which can be up to one mile away from the edge of the unit, and the exposure duration over which risks were calculated. The subsurface migration of some CCW constituents (e.g., lead) may be very slow; therefore, it may take a long time for the contaminant plume to reach the receptor well or nearest waterbody, and the maximum concentration may not occur until a very long time after the WMU ceases operations. This time delay may be on the order of thousands of years. To avoid excessive model run time while not missing significant risk at the receptor point, the groundwater model was run until the observed groundwater concentration of a contaminant at the receptor point dropped below a minimum concentration (10^{-16} mg/L) or until the model had been run for a time period of 10,000 years. The minimum concentration used for all fate and transport simulations (10^{-16} mg/L) is at least a million times below any risk- or health-based criteria.

For the groundwater-to-drinking-water pathway (human health risk), risks were calculated based on a maximum time-averaged concentration around the peak concentration at each receptor well. The exposure duration (which varies from 1 to 50 years)[4] was applied around the peak drinking well concentration to obtain the maximum time-averaged concentration.

For the groundwater-to-surface-water pathway, the groundwater model produces surface water contaminant loads (based on groundwater concentration and flow) for a stream that penetrates the aquifer. Because the surface water model is a steady-state model, there is no temporal component to it and the receptor is exposed to the same concentration over the entire exposure duration. For human health risk, the loadings from groundwater to surface water were averaged over the exposure duration, bracketing the time of the peak groundwater concentration.

[4] Distributions of exposure duration and other exposure variables were obtained from the *Exposure Factors Handbook* (U.S. EPA, 1997c,d,e)

The exposure duration for sensitive ecological receptors is generally a year or less; therefore, for ecological risk, a single peak annual average surface water concentration was used.

For all scenarios, if the groundwater model predicted that the maximum groundwater concentration had not yet occurred after 10,000 years, the actual groundwater concentration at 10,000 years was used in the exposure calculations instead of a maximum time-weighted average concentration around the peak.

3.1.2 Probabilistic Approach

The full-scale analysis evaluates risk in a probabilistic manner and is based on a Monte Carlo simulation that produces a distribution of exposures and risks. The general Monte Carlo approach is shown in Figure 3-1. The foundation of the Monte Carlo simulation is the source data derived from the EPRI survey. These were combined with data from the national CCW constituent database to conduct a Monte Carlo simulation of 10,000 iterations per waste type/WMU type/constituent combination.

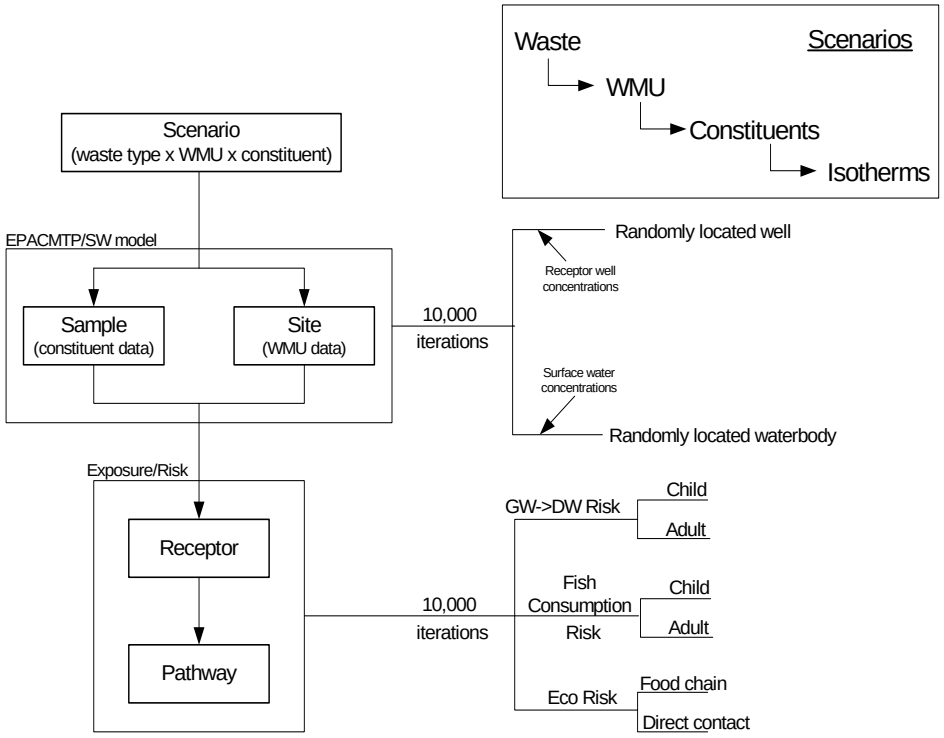


Figure 3-1. Overview of the Monte Carlo approach.

The detailed looping structure for the Monte Carlo analysis is shown in Figure 3-2. For each waste type/WMU combination, two separate loops are run. The first loop (shown with dashed lines in Figure 3-2) prepares a set of input files containing 10,000 sets of WMU and site data (as described in Section 3.1.3). The second loop (shown with solid lines in Figure 3-2) uses those input files to run 10,000 iterations of the source, fate and transport, exposure, and risk models for each constituent.

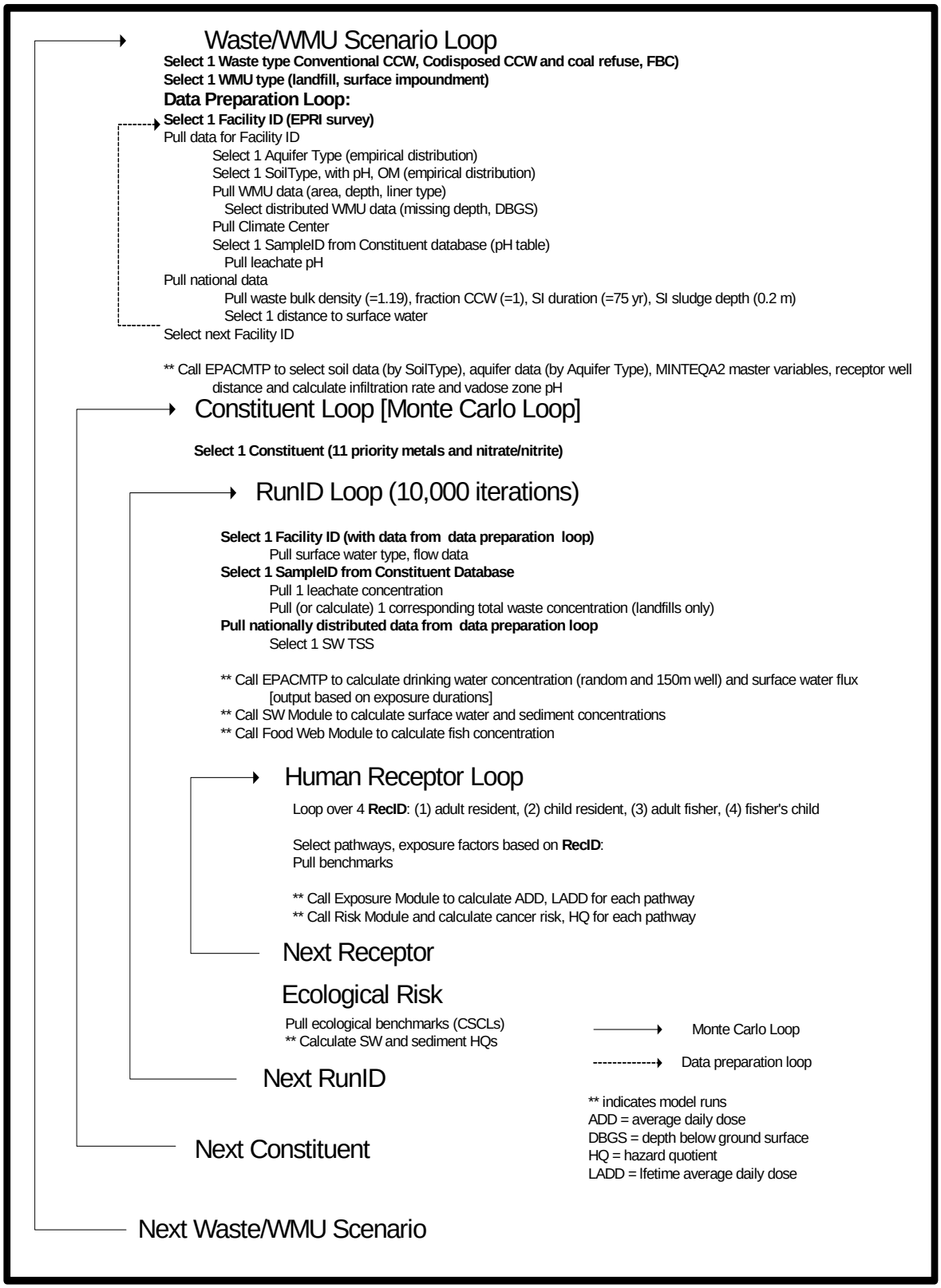


Figure 3-2. Monte Carlo looping structure.

3.1.3 Implementation of Probabilistic Approach

Table 3-1 lists the five waste disposal scenarios addressed in the full-scale analysis. FBC waste landfills were modeled and treated as a separate scenario in the analysis because of the limited number (7) of FBC landfill sites. Each waste disposal scenario modeled in the full-scale assessment included unlined, clay-lined, and composite-lined WMUs. Additional detail on these scenarios can be found in Section 2-1 and Appendix A.

Table 3-1. CCW Waste Management Scenarios Modeled in Full-Scale Assessment

WMU Type	Waste Type
Conventional CCW and CCW Codisposed with Coal Refuse (main analysis)	
Landfill	Conventional CCW (fly ash, bottom ash, boiler slag, FGD sludge)
Landfill	Codisposed CCW and coal refuse
Surface impoundment	Conventional CCW
Surface impoundment	Codisposed CCW and coal refuse
FBC Waste (separate analysis)	
Landfill	FBC waste (fly ash, bottom ash, bed ash)

To capture the national variation in waste management practices for the Monte Carlo analysis, an input database was created with approximately 10,000 iterations for each of the waste type/WMU combinations. This input database provided the source data for 10,000 iterations of the source modeling and the fate and transport modeling. Figure 3-3 provides an overview of the process used to compile these data, which were organized into source data files. As shown in Figure 3-3, seven tasks, some parallel and some sequential, were required to construct these data files, one file for each waste management scenario.

Constructing the source data files for use in the probabilistic analysis involved first developing a 10,000-record data file for each waste type-WMU scenario. This was accomplished by selecting the landfills and surface impoundments from the EPRI survey data that manage each type of waste. Within a scenario, a list of the EPRI plants with that WMU type and waste type was repeated to produce around 10,000 records. For each record, site-based, regional, and national inputs were randomly selected from distributions developed to characterize the regional or national variability in these inputs. Each record in the source data files was identified by a model run identification number (RunID).

The EPRI survey provided most of the WMU data needed, including area, capacity, liner type, and waste type. Additional data were collected to characterize the height and depth below ground surface of typical CCW landfills and surface impoundments (see Appendix B).

The environmental setting in which waste disposal occurs was characterized based on the location of the 181 power plants used in the full-scale analysis. These locations were used to characterize climate, soils, aquifers, and surface water bodies at each site as follows (see Appendix C for details):

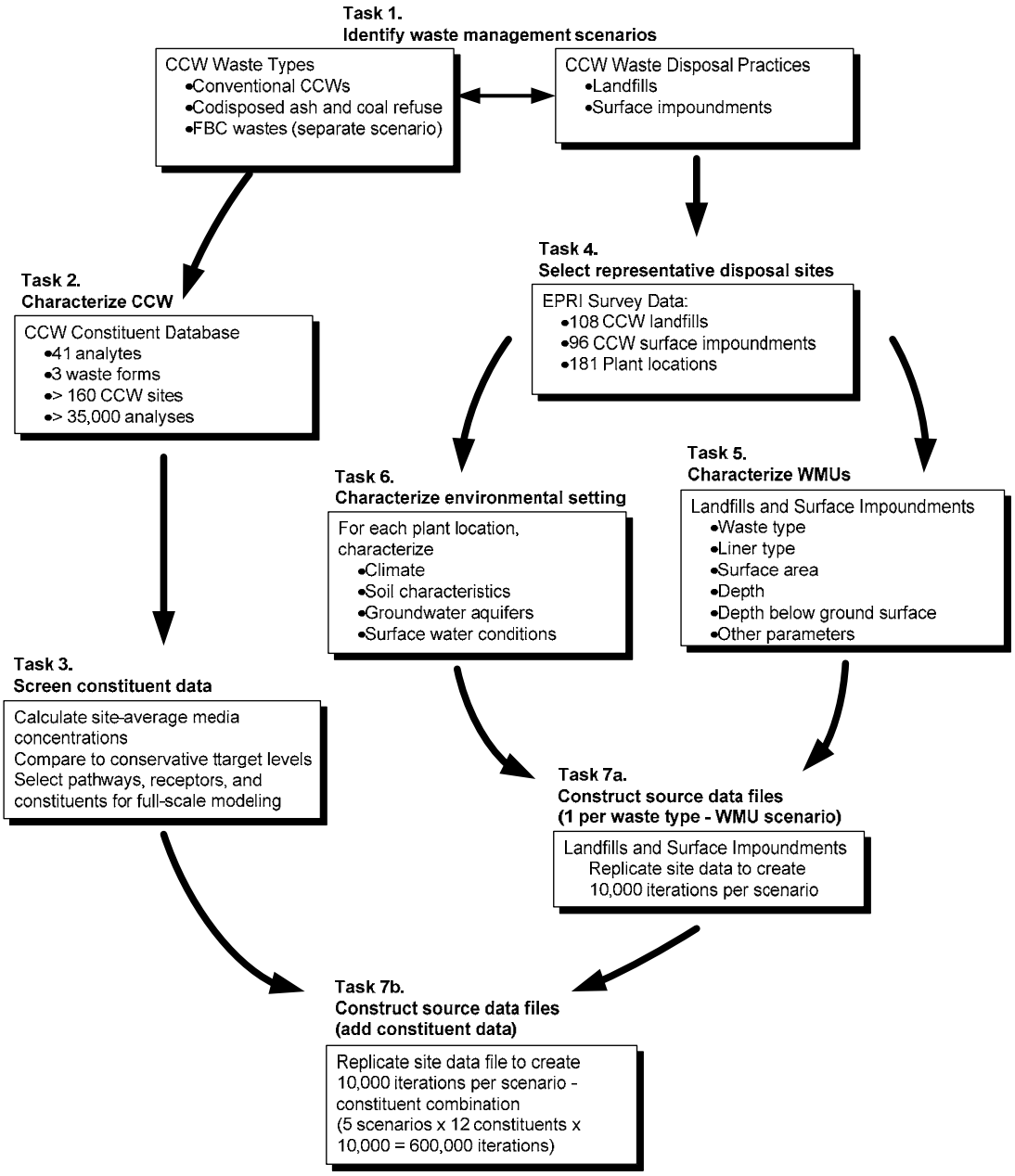


Figure 3-3. Process used to construct the Monte Carlo input database.

- Climatic data, including annual precipitation, temperature, and windspeed, were collected by assigning each site to a nearby meteorologic station.

- Soil and aquifer type were collected within a 5-km radius of each site to account for locational uncertainty for the WMUs.

- Surface water type and flows were collected using a geographic information system (GIS) to identify the nearest stream and by matching plants to the Permit Compliance

System (PCS) database to get the stream segment for each plant's NPDES discharge point.

These site-based data were supplemented with regional data on surface water quality and with national distributions of receptor distances (i.e., distance to drinking water well and distance to nearest surface waterbody). Appendix C describes the site-based approach and data sources used for these site-specific, regional, and national-scale data collection efforts.

The five 10,000-record scenario-specific source data files were then combined with the CCW constituent data for each constituent in the appropriate waste type to develop the final source data files for each scenario. With 12 constituents modeled for most scenarios, this resulted in over 600,000 records in the final input data set.

3.2 Landfill Model

Releases from landfills were modeled using a landfill source-term model contained in EPACMTP. EPA has used EPACMTP and its predecessor models for almost 20 years to conduct groundwater risk assessments in support of regulations for land disposal of hazardous and nonhazardous wastes. In that context, EPACMTP has undergone numerous peer reviews, including multiple reviews by EPA's Science Advisory Board (SAB). Each of these reviews has supported and approved the use of this model for developing national regulations and guidance, including verification that the model and model code are scientifically sound and properly executed. Some of the more important reviews include

- A 1989 review by SAB of the component saturated zone (groundwater) model used in EPACMTP
- A 1993 review by EPA's Office of Research and Development (ORD) of EPACMTP for potential Hazardous Waste Identification Rule applications, which resulted in a number of improvements in the computational modules of EPACMTP
- A 1994 consultation with SAB on the use of EPACMTP for determination of dilution-attenuation factors for EPA's *Soil Screening Guidance*
- A 1994 review by expert modelers Dr. Fred Molz (Auburn University) and Mr. Chris Neville (SS Papadopoulos & Associates), who verified that the mathematical formulation of the model and the code verification testing are scientifically sound
- The peer-reviewed publication of EPACMTP in the *Journal of Contaminant Hydrology* (Kool et al., 1994)
- An in-depth review by SAB related to the use of EPACMTP in the proposed/draft 1995 Hazardous Waste Identification Rule (U.S. EPA, 1995)
- A 1999 peer review by leading modelers of the implementation of EPACMTP in EPA's multimedia, multiple exposure pathway, multiple receptor risk assessment (3MRA) model (U.S. EPA, 1999c)

- A 2003 SAB review of the 3MRA implementation of EPACMTP (SAB, 2004).

An overview and statement of assumptions for the landfill model is presented here, followed by a listing of inputs to the landfill source-term model and a brief discussion of the output generated by the model.

3.2.1 Conceptual Model

The landfill model treats a landfill as a permanent WMU with a rectangular footprint and a uniform depth (see Figure 3-4). If only the area is known (which is the case for the CCW landfills), the landfill source-term model assumes a square footprint. The model assumes that the landfill is filled with waste during the unit's operational life and that upon closure of the landfill, the waste is left in place and a final soil cover is installed.

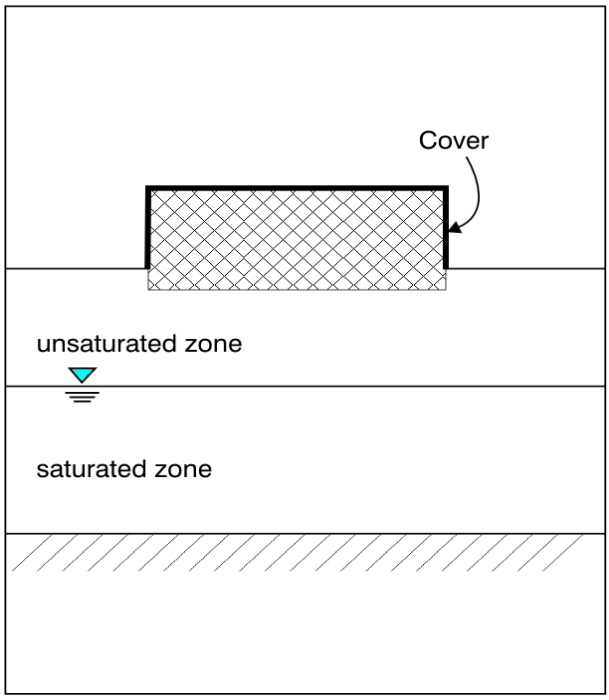


Figure 3-4. Conceptualization of a landfill in the landfill source-term model.

Three liner scenarios were modeled: a no-liner (unlined) scenario, a compacted clay liner, and a composite liner that combines a high-density polyethylene (HDPE) membrane with either geosynthetic or natural clays.

In the unlined scenario, waste is placed directly on local soils, either on grade or excavated to some design depth and without a leachate collection system. After the landfill has been filled to capacity, a 2-foot native soil cover (the minimum required by Subtitle D regulations) is installed and assumed to support vegetation.

In the clay liner scenario, waste is placed directly on a 3-foot compacted clay liner, which is installed on the local soils, either on grade or excavated to some design depth and without a

leachate collection system. After the landfill has been filled to capacity, a 3-foot clay cover is installed and covered with 1 foot of loam to support vegetation and drainage. The hydraulic conductivity of both the liner and cover clays is assumed to be $1x10^{-7}$ cm/sec, the typical design specification for compacted clay liners (U.S. EPA, 1988c).

In the composite liner scenario, wastes are placed on a liner system that consists of a 60 mil HDPE membrane with either an underlying geosynthetic clay liner or a 3-foot compacted clay liner. A leachate collection system is also assumed to exist between the waste and the liner system. After the landfill has been filled to capacity, a 3-foot clay cover is assumed to be installed and covered with 1 foot of loam to support vegetation and drainage (U.S. EPA, 2002b).

As described in Section 3.2.3 (and Appendix B), one of these three liner types was assigned to each CCW landfill or surface impoundment modeled based on the liner type data from the 1995 EPRI Survey (EPRI, 1997).

3.2.2 Modeling Approach and Assumptions

The starting point for the landfill source-term model simulation is the time when the landfill is closed (i.e., when the unit is filled with CCW).[5] As described in detail below, the full-scale analysis modeled contaminants leaching from CCW into precipitation infiltrating the landfill, which exits the landfills as leachate. Contaminant loss in leachate was taken into account at closure by subtracting the cumulative amount of contaminant mass loss that occurred during the unit's active life from the amount of contaminant mass present at the time of landfill closure. Loss calculations in the landfill source-term model continue after closure until the contaminant is depleted from the waste mass in the landfill. This is a conservative assumption, as some metal will not leach from the waste mass.

Infiltration and Leaching

The average rate at which water percolates through the landfill over time (the long-term infiltration rate) drives the leaching process in the landfill, which results from partitioning of the constituent from the waste into the infiltrating water. The methodology, assumptions, and data used to determine infiltration rates for each CCW liner scenario are consistent with the approach used in EPA's Industrial D guidance, as described in Section 4.3 and Appendix A of the *EPACMTP Parameter/Data Background Document* (U.S. EPA, 2003a) and Section 4.2.2 of the *Industrial Waste Evaluation Model (IWEM) Technical Background Document* (U.S. EPA, 2002b). EPA developed the IWEM model as part of a guide for managing nonhazardous industrial wastes in landfills and surface impoundments (http://www.epa.gov/industrialwaste). To help ensure that it was technically sound, the model (including the liner scenarios and algorithms used in the CCW risk assessment) was developed with a large stakeholder working group, including representatives from industry. The model was also subjected to a peer review in 1999 (64 FR 54889–54890, October 8, 1999, *Peer Reviews Associated With the Guide for*

[5] The simple landfill model used in this assessment cannot model a landfill as it is being filled prior to closure. Although leaching does occur during a landfill's operating life, risks from these releases are insignificant when compared to postclosure releases, given the long time it takes metal-bearing wastes to leach and reach peak concentrations in groundwater wells surrounding the landfill. EPA does not believe that the additional risks from the preclosure period justify the additional complexity, data, and effort required to model an operating landfill.

Industrial Waste Management), and the model was updated and improved in response to those comments before its final release in 2003. That update included the addition of a more robust liner leakage database to support the existing algorithms for calculating infiltration rates through composite liner systems.

No-Liner (Unlined) Scenario. For the no-liner scenario, infiltration rates were selected from a database in EPACMTP that contains 306 infiltration rates already calculated using EPA's Hydrologic Evaluation of Landfill Performance (HELP) water balance model (Schroeder, et al., 1994a, 1994b). HELP is a product of an interagency agreement between EPA and the U.S. Army Corps of Engineers Waterways Experiment Station, and was subjected to the Agency's peer and administrative review. All of the infiltration rates were calculated based on the single typical landfill design described in Section 3.2.1, with the only variables that change between HELP simulations being the meteorological data associated with 102 nationwide climate centers and the type of cover soil applied at closure. Three cover soil categories representing coarse-grained soils, medium-grained soils, and fine-grained soils were used. The selection of an infiltration rate from the database depends on the type of cover soil selected for the landfill and the assignment of the landfill to a HELP climate center. The unlined HELP-derived infiltration rates are presented in U.S. EPA (2003a) by climate center. The assignment of HELP climate centers and soil categories to each CCW site modeled is described in Appendix C.

Clay Liner Scenario. The clay liner scenario is very similar to the unlined scenario in that previously calculated HELP infiltration rates for a single clay-lined, clay-capped landfill design were used. The scenario is based on a typical engineered compacted clay liner that is 3 feet thick with a design hydraulic conductivity of $1x10^{-7}$ cm/sec. The one difference from the unlined case is that the clay liner and cover control the rate of water percolation through the landfill and thus infiltration rate does not vary with cover soil (i.e., there is one clay liner infiltration rate per climate center). The clay liner HELP-derived infiltration rates are provided in U.S. EPA (2003a).

Composite Liner Scenario. Composite liner infiltration rates are compiled from monthly average leak detection system (LDS) flow rates for industrial landfill cells reported by TetraTech (2001). The liner configurations are consistent with the composite liner design assumptions presented in Section 3.2.1 and are the same as those assumed for defaults in EPA's Industrial D landfill guidance (U.S. EPA, 2002b). The LDS flow rates were taken from 27 municipal landfill cells and used in the IWEM model (U.S. EPA, 2002b). As shown in Table 3-2, these LDS flow rates include 22 operating landfill cells and 5 closed landfill cells located in eastern United States: 23 in the northeastern region, 1 in the mid-Atlantic region, and 3 in the southeastern region. Each of the landfill cells is underlain by a geomembrane/geosynthetic clay liner which consists of a high-density polyethylene geomembrane of thickness between 1 and 1.5 mm, overlying a 6-mm composite geosynthetic clay layer consisting of two geotextile outer layers with a uniform core of bentonite clay to form a hydraulic barrier. Each liner system is underlain by an LDS.

As described in U.S. EPA (2002b), only a subset of the TetraTech (2001) flow rates were used to develop the composite liner infiltration rates. LDS flow rates for geomembrane/ compacted clay composite-lined landfill cells were not used in the distribution because compacted clay liners (including composite geomembrane/compacted clay liners) can release

water during consolidation and contribute an unknown amount of water to LDS flow, which makes it difficult to determine how much of the LDS flow is due to liner leakage versus clay consolidation. Also, LDS flow rates from three geomembrane/geosynthetic clay lined-cells were not used. For one cell, postclosure flow rates were very high, and were more than twice as high as those recorded during the cell's operating period. Data were not used for two other cells because of inconsistencies with the data for the 27 landfill cells used to develop composite liner infiltration rates (U.S. EPA, 2002b). The composite liner infiltration rates were specified as an empirically distributed input to the landfill model (see U.S. EPA ,2003a).

Table 3-2. Leak Detection System Flow Rate Data Used to Develop Landfill Composite Liner Infiltration Rates

Cell ID	Status	Flow rate (m/y)	Location
G228	Operating	2.1E-04	Mid-Atlantic
G232	Operating	4.0E-04	Northeast
G232	Closed	7.3E-05	Northeast
G233	Operating	0	Northeast
G233	Closed	0	Northeast
G234	Operating	7.3E-05	Northeast
G234	Closed	0	Northeast
G235	Operating	1.5E-04	Northeast
G235	Closed	3.7E-05	Northeast
G236	Operating	3.7E-05	Northeast
G236	Closed	0	Northeast
G237	Operating	7.3E-05	Northeast
G238	Operating	0	Northeast
G239	Operating	7.3E-05	Northeast
G240	Operating	0	Northeast
G241	Operating	0	Northeast
G242	Operating	0	Northeast
G243	Operating	0	Northeast
G244	Operating	0	Northeast
G245	Operating	0	Northeast
G246	Operating	0	Northeast
G247	Operating	0	Northeast
G248	Operating	0	Northeast
G249	Operating	7.3E-05	Northeast
G250	Operating	2.2E-04	Southeast
G251	Operating	0	Southeast
G252	Operating	0	Southeast

Source: U.S. EPA (2002a); original data from TetraTech (2001).

Source Depletion and Mass Balance

For this assessment**,** the landfill source-term model represents releases from landfills as a finite source where the mass of a constituent in a landfill is finite and depleted over time by

leaching. The landfill source-term model is set as a pulse source, where the leachate concentration is constant over a prescribed period of time and then goes to zero when the constituent is depleted from the landfill. A pulse source is appropriate for metals and other constituents whose sorption behavior is nonlinear. Because all but one (nitrate/nitrite) of the constituents addressed in the full-scale analysis are metals, releases from landfills were modeled as pulse sources.

For a pulse source, basic mass balance considerations require leaching from the landfill to stop when all of the constituent mass has leached from the landfill. For the constant concentration pulse source condition, the pulse duration is given by

$$TSOURC = \frac{CWASTE \times DEPTH \times FRACT \times CTDENS}{CZERO \times SINFIL} \quad (3\text{-}1)$$

where

TSOURC = Pulse duration (yr)
CWASTE = Constituent concentration in the waste (mg/kg)
DEPTH = Depth of landfill (m)
FRACT = Volume fraction of the landfill occupied by the waste (unitless)
CTDENS = Waste density (g/cm^3)
CZERO = Initial waste leachate concentration (mg/L)
SINFIL = Annual areal infiltration rate (m/yr).

The landfill source-term model uses the above relationship to determine the leaching duration. More details regarding the waste concentration and WMU parameters in Equation 3-1 are provided below and in Appendices A and B.

3.2.3 Landfill Model Input Parameters

Input parameters required by the landfill source-term model are discussed below. Additional details on how data for these inputs were collected for the CCW risk assessment are provided in Appendix A for leachate and waste concentrations and Appendix B for landfill dimensions and characteristics.

- **Landfill Area.** The model uses landfill area to determine the area over which infiltration rate occurs and, along with landfill depth and waste concentration, to calculate the total contaminant mass in the landfill. CCW landfill area data were obtained from the EPRI comanagment survey (EPRI, 1997). The landfill was assumed to be square.

- **Landfill Depth.** Landfill depth is one of several parameters used by the landfill source-term model to calculate the contaminant mass in the landfill. For CCW landfills, average waste depth was estimated by dividing landfill capacity by landfill area. CCW landfill capacity data were taken from the EPRI comanagement survey (EPRI, 1997).

- **Depth Below Grade.** The depth of the bottom of the landfill below the surrounding ground surface is used, along with depth to groundwater, to determine the thickness of the unsaturated zone. For CCW landfills, depth below grade was determined from a national distribution based on available measurements from a number of CCW landfills (see Appendix B).

- **Waste Fraction.** The landfills were assumed to be CCW monofills, which corresponds to a waste fraction of 1.0.

- **Waste Density.** The average waste bulk density, as disposed, is used to convert waste volume to waste mass. The waste bulk density for all CCW waste types was assumed to be 1.19 g/cm^3 (U.S. EPA, 1998b).

- **Leachate Concentration.** The concentration of waste constituents in leachate was assumed to be constant until all of the contaminant mass initially present in the landfill has leached out, after which the leachate concentration was assumed to be zero. The constant value used for leachate concentration is from EPA's CCW Constituent Database, described in Appendix A.

- **Waste Concentration.** In the finite-source scenario modeled, the total waste concentration is used, along with the waste bulk density and landfill area and depth, to determine the total amount of a constituent available for leaching. Measured total CCW concentrations were paired with leachate concentrations, as described in Appendix A and provided in Attachment A-2.

- **Liner Type.** The type of liner is used to determine the infiltration/leaching scenario used to calculate leachate flux from the landfill. Table 3-3 shows the crosswalk used to assign one of the three liner scenarios to each facility based on the liner data in the 1995 EPRI survey (EPRI, 1997). Attachment B-2 to Appendix B provides these assignments, along with the original EPRI liner type, for each CCW landfill facility modeled. One significant uncertainty in these liner assumptions is how representative the EPRI survey data are of current conditions at coal combustion facilities.

Table 3-3. Crosswalk Between EPRI and CCW Source Model Liner Types

EPRI Liner Type	Model Liner Code	Description
Compacted ash	0	no liner
Compacted clay	1	clay
Composite clay/membrane	2	composite
Double	2	composite
Geosynthetic membrane	2	composite
None/natural soils	0	no liner

3.2.4 Model Outputs

For each year in the simulation, the landfill source-term model uses the average annual leachate concentration and infiltration rate to calculate a constituent flux through the bottom of the landfill. This time series is used as an input for the EPACMTP unsaturated zone model.

3.3 Surface Impoundment Model

Releases from surface impoundments were modeled using a surface impoundment source-term model contained in EPACMTP. An overview and statement of assumptions for the surface impoundment model is presented here, followed by a listing of inputs to the surface impoundment source-term model and a brief discussion of the output generated by the model. The primary differences between the treatment of landfills and surface impoundments are (1) the integration of the surface impoundment source term into the unsaturated flow solution, and (2) clean closure of the impoundment after the operating period is over.

3.3.1 Conceptual Model

The surface impoundment model treats a surface impoundment as a temporary WMU with a prescribed operational life. Unlike the landfill model, clean closure is assumed; that is, at the end of the unit's operational life, the model assumes that all wastes are removed and there is no further release of waste constituents to groundwater. Although this simplifying assumption limits the length of potential exposure, and is not consistent with the practice to close CCW surface impoundments with these wastes in place, the peak annual leachate concentrations on which the CCW risk results are based are not likely to be affected, because they are highest when the surface impoundment is in operation.

Following the unit's closure, the surface impoundment model assumes that the contaminated liquid and sediment in the surface impoundment are replaced by uncontaminated liquid and sediment with otherwise identical configurations and properties. The contaminants that have migrated to the unsaturated zone during operation continue to migrate towards the water table with the same infiltration rate as during operation. By continuing infiltration after the wastes are removed, the infiltration through the surface impoundment unit can be modeled as a single steady-state flow regime until concentrations in groundwater are no longer affected by constituents released from the surface impoundment during its operation.

The EPACMTP surface impoundment model assumes a square footprint and a constant ponding depth during the impoundment's operational life (Figure 3-5). For an unlined impoundment, the model assumes that while the impoundment is in operation, a consolidated layer of sediment accumulates at the bottom of the impoundment. The leakage (infiltration) rate through the unlined impoundment is a function of the ponding depth in the impoundment and the thickness and effective permeability of the consolidated sediment layer at the bottom of the impoundment. The rate of leakage is constrained to ensure that there is not a physically unrealistic high rate of leakage, which would cause groundwater mounding beneath the unit to rise above the ground surface. Underlying the assumption of a constant ponding depth, the surface impoundment source-term model assumes that wastewater in the impoundment is continually replenished while the impoundment is in operation. It also assumes, from the

beginning of the unit's operation, that the sediment is always in equilibrium with the wastewater (i.e., the presence of sediment does not alter the concentration of leachate). Accordingly, the surface impoundment source-term model also assumes that the leachate concentration is constant during the impoundment operational life. Typically, the leachate concentration is equal to the concentration in the wastewater entering the impoundment.

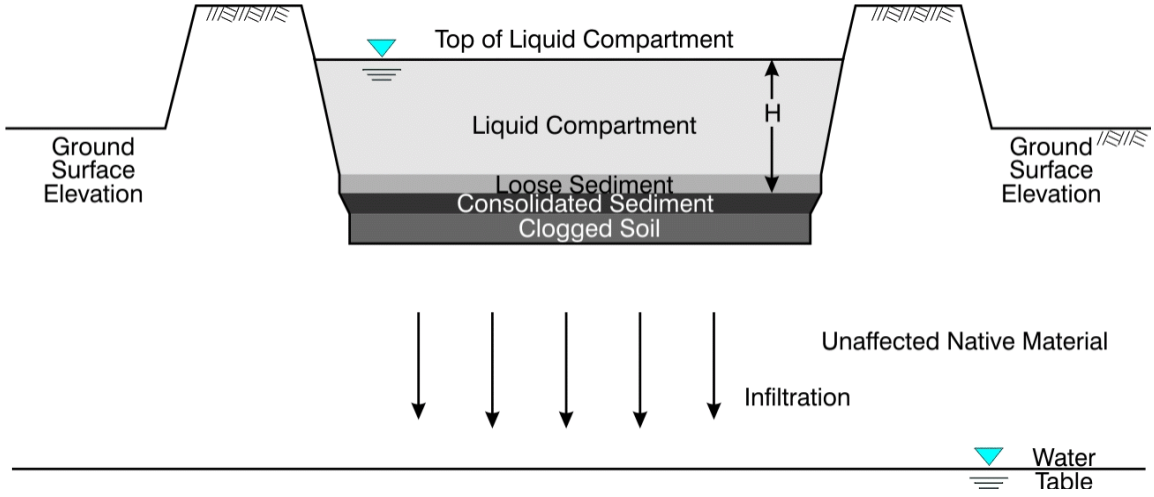


Figure 3-5. Schematic cross-section view of surface impoundment.

Three liner scenarios were modeled: a no-liner (unlined) scenario, a compacted clay liner, and a composite liner.

In the unlined scenario, wastewater is placed directly on local soils and the depth of water is constant over the entire life of the impoundment, pre- and post-closure. As described above, sediments accumulate and consolidate at the bottom of the impoundment and migrate into the underlying native soils, where they clog pore spaces and provide some barrier to flow. The surface impoundment model assumes that the thickness of the consolidated sediments is equal to one-half of the total sediment thickness, which is an input to the model. The sediment thickness was assumed to be 0.2 m for all simulations. The model also assumes that the thickness of the clogged region of native soils is always 0.5 m and has a hydraulic conductivity 10 percent of that of the native soil underlying the impoundment.

In the clay liner scenario, wastewater is placed on a compacted clay liner, which is installed on the local soils. The assumptions for an unlined impoundment also apply to the compacted clay liner scenario, except that a compacted clay liner filters out the sediments that clog the native soils in the unlined case, so the effect of clogging the native materials is not included in the calculation of the infiltration rate. The thickness of the compacted clay liner was assumed to be 3 feet and the hydraulic conductivity was assumed to be $1x10^{-7}$ cm/sec (U.S. EPA, 1988c).

In the composite liner scenario, wastewater is placed on a synthetic membrane with an underlying geosynthetic or natural compacted clay liner with a hydraulic conductivity of $1x10^{-7}$ cm/sec. The membrane liner was assumed to have a number of pinhole leaks of uniform size

(6 mm^2). The distribution of leak densities (expressed as number of leaks per hectare) was compiled from 26 leak density values reported in TetraTech (2001), the best available data on liner leaks. These leak densities are based on liners installed with formal construction quality assurance (CQA) programs. The 26 sites with leak density data are mostly located outside the United States: 3 in Canada, 7 in France, 14 in the United Kingdom, and 2 in unknown locations; we assume that these are representative of U.S. conditions. The WMUs at these sites (8 landfills, 4 surface impoundments, and 14 of unknown type) are underlain by a layer of geomembrane with a thickness varying from 1.14 mm to 3 mm. The majority of the geomembranes (23 of 26) are made from HDPE, and the remaining 3 are made from prefabricated bituminous geomembrane or polypropylene. One of the sites has a layer of compacted clay liner beneath the geomembrane; however, for 25 of the 26 sites, material types below the geomembrane layer are not reported. The empirical distribution used in the analysis can be found in IWEM (U.S. EPA, 2002b), along with a table showing details about the 26 liners used to develop the distribution.

3.3.2 Modeling Approach and Assumptions

Figure 3-5 illustrates a compartmentalized surface impoundment with stratified sediment. Shown in the figure are the liquid compartment, the sediment compartment (with loose and consolidated sediments), and the unsaturated zone (with clogged and unaffected native materials). The model assumes that all sediment layer thicknesses remain unchanged throughout the life of the unit.

The EPACMTP surface impoundment model uses the unsaturated zone flow model to calculate the infiltration rate out of the bottom of the impoundment. This model is designed to simulate steady-state downward flow through an unsaturated (vadose) zone consisting of one or more soil layers. Steady-state means that the rate of flow does not change with time. In the case of flow out of an unlined surface impoundment, the model simulates flow through a system consisting of three layers: a consolidated sediment layer, a clogged soil layer, and a native soil layer.

The native unsaturated soil extends downward to the water table. The steady-state infiltration rate out of the surface impoundment is driven by the head gradient between the water ponded in the impoundment and the head at the water table. The pressure head at the top of the consolidated sediment layer is equal to the water depth in the impoundment plus the thickness of the unconsolidated sediment.

The *EPACMTP Technical Background Document* (U.S. EPA, 2003c) describes the algorithms used in this model to calculate the infiltration rate from surface impoundment units, and discusses in detail the maximum allowable infiltration rate based on the groundwater mounding condition. This information is summarized here.

The EPACMTP surface impoundment source-term model calculates infiltration through the accumulated sediment at the bottom of an impoundment, accounting for clogging of the native soil materials underlying the impoundment, liner conditions, and mounding due to infiltration. The modeled infiltration is governed by the depth of liquid in the impoundment and the following limiting factors:

- **Effective hydraulic conductivity and thickness of the consolidated sediment layer.** As sediment accumulates at the base of the impoundment, the weight of the liquid and upper sediments tends to compress (or consolidate) the lower sediments. The consolidation process reduces the hydraulic conductivity of the sediment layer, and the layer of consolidated sediment will act as a restricting layer for flow out of the impoundment. By contrast, the layer of loose, unconsolidated sediment that overlies the consolidated sediment layer is assumed not to restrict the flow rate out of the unit, so it is not explicitly considered in the surface impoundment flow model.

- **Effective hydraulic conductivity of the clogged native material.** As liquids infiltrate soil underlying the impoundment, suspended particulate matter accumulates in the soil pore spaces, reducing hydraulic conductivity and lowering infiltration rates.

- **Effective hydraulic conductivity and thickness of a clay liner.** When the surface impoundment is underlain by a compacted clay liner, the rate of infiltration is also determined by simulating flow through a three-layer system, substituting the characteristics of the clay liner for those of the clogged soil layer.

- **Leak rate of a composite liner.** For cases where the surface impoundment is underlain by a composite liner (a geomembrane underlain by a low permeability liner such as a compacted clay liner or a geosynthetic clay liner), the surface impoundment source-term model uses a modified equation of Bonaparte et al. (1989) to calculate the infiltration rate. The equation uses, among other inputs, the head generated by the water and unconsolidated sediments in the unit, a leak density selected from an empirical distribution derived from a TetraTech (2001) study of liner leakage, a uniform leak size of 6 mm^2, and an assumed hydraulic conductivity of $1x10^{-7}$ cm/sec for the 3 feet of underlying compacted clay material.

- **Limitations on maximum infiltration rate from mounding.** If the calculated infiltration rate exceeds the rate at which the saturated zone can transport the groundwater, the groundwater level will rise into the unsaturated zone. The model accounts for groundwater mounding when calculating the infiltration rate from the surface impoundment unit and, if necessary, constrains the value to ensure that the groundwater mound does not rise to the bottom of the surface impoundment unit.

3.3.3 Surface Impoundment Model Input Parameters

Input parameters required by the surface impoundment source-term model are discussed below. Additional details on how data for these inputs were collected for the CCW risk assessment are provided in Appendix A for waste concentrations and Appendix B for surface impoundment dimensions and characteristics.

- **Surface Impoundment Area.** The model uses surface impoundment area to determine the area over which infiltration occurs. CCW surface impoundment area data were obtained from the EPRI comanagement survey (EPRI, 1997). The impoundment was assumed to be square.

- **Areal Infiltration Rate.** The surface impoundment leachate infiltration rate (or flux) is computed internally by the surface impoundment source-term model, as described in Section 3.3.2.

- **Depth Below Grade.** The depth of the bottom of the impoundment below the surrounding ground surface is used, along with depth to groundwater, to determine the thickness of the unsaturated zone beneath the impoundment. For CCW impoundments, depth below grade was sampled from an empirical distribution based on available measurements from a number of CCW surface impoundments (see Appendix B).

- **Operating Depth.** The operating (or ponding) depth is the long-term average depth of wastewater and sediment in the impoundment, measured from the base of the impoundment. For CCW surface impoundments, depth was estimated by dividing impoundment capacity by impoundment area. CCW impoundment capacity data were taken from the EPRI comanagement survey (EPRI, 1997).

- **Total Thickness of Sediment.** By default, EPACMTP models unlined surface impoundments with a layer of "sludge" or sediment above the base of the unit. The sediment layer is divided into two sublayers: an upper, loose sediment sublayer and a lower, consolidated sediment sublayer. The consolidated sediment has a relatively low hydraulic conductivity and acts to impede flow. The calculated infiltration rate is inversely related to the thickness of the consolidated sediment sublayer. A thinner consolidated sediment layer will result in a higher infiltration rate and a greater rate of constituent loss from the impoundment. The surface impoundment source-term model uses the total sediment thickness as an input parameter and assumes that it consists of equal thicknesses of loose and consolidated material. Because data were not available on CCW sediment layer thicknesses, the CCW risk assessment used the Tier 1 IWEM model assumption: a total (unconsolidated plus consolidated) sediment layer thickness of 0.2 meters (U.S. EPA, 2002b). It is not known how representative this assumption is with respect to unlined CCW surface impoundments, but it is reasonable to assume that a sediment layer would accumulate and restrict flow from the bottom of a CCW impoundment.

- **Distance to the Nearest Surface Water Body.** The distance to the nearest waterbody is used to determine the location of a fully penetrating surface waterbody at which groundwater mass and water fluxes will be calculated and reported. The distance to the nearest surface waterbody is also used as a surrogate for the distance to the nearest point at which the water table elevation is kept at a fixed value. That distance is used to calculate the estimated height of groundwater mounding underneath the impoundment to ensure that excessively high infiltration rates, which may be calculated for deep, unlined impoundments, do not occur. If necessary, the model reduces the infiltration rate to ensure the predicted water table does not rise above the ground surface. For the CCW sites, distance to surface water was sampled from an empirical distribution developed from aerial photo measurements at 59 coal-fired power plants with onsite landfills or surface impoundments (Appendix C).

- **Leachate Concentration.** The annual average leachate concentration is modeled as a constant concentration pulse with a defined duration. For a particular model run, the leachate concentration was assumed to be constant during the operation of the unit; there is no reduction in leachate concentration until the impoundment ceases operation. Leachate concentrations for CCW impoundments were obtained by waste type from surface impoundment porewater data from EPA's CCW Constituent Database, as described in Appendix A.

- **Source Leaching Duration.** For surface impoundments, the addition and removal of waste during the operational life period are more or less balanced, without significant net accumulation of waste. In the finite-source implementation used for CCW surface impoundments, the duration of the leaching period is assumed to be the same as the operational life of the surface impoundment. Based on industry data (see Appendix B) for CCW surface impoundments, we used a high-end (90th percentile) fixed surface impoundment operating life of 75 years. A high-end value was appropriate because CCW surface impoundments are typically closed with waste in place, while the surface impoundment source-term model assumes clean closure (waste removed). In addition, operating life is not a particularly sensitive parameter in this analysis: the difference between the 50th percentile value (40 years) and the 90th percentile value used (75 years) is less than a factor of two.

- **Liner Type, Thickness, Hydraulic Conductivity, and Leak Density.** The type of liner is used to calculate leachate flux from the impoundment. To assign one of the three liner scenarios to each facility in the EPRI survey (EPRI, 1997), we used the same crosswalk as we used for landfills (see Table 3-2). Attachment B-2 to Appendix B provides these assignments, along with the original EPRI liner type, for each CCW surface impoundment modeled.

As with IWEM (U.S. EPA, 2002b), clay liners were assumed to be 3 feet thick and to have a constant hydraulic conductivity of 10^{-7} cm/s, reflecting typical design specifications for clay liners. For composite liners, infiltration was assumed to result from defects (pin holes) in the geomembrane. The pin holes were assumed to be circular and uniformly sized (6 mm^2). The leak density was defined as the average number of circular pin holes per square meter and was obtained from a study of industrial surface impoundment membrane liner leak rates by Tetra Tech (2001).

3.3.4 Surface Impoundment Model Outputs

For each year in the simulation, the surface impoundment source-term model uses the average annual leachate concentration and calculates an infiltration rate to estimate the constituent flux through the bottom of the impoundment. This time series is used as an input for the EPACMTP unsaturated zone model.

3.4 Groundwater Model

This section describes the methodology and the models that were used to predict the fate and transport of chemical constituents in soil and groundwater to determine impacts on drinking

water wells and surface water that is connected to groundwater. The surface water model used to address the groundwater-to-surface water pathways is described in Section 3.5.

3.4.1 Conceptual Model

The groundwater pathway was modeled to determine the receptor well concentrations and contaminant flux to surface water resulting from the release of waste constituents from a WMU. The release of a constituent occurs when liquid percolating through the WMU becomes leachate as it infiltrates from the bottom of the WMU into the subsurface. For landfills, the liquid percolating through the landfill is from water in the waste and precipitation. For surface impoundments, the percolating liquid is primarily the wastewater managed in the impoundments.

Waste constituents dissolved in the leachate are transported through the unsaturated zone (the soil layer under the WMU) to the underlying saturated zone (i.e., groundwater). Once in the groundwater, contaminants are transported downgradient to a hypothetical receptor well or waterbody. For this analysis, the groundwater concentration was evaluated for three receptor locations, each at a specified distance from the downgradient edge of the WMU:

- The intake point of a hypothetical residential drinking water well (the receptor well), which is used for the residential drinking water pathway
- A nearby river, stream, or lake, which is modeled as a fully penetrating surface waterbody and is used for the fish ingestion and ecological pathways.

Figure 3-6 shows the conceptual model of the groundwater fate and transport of contaminant releases from a WMU to a downgradient receptor well.

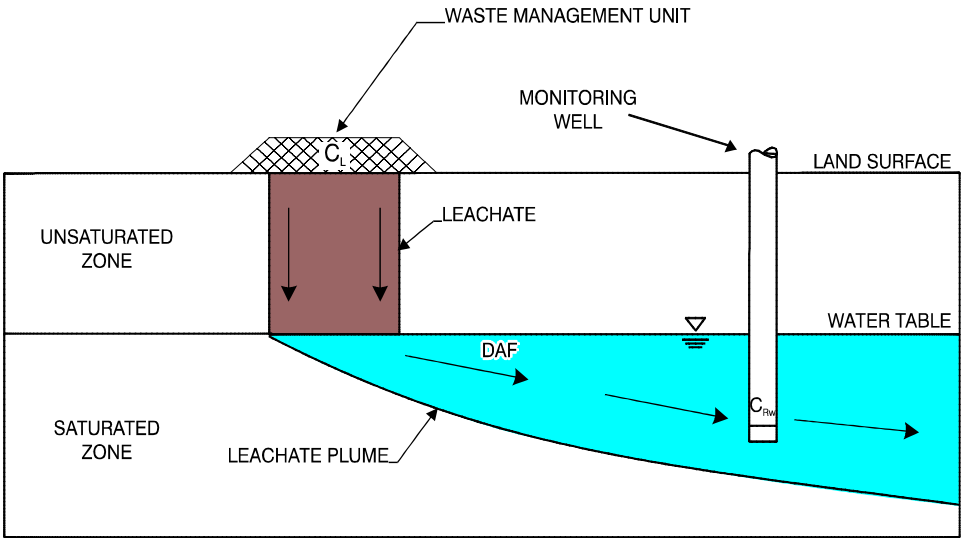


Figure 3-6. Conceptual model of the groundwater modeling scenario.

3.4.2 Modeling Approach and Assumptions

The transport of leachate from the WMU through the unsaturated and saturated zones was modeled using EPACMTP (U.S. EPA, 1996, 1997a, 2003a, 2003d, 2003d). EPACMTP is a

composite model consisting of two coupled modules: (1) a one-dimensional module that simulates infiltration and dissolved contaminant transport through unsaturated soils, and (2) a 3-dimensional saturated zone flow and transport module to model groundwater fate and transport. EPACMTP has been used by EPA to make regulatory decisions for wastes managed in land disposal units (including landfills and surface impoundments) for a number of solid waste and hazardous waste regulatory efforts, and as noted earlier, has undergone extensive peer review. EPACMTP simulates the concentration arriving at a specified receptor location (such as a well or stream).

The primary subsurface transport mechanisms modeled by EPACMTP are (1) downward (1-dimensional) movement along with infiltrating water flow in the unsaturated zone soils and (2) movement and dispersion along with ambient groundwater flow in the saturated zone. EPACMTP models soils and aquifer as uniform porous media and does not account for preferential pathways such as fractures and macropores or for facilitated transport, which may affect migration of strongly sorbing constituents such as metals.

In the unsaturated zone, flow is gravity driven and prevails in the downward direction. Therefore, the flow is modeled in the unsaturated zone as one-dimensional in the vertical direction. The model also assumes that transverse (sideways) dispersion (from both mechanical and molecular diffusion processes) is negligible in the unsaturated zone because the scale of lateral migration due to transverse dispersion is negligible compared with the size of the WMUs. This assumption is also environmentally protective because it allows the leading front of the contaminant plume to arrive at the water table with greater peak concentration in the case of a finite source.

In the saturated zone, the EPACMTP model assumes that movement of chemicals is driven primarily by ambient groundwater flow, which in turn is controlled by a regional hydraulic gradient and hydraulic conductivity in the aquifer formation. The model does take into account the effects of infiltration through the WMU, as well as regional recharge into the aquifer around the WMU. Infiltration through the WMU increases the groundwater flow in all directions under and near the WMU and may result in groundwater mounding. This 3-dimensional flow pattern enhances the horizontal and vertical spreading of the contaminant plume. The effect of recharge (outside the WMU) is to cause a downward (vertical) movement of the contaminant plume as it travels along groundwater flow direction. In addition to advective movement with the groundwater flow, the model simulates mixing of contaminants with groundwater due to hydrodynamic dispersion, which acts along the groundwater flow direction, as well as vertically and in the horizontal transverse direction.

To model sorption of CCW constituents in the unsaturated zone, soil-water partitioning coefficients (K_d values) for metal constituents were selected from nonlinear sorption isotherms generated from the equilibrium geochemical speciation model MINTEQA2 (U.S. EPA, 2001a). Chemicals with low K_d values will have low retardation factors, which means that they will move at nearly the same velocity as the groundwater. Chemicals with high K_d values will have high retardation factors and may move many times slower than groundwater. As described in Appendix D, CCW-specific partition coefficients were developed with MINTEQA2 considering

CCW leachate chemistry, including the highly alkaline chemistries that are characteristic of some CCWs.

MINTEQA2 is a product of ORD, and like EPACMTP, has a long history of peer- and SAB-review during its development, use, and continued improvement for regulatory support over the past two decades. These reviews largely focused on the use of MINTEQA2 to generate sorption isotherms for metals for EPACMTP, which is how it was used in the CCW risk assessment. Two of the more recent peer reviews include one for application within the 3MRA model (U.S. EPA, 1999d) and a review of its use and application to RCRA rulemaking and guidance support, including revisions made to the model to support IWEM and the CCW rulemaking efforts (U.S. EPA, 2003f). In the latter review, three experts found that the revisions made to the MINTEQA2 model were appropriate, but also suggested further improvements in how the model addresses environments with highly alkaline leachate (such as CCW sites). As explained in Appendix D, these comments were addressed in this application of MINTEQA2 to CCW waste transport by the development of sorption isotherms that are specific to geochemical conditions encountered in CCW landfills and surface impoundments.

3.4.3 Model Inputs and Receptor Locations

EPACMTP requires information about soil and aquifer properties as model inputs. For soils, EPACMTP uses soil texture to generate consistent hydrological properties for the unsaturated zone model, and soil pH and organic matter to select appropriate sorption coefficients to model contaminant sorption in the soil. As described in Appendix C, site-specific soil texture, pH, and organic carbon data were collected around each site from the STATSGO soils database. Similarly, the hydrogeological setting around each WMU was used to select appropriate aquifer conditions from EPACMTP's Hydrogeologic Database (HGDB; see Appendix C).

Recharge is water percolating through the soil to the aquifer outside the footprint of the WMU. The recharge rate is determined by precipitation and soil texture. For the CCW landfills and surface impoundments, recharge rates were selected by soil texture and meteorological station assignment from a database of HELP model–derived recharge rates for climate stations across the country that is included in the EPACMTP input files. Further details about how these rates were determined and other options for determining recharge rates outside of the EPACMTP model can be found in the *EPACMTP Parameters/Data Background Document* (U.S. EPA, 2003a).

One of the most important inputs for EPACMTP is receptor location, which for this risk assessment includes residential drinking water wells and surface water bodies. Figure 3-7 shows a schematic of how residential well drinking water intakes were defined in terms of their radial downgradient distance from the WMU and the angle off the contaminant plume centerline. The shaded areas in Figure 3-7 represent the horizontal extent of the contaminant plume.

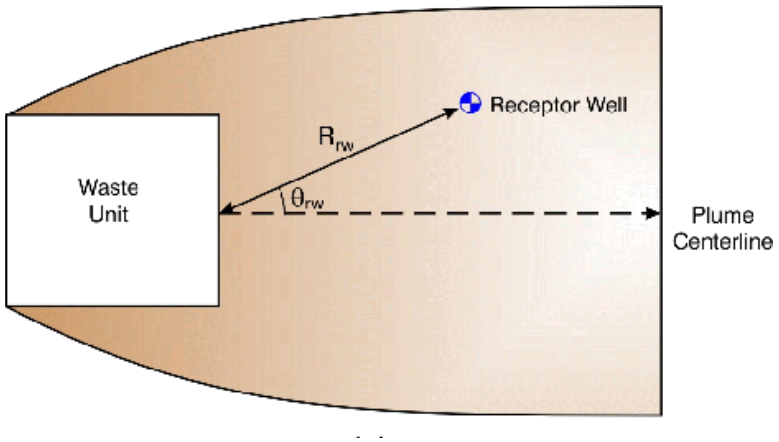


Figure 3-7. Schematic plan view showing contaminant plume and receptor well location.

In this analysis, receptor wells were located randomly within the contaminant plume, as follows:

- Because residential well distance data are not available for CCW WMUs, EPA based the radial downgradient distance on a nationwide distribution of the nearest downgradient residential or municipal wells from a survey of Subtitle D municipal solid waste landfills (U.S. EPA, 1988a; see Appendix C). The maximum radial distance in this survey was 1 mile. EPA believes that this distribution is protective of CCW WMUs, but because information on the actual distance of drinking water wells from CCW facilities is very limited, EPA is seeking comments and additional data that are relevant to this issue.

- The angle off the contaminant plume centerline (θ_{rw} in Figure 3-7) was based on a uniform distribution ranging from zero to ninety degrees.

- Wells were placed within the lateral extent of the contaminant plume (shaded portion in Figure 3-7).

- The depth of the well intake point was based on a uniform distribution with limits of 0 (i.e., well at the water table) to 10 meters (or the total saturated aquifer thickness if the aquifer is less than 10 meters thick).

The location of the surface waterbody intercepting groundwater flow was specified for each flow and transport simulation. The waterbody was constrained to lie across the contaminant plume centerline and its depth was varied uniformly throughout the aquifer thickness or throughout the upper 10 m of the aquifer thickness, whichever was less.

Downgradient distance to the surface waterbody was determined from an empirical distribution of distances measured for CCW landfills and surface impoundments (see Appendix C), which was randomly sampled to develop the distances used in EPACMTP to calculate groundwater concentrations at those distances in the Monte Carlo analysis.

3.4.4 Groundwater Model Outputs

The output of EPACMTP is a prediction of the contaminant concentration arriving at a downgradient groundwater receptor location (either a well or a surface water body). Because a finite-source scenario was used, the concentration is time-dependent. A maximum time-averaged concentration was calculated for each constituent across the exposure duration selected in each Monte Carlo iteration.

3.5 Surface Water Models

For the groundwater-to-surface-water pathway, chemical contaminants leach out of WMUs and into groundwater, and this contaminated groundwater then discharges into a surface waterbody through groundwater discharge. Once in the waterbody, the continued fate and transport of the contaminants is modeled with a surface water model, which uniformly mixes the contaminants in a single stream segment. Surface water flows in and out of the stream segment. Surface water flowing into the stream segment is assumed to have zero constituent concentration, and surface water flowing out has nonzero constituent concentrations due to the groundwater contamination. EPACMTP assumes a fully penetrating stream; therefore, the entire groundwater and contaminant flux is passed to the surface water model. To ensure that an unrealistic flux of contaminated groundwater does not occur, the groundwater flow into the waterbody is compared to the stream flow. If the groundwater flux exceeds the stream flow, it is capped at the stream flow and the contaminant flux is reduced using the ratio of the stream flow to the incoming groundwater flow (i.e., all of the stream flow is assumed to be from groundwater discharge and the total concentration in the stream is equal to the groundwater concentration).

The waterbody considered in the CCW risk assessment is a river, stream, or lake located downgradient of the WMU. As described in Appendix C, the flow characteristics and dimensions for this waterbody are determined by site-specific stream flow data, the width of the groundwater contaminant plume as it intersects the waterbody, and established relationships between flow and stream depth. The stream segment modeled in this assessment is assumed to be homogeneously mixed.

Simple equilibrium partitioning models were used to estimate contaminant concentrations in the water column, suspended and bed sediments (see Section 3.5.1), and aquatic organisms (see Section 3.5.2). Special modeling provisions for aluminum are described in Section 3.5.3.

3.5.1 Equilibrium Partitioning Model

The primary surface water model used to estimate groundwater impacts on waterbodies is a simple steady-state equilibrium-partitioning model adapted from models in EPA's Indirect Exposure Methodology (IEM; U.S. EPA, 1998c) and Human Health Risk Assessment Protocol (HHRAP; U.S. EPA, 1998d). This model is based on the concept that dissolved and sorbed concentrations can be related through equilibrium partitioning coefficients. This model was used for all constituents except aluminum, which was modeled based on a solubility approach (see Section 3.5.3). Although these models have not been specifically peer reviewed in this application, they have been subject to the Agency's peer review process as part of the development of the IEM and HHRAP.

The model partitions the total mass of chemical contaminant in the waterbody into four compartments:

- Constituents dissolved in the water column
- Constituents sorbed onto suspended solids
- Constituents sorbed onto sediment particles at the bottom of the waterbody
- Constituents dissolved in porewater in the sediment layer.

Table 3-4 provides the partitioning coefficients used by the surface water model to estimate contaminant partitioning between water and suspended solids in the water column and between sediment and porewater in the sediment layer. These distributions were derived from published empirical data as described in U.S. EPA (1999b).

Table 3-4. Sediment/Water Partition Coefficients: Empirical Distributions[a]

Chemical	Distribution Type	Minimum	Mean	Maximum	SD
Aluminum	not used				
Antimony	log normal	0.6	3.6	4.8	1.8
Arsenic	log normal	1.6	2.4	4.3	0.7
Barium	log normal	0.9	2.5	3.2	0.8
Boron	log normal	-0.5	0.8	1.4	0.5
Cadmium	log normal	0.5	3.3	7.3	1.8
Cobalt	log normal	2.2	3.9	5.3	0.8
Lead	log normal	2.0	4.6	7.0	1.9
Molybdenum	log normal	1.3	2.2	3.2	0.9
Selenium IV	log normal	1.0	3.6	4.0	1.2
Selenium VI	log normal	-1.4	0.6	3.0	1.2
Thallium	log normal	-0.5	1.3	3.5	1.1
Total Nitrate Nitrogen	constant	0	0	0	0

Source: U.S. EPA (1999b).
SD = standard deviation.
[a] All values are log values.

Following calculation of the constituent loading and loss rates, the surface water model estimates steady-state, equilibrium waterbody contaminant concentrations in each compartment using equations presented in Attachment E-1 to Appendix E. For evaluating risks to human health from fish consumption, the model calculates waterbody concentrations using groundwater loadings that are explicitly averaged over the exposure period for the each human receptor (i.e., adult and child fishers). These average waterbody concentrations are then used to calculate fish concentrations as described in Section 3.5.2. Ecological risks were based on waterbody concentrations calculated using the peak annual groundwater loading value from EPACMTP.

The equilibrium–partitioning model, as implemented, is conservative because there are no loss mechanisms (e.g., burial) for any of the constituents.

3.5.2 Aquatic Food Web Model

An aquatic food web model was used to estimate the concentration of CCW constituents that accumulate in fish. This risk assessment assumes that fish are a food source for a recreational fisher. Trophic level three (TL3) and four (TL4) fish[6] were considered in this analysis because most of the fish that humans eat are T4 fish (e.g., salmon, trout, walleye, bass) and medium to large T3 fish (e.g., carp, smelt, perch, catfish, sucker, bullhead, sauger). The aquatic food web model has been peer reviewed as part of the 3MRA model development effort (see http://www.epa.gov/ epaoswer/hazwaste/id/hwirwste/peer03/aquatic/aqtfooda.pdf).

The aquatic food web model calculates the concentration in fish from the concentration calculated for the waterbody downgradient from the CCW disposal site. The contaminants in the water column consist of dissolved constituents and constituents sorbed to suspended solids. For all constituents, the contaminant concentrations in fish were calculated from the total waterbody concentration (i.e., dissolved plus sorbed to suspended solids) using bioconcentration factors (BCFs), which are presented in Table 3-5. The equations used to model fish tissue concentrations are provided in Attachment E-2 to Appendix E.

Table 3-5. Bioconcentration Factors for Fish

CAS	Chemical	T3 Value	T4 Value	Units	Reference
7429-90-5	Aluminum	ND	ND	L/kg	
7440-36-0	Antimony	0	0	L/kg	Barrows et al. (1980)
22569-72-8	Arsenic (III)	4.0E+00	4.0E+00	L/kg	Barrows et al. (1980)
15584-04-0	Arsenic (V)	4.0E+00	4.0E+00	L/kg	Barrows et al. (1980)
7440-39-3	Barium	ND	ND	L/kg	
7440-42-8	Boron	ND	ND	L/kg	
7440-43-9	Cadmium	2.7E+02	2.7E+02	L/kg	Kumada et al. (1972)
7440-48-4	Cobalt	ND	ND	L/kg	
7439-92-1	Lead	4.6E+01	4.6E+01	L/kg	Stephan (1993)
7439-98-7	Molybdenum	4.0E+00	4.0E+00	L/kg	Eisler (1989)
10026-03-6	Selenium (IV)	4.9E+02	1.7E+03	L/kg	Lemly (1985)
7782-49-2	Selenium (VI)	4.9E+02	1.7E+03	L/kg	Lemly (1985)
7440-28-0	Thallium	3.4E+01	1.3E+02	L/kg	T3: Barrows et al. (1980) T4: Stephan (1993)
14797-55-8	Total Nitrate Nitrogen	ND	ND	L/kg	

ND = No Data. Fish concentrations were not calculated for constituents with no BCF data.

[6] TL3 fish are those that consume invertebrates and plankton; TL4 fish are those that consume other fish.

3.5.3 Aluminum Precipitation Model

A simple precipitation model was used for aluminum in lieu of the equilibrium-partitioning model, because aluminum is generally solubility limited in natural waters. The MINTEQA2 model was used to estimate total soluble aluminum concentrations as a function of pH for a typical surface waterbody (Stumm and Morgan, 1996; Drever, 1988). By assuming the common aluminum silicate mineral gibbsite was the equilibrium solid phase, the computed values of total dissolved aluminum were interpreted as the maximum expected for each pH. If more aluminum were added to the system, it would be expected to precipitate as the mineral gibbsite for the system to maintain equilibrium. Table 3-6 shows the maximum dissolved aluminum concentrations as a function of waterbody pH.

The precipitation model initially calculates the aluminum concentration in the surface water column by assuming that all aluminum in the groundwater flux is dissolved. If this concentration exceeds the maximum soluble concentration based on pH, the dissolved concentration is capped and the excess aluminum is assumed to precipitate as the mineral gibbsite and settle to the benthic sediment layer. The equations used in this model are presented in Appendix E.

Table 3-6. Aluminum Solubility as a Function of Waterbody pH[a]

Minimum pH	Maximum pH	Solubility (mg/L)
3.5	4.5	26.2
4.5	5	1.84
5	5.5	0.196
5.5	6	0.0112
6	6.5	0.00143
6.5	7	0.000662
7	7.5	0.000915
7.5	8	0.00229
8	8.5	0.00682
8.5	9	0.0212
9	9.5	0.0666
9.5	10	0.211
10	10.5	0.668

[a] Computed using MINTEQA2

Only the water column concentration for aluminum was used in subsequent exposure and risk calculations, because there is no available ecological benchmark for aluminum in sediment. The water column concentration was used to calculate human exposure via drinking water ingestion, as well as risk to ecological receptors exposed via direct contact.

3.6 Human Exposure Assessment

The human exposure component of the full-scale analysis assessed the magnitude, frequency, duration, and route of exposure to CCW contaminants that an individual may experience. The term "exposure," as defined by the EPA exposure guidelines (U.S. EPA, 1992), as the condition that occurs when a contaminant comes into contact with the outer boundary of the body. The exposure of an individual to a contaminant completes an exposure pathway (i.e., the course a constituent takes from the WMU to an exposed individual). Once the body is exposed, the constituent can cross the outer boundary and enter the body. The amount of contaminant that crosses and is available for adsorption at internal exchange boundaries is referred to as the "dose" (U.S. EPA, 1992).

This risk assessment evaluated the risk from CCW contaminants to receptors in the vicinity of a WMU. The individuals evaluated were those residents closest to the WMU. The distances from the WMU to the residents were taken from a distribution of distances to the nearest residential drinking water well measured for municipal landfills and, for the recreational fisher, a distribution of the distance of the nearest surface water body from CCW landfills and surface impoundments (see Appendix C).

Section 3.6.1 presents an overview of the receptors and selected exposure pathways considered for this assessment, including a discussion of how childhood exposure is considered in the analysis. Section 3.6.2 presents exposure factors (i.e., values needed to calculate human exposure) used in the analysis. Section 3.6.3 describes the methods used to estimate dose, including average daily dose (ADD) and lifetime average daily dose (LADD).

3.6.1 Receptors and Exposure Pathways

Human receptors may come into contact with constituents present in environmental media through a variety of pathways. The exposure pathways considered in the full-scale analysis were ingestion of drinking water from contaminated groundwater sources and ingestion of fish from surface water contaminated by groundwater.

- **Ingestion of Drinking Water.** Groundwater from an offsite well was assumed to be used for drinking water for residents (adult and child).

- **Ingestion of Fish.** Fish are exposed to constituents via uptake of contaminants from surface water. Adult recreational fishers and their children were assumed to consume fish caught in local waterbodies. Although conservative, EPA considers this assumption to be reasonable and protective for fishers relying on locally caught fish as a food source.

Table 3-7 lists each human receptor type considered in this analysis along with the specific exposure pathways that apply to that receptor. Both adult and child residents are exposed by drinking groundwater, and adult fishers and their children are exposed by eating fish caught in streams and lakes impacted by CCW.

Table 3-7. Receptors and Exposure Pathways

Receptor	Ingestion of Drinking Water	Ingestion of Fish
Adult resident	✓	
Child resident	✓	
Adult recreational fisher		✓
Child of recreational fisher		✓

Childhood Exposure

Children are an important subpopulation to consider in a risk assessment because they may be more sensitive to exposures than adults. Compared with adults, children may eat more food and drink more fluids per unit of body weight. This higher intake-rate-to-body-weight ratio can result in a higher ADD for children than adults.

As children mature, their physical characteristics and behavior patterns change. To capture these changes in the analysis, the life of a child was considered in stages represented by the following cohorts: cohort 1 (ages 1 to 5), cohort 2 (ages 6 to 11), cohort 3 (ages 12 to 19), and cohort 4 (ages 20 to 70). Associated with each cohort are distributions of exposure parameters that reflect the physical characteristics and behavior patterns of that age range. These exposure parameters are required to calculate exposure to an individual. The distributions for the 20- to 70-year-old cohort were the same as those used for adult receptors.

To capture the higher intake-rate-to-body-weight ratio of children, a start age of 1 year was selected for the child receptors. The exposure duration distribution for cohort 1 (a 1- to 5-year-old) was used to define exposure duration for the child receptors for each of the 10,000 iterations in the probabilistic analysis. For each individual iteration, the child receptor is aged through the age cohorts as appropriate until the age corresponding to the selected exposure duration is reached (e.g., if an exposure duration of 25 years was selected for an iteration, the child was aged from 1 year to 25 years, spending 5 years in cohort 1, 6 years in cohort 2, 8 years in cohort 3, and 6 years in cohort 4, for a total of 25 years).

3.6.2 Exposure Factors

The exposure factors used are listed in Table 3-8, along with their data sources and variable type (i.e., whether they were represented as a distribution or a fixed value in the Monte Carlo analysis). These exposure factors were used to calculate the dose of a chemical based on contact with contaminated media or food, the duration of that contact, and the body weight of the exposed individuals.

Table 3-8. Human Exposure Factor Input Parameters and Data Sources

Parameter	Variable Type	Data Source
Body weight (adult, child)	Distribution	U.S. EPA (1997c)
Ingestion rate: fish (adult, child)	Distribution	U.S. EPA (1997d)
Ingestion rate: drinking water (adult, child)	Distribution	U.S. EPA (1997c)
Exposure duration (adult, child)	Distribution	U.S. EPA (1997e)
Exposure frequency (adult, child)	Fixed (constant)	U.S. EPA policy
Fraction contaminated: drinking water	Fixed (constant)	U.S. EPA policy
Fraction contaminated: fish	Fixed (constant)	U.S. EPA policy
Fraction of TL3 fish consumed	Fixed (constant)	U.S. EPA (1997d)
Fraction of TL4 fish consumed	Fixed (constant)	U.S. EPA (1997d)
Human lifetime (used in carcinogenic risk calculation)	Fixed (constant)	U.S. EPA policy

The primary data source of human exposure model inputs used in this risk assessment was EPA's *Exposure Factors Handbook* (EFH; U.S. EPA, 1997c-e). The EFH summarizes data on human behaviors and characteristics related to human exposure from relevant key studies and provides recommendations and associated confidence estimates on the values of exposure factors. These data were carefully reviewed and evaluated for quality before being included in the EFH. EPA's evaluation criteria included peer review, reproducibility, pertinence to the United States, currency, adequacy of the data collection period, validity of the approach, representativeness of the population, characterization of variability, lack of bias in study design, and measurement error (U.S. EPA, 1997c-e). For exposure factors that were varied in the Monte Carlo analysis, probability distribution functions were developed from the values in the EFH.

The data sources and assumptions for intake and other human exposure factors used in this analysis are described below. Appendix F presents the exposure factors used and describes the rationale and data used to select the form of the distributions (e.g., normal, lognormal, gamma, Weibull) for those exposure factors that were varied in the probabilistic analysis.

- **Body Weight.** Distributions of body weight were developed for adult and child receptors based on data from the EFH.

- **Fish Ingestion Rate.** Fish ingestion rates were based on a recreational angler who catches and eats some fish from a waterbody impacted by contaminants released from CCW WMUs. Distributions of fish intake rates were developed for adult fishers based on data from the EFH. Because the EFH does not have fish ingestion rates for children, adult ingestion rates were used (as a conservative assumption).

- **Drinking Water Ingestion Rate.** Distributions of drinking water intake rates were developed for the adult and child resident based on data from the EFH.

- **Exposure Duration.** Exposure duration refers to the amount of time that a receptor is exposed to a contaminant source. Exposure duration was assumed to correspond with the receptor's residence time in the same house. Exposure durations were determined using data on residential occupancy from the EFH. The data used to develop

parameter information for resident receptors were age-specific. Thus, separate exposure duration distributions were developed for adult and child residents.

- **Exposure Frequency.** Exposure frequency is the frequency with which the receptor is exposed to the contaminated source during the exposure duration. Exposure frequency is not expected to vary much, so distributions were not developed for exposure frequency. All receptors were assumed to be exposed to the contaminant source 350 days/year. This value is based on the conservative assumption that individuals are away from their homes (e.g., on vacation) approximately 2 weeks out of the year, but are otherwise exposed daily.

- **Lifetime and Averaging Time.** Averaging time is the period of time over which a receptor's dose is averaged. To evaluate carcinogens, total dose was averaged over the lifetime of the individual, assumed to be 70 years. To evaluate noncarcinogens, dose was averaged over the last year of exposure because noncancer effects may become evident during less-than-lifetime exposure durations if toxic thresholds are exceeded. Essentially, this amounts to setting exposure duration and averaging time equal so that they cancel each other out in the equation for ADD. Thus, neither exposure duration nor averaging time is included in the ADD equation.

3.6.3 Dose Estimates

An exposure assessment estimates the dose to each receptor from the contaminant concentration in the exposure medium (e.g., drinking water, fish) and the intake rate for that medium (e.g., ingestion rate of drinking water, ingestion rate of fish). For this assessment, exposure estimates were based on the *potential* dose (e.g., the dose ingested) rather than the applied dose (e.g., the dose delivered to the gastrointestinal tract) or the internal dose (e.g., the dose delivered to the target organ). Doses from groundwater or fish ingestion were calculated by multiplying the contaminant concentration in groundwater or fish by the respective intake rate on a per kilogram body weight basis. Doses were then summed over the exposure duration, resulting in an ADD received from ingestion exposure. The ADD was used to assess noncancer risk from ingestion exposures and is defined as

$$ADD = C \times IR \tag{3-2}$$

where

C = average concentration (mass/volume or mass/mass)
IR = intake rate (mass/body weight mass/time, or volume/body weight mass/time).

Contaminant concentration represents the concentration of a chemical in a medium that contacts the body. The ADD was calculated from concentrations averaged over the exposure duration for each receptor.

For cancer effects, where the biological response is described in terms of lifetime probabilities even though exposure may not occur over the entire lifetime, dose is presented as a

LADD. The LADD was used to assess cancer risks from each exposure route (i.e., ingestion) and is defined as

$$LADD = \frac{C \times IR \times ED \times EF}{AT \times 365} \quad (3\text{-}3)$$

where

C = average concentration (mass/mass or mass/volume)
IR = intake rate (mass/body weight mass/time, or volume/body weight mass/time)
ED = exposure duration (yr)
EF = exposure frequency (d/yr)
AT = averaging time (yr)
365 = units conversion factor (d/yr).

As with the ADD, contaminant concentration represents the concentration of a chemical in a medium that contacts the body. Intake rate depends on the route of exposure; for example, it might be an inhalation rate or an ingestion rate. Exposure frequency is the number of days per year the receptor is exposed to the contaminated source during the exposure duration.

For cancer effects, biological responses are described in terms of lifetime probabilities, even though exposure may not be lifelong; consequently, the exposure duration (the length of time of contact with a contaminant) was used to average the ADD over a lifetime (70 years). The media concentrations used were averaged over the duration of exposure.

3.7 Toxicity Assessment

A chemical's ability to cause an adverse human health effect depends on the toxicity of the chemical, the chemical's route of exposure to an individual (ingestion, inhalation, or direct contact), the duration of exposure, and the dose received (the amount that a human ingests or inhales). Similar principles apply to ecological receptors, although exposure duration is much shorter than for human receptors because humans generally live longer then ecological receptors. For a risk assessment, the toxicity of a constituent is defined by a human health or ecological benchmark for each route of exposure. A benchmark is a quantitative value used to predict a chemical's possible toxicity and ability to induce an adverse effect at certain levels of exposure. Because different chemicals cause different health effects at different doses, benchmarks are chemical-specific.

Appropriate human health and ecological benchmarks for the constituents of potential concern in CCW wastes were collected as part of the screening assessment. The same benchmarks were used in the full-scale risk assessment, with a few updates. The data sources and collection methodology for these benchmarks are described briefly in Sections 3.7.1 (human health benchmarks) and 3.7.2 (ecological benchmarks), and in more detail in Appendix G (human health benchmarks) and Appendix H (ecological benchmarks). The discussion here is limited to the 12 constituents assessed in the full-scale risk assessment and for humans, covers

only oral benchmarks (because all inhalation pathway risks fell below the screening criteria in the screening assessment). Appendices G and H cover all constituents and routes.

3.7.1 Human Health Benchmarks

Human health benchmarks for chronic oral exposures were needed for the full-scale analysis. These health benchmarks were derived from toxicity data based on animal studies or human epidemiological studies. Each benchmark represents a dose-response estimate that relates the likelihood and severity of adverse health effects to exposure and dose. This section presents the noncancer and cancer benchmarks used to evaluate human health effects that may result from exposure to the constituents modeled.

Chronic human health benchmarks were used to evaluate potential noncancer and cancer risks. These include reference doses (RfDs) to evaluate noncancer risk from oral exposures and oral cancer slope factors (CSFs) to evaluate cancer risk from oral exposures. The benchmarks are chemical-specific and do not vary between age groups.

- The **RfD** is an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily exposure to the human population (including sensitive subgroups) that is likely to be without appreciable risk of deleterious noncancer effects during a lifetime. The RfD provides a reference point to gauge the potential effects (U.S. EPA, 2002c). At exposures increasingly greater than the RfD, the potential for adverse health effects increases. Lifetime exposure above the RfD does not imply that an adverse health effect would necessarily occur.

- The **CSF** is an upper-bound estimate (approximating a 95 percent confidence limit) of the increased human cancer risk from a lifetime exposure to an agent. This estimate is usually expressed in units of proportion (of a population) affected per milligram of agent per kilogram body weight per day (mg/kg-d). Unlike RfDs, CSFs do not represent "safe" exposure levels; rather, they relate levels of exposure with a probability of effect or risk.

Human health benchmarks are available from several sources. Health benchmarks developed by EPA were used whenever they were available. Sources of human health benchmarks were used in the following order of preference:

- Integrated Risk Information System (IRIS) (U.S. EPA, 2002c)
- Superfund Technical Support Center Provisional Benchmarks
- Health Effects Assessment Summary Tables (HEAST) (U.S. EPA, 1997f)
- Various other EPA health benchmark sources
- ATSDR minimal risk levels (MRLs) (ATSDR, 2002).

These sources are described in more detail in Appendix G.

The chronic human health benchmarks used in the full-scale analysis are summarized in Table 3-9. For most constituents, human health benchmarks were available from IRIS. Benchmarks for a few constituents were obtained from ATSDR and Superfund Provisional

Benchmarks U.S. EPA (2001c,d). For chemicals for which purely health-based benchmarks were not available (lead), a drinking water action level was used (U.S. EPA, 2002d).

Cadmium has two RfDs, one for exposures via water and one for exposures via food. The RfD for water was used for drinking water ingestion and the RfD for food was used for fish consumption.

Table 3-9. Human Health Benchmarks Used in the Full-Scale Analysis

Constituent	Type of Benchmark	Value	Units	Source[a]
Cancer Benchmark				
Arsenic	CSF	1.5E+00	$(mg/kg-d)^{-1}$	IRIS
Noncancer Benchmarks				
Aluminum	RfD	2.0E+00	mg/kg-d	ATSDR
Antimony	RfD	4.0E-04	mg/kg-d	IRIS
Barium	RfD	2.0E-01	mg/kg-d	IRIS
Boron	RfD	2.0E-01	mg/kg-d	IRIS
Cadmium	RfD (water)[b]	5.0E-04	mg/kg-d	IRIS
	RfD (food)[c]	1.0E-03	mg/kg-d	IRIS
Cobalt	RfD	2.0E-02	mg/kg-d	Superfund
Lead	MCL	0.015	mg/L	DWAL
Molybdenum	RfD	5.0E-03	mg/kg-d	IRIS
Nitrate/Nitrite	MCL[d]	10	mg/L	DWAL
Selenium	RfD	5.0E-03	mg/kg-d	IRIS
Thallium	RfD	8.0E-05	mg/kg-d	IRIS

[a] References:
ATSDR: Minimal Risk Levels, ATSDR (2002)
DWAL: Drinking Water Action Level, U.S. EPA (2002d)
Superfund: Superfund Risk Issue Paper, U.S. EPA (2001c,d)
IRIS: U.S. EPA (2002c)
HEAST: U.S. EPA (1997f)

[b] Used for drinking water ingestion.

[c] Used for fish ingestion.

[d] For nitrate.

3.7.2 Ecological Benchmarks

The ecological risk assessment addresses two routes of exposure for ecological receptors, direct contact with contaminated media and ingestion of contaminated food items. For each constituent for which ecological effect data were available, HQs were calculated using chemical-specific media concentrations assumed to be protective of ecological receptors of concern. To calculate ecological HQs, these media concentrations (also known as chemical stressor concentration limits [CSCLs]) were divided by the estimated media concentrations. The CSCLs are media-specific environmental quality criteria intended to represent a protective threshold value for adverse effects to various ecological receptors in aquatic ecosystems (surface water and sediment). The CSCLs were developed to be protective of the assessment endpoints chosen for this assessment. An HQ greater than 1 indicates that the predicted concentration exceeds the CSCL, and therefore, the potential for adverse ecological effects exists. In this regard, the use of

CSCLs to calculate an ecological HQ is analogous to the use of the reference concentration (RfC) for human health where the air concentration is compared to the health-based concentration (the RfC), and an HQ greater than 1 is considered to indicate the potential for adverse health effects.

Table 3-10 shows the receptor types assessed for each exposure route (direct contact and ingestion) in each environmental medium addressed by the CCW risk assessment.

Table 3-10. Ecological Receptors Assessed by Exposure Route and Medium (Surface Water or Sediment)

Receptor Type	Surface Water (water column)	Surface Water Sediment
Direct Contact Exposure		
Aquatic Community	✔	
Sediment Community		✔
Amphibians	✔	
Aquatic Plants and Algae	✔	
Terrestrial Plants		
Ingestion Exposure		
Mammals	✔	
Birds	✔	

Ecological receptors that live in close contact with contaminated media are considered to be potentially at risk. These receptors are exposed through direct contact with contaminants in surface water and sediment. The benchmarks for receptor communities (aquatic or sediment communities) are not truly *community-level* concentration limits in that they do not consider predator-prey interactions. Rather, they are based on the theory that protection of 95 percent of the species in the community will provide a sufficient level of protection for the community (see, for example, Stephan et al., 1985, for additional detail). Appendix H summarizes the benchmark derivation methods for each receptor assessed for the direct contact route of exposure.

The ingestion route of exposure addresses the exposure of terrestrial mammals and birds through ingestion of aquatic plants and prey. Thus, the benchmarks for ingestion exposure represent media concentrations that, based on certain assumptions about receptor diet and foraging behavior, are expected to be protective of populations of mammals and birds feeding and foraging in contaminated areas.

For birds and mammals, the derivation of ingestion benchmarks required the selection of appropriate ecotoxicological data based on a hierarchy of sources. The assessment endpoint chosen for birds and mammals was population viability and therefore, the ingestion benchmarks were based on study data for physiological effects that are relevant to populations. These data included measures of reproductive fitness, developmental success, survival, and other toxicological effects that could have a significant impact on the population rather than just the health of an individual animal. Choosing these measures of effect provided the basis to evaluate

the potential for adverse effects at the population level by inference; this analysis does not evaluate the effects on population dynamics in the sense that a reduction in the population is predicted over time in response to exposure to constituents released from CCW. Population-level modeling was well beyond the scope of this risk assessment.

Once an appropriate ingestion exposure study was identified, a benchmark was calculated. Appendix H describes the basic technical approach used to convert avian or mammalian benchmarks (in daily doses) to the CSCLs (in units of concentration) used to assess ecological risks for contaminated surface water and sediment. The methods reflect exposure through the ingestion of contaminated plants, prey, and various media, and include parameters on accumulation (e.g., BCFs), uptake (e.g., consumption rates), and dietary preferences.

Where multiple ecological benchmarks were available for a pathway of interest, the benchmark that produced the lowest (most sensitive) CSCL for each chemical in each medium was used. For example, several types of receptors (the aquatic community, amphibians, aquatic plants, mammals, birds) can be exposed to contaminants in surface water. The surface water criterion for a given constituent represents the lowest CSCL for these receptors, and thus gives the highest (most protective) HQ. The CSCLs used to assess ecological endpoints in the full-scale analysis and the associated receptor are summarized in Table 3-11. Additional details on the CCW ecological benchmarks and CSCLs and their development can be found in Appendix H.

Table 3-11. Ecological Risk Criteria Used in the Full-Scale Analysis

Constituent	Medium[a]	Exposure Route	CSCL	Units	Receptor
Aluminum	Surface Water	Direct contact	0.09	mg/L	Aquatic biota
Arsenic total	Sediment	Ingestion	0.51	mg/kg	Spotted sandpiper
Arsenic III	Surface Water	Direct contact	0.15	mg/L	Aquatic biota
Arsenic IV	Surface Water	Direct contact	8.10E-03	mg/L	Aquatic biota
Barium	Sediment	Ingestion	190	mg/kg	Spotted sandpiper
	Surface Water	Direct contact	4.00E-03	mg/L	Aquatic biota
Boron	Surface Water	Direct contact	1.60E-03	mg/L	Aquatic biota
Cadmium	Sediment	Direct contact	0.68	mg/kg	Sediment biota
	Surface Water	Direct contact	2.50E-03	mg/L	Aquatic biota
Cobalt	Surface Water	Direct contact	0.02	mg/L	Aquatic biota
Lead	Sediment	Ingestion	0.22	mg/kg	Spotted sandpiper
	Surface Water[b]	Ingestion	3.00E-04	mg/L	River otter
Selenium total	Surface Water	Direct contact	5.00E-03	mg/L	Aquatic biota
Selenium IV	Surface Water	Direct contact	0.03	mg/L	Aquatic biota
Selenium VI	Surface Water	Direct contact	9.5E-03	mg/L	Aquatic biota

Source: U.S. EPA (1998)

[a] If a medium (surface water or sediment) is not listed, there were insufficient data to develop a benchmark for it.

[b] Includes ingestion of fish.

Ecological benchmarks for both the screening and full-scale CCW risk assessment were taken directly from the 1998 fossil fuel combustion risk assessment, *Non-Groundwater*

Pathways, Human Health and Ecological Risk Analysis for Fossil Fuel Combustion Phase 2 (FFC2) (U.S. EPA, 1998a). The receptors and endpoints selected for the 1998 analysis were evaluated and considered appropriate for the goals of this risk assessment. The benchmarks were derived for each chemical and receptor to the extent that supporting data were available.

3.8 Risk Estimation

The final step of the risk assessment process is to estimate the risk posed to human and ecological receptors (e.g., residents, fishers; aquatic organisms). In this step, estimates of toxicity (the human health and ecological benchmarks) and exposure doses or exposure concentrations are integrated into quantitative expressions of risk. For the CCW constituents modeled in the full-scale assessment, the CCW human risk assessment uses estimates of dose and toxicity to calculate individual excess lifetime carcinogenic risk estimates and noncancer HQs (Section 3.8.1). The risk calculations for ecological receptors differ from those for humans because the ecological benchmarks are developed as media concentrations (i.e., they are calculated considering ecological exposure). Thus the CCW risk assessment uses estimates of exposure (media) concentrations and toxicity (media-specific concentration limits) to calculate an ecological HQ (Section 3.8.2).

3.8.1 Human Health Risk Estimation

The full-scale analysis focused on two human health exposure pathways: groundwater-to-drinking-water and groundwater-to-surface-water via fish consumption by recreational fishers. The cancer and noncancer health impacts of ingesting groundwater and fish contaminated by CCW leachate were estimated using the risk endpoints shown in Table 3-12. These endpoints were generated for each iteration of the Monte Carlo analysis. Only the cancer endpoint was used for arsenic, because it is the more sensitive endpoint compared to noncancer effects. For the other 11 constituents, only noncancer HQs were calculated, using the appropriate noncancer endpoint.

Table 3-12. Risk Endpoints Used for Human Health

Risk Category	Risk Endpoints	Definition
Cancer Effects (arsenic only)	Lifetime excess cancer risk by pathway and chemical	Lifetime excess cancer risk resulting from single pathway exposure
Noncancer Effects	Ingestion HQ by pathway and chemical	Ingestion HQ resulting from single pathway exposure
	Ingestion HQ based on drinking water action level for lead and copper	Lead and copper ingestion HQ resulting from drinking water pathway
	Average daily dose for fish consumption for lead	Lead exposure resulting from fish ingestion pathway

Cancer risks for arsenic were characterized using lifetime excess cancer risk estimates, which represent the excess probability of developing cancer over a lifetime as a result of exposure to the chemical of interest. Lifetime excess cancer risk estimates use the LADD (see Section 3.6.3) as the exposure metric. Lifetime excess cancer risk estimates are the product of

the LADD for a specific receptor and the corresponding cancer slope factor, as shown in Equation 3-4.

$$Lifetime\ excess\ cancer\ risk_i = LADD_i \times CSF \quad (3\text{-}4)$$

where

LADD = lifetime average daily dose for ingestion pathway i (mg/kg BW/d)
i = pathway index
CSF = cancer slope factor $(mg/kg\ BW/d)^{-1}$.

Noncancer risk is characterized through the use of HQs, which are generated by dividing an ADD (see Section 3.6.3) for ingestion pathways by the corresponding RfD.[7] An HQ establishes whether a particular individual has experienced exposure above a threshold for a specific health effect. Therefore, unlike cancer risk estimates, HQs are not probability statements. Rather, the RfD represents an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily oral exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. It can be derived from a no observed adverse effect level (NOAEL), from a low observed adverse effect level (LOAEL), or from a benchmark dose, with uncertainty factors generally applied to reflect limitations of the data used. Equation 3-5 shows the calculation for the ingestion HQ. This calculation was completed for each pathway considered (i.e., drinking water ingestion and fish consumption).

$$HQ_i = \frac{ADD_i}{RfD} \quad (3\text{-}5)$$

where

ADD_i = average daily dose for ingestion pathway i (mg/kg-d)
i = pathway index
RfD = reference dose (mg/kg-d).

The risk results address risk from exposure via the groundwater-to-drinking-water and groundwater-to-surface-water pathway separately. This is appropriate because the resident consuming contaminated groundwater may not be the recreational fisher who is consuming contaminated fish. Also, the arrival time of the contaminant plume to the stream and the human receptor may not be the same for a particular iteration.[8] However, a resident may consume fish caught from a nearby stream or lake and contaminated drinking water if the travel times are similar, so that possibility should be considered as an uncertainty in this analysis.

For each receptor type, lifetime excess cancer risk estimates for arsenic were calculated separately for the drinking water and fish consumption pathways.

[7] HQs calculated for lead in drinking water were based on the drinking water action level (0.015 mg/L); lead exposures from fish ingestion are reported as an ADD.

[8] Stream distance and well distance were sampled independently in the Monte Carlo analysis.

3.8.2 Ecological Risk Estimation

The full-scale analysis addressed two routes of exposure for ecological receptors: direct contact with contaminated media and ingestion of contaminated food items. HQs were calculated using chemical-specific media concentrations assumed to be protective of ecological receptors of concern through either exposure route (CSCLs). As described in Section 3.7.2, these ecological benchmarks were developed for representative organisms and communities in each environmental medium of concern.

For a particular Monte Carlo iteration, HQs were calculated for sediment and surface water as the ratio between the media concentration and the ecological benchmark. Because the CSCLs were derived for an HQ of 1 (for relevant ecological endpoints), the ratio of a constituent concentration in a media to the media-specific CSCL represents the HQ for that constituent and pathway. For surface water, the HQ was calculated as follows:

$$HQ_{surface\ water} = C_{sw} / CSCL_{sw} \quad (3\text{-}6)$$

where

C_{sw} = total concentration in surface water column (mg/L)
$CSCL_{sw}$ = ecological benchmark for surface water (mg/L).

Similarly, for sediment, the HQ was calculated as

$$HQ_{sediment} = C_{sediment} / CSCL_{sediment} \quad (3\text{-}7)$$

where

$C_{sediment}$ = total concentration in sediment (mg/kg)
$CSCL_{sediment}$ = ecological benchmark for sediment (mg/kg).

Because the sediment and surface water benchmarks were based on separate receptor communities, it is not appropriate to add HQs across pathways.

4.0 Risk Characterization

This section summarizes the results of the full-scale Monte Carlo analysis and characterizes those results in terms of significant uncertainties and the scenarios and factors that influence risks to human health and the environment. Results are presented by receptor, pathway, and WMU type.

An overview of the assessment on which these results are based (e.g., waste management scenarios, analysis framework) is provided in Section 2. Section 3 provides more details on analysis methodologies, parameter values, and assumptions. In this section, Section 4.1 presents results from the human health risk assessment and includes an analysis of how liner conditions influence results. Section 4.2 presents the results from the ecological risk assessment. Tables summarizing the human and ecological results are presented in each section. Section 4.3 describes the sensitivity analysis conducted for the CCW risk assessment, and Section 4.4 discusses how variability and uncertainty have been addressed, including a semi-quantitative review of the potential impact of some of the more significant uncertainties on results.

Probabilistic results are based on a Monte Carlo simulation in which many model input parameter values were varied over 10,000 iterations of the model per waste management scenario to yield a statistical distribution of exposures and risks. Per the *Guidance for Risk Characterization* developed by the EPA Science Policy Council in 1995 (http://www.epa.gov/OSA/spc/pdfs/rcguide.pdf), EPA defined the high end of the risk distribution at the 90th percentile risk or hazard estimate generated during the Monte Carlo simulation. Thus, the 90th percentile risk results are shown in this section as the high end estimate of the risk distribution generated during the Monte Carlo simulation of constituent release, fate and transport, and exposure associated with CCW disposal in landfills and surface impoundments. In addition, the 50th percentile results are presented as the central tendency estimate of that risk distribution.

For exposure scenarios describing the waste management unit type (e.g., lined landfill; unlined surface impoundment), location (e.g., meteorological region), receptor (e.g., child), and health endpoint (e.g., cancer), the 90th percentile risk represents the high-end estimate that is compared to the appropriate risk criteria (for cancer or noncancer) to help determine whether CCW disposal practices are protective of public health. The risk criteria used are defined in terms of estimated lifetime cancer risk and noncancer hazard attributable to CCW disposal. The risk criteria adopted for this assessment are

- For chemical constituents that cause cancer (carcinogens), the criterion is an estimated excess lifetime cancer risk for exposed individuals of 1 case in 100,000 (i.e., $1x10^{-5}$)
- For constituents that cause adverse, noncancer health effects (noncarcinogens), the criterion is a HQ of greater than 1, with the HQ being the ratio of the average daily

exposure level to a protective exposure level corresponding to the maximum level at which no appreciable effects are likely to occur.

In general, the full-scale analysis showed lower risks than the screening analysis, but still showed risks above risk criteria for certain CCW constituents, WMU types, pathways, and receptors at the 90th percentile. At the 50th percentile, risks are still above the risk criteria for both WMU types, but for fewer constituents and pathways. The results presented herein are subject to further interpretation, as EPA queries the CCW risk inputs and outputs to investigate how the results may be affected by (1) waste types and environmental and waste management conditions, (2) assumptions made about these conditions in designing the probabilistic analysis, and (3) the availability of facility data.

4.1 Human Health Risks

This section presents the 90th and 50th percentile risk results for the two human exposure pathways evaluated in the full-scale analysis: (1) groundwater-to-drinking-water and (2) groundwater-to-surface-water (fish consumption). Results are presented for the two WMU types addressed in the analysis: landfills and surface impoundments, and show the distribution of risks across all waste types by liner type (from the EPRI survey data). The human health risk criteria for the analysis were a 10^{-5} excess cancer risk for arsenic and an HQ greater than 1 for the other constituents, each of which exhibits noncarcinogenic effects.

4.1.1 Groundwater-to-Drinking-Water Pathway

Tables 4-1 and 4-2 present the 90th and 50th percentile risk results, respectively, for the groundwater-to-drinking water pathway for landfills and surface impoundments. Results are shown across all units combined (i.e., across all liner types), as well as for each of the three unit types modeled in the analysis (unlined, clay-lined, and composite-lined). Except for arsenic, the results presented are for a child resident, because those risks for noncarcinogens were consistently higher than the risks for the adult resident. For arsenic, a carcinogen, adult risks are presented because the longer exposure duration and higher intake rates cause risks to be slightly higher for adults than for children. Results for arsenic and selenium are based on the arsenic III and selenium VI species, which are more mobile in soil and groundwater (causing higher receptor well concentrations). Results for other arsenic and selenium species for comparison can be found in the model uncertainty discussion in Section 4.4.2.

Figures 4-1 and 4-2 show the 90th and 50th percentile risk results. For each constituent, the graphs plot the 90th percentile (Figure 4-1) or 50th percentile (Figure 4-2) HQ or cancer risk level against the risk criteria (10^{-5} cancer risk or an HQ greater than 1) by the liner types reported in the EPRI survey. As in the table, the constituents are shown in order from highest risk in the full-scale analysis to lowest; the risk criteria are shown by the solid vertical line. Composite liners are not plotted in these figures when risks are below the x-axis minimum.

Note that not all 12 chemicals modeled in the full-scale assessment are presented for each pathway/WMU scenario. Only the chemicals for which the risks in the screening assessment exceeded the screening criteria for the scenario and for which constituent data were adequate to model and assess risks were modeled in the full-scale assessment, and only those modeled

chemical/pathway/WMU scenarios are shown in the tables and figures. For example, antimony and thallium risks are not presented for surface impoundments because of a high proportion of nondetects in the surface impoundment data for these CCW constituents. Similarly, adequate cobalt data were available only for surface impoundments. Screening-level human health risks for barium were below the screening criteria; therefore, barium is shown only in the ecological risk tables and figures. The screening analysis results in Section 2.1 and Table 2-3 show which CCW constituents were modeled for each pathway/WMU scenario.

Table 4-1. Summary of 90th Percentile Full-Scale CCW Human Risk Results: Groundwater-to-Drinking-Water Pathway

Chemical[b]	90th Percentile HQ or Cancer Risk Value[a]			
	All Units Combined[c]	Unlined Units	Clay–Lined Units	Composite–Lined Units
Landfills				
Arsenic (cancer)	3E-04	5E-04	2E-04	0
Thallium	2	3	1	0
Antimony	0.7	1	0.6	0
Molybdenum	0.9	1	0.7	0
Lead (MCL)[d]	0.4	0.9	0.2	0
Cadmium	0.2	0.3	0.2	0
Boron	0.3	0.5	0.3	0
Selenium	0.2	0.4	0.2	0
Nitrate/Nitrite (MCL)[d]	0.1	0.2	0.07	3E-06
Surface Impoundments				
Arsenic (cancer)	6E-03	9E-03	3E-03	4E-07
Molybdenum	4	5	3	7E-03
Cobalt	4	5	0.9	0
Cadmium	4	5	1	2E-09
Lead (MCL)[d]	3	5	0.9	1E-20
Boron	3	3	2	4E-03
Selenium	1	1	0.8	1E-03
Nitrate/Nitrite (MCL)[d]	0.9	1	1	6E-04

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

[b] Note that not every chemical that was selected for full-scale modeling was modeled in every pathway/WMU scenario: only chemicals with adequate data and that were identified in the screening analysis as needing further assessment (see Section 2.1) were modeled for each scenario.

[c] Results across all unit types combined (unlined, clay-lined, and composite-lined).

[d] Values are ratios of exposure concentration to MCL.

Table 4-2. Summary of 50th Percentile Full-Scale CCW Human Risk Results: Groundwater-to-Drinking-Water Pathway

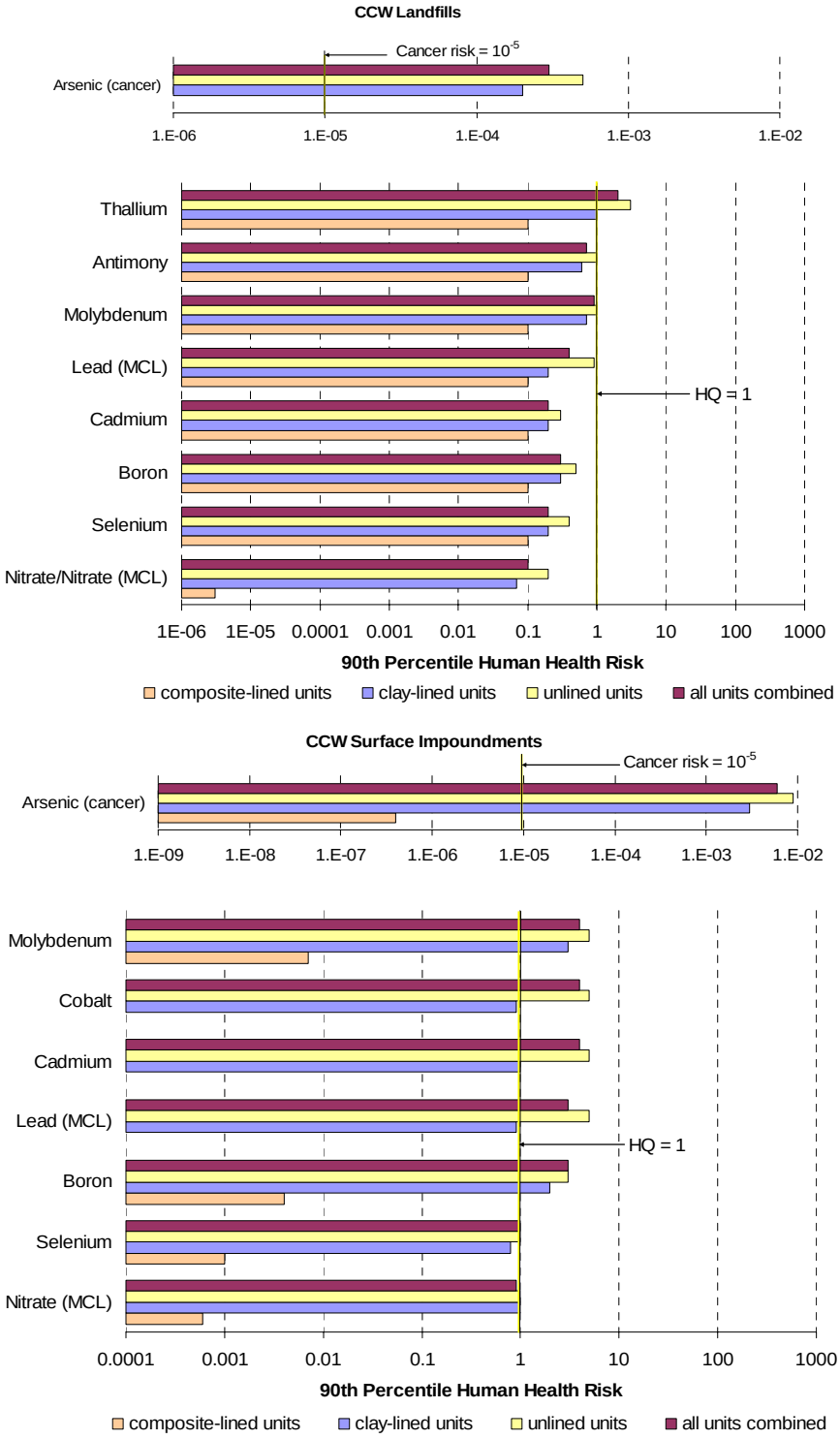
Chemical[b]	50th Percentile HQ or Cancer Risk Value[a]			
	All Units Combined[c]	Unlined Units	Clay–Lined Units	Composite–Lined Units
Landfills				
Arsenic (cancer)	3E-06	1E-05	5E-06	0
Thallium	0.07	0.2	0.09	0
Antimony	0.01	0.05	0.02	0
Molybdenum	0.01	0.03	0.02	0
Lead (MCL)[d]	2E-07	5E-03	6E-08	0
Cadmium	4E-03	0.01	6E-03	0
Boron	4E-03	0.01	7E-03	0
Selenium	6E-03	0.02	8E-03	0
Nitrate/Nitrite (MCL)[d]	4E-03	0.01	5E-03	0
Surface Impoundments				
Arsenic (cancer)	1E-04	3E-04	9E-05	0
Molybdenum	0.6	0.9	0.4	5E-12
Cobalt	9E-03	0.02	3E-03	0
Cadmium	0.06	0.08	0.03	0
Lead (MCL)[d]	0.05	0.09	9E-03	0
Boron	0.1	0.2	0.1	6E-12
Selenium	0.08	0.1	0.05	5E-12
Nitrate/Nitrite (MCL)[d]	0.03	0.04	0.02	7E-08

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

[b] Note that not every chemical that was selected for full-scale modeling was modeled in every pathway/WMU scenario: only chemicals with adequate data and that were identified in the screening analysis as needing further assessment (see Section 2.1) were modeled for each scenario.

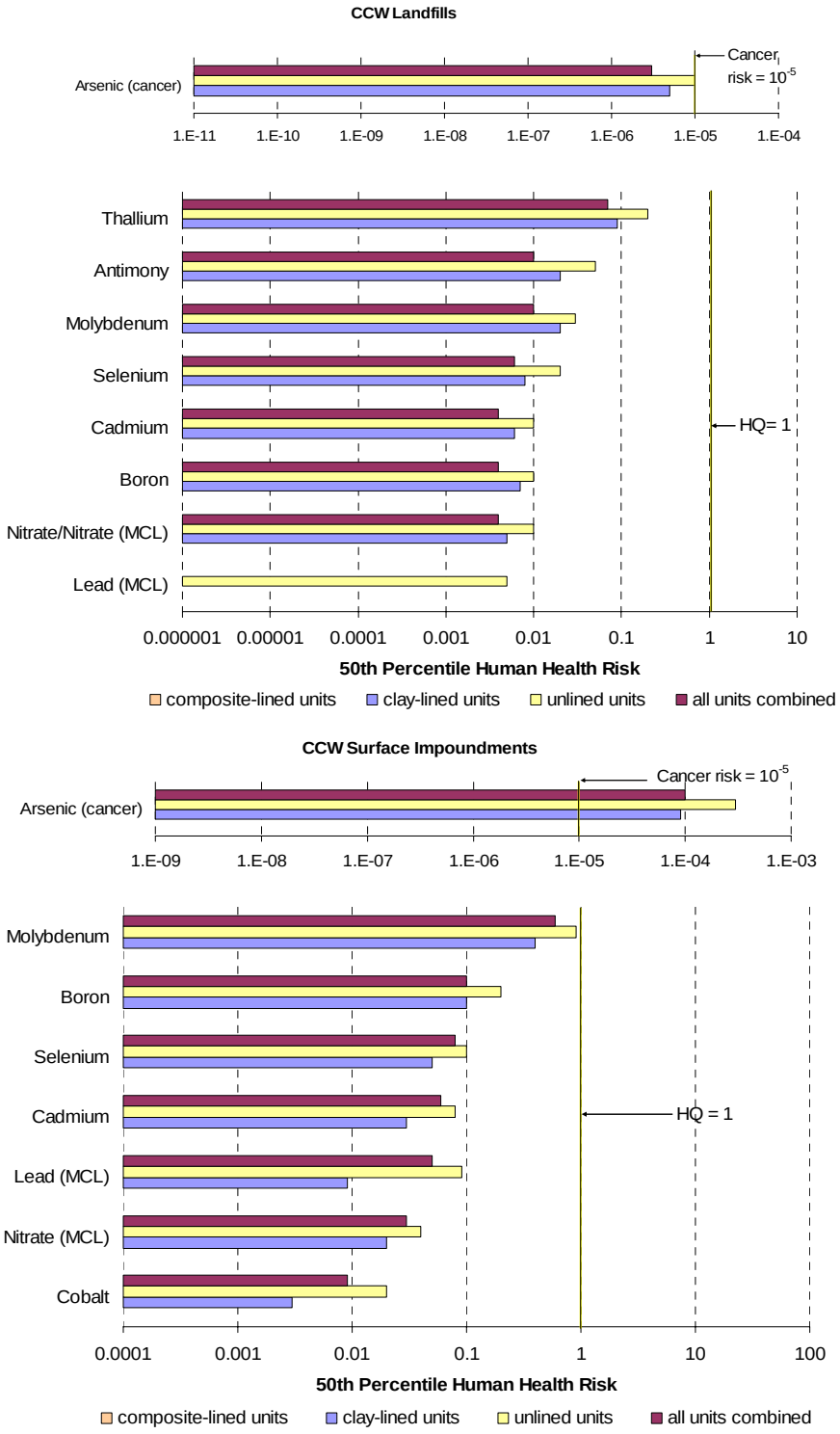
[c] Results across all unit types combined (unlined, clay-lined, and composite-lined).

[d] Values are ratios of exposure concentration to MCL.



A cancer risk of 10^{-5} or an HQ greater than 1 are the risk criteria for this analysis.
Results for "all units combined" are results across all liner types (unlined, clay-lined, composite-lined).
Note: When the composite liner bar does not appear on the chart, the 90th percentile risk index is below the minimum shown on the x-axis.

Figure 4-1. Full-scale 90th percentile risk results for the groundwater-to-drinking-water pathway.



A cancer risk of 10^{-5} or an HQ greater than 1 are the risk criteria for this analysis.
Results for "all units combined" are results across all liner types (unlined, clay-lined, composite-lined).
Note: When the composite liner bar does not appear on the chart, the 50th percentile risk index is below the minimum shown on the x-axis.

Figure 4-2. Full-scale 50th percentile risk results for the groundwater-to-drinking-water pathway.

As can be seen in Figure 4-1, the full-scale analysis produced lower risks for landfills than surface impoundments. For landfills, at the 90th percentile, arsenic shows risks above a cancer risk of $1x10^{-5}$ for both unlined units ($5x10^{-4}$) and clay-lined units ($2x10^{-4}$) and thallium shows a noncancer risk (3) above an HQ of 1 only for unlined units. Figure 4-2 shows that at the 50th percentile, all risks were at or below the risk criteria. Composite-lined units show zero or negligible risks (well below the risk criteria) for all constituents and percentiles examined.

For surface impoundments, the full-scale analysis produced arsenic risk estimates at the 90th percentile above a cancer risk of $1x10^{-5}$ for both unlined units ($9x10^{-3}$) and clay-lined units ($3x10^{-3}$) and a noncancer HQ above the criteria for boron (3), lead (5), cadmium (5), cobalt (5), and molybdenum (5) for unlined units, and for boron (2) and molybdenum (3) for clay-lined units. At the 50th percentile, only arsenic has risks above the 10^{-5} risk criterion for unlined ($3x10^{-4}$) and clay-lined ($9x10^{-5}$) surface impoundments. And as with landfills, the risks from composite-lined surface impoundments are well below the risk criteria.

The higher risks for surface impoundments as compared to landfills reflect higher constituent concentrations in the surface impoundment wastes, a higher proportion of unlined units (see Section 4.1.4), and a higher hydraulic head in an impoundment that drives leachate into the underlying soil with greater force than infiltration in landfills. This higher head results in a greater flux of contaminants to groundwater during the active life of the surface impoundment, especially in unlined units. In combination with the higher CCW constituent concentrations in surface impoundment porewater and a greater proportion of unlined units, these factors lead to more and higher risk exceedances for surface impoundments than for landfills.

The analysis demonstrates that the presence of liners, especially composite liners, reduce leaching and risks from CCW landfills and surface impoundments. Note that 90th percentile risks from composite liners are zero for most constituents for landfills, which means that in 90 percent of the cases, the contaminant did not reach the receptor well in the 10,000 year limit for this analysis. These zero values reflect the liner leakage rates in the empirical data set used to develop composite landfill liner infiltration rates used in this risk assessment (from U.S. EPA, 2002b; see Section 3.2.2), which are mostly zero values or very low in terms of infiltration rate. Although these infiltration rates are based on the best data available to EPA, these data are not specific to CCW facilities and therefore represent an uncertainty in this analysis (see Sections 3.2.2 and 4.4.3.2).

Composite liners also significantly reduced risks for surface impoundments for several constituents at the 90th percentile by 4 to 10 orders of magnitude and generated risk results well below the risk criteria for this analysis. Infiltration rates for composite-lined surface impoundments are largely controlled by leak density (see Section 3.3), which is an empirical distribution from the same source as the landfill infiltration rates (U.S. EPA, 2002b), and are subject to similar uncertainties.

Arrival times for the peak arsenic concentration used to calculate risks are plotted as cumulative distributions for surface impoundments and landfills in Figure 4-3. As can be seen in the figure, the peak arrival time for surface impoundments is usually less than 100 years (i.e., peak concentration occurs shortly after closure); the 50th percentile is 78 years, and the 75th

percentile is 105 years.[2] Arrival times for landfills are much longer, ranging from hundreds to thousands of years; the 50th percentile is 618 years and the 75th percentile is 3,343 years. The shorter arrival times for surface impoundments are primarily due to the hydraulic head of the waste liquids in the unit and the lower prevalence of liners in surface impoundments; by contrast, landfill leaching is driven by infiltration of precipitation through the cap and liner of the unit.

The arrival time of the peak concentration corresponds to the arrival of the maximum risk; however, for runs where the risk exceeds the risk criteria, the concentration that results in risk at the risk criteria will arrive somewhat before the peak concentration. Overall, however, the time to reach the risk criteria should be similar to the peak arrival times shown in Figure 4-3.

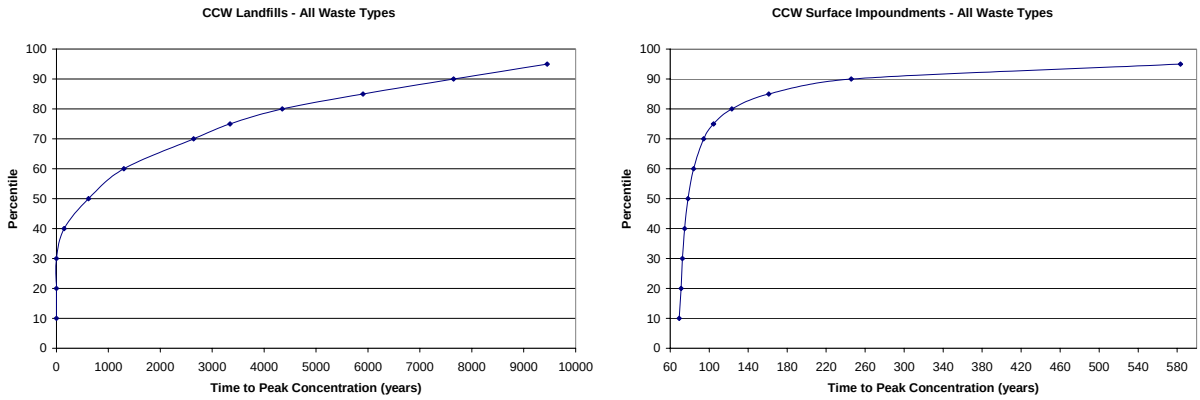


Figure 4-3. Comparison of peak arrival times for arsenic for CCW landfills and surface impoundments.

4.1.2 Groundwater-to-Surface-Water (Fish Consumption) Pathway

Tables 4-3 and 4-4 present the 90th and 50th percentile risk results, respectively, for the fish consumption pathway, where fish are contaminated by groundwater seeping into a waterbody downgradient from the WMU. The results presented are for a fisher's child because those risks were consistently higher than the risks for the adult fisher. Results for arsenic are based on arsenic III, which is more mobile in soil and groundwater (and so had higher receptor concentrations). The selenium results are based on selenium VI, which also represents the highest receptor concentrations. The uncertainty resulting from the model's inability to speciate metals during transport is discussed in Section 4.4.2.

For surface impoundments, 90th percentile selenium and arsenic risks for unlined units are slightly above a cancer risk of $1x10^{-5}$ ($2x10^{-5}$, arsenic) and slightly above a noncancer HQ of 1 (2 for selenium). Risks are below the risk criteria for clay-lined and composite-lined surface impoundments. Again, risks are higher for surface impoundments than for landfills (where risks are below risk criteria for all constituents) because of the higher waste concentrations, higher hydraulic head in these units, and a lower prevalence of liners, as discussed previously for the drinking water pathway. Fish consumption pathway 50th percentile results are well below the risk criteria for all constituents, waste management scenarios, and liner types.

[2] In other words, 50 percent of the arrival times are less than 78 years and 75 percent are less than 105 years.

As with the groundwater-to-drinking-water pathway analysis, the absence of risk from composite-lined units suggests that the composite liners modeled in this analysis are effective at preventing contaminants from reaching the surface waterbodies of interest.

Table 4-3. Summary of 90th Percentile Full-Scale CCW Human Risk Results: Groundwater-to-Surface-Water (Fish Consumption) Pathway

Chemical[b]	90th Percentile HQ or Cancer Risk Value[a]			
	All Units Combined [c]	Unlined Units	Clay-Lined Units	Composite–Lined Units
Landfills				
Arsenic (cancer)	6E-07	1E-06	3E-07	0
Selenium	0.3	0.7	0.1	0
Thallium	0.2	0.4	0.07	0
Cadmium	0.02	0.06	9E-03	0
Surface Impoundments				
Arsenic (cancer)	1E-05	2E-05	7E-06	6E-13
Selenium	2	2	1	2E-06
Cadmium	0.1	0.2	0.09	3E-15

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

[b] Note that not every chemical that was selected for full-scale modeling was modeled in every pathway/WMU scenario: only chemicals with adequate data and that were identified in the screening analysis as needing further assessment (see Section 2.1) were modeled for each scenario.

[c] Results across all unit types combined (unlined, clay-lined, and composite-lined).

Table 4-4. Summary of 50th Percentile Full-Scale CCW Human Risk Results: Groundwater-to-Surface-Water (Fish Consumption) Pathway

Chemical[b]	50th Percentile HQ or Cancer Risk Value[a]			
	All Units Combined[c]	Unlined Units	Clay–Lined Units	Composite–Lined Units
Landfills				
Arsenic (cancer)	6E-11	1E-09	3E-10	0
Selenium	5E-05	7E-04	2E-04	0
Thallium	3E-05	5E-04	2E-04	0
Cadmium	2E-06	5E-05	8E-06	0
Surface Impoundments				
Arsenic (cancer)	2E-08	5E-08	3E-09	0
Selenium	3E-03	7E-03	4E-04	0
Cadmium	3E-04	9E-04	3E-05	0

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

[b] Note that not every chemical that was selected for full-scale modeling was modeled in every pathway/WMU scenario: only chemicals with adequate data and that were identified in the screening analysis as needing further assessment (see Section 2.1) were modeled for each scenario.

[c] Results across all unit types combined (unlined, clay-lined, and composite-lined).

4.1.3 Results by Waste Type/WMU Scenario

As described in Section 3.1, the CCW risk assessment was organized by waste type so that different waste chemistries could be accounted for in the fate and transport modeling. The results discussed so far in this report address conventional CCW (fly ash, bottom ash, boiler slag, FGD sludge) and conventional CCW codisposed with coal refuse.[3] Section 4.1.3.1 presents these results by waste type. FBC wastes were also modeled in this assessment, but because of the small number of FBC waste disposal sites (7) in the EPRI/EPA database, the results are treated separately in Section 4.1.3.2.

4.1.3.1 Conventional CCW and CCW Codisposed with Coal Refuse

Tables 4-5 and 4-6 show 90th- and 50th-percentile risk results, respectively, by waste type and unit type for CCW landfills for the groundwater-to-drinking-water pathway. There was little difference in results between waste types for landfills, which showed very similar risks for conventional CCW and codisposed CCW and coal refuse. Risks are a factor of 2 or 3 greater for unlined landfills than for clay-lined landfills. For conventional CCW in landfills, arsenic cancer risks are $4x10^{-4}$ for unlined units, $2x10^{-4}$ for clay-lined units, and 0 for composite-lined units at

[3] Coal refuse is the waste coal produced from coal handling, crushing, and sizing operations, and tends to have a high sulfur content and low pH. In the CCW constituent database, codisposed coal refuse includes "combined ash and coal gob," "combined ash and coal refuse," and "combined bottom ash and pyrites."

the 90th percentile. Noncancer risks at the 90th percentile exceeded 1 for only thallium in unlined units (3) and clay-lined units (2) and antimony in unlined units (2). For codisposed CCW and coal refuse in landfills, arsenic cancer risks are $5x10^{-4}$ for unlined units, $2x10^{-4}$ for clay-lined units, and 0 for composite-lined units at the 90th percentile. Noncancer hazard quotients at the 90th percentile exceeded 1 for only thallium in unlined units (2) and molybdenum in unlined units (2). 50th percentile risks for the groundwater-to-drinking-water pathway were below the risk criteria for all waste types in all types of landfills. Landfills with composite liners show zero risks as modeled in this assessment (see Section 4.1.4 for a further discussion of risks by liner type).

The difference in risks between waste types is greater for surface impoundments. Tables 4-7 and 4-8 show 90th and 50th percentile risk results, respectively, by waste type and liner type for CCW surface impoundments (for the drinking water pathway). For conventional CCW in surface impoundments, arsenic cancer risks are $2x10^{-3}$ for unlined units, $9x10^{-4}$ for clay-lined units, and below the risk criteria for composite-lined units at the 90th percentile. Noncancer hazard quotients at the 90th percentile exceeded 1 for nitrate/nitrite (20), molybdenum (8), boron (7), selenium (2), and lead (3) in unlined units, and nitrate/nitrite (10), molybdenum (5) and boron (4) in clay-lined units. None of the risk criteria were exceeded at the 90th percentile in composite-lined units. For codisposed CCW and coal refuse in surface impoundments, arsenic cancer risks are $2x10^{-2}$ for unlined units, $7x10^{-3}$ for clay-lined units, and below the risk criteria for composite-lined units at the 90th percentile. Noncancer hazard quotients at the 90th percentile exceeded 1 for cadmium (9), cobalt (8), lead (9), and molybdenum (3) in unlined units, and cadmium (3), cobalt (3), and molybdenum (2) in clay-lined units. None of the risk criteria were exceeded at the 90th percentile in composite-lined units. As noted above, codisposal of CCW and coal refuse in surface impoundments results in risks up to 10-fold greater than those seen for conventional CCW managed in surface impoundments. This is likely due to the higher metal concentrations and the acidity of coal refuse leachate[4] for surface impoundments in the CCW database. As with landfills, clay-lined units show lower risks by a factor of 2 or 3 than unlined units, and composite liners show negligible or zero risks for either waste type.

[4] Metals tend to show greater solubility and mobility in acidic leachate.

Table 4-5. 90th Percentile Risk Results by CCW Type: Landfills, Groundwater-to-Drinking-Water Pathway

Chemical	90th Percentile HQ or Cancer Risk Value[a]			
	All Units Combined[b]	Unlined Units	Clay-Lined Units	Composite-Lined Units
Conventional CCW – 79 landfills				
Arsenic (cancer)	3E-04	4E-04	2E-04	0
Thallium	2	3	2	0
Antimony	1	2	0.8	0
Molybdenum	0.9	1	0.8	0
Lead (MCL)[b]	0.5	1	0.3	0
Cadmium	0.4	0.7	0.4	0
Boron	0.4	0.7	0.4	0
Selenium	0.1	0.2	0.1	0
Nitrate/nitrite (MCL)[c]	0.07	0.1	0.06	2E-06
Codisposed CCW and Coal Refuse – 41 landfills				
Arsenic (cancer)	3E-04	5E-04	2E-04	0
Thallium	1	2	1	0
Molybdenum	0.8	2	0.6	0
Antimony	0.5	0.8	0.3	0
Selenium	0.4	0.7	0.3	0
Lead (MCL)[c]	0.3	0.7	0.09	0
Boron	0.2	0.3	0.1	0
Nitrate/nitrite (MCL)[c]	0.2	0.2	0.1	3E-06
Cadmium	0.1	0.2	0.07	0

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.
[b] HQ or risk across all unit types combined (unlined, clay-lined, and composite-lined).
[c] Values are ratios of exposure concentration to MCL.

Table 4-6. 50th Percentile Risk Results by CCW Type: Landfills, Groundwater-to-Drinking-Water Pathway

Chemical	50th Percentile HQ or Cancer Risk Value[a]			
	All Units Combined[b]	Unlined Units	Clay-Lined Units	Composite-Lined Units
Conventional CCW – 79 landfills				
Arsenic (cancer)	2E-06	6E-06	4E-06	0
Thallium	0.08	0.2	0.1	0
Antimony	0.02	0.04	0.02	0
Molybdenum	0.03	0.05	0.04	0
Lead (MCL)[b]	3E-08	4E-04	2E-08	0
Cadmium	0.005	0.01	0.008	0
Boron	0.007	0.01	0.01	0
Selenium	0.004	0.009	0.006	0
Nitrate/nitrite (MCL)[c]	0.002	0.004	0.003	0
Codisposed CCW and Coal Refuse – 41 landfills				
Arsenic (cancer)	4E-06	2E-05	6E-06	0
Thallium	0.06	0.2	0.07	0
Molybdenum	0.006	0.02	0.006	0
Antimony	0.01	0.05	0.02	0
Selenium	0.008	0.03	0.01	0
Lead (MCL)[c]	6E-07	0.01	2E-07	0
Boron	0.002	0.008	0.003	0
Nitrate/nitrite (MCL)[c]	0.01	0.04	0.009	0
Cadmium	0.003	0.02	0.004	0

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

[b] HQ or risk across all unit types combined (unlined, clay-lined, and composite-lined).

[c] Values are ratios of exposure concentration to MCL.

Table 4-7. 90th Percentile Risk Results by CCW Type: Surface Impoundments, Groundwater-to-Drinking-Water Pathway

Chemical	90th Percentile HQ or Cancer Risk Value[a]			
	All Units Combined[b]	Unlined Units	Clay-Lined Units	Composite-Lined Units
Conventional CCW – 44 surface impoundments				
Arsenic (cancer)	1E-03	2E-03	9E-04	2E-07
Nitrate/nitrite (MCL)[c]	10	20	10	9E-04
Molybdenum	6	8	5	7E-03
Boron	5	7	4	5E-03
Selenium	2	2	1	1E-03
Lead (MCL)[c]	1	3	0.7	1E-21
Cadmium	0.4	0.5	0.3	4E-11
Cobalt	0.01	0.01	6E-03	0
Codisposed CCW and Coal Refuse – 72 surface impoundments				
Arsenic (cancer)	2E-02	2E-02	7E-03	4E-06
Cadmium	8	9	3	5E-05
Cobalt	7	8	3	4E-08
Lead (MCL)[c]	6	9	1	1E-19
Molybdenum	3	3	2	4E-03
Boron	1	1	0.5	2E-03
Selenium	0.8	0.8	0.4	1E-03
Nitrate/nitrite (MCL)[c]	0.3	0.4	0.2	1E-04

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

[b] HQ or risk across all unit types combined (unlined, clay-lined, and composite-lined).

[c] Values are ratios of exposure concentration to MCL.

Table 4-8. 50th Percentile Risk Results by CCW Type: Surface Impoundments, Groundwater-to-Drinking-Water Pathway

Chemical	50th Percentile HQ or Cancer Risk Value[a]			
	All Units Combined[b]	Unlined Units	Clay-Lined Units	Composite–Lined Units
Conventional CCW – 44 surface impoundments				
Arsenic (cancer)	7E-05	1E-04	6E-05	0
Nitrate/nitrite (MCL)[c]	0.05	0.1	0.05	7E-08
Molybdenum	0.6	1.1	0.5	2E-11
Boron	0.2	0.4	0.2	3E-11
Selenium	0.07	0.1	0.07	2E-11
Lead (MCL)[c]	0.02	0.05	0.007	0
Cadmium	0.03	0.05	0.02	0
Cobalt	0.001	0.003	8E-04	0
Codisposed CCW and Coal Refuse – 72 surface impoundments				
Arsenic (cancer)	4E-04	6E-04	2E-04	0
Cadmium	0.1	0.1	0.05	0
Cobalt	0.3	0.4	0.09	0
Lead (MCL)[c]	0.09	0.1	0.01	0
Molybdenum	0.6	0.8	0.3	3E-18
Boron	0.1	0.1	0.06	5E-15
Selenium	0.08	0.1	0.03	5E-15
Nitrate/nitrite (MCL)[c]	0.02	0.03	0.01	4E-08

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.
[b] HQ or risk across all unit types combined (unlined, clay-lined, and composite-lined).
[c] Values are ratios of exposure concentration to MCL.

4.1.3.2 FBC Wastes

Tables 4-9 and 4-10 show the 90th- and 50th-percentile risk results for FBC landfills by unit type. At the 90th percentile in landfills, arsenic cancer risks are $3x10^{-5}$ for unlined units, $6x10^{-5}$ for clay-lined units, and 0 for composite-lined units. Noncancer hazard quotients exceed 1 for only thallium (4) and antimony (3) in clay-lined units. No risks exceeded the risk criteria at the 50th percentile. These results suggest lower risks than for conventional CCW and CCW codisposed with coal refuse. The difference may be attributed to lower FBC leachate concentrations and the alkaline nature of FBC waste.

Note that clay-lined FBC landfills show higher risks than unlined facilities, which is counterintuitive considering how clay-lined and unlined units are designed and operated. This

result reflects the characteristics of the limited number and locations of FBC landfills[5] and illustrates how the probabilistic analysis design and availability of facility data can impact risk results (and why FBC results are treated separately in the risk characterization). As presented in Section 3.1.2 and in Figure 3-2, the Monte Carlo analysis was designed to evaluate risks posed by current waste management practices for a given WMU type, waste type, and waste constituent. This approach limits the effects of data availability for the different liner configurations when the risks are aggregated over all units (lined and unlined) combined. However, when the risk results of an exposure pathway are viewed at a resolution finer than the analysis design, a small sample size for a particular waste and WMU type scenario (as occurs for FBC waste), along with the interactions of liner type with other site-based inputs (notably infiltration rate and the size of the WMU), can produce unexpected results. In the case of FBC wastes, the characteristics (primarily infiltration rate and areas) of the three unlined landfills were such that their risks were lower than the clay-lined FBC landfills.

Table 4-9. 90th Percentile Risk Results for FBC Wastes: Landfills, Groundwater-to-Drinking-Water Pathway

Chemical	90th Percentile HQ or Cancer Risk Value[a]			
	All Units Combined[b]	Unlined Units	Clay-Lined Units	Composite-Lined Units
FBC Waste – 7 landfills				
Arsenic (Cancer)	4E-05	3E-05	6E-05	0
Thallium	2	1	4	0
Antimony	1	0.8	3	0
Lead (MCL)[c]	0.4	0.4	0.6	0
Molybdenum	0.3	0.2	0.5	0
Cadmium	0.2	0.1	0.3	0
Selenium	0.1	0.08	0.1	0
Nitrate/nitrite (MCL)[c]	0.05	0.03	0.07	5E-08
Boron	0.04	0.02	0.07	0

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000-year period of the analysis.
[b] HQ or risk across all unit types combined (unlined, clay-lined, and composite-lined).
[c] Values are ratios of exposure concentration to MCL.

[5] FBC WMU data were available for only seven landfills (3 unlined, 3 clay-lined, and 1 composite-lined), and it is not known how representative these data are with respect to WMU characteristics and locations throughout the United States.

Table 4-10. 50th Percentile Risk Results for FBC Wastes: Landfills, Groundwater-to-Drinking-Water Pathway

Chemical	50th Percentile HQ or Cancer Risk Value[a]			
	All Units Combined[b]	Unlined Units	Clay-Lined Units	Composite-Lined Units
FBC Waste – 7 landfills				
Arsenic (Cancer)	0	0	4E-07	0
Thallium	0.008	0	0.2	0
Antimony	0.002	0	0.09	0
Lead (MCL)[c]	0	0	2E-04	0
Molybdenum	0.003	0	0.04	0
Cadmium	4E-07	0	0.01	0
Selenium	3E-04	0	0.01	0
Nitrate/nitrite (MCL)[c]	1E-04	3E-08	0.004	0
Boron	2E-04	0	0.003	0

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000-year period of the analysis.
[b] HQ or risk across all unit types combined (unlined, clay-lined, and composite-lined).
[c] Values are ratios of exposure concentration to MCL.

4.1.4 Results by Unit Type

The effect of unit type on human health risk for the groundwater-to-drinking-water pathway can be seen in Tables 4-1 and 4-2, which compare 90th and 50th percentile risks, respectively, for WMUs that are unlined, clay lined, and lined with composite liners from the 1995 EPRI survey data (EPRI, 1997). At the 90th percentile, lined units produced lower risk estimates than unlined units for all constituents modeled. Composite liners produced very low to zero risk estimates as compared to clay liners for all constituents modeled for both landfills and surface impoundments. For surface impoundments, clay liners produced higher risk estimates for all constituents as compared to clay liners in landfills. Similar trends are evident at the 50th percentile, where composite liners produced risk estimates of zero or near zero for all constituents for surface impoundments.

Table 4-11 shows the frequency of each of the unit types in the 1995 EPRI survey data modeled in this analysis, and it compares these data with the unit type frequency in the more recent DOE/EPA study (U.S. DOE, 2006). The 56 WMUs surveyed in the U.S. DOE 2006 study were commissioned between 1994 and 2004. Although the actual number of WMUs that were established in that timeframe cannot be verified, based on proxy data (i.e., CCW available for disposal in those states with identified, new WMUs and coal-fired power plant generating capacity), the sample coverage is estimated to be at least between 61 and 63 percent of the total

population of the newly commissioned WMUs.[6] With the exception of one landfill, the newly constructed facilities are all lined, with either clay, synthetic, or composite liners. The single unlined landfill identified in the recent DOE report receives bottom ash, which is characterized as an inert waste by the state, and therefore, a liner is not required. As Table 4-11 shows, there is a marked trend away from unlined WMUs in favor of lined units, with a distinct preference for synthetic or composite liners. Comparison of the 26 coal combustion plants in both the EPRI survey and the DOE/EPA survey (U.S. DOE, 2006) shows that although most of those facilities (17 of 26) were using unlined WMUs in 1995, all 26 are now placing wastes in new or expanded landfills or surface impoundments that are lined with clay, synthetic, or composite liners. However, it is likely that the older unlined units were closed with wastes in place, and that these wastes therefore still pose a threat through groundwater pathways. Also, the number of unlined unit that continue to operate in the United States cannot be determined from the available data.

Table 4-11. Unit Types in EPRI Survey

Liner Type	Landfills	Surface Impoundments
1995 EPRI Survey[a] – 181 facilities		
Unlined	40%	68%
Compacted clay	45%	27%
Synthetic or composite (clay and synthetic)	16%	5%
Total	100%	100%
2004 DOE Survey[b] – 56 Facilities		
Unlined	3%	0%
Compacted clay	29%	17%
Synthetic or composite (clay and synthetic)	68%	83%
Total	100%	100%

[a] EPRI (1997)
[b] U.S.DOE (2006)

As described in Sections 3.2.1 and 3.3.1, the characteristics of the liners used in the CCW risk were taken from the IWEM model as representative of the general performance of each liner type. For landfills, an engineered compacted clay liner (3 feet thick, with a hydraulic conductivity of 1 x 10^{-7} cm/s) reduced the 90th percentile risk by a factor of about 2 to 4 compared to no liner, but did not change the constituents at or above the risk criteria (arsenic and thallium). For surface impoundments, clay liners did reduce the risk to just below the risk criteria for cobalt, lead, and selenium.

Composite (clay and synthetic) liners, as modeled in this risk assessment (see Sections 3.2 and 3.3), were much more effective at reducing risk for all constituents; 90th (and

[6] For additional details as to how these estimates were derived, the reader is referred to the DOE study, pages S-2 – S-3 of the Summary Section and Section 3.1.2..

50th) percentile risks with composite liners for landfills were zero[7] for arsenic and metals and very low or zero for nitrate/nitrite, and were well below the risk criteria for all constituents for surface impoundments. The analysis used data collected for composite liner performance at industrial waste management facilities, including liner leakage rate for landfills and the number of liner perforations for surface impoundments (TetraTech, 2001). Because data on CCW liner leakage rates are not available, there is some uncertainty in applying these Industrial D liner performance data to CCW disposal units. Still, these rates do reflect actual performance data from liners under real WMUs, and they demonstrate that composite liners can be effective in reducing leaching from CCW WMUs and suggest that there will be a significant decrease in risk from CCW disposal if more facilities line their WMUs with composite liners. Information from the more recent DOE/EPA study (U.S. DOE, 2006) indicates that composite liners are much more prevalent in newly constructed facilities, so the risks from CCW disposal should be lower for newer CCW landfills and surface impoundments.

4.1.5 Constituents Not Modeled in the Full-Scale Assessment

As described in Section 2.1.1.2, resources did not allow full-scale modeling to be conducted for all 21 constituents that were above the screening criteria in the initial screening analysis; nine constituents that were judged to likely have generally lower risks to human health and ecological risks were not modeled in the full-scale risk assessment.[8] Five of these chemicals (chromium, fluoride, manganese, vanadium, and nickel) had drinking water pathway HQs in the screening analysis ranging from 1 to less than 6 for surface impoundments, and three (chromium, fluoride, and vanadium) had screening HQs of 2 for landfills.

To address these constituents, we developed surrogate risk attenuation factors by dividing the screening risk results by the full-scale risk results, across all unit types combined, for the constituents modeled in the full-scale assessment. This comparison was done only for the drinking water exposure pathway, the only human health exposure pathway for which the risks for these constituents were above the screening criteria. Table 4-12 shows the risk attenuation factor statistics for the modeled constituents, and Table 4-13 shows the results of applying the median and 10th percentile attenuation factors to the screening risk results for the marginal constituents. Differences in attenuation among the modeled constituents reflects differences in contaminant sorption and mobility. The 10th percentile attenuation factor was selected as a conservative value representing the more mobile constituents, such as arsenic, selenium, and molybdenum. The 50th percentile (or median) risk represents a central tendency value.

For landfills, the risk attenuation factors ranged from 6 to 40, with the lower attenuation factors mainly representing the more mobile constituents (i.e., those with lower soil sorption potential). Both the median and 10th percentile risk attenuation factors were adequate to reduce risks for all nine constituents below an HQ of 1.

[7] The absence of risk indicates that contaminant infiltration rates were too small for the contaminant plume to reach the receptor well during the 10,000 year period of the analysis. See Section 3.2.2 for a discussion of the empirical liner infiltration data used in this analysis.

[8] These constituents of marginal concern had no human health HQs greater than 6 and only one or no ecological HQs greater than 100.

For surface impoundments, risk attenuation factors were considerably lower, ranging from 1 to 9, reflecting higher contaminant mobility due to the higher hydraulic head in surface impoundments (as compared to landfills) and a lower proportion of liners. For the same reason, the screening HQs for surface impoundments were higher than the landfill HQs. As a result of this combination of higher HQs and lower risk attenuation factors, only the HQ for nickel was reduced to below 1 by applying the attenuation factors. The other constituents (chromium, fluoride, manganese, and vanadium) still show risks slightly above the risk criteria, with HQs ranging from 1.4 to 3.5. This is consistent with the general trend in this analysis of surface impoundments showing higher risks and more risks exceeding the risk criteria than CCW landfills.

Table 4-12. Risk Attenuation Factor[a] Statistics for Modeled Constituents—Groundwater to Drinking Water Pathway

Statistic	Landfill	Surface Impoundment
10th percentile	7	1.6
50th percentile	12	2.6
Average	16	3.3
Maximum	40	9.3
Number of data points	9	8

[a] The risk attenuation factor is the ratio of the full-scale analysis risk and screening analysis risk for a constituent modeled in the full-scale analysis.

Table 4-13. Summary of Risk Results for Constituents Using Risk Attenuation Factors—Groundwater-to-Drinking-Water Pathway

	Landfill			Surface Impoundment		
WMU/Pathway	Screening HQ	HQ with Median Attenuation	HQ with 10th Percentile Attenuation	Screening HQ	HQ with Median Attenuation	HQ with 10th Percentile Attenuation
Chromium VI	2.3	0.2	0.3	4.2	1.6	2.6
Fluoride	1.8	0.2	0.3	5.2	2.0	3.3
Manganese	1	0.1	0.1	5.6	2.2	3.5
Vanadium	2.2	0.2	0.3	2.3	0.9	1.4
Nickel	-	-	-	1.3	0.5	0.8

4.2 Ecological Risks

EPA defines ecological risk characterization in terms of (1) the risk estimation, which integrates the exposure and stressor-response profile to estimate the likelihood of adverse ecological effects and (2) the risk description, which synthesizes the overall conclusion of the assessment and addresses assumptions, uncertainty, and limitations.

For assessments that are based on a HQ approach, as this one is, the comparison of modeled exposure concentrations to CSCLs to estimate risk has a binary outcome: either the constituent concentration is above the environmental quality criteria (HQ greater than 1) or the concentration is below the criteria (HQ less than or equal to 1). For the full-scale analysis, an ecological HQ greater than 1 was selected by EPA as a criterion for decision making. Because the CSCLs were based on *de minimis* ecological effects, it is generally presumed that an HQ at or below 1 indicates a low potential for adverse ecological effects for those receptors included in the analysis for which data are available. However, it is important to recognize that although this method provides important insight into the potential for adverse ecological effects, the results are relevant only to those receptors that were included in the assessment and for which data were available. The results have limited utility in interpreting the ecological significance of predicted effects, and caution should be exercised in extrapolating to ecosystems (e.g., wetlands) and receptors (e.g., threatened and endangered species) not explicitly modeled.

This section presents risk results for the two groundwater-to-surface-water ecological exposure pathways investigated in the full-scale analysis: (1) receptors exposed to CCW constituents in the water column (surface water receptors) and (2) receptors exposed to CCW constituents in bed sediment (sediment receptors). Results are presented for the two WMU types addressed in the analysis: landfills and surface impoundments. The ecological risk results are presented for all unit types combined and were not broken out separately for the different unit types.

The ecological risk results suggest the potential for adverse ecological effects to aquatic systems from CCW releases into the subsurface and subsequent connection with surface waters, particularly for CCW managed in unlined surface impoundments. As with human health risks, the higher prevalence of liners in newer facilities should result in lower risks in current and future CCW disposal facilities than those presented in this risk assessment.

4.2.1 Surface Water Receptors

Table 4-14 presents the 90th and 50th percentile results for the groundwater-to-surface-water pathway for surface water receptors for landfills and surface impoundments. For landfills, only boron (200) and lead (4) show HQs above the risk criteria at the 90th percentile. For surface impoundments, boron (2000), lead (20), arsenic (10), selenium (10), cobalt (5), and barium (2) showed 90th percentile risks above the risk criteria. The 50th percentile results are well below an HQ of 1 for landfills and only exceed an HQ of 1 for boron (4) in surface impoundments.

The difference in the number and magnitude of HQs that exceed the risk criterion between landfills and surface impoundments is likely the result of higher CCW constituent concentrations in surface impoundment porewater and the greater flux of contaminants to

groundwater predicted during the active life of the surface impoundment. As discussed in Section 4.1, the higher infiltration rates for surface impoundments result from a higher hydraulic head in the impoundment and a higher proportion of unlined surface impoundments than landfills.

Table 4-14. Summary of Full-Scale CCW Ecological Risk Results: Groundwater-to-Surface-Water Pathway, Aquatic Receptors[a]

Chemical	90th Percentile HQ	50th Percentile HQ	Pathway	Receptor
Landfills				
Boron	200	0.04	direct contact	aquatic biota
Lead	4	2E-08	ingestion	river otter
Selenium	1	3E-04	direct contact	aquatic biota
Arsenic	0.7	9E-10	direct contact	aquatic biota
Barium	0.8	3E-18	direct contact	aquatic biota
Cadmium	0.3	3E-05	direct contact	aquatic biota
Aluminum	0.008	1E-09	direct contact	aquatic biota
Surface Impoundments				
Boron	2000	4	direct contact	aquatic biota
Lead	20	0.02	ingestion	river otter
Arsenic	10	0.01	direct contact	aquatic biota
Selenium	10	0.02	direct contact	aquatic biota
Cobalt	5	0.007	direct contact	aquatic biota
Barium	2	0.003	direct contact	aquatic biota
Cadmium	1	0.004	direct contact	aquatic biota
Aluminum	0.02	0.0003	direct contact	aquatic biota

[a] Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

4.2.2 Sediment Receptors

Table 4-15 presents the 90th and 50th percentile results of the ground-water-to-surface-water pathway for sediment receptors for landfills and surface impoundments. For landfills, lead, (20), arsenic (6), and cadmium (2) show 90th percentile risks above the risk criteria. For surface impoundments, lead (200), arsenic (100), and cadmium (20) showed 90th percentile risks above the risk criteria. Although cadmium was not above the risk criterion in surface water, it did have an HQ of 20 in sediments at the 90th percentile. None of the constituents modeled showed sediment risks at or above the risk criteria at the 50th percentile.

Table 4-15. Summary of Full-Scale CCW Ecological Risk Results: Groundwater-to-Surface-Water Pathway, Sediment Receptors[a]

Chemical	90th Percentile HQ	50th Percentile HQ	Pathway	Receptor
Landfills				
Lead	20	3E-08	ingestion	spotted sandpiper
Arsenic	6	7E-04	ingestion	spotted sandpiper
Cadmium	2	6E-05	direct contact	sediment biota
Antimony	0.9	4E-05	direct contact	sediment biota
Molybdenum	0.05	1E-05	ingestion	spotted sandpiper
Barium	0.002	6E-21	ingestion	spotted sandpiper
Surface Impoundments				
Lead	200	0.05	ingestion	spotted sandpiper
Arsenic	100	0.2	ingestion	spotted sandpiper
Cadmium	20	0.009	direct contact	sediment biota
Molybdenum	0.7	0.002	ingestion	spotted sandpiper
Barium	0.007	8E-06	ingestion	spotted sandpiper

[a] Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

4.2.3 Constituents Not Modeled in the Full-Scale Assessment

As described in Section 2.1.1.2, resources did not allow full-scale modeling to be conducted for 6 constituents with generally lower risks to ecological receptors.[9] These chemicals (chromium, vanadium, beryllium, copper, silver, and zinc), had surface water pathway HQs in the screening analysis ranging from 16 to 110 for landfills, and four (chromium, vanadium, copper, and silver) had screening HQs ranging from 14 to 33 for surface impoundments.

These constituents were addressed using risk attenuation factors developed by dividing the screening risk results by the full-scale risk results for the constituents modeled in the full-scale assessment. Tables 4-16 and 4-17 show the results of this comparison for the surface water ecological risk exposure pathway. Table 4-16 shows the risk attenuation factors for the modeled constituents, and Table 4-17 shows the results of applying the median (central tendency) and 10th percentile (conservative) attenuation factors to the screening risk results for constituents that were not modeled.

For landfills, the risk attenuation factors ranged from 50 to 2,000. Both the median and 10th percentile risk attenuation factors were adequate to reduce risks to an HQ below 1 for all constituents except for silver. Although silver shows an HQ of 1.5 using the 10th percentile

[9] These constituents had only one or no ecological HQs greater than 100.

attenuation factor, silver's low mobility would probably result in a higher attenuation factor (i.e., at the median or greater).

For surface impoundments, risk attenuation factors ranged from 7 to 64, reflecting higher contaminant mobility from the higher hydraulic head in the surface impoundments and a lower prevalence of liners (compared to landfills). HQs were reduced below 1 for all four unmodeled constituents with the median attenuation factor (38), and the HQ for silver was reduced to 0.8 by applying the 10th percentile attenuation factor (17). The other three constituents (chromium, vanadium, and copper) show risks only slightly above the risk criteria with the10th percentile attenuation (HQs ranging from 1.4 to 1.9). It is unlikely that these results represent true risks above the risk criteria: vanadium and copper are likely less mobile than the 10th percentile attenuation factor reflects (thus the true risk is likely lower), and the risks for chromium are based on the highly conservative assumption of 100 percent hexavalent chromium.

Table 4-16. Risk Attenuation Factor[a] Statistics for Modeled Constituents—Ecological Risk, Surface Water Pathway

Statistic	Landfill	Surface Impoundment
10th percentile	75	17
50th percentile	178	38
Average	483	38
Maximum	2,000	64
Number of data points	6	7

[a] The risk attenuation factor is the ratio of the full-scale analysis risk and screening analysis risk for a constituent modeled in the full-scale analysis.

Table 4-17. Summary of Risk Results Using Risk Attenuation Factors—Ecological Risk, Surface Water Pathway

WMU/Pathway	Landfill			Surface Impoundment		
	Screening HQ	HQ with Median Attenuation	HQ with 10th Percentile Attenuation	Screening HQ	HQ with Median Attenuation	HQ with 10th Percentile Attenuation
Chromium VI	18	0.1	0.2	33	0.9	1.9
Vanadium	23	0.1	0.3	24	0.6	1.4
Beryllium	24	0.1	0.3	-	-	-
Copper	16	0.09	0.2	31	0.8	1.8
Silver	110	0.6	1.5	14	0.4	0.8
Zinc	16	0.09	0.2	-	-	-

4.3 Sensitivity Analysis

EPA conducted a sensitivity analysis on the probabilistic risk assessment to determine which model inputs were most important to risk, which in turn will help focus additional analyses or data collection efforts on the most important drivers of risk, and help identify the important factors to consider when evaluating regulatory and management options for CCW. The sensitivity analysis also can help identify parameters that are both sensitive and highly uncertain, which affects the confidence in the results. This sensitivity analysis used a response-surface regression method that derives a statistical model for risk (as the dependent variable) based on the input parameters from the probabilistic analysis (as independent variables).

Environmental concentration (rather than risk) was chosen as the dependent variable for the sensitivity analysis because (1) there is a direct, linear relationship between environmental concentrations and risks and (2) the additional inputs used to calculate risk from environmental concentration (i.e., exposure factors, such as body weight, ingestion rates) are lifestyle variables that are not amenable to regulation to reduce or manage risk. Furthermore, these variables have well-established, peer-reviewed, national distributions, which are regularly used in the probabilistic national risk analyses conducted by EPA. Therefore, the contribution of the exposure factors to the variability in risk is not particularly useful for the purposes of the sensitivity analysis: to help direct additional analyses in support of developing CCW regulatory options, to help focus any future data collection efforts on the most sensitive variables, or to better understand sources of uncertainty in the CCW risk results.

The outputs from the sensitivity analysis are the goodness-of-fit values for the regression models and the relative importance of each input parameter in determining environmental concentrations across different WMU, waste type, and constituent scenarios. The goodness-of-fit values of the regression models were moderate to very good for the drinking water pathway (R^2=0.53–0.90) and good to very good for fish consumption (R^2=0.76–0.90). In general, the drinking water pathway had a larger number of input parameters that were significant (seven) than the fish consumption pathway (three). The most sensitive parameters for most (over 75 percent) of the drinking water scenarios[10] evaluated were parameters impacting groundwater flow:

- Infiltration rate within the WMU footprint
- Leachate concentration from the WMU
- Aquifer hydraulic conductivity and gradient (i.e., groundwater velocity).

For strongly sorbing contaminants (i.e., metals with high soil/water partition coefficients), sorption and travel time parameters become more important, including

- Adsorption isotherm coefficient
- Depth to groundwater
- Receptor well distance.

[10] Scenarios represent unique combinations of WMU, waste type, chemical, exposure pathway, and receptor.

For the fish consumption pathway, only three variables were consistently significant across scenarios:

- Infiltration rate within the WMU footprint
- Leachate concentration from the WMU
- Waterbody flow rate.

Additional detail on how the CCW sensitivity analysis was conducted can be found in U.S. EPA (2005). In terms of the model inputs, the sensitivity analysis found that the most consistent drivers of the risk results are constituent concentration in waste leachate (i.e., the source term for the risk assessment and infiltration rate through the WMU), which is largely controlled by the liner conditions and, to a lesser extent, soil type and (for landfills only) precipitation. These variables and their uncertainties are discussed in the following section.

4.4 Variability and Uncertainty

Variability arises from true heterogeneity in characteristics, such as body weight differences within a population or differences in contaminant levels in the environment.

Uncertainty represents a lack of knowledge about factors such as the nature of adverse effects from exposure to constituents, which may be reduced with additional research to improve data or models.

Variability and uncertainty are different conceptually in their relevance to a probabilistic risk assessment. Variability represents true heterogeneity in characteristics, such as body weight differences within a population or differences in pollutant levels in the environment. It accounts for the distribution of risk within the exposed population. Although variability may be known with great certainty (e.g., age distribution of a population may be known and represented by the mean age and its standard deviation), it cannot be eliminated and needs to be treated explicitly in the assessment. Uncertainty is a description of the imperfection in knowledge of the true value of a particular parameter. In contrast to variability, uncertainty can be reduced through additional information-gathering or analysis (i.e., better data, better models). EPA typically classifies the major areas of uncertainty in risk assessments as scenario uncertainty, model uncertainty, and parameter uncertainty. Scenario uncertainty refers to missing or incomplete information needed to fully define exposure and dose. Model uncertainty is a measure of how well the model simulates reality. Parameter uncertainty is the lack of knowledge regarding the true value of a parameter used in the assessment.

Uncertainty and variability can be addressed two ways:

- By varying parameter values in a probabilistic assessment such as a Monte Carlo analysis
- By comparing the data or results to other data or other studies such as damage cases or alternative results based on different assumptions.

In planning this assessment, we addressed as much of the variability as possible, either directly in the Monte Carlo analysis or through aggregation of the data into discrete elements of the analysis. For example, spatial variability in soil, aquifer, and climate data is accounted for by using distributions for soil and aquifer properties around the facility when the actual

environmental characteristics around a WMU are uncertain. Conversely, variability in waste leachate concentrations was represented by a national database of CCW constituent concentrations from disposal sites around the country. These data were aggregated by waste and WMU types that were defined by statistically significant differences in concentration. Variability in human exposure factors (e.g., body weight, ingestion rates) was accounted for using national distributions that represent the range of possible values.

Because CCW is generated nationwide, its disposal may occur anywhere in the United States. Thus, this assessment characterized environmental conditions that influence the fate and transport of constituents in the environment using site-specific data collected around coal-fired power plants with onsite CCW disposal facilities. Spatial variability in environmental setting was accounted for by the site-to-site variables for the 181 CCW disposal sites modeled in the analysis using 41 different climate regions and 9 different resources regions throughout the contiguous 48 states.

In summary, a distribution of exposures was developed that includes specific consideration of the variability in the following sensitive model parameters

- WMU characteristics, in particular liner type (which strongly influences infiltration rate)
- CCW constituent concentrations in waste leachate
- Distance to nearest well
- Site-specific environmental conditions (especially groundwater flow conditions)
- Human exposure factors.

Uncertainty also was considered in the analysis by using reasonable ranges and distributions when variables were not known exactly. For example, when a soil texture or groundwater flow conditions could not be precisely assigned at a site, multiple soil types or hydrogeologic environments would be sampled based on the soil and aquifer types that are likely to be present at the site.

The treatment of variability and uncertainty in model parameters using a Monte Carlo simulation forms the basis for the national exposure distributions used in this analysis to estimate risk. Previous sections of this document describe how we generated distributions and estimated input parameter values and then used these values in models to estimate risk. The discussion in this section focuses on how this treatment of variability and uncertainty affects the analysis results and on various comparisons we performed on the results or critical input data to evaluate uncertainty.

4.4.1 Scenario Uncertainty

Sources of scenario uncertainty include the assumptions and modeling decisions that are made to represent an exposure scenario. Because this risk assessment attempts to characterize current conditions by estimating risks from actual CCW disposal sites across the country, it is subject to less scenario uncertainty than risk assessments that rely on hypothetical conceptual models. However, certain aspects of the scenario are uncertain.

CCW Management Unit Data. The landfills and surface impoundments modeled in this risk assessment were placed, sized, and lined according to data from the 1995 EPRI survey (EPRI, 1997). New data collected by EPA and DOE since this risk assessment was conducted (U.S. DOE, 2006) indicate that liners are much more prevalent in WMUs constructed or expanded from 1994 through 2004 than in units in place before that. This suggests that the risks may be lower for future CCW disposal facilities (although most of the unlined WMUs have been closed with wastes remaining in the units).

Liner-related questions are especially important because liner configurations greatly influence infiltration rates, one of the most sensitive parameters in the risk assessment. In terms of risks through groundwater pathways, this risk assessment has shown that liners, in particular composite (combined clay and synthetic) liners, can limit risks through subsurface exposure pathway, and the DOE/EPA survey shows that liners are more prevalent in newly constructed WMUs and WMU expansions. Although the DOE/EPA survey does not shed light on how many unlined facilities are still operating today, it does indicate that more units are lined today than were in the 1995 EPRI survey data set on which this risk assessment is based.

Receptor Populations Evaluated. The human receptors evaluated for the CCW risk analysis are a family with children residing near the CCW disposal facility, drinking from a private well screened in a surficial aquifer or eating fish caught from a nearby stream or lake impacted by CCW leachate. Additionally, except for a 15-day vacation, it is assumed that adults and children are exposed daily and that the private well is the only source of drinking water. Although it is possible for other types of individuals to be exposed, the use of the resident adult and child as protective of other receptors and pathways is a conservative, simplifying assumption of the analysis. The lack of information to define and model actual exposure conditions also introduces uncertainty into this assessment, but EPA believes that the national distribution of exposure factors used is appropriate for a national assessment.

Additive Risks Across Pathways. The human receptors evaluated in the CCW risk assessment are assumed not to consume both contaminated fish and drinking water. Although this could potentially miss some higher exposures for a maximally exposed individual, analysis of the individual pathway results does not indicate that adding such risks would significantly change the conclusions of this risk assessment in terms of the constituents and exceeding the risk criteria.

Co-Occurrence of Ecological Receptors and Constituents. As a simplification for national-scale analyses in the absence of site-based data, co-occurrence of the ecological receptors and the constituents of concern is typically assumed. However, the prior probability that a receptor will be found in waterbodies affected by constituent releases from CCW WMUs is not known, nor is it known whether a receptor will forage for food in contaminated areas or if those areas do, in fact, support the type of habitat needed by the receptor. Although the assumption of co-occurrence was necessary for this analysis, relatively few field studies are available to demonstrate the relationship between adverse ecological effects and constituent releases from CCW as it is currently managed.

Ecosystems and Receptors at Risk. One of the most intractable problems in conducting a predictive ecological risk assessment intended to reflect risks at a national scale is evaluating *all* of the receptors and ecosystems at risk. In *Wastes from the Combustion of Coal by Electric Utility Power Plants - Report to Congress* (U.S. EPA, 1988b), the authors pointed out that plants or animals of concern were located within a 5-km radius of the CCW WMUs at 12 to 32 percent of the sites. Although these figures are of limited spatial resolution, they suggest the possibility that threatened and endangered species or critical habitats may be at risk from CCW constituents. Examples of other critical assessment endpoints not evaluated in this analysis include the following:

- **Managed Lands:** Because ecosystem degradation is proceeding at an unprecedented rate, and because protected lands play a critical role in preserving plant and animal species, managed areas in the United States represent well-recognized ecological values. Managed lands refer to a variety of lands designated by the federal government as worthy of protection, including National Wildlife Refuges, National Forests, Wilderness areas, and National Recreation areas.
- **Critical Habitats:** Although critical habitats may be defined in a number of ways (e.g., presence of threatened species, decreasing habitat area), wetlands are widely recognized as serving critical ecological functions (e.g., maintenance of water quality). The U.S. Fish and Wildlife Service estimates that approximately 45 percent of the Nation's threatened and endangered species directly depend on aquatic and wetland habitats. Consequently, impacts of chemical stressors on wetland habitats may have high ecological (and societal) significance. The presence of critical habitats such as wetlands is also used to inform the selection of ecological receptors (e.g., amphibians, waterfowl) and the construction of appropriate food webs.
- **Threatened and Endangered Species:** For most ecological risk assessments of chemical stressors, available data on toxicity and biological uptake are sufficient to support the evaluation of effects on representative species populations or generalized communities (e.g., aquatic community). However, despite their obvious value, threatened and endangered species are frequently excluded from the analytical framework for national rulemakings. The assessment of threatened and endangered species requires a site-based approach in which locations, habitats, and species of concern are identified and characterized with respect to the spatial scale of constituent releases.

4.4.2 Model Uncertainty

Model uncertainty is associated with all models used in a risk assessment because models and their mathematical expressions are simplifications of reality that are used to approximate real-world conditions and processes and their relationships. Computer models are simplifications of reality, requiring exclusion of some variables that influence predictions but that cannot be included in models either because of their complexity or because data are lacking on a particular parameter. Models do not include all parameters or equations necessary to express reality because of the inherent complexity of the natural environment and the lack of sufficient data to describe the natural environment. Because this is a probabilistic assessment that predicts what may occur with the management of CCW under actual scenarios, it is possible to compare the results of these models to specific situations.

The risk assessor needs to consider the importance of excluded variables on a case-by-case basis because a given variable may be important in some instances and not important in others. A similar problem can occur when a model that is applicable under one set of conditions is used for a different set of conditions. In addition, in some instances, choosing the correct model form is difficult when conflicting theories seem to explain a phenomenon equally well. In other instances, EPA does not have established model forms from which to choose to address certain phenomena, such as facilitated groundwater transport.

Models used in this analysis were selected based on science, policy, and professional judgment. These models were selected because they provide the information needed for this assessment and because they are generally considered to reflect the state of the science. Even though the models used in this analysis are used widely and have been accepted for numerous applications, they each retain significant sources of uncertainty. These limitations are well documented in the model development references cited in Section 3.

Although the sources of model uncertainty in this assessment could result in either an overestimation or an underestimation of risk, the models employed in this assessment have been developed over many years to support regulatory applications. As a result they have been designed to be protective towards the impacted populations that they represent. In other words, where simplifying assumptions are necessary, the assumptions are made in a way that will not underestimate risk.

Arsenic Speciation. Because the models used in this assessment do not speciate metals during soil or groundwater transport, arsenic speciation in the subsurface is a significant groundwater modeling uncertainty in this analysis. Arsenic can occur in either a +3 (arsenic III) or +5 (arsenic V) oxidation state in groundwater, with arsenic III being the more mobile form. Because the soil and groundwater models assume one form for each model run, the risk results presented for arsenic are based on arsenic III, which is a conservative, protective assumption (i.e., arsenic III has higher risks than arsenic V). Although arsenic is generally thought to occur in the +3 form in leachate, there is evidence from damage cases at CCW disposal sites that suggests that arsenic III is rapidly converted to arsenic V during subsurface transport, with the result that drinking water standards are rarely exceeded in offsite groundwater in spite of high landfill leachate concentrations (see, for example, U.S. EPA, 2000; U.S. EPA, 2003e; Lang and Schlictmann, 2004; Zillmer and Fauble, 2004). To address this uncertainty (i.e., how much an arsenic III assumption might overpredict offsite well concentrations) the models were run assuming arsenic V as the arsenic species in soil and groundwater. Figure 4-4 compares the risk results for arsenic III and arsenic V. Arsenic V has lower risks than arsenic III by about a factor of two, but the 90th percentile risks are still above risk criteria.

Bioavailability of Constituents to Ecological Receptors. For the purposes of this analysis, the model assumes that all forms of a constituent are equally bioavailable to ecological receptors, and therefore, the actual exposures that may occur in the field tend to be overestimated, thus making this a protective assumption. Both the chemical form and the environmental conditions influence bioavailability and ultimately the expression of adverse effects. For example, as discussed above, the form of arsenic has been shown to profoundly influence mobility and toxicity.

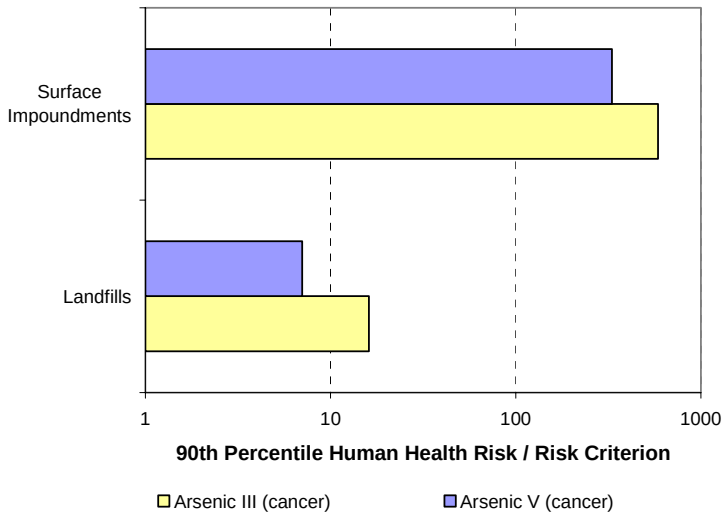


Figure 4-4. Comparison of risk results for arsenic III and arsenic V (based on results for all units combined).

Multiple Constituent Exposures to Receptors. The risk from each constituent was considered separately in this analysis. However, the waste concentration data on CCWs (as well as recent field studies such as U.S. EPA, 2006) suggest that exposure to multiple constituents is highly likely. The synergism or antagonism between different constituent combinations may elicit unexpected adverse impacts to humans and ecosystems. Hence, a single-constituent analysis may underestimate risks associated with multiple chemical stressors.

4.4.3 Parameter Uncertainty and Variability

Parameter uncertainty occurs when (1) there is a lack of data about the values used in the equations, (2) the data that are available are not representative of the particular instance being modeled, or (3) parameter values have not been measured precisely or accurately because of limitations in measurement technology. Random, or sample, errors are a common source of parameter uncertainty that is especially critical for small sample sizes, as illustrated by the FBC waste results discussed in Section 4.1.3.2. More difficult to recognize and address are nonrandom or systematic errors that can bias the analyses from sampling errors, faulty experimental designs, or bad assumptions.

Spatial and temporal variability in parameters used to model exposure account for the distribution in the exposed population. For example, the rainfall or precipitation rates used to calculate infiltration and recharge to groundwater are measured daily by the National Weather Service at many locations throughout the United States, and statistics about these parameters are well documented. Although the distributions of these parameters may be well known, their actual values vary spatially and temporally and cannot be predicted exactly. Thus, the annual average infiltration rates used in the source model for a particular climate station will provide information on average conditions appropriate for this analysis. Additionally, using data from multiple climate stations located throughout the United States can account for some, but not all, spatial variability.

4.4.3.1 Waste Concentrations

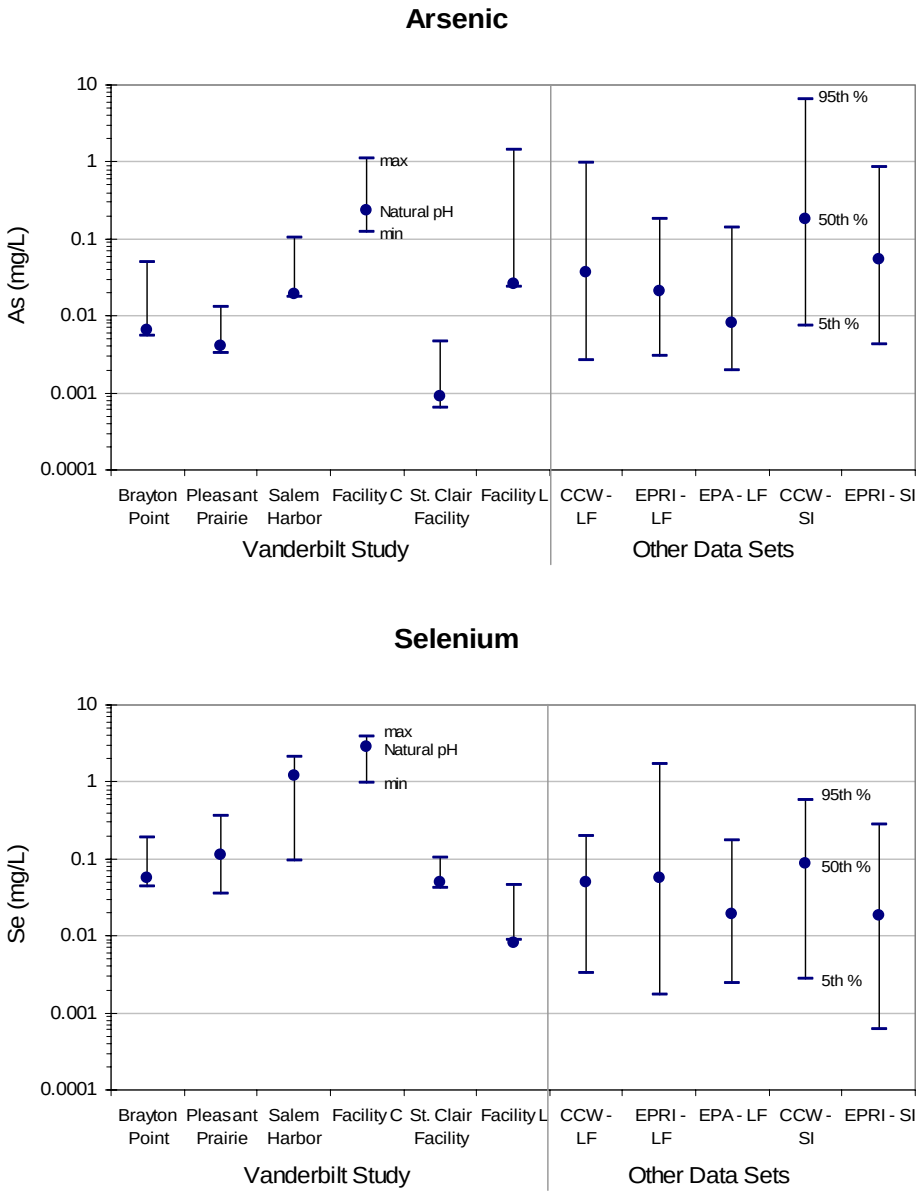
The CCW constituent database used to represent CCW total waste and waste leachate concentrations is arguably the most important data set in terms of driving the risk assessment results. The constituent data are subject to two primary uncertainties beyond the normal sampling and analysis uncertainty associated with environmental measurements: (1) the appropriateness of the landfill leachate data used in the analysis and (2) high percentages of nondetect analyses for some CCW constituents.

Appropriateness of Leachate Data. The CCW leachate data were collected from a varying number of sites using a variety of methods. The available landfill data are largely derived from the TCLP, a laboratory test designed to estimate leachate concentrations in municipal solid waste (MSW) landfills. The TCLP has been shown to both over and underpredict leachate concentrations for other waste disposal scenarios, so the use of the TCLP data to represent CCW leachate is another source of uncertainty. However, as noted below, this does not appear to be a significant source of uncertainty for this analysis.

Surface impoundment leachate is represented by porewater data taken beneath actual impoundments, but although these data arguably should better represent leachate concentrations, they are fewer in number than the landfill data and therefore subject to uncertainty as to how representative they are of all CCW wastes. Antimony, cobalt, mercury, and thallium are represented by one to only a few sites and only a few measurements, and results associated with these metals should be interpreted with caution. Results for surface impoundments for antimony, mercury, and thallium are not presented due to the paucity of leachate data (1 or 2 sites, and 11 or fewer values).

Since the CCW risk assessment was been conducted in 2003, EPA-sponsored research conducted by Vanderbilt University has improved the scientific understanding of the generation of leachate from CCW, in particular for mercury, arsenic, and selenium (U.S. EPA, 2006). Figure 4-5 plots the results from this study for arsenic and selenium, along with data from EPA's Leach2000 database and EPRI (as provided in U.S. EPA, 2006), against the data used for landfills and surface impoundments used in the CCW analysis. For the Vanderbilt leaching study, data are provided for each ash tested, with the minimum, maximum, and value at natural pH plotted on the chart. Percentile values (95th, 50th, 5th) are plotted for the compiled data sets (EPA, EPRI, and CCW), and mercury is not modeled for landfills because of a high number of nondetects.

For arsenic, the CCW values bracket the range found in the other studies. Selenium values also agree fairly well for CCW landfill data, although the CCW landfill values appear to be lower than some of the values from the other studies, suggesting that selenium risks may be somewhat underestimated for landfills in this analysis. This is significant even though selenium risks from landfills were not above the risk criteria in this analysis, because selenium is often reported as a constituent of concern (along with arsenic and boron) in CCW damage cases (U.S. EPA, 2000; U.S. EPA, 2003e; Lang and Schlictmann, 2004; Zillmer and Fauble, 2004).



Key to data sets:

Vanderbilt = U.S. EPA (2006)
CCW = CCW Constituent Database (this analysis)
EPRI = EPRI Leachate data (from U.S. EPA, 2006)
EPA = Leach 2000 data (from U.S. EPA, 2000)
LF = landfills
SI = surface impoundments

Figure 4-5. Comparison of CCW leachate data with other leachate data.

Although the Vanderbilt Study does not cover all of the metals addressed in the CCW analysis, its general agreement with the CCW arsenic and selenium levels does help allay concerns that the TCLP CCW leachate values used in the analysis markedly overestimate or underestimate the concentrations actual CCW leachate.

Mercury and Nondetect Analyses. For certain of the CCW constituents addressed in this analysis, the CCW leachate database contains a large number of nondetect measurements (concentrations below an analytical instrument's ability to measure). Table 4-18 illustrates this point by showing, by WMU type and chemical, the overall percent of nondetect values for each chemical and the percent of site-averaged values[11] that are composed entirely of nondetect measurements. Constituents that could not be addressed in this analysis because of a high number of nondetects include mercury (for landfills and surface impoundments) and thallium, antimony, and cobalt (for surface impoundments only). Mercury is of particular interest because it is the only constituent with significant concern through the fish consumption pathway, and because there is the potential for mercury concentrations in CCW to increase as flue gas mercury controls are installed on coal-fired power plants in response to the Clean Air Interstate Rule (CAIR) and the Clean Air Mercury Rule (CAMR).

Recent work by Vanderbilt University (U.S. EPA, 2006) sheds some light on mercury concentrations in leachate from some CCWs. Figure 4-6 plots the CCW distribution of mercury concentrations (assuming half the detection limit for mercury values below detection) against results from the Vanderbilt work and recent data collected by EPRI (U.S. EPA, 2006). Assuming half the detection limit, the CCW mercury leachate values are about an order of magnitude or more higher than the Vanderbilt or EPRI data. With a single CCW leachate analysis available for surface impoundments, it is difficult to draw firm conclusions, but the concentration value, which corresponds to a 90th percentile HQ of 20, is above the maximum value shown in the other studies. In short, the mercury levels in the CCW database are not useful because of high detection limits. In addition, the Vanderbilt study found that older mercury analyses, like the ones in the CCW database, could be biased high because of cross-contamination issues.

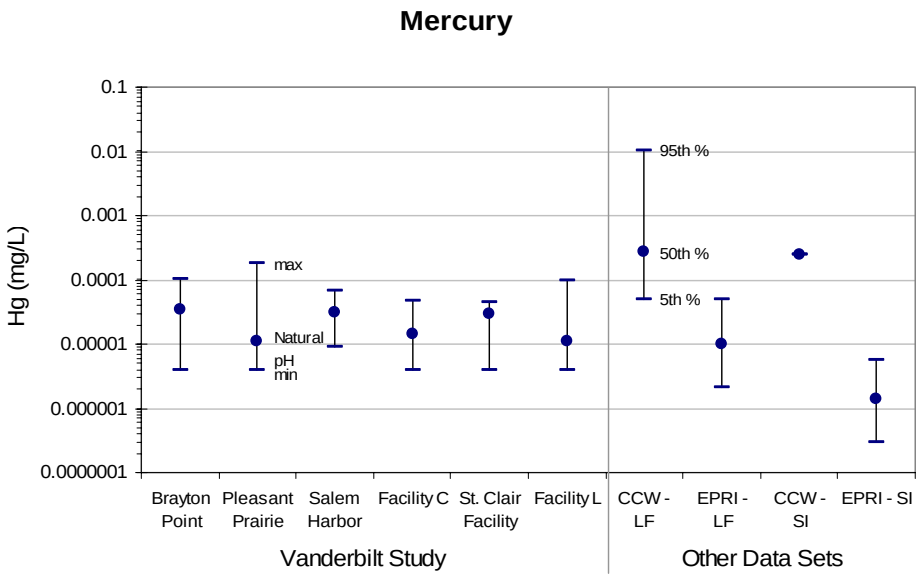
Finally, U.S. EPA (2006) and preliminary results of ongoing EPA studies suggest that both mercury levels and mercury leachability in CCW can vary depending on the flue gas mercury controls used at a power plant. Additional work is underway in this area.

[11] As explained in Appendix A, the CCW risk assessment uses site-averaged constituent concentrations. That is, an average value was used when there were multiple measurements for a chemical at a particular site.

Table 4-18. Proportion of Nondetect Analyses for Modeled CCW Constituents

Chemical	Measurements		Sites	
	Number	% nondetects	Number	% with all nondetects
Landfills				
Aluminum	397	18%	61	5%
Antimony	496	50%	66	41%
Arsenic	1182	49%	128	20%
Barium	1225	11%	126	5%
Boron	930	8%	83	2%
Cadmium	1237	50%	124	31%
Cobalt	559	56%	52	19%
Lead	1109	60%	125	30%
Mercury	***974***	***91%***	***101***	***58%***
Molybdenum	373	24%	58	10%
Nitrate/Nitrite	141	48%	20	15%
Selenium	1227	49%	131	17%
Thallium	402	60%	40	45%
Surface Impoundments				
Aluminum	158	10%	16	6%
Antimony	***11***	***100%***	***2***	***100%***
Arsenic	155	16%	16	6%
Barium	161	14%	16	13%
Boron	164	7%	171	6%
Cadmium	164	68%	16	50%
Cobalt	49	59%	4	50%
Lead	138	78%	14	36%
Mercury	***1***	***100%***	***1***	***100%***
Molybdenum	161	37%	17	24%
Nitrate/Nitrite	267	59%	14	7%
Selenium	140	33%	15	20%
Thallium	***11***	***100%***	***2***	***100%***

Results for constituents shown in ***bold italics*** were not presented in this report because of high detection limits or limited data.



Key to data sets:

Vanderbilt	=	U.S. EPA (2006)
CCW	=	CC Constituent Database (this analysis)
EPRI	=	EPRI Leachate data (from U.S. EPA, 2006)
EPA	=	Leach 2000 data (from U.S. EPA, 2000)
LF	=	landfills
SI	=	surface impoundments

Figure 4-6. CCW mercury concentrations compared with other leachate data.

4.4.3.2 WMU Locations and Characteristics

The locations of the specific sites in the United States where CCW is disposed are known, and EPA used the soil and climatic characteristics of these sites in the Monte Carlo analysis. Because most locations were facility front gates or centroids, the exact location of the CCW landfill or surface impoundment was not known. To account for this uncertainty, soil data were collected for an area around the plant and soil type distributions were sampled in the Monte Carlo analysis. Climate center assignments were combined with the soil texture distributions to select infiltration and recharge rates to use in the analysis.

WMU area, depth, volume, and liner type were not varied in the Monte Carlo analysis because values for these variables were known from the EPRI survey data. More uncertain parameters, like depth below grade, were varied within reasonable ranges. These data were used in the source model calculations to generate the distribution of environmental releases used by the fate and transport modeling.

Three standard WMU liner scenarios (clay, composite, and unlined) were assigned to each facility based on best matches to data in the EPRI survey on liner type. Infiltration through these liners was then modeled using assumptions, models, and data developed in support of EPA's Industrial Subtitle D guidance. How well these assumptions and models represent the

performance of CCW WMU landfills and surface impoundments is an uncertainty in this analysis.

4.4.3.3 Fate and Transport Model Variables

The parameter values required to model contaminant fate and transport in groundwater were obtained from site-specific, regional, and national databases. Hydrogeologic environment was assigned to each site, based on geologic maps and soil conditions; where assignments were uncertain, two or three settings might be used in the Monte Carlo analysis. Because aquifer properties are highly variable and uncertain, reasonable sets of aquifer properties were selected, based on hydrogeologic environment, from a hydrogeologic database.

Receptor Location (Drinking Water Wells). The sensitivity analysis (Section 4.3) showed that distance of a receptor from the contaminant source is an important influence on media concentration, especially for contaminants that strongly sorb to soil and aquifer materials. For the groundwater-to-drinking-water pathway, receptor location was represented as the distance and position, relative to a contaminant plume, of residential drinking water wells from the WMU. Because no data were readily available on the distance of CCW disposal sites from residential wells, EPA used data from a survey of well distances from MSW landfills. Whether or not this is an accurate representation of well distance for CCW landfills and surface impoundment is one of the larger uncertainties in this analysis. EPA believes that the MSW well distance distribution used is protective for CCW landfills and surface impoundments.

Location and Characteristics of Waterbodies. One aspect of the site configuration of particular relevance to the aquatic food chain modeling is the locations and characteristics of the waterbodies. The size of the waterbodies (and the distance from the WMU) affects constituent concentrations and loadings predicted for that waterbody. The location of the waterbody was based on an empirical distribution of measurements, taken from actual CCW sites, of the distance from the edge of the WMU to the nearest stream or lake. The uncertainty posed in this analysis is the sampling of this distribution as compared to a more certain measurement of the actual distance at each CCW site. Surface water variables, including flow and water quality parameters, were collected for the stream reach being modeled, or for a larger hydrologic region where data were not available for a particular reach.

Environmental Parameters. Uncertainties related to environmental parameters (soil, aquifer, surface water, climate data) have already been mentioned. The parameters with the largest impact on results are aquifer hydraulic conductivity and gradient, which are selected from a national database of aquifer properties.

Fish Bioconcentration and Bioaccumulation Factors. For fish consumption, exposure dose is calculated using BCFs to estimate the transfer of pollutants from environmental media into fish. Uncertainty is associated with models used to estimate BCFs for aquatic biota. The aquatic BCFs were developed based on total surface water concentrations and concentrations in aquatic biota.

4.4.3.4 Exposure and Risk Modeling Variables

Exposure parameters and benchmarks for human and ecological risk also contribute to parameter variability and uncertainty.

Human Exposure Factors. Individual physical characteristics, activities, and behavior are quite different, and thus the exposure factors that influence the exposure of an individual, including ingestion rate, body weight, and exposure duration, are quite variable. Exposure modeling relies heavily on default assumptions concerning population activity patterns, mobility, dietary habits, body weights, and other factors. The probabilistic assessment for the adult and child exposure scenario addressed the possible variability in the exposure modeling by using statistical distributions for these variables for each receptor in the assessment: adult and child resident and adult and child recreational fisher. Data on fish consumption rates are not available for children; thus the adult data were used for children in this analysis, which could overestimate risk from this pathway for children. For all exposure factors varied, a single exposure factor distribution was used for adults for both males and females. For child exposures, one age (age 1) was used to represent the age at the start of exposure, because this age group is considered to be most sensitive for most health effects.

The *Exposure Factors Handbook* (U.S. EPA, 1997c,d,e) provides the current state of the science concerning exposure assumptions, and it was used throughout this assessment to establish statistical distributions of values for each exposure parameter for each receptor. There are some uncertainties, however, in the data that were used. Although it is possible to study various populations to determine various exposure parameters (e.g., age-specific soil ingestion rates or intake rates for food) or to assess past exposures (epidemiological studies) or current exposures, risk assessment is about prediction. Therefore, long-term exposure monitoring in this context is infeasible.

Diet Assumptions for Ecological Receptors. National-scale assessments often assume maximum intake of contaminated prey in the diets of primary and secondary consumers (i.e., 100 percent of the diet originates from the contaminated area). Under field conditions, many receptors are opportunistic feeders with substantial variability in both the type of food items consumed as well as the geospatial patterns of feeding and foraging. The actual proportion of wildlife receptors' diets that would be contaminated depends on a number of factors such as the species' foraging range, quality of food source, season, intra- and interspecies competition. Consequently, the exclusive diet of contaminated food items tends to provide a very conservative estimate of potential risks.

Human Health Benchmarks. EPA routinely accounts for uncertainty in its development of RfDs and other human health benchmarks. For example, if certain toxicological data are missing from the overall toxicological database (e.g., reproductive data), EPA accounts for this by applying an uncertainty factor. In general, EPA human health benchmarks are derived using a health-protective approach.

Ecological Criteria. CSCLs were developed for constituents when sufficient data were available. In many cases, sufficient data were unavailable for a receptor/constituent combination, and therefore, the potential risk to a receptor could not be assessed. In particular, insufficient

data were available to derive chronic effects CSCLs for amphibians. Because the risk results can only be interpreted within the context of available data, the absence of data can not be construed to mean that adverse ecological effects will not occur.

In addition to the effects of data gaps on ecological benchmarks, the ecological criteria tend to be fairly conservative because the overall approach is based on "no effects" or "lowest effects" study data. In site-specific assessments, a *de minimis* effects approach is often replaced with an effects level similar to natural population variability (e.g., sometimes as high as a 20 percent effects level). As a result, the CSCLs used in this analysis are likely to overestimate risks for representative species and communities assumed to live in surface waters impacted by CCW WMUs. Because the difference between a lowest observed adverse effect level (LOAEL) and a NOAEL is often about a factor of 10, an HQ exceedance of roughly 10 may not be ecologically significant. In contrast, CSCLs based on no effects data that are developed for the protection of threatened and endangered species are presumed to be protective.

4.5 Summary and Conclusions

One of the most sensitive parameters in the risk assessment is infiltration rate. Infiltration rate is greatly influenced by whether and how a WMU is lined. The 1994 to 2004 DOE/EPA survey results (U.S. DOE, 2006) do not include how many unlined facilities are still operating today, but do indicate that more facilities are lined today than were in the 1995 EPRI survey data set on which this risk assessment is based. This suggests that the risks from future CCW disposal facilities are likely to be lower than the results presented in this report. EPA will continue to work to integrate the DOE/EPA survey data into the CCW risk assessment and is seeking comments on how to address data gaps, in particular: (1) how to estimate the overall prevalence of liners in the CCW disposal facilities today, (2) how to determine the area and capacity of newer CCW landfills and surface impoundments, and (3) how the liners currently in CCW WMUs perform when compared to the industrial liner conditions assumed in this risk assessment.

Composite liners, as modeled in this risk assessment, effectively reduce risks from all pathways and constituents below the risk criteria for both landfills and surface impoundments.[12] The CCW risk assessment suggests that the management of CCW in unlined landfills and unlined surface impoundments may present risks to human health and the environment. Risks from clay-lined units, as modeled, are about one-third to one-half the risks of unlined units, but are still above the risk criteria used for this analysis. These risk results are largely consistent with damage cases compiled by EPA (U.S. EPA, 2000, 2003e, 2007) and others (Lang and Schlictmann, 2004; Zillmer and Fauble, 2004; Carlson and Adriano, 1993). Key risk findings include the following:

- For humans exposed via the groundwater-to-drinking-water pathway, arsenic in CCW landfills poses a 90th percentile cancer risk of $5x10^{-4}$ for unlined units and $2x10^{-4}$ for clay-lined units. The 50th percentile risks are $1x10^{-5}$ (unlined units) and $3x10^{-6}$(clay-lined

[12] These results suggest that with the higher prevalence of composite liners in new CCW disposal facilities, future national risks from onsite CCW disposal are likely to be lower than those presented in this risk assessment (which is based on 1995 CCW WMUs).

units). Risks are higher for surface impoundments, with an arsenic cancer risk of $9x10^{-3}$ for unlined units and $3x10^{-3}$ for clay-lined units at the 90th percentile. At the 50th percentile, risks for unlined surface impoundments are $3x10^{-4}$, and clay-lined units show a risk of $9x10^{-5}$. Five additional constituents have 90th percentile noncancer risks above the criteria (HQs ranging from greater than 1 to 4) for unlined surface impoundments, including boron and cadmium, which have been cited in CCW damage cases referenced above. Boron and molybdenum show HQs of 2 and 3 for clay-lined surface impoundments. None of these noncarcinogens show HQs above 1 at the 50th percentile for any unit type.

- Arrival times of the peak concentrations at a receptor well are much longer for landfills (hundreds to thousands of years) than for surface impoundments (most less than 100 years).
- For humans exposed via the groundwater-to-surface-water (fish consumption) pathway, selenium (HQ = 2) and arsenic (cancer risk = $2x10^{-5}$) pose risks slightly above the risk criteria for unlined surface impoundments at the 90th percentile. For both constituents, lined 90th percentile risks and all 50th percentile risks are below the risk criteria. No constituents pose risks above the risk criteria for landfills at the 90th or 50th percentile.
- Waste type has little effect on landfill risk results, but in surface impoundments, risks are up to 1 order of magnitude higher for codisposed CCW and coal refuse than for conventional CCW.
- The higher risks for surface impoundments than landfills are likely due to higher waste leachate concentrations, a lower proportion of lined units, and the higher hydraulic head from the impounded liquid waste. This is consistent with damage cases reporting wet handling as a factor that can increase risks from CCW management.
- For ecological receptors exposed via surface water, risks for landfills exceed the risk criteria for boron and lead at the 90th percentile, but 50th percentile risks are well below the risk criteria. For surface impoundments, 90th percentile risks for several constituents exceed the risk criteria, with boron showing the highest risks (HQ = 2,000). Only boron exceeds the risk criteria at the 50th percentile (HQ = 4). Exceedances for boron and selenium are consistent with reported ecological damage cases, which include impacts to waterbodies through the groundwater-to-surface-water pathway.
- For ecological receptors exposed via sediment, 90th percentile risks for lead, arsenic, and cadmium exceeded the risk criteria for both landfills and surface impoundments because these constituents strongly sorb to sediments in the waterbody. The 50th percentile risks are generally an order of magnitude or more below the risk criteria.

Sensitivity analysis results indicate that for most of the scenarios evaluated (over 75 percent), the risk assessment model was most sensitive to parameters related to groundwater flow and transport: WMU infiltration rate, leachate concentration, and aquifer hydraulic conductivity and gradient. For strongly sorbing contaminants (such as lead and cadmium), variables related to sorption and travel time (adsorption coefficient, depth to groundwater, receptor well distance) are most important.

There are uncertainties associated with the CCW risk assessment, but scenario uncertainty (i.e., uncertainty about the environmental setting around the plant) has been minimized by basing the risk assessment on conditions around existing U.S. coal-fired power plants around the United States. Uncertainty in environmental setting parameters has been incorporated into the risk assessment by varying these inputs within reasonable ranges when the exact value is not known. Uncertainty in human exposure factors (such as exposure duration, body weight, and intake rates) has also been addressed through the use of national distributions.

Some uncertainties not addressed explicitly in the risk assessment have been addressed through comparisons with other studies and data sources.

- **Appropriateness of CCW leachate data.** Data on another highly sensitive parameter, leachate (porewater) constituent concentration, were available and used for CCW surface impoundments. However, available data for landfills were mainly TCLP analyses, which may not be representative of actual CCW leachate. Comparisons with recent (2006) studies of coal ash leaching processes show very good agreement for arsenic. However, although the selenium CCW data are within the range of the 2006 data, some of the higher concentrations in the 2006 data are not represented by the TCLP data. This suggests that selenium risks may be underestimated, which is consistent with selenium as a common driver of the damage cases.
- **Impacts of mercury rules (CAIR and CAMR).** While CAIR and CAMR will reduce emissions of mercury and other metals from coal-fired power plants, mercury and other more volatile metals will be transferred from the flue gas to fly ash and other air pollution control residues, including the sludge from wet scrubbers. EPA ORD has research underway to evaluate changes to CCW characteristics and leaching of mercury and other metals from CAIR and CAMR. Data from the first report (U.S. EPA, 2006) suggest that although total mercury will increase in CCW from the use of sorbents as mercury controls, the leachability of mercury may be reduced, but this work is ongoing and should be regarded as preliminary and limited at this time. For example, wet scrubbers have yet to be addressed, and initial data from both EPA and industry studies suggest that mercury may not be as stable as found from fly ash in the first report. As these data become available, EPA will consider how best to use them to update the existing risk assessment.
- **Mercury and nondetect analyses.** Because of a high proportion of nondetect values and a limited number of measurements, the risks from mercury in CCW could not be evaluated for either landfills or surface impoundments and for antimony and thallium in surface impoundments. The 2006 leaching study data suggest that mercury levels are fairly low in fly ash from coal combustion, but additional data and analyses would be required to estimate the risks from these levels.
- **Arsenic speciation.** The current model does not speciate metals in the subsurface, which is of particular concern for arsenic. Damage cases and other studies suggest that arsenic readily converts from arsenic III in CCW leachate to the less mobile arsenic V in soil and groundwater. However, model runs conducted for both species suggest that the difference in risk between the two species is only about a factor of 2, which is not enough to reduce the 90th percentile cancer risks to below the risk criteria.

Uncertainties that are more difficult to evaluate with respect to CCW risk results include the following:

- **Well distance.** Nearest well distances were taken from a survey of MSW landfills, as data were not available from CCW sites. EPA believes that this is a protective assumption because MSW landfills generally tend to be in more populated areas, but there are little data available to test this hypothesis.
- **Liner conditions.** Liner design and performance for CCW WMUs were based on data and assumptions EPA developed to be appropriate for nonhazardous industrial waste landfills. EPA believes that CCW landfills should have similar performance characteristics, but does not have the quantitative data to verify that.
- **Data gaps for ecological receptors.** Insufficient data were available to develop screening levels and quantitative risk estimates for terrestrial amphibians, but EPA acknowledges that damage cases indicate risk to terrestrial amphibian and plant communities through exposure to selenium and boron.
- **Ecosystems and receptors at risk.** Certain critical assessment endpoints were not evaluated in this analysis, including impacts on managed lands, critical habitats, and threatened and endangered species. These would be addressed through more site-specific studies on the proximity of these areas and species to CCW disposal units.
- **Synergistic risk.** The impact of exposures of multiple contaminants to human and ecological risks was not evaluated in this analysis. EPA recognizes that a single-constituent analysis may underestimate risks associated with multiple chemical exposures.

These are potentially the more significant uncertainties associated with the CCW risk assessment. Other uncertainties are discussed in Section 4.4.

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Appendix A. Constituent Data

The coal combustion waste (CCW) risk assessment addresses metals and inorganic constituents identified by EPA as potential constituents of concern in CCW (Table A-1). U.S. Environmental Protection Agency (EPA) derived waste concentrations for these constituents from its CCW constituent database, which includes analyte concentration data in three tables representing different types of waste samples: landfill leachate analyses (in mg/L), surface impoundment and landfill porewater analyses (in mg/L), and analyses of whole waste samples (in mg/kg). Each database table specifies, for most samples, the type of waste sampled and the type of coal burned at the facility.

Table A-1. Constituents Addressed in the Screening Analysis

Constituent	CAS ID	Constituent	CAS ID
Metals		***Inorganic Anions***	
Aluminum	7429-90-5	Chloride	16887-00-6
Antimony	7440-36-0	Cyanide	57-12-5
Arsenic	7440-38-2	Fluoride	16984-48-8
Barium	7440-39-3	Total Nitrate Nitrogen	14797-55-8
Beryllium	7440-41-7	Phosphate	14265-44-2
Boron	7440-42-8	Silicon	7631-86-9
Cadmium	7440-43-9	Sulfate	14808-79-8
Chromium	7440-47-3	Sulfide	18496-25-8
Cobalt	7440-48-4	***Inorganic Cations***	
Copper	7440-50-8	Ammonia	7664-41-7
Iron	7439-89-6	Calcium	7440-70-2
Lead	7439-92-1	pH	12408-02-5
Magnesium	7439-95-4	Potassium	7440-09-7
Manganese	7439-96-5	Sodium	7440-23-5
Mercury	7439-97-6	***Nonmetallic Elements***	
Molybdenum	7439-98-7	Inorganic Carbon	7440-44-0
Nickel	7440-02-0	Total Elemental Sulfur	7704-34-9
Selenium	7782-49-2	***Measurements***	
Silver	7440-22-4	Total Dissolved Solids	none
Strontium	7440-24-6	Total Organic Carbon	none
Thallium	7440-28-0	Dissolved Organic Carbon	none
Vanadium	7440-62-2		
Zinc	7440-66-6		

A.1 Data Sources

EPA prepared the CCW constituent database in 2002 and 2003. The 2003 CCW constituent database includes all of the waste characterization data used by EPA in its risk assessments in support of the March 1999 *Report to Congress: Wastes from the Combustion of Fossil Fuels* (the RTC) (U.S. EPA, 1999). In addition to the data set from the March 1999 RTC, EPA supplemented the database with the following data:

- Data submitted with public comments to EPA on the 1999 RTC
- Data submitted with public comments to EPA concerning the May 22, 2000, Final Regulatory Determination
- Data collected by and provided to EPA since the end of the public comment period on the Final Regulatory Determination
- Data identified from literature searches.

The primary sources of these additional data include the electric power industry, state and federal regulatory agencies, and scientific literature. Attachment A-1 is a complete list of the sources of data contained in the 2003 CCW constituent database.

The additional data represent a significant expansion in the quantity of characterization data available to EPA for analysis. For example, the data set used for the risk assessments supporting the RTC covered approximately 50 CCW generation and/or disposal sites. With the addition of the supplemental data, the 2003 CCW constituent database now covers more than 160 sites. The 1999 data set included approximately 10,000 individual samples of CCW. The 2003 CCW constituent database now includes more than 35,000 individual samples.

The additional data also represent an expansion in the scope of characterization data available to EPA for analysis. The 1999 data were obtained exclusively from the electric power industry. As shown in Attachment A-1, the 2003 data set includes data from other sources, such as scientific literature and state and federal regulatory agencies. The 1999 data set included analyses of whole waste samples, surface impoundment and landfill porewater analyses, and analyses of extracts obtained using the Toxicity Characteristic Leaching Procedure (TCLP), the Synthetic Precipitation Leaching Procedure (SPLP), and Extraction Procedure (EP) Toxicity leaching methods. The 2003 data set adds analyses of actual landfill leachate (e.g., obtained from leachate collection systems), analyses of extracts obtained using other leaching methods (including higher retention time leaching methods), and porewater analyses.

The 2003 CCW constituent database represents CCW characteristics across a broad cross section of the generating universe. Not only does the database include data from a large number of sites, but these sites are distributed throughout the United States, as shown in Table A-2. The database includes data for all major types of CCW (i.e., fly ash, bottom ash, flue gas desulfurization [FGD] sludge, fluidized bed combustion [FBC] fly ash, and FBC bed ash), from mixtures of CCW types that are commonly created during disposal operations (e.g., combined fly ash and bottom ash), and from CCW mixed with coal refuse (a common disposal practice). Section A.2 discusses waste types in more detail.

Table A-2. States Included in the CCW Constituent Database

Alaska	Illinois	Maryland
Arkansas	Indiana	Michigan
California	Kentucky	Ohio
Colorado	Missouri	Oklahoma
Connecticut	North Carolina	Pennsylvania
Florida	North Dakota	Tennessee
Georgia	Nebraska	Texas
Hawaii	New Mexico	Wisconsin
Iowa	Louisiana	West Virginia

The database also includes data for CCW generated from combustion of all major coal ranks: bituminous, sub-bituminous, lignite, and anthracite. Although the database does include coal type designations for most of the entries, in many cases the type is not specified. In addition, many coal plants mix coal from different sources (e.g., eastern and western coals), depending on prices and the need to reduce sulfur levels. As a result, correlations of risk results with coal types may be difficult and may not produce significant results.

A.2 Data Preparation

Table A-3 lists the waste types evaluated in the CCW risk assessment, along with the number of sites representing each waste type in the CCW constituent database. Key steps in preparing these data for screening include (1) selection and grouping of waste types to be addressed, (2) selection of the analyte data to be used, and (3) processing of these data to develop the analyte concentrations for the screening analysis.

Table A-3. Waste Streams in CCW Constituent Database

Waste Type **Waste Streams**	**Number of Sites by Waste Type[a]**		
	Landfill Leachate	**Surface Impoundment Porewater**	**Total Waste**
Conventional Combustion Waste	*97*	*13*	*62*
Ash (not otherwise specified)	43	0	30
Fly ash	61	2	33
Bottom ash & slag	24	3	23
Combined fly & bottom ash	7	4	4
FGD sludge	4	6	5
Codisposed Ash & Coal Refuse	9	5	1
Fluidized Bed Combustion Waste	*58*	*0*	*54*
Ash (not otherwise specified)	18	0	10
Fly ash	33	0	32
Bottom and bed ash	26	0	25
Combined fly & bottom ash	20	0	22

[a] Site counts by waste type from leachate, porewater, and whole waste data tables in the 2003 CCW constituent database.

A.2.1 Selection and Grouping of Waste Types of Concern

The CCW constituent database contains a variety of waste types. Some selection and grouping of these types was appropriate so that the risk assessment could evaluate risks consistently for groups of wastes that are expected to behave similarly when disposed in landfills and surface impoundments.

Combustion ash types in the CCW constituent database include fly ash, bottom ash, bed ash, slag, combined fly and bottom ash, and coal ash not otherwise specified. Based on a statistical analysis that showed no significant difference in leachate and porewater chemistry, the analysis combines data for these ash types for landfills and surface impoundments. FGD sludge is also combined with these conventional combustion ash types based on insignificant differences in porewater chemistry and the fact that FGD sludge is usually codisposed with varying amounts of fly ash and bottom ash.

CCW porewater constituent data did show that FBC wastes and codisposed ash and coal refuse (coal waste from coal crushers and other coal preparation and handling operations[1]) differ significantly from coal combustion ash in their composition and leachate chemistry, so these wastes were addressed separately in the risk analysis. FBC waste chemistry is impacted by the limestone injected with coal in FBC units for sulfur capture and tends to be very alkaline with high levels of calcium and sulfate. Coal refuse is high in pyrite, which generates sulfuric acid when disposed. As a result, combustion wastes exhibit a lower pH when codisposed with coal refuse.

A.2.2 Selection of Appropriate Analyte Data

CCW analyte concentration data represent leachate from landfills and surface impoundments and whole waste in landfills, as follows:

- Whole waste analyte concentrations (in mg/kg) represent landfill waste.
- Analyte concentrations (in mg/L) in porewater sampled from surface impoundment sediments represent surface impoundment leachate.
- Analyte concentrations for extracts from leaching methods, analyses of actual landfill leachate, and landfill porewater analyses represent landfill leachate. Because the CCW constituent database includes analyte concentrations from several leaching methods, a decision hierarchy was used to select leachate analyses to use in the risk assessment (Table A-4).

As shown in Table A-4, the methods thought to best represent long-term waste monofill porewater composition (i.e., methods with long equilibration times and low liquid-to-solid ratios) represent only a few sites, with most sites having TCLP and/or SPLP measurements. To best represent CCW landfill waste concentration at a wide variety of sites, the hierarchy rank shown in Table A-4 was used to select the best method for a particular site. For sites where two or more

[1] Coal refuse is the waste coal produced from coal handling, crushing, and sizing operations. In the CCW constituent database, codisposed coal refuse includes “combined ash and coal gob”, “combined ash and coal refuse”, and “combined bottom ash and pyrites”.

methods are available in the same rank (which often occurs for SPLP and TCLP analyses), the screening analysis uses the method with the highest analyte concentrations. This ensures that the data used in the risk assessment are the best that are available and represent a broad variety of waste disposal conditions.

Table A-4. Comparison/Hierarchy of Leaching Methods for Landfills Represented in CCW Constituent Database

Method (Rank)	Description	Advantages	Disadvantages
Landfill leachate (1)	Direct samples of landfill leachate	Most representative of leachate chemistry	Low number of sites represented
Landfill porewater (1)	Direct porewater samples from landfill	Most representative of leachate chemistry	Low number of sites represented
High retention time and low liquid-to-solid ratio (L:S) methods (2)	Waste extractions with long equilibration times (days to weeks) and low L:S	Better representation of landfill equilibration times and L:S	Low number of sites represented
Low L:S methods (3)	Waste extractions with low L:S	Better representation of landfill L:S	Low number of sites represented; equilibrium times relatively short
High retention time methods (3)	Waste extractions with long equilibration times (days to weeks)	Better representation of landfill equilibration times	Low number of sites represented; L:S relatively high
TCLP (4)	Toxicity Characteristic Leaching Procedure waste extractions	Most representative in terms of number of sites, waste types covered	High L:S (20:1) can dilute leachate concentrations; short equilibration time (18 hours) may not allow equilibrium to develop; Na-acetate buffer can overestimate leaching for some constituents (e.g., Pb)
SPLP (4)	Synthetic Precipitation Leaching Procedure and other dilute water waste extractions	More representative in terms of number of sites, waste types covered; extract similar to precipitation	High L:S (20:1) can dilute leachate concentrations; short equilibration time (18 hours) may not allow equilibrium to develop

A.2.3 Development of Waste Constituent Concentrations

To allow risk assessment results to be organized by waste constituent and waste type, CCW data were processed to produce a single concentration per waste stream (surface impoundment porewater, landfill leachate, and landfill whole waste), analyte, and site for use in the risk assessment. Data processing to prepare these analyte concentrations for the CCW risk assessment involved two steps:

1. **Calculation of average constituent concentrations by site for landfill leachate, surface impoundment porewater, and total ash concentrations.** Site averaging avoids potential bias toward sites with many analyses per analyte. During site averaging, any separate waste disposal scenarios occurring at a site (e.g., non-FBC and FBC ash) were treated as separate "sites" and were averaged independently. This approach is consistent with that used in the 1998 CCW risk analysis. As in 1998, nondetects were averaged at one-half the reported detection limit.

2. **Selection of waste concentrations from site-averaged values.** For the Monte Carlo analysis, the analysis randomly selected, by waste type/waste management unit (WMU) scenario, site-averaged leachate concentrations. For landfills, a corresponding total waste analysis was pulled from the database or calculated from a constituent-specific relationship between landfill leachate and total waste analyses.

A.3 Constituent Screening and Selection

The CCW risk assessment employed two steps to narrow the list of CCW constituents for the full-scale Monte Carlo risk assessment. Two steps were conducted to focus the full-scale analysis on the CCW constituents of most concern:

1. **Hazard Identification**, which involved collection of existing human health and ecological benchmarks for the constituents of concern. Only chemicals with benchmarks moved on to risk screening.
2. **Constituent Screening**, which compared health-based concentration benchmarks against very conservative estimates of exposure concentrations (e.g., whole waste concentrations, leaching concentrations) to quickly and simply "screen out" constituents and exposure pathways of no significant concern.

During the hazard identification step of the CCW risk assessment, constituents of potential concern were first identified by searching, from EPA and other reputable sources, for human health and ecological benchmarks for each chemical in the CCW constituent database. Table A-5 shows the result of that search; of the 41 chemicals in the database, 26 chemicals were found to have benchmarks.

Table A-5. Toxicity Assessment of CCW Constituents

Constituent	CAS ID	HHB	EcoB	Constituent	CAS ID	HHB	EcoB
Metals				***Inorganic Anions***			
Aluminum	7429-90-5	✔	✔	Chloride	16887-00-6		
Antimony	7440-36-0	✔	✔	Cyanide	57-12-5	✔	
Arsenic	7440-38-2	✔[a]	✔	Fluoride	16984-48-8	✔	
Barium	7440-39-3	✔	✔	Nitrate	14797-55-8	✔	
Beryllium	7440-41-7	✔[a]	✔	Nitrite	14797-65-0	✔	
Boron	7440-42-8	✔	✔	Phosphate	14265-44-2		
Cadmium	7440-43-9	✔[a]	✔	Silicon	7631-86-9		
Chromium	7440-47-3	✔[a]	✔	Sulfate	14808-79-8		
Cobalt	7440-48-4	✔[a]	✔	Sulfide	18496-25-8		
Copper	7440-50-8	✔[b]	✔	***Inorganic Cations***			
Iron	7439-89-6			Ammonia	7664-41-7	✔	
Lead	7439-92-1	✔[b]	✔	Calcium	7440-70-2		
Magnesium	7439-95-4			pH	12408-02-5		
Manganese	7439-96-5	✔		Potassium	7440-09-7		
Mercury	7439-97-6	✔	✔	Sodium	7440-23-5		
Molybdenum	7439-98-7	✔	✔	***Nonmetallic Elements***			
Nickel	7440-02-0	✔	✔	Carbon	7440-44-0		
Selenium	7782-49-2	✔	✔	Sulfur	7704-34-9		
Silver	7440-22-4	✔	✔	***Measurements***			
Strontium	7440-24-6	✔		Total Dissolved Solids	none		

Constituent	CAS ID	HHB	EcoB	Constituent	CAS ID	HHB	EcoB
Thallium	7440-28-0	✔	✔	Total Organic Carbon	none		
Vanadium	7440-62-2	✔	✔	Dissolved Organic Carbon	none		
Zinc	7440-66-6	✔	✔				

HHB = human health effect benchmark; EcoB = ecological benchmark.
[a] Carcinogen.
[b] Safe Drinking Water Act Action Level only.

To further narrow the list of constituents, a screening analysis (RTI, 2002) was conducted that compared health-based concentration benchmarks against very conservative estimates of exposure concentrations (e.g., 95th percentile whole waste and leachate concentrations) to quickly and simply "screen out" constituents and exposure pathways posing no significant risk to human health or the environment. Based on the number of pathways with screening failures and how much each chemical exceeded a benchmark, the constituents failing this screen were divided into two groups: (1) those of marginal concern and (2) those of greater concern. Table A-6 shows each of these groups. Constituents of greater concern were subjected to the full-scale probabilistic risk assessment described in this document.

Table A-6. Screening Analysis Results: Selection and Prioritization of CCW Chemicals for Further Analysis

Analyte	Human Health – Drinking Water		Human Health – Surface Water[a]		Ecological Risk – Surface Water		Modeling Priority
	LF Rank [maxHQ]	SI Rank [maxHQ]	LF Rank [maxHQ]	SI Rank [maxHQ]	LF Rank [maxHQ]	SI Rank [maxHQ]	
Constituents of Greater Concern (Full-Scale Analysis)							
Arsenic[b]	1 [140]	1 [1,800]	2 [22]	5 [1.7]	7 [4.9]	3 [64]	1
Boron	6 [4.0]	3 [28]	-	-	2 [660]	1 [4,700]	1
Cadmium	7 [3.4]	7 [8.9]	5 [1.4]	4 [3.7]	11 [2.0]	9 [5.2]	1
Lead	4 [16]	5 [12]	-	-	3 [79]	4 [59]	1
Mercury	-	-	1 [700]	1 [65]	1 [1,400]	2 [132]	1
Selenium	11 [1.2]	13 [2.4]	4 [4.7]	3 [9.5]	8 [3.5]	8 [7.1]	1
Thallium	3 [21]	4 [19]	3 [6.3]	2 [5.7]	-	-	1
Aluminum	-	-	-	-	5 [12]	6 [27]	2
Antimony	2 [22]	10 [5.5]	-	-	-	-	2
Barium	-	-	-	-	4 [40]	7 [7.5]	2
Cobalt		6 [11]	-	-	-	5 [27]	2
Molybdenum	5 [4.2]	8 [6.8]	-	-	-	-	2
Nitrate/Nitrite	- / 12 [1.2]	2 [60]/ 15 [1.2]	-	-	-	-	2
Constituents of Marginal Concern							
Chromium VI	8 [2.3]	12 [4.2]	-	-	12 [1.8]	10 [3.3]	3
Fluoride	10 [1.8]	11 [5.2]	-	-	-	-	3
Manganese	13 [1]	9 [5.6]	-	-	-	-	3
Vanadium	9 [2.2]	14 [2.3]	-	-	10 [2.3]	12 [2.4]	3
Beryllium	-	-	-	-	9 [2.4]	-	4

Analyte	Human Health – Drinking Water		Human Health – Surface Water[a]		Ecological Risk – Surface Water		Modeling Priority
	LF Rank [maxHQ]	SI Rank [maxHQ]	LF Rank [maxHQ]	SI Rank [maxHQ]	LF Rank [maxHQ]	SI Rank [maxHQ]	
Constituents of Greater Concern (Full-Scale Analysis)							
Copper	-	-	-	-	14 [1.6]	11 [3.1]	4
Nickel	-	16 [1.3]	-	-	-	13 [1.4]	4
Silver	-	-	-	-	6 [11]	14 [1.4]	4
Zinc	-	-	-	-	13 [1.6]	-	4

LF = landfill; maxHQ = maximum hazard quotient; SI = surface impoundment.
[a] Fish consumption pathway.
[b] Arsenic values for human health are [excess cancer risk / target risk (1E-05)].

A.4 Results

Attachment A-2 provides the site-averaged constituent data used in the full-scale CCW risk assessment by waste type/WMU scenario.

A.5 References

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Attachment A-1: Sources of Data

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Attachment A-2: CCW Constituent Data

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
11 - FBC	LF	Arsenic	0.002916667	3	3	51
11 - FBC	LF	Barium	0.339166667	3	3	174.5
11 - FBC	LF	Cadmium	0.0005	4	4	6.91875
11 - FBC	LF	Lead	0.0025	4	4	39.5
11 - FBC	LF	Mercury	0.00125	4	4	0.1325
11 - FBC	LF	Selenium	0.00225	4	2	45.5
12 - FBC	LF	Aluminum	3.4	1	0	35874.6
12 - FBC	LF	Antimony	0.27	1	0	18
12 - FBC	LF	Arsenic	0.02205	2	0	57.64333333
12 - FBC	LF	Barium	0.196	2	1	203.805
12 - FBC	LF	Boron	0.05	1	1	20.324
12 - FBC	LF	Cadmium	0.005625	2	1	0.279375
12 - FBC	LF	Lead	0.025	1	1	45.66666667
12 - FBC	LF	Mercury	0.00005	2	2	1.2575
12 - FBC	LF	Molybdenum	0.21	1	0	15.5
12 - FBC	LF	Selenium	0.04355	2	0	7.365833333
17 - FBC	LF	Aluminum	4.788	5	0	46194.8
17 - FBC	LF	Antimony	0.0708	5	2	14.60333333
17 - FBC	LF	Arsenic	0.1378	5	0	71.46666667
17 - FBC	LF	Barium	0.3512	5	1	134.975
17 - FBC	LF	Boron	0.4404	5	1	34.06333333
17 - FBC	LF	Cadmium	0.0434	5	2	3.058333333
17 - FBC	LF	Lead	0.2372	5	2	49.65
17 - FBC	LF	Mercury	0.01022	5	5	1.60345
17 - FBC	LF	Molybdenum	0.097	5	1	3.515
17 - FBC	LF	Selenium	0.06315	5	2	3.301666667
18 - FBC	LF	Aluminum	1.333333333	3	0	23501.33333
18 - FBC	LF	Antimony	0.025	3	3	5
18 - FBC	LF	Arsenic	0.025	3	3	53.33333333
18 - FBC	LF	Barium	0.175	3	1	211.3333333
18 - FBC	LF	Boron	1.341666667	3	1	532.3333333
18 - FBC	LF	Cadmium	0.025	3	3	2.5
18 - FBC	LF	Cobalt	0.025	3	3	11
18 - FBC	LF	Lead	0.025	3	3	22
18 - FBC	LF	Mercury	0.0005	3	2	0.268333333
18 - FBC	LF	Molybdenum	0.175	3	1	7.666666667
18 – FBC	LF	Selenium	0.108333333	3	1	0.5

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
18 - FBC	LF	Thallium	0.025	3	3	1
19 - FBC	LF	Arsenic	0.0875	2	1	6.25
19 - FBC	LF	Barium	0.27	2	1	39.2
19 - FBC	LF	Cadmium	0.01375	2	2	2.5
19 - FBC	LF	Lead	0.0675	2	2	3.75
19 - FBC	LF	Mercury	0.00125	2	1	0.125
19 - FBC	LF	Selenium	0.06875	2	2	6.25
20 - FBC	LF	Aluminum	10.81	12	0	34329.16522
20 - FBC	LF	Antimony	0.787	10	0	46.28125
20 - FBC	LF	Arsenic	0.035	12	0	15.03130435
20 - FBC	LF	Barium	0.381818182	11	0	255.4608696
20 - FBC	LF	Boron	0.457142857	7	0	28.0025
20 - FBC	LF	Cadmium	0.03625	8	0	2.089166667
20 - FBC	LF	Lead	0.301111111	9	0	36.20052632
20 - FBC	LF	Mercury	0.29	1	0	0.454
20 - FBC	LF	Molybdenum	0.392857143	7	0	12.10111111
20 - FBC	LF	Selenium	0.088571429	7	0	4.177333333
21 - FBC	LF	Aluminum	1.91	3	0	14677.33167
21 - FBC	LF	Antimony	0.001833333	3	3	1.083333333
21 - FBC	LF	Arsenic	0.012	3	0	10.76666667
21 - FBC	LF	Barium	0.022333333	3	2	176.2666667
21 - FBC	LF	Boron	0.036666667	3	2	14.38333333
21 - FBC	LF	Cadmium	0.002083333	3	3	0.145833333
21 - FBC	LF	Cobalt	0.008333333	3	2	5.756666667
21 - FBC	LF	Lead	0.009166667	3	3	27.3
21 - FBC	LF	Mercury	0.000133333	3	2	0.431666667
21 - FBC	LF	Molybdenum	0.0125	3	3	3.708333333
21 - FBC	LF	Selenium	0.016666667	3	0	10.9
2-18 - Ash	LF	Arsenic	0.41794375	16	3	
2-18 - Ash	LF	Barium	0.4305625	16	0	
2-18 - Ash	LF	Boron	1.0160625	16	0	
2-18 - Ash	LF	Cadmium	0.05825	16	11	
2-18 - Ash	LF	Lead	0.2819375	16	11	
2-18 - Ash	LF	Mercury	0.000115625	16	16	
2-18 - Ash	LF	Selenium	0.01534375	16	8	
22 - FBC	LF	Arsenic	0.055	5	3	
22 - FBC	LF	Barium	0.5405	5	1	
22 - FBC	LF	Cadmium	0.003	5	5	
22 - FBC	LF	Lead	0.015	5	5	
22 - FBC	LF	Mercury	0.0002	5	3	
22 - FBC	LF	Molybdenum	0.0125	2	2	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
22 - FBC	LF	Selenium	0.032	5	5	
23 - FBC	LF	Barium	0.81	4	0	
25 - FBC	LF	Arsenic	0.125	1	1	
25 - FBC	LF	Barium	2.5	1	1	
25 - FBC	LF	Cadmium	0.025	1	1	
25 - FBC	LF	Lead	0.125	1	1	
25 - FBC	LF	Mercury	0.005	1	1	
25 - FBC	LF	Selenium	0.025	1	1	
28 - FBC	LF	Barium	2.525	2	0	235.11875
30 - FBC	LF	Aluminum	6.894555556	18	7	28246.46923
30 - FBC	LF	Antimony	0.548082353	17	2	61.49315385
30 - FBC	LF	Arsenic	0.050694444	18	3	48.55980769
30 - FBC	LF	Barium	0.286388889	18	6	120.0687692
30 - FBC	LF	Boron	0.31759375	16	7	30.83913462
30 - FBC	LF	Cadmium	0.023125	14	3	1.916230769
30 - FBC	LF	Lead	0.240805556	18	4	39.36092308
30 - FBC	LF	Mercury	0.000744444	18	17	10.91689923
30 - FBC	LF	Molybdenum	0.138125	16	10	14.50257692
30 - FBC	LF	Selenium	0.10475	16	10	5.603596154
31 - FBC	LF	Aluminum	0.28	1	0	29437.5
31 - FBC	LF	Antimony	0.00065	1	1	5.0325
31 - FBC	LF	Arsenic	0.0687	4	2	26.825
31 - FBC	LF	Barium	0.58275	4	0	170.25
31 - FBC	LF	Boron	26.7	1	0	930
31 - FBC	LF	Cadmium	0.02775	4	3	5.45
31 - FBC	LF	Cobalt	0.0065	1	0	6.42
31 - FBC	LF	Lead	0.03025	4	3	1.19
31 - FBC	LF	Mercury	0.00095	4	1	0.61
31 - FBC	LF	Molybdenum	0.085	1	0	8
31 - FBC	LF	Selenium	0.06485	4	2	7.54
32 - FBC	LF	Arsenic	0.35	1	1	1.4
32 - FBC	LF	Barium	0.085	1	0	
32 - FBC	LF	Cadmium	0.005	1	1	0.009
32 - FBC	LF	Lead	0.05	1	1	0.45
32 - FBC	LF	Mercury	0.0001	1	1	0.03
32 - FBC	LF	Selenium	0.175	1	1	3.5
33 - FBC	LF	Arsenic	0.015	1	1	
33 - FBC	LF	Barium	42	1	0	
33 - FBC	LF	Boron	0.06	1	0	
33 - FBC	LF	Cadmium	0.00125	1	1	
33 - FBC	LF	Cobalt	0.0025	1	1	
33 - FBC	LF	Mercury	0.00005	1	1	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
33 - FBC	LF	Selenium	0.01	1	1	
35 - FBC	LF	Arsenic	0.015	1	1	
35 - FBC	LF	Barium	2.6	1	0	
35 - FBC	LF	Cadmium	0.009	1	0	
35 - FBC	LF	Lead	0.035	1	1	
35 - FBC	LF	Mercury	0.00025	1	1	
35 - FBC	LF	Selenium	0.2	1	0	
37 - FBC	LF	Arsenic	0.011102941	17	9	5.79
37 - FBC	LF	Barium	2.104705882	17	2	
37 - FBC	LF	Boron	1.125	5	1	15.9
37 - FBC	LF	Cadmium	0.046176471	17	4	4.183333333
37 - FBC	LF	Cobalt	0.246	5	0	
37 - FBC	LF	Lead	0.287352941	17	6	55
37 - FBC	LF	Mercury	0.001314706	17	4	0.01125
37 - FBC	LF	Selenium	0.01075	17	9	3.42
38 - FBC	LF	Aluminum	2.256666667	9	2	26711.25
38 - FBC	LF	Antimony	0.213069444	9	6	11.27770833
38 - FBC	LF	Arsenic	0.024554444	9	3	25.136075
38 - FBC	LF	Barium	0.178888889	9	4	181.0083333
38 - FBC	LF	Boron	0.346555556	9	2	26.98916667
38 - FBC	LF	Cadmium	0.007388889	9	5	0.71625
38 - FBC	LF	Cobalt	0.008566667	3	2	4.515
38 - FBC	LF	Lead	0.0565	9	6	28.54166667
38 - FBC	LF	Mercury	0.000344444	9	8	0.18195
38 - FBC	LF	Molybdenum	0.177375	8	2	14.1875
38 - FBC	LF	Selenium	0.088561111	9	4	7.682450833
39 - FBC	LF	Arsenic	0.075	1	1	14.5
39 - FBC	LF	Barium	0.395	2	1	590
39 - FBC	LF	Boron	0.76	1	0	
39 - FBC	LF	Cadmium	0.005	1	1	0.5
39 - FBC	LF	Lead	0.025	1	1	15
39 - FBC	LF	Mercury	0.00025	1	1	0.17
39 - FBC	LF	Molybdenum	0.14	1	0	13.5
39 - FBC	LF	Selenium	0.025	1	1	21.5
4 - FBC	LF	Aluminum	13.556	5	0	16084.68429
4 - FBC	LF	Antimony	0.2236	5	2	26.78817857
4 - FBC	LF	Arsenic	0.271	5	0	28.03585714
4 - FBC	LF	Barium	0.6346	5	1	154.95
4 - FBC	LF	Boron	0.693	4	0	13.026
4 - FBC	LF	Cadmium	0.0115	5	2	0.646539286
4 - FBC	LF	Lead	0.1834	5	1	18.35671429
4 - FBC	LF	Mercury	0.00005	5	5	0.087192857

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
4 - FBC	LF	Molybdenum	0.286666667	3	0	16.18257143
4 - FBC	LF	Selenium	0.0620625	4	2	1.505421429
41 - FBC	LF	Antimony	0.025	5	5	1.551333333
41 - FBC	LF	Arsenic	0.035471698	53	50	13.72255319
41 - FBC	LF	Barium	0.095694444	54	25	19.05490196
41 - FBC	LF	Cadmium	0.022355769	52	51	0.427826087
41 - FBC	LF	Lead	0.017548077	52	51	0.935208333
41 - FBC	LF	Mercury	0.000596154	52	50	0.119542553
41 - FBC	LF	Selenium	0.024433962	53	51	1.505744681
41 - FBC	LF	Thallium	0.031	5	4	3.662790698
42 - FBC	LF	Arsenic	0.0125	2	2	
42 - FBC	LF	Barium	0.1625	2	1	
42 - FBC	LF	Cadmium	0.005	2	2	
42 - FBC	LF	Lead	0.0075	2	2	
42 - FBC	LF	Mercury	0.0005	2	2	
42 - FBC	LF	Selenium	0.0125	2	2	
43 - FBC	LF	Arsenic	0.0125	2	2	
43 - FBC	LF	Barium	0.0875	2	1	
43 - FBC	LF	Cadmium	0.005	2	2	
43 - FBC	LF	Lead	0.0075	2	2	
43 - FBC	LF	Mercury	0.0005	2	2	
43 - FBC	LF	Selenium	0.08625	2	1	
6 - FBC	LF	Aluminum	0.1525	2	1	42736.5
6 - FBC	LF	Antimony	0.05	2	2	16.25
6 - FBC	LF	Arsenic	0.09125	2	1	126.6
6 - FBC	LF	Barium	0.285	2	0	221.5
6 - FBC	LF	Boron	0.1425	2	1	73.8
6 - FBC	LF	Cadmium	0.0025	2	2	1.29625
6 - FBC	LF	Lead	0.01375	2	2	8.1125
6 - FBC	LF	Mercury	0.00005	2	2	1.16
6 - FBC	LF	Molybdenum	0.09	2	0	1.425
6 - FBC	LF	Selenium	0.1025	2	1	84.5625
Amerikohl - FBC	LF	Aluminum	0.753333333	3	0	51600
Amerikohl - FBC	LF	Antimony	0.345	3	3	20
Amerikohl - FBC	LF	Arsenic	0.024166667	3	3	114
Amerikohl - FBC	LF	Barium	0.1	3	3	140
Amerikohl - FBC	LF	Boron	0.346666667	3	1	60
Amerikohl - FBC	LF	Cadmium	0.004166667	3	3	0.15
Amerikohl - FBC	LF	Cobalt	0.175	3	3	30
Amerikohl - FBC	LF	Lead	0.009166667	3	3	23
Amerikohl - FBC	LF	Mercury	0.0005	3	3	0.15
Amerikohl - FBC	LF	Molybdenum	0.266666667	3	1	10

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Amerikohl - FBC	LF	Nitrate/Nitrite	3.15	3	3	
Amerikohl - FBC	LF	Selenium	0.044166667	3	3	3.5
Arkwright - Ash	LF	Arsenic	0.07	1	0	
Arkwright - Ash	LF	Barium	0.4	1	0	
Arkwright - Ash	LF	Cadmium	0.01	1	0	
Arkwright - Ash	LF	Lead	0.04	1	0	
Arkwright - Ash	LF	Selenium	0.02	1	0	
Barry - Ash	LF	Arsenic	1	1	0	
Barry - Ash	LF	Barium	0.7	1	0	
Barry - Ash	LF	Cadmium	0.005	1	0	
Barry - Ash	LF	Lead	0.04	1	0	
Barry - Ash	LF	Selenium	0.07	1	0	
Belle Ayr - Ash	LF	Aluminum	0.036666667	3	0	
Belle Ayr - Ash	LF	Antimony	0.021	2	0	
Belle Ayr - Ash	LF	Arsenic	0.181	3	0	
Belle Ayr - Ash	LF	Barium	1.163333333	3	0	
Belle Ayr - Ash	LF	Cobalt	0.0075	2	0	
Belle Ayr - Ash	LF	Molybdenum	0.325	3	0	
Belle Ayr - Ash	LF	Selenium	0.652333333	3	0	
Big Gorilla Pit - FBC	LF	Aluminum	3.774166667	12	0	18440.58824
Big Gorilla Pit - FBC	LF	Antimony	0.037166667	12	1	1.244485294
Big Gorilla Pit - FBC	LF	Arsenic	0.023181818	22	21	7.534117647
Big Gorilla Pit - FBC	LF	Barium	0.243636364	11	3	147.7320588
Big Gorilla Pit - FBC	LF	Boron	0.677916667	12	2	29.64058824
Big Gorilla Pit - FBC	LF	Cadmium	0.015227273	22	22	0.58728125
Big Gorilla Pit - FBC	LF	Cobalt	0.008553571	14	11	2.374214286
Big Gorilla Pit - FBC	LF	Lead	0.08125	12	7	19.51823529
Big Gorilla Pit - FBC	LF	Mercury	0.001704545	22	19	0.302990909
Big Gorilla Pit - FBC	LF	Molybdenum	0.1202	10	1	6.429333333
Big Gorilla Pit - FBC	LF	Nitrate/Nitrite	1.755857143	14	3	
Big Gorilla Pit - FBC	LF	Selenium	0.10975	12	1	7.159397059
Bowen - Ash	LF	Arsenic	0.6	1	0	68
Bowen - Ash	LF	Barium	0.3	1	0	974
Bowen - Ash	LF	Cadmium	0.01	1	0	0.7
Bowen - Ash	LF	Lead	0.04	1	0	63.9
Bowen - Ash	LF	Selenium	0.1	1	0	
Branch - Ash	LF	Arsenic	0.04	1	0	
Branch - Ash	LF	Barium	0.5	1	0	
Branch - Ash	LF	Cadmium	0.01	1	0	
Branch - Ash	LF	Lead	0.04	1	0	
Branch - Ash	LF	Selenium	0.06	1	0	
Buckheart Mine - Ash	LF	Antimony	0.01854	40	14	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Buckheart Mine - Ash	LF	Arsenic	0.122357143	42	13	
Buckheart Mine - Ash	LF	Barium	0.364809524	42	0	
Buckheart Mine - Ash	LF	Boron	9.998738095	42	0	
Buckheart Mine - Ash	LF	Cadmium	0.0235	42	8	
Buckheart Mine - Ash	LF	Cobalt	0.048047619	42	17	
Buckheart Mine - Ash	LF	Lead	0.27887619	42	9	
Buckheart Mine - Ash	LF	Mercury	0.000107143	42	40	
Buckheart Mine - Ash	LF	Selenium	0.118266667	42	26	
Buckheart Mine - Ash	LF	Thallium	0.017875	40	10	
Buckheart Mine - FBC	LF	Antimony	0.0018125	8	8	
Buckheart Mine - FBC	LF	Arsenic	0.0465	8	5	
Buckheart Mine - FBC	LF	Barium	0.560125	8	1	
Buckheart Mine - FBC	LF	Boron	3.157	8	0	
Buckheart Mine - FBC	LF	Cadmium	0.0033125	8	7	
Buckheart Mine - FBC	LF	Cobalt	0.02875	8	7	
Buckheart Mine - FBC	LF	Lead	0.036	8	4	
Buckheart Mine - FBC	LF	Mercury	0.0005	8	4	
Buckheart Mine - FBC	LF	Selenium	0.050625	8	5	
Buckheart Mine - FBC	LF	Thallium	0.001	8	8	
CAER - Ash	LF	Arsenic	1.132	5	0	77.32222222
CAER - Ash	LF	Barium	0.315	5	0	537.6666667
CAER - Ash	LF	Cadmium	0.0942	5	0	
CAER - Ash	LF	Lead	0.1	5	2	73.62375
CAER - Ash	LF	Mercury	0.00025	5	5	
CAER - Ash	LF	Selenium	0.103	5	0	
Canton Site - Ash	LF	Aluminum	9.818127778	36	0	
Canton Site - Ash	LF	Arsenic	0.0025	2	2	
Canton Site - Ash	LF	Barium	3.0156	10	0	
Canton Site - Ash	LF	Boron	18.62468571	35	0	
Canton Site - Ash	LF	Cadmium	0.0005	2	2	
Canton Site - Ash	LF	Cobalt	0.02	1	1	
Canton Site - Ash	LF	Lead	0.1865	2	0	
Canton Site - Ash	LF	Mercury	0.0001	1	1	
Canton Site - Ash	LF	Molybdenum	30.9359	20	0	
Canton Site - Ash	LF	Nitrate/Nitrite	0.095	1	0	
Canton Site - Ash	LF	Selenium	0.0374	1	0	
Canton Site - FBC	LF	Aluminum	2.461866667	24	0	
Canton Site - FBC	LF	Arsenic	0.005	1	1	
Canton Site - FBC	LF	Barium	0.02	1	0	
Canton Site - FBC	LF	Boron	1.5602625	16	0	
Canton Site - FBC	LF	Cadmium	0.066	1	0	
Canton Site - FBC	LF	Lead	0.062	1	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Canton Site – FBC	LF	Mercury	0.0005	1	1	
Canton Site – FBC	LF	Molybdenum	1.768009524	21	0	
Canton Site – FBC	LF	Selenium	0.005	1	1	
Central Cleaning Plant - Ash	LF	Antimony	0.008205882	17	17	
Central Cleaning Plant - Ash	LF	Arsenic	0.005	17	17	
Central Cleaning Plant - Ash	LF	Barium	0.168164706	17	0	
Central Cleaning Plant - Ash	LF	Boron	7.213823529	17	0	
Central Cleaning Plant - Ash	LF	Cadmium	0.004117647	17	16	
Central Cleaning Plant - Ash	LF	Cobalt	0.019588235	17	15	
Central Cleaning Plant - Ash	LF	Lead	0.022782353	17	11	
Central Cleaning Plant - Ash	LF	Mercury	0.000568824	17	11	
Central Cleaning Plant - Ash	LF	Selenium	0.040211765	17	0	
Central Cleaning Plant - Ash	LF	Thallium	0.005	17	17	
CL - Ash and Coal Refuse	LF	Aluminum	2.58	3	0	
CL - Ash and Coal Refuse	LF	Antimony	0.0041	3	0	
CL - Ash and Coal Refuse	LF	Arsenic	0.121266667	3	0	
CL - Ash and Coal Refuse	LF	Barium	3.63	3	0	
CL - Ash and Coal Refuse	LF	Boron	0.103133333	3	0	
CL - Ash and Coal Refuse	LF	Cadmium	0.001	3	0	
CL - Ash and Coal Refuse	LF	Cobalt	0.006066667	3	1	
CL - Ash and Coal Refuse	LF	Lead	0.003533333	3	0	
CL - Ash and Coal Refuse	LF	Mercury	0.00005	6	6	
CL - Ash and Coal Refuse	LF	Selenium	0.0452	3	0	
CL - Ash and Coal Refuse	LF	Thallium	0.003483333	3	1	
Coal Creek - Ash	LF	Arsenic	0.0109	2	0	0.086
Coal Creek - Ash	LF	Barium	0.6105	2	0	4.76
Coal Creek - Ash	LF	Boron	6.22	2	0	1.1105
Coal Creek - Ash	LF	Cadmium	0.00015	2	2	0.00045
Coal Creek - Ash	LF	Lead	0.001	2	2	0.02025
Coal Creek - Ash	LF	Mercury	0.000005	2	2	0.0006
Coal Creek - Ash	LF	Selenium	0.0555	2	1	0.00505
Colver Site - FBC	LF	Aluminum	0.248333333	6	1	78878.83333
Colver Site - FBC	LF	Antimony	0.196666667	6	2	166.5
Colver Site - FBC	LF	Arsenic	0.0875	6	1	124.2
Colver Site - FBC	LF	Barium	0.291666667	6	0	443.8333333
Colver Site - FBC	LF	Boron	0.261666667	6	1	62.6
Colver Site - FBC	LF	Cadmium	0.016666667	6	2	9.994166667
Colver Site - FBC	LF	Lead	0.190833333	6	2	192.075
Colver Site - FBC	LF	Mercury	0.00015	6	5	0.586666667
Colver Site - FBC	LF	Molybdenum	0.143333333	6	0	30.65833333
Colver Site - FBC	LF	Selenium	0.48	6	1	68.70833333
Conemaugh - Ash	LF	Aluminum	1.245	2	0	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Conemaugh - Ash	LF	Antimony	0.075	1	1	
Conemaugh - Ash	LF	Arsenic	0.388333333	3	1	
Conemaugh - Ash	LF	Barium	0.331666667	3	0	
Conemaugh - Ash	LF	Boron	0.91	1	0	
Conemaugh - Ash	LF	Cadmium	0.01	3	0	
Conemaugh - Ash	LF	Cobalt	0.026	1	0	
Conemaugh - Ash	LF	Lead	0.1	2	2	
Conemaugh - Ash	LF	Mercury	0.00055	2	2	
Conemaugh - Ash	LF	Molybdenum	0.355	2	0	
Conemaugh - Ash	LF	Selenium	0.295	2	1	
Conemaugh - Ash	LF	Thallium	0.024	1	0	
Conemaugh - Ash and Coal Refuse	LF	Aluminum	1.467666667	3	0	
Conemaugh - Ash and Coal Refuse	LF	Antimony	0.075	3	3	
Conemaugh - Ash and Coal Refuse	LF	Arsenic	0.625	2	2	
Conemaugh - Ash and Coal Refuse	LF	Barium	0.145666667	3	0	
Conemaugh - Ash and Coal Refuse	LF	Boron	0.095	2	0	
Conemaugh - Ash and Coal Refuse	LF	Cadmium	0.002	3	3	
Conemaugh - Ash and Coal Refuse	LF	Cobalt	0.009	1	0	
Conemaugh - Ash and Coal Refuse	LF	Lead	0.073333333	3	2	
Conemaugh - Ash and Coal Refuse	LF	Mercury	0.0004	3	2	
Conemaugh - Ash and Coal Refuse	LF	Molybdenum	0.01	1	0	
Conemaugh - Ash and Coal Refuse	LF	Selenium	0.179833333	3	1	
Conemaugh - Ash and Coal Refuse	LF	Thallium	0.005	1	0	
Crist - Ash	LF	Arsenic	0.02	1	0	
Crist - Ash	LF	Barium	0.1	1	0	
Crist - Ash	LF	Cadmium	0.02	1	0	
Crist - Ash	LF	Lead	0.003	1	0	
Crist - Ash	LF	Selenium	0.05	1	0	
Crown III - Ash	LF	Antimony	0.071159259	54	10	
Crown III - Ash	LF	Arsenic	0.352503226	62	29	
Crown III - Ash	LF	Barium	0.279112903	62	3	
Crown III - Ash	LF	Boron	22.93277419	62	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Crown III - Ash	LF	Cadmium	0.128258065	62	3	
Crown III - Ash	LF	Cobalt	0.101225806	62	17	
Crown III - Ash	LF	Lead	0.605616935	62	19	
Crown III - Ash	LF	Mercury	0.000104839	62	61	
Crown III - Ash	LF	Molybdenum	0.588888889	9	4	
Crown III - Ash	LF	Selenium	0.03946129	62	46	
Crown III - Ash	LF	Thallium	0.0645	54	18	
Crown III - FBC	LF	Antimony	0.0135	17	9	
Crown III - FBC	LF	Arsenic	0.034822581	31	26	3.766666667
Crown III - FBC	LF	Barium	0.346774194	31	2	150
Crown III - FBC	LF	Boron	2.815296296	27	1	
Crown III - FBC	LF	Cadmium	0.011241935	31	22	2.17
Crown III - FBC	LF	Cobalt	0.02475	24	16	
Crown III - FBC	LF	Lead	0.068645161	31	17	8.233333333
Crown III - FBC	LF	Mercury	0.000164516	31	27	0.381
Crown III - FBC	LF	Molybdenum	0.1522	10	2	
Crown III - FBC	LF	Selenium	0.061467742	31	27	3.3
Crown III - FBC	LF	Thallium	0.004941176	17	11	
CTL-V - Ash	LF	Antimony	0.26	1	0	
CTL-V - Ash	LF	Arsenic	0.037	1	0	
CTL-V - Ash	LF	Barium	0.247	1	0	
CTL-V - Ash	LF	Cadmium	0.04	1	0	
CTL-V - Ash	LF	Lead	0.072	1	0	
CTL-V - Ash	LF	Mercury	0.001	1	0	
CTL-V - Ash	LF	Selenium	0.014	1	0	
CTL-V - Ash	LF	Thallium	0.01	1	0	
CY - Ash	LF	Aluminum	4.735	2	0	
CY - Ash	LF	Antimony	0.0078	2	0	
CY - Ash	LF	Arsenic	0.04825	2	0	
CY - Ash	LF	Barium	1.2395	2	0	
CY - Ash	LF	Boron	6.13	2	0	
CY - Ash	LF	Cadmium	0.0002075	2	1	
CY - Ash	LF	Cobalt	0.001915	4	4	
CY - Ash	LF	Lead	0.003555	2	1	
CY - Ash	LF	Mercury	0.000265	2	0	
CY - Ash	LF	Selenium	0.004825	2	1	
CY - Ash	LF	Thallium	0.00196	4	4	
Dairyland Power Coop - Ash	LF	Arsenic	0.0328625	8	0	
Dairyland Power Coop - Ash	LF	Barium	0.058740741	27	0	
Dairyland Power Coop - Ash	LF	Boron	68.03979592	49	0	
Dairyland Power Coop - Ash	LF	Cadmium	0.00539	34	0	
Dairyland Power Coop - Ash	LF	Lead	0.0046	7	2	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Dairyland Power Coop - Ash	LF	Mercury	0.000223	2	1	
Dairyland Power Coop - Ash	LF	Selenium	0.0696375	8	0	
Daniel - Ash	LF	Arsenic	0.2	1	0	
Daniel - Ash	LF	Barium	0.4	1	0	
Daniel - Ash	LF	Cadmium	0.001	1	1	
Daniel - Ash	LF	Lead	0.001	1	1	
Daniel - Ash	LF	Selenium	0.001	1	1	
Deer Ridge Mine - Ash	LF	Aluminum	0.5941	10	1	64681.487
Deer Ridge Mine - Ash	LF	Arsenic	0.0029	10	6	21.29419
Deer Ridge Mine - Ash	LF	Barium	0.1448	10	2	258.468
Deer Ridge Mine - Ash	LF	Boron	1.228	10	2	179.354
Deer Ridge Mine - Ash	LF	Cadmium	0.01365	10	1	0.94425
Deer Ridge Mine - Ash	LF	Lead	0.0253	10	2	58.48
Deer Ridge Mine - Ash	LF	Mercury	0.00011025	10	10	0.1158
Deer Ridge Mine - Ash	LF	Molybdenum	0.0756	10	4	6.6287
Deer Ridge Mine - Ash	LF	Nitrate/Nitrite	0.095	3	2	
Deer Ridge Mine - Ash	LF	Selenium	0.01022	10	2	13.1061
DPC - Ash	LF	Antimony	0.04	2	1	0.475
DPC - Ash	LF	Arsenic	0.051	2	0	55.085
DPC - Ash	LF	Barium	0.28	2	0	37.7
DPC - Ash	LF	Boron	27.945	2	0	404.05
DPC - Ash	LF	Cadmium	0.005	4	4	0.56
DPC - Ash	LF	Lead	0.025	4	4	28.7
DPC - Ash	LF	Mercury	0.001	2	2	0.127
DPC - Ash	LF	Nitrate/Nitrite	2.5	2	0	0.2425
DPC - Ash	LF	Selenium	0.046	2	0	3.4445
EERC - Ash	LF	Mercury	0.000025	4	4	
Elkhart Mine - Ash	LF	Antimony	0.025192308	52	46	
Elkhart Mine - Ash	LF	Arsenic	0.043571429	77	71	
Elkhart Mine - Ash	LF	Barium	0.495324675	77	23	
Elkhart Mine - Ash	LF	Boron	6.88961039	77	0	
Elkhart Mine - Ash	LF	Cadmium	0.022551948	77	41	
Elkhart Mine - Ash	LF	Cobalt	0.012785714	77	57	
Elkhart Mine - Ash	LF	Lead	0.027987013	77	66	
Elkhart Mine - Ash	LF	Mercury	0.000148052	77	68	
Elkhart Mine - Ash	LF	Selenium	0.036649351	77	64	
Elkhart Mine - Ash	LF	Thallium	0.015942308	52	48	
Elkhart Mine - FBC	LF	Antimony	0.021875	16	15	
Elkhart Mine - FBC	LF	Arsenic	0.034512195	41	37	
Elkhart Mine - FBC	LF	Barium	0.525365854	41	5	
Elkhart Mine - FBC	LF	Boron	13.13829268	41	0	
Elkhart Mine - FBC	LF	Cadmium	0.003536585	41	41	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Elkhart Mine - FBC	LF	Cobalt	0.007219512	41	39	
Elkhart Mine - FBC	LF	Lead	0.017195122	41	34	
Elkhart Mine - FBC	LF	Mercury	0.000104878	41	40	
Elkhart Mine - FBC	LF	Selenium	0.035365854	41	33	
Elkhart Mine - FBC	LF	Thallium	0.02390625	16	15	
FBX - Ash	LF	Arsenic	0.0025	2	2	
FBX - Ash	LF	Barium	29.6225	2	1	
FBX - Ash	LF	Cadmium	0.2	2	2	
FBX - Ash	LF	Lead	0.5	2	2	
FBX - Ash	LF	Mercury	0.00025	2	2	
FBX - Ash	LF	Selenium	0.01375	2	2	
FC - Ash and Coal Refuse	LF	Aluminum	13.8	2	0	
FC - Ash and Coal Refuse	LF	Antimony	0.00105	4	4	
FC - Ash and Coal Refuse	LF	Arsenic	0.005	2	0	
FC - Ash and Coal Refuse	LF	Barium	0.602	2	0	
FC - Ash and Coal Refuse	LF	Boron	2.54	2	0	
FC - Ash and Coal Refuse	LF	Cadmium	0.00015	4	4	
FC - Ash and Coal Refuse	LF	Cobalt	0.0029	2	0	
FC - Ash and Coal Refuse	LF	Lead	0.00345	2	0	
FC - Ash and Coal Refuse	LF	Mercury	0.00005	4	4	
FC - Ash and Coal Refuse	LF	Selenium	0.01765	2	0	
FC - Ash and Coal Refuse	LF	Thallium	0.00185	4	4	
Florence Mine - Ash	LF	Aluminum	0.03	1	0	
Florence Mine - Ash	LF	Antimony	0.005	1	1	
Florence Mine - Ash	LF	Arsenic	0.07	1	0	
Florence Mine - Ash	LF	Barium	2.23	1	0	
Florence Mine - Ash	LF	Boron	0.01	1	1	
Florence Mine - Ash	LF	Cadmium	0.01	1	1	
Florence Mine - Ash	LF	Lead	0.001	1	0	
Florence Mine - Ash	LF	Mercury	0.002	1	0	
Florence Mine - Ash	LF	Molybdenum	0.01	1	1	
Florence Mine - Ash	LF	Nitrate/Nitrite	1.2	1	0	
Florence Mine - Ash	LF	Selenium	0.06	1	0	
Fran Site - FBC	LF	Aluminum	0.32	1	0	
Fran Site - FBC	LF	Antimony	0.005	1	1	
Fran Site - FBC	LF	Arsenic	0.02	1	0	
Fran Site - FBC	LF	Barium	0.08	1	0	
Fran Site - FBC	LF	Boron	0.43	1	0	
Fran Site - FBC	LF	Cadmium	0.005	1	1	
Fran Site - FBC	LF	Lead	0.005	1	1	
Fran Site - FBC	LF	Nitrate/Nitrite	1.22	1	0	
Fran Site - FBC	LF	Selenium	0.03	1	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
FW - FBC	LF	Arsenic	0.02525	4	3	
FW - FBC	LF	Barium	0.304	4	0	
FW - FBC	LF	Cadmium	0.005	4	4	
FW - FBC	LF	Lead	0.05	4	4	
FW - FBC	LF	Mercury	0.001	4	4	
FW - FBC	LF	Selenium	0.1	4	4	
Gadsden - Ash	LF	Arsenic	0.2	1	0	
Gadsden - Ash	LF	Barium	0.3	1	0	
Gadsden - Ash	LF	Cadmium	0.01	1	0	
Gadsden - Ash	LF	Lead	0.04	1	0	
Gadsden - Ash	LF	Selenium	0.03	1	0	
Gale - Ash	LF	Aluminum	3.1	1	0	13630
Gale - Ash	LF	Antimony	0.03	1	0	3
Gale - Ash	LF	Arsenic	0.42	1	0	51.5
Gale - Ash	LF	Barium	1.7	1	0	143
Gale - Ash	LF	Boron	0.22	1	0	25
Gale - Ash	LF	Cadmium	0.01	1	0	1
Gale - Ash	LF	Lead	0.23	1	0	21
Gale - Ash	LF	Molybdenum	0.05	1	0	5
Gale - Ash	LF	Selenium	0.1	1	0	4.4
Gaston - Ash	LF	Arsenic	1.8	1	0	
Gaston - Ash	LF	Barium	0.3	1	0	
Gaston - Ash	LF	Cadmium	0.01	1	0	
Gaston - Ash	LF	Lead	0.05	1	0	
Gaston - Ash	LF	Selenium	0.003	1	0	
Gorgas - Ash	LF	Arsenic	1.6	1	0	
Gorgas - Ash	LF	Barium	0.3	1	0	
Gorgas - Ash	LF	Cadmium	0.01	1	0	
Gorgas - Ash	LF	Lead	0.04	1	0	
Gorgas - Ash	LF	Selenium	0.002	1	0	
Greene Co - Ash	LF	Arsenic	1.1	1	0	
Greene Co - Ash	LF	Barium	0.4	1	0	
Greene Co - Ash	LF	Cadmium	0.01	1	0	
Greene Co - Ash	LF	Lead	0.04	1	0	
Greene Co - Ash	LF	Selenium	0.003	1	0	
HA - Ash and Coal Refuse	LF	Aluminum	1.71925	4	0	5666.666667
HA - Ash and Coal Refuse	LF	Antimony	0.003905	4	2	
HA - Ash and Coal Refuse	LF	Arsenic	0.024975	4	0	9.666666667
HA - Ash and Coal Refuse	LF	Barium	1.01675	4	0	186.6666667
HA - Ash and Coal Refuse	LF	Boron	0.64545	4	0	14
HA - Ash and Coal Refuse	LF	Cadmium	0.0039275	4	0	0.25
HA - Ash and Coal Refuse	LF	Cobalt	0.01517875	4	1	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
HA - Ash and Coal Refuse	LF	Lead	0.00378	4	2	8.7
HA - Ash and Coal Refuse	LF	Mercury	0.0001	4	0	0.065
HA - Ash and Coal Refuse	LF	Selenium	0.005025	4	0	0.534166667
HA - Ash and Coal Refuse	LF	Thallium	0.00196	8	8	
Hammond - Ash	LF	Arsenic	0.1	1	0	
Hammond - Ash	LF	Barium	0.3	1	0	
Hammond - Ash	LF	Cadmium	0.01	1	0	
Hammond - Ash	LF	Lead	0.05	1	0	
Hammond - Ash	LF	Selenium	0.02	1	0	
Harrim 3019 - Ash	LF	Aluminum	5.21	1	0	46577
Harrim 3019 - Ash	LF	Antimony	0.0058	1	0	646.4
Harrim 3019 - Ash	LF	Arsenic	0.178	1	0	50.43172727
Harrim 3019 - Ash	LF	Barium	0.32	1	0	319.89
Harrim 3019 - Ash	LF	Molybdenum	0.594	1	0	17.9
Harrim 3019 - Ash	LF	Nitrate/Nitrite	1.99	1	0	
Harrim 3019 - Ash	LF	Selenium	0.0468	1	0	1.405714286
Harrim 3019 - FBC	LF	Aluminum	0.67375	8	0	
Harrim 3019 - FBC	LF	Antimony	0.002	1	0	
Harrim 3019 - FBC	LF	Barium	0.465888889	9	0	
Harrim 3019 - FBC	LF	Boron	0.07	1	0	
Harrim 3019 - FBC	LF	Cobalt	0.1385	6	0	
Harrim 3019 - FBC	LF	Lead	0.24	5	0	
Harrim 3019 - FBC	LF	Molybdenum	0.347714286	7	0	
Harrim 3019 - FBC	LF	Nitrate/Nitrite	0.199333333	3	0	
Harrim 3019 - FBC	LF	Selenium	0.019	2	0	
Industry Mine - Ash	LF	Antimony	0.031597143	70	12	
Industry Mine - Ash	LF	Arsenic	0.050248454	97	51	
Industry Mine - Ash	LF	Barium	0.328329897	97	13	
Industry Mine - Ash	LF	Boron	4.719969072	97	0	
Industry Mine - Ash	LF	Cadmium	0.059061856	97	7	
Industry Mine - Ash	LF	Cobalt	0.120010309	97	30	
Industry Mine - Ash	LF	Lead	3.610544845	97	16	
Industry Mine - Ash	LF	Mercury	0.000284536	97	92	
Industry Mine - Ash	LF	Selenium	0.052408247	97	64	
Industry Mine - Ash	LF	Thallium	0.016984286	70	12	
Industry Mine - FBC	LF	Antimony	0.017077778	9	4	
Industry Mine - FBC	LF	Arsenic	0.031111111	9	7	
Industry Mine - FBC	LF	Barium	9.515666667	9	0	
Industry Mine - FBC	LF	Boron	2.813888889	9	2	
Industry Mine - FBC	LF	Cadmium	0.015888889	9	7	
Industry Mine - FBC	LF	Cobalt	0.029333333	9	8	
Industry Mine - FBC	LF	Lead	0.051877778	9	6	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Industry Mine - FBC	LF	Mercury	0.000222222	9	8	
Industry Mine - FBC	LF	Selenium	0.080388889	9	4	
Industry Mine - FBC	LF	Thallium	0.002288889	9	6	
Key West - Ash	LF	Arsenic	0.005	1	1	
Key West - Ash	LF	Barium	1	2	0	
Key West - Ash	LF	Boron	0.2	1	0	
Key West - Ash	LF	Cadmium	0.07	1	0	
Key West - Ash	LF	Lead	0.4	1	0	
Key West - Ash	LF	Mercury	0.18	1	0	
Key West - Ash	LF	Selenium	0.005	1	1	
Keystone - Ash	LF	Aluminum	2.059	4	0	
Keystone - Ash	LF	Antimony	0.036	1	0	
Keystone - Ash	LF	Arsenic	0.30925	4	0	
Keystone - Ash	LF	Barium	0.40375	4	0	
Keystone - Ash	LF	Boron	0.72	1	0	
Keystone - Ash	LF	Cadmium	0.009625	4	1	
Keystone - Ash	LF	Cobalt	0.023	1	0	
Keystone - Ash	LF	Lead	0.045375	4	1	
Keystone - Ash	LF	Mercury	0.001	1	1	
Keystone - Ash	LF	Molybdenum	0.32	1	0	
Keystone - Ash	LF	Selenium	0.0525	4	2	
Keystone - Ash	LF	Thallium	0.083	1	0	
Keystone - Ash and Coal Refuse	LF	Aluminum	0.842	4	0	
Keystone - Ash and Coal Refuse	LF	Antimony	0.0015	2	2	
Keystone - Ash and Coal Refuse	LF	Arsenic	0.01875	4	4	
Keystone - Ash and Coal Refuse	LF	Barium	0.1925	4	0	
Keystone - Ash and Coal Refuse	LF	Boron	0.06	1	0	
Keystone - Ash and Coal Refuse	LF	Cadmium	0.00225	4	4	
Keystone - Ash and Coal Refuse	LF	Cobalt	0.022	1	0	
Keystone - Ash and Coal Refuse	LF	Lead	0.01875	4	4	
Keystone - Ash and Coal Refuse	LF	Mercury	0.001	1	1	
Keystone - Ash and Coal Refuse	LF	Molybdenum	0.01	2	2	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Keystone - Ash and Coal Refuse	LF	Selenium	0.02	4	4	
Keystone - Ash and Coal Refuse	LF	Thallium	0.028	1	0	
Kraft - Ash	LF	Arsenic	0.02	1	0	
Kraft - Ash	LF	Barium	0.3	1	0	
Kraft - Ash	LF	Cadmium	0.01	1	0	
Kraft - Ash	LF	Lead	0.04	1	0	
Kraft - Ash	LF	Selenium	0.04	1	0	
LIMB Site - Ash	LF	Aluminum	0.102894737	38	37	
LIMB Site - Ash	LF	Antimony	0.29	5	1	25
LIMB Site - Ash	LF	Arsenic	0.033594737	38	6	63
LIMB Site - Ash	LF	Barium	0.036552632	38	0	255
LIMB Site - Ash	LF	Boron	0.521842105	38	31	400
LIMB Site - Ash	LF	Cadmium	0.001031579	38	33	0.31
LIMB Site - Ash	LF	Cobalt	0.005131579	38	37	
LIMB Site - Ash	LF	Lead	0.012789474	38	25	14.5
LIMB Site - Ash	LF	Mercury	0.0001	2	2	
LIMB Site - Ash	LF	Molybdenum	1.527342105	38	1	2.5
LIMB Site - Ash	LF	Nitrate/Nitrite	26	2	0	
LIMB Site - Ash	LF	Selenium	0.0199	38	24	0.25
LIMB Site - Ash	LF	Thallium	0.05	5	5	
Little Sandy #10 Mine - Ash	LF	Aluminum	1.078	6	2	4541.666667
Little Sandy #10 Mine - Ash	LF	Arsenic	0.032336364	11	8	38.293
Little Sandy #10 Mine - Ash	LF	Barium	0.264454545	11	6	48.81
Little Sandy #10 Mine - Ash	LF	Boron	2.630909091	11	3	157.76
Little Sandy #10 Mine - Ash	LF	Cadmium	0.008290909	11	9	1.198
Little Sandy #10 Mine - Ash	LF	Lead	0.022009091	11	10	56.84
Little Sandy #10 Mine - Ash	LF	Mercury	0.000486364	11	10	0.24435
Little Sandy #10 Mine - Ash	LF	Molybdenum	0.177272727	11	5	6.354
Little Sandy #10 Mine - Ash	LF	Selenium	0.059527273	11	9	6.531
Lone Mtn - Ash	LF	Aluminum	28.615	2	0	
Lone Mtn - Ash	LF	Antimony	0.033	2	0	
Lone Mtn - Ash	LF	Arsenic	0.185	2	0	76
Lone Mtn - Ash	LF	Barium	0.167	2	0	1483.2
Lone Mtn - Ash	LF	Cadmium	0.572	2	0	11.86
Lone Mtn - Ash	LF	Cobalt	0.142	2	0	87.3
Lone Mtn - Ash	LF	Mercury	0.0019	1	0	
Lone Mtn - Ash	LF	Molybdenum	0.4295	2	0	
Lone Mtn - Ash	LF	Selenium	0.328	2	0	
LS - Ash and Coal Refuse	LF	Aluminum	1.18	7	0	
LS - Ash and Coal Refuse	LF	Antimony	0.0107	4	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
LS - Ash and Coal Refuse	LF	Arsenic	0.0104525	16	3	
LS - Ash and Coal Refuse	LF	Barium	0.13220625	16	0	
LS - Ash and Coal Refuse	LF	Boron	18.93125	16	0	
LS - Ash and Coal Refuse	LF	Cadmium	0.00148	16	15	
LS - Ash and Coal Refuse	LF	Cobalt	0.011125	4	0	
LS - Ash and Coal Refuse	LF	Lead	0.0025	16	16	
LS - Ash and Coal Refuse	LF	Mercury	0.00007	4	3	
LS - Ash and Coal Refuse	LF	Molybdenum	0.886875	16	0	
LS - Ash and Coal Refuse	LF	Nitrate/Nitrite	3.045	32	16	
LS - Ash and Coal Refuse	LF	Selenium	1.05343125	16	0	
LS - Ash and Coal Refuse	LF	Thallium	0.00185	8	8	
Martins Creek - Ash	LF	Aluminum	3.18335	20	2	114229.3889
Martins Creek - Ash	LF	Antimony	0.005021053	19	11	10.315
Martins Creek - Ash	LF	Arsenic	0.2314	20	1	50.50530556
Martins Creek - Ash	LF	Barium	0.1969	20	2	641.5466667
Martins Creek - Ash	LF	Boron	3.5089	20	1	304.1266667
Martins Creek - Ash	LF	Cadmium	0.0032	20	20	2.025
Martins Creek - Ash	LF	Cobalt	0.024722222	18	18	66.37611111
Martins Creek - Ash	LF	Lead	0.014	20	19	
Martins Creek - Ash	LF	Mercury	0.0001	19	19	
Martins Creek - Ash	LF	Molybdenum	0.195157895	19	10	
Martins Creek - Ash	LF	Nitrate/Nitrite	0.636428571	14	9	
Martins Creek - Ash	LF	Selenium	0.05717	20	8	4.043888889
Martins Creek - Ash	LF	Thallium	0.003263158	19	19	
McCloskey Site - FBC	LF	Aluminum	0.5	2	2	27450
McCloskey Site - FBC	LF	Arsenic	0.001	2	2	45.355
McCloskey Site - FBC	LF	Barium	0.1	2	2	32.55
McCloskey Site - FBC	LF	Boron	0.022	2	1	0.092
McCloskey Site - FBC	LF	Cadmium	0.0375	2	1	0.025
McCloskey Site - FBC	LF	Lead	0.05	2	2	50
McCloskey Site - FBC	LF	Mercury	0.25	2	2	0.4465
McCloskey Site - FBC	LF	Molybdenum	0.15	2	2	0.15
McCloskey Site - FBC	LF	Selenium	0.0515675	2	2	52.315
McDonough - Ash	LF	Arsenic	0.9	1	0	
McDonough - Ash	LF	Barium	0.5	1	0	
McDonough - Ash	LF	Cadmium	0.01	1	0	
McDonough - Ash	LF	Lead	0.04	1	0	
McDonough - Ash	LF	Selenium	0.2	1	0	
McIntosh - Ash	LF	Arsenic	0.09	1	0	
McIntosh - Ash	LF	Barium	0.2	1	0	
McIntosh - Ash	LF	Cadmium	0.6	1	0	
McIntosh - Ash	LF	Lead	0.03	1	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
McIntosh - Ash	LF	Selenium	0.03	1	0	
McKay Site - FBC	LF	Aluminum	0.105	2	0	30000
McKay Site - FBC	LF	Antimony	0.01	2	2	2.5
McKay Site - FBC	LF	Arsenic	0.025	2	2	51.5
McKay Site - FBC	LF	Barium	0.27	2	0	215
McKay Site - FBC	LF	Boron	0.265	2	0	41.5
McKay Site - FBC	LF	Cadmium	0.005	2	2	2.5
McKay Site - FBC	LF	Lead	0.03	2	1	49
McKay Site - FBC	LF	Mercury	0.0001	2	2	0.345
McKay Site - FBC	LF	Molybdenum	0.13	2	0	6.25
McKay Site - FBC	LF	Nitrate/Nitrite	0.0175	2	1	
McKay Site - FBC	LF	Selenium	0.0355	2	1	1
Miller - Ash	LF	Arsenic	1.3	1	0	18
Miller - Ash	LF	Barium	0.1	1	0	7140
Miller - Ash	LF	Cadmium	0.09	1	0	1.6
Miller - Ash	LF	Lead	0.002	1	0	38
Miller - Ash	LF	Selenium	0.03	1	0	
Miller Creek Mine - Ash	LF	Aluminum	4.78597619	42	4	22486.5969
Miller Creek Mine - Ash	LF	Arsenic	0.075817021	47	16	60.54551064
Miller Creek Mine - Ash	LF	Barium	0.147255319	47	0	87.49382979
Miller Creek Mine - Ash	LF	Boron	2.343829787	47	3	167.0508511
Miller Creek Mine - Ash	LF	Cadmium	0.009771277	47	31	1.850959894
Miller Creek Mine - Ash	LF	Lead	0.034382979	47	24	51.50851064
Miller Creek Mine - Ash	LF	Mercury	0.000255319	47	46	0.06780663
Miller Creek Mine - Ash	LF	Molybdenum	0.166808511	47	17	9.819680851
Miller Creek Mine - Ash	LF	Selenium	0.047102128	47	23	6.492617021
Mine 26 - Ash	LF	Antimony	0.0125	6	6	
Mine 26 - Ash	LF	Arsenic	0.022333333	9	8	
Mine 26 - Ash	LF	Barium	0.388111111	9	1	
Mine 26 - Ash	LF	Boron	9.266666667	9	0	
Mine 26 - Ash	LF	Cadmium	0.008555556	9	4	
Mine 26 - Ash	LF	Cobalt	0.021744444	9	5	
Mine 26 - Ash	LF	Lead	0.148111111	9	6	
Mine 26 - Ash	LF	Mercury	0.0003	9	9	
Mine 26 - Ash	LF	Selenium	0.026388889	9	6	
Mine 26 - Ash	LF	Thallium	0.006833333	6	5	
Mine 26 - Ash and Coal Refuse	LF	Antimony	0.01	2	2	
Mine 26 - Ash and Coal Refuse	LF	Arsenic	0.054285714	7	5	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Mine 26 - Ash and Coal Refuse	LF	Barium	0.615714286	7	0	
Mine 26 - Ash and Coal Refuse	LF	Boron	3.504285714	7	0	
Mine 26 - Ash and Coal Refuse	LF	Cadmium	0.010142857	7	4	
Mine 26 - Ash and Coal Refuse	LF	Cobalt	0.032857143	7	2	
Mine 26 - Ash and Coal Refuse	LF	Lead	0.047142857	7	4	
Mine 26 - Ash and Coal Refuse	LF	Mercury	0.0001	7	7	
Mine 26 - Ash and Coal Refuse	LF	Selenium	0.02	7	7	
Mine 26 - Ash and Coal Refuse	LF	Thallium	0.005	2	2	
Mine 26 - FBC	LF	Arsenic	0.03	1	1	
Mine 26 - FBC	LF	Barium	0.51	1	0	
Mine 26 - FBC	LF	Boron	1.3	1	0	
Mine 26 - FBC	LF	Cadmium	0.0025	1	1	
Mine 26 - FBC	LF	Cobalt	0.005	1	1	
Mine 26 - FBC	LF	Lead	0.01	1	1	
Mine 26 - FBC	LF	Mercury	0.0001	1	1	
Mine 26 - FBC	LF	Selenium	0.08	1	0	
Mitchell - Ash	LF	Arsenic	1.3	1	0	
Mitchell - Ash	LF	Barium	0.3	1	0	
Mitchell - Ash	LF	Cadmium	0.01	1	0	
Mitchell - Ash	LF	Lead	0.06	1	0	
Mitchell - Ash	LF	Selenium	0.06	1	0	
MO - Ash and Coal Refuse	LF	Aluminum	4.49	2	0	
MO - Ash and Coal Refuse	LF	Antimony	0.0125	2	0	
MO - Ash and Coal Refuse	LF	Arsenic	0.2855	2	0	
MO - Ash and Coal Refuse	LF	Barium	1.845	2	0	
MO - Ash and Coal Refuse	LF	Boron	0.219	2	0	
MO - Ash and Coal Refuse	LF	Cadmium	0.006	2	0	
MO - Ash and Coal Refuse	LF	Cobalt	0.012	2	0	
MO - Ash and Coal Refuse	LF	Lead	0.0065	2	0	
MO - Ash and Coal Refuse	LF	Mercury	0.00005	4	4	
MO - Ash and Coal Refuse	LF	Selenium	0.1312	2	0	
MO - Ash and Coal Refuse	LF	Thallium	0.01415	2	0	
Murdock Mine - Ash	LF	Antimony	0.0076875	8	8	
Murdock Mine - Ash	LF	Arsenic	0.0080875	8	6	
Murdock Mine - Ash	LF	Barium	0.258625	8	0	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Murdock Mine - Ash	LF	Boron	9.38775	8	0	
Murdock Mine - Ash	LF	Cadmium	0.0458	8	2	
Murdock Mine - Ash	LF	Cobalt	0.0225625	8	2	
Murdock Mine - Ash	LF	Lead	0.00555	8	2	
Murdock Mine - Ash	LF	Mercury	0.0004375	8	8	
Murdock Mine - Ash	LF	Selenium	0.0053875	8	4	
Murdock Mine - Ash	LF	Thallium	0.02325	8	2	
Murdock Mine - FBC	LF	Antimony	0.004	3	3	
Murdock Mine - FBC	LF	Arsenic	0.005	3	3	
Murdock Mine - FBC	LF	Barium	0.368333333	3	0	
Murdock Mine - FBC	LF	Boron	0.436666667	3	0	
Murdock Mine - FBC	LF	Cadmium	0.0015	3	3	
Murdock Mine - FBC	LF	Cobalt	0.0025	3	3	
Murdock Mine - FBC	LF	Lead	0.0015	3	3	
Murdock Mine - FBC	LF	Mercury	0.0004	3	3	
Murdock Mine - FBC	LF	Selenium	0.003533333	3	2	
Murdock Mine - FBC	LF	Thallium	0.005	3	3	
Nepco - FBC	LF	Arsenic	0.025	2	2	21
Nepco - FBC	LF	Cadmium	0.01	1	0	0.5
Nepco - FBC	LF	Lead	0.025	2	2	39
Nepco - FBC	LF	Mercury	0.0002	2	2	0.01
Nepco - FBC	LF	Selenium	0.05	2	2	12.6
No. 1 Contracting Corp - FBC	LF	Aluminum	0.935	2	0	
No. 1 Contracting Corp - FBC	LF	Antimony	0.018	1	0	
No. 1 Contracting Corp - FBC	LF	Arsenic	0.046	2	0	
No. 1 Contracting Corp - FBC	LF	Barium	0.1315	2	0	
No. 1 Contracting Corp - FBC	LF	Boron	0.05	1	0	
No. 1 Contracting Corp - FBC	LF	Cadmium	0.005	1	0	
No. 1 Contracting Corp - FBC	LF	Lead	0.06	1	0	
No. 1 Contracting Corp - FBC	LF	Mercury	0.0002	1	0	
No. 1 Contracting Corp - FBC	LF	Molybdenum	0.105	2	0	
No. 1 Contracting Corp - FBC	LF	Selenium	0.1395	2	0	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Northampton40000201 - Ash	LF	Aluminum	0.38	1	0	24500
Northampton40000201 - Ash	LF	Antimony	0.01	1	0	20
Northampton40000201 - Ash	LF	Arsenic	0.005	1	0	40.6
Northampton40000201 - Ash	LF	Barium	0.21	1	0	242
Northampton40000201 - Ash	LF	Boron	0.2	1	0	17.3
Northampton40000201 - Ash	LF	Cadmium	0.012	1	0	0.5
Northampton40000201 - Ash	LF	Lead	0.1	1	0	18
Northampton40000201 - Ash	LF	Mercury	0.0002	1	0	0.535
Northampton40000201 - Ash	LF	Molybdenum	0.1	1	0	10
Northampton40000201 - Ash	LF	Selenium	0.015	1	0	8.9
Nucla - FBC	LF	Aluminum	0.1	2	2	110050
Nucla - FBC	LF	Arsenic	0.0025	4	4	7.4
Nucla - FBC	LF	Barium	0.08	2	1	190
Nucla - FBC	LF	Boron	0.485	2	1	57.5
Nucla - FBC	LF	Cadmium	0.00055	2	2	1.95
Nucla - FBC	LF	Cobalt	0.005	2	2	10
Nucla - FBC	LF	Lead	0.0016	2	1	35.5
Nucla - FBC	LF	Mercury	0.0001	2	2	
Nucla - FBC	LF	Molybdenum	0.2045	2	0	83
Nucla - FBC	LF	Nitrate/Nitrite	0.1125	2	2	
Nucla - FBC	LF	Selenium	0.00485	2	1	9.35
Nucla2 - FBC	LF	Aluminum	7.18	3	0	100000
Nucla2 - FBC	LF	Antimony	0.1	6	6	46
Nucla2 - FBC	LF	Arsenic	0.00375	6	5	27.93333333
Nucla2 - FBC	LF	Barium	0.093	3	0	246
Nucla2 - FBC	LF	Boron	3.1	3	1	69.16666667
Nucla2 - FBC	LF	Cadmium	0.000475	6	4	0.263333333
Nucla2 - FBC	LF	Cobalt	0.012	3	1	6.1
Nucla2 - FBC	LF	Lead	0.0062	3	0	8.296666667
Nucla2 - FBC	LF	Mercury	0.000566667	6	5	0.214166667
Nucla2 - FBC	LF	Molybdenum	0.303333333	3	0	3.316666667
Nucla2 - FBC	LF	Nitrate/Nitrite	6.591666667	6	4	
Nucla2 - FBC	LF	Selenium	0.048666667	6	2	1.395
Nucla2 - FBC	LF	Thallium	0.05	3	3	6.416666667

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
OK - Ash	LF	Aluminum	11.895	2	0	
OK - Ash	LF	Antimony	0.001575	2	1	
OK - Ash	LF	Arsenic	0.003225	2	1	
OK - Ash	LF	Barium	0.686	2	0	
OK - Ash	LF	Boron	2.68	2	0	
OK - Ash	LF	Cadmium	0.00027	2	1	
OK - Ash	LF	Cobalt	0.00745	2	0	
OK - Ash	LF	Lead	0.00355	2	0	
OK - Ash	LF	Mercury	0.0001	2	1	
OK - Ash	LF	Selenium	0.037	2	0	
OK - Ash	LF	Thallium	0.00185	4	4	
P4 - Ash	LF	Aluminum	6.2196875	8	0	
P4 - Ash	LF	Antimony	0.00105	4	4	
P4 - Ash	LF	Arsenic	0.00420375	8	5	
P4 - Ash	LF	Barium	0.254375	8	0	
P4 - Ash	LF	Boron	1.142697917	8	0	
P4 - Ash	LF	Cadmium	0.00125	8	8	
P4 - Ash	LF	Cobalt	0.00315	2	0	
P4 - Ash	LF	Lead	0.0025	8	8	
P4 - Ash	LF	Mercury	0.00005	4	4	
P4 - Ash	LF	Molybdenum	0.2114375	8	4	
P4 - Ash	LF	Nitrate/Nitrite	1.92075	16	8	
P4 - Ash	LF	Selenium	0.01	8	8	
P4 - Ash	LF	Thallium	0.002775	2	2	
PA - Ash	LF	Aluminum	26.16153846	13	0	
PA - Ash	LF	Antimony	0.0031	2	0	
PA - Ash	LF	Arsenic	0.005991923	13	9	
PA - Ash	LF	Barium	1.043838462	13	0	
PA - Ash	LF	Boron	0.736153846	13	0	
PA - Ash	LF	Cadmium	0.001758462	13	12	
PA - Ash	LF	Cobalt	0.001915	2	2	
PA - Ash	LF	Lead	0.005993077	13	10	
PA - Ash	LF	Mercury	0.000175	2	0	
PA - Ash	LF	Molybdenum	0.138461538	13	4	
PA - Ash	LF	Nitrate/Nitrite	2.544596154	26	15	
PA - Ash	LF	Selenium	0.084376923	13	5	
PA - Ash	LF	Thallium	0.00196	4	4	
Pitt - FBC	LF	Antimony	0.0219	1	0	
Pitt - FBC	LF	Arsenic	0.05	1	1	
Pitt - FBC	LF	Barium	1.167333333	3	1	
Pitt - FBC	LF	Cadmium	0.033333333	3	3	
Pitt - FBC	LF	Lead	0.183333333	3	3	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Pitt - FBC	LF	Mercury	0.005	1	1	
Pitt - FBC	LF	Selenium	0.05	1	1	
Pitt - FBC	LF	Thallium	0.0025	3	3	
Plant 10 - FBC	LF	Arsenic	0.14875	4	0	71.3
Plant 10 - FBC	LF	Cadmium	0.05425	4	1	2.418181818
Plant 10 - FBC	LF	Lead	0.2965	4	1	39.63636364
Plant 10 - FBC	LF	Mercury	0.05005	4	4	1.174
Plant 10 - FBC	LF	Selenium	0.1285	4	0	4.011818182
Plant 12 - FBC	LF	Arsenic	0.004125	8	4	98.62222222
Plant 12 - FBC	LF	Cadmium	0.02	8	8	2.188888889
Plant 12 - FBC	LF	Lead	0.28375	8	2	47.83333333
Plant 12 - FBC	LF	Mercury	0.0004	8	8	1.047777778
Plant 12 - FBC	LF	Selenium	0.006125	8	8	4.263888889
Plant 8 - FBC	LF	Arsenic	0.019868421	19	18	42.04210526
Plant 8 - FBC	LF	Cadmium	0.016826923	52	43	2.288947368
Plant 8 - FBC	LF	Lead	0.007211538	52	37	27.62105263
Plant 8 - FBC	LF	Mercury	0.000289474	19	19	0.065789474
Plant 8 - FBC	LF	Selenium	0.053026316	19	9	33.02263158
Plant 9 - FBC	LF	Arsenic	0.058666667	3	0	2.8
Plant 9 - FBC	LF	Lead	0.105454545	11	8	57.67142857
Plant 9 - FBC	LF	Mercury	0.00025	11	11	0.604285714
Plant 9 - FBC	LF	Selenium	0.065333333	3	0	5.115714286
Portland - Ash	LF	Aluminum	2.648555556	9	0	
Portland - Ash	LF	Antimony	0.075	2	2	
Portland - Ash	LF	Arsenic	0.178666667	9	6	
Portland - Ash	LF	Barium	0.28475	8	0	
Portland - Ash	LF	Boron	4.799333333	3	0	
Portland - Ash	LF	Cadmium	0.006	9	7	
Portland - Ash	LF	Cobalt	0.014	2	1	
Portland - Ash	LF	Lead	0.058333333	9	8	
Portland - Ash	LF	Mercury	0.001	4	4	
Portland - Ash	LF	Molybdenum	0.178666667	3	1	
Portland - Ash	LF	Selenium	0.25625	4	4	
Portland - Ash	LF	Thallium	0.005	4	4	
PP - Ash	LF	Aluminum	2.422	2	0	
PP - Ash	LF	Antimony	0.00245	2	0	
PP - Ash	LF	Arsenic	0.0273375	2	1	
PP - Ash	LF	Barium	0.2435	2	0	
PP - Ash	LF	Boron	6.605	2	0	
PP - Ash	LF	Cadmium	0.0023975	2	1	
PP - Ash	LF	Cobalt	0.0049575	2	1	
PP - Ash	LF	Lead	0.001155	2	1	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
PP - Ash	LF	Mercury	0.00028	2	0	
PP - Ash	LF	Selenium	0.0364	2	0	
PP - Ash	LF	Thallium	0.01518	2	1	
Revloc Site - FBC	LF	Aluminum	0.58	2	1	
Revloc Site - FBC	LF	Antimony	0.002	2	2	
Revloc Site - FBC	LF	Arsenic	0.002	2	1	
Revloc Site - FBC	LF	Barium	0.44	2	2	
Revloc Site - FBC	LF	Boron	0.2585	2	1	
Revloc Site - FBC	LF	Cadmium	0.02	2	2	
Revloc Site - FBC	LF	Cobalt	0.0825	2	1	
Revloc Site - FBC	LF	Lead	0.25	2	0	
Revloc Site - FBC	LF	Mercury	0.0005	2	2	
Revloc Site - FBC	LF	Molybdenum	0.0545	2	1	
Revloc Site - FBC	LF	Selenium	0.0025	2	1	
Scherer - Ash	LF	Arsenic	0.01	1	0	
Scherer - Ash	LF	Barium	0.7	1	0	
Scherer - Ash	LF	Cadmium	0.001	1	0	
Scherer - Ash	LF	Lead	0.001	1	0	
Scherer - Ash	LF	Selenium	0.06	1	0	
Scholz - Ash	LF	Arsenic	0.02	1	0	
Scholz - Ash	LF	Barium	0.2	1	0	
Scholz - Ash	LF	Cadmium	0.04	1	0	
Scholz - Ash	LF	Lead	0.04	1	0	
Scholz - Ash	LF	Selenium	0.02	1	0	
Scrubgrass - FBC	LF	Arsenic	0.025	2	2	59
Scrubgrass - FBC	LF	Cadmium	0.0025	1	0	0.7
Scrubgrass - FBC	LF	Lead	0.025	2	2	50
Scrubgrass - FBC	LF	Mercury	0.0002	2	2	0.01
Scrubgrass - FBC	LF	Selenium	0.05	2	2	21.7
Seward - Ash	LF	Aluminum	2.965	2	0	
Seward - Ash	LF	Antimony	0.075	2	2	
Seward - Ash	LF	Arsenic	0.288666667	3	2	
Seward - Ash	LF	Barium	0.473333333	3	0	
Seward - Ash	LF	Boron	0.57	1	0	
Seward - Ash	LF	Cadmium	0.005833333	3	1	
Seward - Ash	LF	Cobalt	0.014	1	0	
Seward - Ash	LF	Lead	0.1875	1	1	
Seward - Ash	LF	Mercury	0.003733333	3	3	
Seward - Ash	LF	Molybdenum	0.53	1	0	
Seward - Ash	LF	Selenium	0.196666667	3	2	
Seward - Ash	LF	Thallium	0.012	1	0	
Shawnee - FBC	LF	Aluminum	0.231	5	3	38240

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Shawnee - FBC	LF	Antimony	0.296	5	2	15.6
Shawnee - FBC	LF	Arsenic	0.219	10	6	17.3
Shawnee - FBC	LF	Barium	2.001	10	0	799.4
Shawnee - FBC	LF	Boron	0.97	5	3	116.2
Shawnee - FBC	LF	Cadmium	0.005555	10	7	0.622
Shawnee - FBC	LF	Cobalt	0.07	5	2	2.75
Shawnee - FBC	LF	Lead	0.0897	10	5	6.4
Shawnee - FBC	LF	Mercury	0.00029	10	8	0.365
Shawnee - FBC	LF	Molybdenum	0.382	5	0	6.4
Shawnee - FBC	LF	Nitrate/Nitrite	3.786666667	8	4	
Shawnee - FBC	LF	Selenium	0.13005	10	6	0.73
Shawnee - FBC	LF	Thallium	0.197	5	3	8.9
Shawville - Ash	LF	Aluminum	2.0958	5	0	
Shawville - Ash	LF	Antimony	0.075	2	2	
Shawville - Ash	LF	Arsenic	0.4384	5	1	
Shawville - Ash	LF	Barium	0.2172	5	0	
Shawville - Ash	LF	Boron	0.56	1	0	
Shawville - Ash	LF	Cadmium	0.0059	5	2	
Shawville - Ash	LF	Cobalt	0.021	1	0	
Shawville - Ash	LF	Lead	0.1875	1	1	
Shawville - Ash	LF	Mercury	0.001	2	2	
Shawville - Ash	LF	Molybdenum	0.09	1	0	
Shawville - Ash	LF	Selenium	0.191	5	2	
Shawville - Ash	LF	Thallium	0.005	2	2	
Sibley Quarry - Ash	LF	Aluminum	0.6	4	4	
Sibley Quarry - Ash	LF	Arsenic	0.018	4	0	
Sibley Quarry - Ash	LF	Barium	0.265	4	4	
Sibley Quarry - Ash	LF	Cadmium	0.00114125	4	2	
Sibley Quarry - Ash	LF	Lead	0.00305	4	4	
Sibley Quarry - Ash	LF	Mercury	0.0001	4	4	
Sibley Quarry - Ash	LF	Molybdenum	0.725	3	1	
Sibley Quarry - Ash	LF	Selenium	0.18425	4	1	
Silverton - Ash	LF	Aluminum	3.1	1	0	16870
Silverton - Ash	LF	Arsenic	0.375	2	0	48.5
Silverton - Ash	LF	Barium	1.7	1	0	181.5
Silverton - Ash	LF	Boron	0.22	1	0	20.5
Silverton - Ash	LF	Lead	0.23	1	0	29.5
Silverton - Ash	LF	Molybdenum	0.1	1	0	5
Silverton - Ash	LF	Selenium	0.12	2	0	6.7
Smith - Ash	LF	Arsenic	0.02	1	0	
Smith - Ash	LF	Barium	0.2	1	0	
Smith - Ash	LF	Cadmium	0.04	1	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Smith - Ash	LF	Lead	0.01	1	0	
Smith - Ash	LF	Selenium	0.01	1	0	
SW - Ash	LF	Arsenic	0.006679487	195	53	29.495189
SW - Ash	LF	Barium	0.81082716	243	0	2538.862069
SW - Ash	LF	Cadmium	0.003400769	195	47	1.230670103
SW - Ash	LF	Lead	0.001570707	99	97	35.39886598
SW - Ash	LF	Mercury	0.000217677	99	98	0.039255034
SW - Ash	LF	Selenium	0.003534884	172	46	0.6
SX - Ash	LF	Aluminum	1.862	2	0	
SX - Ash	LF	Antimony	0.003275	2	1	
SX - Ash	LF	Arsenic	0.0365	2	0	
SX - Ash	LF	Barium	0.959	2	0	
SX - Ash	LF	Boron	4.5223	2	0	
SX - Ash	LF	Cadmium	0.04425	2	0	
SX - Ash	LF	Cobalt	0.0167	2	0	
SX - Ash	LF	Lead	0.00675	2	0	
SX - Ash	LF	Mercury	0.00005	4	4	
SX - Ash	LF	Selenium	0.048725	2	1	
SX - Ash	LF	Thallium	0.013625	2	1	
Tidd - FBC	LF	Aluminum	0.105	3	1	
Tidd - FBC	LF	Antimony	0.03	5	5	
Tidd - FBC	LF	Arsenic	0.028333333	3	2	
Tidd - FBC	LF	Barium	0.184	2	0	
Tidd - FBC	LF	Boron	0.82	3	0	
Tidd - FBC	LF	Cadmium	0.0015	3	3	
Tidd - FBC	LF	Cobalt	0.021	3	0	
Tidd - FBC	LF	Lead	0.015833333	3	3	
Tidd - FBC	LF	Mercury	0.006733333	3	3	
Tidd - FBC	LF	Molybdenum	0.082	3	0	
Tidd - FBC	LF	Selenium	0.101666667	3	2	
Titus - Ash	LF	Aluminum	4.4135	4	0	
Titus - Ash	LF	Antimony	0.04375	4	4	
Titus - Ash	LF	Arsenic	0.346	2	1	
Titus - Ash	LF	Barium	0.3	4	0	
Titus - Ash	LF	Boron	7.345	2	0	
Titus - Ash	LF	Cadmium	0.0115	4	0	
Titus - Ash	LF	Cobalt	0.027	2	0	
Titus - Ash	LF	Lead	0.19375	2	2	
Titus - Ash	LF	Mercury	0.001	2	2	
Titus - Ash	LF	Molybdenum	0.34	2	0	
Titus - Ash	LF	Selenium	0.144	4	3	
Titus - Ash	LF	Thallium	0.01	2	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Tracy Vein Slope - Ash	LF	Aluminum	0.533833333	6	0	11090
Tracy Vein Slope - Ash	LF	Antimony	0.05	5	0	24.215
Tracy Vein Slope - Ash	LF	Arsenic	0.065166667	6	0	61.33333333
Tracy Vein Slope - Ash	LF	Barium	0.148833333	6	0	99.31666667
Tracy Vein Slope - Ash	LF	Boron	1.4486	5	0	122.4333333
Tracy Vein Slope - Ash	LF	Cadmium	0.044833333	6	0	1.070166667
Tracy Vein Slope - Ash	LF	Lead	0.075	6	0	18.90833333
Tracy Vein Slope - Ash	LF	Mercury	0.001	2	0	1.5888
Tracy Vein Slope - Ash	LF	Molybdenum	0.1662	5	0	7.721666667
Tracy Vein Slope - Ash	LF	Selenium	0.0524	5	0	8.608
Tracy Vein Slope - FBC	LF	Aluminum	1.32	1	0	7240
Tracy Vein Slope - FBC	LF	Arsenic	0.052	1	0	6.97
Tracy Vein Slope - FBC	LF	Barium	0.056	1	0	68.9
Tracy Vein Slope - FBC	LF	Boron	0.043	1	0	7.43
Tracy Vein Slope - FBC	LF	Molybdenum	0.027	1	0	0.84
Tracy Vein Slope - FBC	LF	Selenium	0.039	1	0	3.22
UAPP - Ash	LF	Arsenic	0.0025	2	2	
UAPP - Ash	LF	Barium	0.4	2	1	
UAPP - Ash	LF	Cadmium	0.04	2	2	
UAPP - Ash	LF	Lead	0.1	2	2	
UAPP - Ash	LF	Mercury	0.025	2	2	
UAPP - Ash	LF	Selenium	0.00275	2	1	
Universal - Ash	LF	Aluminum	2.057777778	9	0	6000.222222
Universal - Ash	LF	Arsenic	0.277818182	11	2	41.50909091
Universal - Ash	LF	Barium	0.090181818	11	1	71
Universal - Ash	LF	Boron	2.754545455	11	0	180.2954545
Universal - Ash	LF	Cadmium	0.003227273	11	9	2.115909091
Universal - Ash	LF	Lead	0.022145455	11	7	33.00909091
Universal - Ash	LF	Mercury	0.000386364	11	11	0.137272727
Universal - Ash	LF	Molybdenum	0.134363636	11	1	3.554545455
Universal - Ash	LF	Selenium	0.160090909	11	2	7.106363636
Wansley - Ash	LF	Arsenic	0.05	1	0	
Wansley - Ash	LF	Barium	0.2	1	0	
Wansley - Ash	LF	Cadmium	0.09	1	0	
Wansley - Ash	LF	Lead	0.02	1	0	
Wansley - Ash	LF	Selenium	0.06	1	0	
WEPCO CALEDONIA LANDFILL - Ash	LF	Barium	0.225	2	0	
WEPCO CALEDONIA LANDFILL - Ash	LF	Boron	16.90454545	22	0	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
WEPCO CALEDONIA LANDFILL - Ash	LF	Cadmium	0.000045	3	3	
WEPCO CALEDONIA LANDFILL - Ash	LF	Lead	0.003566667	3	3	
WEPCO CALEDONIA LANDFILL - Ash	LF	Molybdenum	0.77500575	4	3	
WEPCO CALEDONIA LANDFILL - Ash	LF	Selenium	0.046794118	34	0	
WEPCO HWY 32 LANDFILL - Ash	LF	Boron	83.41666667	12	0	
WEPCO HWY 32 LANDFILL - Ash	LF	Selenium	0.006675	12	4	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Arsenic	0.0055	2	0	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Barium	0.1195	2	0	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Boron	14.02134483	29	0	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Cadmium	0.010266667	3	1	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Lead	0.00625	2	1	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Mercury	0.0002	1	0	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Molybdenum	0.000022375	4	4	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Nitrate/Nitrite	1.866666667	3	0	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Selenium	0.06332275	28	0	
Wilton Site - Ash	LF	Aluminum	3	1	0	
Wilton Site - Ash	LF	Arsenic	0.027	1	0	
Wilton Site - Ash	LF	Barium	0.51	1	0	
Wilton Site - Ash	LF	Boron	25	1	0	
Wilton Site - Ash	LF	Cadmium	0.0025	2	2	
Wilton Site - Ash	LF	Lead	0.0025	2	2	
Wilton Site - Ash	LF	Mercury	0.001	2	2	
Wilton Site - Ash	LF	Molybdenum	0.34	1	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Wilton Site - Ash	LF	Nitrate/Nitrite	0.5	1	1	
Wilton Site - Ash	LF	Selenium	0.09	1	0	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Arsenic	0.0014	3	2	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Barium	0.183025	4	1	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Boron	6.363333333	21	1	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Cadmium	0.0047595	8	0	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Lead	0.00668375	8	0	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Mercury	0.000082	5	5	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Selenium	0.011077619	21	1	
Yates1 - Ash	LF	Arsenic	0.1	1	0	
Yates1 - Ash	LF	Barium	0.3	1	0	
Yates1 - Ash	LF	Cadmium	0.02	1	0	
Yates1 - Ash	LF	Lead	0.05	1	0	
Yates1 - Ash	LF	Selenium	0.02	1	0	
Yates2 - Ash	LF	Arsenic	0.09	1	0	
Yates2 - Ash	LF	Barium	0.2	1	0	
Yates2 - Ash	LF	Cadmium	0.02	1	0	
Yates2 - Ash	LF	Lead	0.03	1	0	
Yates2 - Ash	LF	Selenium	0.05	1	0	
AP - Ash	SI	Aluminum	0.553384615	13	0	
AP - Ash	SI	Antimony	0.01	1	1	
AP - Ash	SI	Arsenic	0.070933333	15	0	
AP - Ash	SI	Barium	0.063066667	15	1	
AP - Ash	SI	Boron	12.50986667	15	0	
AP - Ash	SI	Cadmium	0.001042857	14	7	
AP - Ash	SI	Cobalt	0.01	1	1	
AP - Ash	SI	Lead	0.001723333	15	14	
AP - Ash	SI	Molybdenum	0.486733333	15	2	
AP - Ash	SI	Nitrate/Nitrite	0.254809524	29	22	
AP - Ash	SI	Selenium	0.044326667	15	1	
AP - Ash	SI	Thallium	0.0025	1	1	
BR - Ash and Coal Refuse	SI	Aluminum	89.12777778	18	0	
BR - Ash and Coal Refuse	SI	Arsenic	0.775383333	15	4	
BR - Ash and Coal Refuse	SI	Barium	0.188055556	18	14	
BR - Ash and Coal Refuse	SI	Boron	3.857694444	18	2	
BR - Ash and Coal Refuse	SI	Cadmium	0.175	18	7	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
BR - Ash and Coal Refuse	SI	Cobalt	0.204722222	18	11	
BR - Ash and Coal Refuse	SI	Molybdenum	0.5	18	18	
C - Ash	SI	Aluminum	4.192307692	13	0	
C - Ash	SI	Antimony	0.07	10	10	
C - Ash	SI	Arsenic	0.15	10	0	
C - Ash	SI	Barium	0.113769231	13	0	
C - Ash	SI	Boron	10.96428571	14	0	
C - Ash	SI	Cadmium	0.0025	10	10	
C - Ash	SI	Cobalt	0.005	10	10	
C - Ash	SI	Lead	0.00229	10	5	
C - Ash	SI	Molybdenum	0.585384615	13	0	
C - Ash	SI	Nitrate/Nitrite	10.85474359	16	3	
C - Ash	SI	Selenium	0.0175	10	2	
C - Ash	SI	Thallium	0.05	10	10	
CADK - Ash	SI	Aluminum	0.165	2	0	
CADK - Ash	SI	Arsenic	0.0075	2	2	
CADK - Ash	SI	Barium	0.02	2	2	
CADK - Ash	SI	Boron	60.05	2	0	
CADK - Ash	SI	Cadmium	0.001	2	2	
CADK - Ash	SI	Lead	0.1	2	2	
CADK - Ash	SI	Molybdenum	1.165	2	0	
CADK - Ash	SI	Nitrate/Nitrite	11.135	4	0	
CADK - Ash	SI	Selenium	0.125	2	0	
CASJ - Ash	SI	Aluminum	0.1108	5	4	
CASJ - Ash	SI	Arsenic	5.37225	4	0	
CASJ - Ash	SI	Barium	0.0214	5	2	
CASJ - Ash	SI	Boron	46.02	5	0	
CASJ - Ash	SI	Cadmium	0.0156	5	3	
CASJ - Ash	SI	Lead	0.21	5	4	
CASJ - Ash	SI	Molybdenum	0.13	5	5	
CASJ - Ash	SI	Nitrate/Nitrite	1.882	10	8	
CASJ - Ash	SI	Selenium	0.40575	4	0	
CATT - Ash	SI	Aluminum	0.28	2	0	
CATT - Ash	SI	Arsenic	0.206	2	0	
CATT - Ash	SI	Barium	0.085	2	0	
CATT - Ash	SI	Boron	110.5	2	0	
CATT - Ash	SI	Cadmium	0.002	2	1	
CATT - Ash	SI	Lead	0.2275	2	0	
CATT - Ash	SI	Molybdenum	0.655	2	0	
CATT - Ash	SI	Nitrate/Nitrite	0.01	2	0	
CATT - Ash	SI	Selenium	1.025	2	0	
CL - Ash and Coal Refuse	SI	Aluminum	4.680970556	30	2	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
CL - Ash and Coal Refuse	SI	Arsenic	0.493663408	30	2	
CL - Ash and Coal Refuse	SI	Barium	0.550251717	30	0	
CL - Ash and Coal Refuse	SI	Boron	1.092075	30	0	
CL - Ash and Coal Refuse	SI	Cadmium	0.001680507	30	27	
CL - Ash and Coal Refuse	SI	Lead	0.003384333	30	29	
CL - Ash and Coal Refuse	SI	Molybdenum	0.377590556	30	0	
CL - Ash and Coal Refuse	SI	Nitrate/Nitrite	0.6303	60	13	
CL - Ash and Coal Refuse	SI	Selenium	0.147525085	30	9	
CY - Ash	SI	Aluminum	6.0975	4	0	
CY - Ash	SI	Arsenic	0.1975	4	0	
CY - Ash	SI	Barium	0.179725	4	0	
CY - Ash	SI	Boron	0.025	4	4	
CY - Ash	SI	Cadmium	0.0040625	4	4	
CY - Ash	SI	Lead	0.008125	4	4	
CY - Ash	SI	Molybdenum	0.655	4	0	
CY - Ash	SI	Nitrate/Nitrite	750.2625	8	5	
CY - Ash	SI	Selenium	0.086575	4	1	
FC - Ash and Coal Refuse	SI	Aluminum	11.433	10	0	
FC - Ash and Coal Refuse	SI	Arsenic	0.00752	10	8	
FC - Ash and Coal Refuse	SI	Barium	0.14918	10	0	
FC - Ash and Coal Refuse	SI	Boron	0.7445	10	1	
FC - Ash and Coal Refuse	SI	Cadmium	0.001956	10	9	
FC - Ash and Coal Refuse	SI	Lead	0.0025	10	10	
FC - Ash and Coal Refuse	SI	Molybdenum	0.2275	10	10	
FC - Ash and Coal Refuse	SI	Nitrate/Nitrite	0.2	20	20	
FC - Ash and Coal Refuse	SI	Selenium	0.02174	10	0	
HA - Ash	SI	Aluminum	2.830833333	9	2	
HA - Ash	SI	Arsenic	0.086774333	9	2	
HA - Ash	SI	Barium	0.471945556	9	0	
HA - Ash	SI	Boron	2.283583333	9	0	
HA - Ash	SI	Cadmium	0.00125	9	9	
HA - Ash	SI	Lead	0.003503333	9	8	
HA - Ash	SI	Molybdenum	0.107333333	9	4	
HA - Ash	SI	Nitrate/Nitrite	1.968222222	18	10	
HA - Ash	SI	Selenium	0.01	9	9	
HA - Ash and Coal Refuse	SI	Aluminum	0.65	1	0	
HA - Ash and Coal Refuse	SI	Arsenic	0.18	1	0	
HA - Ash and Coal Refuse	SI	Barium	0.11	1	0	
HA - Ash and Coal Refuse	SI	Boron	1.7	1	0	
HA - Ash and Coal Refuse	SI	Cadmium	0.0025	1	1	
HA - Ash and Coal Refuse	SI	Lead	0.025	1	1	
HA - Ash and Coal Refuse	SI	Mercury	0.00025	1	1	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
HA - Ash and Coal Refuse	SI	Molybdenum	0.075	1	1	
HA - Ash and Coal Refuse	SI	Selenium	0.0025	1	1	
L - Ash	SI	Aluminum	0.015	2	2	
L - Ash	SI	Barium	0.001	2	2	
L - Ash	SI	Boron	0.62	2	0	
L - Ash	SI	Cadmium	0.001	2	2	
L - Ash	SI	Molybdenum	0.1675	2	1	
MO - Ash	SI	Aluminum	0.894458333	6	0	
MO - Ash	SI	Arsenic	0.011755993	6	3	
MO - Ash	SI	Barium	0.019379487	6	0	
MO - Ash	SI	Boron	0.085041667	6	2	
MO - Ash	SI	Cadmium	0.00125	6	6	
MO - Ash	SI	Lead	0.003666667	6	5	
MO - Ash	SI	Molybdenum	0.928770833	6	3	
MO - Ash	SI	Nitrate/Nitrite	0.1205	12	10	
MO - Ash	SI	Selenium	0.005	6	6	
MO - Ash and Coal Refuse	SI	Aluminum	296.2888026	19	6	
MO - Ash and Coal Refuse	SI	Arsenic	11.67554177	20	0	
MO - Ash and Coal Refuse	SI	Barium	0.039930301	20	1	
MO - Ash and Coal Refuse	SI	Boron	15.49313158	19	2	
MO - Ash and Coal Refuse	SI	Cadmium	0.124406392	27	9	
MO - Ash and Coal Refuse	SI	Cobalt	4.8377	20	7	
MO - Ash and Coal Refuse	SI	Lead	0.321181411	20	11	
MO - Ash and Coal Refuse	SI	Molybdenum	0.402184211	19	15	
MO - Ash and Coal Refuse	SI	Nitrate/Nitrite	5.165	39	37	
MO - Ash and Coal Refuse	SI	Selenium	0.103823054	20	9	
O - Ash	SI	Arsenic	0.234766667	3	0	
O - Ash	SI	Boron	6.166666667	3	0	
O - Ash	SI	Molybdenum	0.0179	1	0	
O - Ash	SI	Nitrate/Nitrite	461	1	0	
O - Ash	SI	Selenium	0.0029	3	0	
OK - Ash	SI	Aluminum	40.45955556	9	0	
OK - Ash	SI	Arsenic	0.060628889	9	2	
OK - Ash	SI	Barium	0.159055556	9	1	
OK - Ash	SI	Boron	3.148333333	9	0	
OK - Ash	SI	Cadmium	0.01	9	9	
OK - Ash	SI	Lead	0.02	9	9	
OK - Ash	SI	Molybdenum	0.721694444	9	0	
OK - Ash	SI	Nitrate/Nitrite	7.62	18	17	
OK - Ash	SI	Selenium	0.282377778	9	2	
SX - Ash	SI	Aluminum	3.866609827	15	0	
SX - Ash	SI	Arsenic	0.054834273	15	2	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
SX - Ash	SI	Barium	0.079191593	15	0	
SX - Ash	SI	Boron	32.70433889	15	0	
SX - Ash	SI	Cadmium	0.019243353	15	5	
SX - Ash	SI	Lead	0.001228153	15	5	
SX - Ash	SI	Molybdenum	11.40518778	15	0	
SX - Ash	SI	Nitrate/Nitrite	1.6328	30	12	
SX - Ash	SI	Selenium	0.239368793	15	6	

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Appendix B. Waste Management Units

The source models supporting the coal combustion waste (CCW) risk assessment require inputs describing the characteristics of CCW waste management units (WMUs). To satisfy this requirement, the assessment used a data set of WMU area, capacity, liner type, geometry, and waste type managed for a set of individual CCW landfills and surface impoundments that are representative of the national population of coal combustion facilities that are managing their wastes onsite.

The sources for these data sets were responses to two voluntary industry surveys: an Electric Power Research Institute (EPRI) comanagement survey (for conventional utility coal combustion WMUs units) and a Council of Industrial Boiler Owners (CIBO) fluidized bed combustion (FBC) survey (for FBC WMUs). In addition to the individual WMU data, certain assumptions were required regarding (1) liner types and characteristics, (2) surface impoundment operating life, and (3) above- and below-grade geometries for WMUs. The sections below describe the two industry surveys, then discuss the data sources and assumptions made.

B.1 EPRI Comanagement Survey

For conventional utility coal combustion WMUs, the source of data for area, capacity, liner type, and waste type managed was the EPRI Coal Combustion By-Products and Low-Volume Wastes Comanagement Survey (EPRI, 1997a). In 1995, EPRI sent a 4-page questionnaire to all electric utilities with more than 100 megawatts (MW) of coal-fired generating capacity. The survey gathered data on the design of coal combustion management units and the types and volumes of waste managed. From the survey responses, EPRI prepared an electronic database and provided it to the U.S. Environmental Protection Agency (EPA) in support of the March 1999 *Report to Congress: Wastes from the Combustion of Fossil Fuels* (the RTC) (U.S. EPA, 1999a). EPRI also published a report (EPRI, 1997a) documenting the survey format and providing a brief summary of the results.

The EPRI survey responses include information on 323 waste management facilities serving 238 power plants located in 36 states. The total annual volume of CCW reported disposed by respondents to the EPRI comanagement survey is nearly 62 million tons. This quantity is two-thirds of the total generation of CCW in 1995. Therefore, the survey sample encompasses the majority of CCW disposed in terms of volume. Based on comparison with data from other sources, the EPRI survey sample appears representative of the population of coal combustion WMUs in terms of the types of units included (i.e., landfills and surface impoundments). The EPRI survey sample also is believed to be generally geographically representative of the population of conventional utility WMUs, although it may under-represent certain management practices in a few states. The EPA document, *Technical Background Document for the Supplemental Report to Congress on Remaining Fossil Fuel Combustion Wastes: Industry Statistics and Waste Management Practices* (U.S. EPA, 1999b), discusses the

representativeness of the EPRI survey in greater detail and provides extensive summary statistics on the survey responses.

The EPRI comanagement survey includes questions requesting the respondent to report the location of the WMU (by state) and the WMU area, capacity, liner type, and waste type managed. Therefore, the data set used for modeling these variables was extracted directly from the EPRI database for all active landfills and surface impoundments responding to the EPRI survey. Mine placement sites and closed WMUs were excluded from the data set. Also excluded from the data set were three responding WMUs that managed FBC waste. Data for these units were instead combined with the data set for FBC WMUs from the CIBO FBC survey (described below).

The EPRI survey data were provided in blinded form. That is, the original database did not report the identity of each respondent and identified WMU location only by state. To provide a more complete identification of the EPRI waste management locations, each unit in the EPRI database had to be matched with a specific electric utility facility. This matching was accomplished by applying professional judgment in comparing the state, waste quantity, and waste management practice information in the EPRI database with similar data from responses to the U.S. Department of Energy's Energy Information Administration (EIA) Form EIA-767 (Steam-Electric Plant Operation and Design Report) for the same year as the EPRI survey (1995). The latitude and longitude plant locations in the EIA database allowed the pairing of the EPRI WMU data with environmental setting information.

B.2 CIBO Fluidized Bed Combustion Survey

For FBC WMUs, the primary source of data for area, capacity, liner type, and waste type managed was the CIBO Fossil Fuel Fluidized Bed Combustion (FBC) Survey. In 1996, CIBO sent a voluntary questionnaire to every fossil-fuel-fired FBC plant, both utility and nonutility, in the United States. This survey collected general facility information, characterized process inputs and outputs, gathered data on waste generation and characteristics, and captured details of FBC waste management practices. From the survey responses, CIBO prepared an electronic database and provided it to EPA in support of the March 1999 RTC. CIBO also published a report (CIBO, 1997) that includes documentation of the survey format and provides a brief summary of the results.

CIBO reports a total of 84 facilities using FBC technology. Forty-five of these responded to the CIBO FBC survey, with 20 of the respondents providing information about waste management practices. The facilities with waste management data cover 24 percent of all U.S. facilities using FBC. The CIBO sample is geographically representative of the full population, with the exception of two states that appear under-represented in the sample—Pennsylvania and Illinois. EPA's technical background document on industry statistics and waste management practices (U.S. EPA, 1999b) discusses the representativeness of the EPRI survey in greater detail and provides extensive summary statistics on the survey responses.

The CIBO survey includes questions requesting the respondent to report WMU area, capacity, liner type, and waste type managed. Therefore, the data set used for modeling these variables was extracted directly from the CIBO database. The CIBO respondents include both

utility and nonutility (i.e., industrial or institutional facilities that burn coal, but are not primarily engaged in the business of selling electricity) facilities. Because nonutilities are outside the scope of this risk assessment, nonutilities were excluded from the data set. Three additional utility facilities were excluded from the data set because their responses contained insufficient data on the variables of interest (area, capacity, liner type, and waste type). Mine placement sites also were excluded from the data set. Data for the FBC units responding to the EPRI survey (see above) were added to the data set. This resulted in a sample of seven FBC landfills and one FBC surface impoundment for modeling. Table B-1 compares this sample to the waste management practices of the full utility FBC population.

As shown in Table B-1, FBC facilities frequently avoid waste disposal units by directing all of their waste to mine placement or beneficial use. Therefore, although only 8 of the 41 utility FBC facilities are included in the model data set, these 8 facilities represent nearly all of the known FBC landfills and surface impoundments.

Table B-1. Utility FBC Waste Management Practices and Units Modeled

Number of Facilities...	Total	Landfill	Surface Impoundment	Minefill or Beneficial Use	Unknown
in the full population	41	11	1	16	13
modeled	8	7	1	Not applicable	Not applicable

The CIBO survey database identified the location of each WMU in detail (latitude and longitude). Therefore, no additional analysis was necessary to pair the WMU data with environmental setting information.

B.3 Liner Type

The EPRI survey data included information on the liner (if any) for each WMU. For this assessment, the WMUs were assigned to one of three liner scenarios based on the EPRI liner data: an unlined (no liner) scenario, a compacted clay liner, and a composite liner that combines a plastic (e.g., high-density polyethylene (HDPE) membrane) over either geosynthetic or natural clays. These three scenarios correspond to the following conceptual liner scenarios, developed in support of EPA's Industrial Subtitle D guidance (U.S. EPA, 2002), which can be selected in the landfill and surface impoundment models used in this assessment.

- **Unlined Scenario.** For landfills, waste is placed directly on local soils, either on grade or excavated to some design depth and without a leachate collection system. After the landfill has been filled to capacity, a 2-foot native soil cover (the minimum required by Subtitle D regulations) is installed and assumed to support vegetation. For surface impoundments, wastewater is placed directly on local soils, and the depth of water is constant over the entire life of the impoundment, pre- and post-closure. Sediments accumulate and consolidate at the bottom of the impoundment and migrate into the underlying native soils, where they clog pore spaces and provide some barrier to flow.

- **Clay Liner Scenario.** For landfills, waste is placed directly on a 3-foot compacted clay liner, which is installed on the local soils, either on grade or excavated to some design depth and without a leachate collection system. After the landfill has been filled to capacity, a 3-foot clay cover is installed and covered with 1 foot of loam to support vegetation and drainage. The hydraulic conductivity of both the liner and cover clays is assumed to be $1x10^{-7}$ cm/sec. For surface impoundments, wastewater is placed on a compacted clay liner, which is installed on the local soils. The assumptions for an unlined impoundment also apply to the compacted clay liner scenario, except that a compacted clay liner filters out the sediments that clog the native soils in the unlined case, so the effect of clogging the native materials is not included in the calculation of the infiltration rate. The thickness of the compacted clay liner was assumed to be 3 feet and the hydraulic conductivity was assumed to be $1x10^{-7}$ cm/sec.

- **Composite Liner Scenario.** For landfills, wastes are placed on a liner system that consists of a 60 mil HDPE membrane with either an underlying geosynthetic clay liner with a maximum hydraulic conductivity of $5x10^{-9}$ cm/sec, or a 3-foot compacted clay liner with a maximum hydraulic conductivity of $1x10^{-7}$ cm/sec. A leachate collection system is also assumed to exist between the waste and the liner system. After the landfill has been filled to capacity, a 3-foot clay cover is assumed to be installed and covered with 1 foot of loam to support vegetation and drainage. For surface impoundments, wastewater is placed on a synthetic membrane with an underlying geosynthetic or natural compacted clay liner with a hydraulic conductivity of $1x10^{-7}$ cm/sec. The membrane liner was assumed to have a number of pinhole leaks of uniform size (6 mm^2). The number of these leaks was based on an empirical distribution of membrane leak density values obtained from TetraTech (2001), as described in the *IWEM Technical Background Document* (U.S. EPA, 2002).

Table B-2 shows the crosswalk used to assign one of the three liner scenarios to each facility based on the liner data in the EPRI survey data (EPRI, 1997a). Attachment B-2 provides these assignments, along with the original EPRI liner type, for each CCW landfill facility modeled.

Table B-2. Crosswalk Between EPRI and CCW Source Model Liner Types

EPRI Liner Type	Model Liner Code	Description
Compacted ash	0	no liner
Compacted clay	1	clay
Composite clay/membrane	2	composite
Double	2	composite
Geosynthetic membrane	2	composite
None/natural soils	0	no liner

B.4 Surface Impoundment Operating Life

The model runs for surface impoundments required a general assumption about the length of the operating life for these WMUs. Of the surface impoundments in the EPRI comanagement survey, 86 provided responses to questions about both the unit's opening date and expected closure date. From these two dates, an expected operating life for each impoundment can be calculated. An additional 30 impoundments provided an opening date, but no closure date. One possible interpretation of these responses is that these facilities do not expect to close in the foreseeable future, corresponding to a very long or indefinite operating life with dredging of waste to maintain capacity. Figure B-1 shows the distribution of the calculated operating lives, along with a bar showing the facilities with no closure date.

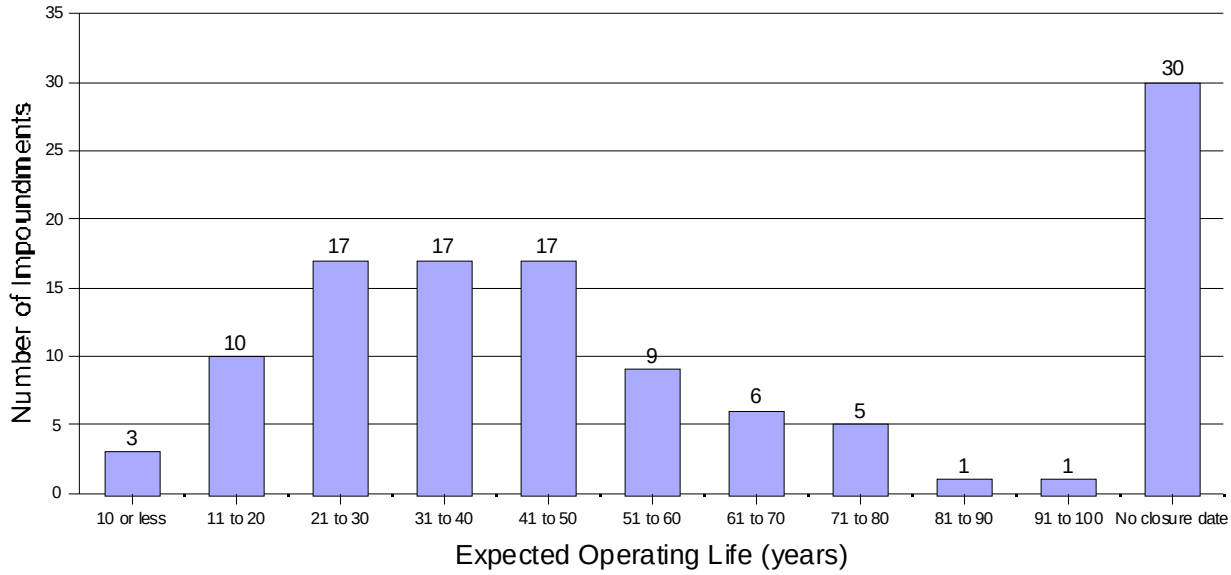

Figure B-1. Operating life of impoundments in the EPRI survey.

Based on these data, a 75-year operating life was chosen. This value corresponds to the 95th percentile of the observed distribution. While the use of a 95th percentile value may appear conservative, if many of the facilities with no closure date do, in fact, plan to operate indefinitely, 75 years would correspond to a much lower percentile in the distribution. More significantly, many CCW surface impoundments close with wastes in place. The selection of 75 years minimizes the underestimation of chronic risks for this scenario, given that EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP) surface impoundment model assumes clean closure after the operating life.

B.5 Above- and Below-Grade Geometry

The model runs for surface impoundments and landfills required general assumptions about the geometry of these units with respect to the ground surface (i.e., how much of the unit's depth is below grade). The CIBO FBC survey included data on this geometry, so, for FBC units, these data were extracted directly from the database along with the other individual WMU data

(e.g., capacity). The EPRI comanagement survey did not contain data describing above- and below-grade geometry. Therefore, for conventional utility coal combustion WMUs, EPA reviewed 17 site-characterization reports published by EPRI (EPRI 1991; 1992; 1994a,b; 1996a,b; 1997b-k) and determined an above- versus below-grade geometry for each unit described in those reports based on schematic diagrams and site descriptions. EPA also extracted data from another CIBO voluntary survey that covered conventional (non-FBC) nonutility coal combustors. Figures B-2 and B-3 display the distributions of the data thus collected.

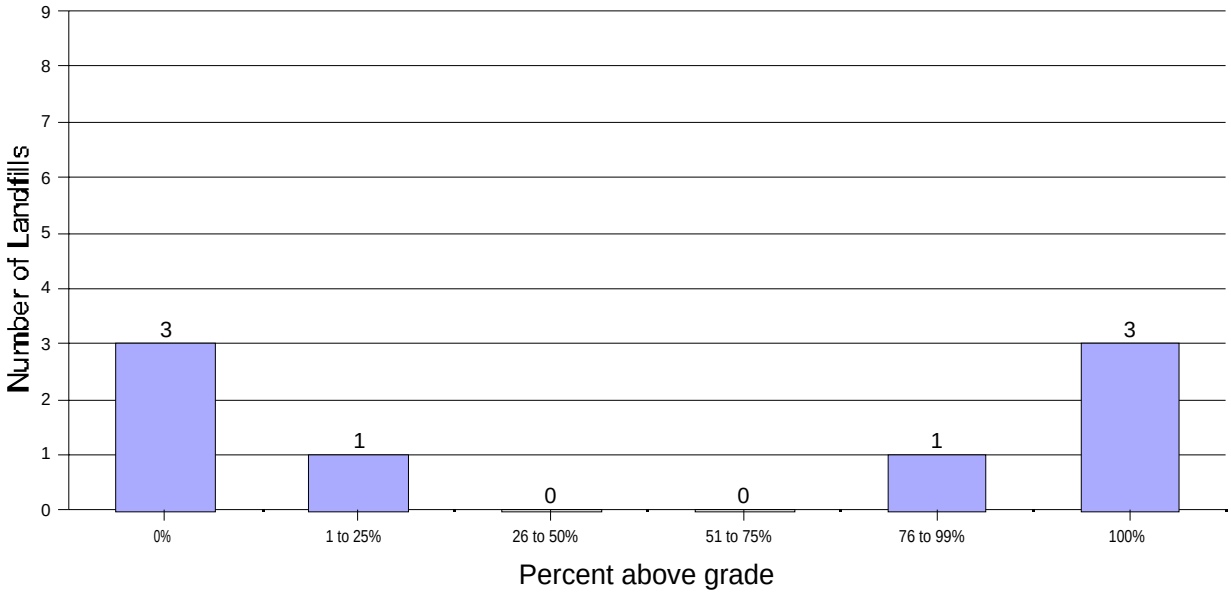

Figure B-2. Above- and below-grade geometry for landfills.

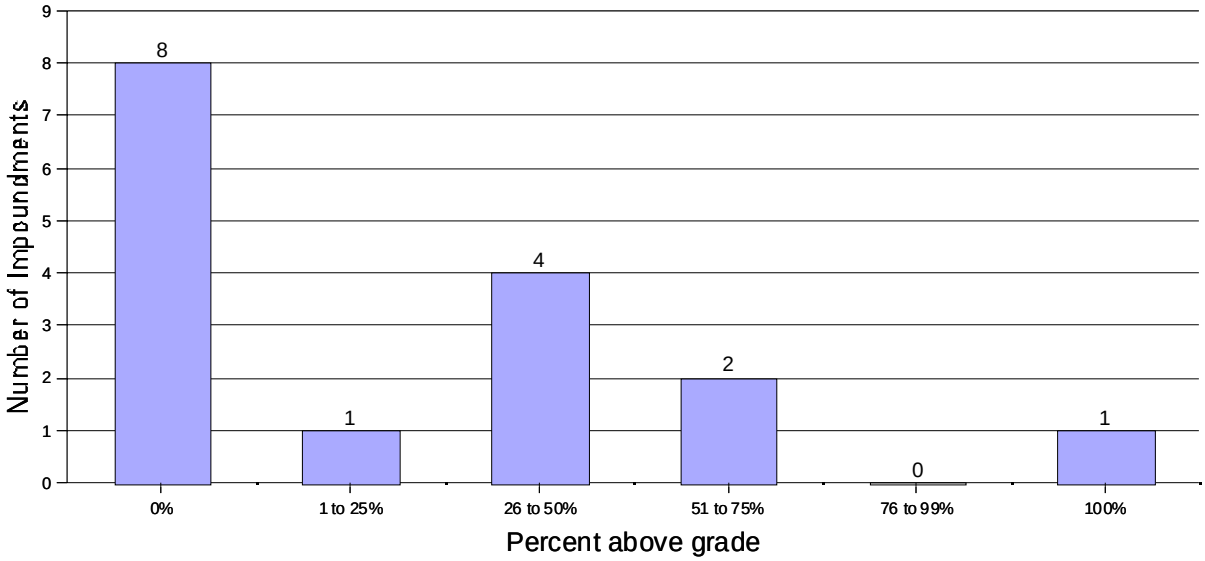

Figure B-3. Above- and below-grade geometry for impoundments.

For landfills, because the data were limited (8 sites), the model runs assume that the percent below grade ranges from 1 to 100 and is uniformly distributed. For each landfill iteration, a random value for percent below grade is picked and applied to the landfill depth to determine depth below ground surface. This value is constrained to be no deeper than the water table and is checked to see that EPACMTP groundwater mounding constraints are not violated.

For surface impoundments, more data were available (16 sites), with 8 sites being constructed entirely below grade and the remaining 8 sites ranging from 7.5 to 45 feet above grade. For each surface impoundment iteration, height above grade at these 15 sites is randomly sampled as an empirical distribution and applied to the overall surface impoundment depth to determine depth below ground surface.

B.6 Calculation of WMU Depth and Imputation of Missing WMU Data

The EPRI survey includes information on the total area and total waste capacity of each landfill and surface impoundment included in the survey. To calculate average depth for each WMU (a necessary EPACMTP model input), the total waste capacity was divided by the area. The resulting depths were then checked for reasonableness. For surface impoundments, one depth (1 foot) was culled as being unrealistically low and one (700 feet) as too high. Two landfill depths less than 2 feet and one depth greater than 350 feet were also removed from the database. In these cases the EPRI waste capacity data were culled and replaced using the regressions described below (i.e., WMU areas are considered more reliable than the capacity estimates in the survey data), and new capacities were estimated as described below.

In addition, four landfills and six surface impoundments had neither area nor capacity data in the EPRI survey. In these cases, the EIA facility locations were used to find the plants and their WMUs on aerial photos from the Terraserver Web site (http://terraserver-usa.com/geographic.aspx), and a geographic information system (GIS) was used to measure the areas of the units in question. Capacities were then estimated as described below.

To impute data for facilities missing either area or capacity data in the EPRI survey, linear regression equations were developed based on WMUs with both area and capacity data, one to predict area from capacity, and one to predict capacity from area. The final regression equations are shown in Figures B-4 and B-5 for landfills and Figures B-6 and B-7 for surface impoundments. In each case, a standard deviation around the regression line was also computed and used during source data file preparation to randomly vary the area or capacity from iteration to iteration within the bounds of the existing data set.

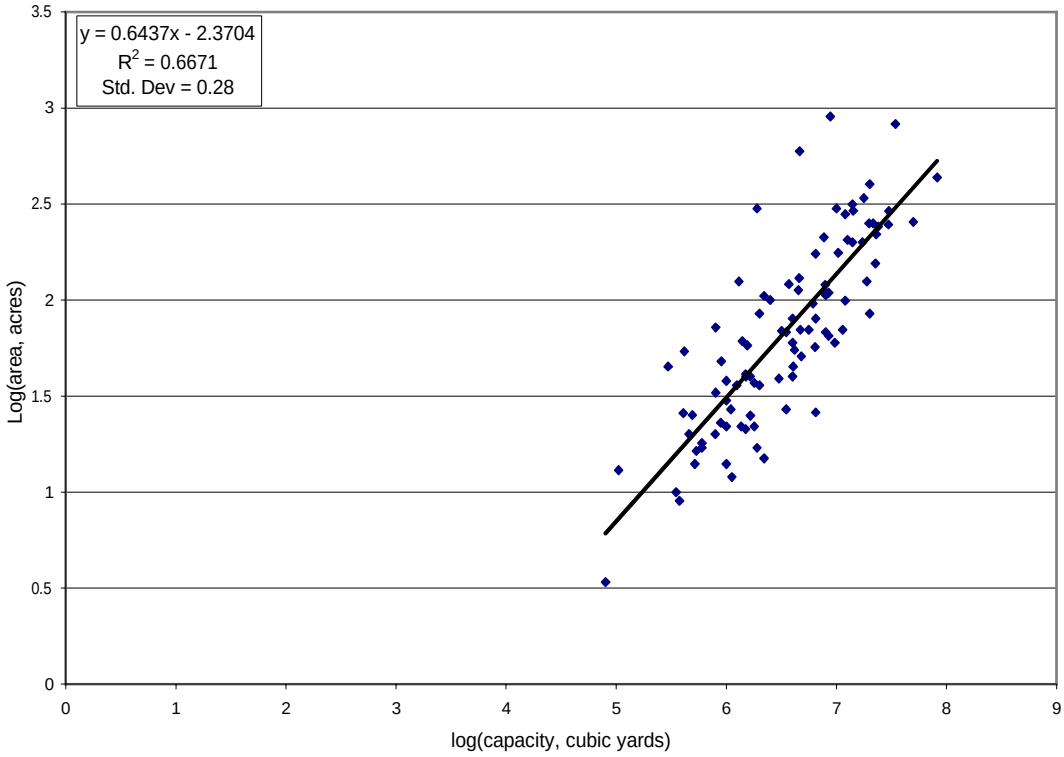

Figure B-4. Linear regression to impute landfill area from capacity.

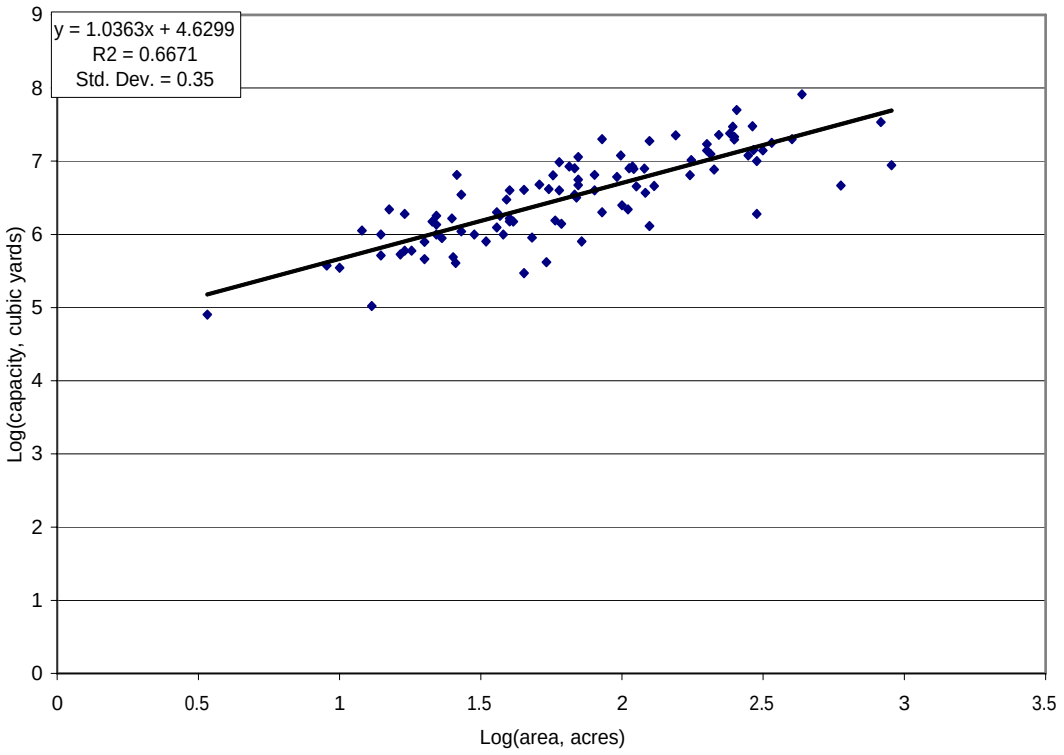

Figure B-5. Linear regression to impute landfill capacity from area.

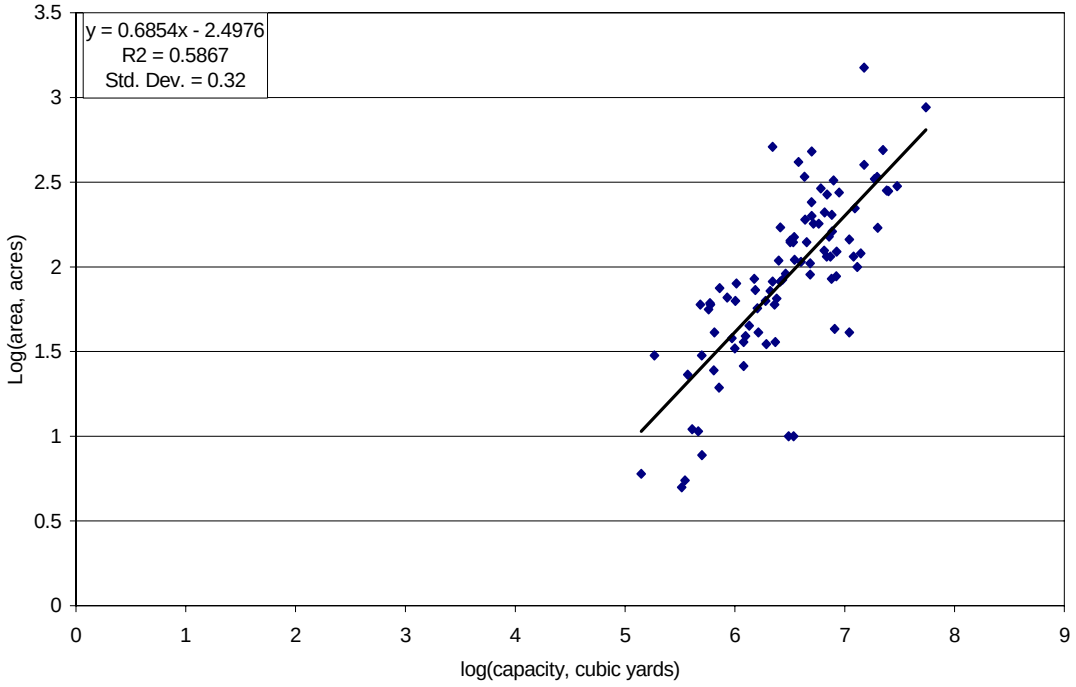

Figure B-6. Linear regression to impute surface impoundment area from capacity.

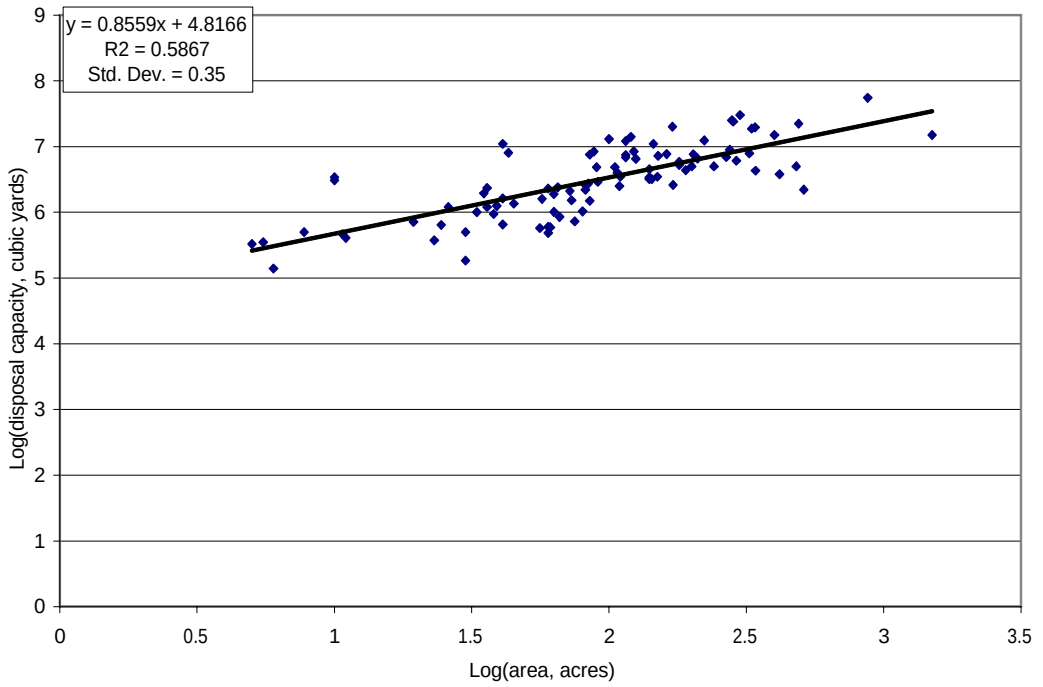

Figure B-7. Linear regression to impute surface impoundment capacity from area.

B.7 Results

Attachment B-1 lists the 181 CCW disposal sites modeled in this risk assessment and their locations. The WMU data used in the CCW risk assessment for each of the 108 landfills and 96 surface impoundments at these coal combustion facilities are presented in Attachment B-2. Missing data that were randomly replaced as described above are not represented in the table (i.e., the fields are left blank).

B.8 References

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Attachment B-1: CCW Disposal Sites (Plants)

Plant Name	Utility Name	County	State	Latitude	Longitude
A B Brown	Southern Indiana Gas & Elec. Co.	Posey	IN	37.9053	87.715
A/C Power - Ace Operations	A.C.E. Cogeneration Co.	San Bernardino	CA	35.75	117.3667
Allen	Tennessee Valley Authority	Shelby	TN	35.0742	90.1492
Alma	Dairyland Power Coop	Buffalo	WI	44.3078	91.905
Antelope Valley	Basin Electric Power Coop	Mercer	ND	47.37	101.8353
Arkwright	Georgia Power Co.	Bibb	GA	32.9269	83.6997
Asheville	Carolina Power & Light Co.	Buncombe	NC	35.4714	82.5431
Baldwin	Illinois Power Co.	Randolph	IL	38.205	89.8544
Barry	Alabama Power Co.	Mobile	AL	31.0069	88.0103
Bay Front	Northern States Power Co.	Ashland	WI	43.4833	89.4
Bay Shore	Toledo Edison Co.	Lucas	OH	41.6925	83.4375
Belews Creek	Duke Power Co.	Stokes	NC	36.2811	80.0603
Ben French	Black Hills Corp.	Pennington	SD	44.0872	103.2614
Big Cajun 2	Cajun Electric Power Coop, Inc.	Pointe Coupee	LA	30.7283	91.3686
Big Sandy	Kentucky Power Co.	Lawrence	KY	38.1686	82.6208
Big Stone	Otter Tail Power Co.	Grant	SD	45.3047	96.5083
Black Dog Steam Plant	Northern States Power Company	Dakota	MN	44.8167	93.25
Blue Valley	Independence, City of	Jackson	MO	39.0919	94.3364
Bowen	Georgia Power Co.	Bartow	GA	34.1256	84.9192
Brandon Shores	Baltimore Gas & Electric Co.	Anne Arundel	MD	39.18	76.5333
Buck	Duke Power Co.	Rowan	NC	35.7133	80.3767
Bull Run	Tennessee Valley Authority	Anderson	TN	36.0211	84.1567
C D McIntosh Jr.	Lakeland, City of	Polk	FL	28.075	81.9292
C P Crane	Baltimore Gas & Electric Co.	Baltimore City	MD	39.2845	76.6207
Cape Fear	Carolina Power & Light Co.	Chatham	NC	35.5989	79.0492
Carbon	PacifiCorp	Carbon	UT	39.7264	110.8639
Cardinal	Cardinal Operating Co.	Jefferson	OH	40.2522	80.6486
Cayuga	PSI Energy, Inc.	Vermillion	IN	39.9008	87.4136
Chalk Point	Potomac Electric Power Co.	Prince Georges	MD	38.5639	76.6806
Cholla	Arizona Public Service Co.	Navajo	AZ	34.9414	110.3003
Cliffside	Duke Power Co.	Cleveland	NC	35.22	81.7594
Clover	Virginia Electric & Power Co.	Halifax	VA	36.8667	78.7
Coal Creek	Coop Power Assn.	McLean	ND	47.3789	101.1572
Coleto Creek	Central Power & Light Co.	Goliad	TX	28.7128	97.2142

(continued)

CCW Disposal Sites (Plants) (continued)

Plant Name	Utility Name	County	State	Latitude	Longitude
Colstrip	Montana Power Co.	Rosebud	MT	45.8844	106.6139
Conemaugh	GPU Service Corporation	Indiana	PA	40.3842	79.0611
Conesville	Columbus Southern Power Co.	Coshocton	OH	40.1842	81.8811
Council Bluffs	MidAmerican Energy Co.	Pottawattamie	IA	41.18	95.8408
Crawford	Commonwealth Edison Co.	Cook	IL	39.8225	90.5681
Crist	Gulf Power Co.	Escambia	FL	30.5658	87.2239
Cross	South Carolina Pub Serv. Auth.	Berkeley	SC	33.3694	80.1119
Cumberland	Tennessee Valley Authority	Stewart	TN	36.3942	87.6539
Dale	East Kentucky Power Coop, Inc.	Clark	KY	37.875	84.25
Dallman	Springfield, City of	Sangamon	IL	39.7547	89.6008
Dan E Karn	Consumers Energy Co.	Bay	MI	43.645	83.8414
Dan River	Duke Power Co.	Rockingham	NC	36.4861	79.7244
Danskammer	Central Hudson Gas & Elec. Corp.	Orange	NY	41.5719	73.9664
Dave Johnston	PacifiCorp	Converse	WY	42.8333	105.7667
Dickerson	Potomac Electric Power Co.	Montgomery	MD	39.144	77.2059
Dolet Hills	CLECO Corporation	De Soto	LA	32.0308	93.5644
Duck Creek	Central Illinois Light Co.	Fulton	IL	40.4644	89.9825
Dunkirk	Niagara Mohawk Power Corp.	Chautauqua	NY	42.4919	79.3469
E D Edwards	Central Illinois Light Co.	Peoria	IL	40.5961	89.6633
E W Brown	Kentucky Utilities Co.	Mercer	KY	37.7911	84.7147
Eckert Station	Lansing, City of	Ingham	MI	42.7189	84.5583
Edgewater	Wisconsin Power & Light Co.	Sheboygan	WI	43.7181	87.7092
Elmer W Stout	Indianapolis Power & Light Co.	Marion	IN	39.7122	86.1975
F B Culley	Southern Indiana Gas & Elec. Co.	Warrick	IN	37.91	87.3267
Fayette Power Prj.	Lower Colorado River Authority	Fayette	TX	29.9172	96.7506
Flint Creek	Southwestern Electric Power Co.	Benton	AR	36.2625	94.5208
Fort Martin	Monongahela Power Co.	Monongalia	WV	39.7	79.9167
Frank E Ratts	Hoosier Energy R E C, Inc.	Pike	IN	38.5186	87.2725
G G Allen	Duke Power Co.	Gaston	NC	35.1897	81.0122
Gadsden	Alabama Power Co.	Etowah	AL	34.0136	85.9703
Gallatin	Tennessee Valley Authority	Sumner	TN	36.3156	86.4006
Gen J M Gavin	Ohio Power Co.	Gallia	OH	38.9358	82.1164
Genoa	Dairyland Power Coop	Vernon	WI	43.5592	91.2333
Gibson	PSI Energy, Inc.	Gibson	IN	38.3589	87.7783
Gorgas	Alabama Power Co.	Walker	AL	33.5111	87.235
Green River	Kentucky Utilities Co.	Muhlenberg	KY	37.3636	87.1214
Greene County	Alabama Power Co.	Greene	AL	32.6	87.7667
H B Robinson	Carolina Power & Light Co.	Darlington	SC	34.4	80.1667
Hammond	Georgia Power Co.	Floyd	GA	34.3333	85.2336

(continued)

CCW Disposal Sites (Plants) (continued)

Plant Name	Utility Name	County	State	Latitude	Longitude
Harllee Branch	Georgia Power Co.	Putnam	GA	33.1942	83.2994
Harrison	Monongahela Power Co.	Harrison	WV	39.3833	80.3167
Hatfield's Ferry	West Penn Power Co.	Greene	PA	39.85	79.9167
Hennepin	Illinois Power Co.	Putnam	IL	41.3028	89.315
Heskett	Montana-Dakota Utilities Co.	Morton	ND	46.8669	100.8839
Holcomb	Sunflower Electric Power Corp.	Finney	KS	37.9319	100.9719
Homer City	GPU Service Corporation	Indiana	PA	40.5142	79.1969
Hoot Lake	Otter Tail Power Co.	Otter Tail	MN	46.29	96.0428
Hugo	Western Farmers Elec. Coop, Inc.	Choctaw	OK	34.0292	95.3167
Hunter	PacifiCorp	Emery	UT	39.1667	111.0261
Huntington	PacifiCorp	Emery	UT	39.3792	111.075
Intermountain	Los Angeles, City of	Millard	UT	39.5108	112.5792
J H Campbell	Consumers Energy Co.	Ottawa	MI	42.9103	86.2031
J M Stuart	Dayton Power & Light Co.	Adams	OH	38.6364	83.7422
J R Whiting	Consumers Energy Co.	Monroe	MI	41.7914	83.4486
Jack McDonough	Georgia Power Co.	Cobb	GA	33.8244	84.475
Jack Watson	Mississippi Power Co.	Harrison	MS	30.4392	89.0264
James H Miller Jr.	Alabama Power Co.	Jefferson	AL	33.6319	87.0597
Jim Bridger	PacifiCorp	Sweetwater	WY	41.75	108.8
John E Amos	Appalachian Power Co.	Putnam	WV	38.4731	81.8233
John Sevier	Tennessee Valley Authority	Hawkins	TN	36.3767	82.9639
Johnsonville	Tennessee Valley Authority	Humphreys	TN	36.0278	87.9861
Joliet 29	Commonwealth Edison Co.	Will	IL	41.4892	88.0844
Keystone	GPU Service Corporation	Armstrong	PA	40.6522	79.3425
Killen Station	Dayton Power & Light Co.	Adams	OH	38.6903	83.4803
Kingston	Tennessee Valley Authority	Roane	TN	35.8992	84.5194
Kraft	Savannah Electric & Power Co	Chatham	GA	32.1333	81.1333
L V Sutton	Carolina Power & Light Co.	New Hanover	NC	34.2831	77.9867
Lansing	Interstate Power Co.	Allamakee	IA	43.3386	91.1667
Laramie R Station	Basin Electric Power Coop	Platte	WY	42.1086	104.8711
Lawrence EC	KPL Western Resources Co.	Douglas	KS	39.0078	95.2681
Lee	Carolina Power & Light Co.	Wayne	NC	35.3778	78.1
Leland Olds	Basin Electric Power Coop	Mercer	ND	47.2833	101.4
Lon Wright	Fremont, City of	Dodge	NE	41.45	96.5167
Louisa	MidAmerican Energy Co.	Louisa	IA	41.3181	91.0931
Marion	Southern Illinois Power Coop	Williamson	IL	37.6167	88.95
Marshall	Duke Power Co.	Catawba	NC	35.5975	80.9658
Martin Lake	Texas Utilities Electric Co.	Rusk	TX	32.2606	94.5708
Mayo	Carolina Power & Light Co.	Person	NC	36.5278	78.8919
Meramec	Union Electric Co.	St Louis	MO	38.6522	90.2397

(continued)

CCW Disposal Sites (Plants) (continued)

Plant Name	Utility Name	County	State	Latitude	Longitude
Merom	Hoosier Energy R E C, Inc.	Sullivan	IN	39.0694	87.5108
Miami Fort	Cincinnati Gas & Electric Co.	Hamilton	OH	39.1111	84.8042
Milton R Young	Minnkota Power Coop, Inc.	Oliver	ND	47.0664	101.2139
Mitchell - PA	West Penn Power Co.	Washington	PA	40.2167	79.9667
Mitchell - WV	Ohio Power Co.	Marshall	WV	39.8297	80.8153
Mohave	Southern California Edison Co.	Clark	NV	35.1667	114.6
Monroe	Detroit Edison Co.	Monroe	MI	41.8911	83.3444
Morgantown	Potomac Electric Power Co.	Charles	MD	38.3611	76.9861
Mountaineer (1301)	Appalachian Power Co.	Mason	WV	38.9794	81.9344
Mt Storm	Virginia Electric & Power Co.	Grant	WV	39.2014	79.2667
Muscatine Plant #1	Muscatine, City of	Muscatine	IA	41.3917	91.0569
Muskogee	Oklahoma Gas & Electric Co.	Muskogee	OK	35.7653	95.2883
Neal North	MidAmerican Energy Co.	Woodbury	IA	42.3167	96.3667
Neal South	MidAmerican Energy Co.	Woodbury	IA	42.3022	96.3622
Nebraska City	Omaha Public Power District	Otoe	NE	40.625	95.7917
New Castle	Pennsylvania Power Co.	Lawrence	PA	40.9383	80.3683
Newton	Central Illinois Pub Serv. Co.	Jasper	IL	38.9364	88.2778
North Omaha	Omaha Public Power District	Douglas	NE	41.33	95.9467
Northeastern	Public Service Co. of Oklahoma	Rogers	OK	36.4222	95.7047
Nucla	Tri-State G & T Assn., Inc.	Montrose	CO	38.2386	108.5072
Oklaunion	West Texas Utilities Co.	Wilbarger	TX	34.0825	99.1753
Paradise	Tennessee Valley Authority	Muhlenberg	KY	37.2608	86.9783
Petersburg	Indianapolis Power & Light Co.	Pike	IN	38.5267	87.2522
Pleasant Prairie	Wisconsin Electric Power Co.	Kenosha	WI	42.5381	87.9033
Port Washington	Wisconsin Electric Power Co.	Ozaukee	WI	43.3908	87.8686
Portland	Metropolitan Edison Co.	Northampton	PA	40.7525	75.3324
Possum Point	Virginia Electric & Power Co.	Prince William	VA	38.5367	77.2806
Potomac River	Potomac Electric Power Co.	Alexandria	VA	38.8078	77.0372
Presque Isle	Wisconsin Electric Power Co.	Marquette	MI	46.5694	87.3933
R Gallagher	PSI Energy, Inc.	Floyd	IN	38.2631	85.8378
R M Schahfer	Northern Indiana Pub. Serv. Co.	Jasper	IN	41.2167	87.0222
Reid Gardner	Nevada Power Co.	Clark	NV	36.6606	114.625
Richard Gorsuch	American Mun. Power-Ohio, Inc.	Washington	OH	39.3672	81.5208
Riverbend	Duke Power Co.	Gaston	NC	35.36	80.9742
Rodemacher	CLECO Corporation	Rapides	LA	31.395	92.7167
Roxboro	Carolina Power & Light Co.	Person	NC	36.4831	79.0711
Sandow	Texas Utilities Electric Co.	Milam	TX	30.5642	97.0639
Scherer	Georgia Power Co.	Monroe	GA	33.0583	83.8072
Shawnee	Tennessee Valley Authority	McCracken	KY	37.1517	88.775
Shawville	GPU Service Corporation	Clearfield	PA	41.0681	78.3661

(continued)

CCW Disposal Sites (Plants) (continued)

Plant Name	Utility Name	County	State	Latitude	Longitude
Sheldon	Nebraska Public Power District	Lancaster	NE	40.5589	96.7842
South Oak Creek	Wisconsin Electric Power Co.	Milwaukee	WI	42.8014	87.8314
Springerville	Tucson Electric Power Co	Apache	AZ	34.3186	109.1636
St Johns River Power	JEA	Duval	FL	30.4308	81.5508
Stanton Energy Ctr.	Orlando Utilities Comm.	Orange	FL	28.4822	81.1678
Stockton Cogen Company	Stockton Cogen Co (operator: Air Products)	San Joaquin	CA	37.9778	121.2667
Syl Laskin	Minnesota Power, Inc.	St Louis	MN	47.53	92.1617
Tecumseh EC	KPL Western Resources Co.	Shawnee	KS	39.0528	95.5683
Texas-New Mexico	Texas-New Mexico Power Company/Sempra Energy	Robertson	TX	31.0928	96.6933
Titus	Metropolitan Edison Co.	Berks	PA	40.3047	75.9072
Trimble County	Louisville Gas & Electric Co.	Trimble	KY	38.5678	85.4139
Tyrone	Kentucky Utilities Co.	Woodford	KY	38.0213	84.7456
Valley	Wisconsin Electric Power Co.	Milwaukee	WI	43.0303	87.925
Vermilion	Illinois Power Co.	Vermilion	IL	40.1781	87.7481
Victor J Daniel Jr.	Mississippi Power Co.	Jackson	MS	30.5322	88.5569
W A Parish	Houston Lighting & Power Co.	Fort Bend	TX	29.4833	95.6331
W H Weatherspoon	Carolina Power & Light Co.	Robeson	NC	34.5889	78.975
W S Lee	Duke Power Co.	Anderson	SC	34.6022	82.435
Wabash River	PSI Energy, Inc.	Vigo	IN	39.5278	87.4222
Walter C Beckjord	Cincinnati Gas & Electric Co.	Clermont	OH	38.9917	84.2972
Wansley	Georgia Power Co.	Heard	GA	33.4167	85.0333
Warrick	Southern Indiana Gas & Elec. Co.	Warrick	IN	37.915	87.3319
Waukegan	Commonwealth Edison Co.	Lake	IL	42.3833	87.8083
Weston	Wisconsin Public Service Corp.	Marathon	WI	44.8617	89.655
Widows Creek	Tennessee Valley Authority	Jackson	AL	34.8825	85.7547
Will County	Commonwealth Edison Co.	Will	IL	38.8639	90.1347
Wyodak	PacifiCorp	Campbell	WY	44.2833	105.4
Yates	Georgia Power Co.	Coweta	GA	33.4631	84.955

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Attachment B-2: CCW WMU Data

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
A B Brown	42	LF	176	10360000	Ash	compacted clay	clay
A/C Power - Ace Operations	3000	LF	18	1030815	FBC	none/natural soils	no liner
Allen	293	SI	85	1500000	Ash	none/natural soils	no liner
Alma	7	LF	85	2000000	Ash and Coal Waste	composite clay/membrane	composite
Antelope Valley	57	LF	27	3500000	Ash	none/natural soils	no liner
Arkwright	198	LF	54	415907	Ash and Coal Waste	none/natural soils	no liner
Asheville	159	SI	140	3200000	Ash	none/natural soils	no liner
Baldwin	2	SI	107	4000000	Ash and Coal Waste	none/natural soils	no liner
Barry	301	SI	63	1900000	Ash and Coal Waste	none/natural soils	no liner
Bay Front	81	LF	10	350000	Ash	none/natural soils	no liner
Bay Shore	32	LF	85		Ash	none/natural soils	no liner
Belews Creek	167	SI	512	2200000	Ash and Coal Waste	none/natural soils	no liner
Belews Creek	168	LF	315	14000000	Ash	compacted ash	no liner
Ben French	14	LF	4.61		Ash	compacted clay	clay
Big Cajun 2	186	SI	241	4990003	Ash	compacted clay	clay
Big Sandy	138	SI	115	12052100	Ash and Coal Waste	none/natural soils	no liner
Big Stone	15	LF	3.4	80000	Ash	compacted clay	clay
Big Stone	41	LF	106	8000000	Ash	none/natural soils	no liner
Black Dog Steam Plant	2700	LF	96	8936296	FBC	compacted clay	clay
Blue Valley	176	SI	23.1	372000	Ash and Coal Waste	compacted clay	clay
Bowen	143	LF	25.24	491400	Ash	compacted ash	no liner
Bowen	144	LF	25.77	406971	Ash	compacted ash	no liner
Brandon Shores	339	LF	246	5600000	Ash and Coal Waste	none/natural soils	no liner

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Buck	235	SI	90	4840000	Ash and Coal Waste	none/natural soils	no liner
Bull Run	296	SI	41	650000	Ash and Coal Waste	none/natural soils	no liner
C D McIntosh Jr.	223	LF	26		Ash and Coal Waste	compacted ash	no liner
C P Crane	338	LF	35	800000	Ash	none/natural soils	no liner
Cape Fear	161	SI	60	2300000	Ash	none/natural soils	no liner
Carbon	263	lf	11.7739066		Ash and Coal Waste	none/natural soils	no liner
Cardinal	126	SI	123	8437500	Ash	none/natural soils	no liner
Cayuga	325	SI	280	25000000	Ash and Coal Waste	none/natural soils	no liner
Chalk Point	292	LF	596	4634000	Ash and Coal Waste	none/natural soils	no liner
Cholla	107	SI	171	2600000	Ash	none/natural soils	no liner
Cliffside	163	SI	82	2200000	Ash	compacted clay	clay
Clover	139	LF	22	1000000	Ash	geosynthetic membrane	composite
Coal Creek	29	LF	70	4700000	Ash	compacted clay	clay
Coal Creek	30	LF	220	23000000	Ash	composite clay/membrane	composite
Coleto Creek	190	si	314.6135409		Ash and Coal Waste	compacted clay	clay
Colstrip	89	LF	9		Ash	none/natural soils	no liner
Conemaugh	101	LF	434	82000000	Ash	geosynthetic membrane	composite
Conesville	250	LF	300	10000000	Ash	compacted clay	clay
Conesville	251	LF	100	2500000	Ash and Coal Waste	none/natural soils	no liner
Council Bluffs	94	SI	200		Ash	none/natural soils	no liner
Crawford	272	SI	24.5	642000	Ash and Coal Waste	compacted clay	clay
Crist	157	LF	12		Ash and Coal Waste	none/natural soils	no liner
Cross	264	LF	320		Ash	compacted ash	no liner
Cross	265	LF	30		Ash and Coal Waste	none/natural soils	no liner
Cross	266	LF	30		Ash and Coal Waste	none/natural soils	no liner
Cross	267	LF	230		Ash and Coal Waste	none/natural soils	no liner
Cross	268	LF	60		Ash and Coal Waste	compacted clay	clay

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Cumberland	294	SI	75	1750000	Ash and Coal Waste	none/natural soils	no liner
Cumberland	303	SI	295	9500000	Ash	none/natural soils	no liner
Dale	151	SI	115	7408274	Ash and Coal Waste	none/natural soils	no liner
Dallman	178	LF	22	1800000	Ash	compacted clay	clay
Dallman	179	SI	417	3800000	Ash	none/natural soils	no liner
Dan E Karn	6	LF	40	1650000	Ash and Coal Waste	geosynthetic membrane	composite
Dan River	234	SI	72	2097000	Ash and Coal Waste	none/natural soils	no liner
Danskammer	24	LF	14	517265	Ash and Coal Waste	geosynthetic membrane	composite
Dave Johnston	13	LF	45	296100	Ash	compacted clay	clay
Dickerson	290	LF	206	12600000	Ash	none/natural soils	no liner
Dolet Hills	245	SI	66	850000	Ash and Coal Waste	none/natural soils	no liner
Dolet Hills	246	LF	109	8500000	Ash	compacted clay	clay
Duck Creek	11	LF	21.3	1500000	Ash	compacted clay	clay
Dunkirk	49	LF	12	1126080	Ash	compacted clay	clay
E D Edwards	276	SI	145	11000000	Ash and Coal Waste	none/natural soils	no liner
E W Brown	313	SI	33	1000000	Ash	none/natural soils	no liner
E W Brown	314	SI	84	2710000	Ash	none/natural soils	no liner
Eckert Station	113	LF	174	6460000	Ash	none/natural soils	no liner
Eckert Station	114	SI	151	7200000	Ash	none/natural soils	no liner
Edgewater	289	LF	25	1655700	Ash and Coal Waste	none/natural soils	no liner
Elmer W Stout	130	SI	10	3420000	Ash	geosynthetic membrane	composite
F B Culley	183	SI	82	2600000	Ash and Coal Waste	none/natural soils	no liner
Fayette Power Prj.	195	SI	190	4351644	Ash	compacted clay	clay
Fayette Power Prj.	196	LF	23	890560	Ash	geosynthetic membrane	composite
Flint Creek	191	LF	40	1508250	Ash and Coal Waste	none/natural soils	no liner
Flint Creek	192	si	35.73857178		Ash and Coal Waste	none/natural soils	no liner
Fort Martin	213	LF	17	1900000	Ash	none/natural soils	no liner

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Fort Martin	214	LF	61	1400000	Ash	double	composite
Fort Martin	215	LF	121	3700000	Ash and Coal Waste	composite clay/membrane	composite
Frank E Ratts	182	SI	39	1250000	Ash and Coal Waste	none/natural soils	no liner
G G Allen	237	SI	210	6545000	Ash and Coal Waste	none/natural soils	no liner
Gadsden	283	SI	60	484000	Ash and Coal Waste	compacted clay	clay
Gallatin	304	SI	341	4300000	Ash and Coal Waste	none/natural soils	no liner
Gen J M Gavin	135	LF	255	50000000	Ash	composite clay/membrane	composite
Gen J M Gavin	136	SI	300	30000000	Ash and Coal Waste	none/natural soils	no liner
Gen J M Gavin	137	LF	99	12000000	Ash	compacted clay	clay
Genoa	244	LF	100		Ash and Coal Waste	none/natural soils	no liner
Gibson	327	SI	875	55000000	Ash and Coal Waste	none/natural soils	no liner
Gibson	329	LF	85	20000000	Ash	compacted clay	clay
Gorgas	280	SI	250		Ash and Coal Waste	compacted clay	clay
Gorgas	281	SI	283	24100000	Ash and Coal Waste	compacted clay	clay
Gorgas	282	SI	1500	15000000	Ash and Coal Waste	compacted clay	clay
Green River	147	SI	36	2331219	Ash and Coal Waste	none/natural soils	no liner
Greene County	279	SI	480	5000000	Ash	compacted clay	clay
H B Robinson	169	SI	30		Ash and Coal Waste	none/natural soils	no liner
Hammond	203	SI	56	576256	Ash and Coal Waste	none/natural soils	no liner
Harllee Branch	204	SI	324	7898277	Ash and Coal Waste	none/natural soils	no liner
Harllee Branch	205	SI	203	7634000	Ash and Coal Waste	none/natural soils	no liner
Harrison	211	LF	79	18000000	Ash and Coal Waste	composite clay/membrane	composite
Harrison	330	SI	300	28000000	Ash	none/natural soils	no liner
Hatfield's Ferry	112	LF	20	790000	Ash and Coal Waste	compacted ash	no liner
Hennepin	274	SI	150	3460600	Ash and Coal Waste	none/natural soils	no liner
Heskett	87	LF	58	1550000	FBC	compacted clay	clay
Holcomb	65	LF	8		Ash	compacted ash	no liner

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Homer City	118	LF	247	29636550	Ash and Coal Waste	geosynthetic membrane	composite
Hoot Lake	40	LF	72	800000	Ash and Coal Waste	none/natural soils	no liner
Hugo	193	LF	40	4000000	Ash	compacted ash	no liner
Hugo	194	si	151.0232271		Ash and Coal Waste	compacted clay	clay
Hunter	256	LF	280	12000000	Ash	none/natural soils	no liner
Huntington	255	LF	70	11400000	Ash	none/natural soils	no liner
Intermountain	224	SI	105	4840000	Ash and Coal Waste	geosynthetic membrane	composite
Intermountain	225	LF	339	17800000	Ash	compacted ash	no liner
Intermountain	226	SI	180	5200000	Ash	geosynthetic membrane	composite
J H Campbell	115	SI	267	6900000	Ash and Coal Waste	none/natural soils	no liner
J M Stuart	125	SI	88	8357000	Ash	none/natural soils	no liner
J R Whiting	129	SI	6	140000	Ash	none/natural soils	no liner
Jack McDonough	202	SI	73	1531893	Ash and Coal Waste	none/natural soils	no liner
Jack Watson	220	SI	100		Ash	none/natural soils	no liner
James H Miller Jr.	300	SI	200	5500000	Ash	compacted clay	clay
Jim Bridger	257	LF	120	7940941	Ash	none/natural soils	no liner
Jim Bridger	258	LF	241	24000000	Ash and Coal Waste	none/natural soils	no liner
Jim Bridger	259	SI	140	3400000	Ash and Coal Waste	none/natural soils	no liner
Jim Bridger	262	SI	125	6500000	Ash and Coal Waste	none/natural soils	no liner
John E Amos	120	SI	100	13000000	Ash	none/natural soils	no liner
John E Amos	121	LF	200	14000000	Ash and Coal Waste	compacted clay	clay
John E Amos	122	SI	10	3078000	Ash	none/natural soils	no liner
John Sevier	297	SI	57	1600000	Ash and Coal Waste	none/natural soils	no liner
John Sevier	298	LF	51	4800000	Ash	compacted clay	clay
John Sevier	309	SI	105	7000000	Ash and Coal Waste	none/natural soils	no liner
Johnsonville	306	SI	91	2900000	Ash and Coal Waste	none/natural soils	no liner
Joliet 29	275	SI	63.1	1012000	Ash and Coal Waste	none/natural soils	no liner

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Keystone	106	LF	155	22663120	Ash and Coal Waste	none/natural soils	no liner
Killen Station	254	SI		99935	Ash and Coal Waste	compacted clay	clay
Kingston	311	SI	41	11000000	Ash and Coal Waste	none/natural soils	no liner
Kingston	312	SI	275	8900000	Ash and Coal Waste	none/natural soils	no liner
Kraft	206	si	59.87027428		Ash and Coal Waste	none/natural soils	no liner
L V Sutton	231	SI	162	7696000	Ash and Coal Waste	none/natural soils	no liner
Lansing	64	SI	15		Ash	compacted clay	clay
Laramie R Station	260	SI	10.7	464156	Ash and Coal Waste	compacted clay	clay
Laramie R Station	261	SI	38	939605	Ash	geosynthetic membrane	composite
Lawrence EC	109	LF	825	34300000	Ash	compacted clay	clay
Lawrence EC	110	LF	22	1360000	Ash	compacted clay	clay
Lawrence EC	111	LF	30	1000000	Ash	compacted clay	clay
Lee	240	SI	35	1936000	Ash and Coal Waste	none/natural soils	no liner
Leland Olds	103	LF	37	1800000	Ash	compacted clay	clay
Leland Olds	104	LF	20	458000	Ash and Coal Waste	none/natural soils	no liner
Lon Wright	98	LF		170000	Ash	none/natural soils	no liner
Louisa	63	SI	30	500000	Ash	compacted clay	clay
Marion	52	LF	105	2200000	Ash	none/natural soils	no liner
Marion	53	LF	38	1000000	Ash	compacted clay	clay
Marshall	232	LF	110	7826000	Ash	none/natural soils	no liner
Marshall	233	SI	340	19689000	Ash and Coal Waste	none/natural soils	no liner
Martin Lake	152	LF	290	30000000	Ash	compacted clay	clay
Mayo	171	SI	30	185000	Ash	none/natural soils	no liner
Mayo	172	SI	65	2400000	Ash	none/natural soils	no liner
Meramec	175	SI	61.1	591200	Ash and Coal Waste	none/natural soils	no liner
Merom	184	LF	65	8500000	Ash	none/natural soils	no liner
Miami Fort	39	LF	80	4000000	Ash	compacted clay	clay

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Milton R Young	100	LF	80	6500000	Ash	compacted clay	clay
Mitchell - PA	208	LF	70	5600000	Ash	none/natural soils	no liner
Mitchell - WV	131	SI		12030000	Ash and Coal Waste	none/natural soils	no liner
Mohave	72	LF	250	21500000	Ash	none/natural soils	no liner
Monroe	26	LF	400	20000000	Ash and Coal Waste	none/natural soils	no liner
Monroe	27	SI	400	15000000	Ash	none/natural soils	no liner
Morgantown	291	LF	212	7700000	Ash and Coal Waste	none/natural soils	no liner
Mountaineer (1301)	212	LF	60	9700000	Ash	composite clay/membrane	composite
Mt Storm	73	LF	125	18920000	Ash	composite clay/membrane	composite
Mt Storm	134	LF	900	8800000	Ash and Coal Waste	compacted clay	clay
Muscatine Plant #1	70	LF	36	2000000	Ash	compacted clay	clay
Muskogee	51	LF	36	1247112	Ash	compacted clay	clay
Neal North	92	SI	150		Ash and Coal Waste	none/natural soils	no liner
Neal North	93	LF	200		Ash	none/natural soils	no liner
Neal South	284	LF	150		Ash	none/natural soils	no liner
Nebraska City	20	LF	17	600000	Ash and Coal Waste	compacted clay	clay
New Castle	66	LF	27	1100000	Ash and Coal Waste	geosynthetic membrane	composite
Newton	180	LF	309		Ash	none/natural soils	no liner
North Omaha	17	LF	13	105000	Ash and Coal Waste	compacted clay	clay
Northeastern	142	LF	69	3185190	Ash	none/natural soils	no liner
Nucla	96	LF	41.2	1500000	FBC	none/natural soils	no liner
Oklaunion	228	SI	11	408940	Ash and Coal Waste	none/natural soils	no liner
Oklaunion	229	SI	19.4	718060	Ash	none/natural soils	no liner
Oklaunion	230	SI	290.8	6056820	Ash	none/natural soils	no liner
Paradise	146	SI	85	7582510	Ash	composite clay/membrane	composite
Paradise	316	SI	200	5000000	Ash	none/natural soils	no liner
Petersburg	155	LF	250	19750000	Ash	compacted clay	clay

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Petersburg	156	si	156.6901408		Ash	none/natural soils	no liner
Pleasant Prairie	243	LF	26	6500000	Ash and Coal Waste	geosynthetic membrane	composite
Port Washington	242	LF	300	1900000	Ash and Coal Waste	compacted clay	clay
Portland	67	LF	15	2200000	Ash and Coal Waste	none/natural soils	no liner
Possum Point	77	SI	56		Ash and Coal Waste	none/natural soils	no liner
Potomac River	140	LF	33	802000	Ash	geosynthetic membrane	composite
Presque Isle	116	LF	292	14200000	Ash	none/natural soils	no liner
R Gallagher	326	SI	170	20000000	Ash and Coal Waste	compacted clay	clay
R M Schahfer	84	SI	80	1030000	Ash and Coal Waste	none/natural soils	no liner
R M Schahfer	85	LF	200	17200000	Ash	none/natural soils	no liner
Reid Gardner	95	LF	112.5	4520000	Ash	none/natural soils	no liner
Richard Gorsuch	36	LF		3003600	Ash	compacted clay	clay
Riverbend	165	SI	143	3200000	Ash	none/natural soils	no liner
Rodemacher	247	SI	36	1200000	Ash	compacted clay	clay
Rodemacher	248	SI	109	2500000	Ash	compacted clay	clay
Roxboro	239	LF	55	4165000	Ash	none/natural soils	no liner
Sandow	153	LF	125	1300000	Ash	compacted clay	clay
Sandow	187	LF	48	903467	Ash and Coal Waste	none/natural soils	no liner
Sandow	188	SI	45	1351973	Ash and Coal Waste	none/natural soils	no liner
Scherer	199	SI	490	22262030	Ash and Coal Waste	none/natural soils	no liner
Shawnee	317	SI	180	5810000	Ash and Coal Waste	none/natural soils	no liner
Shawnee	318	LF	96	6100000	FBC	none/natural soils	no liner
Shawville	209	LF	68	8000000	Ash	none/natural soils	no liner
Sheldon	23	LF	9	375000	Ash	compacted clay	clay
South Oak Creek	3	LF	45	4050000	Ash and Coal Waste	compacted clay	clay
South Oak Creek	4	LF	130	4600000	Ash	none/natural soils	no liner
Springerville	154	LF	57	6400000	Ash	none/natural soils	no liner

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
St Johns River Power	158	lf	128.624166		Ash and Coal Waste	compacted clay	clay
Stanton Energy Ctr.	117	LF	312		Ash	none/natural soils	no liner
Stockton Cogen Company	2000	LF	4	533333	FBC	composite clay/membrane	composite
Syl Laskin	68	SI	75	726000	Ash and Coal Waste	none/natural soils	no liner
Tecumseh EC	177	LF	540		Ash	compacted clay	clay
Texas-New Mexico	3900	LF	61	6142473	FBC	compacted clay	clay
Titus	207	LF	39	3000000	Ash and Coal Waste	composite clay/membrane	composite
Trimble County	69	SI	115	6856667	Ash	compacted clay	clay
Tyrone	148	SI	5.5	351699	Ash	none/natural soils	no liner
Tyrone	149	SI	5	327500	Ash and Coal Waste	none/natural soils	no liner
Tyrone	150	SI	7.75	500123	Ash and Coal Waste	none/natural soils	no liner
Valley	8	LF	16.4	534000	Ash and Coal Waste	compacted clay	clay
Vermilion	55	SI	43	8100000	Ash and Coal Waste	none/natural soils	no liner
Victor J Daniel Jr	287	lf	49.20163084		Ash	compacted clay	clay
Victor J Daniel Jr	288	si	20.03879417		Ash and Coal Waste	composite clay/membrane	composite
W A Parish	189	lf	28.68322214		Ash	compacted clay	clay
W H Weatherspoon	236	SI	26	1200000	Ash and Coal Waste	none/natural soils	no liner
W S Lee	238	SI	41	1634000	Ash and Coal Waste	none/natural soils	no liner
Wabash River	324	SI	120	14000000	Ash and Coal Waste	none/natural soils	no liner
Walter C Beckjord	123	LF	14	1000000	Ash	compacted ash	no liner
Walter C Beckjord	124	SI		2000000	Ash	none/natural soils	no liner
Wansley	200	SI	330	18712850	Ash and Coal Waste	none/natural soils	no liner
Wansley	201	SI	43		Ash	none/natural soils	no liner
Warrick	181	SI	140	4500000	Ash and Coal Waste	compacted clay	clay
Waukegan	54	LF	60	4000000	Ash and Coal Waste	compacted clay	clay
Weston	241	LF	18	600000	Ash	none/natural soils	no liner
Widows Creek	320	SI	110	3500000	Ash and Coal Waste	none/natural soils	no liner

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Widows Creek	321	SI	222	12400000	Ash	compacted clay	clay
Will County	277	SI	60	599256	Ash and Coal Waste	compacted clay	clay
Wyodak	71	LF	68	3500000	Ash	geosynthetic membrane	composite
Yates	197	SI	4.7	115000	Ash	composite clay/membrane	composite

Appendix C. Site Data

The site characteristics used in this analysis were based on site-specific, regional, and national data sources to provide the environmental parameters necessary for modeling the fate and transport of coal combustion waste (CCW) constituents released in landfill or surface impoundment leachate. Site-specific data were collected for the area in the immediate vicinity of the waste management unit (WMU), and included the geographic relationship among important features such as the WMU boundary, residential well location, and streams and lakes. These data were collected at each of the 181 coal-fired power plants selected for the analysis. These 181 locations across the continental United States are intended to represent the geographic distribution of onsite WMUs used for disposal of CCW and were used to capture national variability in meteorology, soils, climate, aquifers, and surface waterbodies at the disposal sites.

C.1 Data Collection Methodology

The CCW risk assessment employed a site-based data collection method. This method used the CCW plant locations from the Energy Information Administration (EIA) database to obtain data for each facility that were representative of the environment immediately surrounding the plant. Depending on the availability of information, data were collected on either a site-specific, regional, or national scale. Where appropriate, distributions were used in the Monte Carlo analysis to capture site-to-site and within-site variability in the parameters collected.

Site-based data were collected using a geographic information system (GIS) that allowed (1) site-specific data to be assembled from the area immediately surrounding the facility and (2) the site to be assigned to a region to collect regional data. To account for locational uncertainty for the CCW WMUs[1], a 5-km radius was used to define the data collection area for aquifer type and soil data. If multiple soil or aquifer types occurred within this radius, multiple types were sent to the model, weighted by the fraction of the collection area that they occupied. Surface waterbody type and stream flows also were collected for each site by identifying the nearest stream segment.

Climate and water quality data were collected by assigning each site to a meteorological station and a U.S. Geological Survey (USGS) hydrologic region. The EPA STOrage and RETrieval (STORET) database was used as the source for water quality data, with parameters selected from distributions queried from this database for each region.

Because the EIA locations were not exact for the WMUs being modeled, a national distribution of stream distances was developed by manually measuring the distance between the WMU and the waterbody at a random sample of the CCW sites. Similarly, a national distribution

[1] The EIA latitudes and longitudes usually represent a facility centroid or front-gate location for each power plant. Because these facilities are often large, the WMUs are frequently located some distance from the plant itself and not at the EIA location.

was used to represent the distance of the nearest residential wells from the CCW WMUs being modeled.

C.2 Receptor Location (National Data)

The residential scenario for the CCW groundwater pathway analysis calculates exposure through use of well water as drinking water. During the Monte Carlo analysis, the receptor well is placed at a distance of up to 1 mile from the edge of the WMU, by sampling a nationwide distribution of nearest downgradient residential well distances taken from a survey of municipal solid waste landfills (U.S. EPA, 1988).

EPA believes that this MSW well-distance distribution (presented in Table C-1) is protective for onsite CCW landfills and surface impoundments at coal-fired utility power plants, but recognizes that this is a significant uncertainty in this analysis. Because CCW plants tend to be in more isolated areas than MSW landfills and because CCW WMUs tend to be larger than municipal landfills, EPA believes that the MSW well distance distribution is a conservative representation of actual well distances at CCW disposal sites. However, data on residential well distances from CCW landfills or surface impoundments will be needed to verify this hypothesis.

As discussed in Section 3.4.3, the groundwater model used in the CCW risk assessment places limits on the lateral direction from the plume centerline (i.e., angle off plume centerline) and depth below the water table to ensure that the well remains within the plume and at a depth appropriate for surficial aquifers across the United States. These limits are consistent with other recent national risk assessments conducted by EPA OSW and provide a protective approach to siting wells for this analysis.

Table C-1. Distribution of Receptor Well Distance

Percentile	x-distance (m)
Minimum	0.6
10	104
20	183
30	305
40	366
50 (Median)	427
60	610
70	805
80	914
90	1,220
Maximum	1,610

Source: U.S. EPA (1988).

C.2.1 Recreational Fisher and Ecological Risk Scenario (Distance to Waterbody)

The recreational fisher scenario was used to estimate risks to recreational fishers and their children who live in the vicinity of the CCW landfills and surface impoundments and catch and

consume fish from a waterbody located adjacent to the buffer. The waterbody was assumed to be a stream or lake located downwind of the WMU, beginning where the buffer area ends (see Figure 2-4), and was also used as the reasonable worst case aquatic system for the ecological risk assessment. Waterbody characteristics were determined based on site-specific, regional, or national data (as described in Section C.6), except for stream length, which was determined by the width of the plume as it intersects the waterbody.

The downgradient distance to the surface water body was determined from a national distribution developed by measuring this distance at 59 CCW landfill and surface impoundment sites randomly selected from the 204 WMUs modeled in this risk assessment. Table C-2 presents this distribution. Figure C-1 provides a map and aerial photo of one of the facilities used to develop this distribution. The development of this distribution is described in Section C.6.4.

Table C-2. Distribution of Surface Water Distances

Percentile	Distance (m)
Minimum	10
0.03	10
0.05	20
0.07	20
0.09	20
0.10	20
0.13	20
0.15	30
0.20	40
0.25	50
0.30	50
0.35	60
0.40	70
0.45	100
0.50 (Median)	120
0.55	130
0.60	150
0.65	250
0.70	400
0.75	440
0.80	500
0.85	700
0.87	775
0.90	800
0.91	1,000
0.93	1,500
0.95	2,125
0.97	2,750
Maximum	3,000

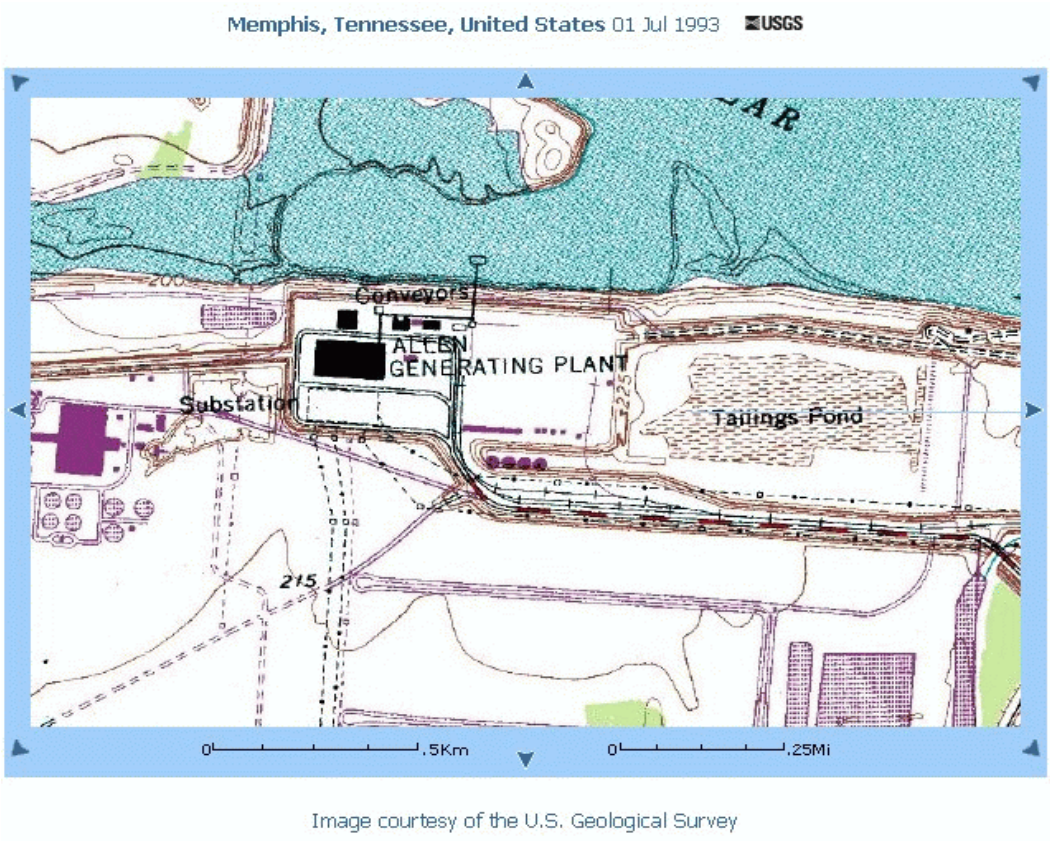

Figure C-1. Example CCW site used to develop waterbody distance distribution.

C.3 Soil Data

The groundwater model used in the CCW risk assessment—EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP)—requires soil properties for the entire soil column to model leachate transport through the vadose zone to groundwater. As with aquifer type, soil data were collected within a 5-km radius of each CCW plant. A GIS was used to identify soil map units within a 20-mile radius around each meteorological station. Database programs were then used to assemble and process soil texture, pH, and soil organic matter data for these map units from the State Soil Geographic (STATSGO) database. Both pH and soil organic matter were processed and indexed by the soil textures present within the 5-km radius. Soil properties are listed by texture for each of the 181 CCW plants in Attachment C-1.

C.3.1 Data Sources

The primary data source for soil properties was the STATSGO database. STATSGO is a repository of nationwide soil properties compiled primarily by the U.S. Department of Agriculture (USDA) from county soil survey data (USDA, 1994). STATSGO includes a 1:250,000-scale GIS coverage that delineates soil map units and an associated database containing soil data for each STATSGO map unit. (Map units are areas used to spatially represent soils in the database.)

In addition, two compilations of STATSGO data, each keyed to the STATSGO map unit GIS coverage, were used in the analysis as a convenient source of average soil properties:

- **USSOILS.** The USSOILS data set (Schwarz and Alexander, 1995) averages STATSGO data over the entire soil column for each map unit.

- **CONUS.** The Conterminous United States Multi-Layer Soil Characteristics (CONUS) data set (Miller and White, 1998) provides average STATSGO data by map unit and a set of 11 standardized soil layers.

Soil organic matter and pH were derived directly from USSOILS and STATSGO data. A complete set of hydrological soil properties[2] was not available from STATSGO. To ensure consistent and realistic values, EPACMTP relies on established, nationwide relationships between hydrologic properties and soil texture. Peer-reviewed publications by Carsel and Parrish (1988) and Carsel et al. (1988) provide a consistent set of correlated hydrologic properties for each soil texture. Soil texture data for the entire soil column were collected from the CONUS database.

C.3.2 Methodology

The soil data collection methodology begins with GIS programs (in Arc Macro Language [AML]). These programs overlay a 5-km radius around each CCW plant location on the STATSGO map unit coverage to determine the STATSGO map units and their area within the radius. These data are then passed to data processing programs that derive soil properties for

[2] Hydrological soil properties required by EPACMTP include bulk density, saturated water content, saturated hydraulic conductivity, and the van Genuchten soil moisture retention parameters alpha and beta.

each site, either through direct calculations or by applying established relationships in lookup tables.

EPACMTP utilizes three soil textures to represent variability in hydrologic soil properties and (along with climate data) to assign infiltration rates to each site. Because STATSGO soils are classified into the 12 U.S. Soil Conservation Service (SCS) soil textures, the crosswalk shown in Table C-3 was used to assign the SCS textures to the EPACMTP megatextures and to calculate the percentage of each megatexture within the 5-km data collection radius. These percentages were sampled for each site when preparing the source data file for each site.

Both soil pH and soil organic matter were derived for each EPACMTP soil megatexture at a site. During source data file preparation, when a megatexture was picked for a particular iteration of a site, the corresponding pH and organic matter values were selected as well.

Table C-3. EPACMTP Soil Texture Crosswalk

STATSGO Texture	EPACMTP Megatexture
Sand	Sandy loam
Loamy sand	
Sandy loam	
Silt loam	Silt loam
Silt	
Loam	
Sandy clay loam	
Clay loam	
Silty clay loam	Silty clay loam
Sandy clay	
Silty clay	
Clay	

C.3.3 Results

Attachment C-1 lists the STATSGO soil textures and EPACMTP megatexture assignments and percentages for each CCW disposal site.

C.4 Hydrogeologic Environments (Aquifer Type)

To assign aquifer properties used by EPACMTP, it was necessary to designate hydrogeologic environments (or aquifer types) for each of the locations modeled so that correlated, national aquifer property data could be used in the analysis. EPACMTP uses the Hydrogeologic Database (HGDB) developed by the American Petroleum Institute (API) (Newell et al., 1989; Newell et al., 1990) to specify correlated probability distributions, which are used to populate the following four hydrogeologic parameters during the Monte Carlo analysis:

- Unsaturated zone thickness
- Aquifer thickness

- Hydraulic gradient
- Saturated hydraulic conductivity.

The HGDB provides correlated data on these hydrogeologic parameters and an aquifer classification for approximately 400 hazardous waste sites nationwide, grouped according to 12 hydrogeologic environments described in Newell et al. (1990). The *EPACMTP User's Guide* (U.S. EPA, 1997) provides the empirical distributions of the four hydrogeologic parameters for each of the hydrogeologic environments.

Average aquifer/vadose zone temperature was also required for the groundwater model and was obtained from a digitized map of groundwater temperatures for the continental United States from the *Water Encyclopedia* (van der Leeden et al., 1990).

The hydrogeologic environment approach to assigning EPACMTP aquifer variables relies upon a hydrogeologic framework originally developed for an attempt by EPA to classify and score groundwater environments according to their potential to be polluted by pesticide application. Although this DRASTIC[3] scoring system was not widely applied to determining groundwater vulnerability to pesticide pollution, the hydrogeologic framework established for the effort has proven very useful in categorizing geologic settings in terms of the aquifer characteristics needed for groundwater modeling. The major components of this modeling framework are Groundwater Regions, hydrogeologic settings, and hydrogeologic environments, as described below:

- The fifteen **Groundwater Regions**, defined by Heath (1984), provide a regional framework that groups hydrogeologic features (i.e., nature and extent of dominant aquifers and their relationship to other geologic units) that influence groundwater occurrence and availability.

- **Hydrogeologic settings** were developed within each Heath region by Aller et al. (1987)[4] to create mappable geological units that are at the proper scale to capture differences in aquifer conditions. Note that there may be the same or similar settings across different regions (e.g., the alluvial settings). Within each region, Aller et al. (1987) describe each setting with a written narrative and provide a block diagram to visualize the geology, geomorphology, and hydrogeology.

- **Hydrogeologic environments** were developed by Newell et al. (1990) as the geologic framework for the API's HGDB. To create the 12 environments, Newell et al. rolled up similar hydrologic settings across the Groundwater Regions to group settings with similar aquifer characteristics (hydraulic conductivity, gradient, thickness, and depth-to-water). Table C-4 shows the crosswalk between hydrologic environment and hydrogeologic setting, organized by Groundwater Region.

[3] The DRASTIC scoring factors are Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone media, and aquifer hydraulic Conductivity.

[4] Aller et al. (1987, p. 14) did not develop settings for Region 15 (Puerto Rico and the Virgin Islands) and reincorporated Region 12 (Alluvial Valleys) into each of the other regions as "river alluvium with overbank deposits" and "river alluvium without overbank deposits."

Because EPACMTP utilizes the HGDB for national and regional analyses (using a regional site-based approach), it was necessary to assign the CCW sites to a hydrogeologic environment so that the correct HGDB data set will be used for modeling each site. The data sources and methodology used to make these assignments are described below.

C.4.1 Data Sources

Data sources used to make hydrogeologic assignments for the sites include:

- A USGS inventory of state groundwater resources (Heath, 1985)
- GIS coverages from *Digital Data Sets Describing Principal Aquifers, Surficial Geology, and Ground-Water Regions of the Conterminous United States* (Clawges and Price, 1999a-d)
- GIS coverages of principal aquifers from the USGS *Groundwater Atlas* (Miller, 1998)
- STATSGO soil texture data (described in Section C.3.2).

These coverages were used in a GIS overlay process to determine the principal aquifers, surficial geologic units, groundwater region, productive aquifers, and general hydrogeologic settings for a 5-km radius around each CCW facility location. Attributes for each of these items were passed to a database for use in assigning hydrogeologic environments.

C.4.2 Assignment Methodology

For each CCW site, hydrogeologic environments were assigned by a professional geologist as follows:

- Determine Heath Groundwater Region (for the Alluvial Valleys region, determine the region in which the alluvial valley is located)
- Assign hydrogeologic setting using state geological descriptions from Heath (1985); aquifer, soil, and surficial geology information obtained using GIS; and narratives and block diagrams from Aller et al. (1987)
- Using the look-up table from Newell et al. (1990), determine hydrogeologic environment from hydrogeologic setting.

In general, the surficial geology coverage had better resolution than the aquifer coverages and was used to develop setting percentages for the 5-km radius. In most cases, there were two settings per site. In cases where a single setting accounted for over 80 percent of the 5-km area, a single setting was assigned.

Because Newell et al. (1990) define two alluvial environments (6, River alluvium with overbank deposits, and 7, River alluvium without overbank deposits), it was necessary to determine which environment an alluvial site fell into. The survey soil layer information was used to distinguish between these two settings by determining whether there were significant fine-grained overbank deposits in the soil column.

Quality assurance/quality control (QA/QC) measures included independent review of the assignments by other geologists with expertise in assigning settings.

C.4.3 Data Processing

HGDB hydrogeologic environment fractions (i.e., the portion of the region assigned to each of the 12 hydrogeological environments) were defined and used in the CCW risk assessment as follows. If the 5-km radius around a site contained only one HGDB environment, the fraction assigned was 1.0 and all groundwater model runs for this location were associated with that hydrological environment. If more than one HGDB environment was present, each environment was assigned a fraction based on the areal percentages of each setting within the 5-km radius.

These fractions were used to generate the hydrogeologic environment for that location for each iteration of the Monte Carlo groundwater modeling analysis. For example, if two hydrogeologic environments were assigned to a CCW site with a fraction of 0.5, half of the realizations would be modeled with the first hydrogeologic environment and half with the second.

Once the hydrogeologic environments were assigned, a preprocessing run of EPACMTP was conducted to construct a set of randomly generated but correlated hydrogeologic parameter values for each occurrence of the hydrogeologic environments in the source data files. Missing values in the HGDB data set were filled using correlations, as described in U.S. EPA (1997).

C.4.4 Results

Attachment C-2 lists the hydrogeologic environment assignments for each CCW disposal site. Table C-4 summarizes these results showing the crosswalk between Groundwater Regions, hydrogeologic settings, and hydrogeologic environments used to make the assignments, along with the number of CCW sites for each setting. Table C-5 totals the number of CCW disposal sites for each hydrogeologic environment sent to EPACMTP.

Table C-4. Groundwater Regions, Hydrogeologic Settings, and Hydrogeologic Environments: CCW Disposal Sites

Hydrogeologic Setting		Hydrogeologic Environment	Number of CCW Sites
Alluvial Basins			
2C	Alluvial Fans	5	1
2E	Playa Lakes	5	1
2Ha	River Alluvium With Overbank Deposits	6	1
Colorado Plateau and Wyoming Basin			
4B	Consolidated Sedimentary Rock	2	7
4C	River Alluvium	7	3
High Plains			
5Gb	River Alluvium Without Overbank Deposits	7	1

(continued)

Table C-4. (continued)

Hydrogeologic Setting		Hydrogeologic Environment	Number of CCW Sites
Nonglaciated Central Region			
6Da	Alternating Sandstone, Limestone, and Shale – Thin Soil	2	22
6Db	Alternating Sandstone, Limestone, and Shale – Deep Regolith	2	6
6E	Solution Limestone	12	9
6Fa	River Alluvium With Overbank Deposits	6	37
6Fb	River Alluvium Without Overbank Deposits	7	4
6H	Triassic Basins	2	4
Glaciated Central Region			
7Aa	Glacial Till Over Bedded Sedimentary Rock	3	12
7Ac	Glacial Till Over Solution Limestone	12	6
7Ba	Outwash	8	1
7Bb	Outwash Over Bedded Sedimentary Rock	2	3
7Bc	Outwash Over Solution Limestone	12	2
7D	Buried Valley	4	11
7Ea	River Alluvium With Overbank Deposits	6	24
7Eb	River Alluvium Without Overbank Deposits	7	6
7F	Glacial Lake Deposits	4	3
7G	Thin Till Over Bedded Sedimentary Rock	3	5
7H	Beaches, Beach Ridges, and Sand Dunes	11	1
Piedmont and Blue Ridge			
8B	Alluvial Mountain Valleys	5	1
8C	Mountain Flanks	2	2
8D	Regolith	1	13
8E	River Alluvium	6	6
Northeast and Superior Uplands			
9E	Outwash	8	3
9F	Moraine	4	1
9Ga	River Alluvium With Overbank Deposits	6	1
Atlantic and Gulf Coastal Plain			
10Aa	Regional Aquifers	4	1
10Ab	Unconsolidated/Semiconsolidated Shallow Surficial Aquifers	10	20
10Ba	River Alluvium With Overbank Deposits	6	7
10Bb	River Alluvium Without Overbank Deposits	7	6
Southeast Coastal Plain			
11A	**Solution Limestone and Shallow Surficial Aquifers**	**12**	**3**
11B	**Coastal Deposits**	**4**	**1**

Table C-5. Hydrogeologic Environments for CCW Disposal Sites

	Hydrogeologic Environment	Number of CCW Sites
1	Metamorphic and Igneous	13
2	Bedded Sedimentary Rock	44
3	Till Over Sedimentary Rock	17
4	Sand and Gravel	17
5	Alluvial Basins Valleys and Fans	3
6	River Valleys and Floodplains With Overbank Deposit	76
7	River Valleys and Floodplains Without Overbank Deposits	20
8	Outwash	4
9	Till and Till Over Outwash	0
10	Unconsolidated and Semiconsolidated Shallow Aquifers	20
11	Coastal Beaches	1
12	Solution Limestone	20

C.5 Climate Data

The CCW risk assessment selected EPACMTP meteorological (or climate) stations for each CCW disposal site to collect the climatic data necessary for fate and transport modeling. For each station, the following data were compiled:

- Mean annual windspeed
- Mean annual air temperature
- Mean annual precipitation.

With respect to precipitation, EPACMTP uses the climate station, along with soil texture, to select the HELP- (Hydrologic Evaluation of Landfill Performance-) modeled infiltration rates to use in the landfill source model and recharge rates to use in EPACMTP (see Section 3.2.2). The surface water model uses mean annual windspeed and average air temperature to estimate volatilization losses from the surface waterbodies modeled in the analysis.

To assign the EPACMTP climate centers to each CCW site, a GIS was used to determine the three meteorological stations closest to the plant. These assignments were passed to a meteorologist, who reviewed the closest stations against plots of the CCW sites and the climate centers on a downloadable map (http://www.nationalatlas.gov/prismmt.html) of annual average precipitation rates for the period from 1961 to 1990 across the contiguous United States. (Figure C-2). The meteorologist compared the 5-year average precipitation range for each EPACMTP climate center to precipitation ranges for each plant from the map. In most cases, the precipitation rate for the nearest climate center fell within the site's expected precipitation range, and the nearest climate center was assigned in those cases. In some cases, the precipitation rates from the nearest climate center did not fall within the site's expected range. When this occurred, the second or third closest climate center was examined and matched based on:

- A 5-year precipitation average within or close to the site's predicted precipitation range

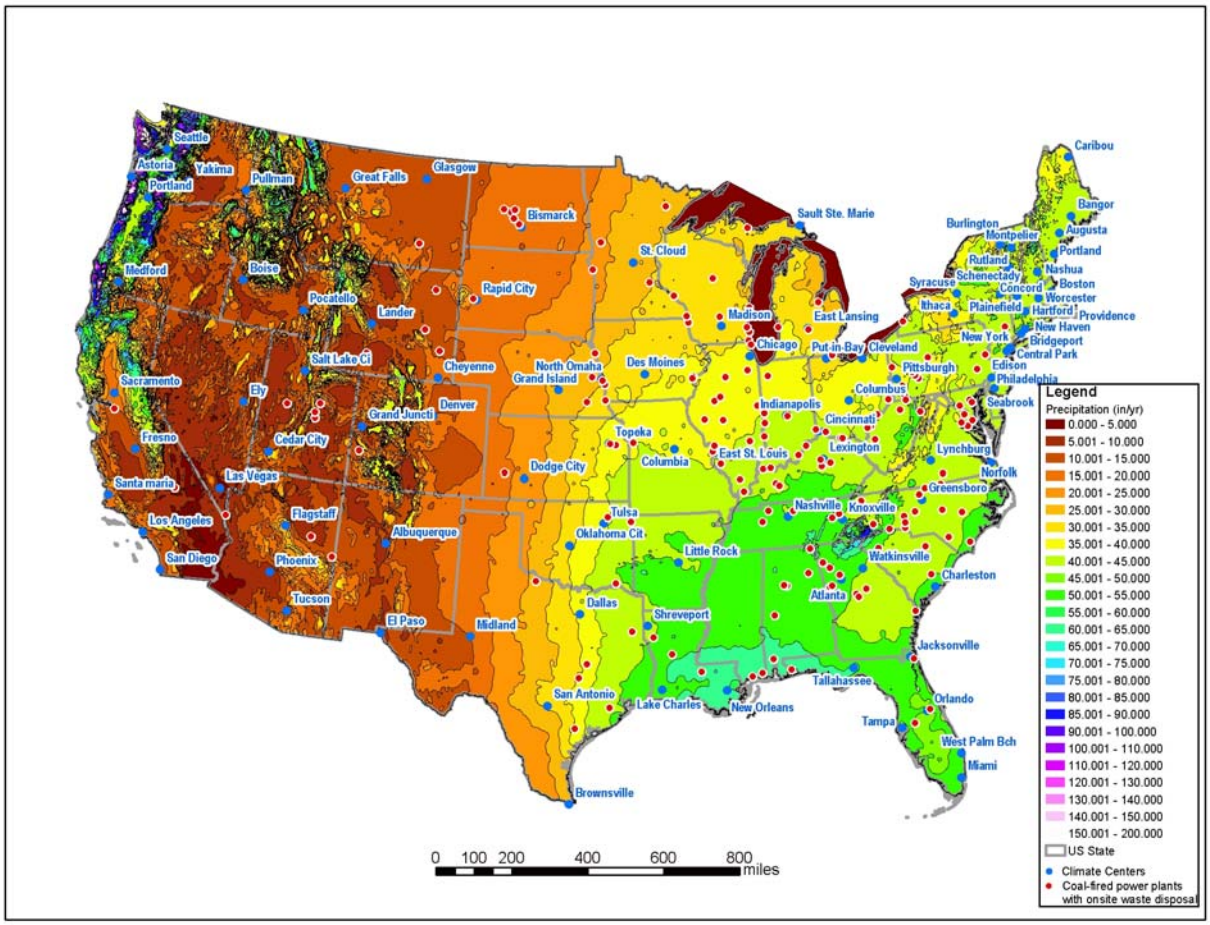

Figure C-2. EPACMTP climate centers, precipitation ranges, and CCW disposal sites.

- Confirmation of a site's average annual rainfall on http://www.weather.com and van der Leeden et al. (1990)
- Geographic similarities between plant and climate center locations
- Best professional judgment.

In a few cases, the three closest climate centers did not reflect the average precipitation rates for a plant's location. In these cases, other nearby stations were examined and the plant was assigned to the closest climate center with similar geography and average precipitation rates. Each assignment was independently checked for accuracy. Attachment C-3 lists the climate center assigned to each CCW disposal site, along with notes for plants not assigned to the nearest center. Table C-6 lists all the climate centers used in the CCW risk assessment along with the number of CCW sites assigned to each station.

Table C-6. EPACMTP Climate Centers Assigned to CCW Disposal Sites

Climate Center		State	Number of CCW Sites
4	Grand Junction	CO	2
6	Glasgow	MT	1
7	Bismarck	ND	5
10	Cheyenne	WY	2
11	Lander	WY	1
13	Sacramento	CA	1
16	Ely	NV	1
17	Rapid City	SD	2
18	Cedar City	UT	1
19	Albuquerque	NM	1
20	Las Vegas	NV	3
21	Phoenix	AZ	1
26	Salt Lake City	UT	1
29	Dodge City	KS	1
31	St. Cloud	MN	3
32	East Lansing	MI	3
33	North Omaha	NE	7
34	Tulsa	OK	2
37	Oklahoma City	OK	1
39	Pittsburgh	PA	12
42	Chicago	IL	8
48	Sault Ste. Marie	MI	1
49	Put-in-Bay	OH	3
50	Madison	WI	9
51	Columbus	OH	2
53	Des Moines	IA	2
54	East St. Louis	IL	8
55	Columbia	MO	1
56	Topeka	KS	3
58	San Antonio	TX	4
66	Ithaca	NY	1
69	Lynchburg	VA	2
71	Philadelphia	PA	2
72	Seabrook	NJ	5
73	Indianapolis	IN	12
74	Cincinnati	OH	11
75	Bridgeport	CT	1
76	Orlando	FL	2
77	Greensboro	NC	11

(continued)

Table C-6. (continued)

Climate Center		State	Number of CCW Sites
78	Jacksonville	FL	1
79	Watkinsville	GA	4
80	Norfolk	VA	2
81	Shreveport	LA	4
85	Knoxville	TN	4
87	Lexington	KY	3
89	Nashville	TN	4
90	Little Rock	AR	1
91	Tallahassee	FL	4
93	Charleston	SC	4
95	Atlanta	GA	9
96	Lake Charles	LA	2

C.6 Surface Water Data

The surface water model used in the CCW risk assessment requires information on surface waterbody type (river or lake), flow conditions, dimensions, and water quality. In addition, the groundwater model requires the distance between the waterbody and the WMU being modeled. Surface waterbody data were collected on a site-based, regional, or national basis depending on the variable and data availability. Collection methods are described below by data source. Attachment C-4 provides a summary of waterbody assignments, waterbody types, and flow conditions.

C.6.1 Waterbody Type, Stream Flow Conditions, and Dimensions

Waterbody type and flow parameters were obtained by matching the CCW plants to stream segments in the Reach File Version 1.0 (RF1) database (U.S. EPA, 1990). Stream flow estimates for all RF1 flowing reaches were estimated in the early 1980s. Statistics developed for each flowing reach are mean annual flow, low flow (approximately $7Q10^5$), and mean monthly flow. RF1 also contains velocities corresponding to mean annual and low flow, estimated from a compendium of time-of-travel studies. For streams and rivers, the CCW risk assessment used the low flow statistic and the corresponding flow velocity, along with a waterbody type also included in the RF1 database. All RF1 data are indexed by USGS cataloging unit and stream segment (CUSEG).

To assign the CCW plants to the nearest downgradient reach (i.e., the nearest waterbody in the direction of groundwater flow), a GIS was used to identify the closest RF1 stream segment to each CCW plant location. Because of several uncertainties in the nearest reach approach (i.e., inaccurate WMU location, unknown direction of groundwater flow, and limited lake coverages), the CCW plants also were matched to standard industrial classification (SIC) code 4911 facilities

[5] The minimum 7-day average flow expected to occur within a 10-year return period (i.e., at least once in 10 years).

in EPA's Permit Compliance System (PCS) database (http://www.epa.gov/enviro/html/pcs/index.html), to obtain the PCS information (e.g., name, CUSEG) on the receiving waterbody for the plants' National Pollutant Discharge Elimination System (NPDES) discharge point(s). When the two sources matched, the reach was selected for modeling. When they differed, the PCS data were used, because it was judged more likely that the NPDES receiving waterbody would also be receiving loads from the WMU through the groundwater-to-surface-water pathway. CCW plants that could not be matched to the PCS database were simply assigned the nearest RF1 waterbody.

The next step in the assignment process was to review the waterbody names (especially those from PCS) to identify lakes and reservoirs. Finally, visual review, using aerial photos and topographic maps from the Terraserver Web site (http://terraserver.usa.com), was used to check all low-flow streams and RF1 reaches whose identity was not clear. Attachment C-4 provides the RF1 stream assignments, flows, and waterbody types for the CCW disposal sites.

With respect to waterbody type, the RF1 data include several types of waterbodies, including streams and rivers, and types with zero flows such as lakes, Great Lakes, wide rivers, and coastline features. Each of these waterbody types needed to be designated as a river or a lake for the simple waterbody model used in the full-scale CCW risk assessment. Because only the streams and rivers have flow data in RF1 (i.e., are flowing reaches), all other types were assigned to the lake modeling category. Modeling these features as a simple model lake is a considerable uncertainty in the CCW risk assessment and risk results for these waterbodies should be regarded as preliminary until a more sophisticated surface water model can be parameterized for these special cases. Table C-7 lists the RF1 waterbody types for the waterbodies assigned to the CCW disposal sites, along with the number of CCW plants assigned to each type and the crosswalk to the river (R) or lake (L) waterbody type used in this risk assessment.

Table C-7. RF1 Reach Types Assigned to CCW Disposal Sites

RF1 Code	RF1Name	Description	Reach Model Type[a]	Number of CCW Plants
Flowing Reaches				
M	Artificial Open Water Reach	An artificial reach within any open water, other than a lake or reservoir, to provide connection between input and output reaches of the open water.	R	1
R	Regular Reach	A reach that has upstream and downstream reaches connected to it and that is not classified as another type of reach.	R	106
S	Start Reach	A headwater reach that has no reaches above it and either one or two transport reaches connected to its downstream end.	R	16
T	Terminal Reach	A reach downstream of which there is no other reach (for example, a reach that terminates into an ocean, a land-locked lake, or the ground). This type of reach has either one or two reaches connected to its upstream end.	R	2

(continued)

Table C-7. (continued)

RF1 Code	RF1Name	Description	Reach Model Type[a]	Number of CCW Plants
Reaches with Zero RF1 Flow				
C	Coastal/Continental Shoreline Segment	A reach that represents a segment of a shoreline of a gulf, sea, or ocean.	L	3
G	Great Lakes Shoreline Segment	A reach that represents a segment of a shoreline of the Great Lakes.	L	12
L	Lake Shoreline Segment	A segment that follows the shoreline of a lake other than one of the Great Lakes.	L	36
W	Wide-River Shoreline Segment	A reach that represents a segment of the left or right bank of a stream.	L	5

[a] R = river; L = lake.

Stream dimensions were calculated from the flow data as follows. First, the length of the modeled stream segment was set to be the width of the groundwater plume as it enters the waterbody. Stream width was then determined from flow (Q) using a liner regression equation derived from empirical data by Kocher and Sartor (1997):

$$Width = 5.1867Q^{0.4559} \quad \text{(C-1)}$$

Water column depth (dwc) was derived from width, velocity (V), and flow using the continuity equation:

$$dwc = \frac{Q}{v \times Width} \quad \text{(C-2)}$$

C.6.2. Lake Flow Conditions and Dimensions

Areas and depths for many of the lakes assigned to the CCW plant sites were not readily available from RF1, Reach File Version 3 (RF3), the National Hydrography Dataset (NHD), or other sources. In addition, many plants are located on very large waterbodies (e.g., the Great Lakes, wide rivers, or coastlines) where applying the simple steady-state, single-compartment model used in this analysis to the entire lake would not be appropriate. For these reasons, a model lake approach was used to represent all lakes and other nonflowing waterbodies assigned to the CCW disposal site.

The model lake chosen was Shipman City Lake in Illinois, a well-characterized 13-acre lake that EPA has chosen as the index reservoir for modeling drinking water exposures to pesticides (Jones et al., 1998). The parameter values shown in Table C-8 for Shipman City Lake were used to model all lakes in this initial analysis. Given that many of the lakes assigned to CCW plants are much larger than 13 acres, this will produce conservative risk results. However, given that many of the plants are located on very large waterbodies, this necessary simplification is one of the largest uncertainties in defining the environmental settings for the CCW risk

assessment. Options can be developed to more accurately parameterize and model such large nonflowing waterbodies.

Table C-8. Model Lake Used in CCW Risk Assessment

Parameter	Value
Area [a]	13 acres
Water column depth (dwc)[a]	9 feet
Hydraulic residence time (HRT)	Random, triangular distribution: Minimum = 1 month Mean = 6 months Maximum = 24 months
Annual flow mixing volume	= (Area × dwc) / HRT

[a] Source: Shipman City Lake, IL (Jones et al., 1998).

C.6.3 Water Quality Data

Surface water temperature, total suspended solids (TSS), and pH data were collected by USGS hydrologic region from the STORET database. EPA's STORET system is the largest single source of water quality data in the country. The Legacy STORET database contains over 275 million analyses performed on more than 45 million samples collected from 800,000 stations across the United States for the period 1960 through 1998. STORET can be accessed from the Web at http://www.epa.gov/OWOW/STORET.

STORET water quality data are notoriously "noisy" because they are influenced by hydrology, point sources, nonpoint sources, stream/lake morphology, and varying data quality. The following issues in using STORET data must be considered before using the data:

- Not all of the data have undergone rigorous QA/QC.
- STORET site locations can be biased, especially to known "problem" waters.
- The sample times are often at critical periods, such as summer low flows.

Statistical analysis techniques were employed taking into account the above issues (including coordination with gage statistical analysis and Reach Files, the use of median values to avoid bias in central tendency estimates, and specification of a minimum number of measurements to estimate median values). As a result of these techniques, which can be thought of as extracting the underlying "signal" of water quality from the inherent "noise" of water quality data, the above issues were manageable.

Surface water temperature data were collected as median values for each hydrologic region. These data are shown in Table C-9 along with the number of the modeled CCW plants in each region.

Table C-9. Regional Surface Water Temperatures: CCW Disposal Sites

Hydrologic Region	Surface Water Temperature (°C)	Number of CCW Plants
2	16	12
3	21	37
4	14	14
5	17	43
6	18	6
7	15	20
8	20	2
9	10	1
10	13	20
11	17	8
12	21	6
14	9	5
15	17	4
16	9	1
18	15	2

Data source: Legacy STORET database.

Total suspended solids data were collected separately for streams/rivers and lakes because lakes tend to have lower TSS levels. Annual median values were used to develop statistics. For rivers, the minimum, maximum, and geometric mean values were used to define log triangular distributions for each hydrologic region (Table C-10); these distributions were then sampled during the preparation of the source data files. (The geometric means were weighted by the annual number of measurements.) For lakes, data were limited and national statistics were developed, with the geometric mean of the median values being weighted by the number of measurements per year and the number of annual values in each region.

Table C-10. Surface Water Total Suspended Solids (TSS) Distributions

Hydrologic Region	Number of CCW Plants	No. of Measure-ments	No. of Annual Medians	Annual Median TSS (log triangular distribution)			Geometric Mean
				Minimum	Maximum	Weighted Geometric Mean	
1	0	9,007	33	3.2	40	8.0	6.0
2	12	47,202	38	10	316	32	40
3	37	43,395	36	6.3	79	25	25
4	14	29,577	37	6.3	794	25	25
5	43	39,900	38	4.0	100	25	25
6	6	4,137	28	5.0	316	16	20

(continued)

Table C-10. (continued)

Hydrologic Region	Number of CCW Plants	No. of Measure-ments	No. of Annual Medians	Annual Median TSS (log triangular distribution)			Geometric Mean
				Minimum	Maximum	Weighted Geometric Mean	
7	20	34,494	37	32	1,585	63	100
8	2	46,231	38	50	316	158	126
9	1	3,254	35	13	3,162	32	63
10	20	62,791	38	10	398	126	126
11	8	48,969	38	25	794	200	126
12	6	7,280	35	40	1,995	79	126
13	0	13,974	37	32	79,433	200	398
14	5	26,699	38	16	5,012	158	251
15	4	9,162	37	20	19,953	200	398
16	1	19,965	33	4	2,512	16	25
17	0	173,136	37	2	316	6.0	10
18	2	42,022	37	13	398	63	50
Lakes (national)	56	4,360	99	1	398	25	25

Data source: Legacy STORET database.

For **surface water pH**, the minimum, maximum, and weighted average annual median values were used to specify triangular distributions for each hydrologic region. Table C-11 provides these regional statistics, which were applied to both rivers and lakes.

To prepare the water quality data for the source datafile, the 181 CCW disposal sites were assigned to a hydrogeologic region using a GIS. For each region, 10,000-record TSS and pH data sets were created by sampling the distributions shown in Tables C-10 and C-11. During source data file preparation, TSS data were pulled from the appropriate regional data set sequentially for each iteration at a site.

Table C-11. Regional Surface Water pH Distributions

Hydrologic Region	Number of CCW Plants	No. of Measurements	No. of Annual Median Values	Annual Median pH (triangular distribution)			Average Median pH
				Minimum	Maximum	Weighted Average	
1	0	232,025	38	5.9	7.7	6.5	6.8
2	12	447,166	39	7.2	7.6	7.4	7.4
3	37	1,595,237	39	6.3	7.2	7.0	7.0
4	14	335,261	39	7.6	8.2	8.1	8.0
5	43	684,235	41	3.5	7.5	7.2	7.1
6	6	382,915	39	6.3	7.7	7.2	7.4

(continued)

Table C-11. (continued)

Hydrologic Region	Number of CCW Plants	No. of Measurements	No. of Annual Median Values	Annual Median pH (triangular distribution)			Average Median pH
				Minimum	Maximum	Weighted Average	
7	20	234,589	39	7.6	8.1	7.9	7.8
8	2	171,643	39	6.9	7.8	7.1	7.2
9	1	23,038	38	7.5	8.4	7.9	7.9
10	20	269,570	39	7.6	8.2	8.0	8.0
11	8	311,768	39	7.4	8.1	7.8	7.8
12	6	178,990	39	7.0	7.9	7.8	7.6
13	0	35,355	39	7.0	8.1	8.0	7.9
14	5	77,041	39	7.9	8.3	8.1	8.1
15	4	75,145	38	7.7	8.3	8.0	8.0
16	1	68,581	38	7.5	8.3	8.0	8.0
17	0	293,909	39	6.9	8.0	7.5	7.4
18	2	182,049	38	7.4	8.6	7.8	7.8

Data source: Legacy STORET database.

C.6.4 Distance to Surface Water

Because the CCW plant locations were not accurate in terms of locating the WMUs, a national empirical distribution of distances between the WMU and the nearest downgradient surface waterbodies (discussed in Appendix C, Section C.2.1) was developed using manual measurements on online maps and aerial photographs for a random selection of 30 CCW landfills and 29 CCW surface impoundments. Scaled USGS maps and aerial photographs were obtained from the Terraserver Web site (http://terraserver.usa.com/geographic.aspx) by entering each plant's longitude and latitude. Labels on the maps, features on the photographs, and best professional judgment were used to identify the power plant and the surface impoundment or landfill in question, along with the nearest downgradient waterbody.

The nearest waterbody matching one of the following descriptions was used in the analysis:

- Lakes or rivers beyond the facility boundary
- Streams originating in or passing through the facility boundary and then coursing downstream beyond the property boundary
- Streams with an order of 3 or greater (i.e., fishable waterbodies).

Stream order was determined by tracing the convergence of tributaries with order 1 assigned to the furthest upstream segment indicated on the map (both ephemeral and perennial streams were assigned as order 1). Topography on the map was used to determine if the waterbody was downgradient of the plant. Many CCW WMUs in the sample were located on a large waterbody.

Once the waterbody was identified, the scale provided on the maps and photos was used to measure the horizontal distance between the CCW impoundment or landfill and the waterbody. All assignments and measurements were independently checked for accuracy.

The two distributions (landfills and surface impoundments) were statistically compared using (1) a Wilcoxon Rank Sum Test (to determine whether one distribution is shifted to the right or left of the other distribution) and (2) a Quantile Test (to test for differences, that is, differing numbers of observations) between the two distributions for the values above a given percentile. The results of the Wilcoxon test showed a p value of 0.64, indicating no significant difference in the shape of the distributions. The Quantile Test evaluated every decile from 0.1 to 0.9, with adjustments to the lower percentiles to be estimated for large numbers of ties in the ranks for the lower end of the data. The nonsignificant p values ranged from 0.33 (for 90th percentile) to 0.17 (for the 40th percentile). One significant p value indicating differences between the two distributions occurred at the 17th percentile (p value = 0.066), but the remainder of the tests showed no significant differences. Based on these results, the distributions were judged to be similar and combined to produce the single distribution of 59 values used to produce a single empirical distribution (previously shown in Table C-2) that was applied nationally to both landfills and surface impoundments at the CCW sites.

C.5 References

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Attachment C-1: Soil Data

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
A B Brown	43.9	SCL	6.0	1.2
A B Brown	51.1	SLT	6.5	1.6
A B Brown	5.0	SNL	6.9	1.4
A/C Power- Ace Operations	8.9	SCL	8.9	0.21
A/C Power- Ace Operations	32.0	SLT	8.4	0.46
A/C Power- Ace Operations	59.1	SNL	8.0	0.46
Allen	48.9	SCL	7.1	0.98
Allen	19.2	SLT	6.2	1.1
Allen	32.0	SNL	7.1	1.1
Alma	18.9	SCL	6.6	1.7
Alma	59.4	SLT	6.5	3.4
Alma	21.7	SNL	5.6	0.69
Antelope Valley	8.4	SCL	7.6	3.2
Antelope Valley	68.5	SLT	7.6	1.7
Antelope Valley	23.1	SNL	7.8	2.4
Arkwright	50.7	SCL	5.4	0.5
Arkwright	24.7	SLT	5.6	0.88
Arkwright	24.5	SNL	5.4	0.64
Asheville	6.3	SCL	5.4	0.43
Asheville	77.8	SLT	5.2	0.99
Asheville	15.8	SNL	5.4	1
Baldwin	39.5	SCL	6.2	1.3
Baldwin	58.6	SLT	6.0	1.6
Baldwin	1.9	SNL	6.5	1.4
Barry	35.8	SCL	4.8	3.6
Barry	23.5	SLT	4.8	7
Barry	40.7	SNL	4.8	4.4
Bay Front	11.7	SCL	7.3	4
Bay Front	21.1	SLT	7.1	3.8
Bay Front	67.2	SNL	7.1	1.4
Bay Shore	90.8	SCL	7.1	4.1
Bay Shore	4.3	SLT	7.2	2.6
Bay Shore	4.9	SNL	7.7	9.3
Belews Creek	69.2	SCL	5.2	0.34
Belews Creek	14.0	SLT	5.4	1

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Belews Creek	16.8	SNL	5.2	0.4
Ben French	25.3	SCL	8.0	0.87
Ben French	59.7	SLT	7.7	1.8
Ben French	15.0	SNL	7.1	1.7
Big Cajun 2	66.4	SCL	7.1	1.1
Big Cajun 2	28.4	SLT	6.3	1.2
Big Cajun 2	5.2	SNL	6.0	1.3
Big Sandy	54.8	SCL	5.4	1.6
Big Sandy	41.5	SLT	5.3	1.9
Big Sandy	3.7	SNL	5.1	2.6
Big Stone	7.3	SCL	7.5	5.7
Big Stone	45.0	SLT	7.7	3.1
Big Stone	47.7	SNL	7.5	1.1
Black Dog Steam Plant	8.2	SCL	6.9	4.2
Black Dog Steam Plant	41.4	SLT	6.8	2.5
Black Dog Steam Plant	50.4	SNL	6.9	1.8
Blue Valley	63.8	SCL	6.3	1.5
Blue Valley	31.6	SLT	6.6	2.8
Blue Valley	4.6	SNL	6.5	1.1
Bowen	18.1	SCL	5.0	1.2
Bowen	81.9	SLT	5.0	0.74
Brandon Shores	18.2	SCL	4.5	0.47
Brandon Shores	16.8	SLT	4.6	3.4
Brandon Shores	64.9	SNL	4.8	0.88
Buck	79.1	SCL	5.4	0.39
Buck	18.9	SLT	5.6	1
Buck	2.0	SNL	5.3	0.6
Bull Run	76.7	SCL	5.2	0.92
Bull Run	18.2	SLT	5.6	1.7
Bull Run	5.1	SNL	5.0	0.67
C D McIntosh Jr	6.5	SCL	8.1	2.3
C D McIntosh Jr	93.5	SNL	5.5	1.8
C P Crane	34.1	SCL	4.8	0.52
C P Crane	34.3	SLT	4.7	1
C P Crane	31.6	SNL	4.9	1.1
Cape Fear	67.6	SCL	5.1	0.97
Cape Fear	24.7	SLT	5.4	1.5
Cape Fear	7.7	SNL	5.2	0.66
Carbon	0.4	SCL	6.3	7.4

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Carbon	95.8	SLT	7.8	3.4
Carbon	3.8	SNL	8.2	1.4
Cardinal	69.1	SCL	5.8	1
Cardinal	30.4	SLT	5.7	1.7
Cardinal	0.5	SNL	6.4	2
Cayuga	32.3	SCL	6.6	1.9
Cayuga	48.7	SLT	7.1	1.4
Cayuga	19.0	SNL	6.8	1.1
Chalk Point	6.9	SCL	4.6	0.58
Chalk Point	16.4	SLT	4.8	8.8
Chalk Point	76.7	SNL	4.6	1.1
Cholla	27.3	SCL	8.4	1.9
Cholla	61.0	SLT	8.1	0.62
Cholla	11.6	SNL	8.3	0.75
Cliffside	66.4	SCL	5.2	0.31
Cliffside	13.6	SLT	5.5	0.77
Cliffside	20.0	SNL	5.2	0.27
Clover	71.0	SCL	5.3	0.71
Clover	23.3	SLT	5.3	1.3
Clover	5.7	SNL	5.1	0.65
Coal Creek	6.1	SCL	6.8	3
Coal Creek	82.7	SLT	7.6	1.7
Coal Creek	11.2	SNL	8.2	2.8
Coleto Creek	12.1	SCL	7.0	1.1
Coleto Creek	86.0	SLT	7.4	0.78
Coleto Creek	1.8	SNL	6.2	0.75
Colstrip	9.0	SCL	8.0	0.79
Colstrip	63.0	SLT	8.2	0.73
Colstrip	27.9	SNL	8.3	0.54
Conemaugh	11.8	SCL	5.0	2.7
Conemaugh	81.4	SLT	4.8	1.3
Conemaugh	6.8	SNL	4.5	1.8
Conesville	44.0	SCL	5.4	2.2
Conesville	45.5	SLT	5.6	1.9
Conesville	10.5	SNL	5.0	2.2
Council Bluffs	43.3	SCL	7.5	1.5
Council Bluffs	47.2	SLT	7.6	1.2
Council Bluffs	9.6	SNL	7.7	0.74
Crawford	48.4	SCL	6.8	1.9

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Crawford	23.6	SLT	6.7	1.4
Crawford	28.0	SNL	6.7	0.82
Crist	18.8	SCL	5.4	4.5
Crist	32.3	SLT	5.3	1.1
Crist	48.8	SNL	5.4	3.3
Cross	3.0	SCL	5.0	1.3
Cross	46.0	SLT	4.6	0.58
Cross	51.0	SNL	4.9	1.2
Cumberland	61.1	SCL	5.3	1.6
Cumberland	34.2	SLT	5.7	0.98
Cumberland	4.8	SNL	5.2	1.3
Dale	91.7	SCL	6.4	1.9
Dale	8.2	SLT	6.4	2
Dale	0.1	SNL	6.7	1.3
Dallman	66.2	SCL	6.4	1.8
Dallman	33.3	SLT	6.7	1.2
Dallman	0.5	SNL	7.0	1.1
Dan E Karn	0.01	SCL	7.0	3
Dan E Karn	53.6	SLT	7.9	4.2
Dan E Karn	46.3	SNL	7.8	5.4
Dan River	73.3	SCL	5.0	0.39
Dan River	12.0	SLT	5.3	1.4
Dan River	14.7	SNL	5.1	0.6
Danskammer	89.8	SLT	5.8	2.9
Danskammer	10.2	SNL	6.9	2.8
Dave Johnston	2.2	SCL	8.9	0.96
Dave Johnston	36.6	SLT	8.2	1.2
Dave Johnston	61.2	SNL	8.2	1.1
Dickerson	6.1	SCL	5.1	0.52
Dickerson	93.9	SLT	5.2	0.68
Dolet Hills	65.7	SCL	4.8	0.97
Dolet Hills	21.6	SLT	5.0	0.77
Dolet Hills	12.7	SNL	5.1	1.1
Duck Creek	65.5	SCL	6.4	0.82
Duck Creek	33.6	SLT	6.5	0.6
Duck Creek	0.9	SNL	7.0	0.98
Dunkirk	8.8	SCL	7.3	5.4
Dunkirk	79.6	SLT	6.9	4.6
Dunkirk	11.6	SNL	6.5	2.7

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
E D Edwards	49.5	SCL	6.4	1.1
E D Edwards	29.8	SLT	6.3	1.2
E D Edwards	20.6	SNL	6.8	1.1
E W Brown	92.9	SCL	6.4	3.7
E W Brown	7.1	SLT	6.6	3.8
Eckert Station	4.8	SCL	7.2	4.5
Eckert Station	82.0	SLT	6.9	1.2
Eckert Station	13.2	SNL	6.7	0.5
Edgewater	58.5	SCL	7.3	3.3
Edgewater	3.7	SLT	7.3	1.2
Edgewater	37.8	SNL	6.8	2.2
Elmer W Stout	29.9	SCL	6.7	1.9
Elmer W Stout	56.7	SLT	7.0	1.2
Elmer W Stout	13.3	SNL	6.8	0.8
F B Culley	45.3	SCL	5.9	0.93
F B Culley	48.9	SLT	6.5	2
F B Culley	5.8	SNL	6.9	1.1
Fayette Power Prj	51.9	SCL	7.7	3.8
Fayette Power Prj	35.7	SLT	7.6	1.2
Fayette Power Prj	12.5	SNL	7.1	1
Flint Creek	62.2	SCL	4.9	0.87
Flint Creek	37.8	SLT	5.3	0.69
Fort Martin	45.9	SCL	5.6	1.2
Fort Martin	54.1	SLT	5.2	1.9
Fort Martin	0.04	SNL	4.6	2.5
Frank E Ratts	30.9	SCL	5.8	1.5
Frank E Ratts	58.0	SLT	6.3	1.1
Frank E Ratts	11.1	SNL	7.0	0.73
G G Allen	85.9	SCL	5.3	0.36
G G Allen	11.9	SLT	5.6	1.1
G G Allen	2.2	SNL	5.2	0.28
Gadsden	45.2	SCL	4.8	0.68
Gadsden	46.4	SLT	5.3	1.3
Gadsden	8.5	SNL	5.1	0.97
Gallatin	56.1	SCL	5.6	0.94
Gallatin	43.9	SLT	5.4	0.94
Gen J M Gavin	35.9	SCL	6.0	1.4
Gen J M Gavin	46.1	SLT	5.6	2.1
Gen J M Gavin	18.0	SNL	5.1	1.3

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Genoa	14.3	SCL	6.1	2.3
Genoa	64.6	SLT	6.6	1.8
Genoa	21.0	SNL	6.1	0.97
Gibson	55.3	SCL	6.6	1.5
Gibson	43.2	SLT	6.4	1.1
Gibson	1.5	SNL	7.3	0.67
Gorgas	17.0	SCL	4.6	0.42
Gorgas	53.0	SLT	5.1	0.77
Gorgas	30.0	SNL	5.2	0.73
Green River	48.4	SCL	5.9	1
Green River	51.6	SLT	6.0	1.4
Greene County	19.5	SCL	5.1	1.8
Greene County	72.6	SLT	5.2	1.4
Greene County	7.9	SNL	4.9	1.6
H B Robinson	0.1	SCL	5.2	0.75
H B Robinson	32.6	SLT	4.8	1
H B Robinson	67.3	SNL	5.3	0.6
Hammond	54.7	SCL	5.1	0.74
Hammond	33.8	SLT	5.3	1.3
Hammond	11.5	SNL	5.0	0.75
Harllee Branch	54.7	SCL	5.3	0.49
Harllee Branch	15.3	SLT	5.6	0.97
Harllee Branch	30.0	SNL	5.3	0.47
Harrison	48.8	SCL	5.6	1
Harrison	51.2	SLT	5.0	2.1
Hatfield's Ferry	39.3	SCL	5.7	1.8
Hatfield's Ferry	60.4	SLT	5.3	1.6
Hatfield's Ferry	0.3	SNL	4.6	2.5
Hennepin	44.6	SCL	6.4	1.5
Hennepin	38.2	SLT	6.7	1.1
Hennepin	17.2	SNL	7.0	1.3
Heskett	39.9	SCL	8.0	2.1
Heskett	44.1	SLT	7.6	2.4
Heskett	16.0	SNL	7.7	1.9
Holcomb	4.4	SLT	7.9	0.67
Holcomb	95.6	SNL	7.3	0.75
Homer City	11.0	SCL	4.9	2.9
Homer City	84.5	SLT	4.8	1.6
Homer City	4.5	SNL	4.5	2.1

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Hoot Lake	3.1	SCL	7.5	5.4
Hoot Lake	38.9	SLT	7.7	2.6
Hoot Lake	58.1	SNL	7.5	1.3
Hugo	55.1	SCL	6.6	1.4
Hugo	35.8	SLT	6.7	1.6
Hugo	9.2	SNL	5.3	0.7
Hunter	90.8	SCL	8.3	0.73
Hunter	3.5	SLT	8.2	2
Hunter	5.7	SNL	8.5	0.75
Huntington	4.5	SCL	8.6	1.5
Huntington	79.5	SLT	8.0	2.4
Huntington	15.9	SNL	8.6	1.3
Intermountain	46.9	SCL	8.6	0.7
Intermountain	8.3	SLT	8.9	0.51
Intermountain	44.8	SNL	8.8	0.44
J H Campbell	5.0	SLT	7.1	1.8
J H Campbell	95.0	SNL	5.9	1.2
J M Stuart	73.5	SCL	6.5	1.6
J M Stuart	24.8	SLT	6.8	2.4
J M Stuart	1.7	SNL	5.5	2
J R Whiting	80.6	SCL	7.1	4.2
J R Whiting	17.1	SLT	7.1	2.1
J R Whiting	2.3	SNL	6.8	2.8
Jack McDonough	58.9	SCL	5.2	0.46
Jack McDonough	7.8	SLT	5.6	1.1
Jack McDonough	33.3	SNL	5.3	0.37
Jack Watson	20.5	SCL	6.7	11
Jack Watson	46.8	SLT	4.8	3
Jack Watson	32.8	SNL	4.9	3.8
James H Miller Jr	17.0	SCL	4.6	0.42
James H Miller Jr	53.0	SLT	5.1	0.77
James H Miller Jr	30.0	SNL	5.2	0.73
Jim Bridger	1.4	SCL	8.7	0.75
Jim Bridger	37.9	SLT	8.6	0.52
Jim Bridger	60.6	SNL	8.2	0.64
John E Amos	35.8	SCL	6.3	1.6
John E Amos	64.2	SLT	5.1	2.2
John Sevier	43.2	SCL	6.2	1.6
John Sevier	56.7	SLT	5.8	1.2

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
John Sevier	0.2	SNL	5.0	0.67
Johnsonville	39.2	SCL	5.1	1.7
Johnsonville	57.3	SLT	5.2	1.3
Johnsonville	3.5	SNL	4.7	1.5
Joliet 29	52.8	SCL	7.1	2.7
Joliet 29	43.5	SLT	7.0	2.1
Joliet 29	3.7	SNL	7.1	1.8
Keystone	7.7	SCL	4.9	2.8
Keystone	90.1	SLT	4.9	1.4
Keystone	2.2	SNL	4.5	2.2
Killen Station	74.3	SCL	6.0	1.9
Killen Station	24.0	SLT	6.3	2.2
Killen Station	1.8	SNL	6.2	1.7
Kingston	66.7	SCL	5.0	1.2
Kingston	21.0	SLT	5.5	1.7
Kingston	12.3	SNL	5.0	0.67
Kraft	57.1	SCL	7.2	11
Kraft	22.8	SLT	5.0	1.3
Kraft	20.1	SNL	5.0	1.4
L V Sutton	18.0	SCL	6.1	3.9
L V Sutton	32.4	SLT	5.0	3.7
L V Sutton	49.6	SNL	5.0	1.6
Lansing	9.0	SCL	5.8	2.6
Lansing	67.7	SLT	6.8	2.1
Lansing	23.3	SNL	6.2	1.4
Laramie R Station	41.1	SLT	8.1	0.87
Laramie R Station	58.9	SNL	7.9	1.2
Lawrence EC	51.5	SCL	6.6	1.9
Lawrence EC	47.7	SLT	6.8	2.9
Lawrence EC	0.8	SNL	7.5	0.75
Lee	16.4	SCL	5.0	1.3
Lee	51.1	SLT	5.0	1.3
Lee	32.5	SNL	5.1	0.96
Leland Olds	13.5	SCL	7.8	2.6
Leland Olds	52.9	SLT	7.6	1.9
Leland Olds	33.6	SNL	7.5	2
Lon Wright	25.7	SCL	7.5	1.5
Lon Wright	8.4	SLT	7.0	2.1
Lon Wright	65.9	SNL	7.8	1.4

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Louisa	35.5	SCL	6.7	1.8
Louisa	16.6	SLT	6.3	1.5
Louisa	47.9	SNL	6.6	0.96
Marion	10.9	SCL	5.6	0.96
Marion	88.8	SLT	5.2	0.95
Marion	0.3	SNL	6.6	1
Marshall	72.1	SCL	5.2	0.33
Marshall	12.9	SLT	5.5	0.87
Marshall	15.0	SNL	5.2	0.27
Martin Lake	34.3	SCL	4.9	1
Martin Lake	25.1	SLT	5.1	0.8
Martin Lake	40.6	SNL	5.1	0.73
Mayo	71.9	SCL	5.6	0.61
Mayo	27.9	SLT	5.6	1
Mayo	0.2	SNL	5.2	0.76
Meramec	87.9	SCL	6.4	1.3
Meramec	12.1	SLT	6.5	1.3
Merom	30.2	SCL	5.5	0.84
Merom	59.2	SLT	5.8	0.96
Merom	10.6	SNL	6.4	0.77
Miami Fort	69.6	SCL	6.5	1.7
Miami Fort	27.3	SLT	6.8	2
Miami Fort	3.1	SNL	6.7	1.2
Milton R Young	4.6	SCL	7.6	3.1
Milton R Young	92.9	SLT	7.7	1.5
Milton R Young	2.5	SNL	7.5	1.8
Mitchell - PA	19.1	SCL	5.9	2.1
Mitchell - PA	80.9	SLT	5.5	1.4
Mitchell - WV	39.9	SCL	6.0	1.7
Mitchell - WV	59.9	SLT	5.2	2
Mitchell - WV	0.2	SNL	6.0	1.3
Mohave	29.0	SLT	8.1	0.26
Mohave	71.0	SNL	8.1	0.31
Monroe	38.5	SCL	7.0	3
Monroe	49.5	SLT	7.2	3.1
Monroe	12.0	SNL	6.8	3.5
Morgantown	21.7	SCL	4.6	1.2
Morgantown	39.3	SLT	4.7	3.2
Morgantown	39.0	SNL	4.9	1.3

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Mountaineer (1301)	56.1	SCL	6.0	1.6
Mountaineer (1301)	34.2	SLT	5.9	2.2
Mountaineer (1301)	9.8	SNL	4.9	2.5
Mt Storm	4.1	SCL	5.0	2.9
Mt Storm	65.3	SLT	4.7	1.4
Mt Storm	30.6	SNL	4.4	1
Muscatine Plant #1	46.8	SCL	6.6	1.8
Muscatine Plant #1	27.4	SLT	6.4	1.4
Muscatine Plant #1	25.8	SNL	6.6	0.84
Muskogee	30.9	SCL	6.5	1.7
Muskogee	53.1	SLT	6.8	1.1
Muskogee	16.0	SNL	6.7	1
Neal North	36.7	SCL	7.9	1.1
Neal North	46.5	SLT	7.9	0.67
Neal North	16.9	SNL	7.7	0.73
Neal South	34.0	SCL	7.8	1.1
Neal South	50.7	SLT	7.8	0.69
Neal South	15.3	SNL	7.7	0.73
Nebraska City	55.5	SCL	7.4	1.4
Nebraska City	35.5	SLT	7.3	1.7
Nebraska City	9.0	SNL	7.7	0.74
New Castle	5.1	SCL	7.7	0.73
New Castle	81.6	SLT	5.9	2.8
New Castle	13.2	SNL	6.1	1.5
Newton	37.9	SCL	5.5	0.54
Newton	61.3	SLT	5.5	0.53
Newton	0.7	SNL	6.5	0.85
North Omaha	29.0	SCL	7.4	1.5
North Omaha	60.1	SLT	7.7	0.82
North Omaha	11.0	SNL	7.7	0.74
Northeastern	76.9	SCL	6.7	2.1
Northeastern	21.3	SLT	6.3	2.2
Northeastern	1.8	SNL	5.6	2
Nucla	61.2	SLT	7.9	0.98
Nucla	38.8	SNL	8.1	0.55
Oklaunion	92.2	SCL	8.0	1.7
Oklaunion	7.0	SLT	7.9	0.94
Oklaunion	0.7	SNL	7.3	1.5
Paradise	14.8	SCL	5.6	1.4

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Paradise	85.2	SLT	5.9	1.2
Petersburg	29.7	SCL	5.9	1.5
Petersburg	62.9	SLT	6.3	1.2
Petersburg	7.5	SNL	7.2	0.59
Pleasant Prairie	97.2	SCL	7.1	1.7
Pleasant Prairie	2.8	SNL	7.3	1.5
Port Washington	86.3	SCL	7.3	3.3
Port Washington	7.7	SLT	7.5	0.68
Port Washington	6.1	SNL	7.3	3
Portland	8.7	SCL	5.8	0.58
Portland	90.8	SLT	5.5	1.1
Portland	0.5	SNL	6.0	1.8
Possum Point	6.3	SCL	4.6	0.58
Possum Point	43.0	SLT	4.9	3
Possum Point	50.7	SNL	4.9	0.8
Potomac River	13.3	SCL	4.5	0.56
Potomac River	35.5	SLT	4.9	2.8
Potomac River	51.2	SNL	5.0	1.1
Presque Isle	18.7	SLT	5.2	2.5
Presque Isle	81.3	SNL	5.3	3.1
R Gallagher	40.4	SCL	5.6	1.5
R Gallagher	59.0	SLT	5.9	2.1
R Gallagher	0.5	SNL	6.9	1.4
R M Schahfer	2.1	SCL	7.1	3.8
R M Schahfer	6.5	SLT	6.9	2.9
R M Schahfer	91.4	SNL	6.6	1.5
Reid Gardner	13.3	SCL	8.4	0.29
Reid Gardner	21.6	SLT	8.3	0.58
Reid Gardner	65.1	SNL	8.4	0.34
Richard Gorsuch	69.9	SCL	6.1	1.7
Richard Gorsuch	27.0	SLT	5.9	2.4
Richard Gorsuch	3.0	SNL	5.1	2.6
Riverbend	77.4	SCL	5.3	0.37
Riverbend	20.1	SLT	5.7	1.1
Riverbend	2.5	SNL	5.2	0.45
Rodemacher	42.9	SCL	6.5	0.96
Rodemacher	51.4	SLT	6.5	0.92
Rodemacher	5.7	SNL	5.3	0.85
Roxboro	40.3	SCL	5.5	0.47

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Roxboro	55.7	SLT	6.0	0.79
Roxboro	4.0	SNL	5.5	1.4
Sandow	0.8	SCL	6.9	0.5
Sandow	37.4	SLT	6.3	0.66
Sandow	61.8	SNL	6.3	0.64
Scherer	58.5	SCL	5.3	0.39
Scherer	12.8	SLT	5.5	0.97
Scherer	28.7	SNL	5.3	0.42
Shawnee	9.5	SCL	5.8	1
Shawnee	84.2	SLT	5.6	1.4
Shawnee	6.3	SNL	6.5	1.1
Shawville	5.2	SCL	5.0	3
Shawville	82.6	SLT	4.9	1.1
Shawville	12.2	SNL	4.4	1.2
Sheldon	62.7	SCL	6.8	2.3
Sheldon	33.2	SLT	7.0	1.6
Sheldon	4.1	SNL	6.9	2
South Oak Creek	95.5	SCL	7.1	1.9
South Oak Creek	4.5	SNL	7.3	1.6
Springerville	10.0	SLT	8.1	0.79
Springerville	90.0	SNL	7.9	0.79
St Johns River Power	27.1	SCL	6.9	49
St Johns River Power	0.4	SLT	5.0	1.3
St Johns River Power	72.5	SNL	5.2	1.1
Stanton Energy Ctr	0.8	SCL	7.0	10
Stanton Energy Ctr	2.4	SLT	7.7	1
Stanton Energy Ctr	96.8	SNL	5.3	4.8
Stockton Cogen Company	89.9	SCL	7.6	1.8
Stockton Cogen Company	6.6	SLT	7.5	1.5
Stockton Cogen Company	3.5	SNL	6.8	0.51
Syl Laskin	8.5	SCL	6.5	3.2
Syl Laskin	4.6	SLT	6.3	6.3
Syl Laskin	86.9	SNL	5.8	3.1
Tecumseh EC	55.2	SCL	6.6	2
Tecumseh EC	41.9	SLT	6.9	2.6
Tecumseh EC	2.9	SNL	7.6	0.62
Texas-New Mexico	4.4	SCL	7.0	0.61
Texas-New Mexico	43.5	SLT	6.3	0.67
Texas-New Mexico	52.1	SNL	6.0	0.77

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Titus	31.8	SCL	6.0	0.76
Titus	63.6	SLT	5.6	1.4
Titus	4.6	SNL	5.0	0.98
Trimble County	57.3	SCL	6.3	2
Trimble County	41.9	SLT	6.5	1.9
Trimble County	0.8	SNL	5.9	1.7
Tyrone	92.1	SCL	6.3	3.7
Tyrone	7.9	SLT	6.6	3.9
Valley	98.5	SCL	6.9	1.2
Valley	0.2	SLT	7.5	0.45
Valley	1.3	SNL	7.4	1.3
Vermilion	82.5	SCL	6.9	1.3
Vermilion	16.6	SLT	7.0	1.2
Vermilion	0.8	SNL	7.2	1.1
Victor J Daniel Jr	46.2	SCL	4.6	2.2
Victor J Daniel Jr	27.7	SLT	4.7	2.3
Victor J Daniel Jr	26.1	SNL	4.7	16
W A Parish	95.8	SCL	7.4	1.4
W A Parish	4.2	SLT	7.9	0.74
W H Weatherspoon	7.4	SCL	5.5	1.9
W H Weatherspoon	50.4	SLT	4.7	2.2
W H Weatherspoon	42.2	SNL	4.8	1.3
W S Lee	68.0	SCL	5.3	0.48
W S Lee	9.0	SLT	5.7	1
W S Lee	23.0	SNL	5.3	0.41
Wabash River	22.0	SCL	6.4	1.6
Wabash River	48.5	SLT	6.9	1.2
Wabash River	29.5	SNL	6.7	1.2
Walter C Beckjord	71.6	SCL	6.3	1.4
Walter C Beckjord	26.5	SLT	6.7	2
Walter C Beckjord	1.9	SNL	6.6	1.1
Wansley	46.3	SCL	5.2	0.52
Wansley	18.1	SLT	5.6	1.2
Wansley	35.5	SNL	5.4	0.5
Warrick	45.8	SCL	6.0	0.95
Warrick	48.6	SLT	6.5	1.9
Warrick	5.6	SNL	7.0	1.1
Waukegan	43.9	SCL	6.6	1
Waukegan	18.1	SLT	6.6	1.4

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Waukegan	38.0	SNL	6.7	0.8
Weston	33.5	SLT	5.6	1.7
Weston	66.5	SNL	6.0	1.4
Widows Creek	64.5	SCL	5.3	0.88
Widows Creek	20.0	SLT	5.2	1.4
Widows Creek	15.5	SNL	5.4	1.2
Will County	40.0	SCL	6.8	1.8
Will County	52.7	SLT	7.0	0.96
Will County	7.2	SNL	7.1	0.98
Wyodak	1.3	SCL	8.1	0.38
Wyodak	40.2	SLT	7.9	1.1
Wyodak	58.5	SNL	7.9	0.93
Yates	47.8	SCL	5.2	0.48
Yates	17.7	SLT	5.6	1.2
Yates	34.5	SNL	5.3	0.48

Attachment C-2: Hydrogeologic Environment

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Big Cajun 2	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting (100% alluvium); soils have significant fines (SCL+SLT = 95%)
A B Brown	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting; soils have significant fines (SCL+SLT = 95%)
A/C Power-Ace Operations	2C	Alluvial Fans	5	Alluvial Basins Valleys and Fans	100	Based on surficial geology; consistent with alluvial fan setting
Allen	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on aquifer coverages, surficial geology; Heath (1985) and soils indicate overbank deposits
Alma	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Percentage based on SNL/SCL soils; setting based on productive aquifers and surficial geology
Alma	7Eb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	50	Percentage based on SNL/SCL soils; setting based on productive aquifers and surficial geology
Antelope Valley	7G	Thin Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on principal aquifer and surficial geology coverages
Arkwright	8D	Regolith	1	Metamorphic and Igneous	100	Most common Piedmont setting (residuum)
Asheville	8B	Alluvial Mountain Valleys	5	Alluvial Basins Valleys and Fans	100	Appropriate for alluvial blue ridge valley (colluvium)
Baldwin	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage based on surficial geology (74% Floodplain and alluvium gravel terraces)
Baldwin	7G	Thin Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	30	Percentage based on surficial geology (74% Floodplain and alluvium gravel terraces)

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Barry	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting, significant fine grained soils = overbank deposits
Bay Front	7Bb	Outwash Over Bedded Sedimentary Rock	2	Bedded Sedimentary Rock	70	Percentage based on productive aquifers
Bay Front	7D	Buried Valley	4	Sand and Gravel	30	Percentage based on productive aquifers
Bay Shore	7Ac	Glacial Till Over Solution Limestone	12	Solution Limestone	100	Closest setting considering carbonate aquifers, high SCL soils, and lake deposits surficial geology
Belews Creek	6H	Triassic Basins	2	Bedded Sedimentary Rock	50	Sources somewhat dissimilar; fraction based on surficial geology; Triassic basin
Belews Creek	8D	Regolith	1	Metamorphic and Igneous	50	Sources somewhat dissimilar; fraction based on surficial geology
Ben French	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	60	Percentage, thin soils based on surficial geology
Ben French	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage based on surficial geology; significant fine soils (25% SCL)
Big Sandy	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	50	Percentage based on surficial geology; thin soils inferred from colluvium
Big Sandy	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Percentage based on surficial geology; soils have significant fines (SCL+SLT = 95%)
Big Stone	7Ba	Outwash	8	Outwash	100	Based on surficial geology
Black Dog Steam Plant	7Bb	Outwash Over Bedded Sedimentary Rock	2	Bedded Sedimentary Rock	100	Based on surficial geology, aquifer coverages
Blue Valley	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	80	Percentage based on Heath (1985), productive aquifers

(continued)

Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Blue Valley	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	20	Percentage based on Heath (1985), productive aquifers
Bowen	6Db	Alternating Sandstone, Limestone and Shale - Deep Regolith	2	Bedded Sedimentary Rock	100	Based on aquifers, surficial residuum (massive red clay); metamorphic surficial geology not consistent with Valley and Ridge
Brandon Shores	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Assigned based on location and aquifer and surficial geology coverages; Heath region incorrect (it's Atlantic Coastal Plain, not Piedmont)
Buck	8E	River Alluvium	6	River Valleys and Floodplains with Overbank Deposit	100	Based on productive aquifer & Heath region coverages
Bull Run	6Db	Alternating Sandstone, Limestone and Shale - Deep Regolith	2	Bedded Sedimentary Rock	60	Percentage based on surficial geology
Bull Run	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage based on surficial geology; high SCL (77%) = overbank deposits
C D McIntosh Jr	11A	Solution Limestone and Shallow Surficial Aquifers	12	Solution Limestone	100	Based on both aquifer coverages
C P Crane	10Aa	Regional Aquifers	4	Sand and Gravel	50	Appears to be on border between Piedmont and Coastal Plain
C P Crane	8D	Regolith	1	Metamorphic and Igneous	50	Appears to be on border between Piedmont and Coastal Plain
Cape Fear	6H	Triassic Basins	2	Bedded Sedimentary Rock	20	Percentage based on productive aquifer & Heath region coverages; Triassic basin
Cape Fear	8E	River Alluvium	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on productive aquifer & Heath region coverages
Carbon	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	100	Setting based on aquifer and surficial geology coverages

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Cardinal	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	30	Percentage based on surficial geology; soils with low (<1%) SNL
Cardinal	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage based on surficial geology; soils with low (<1%) SNL
Cayuga	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer overlaid by alluvial deposits
Chalk Point	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Predominant setting
Cholla	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	20	Percentage based on surficial geology (83% Floodplain and alluvium gravel terraces)
Cholla	4C	River Alluvium	7	River Valleys and Floodplains without Overbank Deposits	80	Percentage based on surficial geology (83% Floodplain and alluvium gravel terraces)
Cliffside	8D	Regolith	1	Metamorphic and Igneous	100	Based on surficial geology
Clover	6H	Triassic Basins	2	Bedded Sedimentary Rock	20	Percentage based on surficial geology; Triassic Basin from Heath (1985) and principal aquifer coverage
Clover	8E	River Alluvium	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology
Coal Creek	7G	Thin Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on principal aquifer and surficial geology coverages
Coleto Creek	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Setting based on aquifer and surficial geology coverages
Colstrip	6da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Based on all coverages

(continued)

Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Conemaugh	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Setting based on aquifer coverages & Heath (1985); thin regolith inferred from colluvium
Conesville	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	40	Percentage based on surficial geology; soils with low (10%) SNL
Conesville	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage based on surficial geology; soils with low (10%) SNL
Council Bluffs	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on productive aquifers
Crawford	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Assigned based on predominant surficial geology (98% Floodplain and alluvium gravel terraces), productive aquifer coverage
Crist	10Bb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	100	Assigned based on predominant surficial geology (96% Floodplain and alluvium gravel terraces), coarse-grained soil (49% SNL)
Cross	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Setting based on aquifers, surficial geology, soils, Heath (1985)
Cumberland	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on surface geology; high (61%) SCL = overbank deposits
Dale	6E	Solution Limestone	12	Solution Limestone	20	Percentage based on surficial geology; setting from principal aquifers (carbonate)
Dale	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology; soils have significant fines (SNL = 0.1%)
Dallman	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on soils, surficial geology, principal aquifer
Dan E Karn	7F	Glacial Lake Deposits	4	Sand and Gravel	100	Based on surficial geology, soils

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Dan River	6H	Triassic Basins	2	Bedded Sedimentary Rock	100	Based on surfucial geology, principal aquifers; Triassic basin
Danskammer	7D	Buried Valley	4	Sand and Gravel	100	Based on predominant Heath region, productive aquifers; little coarse-grained soils
Dave Johnston	4C	River Alluvium	7	River Valleys and Floodplains without Overbank Deposits	100	Based on aquifer and surficial geology coverages, Heath (1985)
Dickerson	8D	Regolith	1	Metamorphic and Igneous	100	Predominant setting
Dolet Hills	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Predominant shallow unconsolidated aquifer system
Duck Creek	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Assigned based on predominant surficial geology (100% Floodplain and alluvium gravel terraces), Heath Alluvial Valley Region
Dunkirk	7H	Beaches, Beach Ridges and Sand Dunes	11	Coastal Beaches	100	Based on location, surficial geology
E D Edwards	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	20	Percentage based on surficial geology (83% Floodplain and alluvium gravel terraces)
E D Edwards	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology (83% Floodplain and alluvium gravel terraces)
E W Brown	6E	Solution Limestone	12	Solution Limestone	20	Percentage based on surficial geology (76% alluvium, 23% clay); soils have significant fine-grained (0% SNL)
E W Brown	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology (76% alluvium, 23% clay); soils have significant fine-grained (0% SNL)
Eckert Station	7Bb	Outwash Over Bedded Sedimentary Rock	2	Bedded Sedimentary Rock	30	Percentage based on productive aquifer coverage, Heath regions

(continued)

Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Eckert Station	7Eb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	70	Percentage based on productive aquifer coverage, Heath regions
Edgewater	7Bc	Outwash Over Solution Limestone	12	Solution Limestone	100	Setting based on aquifer and surficial geology coverages
Elmer W Stout	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer overlaid by alluvial deposits
F B Culley	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting; soils have significant fines (SCL+SLT = 94%)
Fayette Power Prj	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Setting based on aquifer and surficial geology coverages
Flint Creek	6Db	Alternating Sandstone, Limestone and Shale - Deep Regolith	2	Bedded Sedimentary Rock	100	Ozark plateau; Heath (1985) indicates dolomite, sandy dolomite, sandstone, with no indication of solutioning. Surficial geology (cherty red clay) noted as thick regolith in Aller et al. (1987)
Fort Martin	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on surficial geology; low SNL (< 1%) = overbank deposits
Frank E Ratts	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer in alluvial valley region (99%)
G G Allen	8D	Regolith	1	Metamorphic and Igneous	100	Based on surficial geology
Gadsden	6Db	Alternating Sandstone, Limestone and Shale - Deep Regolith	2	Bedded Sedimentary Rock	30	Percentage assigned based on productive aquifer coverage
Gadsden	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage assigned based on productive aquifer coverage; soils have significant fines (SCL+SLT > 25%)
Gallatin	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on surface geology; high (56%) SCL = overbank deposits

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Gen J M Gavin	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on productive aquifers, surficial geology
Genoa	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Percentage based on SNL/SCL soils; setting based on surficial geology and productive aquifers
Genoa	6Fb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	50	Percentage based on SNL/SCL soils; setting based on surficial geology and productive aquifers
Gibson	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting; soils have significant fines (SCL+SLT = 99%)
Gorgas	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	30	Percentage based on surficial geology; alluvial setting with coarser soils (= no overbank deposits)
Gorgas	6Fb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	70	Percentage based on surficial geology; alluvial setting with coarser soils (= no overbank deposits)
Green River	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting (>85% alluvium); soils have significant fines (SNL = 0%)
Greene County	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	30	Percentage based on surficial geology; soils have significant fines (SCL+SLT > 90%)
Greene County	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage based on surficial geology; soils have significant fines (SCL+SLT > 90%)
H B Robinson	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Setting based on aquifers, surficial geology, soils, Heath (1985); Heath region coverage incorrect (Coastal Plain, not Piedmont)

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Hammond	6Db	Alternating Sandstone, Limestone and Shale - Deep Regolith	2	Bedded Sedimentary Rock	100	Based on aquifers, surficial residuum (massive red clay)
Harllee Branch	8E	River Alluvium	6	River Valleys and Floodplains with Overbank Deposit	100	Assigned based on predominant surficial geology (99% floodplain and alluvium gravel terraces)
Harrison	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	20	Percentage based on surficial geology; thin soils inferred from surficial geology
Harrison	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology; 0%SNL = overbank deposits
Hatfield's Ferry	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	40	Percentage based on surficial geology; thin regolith inferred from colluvium
Hatfield's Ferry	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage based on surficial geology; soils < 1% SNL
Hennepin	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	30	Percentage to capture uncertainty in soils, surficial geology, principal aquifer
Hennepin	7Bb	Outwash Over Bedded Sedimentary Rock	2	Bedded Sedimentary Rock	30	Percentage to capture uncertainty in soils, surficial geology, principal aquifer
Hennepin	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage to capture uncertainty in soils, surficial geology, principal aquifer
Heskett	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvium surficial geology(96%); mixed soils
Holcomb	5Gb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	100	Alluvial valley with very coarse soils
Homer City	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Setting based on aquifer coverages & Heath (1985); thin regolith inferred from colluvium

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Hoot Lake	9E	Outwash	8	Outwash	100	Based on productive aquifer, soils, surficial geology
Hugo	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	40	Percentage based on surficial geology; soil/regolith thickness inferred from Heath (1985)
Hugo	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage based on surficial geology; fine soils with about 10% SNL
Hunter	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	100	Setting based on aquifer and surficial geology coverages
Huntington	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	100	Setting based on aquifer and surficial geology coverages
Intermountain	2E	Playa Lakes	5	Alluvial Basins Valleys and Fans	100	Setting based on surficial geology coverage, Heath (1985)
J H Campbell	7F	Glacial Lake Deposits	4	Sand and Gravel	100	Based on surficial geology, soils
J M Stuart	6E	Solution Limestone	12	Solution Limestone	50	Percentage based on surficial geology; low (< 2%) SNL
J M Stuart	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Percentage based on surficial geology; low (< 2%) SNL
J R Whiting	7F	Glacial Lake Deposits	4	Sand and Gravel	100	Based on surficial geology
Jack McDonough	8C	Mountain Flanks	2	Bedded Sedimentary Rock	100	Assigned based on predominant surficial geology (94% stony colluvium on metamorphic rocks; less silt and clay than in colluvium over limestone)
Jack Watson	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Based on all coverages
James H Miller Jr	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	20	Percentage based on surficial geology; soils have significant fines (SCL+SLT > 25%)

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
James H Miller Jr	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology; soils have significant fines (SCL+SLT > 25%)
Jim Bridger	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	100	Based on aquifer and surficial geology coverages, Heath (1985)
John E Amos	6da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	40	Percentage based on surficial geology; thin soils inferred from surficial geology
John E Amos	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage based on surficial geology; 0%SNL = overbank deposits
John Sevier	6E	Solution Limestone	12	Solution Limestone	50	Percentage based on surface geology; setting based on surface geology and aquifer type, with possibility of solution limestone from Heath (1985)
John Sevier	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Percentage, setting based on surface geology; low (<1%) SNL = overbank deposits
Johnsonville	6E	Solution Limestone	12	Solution Limestone	30	Percentage based on surface geology; setting based on aquifer coverages, Heath (1985); placed in Nonglaciated Central region based on aquifer coverages and Heath (1985)
Johnsonville	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage, setting based on surface geology; low (3%) SNL = overbank deposits; placed in Nonglaciated Central region based on aquifer coverages and Heath (1985)
Joliet 29	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on aquifers, soils; soils don't suggest outwash like surficial geology does
Keystone	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Setting based on aquifer coverages & Heath (1985); thin regolith inferred from colluvium
Killen Station	6E	Solution Limestone	12	Solution Limestone	30	Percentage based on surficial geology; low (< 2%) SNL

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Killen Station	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage based on surficial geology; low (< 2%) SNL
Kingston	6E	Solution Limestone	12	Solution Limestone	20	Percentage based on surface geology; setting based on surface geology and aquifer type, with possibility of solution limestone from Heath (1985)
Kingston	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage, setting based on surface geology; high (67 %) SCL = overbank deposits
Kraft	11A	Solution Limestone and Shallow Surficial Aquifers	12	Solution Limestone	100	Only possible assignment; predominant alluvium (84%) not well represented
L V Sutton	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	20	Percentage based on surficial geology; sandy soils
L V Sutton	10Bb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	80	Percentage based on surficial geology; sandy soils
Lansing	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	40	Percentage based on surficial geology, productive aquifers; loess = thin soils
Lansing	6Fb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	60	Percentage based on surficial geology, productive aquifers; coarse-grained soils
Laramie R Station	6Fb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	100	Based on aquifer and surficial geology coverages, Heath (1985)
Lawrence EC	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Alluvial valley with low coarse soils (<1% SNL)
Lee	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	30	Percentage based on surficial geology; sandy soils
Lee	10Bb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	70	Percentage based on surficial geology; sandy soils

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Leland Olds	7Eb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	50	Percentage based on surficial geology; assumed coarse soils
Leland Olds	7G	Thin Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	50	Percentage based on surficial geology; assumed coarse soils
Lon Wright	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	30	Alluvial based on predominant Heath, productive aquifer; percentage based on soil textures
Lon Wright	7Eb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	70	Alluvial based on predominant Heath, productive aquifer; percentage based on soil textures
Louisa	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Alluvial Valley; significant coarse-grained deposits
Louisa	7Eb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	50	Alluvial Valley; significant coarse-grained deposits
Marion	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Assigned to Glaciated Central region based on surficial geology (pre-Wisconsin drift)
Marshall	8D	Regolith	1	Metamorphic and Igneous	100	Based on surficial geology
Martin Lake	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Setting based on aquifer and surficial geology coverages
Mayo	8D	Regolith	1	Metamorphic and Igneous	100	Based on surficial geology
Meramec	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Based on surficial, predominant Heath
Merom	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer overlaid by alluvial deposits
Miami Fort	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Assigned based on productive aquifers, surficial geology and soil (3% SNL)

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Milton R Young	7G	Thin Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on principal aquifer and surficial geology coverages
Mitchell	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	60	Percentage based on surficial geology; thin regolith inferred from colluvium
Mitchell	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage based on surficial geology; soils 0 % SNL
Mitchell	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on surficial geology; low SNL (< 1%) = overbank deposits
Mohave	2Ha	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on predominant surficial geology, Heath (1985)
Monroe	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Based on Heath region, productive aquifers, soils
Morgantown	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Assigned based on location and aquifer and surficial geology coverages; Heath region incorrect (it's Atlantic Coastal Plain, not Piedmont)
Mountaineer (1301)	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on surficial geology; low SNL (10%) = overbank deposits
Mt Storm	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Setting based on surficial geology, aquifer coverages; thin soils inferred from surficial geology
Muscatine Plant #1	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Alluvial Valley; significant coarse-grained deposits
Muscatine Plant #1	7Eb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	50	Alluvial Valley; significant coarse-grained deposits
Muskogee	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Surficial geology indicates alluvium/colluvium; Heath (1985) indicates fine soils over sands and gravels

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Neal North	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Alluvial Valley setting
Neal South	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Alluvial Valley setting
Nebraska City	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Alluvial based on predominant Heath, productive aquifer, soil textures
New Castle	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	20	Percentage and setting based on Heath region & surficial geology; thin regolith inferred from colluvium
New Castle	7D	Buried Valley	4	Sand and Gravel	80	Percentage and setting based on Heath region & book
Newton	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on soils, surficial geology, aquifer coverages
North Omaha	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Alluvial based on predominant Heath, productive aquifer; soil texture (28% SCL, 10% SNL) = overbank deposits
Northeastern	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	40	Percentage based on surficial geology, which indicates thin residual soils
Northeastern	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage based on surficial geology; soils < 2% SNL
Nucla	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	100	Based on surficial geology, aquifer coverages
Oklaunion	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Setting based on surficial geology; thin soil inferred
Paradise	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting (93% alluvium); soils have significant fines (SNL = 0%)
Petersburg	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer in alluvial valley region (similar to 1043)

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Pleasant Prairie	7Ac	Glacial Till Over Solution Limestone	12	Solution Limestone	100	Setting based on aquifer and soil coverages (high SCL soils)
Port Washington	7Ac	Glacial Till Over Solution Limestone	12	Solution Limestone	100	Setting based on aquifer and soil coverages (high SCL soils)
Portland	7Ac	Glacial Till Over Solution Limestone	12	Solution Limestone	100	Setting based on aquifer and surficial geology coverage
Possum Point	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Based on productive aquifer coverage; Heath region incorrect
Potomac River	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	50	Percentage based on surficial geology coverage; Heath region incorrect
Potomac River	10Bb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	50	Percentage based on surficial geology coverage; sandy soils (51% SNL) = no overbank deposits; Heath region incorrect
Presque Isle	9F	Moraine	4	Sand and Gravel	100	Based on surficial geology, Heath region, soils
R Gallagher	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting; soils have significant fines (SCL+SLT = 99%)
R M Schahfer	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer in alluvial valley region
Reid Gardner	2C	Alluvial Fans	5	Alluvial Basins Valleys and Fans	100	Based on surficial geology; consistent with productive aquifers
Richard Gorsuch	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Assigned based on productive aquifers, surficial geology and soil (3% SNL)
Riverbend	8D	Regolith	1	Metamorphic and Igneous	100	Based on surficial geology
Rodemacher	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	50	Setting percentage determined from Heath, productive aquifer, and surficial geology coverages

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Rodemacher	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Setting percentage determined from Heath, productive aquifer, and surficial geology coverages
Roxboro	8D	Regolith	1	Metamorphic and Igneous	100	Based on surficial geology, productive aquifers
Sandow	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Setting based on aquifer and surficial geology coverages; Heath region coverage is incorrect (based on Heath [1985] and aquifer coverages)
Scherer	8D	Regolith	1	Metamorphic and Igneous	100	Most common Piedmont setting (residuum)
Shawnee	10Bb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	100	Predominant alluvial setting (100% alluvium); soils have low fines (SCL = 9%)
Shawville	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Setting based on aquifer coverages & Heath (1985); thin regolith inferred from colluvium
Sheldon	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	30	Percentage based on productive aquifer coverage; buried valley indicated by Heath (1985)
Sheldon	7D	Buried Valley	4	Sand and Gravel	70	Percentage based on productive aquifer coverage; buried valley indicated by Heath (1985)
South Oak Creek	7Ac	Glacial Till Over Solution Limestone	12	Solution Limestone	100	Setting based on aquifer and soil coverages (high SCL soils)
Springerville	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	100	Assigned based on productive aquifers (consolidated sandstone)
St Johns River Power	11B	Coastal Deposits	4	Sand and Gravel	100	Based on sea island surficial geology
Stanton Energy Ctr	11A	Solution Limestone and Shallow Surficial Aquifers	12	Solution Limestone	100	Based on both aquifer coverages

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Stockton Cogen Company	2C	Alluvial Fans	5	Alluvial Basins Valleys and Fans	50	Percentage based on surficial geology; Central Valley soils show significant fines
Stockton Cogen Company	2Ha	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Percentage based on surficial geology; Central Valley soils show significant fines
Syl Laskin	9E	Outwash	8	Outwash	60	Percentage based on surficial geology
Syl Laskin	9Ga	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage based on surficial geology
Tecumseh EC	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Alluvial valley with low coarse soils (<3% SNL)
Texas-New Mexico	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Based on productive aquifers, Heath (1985) (Heath region coverage is incorrect)
Titus	6Db	Alternating Sandstone, Limestone and Shale - Deep Regolith	2	Bedded Sedimentary Rock	100	Setting based on aquifer and surficial geology coverage; deep regolith inferred from red, massive clay
Trimble County	6E	Solution Limestone	12	Solution Limestone	40	Heath incorrect; Percentage based on surficial geology (56% alluvium, 44% clay); soils have significant fine-grained (1% SNL)
Trimble County	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Heath incorrect; Percentage based on surficial geology (56% alluvium, 44% clay); soils have significant fine-grained (1% SNL)
Tyrone	6E	Solution Limestone	12	Solution Limestone	100	Based on principal aquifer coverage
Valley	7Ac	Glacial Till Over Solution Limestone	12	Solution Limestone	100	Setting based on aquifer and soil coverages (high SCL soils)
Vermilion	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on aquifers, soils; soils don't suggest outwash like surficial geology does
Victor J Daniel Jr	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	60	Percentage based on surficial geology

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Victor J Daniel Jr	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage based on surficial geology, soils
W A Parish	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	30	Percentage based on surficial geology and productive aquifer coverages
W A Parish	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage based on surficial geology and productive aquifer coverages; high SCL (96%) = overbank deposits
W H Weatherspoon	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	30	Percentage based on surficial geology; sandy soils
W H Weatherspoon	10Bb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	70	Percentage based on surficial geology; sandy soils
W S Lee	8D	Regolith	1	Metamorphic and Igneous	100	Setting based on aquifers, surficial geology, soils, Heath (1985)
Wabash River	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer in Alluvial Valley region
Walter C Beckjord	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	60	Percentage based on surficial geology; placed in glaciated central based on Heath (1985); soils 2% SNL
Walter C Beckjord	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage based on surficial geology; placed in glaciated central based on Heath (1985); soils 2% SNL
Wansley	8C	Mountain Flanks	2	Bedded Sedimentary Rock	30	Percentage based on surficial geology
Wansley	8E	River Alluvium	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage based on surficial geology
Warrick	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting; soils have significant fines (SCL+SLT = 94%)
Waukegan	7Bc	Outwash Over Solution Limestone	12	Solution Limestone	100	Based on soils, surficial geology, aquifer coverages

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Weston	9E	Outwash	8	Outwash	100	Setting based on productive aquifer, surficial geology coverages
Widows Creek	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	20	Percentage based on surficial geology; thin soils inferred from colluvium
Widows Creek	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology; soils have significant fines (SCL+SLT > 25%)
Will County	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	40	Percentage based on surficial geology (65% Floodplain and alluvium gravel terraces)
Will County	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage based on surficial geology (65% Floodplain and alluvium gravel terraces)
Wyodak	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Based on aquifer and surficial geology coverages, Heath (1985)
Yates	8D	Regolith	1	Metamorphic and Igneous	40	Percentage assigned based on surficial geology (59% alluvium/colluvium, 42% residuum)
Yates	8E	River Alluvium	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage assigned based on surficial geology (59% alluvium/colluvium, 42% residuum)

SCL = silty clay loam; SNL = sandy loam; SLT = silt loam.

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Attachment C-3: Climate Center Assignments

Plant	Climate Center	Explanation If Not Closest Climate Center
A B Brown	Indianapolis, IN	Closest Met Station (Nashville) receives much more precipitation (12.26" out of range) than the site location. Used second closest because only slightly below (1.3) expected precipitation range for plant.
A/C Power- Ace Operations	Las Vegas, NV	
Allen	Little Rock, AR	
Alma	Madison, WI	Closest Met Station (St. Cloud) receives less rain than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Antelope Valley	Bismarck, ND	
Arkwright	Watkinsville, GA	Closest Met Station (Atlanta) receives 6.96" more precipitation than plant location. Used second closest Met Station because 5-year averages are only slightly above (0.2) expected precipitation range for the plant.
Asheville	Knoxville, TN	
Baldwin	East St. Louis, IL	
Barry	Tallahassee, FL	Closest Met Station (New Orleans) receives much more precipitation (5.06" out of range) than the site location. Used second closest because only slightly above (3.4) expected precipitation range for plant.
Bay Front	Madison, WI	
Bay Shore	Put-in-Bay, OH	
Belews Creek	Greensboro, NC	
Ben French	Rapid City, SD	
Big Cajun 2	Lake Charles, LA	Closest Met Station (New Orleans) receives much more precipitation (5.06" out of range) than the site location. Used second closest because only slightly below (2.77) expected precipitation range for plant.
Big Sandy	Cincinnati, OH	Closest Met Station (Lexington) receives much more precipitation (8.35" out of range) than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Big Stone	St. Cloud, MN	

(continued)

Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
Black Dog Steam Plant	Madison, WI	Closest Met Station (St Cloud) is dryer (<27.5") than the 28-33" that the site receives. Madison fits in precipitation range (32.5") and is second closest.
Blue Valley	Topeka, KS	
Bowen	Atlanta, GA	
Brandon Shores	Seabrook, NJ	
Buck	Greensboro, NC	
Bull Run	Knoxville, TN	
C D McIntosh Jr	Orlando, FL	Closest Met Station (Tampa) receives less precipitation (5.31" out of range) than site location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
C P Crane	Seabrook, NJ	
Cape Fear	Greensboro, NC	
Carbon	Salt Lake City, UT	
Cardinal	Pittsburgh, PA	
Cayuga	Indianapolis, IN	
Chalk Point	Seabrook, NJ	
Cholla	Phoenix, AZ	Closest Met Station (Flagstaff) receives much more precipitation (13.92" out of range) than plant location. Used second closest Met Station because 5-year averages were close (.31 higher) than the expected precipitation range for the plant.
Cliffside	Greensboro, NC	
Clover	Lynchburg, VA	
Coal Creek	Bismarck, ND	
Coleto Creek	San Antonio, TX	
Colstrip	Glasgow, MT	
Conemaugh	Pittsburgh, PA	
Conesville	Columbus, OH	
Council Bluffs	North Omaha, NE	
Crawford	East St. Louis, IL	
Crist	Tallahassee, FL	

(continued)

Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
Cross	Charleston, SC	
Cumberland	Nashville, TN	
Dale	Lexington, KY	
Dallman	East St. Louis, IL	
Dan E Karn	East Lansing, MI	
Dan River	Greensboro, NC	
Danskammer	Bridgeport, CT	
Dave Johnston	Cheyenne, WY	
Dickerson	Seabrook, NJ	
Dolet Hills	Shreveport, LA	
Duck Creek	East St. Louis, IL	
Dunkirk	Ithaca, NY	
E D Edwards	Chicago, IL	
E W Brown	Lexington, KY	
Eckert Station	East Lansing, MI	
Edgewater	Madison, WI	
Elmer W Stout	Indianapolis, IN	
F B Culley	Indianapolis, IN	Closest Met Station (Nashville) receives much more precipitation (12.26” out of range) than plant location. Used second closest Met Station because 5-year & 30-year averages fell within expected precipitation range for the plant.
Fayette Power Prj	San Antonio, TX	
Flint Creek	Columbia, MO	Used http://www.weather.com and Envirofacts to determine that avg. precipitation for site was ~47”. The closest Met Station (Tulsa) receives much less (~17”) precipitation per year. Used second closest station.
Fort Martin	Pittsburgh, PA	
Frank E Ratts	Indianapolis, IN	
G G Allen	Greensboro, NC	
Gadsden	Atlanta, GA	

(continued)

Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
Gallatin	Nashville, TN	
Gen J M Gavin	Cincinnati, OH	Closest Met Station (Columbus) receives less rain than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant. Also average precipitation for the second closest Met Station was nearest to http://www.weather.com
Genoa	Madison, WI	
Gibson	Indianapolis, IN	
Gorgas	Atlanta, GA	
Green River	Indianapolis, IN	Closest Met Station (Nashville) receives much more precipitation (12.26" out of range) than plant location. Used third closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Greene County	Atlanta, GA	
H B Robinson	Charleston, SC	
Hammond	Atlanta, GA	
Harllee Branch	Watkinsville, GA	
Harrison	Pittsburgh, PA	
Hatfield's Ferry	Pittsburgh, PA	
Hennepin	Chicago, IL	
Heskett	Bismarck, ND	
Holcomb	Dodge City, KS	
Homer City	Pittsburgh, PA	
Hoot Lake	St. Cloud, MN	
Hugo	Shreveport, LA	Closest Met Station (Dallas) receives less precipitation (6.45" out of range) than plant location. Used second closest because only slightly above (2.07) expected precipitation range for plant.
Hunter	Grand Junction, CO	Closest Met Station (Salt Lake City) receives 8.6" more precipitation than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Huntington	Cedar City, UT	Two closest Met Stations are out of range. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Intermountain	Ely, NV	Closest Met Station (Salt Lake City) receives 6.1" more precipitation than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
J H Campbell	East Lansing, MI	

(continued)

Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
J M Stuart	Cincinnati, OH	
J R Whiting	Put-in-Bay, OH	
Jack McDonough	Atlanta, GA	
Jack Watson	Tallahassee, FL	Closest Met Station (New Orleans) receives much more precipitation (5.06" out of range) than the site location. http://www.weather.com predicted average precipitation at plant location to be 65.2. Used third closest because its average was closest.
James H Miller Jr	Atlanta, GA	
Jim Bridger	Lander, WY	
John E Amos	Cincinnati, OH	The two closest Met Stations are out of the site's precipitation range. Used third closest Met Station because 5-year averages fell within expected precipitation range for the plant. Also average precipitation for the second closest Met Station was nearest to http://www.weather.com average.
John Sevier	Knoxville, TN	
Johnsonville	Nashville, TN	
Joliet 29	Chicago, IL	
Keystone	Pittsburgh, PA	
Killen Station	Cincinnati, OH	
Kingston	Knoxville, TN	
Kraft	Charleston, SC	
L V Sutton	Charleston, SC	
Lansing	Madison, WI	
Laramie R Station	Cheyenne, WY	
Lawrence EC	Topeka, KS	
Lee	Greensboro, NC	
Leland Olds	Bismarck, ND	
Lon Wright	North Omaha, NE	
Louisa	Des Moines, IA	
Marion	East St. Louis, IL	
Marshall	Greensboro, NC	

(continued)

Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
Martin Lake	Shreveport, LA	
Mayo	Lynchburg, VA	
Meramec	East St. Louis, IL	
Merom	Indianapolis, IN	
Miami Fort	Cincinnati, OH	
Milton R Young	Bismarck, ND	
Mitchell - PA	Pittsburgh, PA	
Mitchell - WV	Pittsburgh, PA	
Mohave	Las Vegas, NV	
Monroe	Put-in-Bay, OH	
Morgantown	Norfolk, VA	
Mountaineer (1301)	Cincinnati, OH	Closest Met Station (Columbus) receives more rain than plant location. Although second closest site also falls within range, used third closest Met Station because site geography was similar and the station's 5-year averages fell within expected precipitation range for the plant.
Mt Storm	Pittsburgh, PA	
Muscatine Plant #1	Des Moines, IA	
Muskogee	Tulsa, OK	
Neal North	North Omaha, NE	
Neal South	North Omaha, NE	
Nebraska City	North Omaha, NE	
New Castle	Pittsburgh, PA	
Newton	Indianapolis, IN	Closest Met Station (East St. Louis) receives less rain than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant. Also average precipitation for the second closest Met Station was nearest to http://www.weather.com
North Omaha	North Omaha, NE	
Northeastern	Tulsa, OK	
Nucla	Grand Junction, CO	

(continued)

Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
Oklaunion	Oklahoma City, OK	
Paradise	Cincinnati, OH	Closest Met Station (Nashville) receives much more precipitation (12.26" out of range) than plant location. Used third closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Petersburg	Indianapolis, IN	
Pleasant Prairie	Chicago, IL	
Port Washington	Madison, WI	
Portland	Philadelphia, PA	
Possum Point	Norfolk, VA	
Potomac River	Seabrook, NJ	
Presque Isle	Sault Ste. Marie, MI	
R Gallagher	Cincinnati, OH	Closest Met Station (Lexington) receives much more precipitation (8.35" out of range) than plant location. Used second closest Met Station because 5-year & 30-year averages fell within expected precipitation range for the plant.
R M Schahfer	Chicago, IL	
Reid Gardner	Las Vegas, NV	
Richard Gorsuch	Columbus, OH	
Riverbend	Greensboro, NC	
Rodemacher	Lake Charles, LA	
Roxboro	Greensboro, NC	
Sandow	San Antonio, TX	
Scherer	Watkinsville, GA	Closest Met Station (Atlanta) receives 6.96" more precipitation than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Shawnee	East St. Louis, IL	
Shawville	Pittsburgh, PA	
Sheldon	North Omaha, NE	

(continued)

Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
South Oak Creek	Chicago, IL	
Springerville	Albuquerque, NM	Closest Met Station (Flagstaff) receives much more precipitation (8.92" out of range) than plant location. Used second closest Met Station because 5-year averages were within the expected precipitation range for the plant.
St Johns River Power	Jacksonville, FL	
Stanton Energy Ctr	Orlando, FL	
Stockton Cogen Company	Sacramento, CA	
Syl Laskin	St. Cloud, MN	
Tecumseh EC	Topeka, KS	
Texas-New Mexico	San Antonio, TX	Closest Met Station (Dallas) received less precipitation than site location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant. Also average precipitation for the second closest Met Station was nearest to http://www.weather.com
Titus	Philadelphia, PA	
Trimble County	Cincinnati, OH	
Tyrone	Lexington, KY	
Valley	Madison, WI	
Vermilion	Chicago, IL	Closest Met Station (Indianapolis) receives more precipitation than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Victor J Daniel Jr	Tallahassee, FL	Closest Met Station (New Orleans) receives much more precipitation (5.06" out of range) than the site location. Used second closest because only slightly above (3.4) expected precipitation range for plant.
W A Parish	Shreveport, LA	2 Closest Met Stations (Lake Charles & San Antonio) are more than 4" out of range. Used third closest because only slightly above (1.65") expected precipitation range for plant.
W H Weatherspoon	Greensboro, NC	
W S Lee	Watkinsville, GA	
Wabash River	Indianapolis, IN	
Walter C Beckjord	Cincinnati, OH	
Wansley	Atlanta, GA	
Warrick	Indianapolis, IN	Closest Met Station (Nashville) receives 12.2" more precipitation than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.

(continued)

Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
Waukegan	Chicago, IL	
Weston	Madison, WI	
Widows Creek	Nashville, TN	
Will County	East St. Louis, IL	
Wyodak	Rapid City, SD	
Yates	Atlanta, GA	

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Attachment C-4: Waterbody Assignments and Flow

Plant	CUSEG	Nearest Reach	Reach_Type	QLOW	QMEAN
A B Brown	05140202014	OHIO R	Regular Reach	9167.38965	150031.6875
A/C Power- Ace Operations	18090205005	SEARLES L	Lake Shoreline		
Allen	08010211007	HORN LAKE CUTOFF	Lake Shoreline		
Alma	07040003009	MISSISSIPPI R	Regular Reach	5683.02002	25397.4707
Antelope Valley	10130201005	ANTELOPE CR	Start Reach	0	96.87
Arkwright	03070103007	OCMULGEE R	Regular Reach	428.79999	2708.53003
Asheville	06010105026	FRENCH BROAD R	Regular Reach	412.04999	1722.34998
Baldwin	07140204004	KASKASKIA R	Regular Reach	351.72	3832.12012
Barry	03160204014	MOBILE R	Regular Reach	7561.14014	63275.23828
Bay Front	07070005036	L SUPERIOR	Great Lakes Shoreline		
Bay Shore	04100010003	L ERIE, U.S. SHORE	Great Lakes Shoreline	0	0
Belews Creek	03010103098	BELEWS L	Lake Shoreline		
Ben French	10120110010	CASTLE CR	Start Reach	2.96	18.62
Big Cajun 2	08070100005	MISSISSIPPI R	Regular Reach	100937.8125	466865.5625
Big Sandy	05070204008	BIG SANDY R	Regular Reach	152.02	5746.95996
Big Stone	07020001033	BIG STONE LAKE	Lake Shoreline		
Black Dog Steam Plant	07020012001	BLACK DOG LAKE	Lake Shoreline		
Blue Valley	10300101034	LITTLE BLUE R	Regular Reach	23.2	141.75
Bowen	03150104008	ETOWAH R	Regular Reach	413.13	2294.86011
Brandon Shores	02060003037	CURTIS BAY	Coastal Shoreline	0	0
Buck	03040103040	YADKIN R	Regular Reach	912.72998	4722.54004
Bull Run	06010207015	CLINCH R	Regular Reach	102.46	4732.3501
C D McIntosh Jr	03100205014	NO LAKE PARKER	Lake Shoreline		

(continued)

Waterbody Assignments and Flow (continued)

Plant	CUSEG	Nearest Reach	Reach_Type	QLOW	QMEAN
C P Crane	02060003025	CURTIS BAY	Coastal Shoreline	0	0
Cape Fear	03030002001	HAW R	Regular Reach	58.98	1584.83997
Carbon	14060007018	PRICE R	Regular Reach	1.92	77
Cardinal	05030106033	OHIO R	Regular Reach	3391.62012	37533.17188
Cayuga	05120108001	WABASH R	Regular Reach	965.09003	10100.21973
Chalk Point	02060006009	PATUXENT R	Wide-River Shoreline	0	0
Cholla	15020008017	CHOLLA COOLING POND	Lake Shoreline		
Cliffside	03050105031	BROAD R	Regular Reach	332.17001	1510.08997
Clover	03010102027	ROANOKE R	Regular Reach	408.64001	2702.59009
Coal Creek	10130101018	UNKNOWN LAKE	Lake Shoreline		
Coleto Creek	12100303014	MARCELINAS CR	Start Reach	1.11	3.79
Colstrip	10100001108	ARMELLS CR, E FK	Start Reach	0	18.64
Conemaugh	05010007002	CONEMAUGH R	Regular Reach	194.53999	1553.52002
Conesville	05040004071	MUSKINGUM R	Regular Reach	447.98001	4707.08008
Council Bluffs	10230006004	MISSOURI R	Regular Reach	4402.58984	31444.83008
Crawford	07130011018	ILLINOIS R	Regular Reach	3444.66992	20788.71094
Crist	03140305001	ESCAMBIA R	Terminal Reach	845.46002	6772.5498
Cross	03050201022	DIVERS CANAL TO LAKE MOU	Lake Shoreline		
Cumberland	05130205017	CUMBERLAND R	Regular Reach	536.47998	25322.66016
Dale	05100205047	KENTUCKY R	Regular Reach	35.32	5213.06982
Dallman	07130007003	LAKE SPRINGFIELD	Lake Shoreline		
Dan E Karn	04080103005	L HURON U.S. SH SAGINAW BAY	Great Lakes Shoreline	0	0
Dan River	03010103014	DAN R	Regular Reach	358.12	1954.15002
Danskammer	02020008022	HUDSON R	Wide-River Shoreline	0	0
Dave Johnston	10180007005	N PLATTE R	Regular Reach	65.24	502.87
Dickerson	02070008013	POTOMAC R	Regular Reach	895.57001	10528.36035
Dolet Hills	11140206019	BAYOU PIERRE LAKE	Lake Shoreline		

(continued)

Waterbody Assignments and Flow (continued)

Plant	CUSEG	Nearest Reach	Reach_Type	QLOW	QMEAN
Duck Creek	07130003010	L CHAUTAUQUA	Lake Shoreline		
Dunkirk	04120101003	L ERIE, U.S. SHORE	Great Lakes Shoreline	0	0
E D Edwards	07130003018	ILLINOIS R	Regular Reach	2998.32007	13899.62988
E W Brown	05100205015	HERRINGTON LAKE	Lake Shoreline		
Eckert Station	04050004003	GRAND R	Regular Reach	73.47	484.28
Edgewater	04030101002	L MICHIGAN	Great Lakes Shoreline	0	0
Elmer W Stout	05120201005	WHITE R	Regular Reach	70.17	1429.92004
F B Culley	05140201001	OHIO R	Regular Reach	8728.7002	131543.0625
Fayette Power Prj	12090301003	CEDAR CREEK RESERVOIR	Lake Shoreline		
Flint Creek	11110103031	SWEPCO RSRVR,LT FLINT CK	Lake Shoreline		
Fort Martin	05020003001	MONONGAHELA R	Regular Reach	293.66	4497.75
Frank E Ratts	05120202003	WHITE R	Regular Reach	343.59	11525.13965
G G Allen	03050101009	CATAWBA R	Regular Reach	462.92001	2958.09009
Gadsden	03150106041	COOSA R	Regular Reach	1096.10999	9468
Gallatin	05130201006	OLD HICKORY L	Lake Shoreline		
Gen J M Gavin	05030202005	OHIO R	Regular Reach	4258.12012	55143.35938
Genoa	07060001017	MISSISSIPPI R	Regular Reach	6434.18018	29379.25
Gibson	05120113013	WABASH R	Regular Reach	2247.6001	26799.73047
Gorgas	03160109002	BLACK WARRIOR R, MULBERRY F	Lake Shoreline		
Green River	05110003001	GREEN R	Regular Reach	320.06	9752
Greene County	03160113011	BLACK WARRIOR R	Regular Reach	304.73001	9820.04004
H B Robinson	03040201042	L ROBERTSON	Lake Shoreline		
Hammond	03150105025	COOSA R	Regular Reach	1196.82996	6569.95996
Harllee Branch	03070101006	L SINCLAIR	Lake Shoreline		
Harrison	05020002008	WEST FORK R	Regular Reach	33.03	1038.32996
Hatfield's Ferry	05020005026	MONONGAHELA R	Regular Reach	479.79999	8278.94043
Hennepin	07130001026	ILLINOIS R	Regular Reach	3233.23999	13146.83984

(continued)

Waterbody Assignments and Flow (continued)

Plant	CUSEG	Nearest Reach	Reach_Type	QLOW	QMEAN
Heskett	10130101001	MISSOURI R	Regular Reach	3461.55005	22744.26953
Holcomb	11030001001	ARKANSAS R	Regular Reach	0	197.92999
Homer City	05010007015	TWO LICK CR	Regular Reach	4.53	295.22
Hoot Lake	09020103002	OTTER TAIL R	Regular Reach	12.45	271.35999
Hugo	11140105041	KIAMICHI CR, N FK	Start Reach	2.55	53.16
Hunter	14060009034	ROCK CANYON CR	Start Reach	0	0.1
Huntington	14060009020	HUNTINGTON CR	Regular Reach	10.75	91.1
Intermountain		none		0	0
J H Campbell	04050002001	L MICHIGAN	Great Lakes Shoreline	0	0
J M Stuart	05090201024	OHIO R	Regular Reach	6767.47021	92214.6875
J R Whiting	04100001002	L ERIE, U.S. SHORE	Great Lakes Shoreline	0	0
Jack McDonough	03130002044	CHATTAHOOCHEE R	Regular Reach	726.45001	2952.18994
Jack Watson	03170009034	BILOXI BAY	Coastal Shoreline	0	0
James H Miller Jr	03160111005	BLACK WARRIOR R, LOCUST FK	Lake Shoreline		
Jim Bridger	14040105011	UNKNOWN LAKE	Lake Shoreline		
John E Amos	05050008007	KANAWHA R	Regular Reach	1390.22998	14930.83984
John Sevier	06010104011	HOLSTON R	Regular Reach	633	4079.15991
Johnsonville	06040005007	KENTUCKY L	Lake Shoreline		
Joliet 29	07120004004	DES PLAINS R	Regular Reach	1029.93005	3809.69995
Keystone	05010006002	CROOKED CR	Regular Reach	30.72	422.14999
Killen Station	05090201024	OHIO R	Regular Reach	6767.47021	92214.6875
Kingston	06010207001	CLINCH R	Regular Reach	266.35999	7347.89014
Kraft	03060109007	SAVANNAH R	Regular Reach	3570.52002	12365
L V Sutton	03030005011	CAPE FEAR R	Regular Reach	619.95001	8594.57031
Lansing	07060001009	MISSISSIPPI R	Regular Reach	7684.02002	32253.15039
Laramie R Station	10180011002	LARAMIE R	Regular Reach	28.53	90.8
Lawrence EC	10270104021	KANSAS R	Regular Reach	403.81	6720.29004

(continued)

Waterbody Assignments and Flow (continued)

Plant	CUSEG	Nearest Reach	Reach_Type	QLOW	QMEAN
Lee	03020201007	NEUSE R	Regular Reach	76.18	1657.39001
Leland Olds	10130101020	MISSOURI R	Regular Reach	4270.4502	21650.67969
Lon Wright	10220003048	RAWHIDE CR	Start Reach	0.94	11.59
Louisa	07080101003	MISSISSIPPI R	Regular Reach	15067.92969	54665.96094
Marion	05140204030	L OF EGYPT	Lake Shoreline		
Marshall	03050101015	L NORMAN	Lake Shoreline		
Martin Lake	12010002050	MARTIN LAKE	Lake Shoreline		
Mayo	03010104045	MAYO CR	Start Reach	5.99	61.03
Meramec	07140101014	MISSISSIPPI R	Regular Reach	33305	177021.1875
Merom	05120111011	TURTLE CR RESERVOIR	Lake Shoreline		
Miami Fort	05090203012	OHIO R	Regular Reach	6516.18994	98615.0625
Milton R Young	10130101024	NELSON LAKE AND MISSOURI RIVER	Lake Shoreline		
Mitchell - PA	05020005002	MONONGAHELA R	Regular Reach	848.58002	9284.13965
Mitchell - WV	05030106013	OHIO R	Regular Reach	3419.20996	38713.19922
Mohave	15030101011	COLORADO R	Regular Reach	1916.72998	12134.36035
Monroe	04100001002	L ERIE, U.S. SHORE	Great Lakes Shoreline	0	0
Morgantown	02070011051	POTOMAC R	Wide-River Shoreline	0	0
Mountaineer (1301)	05030202008	OHIO R	Regular Reach	4242.58984	54823.21094
Mt Storm	02070002027	STONY R RES	Lake Shoreline		
Muscatine Plant #1	07080101005	MISSISSIPPI R	Regular Reach	14573.71973	54469.48047
Muskogee	11110102012	ARKANSAS R	Regular Reach	227.57001	21258.39062
Neal North	10230001021	MISSOURI R	Regular Reach	4217.7998	29486.82031
Neal South	10230001021	MISSOURI R	Regular Reach	4217.7998	29486.82031
Nebraska City	10240001002	MISSOURI R	Regular Reach	5807.77002	36764.01172
New Castle	05030104002	BEAVER R	Regular Reach	268.48001	2425.32007
Newton	05120114006	NEWTON LAKE	Lake Shoreline		
North Omaha	10230006009	MISSOURI R	Regular Reach	4365.6499	31400.93945

(continued)

Waterbody Assignments and Flow (continued)

Plant	CUSEG	Nearest Reach	Reach_Type	QLOW	QMEAN
Northeastern	11070105012	VERDIGRIS R	Regular Reach	3.85	2168.47998
Nucla	14030003012	SAN MIGUEL R	Regular Reach	8.1	307.64001
Oklaunion	11130302061	BOGGY CR	Start Reach	0.09	14.93
Paradise	05110003003	GREEN R	Regular Reach	316.59	9663.71973
Petersburg	05120202003	WHITE R	Regular Reach	343.59	11525.13965
Pleasant Prairie	07120004012	L MICHIGAN AND J	Lake Shoreline		
Port Washington	04030101002	L MICHIGAN	Great Lakes Shoreline	0	0
Portland	02040105012	DELAWARE R	Regular Reach	1995.12	9089.00977
Possum Point	02070011074	POTOMAC R	Wide-River Shoreline	0	0
Potomac River	02070010025	POTOMAC R	Artificial Open Water Reach	919.89001	11721.87988
Presque Isle	04020105002	L SUPERIOR, U.S. SHORE	Great Lakes Shoreline	0	0
R Gallagher	05140101001	OHIO R	Regular Reach	7634.39014	119152.1875
R M Schahfer	07120001012	KANAKEE R	Regular Reach	458.92001	1410.56006
Reid Gardner	15010012006	MUDDY R	Regular Reach	0.68	19.22
Richard Gorsuch	05030202039	OHIO R	Regular Reach	4079.81006	48956.14062
Riverbend	03050101012	CATAWBA R	Regular Reach	412.28	2623.09009
Rodemacher	11140207020	RODEMACHER LAKE	Lake Shoreline		
Roxboro	03010104034	HYCO L	Lake Shoreline		
Sandow	12070102012	ALCOA LAKE	Lake Shoreline		
Scherer	03070103012	OCMULGEE R	Start Reach	655.48999	2490.72998
Shawnee	05140206009	OHIO R	Regular Reach	21748.59961	288452.1875
Shawville	02050201002	SUSQUEHANNA R, W BR	Regular Reach	96.9	1947.33997
Sheldon	10240008030	UNKNOWN LAKE	Lake Shoreline		
South Oak Creek	04040002004	L MICHIGAN	Great Lakes Shoreline	0	0
Springerville	15020002025	*A	Start Reach	0	2.49
St Johns River Power	03080103003	ST JOHNS R	Wide-River Shoreline	0	0
Stanton Energy Ctr	03080101036	ECOHLOCKHATCHEE R	Start Reach	5.95	131.42999

(continued)

Waterbody Assignments and Flow (continued)

Plant	CUSEG	Nearest Reach	Reach_Type	QLOW	QMEAN
Stockton Cogen Company	18040002005	LITTLEJOHNS CR	Start Reach	0.21	50.61
Syl Laskin	04010201034	COLBY L AND PARTRIDGE R	Lake Shoreline		
Tecumseh EC	10270102003	KANSAS R	Regular Reach	388.51999	5923.74023
Texas-New Mexico	12070101008	LITTLE BRAZOS R	Start Reach	0.55	139.05
Titus	02040203010	SCHUYLKILL R	Regular Reach	91.25	1880.77002
Trimble County	05140101007	OHIO R	Regular Reach	7524.29004	117896.3125
Tyrone	05100205013	KENTUCKY R	Regular Reach	154.36	7097.54004
Valley	04040003001	MILWAUKEE R	Terminal Reach	10.71	540.60999
Vermilion	05120109006	VERMILION R, M FK	Regular Reach	3.45	340.35999
Victor J Daniel Jr	03170006007	PASCAGOULA R	Regular Reach	1256.55005	12878.25
W A Parish	12070104021	SMITHERS L	Lake Shoreline		
W H Weatherspoon	03040203016	LUMBER R	Regular Reach	97.9	865.13
W S Lee	03050109066	SALADA R	Regular Reach	20.68	461.51001
Wabash River	05120111018	WABASH R	Regular Reach	985.53998	10551.67969
Walter C Beckjord	05090201001	OHIO R	Regular Reach	6416.77002	92084.0625
Wansley	03130002032	CHATTAHOOCHEE R	Regular Reach	702.71002	4400.72021
Warrick	05140201022	LITTLE PIGEON CR	Regular Reach	61.57	1149.60999
Waukegan	04040002002	L MICHIGAN	Great Lakes Shoreline	0	0
Weston	07070002023	WISCONSIN R	Regular Reach	1069.30005	3484.32007
Widows Creek	06030001049	TENNESSEE R	Regular Reach	7221.95996	38237.07031
Will County	07110009002	WOOD R	Start Reach	29	87.81
Wyodak	10120201038	DONKEY CR	Start Reach	0	4.4
Yates	03130002061	CHATTAHOOCHEE R	Regular Reach	702.21997	4063.29004

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Appendix D. MINTEQA2 Nonlinear Sorption Isotherms

D.1 Overview of MINTEQA2 Modeling

Chemicals in leachate can be subject to complex geochemical interactions in soil and groundwater, which can strongly affect their rate of transport in the subsurface. The U.S. Environmental Protection Agency's Composite Model for Leachate Migration with Transformation Products (EPACMTP) treats these interactions as equilibrium sorption processes. The equilibrium assumption means that the sorption process occurs instantaneously, or at least very quickly relative to the time scale of constituent transport. Although sorption—or the attachment of leachate constituents to solid soil or aquifer particles—may result from multiple chemical processes, EPACMTP lumps these processes together into an effective soil-water partition coefficient (K_d). The retardation factor (R) accounts for the effects of equilibrium sorption of dissolved constituents onto the solid phase. R, a function of the constituent-specific K_d and the soil or aquifer properties, is calculated as:

$$R = 1 + \frac{\rho_b \times K_d}{\Phi} \qquad \text{(D-1)}$$

where

R = Retardation factor
ρ_b = Soil or aquifer bulk density (mg)
K_d = Solid-water partition coefficient (g/cm^3)
ϕ = Water content (in unsaturated zone) or porosity (in saturated zone).

An isotherm is an expression of the equilibrium relationship between the aqueous concentration and the sorbed concentration of a metal (or other constituent) at a constant temperature. For metals, EPACMTP accounts for more complex geochemical reactions by using effective sorption isotherms generated using EPA's geochemical equilibrium speciation model for dilute aqueous systems, MINTEQA2 (U.S. EPA, 1991).

The MINTEQA2 model is used to generate one set of isotherms for each metal reflecting the range in geochemical environments expected at waste sites across the nation. The variability in geochemical environments at coal combustion waste (CCW) sites across the country is represented by five geochemical master variables (groundwater composition, pH, concentration of iron oxide adsorption sites, leachate ionic strength, and concentration of dissolved and particulate natural organic matter), and the MINTEQA2 modeling is repeated (separately for each metal) for numerous combinations of master variable settings. This procedure results in nonlinear K_d versus aqueous metal concentration curves for combinations of master variable settings spanning the range of reasonable values (U.S. EPA 2003a).

For each metal, the resulting set of isotherms is tabulated into a supplementary input data file for use by the EPACMTP model, hereafter referred to as an "empirical nonlinear isotherm." In the fate and transport modeling for a particular metal, EPACMTP is executed and the national probability distributions for these five master variables form the basis for the Monte Carlo selection of the appropriate adsorption isotherm.

In modeling metals transport in the unsaturated zone, EPACMTP uses a range of K_d values from the nonlinear sorption isotherms. However, in modeling metals transport in the saturated zone, EPACMTP selects the lowest from all available K_d values corresponding to concentrations less than or equal to the maximum water table concentration. For more details see the *EPACMTP Technical Background Document* (U.S. EPA, 2003b).

This simplification in the saturated zone is required for all solution options and is based on the assumption that after dilution of the leachate plume in groundwater, the concentrations of metals will typically be in a range where the isotherm is approximately linear. However, this assumption may not be valid when the metal concentrations in the leachate are exceedingly high. Although EPACMTP is able to account for the effect of the geochemical environment at a site on the mobility of metals, the model assumes that the geochemical environment at a site is constant and not affected by the presence of the leachate plume. In reality, the presence of a leachate plume may alter the ambient geochemical environment.

D.2 Previous CCW Metals Modeling Effort

In a previous risk assessment for fossil fuel combustion wastes (FFCWs) conducted in 1998 (U.S. EPA, 1998), sorption isotherms generated using MINTEQA2 were used in EPACMTP to account for metal partitioning. However, these isotherms were not calculated specifically for use in FFCW modeling—they had been computed using MINTEQA2 in 1995 for use in modeling support for the Hazardous Waste Identification Rule (HWIR).

The disposal scenario for HWIR was the industrial Resource Conservation and Recovery Act (RCRA) Subtitle D nonhazardous waste landfill. In fact, the MINTEQA2 modeling that produced the isotherms had originally been designed to represent municipal solid waste landfills, and leachate from those landfills had been sampled so that appropriate forms of leachate organic acids at various concentrations could be included in the modeling. For the HWIR analysis, the scenario was changed to industrial Subtitle D, and only the isotherms corresponding to low concentrations of the leachate organic acids were used for HWIR modeling. The same isotherms were used in the 1998 FFCW risk assessment. As in the HWIR modeling, only the isotherms corresponding to the lowest setting of leachate organic carbon were used.

In 1999, EPA received review comments concerning the use of the industrial Subtitle D metal partitioning isotherms in the 1998 risk assessment. The most comprehensive review was prepared by Charles Norris and Christina Hubbard on behalf of the Environmental Defense Fund and other environmental advocacy groups (Norris and Hubbard, 1999). The Norris and Hubbard report criticized the 1998 risk assessment for using MINTEQA2 isotherms designed for a different scenario (nonhazardous industrial landfills). Norris and Hubbard also offered 20 specific criticisms on the input parameters and other factors involved in the MINTEQA2 modeling. EPA responded by evaluating each of these criticisms through review and assessment

of MINTEQA2 input values, model sensitivity tests, and consultations with experts. This review is documented in U.S. EPA (2000, 2001a). The evaluation of the Norris and Hubbard comments resulted in suggested revisions in the MINTEQA2 modeling strategy, as described in U.S. EPA (2001b).

Based on a review of available information on CCW leachate composition and an analysis of the potential effects of this composition on metals mobility, EPA (U.S. EPA, 2001b) also determined that if MINTEQA2 is to be used at CCW sites, leachate from CCW facilities should be studied to look for trends in composition, especially with regard to the concentrations of constituents that may

- Contribute to elevated groundwater pH
- Compete with the contaminant metal for sorption sites and thus result in reduced metal sorption (e.g., Ca, Mg, SO_4, other metals)
- Complex with the contaminant metal so that the metal is less likely to be sorbed (e.g., SO_4, CO_3, organic ligands)
- Precipitate with the contaminant metal (e.g., SO_4, CO_3).

D.3 MINTEQA2 Modeling Revisions for CCW Risk Assessment

Many of the suggested revisions from U.S. EPA (2001b) were implemented in the MINTEQA2 modeling for the current CCW risk assessment. Some of the suggested revisions were not implemented, either because they are not applicable (e.g., organic carbon assumptions should not be changed because CCW leachate has negligible organic carbon) or because models or data were not adequate to carry forth the recommendation. These revisions are discussed in greater detail in U.S. EPA (2003c).

In addition to revising the MINTEQA2 model, EPA compiled leachate characteristics into the CCW constituent database (see Appendix A) and statistically analyzed these data to identify three chemically distinct CCW leachate types: conventional CCW (including ash and flue gas desulfurization [FGD] sludge), codisposed CCW and coal cleaning wastes, and fluidized bed combustion (FBC) waste. Leachate concentration ranges for major ions (e.g., Ca, SO_4, Mg, Na, Cl, etc.) and pH were developed for each of these waste types and were used to represent CCW leachate during MINTEQA2 modeling.

As needed, sorption reactions were included for those CCW constituents known to undergo significant sorption. Including elevated concentrations of leachate constituents and their corresponding sorption reactions in the MINTEQA2 model allows for full competition with the contaminant metal for sorption sites. The metal solubilizing effect through complexation between the contaminant metal and dissolved ligands is also included, as is the potential for metal precipitation. Because precipitation of the metal can serve to attenuate the transportable concentration, the equilibrium fraction in all three phases (dissolved, sorbed, and precipitated) were stored and made available for use by EPACMTP. The precipitated fraction was used to develop a solubility limit that was used during EPACMTP modeling (U.S. EPA, 2003c).

D.4 MINTEQA2 Modeling for CCW Risk Assessment

The expected natural variability in K_d for a particular metal was represented during the MINTEQA2 modeling effort by varying the input parameters that most impact K_d: groundwater type (carbonate or noncarbonate), pH, concentration of aquifer sorbents, composition and concentration level of CCW leachate, and concentration of the contaminant metal. The natural pH range for the two groundwater types was sampled from a range of 7 to 8 for carbonate aquifers and 4 to 10 for noncarbonate aquifers (U.S. EPA, 2003c).

In addition, CCW leachate ranges from acidic (pH < 2) to highly alkaline (pH > 12) and can impact vadose zone and groundwater pH. To account for this possibility, the CCW leachate/ groundwater system was equilibrated at a series of pH values that span the range of expected variability in mixed CCW leachate-groundwater systems (U.S. EPA, 2003c).

To account for the variability in the sorption capacity of soil and aquifer materials, the soil and groundwater systems were equilibrated with various concentrations of two commonly occurring natural sorbents: ferric (iron) oxyhydroxide (FeOx) and particulate organic matter (POM). CCW leachate can include elevated concentrations of inorganic constituents such as calcium, sulfate, sodium, potassium, and chloride, which may reduce sorption of metals due to competition for sorption sites or complexation with metals in solution. To account for this effect, these leachate components were added to the MINTEQA2 model inputs at concentrations representative of the three CCW waste types (conventional CCWs, codisposed CCW and coal cleaning wastes, and FBC wastes). This new MINTEQA2 master variable is termed leachate "richness" or ionic strength (U.S. EPA, 2003c).

The results of each MINTEQA2 model run were compiled as the equilibrium distribution of the contaminant metal among dissolved, sorbed, and precipitated fractions for each metal concentration, and were saved in a separate file indexed with the settings of all variables used to define the system. These files were produced for all possible values for the variables defining the system, and were compiled into a database of indexed K_d values for use in the EPACMTP fate and transport model (U.S. EPA, 2003c).

D.5 EPACMTP Modeling Revisions to Accommodate MINTEQA2 Updates

EPA updated EPACMTP to support the new system variable (leachate ionic strength) for isotherm selection, to address issues regarding the impacts of leachate pH on ambient soil and aquifer pH, and to address issues regarding solubility limits for metals in solution. A brief description of these model changes are discuss below, with more detail provided in U.S. EPA (2003d).

Ionic Strength. A new system or "master" variable was added to include ionic strength as a key for choosing the representative isotherm from the database for both the unsaturated and saturated zones.

Leachate Effects on Geochemical Environment. These effects were addressed in EPACMTP under the following constraints: (1) no significant impairment of the computational efficiency for probabilistic applications; (2) data requirements limited to readily available data;

and (3) a scientifically defensible approach, given significant uncertainties with respect to the true impacts of leachate pH on the subsurface. Two modifications to the EPACMTP were considered: (1) determine the governing pH in the soil column (either the pH of the leachate or the native soils); and (2) determine the pH of the saturated zone as a result of the infiltrating leachate.

The approach selected for determining the governing pH of the soil column (vadose zone) beneath the waste management unit (WMU) compares the operational life of the WMU (the duration of leaching) to an estimate of the first arrival time of the contaminant front at the water table (a surrogate for the residence time of the contaminant in the soil column). If the operational life of the WMU is *relatively* long compared to the time required for the contaminant to migrate to the water table, there is a high likelihood that the leachate permeates the soil column and that the pH environment is governed by the leachate.

Conversely, a relatively short operational life and retarded contaminant migration would favor ambient soil pH conditions. An analysis of the relationship between operational life and travel time indicated that a ratio of approximately 5 (operational life over travel time) would, in many cases, result in a balanced selection of cases where leachate pH governs versus cases where soil pH governs over approximately 10,000 Monte Carlo iterations.

For each iteration of EPACMTP, the operational life was compared to a travel-time estimate based on a K_d averaged from isotherms selected based on the leachate pH and soil pH. If the ratio was greater than 5, the pH of the leachate was assumed to govern, and the pH of the leachate was used to select the isotherm for transport in the unsaturated zone. If the ratio was less than 5, the soil pH was used to select the isotherm.

In the saturated zone, the impacts of leachate pH were handled using a simple homogeneous mixing calculation. The volume of leachate released from the WMU was mixed with the volume of the aquifer that was likely to be impacted by a plume. The resulting mixed pH was used to select the isotherm for transport in the saturated zone with one limitation: in carbonate environments, the mixed pH in the aquifer was not allowed to drop below a pH of 6. Such acid conditions would likely result in significant dissolution of the soil matrix.

Metal Solubility Limits. As mentioned above, each sorption isotherm comprises equilibrium concentrations of the three contaminant phases (dissolved, sorbed, and precipitated) over a range of total concentration values. An examination of the change in the dissolved-phase concentrations relative to changes in the total concentration in any isotherm reveals solubility behavior for that contaminant: if the dissolved component does not change with increasing total concentration, a solubility limit has been achieved. If, however, the dissolved component increases along with the total concentration, then there is capacity for more dissolved mass in the groundwater or soil porewater.

EPACMTP uses this information (contained in each isotherm file) to determine if a solubility limit should be imposed in the saturated zone. Once an isotherm has been selected (after pH considerations have been addressed), the equilibrium states corresponding to the three highest total concentrations are examined. If the dissolved concentration changes more than one tenth of one percent over the last three points, then EPACMTP assumes there is no solubility

limit. If the change in dissolved concentration is less than one tenth of one percent, EPACMTP assumes a solubility limit has been reached and caps the concentration of the leachate entering the saturated zone at the water table to that limit.

D.5 References

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Appendix E. Surface Water, Fish Concentration, and Contaminant Intake Equations

This appendix presents the equations used to model surface water and fish concentrations and intake of drinking water and fish. These equations are presented in the following attachments:

- Attachment E-1 provides the equations comprising the surface water equilibrium partitioning model, including equations that estimate steady state concentrations in the water column (dissolved and total) and sediments.
- Attachment E-2 provides the equations that use bioconcentration factors (BCFs) to calculate fish tissue concentrations from total.
- Attachment E-3 provides the equations used to calculate daily contaminant intake rates from drinking water and fish consumption.

E.1 Aluminum Surface Water Precipitation

Because the fate and transport of aluminum is controlled more by solubility than by sorption in surface water, the surface water model includes algorithms to estimate aluminum concentrations in the water column and sediments by accounting for precipitation and fallout of aluminum in the water column. These calculations proceed in a stepwise fashion, as follows.

Step 1. Initially, assume all influent aluminum is dissolved in the water column.

Fraction in water column (fwater) = 1
Fraction in sediment layer (fbenth) = 0
Fraction dissolved (fd) = 1

Total water column concentration (Cwctot) = dissolved water column concentration (Cwd).

Step 2. Compare the dissolved water column concentration (Cwd) to the maximum soluble concentration (Csol) calculated in MINTEQA2 for the waterbody pH (see Section 3.5.4, Table 3-6 for aluminum solubilities and Appendix C, Section C.6.3, Table C-11 for waterbody pH).

Step 3. If the dissolved water concentration (Cwd) is greater than the solubility limit (Csol), reset the dissolved water concentration to the solubility limit, and precipitate and settle out the excess aluminum to the benthic sediment layer.

If Cwctot > Csol, then

Fwater	=	Csol / Cwctot
Fbenth	=	(Cwctot - Csol) / Cwctot
Cwbs	=	(Cwctot - Csol) * dwc / db
Cwtot	=	Cwctot * dwc / dz
Cdw	=	Csol
Cwctot	=	Csol

Else

Cdw	=	Cwctot
Cwbs	=	0
Cwtot	=	Cwctot * rsParam!dwc / rsParam!dz

End If

where:

Cdw	=	issolved waterbody concentration
Csol	=	maximum soluble concentration
Cwbs	=	total concentration in bed sediment
Cwtot	=	total waterbody concentration from loading
db	=	depth of the upper benthic layer
dwc	=	depth of the water column
dz	=	depth of the waterbody
fbenth	=	fraction in sediment layer
fd	=	fraction dissolved
fwater	=	fraction in water column

Table E-1-1. Fraction of Contaminant in Water Column (unitless)

f_{Water}

$$d_w = d_z - d_b$$

$$f_{Water} = \frac{\left[1 + \left(K_{dsw} \times TSS \times 0.000001\right)\right] \times \frac{d_w}{d_z}}{\left[\left[1 + \left(K_{dsw} \times TSS \times 0.000001\right)\right] \times \frac{d_w}{d_z}\right] + \left[\left(bsp + K_{dbs} \times bsc\right) \times \frac{d_b}{d_z}\right]}$$

Name	Description	Value
bsc	Bed sediment particle concentration (g/cm^3) or (kg/L)	1
bsp	Bed sediment porosity (cm^3/cm^3)	0.6
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Site Data; See Appendix C
d_z	Depth of the waterbody (m)	Calculated
K_{dbs}	Sedment-water partition coefficient (mL/g)	Chemical Data; See Section 3
K_{dsw}	Suspended sediment-water partition coefficient (mL/g)	Chemical Data; See Section 3
TSS	Total suspended solids (mg/L)	Site Data; See Appendix C
0.000001	Conversion factor (L/ml)(g/mg)	

Table E-1-2. Fraction of Contaminant in Benthic Sediments (unitless)

f_{Benth}

$$f_{Benth} = \frac{(bsp + K_{dbs} \times bsc) \times \frac{d_b}{d_z}}{\left[(1 + K_{dsw} \times TSS \times 0.000001) \times \frac{d_W}{d_z}\right] + \left[(bsp + K_{dbs} \times bsc) \times \frac{d_b}{d_z}\right]}$$

Name	Description	Value
bsc	Bed sediment particle concentration (g/cm^3) or (kg/L)	1
bsp	Bed sediment porosity (cm^3/cm^3)	0.6
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Site Data; See Appendix C
d_z	Depth of the waterbody (m)	Calculated
K_{dbs}	Sedment-water partition coefficient (mL/g)	Chemical Data; See Section 3
K_{dsw}	Suspended sediment-water partition coefficient (mL/g)	Chemical Data; See Section 3
TSS	Total suspended solids (mg/L)	Site Data; See Appendix C
0.000001	Conversion factor (L/ml)(g/mg)	

Table E-1-3. Dissolved Fraction (unitless)

f_d

$$f_d = \frac{1}{1 + K_{dsw} \times TSS \times 0.000001}$$

Name	Description	Value
K_{dsw}	Suspended sediment-water partition coefficient (mL/g)	Chemical Data; See Section 3
TSS	Total suspended solids (mg/L)	Site Data; See Appendix C
0.000001	Conversion factor (L/ml)(g/mg)	

Table E-1-4. Water Concentration Dissipation Rate Constant (1/d)

K_{wt}

$$K_{wt} = \left(f_{Water} \times f_d \times k_{vol}\right) + \left(f_{benth} \times K_b\right) + \left(f_{Water} \times k_{sw}\right) + \left(f_{benth} \times k_{sed}\right) + k_h$$

$$K_b = \frac{WB}{d_b}$$

$$k_{vol} = \frac{K_v}{d_w}$$

Name	Description	Value
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Site Data; See Appendix C
F_b	Fraction of contaminant in benthic sediments (unitless)	Calculated
f_d	Dissolved fraction (unitless)	Calculated
f_{Water}	Fraction of contaminant in water column (unitless)	Calculated
K_b	Benthic burial rate constant (1/day)	Calculated
k_h	Hydrolysis rate (1/day)	0
k_{sed}	Degradation rate for sediment (1/day)	0
k_{sw}	Degradation rate for water column (1/day)	0
K_v	Diffusion transfer rate (m/day)	Calculated (mercury only)
k_{vol}	Water column volatilization rate constant (1/day)	Calculated (mercury only)
WB	Rate of Burial (m/day)	0

Table E-1-5. Total Waterbody Concentration from Loading (g/m^3 or mg/L)

Cw_{Tot}

$$V = Area_{WB} \times d_z$$

$$Cw_{Tot} = \frac{L_{total}}{V_{fx} \times f_{Water} \times \frac{d_z}{d_w} + K_{wt} \times V}$$

Name	Description	Value
$Area_{WB}$	Area of the waterbody (m^2)	Site Data; See Appendix C
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Site Data; See Appendix C
d_z	Depth of the waterbody (m)	Calculated
f_{Water}	Fraction of contaminant in water column (unitless)	Calculated
K_{wt}	Water Concentration Dissipation Rate Constant (1/day)	Calculated
L_{Total}	Total waterbody load (g/day)	Calculated By EPACMTP
V	Flow independent mixing volume (m^3)	Calculated
V_{fx}	Waterbody annual flow mixing volume (m3/day)	Site Data; See Appendix C

Table E-1-6. Total Water Column Concentration (g/m^3 or mg/L)

C_{wcTot}

$$d_w = d_z - d_b$$

$$C_{wcTot} = C_{wTot} \times f_{water} \times \frac{d_z}{d_w}$$

Name	Description	Value
Cw_{Tot}	Total Waterbody Concentration from Loading (g/m^3 or mg/L)	Calculated
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Site Data; See Appendix C
d_z	Depth of the waterbody (m)	Calculated
f_{Water}	Fraction of contaminant in water column (unitless)	Calculated

Table E-1-7. Dissolved Waterbody Concentration (mg/L)

C_{dw}

$$d_w = d_z - d_b$$

$$C_{dw} = Cw_{Tot} \times f_{Water} \times f_d \times \frac{d_Z}{d_w}$$

Name	Description	Value
Cw_{Tot}	Total Waterbody Concentration from Loading (g/m^3 or mg/L)	Calculated
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Site Data; See Appendix C
d_z	Depth of the waterbody (m)	Calculated
f_d	Dissolved fraction (unitless)	Calculated
f_{Water}	Fraction of contaminant in water column (unitless)	Calculated

Table E-1-8. Total Concentration in Bed Sediment (g/m^3 or mg/L)

C_{wbs}

$$d_z = d_w + d_b$$

$$C_{bs} = C_{wTot} \times f_{benth} \times \frac{d_z}{d_b}$$

Name	Description	Value
Cw_{Tot}	Total Waterbody Concentration from Loading (g/m^3 or mg/L)	Calculated
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Site Data; See Appendix C
d_z	Depth of the waterbody (m)	Calculated

Table E-2-1. Concentration in Fish at Different Trophic Levels (mg/kg)

C_{fish}

For Non-Volatile Metals:

$$C_{fish} = Cw_{tot} \times BCF$$

Name	Description	Value
BCF	Bioconcentration factor for specified trophic level (L/kg)	Chemical Data; See Section 3
C_{dw}	Dissolved waterbody concentration (mg/L)	Calculated
Cw_{Tot}	Total waterbody concentration from loading (g/m^3 or mg/L)	Calculated
0.15	Fraction of dissolved mercury assumed to be methyl mercury (unitless)	

Table E-2-2. Average Fish Fillet Concentration Ingested by Humans (mg/kg)

C_{fish_fillet}

$$C_{fish_fillet} = F_{T3} \times C_{fishT3F} + F_{T4} \times C_{fishT4F}$$

Name	Description	Value
$C_{fishT3F}$	Concentration of contaminant in fish at different trophic levels (mg/kg)	Calculated
$C_{fishT4F}$	Concentration of contaminant in fish at different trophic levels (mg/kg)	Calculated
F_{T3}	Fraction of trophic level 3 intake (unitless)	0.36
F_{T4}	Fraction of trophic level 4 intake (unitless)	0.64

Table E-3-1. Contaminant Intake from Drinking Water (mg/kg-d)

Idw

$$I_{dw} = \frac{C_{dw} \times CR_{dw} \times F_{dw}}{BW * 1000}$$

Name	**Description**	**Value**
BW	Body weight (kg)	Exposure Data; See Appendix F
C_{dw}	Dissolved waterbody concentration (mg/L)	Calculated
CR_{dw}	Consumption rate of water (mL/day)	Exposure Data; See Appendix F
F_{dw}	Fraction of drinking water ingested that is contaminated (unitless)	1
1000	Conversion factor (mL/L)	

Table E-3-2. Daily Intake of Contaminant from Fish Ingestion (mg/kg BW/day)

I_{fish}

$$I_{fish} = \frac{C_{fish_fillet} \times CR_{fish} \times F_{fish}}{1000 \times BW}$$

Name	**Description**	**Value**
BW	Body weight (kg)	Exposure Data; See Appendix F
C_{fish_fillet}	Average fish fillet concentration ingested by humans (mg/kg)	Calculated
CR_{fish}	Consumption rate of fish (g WW/day)	Exposure Data; See Appendix F
F_{fish}	Fraction of fish intake from contaminated source (unitless)	1
1000	Conversion factor (g/kg)	

Appendix F. Human Exposure Factors

Exposure factors are data that quantify human behavior patterns (e.g., ingestion rates of fish and drinking water) and characteristics (e.g., body weight) that affect a person's exposure to environmental contaminants. These data can be used to construct realistic assumptions concerning an individual's exposure to and subsequent intake of a contaminant in the environment. The exposure factors data also enable the U. S. Environmental Protection Agency (EPA) to differentiate the exposures of individuals of different ages (e.g., a child vs. an adult). The derivation and values used for the human exposure factors in this risk assessment are described below, and the exposure factors selected for the probabilistic analyses are also presented.

F.1 Exposure Parameters Used in Probabilistic Analysis

F.1.1 Introduction

The general methodology for collecting human exposure data for the probabilistic analysis relied on the *Exposure Factors Handbook*, or EFH (U.S. EPA, 1997a-c), which was used in one of three ways:

1. When EFH percentile data were adequate (most input variables), maximum likelihood estimation was used to fit selected parametric models (gamma, lognormal, Weibull, and generalized gamma) to the EFH data. The chi-square measure of goodness of fit was then used to choose the best distribution. Parameter uncertainty information (e.g., for averages, standard deviations) also was derived using the asymptotic normality of the maximum likelihood estimate or a regression approach.

2. When EFH percentile data were not adequate for statistical model fitting (a few variables), models were selected on the basis of results for other age cohorts or, if no comparable information was available, by assuming lognormal as a default distribution and reasonable coefficients of variation (CVs).

3. When data were not adequate for either 1 or 2 above, variables were fixed at EFH-recommended mean values or according to established EPA policy.

Table F-1 lists all of the parameters used in the probabilistic analysis. Both fixed variables and the values used to define distributed data are provided.

Probabilistic risk analyses involve "sampling" values from probability distribution functions (PDFs) and using the values to estimate risk. In some cases, distributions are infinite, and there is a probability, although very small, that very large or very small values might be selected from the distributions. Because selecting extremely large or extremely small values is unrealistic (e.g., the range of adult body weights is not infinite), maximum and minimum values

were imposed on the distributions. The minimum and maximum values are included in Table F-1.

F.1.2 Exposure Parameter Distribution Methodology

This section describes how stochastic or distributed input data for each exposure factor were collected and processed. Exposure parameter distributions were developed for use in the Monte Carlo analysis. For most variables for which distributions were developed, exposure factor data from the EFH were analyzed to fit selected parametric models (i.e., gamma, lognormal, Weibull). Steps in the development of distributions included preparing data, fitting models, assessing fit, and preparing parameters to characterize distributional uncertainty in the model inputs.

For many exposure factors, EFH data include sample sizes and estimates of the following parameters for specific receptor types and age groups: mean, standard deviation, standard error, and percentiles corresponding to a subset of the following probabilities: 0.01, 0.02, 0.05, 0.10, 0.15, 0.25, 0.50, 0.75, 0.85, 0.90, 0.95, 0.98, and 0.99. These percentile data, where available, were used as a basis for fitting distributions. Although in no case were all of these percentiles actually provided for a single factor, seven or more are typically present in the EFH data. Therefore, using the percentiles is a fuller use of the available information than fitting distributions simply based on the method of moments (e.g., selecting models that agree with the data mean and standard deviation). For some factors, certain percentiles were not used in the fitting process because sample sizes were too small to justify their use. Percentiles were used only if at least one data point was in the tail of the distribution. If the EFH data repeated a value across several adjacent percentiles, only one value (the most central or closest to the median) was used in most cases (e.g., if both the 98^{th} and 99^{th} percentiles had the same value, only the 98^{th} value was used).

The EFH does not use standardized age cohorts across exposure factors. Different exposure factors have data reported for different age categories. Therefore, to obtain the percentiles for fitting the four standardized age cohorts (i.e., ages 1 to 5, 6 to 11, 12 to 19, and more than 20), each EFH cohort-specific value for a given exposure factor was assigned to one of these four cohorts. When multiple EFH cohorts fit into a single cohort, the EFH percentiles were averaged within each cohort (e.g., data on 1- to 2-year-olds and 3- to 5-year-olds were averaged for the 1- to 5-year-old cohort). If sample sizes were available, weighted averages were used, with weights proportional to sample sizes. If sample sizes were not available, equal weights were assumed (i.e., the percentiles were simply averaged).

Table F-1. Summary of Exposure Parameters Used in Probabilistic Analysis

Parameter	Units	Variable Type	Constants	Mean (or shape)	Std Dev (or scale)	Minimum	Maximum	Reference
Averaging time for carcinogens	yr	Constant	7.00E+01					U.S. EPA (1989)
Body weight (adult)	kg	Lognormal		7.12E+01	1.33E+01	1.50E+01	3.00E+02	U.S. EPA (1997a); Tables 7-2, 7-4, 7-5
Body weight (child 1)	kg	Lognormal		1.55E+01	2.05E+00	4.00E+00	5.00E+01	U.S. EPA (1997b); Tables 7-3, 7-6, 7-7
Body weight (child 2)	kg	Lognormal		3.07E+01	5.96E+00	6.00E+00	2.00E+02	U.S. EPA (1997a); Tables 7-3, 7-6, 7-7
Body weight (child 3)	kg	Lognormal		5.82E+01	1.02E+01	1.30E+01	3.00E+02	U.S. EPA (1997a); Tables 7-3, 7-6, 7-7
Consumption rate: fish (adult, child)	g/d	Lognormal		6.48E+00	1.99E+01	0.00E+00	1.50E+03	U.S. EPA (1997b); Table 10-64
Exposure duration (adult resident)	yr	Weibull		1.34E+00	1.74E+01	1.00E+00	5.00E+01	U.S. EPA (1999) (ACS)
Exposure duration (child)	yr	Weibull		1.32E+00	7.06E+00	1.00E+00	5.00E+01	U.S. EPA (1999) (ACS)
Exposure frequency (adult resident)	d/yr	Constant	3.50E+02					U.S. EPA Policy
Fraction contaminated: drinking water	Fraction	Constant	1.00E+00					U.S. EPA Policy
Fraction contaminated: fish	Fraction	Constant	1.00E+00					U.S. EPA Policy
Fraction of fish consumed that is trophic level (T3) fish	Fraction	Constant	3.60E-01					U.S. EPA (1997b); Table 10-66
Fraction of fish consumed that is trophic level 4 (T4) fish	Fraction	Constant	6.40E-01					U.S. EPA (1997b); Table 10-66
Ingestion rate: drinking water (adult resident)	mL/d	Gamma		3.88E+00	3.57E+02	1.04E+02	1.10E+04	U.S. EPA (1997a); Table 3-6
Ingestion rate: drinking water (child 1 resident)	mL/d	Gamma		2.95E+00	2.37E+02	2.60E+01	3.84E+03	U.S. EPA (1997a); Table 3-6
Ingestion rate: drinking water (child 2 resident)	mL/d	Gamma		3.35E+00	2.35E+02	3.40E+01	4.20E+03	U.S. EPA (1997a); Table 3-6
Ingestion rate: drinking water (child 3 resident)	mL/d	Gamma		2.82E+00	3.42E+02	3.30E+01	5.40E+03	U.S. EPA (1997a); Table 3-6

Because the EFH data are always positive and are almost always skewed to the right (i.e., have a long right tail), three two-parameter probability models commonly used to characterize such data (gamma, lognormal, and Weibull) were selected. In addition, a three-parameter model (generalized gamma) was used that unifies them[1] and allows for a likelihood ratio test of the fit of the two-parameter models. However, only the two-parameter models were selected for use in the analysis because the three-parameter generalized gamma model did not significantly improve the goodness of fit over the two-parameter models. This simple setup constitutes a considerable improvement over the common practice of using a lognormal model in which adequate EFH data are available to support maximum likelihood estimation.

Lognormal, gamma, Weibull, and generalized gamma distributions were fit to each factor data set using maximum likelihood estimation (Burmaster and Thompson, 1998). When sample sizes were available, the goodness of fit was calculated for each of the four models using the chi-square test (Bickel and Doksum, 1977). When percentile data were available but sample sizes were unknown, a regression F-test for the goodness of fit against the generalized gamma model was used. For each of the two-parameter models, parameter uncertainty information (i.e., mean, standard deviation, scale, and shape) was provided as parameter estimates for a bivariate normal distribution that could be used for simulating parameter values (Burmaster and Thompson, 1998). The information necessary for such simulations includes estimates of the two model parameters, their standard errors, and their correlation. To obtain this parameter uncertainty information, the asymptotic normality of the maximum likelihood estimate (Burmaster and Thompson, 1998) was used when sample sizes were available, and a regression approach was used when sample sizes were not available (Jennrich and Moore, 1975; Jennrich and Ralston, 1979). In either case, uncertainty can be expressed as a bivariate normal distribution for the model parameters.

Section F.1.3 discusses fixed parameters. Section F.1.4 describes, for each exposure factor, the EFH data used to develop the distributions, along with the final distributional statistics.

F.1.3 Fixed Parameters

Certain parameters were fixed, based on central tendency values from the best available source (usually EFH recommendations), either because no variability was expected or because the available data were not adequate to generate distributions. Fixed (constant) parameters are shown in Table F-2 along with the value selected for the risk analysis and the data source. These constants include variables for which limited or no percentile data were provided in the EFH: exposure frequency, fractions of T3 and T4 fish consumed, and fraction contaminated for the various media. Most of these values were extracted directly from the EFH. When evaluating carcinogens, total dose is averaged over the lifetime of the individual, assumed to be 70 years.

[1] Gamma, Weibull, and lognormal distributions are all special cases of the generalized gamma distribution.

Table F-2. Summary of Human Exposure Factor Data Used in Modeling: Constants

Description	Value	Units	Source
Fraction contaminated: drinking water	1	Fraction	EPA policy
Fraction contaminated: fish	1	Fraction	EPA policy
Fraction of T3 fish consumed	0.36	Fraction	U.S. EPA (1997b); Table 10-66
Fraction of T4 fish consumed	0.64	Fraction	U.S. EPA (1997b); Table 10-66
Exposure frequency (adult, child)	350	d/yr	EPA policy
Averaging time for carcinogens (adult, child)	70	yr	U.S. EPA (1989)

The fraction contaminated for drinking water was assumed to be 1 (i.e., all drinking water available for consumption at a site is potentially contaminated), with actual concentrations depending on fate and transport model results. Thus, households for which the drinking water pathway was analyzed were assumed to get 100 percent of their drinking water from groundwater. Exposure frequency was set to 350 days per year in accordance with EPA policy, assuming that residents take an average of 2 weeks' vacation time away from their homes each year.

F.1.4 Variable Parameters

F.1.4.1 Fish Consumption

Table F-3 presents fish consumption data and distributions. Fish consumption data were obtained from Table 10-64 of the EFH (U.S. EPA, 1997b). Data (in g/d) were available for adult freshwater anglers in Maine. The Maine fish consumption study was one of four recommended freshwater angler studies in the EFH (U.S. EPA, 1997b). The other recommended fish consumption studies (i.e., Michigan and New York) had large percentages of anglers who fished from Great Lakes, which is not consistent with the modeling scenarios used in this risk analysis. The anglers in the Maine study fished from streams, rivers, and ponds; these data are more consistent with our modeling scenarios. Although the Maine data have a lower mean than the Michigan data, the Maine data compared better with a national U.S. Department of Agriculture (USDA) study. Also, the Maine study included percentile data, which were necessary to develop a distribution.

Percentile data were used to fit parametric models (gamma, lognormal, and Weibull), and measures of goodness of fit were used to select lognormal as the most appropriate model. The fraction of fish intake that is locally caught was assumed to be 1 (in accordance with EPA policy). The fraction of consumed T3 and T4 fish was 0.36 and 0.64, respectively (Table 10-66, U.S. EPA, 1997b).

Table F-3. Fish Consumption Data and Distribution

EFH Data (g/d)									Distribution		
Age Cohort	N	Data Mean	Data SD	P50	P66	P75	P90	P95	Distribution	Pop-Estd Mean	Pop-Estd SD
All ages	1,053	6.4		2	4	5.8	13	26	Lognormal	6.48	19.9

N = Number of samples; P50–P95 = Percentiles; Pop-Estd = Population-estimated; SD = Standard deviation.

F.1.4.2 Drinking Water Intake

Table F-4 presents drinking water intake data and distributions. Drinking water intake data were obtained from Table 3-6 of the EFH (U.S. EPA, 1997a). Data (in mL/d) were presented by age groups. Weighted averages of percentiles, means, and standard deviations were calculated for the three child age groups and adults. Percentile data were used to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select the most appropriate model. The fraction of drinking water contaminated was assumed to be 1 (in accordance with EPA policy).

Table F-4. Drinking Water Intake Data and Distributions

EFH Data (mL/d)													Distributions		
Age Cohort	N	Data Mean	Data SD	P01	P05	P10	P25	P50	P75	P90	P95	P99	Distribution	Pop-Estd Mean	Pop-Estd SD
1–5	3,200	697.1	401.5	51.62	187.6	273.5	419.2	616.5	900.8	1,236	1,473	1,917	Gamma	698	406
6–11	2,405	787	417	68	241	318	484	731	1,016	1,338	1,556	1,998	Gamma	787	430
12–19	5,801	963.2	560.6	65.15	241.4	353.8	574.4	868.5	1,247	1,694	2,033	2,693	Gamma	965	574
20+	13,394	1,384	721.6	207.6	457.5	607.3	899.6	1,275	1,741	2,260	2,682	3,737	Gamma	1,383	703

N = Number of samples; P01–P99 = Percentiles; Pop-Estd = Population-estimated; SD = Standard deviation.

F.1.4.3 Body Weight

Table F-5 presents body weight data and distributions. Body weight data were obtained from Tables 7-2 through 7-7 of the EFH (U.S. EPA, 1997a). Data (in kg) were presented by age and gender. Weighted averages of percentiles, means, and standard deviations were calculated for 1- to 5-year-olds, 6- to 11-year-olds, 12- to 19-year olds, and adult age groups; male and female data were weighted and combined for each age group. These percentile data were used as the basis for fitting distributions. These data were analyzed to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select the most appropriate model.

Table F-5. Body Weight Data and Distributions

EFH Data (kg)													Distributions		
Age Cohort	N	Data Mean	Data SD	P05	P10	P15	P25	P50	P75	P85	P90	P95	Distribution	Pop-Estd Mean	Pop-Estd SD
1–5	3,762	15.52	3.719	12.5	13.1	13.45	14.03	15.26	16.67	17.58	18.32	19.45	Lognormal	15.5	2.05
6–11	1,725	30.84	9.561	22.79	24.05	25.07	26.44	29.58	33.44	36.82	39.66	43.5	Lognormal	30.7	5.96
12–19	2,615	58.45	13.64	43.84	46.52	48.31	50.94	56.77	63.57	68.09	71.98	79.52	Lognormal	58.2	10.2
20+	12,504	71.41	15.45	52.86	55.98	58.21	61.69	69.26	78.49	84.92	89.75	97.64	Lognormal	71.2	13.3

N = Number of samples; P05–P95 = Percentiles; Pop-Estd = Population-estimated; SD = Standard deviation.

F.1.4.4 Exposure Duration

Table F-6 presents exposure duration data and distributions. Exposure duration was assumed to be equivalent to the average residence time for each receptor. Exposure durations for adult and child residents were determined using data on residential occupancy from the EFH Table 15-168 (U.S. EPA, 1997c). The data represent the total time a person is expected to live at a single location, based on age. The table presents male and female data combined. Adult residents aged 21 to 90 were pooled. For child residents, the 3-year-old age group was used for the 1- to 5-year-olds. The 6- and 9-year-old age groups were pooled for the 6- to 11-year-old cohort.

Table F-6. Exposure Duration Data and Distributions

EFH Data		Distributions		
Age Cohort	Data Mean (yr)	Distribution	Pop-Estd Shape (yr)[a]	Pop-Estd Scale (yr)
1–5	6.5	Weibull	1.32	7.059
6–11	8.5	Weibull	1.69	9.467
Adult	16.0	Weibull	1.34	17.38

Pop-Estd = Population-estimated.
[a] Distributions used in risk assessment.

In an analysis of residential occupancy data, Myers et al. (U.S. EPA, 2000) found that the data, for most ages, were best fit by a Weibull distribution. The Weibull distribution as implemented in Crystal Ball® is characterized by three parameters: location, shape, and scale. Location is the minimum value and, in this case, was presumed to be 0. Shape and scale were determined by fitting a Weibull distribution to the pooled data, as follows. To pool residential occupancy data for the age cohorts, an arithmetic mean of data means was calculated for each age group. Then, assuming a Weibull distribution, the variance within each age group (e.g., 6-year-olds) was calculated in the age cohort. These variances in turn were pooled over the age cohort using equal weights. This is not the usual type of pooled variance, which would exclude the variation in the group means. However, this way, the overall variance reflected the variance of means within the age groups (e.g., within the 6-year-old age group). The standard deviation was estimated as the square root of the variance. The coefficient of variation was calculated as the ratio of the standard deviation divided by the Weibull mean. For each cohort, the population-estimated parameter uncertainty information (e.g., shape and scale) was calculated based on a Weibull distribution, the calculated data mean for the age cohort, and the CV.

F.2 References

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Appendix G. Human Health Benchmarks

The coal combustion waste (CCW) risk assessment will require human health benchmarks to assess potential risks from chronic oral and inhalation exposures. The U.S. Environmental Protection Agency (EPA) uses reference doses (RfDs) and reference concentrations (RfCs) to evaluate noncancer risk from oral and inhalation exposures, respectively. Oral cancer slope factors (CSFs), inhalation unit risk factors (URFs), and inhalation CSFs are used to evaluate risk for carcinogens.

This appendix provides the human health benchmarks used in the CCW screening and risk assessment. Section G.1 describes the data sources and general hierarchy used to collect these benchmarks. Section G.2 provides the benchmarks along with discussions of individual human health benchmarks extracted from a variety of sources.

G.1 Methodology and Data Sources

Several sources of health benchmarks are available. The hierarchy used health benchmarks developed by EPA to the extent that they were available. The analysis used available benchmarks from non-EPA sources for chemicals for which EPA benchmarks were not available, and ranked human health benchmark sources in the following order of preference:

- Integrated Risk Information System (IRIS)
- Superfund Technical Support Center Provisional Benchmarks
- Health Effects Assessment Summary Tables (HEAST)
- EPA health assessment documents
- Various other EPA health benchmark sources
- Agency for Toxic Substances and Disease Registry (ATSDR) minimal risk levels (MRLs)
- California Environmental Protection Agency (CalEPA) chronic inhalation reference exposure levels (RELs) and cancer potency factors.

G.1.1 Integrated Risk Information System (IRIS)

Benchmarks in IRIS are prepared and maintained by EPA, and RTI used values from IRIS whenever available. IRIS is EPA's electronic database containing information on human health effects (U.S. EPA, 2002). Each chemical file contains descriptive and quantitative information on potential health effects. Health benchmarks for chronic noncarcinogenic health

effects include RfDs and RfCs. Cancer classification, oral CSFs, and inhalation URFs are included for carcinogenic effects. IRIS is the official repository of Agency-wide consensus of human health risk information.

Inhalation CSFs are not available from IRIS, so we calculated them from inhalation URFs (which are available from IRIS) using the following equation:

$$inh\ CSF = inh\ URF \times 70\,kg \div 20\,m^3/d \times 1000\,\mu g/mg$$

In this equation, 70 kg represents average body weight; 20 m^3/d represents average inhalation rate; and 1000 µg/mg is a units conversion factor (U.S. EPA, 1997). EPA uses these standard estimates of body weight and inhalation rate in the calculation of the URF; therefore, we used these values to calculate inhalation CSFs.

G.1.2 Superfund Provisional Benchmarks

The Superfund Technical Support Center (EPA's National Center for Environmental Assessment [NCEA]) derives provisional RfCs, RfDs, and CSFs for certain chemicals. These provisional health benchmarks can be found in Risk Assessment Issue Papers. Some of the provisional values have been externally peer reviewed. These provisional values have not undergone EPA's formal review process for finalizing benchmarks and do not represent Agency-wide consensus information.

G.1.3 Health Effects Assessment Summary Tables

HEAST is a listing of provisional noncarcinogenic and carcinogenic health toxicity values (RfDs, RfCs, URFs, and CSFs) derived by EPA (U.S. EPA, 1997). Although the health toxicity values in HEAST have undergone review and have the concurrence of individual EPA program offices, either they have not been reviewed as extensively as those in IRIS or their data set is not complete enough to be listed in IRIS. HEAST benchmarks have not been updated in several years and do not represent Agency-wide consensus information.

G.1.4 Other EPA Health Benchmarks

EPA has also derived health benchmark values in other risk assessment documents, such as Health Assessment Documents (HADs), Health Effects Assessments (HEAs), Health and Environmental Effects Profiles (HEEPs), Health and Environmental Effects Documents (HEEDs), Drinking Water Criteria Documents, and Ambient Water Quality Criteria Documents. Evaluations of potential carcinogenicity of chemicals in support of reportable quantity adjustments were published by EPA's Carcinogen Assessment Group (CAG) and may include cancer potency factor estimates. Health benchmarks derived by EPA for listing determinations (e.g., solvents) or studies (e.g., Air Characteristic Study) are also available. Health toxicity values identified in these EPA documents are usually dated and are not recognized as Agency-wide consensus information or verified benchmarks.

G.1.5 ATSDR Minimal Risk Levels

The ATSDR MRLs are substance-specific health guidance levels for noncarcinogenic endpoints (ATSDR, 2002). An MRL is an estimate of the daily human exposure to a hazardous substance that is likely to be without appreciable risk of adverse noncancer health effects over a specified duration of exposure. MRLs are based on noncancer health effects only and are not based on a consideration of cancer effects. MRLs are derived for acute, intermediate, and chronic exposure durations for oral and inhalation routes of exposure. Inhalation and oral MRLs are derived in a manner similar to EPA's RfCs and RfDs, respectively (i.e., ATSDR uses the no observed adverse effect level/uncertainty factor [NOAEL/UF] approach); however, MRLs are intended to serve as screening levels and are exposure duration specific. Also, ATSDR uses EPA's (U.S. EPA, 1994) inhalation dosimetry methodology in the derivation of inhalation MRLs.

G.1.6 CalEPA Cancer Potency Factors and Reference Exposure Levels

CalEPA has developed cancer potency factors for chemicals regulated under California's Hot Spots Air Toxics Program (CalEPA, 1999a). The cancer potency factors are analogous to EPA's oral and inhalation CSFs. CalEPA has also developed chronic inhalation RELs, analogous to EPA's RfC, for 120 substances (CalEPA, 1999b, 2000). CalEPA used EPA's (U.S. EPA, 1994) inhalation dosimetry methodology in the derivation of inhalation RELs. The cancer potency factors and inhalation RELs have undergone internal peer review by various California agencies and have been the subject of public comment.

G.1.7 Surrogate Health Benchmarks

If no human health benchmarks were available from EPA or alternative sources, we sought benchmarks for similar chemicals to use as surrogate data. For example, the health benchmark of a mixture could serve as the surrogate benchmark for its components or a benchmark of a metal salt could serve as the surrogate for an elemental metal.

G.2 Human Health Benchmarks

The chronic human health benchmarks used to calculate the health-based numbers (HBNs) in the CCW risk assessment are summarized in Table G-1, which provides the Chemical Abstract Service Registry Number (CASRN), constituent name, RfD (mg/kg-d), RfC (mg/m^3), oral CSF ($mg/kg\text{-}d^{-1}$), inhalation URF [$(\mu g/m^3)^{-1}$], inhalation CSF ($mg/kg\text{-}d^{-1}$), and reference for each benchmark. A key to the references cited and abbreviations used is provided at the end of the table.

For a majority of constituents, human health benchmarks were available from IRIS (U.S. EPA, 2002), Superfund Provisional Benchmarks, or HEAST (U.S. EPA, 1997). Benchmarks also were obtained from ATSDR (2002) or CalEPA (1999a, 1999b, 2000). This section describes benchmarks obtained from other sources, along with the Superfund Provisional Benchmarks values and special uses of IRIS benchmarks.

Provisional inhalation health benchmarks were developed in the Air Characteristic Study (U.S. EPA, 1999) for several constituents lacking IRIS, HEAST, alternative EPA, or ATSDR

values. For vanadium, the study on which the ATSDR acute inhalation MRL is based was used but was adjusted for chronic exposure. Additional details on the derivation of this inhalation benchmark can be found in the *Revised Risk Assessment for the Air Characteristic Study* (U.S. EPA, 1999).

The provisional RfD of 0.02 mg/kg-d developed by NCEA for the Superfund Technical Support Center (U.S. EPA, 2001a) was used for cobalt.

Table G-1. Human Health Benchmarks Used in CCW Risk Assessment

Constituent Name	CASRN	RfD (mg/kg-d)	Ref	RfC (mg/m^3)	Ref	CSFo (per mg/kg-d)	Ref	URF (per µg/m3)	Ref	CSFi (per mg/kg-d)	Ref	MCL (mg/L)	Notes
Aluminum	7429-90-5	2.0E+00	A										RfD is for intermediate duration
Ammonia	7664-41-7	9.7E-01	H	1.0E-01	I								RfD= 34 mg/L
Antimony	7440-36-0	4.0E-04	I	2.0E-04	I								RfC is for antimony trioxide
Arsenic, inorganic	7440-38-2	3.0E-04	I	3.0E-05	Cal00	1.5E+0	I	4.3E-3	I	1.5E+1	calc		
Barium	7440-39-3	7.0E-02	I	5.0E-04	H								
Beryllium	7440-41-7	2.0E-03	I	2.0E-05	I			2.4E-3	I	8.4E+0	calc		
Boron	7440-42-8	9.0E-02	I	2.0E-02	H								
Cadmium	7440-43-9	5.0E-04	I	2.0E-05	Cal00			1.8E-3	I	6.3E+0	calc		RfD for H_2O (food = 1E-3)
Chloride	16887-00-6											250	
Chromium (III), insoluble salts	16065-83-1	1.5E+00	I										
Chromium (VI)	18540-29-9	3.0E-03	I	1.0E-04	I			1.2E-2	I	4.2E+1	calc		
Cobalt (and compounds)	7440-48-4	2.0E-02	SF	1.0E-04	A			2.8E-3	SF	9.8E+0	calc		
Copper	7440-50-8											1.3	
Cyanide (amenable)	57-12-5	2.0E-02	I										
Divalent mercury		3.0E-04	H										RfD is for mercuric chloride; used for food, water, soil
Divalent mercury		1.0E-04	I										RfD is for methyl mercury; used for fish only
Fluoride	16984-48-8	1.2E-01	I										RfD is for fluorine; the alternative IRIS value (for skeletal, rather than dental, fluorosis) was used
Iron	7439-89-6											0.3	
Lead and compounds (inorganic)	7439-92-1											0.015	
Manganese	7439-96-5	1.4E-01	I	5.0E-05	I								RfD for food; H_2O and soil = 4.7E-2 mkd
Molybdenum	7439-98-7	5.0E-03	I										

(continued)

Table G-1. (continued)

Constituent Name	CASRN	RfD (mg/kg-d)	Ref	RfC (mg/m^3)	Ref	CSFo (per mg/kg-d)	Ref	URF (per µg/m3)	Ref	CSFi (per mg/kg-d)	Ref	MCL (mg/L)	Notes
Nickel, soluble salts	7440-02-0	2.0E-02	I	2.0E-04	A								
Nitrate	14797-55-8	1.6E+00	I									10	
Nitrite	14797-65-0	1.0E-01	I										
Selenium	7782-49-2	5.0E-03	I	2.0E-02	Cal00								
Silver	7440-22-4	5.0E-03	I										
Strontium	7440-24-6	6.0E-01	I										
Sulfate	14808-79-8											250	
Thallium, elemental	7440-28-0	8.0E-05	I										RfD is for thallium chloride
Total dissolved solids												500	
Vanadium	7440-62-2	7.0E-03	H	7.0E-05	AC								
Zinc	7440-66-6	3.0E-01	I										

Key: CASRN = Chemical Abstract Service registry number. CSFo = Oral cancer slope factor.
RfD = Reference dose. CSFi = Inhalation cancer slope factor.
RfC = Reference concentration. URF = Unit risk factor.
MCL = Maximum contaminant level.

[a] Sources:
A = ATSDR MRLs (ATSDR, 2002)
AC = Developed for the Air Characteristic Study (U.S. EPA, 1999)
calc = Calculated
Cal00 = CalEPA chronic REL (CalEPA, 2000)
H = HEAST (U.S. EPA, 1997)
I = IRIS (U.S. EPA, 2002)
SF = Superfund Risk Issue Paper (U.S. EPA, 2001a,b)

For several constituents, IRIS benchmarks for similar chemicals were used as surrogate data. The rationale for these recommendations is as follows:

- The RfC for antimony trioxide (2E-04 mg/m^3) was used as a surrogate for antimony.
- Fluoride was based on fluorine. The IRIS RfD for fluorine is based on soluble fluoride. The primary RfD cited in IRIS (6E-02 mg/kg-d) is for dental fluorosis, a cosmetic effect. In this analysis, an alternative IRIS value (1.2E-01 mg/kg-d) for skeletal fluorosis in adults was used instead.
- The RfC for mercuric chloride (9E-05 mg/m^3) was used as a surrogate for elemental mercury. The RfDs for mercuric chloride (3E-04 mg/kg-d) and methyl mercury (1E-04 mg/kg-d) were used as surrogates for elemental mercury for assessing potential risks from food, soil, and water ingestion, and fish ingestion, respectively.
- Thallium was based on thallium chloride. There are several thallium salts that have RfDs in IRIS. The lowest value among the thallium salts (8E-05 mg/kg-d) is routinely used to represent thallium in risk assessments.

G.3 References

ATSDR (Agency for Toxic Substances and Disease Registry). 2002. *Minimal Risk Levels (MRLs) for Hazardous Substances.* Available: http://www.atsdr.cdc.gov/mrls.html

CalEPA (California Environmental Protection Agency). 1999a. *Air Toxics Hot Spots Program Risk Assessment Guidelines: Part II. Technical Support Document for Describing Available Cancer Potency Factors*. Office of Environmental Health Hazard Assessment, Berkeley, CA. Available: http://www.oehha.org/air/cancer_guide/hsca2.html

CalEPA (California Environmental Protection Agency). 1999b. *Air Toxics Hot Spots Program Risk Assessment Guidelines: Part III. Technical Support Document for the Determination of Noncancer Chronic Reference Exposure Levels*. SRP Draft. Office of Environmental Health Hazard Assessment, Berkeley, CA. Available (in two sections): http://www.oehha.org/air/chronic_rels/ragsii.html, http://www.oehha.org/air/chronic_rels/RAGSp3draft.html.

CalEPA (California Environmental Protection Agency). 2000. *Air Toxics Hot Spots Program Risk Assessment Guidelines: Part III. Technical Support Document for the Determination of Noncancer Chronic Reference Exposure Levels*. Office of Environmental Health Hazard Assessment, Berkeley, CA. Available (in four sections): http://www.oehha.org/air/chronic_rels/22RELS2k.html http://www.oehha.org/air/chronic_rels/42kChREL.html http://www.oehha.org/air/chronic_rels/Jan2001ChREL.html http://www.oehha.org/air/chronic_rels/1201Crels.html

U.S. EPA (Environmental Protection Agency). 1994. *Methods for Derivation of Inhalation Reference Concentrations and Application of Inhalation Dosimetry*. EPA/600/8-90-066F.

Environmental Criteria and Assessment Office, Office of Health and Environmental Assessment, Office of Research and Development, Research Triangle Park, NC.

U.S. EPA (Environmental Protection Agency). 1997. *Health Effects Assessment Summary Tables (HEAST)*. EPA-540-R-97-036. FY 1997 Update. Office of Solid Waste and Emergency Response, Washington, DC.

U.S. EPA (Environmental Protection Agency). 1999. *Revised Risk Assessment for the Air Characteristic Study*. EPA-530-R-99-019a. Volume 2. Office of Solid Waste, Washington, DC.

U.S. EPA (Environmental Protection Agency). 2001a. *Risk Assessment Paper for Derivation of a Provisional RfD for Cobalt and Compounds (CASRN 7440-48-4).* 00-122/3-16-01. National Center for Environmental Assessment. Superfund Technical Support Center, Cincinnati, OH.

U.S. EPA (Environmental Protection Agency). 2001b. *Risk Assessment Paper for Derivation of a Provisional Carcinogenicity Assessment for Cobalt and Compounds (CASRN 7740-48-4).* 00-122/3-16-01. National Center for Environmental Assessment. Superfund Technical Support Center, Cincinnati, OH.

U.S. EPA (Environmental Protection Agency). 2002. Integrated Risk Information System (IRIS). National Center for Environmental Assessment, Office of Research and Development, Washington, DC. Available: http://www.epa.gov/iris/

Appendix H. Ecological Benchmarks

Both the screening and full-scale CCW assessments include an ecological risk assessment that parallels the human health risk assessment. The ecological risk assessment addresses two routes of exposure for ecological receptors: direct contact with contaminated media and ingestion of contaminated food items. For each CCW chemical for which ecological effect data were available, hazard quotients (HQs) were calculated using chemical-specific media concentrations assumed to be protective of ecological receptors of concern.

This appendix provides the ecological benchmarks used in both the CCW screening and full-scale risk assessment. Section H.1 describes the data sources and methods used to develop these benchmarks. Additional details can be found in U.S. EPA (1998). Section H.2 provides the benchmarks.

H.1 Data Sources and Methodology

To calculate ecological HQs, the concentration-based ecological benchmarks (also known as chemical stressor concentration limits, or CSCLs) were divided by the estimated concentrations of constituents in environmental media contaminated by CCW. The CSCLs are environmental quality criteria intended to represent a protective threshold value for adverse effects to various ecological receptors in terrestrial (soil) and aquatic ecosystems (surface water and sediment). An HQ greater than target of 1 indicates that the predicted concentration will be above the CSCL and, therefore, the potential for adverse ecological effects exists. In this regard, the use of CSCLs to calculate an ecological HQ is analogous to the use of the reference concentration (RfC) for human health where the air concentration is compared to the health-based concentration (the RfC), and an HQ greater than the target value of 1 is considered to indicate the potential for adverse health effects. Table H-1 shows the receptor types assessed for each exposure route in each environmental medium addressed by the CCW risk assessment.

Table H-1. Ecological Receptors Assessed by Medium Impacted by CCW

Receptor Type	Surface Water	Sediment	Soil
Direct Contact Exposure			
Aquatic Community	✔		
Sediment Community		✔	
Soil Community			✔
Amphibians	✔		
Aquatic Plants and Algae	✔		
Terrestrial Plants			✔
Ingestion Exposure			
Mammals	✔		✔
Birds	✔		✔

Ecological benchmarks for the CCW risk assessment were taken directly from the 1998 fossil fuel combustion risk analysis, *Non-Groundwater Pathways, Human Health and Ecological Risk Analysis for Fossil Fuel Combustion Phase 2 (FFC2)* (U.S. EPA, 1998). The receptors and endpoints selected for the 1998 analysis were evaluated and considered appropriate for the goals of this risk assessment. The benchmarks were derived for each chemical and receptor to the extent that supporting data were available.

As in 1998, the lowest (most sensitive) benchmark for each chemical in each medium was selected to calculate HQs in the CCW risk assessment. For example, several receptors (soil invertebrates, terrestrial plants, mammals, and birds) are exposed to constituents in soils. The soil HQ for a given chemical was calculated using whichever soil benchmark was lowest and would thus give the highest (most conservative) HQ.

H.1.1 Direct Contact Exposure

Ecological receptors that live in close contact with contaminated media are considered to be potentially at risk. These receptors are exposed through direct contact with contaminants in surface water, sediment, and soil. The receptors selected to assess the direct contact exposure route for each medium were previously summarized in Table H-1. The benchmarks for receptor communities are not truly *community-level* concentration limits in that they do not consider predator-prey interactions. Rather, they are based on the theory that protection of 95 percent of the species in the community will provide a sufficient level of protection for the community (see, for example, Stephan et al., 1985, for additional detail). The following sections summarize the benchmark derivation methods for each receptor assessed for the direct contact route of exposure.

Aquatic Community Benchmarks

The aquatic community receptor comprises fish and aquatic invertebrates exposed through direct contact with constituents in surface water. For the aquatic community, the final chronic value (FCV), developed either for the Great Lakes Water Quality Initiative (U.S. EPA, 1993) or the National Ambient Water Quality Criteria (NAWQC) (U.S. EPA, 1995a,b), was the preferred source for the benchmark. If an FCV was unavailable and could not be calculated from available data, a secondary chronic value (SCV) was estimated using methods developed for wildlife criteria for the Great Lakes Initiative (e.g., 58 FR 20802; U.S. EPA, 1993). The SCV methodology is based on the original species data set established for the NAWQC; however, it requires fewer data points and includes statistically derived adjustment factors. For benchmark derivation, the minimum data set required at least one data point.

Amphibian Benchmarks

For amphibian populations, data availability severely limited benchmark development. A review of several compendia presenting amphibian ecotoxicity data (e.g., U.S. EPA, 1996; Power et al., 1989), as well as primary literature sources, found a lack of standard methods on endpoints, species, and test durations necessary to derive a chronic benchmark for amphibians. Consequently, an acute benchmark was derived for aqueous exposures in amphibians by taking a geometric mean of LC_{50} (i.e., concentration lethal to 50 percent of test subjects) data identified in studies with exposure durations less than 8 days. Although the use of acute effects levels is not

consistent with other benchmarks, the sensitivity of these receptors warrants their use in lieu of chronic concentration limits. Recent studies (Hopkins and Rowe, 2004; Hopkins et al., 2006) have confirmed that amphibians are among the most sensitive taxa to metals found in CCW, and selenium appears to be a significant stressor in CCW disposal scenarios. The endpoints considered in these studies were related to population sustainability and, consequently, are highly relevant to ecological risk assessment. However, these field studies are confounded by the fact that wildlife were exposed to multiple chemical pollutants (including radionuclides) and, as a result, acute effects data on individual metals remain the most appropriate source for quantitative benchmarks to assess the potential for adverse effects in amphibians.

Sediment Community Benchmarks

For the sediment community, benchmarks were selected based on a complete assessment of several sources proposing sediment benchmark values. Primary sources evaluated for developing sediment community benchmarks are shown in Table H-2.

Table H-2. Primary Sources Evaluated for Developing Sediment Community Benchmarks

Long, E.R., and L.G. Morgan. 1991. *The Potential for Biological Effects of Sediment-Sorbed Contaminants Tested in the National Status and Trends Program*. Technical Memorandum NOS OMA 52. National Oceanic and Atmospheric Administration (NOAA), Washington, DC.
Jones, D.S., G.W. Suter, II, and R.N. Hull. 1997. *Toxicological Benchmarks for Screening Contaminants of Potential Concern for Effects on Sediment-Associated Biota: 1997 Revision.* Oak Ridge National Laboratory, Oak Ridge, TN.
U.S. EPA (Environmental Protection Agency). 1997. *Protocol for Screening Level Ecological Risk Assessment at Hazardous Waste Combustion Facilities*. Internal Review Draft, February 28. Office of Solid Waste, Washington, DC.
U.S. EPA (Environmental Protection Agency). 1995. *Technical Support Document for the Hazardous Waste Identification Rule: Risk Assessment for Human and Ecological Receptors.* Office of Solid Waste, Washington, DC.
MacDonald, D.D. 1994. *Approach to the Assessment of Sediment Quality in Florida Coastal Waters. Volume 1*. Florida Department of Environmental Protection, Tallahassee, FL.

Soil Community Benchmarks

For the soil community, the preferred methods for deriving benchmarks are analogous to those used in deriving the NAWQC. Benchmark values for soil fauna were estimated to protect 95 percent of the species found in a typical soil community, including earthworms, insects, and various other soil fauna. The methodology presumes that protecting 95 percent of the soil species with a 50^{th} percentile level of confidence will ensure long-term sustainability of a functioning soil community. The toxicity data on soil fauna were taken from several major compendia and supplemented with additional studies identified in the open literature.

The approach to calculating benchmarks for the soil community is based on efforts by Dutch scientists (i.e., the Netherlands' National Institute of Public Health and Environmental Protection [RIVM] methodology) to develop hazardous concentrations (HCs) at specified levels

of protection (primarily 95 percent) at both a 95th percentile and a 50th percentile level of confidence (Sloof, 1992). For the soil fauna benchmarks, the 50th percentile level of confidence was selected because the 95th percentile appeared to be overly conservative for a "no effects" approach. The RIVM methodology follows two steps: (1) fitting a distribution to the log of the selected endpoints, and (2) extrapolating to a benchmark concentration based on the mean and standard deviation of a set of endpoints. The key assumptions in the Dutch methodology are that (1) lowest observed effects concentration (LOEC) data are distributed logistically, and (2) the 95 percent level of protection is ecologically significant. The following formula was used to calculate soil fauna benchmarks:

$$HC_{5\%} = \left[x_m - k_1 s_m\right] \quad \text{(H-1)}$$

where

$HC_{5\%}$ = soil concentration protecting 95 percent of the soil species
x_m = sample mean of the log LOEC data
k_l = extrapolation constant for calculating the one-sided leftmost confidence limit for a 95 percent protection level
s_m = sample standard deviation of the log LOEC data.

Sufficient data were available to develop benchmarks using this methodology for four of the metals of concern: cadmium, copper, lead, and zinc. For the remaining constituents, benchmark studies identifying effects to earthworms and other soil biota proposed by Oak Ridge National Laboratory (Efroymson et al., 1997a) or criteria developed by the Canadian Council of Ministers of the Environment (CCME, 1997) were used to estimate protective soil concentrations.

Algae and Aquatic Plant Benchmarks

For algae and aquatic plants, adverse effects concentrations are identified in the open literature or from a data compilation presented in *Toxicological Benchmarks for Screening Potential Contaminants of Concern for Effects on Aquatic Biota: 1996 Revision* (Suter and Tsao, 1996). For most contaminants, studies were not available for aquatic vascular plants, and lowest effects concentrations were identified for algae. The benchmark for algae and aquatic plants was based on (1) an LOEC for vascular aquatic plants or (2) an effective concentration (EC_{xx}) for a species of freshwater algae, frequently a species of green algae (e.g., *Selenastrum capricornutum*). Because of the lack of data for this receptor group and the differences between vascular aquatic plants and algae sensitivity, the lowest value of those identified was usually chosen.

Terrestrial Plant Benchmarks

For the terrestrial plant community, ecotoxicological data were identified from a summary document prepared at the Oak Ridge National Laboratory: *Toxicological Benchmarks for Screening Contaminants of Potential Concern for Effects on Terrestrial Plants: 1997 Revision* (Efroymson et al., 1997b). The measurement endpoints are generally limited to growth and yield parameters because (1) they are the most common class of response reported in phytotoxicity studies and, therefore, will allow for criterion calculations for a large number of

constituents, and (2) they are ecologically significant responses both in terms of plant populations and, by extension, the ability of producers to support higher trophic levels. As presented in Efroymson et al. (1997a), benchmarks for phytotoxicity were selected by rank ordering the LOEC values and then approximating the 10^{th} percentile. If there were 10 or fewer values for a chemical, the lowest LOEC was used. If there were more than 10 values, the 10^{th} percentile LOEC was used.

H.1.2 Ingestion Exposure

The ingestion route of exposure addresses the exposure of terrestrial mammals and birds through ingestion of plants and prey and incidental soil ingestion. Thus, the CCW ecological benchmarks for ingestion exposure express media concentrations that, based on certain assumptions about receptor diet and foraging behavior, are expected to be protective of populations of mammals and birds feeding and foraging in contaminated areas.

The derivation of ingestion benchmarks begins with the selection of appropriate ecotoxicological data based on a hierarchy of data sources. The assessment endpoint for the CCW ecological risk assessment is population viability; therefore, ecological benchmarks were developed from measures of reproductive/developmental success or, if unavailable, from other effects that could conceivably impair population dynamics. Population-level benchmarks are preferred over benchmarks for individual organisms; however, very few population-level benchmarks have been developed. Therefore, the CCW risk assessment uses benchmarks derived from individual organism studies, and protection is inferred at the population level.

Once an appropriate ingestion exposure study was identified, a benchmark was calculated using a three-step process. The remainder of this section outlines the basic technical approach used to convert avian or mammalian benchmarks (in daily doses) to the media concentration benchmarks (in units of concentration) used to assess ecological risks for surface water and soil contaminated by CCW waste constituents. The methods reflect exposure through the ingestion of contaminated plants, prey, and various media, and include parameters on accumulation (e.g., bioconcentration factors), uptake (e.g., consumption rates), and dietary preferences.

Step 1: Scale Benchmark

The benchmarks derived for test species can be extrapolated to wildlife receptor species within the same taxon using a cross-species scaling equation (Equation H-2) (Sample et al., 1996). This is the default methodology EPA proposed for carcinogenicity assessments and reportable quantity documents for adjusting animal data to an equivalent human dose (57 FR 24152).

$$Benchmark_w = LOAEL_t \times \left(\frac{bw_t}{bw_w} \right)^{1/4} \quad \text{(H-2)}$$

where

$Benchmark_w$ = scaled ecological benchmark for species *w* (mg/kg/d)
$LOAEL_t$ = lowest observed adverse effects level for test species (mg/kg/d)
bw_t = body weight of the surrogate test species (kg)
bw_w = body weight of the representative wildlife species (kg).

Step 2: Identify Bioconcentration Factors / Bioaccumulation Factors

For metal constituents, whole-body bioconcentration factors (BCFs) and bioaccumulation factors (BAFs) were identified for aquatic and terrestrial organisms that may be used as food sources (e.g., fish, plants, earthworms). The Oak Ridge National Laboratory has proposed methods and data that are useful in predicting bioaccumulation in earthworms and small mammals (Sample et al. 1998a,b). These values were typically identified in the open literature and EPA references.

Step 3: Calculate Benchmarks

The following equation provides the basis for calculating surface water benchmarks using a population-inference benchmark (e.g., endpoint on fecundity).

$$Benchmark = \frac{\left[I_{fish} \times \left(BAF \;\; C_w\right)\right] + \left(I_w \times C_w\right)}{bw} \quad \text{(H-3)}$$

where

I_{fish} = intake of contaminated fish (kg/d)
BAF = whole-body bioaccumulation factor (L/kg)
bw = weight of the representative species (kg)
I_w = intake of contaminated water (L/d)
C_w = total concentration in the water (mg/L).

For chemicals that bioaccumulate significantly in fish tissue, the ingestion of contaminated food will tend to dominate the exposure (i.e., $[I_{fish} \times C_{fish}] >> [I_w\ C_w]$), and the water term (i.e., $[I_w \times C_w]$) can be dropped from Equation H-3, resulting in Equation H-4:

$$Benchmark \;=\; \frac{I_{fish} \;\times\; \left(BAF \;\times\; C_w\right)}{bw} \quad \text{(H-4)}$$

At the benchmark dose (mg/kg/d), the concentration in water is equivalent to the chemical stressor concentration limit for that receptor as a function of body weight, ingestion rate, and the bioaccumulation potential for the chemical of concern. Hence, Equation H-4 can be rewritten to solve for the surface water ($CSCL_{sw}$) as follows:

$$CSCL_{sw} \;=\; \frac{benchmark \;\times\; bw}{I_w \;+\; \left(I_{fish} \;\times\; BAF\right)} \quad \text{(H-5)}$$

For wildlife populations of mammals and birds in terrestrial systems, the soil benchmark ($CSCL_{soil}$) for a given receptor was calculated using Equation H-6:

$$CSCL_{soil} = \frac{benchmark \times bw}{I_{food} \sum \left(BCF_j \times F_j \times AB_j\right) + I_{soil}} \quad \text{(H-6)}$$

where

bw	=	body weight (kg)
I_{food}	=	total daily food intake of species (kg/d)
I_{soil}	=	total daily soil intake of species (kg/d)
BCF_j	=	bioaccumulation factor in food item *j* (assumed unitless)
F_j	=	fraction of diet consisting of food item *j* (unitless)
AB_j	=	absorption of chemical in the gut from food item *j*.

H.2 Ecological Benchmarks

The ecological benchmarks used to calculate ecological HQs in the CCW risk assessment are summarized in Table H-3, which provides the constituent name; the criterion and receptor for soil, sediment, and aquatic receptors; and the source for each benchmark.

Table H-3. Ecological Benchmarks Used in the CCW Risk Assessment

Constituent	Soil Criterion (mg/kg)	Terrestrial Receptor	Sediment Criterion (mg/kg)	Sediment Receptor	Aquatic Criterion (mg/L)	Aquatic Receptor	Source
Aluminum	ID	--	ID	--	0.09	Aquatic Biota	U.S. EPA (1998)
Antimony	14	Raccoon	2	Sediment biota	0.03	Aquatic Biota	U.S. EPA (1998)
Arsenic total	10	Plants	0.51	Spotted sandpiper	ID	--	U.S. EPA (1998)
Arsenic III	ID	--	ID	--	0.15	Aquatic Biota	U.S. EPA (1998)
Arsenic IV	ID	--	ID	--	8.10E-03	Aquatic Biota	U.S. EPA (1998)
Barium	500	Plants	190	Spotted sandpiper	4.00E-03	Aquatic Biota	U.S. EPA (1998)
Beryllium	ID	--	ID	--	6.60E-04	Aquatic Biota	U.S. EPA (1998)
Boron	0.5	Plants	ID	--	1.60E-03	Aquatic Biota	U.S. EPA (1998)
Cadmium	1	Soil invertebrates	0.68	Sediment biota	2.50E-03	Aquatic Biota	U.S. EPA (1998)
Chromium total	64	Soil invertebrates	16.63	Spotted sandpiper	ID	--	U.S. EPA (1998)
Chromium IV	ID	--	ID	--	0.09	Aquatic Biota	U.S. EPA (1998)
Chromium VI	ID	--	ID	--	0.01	Aquatic Biota	U.S. EPA (1998)
Cobalt	1000	Soil invertebrates	ID	--	0.02	Aquatic Biota	U.S. EPA (1998)
Copper	21	Soil invertebrates	18.7	Sediment biota	9.30E-03	Aquatic Biota	U.S. EPA (1998)
Lead	28	Soil invertebrates	0.22	Spotted sandpiper	3.00E-04	River Otter	U.S. EPA (1998)
Mercury	0.1	Soil invertebrates	0.11	Spotted sandpiper	1.90E-07	Kingfisher	U.S. EPA (1998)
Molybdenum	42.08	Amer. woodcock	34	Spotted sandpiper	0.37	Aquatic Biota	U.S. EPA (1998)
Nickel	30	Plants	15.9	Sediment biota	0.05	Aquatic Biota	U.S. EPA (1998)
Selenium total	1	Plants	ID	--	5.00E-03	Aquatic Biota	U.S. EPA (1998)
Selenium IV	ID	--	ID	--	0.03	Aquatic Biota	U.S. EPA (1998)

(continued)

Table H-3. (continued)

Constituent	Soil Criterion (mg/kg)	Terrestrial Receptor	Sediment Criterion (mg/kg)	Sediment Receptor	Aquatic Criterion (mg/L)	Aquatic Receptor	Source
Selenium VI	ID	--	ID	--	9.50E-03	Aquatic Biota	U.S. EPA (1998)
Silver	ID	--	0.73	Sediment biota	3.60E-04	Aquatic Biota	U.S. EPA (1998)
Thallium	ID	--	ID	--	0.01	Aquatic Biota	U.S. EPA (1998)
Vanadium	130.00	Soil invertebrates	18	Spotted sandpiper	0.02	Aquatic Biota	U.S. EPA (1998)
Zinc	50	Plants	120	Sediment biota	0.12	Aquatic Biota	U.S. EPA (1998)

ID = insufficient data.

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Document 23

USEPA, Human and Ecological Risk Assessment of Coal Combustion Residuals, 2050-AE81 (December 2014) (Deposition Exhibit 17)

HUMAN AND ECOLOGICAL RISK ASSESSMENT OF COAL COMBUSTION RESIDUALS

Final

December 2014

U.S. Environmental Protection Agency
Office of Solid Waste and Emergency Response
Office of Resource Conservation and Recovery

Regulation Identifier Number: 2050-AE81

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Executive Summary

Purpose

The purpose of the risk assessment is to characterize the risks that may result from the current disposal practices for coal combustion residuals (CCRs) and provide a scientific basis for the development of regulations necessary to protect human health and the environment under the Resource Conservation and Recovery Act (RCRA).

Scope

CCR is a broad term used to refer to the byproducts that are generated either directly by coal combustion or as a result of applying certain pollution control devices to emissions from coal-fired combustion units. The distinct CCR categories identified in the rulemaking include fly ash, bottom ash, boiler slag, and flue gas desulfurization (FGD) materials. All coal-fired electric utility plants in the United States generate at least one of these wastes. These different CCR wastes may be generated separately or mixed together. Once generated, CCRs may be either beneficially used or disposed of in surface impoundments and landfills (collectively referred to as "waste management units" or "WMUs"). The regulatory scope of this rulemaking is limited to current disposal practices for CCRs generated by coal-fired electric utilities and independent power producers covered by the North American Industry Classification System (NAICS) code 221112. The scope of this risk assessment is limited accordingly. The United Stated Environmental Protection Agency (EPA) did not evaluate disposal of wastes other than CCRs, disposal of CCRs at off-site locations, WMUs that have ceased receiving waste, or historical disposal of CCRs by facilities that are no longer operating or not otherwise covered by NAICS code 221112.

Some coal-fired power plants conduct coal preparation activities prior to combustion. These activities may include, but are not limited to, coal handling by conveyor systems, coal washing for removing mineral matter, and coal "sizing" to reduce the average particle size of coal. The wastes generated from these coal preparation activities are collectively referred to as "coal refuse." However, some facilities are known to dispose of coal refuse together with CCRs because the chemical characteristics of the coal refuse can have a pronounced effect on the release of chemical constituents from CCRs, EPA also considered the codisposal of this additional waste stream (referred to as "ash and coal refuse") in the risk assessment.

Overview of Risk Assessment

EPA used mathematical models to determine the rate at which chemical constituents may be released from different WMUs, to predict the fate and transport of these constituents through the environment, and to estimate the resulting risks to human and ecological receptors. Modeling was conducted in a stepwise fashion, with more refined analyses used at each subsequent step. The findings at each of the analyses conducted for this risk assessment are summarized below.

Problem Formulation

EPA first developed conceptual models to illustrate a general layout of surface impoundments and landfills, the chemical constituents that may be released from these WMUs, the routes through which these constituents may migrate through environmental media, and the types of exposures that may result. These conceptual models were used as the basis for all subsequent data collection efforts. EPA first collected data on the coal-fired power plants and CCR WMUs located across the United States. EPA then collected regional and national data to characterize the environment and receptor population surrounding each WMU. The data assembled represent the most current and comprehensive information available to the Agency at the time this risk assessment was conducted. Using the data collected, EPA first conducted a simplified hazard identification to determine which constituents warranted further evaluation. At this stage, EPA considered the presence of a constituent in CCR waste, combined with the availability of at least one toxicity benchmark, sufficient evidence of hazard potential. **Table ES-1** presents a summary of the different chemical constituents retained as constituents of potential concern (COPCs) for further analysis.

Table ES-1. List of Chemical Constituents Evaluated in the CCR Risk Assessment

▪ Aluminum	▪ Cadmium	▪ Iron	▪ Molybdenum	▪ Strontium
▪ Ammonia	▪ Calcium	▪ Lanthanum	▪ Nickel	▪ Sulfate
▪ Antimony	▪ Chloride	▪ Lead	▪ Nitrate / Nitrite	▪ Sulfide
▪ Arsenic	▪ Chromium	▪ Lithium	▪ Selenium	▪ Thallium
▪ Barium	▪ Cobalt	▪ Magnesium	▪ Silicon	▪ Uranium
▪ Beryllium	▪ Copper	▪ Manganese	▪ Silver	▪ Vanadium
▪ Boron	▪ Fluoride	▪ Mercury	▪ Sodium	▪ Zinc

All risks identified in subsequent analyses were compared against risk criteria of cancer risk greater than 1×10^{-5} or a noncancer hazard quotient (HQ) greater than 1. EPA typically relies on a risk range to determine the point at which regulation is appropriate. EPA uses as an initial cancer risk "level of concern" a calculated risk level of 1×10^{-5} (one in one hundred thousand) or an HQ above 1.0 for any noncarcinogens. For example, waste streams for which the calculated high-end individual cancer-risk level is 1×10^{-5} or higher generally are considered candidates for regulation. Waste streams whose risks are calculated to be 1×10^{-4} or higher generally will be considered to pose a substantial present or potential hazard to human health and the environment and generally will be regulated. Waste streams for which these risks are calculated to be 1×10^{-6} or lower, and lower than 1.0 HQs or EQs for any noncarcinogens, generally will be considered not to pose a substantial present or potential hazard to human health and the environment and generally will not regulated. See 59 FR 66075–66077, December 22, 1994.

Screening Analysis

EPA conducted separate screening analyses for each exposure pathway to identify which COPCs are most likely to pose risk to receptors. The results of this screening generally do not provide a

precise characterization of individual risks that may occur, but rather identify those COPCs that are most likely to exceed risk criteria. In cases where well established, post-construction management practices ("controls") have been shown to minimize releases from WMUs, EPA considered exposures for both an uncontrolled and controlled management scenario.

This screening analysis identified potential risks to human and ecological receptors resulting from the releases of particulate matter and the chemical constituents contained therein through wind and run-off. Under an uncontrolled management scenario, risks to human receptors resulted from the inhalation of windblown particulates in ambient air and the ingestion of soil and animal products (i.e., meat and dairy), while risks to ecological receptors resulted from exposures to soil and sediment. Under a controlled management scenario, which consisted of fugitive dust controls and run-on/run-off controls, all risks associated with these exposure pathways decreased to below the criteria. Due to the conservative nature of the screening, there is a great deal of uncertainty surrounding the specific risks calculated for these exposure pathways. These risks represent a protective, but unlikely, combination of conditions that reflect at least an upper bound on potential exposures. Thus, the cumulative effect of these uncertainties results in an overestimation of nationwide risks to most or all receptors. Therefore, EPA makes no direct findings concerning the magnitude of the risks that may occur under either an uncontrolled or controlled management scenario, but concludes with a high degree of confidence that the reductions achievable with standard management practices are sufficient to be protective even under this conservative screening assessment. Based on these lines of evidence, EPA concluded that no further characterization was warranted for these exposure pathways.

These screening analyses identified potential risks to human and ecological receptors from leaching of chemical constituents from CCR waste into surrounding environmental media. Risks to human health resulted from ingestion of ground water and fish, while risks to ecological receptors resulted from exposure to surface water. There was no simple method to estimate the effect controls may have for these pathways. However, considerable dilution and attenuation may occur before COPCs reach downgradient private wells and surface water bodies. Therefore, EPA retained all of the COPCs found to be above risk criteria in ground water and surface water for further characterization. In addition, EPA used the uncontrolled screening results for the above ground sediment pathway as a conservative proxy for the ground water to surface water sediment pathway. As a result, sediment exposures of four COPCs were retained for further characterization. **Table ES-2** presents a summary of the chemical constituents retained as COPCs for each pathway.

Table ES-2. List of Chemical Constituents Retained for Probabilistic Analysis

Human Health		Ecological					
Ingestion of Ground Water	Ingestion of Fish	Surface Water Exposure				Sediment Exposure	
▪ Antimony	▪ Arsenic	▪ Aluminum	▪ Iron			▪ Antimony	
▪ Arsenic	▪ Cadmium	▪ Arsenic	▪ Lead			▪ Arsenic	
▪ Boron	▪ Mercury	▪ Barium	▪ Molybdenum			▪ Silver	
▪ Cadmium	▪ Selenium	▪ Beryllium	▪ Nickel			▪ Vanadium	
▪ Cobalt	▪ Thallium	▪ Boron	▪ Selenium				
▪ Fluoride		▪ Cadmium	▪ Silver				
▪ Lead		▪ Chloride	▪ Vanadium				
▪ Lithium		▪ Chromium	▪ Zinc				
▪ Molybdenum		▪ Cobalt					
▪ Thallium		▪ Copper					

These screening analyses also identified potential risks to ecological receptors from direct exposure to impoundment wastewater. Unlike the other exposure pathways, no dilution or attenuation will occur within impoundment wastewater prior to ecological exposures. Thus, the direct exposures considered in the screening analysis provide a reasonable estimate of the relative magnitude of risks. Based on the screening analyses, EPA concluded that HQs for ecological receptors exceeded 1 for the following constituents (listed from highest to lowest potential): arsenic (100), barium (50), aluminum (30), boron (30), selenium (20), cadmium (10), vanadium (10), beryllium (2), chloride (2) and chromium (2). Because the screening analysis provides sufficient characterization of these exposures, this pathway was not carried forward for further analysis.

Probabilistic Analysis

EPA conducted a national-scale, probabilistic analysis to better characterize the potential risks to human and ecological receptors associated with leachate released from surface impoundments and landfills. The specific exposure routes evaluated for these releases were human ingestion of ground water used as a source of drinking water and fish caught from freshwater lakes or streams, as well as ecological contact with and ingestion of surface water and sediment. A combination of models was used to predict COPC fate and transport through the environment, receptor exposures, and the resulting risks. Site-specific data were used, supplemented by regional and national data sets, to capture the national variability of disposal practices, environmental conditions and receptor behavior. EPA modeled risks for both highly exposed individuals (90th percentile risks) and more moderately exposed individuals (50th percentile risks). In instances where the speciation of a COPC has been shown to greatly affect fate and transport, EPA modeled multiple species to provide a bounding on potential exposures.

Table ES-3 shows the 90th percentile human health risks to the most sensitive age cohorts for constituents that exceeded the risk criteria. Risks are presented for arsenic modeled entirely as two different species (III and V) to provide a bounding on potential risks. Values that exceed the selected risk criteria (cancer risk > 1×10^{-5} or noncancer HQ > 1) are shown in **bold**. No 90th percentile risks above ecological criteria were identified for either surface impoundment or landfills. No 50th percentile risks above human health or ecological criteria were identified for either surface impoundment or landfills.

Table ES-3. 90th Percentile Nationwide Probabilistic Risk Results

COPC	Ingestion of Ground Water	
	Surface Impoundments	Landfills
Cancer Risks		
Arsenic III	**2×10^{-4}**	5×10^{-6}
Arsenic V	1×10^{-5}	7×10^{-8}
Noncancer Risks		
Arsenic III	**5**	0.1
Arsenic V	0.4	< 0.01
Lithium	**2**	--[a]
Molybdenum	**2**	< 0.01

a) Leachate data were not available to model this COPC for landfills.

- **Surface Impoundments:** Ingestion of ground water was the only exposure pathway that resulted in risks above a cancer risk of 1×10^{-5} or noncancer HQ of 1. 90th percentile cancer risks above 1×10^{-5} were identified for arsenic III (2×10^{-4}). The 90th percentile noncancer risks above an HQ of 1 were identified for arsenic III (5), lithium (2) and molybdenum (2).
- **Landfills:** All 90th percentile cancer and noncancer risks were below human health criteria.

High-end risks identified for surface impoundments are consistently higher than those for landfills. These results are attributed to the higher infiltration rates through surface impoundments, which are driven by the hydraulic head of the ponded water. Median risks for both surface impoundments and landfills were substantially lower than both the high-end risks in this risk assessment and the median risks modeled in the 2010 Risk Assessment (U.S. EPA, 2010a). This decrease is attributed primarily to the interception of ground water by surface water bodies, which is accounted for in the revised risk assessment to provide a more accurate mass balance of constituent mass during transport. It is common for coal-fired utilities to be located near water bodies, which are used as a source of cooling water and conveyance of waste. As a result, in the majority of model iterations, the interception of ground water by surface water bodies resulted in negligible downstream well concentrations.

Based on the results of the probabilistic analysis, EPA concludes that leaching from CCR waste management units has the potential to pose risk to receptors. Arsenic, lithium and molybdenum are the chemical constituents found to pose the greatest risks from surface impoundments, while

arsenic posed the greatest risks from landfills. Available toxicological profiles indicate that risks from arsenic ingestion are linked to an increased likelihood of cancer in the skin, liver, bladder and lungs, as well as nausea, vomiting, abnormal heart rhythm, and damage to blood vessels;[1] risks from lithium ingestion are linked to neurological and psychiatric effects, decreased thyroid function, renal effects, cardiovascular effects, skin eruptions, and gastrointestinal effects;[2] and risks from molybdenum ingestion are linked to higher levels of uric acid in the blood, gout-like symptoms, and anemia.[3]

Sensitivity and Uncertainty Analyses

The modeled probabilistic risks capture the range of current, nationwide CCR disposal practices. However, because of the broad scope of the analysis, there are a number of sources of variability and uncertainty present. Therefore, to confirm the results of the probabilistic analysis and to better understand whether any particular subset of disposal practices drives the risks identified, EPA conducted additional sensitivity and uncertainty analyses.

EPA reviewed the models used, as well as the data and assumptions input into these models, to better understand the sources of variability and uncertainty inherent in the probabilistic analysis. The Agency then qualitatively and, to the extent possible, quantitatively analyzed these sources to understand the potential effects each may have on the modeled risk results. During this review, specific attention was focused on the parameters shown to have the greatest influence on model results. As a further method of validation, EPA compared the results of the sensitivity and uncertainty analyses with proven and potential damage cases. Together these analyses and comparisons show that there is a high degree of confidence in the principal findings of the probabilistic analysis. However, the review of sensitive parameters revealed some specific disposal practices that may result in greater risks than identified in the probabilistic modeling.

Through these additional sensitivity and uncertainty analyses, which explored different subsets of national disposal practices, EPA identified the potential for higher risks than those identified in the broader, national analysis. In particular, consideration of different waste pH values showed higher risks for arsenic at more acidic and basic pH values, as well as additional risks for boron, cobalt, fluoride and mercury at these more extreme pH values. Consideration of specific liner types showed that ground water risks are driven by disposal in unlined units and, in particular, unlined surface impoundments. For these units, EPA identified higher risks for arsenic and molybdenum, as well as additional risks for thallium. Clay-lined units were found to pose lower risks than unlined units. Composite-lined units were found to be the most protective disposal practice, resulting in risks far below all criteria identified in this risk assessment.

[1] Profile for arsenic available online at: www.epa.gov/iris/subst/0278.htm and www.atsdr.cdc.gov/toxprofiles/tp2.pdf

[2] Profile for lithium available online at: hhpprtv.ornl.gov/issue_papers/Lithium.pdf

[3] Profile for molybdenum available online at: www.epa.gov/iris/subst/0425.htm

Conclusions

Based on the analyses presented in this document, EPA concludes that current management practice of placing CCR waste in surface impoundments and landfills poses risks to human health and the environment within the range that OSWER typically regulates. On a national scale, surface impoundments presented higher risks than landfills. Risks to ecological receptors were identified from exposures to aluminum, arsenic, barium, beryllium, boron, cadmium, chloride, chromium, selenium and vanadium through direct exposure to impoundment wastewater. Risks to residential receptors were identified primarily from exposures to arsenic and molybdenum in ground water used as a source of drinking water, but additional risks from boron, cadmium, cobalt, fluoride, mercury and thallium were identified for specific subsets of national disposal practices.

Sensitivity analyses on liner type indicate that disposal of CCR wastes in unlined surface impoundments and landfills presents the greatest risks to human health and the environment. As modeled, the national risks from clay-lined units are lower than those for unlined units, but such units can exceed risk criteria at individual sites. Composite liners were the only liner type modeled that effectively reduced risks from all pathways and constituents far below human health and ecological criteria in every sensitivity analysis conducted. Sensitivity analyses on waste type indicate that the acidic conditions that result from codisposal of CCR waste with coal refuse and the basic conditions that result from disposal of FGD waste result in higher risks from arsenic and other constituents than CCR waste disposed alone.

The risk results are consistent with the ground water damage cases compiled by EPA. These damage cases were primarily associated with unlined units and were most frequently associated with releases of arsenic. Recent surveys of the industry indicate the majority of newly constructed units are lined, and that that the practice of codisposal with coal refuse has declined. However, this risk assessment presents a static snapshot of current disposal practices. While newer units may be managed in a more protective manner, older units, which still comprise the majority of current units, continue to operate in a manner that poses risks to human health and the environment within the range that OSWER typically regulates.

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List of Abbreviations and Acronyms

3MRA	Multimedia, Multiple Exposure Pathway, Multiple Receptor Risk Assessment
ACI	Activated carbon injection
ADD	Average daily dose
AEGL	Acute Exposure Guideline Levels
AERMOD	American Meteorological Society/EPA Regulatory Model
ATSDR	Agency For Toxic Substances And Disease Registry
BCF	Bioconcentration factors
BTF	Biotransfer factors
CAIR	Clean Air Interstate Rule
CalEPA	California EPA
CAMR	Clean Air Mercury Rule
CASRN	Chemical Abstract Service Registry Number
CBI	Confidential Business Information
CCC	Criterion Continuous Concentration
CCR	Coal combustion residual
CIBO	Council of Industrial Boiler Owners
COMID	Common Identifier
CONUS-SOIL	Conterminous United States Multilayer Soil Characteristics
COPC	Constituent of Potential Concern
CSEFH	Child-Specific Exposure Factors Handbook
CSF	Cancer slope factor
CSFo	Oral cancer slope factor
DAF	Dilution attenuation factor
DBGS	Depth below ground surface
DOC	Dissolved organic carbon
DOE	U.S. Department Of Energy
DOM	Dissolved organic matter
DW	Drinking water
Eco-SSL	Ecological Soil Screening Levels
EFH	Exposure Factors Handbook
EIA	Energy Information Agency
ELG	Effluent Limitation Guidelines
EPA	U.S. Environmental Protection Agency
EPACMTP	EPA's Composite Model for Leachate Migration with Transformation Products
EPRI	Electric Power Research Institute
ERL	Effects range low

ERPG	Emergency Response Planning Guidelines
ESP	Electrostatic precipitator
FBC	Fluidized-bed combustion
FCV	Final Chronic Value
FGD	Flue gas desulfurization
GIS	Geographic information system
GW	Ground water
HDPE	High-density polyethylene
HEAST	Health Effects Assessment Summary Tables
HEI	Highly exposed individual
HELP	Hydrologic Evaluation Of Landfill Performance
HFO	Hydrous ferric oxide
HGDB	Hydrogeologic Database
HHRAP	Human Health Risk Assessment Protocol
HQ	Hazard quotient
HSDB	Hazardous Substances Data Bank
ID	Identification
IDLH	Immediately Dangerous to Life or Health
IEM	Indirect Exposure Methodology
IEUBK	Integrated Exposure and Uptake Biokinetic model
IRIS	Integrated Risk Information System
IWAIR	Industrial Waste Air Model
IWEM	Industrial Waste Evaluation Model
K_d	Soil-water partition coefficient
L/S	Liquid-to-solid ratio
LADD	Lifetime average daily dose
LEAF	Leaching Evaluation Assessment Framework
LF	Landfill
LOAEL	Lowest observed adverse exposure level
MCL	Maximum Concentration Limit
MINTEQA2	Metal Speciation Equilibrium Model For Surface And Ground Water
MODHMS	MODFLOW-based Hydrologic Modeling System
MRL	Minimal Risk Level
MSW	Municipal solid waste
NAAQS	National Ambient Air Quality Standards
NAICS	North American Industry Classification System
NAWQP	National Ambient Water Quality Program
NED	National Elevation Data set

NHD	National Hydrography Data set
NJDEP	New Jersey Department of Environmental Protection
NOAA	National Oceanic and Atmospheric Administration
NOAEL	No observed adverse exposure level
NODA	Notice of Data Availability
OSWER	Office of Solid Waste And Emergency Response
PM	Particulate matter
POM	Particulate organic matter
PPRTV	Provisional Peer-Reviewed Toxicity Values
RAGS	Risk Assessment Guidance For Superfund
RCRA	Resource Conservation And Recovery Act
REL	Reference Exposure Levels
RfC	Reference concentration
RfD	Reference dose
RME	Reasonable Maximum Exposure
RTC	Report To Congress
SAB	Science Advisory Board
SCV	Secondary Chronic Value
SD	Standard deviation
SI	Surface impoundment
SPLP	Synthetic Precipitation Leaching Procedure
SQuiRTs	Screening Quick Reference Tables
STATSGO	State Soil Geographic Database
STORET	Storage And Retrieval Data Warehouse
SW	Surface Water
TCLP	Toxicity Characteristic Leaching Procedure
TEEL	Temporary Emergency Exposure Limits
TEL	Threshold effect level
TL3	Trophic level 3
TL4	Trophic level 4
TSS	Total suspended solids
URF	Unit risk factors
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WBD	Watershed Boundary Data set
WMU	Waste management unit

1 Introduction

The U.S. Environmental Protection Agency (EPA or the Agency) has taken many steps toward characterizing the risks that may result from the current disposal practices for coal combustion residuals (CCRs) and developing the regulations necessary to protect human health and the environment under the Resource Conservation and Recovery Act (RCRA). A full timeline of the Agency's previous work on CCRs can be found on the EPA website.[4]

The revised risk assessment presented in this document builds on the two most recently completed analyses in that timeline, *Non-ground water Pathways, Human Health and Ecological Risk Analysis for Fossil Fuel Combustion Phase 2* (U.S. EPA, 1998) and *Human and Ecological Risk Assessment of Coal Combustion Wastes* (U.S. EPA, 2010a). Specifically, EPA has revised the 2010 Risk Assessment to incorporate new data and to address the comments received from both independent external peer reviewers and public commenters on the methodology, data sources and assumptions used by the Agency. The scope of the peer review was a draft of the 2010 Risk Assessment. The scope of public comments was a 2007 Notice of Data Availability (NODA), the 2010 Risk Assessment, and two subsequent NODAs in 2011 and 2013.[5] The Agency responses to these comments are available in separate documents for the peer review and the public in the docket for the final rule.

1.1 Purpose and Scope of the Risk Assessment

The purpose of this document is to characterize the risks associated with current CCR disposal practices to aid in the review and revision of the Agency's 2010 proposed rulemaking. To accomplish this, EPA characterized the current state of CCR disposal practices, identified the different releases that may occur from these waste management units (WMUs), and evaluated the resulting risks to human and ecological receptors. The regulatory scope of the rulemaking is limited to current disposal practices for CCRs generated by coal-fired electric utilities and independent power producers covered by the North American Industry Classification System (NAICS) code 221112. The scope of this risk assessment is limited accordingly. EPA did not evaluate disposal of wastes other than CCRs, disposal of CCRs at off-site locations, WMUs that have ceased receiving waste, or historical disposal of CCRs by facilities that are no longer operating or not otherwise covered by NAICS code 221112.

1.2 Overview of Risk Assessment Methodology

In total, this risk assessment is divided into seven main sections and eleven appendices. The main text summarizes the different data sources relied upon, analyses performed, model results and final Agency conclusions. The appendices provide a more detailed discussion of the data and models underlying the analyses summarized in the main text. The remainder of this section provides

[4] Available online at: www.epa.gov/osw/nonhaz/industrial/special/fossil/regs.htm

[5] Available online in docket numbers EPA-HQ-RCRA-2011-0392 and EPA-HQ-RCRA-2012-0028 at: www.regulations.gov

further information about the contents of each section and appendix, while **Figure 1-1** provides a decision flowchart followed throughout the risk assessment.

- **Section 2, Problem Formulation:** describes the conceptual models used to identify the potential exposure pathways associated with CCR WMUs, summarizes the sources of data available to characterize these exposure pathways, and presents the results of hazard identification used to identify an initial list of constituents of potential concern (COPCs) carried forward for further analysis.
- **Section 3, Screening Analysis:** describes the framework used to conduct a conservative screening analysis for human and ecological receptors. The results of this screening analysis are presented and used to identify pathways and constituents for further modeling.
- **Section 4, Probabilistic Analysis:** describes the probabilistic modeling used to (1) estimate the magnitude of COPC releases from CCR WMUs for all pathways not sufficiently characterized in the screening analysis, (2) model the fate and transport of constituents through environmental media, (3) calculate potential exposures for human and ecological receptors, and (4) estimate resulting risks to these receptors. The results of this analysis are presented as separate national estimates for impoundments and landfills.
- **Section 5, Sensitivity and Uncertainty Analyses:** describes the various sources of variability and uncertainty present in the risk assessment. To the extent possible, these sources are quantitatively and qualitatively characterized to identify the potential for higher or lower risks than those modeled in the probabilistic analysis.
- **Section 6, Final Risk Characterization:** synthesizes available information from all sections of the risk assessment to reach final conclusions about the risks that may result from current CCR disposal practices.
- **Section 7, References:** provides citations for all documents referenced throughout the text.

The first five appendices provide the underlying data used in the risk assessment. **Appendix A** describes the site-based data used to characterize CCR surface impoundments and landfills (e.g., geographic location, surface area, capacity, geometry, liner status). **Appendix B** describes the regional and national data used to characterize the environmental setting around each facility and WMU (e.g., meteorology, climate, soils, aquifers and water bodies). **Appendix C** describes the chemical constituents present in and released from different CCR wastes. **Appendix D** details the collection and prioritization of human exposure factors. **Appendix E** details the collection and prioritization of toxicity benchmarks for human and ecological receptors.

The next six appendices provide detailed information on the specific models and equations used in the various analyses. **Appendix F** provides models and data used to estimate COPC concentrations suspended in ambient air and deposited on downgradient plants. **Appendix G** provides the equations and data used to estimate the accumulation of COPCs within the food chain. **Appendix H** details the development of soil-water partitioning coefficients used to model COPC concentrations in ground water. **Appendix I** describes the development of the landfill source term. **Appendix J** provides the models and data used to estimate COPC concentrations in surface water

and sediment. **Appendix K** provides a summary of several of the sensitivity and uncertainty analyses performed.

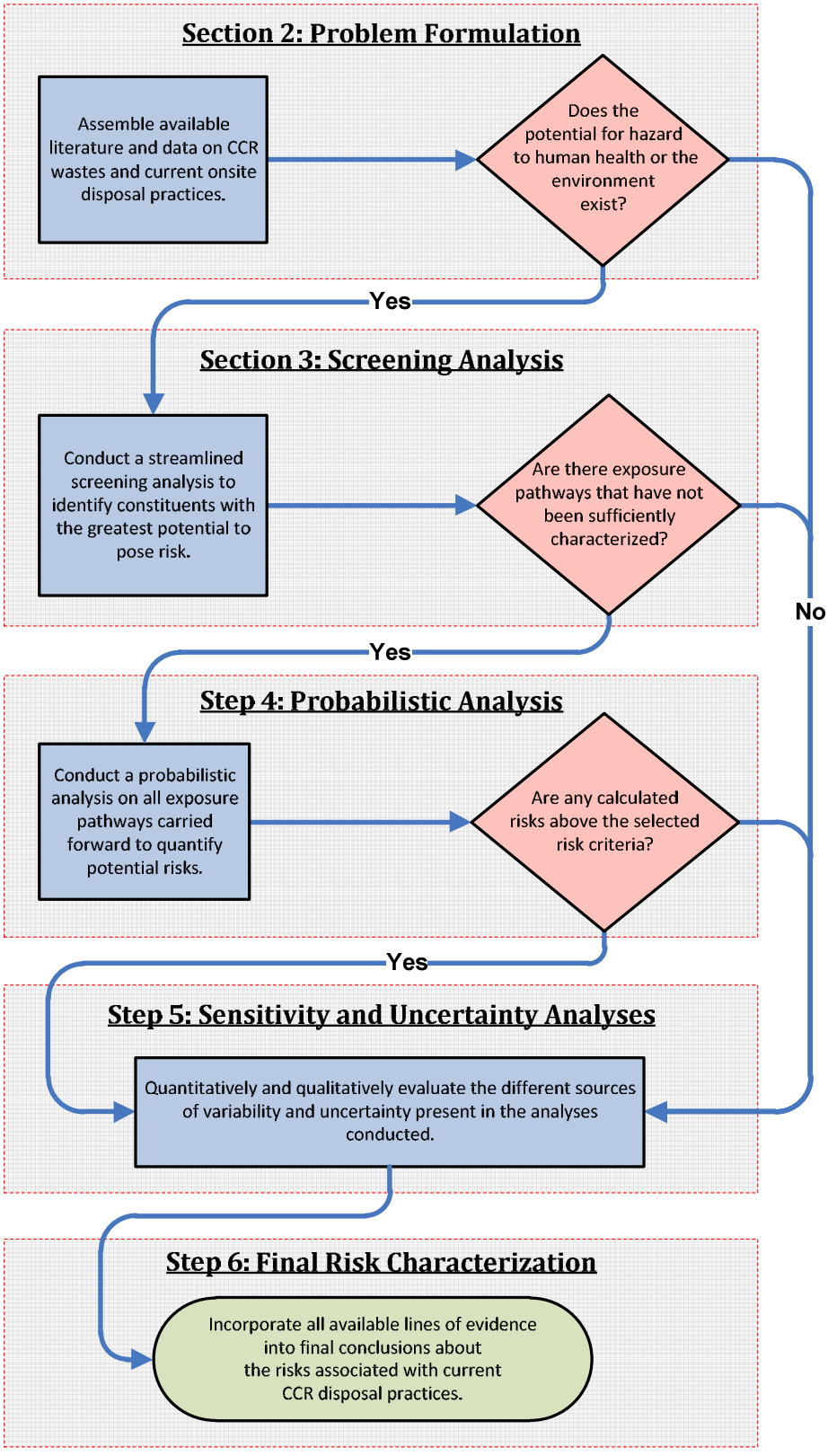

Figure 1-1. Decision flowchart for CCR risk assessment.

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2 Problem Formulation

This purpose of this section is to describe the development of the conceptual models that form the basis for the analysis of surface impoundments and landfills. This section also provides a summary of the data sources used to characterize coal-fired facilities, waste management practices, constituent releases and receptor behavior. Finally, this section includes a preliminary hazard identification to identify the COPCs to be carried forward for further analysis. This section is divided into the following subsections:

- **Section 2.1** provides an overview of the source and properties of each major type of CCR.
- **Section 2.2** provides the conceptual models developed for surface impoundments and landfills that identify each relevant release route, transport pathway, and receptor.
- **Section 2.3** summarizes the data sources incorporated into the risk analysis.
- **Section 2.4** provides the risk criteria used to evaluate risks throughout the assessment.
- **Section 2.5** identifies the potential hazards that warrant further evaluation.

2.1 Overview of Coal Combustion and Residuals

CCR is a broad term used to refer to the byproducts that are generated either directly by coal combustion or as a result of applying certain pollution control devices to emissions from coal-fired combustion units, with the resulting wastes destined for disposal. CCRs may be generated wet or dry; however, this composition may change after generation. Some CCRs are dewatered, while others are mixed with water to facilitate transport (i.e., sluiced). When multiple types of CCRs are generated at the same facility, mixing and codisposal may occur. The distinct CCR categories identified in the 2010 Proposed Rulemaking include fly ash, bottom ash, boiler slag, and flue gas desulfurization (FGD) materials:

- **Fly ash** is the fraction of combusted coal that becomes suspended in plant flue gases. It is a very fine, powdery material composed primarily of silica. Fly ash is removed from the plant exhaust gases primarily by electrostatic precipitators (ESPs) or baghouses that contain fabric filters. In facilities that use activated carbon injection (ACI) before fly ash collection, the fly ash waste stream will also contain the carbon, along with other mercury control wastes. However, where ACI occurs after fly ash collection, a separate waste stream may result.
- **Bottom ash** consists of ash particles that are too large to become entrained in the flue gas during combustion. It is coarse, with grain sizes that range from fine sand to fine gravel, and quite angular, with a porous surface structure. Bottom ash is collected from the furnace after it collides with and agglomerates to furnace walls or falls through open grates to an ash hopper beneath the furnace.
- **Boiler slag** is molten bottom ash that has been quenched with water. When the molten ash comes in contact with the water, it crystallizes, fractures and forms pellets that are hard with

a smooth, glassy appearance. Boiler slag is collected from the base of either slag tap or cyclone type furnaces.

- **FGD materials** are produced through a process used to reduce sulfur dioxide (SO_2) emissions from the exhaust gas system of a coal-fired boiler. The physical nature of these materials varies from a wet sludge to a dry powdered material, depending on the pollution control technology, and the composition consists of sulfites, sulfates or a mixture thereof.

These different CCR wastes may be generated separately or mixed together. Even when generated separately, facilities often codispose of multiple waste types in a single WMU. **Figure 2-1** provides the layout of a hypothetical coal-fired plant. This simplified layout is intended to demonstrate some of the major pollution control technologies, waste streams and collection points associated with coal combustion. It is intended to be illustrative and does not capture all possible control technologies or plant layouts.

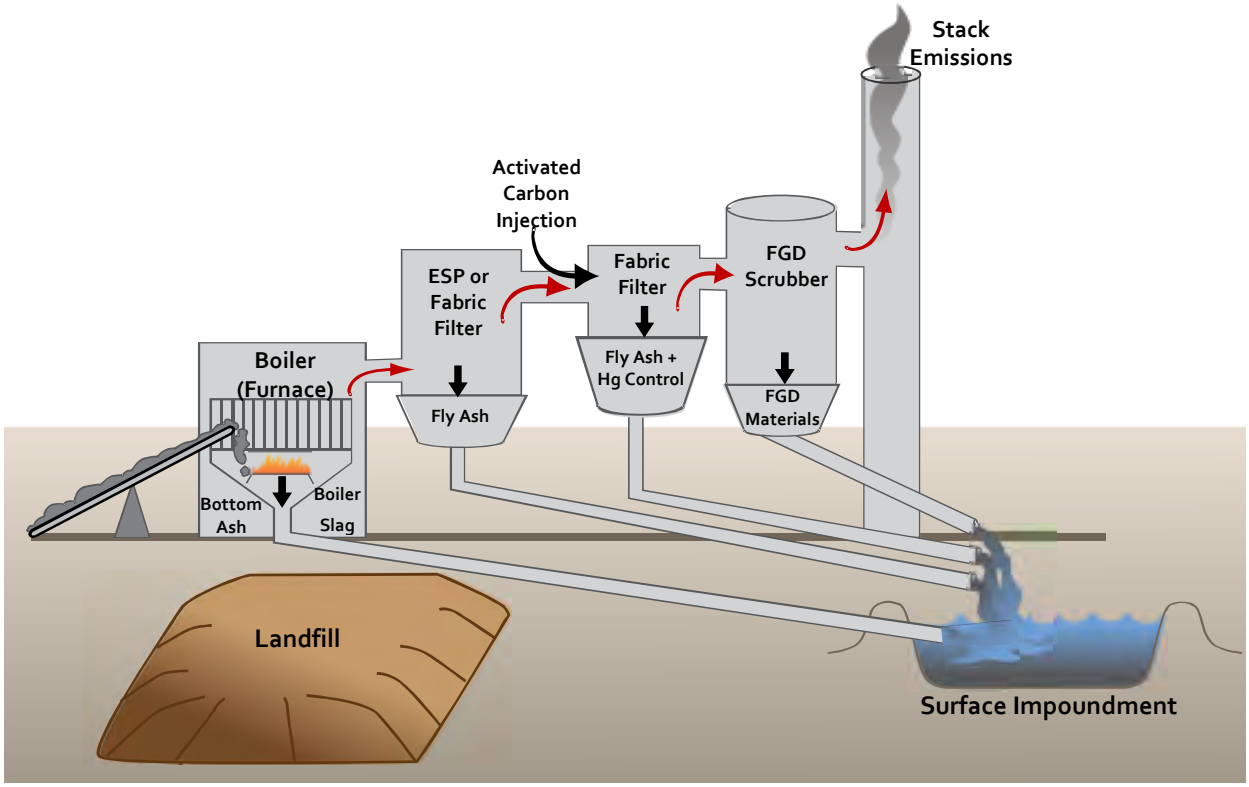

Figure 2-1. Generalized coal-fired power plant layout.

2.2 Conceptual Models

Once disposed in WMUs, the chemical constituents present in CCRs may be released to the surrounding environment. To evaluate the risks to human health and the environment that may result from these releases, EPA first developed conceptual models to specify the layout of surface impoundments and landfills, the types of releases that may occur from these WMUs, and the types of exposures that may result. These conceptual models were developed to represent generic WMU layouts and are not intended to reflect any specific facility or WMU. These conceptual models were used to form the basis for data collection and modeling efforts.

Neither conceptual model includes direct, point source discharges to surface water. These types of releases are permitted under the National Pollutant Discharge Elimination System of the Clean Water Act and have been evaluated separately in the *Environmental Assessment for the Proposed Effluent Limitation Guidelines and Standards for the Steam Electric Power Generating Point Source Category* (U.S. EPA, 2013). The risk assessment for direct discharges was conducted in support of proposed effluent limitation guidelines (ELG) for the steam electric power generating point source category.[6] That assessment is under revision by EPA in response to the public comments received on the proposal and will be released in conjunction with the final ELG rule.

Surface water used as a source of potable water is not included in either conceptual model. Surface water is assumed to be routed through a municipal water treatment facility prior to consumption, reducing constituent levels present. Furthermore, neither conceptual model includes incidental ingestion of, inhalation of, or dermal contact with COPCs in surface water that may occur during swimming or other activities near a water body. For human receptors, it is assumed that these exposures are infrequent and small in comparison to similar exposures from ground water.

2.2.1 Surface Impoundment Conceptual Model

Surface impoundments are conceptualized as square units that are constructed anywhere from entirely above grade to entirely below ground surface. During operation, a surface impoundment receives waste sluiced from the facility. Over time, impoundment water may be lost to some combination of infiltration, evaporation, and controlled discharges to other impoundments and nearby water bodies, while the CCR solids either accumulate until the surface impoundment's capacity is reached or are periodically dredged for final disposition elsewhere. To reflect that the majority of impoundments are periodically dredged, the conceptual model assumes that dredging losses are balanced out by continued loading from the facility, resulting in a constant ponding depth over the operational life. It is assumed that all waste is removed from most units prior to closure (i.e., clean closure). However, in some instances, waste is left in place and the unit is closed and capped. Closed surface impoundments are assumed to behave the same as a closed landfill. **Figure 2-2** depicts a cross-section of the conceptual layout for operating impoundments.

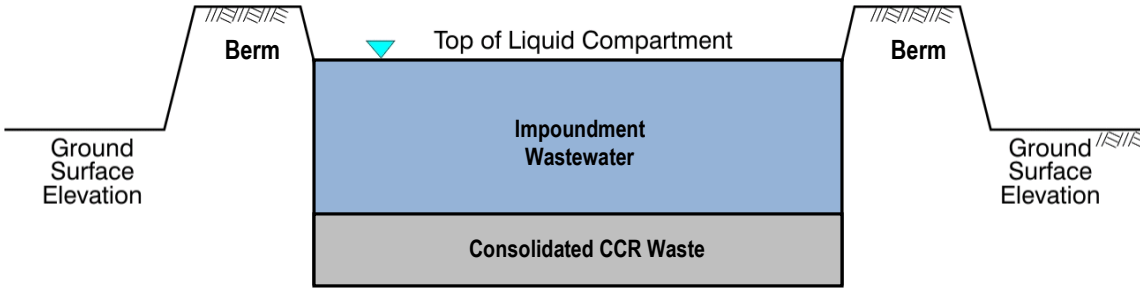

Figure 2-2. Cross-sectional view of generic surface impoundment site model.

Chemical constituents can be released from surface impoundments through the leaching of soluble constituents into the water that comes in contact with the CCRs and percolation of the resulting

[6] Available online in docket number EPA-HQ-OW-2009-0819 at: www.regulations.gov.

leachate into the subsurface soil and ground water. Constituents can then be transported underground through the ground water (GW) to downgradient drinking water (DW) wells (GW→DW pathway), where residents may be exposed through ingestion of contaminated drinking water, as well as dermal contact with and inhalation of constituents through bathing and showering in that water. Contaminated ground water may also discharge to surface water (SW) bodies (GW→SW pathway), where human receptors may be exposed through the ingestion of fish that live in the surface water body and ecological receptors may be exposed by living in or foraging in contaminated surface water or sediment. The CCR solids, along with any constituents contained within them, may also be released aboveground from operating impoundments through particulate matter disturbed by wind or runoff if the water level above the waste decreases. Additional aboveground exposures may result from ecological receptor contact with surface impoundment wastewater. **Figure 2-3** depicts the different exposure pathways considered for impoundments.

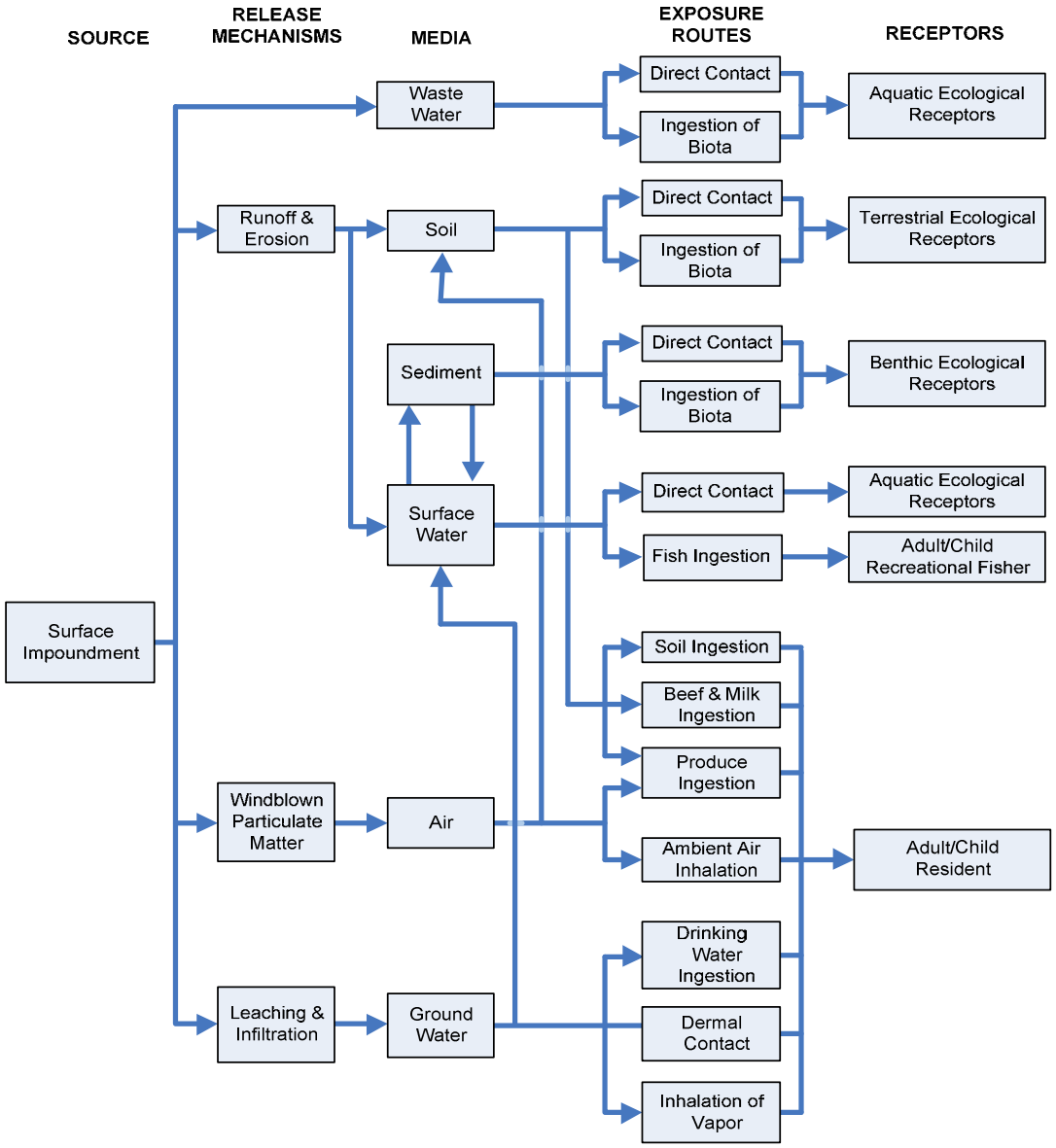

Figure 2-3. Surface impoundment conceptual exposure model.

2.2.2 Landfill Conceptual Model

Landfills are conceptualized as square units that are constructed anywhere from entirely above grade to entirely below ground surface. During operation, landfills gradually accumulate CCRs in a smaller, active portion of the landfill, until the capacity is reached. During closure, waste is left in place and the entire landfill is capped. **Figure 2-4** depicts a cross-section of the conceptual layout for closed landfills.

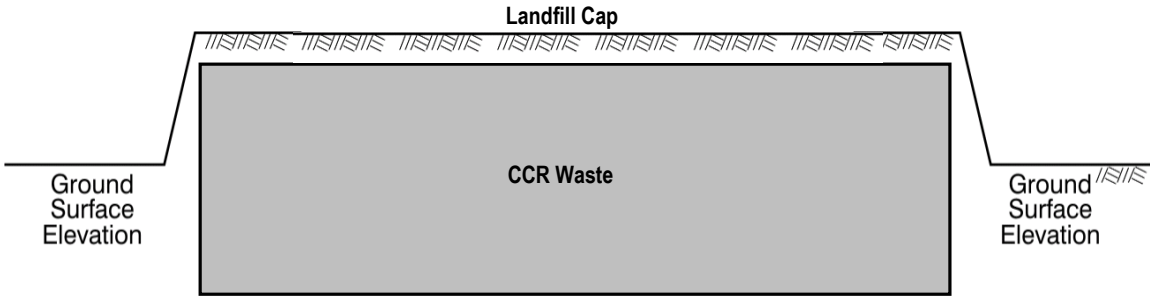

Figure 2-4. Cross-sectional view of generic landfill site model.

Chemical constituents can be released from landfills through leaching of soluble constituents into the water that comes in contact with the CCRs and percolation of the resulting leachate into subsurface soil and ground water. Constituents can then be transported underground through the ground water to downgradient drinking water wells, where residents may be exposed through ingestion of contaminated drinking water, as well as dermal contact with and inhalation of constituents through bathing and showering in that water. Contaminated ground water may also discharge to surface water bodies, where human receptors may be exposed through the ingestion of fish that live in the surface water body and ecological receptors may be exposed through living in or foraging in contaminated surface water or sediment. The CCR solids, along with any constituents contained within them, may also be released aboveground from operating landfills through particulate matter disturbed by wind; overland run-off; and mechanical disturbances, such as truck traffic, unloading operations, or spreading and compacting operations. These constituents are then transported downgradient where they may be directly inhaled by residents or settle out onto nearby soils and produce, where they may be ingested by ecological receptors or accumulated in crops and livestock that are subsequently ingested by residents. **Figure 2-5** depicts the different exposure pathways considered for landfills.

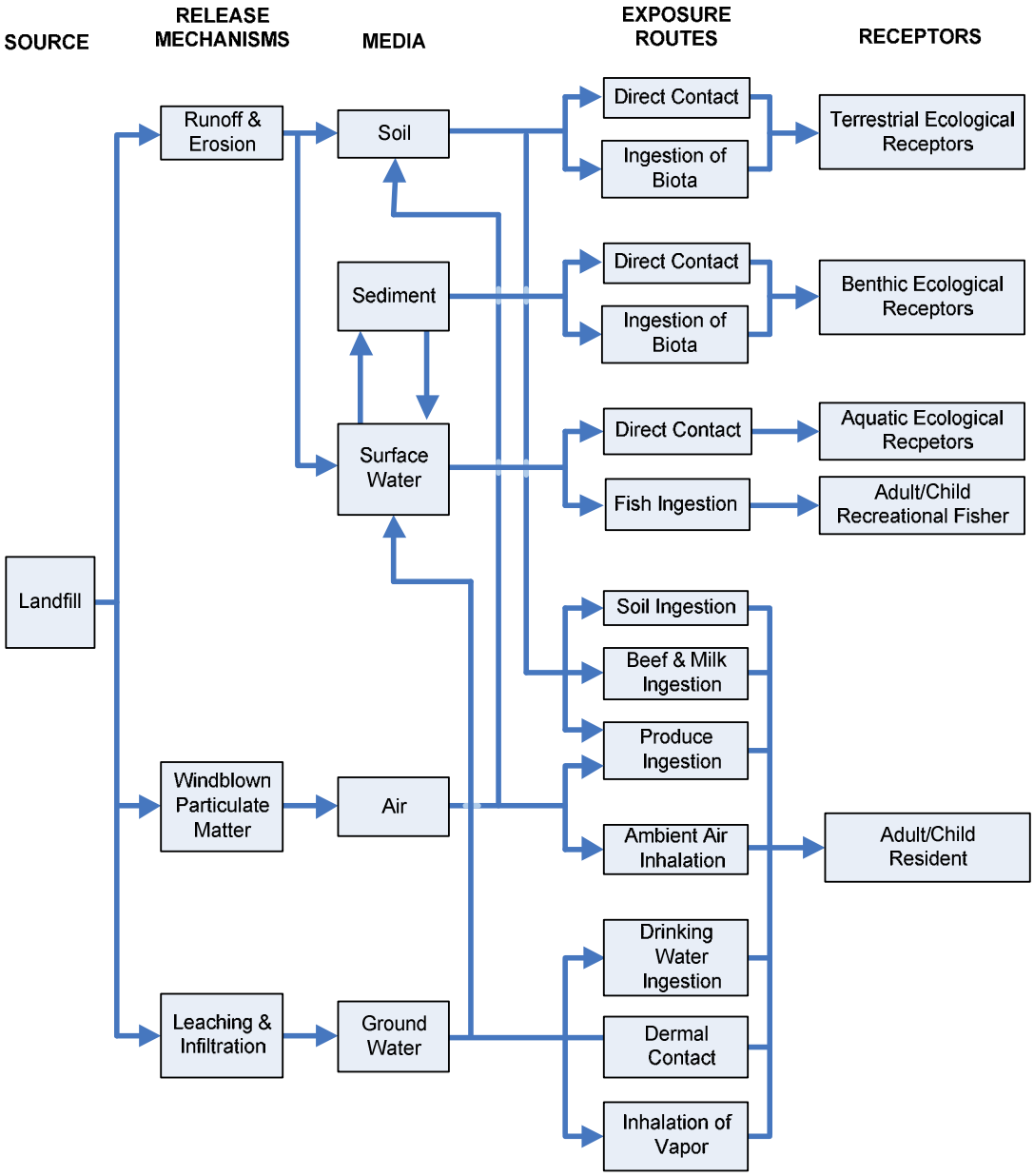

Figure 2-5. Landfill conceptual exposure model.

2.3 Data Collection

2.3.1 Facility and Waste Management Unit Data

EPA relied on the U.S. Department of Energy (DOE) Energy Information Agency (EIA) Database for information on the location, generating capacity and coal burned for each coal-fired utility power plant (hereafter referred to as "facilities"). The 2005 EIA Database used in the 2010 Risk Assessment reported a total of 495 facilities in operation, while the 2009 EIA database used in the revised risk assessment updated this number to 507 facilities. At the time that these data were collected, the 2009 EIA database was the most recent version available.

Although the EIA Database provides information on the tons of CCRs generated annually, as well as their disposition (e.g., landfilled), it does not provide information on the characteristics of the WMUs where the disposed CCRs are managed. The 2010 Risk Assessment (U.S. EPA, 2010a) relied on a 1997 Electric Power Research Institute (EPRI) survey to characterize the type, size, design and location of CCR surface impoundments and landfills. However, two more-recent EPA surveys of on-site WMUs have since been completed:

- 2009 *Information Request Responses* [obtained under Section 104(e) of the Comprehensive Environmental Response, Compensation, and Liability Act][7] together with *Impoundment Assessment Reports*,[8] hereafter jointly referred to as "the 2009 EPA Survey"; and
- 2010 Questionnaire for the Steam Electric Power Generating Effluent Guidelines, hereafter referred to as "the 2010 EPA Survey."[9]

The new data from these EPA surveys are hereafter collectively referred to as the "CCR WMU database." Although facilities and WMUs are constantly opening and closing, the CCR WMU database comprehensively covered all operating facilities at that time it was compiled. As a result, these surveys identified more than twice as many facilities with on-site disposal, as well as substantially more individual WMUs located at these facilities. Thus, the revised risk assessment provides a more complete snapshot of current disposal practices. **Table 2-1** shows the increase in coverage provided by the updated data sets.

Table 2-1. Number of On-site Surface Impoundments and Landfills Contained in the 1995 EPRI Survey and CCR WMU Database

Data Source	EIA Facilities	Facilities with On-site WMUs	Total On-site Impoundments	Total On-site Landfills
1995 EPRI Survey	495	181	96	108
CCR WMU Database	507	384	953	431

The CCR WMU database represents the most current and complete data on WMUs available and provides a significant increase in coverage of the relevant facilities. However, some data gaps remain in the CCR WMU database. Information on some parameters, such as WMU size, is missing for a subset of WMUs. To fill these data gaps, EPA probabilistically sampled from distributions compiled from the available data for other WMUs. Further information about the methods used to collect and analyze these data is provided in **Appendix A**, with the underlying raw data available in following attachments:

[7] Available online at: www.epa.gov/osw/nonhaz/industrial/special/fossil/surveys/index.htm

[8] Additional impoundment assessment reports have been conducted since the model inputs were developed. Available online at: www.epa.gov/osw/nonhaz/industrial/special/fossil/surveys2/index.htm

[9] Available online at: water.epa.gov/scitech/wastetech/guide/steam_index.cfm

- **Attachment A-1** provides data collected for each facility geographic location, number of surface impoundments and landfills present, amount of coal burned and the associated coal use quartile.
- **Attachment A-2** provides the WMU-specific data used in the CCR risk assessment, including geographic locations, CCR type, dimensions, liner type and first year of operation for each of the surface impoundments and landfills modeled.

2.3.2 Environmental Parameters Data

EPA collected data on the surrounding environmental conditions with the aid of geographic information system (GIS) software. In the 2010 Risk Assessment, these data were selected based on the geographic location of each facility. The latitudes and longitudes reported in the EIA Database often represent a centroid or front gate location for each facility. However, WMUs can be located some distance away from the main facility. Therefore, where possible, the revised risk assessment used the newly available data from the CCR WMU database to identify the locations of individual WMUs, and only relied on facility locations when no WMU-specific data were available. The reported locations for both facilities and WMUs were then reviewed based on visual inspection of aerial photography using Google Earth and adjusted as appropriate.

EPA used the facility and WMU locations to identify site-specific data on soil type, hydrogeologic environment and distance to nearest water body. However, because uncertainty remained about the precise location for some units, EPA pulled data from a two-kilometer radius around the reported location to effectively capture local variability. Regional data were collected by assigning each facility to the nearest reference point in national databases, such as the Hydrologic Evaluation of Landfill Performance (HELP) model climate stations and the U.S. Geological Survey (USGS) hydrological regions. Whenever environmental parameters could not be linked based on location, EPA relied on national distributions. Further information about the methods used to collected and analyze these data is provided in **Appendix B**, with the data available in the following attachments:

- **Attachment B-1** provides the specific soil texture, pH and organic carbon content associated with each facility.
- **Attachment B-2** provides hydrogeologic environments.
- **Attachment B-3** provides climate center, precipitation rate and infiltration rate.
- **Attachment B-4** provides USGS Hydrologic Region; distance to nearest water body; and water body mean recharge, area, length, mean annual flow and mean annual velocity.

Figure 2-6 maps the coal-fired utilities within the contiguous United States for which on-site disposal of CCRs is known to take place. Although these facilities are concentrated in the eastern United States, they are located in nearly every state, in both urban and rural settings. One additional facility in Alaska, with a single on-site surface impoundment, is not shown on this figure. Because soil and hydrogeologic data were unavailable for Alaska, data on this one facility and surface impoundment were not incorporated in the revised risk assessment.

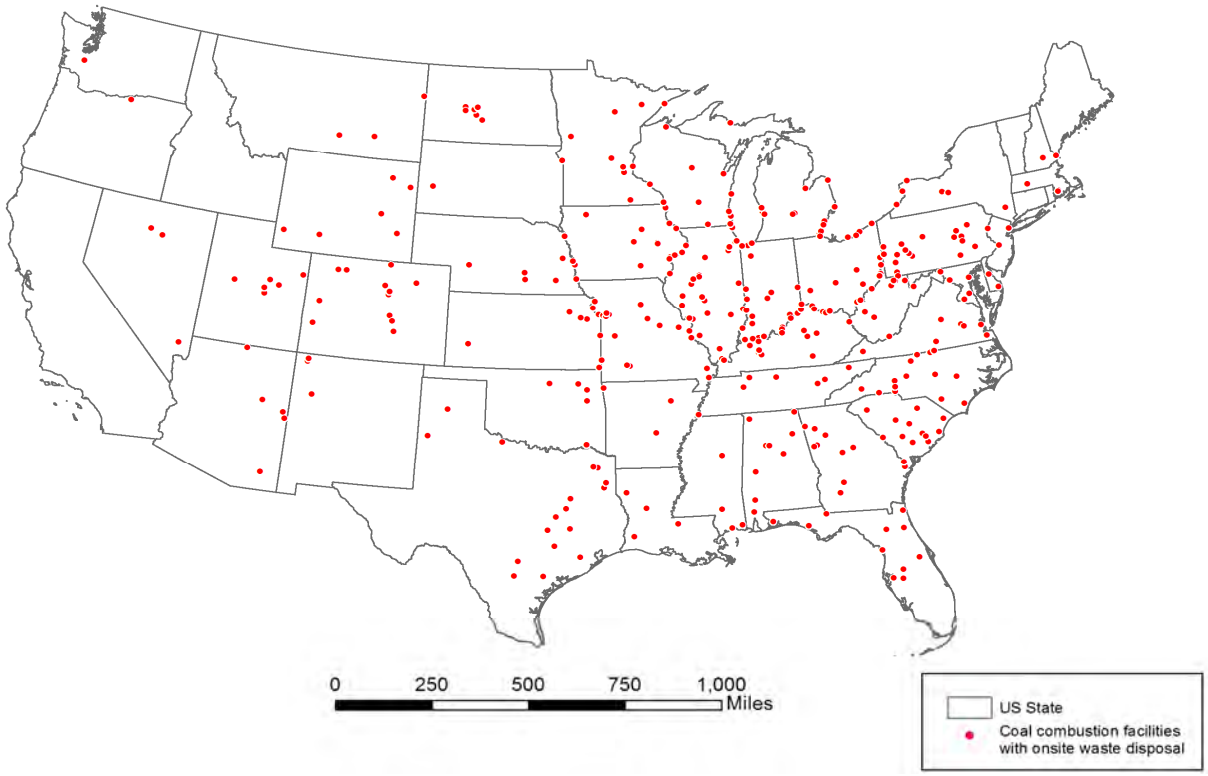

Figure 2-6. Coal-fired facilities in the conterminous United States with both on-site disposal and available soil and hydrogeological data.

2.3.3 Constituent Data

The revised risk assessment relies on a database that contains all of the constituent data collected since the 1998 Risk Assessment (U.S. EPA, 1998a,b), referred to as the "CCR constituent database." This database includes information on both the identity and concentrations of the different constituents that may be present in and released from different CCRs. EPA has continued to incorporate new data as it becomes available through public comment and Agency collection efforts. The available data comprise the most recent and complete data set available at the time of this assessment. Further information about this database is provided in **Appendix C**, with the data available in the following attachments:

- **Attachment C-1** provides a complete list of data sources in the updated database.
- **Attachment C-2** provides the surface impoundment pore water concentration data used to characterize leaching from these units.
- **Attachment C-3** provides the surface impoundment wastewater concentration data used to characterize surface water within these units.
- **Attachment C-4** provides the whole waste concentration data ("totals") used to characterize the mass of COPCs present in the CCR waste.
- **Attachment C-5** provides leachate data collected with EPA Leaching Evaluation Assessment Framework (LEAF) methods used to characterize landfills.

2.3.4 Exposure Factors

EPA previously used data from the 1997 *Exposure Factors Handbook* (EFH) (U.S. EPA, 1997b,c,d) to characterize human exposure factors. In the revised risk assessment, EPA reviewed and incorporated the data and recommendations from the 2008 *Child-Specific Exposure Factor's Handbook* (CSEFH; U.S. EPA, 2008a), including the subdivision of child receptors into specific age cohorts. Because the 2008 CSEFH does not provide additional data for adult exposures, the data from the 1997 EFH were retained for these adult receptors. Where sufficient data were available, the percentiles and corresponding data points drawn from these two sources were used to develop a distribution in order to reflect the variability within the U.S. population. Otherwise, EPA relied on point values selected based on either the recommendations of the EFH/CSEFH or established Agency guidance.

The 2011 *Exposure Factors Handbook* (U.S. EPA, 2011) has been completed and updates some of the data from the 1997 EFH. During the finalization of this risk assessment, EPA released *OSWER Directive 9200.1-120* (U.S. EPA, 2014c). Although this document provides default exposure factors to use for point estimates, EPA is still in the process of updating the full distributions necessary for probabilistic analysis. Therefore, this risk assessment does not incorporate the data from the 2011 EFH. Further information about the methods used to collected and analyze these exposure data is provided in **Appendix D.**

2.3.5 Toxicity Benchmarks

Ingestion Benchmarks

For human health exposures from the ingestion of soil and water, EPA updated the chronic toxicity values used in the 2010 Risk Assessment. The benchmarks collected in this report reflect current toxicity data as of January 2012. Values were selected according to the hierarchy established in the 2003 *Office of Solid Waste and Emergency Response Directive 9285.7-53* (U.S. EPA, 2003f), which encourages the prioritization of toxicity values from sources that are current, transparent and publicly available, and that have been peer reviewed. During this update, two new benchmarks were identified: a noncancer benchmark for lanthanum was identified from the National Sanitation Foundation International and a cancer benchmark for chromium VI from the New Jersey Department of Environmental Protection (NJDEP). Benchmarks were drawn from the following sources:

- **Tier I:** EPA Integrated Risk Information System (IRIS).
- **Tier II:** Provisional Peer-Reviewed Toxicity Values for Superfund.
- **Tier III:** Agency for Toxic Substances and Disease Registry minimal risk levels, California Environmental Protection Agency (CalEPA) cancer potency factors, the International Toxicity Estimates for Risk database, NJDEP, and the EPA Health Effects Assessment Summary Table.

For lead, there is currently has no consensus on the development or identification of an effect threshold needed to develop benchmarks within these tiers. Therefore, the maximum contaminant level (MCL) was used as an alternative benchmark for approximating human health risk.

Inhalation Benchmarks

EPA collected National Ambient Air Quality Standards (NAAQS) for evaluating inhalation of particulate matter (PM) and lead. Because the fugitive dust screening summarized in the 2010 Risk Assessment identified the potential for acute exposures to exceed these standards, EPA also collected acute inhalation toxicity values to evaluate additional constituents that may be sorbed to the particulate surface. Guidelines intended to protect against mild adverse health effects (e.g., respiratory irritation) were gathered. If these guidelines were not available, the severe effect guidelines were used with a safety factor of 10 to approximate a milder effect level, based on the recommendations in *Human Health Risk Assessment Protocol for Hazardous Waste Combustion Facilities* (U.S. EPA, 2005). All sources considered have either undergone peer review or were developed based on a peer-reviewed process. In addition, the reference exposure levels (RELs) and acute exposure guideline levels (AEGLs) have been made available for public review and comment. Benchmarks for inhalation were drawn from the following sources, listed in order of preference:

- CalEPA acute RELs,
- U.S. EPA AEGLs,
- American Industrial Hygiene Association emergency response planning guidelines ,
- U.S. DOE temporary emergency exposure limits, and
- National Institute for Occupational Safety and Health immediately dangerous to life or health divided by an uncertainty factor of 10.

Ecological Benchmarks

EPA updated the concentration-based benchmarks used in the 2010 Risk Assessment for ecological exposures that result from direct contact with and foraging in soil, surface water and sediment. These benchmarks are based on classes of receptors (e.g., invertebrates, mammals) and do not consider predator–prey interactions. Ecological benchmarks for the revised risk assessment were obtained from the following sources listed below in order of preference for each medium, with further information about each source provided in **Appendix E**:

- **Surface Water:** Criterion Continuous Concentrations developed under the EPA National Ambient Water Quality Program, Final Chronic Values implemented under the Great Lakes Water Quality Initiative, and Secondary Chronic Values presented in Suter and Tsao (1996).
- **Sediment:** Threshold Effect Level drawn from Buchman (2008) and Effects Range Low Levels drawn from various literature sources.
- **Soil:** Ecological Soil Screening Levels developed by multi-stakeholder workgroup led by EPA and Oak Ridge National Lab screening benchmarks developed for the U.S. DOE.

2.4 Risk Criteria

One of the primary goals of this risk assessment is to identify the likelihood of adverse effects. An adverse effect is a broad term for any abnormal, harmful, or undesirable change that may results from chemical constituent exposures. These effects can be divided into two broad types: carcinogenic and noncarcinogenic. Carcinogenic effects are those that ultimately result in the occurrence of cancer somewhere in the individual. The likelihood of carcinogenic effects is expressed as the increased lifetime probability of cancer that results from an incremental exposure. Noncarcinogenic effects are those that result in adverse health effects other than cancer. The likelihood of noncarcinogenic effects is expressed as a ratio of the exposure level and the level below which no adverse effects are known or anticipated to occur. To evaluate adverse effects in this risk assessment, EPA used the following criteria:

- **Human Health Cancer Risk:** EPA considered excess lifetime cancer risks within the OSWER risk range of between a 1 in 1,000,000 (1×10^{-6}) and a 1 in 10,000 (1×10^{-4}) excess cancer risk. EPA has historically used a 1×10^{-5} excess cancer risk as the point of departure for RCRA hazardous waste listings (59 FR 66075). Thus, in determining whether to retain constituents for further analysis, EPA used a 1×10^{-5} excess lifetime cancer risk. Cancer risk represents the increased risk of developing cancer for members of the exposed population over their lifetime.
- **Human Health Noncancer Risk:** An HQ > 1 was selected, based on the recommendations of U.S. EPA (1989). An HQ represents the ratio of actual exposure and the highest exposure level at which no adverse health effects are likely to occur. An HQs > 1 indicates that an adverse effect may occur, with a higher HQ indicating a greater likelihood of occurrence. However, this ratio does not correspond to an exact probability of noncancer adverse effects for members of the exposed population.
- **Ecological Risk:** An HQ > 1 was selected to evaluate adverse effects to ecological receptors.

2.5 Hazard Identification

Hazard potential exists where a constituent is present and is either known or anticipated to cause adverse effects to human health or the environment. For purposes of this preliminary stage of the assessment, EPA considered the presence of a constituent with one or more toxicity benchmarks sufficient evidence of hazard potential. A review of available data identified a total of 34 constituents for which both concentration data and toxicity benchmarks were available. EPA retained each of these constituents for further evaluation as COPCs. The hazard identification results are shown in **Table 2-2**. Those constituents that had no toxicity value or concentration for a given pathway could not be carried forward for further quantitative analysis. Instead, these exposures are further discussed qualitatively as part of the uncertainty analyses in **Section 5**.

Table 2-2. Hazard Identification Results

Constituent	CASRN	Human Health			Ecological		
		Chronic Oral	Acute Inhalation	Chronic Inhalation	Soil	Surface Water	Sediment
Aluminum	7429-90-5	✓	✓	✓	—	✓	—
Ammonia	7664-41-7	✓	—	—	—	—	—
Antimony	7440-36-0	✓	✓	✓	✓	✓	✓
Arsenic	7440-38-2	✓	✓	✓	✓	✓	✓
Barium	7440-39-3	✓	✓	—	✓	✓	✓
Beryllium	7440-41-7	✓	✓	✓	✓	✓	—
Boron	7440-42-8	✓	✓	—	✓	✓	—
Cadmium	7440-43-9	✓	✓	✓	✓	✓	✓
Calcium	7440-70-2	—	✓	—	—	—	—
Chloride	16887-00-6	—	✓	—	—	✓	—
Chromium	7440-47-3	✓	✓	✓	✓	✓	✓
Cobalt	7440-48-4	✓	✓	✓	✓	✓	—
Copper	7440-50-8	✓	✓	—	✓	✓	✓
Fluoride	16984-48-8	✓	✓	—	—	—	—
Iron	7439-89-6	✓	✓	—	—	✓	—
Lanthanum	7439-91-0	✓	✓	—	—	—	—
Lead	7439-92-1	✓	✓	—	✓	✓	✓
Lithium	7439-93-2	✓	—	—	—	—	—
Magnesium	7439-95-4	—	✓	—	—	—	—
Manganese	7439-96-5	✓	✓	✓	✓	✓	—
Mercury	7439-97-6	✓	✓	✓	✓	✓	✓
Molybdenum	7439-98-7	✓	✓	—	✓	✓	✓
Nickel	7440-02-0	✓	✓	✓	✓	✓	✓
Nitrate/Nitrite	14797-55-8/-65-0	✓	✓	—	—	—	—
Selenium	7782-49-2	✓	✓	✓	✓	✓	—
Silicon	7631-86-9	—	✓	—	—	—	—
Silicon	7631-86-9	—	✓	—	—	—	—
Silver	7440-22-4	✓	✓	—	✓	✓	✓
Sodium	7440-23-5	—	✓	—	—	—	—
Strontium	7440-24-6	✓	✓	—	—	—	—
Sulfate	14808-79-8	—	✓	—	—	—	—
Sulfide	18496-25-8	—	—	—	—	✓	—
Thallium	7440-28-0	✓	✓	—	—	✓	—
Uranium	7440-61-1	✓	✓	✓	—	—	—
Vanadium	7440-62-2	✓	✓	✓	✓	✓	✓
Zinc	7440-66-6	✓	✓	—	✓	✓	✓

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3 Screening Analysis

EPA conducted a screening analysis for each of the exposure pathways identified in the conceptual models developed in **Section 2**. Consistent with the regional screening tables used in the Superfund program, EPA screened risks using children and adult age cohorts, but not infants. The results of this screening are not intended to provide a precise characterization of individual risks that may occur, but rather to identify those COPCs that are most likely to pose risk. Because this screening analysis is deterministic, it does not account for site-based variability. Based on the results of this screening, EPA determined which pathways and associated COPCs to retain for further characterization with more refined, probabilistic modeling summarized in **Section 4**. The discussion of the screening analysis is divided into the following sections:

- **Section 3.1** discusses the development of source concentrations used to characterize releases from WMUs in the screening.
- **Section 3.2** provides an overview of the screening for exposures through ambient air that result from transport of CCR waste by wind.
- **Section 3.3** provides an overview of the screening for exposures through soil, sediment, produce and livestock that result from transport of CCR waste by wind and overland run-off.
- **Section 3.4** provides an overview of the screening for exposures through ground water, surface water, and fish that result from transport of leachate through ground water.
- **Section 3.5** summarizes the results and conclusions of the screening and identifies the COPCs and exposure pathways retained for further probabilistic modeling.

3.1 Waste Source Concentrations

EPA used the data contained in the CCR constituent database (**Appendix C**) as the basis for calculating COPC concentrations present in and released from surface impoundments and landfills. These data have been collected over time from many facilities and are intended to capture national variability. EPA calculated 90th percentile concentrations to represent high-end releases from WMUs. Prior to calculation, all available data were processed to minimize bias, as described below. The resulting 90th percentile values are presented in **Table 3-1** at the end of this subsection.

- **Treatment of Nondetects:** Nondetect measurements represent constituent concentrations below the capability of an analytical methodology to differentiate from background noise and do not provide definitive evidence that a constituent is or is not present. However, nondetect measurements do indicate that the constituents are not present at concentrations above the detection limit. Thus, eliminating nondetects outright will unduly bias the remaining, truncated data set toward the higher, detected values. The revised risk assessment replaced nondetect values with half of the reported detection limit according to the recommendations in *Risk Assessment Guidance for Superfund (RAGS) Part A* (U.S. EPA, 1989) and *EPA Region 3 Guidance on Handling Chemical Concentration Data near the Detection Limit in Risk Assessments* (U.S. EPA, 1991).

- **Data for Mercury.** With the exception of mercury, EPA used all available data in the CCR constituent database to characterize exposures. The majority of mercury data measured prior to 2010 had high detection limits and a large proportion of nondetects. Newer data made available to the Agency since the 2010 Risk Assessment (U.S. EPA, 2010a) were measured using newer methods with significantly lower detection limits. In many cases, the mercury concentrations detected with the new methods were less than half the older detection limits. Because use of the older mercury data has the potential to introduce a large bias into the analysis, EPA chose to use only the post-2010 mercury data in the revised risk assessment. These data contain few nondetects and are more likely to accurately represent the mercury concentrations present in and released from CCR WMUs.
- **Development of Waste Types:** Given the large size of the WMUs and the generally basic nature of CCR leachate, it is possible that leachate could alter the subsurface geochemistry that governs the migration of inorganic constituents. Therefore, a statistical analysis of the concentrations of major ions (e.g., calcium, sulfate, hydrogen ions) in the pore water was conducted to identify distinct waste types (**Appendix H**). These waste types are considered separately to better capture the behavior of COPCs released from these wastes in the subsurface environment. The three distinct waste types considered in this analysis are:
  - **Ash and Coal Refuse:** Includes any CCR that is codisposed with coal refuse, which is waste coal produced from coal handling, crushing and sizing operations. This waste type is characterized by a low to moderate pH (1.7–8.2) and high levels of sulfate, iron and manganese.
  - **FGD Wastes:** Includes any type of wet or dry FGD waste when disposed in dedicated monofills. This waste type is characterized by a moderate to high pH (8.7–11.3) and high levels of calcium, sulfate, sodium and chlorine.
  - **Combined Ash:** Includes any CCRs other than those listed above (e.g., fly ash, bottom ash, boiler slag) either monofilled or in combination with each other. Due to the variability in disposal practices, this waste type is characterized by a broad range in pH (3.9–12.3), sulfate and calcium levels.
- **Site Quartiles:** Some sample sites in the CCR constituent database have many data points, while others have only a few. Thus, the available data would tend to bias concentrations toward those sites where more samples were collected. To avoid this, EPA developed quartiles of the COPC concentrations for each site. This approach provides equal weighting to each site while also retaining some of the intrasite variability that would be lost through the use of a single summary statistic for each site, such as an average. To develop the site quartiles, EPA first separated the data at each site into the different waste types reported at that site. This was done because combining the data for the different waste types into a single set of quartiles for a site might bias concentrations toward the most sampled waste types. Where only one sample was available for a waste type at a sample site, all of the quartiles were set to this value to ensure equal weighting. For the purposes of this screening, all

quartiles developed were then combined into a single distribution representing all sites and all waste types, from which a 90th percentile concentration was drawn.

Table 3-1. 90th Percentile Concentrations Used for Screening Analysis

Constituent	Impoundment Pore Water (mg/L)	Impoundment Wastewater (mg/L)	Whole Waste (mg/kg)
Aluminum	12.3	2.3	91,500
Ammonia	5.1	–	–
Antimony	0.04	0.02	47.0
Arsenic	0.78	0.13	106
Barium	0.21	0.43	1,103
Beryllium	0.001	0.001	18.3
Boron	97.8	36.2	388
Cadmium	0.06	0.003	3.8
Calcium	592	577	114,750
Chloride	2,023	345	384
Chromium	0.2	0.03	153
Cobalt	0.05	0.02	65.9
Copper	0.13	0.01	226
Fluoride	21.3	–	25
Iron	11.9	0.04	42,426
Lanthanum	–	–	58.6
Lead	0.10	0.0006	75.3
Lithium	0.45	1.99	–
Magnesium	174	1,990	17,550
Manganese	1.8	0.56	413
Mercury	0.000007	0.00003	1.1
Molybdenum	7.1	0.42	31.0
Nickel	0.3	0.07	199
Nitrate	13.7	–	0.25
Nitrite	5.0	–	–
Potassium	221	40	9,622
Selenium	0.32	0.10	18.2
Silicon	19.0	12.7	262,700
Silver	0.005	0.0001	11.1
Sodium	3,288	743	3,557

Table 3-1. 90th Percentile Concentrations Used for Screening Analysis

Constituent	Impoundment Pore Water (mg/L)	Impoundment Wastewater (mg/L)	Whole Waste (mg/kg)
Strontium	9.1	4.3	891
Sulfate	4,398	10,400	9,630
Sulfide	–	–	26.2
Sulfur	3,842	–	36,000
Thallium	0.003	0.009	33.9
Uranium	0.01	0.004	5.0
Vanadium	0.52	0.23	562
Zinc	0.19	0.06	269

These 90th percentile values represent the concentrations present in and released from CCR wastes. Impoundment pore water is the water present within interstitial spaces of the settled CCRs. Impoundment wastewater is the free water ponded on top of the settled CCR waste. Whole waste represents the concentrations present within CCRs at the time of generation. However, most receptors will not come in direct contact with CCR wastes. Instead, receptors are exposed to environmental media, such as air; soil and water, that have been contaminated by releases from these wastes. To estimate the concentrations that may be present in these environmental media, EPA used conservative assumptions to account for fate and transport of COPCs through the environment. The calculation of these media-specific exposure concentrations are discussed in the following subsections.

3.2 Ambient Air Screening

This subsection summarizes the screening for exposure pathways associated with two management scenarios: uncontrolled and controlled releases. Uncontrolled releases occur when no action is taken to reduce particulate emissions. Controlled releases occur when management practices are put in place to minimize the rate of particulates emissions. The controls considered in this analysis include wetting and/or the use of surfactants.[10] Yet, even with the best available management practices, some emissions may still occur. Relevant exposure pathways include human inhalation of particulate matter and any COPCs contained therein. The greatest source of these pathways are landfills during operation, as water cover for impoundments and postclosure cap for landfills will limit the release of particulate matter. Therefore, EPA screened these pathways for landfills and the results were also used to identify any COPCs for surface impoundments.

[10] Surfactants refer to compounds that lower the surface tension (or interfacial tension) between a liquid and a solid, and can increase the effectiveness of water as a dust control mechanism.

3.2.1 Exposure Concentrations

EPA used the 90th percentile whole waste concentrations presented in **Table 3-1** to estimate exposures to ambient air. However, these whole waste concentrations represent the mass of COPCs present within CCR wastes. To translate the concentrations in CCR waste to those in ambient air, EPA conducted modeling in two phases with the American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) and the corresponding screening model, AERSCREEN. Unitized particulate emission rates of 1 g/s and 1 µg/s-m^2 were used as inputs for AERSCREEN and AERMOD, respectively, to calculate a set of unitized dispersion factors. The purpose of these unitized factors was to allow for quick and easy scaling of the model results and to minimize the number of model runs required. Further discussion of this approach and the inputs used to run and scale these models is provided in **Appendix F**.

EPA first used AERSCREEN to calculate maximum unitized dispersion factors that could occur over one hour with weather data from a number of climate stations. This 1-hour averaging time was chosen as the most appropriate value to represent short-term exposures. AERSCREEN also calculates maximum air concentrations for other averaging times (i.e., 3-hour, 8-hour, 24-hour, annual) by scaling the 1-hour concentration. However, for area sources such as landfills, the screening model uses a scaling factor of 1 for these longer averaging times, which results in overly conservative long-term concentrations that are equal to the 1-hour concentration. Instead, a second phase of modeling was conducted with AERMOD to calculate unitized dispersion factors for 24-hour, monthly and annual averaging times. To minimize the resources required, EPA conducted a single AERMOD model run using five years of weather data from the climate station associated with the 90th percentile unitized dispersion factor from AERSCREEN. For both models, EPA selected the modeled unitized dispersion factors from the distance that resulted in the highest value and scaled each using **Equation 3-1**:

(3-1) $$C_{air} = \frac{E \cdot DF \cdot C_{waste}}{A \cdot \left(10^9 \frac{\mu g}{kg}\right)}$$

Where:

C_{air} = Air concentration of constituent (mg/m^3),
E = Aggregate emission rate (g/s),
DF = Unitized dispersion factor (µg/m^3 per g/m^2-s),
C_{waste} = 90th percentile constituent-specific whole waste concentration (mg/kg),
A = Active area of landfill (m^2).

Emission rates were calculated for particles 10 micrometers in diameter or smaller (PM_{10}), and were separately scaled for the fraction of PM_{10} that are 2.5 micrometers in diameter or smaller ($PM_{2.5}$). These are the particles most likely pass through the nose and throat and enter the lungs, dramatically increasing the risk of adverse health effects. Emission rates were calculated for four specific sources: wind erosion, vehicular activity, loading/unloading and spreading/compaction using equations from *AP-42: Compilation of Air Pollutant Emission Factors* (U.S. EPA, 1985a) and *Rapid Assessment of Exposure to Particulate Emissions from Surface Contamination Sites*

(U.S. EPA, 1985b). To capture the variability of national meteorological conditions, emission estimates were developed for a range of active landfill sizes with data from more than 40 meteorological stations that represent locations throughout the conterminous United States where CCR disposal in landfills are known to occur. Each of these emission rates was developed for both uncontrolled and controlled management scenarios. For each set of conditions evaluated, EPA summed the contributions from the four sources together to obtain an aggregate PM_{10} emission rate (E_{10}) and an aggregate $PM_{2.5}$ emission rate ($E_{2.5}$).

AERSCREEN and AERMOD results were scaled using every combination of PM_{10} emission rates, whole waste concentrations from **Table 3-1**, and active landfill sizes drawn from EPA surveys to obtain COPC concentrations in ambient air. A second scaling was conducted without the whole waste concentration data, to obtain PM_{10} and $PM_{2.5}$ concentrations in ambient air. From each of these sets of calculations, EPA selected the highest air concentrations from each management scenario for comparison in the screening.

3.2.2 Air Risks

EPA used the calculated air concentrations of particulates and COPCs to estimate risks for human receptors. EPA considered human health risks from inhalation of particulates and the COPCs contained on or in those particulates. Because air concentrations can vary considerably over time, EPA considered multiple averaging times to screen both short-term (i.e., acute) and long-tem (i.e., chronic) exposures.

Acute Human Inhalation Risks

Acute human health risks associated with the inhalation of COPCs present in ambient air were evaluated using concentration-based benchmarks (**Appendix E**). These benchmarks represent air concentrations below which no acute adverse effects are known or anticipated to occur for short exposure durations. Acute risks were evaluated by comparing these benchmarks to the maximum 1-hour concentrations calculated with AERSCREEN. The resulting noncancer risks were calculated using **Equation 3-2**:

(3-2) $$HQ_A = \frac{C_{air}}{RfC_A}$$

Where:

HQ_A = Acute hazard quotient (unitless)
C_{air} = 1-hour air concentration (mg/m^3)
RfC_A = Acute reference concentration (mg/m^3)

Table 3-2 presents these screening results for acute health risks resulting from inhalation of the COPCs from airborne particulates. These conservative results are presented for each COPC under both the controlled and uncontrolled management scenarios. Values found to be above the selected risk criteria (i.e., an $HQ_A > 1$) are shown in **bold**.

Table 3-2. Screening Results for Acute Human Health Risks Resulting from the Inhalation of Ambient Air

COPC	Management Scenario	
	Uncontrolled	Controlled
Aluminum	0.1	0.03
Antimony	< 0.01	< 0.01
Arsenic	**2**	0.5
Barium	< 0.01	< 0.01
Beryllium	0.02	< 0.01
Boron	< 0.01	< 0.01
Cadmium	< 0.01	< 0.01
Calcium	0.01	< 0.01
Chloride	< 0.01	< 0.01
Chromium	< 0.01	< 0.01
Cobalt	< 0.01	< 0.01
Copper	< 0.01	< 0.01
Fluoride	< 0.01	< 0.01
Iron	0.02	0.01
Lanthanum	< 0.01	< 0.01
Lead	< 0.01	< 0.01
Magnesium	0.01	< 0.01
Manganese	< 0.01	< 0.01
Mercury (elemental)	< 0.01	< 0.01
Molybdenum	< 0.01	< 0.01
Nickel	0.1	0.03
Nitrate/Nitrite	< 0.01	< 0.01
Potassium	0.2	0.05
Selenium	< 0.01	< 0.01
Silicon	0.02	< 0.01
Silver	< 0.01	< 0.01
Sodium	< 0.01	< 0.01
Strontium	< 0.01	< 0.01
Sulfate	< 0.01	< 0.01
Thallium	< 0.01	< 0.01
Uranium	< 0.01	< 0.01
Vanadium	< 0.01	< 0.01
Zinc	< 0.01	< 0.01

Noncancer risks above the risk criteria were identified for arsenic by a factor of 2 under the uncontrolled management scenario, but decreased below risk criteria when fugitive dust controls were considered. All other COPCs were below the risk criteria under the uncontrolled management scenario, and were over an order of magnitude below the criteria for the controlled management scenario.

Chronic Human Inhalation Risks

Chronic human health risks associated with the inhalation of COPCs present in ambient air were evaluated using concentration-based benchmarks. These benchmarks represent air concentrations below which no adverse effects are known or anticipated to occur over a lifetime of chronic exposure. Chronic risks were evaluated by comparing these benchmarks to the maximum annual concentrations calculated with AERMOD. Cancer risks were calculated using **Equation 3-3**:

(3-3) $$\mathrm{Risk_{Inhal}} = \mathrm{C_{air}} \cdot \mathrm{URF_{inhal}} \cdot 1{,}000 \left(\frac{\mu g}{mg}\right)$$

Where:

$\mathrm{Risk_{Inhal}}$ = Individual cancer risk from inhalation of contaminants (unitless)
$\mathrm{C_{air}}$ = Annual air concentration (mg/m^3)
$\mathrm{URF_{inhal}}$ = Inhalation unit risk factor (per $\mu g/m^3$)

While noncancer HQs were calculated using **Equation 3-4**:

(3-4) $$\mathrm{HQ_C} = \frac{\mathrm{C_{air}}}{\mathrm{RfC_C}}$$

Where:

$\mathrm{HQ_C}$ = Chronic hazard quotient (unitless)
$\mathrm{C_{air}}$ = Annual air concentration (mg/m^3)
$\mathrm{RfC_C}$ = Chronic reference concentration (mg/m^3).

Table 3-3 presents the screening results for both cancer and noncancer risks. Where benchmarks were available for multiple species of a constituent, the most conservative was used in the screening calculations. These conservative results are presented for each COPC under controlled and uncontrolled management scenarios. No values were found to be above either the cancer or noncancer criteria for either scenario.

Table 3-3. Screening Results for Chronic Human Health Risks Resulting from Inhalation of Ambient Air

COPC	Management Scenario	
	Uncontrolled	Controlled
Carcinogenic Risks		
Arsenic	2×10^{-6}	7×10^{-7}
Beryllium	2×10^{-7}	7×10^{-8}
Cadmium	4×10^{-8}	1×10^{-8}
Chromium	9×10^{-6}	3×10^{-6}
Cobalt	3×10^{-6}	9×10^{-7}

(continued)

Table 3-3. Screening Results for Chronic Human Health Risks Resulting from Inhalation of Ambient Air

COPC	Management Scenario	
	Uncontrolled	Controlled
Noncarcinogenic Risks		
Aluminum	0.6	0.2
Antimony	< 0.01	< 0.01
Arsenic	0.2	0.07
Beryllium	0.03	0.01
Cadmium	0.01	< 0.01
Chromium	0.05	0.02
Cobalt	0.4	0.1
Manganese	0.3	0.09
Mercury	< 0.01	< 0.01
Nickel	0.08	0.02
Selenium	< 0.01	< 0.01
Sulfide	< 0.01	< 0.01
Uranium	< 0.01	< 0.01
Vanadium	0.2	0.06

National Ambient Air Quality Standards

NAAQS are concentration-based regulatory limits developed for several priority pollutants by EPA. These benchmarks represent air concentrations protective of public health, including sensitive populations, such as asthmatics, children and the elderly. NAAQS exceedances were evaluated by comparing these benchmarks to the concentrations calculated with AERMOD for the available averaging time closest to that specified by the NAAQS standards. Annual concentrations were used for PM_{10} while both annual and 24-hour concentrations were used for $PM_{2.5}$. The specified averaging time for lead is a rolling 3-month average, which is not an available output from either AERSCREEN or AERMOD. Instead, lead concentrations were evaluated using a more protective monthly average concentration. The HQs were calculated using **Equation 3-5**:

$$\textbf{(3-5)} \quad \text{Ratio} = \frac{C_{air}}{NAAQS}$$

Where:

Ratio = Exposure ratio (unitless)
C_{air} = 24-hour/monthly/annual air concentration (mg/m^3)
NAAQS = National ambient air quality standard (mg/m^3).

Table 3-4 presents the screening results for both NAAQS standards. These conservative results are presented for each COPC under both the controlled and uncontrolled management scenarios. Values found to be above the selected risk criteria (i.e., a ratio > 1) are shown in **bold**.

Table 3-4. Screening Results for NAAQS

COPC	Averaging Time	Management Scenario	
		Uncontrolled	Controlled
PM_{10}	24-hour	0.4	0.1
$PM_{2.5}$	Annual	0.5	0.3
$PM_{2.5}$	24-hour	**2**	1
Lead	Monthly	0.03	0.02

An air concentration above the NAAQS for 24-hr $PM_{2.5}$ by a factor of 2 was identified under an uncontrolled management scenario, but decreased below relevant NAAQS when fugitive dust controls were considered.

3.3 Soil, Sediment, Plant and Animal Screening

This section summarizes the screening for all exposure pathways that result from aboveground transport of COPCs to downgradient soil and sediment. Aboveground transport occurs through windblown dust and particulates suspended in overland run-off. Two management scenarios are considered: uncontrolled and controlled releases. Uncontrolled releases occur when no action is taken to control particulate releases. Controlled releases occur when there is active management of CCR waste to minimize the rate of particulates emissions. These management practices include the use of wetting and surfactants to reduce windblown dust, and run-on/run-off controls to collect or otherwise control run-off from all rainfall events less than the maximum storm predicted for each 25-year interval in the area.

Relevant human exposure pathways include incidental ingestion of contaminated soils, as well as ingestion of any crops or livestock raised on contaminated soils. Relevant ecological exposures include direct contact with and ingestion of contaminated soils and sediment, as well as ingestion of any biota living around contaminated soil and sediment. Sediment exposures were screened through this pathway under the assumption that overland transport would contribute substantially higher loadings to downgradient water bodies than subsurface transport through ground water. Each of these exposure pathways are primarily associated with landfills during operation, as the constant water cover in impoundments and the postclosure cap in landfills will limit the transport of particulates by wind and overland run-off.

3.3.1 Exposure Concentrations

EPA used the 90th percentile whole waste concentrations listed in **Table 3-1** to estimate exposures to soil, sediment, produce and animal products. However, these whole waste concentrations represent the total mass of COPCs present in CCR wastes. To translate the concentrations in CCR waste to those in soil, sediment, produce and livestock, additional calculations were necessary.

Soil and Sediment Concentrations

EPA used dilution attenuation factors (DAFs) to estimate the COPC concentrations that may accumulate in downgradient soils and sediments under the uncontrolled management scenario. A DAF is a ratio of the initial constituent concentration at the point of release to the final constituent concentration at the point of exposure. EPA identified an appropriate DAF for the uncontrolled management scenario from the 1998 Risk Assessment (U.S. EPA, 1998a), which considered unmitigated transport of CCR waste from uncovered CCR landfills by wind and overland runoff. **Figure 3-1** plots the DAFs for each modeled constituent against the corresponding soil–water partition coefficient (K_d). K_d values are a measure of the tendency of a constituent to distribute between the solid and liquid phases. A strong inverse relationship can be seen between the DAFs and the K_d values for the COPCs. This is because the constituents most likely to leach out (i.e., those with low K_d values) will not accumulate in surficial soils to the same degree as those least likely to leach out (i.e., those with high K_d values).

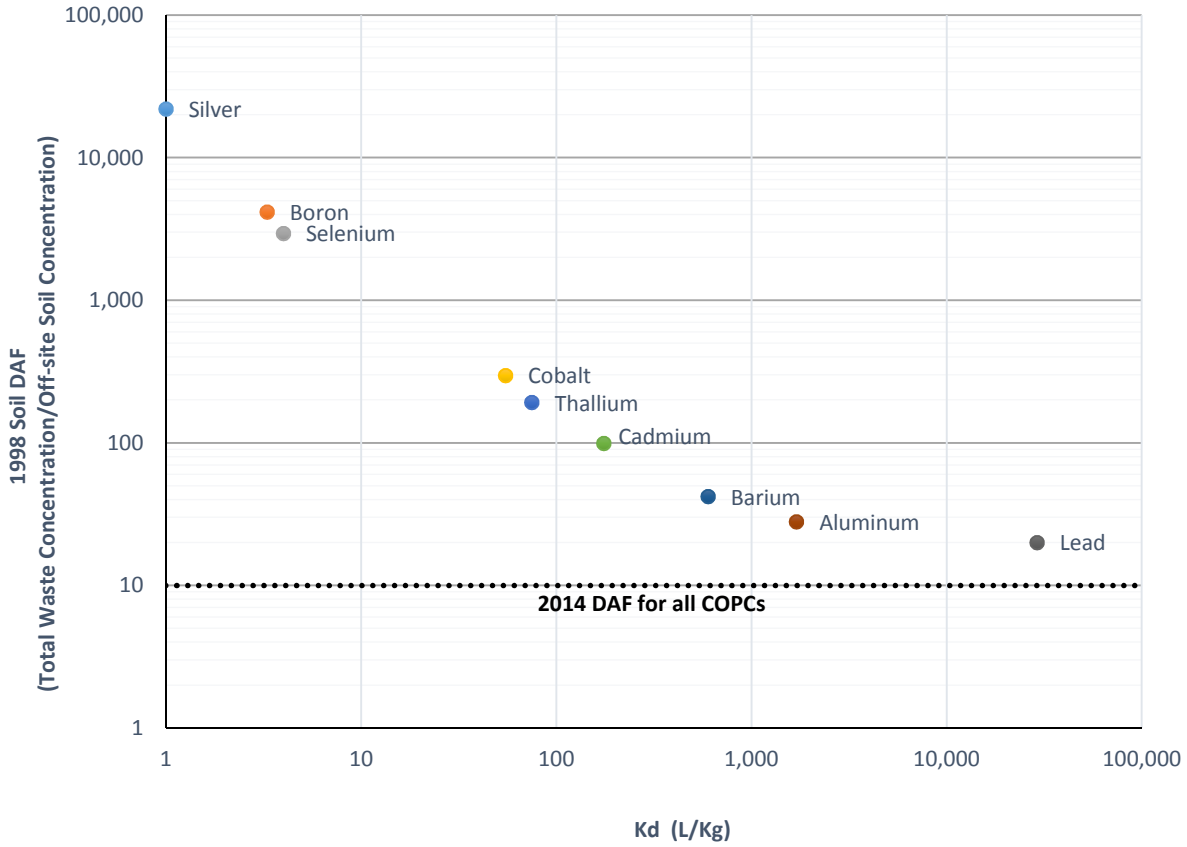

Figure 3-1. Dilution-attenuation factors as a function of K_d values as modeled in the 1998 risk assessment (adapted from U.S. EPA, 1998a).

For ease of calculation and to ensure that potential exposures were not underestimated, the revised risk assessment applied a single DAF of 10 to all COPCs for the uncontrolled management scenario. The selected DAF is below the lowest value identified in U.S. EPA (1998a) for lead, which had the highest K_d value of any COPC modeled. EPA divided the 90th percentile whole

waste concentrations by the DAF of 10 to generate downgradient concentrations used to screen exposures to both soil and sediment for the uncontrolled management scenario.

For the controlled management scenario, run-on and run-off controls for landfills require collection and control of all run-off up to that of a 24-hour, 25-year event. These controls would essentially eliminate all off-site migration through overland run-off on an annual basis. Thus, EPA assumed that run-off was negligible. Instead, soil and sediment concentrations were calculated assuming that transport resulted only from the deposition of windblown particulates onto soil. EPA calculated a total deposition rate onto soils with **Equation 3-6**:

(3-6) $$D_p = \left[\frac{E_{10} \cdot C_{waste}}{A \cdot \left(10^6 \frac{mg}{kg}\right)}\right] \cdot \left[D_{ydp} + D_{wdp}\right]$$

Where:

D_p = Deposition rate (g/m^2-yr)
E_{10} = PM_{10} emission rate (g/s)
C_{waste} = 90th percentile constituent-specific whole waste concentration (mg/kg)
A = Active landfill area (m^2)
D_{ydp} = Unitized dry deposition rate (g/m^2-yr per g/m^2-s)
D_{wdp} = Unitized wet deposition rate (g/m^2-yr per g/m^2-s).

The unitized dry and wet deposition rates are outputs generated by AERMOD during the model runs conducted to screen ambient air concentrations. Thus, all inputs were the same. Further detail on the inputs used for AERMOD is provided in **Appendix F**. The soil and sediment concentrations that result from deposition under the controlled management scenario were calculated using the conservative assumption that the deposition of particulates occurs continuously without any losses over the course of 10 years, consistent with an average exposure duration for adults. The settled particulates are uniformly mixed within the first centimeter of topsoil and surface sediment, which has a fixed density of 1,300 kg/m^3.

Concentrations in Produce

COPCs present in the soil can be drawn into plants through the root systems and consumed along with the edible portion of the plant. Plants may also become contaminated from windblown particulates that settle out on the plant surface. Both root uptake and air deposition may happen simultaneously, and thus, the resulting exposures are assumed to be additive. However, air deposition will not contribute to exposures for some produce categories because the plants have protective outer layers that are discarded prior to consumption. **Table 3-5** provides a breakdown of the different types of plants considered. Some of these plant categories (i.e., silage, forage) are considered as feed for cattle raised as a source of beef and milk for human consumption.

Table 3-5. Potential Routes of Contamination for Different Plant Types

Produce/Plant Category	Example	Root Uptake	Air Deposition
Exposed Fruits	Strawberry	✓	✓
Exposed Vegetables	Lettuce	✓	✓
Silage	Alfalfa	✓	✓
Forage	Grass	✓	✓
Protected Fruit	Watermelon	✓	–
Protected Vegetables	Onion	✓	–
Grains	Wheat	✓	–
Root Vegetables	Carrot	✓	–

The degree to which COPCs are taken up from the soil by different plants varies. To represent these differences, EPA used bioconcentration factors (BCFs) drawn from the available literature for each of the eight plant types listed above. BCFs provide information on the amount of uptake and accumulation of a substance from soil and are expressed as a concentration in the plant per unit of concentration in the soil. The COPC concentration in the edible portion of the plant was calculated by multiplying the concentration in the soil by the appropriate BCF. The resulting concentrations are in terms of dry weight, but human consumption data are available on a wet weight basis. Therefore, the calculated dry weight concentrations were multiplied by a water adjustment factor to scale to wet weight. The specific equations, BCFs and other inputs used for this pathway are presented in **Appendix G**.

In addition to soil uptake, several plant types also accumulate particulates on exposed surfaces from air deposition. The deposition to soils in **Equation 3-6** was adjusted to account for the fraction of deposition that will not adhere to the plant surface, resulting in **Equation 3-7**:

(3-7)
$$D_p = \left[\frac{E_{10} \cdot C_{waste}}{A \cdot \left(10^6 \frac{mg}{kg}\right)}\right] \cdot \left[D_{ydp} + \left(F_w \cdot D_{wdp}\right)\right]$$

Where:

D_p = Deposition rate (g/m^2-yr)
E_{10} = PM_{10} emission rate (g/s)
C_{waste} = 90th percentile constituent-specific whole waste concentration (mg/kg)
A = Active landfill area (m^2)
D_{ydp} = Unitized dry deposition rate (g/m^2-yr per g/m^2-s)
D_{wdp} = Unitized wet deposition rate (g/m^2-yr per g/m^2-s)
F_w = Fraction of wet deposition adhering to plant surface (unitless).

As with deposition onto soil, the unitized dry and wet dry deposition rates are outputs generated by AERMOD during the model runs conducted to screen ambient air concentrations. Thus, all weather data, active landfill area, emission rates and other inputs were the same. **Appendix G**

provides the plant-specific parameters (i.e., F_w) used in this equation, as well as the other equations used to convert the deposition rate into a concentration for aboveground produce.

Concentrations in Livestock

COPCs may concentrate in livestock through the ingestion of contaminated soil and feedstock. To represent this accumulation, EPA used biotransfer factors (BTFs) drawn from the available literature. BTFs provide information on the amount of accumulation of a chemical compound in animal products (e.g., beef, milk) based on the rate of consumption of feed and soil. The COPC concentrations in beef and milk were calculated for uncontrolled and controlled management scenarios by multiplying the mass of contaminant consumed each day by the appropriate BTF. The mass consumed was calculated by multiplying the quantity of feed or soil consumed by the concentration in the feed or soil and then summed across the types of feed plus soil. For both the uncontrolled and controlled management scenarios, EPA assumed all feedstock consumed by cattle were grown on contaminated soils, and that any soil consumed while foraging was also contaminated. The specific equations and BTFs used are presented in **Appendix G.**

3.3.2 Receptor Risks

EPA used the COPC concentrations calculated for each environmental media to estimate risks for human and ecological receptors under both uncontrolled and controlled management scenarios. EPA considered human health risks from ingestion of media from around home-based farm and ecological risks from ingestion of and direct contact with media. All pathways were evaluated for adverse effects resulting from chronic exposures. Generally, adverse effects from chronic exposures occur at lower media concentrations than acute exposures. Therefore, the constant, high-end concentrations used to screen chronic exposures will also be protective of acute exposures.

Human Health Risk from Ingestion

Human health risks associated with ingestion are evaluated using dose-based benchmarks. In order to translate the calculated exposure concentrations for each medium into risks, EPA first had to characterize the potential receptors. This was done for each receptor cohort by calculating an average daily dose (ADD), which is the intake rate averaged over specified exposure duration and expressed as a daily dose per unit of body weight. For noncancer risks, the dose was averaged on an annual basis using **Equation 3-8**.

(3-8) $$ADD = \sum_{i=s}^{n} \left[\frac{I_i \cdot ED_i}{ED_{total}} \right]$$

Where:

ADD = Average daily dose (mg/kg-day)
I_i = Intake for receptor age cohort i (mg/kg-day) (calculated in **Appendix G**)
ED_i = Exposure duration of age cohort i (yr) (cannot exceed length of age cohort)
ED_{total} = Total exposure duration (yr).

For cancer risks, the dose averaged over the lifetime of the individual using **Equation 3-9**, resulting in a lifetime average daily dose (LADD).

(3-9) $$\text{LADD} = \sum_{i=s}^{n} \left[\frac{\text{ADD} \cdot \text{ED}_i \cdot \text{EF}_i}{\text{AT} \cdot \left(365 \frac{\text{days}}{\text{year}}\right)} \right]$$

Where:

LADD = Lifetime average daily dose (mg/kg-day)
EF_i = Exposure frequency for age cohort i (day/yr)
AT = Averaging time (yr).

To calculate these dose rates, EPA used central tendency exposure factors. These factors were chosen to balance some of the conservatism present elsewhere in the screening. Exposures were considered separately for receptors starting in seven different age cohorts (i.e., 1 to < 2 yrs, 2 to < 3 yrs, 3 to < 6 yrs, 6 to < 11 yrs, 11 to < 16 yrs, 16 to < 21 yrs, and > 21 yrs). Since some exposure factors were specific to an age cohort, exposure calculations aged receptors from the beginning of the specified cohort through subsequent cohorts until the full exposure duration had been reached.

ADD and LADD were calculated on a COPC-specific basis for each age cohort. The calculated doses were compared to human health benchmarks for noncancer and cancer effects, respectively. A reference dose (RfD), which is an estimate of a daily exposure that is likely to be without appreciable risk, was used to estimate HQs for noncancer effects. These HQs were calculated using **Equation 3-10**.

(3-10) $$\text{HQ}_C = \frac{\text{ADD}}{\text{RfD}}$$

Where:

HQ_C = Noncancer risk from ingestion (unitless)
RfD = Reference dose (mg/kg-day).

A cancer slope factor (CSF), which is an upper-bound estimate of the increased human cancer risk from a lifetime of daily exposure, was used to estimate cancer risks. These cancer risks were calculated using **Equation 3-11**.

(3-11) $$\text{Risk}_{\text{Ing}} = \text{LADD} \cdot \text{CSF}_{\text{oral}}$$

Where:

$Risk_{Ing}$ = Cancer risk from ingestion (unitless)
CSF_{oral} = Oral cancer slope factor (risk per mg/kg-day)

Table 3-6 presents the screening results for human exposures to soil, produce, and animal products. Where benchmarks were available for multiple species of a constituent, the most conservative was used in the screening calculations. Results are presented for both the controlled and uncontrolled management scenarios. For both scenarios, these conservative results are based on the most sensitive age cohorts for cancer risks and noncancer risks. For cancer risks, this was 1 to < 2-year-olds for soil ingestion and adults for produce, beef, and milk ingestion. For noncancer risks, this was 1 to < 2-year-olds for all pathways. Results are presented under both the controlled

and uncontrolled management scenarios. Values found to be above the selected risk criteria (i.e., an HQ > 1) are shown in **bold**.

Table 3-6. Screening Results for Human Health Risks Resulting from Soil, Produce, Beef and Milk Ingestion

COPC	Uncontrolled				Controlled			
	Soil	Produce	Beef	Milk	Soil	Produce	Beef	Milk
Cancer Effects								
Arsenic	7×10^{-6}	9×10^{-6}	6×10^{-6}	2×10^{-6}	6×10^{-8}	8×10^{-7}	3×10^{-7}	7×10^{-8}
Chromium	3×10^{-6}	7×10^{-7}	4×10^{-6}	9×10^{-6}	3×10^{-8}	4×10^{-7}	3×10^{-7}	8×10^{-7}
Noncancer Effects								
Aluminum	0.06	0.02	0.01	0.02	< 0.01	< 0.01	< 0.01	< 0.01
Antimony	0.08	0.9	0.07	0.1	< 0.01	0.01	< 0.01	< 0.01
Arsenic	0.2	0.1	0.1	0.05	< 0.01	0.01	< 0.01	< 0.01
Barium	< 0.01	0.03	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.01
Beryllium	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Boron	< 0.01	0.6	0.02	0.5	< 0.01	0.01	< 0.01	< 0.01
Cadmium	< 0.01	0.05	< 0.01	0.06	< 0.01	< 0.01	< 0.01	< 0.01
Chromium	0.03	< 0.01	0.02	0.08	< 0.01	< 0.01	< 0.01	< 0.01
Cobalt	0.1	0.3	0.6	0.8	< 0.01	< 0.01	0.03	0.05
Copper	0.01	0.7	0.2	0.6	< 0.01	< 0.01	< 0.01	< 0.01
Fluoride	< 0.01	< 0.01	–	–	< 0.01	< 0.01	–	–
Iron	0.04	< 0.01	0.1	0.02	< 0.01	< 0.01	< 0.01	< 0.01
Lanthanum	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Manganese	< 0.01	0.03	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.01
Mercury	< 0.01	0.05	0.1	0.6	< 0.01	< 0.01	< 0.01	< 0.01
Molybdenum	< 0.01	0.08	0.03	0.1	< 0.01	< 0.01	< 0.01	< 0.01
Nickel	< 0.01	0.06	< 0.01	0.02	< 0.01	< 0.01	< 0.01	< 0.01
Nitrate/Nitrite	< 0.01	< 0.01	–	–	< 0.01	< 0.01	–	–
Selenium	< 0.01	0.01	< 0.01	0.03	< 0.01	< 0.01	< 0.01	< 0.01
Silver	< 0.01	0.04	< 0.01	0.7	< 0.01	< 0.01	< 0.01	0.01
Strontium	< 0.01	0.1	< 0.01	0.2	< 0.01	< 0.01	< 0.01	< 0.01
Thallium	**2**	0.6	**10**	**8**	0.03	0.09	0.8	0.6
Uranium	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Vanadium	0.04	0.03	0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Zinc	< 0.01	0.08	0.07	0.1	< 0.01	< 0.01	< 0.01	< 0.01

– Indicates that no BCF or BTF was available

All cancer risks fell below human health risk criteria under both uncontrolled and controlled scenarios. Noncancer risks were identified above human health criteria for thallium in soil (2), beef (10) and milk (8) under the uncontrolled management scenario. When management controls were considered, all human health risks fell below the risk range.

Ecological Risk

Ecological risks from direct contact with and ingestion of environmental media were evaluated using concentration-based benchmarks (**Appendix E**). These benchmarks, which represent concentrations below which no adverse effects are known or anticipated to occur, were used to estimate HQs using **Equation 3-12**.

(3-12) $$HQ = \frac{C_{soil}}{Eco_{soil}} \text{ or } \frac{C_{sed}}{Eco_{sed}}$$

Where:

C_{soil} = Soil concentration (mg/kg)
C_{sed} = Sediment concentration (mg/kg)
Eco_{soil} = Ecological soil benchmark (mg/kg)
Eco_{sed} = Ecological sediment benchmark (mg/kg).

Table 3-7 presents the screening results for ecological exposures to soil and sediment. Where benchmarks were available for multiple species of a constituent, the most conservative was used in the screening calculations. Results are presented for both the controlled and uncontrolled management scenarios. For both scenarios, these conservative results are based on the most sensitive receptors, specified by the toxicity benchmarks. Values that exceed the selected risk criteria (i.e., HQ > 1) are shown in **bold**.

Table 3-7. Screening Results for Ecological Risks Resulting from Soil and Sediment Exposures

COPC	Uncontrolled		Controlled	
	Soil	Sediment	Soil	Sediment
Antimony	**20**	**2**	0.1	< 0.01
Arsenic	0.6	**2**	< 0.01	< 0.01
Barium	0.3	0.6	< 0.01	< 0.01
Beryllium	0.1	–	< 0.01	–
Boron	**80**	–	0.6	–
Cadmium	1	0.7	< 0.01	< 0.01
Chromium	0.6	0.4	< 0.01	< 0.01
Cobalt	0.5	–	< 0.01	–
Copper	0.8	0.6	< 0.01	< 0.01
Lead	0.7	0.2	< 0.01	< 0.01
Manganese	0.2	–	< 0.01	–
Mercury	1	0.6	< 0.01	< 0.01
Molybdenum	0.1	0.1	< 0.01	< 0.01
Nickel	0.5	1	0.01	< 0.01
Selenium	**3**	–	0.03	–
Silver	0.3	**2**	< 0.01	< 0.01
Vanadium	**7**	**3**	0.1	< 0.01
Zinc	0.6	0.2	< 0.01	< 0.01

– Indicates that no benchmark was available for these receptors

Ecological soil risks above an HQ of 1 were identified were identified for the following constituents: boron (80) antimony (20) vanadium (7) and selenium (3). Ecological sediment risks were also identified above an HQ of 1 for the following constituents: vanadium (3), antimony (2), arsenic (2) and silver (2). When fugitive dust and run-off controls were considered, all ecological risks fell below the ecological risk criteria.

3.4 Ground Water, Surface Water, Wastewater and Fish Screening

This section summarizes the screening for all exposure pathways that result from leaching of COPCs into water. These exposure pathways are associated with both landfills and surface impoundments as a result of rainfall and/or wastewater percolating through the WMU. Relevant pathways include ecological exposures to impoundment wastewater, ecological exposure to downgradient surface waters, human consumption of ground water and fish, and human dermal and inhalation exposure through bathing and showering. While these pathways may be present for both impoundments and landfills, the 2010 Risk Assessment demonstrated that risks from surface impoundments are consistently higher than those from landfills. Therefore, EPA screened these pathways for surface impoundments and the results also were used to identify COPCs for landfills.

3.4.1 Exposure Concentrations

EPA used the 90th percentile concentrations for impoundment pore water and wastewater listed in **Table 3-1** to estimate exposures to ground water, surface water, wastewater and fish. Impoundment wastewater concentrations were used to screen exposures for ecological receptors that live in and around surface impoundments. These concentrations were collected from the surface water within surface impoundments after CCR solids settled out. Since wastewater concentrations are representative of the environment that these ecological receptors would inhabit, the measured concentrations were used directly in the screening. Impoundment pore water concentrations were used to screen human exposures to ground water and fish, as well as exposures for ecological receptors that live in and around downgradient surface water bodies. Pore water concentrations were collected from the interstitial water between waste particles at the bottom of the surface impoundment. These concentrations are representative of leachate released from impoundments to downgradient receptor wells and surface water bodies.

Dilution Attenuation Factors

DAFs were used to conservatively account for the reduction in concentrations that would occur during subsurface transport between a WMU and a downgradient water body. The 2010 Risk Assessment yielded a 10th percentile DAF of approximately 2 across all modeled constituents. For ease of calculation and to ensure that potential exposures were not underestimated, the revised risk assessment applied a single DAF of 1 to all water pathways. This DAF is equivalent to direct exposure to pore water. The 90th percentile pore water concentrations were divided by the selected DAF to generate exposure concentrations.

Bioconcentration in Fish

The fish caught and consumed by recreational fishers and their families were assumed to be exposed to undiluted pore water. EPA assumed that all of the fish consumed by receptors originated from the third trophic level (TL3) and fourth trophic level (TL4). TL3 consists of carnivores that eat herbivores or secondary consumers such as invertebrates and plankton (e.g., carp, smelt, perch, catfish, sucker, bullhead, sauger), while TL4 consists of carnivores that eat other carnivores (e.g., salmon, trout, walleye, bass). While specific fish may not fit entirely into one category, EPA chose conservative categorizations for these fish to remain protective of human health. Because the degree of bioconcentration may differ between these two trophic levels, the Agency used separate BCFs for these two trophic levels, when available. For BCFs and the equations used to calculate fish concentrations, see **Appendix G**.

3.4.2 Ground Water, Surface Water, Wastewater and Fish Risks

EPA used the calculated concentrations in the different media to calculate risks for human and ecological receptors. EPA considered human health risks from ingestion of ground water and fish, as well as dermal contact with ground water and inhalation of volatilized COPCs. EPA considered ecological risks from ingestion of and direct contact with impoundment wastewater and downgradient surface water. All pathways were evaluated for adverse effects resulting from chronic exposures. Generally, adverse effects from chronic exposures occur at lower media concentrations than acute exposures. Therefore, the constant, high-end concentrations used to screen chronic exposures will also be protective of acute exposures.

Chronic Human Ingestion Risks

Human health risks associated with ingestion were evaluated using dose-based benchmarks. In order to translate the calculated exposure concentrations for each media into risks, EPA first had to characterize the potential receptors. For most COPCs, this was done for each receptor cohort by calculating either a noncancer ADD using **Equation 3-8** or a cancer LADD using **Equation 3-9**. The calculated ADD and LADD were then used to calculate HQs using **Equation 3-10** and cancer risks using **Equation 3-11**, respectively. In contrast, lead risks were characterized by comparing the ground water concentrations directly to the concentration-based MCL because no dose-based benchmark is currently available. This was done using **Equation 3-13**.

(3-13) $$\text{Ratio} = \frac{C_{DW}}{MCL}$$

Where:

Ratio = Exposure Ratio (unitless)
C_{DW} = Drinking water concentration (mg/L)
MCL = Maximum contaminant level (mg/L).

Table 3-8 presents the screening results for chronic exposures to ground water and fish. Where benchmarks were available for multiple species of a constituent, the most conservative was used in the screening calculations. For both scenarios, these conservative results are based on the most

sensitive age cohorts for cancer risks (adults) and noncancer risks (children ages 1 to < 2). Values that exceed the selected criteria (i.e., a cancer risk > 1×10^{-5} or an HQ > 1) are shown in **bold**.

Table 3-8. Screening Results for Human Health Risks Resulting from Ground Water and Fish Ingestion

COPC	Ground Water Ingestion	Fish Ingestion
Cancer Effects		
Arsenic	**3×10^{-3}**	**4×10^{-5}**
Chromium	**3×10^{-4}**	5×10^{-7}
Noncancer Effect		
Aluminum	0.2	0.06
Ammonia	0.1	–
Antimony	**2**	< 0.01
Arsenic	**50**	1
Barium	0.02	0.02
Beryllium	0.01	< 0.01
Boron	**10**	–
Cadmium	**2**	**2**
Chromium	1	< 0.01
Cobalt	**3**	–
Copper	0.2	< 0.01
Fluoride	**7**	0.1
Iron	0.3	0.04
Lead	**7**	–
Lithium	**4**	–
Manganese	0.8	< 0.01
Mercury	< 0.01	**7**
Molybdenum	**30**	0.7
Nickel	0.3	< 0.01
Nitrate/Nitrite	0.2	–
Selenium	1	**10**
Silver	0.02	–
Strontium	0.3	0.02
Thallium	**6**	**4**
Uranium	0.08	0.02
Vanadium	1	0.2
Zinc	0.01	0.03

–Indicates no BCF was available

Ingestion of ground water resulted in risks above the human health criteria. Cancer risks above 1×10^{-5} were identified for arsenic (3×10^{-3}) and chromium VI (3×10^{-4}). Noncancer risks above an HQ of 1 were identified were identified for: arsenic (50), molybdenum (30), boron (10), fluoride (7), lead (7) thallium (6), lithium (4), cobalt (3), antimony (2) and cadmium (2).

Ingestion of fish resulted in risks above the human health criteria. Cancer risks above 1×10^{-5} were identified for arsenic (4×10^{-5}). Noncancer risks above an HQ of 1 were identified were identified for: selenium (10), mercury (7), thallium (4) and cadmium (2).

Human Health Risks from Inhalation

In addition to dermal exposure during showering and bathing, receptors may also be exposed to volatile COPCs present in the ground water through inhalation of any vapors released. The elevated temperature and physical disturbance of water as it is forced through faucets and showerheads for baths and showers may facilitate the volatilization of COPCs. The extent to which a constituent will volatilize from shower water depends on a number of factors, including chemical properties, the water temperature, the type of shower nozzle, and the duration of showering. Elemental mercury is the only COPC identified that may volatilize to any appreciable degree under the relevant range of household conditions. Based on an estimate of air concentrations calculated by multiplying the 90th percentile mercury pore water concentration by the Andelman volatilization factor of 0.5 L/m^3 (U.S. EPA, 1991), this exposure pathway resulted in an HQ below the risk criteria using **Equation 3-4**. Therefore, this pathway was not retained for further evaluation.

Human Health Risks from Dermal Contact

Human receptors may be exposed to COPC concentrations in ground water through prolonged dermal contact with contaminated water during showering or bathing. EPA screened these dermal exposures based on the recommendations in *Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual* (*Part E, Supplemental Guidance for Dermal Risk Assessment*) (U.S. EPA, 2004), which recommends that dermal exposure should be retained for evaluation if the dermal exposure is greater than 10 percent of oral exposure. Prior performing the calculations, EPA reviewed the literature to ensure the use of the most appropriate values. Based the *Public Health Goals for Chemicals in Drinking Water: Hexavalent Chromium (Cr VI)* (CalEPA, 2011), the dermal permeability coefficient (K_p) was updated to 7×10^{-6} cm/hr and gastrointestinal absorption updated to 1% for Chromium VI. Values provided by RAGS Part E were used for all other constituents. Using the process demonstrated in Exhibit B-4 of RAGS Part E, EPA determined that a screening assessment should be conducted for barium, beryllium, cadmium, chromium III, manganese, mercury (divalent), silver, vanadium, and zinc.[11]

Risk calculations were performed for a showering adult, identified in RAGS Part E as the most highly exposed receptor, using *Inorganic Chemicals in Water* spreadsheet provided in U.S. EPA (2004). The spreadsheet was updated to reflect residential exposure assumptions consistent with

[11] Because gastrointestinal adsorption of zinc is listed as highly variable, a conservative value of 1% was used for the purposes of this screening.

the ingestion screening (see **Appendix D**). **Table 3-9** Results are presented for each COPC under controlled and uncontrolled management scenarios. No values were found to be above noncancer criteria.

Table 3-9. Screening Results for Human Health Risks Resulting from Dermal Contact

COPC	Dermal Contact
Noncancer Risks	
Barium	< 0.01
Beryllium	< 0.01
Cadmium	0.7
Chromium	< 0.01
Manganese	0.09
Mercury	< 0.01
Silver	< 0.01
Vanadium	0.3
Zinc	0.2

Ecological Risk

Ecological risks associated with direct contact with and ingestion of environmental media were evaluated using concentration-based benchmarks. These benchmarks, which represent media concentrations below which no adverse effects are known or anticipated to occur for the species, were used to estimate HQs using **Equation 3-13**.

(3-13) $$HQ = \frac{C_{sw}}{Eco_{water}} \text{ or } \frac{C_{ww}}{Eco_{water}}$$

Where:

HQ = Hazard quotient (unitless)
C_{sw} = Surface water concentration (mg/L)
C_{ww} = Wastewater concentration (mg/L)
Eco_{water} = Ecological water benchmarks (mg/L).

Table 3-10 presents the screening results for direct ecological exposures to surface water and impoundment wastewater. Where benchmarks were available for multiple species of a constituent, the most conservative was used in the screening calculations. These results are based on the most sensitive receptors for each COPC, specified by the selected toxicity benchmark. Values that exceed the selected risk criteria (i.e., an HQ > 1) are shown in **bold**.

Table 3-10. Screening Result for Ecological Risks Resulting from Surface Water and Impoundment Water Exposure

COPC	Surface Water	Impoundment Wastewater
Aluminum	**100**	**30**
Antimony	1	0.7
Arsenic	**100**	**20**
Barium	**50**	**100**
Beryllium	**2**	**2**
Boron	**100**	**30**
Cadmium	**200**	**10**
Chloride	**9**	**2**
Chromium	**20**	**2**
Cobalt	**2**	0.8
Copper	**10**	1
Iron	**10**	0.05
Lead	**40**	0.2
Mercury	0.4	< 0.01
Molybdenum	**20**	1
Nickel	**6**	1
Selenium	**60**	**20**
Silver	**10**	0.3
Thallium	0.3	0.7
Vanadium	**30**	**10**
Zinc	**2**	0.5

Direct contact with and ingestion of surface water resulted in risks above ecological criteria. Ecological risks above an HQ of 1 were identified were identified for, listed from highest to lowest: cadmium (200), aluminum (100), arsenic (100), boron (100), selenium (60), barium (50), lead (40), vanadium (30), chromium III (20), molybdenum (20), copper (10), iron (10), silver (10), chloride (9), nickel (6), beryllium (2), cobalt (2) and zinc (2).

Direct contact with and ingestion of impoundment wastewater resulted in risks above ecological criteria. Ecological risks above an HQ of 1 were identified were identified for, listed from highest to lowest: arsenic (100), barium (50), aluminum (30), boron (30), selenium (20), cadmium (10), vanadium (10), beryllium (2), chloride (2) and chromium (2).

3.5 Screening Analysis Conclusions

EPA conducted this screening analysis to determine which COPCs are most likely to pose risk to receptors for each of the exposure pathways identified in **Section 2**. Based on the results of this

conservative screening, EPA determined which pathways to retain for further characterization with more refined, probabilistic modeling discussed in **Section 4**. The following subsection summarizes the results of the different screening analyses and the Agency's conclusions.

3.5.1 Ambient Air Conclusions

EPA calculated ambient air concentrations that result from windblown dust from landfills under uncontrolled and controlled management scenarios. Risks were estimated for based on short-term (i.e., acute) and long-term (i.e., chronic) exposures. Under the uncontrolled management scenario, concentrations of arsenic were found to pose acute risks and $PM_{2.5}$ was found to exceed the 24-hour NAAQS. However, all risks fell below selected criteria under the controlled management scenario. Based on these results, EPA did not retain exposures to ambient air for further analysis. Even with the conservative assumptions used here, risks fell below selected criteria when dust controls were considered. Thus, these screening results are sufficient to characterize high-end risks for this pathway, and the controls required by the rule are considered protective.

3.5.2 Soil, Sediment, Produce and Animal Product Conclusions

EPA calculated downgradient soil, sediment, produce, beef and milk concentrations that result from windblown dust and run-off from landfills under uncontrolled and controlled management scenarios. Under the uncontrolled management scenario, thallium was found to pose human health risks for multiple pathways, while multiple constituents were found to pose ecological risks for soil and sediment. However, all risks fell below selected criteria under the controlled management scenario. Based on these results, EPA did not retain these aboveground pathways for further analysis. Even with the conservative assumptions used here, risks fell below all benchmarks when fugitive dust and run-on/run-off controls were considered. Thus, these screening results are sufficient to characterize high-end risks for this pathway, and the controls required by the rule are considered protective.

Although aboveground transport of CCR waste was not retained for further analysis, the sediment screening was used as a more conservative estimate of sediment concentrations than may occur due belowground transport of leachate from CCR waste water. Thus, these results were used to identify COPCs for subsurface transport through ground water. As a result, EPA retained antimony, arsenic, silver and vanadium for further characterization through the ground water to surface water sediment pathway.

3.5.3 Ground Water, Surface Water, Wastewater and Fish Conclusions

These conservative screening analyses identified potential risks to human and ecological receptors from leaching of chemical constituents from CCR waste into surrounding environmental media. Risks to human health resulted from ingestion of ground water and fish, while risks to ecological receptors resulted from exposure to surface water. While EPA did not consider the various controls that may mitigate these releases, considerable dilution and attenuation may occur before COPCs reach downgradient private wells and surface water bodies. Nevertheless, EPA retained all of the COPCs found to be above risk criteria in ground water and surface water for further

characterization in the probabilistic analysis. A summary of the COPCs retained for ground water, surface water, and sediment is presented in **Table 3-11**.

Table 3-11. Summary of the Exposure Pathways and COPCs Carried Forward for Probabilistic Analysis

COPC	Human Health		Ecological	
	Ground Water Ingestion	Fish Ingestion	Surface Water	Sediment
Carcinogenic Effects				
Arsenic	✓	✓	–	–
Chromium	✓	–	–	–
Noncarcinogenic Effects				
Aluminum	–	–	✓	–
Ammonia	–	–	–	–
Antimony	✓	–	–	✓
Arsenic	✓	–	✓	✓
Barium	–	–	✓	–
Beryllium	–	–	✓	–
Boron	✓	–	✓	–
Cadmium	✓	✓	✓	–
Chloride	–	–	✓	–
Chromium	–	–	✓	–
Cobalt	✓	–	✓	–
Copper	–	–	✓	–
Fluoride	✓	–	–	–
Iron	–	–	✓	–
Lead	✓	–	✓	–
Lithium	✓		–	–
Manganese	–	–	–	–
Mercury	–	✓	–	–
Molybdenum	✓	–	✓	–
Nickel	–	–	✓	–
Nitrate/Nitrite	–	–	–	–
Selenium	–	✓	✓	–
Silver	–	–	✓	✓
Strontium	–	–	–	–
Thallium	✓	✓	–	–
Uranium	–	–	–	–
Vanadium	–	–	✓	✓
Zinc	–	–	✓	–

These screening analyses also identified potential risks to ecological receptors from direct exposures to impoundment wastewater. Unlike the other exposure pathways, no dilution or attenuation will occur within impoundment wastewater prior to ecological exposures. Because of this, the screening analysis provides sufficient characterization of these exposures. Based on these results, EPA concludes that there is the potential for risks to ecological receptors from aluminum, arsenic, barium, beryllium, boron, cadmium, chloride, chromium, selenium and vanadium based on direct contact with surface impoundment wastewater. Therefore, this exposure pathway was not carried forward for further analysis, but is discussed in the risk characterization.

4 Probabilistic Analysis

The screening analysis presented in **Section 3** identified the potential for risks to human health and the environment through multiple exposure pathways. This screening provided adequate characterization of the risks associated with several of the evaluated pathways. However, due to the conservative nature of the screening, additional characterization of human ingestion of ground water and fish, as well as ecological contact with and ingestion of surface water and sediment, were necessary to support a robust set of conclusions about current CCR disposal practices. The Agency conducted this further analysis using a probabilistic, site-based approach that combined site-specific data with regional and national data. This section describes the overarching analytical framework, as well as the specific models and inputs used within this framework to predict the fate and transport of COPCs through subsurface soils and ground water. The discussion of the probabilistic analysis is divided into the following sections:

- **Section 4.1:** Outlines the probabilistic modeling framework used by EPA to quantify the potential risks to human and ecological receptors that result from WMU leaching.
- **Section 4.2:** Details the selection of modeled leachate concentrations.
- **Section 4.3:** Details the selection of modeled leaching durations.
- **Section 4.4:** Details the selection of modeled infiltration rates.
- **Section 4.5:** Details the selection of modeled depth of WMUs below ground surface.
- **Section 4.6:** Details the selection of modeled receptor locations.
- **Section 4.7:** Provides an overview of subsurface transport modeling used to calculate exposures resulting from drinking water ingestion (human health).
- **Section 4.8:** Provides an overview of the surface water models used to calculate exposures resulting from ingestion of fish (human health) and direct contact with both surface water and sediment (ecological).
- **Section 4.9:** Provides an overview of the exposure and risk models used to quantify the risks associated with calculated exposure concentrations.
- **Section 4.10**: Presents the modeled probabilistic risks results.

4.1 General Analytical Framework

Ground water fate and transport modeling was conducted with the EPA Composite Model for Leachate Migration with Transformation Products (EPACMTP) (U.S. EPA, 1996a, 1997a, 2003a,b,c). EPACMTP consists of two coupled modules: a one-dimensional module that simulates infiltration and dissolved constituent transport through unsaturated soils in the vadose zone and a three-dimensional module that simulates transport through ground water. EPACMTP models ground water concentrations present at a specified location (such as a private well or a stream) as

a function of time. The outputs from EPACMTP were fed into additional models that calculate surface water concentrations, sediment concentrations, receptor exposure rates, and receptor risks.

The probabilistic framework used in this risk assessment is a Monte Carlo analysis, which is a statistical technique where a quantity (in this case, risk) is calculated through repeated simulations using values selected probabilistically from an assigned parameter distribution for each model run (or iteration). The results approximate the range of possible outcomes and the likelihood of each outcome. This framework includes a separate data preparation loop and calculation loop. The data preparation loop created a single file that contained all of the input data necessary for every iteration of EPACMTP and the other models. In this file, approximately 100 entries were created for each WMU, with each entry representing the data for a distinct model iteration. EPA selected this number of entries to effectively sample the variability of each site. Where site-specific data were known for a WMU, a fixed value was assigned to all entries for that unit and held constant for each model iteration. Otherwise, a distribution was assigned based on available site, regional or national data sources, and a different value was probabilistically sampled during each model iteration. **Table 4-1** provides a list of the different data included in this file.

Table 4-1. Summary of Parameters in the Probabilistic Analysis

Description	Resolution	Fixed or Variable*	Source
WMU Type	Site-Based	Fixed	Appendix A
Waste Type	Site-Based	Fixed	
WMU Dimensions	Site-Based	Fixed	
WMU Depth Below Ground Surface	Site-Based	Variable	
Impoundment Ponding Depth	Site-Based	Variable	
Sediment Depth	Single Value	Fixed	
Liner Type	Site-Based	Fixed	
Clay-lined Hydraulic Conductivity	Single Value	Fixed	
Thickness Of Clay Liner	Single Value	Fixed	
Water Body Type	Site-Based	Variable	Appendix B
Distance To Water Body	Site-Based	Variable	
Water Body Dimensions	Site-Based	Fixed	
Water Velocity	Site-Based	Fixed	
Base flow per unit length	Site-Based	Fixed	
Stream annual flow mixing volume	Regional	Fixed	
Lake annual flow mixing volume	Regional	Variable	
Total Suspended Solids	Regional	Variable	
Surface Water Temperature	Regional	Fixed	
Aquifer Temperature	Regional	Fixed	
Water pH	Regional	Variable	

(continued)

Table 4-1. Summary of Parameters in the Probabilistic Analysis

Description	Resolution	Fixed or Variable*	Source
Climate Center	Regional	Fixed	Appendix B
Mean annual wind speed	Regional	Fixed	
Soil Type	Regional	Variable	
Natural Organic Matter in Soil	Regional	Variable	
Soil pH	Regional	Variable	
Hydrogeological Environment	Regional	Variable	
Leachable Mass	Site-Based	Variable	Appendix C
Leachate Concentration	Site-Based	Variable	
Leachate pH	Site-Based	Variable	
Exposure Averaging Time	Single Value	Fixed	Appendix D
Exposure Frequency	Single Value	Fixed	
Fraction of Drinking Water from Well	Single Value	Fixed	
Fraction of Ingested Fish Contaminated	Single Value	Fixed	
Fraction of Fish in Tropic Levels 3 and 4	Single Value	Fixed	
Water Ingestion Rate	National	Variable	
Fish Ingestion Rate	National	Variable	
Body Weight	National	Variable	
Exposure Duration	National	Variable	
Ecological Surface Water Benchmark	National	Fixed	Appendix E
Ecological Sediment Benchmark	National	Fixed	
Human Cancer Slope Factor	National	Fixed	
Human Noncancer Reference Dose	National	Fixed	
Fish Bioconcentration Factors	Single Value	Fixed	Appendix G
Landfill Leaching Duration	Site-Based	Variable	Appendix I
Bed Sediment Particle Concentration	Single Value	Fixed	Appendix J
Bed Sediment Porosity	Single Value	Fixed	
Depth of Upper Benthic Layer	Single Value	Fixed	
Bed Sediment K_d Value	National	Variable	
Suspended Sediment K_d Value	National	Variable	

* In some cases, variables listed as "fixed" were not known for a subset of WMUs, and were probabilistically selected instead.

Once the data preparation loop was complete, the generated data file was fed into the calculation loop. Each calculation loop consisted of numerous model iterations, one for each entry in the data file. In total, approximately 100,000 model iterations were conducted for all WMUs, which forms the basis for the probabilistic risk results presented in this section. Each model iteration pulled a different set of values from the data files based on the assigned probability distributions. **Figure 4-1** shows the looping structure of the Monte Carlo framework used in this risk assessment.

The majority of the site, regional or national data used in the probabilistic analyses could be applied directly to the models in the probabilistic framework as collected. However, in certain instances, it was necessary to account for additional considerations to appropriately reflect the conditions present in surface impoundments and landfills. The following subsections describe the various considerations involved in the selection and application of these inputs to the modeling framework.

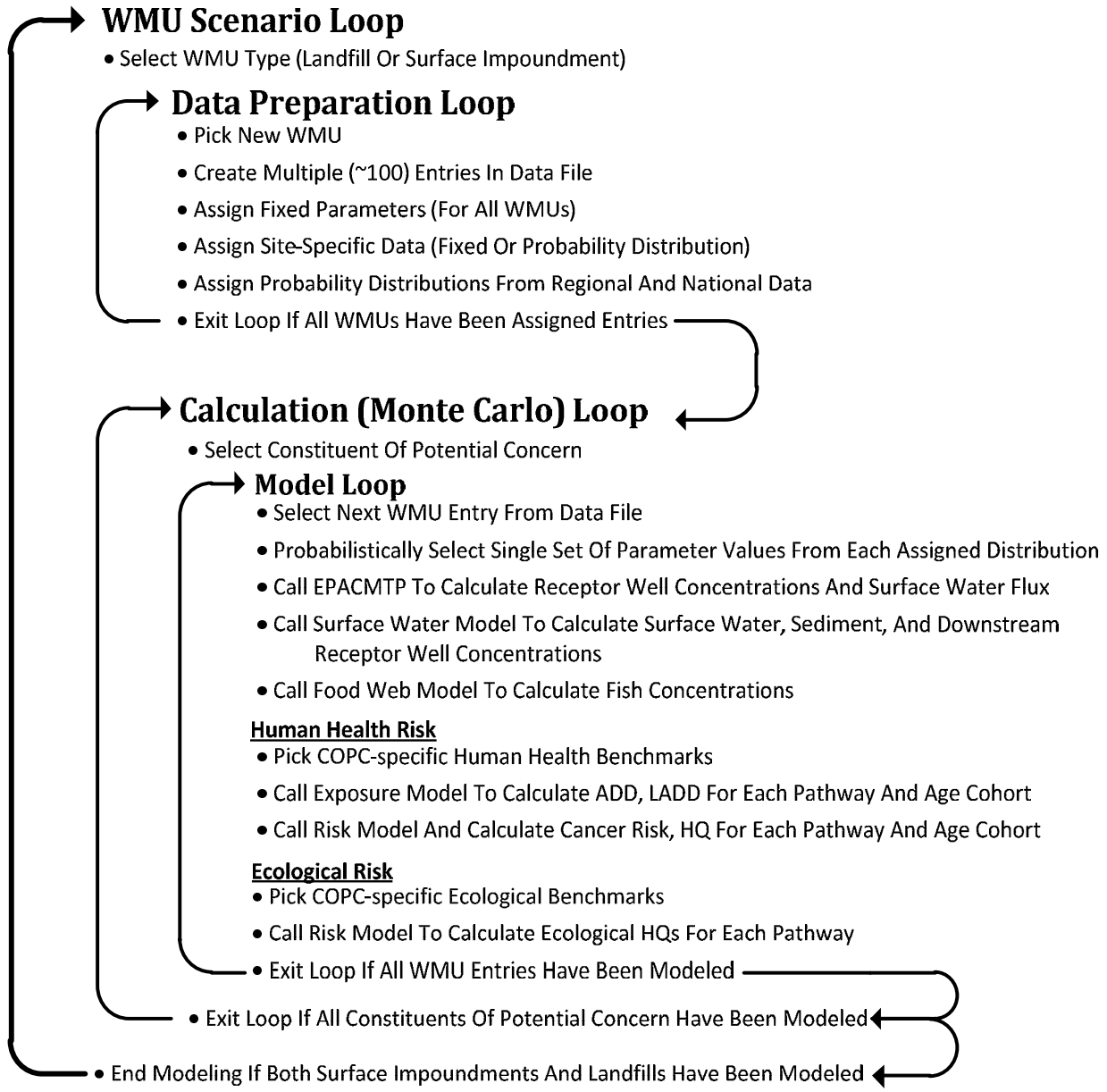

Figure 4-1. Looping structure of the CCR probabilistic modeling framework.

4.2 Source Leachate Concentrations

The following subsection summarizes the approach used to assign leachate concentrations to each WMU within the probabilistic framework. Over time, EPA has compiled a great deal of leachate data, collected and analyzed through different methods. While all of these data represent leaching

from CCR waste, some better reflect the specific environmental conditions present at surface impoundments and landfills. Therefore, to make the best use of the available data, EPA used different data sets to characterize leachate from surface impoundments (**Section 4.2.1**) and landfills (**Section 4.2.2**).

4.2.1 Surface Impoundments

Similar to the screening analysis described in **Section 3**, EPA relied on pore water concentrations to characterize leaching from impoundments. These concentrations are collected from the interstitial water between waste particles in surface impoundments as it occurs in the field, and best reflect leachate as it is released into underlying soils. Within the CCR constituent database, some facilities have more than one sample site. Some of these sample sites have many data points, while others have only a few. Similarly, some of the waste types (i.e., combined ash, ash and coal refuse, and FGD waste) disposed at these sites may have more data points than others. Thus, combining all of the available data into a single distribution would bias the modeled concentrations toward individual facilities, sites, and waste types with more samples. To avoid this, EPA developed quartiles from the pore water data available for each waste type at each sample site. Where only one sample was available for a waste type or a sample site, all of the quartiles were set equal to that one value. This approach provides equal weighting while also retaining some intra-site variability that would have been lost through the use of a single summary statistic, such as an average.

Unlike the screening analysis, the quartiles were combined into three separate probability distributions, one for each waste type. During the data preparation loop, a fixed waste type was assigned to each surface impoundment if known from survey data. In the absence of site-specific data, a probability distribution was assigned based on the prevalence of waste types known to be present in other surface impoundments. From the assigned waste type, the data preparation loop assigned a waste-specific probability distribution for the pore water concentration of each COPC. During the calculation loop, the models probabilistically sampled from the assigned concentration distribution for every entry in the data file. The selected concentration was held constant for the entire duration of leaching.

4.2.2 Landfills

To characterize leaching from landfills, EPA collected samples of CCR waste from over 30 facilities that reflect the range of coal rank burned and likely air pollution control technology configurations at the time of this risk assessment. The leaching behavior of these samples was characterized with the SW-846 LEAF methods. These methods, described in greater detail in **Appendix C**, provide information on the leaching behavior of each sample under a range of environmental conditions. Because of this information available for each sample, it was not necessary to combine these samples into separate waste types to capture the variability of potential behavior in the subsurface environment.

During the data preparation loop, a single pH distribution that ranged between 2.8 and 12.8 was assigned to all landfill entries based on nationwide field measurements (U.S. EPA, 2009a). The

data preparation loop also assigned a specific waste sample to each landfill entry, with an equal probability assigned to each sample. During the calculation loop, the models probabilistically sampled the assigned pH distribution during each model iteration. This pH was used to identify the pH-specific leachate concentration measured with LEAF Method 1313. The modeled leachate concentration was calculated in one of two ways, based on the type of leaching behavior exhibited by the waste sample at that pH (discussed further in **Appendix I**):

- **Solubility-Controlled Leaching** occurs when the total COPC mass available to be released from the waste is greater than the maximum amount that can be dissolved in the mass of water present. Because the solubility limit is reached at the higher liquid-to-solid ratio (L/S ratio) of 10:1 used in Method 1313, it will also be reached at the lower L/S ratio of around 1:2 typical of landfills. Thus, the concentrations measured with Method 1313 accurately reflect solubility-controlled leaching from landfills and the measured concentration was used for the model iteration.
- **Washout-Controlled Leaching** occurs when the total COPC mass available to be released from the waste is less than or equal to the maximum amount that can be dissolved in the mass of water present. Because the solubility limit is not reached for the higher L/S ratio of 10:1 used in Method 1313, the water concentration will increase as the L/S ratio decreases until the solubility limit is reached. Thus, washout-controlled leaching from landfills will be higher than the concentrations measured with Method 1313. To account for the difference in L/S ratios between Method 1313 and landfills, the measured Method 1313 concentration was multiplied by a factor of 20. This calculated concentration was used for the model iteration.

4.3 Leaching Duration

The following subsection summarizes the approach used to assign leaching durations to each WMU within the probabilistic framework. Leaching duration is the length of time that a WMU releases leachate into underlying soils. Because the aim of this probabilistic analysis is to provide an accurate estimate of peak concentrations, the leaching duration of interest for a WMU may not be the same as the total leaching duration. The duration of interest differs for surface impoundments and landfills because of the distinct leaching behavior of the two WMUs during operation and postclosure. Therefore, EPA used different data to characterize the leaching duration for surface impoundments (**Section 4.3.1**) and landfills (**Section 4.3.2**).

4.3.1 Surface Impoundments

Most surface impoundments are known to be periodically dredged. Since this dredging would remove any potential source postclosure, only the operational phase of a surface impoundment was modeled. The highest releases from surface impoundments are anticipated to occur during operational life due to the presence of a large hydraulic head that will drive infiltration rates. As a result, the length of the operating life was a key parameter for this analysis. Data on impoundment operating life were drawn from EPRI (1997a). A total of 86 of the 116 surveyed impoundments provided both an opening date and projected closure date, from which EPA calculated the expected operating life. No projected closure date was provided for the other 30 surface impoundments.

Figure 4-2 shows the distribution of the calculated operating lives, along with a separate bar representing units with no reported closure date.

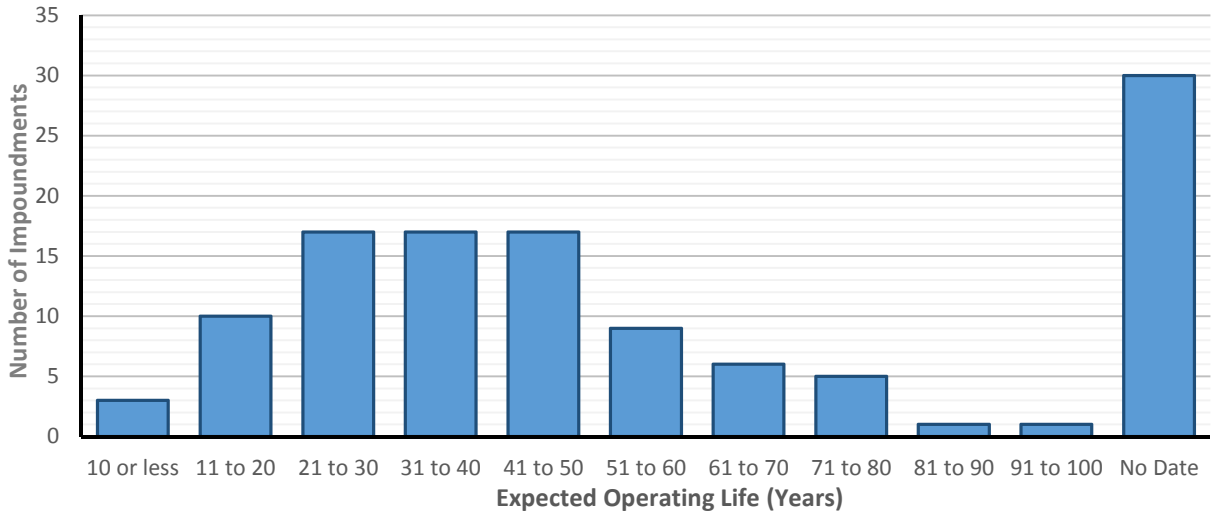

Figure 4-2. Distribution of operating life for surface impoundments from EPRI (1997a).

The calculated 50th percentile impoundment operating period was 40 years, while the 95th percentile value was 75 years. More recent information available in the CCR WMU database corroborates the distribution of expected operating life, and shows that many impoundments are currently approaching 40 years of age. At the same time, the EIA reported a large decrease in wet handling between 2009 and 2012 and many facilities have publicly announced plans to close surface impoundments.[12] Due to the uncertainty in operational lifetime for nearly a quarter of these units, and the potential for extended operational life through dredging, EPA selected a 95th percentile value of 75 years was assigned to all surface impoundments during the data preparation loop.

4.3.2 Landfills

Leaching from landfills was assumed to start at closure when the unit is filled to capacity with CCR waste. This point was chosen because EPACMTP requires a fixed WMU size, and the size at closure represents the largest possible footprint. Postclosure landfills were modeled as a finite source because the buried waste is not replenished as it leaches. For all COPCs except arsenic, leaching was idealized as a single, constant source that continued until the total available mass of a COPC had been depleted. For these COPCs, the total available mass was estimated as the maximum mass released at any pH over the range of 2.8 and 12.8 measured with Method 1313. The exact leaching duration varied between model iterations based on the modeled leachate concentration, total available mass and the leaching rate.

[12] Wilson, Mark. 2009. "Coal ash disposal varies from company to company." Evansville Courier & Press. October 24. Available online at: www.courierpress.com/lifestyle/health-and-fitness/coal-ash-disposal-varies-from-company-to-company

For arsenic, the available data collected with the LEAF methods have demonstrated that the leaching of arsenic can be limited through oxidation by and complexation with calcium. As a result, the duration of arsenic leaching from CCRs is better represented by accounting for the presence of calcium. Arsenic leaching from landfills was modeled as having one of the following two relationships with dissolved calcium concentrations as a function of the cumulative L/S ratio (discussed further in **Appendix I**):

- **Case 1, Low Calcium Concentration (≤ 5,000 mg/kg):** Arsenic leaching begins at an initial concentration defined by the LEAF Method 1313 data and is held constant until the total available mass is depleted.
- **Case 2, High Calcium Concentration (> 5,000 mg/kg):** Arsenic leaching begins at an initial concentration defined by the LEAF Method 1313 data and is held constant until all of the free arsenic has been depleted. Empirical data available in LEACHXS Lite have shown that this generally occurs when the cumulative amount of water that has infiltrated through the ash relative to the mass of waste present approaches a ratio of 1. A typical landfill may take around a hundred years of leaching to reach this cumulative L/S ratio. At this point, further arsenic leaching is inhibited by the calcium present and effectively ceases until the time at which around 90 percent of the available calcium has been leached away. Arsenic then begins to leach again at the previous concentration until all remaining available arsenic is depleted.

4.4 Infiltration Rate

The following subsection summarizes the approach used to assign infiltration rates to each WMU within the probabilistic framework. Infiltration is the process through which water migrates through WMUs and enters the subsurface environment. The rate at which water can pass through a WMU is limited primarily by the hydraulic conductivity of the liner (if any) present. The 2009/2010 EPA Surveys contained information on the type of liner at different WMUs. Based on the descriptions of liners reported in survey responses, each surface impoundment and landfill was assigned one of three modeled liner types: no liner, clay liner or composite liner. These three liner types are the conceptual liner scenarios developed in support of EPA's Industrial Subtitle D Guidance (U.S. EPA, 2006b), and are described as follows:

- **No Liner Scenario:** Waste is placed directly on local soils, either on grade or excavated to some design depth and without a leachate collection system. At closure, two feet of native soil cover, the minimum required by Subtitle D regulations, is installed and assumed to support vegetation.
- **Clay Liner Scenario:** Waste is placed on a three-foot compacted clay liner that is installed over local soils without a leachate collection system, either on grade or excavated to some design depth. At closure, a three-foot clay cover is installed and covered with one foot of loam to support vegetation and drainage.
- **Composite Liner Scenario:** Waste is placed on a liner system that consists of a plastic liner (e.g., high-density polyethylene membrane) underlain by either a natural or geosynthetic clay

liner. A leachate collection system is assumed to exist between the waste and the liner system. At closure, a three-foot clay cover (graded and otherwise designed to prevent ponding) or functional equivalent is assumed to be installed and covered with a one foot of loam to support vegetation and drainage.

During the data preparation loop, liner types were assigned to each WMU where known from survey data. In cases where available survey data indicated that a WMU was lined, but did not specify the type of liner, a clay or composite liner was selected probabilistically based on the relative prevalence of those liner types. In cases where neither the presence nor absence of a liner was specified in the available survey data, one of these three types was probabilistically assigned to that WMU based on the prevalence of liner types reported for other surface impoundments or landfills, as appropriate. During the Monte Carlo loop, EPACMTP used the assigned liner type, together with the assigned WMU type and local climate data to calculate an infiltration rate, as described in Appendix A of the EPACMTP background document (U.S. EPA, 2003b).

4.5 Depth Below Grade

The following subsection summarizes the approach used to assign a depth below grade to each WMU within the probabilistic framework. Depth below grade represents the total depth that a given WMU extends below the ground surface. This parameter was used during model iterations to determine the distance from the bottom of the WMU to the ground water table. EPA used the following two data sources to characterize this parameter for both surface impoundments and landfills:

- A collection of site-characterization reports published by EPRI (EPRI 1991; 1992; 1994a,b; 1996a,b; and 1997b-k); and
- A Council of Industrial Boiler Owners (CIBO) voluntary survey (CIBO, 1997).

The EPRI/CIBO reports provide diagrams of the layout of different WMUs that EPA used to determine the total depth that each extended below ground. These data were used to compile distributions that were probabilistically sampled during each model iteration. Because the designs of surface impoundments and landfills differ, separate distributions were developed for each. The selected value was constrained to be no deeper than the water table present in that model iteration. During a given model iteration, if the resulting depth below grade resulted in a unit below the ground water table, a new value was selected until the unit fell at or above the water table.

Figure 4-3 below displays the distributions of the data collected for surface impoundments. EPRI and CIBO provided data on a total of 16 surface impoundments. These reported depths tended to be mostly or entirely below-grade. The measured depths below grade at these 16 facilities were used to create an empirical distribution that was sampled during each model iteration.

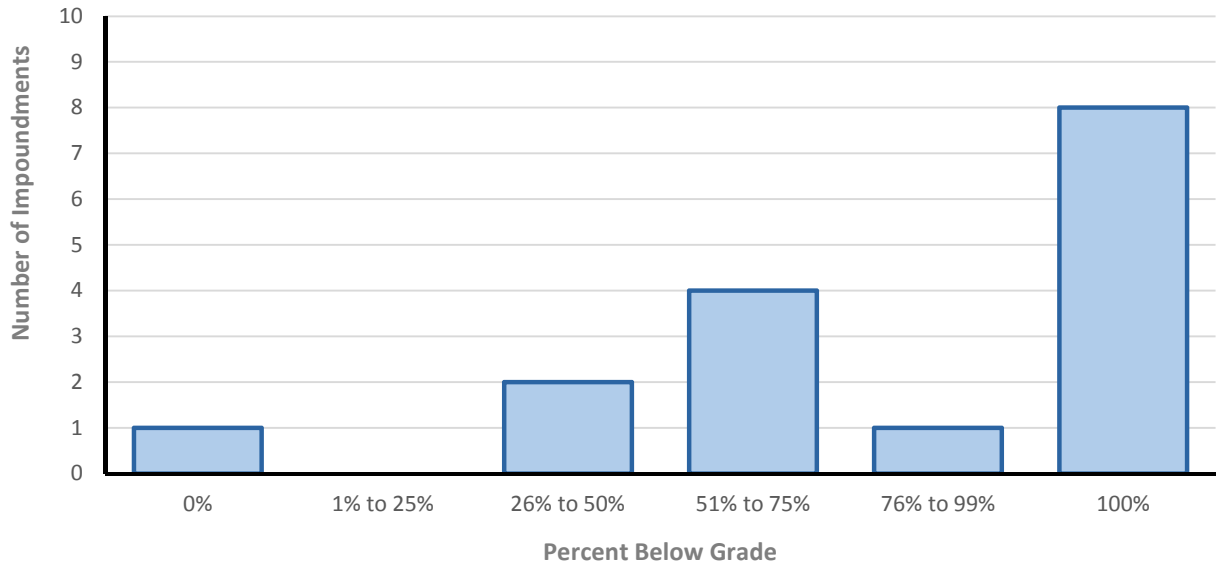

Figure 4-3. Distribution of below-grade geometry for surface impoundments from EPRI/CIBO reports.

Figure 4-4 below displays the distributions of the data collected from landfills. EPRI and CIBO provided data on a total of eight landfills. The depths reported ranged from entirely below-grade to entirely above-grade. Due to the symmetry of the available data and the relatively small available data set, EPA assumed that the percentage below-grade was uniformly distributed over the probabilistic analysis. Thus, a random value for percentage below grade between 0 and 100 percent was probabilistically sampled for each model iteration.

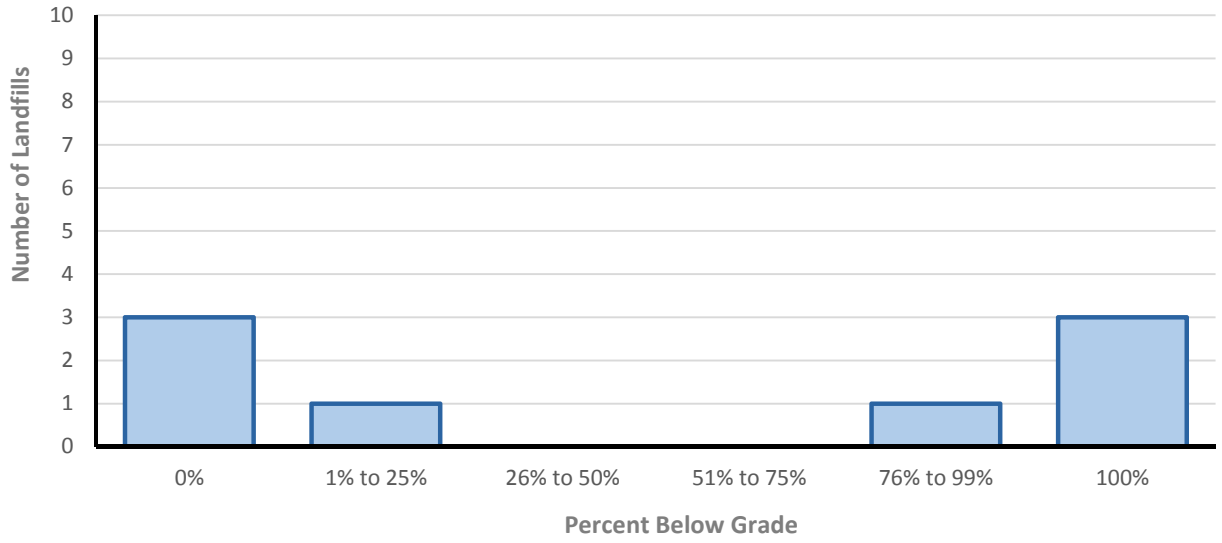

Figure 4-4. Distribution of below-grade geometry for landfills from EPRI/CIBO reports.

4.6 Receptor Location

The following section summarizes the approach used to assign receptor locations to each WMU within the probabilistic framework. After the characteristics of the WMU have been selected, a receptor location was identified. The receptor location is the geographic location of residential drinking water wells or surface water bodies relative to the WMU. To capture the highly exposed individual (HEI), receptor wells and surface water bodies were placed probabilistically within the areal extent of the ground water plume, as estimated from the modeled WMU size and soil properties selected for that model iteration. **Figure 4-5** shows a schematic of how residential well drinking water intakes and surface water bodies were defined by the model. This figure is intended to be illustrative and does not capture all possible receptor well and water body locations.

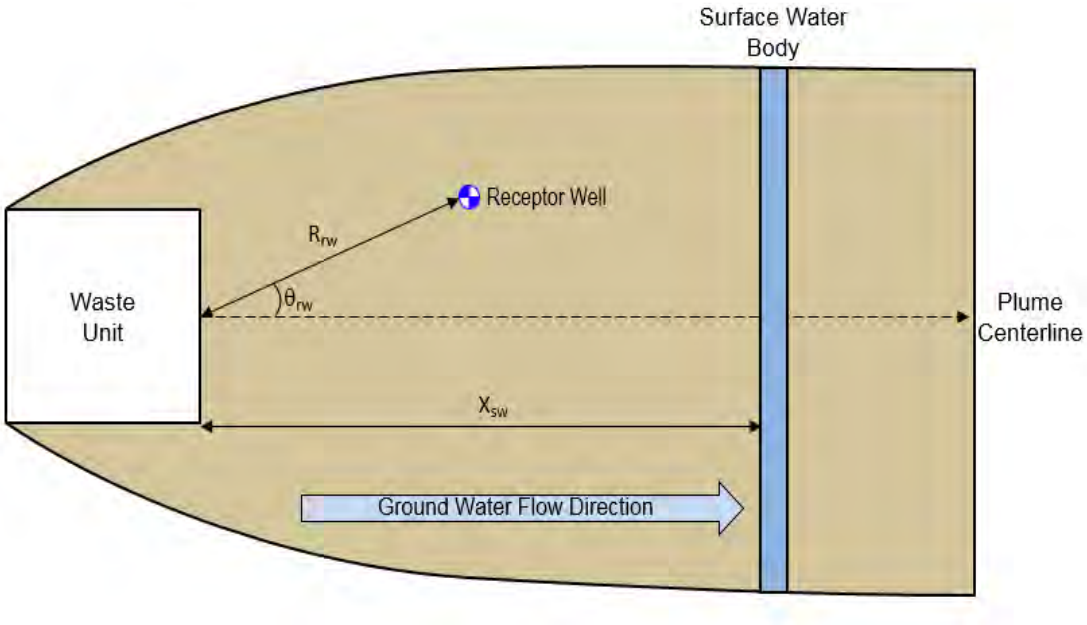

Figure 4-5. Aerial view of conceptual model for receptor location.

For wells, a radial distance (R_{rw}) from the downgradient edge of the WMU was probabilistically selected from a nationwide distribution developed by EPA based on known WMU locations and predicted household locations that incorporate 2000 Census data. The angle offset from plume centerline (θ_{rw}) was then selected from a uniform distribution ranging from 0 to 90 degrees. If the selected receptor well fell within the maximum boundary of the plume, then that well location was used. Otherwise, new values for R_{rw} and θ_{rw} were generated until the well fell within the plume. Once located, the depth of the well intake point was based on a uniform distribution ranging from the top of the water table to either the full saturated thickness of the aquifer or ten meters, whichever was less. This constraint is further discussed in U.S. EPA (2003b).

For surface water bodies, the straight-line distance (X_{sw}) from the downgradient edge of the WMU to the nearest surface water body was probabilistically selected from a nationwide distribution developed by EPA using GIS. The GIS tool used the geographic locations of the WMU and surrounding water bodies, along with topographical data, to determine the shortest flow path to nearby water bodies.

4.7 Subsurface Transport

The following subsection provides an overview of the subsurface modeling conducted with EPACMTP. This model consists of two coupled modules that address subsurface transport through unsaturated and saturated zones. These modules treat soils as a uniform, porous medium and do not account for preferential pathways or facilitated transport. In the unsaturated zone, the flow of water is driven primarily by gravity. Therefore, flow is modeled entirely in the vertical direction, with negligible lateral (i.e., sideways) migration. This assumption can be made because the scale of lateral migration due to dispersion will be orders of magnitude less than the scale of vertical migration through WMU footprints (U.S. EPA, 2003b). In the saturated zone, EPACMTP assumes that the movement of COPCs is driven primarily by the ground water advection. Flow in the saturated zone is controlled primarily by the hydraulic conductivity of the aquifer and the regional hydraulic gradient. However, the flow may be altered both by mounding underneath the WMU from high volumes of leachate, which enhances the spreading of the constituent plume in all directions, and by uncontaminated recharge from precipitation that falls around the WMU, which increases mixing in the vertical direction. In addition to advection, EPACMTP also accounts for the mixing of ground water due to dispersion, which occurs to some degree in all directions.

During transport through both the unsaturated and saturated zones, COPCs may sorb to the surrounding soils. This process is represented by K_d. For most inorganics, K_d values are strongly dependent on the concentration present in leachate, with the K_d values generally decreasing with higher concentrations. For most COPCs[13], the K_d values used in this analysis were drawn from COPC-specific distributions of K_d values versus leachate concentrations, also known as sorption isotherms. EPA selected nonlinear isotherms as the most representative of changes in sorption as leachate concentrations decrease during transport through soil and ground water. CCR-specific nonlinear sorption isotherms were generated by Metal Speciation Equilibrium Model for Surface and Ground Water (MINTEQA2) (U.S. EPA, 2001) for this risk assessment based on CCR leachate chemistry. The development of these isotherms is described in detail in **Appendix H**.

- **Surface Impoundments.** To select K_d values for surface impoundments, one of the three waste types was probabilistically assigned to the surface impoundment at the start of each model iteration. A pore water sample was then selected based on the selected waste type to provide leachate pH.[14] Where pH data were not available for a particular waste sample, a value was probabilistically selected from the empirical distribution of pH data available for that waste type. Iron oxide, natural organic matter and leachate ionic strength were then probabilistically selected based on the selected waste type. These data were used together with COPC concentrations to identify isotherms for that model iteration. The pore water concentrations exiting the surface impoundment were used to select K_d values for the

[13] A single (constant) soil K_d value from Baes et al. (1984) was used for iron and both chloride and lithium were modeled as conservative tracers (Eriksson and Kunakasem, 1969) by setting the K_d values to 0 because data were not available to determine valid ranges or distributions for these three COPCs.

[14] No leachate data were available for antimony, beryllium, lithium, and thallium in ash and coal refuse.

unsaturated zone module, while the soil pore water concentrations at the boundary of the unsaturated and saturated zones were used to select K_d values for the saturated zone module.

- **Landfills.** Because of inherent differences between the pore water samples used for surface impoundments and the LEAF data used for landfills, MINTEQA2 isotherms were selected somewhat differently for landfills. During the sampling conducted to develop the LEAF data set, EPA determined that the range and variability of waste pH was best represented by a single leachate pH distribution across all waste types (U.S. EPA, 2009a). To accommodate this single pH distribution, all other waste data, such as iron oxide, were drawn from the same distributions developed for the combined ash waste type. To select a MINTEQA2 isotherm for each model iteration, a leachate pH was randomly selected from the distribution. Based on the pH, iron oxide, natural organic matter and leachate ionic strength were probabilistically selected from the distributions. These data were used together with COPC concentrations to identify isotherms for that model iteration. The leachate concentrations exiting the landfill were used to select K_d values for the unsaturated zone module, while the soil pore water concentrations at the boundary of the unsaturated and saturated zones were used to select K_d values for the saturated zone module.

Constituents with low K_d values will have low retardation factors and may move at nearly the same velocity as the ground water. Constituents with high K_d values will have high retardation factors and may move much more slowly than ground water. The subsurface migration of some constituents may be very slow and it may take a substantial amount of time for the constituent plume to reach the downgradient receptors. As a result, the maximum concentration may not occur until thousands of years after the WMU has ceased operations. To prevent prohibitive model run times, while not missing significant risks to potential receptors, EPA ran the model until either the observed ground water concentration of a constituent at the receptor point peaked and then fell below a model-specified minimum concentration (10^{-16} mg/L), or the model had been run for a total duration of 10,000 years.

4.8 Surface Water Modeling

The following section provides an overview of the surface water modeling within the probabilistic framework. Downgradient surface water bodies can be impacted through the discharge of contaminated ground water. EPA first developed a separate surface water model used in conjunction with EPACMTP to calculate the fraction of the ground water plume that is intercepted by a surface water body (**Section 4.8.1**). Next, an equilibrium partitioning model, which calculated the steady-state into water and sediment (**Section 4.8.2**), and a precipitation model specifically for aluminum, which partitioned based on the maximum amount that may be dissolved in a water body (**Section 4.8.3)** were used to calculate the equilibrium COPC concentrations present in surface water and sediments. Finally, a food web model was used to calculate the COPC concentrations in fish (**Section 4.8.4**). Further discussion of each of these models and the associated inputs is presented in **Appendix J**.

4.8.1 Interception by Water Body

EPACMTP outputs COPC concentrations at a downgradient receptor location as a function of time. A separate surface water model used these ground water concentrations, together with the velocity of both the ground water and surface water, to calculate a mass flux of ground water into a water body. To do so, the following simplifying assumptions were required:

- The direction of regional ground water flow is perpendicular to the water body;
- The water body intercepts the entire width of the ground water plume;
- The water body receives flow from the ground water year-round;
- Lakes always intercept the entire vertical extent of the ground water plume;
- Smaller streams may only partially penetrate the shallow aquifer, allowing some or all of the mass in the contaminated ground water to be transferred to the surface water;
- If the average annual stream flow in a reach was less than the rate of ground water flow, all of the stream flow is assumed to originate from ground water discharge, and the total COPC concentration in the stream is equal to the concentration in ground water;
- There is instantaneous mixing in the stream, resulting in full and homogenous mixing of the ground water with the surface water in the stream segment.

EPACMTP is not designed to account for the mass loss calculated by other models. Instead, EPACMTP first calculated well concentrations as though water bodies were not present. A second model adjusted these well concentrations to account for surface water interception. If the entire ground water plume was intercepted, the model revised the well concentration to zero. If some of the ground water plume was not intercepted and continued to migrate toward the receptor well, then the model used the rate of discharge into the water body to iteratively solve the ground water fate and transport equations used by EPACMTP and calculate a new well concentration by translating the mass lost to the water body into additional dilution and dispersion in ground water.

4.8.2 Equilibrium Partitioning Model

A steady-state equilibrium-partitioning model was used to determine the relative amounts of each COPC entering a water body that would remain dissolved in the water and that would sorb to sediments. This model was adapted from the EPA Indirect Exposure Methodology (U.S. EPA, 1998b) and Human Health Risk Assessment Protocol (U.S. EPA, 2005k), and was used for all constituents except aluminum (see **Section 4.8.3**). With this model, COPC loading rates (mass/time) were first divided by the water body flow rates (volume/time) to yield an overall water body concentration. The model then used partitioning coefficients to divide the mass of each COPC entering the water body into the separate fractions dissolved in the water column, sorbed onto suspended solids, sorbed onto sediment particles at the bottom of the water body, and dissolved in pore water in the sediment layer. This risk assessment does not account for potential COPC losses due to burial.

4.8.3 Aluminum Precipitation Model

A separate model was used to identify the concentration of aluminum in surface water bodies. Unlike the other constituents modeled, the maximum concentration of aluminum that can be present in natural waters can be limited by solubility as a result of changes in the prevailing environmental conditions (e.g., pH) between ground water and a surface water body. Therefore, a precipitation model from MINTEQA2 was used to calculate aluminum concentrations in place of the equilibrium-partitioning model used for other COPCs. The maximum soluble aluminum concentration was calculated as a function of pH for a simplified surface water body using relationships drawn from the literature (Stumm and Morgan, 1996; Drever, 1988). The common aluminum mineral gibbsite (aluminum hydroxide) was assumed to be the solid phase for all precipitant, and the upper bound on dissolved water concentrations was assumed to be the highest solubility limit reported for each pH value. The precipitation model initially calculated the aluminum concentration in the surface water column by assuming that all aluminum entering the water body was dissolved. If this concentration exceeded the maximum soluble concentration based on the pH of the water body, the dissolved concentration was capped and all excess aluminum precipitated out as the mineral gibbsite to the benthic sediment layer.

4.8.4 Aquatic Food Web Model

An aquatic food web model was used to estimate the COPC concentrations in fish. The model uses COPC concentrations dissolved in the water column and sorbed to suspended solids to calculate the resulting concentration in fish tissue based on BCFs that account for both sources. The Agency considered exposures to TL3 and TL4 fish separately because the degree of bioconcentration may differ between these two trophic levels. TL3 consists of carnivores (i.e., carp, smelt, perch, catfish, sucker, bullhead, sauger) that eat herbivores or secondary consumers, while TL4 consists of carnivores (i.e., salmon, trout, walleye, bass) that eat other carnivores. Together, these two trophic levels are assumed to comprise all of the fish consumed by receptors.

4.9 Exposure and Risk

Each model iteration generated COPC concentrations at a specified location (receptor well or water body) as a function of time. For every model iteration, the maximum (i.e., peak) concentration at each time step was identified. Next, the single year of highest concentration across all modeled time steps was identified. Finally, a time-weighted exposure concentration was calculated by averaging the peak concentrations for each COPC at each time step over the specified exposure duration, centered around the year of highest concentration. For the GW→DW pathway, HEI exposures were calculated using a probability distribution of exposure durations that ranged anywhere from one to fifty years, based on the amount of time spent at a given residence. For the GW→SW pathway, HEI exposures were calculated based on the same distribution. Due to uncertainties about the ecological exposure durations, these exposures were based on the single year of highest concentration. In cases where the ground water concentration was found to still be increasing after 10,000 years, EPACMTP stopped modeling and used the ground water concentration at that final year to estimate exposures for all receptors.

Risks were calculated using the same equations as the screening analysis in **Section 3**. However, to the extent that data were available, full probability distributions were used to characterize each of the human exposure factors (See **Appendix D**). The risks calculated for each model iteration were aggregated into separate probability distributions for the different combinations of WMU, exposure pathway, and receptor type. From these distributions, EPA selected high-end and median risk estimates to characterize the range of risks posed to human health and the environment from current CCR disposal practices. For the purposes of this risk assessment, EPA defined high-end risk based on the recommendations of the *Guidance for Risk Characterization* (U.S. EPA, 1995) as the 90th percentile of risks to the exposed population generated by the Monte Carlo simulation. These risks were compared to the selected risk criteria of cancer risks > 1×10^{-5} and HQs > 1.

4.10 Probabilistic Risk Analysis Results

EPA modeled the full universe of facilities, landfills and impoundments discussed throughout this document. However, after modeling was completed, a number of facilities, surface impoundments and landfills were discovered to be outside the scope of the rule for one of the following reasons:

- The facility was no longer a coal-fired electric utility according to the 2012 EIA database;
- The landfill or surface impoundment was found to be inactive or retired; or
- The surface impoundment was not designed to accumulate CCRs (e.g., cooling water ponds).

In total, 218 surface impoundments and 122 landfills that were modeled met these criteria, and were filtered from the results. A column denoting whether or not a WMU was excluded can be found in **Attachment A-2**. For the remaining impoundments, risks are presented for all COPCs found to exceed risk criteria in the screening analysis in **Section 3**. Because the 2010 Risk Assessment (U.S. EPA, 2010) demonstrated that risks from surface impoundments are consistently higher than those from landfills, these impoundment results were used as a secondary screening to identify COPCs to be modeled for landfills. To ensure that this approach did not underestimate risks, landfill modeling included all COPCs found to exceed risk criteria for any subset of surface impoundments during subsequent sensitivity analyses discussed in **Section 5**.

4.10.1 Human Health Risk Results

90th percentile risks for human receptors are presented in **Table 4-2**. These risks represent all of the modeled impoundments and landfills subject to the rulemaking. Both cancer and noncancer risks are presented for the highest exposed receptor group. For drinking water ingestion, the highest cancer risks were for adults (Ages > 21 years), while the highest noncancer risks were for infants (Age < 1 year). For fish ingestion, the highest cancer and noncancer risks were for children (Ages 1 to < 2 years). Values that exceed the selected risk criteria (i.e., cancer risk > $1x10^{-5}$ or HQ > 1) are shown in **bold**.

Table 4-2. 90th Percentile Nationwide Risk Results for Human Health

COPC	Surface Impoundments		Landfills	
	Drinking Water Ingestion	Fish Ingestion	Drinking Water Ingestion	Fish Ingestion
Carcinogenic Effects				
Arsenic III	**2×10^{-4}**	2×10^{-7}	5×10^{-6}	–
Arsenic V	1×10^{-5}	5×10^{-9}	7×10^{-8}	–
Chromium VI	6×10^{-7}	–	7×10^{-8}	–
Noncarcinogenic Effects				
Arsenic III	**5**	–	0.1	–
Arsenic V	0.4	–	< 0.01	–
Boron	0.6	–	< 0.01	–
Cadmium	0.04	< 0.01	–	–
Cobalt	0.01	–	< 0.01	–
Fluoride	0.2	–	– [a]	–
Lead	< 0.01	–	–	–
Lithium	**2**	–	– [b]	–
Mercury	–	0.02	–	0.01
Molybdenum	**2**	–	< 0.01	–
Selenium IV	–	< 0.01	–	–
Selenium VI	–	0.05	–	–
Thallium	0.9	0.04	0.08	–

– Constituent was not modeled for this pathway

a) Fluoride was found to slightly exceed risk criteria during one sensitivity analyses conducted for surface impoundments; however, Method 1313 data were not available to model this COPC for landfills.

b) Lithium was found to slightly exceed risk criteria in the probabilistic analysis for surface impoundments; however, Method 1313 data were not available in the literature to model this COPC for landfills.

For impoundments, the 90th percentile risks associated with ingestion of ground water were above cancer and noncancer criteria for arsenic III (risk = 2×10^{-4}, HQ = 5) and noncancer criteria for both lithium (HQ = 2) and molybdenum (HQ = 2). No risks above the human health criteria were identified for ingestion of fish. For landfills, no risks above the human health criteria were identified for any pathway. Consistent with the findings of the 2010 Risk Assessment, risks from landfills are consistently lower than those from surface impoundments. 50th percentile risks were also calculated for both surface impoundments and landfills, but are not shown because risks fell below all criteria.

4.10.2 Ecological Risk Results

90th percentile risks for ecological receptors are presented in **Table 4-3**. These risks represent all of the modeled impoundments and landfills subject to the rulemaking. For all surface water and sediment risks, the sensitive ecological receptor is defined by the available benchmarks.

Table 4-3. 90th Percentile Nationwide Risk Results for Ecological Receptors

COPC	Surface Impoundments		Landfills	
	Surface Water	Sediment	Surface Water	Sediment
Aluminum	< 0.01	–	–	–
Antimony	–	0.06	–	–
Arsenic III	0.02	0.1	–	0.02
Arsenic V	< 0.01	< 0.01	< 0.01	–
Barium	< 0.01	–	–	–
Beryllium	< 0.01	–	–	–
Boron	0.3	–	< 0.01	–
Cadmium	0.1	–	–	–
Chloride	0.03	–	–	–
Chromium III	< 0.01	–	–	–
Chromium VI	< 0.01	–	–	–
Cobalt	< 0.01	–	–	–
Copper	< 0.01	–	–	–
Iron	< 0.01	–	–	–
Lead	< 0.01	–	–	–
Molybdenum	0.09	–	–	–
Nickel	< 0.01	–	–	–
Selenium IV	< 0.01	–	–	–
Selenium VI	0.1	–	–	–
Silver	0.06	0.02	–	–
Vanadium	< 0.01	< 0.01	–	–
Zinc	< 0.01	–	–	–

– Constituent was not modeled for this pathway

No 90th percentile risks above the ecological criteria were identified for either surface water or sediment for either surface impoundments or landfills. 50th percentile risks were also calculated for both surface impoundments and landfills, but are not shown because all fell well below the selected risk criteria.

4.10.3 Summary of Probabilistic Analysis

EPA conducted the probabilistic analysis described in this section to better characterize the potential risks to human and ecological receptors associated with leaching from WMUs to ground water. The potential exposure routes identified for this pathway were human ingestion of ground water and fish and ecological contact with and ingestion of surface water and sediment. To evaluate each of these exposure routes, the probabilistic analysis combined site-specific data with regional and national data to conduct a total of approximately 100,000 model iterations per COPC that

capture the full range and frequency of disposal practices known to occur. These iterations form the basis for the risk results.

The modeling results showed 90th percentile risks above the human health criteria from surface impoundments. Human health exposures from the ingestion of ground water resulted in the highest risks, with a cancer risk of 2×10^{-4} and noncancer HQ of 5 for arsenic III and a noncancer HQ of 2 for molybdenum. Human health exposures from ingestion of fish, as well as all ecological exposures fell below risk criteria. All 90th percentile risks for landfills also fell below these thresholds.

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5 Sensitivity and Uncertainty Analyses

The probabilistic analysis presented in **Section 4** identified the potential for risks to human health through the ingestion of ground water that results from leaching of arsenic and molybdenum from surface impoundments. These risks reflect the full range of current, nationwide CCR disposal practices and, because of this broad scope, there are numerous sources of uncertainty present within the probabilistic analysis. To better understand the effect of these uncertainties on the modeled risks and to determine if any particular subset of disposal practices drive the risks identified, EPA conducted additional sensitivity and uncertainty analyses. The purpose of this section is to describe the results of these additional analyses, to identify the model parameters with the greatest potential to influence calculated risks and, to characterize the potential effects of these parameters on the principal results of the probabilistic analysis. This discussion is divided into the following subsections:

- **Section 5.1** provides an overview of the major sources of uncertainty in the probabilistic analysis, as well as a qualitative and, where possible, quantitative characterization of each.
- **Section 5.2** presents a summary of the sensitivity analysis conducted in support of the 2010 Risk Assessment (U.S. EPA, 2010a) and compares the sensitive parameters identified with the findings of the revised sensitivity and uncertainty analyses;
- **Section 5.3** compares trends in the characteristics of proven and potential damage cases with the findings of the revised sensitivity and uncertainty analyses;
- **Section 5.4** summarizes the results for the revised sensitivity and uncertainty analyses, as well as for the comparisons of these results with the previous sensitivity analysis and the proven and potential damage cases.

5.1 Variability, Data Uncertainty and Model Error

Uncertainty exists to some degree in any quantitative evaluation, and it may bias the calculated results higher or lower than actual values. It is important to understand both the direction and magnitude of uncertainties present in a risk assessment. The direction of uncertainty is the tendency for that uncertainty to push a predicted value higher or lower than the actual value, while the magnitude of uncertainty is the extent to which that uncertainty may push a predicted value away from the true value. Characterizing these uncertainties helps to ensure that the overall conclusions of the evaluation would not change with the consideration of additional information. There are three primary causes of uncertainty:

- Variability is the extent to which characteristics of environmental systems are heterogeneous, and is reflected in the parameter distributions used as inputs for the models. Although variability can be better captured by collecting additional data, it cannot be eliminated and must be treated explicitly in the assessment.

- Data uncertainty is a description of the imperfection in knowledge of the true value of a particular parameter. Uncertainty is generally reducible through additional research and information-gathering.
- Model error occurs because models and their mathematical expressions are simplifications of reality that are used to approximate real-world conditions, processes and their relationships. These assumptions are sometimes necessary to solve complex mathematical equations or to fill gaps in available knowledge. However, the simplification of complex systems may misrepresent real-world conditions to an unknown degree.

The uncertainties identified in the probabilistic analysis were managed to the extent practicable to minimize potential effects on the model results. Variability was addressed to the extent possible by compiling available data into probabilistic distributions for each parameter. Uncertainty about the exact range or distribution of a parameter was addressed through the use of estimated point values or distributions intended to appropriately bound the true range, biased toward protection of human health and the environment. **Table 5-1** lists the general categories of uncertainties identified, along with the different portions of the document text where these topics are discussed.

Table 5-1. Summary of the Categories of Uncertainty Present in the Probabilistic Analysis and the Discussion Locations within the Risk Assessment Text

Uncertainty	Location of Original Discussion	Location of Corresponding Uncertainty Discussion
CCR WMU Database	Section 2 and Appendix A	Section 5.1.1
Environmental Parameters	Section 2 and Appendix B	Section 5.1.2
CCR Constituent Database	Section 2 and Appendix C	Section 5.1.3
Human Exposure Factors	Section 2 and Appendix D	Section 5.1.4
Human Health & Ecological Benchmarks	Section 2 and Appendix E	Section 5.1.5
Bioconcentration Factors	Section 3 and Appendix G	Section 5.1.6
WMU Source Term Models	Section 4 and Appendix I	Section 5.1.7
MINTAQA2 Isotherm Model	Section 4 and Appendix H	Section 5.1.8
EPACMTP Ground Water Model	Section 4 and Appendix I	Section 5.1.9
Surface Water Model	Section 4 and Appendix J	Section 5.1.10
Risk Models	Section 4	Section 5.1.11

5.1.1 CCR WMU Database

The CCR WMU database was populated with data from two EPA surveys conducted in 2009 and 2010. These surveys provide data on a total of 952 surface impoundments and 431 landfills at 383 facilities out of the known universe of 507 facilities that burn coal and dispose of the resulting waste on-site. The inclusion of data from these surveys greatly increased the information available on the characteristics of WMUs. The total number of facilities and WMUs will fluctuate over time. However, the CCR WMU database provides broad representation of operating facilities at the time

it was compiled. Some gaps do exist in the database as a result of survey design, erroneous or unclear responses, and claims of confidential business information. These gaps were filled probabilistically, based on the distributions of available data. As discussed below, because the available data are far more representative sample than previously available and cover a large proportion of existing facilities, it is unlikely that this represent a major source of uncertainty.

Geographic Location Data

When locations were known for a specific WMU, the probabilistic analysis held this parameter constant for all model iterations associated with that unit. Because many of the environmental parameters used in the models were selected based on geographic location, the location does influence the analysis. Specific geographic coordinate locations were known for 67 percent of surface impoundments and for 81 percent of landfills. In cases where locations were not known, the location of the facility front gate or centroid reported in the 2009 EIA were used to place these units as close to actual locations as possible. In addition, where possible, the locations were verified by reviewing geo-referenced aerial photographs in GIS. While there is still some uncertainty associated with exact locations for a portion of WMUs in the full data set, the influence on results is anticipated to be small given the regional-scale resolution of most environmental data.

WMU Dimension Data

When area, thickness, or capacity was known for a specific WMU, the probabilistic analysis held these parameters constant for all model iterations associated with that unit. When no data were available or reported values were found to be unrealistic, these data gaps were filled during each model iteration by sampling probabilistically from the distributions developed from WMUs with data (see **Appendix A**). Area measurements were known for 92 percent of the surface impoundments and for 39 percent of landfills.

The full distribution of known area measurements for both surface impoundments and landfills were divided into separate distributions based on the annual amount of coal burnt (or "coal use"), available in the 2009 EIA database. First, the coal use reported for every facility was compiled into a single distribution and then divided into quartile ranges. The area measurements for the surface impoundments and landfills present at each facility in a coal use quartile range were combined into a total of four new area distributions. Where area measurements were unknown for a given unit, a fixed area distribution was assigned and probabilistically sampled based on the coal use reported for the corresponding facility. This approach ensured that the larger area measurements for large WMUs were not inadvertently assigned to smaller facilities. This coal use quartile-based probabilistic sampling may over- or underestimate dimensions for individual model iterations. However, the aggregate results reflect a national distribution with the best available data. As a result, this approach is unlikely to introduce much additional uncertainty.

Liner Data

When liner types were known for a specific WMU, the probabilistic analysis held these parameters constant for all model iterations associated with that unit. Specific liner types were known for 64 percent of surface impoundments and for 53 percent of landfills. When no data were available on

liner type, this data gap was filled during each model iteration by sampling probabilistically from the distribution developed from WMUs with data. In cases where survey responses indicated the presence of a liner, but did not specify the type (additional 5 percent of surface impoundments and 34 percent of landfills), each model iteration sampled probabilistically from the distribution developed from WMUs with liners. This probabilistic sampling may not accurately represent liner type for specific WMUs, but the aggregate results likely reflect the larger national distribution due to the high proportion of known liner types. Thus, this approach is unlikely to result in much additional uncertainty.

Liner Assignment

The three liner types modeled in the probabilistic analysis are unlined, clay-lined and composite-lined. Although a number of different liner configurations were reported in the 2009/2010 EPA surveys, each was modeled as one of these three types. WMUs reported as lined with CCR waste, concrete, asphalt or other nonstandard liner materials were categorized as unlined because of the high likelihood cracks that would eliminate the effectiveness of the liner without constant maintenance. WMUs reported as lined with some form of natural or synthetic clay were categorized as clay-lined. WMUs reported as lined with some form of composite or flexible membrane liner were categorized as composite-lined. These three liner types were assigned because site-specific information on the effective hydraulic conductivities in the field were not readily available. Even if this type of data were available, the hydraulic conductivity of these liners as designed or currently measured may not capture higher leakage rates that result from cracks and tears that develop over time without proper monitoring and corrective action. The binning of reported liners into the three modeled categories is believed to best represent the range of liner behavior and introduce a small amount of uncertainty into the probabilistic analysis.

Liner Prevalence

A recent 2006 study conducted jointly by EPA and DOE (U.S. DOE, 2006) found that liners are more likely to be present in newly constructed WMUs and new expansions of existing WMUs. Between 1994 and 2004, 100 percent of the new impoundments (out of 20) and 97 percent of the new landfills (out of 42) included in the study contained some type of liner. **Table 5-2** provides a full comparison of the liner information in the CCR WMU database.

Table 5-2. Number and Percentages of WMUs with Different Liner Types Constructed Before and After 2000

Liner Type	Surface Impoundments						Landfills					
	Pre-2000		Post-2000		Unknown Date		Pre-2000		Post-2000		Unknown Date	
Total	**952**						**431**					
Unlined	371	(48%)	7	(12%)	28	(24%)	154	(52%)	12	(20%)	7	(10%)
Lined	198	(25%)	38	(63%)	16	(14%)	140	(47%)	48	(80%)	13	(17%)
Unknown	207	(27%)	15	(25%)	72	(62%)	3	(1%)	0	(0%)	54	(73%)

Note: Counts are derived by start year using the 2009/2010 EPA surveys. Some WMUs did not contain start years (unknown date column), while others may contain start years but not liner type information (unknown row).

Even though most of the recently constructed surface impoundments and landfills are lined in some fashion, the majority of units currently in operation remain unlined. Because this risk assessment evaluated current waste management practices, it does not examine the potential for future changes in liner types. However, because the majority of units in operation are unlined, EPA did consider the extent to which these units drive the modeled risks presented in **Section 4**. This sensitivity analysis was conducted by filtering the full distribution of risks into three separate distributions, one for each liner type, for surface impoundments and for landfills.

Table 5-3 shows the 90th percentile human and ecological risks separated out for unlined, clay-lined and composite-lined surface impoundments. Risks are presented for each constituent modeled in the probabilistic analysis that was also above risk criteria in this sensitivity analysis. Arsenic V risks are provided even where below criteria to provide a bound on arsenic speciation. Values that exceed the risk criteria (i.e., cancer risk > $1x10^{-5}$ or HQ > 1) are shown in **bold**.

Table 5-3. 90th Percentile Risk Exceedances by Liner Type: Surface Impoundments

COPC	Liner Type	Percent of Iterations	Human Health		Ecological	
			GW→DW Tap Water Ingestion	GW→SW Fish Ingestion	GW→SW Surface Water	GW→SW Sediment
Cancer Risk						
Arsenic III	Unlined	65%	**3×10^{-4}**	7×10^{-7}	—	—
	Clay Lined	18%	7×10^{-6}	2×10^{-9}	—	—
	Composite Lined	17%	$< 1 \times 10^{-10}$	$< 1 \times 10^{-10}$	—	—
Arsenic V	Unlined	65%	**4×10^{-5}**	3×10^{-8}	—	—
	Clay Lined	18%	1×10^{-7}	$< 1 \times 10^{-10}$	—	—
	Composite Lined	17%	$< 1 \times 10^{-10}$	$< 1 \times 10^{-10}$	—	—
Noncancer Risk						
Arsenic III	Unlined	65%	**8**	—	0.06	0.4
	Clay Lined	18%	0.2	—	< 0.01	< 0.01
	Composite Lined	17%	< 0.01	—	< 0.01	< 0.01
Arsenic V	Unlined	65%	1	—	0.06	0.02
	Clay Lined	18%	< 0.01	—	< 0.01	< 0.01
	Composite Lined	17%	< 0.01	—	< 0.01	< 0.01
Lithium	Unlined	65%	**3**	—	—	—
	Clay Lined	18%	**2**	—	—	—
	Composite Lined	17%	< 0.01	—	—	—
Molybdenum	Unlined	65%	**4**	—	0.2	—
	Clay Lined	18%	0.1	—	< 0.01	—
	Composite Lined	17%	< 0.01	—	< 0.01	—
Thallium	Unlined	65%	**2**	0.1	—	—
	Clay Lined	18%	0.02	< 0.01	—	—
	Composite Lined	17%	< 0.01	< 0.01	—	—

As seen in the table above, unlined units present the greatest risks. These unlined units result in cancer risks above 1×10^{-5} for arsenic III (3×10^{-4}) and arsenic V (4×10^{-5}), as well as noncancer risks above an HQ of 1 for arsenic III (8), molybdenum (4) and thallium (2). In many cases, due to the prevalence of unlined units, the risks for these units alone are similar to those for all units in the full-scale probabilistic modeling (**Section 4**). Clay-lined units present risks lower than unlined units, with noncancer risks above an HQ of 1 for lithium (2). Composite-lined units present risks far below all relevant risk criteria for all constituents.

Table 5-4 shows the 90th percentile human and ecological risks separated out for unlined, clay-lined and composite-lined landfills. Risks are presented for each constituent modeled in the probabilistic analysis that was also above risk criteria in this sensitivity analysis. In some instances, arsenic V risks are provided even where below criteria to provide a complete bounding on arsenic speciation. Values that exceed the selected risk criteria (i.e., cancer risk > $1x10^{-5}$) are shown in **bold**. No noncancer risks above human health criteria were identified.

Table 5-4. 90th Percentile Risk Exceedances by Liner Type: Landfills

COPC	Liner Type	Percent of Iterations	Human Health	
			GW→DW Tap Water Ingestion	GW→SW Fish Ingestion
Cancer				
Arsenic III	Unlined	42%	**2×10^{-5}**	—
	Clay Lined	25%	1×10^{-5}	—
	Composite Lined	33%	$< 1 \times 10^{-10}$	—
Arsenic V	Unlined	42%	1×10^{-6}	—
	Clay Lined	25%	3×10^{-7}	—
	Composite Lined	33%	$< 1 \times 10^{-10}$	—

Similar to surface impoundments, unlined landfills present the greatest risks. Unlined landfills result in cancer risks above 1×10^{-5} for arsenic III (2×10^{-5}). Clay-lined landfills present risks lower than unlined units and composite-lined units present risks far below all relevant risk criteria.

Impoundment Waste Type Assignment:

Waste pH is the primary factor used to determine appropriate K_d values, which dictate the rate at which COPCs move through the subsurface environment. EPA identified insufficient data to develop a national pH distribution for wastes disposed in surface impoundments. Instead, this risk assessment divided the available data into discrete waste types that reflect similar leachate pH conditions and ion concentrations. The modeled waste types include combined ash, ash and coal refuse, and FGD waste. When the type of CCR type disposed in an impoundment was known, the analysis assigned a fixed waste type based on the CCRs disposed for all model iterations. CCR types were known for 97 percent of the impoundments. When no data were available on the CCR type disposed in a unit, this data gap was filled during each model iteration by sampling probabilistically from the distribution of known waste types for other WMUs. This probabilistic sampling may over- or under-estimate leachate concentrations for individual model iterations.

However, given that waste types are known for the vast majority of units, this uncertainty is likely to have a negligible impact on the modeled national-scale risks.

Landfill Waste Type Assignment

Waste pH is the primary factor used to determine appropriate K_d values, which determine the rate at which COPCs move through the subsurface environment. Unlike for surface impoundments, a representative national distribution of pH values was available for landfills. This information was drawn from a nation-wide distribution of CCR waste pH compiled as part of U.S. EPA (2009a). **Figure 5-1** provides a graph of this pH distribution for landfills. Because a representative distribution was available for landfills, the segregation of different waste types was not needed to identify appropriate K_d ranges for each unit.

The pH of CCR wastes as managed range from around 3 to 13. Although the total pH range is wide, the majority of wastes are more basic, with a median value between 10 and 11. CCR wastes managed with coal refuse can be substantially more acidic, which accounts for some of the distribution far below a pH of 7. Similarly, FGD materials can be very basic, which accounts for some of the distribution above a pH of 11. Because this pH distribution provides the full range and relative frequency for different waste pH, treatment of CCRs disposed in landfills as a single waste type still captures the possible variations in K_d values. Thus, this introduces minimal uncertainty.

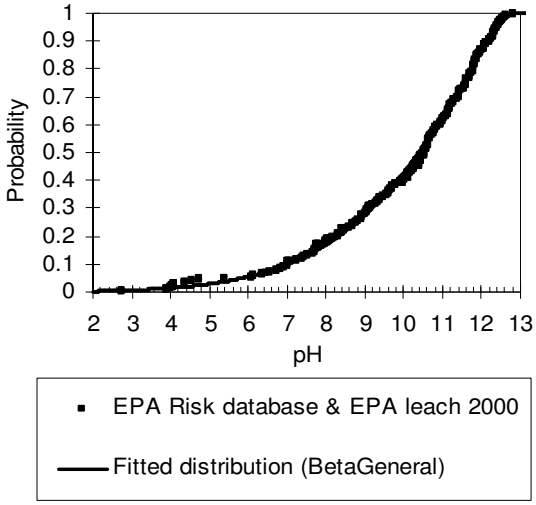

Figure 5-1. Measured landfill CCR waste pH values [Adapted from U.S. EPA (2009a)].

Waste Type Prevalence

A survey conducted by EPRI in 1995 showed that 34 percent of unlined landfills and 68 percent of unlined surface impoundments actively managed CCR wastes with coal refuse. However, the more recent 2009/2010 EPA surveys indicate that this management practice has declined significantly to around five percent of current units. At present, EPA has no data on trends in the generation of FGD waste. Because this risk assessment evaluated current waste management practices, it does not examine the potential for future shifts in the relative amounts of different waste types disposed. Yet, waste pH has been shown to be a key factor in leachate concentrations and these two waste types are more likely to have an extreme pH. Therefore, EPA did consider the extent to which management of these different waste types may drive the probabilistic risks presented in **Section 4**.

For surface impoundments, this sensitivity analysis was conducted by filtering the full distribution of risks into three separate distributions, one for each waste type. **Table 5-5** shows the 90th percentile human and ecological risks separated out for combined ash, ash and coal refuse, and FGD wastes. Risks are presented for each constituent modeled in the probabilistic analysis that was also above risk criteria in this sensitivity analysis. Values that exceed the risk criteria (i.e., cancer risk > 1×10^{-5} or HQ > 1) are shown in **bold**.

Table 5-5. 90th Percentile Risk Exceedances by Waste Type: Surface Impoundments

Constituent	Waste Type	Percent of Iterations	Human Health		Ecological	
			GW→DW Tap Water Ingestion	GW→SW Fish Ingestion	GW→SW Surface Water	GW→SW Sediment
Cancer Risks						
Arsenic III	Combined Ash	85%	**2×10^{-4}**	2×10^{-7}	—	—
	Ash & Coal Refuse	5%	**1×10^{-3}**	1×10^{-6}	—	—
	FGD Waste	10%	**2×10^{-4}**	2×10^{-7}	—	—
Arsenic V	Combined Ash	85%	1×10^{-5}	3×10^{-9}	—	—
	Ash & Coal Refuse	5%	**4×10^{-4}**	3×10^{-7}	—	—
	FGD Waste	10%	**2×10^{-5}**	1×10^{-8}	—	—
Noncancer Risks						
Arsenic III	Combined Ash	85%	**4**	—	0.02	0.1
	Ash & Coal Refuse	5%	**26**	—	0.1	0.8
	FGD Waste	10%	**5**	—	0.02	0.1
Arsenic V	Combined Ash	85%	0.3	—	< 0.01	< 0.01
	Ash & Coal Refuse	5%	**14**	—	0.7	0.2
	FGD Waste	10%	0.5	—	0.03	< 0.01
Boron	Combined Ash	85%	0.6	—	0.3	—
	Ash & Coal Refuse	5%	0.2	—	0.3	—
	FGD Waste	10%	**2**	—	**5**	—
Cadmium	Combined Ash	85%	0.03	< 0.01	0.1	—
	Ash & Coal Refuse	5%	0.6	0.04	**3**	—
	FGD Waste	10%	0.06	< 0.01	0.2	—
Cobalt	Combined Ash	85%	0.01	—	< 0.01	—
	Ash & Coal Refuse	5%	**13**	—	0.05	—
	FGD Waste	10%	0.02	—	< 0.01	—
Fluoride	Combined Ash	85%	0.1	—	—	—
	Ash & Coal Refuse	5%	0.2	—	—	—
	FGD Waste	10%	**2**	—	—	—
Lithium	Combined Ash	89%	**3**	—	—	—
	Ash & Coal Refuse	—	—[a]	—	—	—
	FGD Waste	11%	0.4	—	—	—
Mercury	Combined Ash	85%	—	0.02	—	—
	Ash & Coal Refuse	5%	—	**5**	—	—
	FGD Waste	10%	—	< 0.01	—	—
Molybdenum	Combined Ash	85%	**2**	—	0.1	—
	Ash & Coal Refuse	5%	1	—	0.1	—
	FGD Waste	10%	1	—	0.03	—

a) Leachate data were not available to model ash & coal refuse.

Disposal of combined ash resulted in risks very similar to those identified in the full probabilistic modeling because this waste type comprised the majority of model iterations. Codisposal of ash

and coal refuse resulted in risks for select constituents higher than for combined ash and above human health and ecological criteria. Cancer risks above 1×10^{-5} were identified for arsenic III (1×10^{-3}) and arsenic V (4×10^{-4}) from ingestion of ground water. Noncancer risks above an HQ of 1 were identified for arsenic III (26), arsenic V (14), and cobalt (13) from ingestion of ground water; for mercury (5) from fish ingestion; and for cadmium (3) from ecological exposure to surface water. Disposal of FGD waste also resulted in higher risks for select constituents than for combined ash. Cancer risks above 1×10^{-5} were identified for arsenic III (2×10^{-4}) and arsenic V (2×10^{-5}) from ingestion of ground water. Noncancer risks above an HQ of 1 were found for arsenic III (5), boron (2) and fluoride (2) from ingestion of ground water.

For landfills, this sensitivity analysis was conducted by filtering the full risk distribution into discrete pH ranges. Since it was the main risk driver for landfills, this sensitivity analyses was conducted for arsenic (both III and V). **Table 5-6** shows the 90th percentile human and ecological risks separated out for the target pH ranges specified by Method 1313 (U.S. EPA, 2012d). No risks were found to be above either the cancer or noncancer criteria. (i.e., cancer risk > 1×10^{-5} or HQ > 1).

Table 5-6. 90th Percentile Ground Water Ingestion Risk Exceedances by Waste pH: Landfills

pH Range	Percent of Iterations*	Cancer		Noncancer	
		As (III)	As (V)	As (III)	As (V)
3.5 – 4.5	1%	5×10^{-6}	4×10^{-6}	0.2	0.2
5.0 – 6.0	3%	3×10^{-6}	7×10^{-7}	0.1	0.02
6.5 – 7.5	6%	4×10^{-6}	$< 1 \times 10^{-10}$	0.1	< 0.01
7.5 – 8.5	9%	5×10^{-6}	$< 1 \times 10^{-10}$	0.2	< 0.01
8.5 – 9.5	13%	4×10^{-6}	2×10^{-10}	0.1	< 0.01
10.0 – 11.0	20%	4×10^{-6}	3×10^{-9}	0.1	< 0.01
11.5 – 12.5	22%	5×10^{-6}	8×10^{-7}	0.1	0.03
12.5 – 13.5	4%	1×10^{-5}	6×10^{-6}	0.2	0.1

* The pH ranges reflect specific ranges specified by Method 1313 for reference. Because the pH distribution is not continuous, the percentage of runs does not add up to exactly 100%.

Exclusion of FBC Waste Type

In addition to the waste types modeled in this risk assessment, EPA also identified fluidized-bed combustion (FBC) wastes as a distinct waste type. The 2010 Risk Assessment modeled the FBC waste type separately for landfills, but not surface impoundments, because of the lack of impoundment pore water data available. This modeling showed that the risks associated with disposal of FBC waste in landfills were lower than those for other CCR waste types and below all risk criteria. Given these results and the lack of additional leachate data available since 2010, EPA did not re-evaluate FBC wastes in the revised risk assessment. Disposal of FBC as a monofill is only known to occur at two facilities. Given the rarity of this waste type and the lower risks modeled, exclusion of FBC waste from the revised risk assessment is unlikely to have an appreciable impact on modeled national-scale risks.

Below-Grade Geometry

The WMU depth below grade was used along with depth to water table to calculate the distance from the bottom of the WMU to ground water (the "depth to ground water" used in the unsaturated zone transport model). A data set drawn from an EPRI 1997 survey was utilized to generate the distribution of WMU depths below grade. The 2009/2010 EPA surveys indicate the potential for a larger proportion of surface impoundments to have above-grade construction, and fewer impoundments that are mostly or entirely below grade than modeled. This difference could result in greater depths to ground water associated with the 2009/2010 EPA survey data when compared with the EPRI 1997 data used in the risk assessment. EPA conducted a sensitivity analysis to assess the extent to which depth to ground water changes the risk results. For this analysis, depths were broken out into quartiles and model results were filtered into the four corresponding bins. Results are presented in **Table 5-7**. The 90th percentile results for the middle two quartiles, which make up the inner-quartile range, were the same for all constituents, and are reported as a single value. Values that exceed the risk criteria (i.e., cancer risk > 1×10^{-5} or HQ > 1) are shown in **bold**.

Table 5-7. 90th Percentile Ground Water Ingestion Risk Exceedances by Depth to Ground Water: Surface Impoundments

COPC	Depth to Ground Water Quartiles			
	Full Range of Depths	Lower Quartile (≤ 0.95 m)	Inner-Quartile (0.95 to ≤ 19 m)	Upper Quartile (> 19 m)
Cancer Risks				
Arsenic III	**2×10^{-4}**	**3×10^{-4}**	**1×10^{-4}**	**7×10^{-5}**
Arsenic V	1×10^{-5}	**2×10^{-5}**	1×10^{-5}	4×10^{-6}
Noncancer Risks				
Arsenic III	**5**	**6**	**4**	**2**
Arsenic V	0.4	0.6	0.3	0.1
Lithium	**2**	**2**	**2**	**3**
Molybdenum	**2**	**3**	**2**	1

While data from the 2009 EPA survey for surface impoundments indicates that a greater number of units may be constructed above grade, the focus of many of these surveys was on above-grade impoundments at risk of structural failure. Therefore, these data may be biased toward units with a greater fraction of the unit above the water table. Conversely, it is known from reported damage cases that some CCR WMUs come in direct contact with the water table for at least part of the year. The probabilistic analysis limited the depth of every WMU to the boundary of the water table because EPACMTP is not designed to solve for leaching from within the water table. Furthermore, EPACMTP considers the annualized transport of constituents. Modeling WMUs below the water table would effectively treat WMUs as submerged year-round, which is often not realistic given seasonally fluctuating water tables. Thus, the probabilistic analysis may over- or underestimate risk on a case-by-case basis. The exact magnitude of this uncertainty is unknown. However, even with greater depths to ground water, risks above cancer and noncancer criteria were still identified.

Given that there is potential for both higher and lower risks than modeled, this uncertainty is unlikely to have an appreciable effect on the principal findings of the probabilistic analysis.

Pollution Control Technology

Because this risk assessment evaluated current management practices, it did not examine the potential for future changes in air pollution technologies to alter the composition of CCR wastes. However, it has been established that mercury pollution controls can affect both the mercury content and the general leaching behavior of ash (U.S. EPA, 2006a, 2008b, 2009a). Therefore, EPA considered the extent to which these mercury-control wastes may drive the modeled risks presented in **Section 4**. This sensitivity analysis was conducted by filtering the full risk results for the subset of fly ash samples generated by facilities with ACI. These samples were collected from a total of five different facilities with the ACI system turned on and off. This comparison allows a consistent frame of reference to judge the effect of ACI on releases from fly ash. **Table 5-8** shows a comparison of 90th percentile risk results for these samples. The table presents results for arsenic because it is the primary risk driver and mercury because public commenters raised concerns about the potential for new pollution control technologies to result in higher releases of this constituent.

Table 5-8. Comparison of 90th Percentile Landfill Risks for Facilities with Activated Carbon Injection (ACI) Turned On and Off

Constituent	ACI Status	Percent of Iterations per COPC	Human Health		Ecological	
			GW→DW Tap Water Ingestion	GW→SW Fish Ingestion	GW→SW Surface Water	GW→SW Sediment
Cancer Risks						
Arsenic III	Turned On	9%	8×10^{-6}	—	—	—
	Turned Off	9%	1×10^{-5}	—	—	—
Arsenic V	Turned On	9%	6×10^{-8}	—	—	—
	Turned Off	9%	8×10^{-8}	—	—	—
Noncancer Risks						
Arsenic III	Turned On	9%	0.2	< 0.01	< 0.01	0.04
	Turned Off	9%	0.2	< 0.01	< 0.01	0.03
Arsenic V	Turned On	9%	< 0.01	< 0.01	< 0.01	< 0.01
	Turned Off	9%	< 0.01	< 0.01	< 0.01	< 0.01
Mercury	Turned On	9%	< 0.01	< 0.01	< 0.01	< 0.01
	Turned Off	9%	< 0.01	0.01	< 0.01	< 0.01

There is some difference in landfill risks modeled for ashes generated with and without ACI. In some instances, risks actually decreased slightly with the addition of activated carbon. Yet, the observed decreases were small enough that they may be an artifact of the relatively small number of model iterations conducted for these wastes. Based on the data available, the variations in risk observed would not alter the principal findings of the risk assessment that current disposal practices pose risks within the range where OSWER typically regulates. However, EPA draws no

conclusions about the exact effects of changing pollution control technologies (including ACI) on future risks.

Summary

A summary of the different uncertainties associated with the CCR WMU database, as well as the potential for each to affect the risks modeled in the probabilistic analysis is shown in **Table 5-9**. The majority of uncertainties identified are unlikely to have an appreciable impact on the principal risk results. However, the sensitivity analyses conducted for specific liner types and specific waste pH identified subsets of disposal practices that result in appreciably higher risks than identified in the full probabilistic modeling.

Table 5-9. Likely Effect on Modeled Risks from CCR WMU Database Uncertainties

Uncertainty	Potential to Affect Probabilistic Analysis Results		
	Uncertain	Low	High
Geographic Location Data		●	
WMU Dimension Data		●	
Liner Data		●	
Liner Assignment		●	
Liner Prevalence			●
Impoundment Waste Type Assignment		●	
Landfill Waste Type Assignment			
Waste Type Prevalence			●
Exclusion of FBC Waste Type		●	
Below-Grade Geometry		●	
Pollution Control Technology		●	

5.1.2 Environmental Parameters

This risk assessment characterized the environmental conditions that may influence the fate and transport of constituents in the environment using region-specific data collected around each WMU or facility, based on the availability of geographic data. As discussed in **Section 5.1.1** above, some uncertainty exists with respect to the locations of WMUs which were derived from the 2009 EIA facility centroids. This section discusses how the variability and uncertainty associated with each location-based parameter were addressed.

Soil Data

For soil data, variability was accounted for through a probabilistic sampling of all soil types that fall within the WMU footprint (where available) or a two-kilometer radius around the facility centroid. The soil types were drawn from national databases that provide a regional resolution for these soil types. The use of these soil data sets have been thoroughly peer-reviewed and documented as part of the development and implementation of EPACMTP (see **Section 5.1.9**). In

instances where the exact location of a WMU was not known, EPA addressed this uncertainty by collecting information on the different soil types present within a two kilometer radius around the centroid of the facility. The different soil types were sampled probabilistically during each model iteration based on relative prevalence at a given WMU. This approach effectively captures regional variability. Even though soil properties can be highly variable, the regional averaging of these parameters is believed to provide a good resolution for the transport distances considered in the probabilistic analysis. Therefore, the uncertainty introduced by the use of these data is believed to be minimal.

Aquifer Data

EPA assessed risks that result from contamination of surficial aquifers. For each WMU, the hydrogeologic environment of the surficial aquifer was assigned based on the geology and soil megatextures identified beneath the WMUs (see **Appendix B**). In instances where the exact location of a WMU was not known, EPA addressed this uncertainty by collecting information on the different hydrogeologic environments present within a two kilometer radius around the centroid of the facility. These environments were sampled probabilistically based on relative prevalence at a given WMU during each model iteration. The EPACMTP parameters with the largest impact on results are aquifer hydraulic conductivity and gradient. These parameters were selected from a database that contains regional aquifer properties across the conterminous United States. Even though aquifer properties can be highly variable, these regional data are believed to provide a good resolution for the transport distances considered in the probabilistic analysis. Therefore, the uncertainty introduced by the use of these data is believed to be minimal.

Ground Water Flow Direction and Water Body Selection

EPA used a raindrop tool to identify the nearest surface water body and to assign a ground water flow direction and distance (see **Appendix B**). The raindrop tool estimates the direction of overland run-off based on topographic elevations and is therefore an indirect representation of ground water flow. EPA received multiple public comments on the Agency's use of the tool, pointing to site-specific factors that may lead to alternate ground water flow directions, including:

- Localized ground water mounding;
- Ground water flow parallel to the surface water body;
- Water bodies that lose water to underlying aquifers for some or all of the year;
- Seasonal variations in the water table height and flow directions; and
- Anthropogenic influences, such as nearby ground water pumping.

EPA agrees that the direction of ground water flow can differ from the direction of the surface topographic gradient. However, without external stresses (e.g., pumping) or unique hydrogeologic conditions, ground water flow directions will generally mimic surface topographic gradients. Accurate characterization of ground water flow conditions at specific WMUs would require extensive site-specific spatial and temporal hydrogeologic data collection and analysis. Such effort was not feasible in support of this annualized, national-scale analysis. The method adopted by the

Agency incorporated potential variability by allowing multiple transport pathways from each WMU with multiple nearby surface water bodies potentially receiving ground water (e.g., if the WMU was surrounded by more than one water body). In this way, a range of potential transport distances and receiving water bodies for each WMU were incorporated into the probabilistic analysis. The assumption of a straight-line ground water flow direction may overestimate risks in some model iterations due to the decreased sorption and dispersion from shorter than actual transport distances. However, the approach may also underestimate risks for other model iterations if the actual flow of ground water to surface water is more direct than suggested by topographic gradients. Overall, this uncertainty is anticipated to have a minimal effect on calculated risks. For GW→DW pathways, a stream that fully intercepts ground water will do so regardless of the exact distance from the WMU, resulting in a negligible well concentration. The high-end ground water risks for these pathways will be driven by model iterations where no surface water interception occurs. For GW→SW pathways, many plants are located very close to the water body due to the use of water in facility operations. The high-end surface water risks for these pathways will be driven by the WMUs directly adjacent to the water bodies, and any variations in the already short transport distances will have minimal impact on modeled risks.

Water Body Flow Rate

One of the most sensitive parameters identified for the GW→SW pathways was the surface water flow rate. In this risk assessment, EPA used average annual flow rates to estimate surface water risks. These rates are considerably higher than the low flow rates used in the 2010 Risk Assessment. Public commenters pointed out that average annual flows may not represent the typical flow of a water body because of lower median and low flow rate conditions that occur over most of the year. One specific example provided by commenters is Lick Creek in Indiana. **Table 5-10** presents the flow rate data provided by the commenters for this water body.

Table 5-10. Example Flow Rate Data for Lick Creek, Indiana

Annual Flow Rates			Ratios	
Average Annual	Median	Low	Average / Median	Average / Low
21 ft^3/s	7 ft^3/s	< 1 ft^3/s	3	> 20

As seen in the table above, the average flow rate is three times higher than the median flow rate, and over twenty times higher than the low flow rate. For this water body, and similarly behaving ones, the use of an average annual flow represents a stage of the river that occurs less than half of the year. Thus, use of an annual average value could overestimate the volume of water present in the water body and, consequently, the dilution of ground water concentrations entering the water body at certain times throughout the year. However, both EPACMTP and the surface water model used in this risk assessment consider fate and transport in yearly time steps. Therefore, EPA considered how best to reflect seasonal fluctuations when developing annualized inputs for these models.

Ground water and surface water are interconnected. Just as the surface water flow rates vary throughout the year, hydraulic gradients are also subject to change in response to precipitation rates, among other factors (Sophocleous, 2002). Precipitation rates, ground water flow, and many other annual variables used in this risk assessment may all vary seasonally. Thus, varying one (i.e., surface water flow rates) but not the others would not capture actual interactions. Periods of naturally low ground water (e.g., drought) that also lead to low flow rates would be accompanied by decreased flux from the ground water to surface water, or could even transition to a net losing water body, as shown in **Figure 5-2**. Thus, while the use of average annual flow rates may overstate the volume of water passing through a water body for some portion of the year, this is the most appropriate flow rate in light of the annual increments used for all other variables.

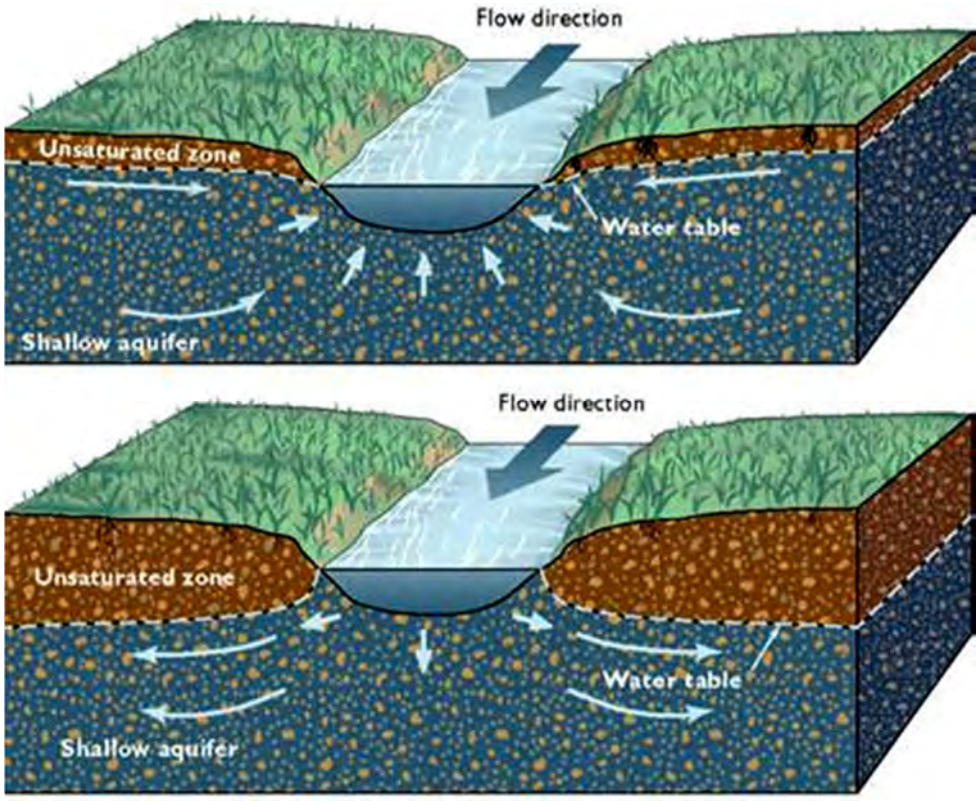

Figure 5-2. Interaction of ground water and surface water flow [reproduced from Winter et al., 1998).

Climate Data Selection

Climate regions were developed for this risk assessment to represent climate patterns within specified geographic regions. Data were collected for each WMU from the closest climate data center within each region that best matched the precipitation reported at that facility location. To the extent that actual climate data (e.g., precipitation rates) from a climate data center does not reflect the conditions at a specific WMU location, there is the potential to either overestimate or underestimate climate data on an annual basis. However, because EPA matched each unit with the most representative center, the potential effect of this uncertainty on modeled risks is likely to be small.

Climate Change

The climate data used in this risk assessment was collected for a period from 1961 through 1990. Therefore, some uncertainty is introduced because any potential effects from climate change that have occurred since 1990 are not reflected in this data set. The National Climate Assessment Report documents region-specific changes in rainfall, temperature and episodic rainfall events over recent decades (Melillo et al., 2014). This may result in an increase or decrease in risk on a case-by-case basis. The potential effect of this uncertainty on modeled risks is unknown.

Distance to Nearest Ground Water Receptor

EPA used a probability distribution to characterize the distance to nearest ground water receptor for surface impoundments created from combining U.S. Census data with the locations of a total of 729 impoundments drawn from the 2009 EPA survey. This distribution was compiled and incorporated into the analysis before data on an additional 223 impoundments from the 2010 EPA survey were processed and available for use. Much of the data on the additional surface impoundments were incorporated into the probabilistic analysis through further model iterations; however, due to the time intensive nature of the process to link receptor and WMU location, the distribution of distances to nearest receptor was not updated at that time. To characterize the uncertainty associated with the use of a distribution based on a subset of 729 surface impoundments, EPA later generated a revised probability distribution based on all 952 surface impoundments. **Figure 5-3** compares this combined nearest-receptor distribution with both the distribution used for modeling, as well as the distribution utilized in the 2010 Risk Assessment, which was based on receptor distances from municipal solid waste landfills.

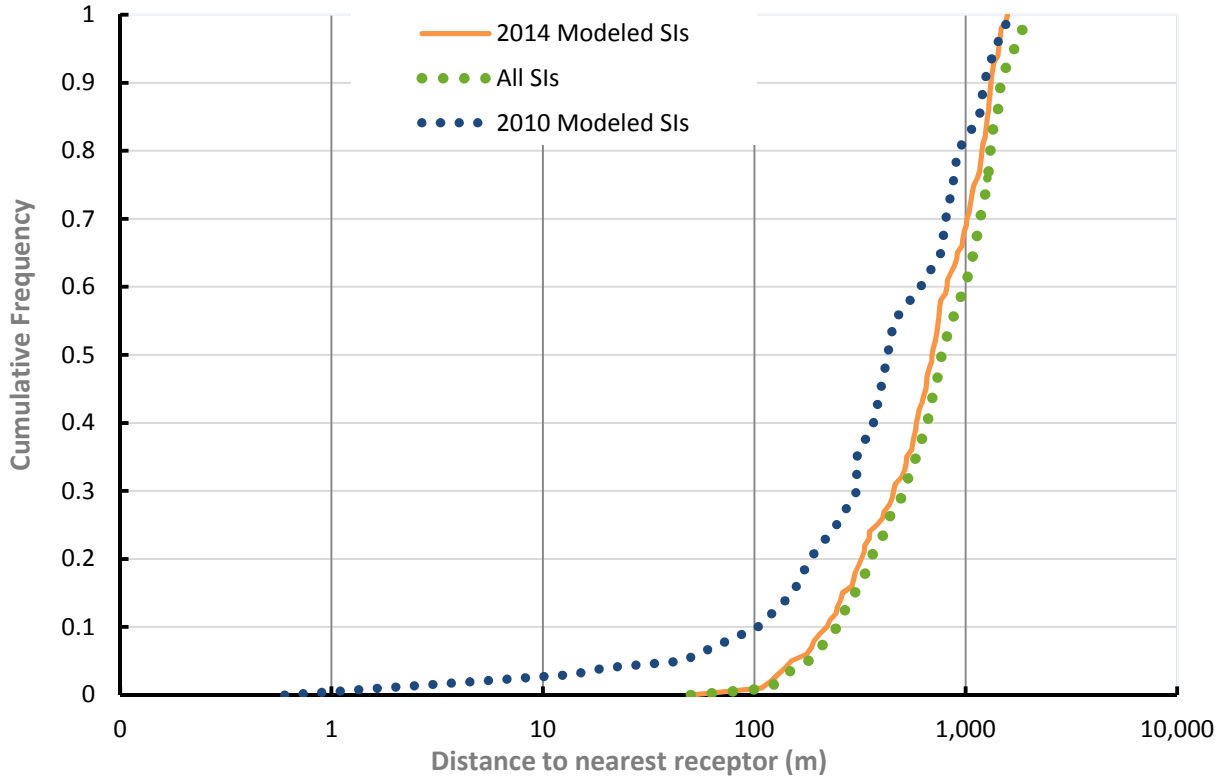

Figure 5-3. Distance to nearest ground water receptor distribution among data sets.

As seen in the figure above, the combined surface impoundment data set results in slightly greater distances to ground water receptors. It also shows that the distribution for 729 impoundments used in the revised risk assessment is far more similar to the distribution of all 952 impoundments than to the distances used previously in the 2010 Risk Assessment. Given the small difference between the distributions for the 729 and all 952 surface impoundments, the potential impact of this uncertainty on the modeled risks is negligible.

Summary

A summary of the different uncertainties associated with environmental parameter data, as well as the potential for each to affect the risks modeled in the probabilistic analysis is shown in **Table 5-11**. The majority of uncertainties identified are unlikely to have an appreciable impact on the principal risk results. EPA was not able to characterize the potential magnitude or direction of the uncertainties associated with climate change. The Agency relied on the best data available at the time of the analysis; however, the potential of these uncertainties to overestimate or underestimate risk results is uncertain.

Table 5-11. Likely Effect on Risk from Environmental Parameter Uncertainties

Uncertainty	Potential to Affect Probabilistic Analysis Results		
	Uncertain	Low	High
Soil Data		●	
Aquifer Data		●	
Ground Water Flow Direction & Water Body Selection		●	
Water Body Flow Rate		●	
Climate Data Selection		●	
Climate Change	●		
Distance to Nearest Residential Receptor		●	

5.1.3 CCR Constituent Database

Where possible, EPA used government sources and peer-reviewed primary literature for input data. EPA also preferentially used sources where the test methods and quality assurance/quality control protocols were well documented. Although additional data were made available through public comments received since the 2010 proposed rulemaking, there are relatively few data points available for some constituents (e.g., mercury). As a result, there is some uncertainty regarding how well these data reflect the range of CCR waste types.

Representativeness

Pore water data were determined to be the most representative data available for impoundments because these data are field-measured concentrations of leachate present at the bottom of these WMUs. In instances where the risks identified for surface impoundments are based on a limited

data set, uncertainty exists with respect to the representativeness of the results. Of the modeled constituents found to be near or above risk criteria, thallium was the single one with a limited data set. Thallium had a total of 38 pore water samples from 14 distinct sample sites. In contrast, arsenic, boron, cadmium, fluoride, molybdenum and selenium had a much greater number of measurements (~ 200) from a greater number of sample sites (~ 30). While the more limited data set for thallium adds some uncertainty for this one constituent, it will not impact the principal results of the probabilistic analysis based on other risk drivers with more robust data sets.

Nondetects

The CCR constituent database contains a large number of nondetect data for some constituents. For each of these data points, EPA substituted half the reported detection limit. Because the evaluation relied on a value halfway between zero and the detection limit, the true value is equally likely to be higher or lower than the value assigned. Typically, the upper percentile risks calculated in the probabilistic assessment are associated with higher, detectable, concentrations rather than nondetects. Unless nondetect data account for a high percentage of the total data set or the detected values fall near the detection limit, the specific treatment of nondetect values has little effect on the upper percentile risks relied upon in this risk assessment.

Table 5-12 lists the constituents for which 50 percent or more of site data for impoundment wastewater were nondetects. These constituents are beryllium, lead, iron and silver. Beryllium is the only constituent that both failed the screening and has a high percentage of sites with nondetects (73 percent). All other constituents that failed the screening for this exposure pathway have nondetect percentages less than 25 percent. This introduces considerable uncertainty for beryllium. However, given the risks identified for multiple other constituents with well-defined data, these uncertainties do not change the ultimate conclusions that direct contact with impoundment wastewater has the potential to pose risk to ecological receptors.

Table 5-12. Review of Nondetects for Impoundment Wastewater

Constituent	Individual Nondetect Measurements		Sample Sites with All Nondetects	
	Total Count	Percent	Total Count	Percent
Silver	26	100%	11	100%
Beryllium	26	81%	11	73%
Iron	26	58%	11	64%
Lead	26	69%	11	55%

Table 5-13 lists the constituents for which 50 percent or more of site data for impoundment pore water were nondetects. These constituents are beryllium, chromium and silver. None of these constituents were found near risk criteria in the full probabilistic analysis; however, chromium did fall above a risk of 1×10^{-5} in the sensitivity analysis for waste types for both ash and coal waste (3×10^{-5}) and FGD waste (4×10^{-5}). Therefore, there is the potential for somewhat higher risks associated with chromium risks. However, because high-end risks are likely associated with the

50 percent of higher, detected chromium concentrations, any increase is likely to be small. Of the constituents that posed risks in the full probabilistic analysis, arsenic and molybdenum have nondetect percentages of 19% and 36%, respectively. These relatively low nondetect percentages result in low uncertainty for these results. Therefore, the uncertainties associated with pore water are unlikely to change the ultimate conclusions that ingestion of ground water has the potential to pose risk to human receptors.

Table 5-13. Review of Nondetects for Impoundment Pore Water

Constituent	Individual Nondetect Measurements		Sample Sites with All Nondetects	
	Total Count	Percent	Total Count	Percent
Beryllium	38	97%	14	93%
Silver	76	95%	20	85%
Chromium	194	71%	30	50%

Table 5-14 lists the constituents for which 50 percent or more of site data for whole waste were nondetects. These constituents are nitrate, thallium and uranium. Thallium was the single constituent that failed the uncontrolled soil exposures for human health screening based on whole waste concentration; however, all risks fell below criteria based on consideration of dust and run-off controls. Because high-end risks are likely associated with the 45 percent of higher, detected thallium concentrations, any increase is likely to be small. Thus, the treatment of nondetects does not add significant uncertainty to these data.

Table 5-14. Review of Nondetects for Whole Waste

Constituent	Individual Nondetect Measurements		Sample Sites with All Nondetects	
	Total Count	Percent	Total Count	Percent
Nitrate	2	100%	2	100%
Uranium	9	100%	1	100%
Thallium	55	55%	18	50%

The LEAF data used in this analysis originated from CCR concentration data collected from CCR management operations that were selected to represent the range of coal-fired power plants, control technologies, and coal types in current use across the United States (U.S. EPA, 2009a). U.S. EPA (2006a, 2008b and 2009a) all contained data with low detection limits. Thus, for landfill leachate, nondetect percentages were very low (less than 1%) for most constituents, and still low for mercury (25%). Thus, the treatment of nondetects does not add significant uncertainty to these data.

Site Quartiles

This risk assessment divided pore water and whole waste constituent concentration data into quartiles (i.e., 25th, 50th, 75th) for each sample site and waste type. Compared to the site averages used in the 2010 Risk Assessment, this approach better captures the variability at each sample site. **Table 5-15** below shows the 2010 site averaged pore water distribution and 2014 site quartile

distributions for arsenic. The ash waste type used previously in the 2010 Risk Assessment was separated into the combined ash waste type and the FGD waste type.

Table 5-15. Comparison of Arsenic Pore Water Concentrations Resulting from Data Processing: 2010 Averages versus 2014 Quartiles

Waste Type Name	Year	Data Treatment	Arsenic Pore Water Concentration Percentile (mg/L)				
			25th	50th	75th	90th	95th
Conventional Ash	2010	Average	0.02	0.07	0.29	1.0	1.3
Combined Ash	2014	Quartile	0.04	0.07	0.16	0.26	0.49
FGD Waste	2014	Quartile	0.02	0.21	0.80	2.86	6.41
Codisposed Ash	2010	Average	0.02	0.02	0.12	0.63	0.63
Ash & Coal Refuse	2014	Quartile	0.01	0.18	0.53	3.41	7.85

In general, the median and low-end concentrations changed very little as a result of the use of quartiles. Decreases in the combined ash arsenic concentrations in high-end percentiles are attributed to the separation of FGD waste data. The considerable increase ash and coal refuse arsenic concentrations in high-end percentiles is attributed to better characterization of intra-site variability. While some uncertainty remains because the quartile approach does not fully capture extreme values at some sites, these individual samples are reflected in the quartiles without assigning an undue weight to what may be an outlier within the larger site by using an empirical distribution. Because the use of quartiles provides much better resolution on the variability of pore water concentrations, EPA believes the uncertainty associated with this approach is minimal.

Summary

A summary of the different uncertainties associated with constituent data, as well as the potential for each to affect the risks modeled in the probabilistic analysis is shown in **Table 5-16**. The uncertainties identified are unlikely to have an appreciable impact on the principal risk results.

Table 5-16. Likely Effect on Risk from Constituent Data Uncertainties

Uncertainty	Potential to Affect Probabilistic Analysis Results		
	Unknown	Low	High
Representativeness		●	
Nondetect Data		●	
Site Quartiles		●	

5.1.4 Human Exposure Factors

This risk assessment relied on the 1997 *EFH* (U.S. EPA, 1997b,c,d) and the 2008 *CSEFH* (U.S. EPA, 2008a) for information on human exposure factors for the U.S. population. EPA's evaluation criteria included peer-review status, reproducibility, pertinence to the United States, currency, adequacy of the data collection period, validity of the approach, representativeness of the

population, characterization of the variability, lack of bias in study design, and measurement error. The data contained in these documents were used throughout this risk assessment to establish distributions for each exposure parameter and receptor. Both documents have undergone extensive external peer review.

2011 Exposure Factor Updates

The 2011 *Exposure Factors Handbook* (U.S. EPA, 2011b) has been completed and updates some of the data from the 1997 EFH. During the finalization of this risk assessment, EPA released OSWER Directive 9200.1-120 (U.S. EPA, 2014c). While this document provides default exposure factors to use for point estimates, EPA is still in the process of updating the full distributions necessary for probabilistic risk assessment. Therefore, this risk assessment does not incorporate the data from the 2011 EFH. The adult water consumption rates provided in the U.S. EPA (2011b) are somewhat lower than those found in the 1997 *EFH*, while adult body weights are somewhat higher. All other exposure factors used in the CCR risk assessment remained the same between the 1997 and 2011 Handbooks. As a result, risks for the drinking water ingestion and fish ingestion pathways may be slightly overestimated.

Drinking Water Ingestion Rate

Drinking water ingestion rate data for infants that consume formula (birth to < 1 month, 1 to < 3 months, 3 to < 6 months, and 6 to < 12 months) are available from the *CSEFH* (U.S. EPA, 2008a). As drinking water concentrations are provided by the model as annual averages, the consumption rate data were averaged to estimate a full year of exposure. The distribution of infant drinking water ingestion rates used in this analysis reflects sampling from percentiles averaged across all infant age ranges. The sample size associated with each age range was used to calculate a weighted average for each percentile. The data were weighted by sample size because the small sample sizes did not meet minimum requirements as described in the *Third Report on Nutrition Monitoring in the United States* (Life Sciences Research Office, 1995) for percentiles in several subcohorts. The resulting average percentiles were sampled to develop the infant drinking water distribution. As noted by the CSEFH, some of the reported sample sizes did not meet minimum requirements. These small sample sizes for certain infant subcohorts introduce some amount of uncertainty to the modeled risk results. Because infants were found to be the most sensitive age cohort for some exposure pathways, EPA conducted a sensitivity analysis comparing the drinking water risks for the infant cohort with those for other age cohorts to determine the potential magnitude of this uncertainty. **Table 5-17** provides the results of this comparison for each constituent that was modeled in the probabilistic analysis and that was above risk criteria in this sensitivity analysis for one or more age cohorts. Arsenic V risks are provided even where below criteria to provide a complete bounding on arsenic speciation. Values that exceed the risk criteria (i.e., cancer risk > $1x10^{-5}$ or HQ > 1) are shown in **bold**.

Table 5-17. 90th Percentile Human Health Risk Results for Surface Impoundment GW→DW Pathway by Age Cohort

COPC	Age Cohorts							
	Infant	1 to < 2	2 to < 3	3 to < 6	6 to < 11	11 to < 16	16 to < 21	Adult
Cancer								
Arsenic III	**1×10^{-4}**	**1×10^{-4}**	**9×10^{-5}**	**8×10^{-5}**	**8×10^{-5}**	**8×10^{-5}**	**8×10^{-5}**	**2×10^{-4}**
Arsenic V	1×10^{-5}	7×10^{-6}	7×10^{-6}	6×10^{-6}	6×10^{-6}	6×10^{-6}	6×10^{-6}	1×10^{-5}
Noncancer								
Arsenic III	**5**	**3**	**3**	**3**	**2**	**2**	**2**	**3**
Arsenic V	0.4	0.2	0.2	0.2	0.2	0.1	0.1	0.2
Lithium	**2**	1	1	1	1	0.8	0.9	1
Molybdenum	**2**	1	1	1	0.8	0.7	0.8	1

As seen in the table above, the infant cancer risks for arsenic are slightly less than the adult cancer risks. Because infants were not the most sensitive receptors for these exposures, the magnitude of uncertainty introduced by the small sample sizes of the infant exposure factors is minimal. Infants are the most sensitive receptor for noncancer risks. However, the infant risk estimates are no more than a factor of two higher than the values modeled for other cohorts. In addition, exceedances of the arsenic risk criteria were identified for all age cohorts. Because the infant exposures are not the most sensitive age group for cancer risks and noncancer risks do no differ substantially across age groups, any uncertainty associated with the infant drinking water ingestions rates will have minimal impact on the final conclusions of the risk assessment.

Human Fish Consumption

Data on site-specific fish consumption rates were not available for use in this analysis. Instead, fish consumption rates were drawn from a study of Maine anglers that fished from streams, rivers, and ponds. This study was one of four recommended freshwater angler studies in the 1997 *Exposure Factors Handbook*. This evaluation selected the Maine data based on the completeness of the data set and because it agrees most closely with a separate U.S. Department of Agriculture (USDA) study of national fish consumption (USDA, 1992). However, applying Maine angler consumption rates to other parts of the country may under- or overestimate exposures on a case-by-case basis. For example, subsistence fishers were not evaluated, as the wide variety of possible consumption rates makes evaluation more appropriate at a site-specific level, rather than the national assessment conducted here. Additionally, data were available only for adult anglers. Because age-specific data for children were not available, all child cohorts were assumed to consume the same amount of fish as the adult cohort. This issue introduces uncertainty into the analysis, and likely results in an overestimate of risks from fish consumption among child cohorts. Furthermore, all fish consumed by both adult and child receptors is assumed to be contaminated. This assumption will also overestimate risks from contaminated fish consumption. The magnitude

of these overestimations are unknown; however, given that all risks associated with the fish ingestion pathway fell at least an order of magnitude below risk criteria, the potential for this overestimation to alter the conclusions of the probabilistic analysis is negligible.

Bioavailability

A host of different environmental factors such as the pH, particle size, moisture, and redox potential of the environment influence bioavailability. The individual receptor's age, sex, nutritional state, and physiological state also affect bioavailability (U.S. EPA, 2007a). For the purposes of this analysis, the model conservatively assumed that all forms of a constituent were equally bioavailable. For example, although U.S. EPA (2012b) recommends the use of a default bioavailability rate of 60 percent for arsenic in soils, EPA assumed 100 percent bioavailability in this risk assessment. Therefore, the actual exposures that may occur in the field will tend to be overestimated, making this a high-end assumption that will tend to overestimate risk. That magnitude of these overestimations are unknown; however, given that all risks associated with the soil, produce, beef, and milk ingestion screened out under a controlled management scenario, the potential for this overestimation to alter the conclusions of the probabilistic analysis is negligible.

Noncorrelation of Exposure Factors

While exposure factors were selected for specific age groups, the distributions for each exposure factor were not correlated with each other within each of these age groups. Instead, for each modeling run, each exposure factor was selected from its age-group-based distribution independently. Insufficient data are currently available to correlate these variables. This introduces some uncertainty into the evaluation because some combinations of exposure factors, such as a high fish consumption rate combined with small body weight, while possible, are unlikely. Therefore, this remains an uncertainty in the analysis that may under- or overestimate exposures for individual model iterations. The magnitude and direction of this uncertainty are unknown.

Consumption of Wildlife/Game

Neither the screening analysis nor the full-scale CCR risk assessment considered ingestion of game, which may pose non-negligible risks if humans consume wildlife contaminated by CCR constituents. Results of the screening analysis (**Section 3.5.2**) of the revised risk assessment show that consumption of contaminated beef and dairy from cows that consume contaminated soil and produce grown in contaminated soil may pose risks to human health for thallium. **Table 5-18** provides a comparison of the per capita intake rates for beef, dairy and game.

Table 5-18. Comparison of Per Capita Beef, Dairy & Wild Game Consumption Rates

Food	Percent of Population	Percentile (g/kg-day)								
		1st	5th	10th	25th	50th	75th	90th	95th	99th
Beef	91%	0	0	0.06	0.27	0.63	1.2	1.8	2.3	3.5
Dairy	97%	0	0.16	0.40	1.4	3.6	8.2	18.7	29.7	72.2
Game	1.2%	0	0	0	0	0	0	0	0	0.1

Rounded values drawn from EFH (U.S. EPA, 1997c) Tables 11-2, 11-3, and 11-6

Although EPA did not collect biotransfer factors for deer and other game, the following considerations make this pathway less of a concern than the beef and dairy pathways evaluated. First, only 1.2 percent of the population consumes game species. Second, the table also shows that the consumption rates for game species are typically orders of magnitude below the consumption rates of beef and dairy. Finally, beef and dairy cattle are assumed to get 100 percent of their diet from contaminated soil, forage, silage, and grains, whereas game species would forage throughout their natural habitat range, with direct ingestion of CCRs the only exposure pathway available. Thus, EPA does not consider the exclusion of this pathway to be a significant uncertainty nationally.

Summary

A summary of the different uncertainties associated with human exposure factors, as well as the potential for each to affect the risks modeled in the probabilistic analysis is shown in **Table 5-19**. The majority of uncertainties identified are unlikely to have an appreciable impact on the principal risk results. EPA was not able to characterize the potential magnitude or direction of the uncertainties associated with the correlation of exposure factors. The Agency relied on the best data available at the time of the analysis; however, the potential of these uncertainties to overestimate or underestimate risk results is uncertain.

Table 5-19. Likely Effect on Risk from Human Exposure Factor Uncertainties

Uncertainty	Potential to Affect Probabilistic Analysis Results		
	Uncertain	Low	High
2011 Exposure Factor Updates		●	
Drinking Water Ingestion Rate		●	
Human Fish Consumption		●	
Bioavailability		●	
Noncorrelation of Exposure Factors	●		
Consumption of Wildlife/Game		●	

5.1.5 Human Health and Ecological Benchmarks

Use of Chronic Human Health Benchmarks for Less Than Lifetime Exposures

The uncertainties generally associated with human health benchmarks are discussed in detail in EPA's *Guidelines for Carcinogen Risk Assessment* (U.S. EPA, 2005) and the IRIS website (U.S. EPA, 2012a). EPA defines the RfD as "an estimate of a daily exposure to the human population (including sensitive subgroups) that is likely to be without appreciable risk of deleterious effects during a lifetime." The CSF is an upperbound estimate of the human cancer risk per mg of chemical per kg body weight per day. Because calculated exposures were often less than lifetime, some uncertainty was introduced in the noncancer hazard and cancer risk estimates, though the magnitude and direction of this uncertainty is unknown.

Use of MCL for Lead

For lead, EPA has no consensus on the development of an RfD or CSFo because of the difficulty associated with identifying an effect threshold needed to develop these benchmarks. Therefore, the MCL for drinking water was used as an alternative method of approximating human health risk. To ensure that risks were not underestimated, EPA separately considered lead exposures with the Integrated Exposure and Uptake Biokinetic (IEUBK) model (U.S. EPA, 2010b) to predict blood lead levels that may result from CCR disposal. The conservative exposure concentrations developed in **Section 3** for soil, fish, and drinking water were used to evaluate lead through separate IEUBK model runs. The methodology and default parameters EPA used are described in detail in the IEUBK *User's Guide* (U.S. EPA, 2007b). With the exception of drinking water, the estimated screening blood levels were below the current CDC target blood level of 5 μg/dL. However, lead was already retained for the GW→DW pathway because screening lead concentrations exceeded the MCL. The national-scale probabilistic modeling conducted in **Section 4** showed that lead concentrations fell several orders of magnitude below risk criteria based on the MCL. Thus, consideration of a lower blood lead level with IEUBK may have resulted in somewhat higher risks, these results would not have changed the findings of the risk assessment for this constituent.

Use of Proxy Benchmarks

Chemical-specific health benchmarks were used for all constituents assessed in the analyses. However, the RfD for fluoride was based on fluorine and the RfD for thallium was based on thallium chloride. The use of these surrogate data provides the best estimate of potential risks available, but may over- or underestimate risks to an unknown degree. However, because risks were identified for other constituents, this uncertainty is unlikely to affect the final conclusions of the risk assessment.

Ecological Benchmarks

Ecological benchmarks were obtained for CCR constituents when available and compared with the modeled media concentrations (e.g., surface water, sediment) to estimate the HQs used to characterize ecological risk. These benchmarks represent the best available estimates of receptor responses based "no effects" (NOAEL) or "lowest effects" (LOAEL) study data. In some scenarios, these benchmarks may be represent species not actually present in the field. In others, these benchmarks may not capture the most sensitive possible receptor at every site or for each constituent. While some benchmarks have factors of safety included to account for these or other uncertainties, there remains is the potential for the ecological benchmarks used to underestimate risks for the specific species and communities that live in surface waters impacted by CCR WMUs. The magnitude of this uncertainty is unknown. Consideration of any additional sensitive species not captured by the current benchmarks may result in some additional constituents above risk criteria in the probabilistic analysis. EPA notes that these some of these ecological risks are reflected in damage cases. However, this site-specific uncertainty is unlikely to affect the final, national conclusions of the risk assessment.

Constituents with No Benchmarks

Constituents with no human health or ecological benchmarks could not be quantitatively evaluated in either the screening or full-scale modeling. Only three constituents (carbon, phosphate and potassium) for which constituent data were available did not have corresponding toxicity values for any pathway. However, most of these constituents are known to be essential human nutrients that are likely to be harmful only at very high doses. Other constituents have toxicity values available for some, but not all, exposure pathways evaluated. In these cases, the potential risks to receptors in these media could not be quantified. In particular, ecological benchmarks for chronic effects on amphibians are not available for many constituents. The absence of a toxicity value is not necessarily equivalent to the absence of risk. These constituents may pose pathway-specific risks or may influence either the fate and transport or toxicity of another constituent, resulting in an underestimation of rusk. The magnitude of this underestimation is unknown. However, because risks were identified for the available benchmarks, it is unlikely that this uncertainty would affect the final conclusions of the risk assessment.

Summary

A summary of the different uncertainties associated with toxicity benchmarks, as well as the potential for each to affect the risks modeled in the probabilistic analysis is shown in **Table 5-20**. The majority of uncertainties identified are unlikely to have an appreciable impact on the principal risk results. EPA was not able to characterize the potential magnitude or direction of the uncertainties associated with the use of chronic benchmarks for less than lifetime exposures and the use of proxy benchmarks. The Agency relied on the best data available at the time of the analysis; however, the potential of these uncertainties to overestimate or underestimate risk results is uncertain.

Table 5-20. Likely Effect on Modeled Risk from Human Health and Ecological Benchmark Uncertainties

Uncertainty	Potential to Affect Probabilistic Analysis Results		
	Uncertain	Low	High
Use of Chronic Human Health Benchmarks for Less Than Lifetime Exposures	●		
Use of MCL for Lead		●	
Use of Proxy Human Health Benchmarks		●	
Ecological Benchmarks		●	
Constituents with No Benchmarks		●	

5.1.6 Bioconcentration Factors

Human exposures to constituents from fish consumption were calculated using BCFs for TL3 and TL4 freshwater fish to estimate the accumulation of constituents from surrounding environmental media into fish tissue. **Appendix G** lists the BCFs used in this risk assessment, as well as the literature sources from which they were drawn. BCFs are developed by dividing measured constituent concentrations in aquatic biota by total surface water constituent concentrations. In the

revised risk assessment, the evaluation only used BCFs empirically measured from laboratory or field studies of TL3 and TL4 fish, rather than values estimated from physical or chemical properties [e.g., octanol-water partition coefficient (K_{ow})]. There are several sources of uncertainty associated with the models used to estimate BCFs for aquatic biota:

- Error may originate from the relatively short exposure timeframe used in a study compared to lifetime exposure (Arnot and Gobas, 2006; and CalEPA, 2012);
- Laboratory-prepared water may have constant and unrealistically high concentrations (Arnot and Gobas, 2006; and CalEPA, 2012);
- Radiolabeled compounds may be used without adequate correction for the parent signal (Arnot and Gobas, 2006; and CalEPA, 2012);
- Imprecise analytical methods may be used to analyze samples (Arnot and Gobas, 2006; and CalEPA, 2012);
- BCFs may be based on whole-body concentrations for fish which include organs and muscle tissues, rather than just the edible portion of the fish (du Preez et al., 1993);
- BCFs may be measured from juvenile fish, whereas metal concentrations in tissues decrease as fish size or weight increases (Liao et al., 2003, as cited by CalEPA, 2012);
- BCFs are based only on concentrations in environmental media, whereas consumption of sediment-dwelling invertebrates by bottom-dwelling fish species may also contribute to metal uptake by these fish (CalEPA, 2012); and
- BCFs may be collected for a particular species of fish that may or may not be present at the sites modeled in this risk assessment.

Significantly more research has been conducted for mercury than for other constituents. This mercury-specific data allowed EPA to address some of the concerns above (e.g., consumption of sediment-dwelling invertebrates) through the use of a bioaccumulation factor for methylmercury that takes into account accumulation in the entire food chain rather than just the water column. However, for the reasons stated above, reliance on BCFs to estimate fish exposure may overestimate or underestimate the actual accumulation of inorganics in fish tissue.

Summary

A summary of the different uncertainties associated with bioconcentration, as well as the potential for each to affect the risks modeled in the probabilistic analysis is shown in **Table 5-21**. EPA was not able to characterize the potential magnitude or direction of the uncertainties associated with the use of bioconcentration factors. The Agency relied on the best data available at the time of the analysis; however, the potential of these uncertainties to overestimate or underestimate risk results is uncertain.

Table 5-21. Likely Effect on Modeled Risk from Toxicity Benchmark Uncertainties

Uncertainty	Likely Effect on Risk		
	Uncertain	Low	High
Bioconcentration Factor	•		

5.1.7 WMU Source Term Models

Scaling of Washout Constituent Concentrations

Leaching profiles of washout phase constituents are characterized by an initial high-concentration pulse of 20 times the Method 1313 equilibrium concentration followed by a lower concentration pulse that continues until the leachable content is depleted. The use of a factor of 20 is supported by field data, as seen in U.S. EPA (2014b). However, in some cases, preferential flow or other considerations may result in concentrations only 10 times the Method 1313 equilibrium concentration. Therefore, this is unlikely to result in a significant uncertainty to the analysis.

Constant Leachate Concentrations

The nonlinear fate and transport solution used for inorganic constituents in the unsaturated zone module of EPACMTP requires constituent concentrations leached from the bottom of WMUs to remain constant for the entire duration of leaching (U.S. EPA, 2003b). However, empirical evidence reported in U.S. EPA (2009a) indicates that constituents can exhibit a leaching profile that changes over time. EPA conducted a sensitivity analysis to estimate the potential magnitude of error introduced by modeling a single, high-concentration pulse for washout constituents. This analysis, presented in **Appendix I**, found that there was a negligible (< 1 percent) difference in the peak time-averaged drinking water concentrations using a single, high-concentration pulse until depletion, or two pulses representing a high concentration followed by a low-concentration pulse until depletion. Although a leaching profile that changes over time may be more realistic, the simplified leaching profile used by the model provides very good approximations for peak ground water concentrations overall, and thus has a minimal effect on the risk results.

Surface Impoundment Leaching Duration

Leaching from surface impoundments was modeled based on the assumption that these units are periodically dredged during operation, resulting in a constant source that is continuously replenished. To reflect this assumption, the leachable mass was set equal to the total constituent mass in EPACMTP. This indirectly accounted for the constant source because an operating time of 75 years for impoundments is not enough to deplete the entire constituent mass present in CCR waste. After this timeframe, the model assumed clean closure of impoundments. EPA received public comments that indicated this approach is not consistent with the current practice of closing with wastes in place at some surface impoundments.

EPA considered the potential impact of postclosure releases through a sensitivity analysis (see **Appendix K**). This sensitivity analysis modeled closed surface impoundments equivalent to closed landfills, with the full constituent mass still available to leach without replacement. The results of this comparison show that releases from surface impoundments drop dramatically after

closure, even with waste in place. This is because the large hydraulic head present during operation forces leachate into the underlying soils at a faster rate, resulting in higher releases to ground water than can occur postclosure. Based on these findings, EPA concluded that the assumption of clean closure has a negligible effect on modeled risks.

Landfill Leachable Content

It is likely that there may be some insoluble or otherwise unleachable constituent mass that remains bound within any waste. To account for the presence of this recalcitrant fraction, EPA used empirically derived estimates of the leachable mass of each constituent based on data collected using SW-846 Method 1313. However, long-term leachate studies have shown that short-term test methods may underestimate the total mass of constituents that can leach over longer periods of time (U.S. EPA, 2009a). For example, additional mass may become available as the physical matrix of the waste degrades over time.

EPA conducted a sensitivity analysis to provide a bound on the effects that the availability of this additional mass could have on modeled risks. In this sensitivity analysis, the Agency reran EPACMTP for landfills the same as in the full probabilistic analysis, except with the total constituent mass used in place of the leachable mass. This was done for 62 out of 69 CCR wastes sampled with Method 1313 for which data on total constituent mass were available. Since it was the only constituent to exceed any risk criteria in other sensitivity analyses conducted for landfills, arsenic (both III and V) was modeled for this analysis.

The use of total constituent mass resulted in an increase in arsenic III by a factor of less than 2, and an increase in arsenic V by a factor of 3 or less. These increases are not sufficient to push the modeled probabilistic risks above either cancer or noncancer criteria for either species. Furthermore, even if the total mass present in CCR waste were available to leach, it is unlikely that this mass would be released as a continuous pulse or at the same rate as early releases. Therefore, given that this conservative bound on releases modeled with total mass did not appreciably increase risks, the impact of this uncertainty on the modeled risks is negligible.

Closed Landfill Source Term

Landfills were only modeled postclosure because the nonlinear sorption isotherms used by EPACMTP require the infiltration rate to be held constant. The landfill source model assumes that the full footprint of the landfill is filled to capacity at the start of modeling, and that a cap no less permeable than the soil or liner underlying the WMU is present to avoid accumulation of water within the landfill. However, during operation, only a portion of the landfill will actively receive CCR wastes at any given time. The active portion of a landfill would be exposed directly to the elements. While the cap modeled on the closed landfill will limit infiltration, the filled capacity will overestimate the initial loadings into ground water. Because these uncertainties affect the results in opposite directions, the ultimate effect on risks is uncertain.

CCR Compaction

The landfill source model does not consider further compaction of CCR waste that may occur over time as a result of anthropogenic activities, gravity or infiltrating water. This decrease in space

between the particulates can reduce hydraulic conductivity and inhibit water infiltration. However, no data on either the rate or degree to which these processes may occur were identified. As a result, the current full-scale modeling approach will likely overestimate long-term infiltration rates to some degree. However, the magnitude of this overestimation is unknown.

Clay Liner Thickness

Limited data are available on exact liner thickness of clay-lined WMUs. The probabilistic analysis assigned a fixed liner thickness of three feet for all units. There may be a wider range of thicknesses used in practice, with a minimum of two feet specified in Industrial Subtitle D Guidance (U.S. EPA, 2006b). EPA conducted a sensitivity analysis to provide a bound on the effects that different liner thickness may have on modeled risks. In this sensitivity analysis, the Agency reran EPACMTP for clay-lined surface impoundments the same as in the full probabilistic analysis, except with a fixed liner thickness of two feet for all units. Arsenic (both III and V) and boron were modeled in this sensitivity analysis to represent constituents with the highest risks and the fastest travel times, respectively. **Table 5-22** provides a comparison of the modeled risks for clay-lined surface impoundments modeled with a three-foot and two-foot liner.

Table 5-22. Comparison of 90th Percentile Ground Water Ingestion Risks for Clay-Lined Impoundments with Two- and Three-Foot Thick Liners

COPC	3-Foot Liner	2-Foot Liner	Ratio
Cancer Risks			
Arsenic III	6×10^{-6}	2×10^{-5}	3.3
Arsenic V	1×10^{-7}	4×10^{-7}	4.0
Noncancer Risks			
Arsenic III	0.2	0.6	3.0
Arsenic V	< 0.01	0.01	2.5
Boron	0.02	0.06	3.0

Risks from two-foot clay liners were up to four times higher than the risks from three-foot liners. This increase is sufficient to push arsenic III, which was already within the OSWER risk range, slightly above a cancer risk of 1×10^{-5}. Thus, the presence of a thinner liner than modeled in the full probabilistic analysis could lead to increased risks for clay-lined surface impoundments and landfills than modeled in the probabilistic analysis. Conversely, the presence of a thicker liner would result in lower risks than those modeled. The sensitivity analysis results for a two-foot thick liners at all units represents a conservative bound on potential risks. Thus, to the extent that clay-lined units in the field differ from those modeled, there is the potential for higher risks above cancer criteria. Without more detailed information on the actual thickness of liners present each WMU, the ultimate direction and magnitude of this uncertainty is uncertain.

Clay Liner Performance

This risk assessment assumed that compacted clay liners were designed and installed to be three feet thick and achieve a hydraulic conductivity of 1×10^{-7} cm/sec, consistent with the Industrial

Subtitle D Guidance (U.S. EPA, 2006b). Peer reviewers and public commenters noted that clay liners designed to meet a 1×10^{-7} cm/sec hydraulic conductivity may perform differently in practice due to compaction, thixotropy and other factors. Moo-Young et al. (2004) investigated several clay-lined surface impoundments and landfills designed to a 1×10^{-7} cm/sec hydraulic conductivity. This study found clay-lined impoundments to have field hydraulic conductivities ranging from 3.0×10^{-6} to 3.2×10^{-5} cm/sec and clay-lined landfills have field hydraulic conductivities ranging from 2.0×10^{-9} to 4.4×10^{-8} cm/sec. Given the relatively small sample size, EPA draws no conclusions about actual range of hydraulic conductivities that may occur in the field or the tendency of different WMUs to perform better or worse than designed. However, these data do indicate that the assumption of a fixed hydraulic conductivity of 1×10^{-7} cm/sec could under- or overestimate risks on a case-by-case basis.

Composite Liner Leakage Rates

The composite liner leakage rates used in the probabilistic analysis were originally developed and peer-reviewed as part of the Industrial Waste Management Evaluation Model (U.S. EPA, 2002a). EPA excluded measurements for composite liners with a compacted clay layer from the distribution. This exclusion was based on the assumption that significant volumes of water can be released from clay due to consolidation from mechanical compaction from the weight of overlying waste. Several researchers have compared the chemical composition of leachate versus leak detection system water and concluded that a significant fraction of the water released is due to consolidation of the clay liner, rather than leachate from the overlying waste (Bonaparte et al., 2002; Bergstrom et al., 1993; Gross et al., 1990; Workman, 1993; Feeney and Maxson, 1993). Although clay liners have been shown to release consolidation water, the fraction of leakage attributable to consolidation has not been well quantified to date. These data were excluded due to the absence of consensus on an approach to determine the difference between consolidation flow and liner leakage. EPA conducted a sensitivity analysis as part of the 2010 Risk Assessment to provide a bound on the effects that different leakage rates may have on modeled risks. In this sensitivity analysis, the Agency reran EPACMTP for composite-lined landfills the same as in the full probabilistic analysis, except with all composite liner leakage rates. **Figure 5-4** compares the resulting distribution of DAFs for landfill runs with arsenic.

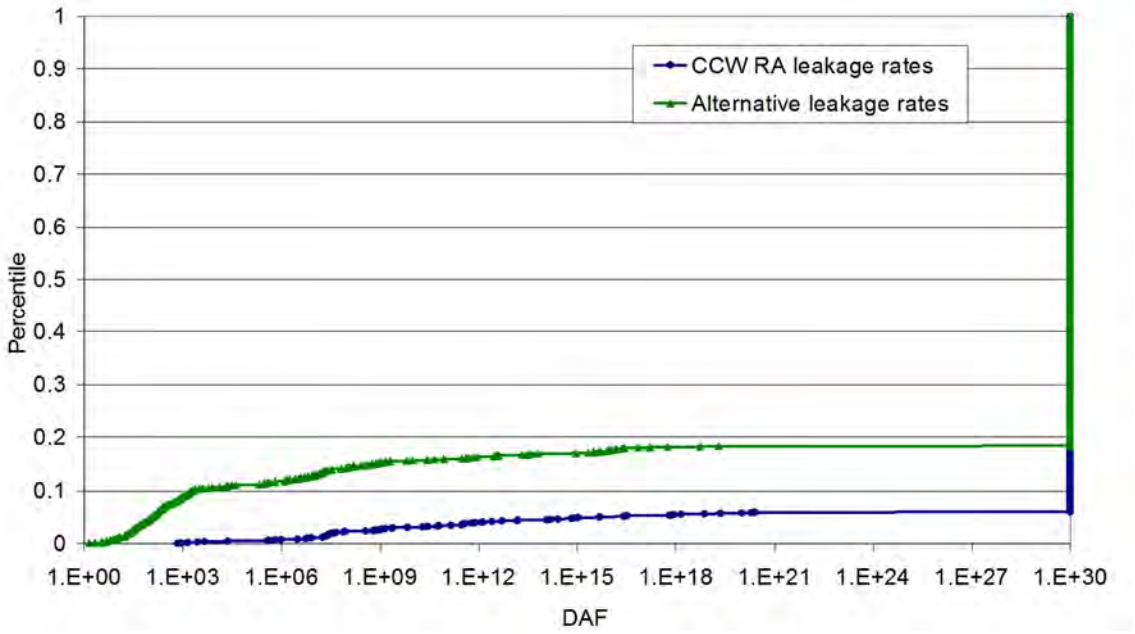

Figure 5-4. DAF Comparison for different leakage rates (landfills, arsenic).

In the figure above, the dramatic increase at a DAF of 1×10^{30} represents simulations where the constituent did not reach the receptor within the modeled timeframe. As anticipated, the use of higher infiltration rates for compacted clay layer units resulted in lower dilution and attenuation and a greater fraction of model iterations where the constituents reach the receptor well. Although use of all liner leakage rates would increase risks modeled for composite-lined facilities, the magnitude of the increase would not alter the finding that risks from composite-lined landfills are far lower risks than unlined and clay-lined landfills. Therefore, given that this conservative bound on releases from composite-lined releases would not appreciably increase risks, the potential impact of this uncertainty on the modeled risks is negligible.

Cap Degradation

For both unlined and clay-lined landfills, EPA used HELP Model–derived infiltration rates. These infiltration rates assume that the cap placed on top of the landfill at closure will remain intact for the duration of the probabilistic analysis, which extends up to a maximum of 10,000 years. Peer reviewers pointed out that the hydraulic conductivity of a clay cap may increase by orders of magnitude due to desiccation resulting from natural temperature cycles. In the near term, landfill caps will be maintained through periodic inspection and maintenance, but may degrade in the future without proper maintenance (Suter et al., 1993). However, predictions about the management and resulting performance of landfill caps centuries or more into the future would be speculative. To the extent that the performance of the cap does decrease over time, the modeled infiltration rates may underestimate infiltration into the landfill. However, since high-end risks will occur in on a shorter timeframe, the impact of this uncertainty on risk results is anticipated to be small.

Summary

A summary of the different uncertainties associated with source term models, as well as the potential for each to affect the risks modeled in the probabilistic analysis is shown in **Table 5-23**. The majority of uncertainties identified are unlikely to have an appreciable impact on the principal risk results. EPA was not able to characterize the potential magnitude or direction of the uncertainties associated with modeling landfills postclosure or variations in clay-liner design and performance. The Agency relied on the best data available at the time of the analysis; however, the potential of these uncertainties to overestimate or underestimate risk results is uncertain.

Table 5-23. Likely Effect on Risk from Source Term Model Uncertainties

Uncertainty	Potential to Affect Probabilistic Risk Results		
	Uncertain	Low	High
Scaling of Washout Constituent Concentrations		●	
Constant Leachate Concentrations		●	
Surface Impoundment Leachate Duration		●	
Landfill Leachable Content		●	
Closed Landfill Source Term	●		
CCR Compaction		●	
Clay Liner Thickness	●		
Clay Liner Performance	●		
Composite Liner Leakage Rates		●	
Cap Degradation		●	

5.1.8 Isotherm Model

MINTEQA2

MINTEQA2 has a long history of both internal review by the EPA Science Advisory Board (SAB) and external peer review during model development and implementation over the past two decades. These reviews largely focused on the use of MINTEQA2 to generate metal sorption isotherms for EPACMTP. During the most recent review, peer reviewers found that the revisions made to the MINTEQA2 model to account for CCR wastes were appropriate, but suggested further improvements that could be made to address the basic environments that are characteristic of many CCRs (U.S. EPA, 2003e). The version of MINTEQA2 used in this risk assessment addressed these recommendations by developing sorption isotherms specific to the geochemical conditions encountered in CCR surface impoundments and landfills. Due to the extensive peer reviews conducted, EPA has a high level of confidence in the model. However, there are many assumptions inherent in the application of MINTEQA2 to the revised risk assessment. These assumptions and the resulting limitations, discussed in detail in **Appendix H**, include:

- Site-specific data on the ground water chemistry was not available.
- The types and numbers of sorption sites modeled likely do not reflect the full range of sorption sites possible in nature.
- There was more limited data on the specific ion concentrations present in CCR leachate that may influence K_d values.
- The model did not account for the potential of redox to influence K_d values.
- Because each constituent was considered separately, the model did not account for potential competition between constituents for sorption sites.

Although the direction of the potential uncertainties are apparent for some of these uncertainties, it is difficult to quantify the magnitude of the resulting uncertainty. Thus, the direction and magnitude of this class of uncertainties is unknown.

Lithium

At the time the probabilistic analysis was conducted, sufficient information was not available to develop chemical-specific K_d values for lithium. MINTEQA2 could not be used because iron oxide is not an appropriate sorbent for this constituent. Available literature indicates that lithium does adsorb weakly to clay soils, resulting in low retardation (Fuentes, 1989). This has resulted in its use as a conservative environmental tracer in some studies (LeBlanc et al., 1991; Anghel et al. 2002). The current evaluation used a conservative K_d of 0 to estimate lithium fate and transport. This may result in an overestimation of downgradient exposures. Given the moderate exceedance of noncancer risk criteria observed, it is possible that accounting for this low amount of retardation in the environment may reduce national-scale risks below risk criteria. However, as demonstrated by identified damage cases, lithium risks may be present on a site-specific basis. Thus, this uncertainty is unlikely to alter the final conclusions of the risk assessment.

Summary

A summary of the different uncertainties associated with MINTEQA2, as well as the potential for each to affect the risks modeled in the probabilistic analysis is shown in **Table 5-24**. There are multiple uncertainties associated with the implementation of MINTEQA2, many of which were associated with the absence of site-specific data. Given the broad, national scope of the risk assessment, the potential magnitude or direction of this uncertainty remains uncertain.

Table 5-24. Likely Effect on Risk from Isotherm Model Uncertainties

Uncertainty	Potential to Affect Probabilistic Risk Results		
	Unknown	Low	High
MINTAQA2	●		
Lithium		●	

5.1.9 EPACMTP Ground Water Modeling

EPA has used EPACMTP and its predecessors to conduct ground water risk assessments in support of numerous regulations for land disposal of hazardous and nonhazardous wastes. During this time, EPACMTP has undergone multiple rounds of internal and external review, including several by the EPA SAB. Each of these reviews has determined that the use of this model for developing national regulations and guidance is appropriate. Some of the reviews include the following:

- **1994:** Consultation with the SAB on the use of EPACMTP for determining DAFs for the EPA's Soil Screening Guidance (U.S. EPA, 1996c); and peer-reviewed publication of EPACMTP in the Journal of Constituent Hydrology (Kool et al., 1994);
- **1995:** In-depth SAB review on the use of EPACMTP in the proposed/draft 1995 Hazardous Waste Identification Rule (U.S. EPA, 1996b);
- **1999:** Peer review of the implementation of EPACMTP in the EPA's multimedia, multiple exposure pathway, multiple receptor risk assessment (3MRA) model (U.S. EPA, 1999); and
- **2003:** SAB review of the 3MRA implementation of EPACMTP (SAB, 2004).

These reviews verified that the mathematical formulation of the model is scientifically sound and the code executes properly. In addition, recommendations from these reviews have been incorporated, resulting in a number of improvements to the model. Due to the high level of review and comment that this model has received, EPA has a high confidence in the accuracy of the model. Thus, EPA limited the discussion of uncertainties associated with EPACMTP in this document to those that were raised through public comments or that arose from the specific handling of inputs in this risk assessment. For a further discussion of the uncertainties associated with EPACMTP, see U.S. EPA (2003b).

10,000 Year Time Frame

This risk assessment assumed a constant hydrogeological environment and population distribution over the modeled timeframe. Peer reviewers and public commenters questioned the accuracy of using a maximum 10,000 year model duration. However, EPACMTP only ran to 10,000 years if a peak concentration had not been reached before that time. Arrival times for the peak well concentrations used to calculate ground water to drinking water risks for select CCR constituents (arsenic, boron, cobalt, selenium, and thallium) are plotted as cumulative distributions for surface impoundments and landfills in the figures in **Appendix K.** These constituents were selected both to capture those with the highest risks and highest mobility.

Tables 5-25 summarizes the time of travel results from the 2010 Risk Assessment sensitivity analysis by showing selected percentiles from these distributions for surface impoundments. For both unlined and clay-lined surface impoundments, the 10th percentile time to peak was less than 100 years for all constituents considered. The 50th percentile time to peak also remained under 100 years for multiple constituents, though the time for less mobile constituents increased appreciably. For composite-lined surface impoundments, even the faster time to peak approached 1,000 years. High-end risks will be associated with these lower percentile times. Thus, for unlined

and clay-lined surface impoundments, the uncertainties about future environmental settings have minimal impact on the peak risks. Uncertainties are much higher for composite-lined units. However, risks for these units were all well below all cancer and noncancer criteria. Therefore, use of a 10,000 year modeling timeframe adds a low uncertainty to the results of the probabilistic analysis.

Table 5-25. Years to Peak Well Concentration for Surface Impoundments by Liner Type

Percentile	Boron	Selenium VI	Arsenic III	Cobalt	Arsenic V	Selenium IV	Thallium
Unlined							
10th	70	70	70	71	73	76	—
50th	74	74	78	97	220	4,400	—
90th	110	110	170	970	6,500	> 10,000	—
Clay							
10th	75	75	75	86	95	81	—
50th	90	90	110	270	1,300	7,900	—
90th	150	150	340	3,100	10,000	>10,000	—
Composite							
10th	960	990	1,300	9,500	10,000	1,900	—
50th	4,400	4,600	8,600	>10,000	>10,000	>10,000	—
90th	10,000	10,000	>10,000	>10,000	>10,000	>10,000	—

Notes: Arrival times have been rounded to two significant digits.

A value of 10,000 means the concentration at the end of the maximum simulation time, 10,000 years, was the highest observed during the simulation. A value of >10,000 indicates that the constituent plume did not reach the receptor well during the modeled period.

Table 5-26 summarizes the time of travel results from the 2010 Risk Assessment sensitivity analysis by showing selected percentiles from these distributions for landfills. For both unlined and clay-lined landfills, the 10th percentile time to peak were all several hundred years. For both unlined and clay-lined landfills, the 50th percentile time to peak were all several thousand years. For all units, 90th percentile time to peak took more than 10,000 years to reach the receptor well for many constituents. Thus, for landfills, uncertainties about future environmental settings have much greater impact on peak risks than for surface impoundments. The potential magnitude of these uncertainties is unknown.

Table 5-26. Years to Peak Well Concentration for Landfills by Liner Type

Percentile	Boron	Selenium VI	Arsenic III	Thallium	Cobalt	Arsenic V	Selenium IV
Unlined							
10th	300	400	400	580	1,200	2,000	4,600
50th	2,000	2,600	2,800	2,300	7,800	9,700	10,000
90th	9,400	10,000	>10,000	9,700	>10,000	>10,000	>10,000
Clay							
10th	550	400	400	570	1,400	1,900	8,100
50th	5,600	5,100	4,000	4,300	10,000	10,000	>10,000
90th	>10,000	>10,000	>10,000	>10,000	>10,000	>10,000	>10,000
Composite							
10th	9,600	9,000	10,000	>10,000	>10,000	>10,000	10,000
50th	>10,000	>10,000	>10,000	>10,000	>10,000	>10,000	>10,000
90th	>10,000	>10,000	>10,000	>10,000	>10,000	>10,000	>10,000

Notes: Arrival times have been rounded to two significant digits.
A value of 10,000 means the concentration at the end of the maximum simulation time, 10,000 years, was the highest observed during the simulation. A value of >10,000 indicates that the constituent plume did not reach the receptor well during the modeled period.

The arrival times presented in these tables correspond to the arrival of the maximum estimated risks for each model run. However, for model runs where risk criteria were exceeded, the first exceedance may occur long before the maximum risks arrive.

Arsenic, Chromium, and Selenium Speciation

The speciation of arsenic, chromium and selenium can impact the mobility of these constituents in the environment, as well as the resulting toxicity to receptors. Arsenic can occur in either a +3 (arsenic III) or +5 (arsenic V) oxidation state, with arsenic III as the more mobile form. Chromium can occur in either a +3 (chromium III) or +6 (chromium VI) oxidation state, with chromium VI as the more mobile form. Selenium can occur in either a +4 (selenium IV) or +6 (selenium VI) oxidation state, with selenium VI as the more mobile form.

Although arsenic is generally thought to occur as arsenic III in leachate (Turner, 1981), evidence from damage cases suggests arsenic III can be converted to arsenic V during subsurface transport at some facilities (U.S. EPA, 2000a, 2003d; Lang and Schlictmann, 2004; Zillmer and Fauble, 2004). Similarly, although the dominant form of chromium leached from CCR wastes is chromium VI (Huggins et al., 1999; Stam et al., 2011), it is known to be converted to much less mobile chromium III form in ground water and soils (Palmer and Puls, 1994). However, the models used in this risk assessment do not consider changes to the speciation of metals during transport through the environment. To address this uncertainty, EPACMTP was run twice for both valence states of arsenic, chromium and selenium. The results from the two model runs bracket the full range of possible risks, given that there is likely some change in oxidation state during subsurface transport.

As a result of changes in speciation during fate and transport, actual risks could fall anywhere in the range presented in each table, with arsenic III, chromium VI and selenium VI providing an upper bound and arsenic V, chromium III and selenium IV providing a lower bound. Both chromium and selenium fell below risk criteria for each species. For arsenic, arsenic III fell above risk criteria, while arsenic V fell just below a cancer risk of 1×10^{-5}. Because risks for both species fell mostly above or below criteria, this uncertainty has minimal effect on the results of the probabilistic analysis.

Aquifer pH

In the field, leachate plumes mix gradually with ground water over time through advection and diffusion. However, the probabilistic analysis assumed that leachate pH equilibrated with the ambient ground water on contact. Because the solubility of inorganic constituents can vary drastically with minor changes in pH (U.S. EPA, 2009b), EPA conducted a sensitivity analysis as part of the 2010 Risk Assessment to provide an upper bound on the potential effect this simplifying assumption may have on modeled risks. This sensitivity analysis consisted of an additional run of EPACMTP for landfills that assumed leachate does not mix with ground water at all, and that the pH of the plume is driven solely by the initial characteristics of the leachate. EPA chose to model the fate and transport of arsenic as both arsenic III and arsenic V for the following reasons:

- Arsenic is the constituent found to pose the greatest ground water risks for both surface impoundments and landfills.
- For the sorbents considered in this risk assessment, these arsenic species respond differently to changes in pH. For arsenic III, K_d values tend to decrease (i.e., increased mobility) as pH transitions from acidic to basic. For arsenic V, K_d values tend to increase (i.e., decreased mobility) as pH moves from acidic to neutral, and then decrease as the pH becomes more basic. Differences between K_d values for these species can be orders of magnitude.

The results from this model run were compared with the results of the full modeling conducted in 2010. **Table 5-27** summarizes the percent change in peak arsenic III and arsenic V well concentrations that results from modeling leachate pH as unchanged in the aquifer.

Table 5-27. Change in Peak Receptor Well Concentrations for CCR Waste Disposed in Landfills Assuming Leachate Does Not Mix in Aquifer

Percentile	Percent Decrease	
	Arsenic III	Arsenic V
10th	0.0 %	0.0 %
30th	0.9 %	0.0 %
50th	0.3 %	2.3 %
70th	0.2 %	58.0 %
90th	0.0 %	11.8 %

The modeled well concentrations of arsenic V are somewhat sensitive to changes in pH, while those of arsenic III are not at all. This is because, while K_d values for both arsenic III and V increase

as the pH becomes more basic, the magnitude of the increase for arsenic V are much larger. As a result, while both species tend to sorb more at higher pH values, the effects are more pronounced for arsenic V. These results indicate that the assumption of complete equilibrium may slightly overestimate risks for constituents that behave similar to arsenic V. However, because the fate and transport of arsenic III is not sensitive to changes in pH, and because the predicted decrease in high-end arsenic V concentrations is minimal, this uncertainty will have no appreciable effect on the conclusions of the analysis.

Lateral Dispersion

EPACMTP simplifies flow in both the vadose zone (i.e., unsaturated soil) and in the aquifer. In the vadose zone, flow is modeled as vertical (one-dimensional) movement of infiltrating water flow. Since lateral migration is not modeled in the vadose zone, the concentration reaching the ground water table is somewhat higher than it may be in real-world conditions. Thus, this simplification may lead to an overestimation of risks. However, the magnitude of lateral dispersion in the vadose zone is typically relatively small, with a magnitude of one hundredth the vertical dispersivity as a reasonable first approximation (Simunek and van Genuchten, 2006), Because the areal extent of WMUs from which leachate occurs is orders of magnitude larger than the additional spreading that may occur in the vadose zone from lateral diffusion, the magnitude of this overestimation is likely to be small.

Preferential Flows

Ground water advection in the saturated zone is also modeled as a one-dimensional process in a homogeneous aquifer subject to surface infiltration and recharge. The flow direction is aligned with the regional flow direction. As the aquifer properties are regionally averaged, EPACMTP does not explicitly account for preferential pathways such as fractures and macropores. These assumptions could lead to either an overestimation of risk if actual flow paths direct flow away from receptors, or an underestimation of risk if preferential pathways lead to more streamlined transport than modeled. Without detailed, site-specific data on hydrogeologic conditions, the exact magnitude and direction of this uncertainty is unknown.

Ground Water Receptor Well Placement

Ground water wells were placed using a distribution of nearest wells described in **Appendix B**. Based on this distribution, wells were placed within approximately 1,600 meters for surface impoundments and 2,100 meters for landfills. However, it is possible that receptor wells may be located even further downgradient. EPA conducted a sensitivity analysis to examine the effect of not evaluating these further wells. First, EPA modeled arsenic as arsenic III in EPACMTP for wells at a variety of distances from surface impoundments and landfills. Wells were constrained to be within 5 m of the centerline of the plume where concentrations would be highest. EPA then calculated the percent of model runs where ground water concentrations exceeded the MCL for arsenic (10 µg/L). The results of the sensitivity analysis show that, while 2.2 percent of surface impoundment runs between 1,000 m and 1,500 meters exceeded the MCL, only 0.1 percent of model runs beyond 1,500 meters exceeded the MCL. Landfill model runs resulted in an even lower percent of MCL exceedances at both distances. The results of the sensitivity analysis show that

arsenic concentrations fall dramatically as the distance from the WMUs increases. This supports EPA's choice of a distribution of nearest receptor wells to represent a highly exposed individual, rather than considering even further distances. Thus, EPA finds that the placement of ground water receptor wells has a minimal effect on the highly exposed individual risks.

Ground Water Receptor Well Depth

Ground water receptor well concentrations were drawn from a single aquifer depth for each model iteration. Actual wells may be screened across an extended depth, resulting in capture of a combination of contaminated and pristine ground water. Sampling from a single depth may overestimate or underestimate risks on a case-by-case basis. However, given the size of the WMUs and the range receptors distances modeled in this analysis, the constituent plume within the first ten meters is expected to be fairly well mixed. Thus, the magnitude of this uncertainty is likely to be small.

Summary

A summary of the different uncertainties associated with the use of EPACMTP to model ground water transport, as well as the potential for each to affect the risks modeled in the probabilistic analysis is shown in **Table 5-28**. The majority of uncertainties identified are unlikely to have an appreciable impact on the principal risk results. EPA was not able to characterize the potential magnitude or direction of the uncertainties associated with site-specific preferential flow in the subsurface. The Agency relied on the best regional data available at the time of the analysis; however, the potential of these uncertainties to overestimate or underestimate national risks remains uncertain.

Table 5-28. Likely Effect on Risk from EPACMTP Uncertainties

Uncertainty	Potential to Affect Probabilistic Analysis Results		
	Uncertain	Low	High
10,000 Year Time Frame		●	
Arsenic, Chromium and Selenium Speciation		●	
Aquifer pH		●	
Lateral Dispersion		●	
Preferential Flows	●		
Ground Water Receptor Well Placement		●	
Ground Water Receptor Well Depth		●	

5.1.10 Surface Water Fate and Transport Modeling

Surface Water Plume Interception

An EPACMTP post-processor was created to calculate the fraction of the ground water plume that is intercepted by a surface water body. This calculation assumes that ground water continues to flow in the same direction on the opposite side of the water body. In the field, ground water on both sides can flow toward the same water body. Overall, this uncertainty is anticipated to have a

minimal effect on modeled risk results. For GW→DW exposure pathways, the high-end ground water risks for these pathways will be driven by model iterations where no surface water interception occurs. For GW→SW exposure pathways, the additional flow of uncontaminated ground water may result in further dilution of the constituent plume than predicted by the model and an overestimation of risks. Because this type of site-specific data is not available, the exact magnitude of this overestimation is unknown. However, given that the modeled risks for these pathways all fell below risk criteria, the potential for this overestimation to alter the results of the probabilistic analysis is negligible.

Equilibrium Partitioning

The equilibrium partitioning model used in the probabilistic analysis divided constituent loading rate (mass/time) by the water body flow rate (volume/time) to obtain an overall water body concentration. Following calculation of the constituent loading rates, the partitioning model determined the equilibrium constituent concentrations in each of the four compartments. As implemented in this analysis, the model does not account for losses that may result from burial. This is a conservative assumption that will overestimate risks to sediment receptors to some degree. However, given that all risks associated with sediment exposures fell at least an order of magnitude below risk criteria, the potential for this overestimation to alter the conclusions of the probabilistic analysis is negligible.

Summary

A summary of the different uncertainties associated with constituent data, as well as the potential for each to affect the risks modeled in the probabilistic analysis is shown in **Table 5-29**. The uncertainties identified are unlikely to have an appreciable impact on the principal risk results.

Table 5-29. Likely Effect on Risk from Surface Water Model Uncertainties

Uncertainty	Potential to Affect Probabilistic Analysis Results		
	Unknown	Low	High
Surface Water Interception		●	
Equilibrium Partitioning		●	

5.1.11 Risk Models

Cumulative Pathways for Human Health Risk

This risk assessment considered the potential risks to human health from individual constituents and individual pathways. It is possible that individuals could be exposed to risks from drinking contaminated ground water, as well as eating contaminated fish from a local surface water body. However, it is unlikely that this will occur with any frequency in the real world for the following reasons:

- Only 27.5 million U.S. residents out of 312 million, or approximately 9 percent of the population, are recreational fishers (U.S. Census, 2012).

- Of those who fish recreationally, approximately 49 percent eat at least some of the fish that are caught (Table 10-63, U.S. EPA, 2011).
- EPA assumes that the contaminated water bodies in this assessment are fishable, and that preferential fishing locations are not located nearby.
- On average, recreational fishers have been shown to travel between 35 to 41 miles to fish (Table 10-81 and Table 10-85, U.S. EPA, 2011). This provides a large area around a contaminated surface water body that individuals could come from to fish, and thus a smaller probability that they are also from an area within the contaminated ground water plume.
- If a fisher also resides within the ground water plume, approximately 15 percent of U.S. households rely on ground water as a source of potable water (U.S. EPA, 2002b).
- If the receptor lives close to the water body, there is a greater potential that the receptor well will be located downgradient from the water body, resulting in surface water interception of some or all constituent mass and lower drinking water risks than reported in this document.
- Were an individual exposed through both pathways, the different locations of the well and water body would result in different transit times until peak risks. Therefore, the cumulative exposure would be less than predicted by adding the risks reported in this document.

Because of the considerations listed above, EPA did not consider cumulative exposures from these pathways. This is a source of uncertainty that may result in an underestimation of risks to some individuals. However, given that risks were identified for individual COPCs and that these additional exposures will occur with a low frequency, the potential for any underestimation of risk to alter the principal results of the probabilistic analysis is small.

Cumulative COPCs for Human Health Risk

It is possible for an individual to be exposed to multiple constituents through a single pathway. This is a likely scenario because, as demonstrated by the available data, CCRs may leach multiple inorganic constituents. An individual COPC may interact with other constituents present, resulting in synergistic or antagonistic effects that exacerbate or diminish the health impacts predicted by evaluating each COPC independently. Where the potential for simultaneous exposure to multiple constituents exists, current EPA policy is to assume that the risks resulting from these exposures are additive (U.S. EPA, 2000b). However, the revised risk assessment did not consider additivity for the following reasons:

- The time to peak results presented earlier in this section indicate that while some constituents will migrate and reach peak concentrations in tens or hundreds of years, others may take thousands or tens of thousands of years. Thus, not all constituents will reach a receptor at the same time.
- Individual WMUs would not leach all constituents at the high-end concentrations considered in this risk assessment.
- EPACMTP is designed to use variable time steps to minimize computer processing time. These time steps are determined based on the rate of change of the modeled constituent

concentration, with longer time steps used for slowly changing concentrations. To account for cumulative exposures, EPACMTP would need to undergo significant modifications to make the time steps the same for every constituent run so that risks from combined constituent concentrations could be modeled.

- The human health benchmarks used are based on the most sensitive adverse effect. Thus, the addition of constituent risks along the range of potentially affected organ systems would overestimate cumulative risks to less sensitive organ systems.

Because of the considerations listed above, EPA did not consider cumulative risk. This is a source of uncertainty that may result in an underestimation of risk. However, the probabilistic analysis identified individual constituents above risk criteria. Many of the other constituents modeled resulted in risks an order of magnitude or more below risk criteria. Thus, the consideration of additive risk, even with the high-end risks modeled in this risk assessment, is unlikely to alter the principal results of the probabilistic analysis.

Presence of Sensitive Ecological Receptors

Unlike for human receptors, where Census and other population statistics can be used to locate potential receptors with some accuracy, site-specific surveys are needed to confirm the presence of specific ecological receptors. In the absence of site-specific data, this risk assessment made the assumption of co-occurrence of sensitive ecological receptors and waste sites. However, the likelihood that sensitive receptors will be found downgradient from CCR WMUs is unknown. Nor is it known whether those areas support the type of habitat needed by these receptors. Therefore, this assumption may overestimate the potential risks to ecological receptors. The magnitude of this overestimation is unknown. However, given that the modeled risks for these receptors all fell below risk criteria, the potential for this overestimation to alter the results of the probabilistic analysis is negligible.

Ecological Receptor Diet

This analysis assumed that the entire diet of modeled receptors originates from the contaminated area downgradient of WMUs. This may be an appropriate assumption for plants and other relatively sedentary receptors. However, in the wild, many animals are opportunistic feeders with substantial variability in both the type of food items consumed and the geospatial patterns of feeding and foraging. Therefore, the actual proportion of wildlife receptors' diets that would be contaminated depends on a number of factors such as species foraging range, quality of food source, season, climate, and intra- or interspecies competition. Therefore, this assumption may overestimate the potential risks to some ecological receptors. The magnitude and frequency of this overestimation is unknown. However, given that the modeled risks for these receptors all fell below risk criteria, the potential for this overestimation to alter the results of the probabilistic analysis is negligible.

Indirect Ecological Effects

Indirect ecological effects (e.g., depletion of food resources) resulting from the on-site disposal of CCRs were not considered in the probabilistic analysis. Identifying the ways that impacts on food

supply and habitat quality may adversely impact the overall health of ecological receptors is difficult, even for a site-specific evaluation, and is not currently possible on a national scale. However, for any given facility, the spatial scale of potential contamination would generally be a small fraction of the full home range for many species. In addition, many species are opportunistic feeders that will actively seek other food sources if those near the CCR facilities decline, regardless of the cause of this decline. Exclusion of these indirect effects may underestimate the potential risks to ecological receptors. The magnitude of this underestimation is unknown, but not anticipated to affect the final conclusions of the risk assessment.

Ecosystems and Ecological Receptors at Risk

One challenge in conducting a national risk assessment is representing all receptors and ecosystems at risk. In *Wastes from the Combustion of Coal by Electric Utility Power Plants - Report to Congress* (Exhibit 5-27; U.S. EPA, 1988), EPA noted that managed lands, critical habitats, or threatened and endangered species were located within a five kilometer radius of CCR WMUs at between 12 and 32 percent of facilities:

- **Managed Lands:** Because protected lands play a critical role in preserving plant and animal species, managed areas in the United States represent well recognized ecological values. Managed lands refer to a variety of lands designated by the federal government as worthy of protection, including National Wildlife Refuges, National Forests, Wilderness areas, and National Recreation areas.
- **Critical Habitats:** Critical habitats may be defined in a number of ways (e.g., presence of threatened species, fragmented habitat area). Wetlands are widely recognized as an important habitat serving critical ecological functions (e.g., maintenance of water quality). The U.S. Fish and Wildlife Service estimates that approximately 45 percent of the Nation's threatened and endangered species directly depend on aquatic and wetland habitats. Consequently, impacts of chemical stressors on wetland habitats may have high ecological (and societal) significance.
- **Threatened and Endangered Species:** A threatened species is one that "is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range." An endangered species is one that "is in danger of extinction throughout all or a significant portion of its range."

EPA did not consider impacts to managed lands and critical habitats for similar reasons as indirect ecological effects, as the necessary data on the negative impact on overall ecosystem health is difficult to quantify, even for a site-specific evaluation. Direct risks to threatened and endangered species were not explicitly evaluated as part of this risk assessment because of the lack of species-specific toxicity data. While these species were not explicitly considered, the ecological benchmarks used are based on the most sensitive receptors for which data are available, which are believed to be protective of the majority of species. In certain instances, exclusion of these effects to habitat and specific species may underestimate risks. The magnitude of this underestimation is unknown, but not anticipated to affect the final conclusions of the risk assessment.

Summary

A summary of the different uncertainties associated with the implementation of risk models, as well as the potential for each to affect the risks modeled in the probabilistic analysis is shown in **Table 5-30**. The uncertainties identified are unlikely to have an appreciable impact on the principal risk results.

Table 5-30. Likely Effect on Risk from Risk Model Uncertainties

Uncertainty	Potential to Affect Probabilistic Analysis Results		
	Unknown	Low	High
Cumulative Pathways for Human Health Risk		●	
Cumulative COPCs for Human Health Risk		●	
Presence of Sensitive Ecological Receptors		●	
Ecological Receptor Diet		●	
Indirect Ecological Effects		●	
Ecosystems and Ecological Receptors at Risk		●	

5.2 Results of the 2009 Sensitivity Analysis

The discussion of uncertainties in **Section 5.1** considered each uncertainty in isolation; however, the effects of these different sources can compound. In support of the 2010 Risk Assessment, EPA conducted a sensitivity analysis to determine the combination of parameters and associated uncertainties that have the greatest impact on calculated risks (U.S. EPA, 2009b). In this risk assessment, EPA used the results of the 2009 analysis to validate the findings of the revised sensitivity and uncertainty analyses. Although some of the data sources used in the revised risk assessment have changed, the type of inputs used by EPACMTP remained the same. Thus, for the purposes of understanding the sensitivities of the model, the results of this sensitivity analysis are still as relevant.

The 2009 sensitivity analysis used a response-surface regression method to derive a statistical model for ground water concentration (as the dependent variable) based on the input parameters from the probabilistic analysis (as independent variables). Concentration, rather than risk, was chosen as the dependent variable for the sensitivity analysis because the additional exposure factors used to calculate human health risk from environmental concentration (e.g., body weight) have well established, peer-reviewed distributions based on EPA policy. The outputs of the sensitivity analysis were goodness-of-fit values used to determine the relative importance of each input parameter. The most sensitive parameters identified are presented in **Table 5-31**.

Table 5-31. Parameters Identified in the 2009 Sensitivity Analysis

Pathway:	GW→DW Pathway		GW→SW Pathway
Constituents:	**All Constituents**	**Strongly Sorbing**	**All Constituents**
Sensitive Parameters	▪ Infiltration Rate ▪ Leachate Concentration ▪ Hydraulic Gradient ▪ Hydraulic Conductivity	▪ K_d Value ▪ Depth to Ground Water ▪ Distance to Receptor Well	▪ Infiltration Rate ▪ Leachate Concentration ▪ Water Body Flow Rate

As seen in the table above, the GW→DW exposure pathway had more input parameters that were highly sensitive (seven) than the GW→SW exposure pathways (three). The most sensitive parameters for the GW→DW pathways were parameters that impact flux (infiltration rate and leachate concentration) and ground water flow (hydraulic conductivity and gradient). When modeling strongly sorbing constituents, the K_d values and distance to receptor also become important. The most sensitive parameters for the GW→SW exposure pathways were parameters impacting flux (infiltration rate and leachate concentration) and the water body flow rate.

In the probabilistic analysis, risks were identified for the GW→DW exposure pathway. Further sensitivity and uncertainty analyses identified two input parameters with the greatest potential to affect the probabilistic risk results. These parameters align well with the findings of the 2009 sensitivity analysis:

- **Liner Type:** Liner type and design was shown to have one of the most significant effects on modeled risks. The higher hydraulic conductivity of unlined units resulted in the highest risks. Risks from clay-lined units were lower than unlined units, but still close to criteria. Thus, changes to the configuration of the liner, such as adjusting the thickness from three to two feet, has the potential to result in risks above the criteria. Composite liners, with the lowest hydraulic conductivity of any units, resulted in the lowest risks. This is consistent with the finding that infiltration rate is one of the most sensitive parameters, as the hydraulic conductivity of the liner is one of the major factors determining infiltration rate at each unit.
- **Waste pH:** Waste pH was shown to have a significant effect on risk. Multiple constituents presented higher risks when considered in WMUs managing ash and coal refuse at more acidic pHs or FGD wastes at more basic pHs. This is consistent with the finding that leachate concentrations and K values are two of the most sensitive parameters of the model, as pH is one of the driving factors for both parameters.

5.3 Field Comparisons

The comparison of model inputs and results to data collected in the field is a useful means of validation. As discussed previously, EPACMTP has been extensively reviewed and validated, but the specific set of inputs and assumptions applied to the model results in additional sources of

uncertainty. EPA used two comparisons to assess whether the results of the probabilistic analysis accurately reflect with what may occur in the field. First, EPA examined the leachate data measured with LEAF methods and compared these concentrations to those measured in the field. Second, EPA examined the damage cases to identify the WMU types and constituents most frequently found at damage cases and compared these to the result of the sensitivity and uncertainty analyses.

Leachate Concentrations

EPA characterized leachate from surface impoundments using pore water data and leachate from landfills using LEAF data. Pore water data were collected from core samples both in and beneath surface impoundments. Since the cores take leachate directly from the field, these data are known to represent field conditions and no further comparison is necessary. For landfills, U.S. EPA (2014b) compared LEAF test methods to actual field leachate, both in Europe and the United States. In general, the report demonstrates that LEAF methods accurately capture the leachate characteristics found in the field. Properly accounting for both the pH of the waste in field conditions, as well as the liquid-to-solid ratio of the leachate and waste, was shown to result in lab results very close to those found in the corresponding field conditions.

Comparison of Results to Damage Cases

EPA reviewed the available data on both proven and potential damage cases and compared the findings with the results of the sensitivity and uncertainty analyses. Each damage case reflects a combination of site-specific conditions present at that site. This contrasts with the risk assessment, which is nationwide. Due to the differing nature of these two sources of information, a direct comparison would not be relevant. However, general characteristics and conclusions from the damage cases are relevant to support the findings of the risk assessment, and are discussed below.

The vast majority of damage cases were associated with unlined surface impoundments and landfills. No damage cases were identified for composite-lined units. This agrees well with the results of the sensitivity analyses, which showed that risks were significantly higher for unlined WMUs than for other units, and that risks for composite-lined units were far below all cancer and noncancer criteria.

Arsenic was by far the most common constituent associated with damage cases. Similarly, it was the constituent that exceeded the risk criteria in the most scenarios, and by the greatest magnitude. Other common constituents from the damage cases such as boron and cadmium also exceeded the criteria in the sensitivity analyses. Additional damage cases were identified for other constituents for which no risks were identified in the sensitivity analyses. There are a number of reasons why modeled ground water risks and damage cases do not perfectly align:

- **Different Benchmarks:** In some cases, state standards are more conservative than EPA standards. Other times, state standards exist for constituents where EPA has not yet established a benchmark.
- **Closer Monitoring Distances:** In many of the potential damage cases, ground water exceedances were discovered near the boundary of the WMU. The risk assessment

considered further dilution and attenuation would occur between the WMU and potential ground water receptors. Thus, concentrations should be higher for all constituents in the damage cases than they would be at the modeled distances in the risk assessment. This is borne out by the fact that so many fewer proven damage cases exist, as these damage cases require, for example, off-site migration.

- **Disposal Practices:** Some damage cases occurred for disposal practices that could not be modeled in the risk assessment. For example, disposal below the water table. In this situation, the sorption that occurs in the unsaturated zone of the risk assessment model does not occur in the field. This and other site-specific risk factors could lead to additional contamination beyond what was modeled nationwide.

These differences between the modeled risks and site-specific damage cases provide examples of why a direct comparison of the risk assessment results to the damage cases is difficult. However, since the scenarios and constituents presenting the most risk are in general agreement, it still strengthens the results of the risk assessment.

5.4 Conclusions

In **Section 5.1**, the uncertainties were discussed in light of their ability to affect the risks of the full probabilistic analysis. Several of the uncertainties related to collecting data and filling data gaps, while the remaining uncertainties were a result of model development and use. **Table 5-32** presents the estimated effect of these uncertainties.

Table 5-32. Summary of Potential Effects of Uncertainty on Risk Results

Uncertainty	Potential to Affect Probabilistic Analysis Results		
	Uncertain	Low	High
CCR WMU Database	0	8	2
Environmental Parameters	1	6	0
CCR Constituent Database	0	3	0
Human Exposure Factors	1	5	0
Human Health and Ecological Benchmarks	2	3	0
Bioconcentration Factors	1	0	0
WMU Source Term Models	3	7	0
MINTAQA2 Isotherm Model	1	0	0
EPACMTP Ground Water Model	1	6	0
Surface Water Model	0	2	0
Risk Models	0	6	0
All Uncertainties	**10**	**46**	**2**

The majority of uncertainties identified (46) are expected to have a minimal effect on the principal results of the probabilistic analysis. EPA was unable to fully characterize the effects of several

uncertainties (10). These uncertainties have the potential to underestimate or overestimate risks on a case-by-case basis. However, the Agency used the best available data sources to characterize these parameters and minimize potential influence of these uncertainties on modeled results. The remaining uncertainties (2), liner prevalence and waste type prevalence, had a strong influence on modeled results and resulted in appreciably higher risks when different subsets of national disposal practices were considered.

The 2009 sensitivity analysis discussed in **Section 5.2** identified the input parameters that have the greatest potential to influence the fate and transport of constituents. The two uncertainties found to have a high potential to affect modeled risks aligned well with sensitive parameters identified in the 2009 analysis.

Finally, as discussed in **Section 5.3**, EPA compared the risk assessment to field data and damage cases to validate the results. In general, leachate data were strongly corroborated by leachate concentrations observed in the field. The risk assessment results also generally agreed with the damage cases in that they both showed the same type of liners and constituents to cause the most risk to human health and the environment, and resulted in the same constituents exceeding the risk criteria most frequently. Where differences were observed, these were likely due to site-specific considerations that were not modeled in the risk assessment (e.g., placement of waste below the water table). As a result of these comparisons, and the analysis of the sensitivities and uncertainties of the model, EPA finds that the risk assessment provides a good representation of real-world, national-scale risks.

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6 Risk Characterization

The purpose of this document is to characterize the risks associated with current CCR disposal practices across the United States. To accomplish this task, EPA used mathematical models to estimate the rate at which chemical constituents are released from surface impoundments and landfills, the fate and transport of these constituents through the environment, and the potential risk of adverse effects to individual receptors within the exposed population. Modeling for each potential exposure pathway was conducted in a stepwise fashion, with more refined analyses used at each subsequent step until risks were sufficiently characterized. The purpose of this section is to summarize the analyses conducted and results obtained for each exposure pathway, provide further context for these results, and present the final Agency conclusions. This discussion is divided into the following subsections:

- **Section 6.1:** exposures to ambient air that result from the release of fugitive dust by wind.
- **Section 6.2:** exposures to soil, sediment, produce and animal products that result from the release of particulates by wind and overland run-off.
- **Section 6.3:** exposures to impoundment wastewater, ground water, surface water, and sediment that result from the release of leachate.

6.1 Exposure to Ambient Air

6.1.1 Problem Formulation

Many CCR wastes are composed of fine particulates that may become suspended in the air by the wind. These pathways are primarily associated with landfills during operation, as the postclosure cap for landfills and constant water cover for impoundments will limit the release of particulate matter. Although airborne releases may occur from surface impoundments if water levels decrease due to evaporation or other irregular events, EPA focused the analysis on landfills because of the potential for higher and more frequent releases. These particulates may be carried downwind, where the fine particulates and any chemical constituents contained therein may be inhaled by receptors. **Figures 6-1** depicts the potentially complete exposure pathways for these releases.

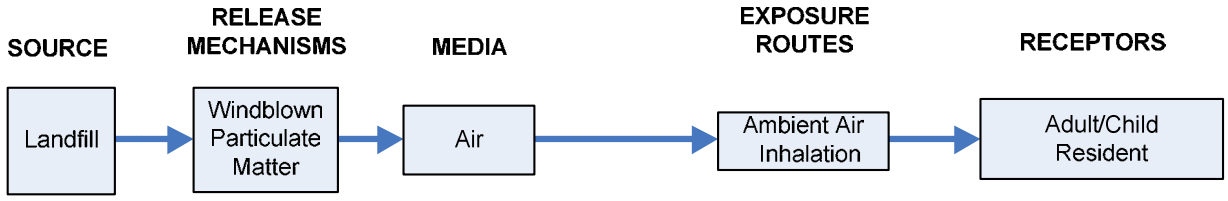

Figure 6-1. Conceptual model for ambient air exposures.

EPA first conducted a simplified hazard identification to identify the constituents that could be quantitatively evaluated. The confirmed presence of a constituent in CCR wastes, combined with the availability of at least one toxicity benchmark, was considered sufficient demonstration of

hazard potential. Because air concentrations can vary considerably over time, EPA considered three sets of toxicity benchmarks to capture the range of potential exposures. The first are acute benchmarks, which represent short-term exposures. The second were chronic cancer and noncancer benchmarks, which represent long-term exposures. The third were NAAQS, which represent EPA-developed regulatory standards based on varying exposure durations. **Table 6-1** lists each of the constituents which both concentration data and toxicity benchmarks were available. Each of these constituents was retained as COPCs for further analysis.

Table 6-1. List of Constituents Evaluated for Ambient Air Exposures

COPC (Benchmark)		COPC (Benchmark)		COPC (Benchmark)		COPC (Benchmark)	
Aluminum	(A,C)	Antimony	(A,C)	Arsenic	(A,C)	Barium	(A)
Beryllium	(A,C)	Boron	(A)	Cadmium	(A,C)	Calcium	(A)
Chloride	(A)	Chromium	(A,C)	Cobalt	(A,C)	Copper	(A)
Fluoride	(A)	Iron	(A)	Lanthanum	(A)	Lead	(A,N)
Magnesium	(A)	Manganese	(A,C)	Mercury	(A,C)	Molybdenum	(A)
Nickel	(A,C)	Nitrate/Nitrite	(A)	Selenium	(A,C)	Silicon	(A)
Silver	(A)	Sodium	(A)	Strontium	(A)	Sulfate	(A)
Thallium	(A)	Uranium	(A,C)	Vanadium	(A,C)	Zinc	(A)
PM_{10}	(N)	$PM_{2.5}$	(N)				

A – Acute Toxicity Benchmark
C – Chronic Toxicity Benchmark
N – National Ambient Air Quality Standard.

6.1.2 Screening Analysis

The screening analysis was conducted using the steady-state plume models, AERSCREEN and AERMOD. These models were used to calculate the maximum air concentrations that may occur, averaged over the course of 1 hour, 24 hours, 1 month and 1 year. Each of these exposure durations was calculated for two management scenarios: uncontrolled and controlled releases. Uncontrolled releases occur when no action is taken to reduce particulate emissions, while controlled releases occur when management practices are put in place to minimize the rate of particulates emissions. Yet, even with the best available fugitive dust controls, some emissions may still occur. Therefore, EPA modeled these reduced releases based on available field data. The modeled air concentrations reflect a combination of multiple high-end parameters, including emission rate, landfill size, weather, distance to receptor and waste COPC concentration. EPA used these air concentrations, together with available toxicity benchmarks, to estimate the likelihood of adverse effects to downgradient receptors.

- **Acute Risks** were calculated based on the maximum 1-hour concentration. Risks above an HQ_A of 1 was identified for arsenic (2) under an uncontrolled management scenario, but decreased below risk criteria when fugitive dust controls were considered.

- **Chronic Risks** were calculated based on the maximum annual concentration. All risks fell below the selected human health risk criteria under both a controlled and uncontrolled management scenario.
- **NAAQS** exceedances were calculated based on the available averaging time closest to that specified by the standards. An air concentration above the NAAQS for 24-hr $PM_{2.5}$ by a factor of 2 was identified under an uncontrolled management scenario, but decreased below risk criteria when fugitive dust controls were considered.

The screening analysis shows the potential for risks under an uncontrolled management scenario for acute arsenic exposure; chronic arsenic, cobalt and chromium VI exposures; and short-term $PM_{2.5}$ exposures. Due to the conservative nature of the screening, there is a great deal of uncertainty surrounding the calculated risks. The modeled ambient air concentrations represent a protective, but unlikely, combination of conditions that reflect at least an upper bound on potential exposures. Thus, the cumulative effect of these uncertainties results in an overestimation of potential risks to most or all receptors. Therefore, EPA makes no direct findings concerning the magnitude of the risks that may occur under either an uncontrolled or controlled management scenario, but concludes with a high degree of confidence that the reductions achievable with available management practices are sufficient to be protective even under this conservative screening assessment. Based on these lines of evidence, EPA concluded that no further characterization of is warranted.

6.2 Releases to Soil

6.2.1 Problem Formulation

Many CCR wastes are composed of fine particulates that may become suspended in the air by the wind or washed away overland by run-off and erosion. These pathways are primarily associated with landfills during operation, as the postclosure cap for landfills and constant water cover for impoundments will limit the release of particulate matter. Although these releases may occur from surface impoundments if water levels decrease due to evaporation, overtopping from extreme rainfall or other irregular events, EPA focused the analysis on landfills because of the potential for higher and more frequent releases. Released particulates may be carried downgradient, where COPCs may accumulate on top of soil, sediment and plant surfaces, as well as concentrate within plants and animals raised on contaminated soils. Receptors may be exposed through contact with or ingestion of the contaminated media. **Figures 6-2** depicts the potentially complete exposure pathways for these releases.

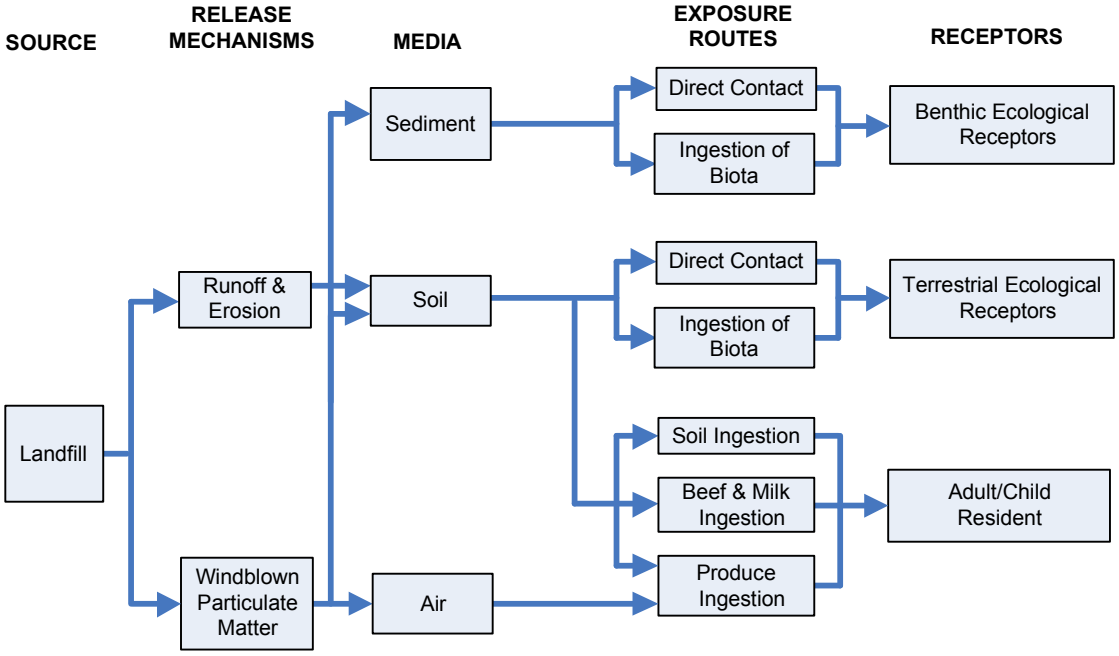

Figure 6-2. Conceptual model for soil exposures.

EPA first conducted a simplified hazard identification to identify the chemical constituents to be quantitatively evaluated. The confirmed presence of a constituent in CCR wastes, combined with the availability of at least one toxicity benchmark, was considered sufficient demonstration of hazard potential. EPA used chronic toxicity benchmarks to evaluate these exposures. Adverse effects from chronic exposures occur at lower concentrations than acute exposures. Therefore, the risks calculated for chronic exposures will also be protective of more acute exposures. **Table 6-2** lists each of the constituents for which both concentration data and toxicity benchmarks were available. Each of these constituents were retained as COPCs for further analysis.

Table 6-2. List of Constituents Evaluated for Soil, Sediment, Produce and Animal Product Exposures

COPC (Benchmark)		COPC (Benchmark)		COPC (Benchmark)		COPC (Benchmark)	
Aluminum	(N,E)	Antimony	(N,S,D)	Arsenic	(C,N,S,D)	Barium	(N,S,D)
Beryllium	(N,S)	Boron	(N,S)	Cadmium	(N,S,D)	Chromium	(C,N,S,D)
Cobalt	(N,S)	Copper	(N,S,D)	Fluoride	(N)	Iron	(N)
Lanthanum	(N)	Lead	(S,D)	Manganese	(N,S)	Mercury	(N,S,D)
Molybdenum	(N,S,D)	Nickel	(N,S,D)	Nitrate/Nitrite	(N)	Selenium	(N,S)
Silver	(N,S,D)	Strontium	(N)	Thallium	(N)	Uranium	(N)
Vanadium	(N,S,D)	Zinc	(N,S,D)				

C – Human Health Cancer Benchmark
N – Human Health Noncancer Benchmark
S – Ecological Soil Benchmark
D – Ecological Sediment Benchmark

6.2.2 Screening Analysis

The screening analysis was conducted using a combination of a conservative DAF of 10 and deposition rates calculated with AERMOD. Exposures were calculated for two management scenarios: uncontrolled and controlled releases. Uncontrolled releases occur when no action is taken to reduce particulate emissions. Controlled releases occur when management practices are put in place to minimize the rate of particulates emissions. Yet, even with the best available management practices, some emissions may still occur. Therefore, EPA modeled these reduced releases based on available field data. The modeled media concentrations reflect a combination of multiple high-end parameters, including emission rate, landfill size, weather, distance to receptor and waste COPC concentration. EPA used the modeled media concentrations, together with available toxicity benchmarks, to estimate the likelihood of adverse effects.

- **Human Health Cancer Risks** all fell below the selected human health risk criteria under both a controlled and uncontrolled management scenario.
- **Human Health Noncancer Risks** above an HQ of 1 were identified under the uncontrolled scenario. Thallium risks were identified for exposures to soil (2), beef (10) and milk (8). When fugitive dust and run-off controls were considered, all cancer risks fell below the risk range.
- **Ecological Soil Risks** above relevant criteria were identified under the uncontrolled scenario. Ecological risks above an HQ of 1 were identified were identified for, listed from highest to lowest: boron (80) antimony (20) vanadium (7) and selenium (3). When fugitive dust and run-off controls were considered, all risks fell below the risk range.
- **Ecological Sediment Risks** above relevant criteria were identified under the uncontrolled scenario. Ecological risks above an HQ of 1 were identified were identified for, listed from highest to lowest: vanadium (3), antimony (2), arsenic (2) and silver (2). When fugitive dust and run-off controls were considered, all risks fell below the risk range.

The screening analysis shows the potential for risks to both human and ecological receptors under an uncontrolled management scenario. Risks to human health resulted from ingestion of arsenic, chromium and thallium present in soil, produce and animal products. Ecological risks resulted from antimony, boron, selenium and vanadium present in soils and antimony, arsenic, silver and vanadium present in sediments. Due to the conservative nature of the screening, there is a great deal of uncertainty surrounding the calculated risks. The modeled media concentrations represent a protective, but unlikely, combination of conditions that most likely reflects an upper bound on potential exposures. The cumulative effect of these uncertainties results in an overestimation of potential risks. Therefore, EPA makes no direct findings concerning the magnitude of the risks that may occur under either an uncontrolled or controlled management scenario, but concludes with a high degree of confidence that the reductions achievable with available management practices are sufficient to be protective even under this conservative screening assessment.

Based on these lines of evidence, EPA concluded that no further characterization of soil, produce, or animal products is warranted. Although sediment exposures also screened out under the

controlled management scenario, EPA did retain sediment for further characterization. The results of the uncontrolled exposure scenario were used as a conservative screen for risks that may occur from subsurface transport of COPCs through ground water to sediment.

6.3 Releases to Ground Water

6.3.1 Problem Formulation

When CCR wastes are disposed on the ground, it may result in leaching to ground water. Many of these pathways are associated with both surface impoundments and landfills. Once mixed with ground water, the COPCs may migrate downgradient to private wells where it is ingested by receptors, to water bodies were **Figures 6-3** depicts the potentially complete exposure pathways for these releases.

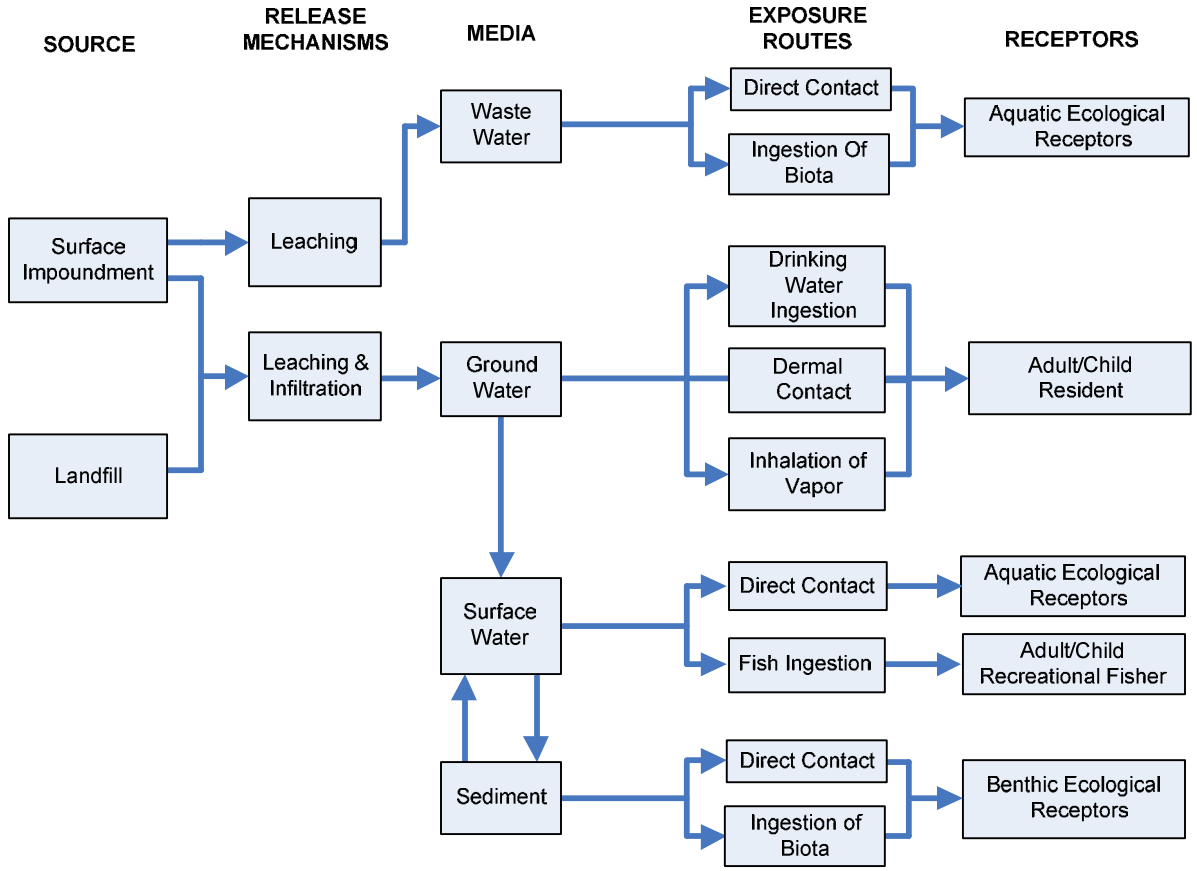

Figure 6-3. Conceptual model for ground water exposures.

EPA first conducted a simplified hazard identification to identify the constituents that could be quantitatively evaluated. The confirmed presence of a constituent in CCR wastes, combined with the availability of at least one toxicity benchmarks, was considered sufficient demonstration of hazard potential. EPA used chronic toxicity benchmarks to evaluate these exposures. Adverse effects from chronic exposures occur at lower concentrations than acute exposures. Therefore, the risks calculated for chronic exposures will also be protective of more acute exposures. **Table 6-3**

lists each of the constituents for which both concentration data and toxicity benchmarks were available. Each of these constituents were retained as COPCs for further analysis.

Table 6-3. List of Constituents Evaluated for Ground Water, Surface Water and Wastewater Exposures

COPC (Benchmark)		COPC (Benchmark)		COPC (Benchmark)		COPC (Benchmark)	
Aluminum	(N,E)	Ammonia	(N)	Antimony	(N,E)	Arsenic	(C,N,E)
Barium	(N,E)	Beryllium	(N,E)	Boron	(N,E)	Cadmium	(N,E)
Chloride	(E)	Chromium	(C,N,E)	Cobalt	(N,E)	Copper	(N,E)
Fluoride	(N)	Iron	(N,E)	Lanthanum	(N)	Lead	(M,E)
Lithium	(N)	Manganese	(N,E)	Mercury	(N,E)	Molybdenum	(N,E)
Nickel	(N,E)	Nitrate/Nitrite	(N)	Selenium	(N,E)	Silver	(N,E)
Strontium	(N)	Sulfide	(E)	Thallium	(N,E)	Uranium	(N)
Vanadium	(N,E)	Zinc	(N,E)				

C – Human Health Cancer Benchmark
N – Human Health Noncancer Benchmark
M – Maximum Contaminant Limit
E – Ecological Surface Water Benchmark

6.3.2 Screening Analysis

EPA used a conservative DAF of 1 to estimate the COPC concentrations that may be present in ground water, surface water and wastewater. The resulting exposure concentrations are equivalent to direct receptor exposures to undiluted CCR leachate. For these exposure pathways, EPA did not identify any post-construction management practices that could mitigate releases, so only one release scenario was considered. In addition, because the 2010 Risk Assessment (U.S. EPA, 2010a) previously demonstrated that risks from surface impoundments are consistently higher than those from landfills, EPA used the screening results for surface impoundments to also identify the initial set of COPCs for landfills. A summary of the modeled risks above relevant human health or ecological criteria is provided below:

- **Ground Water:** Ingestion of ground water resulted in risks above the human health criteria. Cancer risks above 1×10^{-5} were identified for arsenic (3×10^{-3}) and chromium VI (2×10^{-4}). Noncancer risks above an HQ of 1 were identified, from highest to lowest, for: arsenic (50), molybdenum (30), boron (10), fluoride (7), thallium (6), lithium (4), cobalt (3), antimony (2) and cadmium (2).
- **Surface Water:** Ingestion of fish resulted in risks above the human health criteria. Cancer risks above 1×10^{-5} were identified for arsenic (4×10^{-5}). Noncancer risks above an HQ of 1 were identified, from highest to lowest, for: selenium (10), mercury (7), thallium (4) and cadmium (2).
- **Surface Water:** Direct contact with and ingestion of surface water resulted in risks above ecological criteria. Ecological risks above an HQ of 1 were identified, from highest to lowest,

for: cadmium (200), aluminum (100), arsenic (100), boron (100), selenium (60), barium (50), lead (40), vanadium (30), chromium III (20), molybdenum (20), copper (10), iron (10), silver (10), chloride (9), nickel (6), beryllium (2), cobalt (2) and zinc (2).

- **Wastewater:** Direct contact with and ingestion of impoundment wastewater resulted in risks above ecological criteria. Ecological risks above an HQ of 1 were identified, from highest to lowest, for: arsenic (100), barium (50), aluminum (30), boron (30), selenium (20), cadmium (10), vanadium (10), beryllium (2), chloride (2) and chromium (2).

Multiple COPCs resulted in risks above human health and ecological criteria. For these pathways, there were no post-construction management practices identified to mitigate releases. However, considerable dilution and attenuation may occur before leachate reaches downgradient private wells, surface water and sediments. Therefore, EPA retained all of the COPCs found to be above risk criteria in ground water and surface water for further characterization in the probabilistic analysis. In addition, EPA carried forward the COPCs identified in the sediment screening previously discussed in **Section 6.2.2**.

Unlike the other exposure pathways, there will be little to no dilution and attenuation that will occur in impoundment wastewater prior to ecological exposures. Because of this, the screening analysis conducted provides sufficient characterization of this exposure pathway. Therefore, EPA concludes that there is the potential for risks to ecological receptors from concentrations of aluminum, arsenic, barium, beryllium, boron, cadmium, chloride, chromium, selenium and vanadium in surface impoundment wastewater.

6.3.3 Probabilistic Analysis

EPA conducted national-scale, probabilistic modeling to better characterize the risks to human and ecological receptors associated with leachate released from surface impoundments and landfills. A combination of models were used to predict COPC fate and transport through the environment, receptor exposures, and the resulting risks. EPA used the most complete and current data sets available to run these models. Site-specific data were used, supplemented by regional and national data sets, to capture the national variability of disposal practices, environmental conditions and receptor behavior. EPA modeled risks for both highly exposed individuals (90th percentile risks) and moderately exposed individuals (50th percentile risks). A summary of the modeled risks above relevant human health or ecological criteria is provided below:

- **Surface Impoundments:** Ingestion of ground water was the only exposure pathway that resulted in risks above the relevant criteria. 90th percentile cancer risks above 1×10^{-5} were identified for arsenic III (2×10^{-4}). 90th percentile noncancer risks above an HQ of 1 were identified for arsenic III (5), lithium (2), and molybdenum (2).
- **Landfills:** 90th percentile cancer and noncancer risks were all below human health criteria.

High-end risks for surface impoundments are consistently higher than those for landfills. These results are attributed primarily to the higher infiltration rates through surface impoundments, which is controlled by the hydraulic head of ponded water. Median risks for both surface impoundments

and landfills were substantially lower than both the high-end risks in this risk assessment and the median risks modeled in the 2010 Risk Assessment. This decrease is attributed primarily to the interception of ground water by surface water bodies, which is accounted for in the revised risk assessment to provide a more accurate mass balance of constituent mass during transport. It is common for coal-fired utilities to be located near water bodies, which are used as a source of cooling water and conveyance of waste. As a result, in the majority of model iterations, the interception of ground water by surface water bodies resulted in negligible downstream well concentrations.

The modeled probabilistic risks capture the range of current, nationwide CCR disposal practices. However, because of the broad scope of the analysis, there are a number of sources of variability and uncertainty present. Therefore, to confirm the results of the probabilistic analysis and to better understand whether any particular subset of disposal practices drives the risks identified, EPA retained each of the exposure pathways from the probabilistic analyses for additional sensitivity and uncertainty analyses.

6.3.4 Sensitivity and Uncertainty Analyses

EPA reviewed the models used, as well as all of the data and assumptions input into these models, to better understand the sources of variability and uncertainty inherent in the probabilistic analysis. The Agency then qualitatively and, where possible, quantitatively analyzed these sources to understand the potential effects each may have on the modeled risk results. During this review, specific attention was focused on the parameters shown to have the greatest influence on model results. The review found that, on the whole, the risk assessment results do not appear to be strongly biased toward overestimation or underestimation of risks, and there is a high degree of confidence in the principal findings of the probabilistic analysis. However, the review of sensitive parameters revealed some specific disposal practices that may result in greater risks than identified in the probabilistic modeling.

Two sensitive parameters are the leachate concentration and the subsurface K_d values. Both of these parameters are greatly influenced by the pH of the disposed waste. To explore the effect of pH on modeled risk results, EPA separated the full-scale national results into separate distributions to capture changes in risk at different pH values. Because of the very low 50th percentile risks identified in the probabilistic analyses, all risks presented are 90th percentile.

- **Surface Impoundments (low pH):** More acidic wastes, represented by the codisposal of ash and coal refuse (pH 1.7–8.2) resulted in risks above human health and ecological criteria. Cancer risks above 1×10^{-5} were identified for arsenic III (1×10^{-3}) and arsenic V (4×10^{-4}) from ingestion of ground water. Noncancer risks above an HQ of 1 were identified for arsenic III (26), arsenic V (14) and cobalt (13) from ingestion of ground water; for mercury (5) from fish ingestion; and for cadmium (3) from ecological exposure to surface water.
- **Surface Impoundments (high pH):** More basic wastes, represented by the disposal of FGD materials (pH 8.7–11.3) resulted in risks above human health criteria. Cancer risks above 1×10^{-5} were identified for arsenic III (2×10^{-4}) and arsenic V (2×10^{-5}) from ingestion of

ground water. Noncancer risks above an HQ of 1 were identified for arsenic III (5), boron (2) and fluoride (2) from ingestion of ground water.

- **Landfills:** 90th percentile cancer and noncancer risks were all below human health criteria over the relevant pH range.

The results show that the potential for higher risks from disposal of CCRs under more acidic and basic conditions. Additional risks from surface impoundments were identified for boron, cobalt, fluoride and mercury. Given the smaller fraction of units that manage wastes at these pH values, there is greater uncertainty associated with these risks. However, damage cases were identified for all of these constituents except fluoride.

Another sensitive parameter is the rate at which leachate can infiltrate through the WMU and into underlying soils. This parameter is controlled primarily by the type of liner present. To explore the effect of liner type on modeled risk results, EPA divided full-scale national results for surface impoundments and landfills into three separate distributions, one for each liner type modeled. Because of the very low 50th percentile risks identified in the probabilistic analyses, all risks presented are 90th percentile.

- **Unlined Units** were found to present the greatest risks. Unlined impoundments result in cancer risks above 1×10^{-5} for arsenic III (3×10^{-4}) and arsenic V (4×10^{-5}), as well as noncancer risks above an HQ of 1 for arsenic III (8), molybdenum (4), lithium (3) and thallium (2). Unlined landfills result in cancer risks above 1×10^{-5} for arsenic III (2×10^{-5}).
- **Clay-lined Units** were found to present risks lower than unlined units. Clay-lined impoundments result in noncancer risks for lithium (2).
- **Composite-lined Units** were found to result in risks far below all relevant risk criteria.

As modeled, unlined units present the greatest risks to human health and the environment. There is a high degree of confidence in these modeled results. EPA modeled these units with site-based soil hydraulic conductivities selected based on geographic location. In addition, these findings are corroborated by field observations that show the vast majority of damage cases to be associated with unlined units. The hydraulic conductivity of clay liners is based on a single value specified by the EPA Industrial Subtitle D Guidance (U.S. EPA, 2006b). Therefore, to the extent that clay-lined units behave differently in the field; because of a different effective hydraulic conductivity, liner thickness, or other factors; the risk assessment may over- or underestimate risks from these units. The hydraulic conductivity of composite-lined units was based on a range of field-measured values. Given the very low risks associated with these units, the various uncertainties are unlikely to affect the modeled results.

Additional damage cases were identified for other constituents for which no risks were identified in these sensitivity analyses (e.g., beryllium, lead, selenium). There are a number of reasons why modeled ground water risks and damage cases do not perfectly align. EPA considered a range of distances to receptor wells, whereas damage cases for ground water are typically associated with monitoring wells near the WMU. Furthermore, some individual damage cases reflect site-specific

disposal scenarios, such as placement of waste in contact with the water table, which could not be explicitly modeled. Therefore, EPA believes that these real-world risks validate those identified in the probabilistic and sensitivity analyses.

6.3.5 Conclusions

Based on the results of the probabilistic analysis, EPA concludes that leaching from CCR waste management units has the potential to pose risk to both human and ecological receptors. Arsenic, lithium and molybdenum are the chemical constituents found to pose the greatest risks from surface impoundments, while arsenic posed the greatest risks from landfills. Risks from arsenic ingestion are linked to an increase the risk of cancer in the skin, liver, bladder and lungs, as well as nausea, vomiting, abnormal heart rhythm, and damage to blood vessels. Risks from lithium ingestion are linked to neurological and psychiatric effects, decreased thyroid function, renal effects, cardiovascular effects, skin eruptions, and gastrointestinal effects. Risks from molybdenum ingestion are linked to higher levels of uric acid in the blood, gout-like symptoms, and anemia. EPA found that there is a high degree of confidence in underlying data for these modeled risks. In addition, these results are supported by damage cases. Arsenic is the constituent found most frequently in ground water damage cases and, while no MCL exists for lithium or molybdenum, exceedances of other criteria were identified for these two constituents in ground water damage cases.

Through additional sensitivity and uncertainty analyses that explored different subsets of disposal practices, EPA identified the potential for higher risks than those identified in the broader, national analysis. Consideration of different waste pH values showed higher risks for arsenic at more acidic and basic pH values, as well as additional risks for boron, cadmium, cobalt, fluoride and mercury at these more acidic and basic pHs. Consideration of specific liner types showed that ground water risks are driven by disposal in unlined units and, in particular, unlined surface impoundments. For these units, EPA identified higher risks for arsenic, lithium and molybdenum, as well as additional risks for thallium. Clay-lined units were found to pose risks that, while lower than unlined units, were still above the noncancer risk criteria for lithium. Consideration of uncertainties associated with the analysis of clay-lined units may result in somewhat lower or higher risks, which may decrease lithium risks below noncancer criteria, but may also result in additional constituents above cancer or noncancer risk criteria. Composite-lined units were found to be the most protective disposal practice, resulting in risks far below all criteria identified in this risk assessment.

The comparison of recent 2009/2010 EPA surveys with an older, 1995 EPRI survey indicates that the majority of newly constructed units are lined, and that that the practice of codisposal with coal refuse is declining. However, this risk assessment presents a static snapshot of current disposal practices. While newer units may be managed in a more protective manner, older units, which still comprise the majority of currently operating units, continue to operate in a manner that may pose risks to human health and the environment.

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Appendix A.

CCR Waste Management Unit Database

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A.1 Introduction

The U.S. Environmental Protection Agency (EPA or the Agency) relied on the U.S. Department of Energy (DOE) Energy Information Agency (EIA) Database for information on the location, generating capacity, and coal burned for each coal-fired utility power plant (hereafter referred to as "facilities"). The 2009 EIA database contained information on the tons of coal combustion residuals (CCRs) generated annually, as well as their disposition (e.g., landfilled) at 507 facilities. However, EIA does not provide information on the characteristics of the waste management units (WMUs) where the disposed CCRs are managed. For this information, two recent EPA surveys of on-site WMUs have since been completed:

- 2009 *Information Request Responses* [obtained under Section 104(e) of the Comprehensive Environmental Response, Compensation, and Liability Act][1] together with *Impoundment Assessment Reports*,[2] hereafter jointly referred to as "the 2009 EPA Survey"; and
- 2010 Questionnaire for the Steam Electric Power Generating Effluent Guidelines, hereafter referred to as "the 2010 EPA Survey.[3]"

A.1.1 2009 EPA Information Request Letters and Impoundment Assessment Reports

Following the massive coal ash spill at the Tennessee Valley Authority's Kingston facility in December 2008, EPA took aggressive steps to assess surface impoundments and other WMUs that manage residuals from coal combustion and that contain free liquids. Beginning on March 9, 2009, EPA mailed information request letters to electric utilities and corporations that reported wet CCR disposal to EIA in 2005. These letters requested information on the location (latitude/longitude) of each surface impoundment, as well as the surface impoundment area, capacity, liner type, operating period and waste type managed.

The Agency also conducted site assessments at many of these impoundments using contractors with expertise in dam integrity. To ensure that surface impoundment data were as accurate as possible, the site assessment reports were reviewed by EPA for the same information requested in the information request letters. The data from these two sources included information on a total of 729 surface impoundments as of June 2011. These data were extracted for inputs in the revised risk assessment. Further impoundment assessment reports have been compiled since this time, but the data from these reports are not reflected in this analysis. However, the Agency has continued to update this information on its website.[4]

[1] Available online at: www.epa.gov/osw/nonhaz/industrial/special/fossil/surveys/index.htm

[2] Additional impoundment assessment reports have been conducted since the model inputs were developed. Available online at: www.epa.gov/osw/nonhaz/industrial/special/fossil/surveys2/index.htm

[3] Available online at: water.epa.gov/scitech/wastetech/guide/steam_index.cfm

[4] Available online at: www.epa.gov/wastes/nonhaz/industrial/special/fossil/coalashletter.htm

A.1.2 2010 Questionnaire for the Steam Electric Power Generating Effluent Guidelines

In 2010, EPA distributed questionnaires to approximately 700 fossil- and nuclear-fueled steam electric power plants to support its proposed rule amending the effluent guidelines for the Steam Electric Power Generating category. The questionnaire requested information about many facets of facility operation, including surface impoundment and landfill operations. To reduce burden under the Paperwork Reduction Act (44 U.S.C. §3501 et seq.), the survey was comprised of nine sections (A through I), and EPA organized the respondents into four groups that completed different sections. Most coal-fired power plants received only Parts A through D, H and I of the survey. However, a statistically representative subset received all sections of the survey (Parts A through I).

The 2009 survey discussed above only contained surface impoundments information from facilities and companies that reported wet disposal to EIA in 2005. However, this survey captured both surface impoundment and landfill information from all facilities within the regulatory scope of the rulemaking. Thus, it accounted for both surface impoundments at facilities that did not report a wet disposal tonnage in EIA 2005 and landfills. Information included geographic location, dimensions (area, capacity and thickness), waste type, liner status and type, and operating period. These parameters were extracted from a database assembled to exclude data considered confidential business information (CBI). This database provided information on a total of 431 landfills and an additional 223 impoundments that had not been captured in the 2009 EPA survey.

A.2 Filling Data Gaps

The data from the surveys discussed above are hereafter collectively referred to as the CCR WMU database. Although facilities and WMUs are constantly opening and closing, the CCR WMU database identified all operating facilities at that time it was compiled. However, some data gaps still existed in the CCR WMU database, with information on some parameters (e.g., WMU size) missing for a subset of the WMUs. This occurred for four reasons. First, as part of its efforts to comply with the Paperwork Reduction Act, EPA sent different, incomplete versions of its 2010 survey to a number of facilities. Second, even when a facility received and answered all relevant questions, those facilities sometimes did not know the answer to some questions, or otherwise provided nonresponsive answers. Finally, even when a response was received, it was sometimes claimed as CBI. The data claimed as CBI that EPA was unable to successfully challenge by the time the data set was compiled for the analysis could not be presented in this document. Thus, to maintain the transparency of this report, EPA chose not to rely on it here.

To fill in data gaps, EPA first attempted to calculate the missing data for a WMU based on other available data for the same WMU. Where this was not possible, EPA filled in the gaps by drawing from a probability distribution created from surface impoundments and landfills with data. If the parameter in question was not anticipated to correlate to plant size (e.g., liner type), then EPA used the distributions developed for all impoundments or landfills. However, if the parameter in question may correlate to plant size (e.g., WMU size), EPA further divided the distributions into

quartiles based on the amount of coal burnt at each facility to avoid unrealistic combinations (e.g., largest WMU size and smallest facility). EPA defined the quartiles based on the coal use reported in the 2009 EIA database. All of the WMUs associated with facilities within a quartile were aggregated to create a new distribution. EPA then drew from the distribution type located at facilities in the same coal use quartile.

A description of the gap-filling procedures for each parameter is included below. **Attachment A-1** provides a summary of the data collected for each facility on geographic location, number of surface impoundments and landfills present, amount of coal burned and the associated coal use quartile. **Attachment A-2** provides a summary of the WMU-specific data collected for the CCR risk assessment, including geographic locations, dimensions, waste type, and liner type. Missing data for individual facilities and WMUs are listed in the attachment as blank fields.

A.2.1 Geographic Location

Each WMU in the survey was matched with a specific electric utility facility in the U.S. Department of Energy's EIA Forms EIA-860 (Annual Electric Generator Report) and EIA-923 (Power Plant Operations Report) using the Office of the Regulatory Information System facility identification code assigned by the EIA. This was done to provide a complete data set of approximate WMU locations. The latitudes and longitudes reported in the EIA Database often represent a centroid or front-gate location for each facility. However, WMUs can be located some distance away from the main facility. Therefore, where possible, the revised risk assessment used the available data from the CCR WMU database to identify the specific locations of individual WMUs and only relied on facility locations when no WMU-specific data was available. The reported locations for both facilities and WMUs were then reviewed based on visual inspection of aerial photography using Google Earth and adjusted, as appropriate. Obtaining and checking the latitude and longitude centroid locations missing in the survey data allowed greater accuracy for collecting the WMU-specific environmental setting information described in **Appendix B**.

A.2.2 Dimensions

The CCR WMU database includes information on the total surface area and total volumetric waste capacity of most surface impoundments and landfills included in the survey. Because the final capacity of a WMU was not always known, the capacity at closure was preferred when multiple values were available, followed by constructed capacity and current capacity as the best estimates for surface impoundment or landfill volume. To impute data for facilities missing either area or capacity data, but not both, linear regression equations were developed based on WMUs with both area and capacity data. The final regression equations are shown in **Figures A-1** and **A-2** for surface impoundments[5] and **Figures A-3** and **A-4** for landfills. In each case, the standard error around the regression line was used during source data file preparation to randomly vary the area or capacity from iteration to iteration within the bounds defined by the standard error. In cases where neither area nor capacity data were available, an area and capacity pairing was

[5] At the time these regressions were developed, EPA had data on 729 surface impoundments from the 2009 survey.

probabilistically selected from available data for units in the same coal use quartile as the units with the missing data.

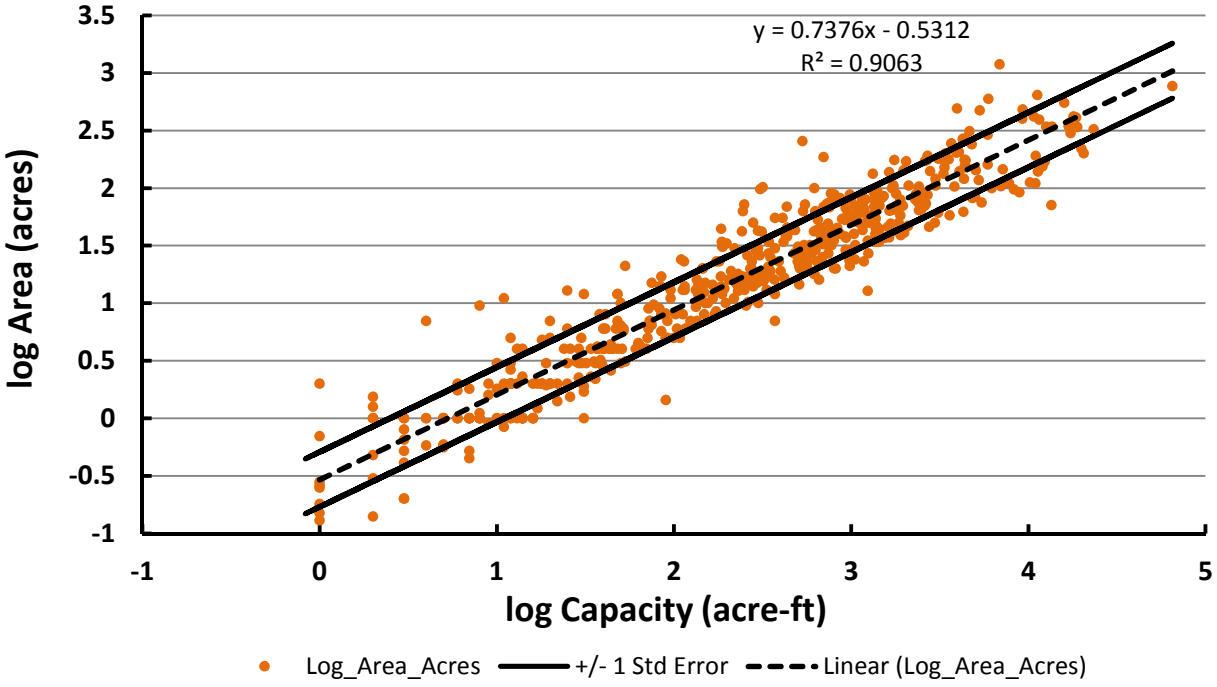

Figure A-1. Linear regression to impute surface impoundment area from capacity.

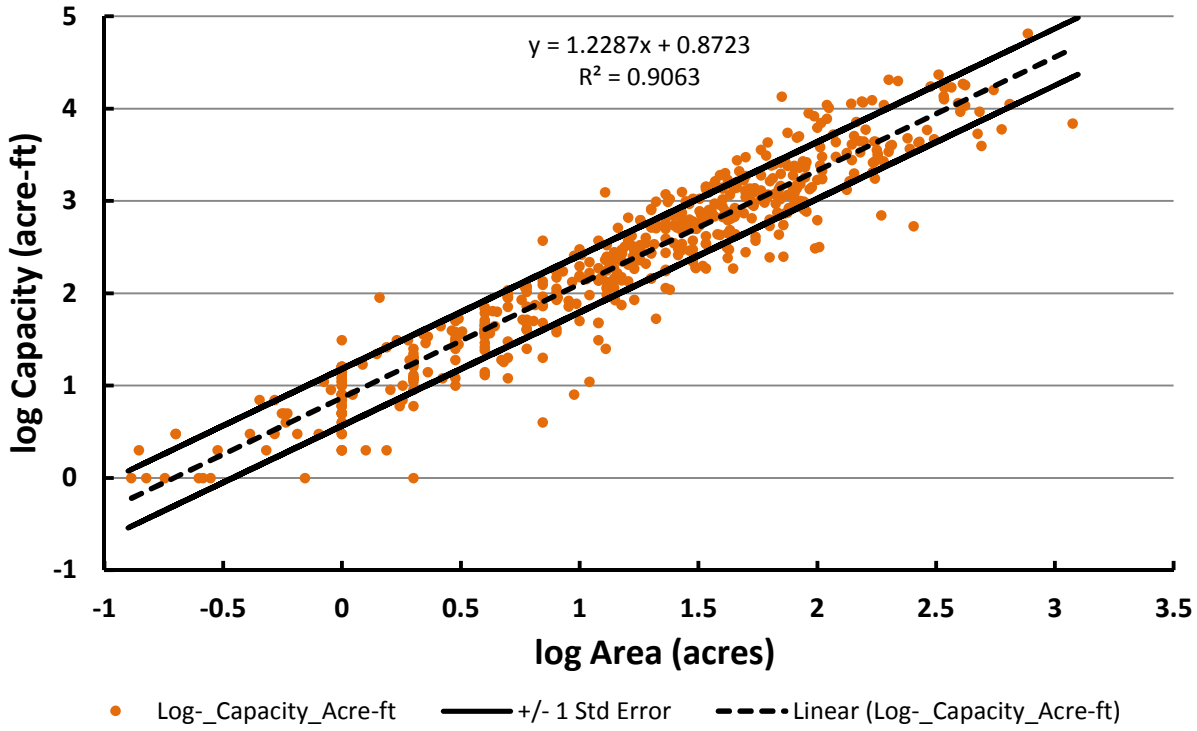

Figure A-2. Linear regression to impute surface impoundment capacity from area.

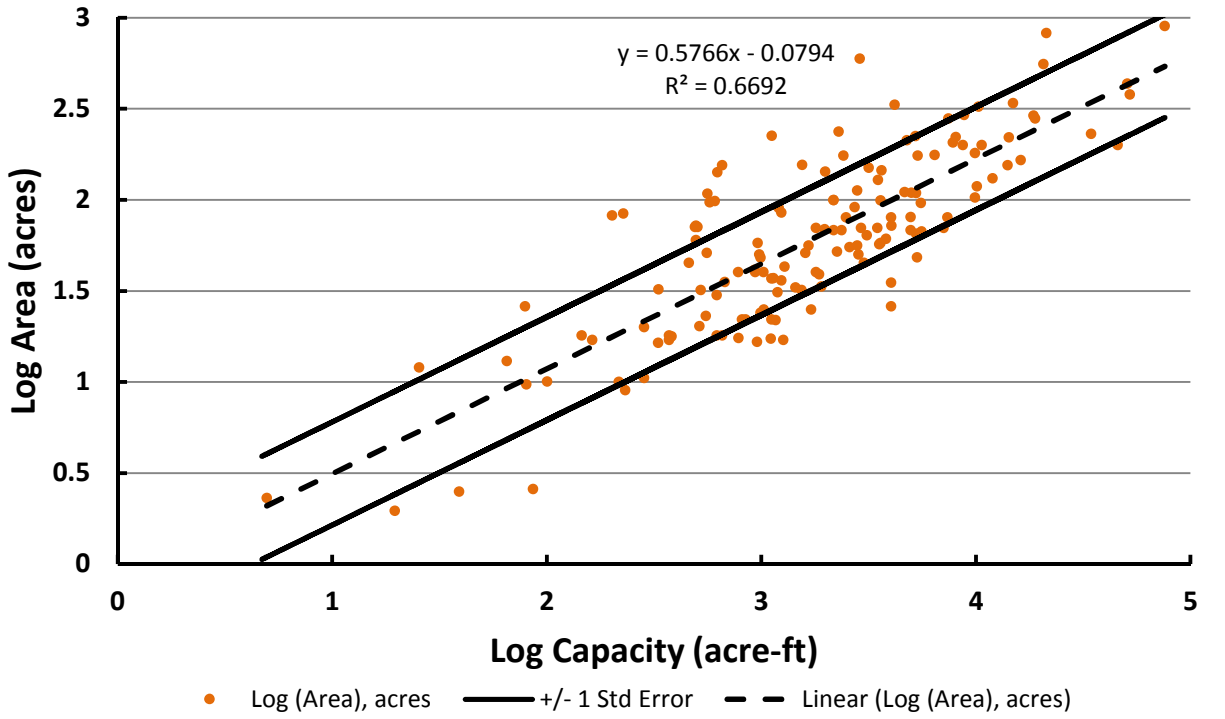

Figure A-3. Linear regression to impute landfill area from capacity.

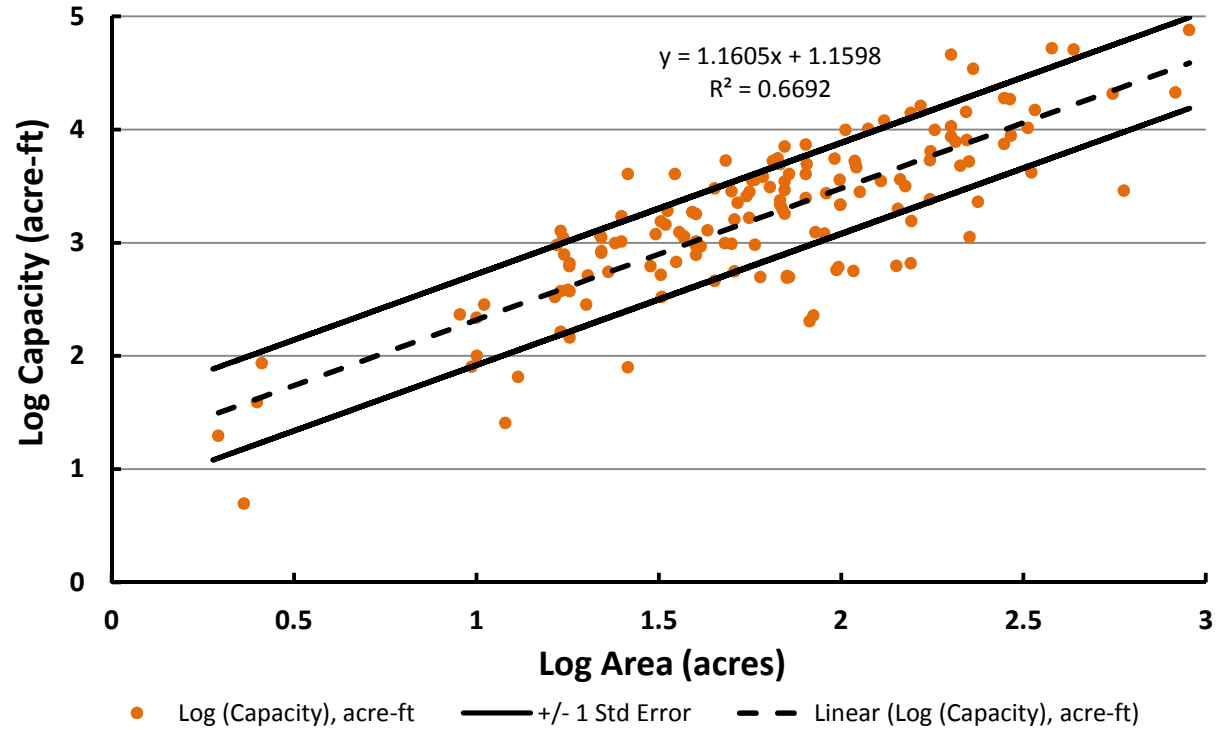

Figure A-4. Linear regression to impute landfill capacity from area.

The survey data do not include total unit depth, so it was calculated from area and capacity. For WMUs with both area and capacity reported, an average depth was calculated by dividing capacity by area. Where either area or capacity was missing, the missing value was imputed using a linear regression of capacity and area combinations reported for other WMUs. The resulting depths were then checked against the depths calculated for WMUs with both capacity and area data. For landfills, depths were compared to the minimum and maximum calculated depths (2 and 240 feet). For surface impoundments, depths were compared to the 1st and 99th percentile of the calculated depths (2 and 91 feet). Where depths for WMUs with imputed area or capacity were outside of these constraints, the imputed area or capacity was discarded and replaced with a new selection based on probabilistic selection within the standard error bounds surrounding the regression line, and the depth recalculated. No range check was performed on depths calculated when both area and capacity were reported; thus, a few surface impoundment depth values fall outside the 2- to 91-foot range.

A.2.3 Waste Type

The CCR WMU database included information on the type of CCRs managed in the WMUs. Waste types are necessary to account for differences in soil-water partition coefficient due to, for example, differences in pH. Based on the types of CCRs reported, the WMUs were assigned to one of three waste types: combined ash, ash and coal refuse, and flue gas desulfurization (FGD) waste. The three model waste types that EPA assigned to each WMU were:

- **Ash and Coal Refuse**: Includes any CCR that is codisposed with coal refuse, which is waste coal produced from coal handling, crushing and sizing operations. This waste type is characterized by a low to moderate pH (1.7–8.2) and high levels of sulfate, iron and manganese.
- **FGD Wastes**: Includes any type of wet or dry FGD waste when disposed in dedicated monofills. This waste type is characterized by a moderate to high pH (8.7–11.3) and high levels of calcium, sulfate, sodium and chlorine.
- **Combined Ash**: Includes any CCRs other than those listed above (e.g., fly ash, bottom ash, boiler slag) either monofilled or in combination with each other. Due to the variability in disposal practices, this waste type is characterized by a broad range in pH (3.9–12.3), sulfate and calcium levels.

In cases where the CCRs were not specified, one of these three waste types was probabilistically assigned to that WMU during each model run based on the prevalence of each among WMUs with reported waste types. **Table A-1** shows the crosswalk used to match reported CCRs to the different waste types for modeling surface impoundments. For landfills all waste types were modeled as combined ash.

Table A-1. Crosswalk Between Reported and Modeled Waste Type for Surface Impoundments

Reported CCRs	Model Waste Type
Fly ash[1,2]	Combined ash
Boiler slag[1], Slag[2]	
Bottom ash[1,2]	
Pozzolonic material[2]	
Any combination of FGD residues and other ash materials	
Flue gas emission control residuals[1]	FGD Waste
Gypsum[2]	
Ca sulfite[2]	
Dry FGD[2]	
Any of the above plus "Other" field containing coal refuse, such as pyrite(s), pyritic material, coal, coal fines, coal pile sludge, coal impurities, coal mill rejects, mill rejects, coal prep plant solids, coal pulverizer rejects, or coal refuse	Ash and coal refuse

1) Specified in 2009 Section 104(e) Information Request
2) Specified in 2010 Questionnaire for the Steam Electric Power Generating Effluent Guidelines

In addition to the waste types modeled in the revised risk assessment, EPA also identified FBC wastes as a distinct waste type. The 2010 Risk Assessment modeled the FBC waste type separately for landfills, but not surface impoundments, because of a lack of pore water data available at that time. This modeling showed that the risks associated with disposal of FBC waste in landfills were lower than those for other CCR waste types and below all risk criteria. Given these results and the lack of additional leachate data available since 2010, EPA did not re-evaluate FBC wastes in the revised risk assessment.

A.2.4 Liner Type

The CCR WMU database included information on the type of liner (if any) for the WMUs. Based on the type of liner reported, the WMUs were assigned to one of three liner types: an unlined (no liner) scenario, a compacted clay liner, and a composite liner that combines a plastic liner (e.g., high-density polyethylene membrane) over either geosynthetic or natural clays. These three liner types are the conceptual liner scenarios developed in support of EPA's *Guide for Industrial Waste Management* (U.S. EPA, 2002), and are described as follows:

- **No Liner Scenario:** Waste is placed directly on local soils, either on grade or excavated to some design depth and without a leachate collection system. At closure, two feet of native soil cover, the minimum required by Subtitle D regulations, is installed and assumed to support vegetation.
- **Clay Liner Scenario:** Waste is placed on a three-foot compacted clay liner that is installed over local soils without a leachate collection system, either on grade or excavated to some

design depth. At closure, a three-foot clay cover is installed and covered with one foot of loam to support vegetation and drainage.

- **Composite Liner Scenario:** Waste is placed on a liner system that consists of a plastic liner (e.g., high-density polyethylene membrane) underlain by either a natural or geosynthetic clay liner. A leachate collection system is assumed to exist between the waste and the liner system. At closure, a three-foot clay cover (graded and otherwise designed to prevent ponding) or functional equivalent is assumed to be installed and covered with one foot of loam to support vegetation and drainage.

In cases where the presence of a liner was not specified, one of these three scenarios was probabilistically assigned to that WMU during each model iteration based on the prevalence of these scenarios reported for impoundments or landfills. In cases where the survey indicated that a WMU was lined, but did not specify the type of liner, a clay or composite scenario was assigned probabilistically based on the prevalence of the different liner types reported for impoundments or landfills. **Table A-2** shows the crosswalk used to match these three conceptual liner scenarios to the different types reported in the CCR WMU database. The five impoundments lined with asphalt and 12 impoundments lined with concrete were treated as effectively unlined because these materials tend to crack, eliminating the effectiveness of the liner without regular maintenance. Thus, these materials are not considered to be adequate liners for regulated waste disposal facilities. The two "natural clay" lined impoundments were also considered to be unlined because they are unlikely to meet the design specifications of the clay-lined scenario.

Table A-2. Crosswalk Between Survey Data and CCR Source Model Liner Types for CCR Surface Impoundments and Landfills

Reported Survey Liner Type	Model Liner Description
Surface Impoundment Liners	
None	Unlined
Natural clay	
Asphalt	
Concrete	
Clay	Clay-Lined
Bentonite	
Composite	Composite-Lined
Flexible Membrane Liner	
Yes	Clay or Composite*
Confidential Business Information	Blank

(continued)

Table A-2. Crosswalk Between Survey Data and CCR Source Model Liner Types for CCR Surface Impoundments and Landfills

Reported Survey Liner Type	Model Liner Description
Landfill Liners	
None	Unlined
Coal Combustion Residual	
Clay	Clay-Lined
Composite	Composite-Lined
Flexible Membrane Liner	
Yes	Clay or Composite*

*Randomly selected from these two options based on the frequency of occurrence of each type in the database for landfills.

A.3 References

U.S. EPA (Environmental Protection Agency). 2002. *Industrial Waste Management Evaluation Model (IWEM) Technical Background Document.* EPA 530-R-02-012. Office of Solid Waste, Washington, DC. August.

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Attachment A-1.
Plant Information

Attachment A-1. Plant Information

Oris Code	Plant Name	City	County	State	Latitude	Longitude	# of SIs	# of LFs	Coal Use (short tons)	Coal Use Quartile
6137	A. B. Brown Generating Station	Mount Vernon	Posey	IN	37.9053	-87.715	2	1	1,073,131	3
2535	AES Cayuga, LLC	Lansing	Tompkins	NY	42.6028	-76.6336	0	1	660,804	2
2527	AES Greenidge	Dresden	Yates	NY	42.6789	-76.9483	2	1	186,643	1
994	AES Petersburg	Petersburg	Pike	IN	38.5267	-87.2525	4	1	5,137,697	4
6082	AES Somerset LLC	Barker	Niagara	NY	43.3561	-78.6039	1	2	1,276,355	3
3942	Albright Power Station	Albright	Preston	WV	39.4883	-79.6367	2	2	161,122	1
1915	Allen S King	Bayport	Washington	MN	45.03	-92.7786	0	1	1,953,756	3
3393	Allen Steam Plant	Memphis	Shelby	TN	35.0742	-90.1492	2	0	2,836,020	4
4140	Alma	Alma	Buffalo	WI	44.302886	-91.912731	0	2	232,721	1
1122	Ames Electric Services Power Plant	Ames	--	IA	42.025244	-93.607994	1	0	238,410	1
6469	Antelope Valley Station	Beulah	Mercer	ND	47.37	-101.8353	2	2	5,785,560	4
160	Apache Station	Cochise	Cochise	AZ	32.061431	-109.894189	10	0	1,127,721	3
465	Arapahoe	Denver	Denver	CO	39.67	-105.0028	6	0	552,381	2
3178	Armstrong Power Station	Adrian	Armstrong	PA	40.9289	-79.4658	0	2	254,872	2
2076	Asbury	Asbury	Jasper	MO	37.361322	-94.589235	3	0	789,610	2
2706	Asheville Steam Electric Plant	Arden	Buncombe	NC	35.4714	-82.5431	2	0	949,209	2
2835	Ashtabula	Ashtabula Township	Ashtabula	OH	41.9083	-80.7667	1	0	305,324	2
1961	Austin Northeast	Austin	Mower	MN	43.701292	-92.962461	0	1	690	1
2836	Avon Lake	Avon Lake	Lorain	OH	41.504175	-82.055917	2	1	1,245,125	3
995	Bailly	Chesterton	Porter	IN	41.6433	-87.1225	6	2	1,146,280	3
889	Baldwin Energy Complex	Baldwin	Randolph	IL	38.205	-89.855	1	0	7,281,194	4
3	Barry	Bucks	Mobile	AL	31.0069	-88.0103	1	0	3,526,534	4
3982	Bay Front	Ashland	Ashland	WI	46.5869	-90.9017	2	2	99,729	1
2878	Bay Shore	Oregon	Lucas	OH	41.6925	-83.4375	1	1	1,005,669	3
8042	Belews Creek Steam Station	Belews Creek	Stokes	NC	36.2811	-80.0603	1	3	5,544,561	4
6034	Belle River	China Township	St Clair	MI	42.7748	-82.4945	1	1	5,239,679	4
3325	Ben French	Rapid City	Pennington	SD	44.0872	-103.2614	1	0	138,345	1
645	Big Bend	Apollo Beach	Hillsborough	FL	27.7944	-82.4036	8	1	3,730,004	4
3497	Big Brown	Fairfield	Freestone	TX	31.8206	-96.0561	4	4	5,598,198	4
6055	Big Cajun 2	New Roads	Pointe Coupee	LA	30.7261	-91.3669	3	1	7,622,197	4
1353	Big Sandy	Louisa	Lawrence	KY	38.169873	-82.618975	3	0	2,507,625	3
6098	Big Stone	Big Stone City	Grant	SD	45.3047	-96.5103	1	1	1,968,292	3
1904	Black Dog	Burnsville	Dakota	MN	44.8108	-93.2501	1	1	824,624	2
6106	Boardman	Boardman	Morrow	OR	45.6933	-119.8056	3	1	1,854,042	3
7790	Bonanza Power Plant	Vernal	Uintah	UT	40.0864	-109.2844	3	2	1,830,397	3
1893	Boswell Energy Center	Cohasset	Itasca	MN	47.2603	-93.6531	3	3	3,647,016	4
703	Bowen	Cartersville	Bartow	GA	34.1256	-84.9192	1	1	8,563,992	4
602	Brandon Shores	Baltimore	Anne Arundel	MD	39.180082	-76.5393	2	0	2,804,331	3
1619	Brayton Point	Somerset	Bristol	MA	41.7125	-71.1914	10	5	2,951,760	4
3796	Bremo Bluff	Bremo Bluff	Fluvanna	VA	37.7089	-78.2878	2	0	394,451	2
6094	Bruce Mansfield	Shippingport	Beaver	PA	40.6344	-80.42	5	0	6,803,553	4
2720	Buck	Salisbury	Rowan	NC	35.7133	-80.3767	3	0	203,504	1
3396	Bull Run	Clinton	Anderson	TN	36.0211	-84.1567	4	2	1,244,205	3
1104	Burlington	Burlington	Des Moines	IA	40.741617	-91.117447	5	0	764,035	2
676	C D McIntosh Jr	Lakeland	Polk	FL	28.0809	-81.9256	0	2	702,933	2
468	Cameo	Palisade	Mesa	CO	39.148759	-108.318221	2	0	242,481	1
3280	Canadys Steam	Canadys	Colleton	SC	33.0648	-80.623906	3	0	466,851	2
1363	Cane Run	Louisville	Jefferson	KY	38.1828	-85.8894	5	1	1,575,971	3
2708	Cape Fear Steam Electric Plant	Moncure	Chatham	NC	35.595	-79.0492	5	0	733,115	2
3644	Carbon Plant	Helper	Carbon	UT	39.7264	-110.8639	2	2	561,457	2
2828	Cardinal	Brilliant	Jefferson	OH	40.2522	-80.6486	2	1	4,477,802	4
1001	Cayuga	Cayuga	Vermillion	IN	39.9239	-87.4272	4	1	2,393,527	3
1571	Chalk Point LLC	Aquasco	Prince Georges	MD	38.5444	-76.6861	0	2	1,452,908	3
2169	Chamois Power Plant	Chamois	Osage	MO	38.6853	-91.7556	1	0	267,468	2
56	Charles R. Lowman	Leroy	Washington	AL	31.484791	-87.914365	4	1	1,400,093	3
469	Cherokee	Denver	Adams	CO	39.807872	-104.964447	6	0	1,533,203	3
3803	Chesapeake Energy Center	Chesapeake	Chesapeake	VA	36.7711	-76.3019	1	1	1,458,128	3
3797	Chesterfield	Chester	Chesterfield	VA	37.3822	-77.3833	2	0	3,299,383	4
8226	Cheswick Power Plant	Springdale	Allegheny	PA	40.538427	-79.790906	2	1	1,163,744	3
113	Cholla	Joseph City	Navajo	AZ	34.9414	-110.3003	2	1	3,934,490	4
2721	Cliffside	Cliffside	Cleveland	NC	35.22	-81.7594	3	0	1,327,943	3
983	Clifty Creek	Madison	Jefferson	IN	38.7383	-85.4192	2	2	4,352,443	4
3775	Clinch River	Cleveland	Russell	VA	36.9333	-82.1997	2	1	659,643	2
7213	Clover	Clover	Halifax	VA	36.869415	-78.704332	5	2	2,281,319	3
6030	Coal Creek	Underwood	McLean	ND	47.3789	-101.1572	2	6	8,037,582	4
861	Coffeen	Coffeen	Montgomery	IL	39.0586	-89.4031	2	1	2,582,575	3
47	Colbert	Tuscumbia	Colbert	AL	34.744214	-87.848825	3	1	1,437,063	3
6178	Coleto Creek	Fannin	Goliad	TX	28.7128	-97.2142	2	0	3,072,440	4
6076	Colstrip	Colstrip	Rosebud	MT	45.8844	-106.6139	8	0	8,344,993	4
10784	Colstrip Energy LP	Colstrip	Rosebud	MT	45.880278	-106.61333	0	2	242,424	1
8023	Columbia	Pardeville	Columbia	WI	43.4864	-89.4203	4	2	4,053,332	4
2123	Columbia	Columbia	Boone	MO	38.9658	-92.3175	1	0	41,364	1

Attachment A-1. Plant Information

Oris Code	Plant Name	City	County	State	Latitude	Longitude	# of SIs	# of LFs	Coal Use (short tons)	Coal Use Quartile
470	Comanche	Pueblo	Pueblo	CO	38.2081	-104.5747	5	1	2,869,801	4
3118	Conemaugh	New Florence	Indiana	PA	40.3842	-79.0611	5	2	4,546,143	4
2840	Conesville	Conesville	Coshocton	OH	40.1842	-81.8811	1	2	2,817,418	3
1710	Consumers Energy - J.H. Campbell	West Olive	Ottawa	MI	42.9103	-86.2036	1	4	5,175,189	4
1384	Cooper Station.	Somerset	Pulaski	KY	36.999267	-84.591617	0	1	685,149	2
7210	Cope	Cope	Orangeburg	SC	33.3642	-81.03	0	1	982,303	3
6177	Coronado Generating Station	St. Johns	Apache	AZ	34.5778	-109.2717	1	2	3,241,666	4
8222	Coyote	Beulah	Mercer	ND	47.2217	-101.8139	3	4	2,032,400	3
2549	CR Huntley Generating Station	Tonawanda	Erie	NY	42.97	-78.93	3	1	1,188,116	3
6021	Craig	Craig	Moffat	CO	40.4627	-107.5912	2	1	4,695,209	4
867	Crawford	Chicago	Cook	IL	41.8278	-87.7236	1	0	1,531,424	3
753	Crisp Plant	Warwick	Worth	GA	31.844713	-83.940655	1	0	37	1
641	Crist	Pensacola	Escambia	FL	30.5658	-87.2239	7	1	1,573,176	3
130	Cross	Pineville	Berkeley	SC	33.3692	-80.1119	3	4	5,716,190	4
628	Crystal River Power Plant	Crystal River	Citrus	FL	28.957539	-82.700478	0	1	4,749,124	4
3399	Cumberland	Cumberland City	Stewart	TN	36.3903	-87.6539	3	1	6,517,310	4
6823	D B Wilson	Centertown	Ohio	KY	37.45002	-87.07687	0	2	898,927	2
1702	D.E. Karn	Essexville	Bay	MI	43.645	-83.8414	2	1	1,422,822	3
1385	Dale Station	Winchester	Clark	KY	37.8807	-84.2634	3	0	389,154	2
963	Dallman	Springfield	Sangamon	IL	39.7547	-89.6008	1	2	1,045,347	3
2723	Dan River	Eden	Rockingham	NC	36.485975	-79.720814	3	0	84,887	1
2480	Danskammer Generating Station	Newburgh	Orange	NY	41.571403	-73.975069	0	1	843,688	2
4158	Dave Johnston Plant	Glenrock	Converse	WY	42.837966	-105.776594	8	1	3,572,403	4
996	Dean H Mitchell	Gary	Lake	IN	41.6394	-87.4069	8	0	-	1
663	Deerhaven Generating Station	Gainsville	Alachua	FL	29.7586	-82.3883	1	1	555,951	2
1572	Dickerson	Dickerson	Montgomery	MD	39.2086	-77.4644	0	1	949,178	2
51	Dolet Hills	Mansfield	De Soto	LA	32.0306	-93.5692	7	1	3,727,310	4
3317	Dolphus M Grainger	Conway	Horry	SC	33.8253	-79.0528	2	0	76,913	1
1046	Dubuque	Dubuque	Dubuque	IA	42.503036	-90.658408	1	0	108,348	1
6016	Duck Creek	Canton	Fulton	IL	40.4663	-89.9841	3	1	1,078,018	3
2554	Dunkirk Generating Plant	Dunkirk	Chautauqua	NY	42.4919	-79.3469	3	1	1,595,419	3
26	E. C. Gaston	Wilsonville	Shelby	AL	33.244063	-86.457147	1	0	3,299,127	4
1355	E.W. Brown	Harrodsburg	Mercer	KY	37.7889	-84.7139	2	0	1,092,651	3
991	Eagle Valley	Martinsville	Morgan	IN	39.484911	-86.418192	5	0	548,714	2
1217	Earl F Wisdom	Spencer	Clay	IA	43.1606	-95.2569	0	1	2,615	1
6018	East Bend Station	Rabbit Hash	Boone	KY	38.9031	-84.8511	3	1	1,913,481	3
2837	Eastlake	Eastlake	Lake	OH	41.6713	-81.4432	1	1	2,548,374	3
856	ED Edwards	Bartonville	Peoria	IL	40.5958	-89.6631	3	0	2,869,904	4
4050	Edgewater	Sheboygan	Sheboygan	WI	43.7181	-87.7092	6	2	2,472,707	3
1004	Edwardsport	Edwardsport	Knox	IN	38.8067	-87.2472	2	1	35,077	1
1374	Elmer Smith Station	Owensboro	Daviess	KY	37.795285	-87.059517	4	0	1,197,428	3
3098	Elrama Power Plant	Elrama	Washington	PA	40.253219	-79.917297	4	1	173,581	1
1832	Erickson Station	Lansing	Eaton	MI	42.6919	-84.6572	1	0	580,153	2
87	Escalante	Prewitt	McKinley	NM	35.4159	-108.082	5	1	1,097,758	3
1012	F. B. Culley	Newburgh	Warrick	IN	37.91	-87.3267	2	0	775,722	2
1218	Fair Station	Muscatine	Muscatine	IA	41.457127	-90.823729	2	1	117,062	1
6179	Fayette Power Project	La Grange	Fayette	TX	29.9172	-96.7506	2	1	6,964,482	4
886	Fisk	Chicago	Cook	IL	41.8508	-87.6533	3	0	1,001,069	3
6138	Flint Creek	Gentry	Benton	AR	36.2561	-94.5241	2	1	1,751,468	3
3943	Fort Martin Power Station	Maidsville	Monongalia	WV	39.7107	-79.9275	2	2	1,884,600	3
10343	Foster Wheeler Mt Carmel Cogen	MARION HEIGHTS	Northumberland	PA	40.8092	-76.4539	0	1	470,797	2
2442	Four Corners	Fruitland	San Juan	NM	36.69	-108.4814	5	2	8,826,370	4
1043	Frank E. Ratts	Petersburg	Pike	IN	38.5183	-87.2722	8	0	731,704	2
2718	G G Allen	Belmont	Gaston	NC	35.1897	-81.0122	3	1	1,513,392	3
7	Gadsden	Gadsden	Etowah	AL	34.012872	-85.97065	1	0	133,915	1
3403	Gallatin	Gallatin	Sumner	TN	36.3156	-86.4006	3	0	3,886,195	4
8102	General James M. Gavin	Cheshire	Gallia	OH	38.9347	-82.1158	2	1	7,984,101	4
4143	Genoa	Genoa	Vernon	WI	43.5592	-91.2333	0	2	984,696	3
1091	George Neal North	Sergeant Bluff	Woodbury	IA	42.324274	-96.379052	3	5	3,779,259	4
7343	George Neal South	Salix	Woodbury	IA	42.3022	-96.3622	1	1	2,431,599	3
6077	Gerald Gentleman	Sutherland	Lincoln	NE	41.081192	-101.141087	0	1	6,011,209	4
1356	Ghent	Ghent	Carroll	KY	38.7497	-85.035	5	0	5,331,887	4
6136	Gibbons Creek Steam Electric Station	Anderson	Grimes	TX	30.6167	-96.0778	4	2	2,057,295	3
6113	Gibson	Owensville	Gibson	IN	38.3722	-87.7661	6	2	8,691,426	4
3776	Glen Lyn	Glen Lyn	Giles	VA	37.370314	-80.863778	2	1	187,903	1
8	Gorgas	Parrish	Walker	AL	33.6446	-87.2003	2	1	2,251,490	3
1825	Grand Haven City of J.B. Sims	Grand Haven	Ottawa	MI	43.069233	-86.233953	2	0	156,699	1
10151	Grant Town Power Plant	GrantTown	Marion	WV	39.5611	-80.1642	5	3	590,673	2
165	GRDA	Chouteau	Mayes	OK	36.1906	-95.2889	1	1	4,506,123	4
1357	Green River	Central City	Muhlenberg	KY	37.3636	-87.1214	5	0	303,105	2
10	Greene County	Forkland	Greene	AL	32.6017	-87.7811	1	0	1,014,259	3

Attachment A-1. Plant Information

Oris Code	Plant Name	City	County	State	Latitude	Longitude	# of SIs	# of LFs	Coal Use (short tons)	Coal Use Quartile
6041	H L Spurlock Station	Maysville	Mason	KY	38.7	-83.8175	1	1	3,567,030	4
2709	H.F. Lee Plant	Goldsboro	Wayne	NC	35.379904	-78.087722	5	0	823,583	2
708	Hammond	Rome	Floyd	GA	34.2533	-85.3456	4	1	1,507,985	3
1731	Harbor Beach Power Plant	Harbor Beach	Huron	MI	43.851856	-82.643811	1	0	70,624	1
990	Harding Street	Indianapolis	Marion	IN	39.7119	-86.1975	5	0	1,783,189	3
709	Harllee Branch	Milledgeville	Putnam	GA	33.1942	-83.2994	5	0	2,604,594	3
6193	Harrington	Amarillo	Potter	TX	35.2972	-101.7475	0	2	4,336,723	4
3944	Harrison Power Station	Haywood	Harrison	WV	39.384521	-80.332908	1	1	4,153,187	4
3179	Hatfield's Ferry Power Station	Masontown	Greene	PA	39.856043	-79.92796	5	1	3,886,391	4
891	Havana	Havana	Mason	IL	40.2797	-90.0775	2	0	1,345,638	3
2079	Hawthorn	Kansas City	Jackson	MO	39.130668	-94.477876	1	1	2,442,255	3
525	Hayden	Hayden	Routt	CO	40.487247	-107.185218	6	2	1,516,188	3
3251	HB Robinson / Darlington Electric Power Plant	Hartsville	Darlington	SC	34.4017	-80.1589	1	0	408,053	2
892	Hennepin Power Station	Hennepin	Putnam	IL	41.3028	-89.315	1	1	1,246,097	3
1382	HMP&L Station Two Henderson	Robards	Henderson	KY	37.6472	-87.5028	2	1	751,395	2
108	HOLCOMB	HOLCOMB	Finney	KS	37.9306	-100.9725	0	1	1,636,686	3
3122	Homer City Station	Homer City	Indiana	PA	40.5142	-79.1969	14	3	4,572,113	4
1943	Hoot Lake	Fergus Falls	Otter Tail	MN	46.29	-96.0428	0	7	370,078	2
10771	Hopewell	Hopewell	Hopewell City	VA	37.297747	-77.282104	1	0	51,795	1
6772	Hugo	Fort Towson	Choctaw	OK	34.0158	-95.3206	4	1	2,011,996	3
3176	Hunlock Power Station	Hunlock Creek	Luzerne	PA	41.2033	-76.0683	2	0	194,691	1
6165	Hunter Plant	Castle Dale	Emery	UT	39.173597	-111.029432	1	1	4,428,980	4
8069	Huntington Plant	Huntington	Emery	UT	39.379164	-111.078356	2	3	2,743,739	3
863	Hutsonville	Hutsonville	Crawford	IL	39.1333	-87.6597	4	0	349,618	2
6065	Iatan	Weston	Platte	MO	39.447967	-94.979744	1	1	2,313,427	3
6641	Independence	Newark	Independence	AR	35.6733	-91.4083	0	1	6,820,983	4
2132	Independence Power & Light - Blue Valley Station	Independence	Jackson	MO	39.0919	-94.3261	3	0	95,597	1
594	Indian River Generating Station	Dagsboro	Sussex	DE	38.585411	-75.234872	2	2	1,085,100	3
6481	Intermountain Power Project	Delta	Millard	UT	39.5108	-112.5792	6	0	5,943,436	4
7097	J K Spruce	San Antonio	Bexar	TX	29.3064	-98.3203	6	1	2,149,348	3
2850	J M Stuart	Aberdeen	Adams	OH	38.6361	-83.6939	6	2	6,749,846	4
6181	J T Deely	San Antonio	Bexar	TX	29.3072	-98.3228	6	2	2,770,903	3
1720	J.C. Weadock	Essexville	Bay	MI	43.643903	-83.841217	4	1	934,487	2
1723	J.R Whiting	Erie	Monroe	MI	41.7917	-83.4486	4	2	1,017,083	3
710	Jack McDonough	Smyrna	Cobb	GA	33.8244	-84.475	4	1	865,958	2
2049	Jack Watson	Gulfport	Harrison	MS	30.4392	-89.0264	1	1	1,300,445	3
1830	James De Young	Holland	Ottawa	MI	42.7956	-86.1133	1	1	119,322	1
6002	James H. Miller Jr.	Quinton	Jefferson	AL	33.6319	-87.0597	1	0	12,161,264	4
2161	James River Power Station	Springfield	Greene	MO	37.1086	-93.2592	1	1	806,629	2
2187	JE Corette Plant	Billings	Yellowstone	MT	45.7747	-108.4803	2	1	694,842	2
3319	Jefferies	Moncks Corner	Berkeley	SC	33.2422	-79.9875	2	0	99,857	1
6068	Jeffrey Energy Center	St Marys	Pottawatomie	KS	39.287164	-96.118144	3	2	8,638,976	4
8066	Jim Bridger Plant Units 1-4	Point of Rocks	Sweetwater	WY	41.738008	-108.786719	2	1	8,344,833	4
3935	John E. Amos	Winfield	Putnam	WV	38.4731	-81.8233	2	2	5,498,720	4
4271	John P. Madgett	Alma	Buffalo	WI	44.3022	-91.9142	0	2	1,499,381	3
3405	John Sevier	Rogersville	Hawkins	TN	36.3767	-82.9639	2	1	1,536,343	3
3406	Johnsonville	New Johnsonville	Humphreys	TN	36.0278	-87.9861	2	2	2,452,565	3
384	Joliet 29	Joliet	Will	IL	41.4947	-88.125	1	1	3,790,190	4
874	Joliet 9	Joliet	Will	IL	41.4931	-88.1153	2	0	811,962	2
887	Joppa Steam	Joppa	Massac	IL	37.2103	-88.8606	1	1	4,383,292	4
3947	Kammer	Moundsville	Marshall	WV	39.8464	-80.8189	1	0	852,381	2
3936	Kanawha River	Glasgow	Kanawha	WV	38.2056	-81.4211	1	0	699,984	2
1381	Kenneth C Coleman	Hawesville	Hancock	KY	37.9628	-86.7917	3	0	1,278,540	3
3136	Keystone	Shelocta	Armstrong	PA	40.6604	-79.3411	11	3	3,992,921	4
6031	Killen Station	Manchester	Adams	OH	38.6903	-83.4803	2	0	1,864,977	3
876	Kincaid Generation LLC	Kincaid	Christian	IL	39.591472	-89.496897	1	1	4,224,227	4
3407	Kingston	Harriman	Roane	TN	35.8992	-84.5194	2	0	989,568	3
733	Kraft	Port Wentworth	Chatham	GA	32.1486	-81.1458	1	1	422,035	2
2876	Kyger Creek	Cheshire	Gallia	OH	38.9161	-82.1281	2	1	3,602,671	4
2713	L.V. Sutton Electric Plant	Wilmington	New Hanover	NC	34.2831	-77.9867	2	0	1,097,862	3
1241	La Cygne	La Cygne	Linn	KS	38.348094	-94.644683	2	1	5,718,291	4
2103	Labadie	Labadie	Franklin	MO	38.561429	-90.837277	2	0	10,122,717	4
2098	Lake Road	St. Joseph	Buchanan	MO	39.723933	-94.877747	2	1	404,999	2
2838	Lake Shore	Cleveland	Cuyahoga	OH	41.535458	-81.641633	1	0	182,014	1
964	Lakeside	Springfield	Sangamon	IL	39.7539	-89.6011	1	0	1,480	1
1047	Lansing	Lansing	Allamakee	IA	43.336125	-91.166833	2	2	862,048	2
643	Lansing Smith	Southport	Bay	FL	30.2689	-85.7003	1	1	652,366	2
6204	Laramie River Station	Wheatland	Platte	WY	42.1103	-104.8828	2	1	7,132,436	4
1891	Laskin Energy Center	Hoyt Lakes	St Louis	MN	47.5306	-92.1619	2	0	354,312	2
1250	Lawrence Energy Center	Lawrence	Douglas	KS	39.0078	-95.2681	4	3	2,058,823	3

Attachment A-1. Plant Information

Oris Code	Plant Name	City	County	State	Latitude	Longitude	# of SIs	# of LFs	Coal Use (short tons)	Coal Use Quartile
2817	Leland Olds	Stanton	Mercer	ND	47.2819	-101.3194	3	2	3,412,913	4
6089	Lewis & Clark	Sidney	Richland	MT	47.678875	-104.157014	5	3	307,772	2
298	Limestone	Jewett	Limestone	TX	31.423386	-96.251653	9	1	8,508,363	4
2240	Lon Wright	Freemont	Dodge	NE	41.4275	-96.4619	0	1	279,452	2
6664	Louisa	Muscatine	Louisa	IA	41.3153	-91.0936	2	1	2,964,296	4
976	Marion Generating Station	Marion	Williamson	IL	37.6206	-88.955	12	1	1,064,499	3
2727	Marshall	Terrell	Catawba	NC	35.5975	-80.9658	1	2	4,776,946	4
492	Martin Drake	Colorado Springs	El Paso	CO	38.8244	-104.8331	4	1	968,628	3
6146	Martin Lake	Tatum	Rusk	TX	32.2597	-94.5703	4	5	13,195,519	4
6250	Mayo Electric Generating Facility	Roxboro	Person	NC	36.5278	-78.8917	1	0	1,778,603	3
6124	McIntosh	Rincon	Effingham	GA	32.3558	-81.1683	1	0	-	1
3287	McMeekin	Columbia	Lexington	SC	34.0533	-81.2178	0	1	382,435	2
2104	Meramec	St. Louis	St Louis	MO	38.4017	-90.3358	5	0	3,250,555	4
864	Meredosia	Meredosia	Morgan	IL	39.8194	-90.5647	2	0	329,623	2
6213	Merom	Sullivan	Sullivan	IN	39.0694	-87.5108	1	2	3,549,562	4
2364	Merrimack Station	Bow	Merrimack	NH	43.1411	-71.4692	2	1	956,935	3
2832	Miami Fort	North Bend	Hamilton	OH	39.1131	-84.8031	2	2	3,579,522	4
997	Michigan City	Michigan City	La Porte	IN	41.7203	-86.9097	6	0	1,156,086	3
1364	Mill Creek	Louisville	Jefferson	KY	38.0531	-85.91	5	3	4,748,412	4
2823	Milton R. Young Station	Center	Oliver	ND	47.0664	-101.2139	4	5	4,124,626	4
2171	Missouri City	Missouri City	Clay	MO	39.23196	-94.307989	1	0	12,865	1
3948	Mitchell	Moundsville	Marshall	WV	39.8297	-80.8153	2	0	3,678,634	4
727	Mitchell	Albany	Dougherty	GA	31.4442	-84.135456	3	0	9,734	1
3181	Mitchell Power Station	Courtney	Washington	PA	39.8297	-80.8153	0	2	373,494	2
1048	ML Kapp	Clinton	Clinton	IA	41.807941	-90.234369	4	0	515,844	2
1733	Monroe Power Plant	Monroe	Monroe	MI	41.8917	-83.3461	2	0	9,261,743	4
6147	Monticello	Mt. Pleasant	Titus	TX	33.0917	-95.0417	4	3	10,757,329	4
2080	Montrose	Clinton	Henry	MO	38.3108	-93.9331	3	1	2,068,649	3
1573	Morgantown Generating Plant	Newburg	Charles	MD	38.3592	-76.9767	0	2	2,500,524	3
1606	Mount Tom	Holyoke	Hampden	MA	42.2814	-72.6053	3	1	248,386	2
6264	Mountaineer	New Haven	Mason	WV	38.9794	-81.9344	1	1	3,727,529	4
3954	Mt. Storm	Mt. Storm	Grant	WV	39.2014	-79.2667	0	4	3,991,565	4
1167	Muscatine #1	Muscatine	Muscatine	IA	41.391592	-91.05636	1	1	873,871	2
2872	Muskingum River	Waterford	Washington	OH	39.5908	-81.6797	4	0	2,869,762	4
2952	Muskogee	Fort Gibson	Muskogee	OK	35.7617	-95.2847	3	0	5,139,684	4
4162	Naughton Plant	Kemmerer	Lincoln	WY	41.7572	-110.5986	4	1	2,491,422	3
4941	Navajo Generating Station	Page	Coconino	AZ	36.90422	-111.388906	0	1	7,530,160	4
6064	Nearman Creek	Kansas City	Wyandotte	KS	39.1714	-94.6958	1	2	905,954	2
6096	Nebraska City	Nebraska City	Otoe	NE	40.6215	-95.7765	2	2	4,282,248	4
4054	Nelson Dewey	Cassville	Grant	WI	42.7247	-91.0058	2	1	484,540	2
3138	New Castle Plant	West Pittsburg	Lawrence	PA	40.9383	-80.3683	2	1	292,388	2
2167	New Madrid	Marston	New Madrid	MO	36.5147	-89.5617	4	1	4,266,998	4
6017	Newton	Newton	Jasper	IL	38.9361	-88.2778	2	2	4,604,471	4
2291	North Omaha	Omaha	Douglas	NE	41.33	-95.9467	3	2	1,872,463	3
8224	North Valmy	Valmy	Humboldt	NV	40.880608	-117.152216	0	1	1,705,618	3
2963	Northeastern	Oologah	Rogers	OK	36.4317	-95.7008	1	1	4,083,677	4
667	Northside Generating Station	JACKSONVILLE	Duval	FL	30.430967	-81.550775	0	1	131,582	1
10030	NRG Energy Center Dover	Dover	Kent	DE	39.1467	-75.5461	1	0	47,581	1
527	Nucla	Nucla	Montrose	CO	38.2386	-108.5072	1	1	370,948	2
2848	O H Hutchings	Miamisburg	Montgomery	OH	39.6094	-84.2931	3	0	50,479	1
6180	Oak Grove	Franklin	Robertson	TX	31.182054	-96.487494	1	3	2,590,468	3
127	Oklaunion	Vernon	Wilbarger	TX	34.0825	-99.1753	3	1	1,800,551	3
4151	Osage	Osage	Weston	WY	43.970041	-104.411635	2	2	247,093	1
1831	Otto E. Eckert Station	Lansing	Ingham	MI	42.7183	-84.5586	1	0	618,929	2
6254	Ottumwa	Ottumwa	Wapello	IA	41.0961	-92.5556	4	1	2,487,180	3
1378	Paradise	Drakesboro	Muhlenberg	KY	37.2608	-86.9783	3	0	6,331,623	4
6248	Pawnee	Brush	Morgan	CO	40.2217	-103.6803	7	1	1,324,186	3
6238	Pearl Station	Pearl	Pike	IL	39.4489	-90.6142	1	0	26,057	1
3938	Philip Sporn	New Haven	Mason	WV	38.9669	-81.9231	2	1	1,074,116	3
2843	Picway	Lockbourne	Pickaway	OH	39.7933	-83.0097	1	0	61,270	1
7902	Pirkey	Hallsville	Harrison	TX	32.4607	-94.4852	6	1	2,939,060	4
59	Platte	Grand Island	Hall	NE	40.855508	-98.348199	0	2	390,640	2
6170	Pleasant Prairie	Pleasant Prairie	Kenosha	WI	42.5381	-87.9033	0	1	4,761,560	4
6004	Pleasants Power Station	Willow Island	Pleasants	WV	39.3668	-81.2944	1	1	2,404,993	3
7242	Polk	Mulberry	--	FL	27.7286	-81.9897	0	1	508,207	2
3113	Portland	Mt. Bethel	Northampton	PA	40.91	-75.0789	3	4	899,978	2
879	Powerton	Pekin	Tazewell	IL	40.5408	-89.6786	7	0	5,813,360	4
3140	PPL Brunner Island	Mt. Wolf	York	PA	40.094914	-76.696786	3	1	3,364,135	4
3149	PPL Montour	Washingtonville	Montour	PA	41.071444	-76.666849	5	2	3,750,432	4
1073	Prairie Creek	Cedar Rapids	Linn	IA	41.9378	-91.639641	10	0	59,034	1
1769	Presque Isle	Marquette	Marquette	MI	46.578947	-87.395044	0	3	1,572,482	3
2403	PSEG Hudson Generating Station	Jersey City	Hudson	NJ	40.7478	-74.0719	2	1	796,708	2

Attachment A-1. Plant Information

Oris Code	Plant Name	City	County	State	Latitude	Longitude	# of SIs	# of LFs	Coal Use (short tons)	Coal Use Quartile
2408	PSEG Mercer Generating Station	Mercer	Mercer	NJ	40.1797	-74.7325	2	1	553,756	2
4072	Pulliam	Green Bay	Brown	WI	44.5397	-88.0083	1	1	945,855	2
1295	Quindaro	Kansas City	Wyandotte	KS	39.150759	-94.636563	0	1	683,410	2
6639	R D Green	Robards	Webster	KY	37.6467	-87.5006	1	1	1,176,462	3
2864	R. E. Burger	Shadyside	Belmont	OH	39.9094	-80.7608	2	1	328,250	2
1008	R. Gallagher	New Albany	Floyd	IN	38.2636	-85.8381	2	9	839,443	2
1570	R. Paul Smith Power Station	Williamsport	Washington	MD	39.595039	-77.826792	2	1	64,727	1
2790	R.M. Heskett Station	Mandan	Morton	ND	46.8669	-100.8839	0	2	536,721	2
6085	R.M. Schahfer	Wheatfield	Jasper	IN	41.2175	-87.0239	7	1	4,834,326	4
6761	Rawhide	Wellington	Larimer	CO	40.8611	-105.0206	2	2	1,333,960	3
8219	Ray D Nixon	Fountain	El Paso	CO	38.6306	-104.7056	1	1	959,694	3
55076	Red Hills Generating Facility	Ackerman	Choctaw	MS	33.3761	-89.2183	1	1	3,744,477	4
2324	Reid Gardner	Moapa	Clark	NV	36.655704	-114.632408	8	1	1,477,313	3
1740	River Rouge Power Plant	River Rouge	Wayne	MI	42.2733	-83.1131	1	0	1,719,332	3
2732	Riverbend	Mt. Holly	Gaston	NC	35.36	-80.9742	2	0	222,209	1
1081	Riverside	Bettendorf	Scott	IA	41.540506	-90.44815	2	0	464,395	2
1927	Riverside	Minneapolis	Hennepin	MN	45.0203	-93.2753	1	0	-	1
1239	Riverton	Riverton	Cherokee	KS	37.0719	-94.6986	1	0	245,628	1
3945	Rivesville Power Station	Rivesville	Marion	WV	39.5314	-80.113	4	2	10,415	1
6166	Rockport	Rockport	Spencer	IN	37.9256	-87.0372	1	1	10,265,905	4
6190	Rodemacher	Lena	Rapides	LA	31.395	-92.7167	3	0	2,089,934	3
2712	Roxboro Steam Electric Plant	Semora	Person	NC	36.4833	-79.0731	4	1	6,262,948	4
1393	RS Nelson	Westlake	Calcasieu	LA	30.287587	-93.29391	2	2	2,282,209	3
6155	Rush Island	Festus	Jefferson	MO	38.1306	-90.2625	1	1	4,826,892	4
2451	San Juan	Waterflow	San Juan	NM	36.8006	-108.4386	1	0	6,588,396	4
6183	San Miguel	Christine	Atascosa	TX	28.704903	-98.476883	3	2	3,303,265	4
6648	Sandow No 4	Rockdale	Milam	TX	30.5642	-97.0639	1	5	4,027,601	4
6257	Scherer	Juliette	Monroe	GA	33.0583	-83.8072	2	0	14,030,288	4
2367	SCHILLER	Portsmouth	Rockingham	NH	43.0978	-70.7842	0	1	250,999	2
642	Scholz	Sneads	Jackson	FL	30.669158	-84.8875	3	0	3,621	1
136	Seminole Generating Station	Palatka	Putnam	FL	29.733848	-81.632368	0	1	2,916,317	4
1379	Shawnee	West Paducah	McCracken	KY	37.1517	-88.775	2	2	4,090,940	4
3131	Shawville	Shawville	Clearfield	PA	41.067	-78.3656	4	2	974,359	3
2277	Sheldon Station	Hallam	Lancaster	NE	40.5589	-96.7842	1	4	1,020,516	3
6090	Sherburne County	Becker	Sherburne	MN	45.3792	-93.8958	6	1	9,171,628	4
2094	Sibley	Sibley	Jackson	MO	39.1778	-94.1861	2	1	1,648,794	3
6768	Sikeston Power Station	Sikeston	Scott	MO	36.8786	-89.6169	2	0	1,096,237	3
2107	Sioux	West Alton	St Charles	MO	38.915429	-90.291115	2	0	3,142,617	4
1058	Sixth Street	Cedar Rapids	Linn	IA	41.984207	-91.667517	4	0	--	--
1613	Somerset Station	Somerset	Bristol	MA	41.737	-71.146	4	0	58,047	1
6095	Sooner	Red Rock	Noble	OK	36.45	-97.0531	2	0	3,877,889	4
6061	South Mississippi El Pwr Assn	Purvis	Lamar	MS	31.2194	-89.3933	2	3	823,757	2
4041	South Oak Creek	Oak Creek	Milwaukee	WI	42.8457	-87.8294	0	3	2,565,605	3
6195	Southwest Power Station	Springfield	Greene	MO	37.1519	-93.3892	2	2	699,635	2
8223	Springerville	Springerville	Apache	AZ	34.3186	-109.1636	1	1	4,854,606	4
1743	St Clair Power Plant	East China Township	St Clair	MI	42.7625	-82.4722	1	0	3,751,842	4
207	St Johns River Power Park	Jacksonville	Duval	FL	30.4311	-81.5508	0	3	3,733,618	4
2824	Stanton	Stanton	Mercer	ND	47.2872	-101.3314	3	3	663,440	2
564	Stanton Energy Center	Orlando	Orange	FL	28.4836	-81.1686	0	1	2,381,605	3
1131	Streeter Station	Cedar Falls	Black Hawk	IA	42.526822	-92.440176	0	1	14,253	1
3152	Sunbury Generation LP	Shamokin Dam	Snyder	PA	40.8361	-76.825	1	0	613,993	2
50951	Sunnyside Cogen Associates	Sunnyside	Carbon	UT	39.546486	-110.391153	0	1	417,241	2
1077	Sutherland	Marshalltown	Marshall	IA	42.0472	-92.857721	3	2	292,568	2
10075	Taconite Harbor Energy Center	Schroeder	Cook	MN	47.5314	-90.9111	0	3	664,576	2
988	Tanners Creek	Lawrenceburg	Dearborn	IN	39.0831	-84.8581	5	1	1,358,323	3
1252	Tecumseh Energy Center	Tecumseh	Shawnee	KS	39.054072	-95.568775	2	3	894,924	2
2168	Thomas Hill	Clifton Hill	Randolph	MO	39.5531	-92.6392	6	1	4,356,018	4
3115	Titus	Birdsboro	Berks	PA	40.3061	-75.9081	0	4	424,803	2
6194	Tolk	Sudan	Lamb	TX	34.1847	-102.5686	0	1	4,080,504	4
3845	TransAlta Centralia Generation	Centralia	Lewis	WA	46.755636	-122.857583	0	1	4,974,233	4
1745	Trenton Channel Power Plant	Trenton	Wayne	MI	42.1236	-83.1811	1	1	2,012,466	3
6071	Trimble Co.	Bedford	Trimble	KY	38.5847	-85.4117	1	0	1,409,667	3
56224	TS Power Plant	Dunphy	Eureka	NV	40.708739	-116.529021	0	1	638,633	2
7030	Twin Oaks Power One	Bremond	Robertson	TX	31.0928	-96.6933	0	1	1,712,108	3
1361	Tyrone	Versailles	Woodford	KY	38.047838	-84.848337	2	0	12,091	1
3295	Urquhart	Beech Island	Aiken	SC	33.435	-81.9111	3	1	151,533	1
4042	Valley	Milwaukee	Milwaukee	WI	43.0303	-87.925	0	4	611,825	2
477	Valmont	Boulder	Boulder	CO	40.0195	-105.202	3	2	536,002	2
897	Vermilion	Oakwood	Vermilion	IL	40.1781	-87.7481	2	1	433,469	2
6073	Victor J. Daniel Jr	Moss Point	Jackson	MS	30.5335	-88.5574	1	4	2,554,163	3
6019	W H Zimmer	Moscow	Clermont	OH	38.8689	-84.2286	1	1	3,044,248	4
3470	W. A. Parish	Thompsons	Fort Bend	TX	29.4828	-95.6311	8	1	11,517,217	4

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Oris Code	Plant Name	City	County	State	Latitude	Longitude	# of SIs	# of LFs	Coal Use (short tons)	Coal Use Quartile
2866	W. H. Sammis	Stratton	Jefferson	OH	40.5308	-80.6311	2	1	4,200,741	4
3264	W. S. Lee	Belton	Anderson	SC	34.6022	-82.435	2	0	196,442	1
2716	W.H. Weatherspoon Plant	Lumberton	Robeson	NC	34.5889	-78.975	1	0	143,957	1
1010	Wabash River	West Terre Haute	Vigo	IN	39.53	-87.4247	4	0	1,609,012	3
2830	Walter C Beckjord	New Richmond	Clermont	OH	38.9917	-84.2972	4	2	2,310,221	3
1082	Walter Scott Jr. Energy Center	Council Bluffs	Pottawattamie	IA	41.18	-95.8408	2	1	6,577,427	4
6052	Wansley	Carrollton	Heard	GA	33.4112	-85.0341	1	0	2,905,006	4
6705	Warrick Power Plant	Newburgh	Warrick	IN	37.915	-87.3319	1	0	2,223,793	3
3297	Wateree	Eastover	Richland	SC	33.8264	-80.6218	2	1	1,331,447	3
883	Waukegan	Waukegan	Lake	IL	42.3833	-87.8133	2	0	2,568,340	3
6139	Welsh	Pittsburg	Titus	TX	33.054539	-94.840542	3	1	6,615,744	4
4078	Weston	Rothschild	Marathon	WI	44.8606	-89.6553	6	2	3,314,523	4
60	Whelan Energy Center Unit 1 (WEC1)	Hastings	Adams	NE	40.5806	-98.3106	1	0	326,208	2
6009	White Bluff	Redfield	Jefferson	AR	34.4236	-92.1392	0	1	6,421,536	4
1040	Whitewater Valley	Richmond	Wayne	IN	39.8028	-84.8953	5	0	105,300	1
4057	WI Power & Light Co -Rock River Generating	Beloit	Rock	WI	42.583275	-89.035401	4	0	--	--
50	Widows Creek	Stevenson	Jackson	AL	34.8825	-85.7547	12	0	2,263,802	3
884	Will County	Romeoville	Will	IL	41.634093	-88.062381	1	0	3,118,919	4
3298	Williams	Goose Creek	Berkeley	SC	33.0163	-79.9285	0	2	1,452,860	3
3946	Willow Island	Willow Island	Pleasants	WV	39.3672	-81.3006	0	1	58,263	1
6249	Winyah	Georgetown	Georgetown	SC	33.329692	-79.357933	6	1	2,452,036	3
898	Wood River	Alton	Madison	IL	38.863454	-90.134001	2	0	1,988,950	3
50611	WPS Westwood Generation, LLC	Tremont	Schuylkill	PA	40.618731	-76.450706	0	1	408,017	2
6101	Wyodak Plant	Gillette	Campbell	WY	44.28795	-105.385236	1	1	2,005,001	3
728	Yates	Newnan	Coweta	GA	33.4622	-84.8986	8	2	1,875,227	3
3809	Yorktown	Yorktown	York	VA	37.2144	-76.4611	1	1	681,147	2

Attachment A-2.
WMU Information

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
6137	A. B. Brown Generating Station	88	SI	Lower Ash Pond	37.90488889	-101.8346944	53	930	17.54716981	Ash & Coal Refuse	None	--
6137	A. B. Brown Generating Station	1163	LF	FGD Lanfill	37.91361111	-87.70916667	176	6421.487603	36.48572502	Combined Ash	Yes	--
6137	A. B. Brown Generating Station	89	SI	Upper Ash Pond	37.9	-87.7	103	2417	23.46601942	Combined Ash	None	--
2535	AES Cayuga, LLC	1102	LF	Ash Site Landfill	42.60871111	-76.61863056	--	--	--	Combined Ash	Yes	--
2527	AES Greenidge	1286	SI	Lookwood Sedimentation/naturalization Basin	42.67595833	-76.96069167	1.75151515	5.919421488	3.379600503	Combined Ash	Clay	--
2527	AES Greenidge	1101	LF	AES Lockwood	42.6813	-76.948687	--	--	--	Combined Ash	Yes	--
2527	AES Greenidge	1285	SI	Bottom Ash Pond C-Pond	42.68086667	-76.94438056	2.61707989	13.08539945	5	Combined Ash	None	--
994	AES Petersburg	431	SI	Pond A - Discharge	38.53353611	-87.24662778	5	108	21.6	Combined Ash	None	--
994	AES Petersburg	432	SI	Pond B	38.53639722	-87.24515833	35	1240	35.42857143	Combined Ash	None	Excluded
994	AES Petersburg	430	SI	Pond A - Active	38.53194444	-87.24491944	67	930	13.88059701	Combined Ash	None	--
994	AES Petersburg	433	SI	Pond C	38.53921667	-87.24106944	30	1054	35.13333333	Combined Ash	None	Excluded
994	AES Petersburg	989	LF	RWS Type III	38.53035278	-87.23888056	118.5	10103.30579	85.25996443	Combined Ash	Yes	--
6082	AES Somerset LLC	1287	SI	Sludge Basin	43.352783	-78.605356	2.181	--	--	FGD Waste	Yes	--
6082	AES Somerset LLC	1106	LF	SWDA 1	43.359	-78.58375	84	227.2727273	2.705627706	Combined Ash	Clay	Excluded
6082	AES Somerset LLC	1105	LF	SWDA 2	43.35161111	-78.58358333	82	202.020202	2.463661	Combined Ash	Composite	--
3942	Albright Power Station	1385	SI	North Lagoon	39.49	-79.64083333	1.02846648	9.794811754	9.523705357	Combined Ash	Clay	--
3942	Albright Power Station	1386	SI	South Lagoon	39.486978	-79.635108	1.13406795	9.821297062	8.660236842	Combined Ash	Clay	--
3942	Albright Power Station	931	LF	Active CCB Landfill	39.48676944	-79.60292778	45	3006.198347	66.80440771	Combined Ash	None	--
3942	Albright Power Station	930	LF	Closed CCB Landfill	39.49138889	-79.60263333	70	1797.520661	25.67886659	Combined Ash	None	Excluded
1915	Allen S King	927	LF	AS King Ash Disposal Facility	45.03444444	-92.79916667	--	--	--	Combined Ash	Yes	--
3393	Allen Steam Plant	119	SI	East Ash Stilling Pond	--	--	23	180	7.826086957	Combined Ash	--	--
3393	Allen Steam Plant	120	SI	East Ash Disposal	--	--	70	1100	15.71428571	Combined Ash	--	--
4140	Alma	993	LF	--	--	--	85	1239.669422	14.58434614	Combined Ash	--	--
4140	Alma	994	LF	--	--	--	--	--	--	Combined Ash	--	Excluded
1122	Ames Electric Services Power Plant	1202	SI	Ash Pond	42.028175	-93.59932778	4.14	--	--	Ash & Coal Refuse	Yes	--
6469	Antelope Valley Station	212	SI	Spray Drier Ash Water Make-Up Pond	47.373	-101.8346944	3.1	28	9.032258065	Combined Ash	Composite	Excluded
6469	Antelope Valley Station	923	LF	SP-025	47.38347	-101.82575	63.8	3099.173554	48.57638799	Combined Ash	Clay	--
6469	Antelope Valley Station	922	LF	SP-160	47.38922222	-101.81725	102.7	9917.355372	96.56626458	Combined Ash	Clay	--
6469	Antelope Valley Station	213	SI	Decant Pond (Temporary Pond)	--	--	3	19	6.333333333	Combined Ash	Clay	Excluded
160	Apache Station	299	SI	Scrubber Sludge Pond 1	32.07277778	-109.9127778	41.7	314	7.529976019	Combined Ash	Composite	--
160	Apache Station	297	SI	Scrubber Sludge Pond 2	32.07666667	-109.9127778	42	446	10.61904762	Combined Ash	Composite	--
160	Apache Station	295	SI	Evaporation Pond	32.07416667	-109.9083333	80	--	--	Combined Ash	Composite	--
160	Apache Station	296	SI	Ash Pond 3	32.07611111	-109.905	32.6	720	22.08588957	Combined Ash	Composite	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
160	Apache Station	294	SI	Ash Pond 2	32.07222222	-109.9044444	32.6	720	22.08588957	Combined Ash	Composite	--
160	Apache Station	298	SI	Ash Pond 4	32.07589722	-109.9019528	32.6	693	21.25766871	Combined Ash	Composite	--
160	Apache Station	293	SI	Ash Pond 1	32.07222222	-109.9011111	32.6	717	21.99386503	Combined Ash	Composite	--
160	Apache Station	287	SI	Low Volume Wastewater Pond	--	--	42	618	14.71428571	Combined Ash	--	--
160	Apache Station	288	SI	Evaporation 1	--	--	--	823	--	Combined Ash	Composite	--
160	Apache Station	292	SI	Cooling Tower Blowdown Pond	--	--	--	7	--	Combined Ash	--	--
465	Arapahoe	310	SI	Ash Pump Pond	--	--	--	4	--	Combined Ash	--	--
465	Arapahoe	311	SI	Discharge Pond	--	--	1	7	7	Combined Ash	--	Excluded
465	Arapahoe	312	SI	North Storm Water/Process Water Pond	--	--	1	8	8	Combined Ash	--	Excluded
465	Arapahoe	313	SI	South Storm Water/Process Water Pond	--	--	1	14	14	Combined Ash	--	Excluded
465	Arapahoe	314	SI	South Ash Pond	--	--	1	14	14	Combined Ash	--	--
465	Arapahoe	315	SI	Emergency Pond	--	--	2	12	6	Combined Ash	--	Excluded
3178	Armstrong Power Station	926	LF	Closed Ash Site	40.915954	-79.47162	--	--	--	Combined Ash	None	Excluded
3178	Armstrong Power Station	921	LF	Active Ash Site	40.92222222	-79.47083333	--	--	--	Combined Ash	Yes	--
2076	Asbury	598	SI	Upper Pond	37.35972222	-94.58555556	17.6	--	--	--	None	--
2076	Asbury	597	SI	Lower Pond	37.36055556	-94.58166667	63	--	--	Combined Ash	None	--
2076	Asbury	596	SI	Ash Impoundment	--	--	92	--	--	Combined Ash	--	--
2706	Asheville Steam Electric Plant	649	SI	1964 Pond	35.4675	-82.54805556	45	1380	30.66666667	Combined Ash	Composite	--
2706	Asheville Steam Electric Plant	650	SI	1982 Pond	35.46472222	-82.54416667	46	1400	30.43478261	Combined Ash	None	--
2835	Ashtabula	1263	SI	Combined Treatment Basin	41.90833333	-80.7625	0.40174472	2.0087236	5	Combined Ash	None	--
1961	Austin Northeast	958	LF	Coal Ash Monofill	43.69878611	-92.96217222	--	--	--	Combined Ash	None	Excluded
2836	Avon Lake	1175	SI	Primary Ash Settling Basin	41.50531111	-82.05285	0.09022039	1.082644628	12	Combined Ash	None	--
2836	Avon Lake	1176	SI	Secondary Ash Settling Basin	41.50551667	-82.05202778	0.09022039	1.082644628	12	Combined Ash	None	--
2836	Avon Lake	975	LF	--	--	--	--	--	--	Combined Ash	--	--
995	Bailly	434	SI	Forebay	41.644381	-87.125098	0.14	2	14.28571429	Combined Ash	--	Excluded
995	Bailly	439	SI	Bottom Ash Pond	41.638356	-87.121326	1	2	2	Combined Ash	--	--
995	Bailly	436	SI	Primary 1	41.638387	-87.118974	6	41	6.833333333	Combined Ash	--	--
995	Bailly	437	SI	Primary 2	41.638357	-87.115771	6	47	7.833333333	Combined Ash	--	--
995	Bailly	438	SI	Secondary 2	41.638375	-87.11335	3	30	10	Combined Ash	--	--
995	Bailly	435	SI	Secondary 1	41.637988	-87.111999	2	18	9	Combined Ash	--	--
995	Bailly	939	LF	BGS South Landfill	41.63619167	-87.102575	--	--	--	Combined Ash	None	Excluded

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
995	Bailly	952	LF	BGS North Landfill	41.63854167	-87.102575	--	--	--	Combined Ash	None	Excluded
889	Baldwin Energy Complex	391	SI	Ash Pond System	38.19286	-89.867555	492	3957	8.042682927	Combined Ash	--	--
3	Barry	252	SI	Barry Ash Pond	--	--	597	5965	9.991624791	Combined Ash	None	--
3982	Bay Front	946	LF	Woodfield	46.52152778	-90.93394444	10	216.9421489	21.69421489	Combined Ash	Yes	--
3982	Bay Front	945	LF	Deer Creek	46.47444444	-90.92805556	--	--	--	Combined Ash	None	Excluded
3982	Bay Front	162	SI	Polishing Pond	46.585243	-90.902906	0.41	3	7.317073171	Combined Ash	--	--
3982	Bay Front	163	SI	Surge Basin	46.585471	-90.902568	0.15	1	6.666666667	Combined Ash	--	--
2878	Bay Shore	1326	SI	Bottom Ash Pond	41.69611111	-83.43833333	0.99862259	5.492424242	5.5	Combined Ash	None	--
2878	Bay Shore	977	LF	--	--	--	85	--	--	Combined Ash	--	--
8042	Belews Creek Steam Station	1009	LF	Closed Pine Hall Road Landfill	36.28277778	-80.07861111	68	--	--	Combined Ash	None	Excluded
8042	Belews Creek Steam Station	243	SI	Active Ash Pond	36.296519	-80.075439	342	12654	37	Combined Ash	None	--
8042	Belews Creek Steam Station	1079	LF	Craig Road Ash Landfill	36.26888889	-80.0675	31	1190.96281	38.41815516	Combined Ash	Composite	--
8042	Belews Creek Steam Station	1010	LF	FGD Residual Landfill	36.27444444	-80.05666667	24	991.7355372	41.32231405	Combined Ash	Composite	--
6034	Belle River	1035	LF	Range Road	42.792242	-82.506315	--	--	--	Combined Ash	Yes	--
6034	Belle River	33	SI	Pond	--	--	--	--	--	Combined Ash	--	--
3325	Ben French	1379	SI	Ash Pond	44.08916667	-103.2641667	0.31955923	0.764876033	2.393534483	Combined Ash	Clay	--
645	Big Bend	347	SI	South Bottom Ash Pond	27.79111111	-82.39888889	6	--	--	Combined Ash	Composite	--
645	Big Bend	345	SI	North Bottom Ash	27.79166667	-82.39888889	5.7	--	--	Combined Ash	Composite	--
645	Big Bend	1164	LF	FGD Storage Area	27.78388889	-82.39638889	--	--	--	Combined Ash	None	--
645	Big Bend	343	SI	South Economizer Ash Pond	27.79083333	-82.395	6	--	--	Ash & Coal Refuse	Composite	--
645	Big Bend	344	SI	North Economizer Ash Pond	27.79166667	-82.395	5.5	--	--	Ash & Coal Refuse	Composite	--
645	Big Bend	342	SI	North Recycle Pond	--	--	3	--	--	FGD Waste	--	--
645	Big Bend	346	SI	Longterm Flyash Pond	--	--	12	--	--	Combined Ash	--	--
645	Big Bend	348	SI	Settling Pond	--	--	1	--	--	FGD Waste	--	--
645	Big Bend	349	SI	South Recycle Pond	--	--	9	--	--	FGD Waste	--	--
3497	Big Brown	784	LF	Class 3 bottom ash landfill Area B	31.81666667	-96.0725	1.96	19.6	10	Combined Ash	None	Excluded
3497	Big Brown	1179	SI	Bottom Ash Pond(s)	31.82	-96.06472222	19.2837466	227.3428834	11.78935238	Combined Ash	Clay	--
3497	Big Brown	1178	SI	Operating Pond	31.82805556	-96.05972222	14.6923783	229.135124	15.59550938	Combined Ash	Clay	Excluded
3497	Big Brown	776	LF	Class 3 bottom ash landfill Area A	31.829465	-96.054781	10.029	100.2899908	9.999999084	Combined Ash	None	Excluded
3497	Big Brown	790	LF	Ash Disposal Area 1	31.82944444	-96.05472222	128.595	3499.999587	27.21722918	Combined Ash	Clay	Excluded
3497	Big Brown	1177	SI	Lignite Retention Pond	31.82416667	-96.04972222	15.5	66.22651515	4.272678397	Combined Ash	Yes	Excluded
3497	Big Brown	1180	SI	Settling Pond	31.82444444	-96.04527778	0.51652893	5.155716253	9.981466667	Combined Ash	Yes	--
3497	Big Brown	791	LF	Ash Disposal Area 2	31.83555556	-96.04166667	331.993	4183.8843	12.60232686	Combined Ash	Clay	--
6055	Big Cajun 2	815	LF	Fly Ash	30.725	-91.38972222	175	2417.355372	13.81345927	Combined Ash	Clay	--

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Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
6055	Big Cajun 2	36	SI	Bottom Ash Unit	--	--	66	1188	18	Combined Ash	Clay	--
6055	Big Cajun 2	37	SI	Fly Ash Unit	--	--	175	1750	10	Combined Ash	Clay	--
6055	Big Cajun 2	38	SI	Water Treatment Unit	--	--	32	585	18.28125	Combined Ash	Clay	--
1353	Big Sandy	521	SI	Horseford Run Dam	38.18666667	-82.6325	176	--	--	Combined Ash	Clay	--
1353	Big Sandy	523	SI	Fly Ash	38.186667	-82.6325	97	8302	85.58762887	Combined Ash	--	--
1353	Big Sandy	522	SI	Bottom Ash Complex	38.17111111	-82.62194444	6	40	6.666666667	Combined Ash	None	--
6098	Big Stone	1261	SI	Ash Pond	45.30001389	-96.51001944	2.1	21	10	Combined Ash	None	--
6098	Big Stone	814	LF	Ash Disposal Site	45.30443889	-96.49121667	109.4	5008.264463	45.77938266	Combined Ash	None	--
1904	Black Dog	799	LF	Ash Storage Area	44.82048056	-93.23732778	96	5539.026446	57.69819215	Combined Ash	None	Excluded
1904	Black Dog	593	SI	Settling Ponds 1-4	--	--	17	218	12.82352941	Combined Ash	None	--
6106	Boardman	1339	SI	Carty	45.701206	-119.809153	1450	38000	26.20689655	Combined Ash	None	Excluded
6106	Boardman	1341	SI	-999	45.701206	-119.809153	10.28	--	--	Combined Ash	Yes	Excluded
6106	Boardman	1340	SI	Settling Pond	45.691617	-119.806178	1.26262626	17.21763085	13.63636364	Combined Ash	None	Excluded
6106	Boardman	746	LF	Ash Pit	45.67916667	-119.7816667	240	--	--	Combined Ash	None	--
7790	Bonanza Power Plant	1207	SI	Emergency Holding Pond 1 (EHP-1)	40.08825	-109.513461	0.91827365	11.01928375	12	FGD Waste	Clay	--
7790	Bonanza Power Plant	735	LF	Bottom Ash	40.30555556	-109.45	50	977.0431589	19.54086318	Combined Ash	None	--
7790	Bonanza Power Plant	1208	SI	Emergency Holding Pond 2 (EHP-2)	40.08222222	-109.2802778	6.50505051	65.05050505	10	FGD Waste	None	--
7790	Bonanza Power Plant	1209	SI	Emergency Holding Pond 3 (EHP-3)	40.08361111	-109.28	4.93572084	68.87052342	13.95348837	FGD Waste	None	--
7790	Bonanza Power Plant	737	LF	Fly ash/Scrubber sludge	40.21138889	-109.2725	25	1709.825528	68.39302112	Combined Ash	None	--
1893	Boswell Energy Center	862	LF	SE Units 1,2 and 3 Dry Fly Ash Landfill	47.27277778	-93.67916667	110	4648.760331	42.26145755	Combined Ash	None	--
1893	Boswell Energy Center	591	SI	Inactive Bottom Ash Pond	47.26361111	-93.67083333	200	3413	17.065	Combined Ash	Clay	Excluded
1893	Boswell Energy Center	590	SI	Complex: Pond 3, 4, and Bottom Ash Pond	47.26972222	-93.66777778	645	11236	17.42015504	Combined Ash	Clay	--
1893	Boswell Energy Center	853	LF	Industrial Solid Waste Landfill	47.26194444	-93.66722222	336	--	--	Combined Ash	None	--
1893	Boswell Energy Center	796	LF	Hibbing Ash Cell	47.26305556	-93.66694444	20	--	--	Combined Ash	None	Excluded
1893	Boswell Energy Center	592	SI	Wastewater Treatment Plant Pond	47.25944444	-93.64972222	1.6	9	5.625	Combined Ash	Clay	--
703	Bowen	1103	LF	CCB Disposal Facility	34.13722222	-84.90222222	51.01	556.8415289	10.9163209	Combined Ash	Yes	--
703	Bowen	350	SI	Ash Pond	--	--	245	3676	15.00408163	Combined Ash	Clay	--
602	Brandon Shores	1289	SI	01 Lagoon	39.18444444	-76.53666667	0.66574839	4.017447199	6.034482759	Combined Ash	Composite	--
602	Brandon Shores	1290	SI	02 Lagoon	39.18444444	-76.53666667	0.66574839	4.017447199	6.034482759	Combined Ash	Composite	--
1619	Brayton Point	731	LF	Cells 1 - 8	41.71835083	-71.193638	--	--	--	Combined Ash	Yes	Excluded
1619	Brayton Point	1191	SI	EQ Basin	41.71312889	-71.19279833	0.40495868	3.682667585	9.09393424	Combined Ash	None	Excluded
1619	Brayton Point	1187	SI	Recycle	41.71313283	-71.19277083	1.81	--	--	Combined Ash	None	Excluded
1619	Brayton Point	1188	SI	Basin 1	41.716621	-71.191151	1.81	--	--	Combined Ash	Yes	Excluded
1619	Brayton Point	1189	SI	Basin 2	41.718367	-71.190972	1.81	--	--	Combined Ash	Yes	Excluded
1619	Brayton Point	824	LF	Cell 9	41.720545	-71.19089083	--	--	--	Combined Ash	Yes	Excluded

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Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
1619	Brayton Point	800	LF	Cell 1A	41.717322	-71.19035483	--	--	--	Combined Ash	Yes	Excluded
1619	Brayton Point	1190	SI	Basin 3	41.71997783	-71.189987	1.81	--	--	Combined Ash	None	Excluded
1619	Brayton Point	1194	SI	Basin A	41.712899	-71.18957183	0.48209366	2.838751148	5.888380952	Combined Ash	Composite	--
1619	Brayton Point	1193	SI	52 Basin	41.717186	-71.188797	1.68044077	14.35009183	8.539480874	Combined Ash	Composite	Excluded
1619	Brayton Point	1192	SI	51 Basin	41.71805556	-71.18833333	1.65748393	14.35009183	8.657756233	Combined Ash	Composite	Excluded
1619	Brayton Point	1195	SI	Basin B	41.712879	-71.18825983	0.73461892	6.137764004	8.35503125	Combined Ash	Composite	--
1619	Brayton Point	1196	SI	Basin C	41.71323683	-71.18783383	0.73461892	6.137764004	8.35503125	Combined Ash	Composite	--
1619	Brayton Point	761	LF	Cell 10	41.71899483	-71.18704483	--	--	--	Combined Ash	Yes	--
1619	Brayton Point	760	LF	Cell 10A	41.718431	-71.18656183	--	--	--	Combined Ash	Yes	Excluded
3796	Bremo Bluff	148	SI	West Ash Pond	37.71111111	-78.29222222	17	290	17.05882353	Combined Ash	None	--
3796	Bremo Bluff	149	SI	North Ash Pond	37.70805556	-78.27833333	62	4300	69.35483871	Combined Ash	None	--
6094	Bruce Mansfield	79	SI	Little Blue Run Dam	40.62781667	-80.51291667	770	65000	84.41558442	Combined Ash	None	--
6094	Bruce Mansfield	75	SI	North LDS Pond (N-LDS)	40.63643333	-80.41331111	3.2	38.5	12.03125	Combined Ash	None	--
6094	Bruce Mansfield	78	SI	South LDS Pond (S-LDS)	40.63603611	-80.41256667	3.1	35.3	11.38709677	Combined Ash	None	--
6094	Bruce Mansfield	76	SI	West HDS Pond (W-HPDS)	40.63459444	-80.41128333	2.9	39.5	13.62068966	Combined Ash	None	--
6094	Bruce Mansfield	77	SI	East HDS (Decommissioned in 2003) (Add this unit to DB)	--	--	--	--	--	--	None	--
2720	Buck	672	SI	Additional Primary Cell Basin	35.70431667	-80.37264167	73.5	2645	35.98639456	Combined Ash	None	--
2720	Buck	671	SI	Old Primary Cell	35.70537778	-80.36640833	46	1610	35	Combined Ash	None	--
2720	Buck	673	SI	Secondary Pond	35.70982222	-80.36273611	14.5	510	35.17241379	Combined Ash	None	--
3396	Bull Run	889	LF	East/West Dredge Cell	36.006672	-84.14839	--	--	--	Combined Ash	None	Excluded
3396	Bull Run	890	LF	Fly Ash Stack	36.02506667	-84.14698889	--	--	--	Combined Ash	None	--
3396	Bull Run	121	SI	Bottom Ash Disposal Area 1	--	--	32	543	16.96875	Combined Ash	--	--
3396	Bull Run	122	SI	Fly Ash Pond & Stilling Basin Area 2	--	--	49	1674	34.16326531	Combined Ash	--	--
3396	Bull Run	123	SI	Gypsum Disposal Area 2A	--	--	42	1700	40.47619048	Combined Ash	--	--
3396	Bull Run	124	SI	Dry Fly Ash Disposal Area	--	--	50	2975	59.5	Combined Ash	--	--
1104	Burlington	507	SI	Ash Seal & Storm Water Pond	--	--	4	68	17	Combined Ash	None	Excluded
1104	Burlington	508	SI	Upper Ash Pond	--	--	13	133	10.23076923	Combined Ash	None	--
1104	Burlington	509	SI	Economizer Ash Pond	--	--	11	166	15.09090909	Combined Ash	None	--
1104	Burlington	510	SI	Lower Ash Pond	--	--	23	114	4.956521739	Combined Ash	None	--
1104	Burlington	511	SI	Main Ash Pond	--	--	17	85	5	Combined Ash	None	--
676	C D McIntosh Jr	885	LF	Northeast Landfill	28.08472222	-81.91722222	17.3	1106.97888	63.98721848	Combined Ash	None	Excluded
676	C D McIntosh Jr	888	LF	Landfill (active)	28.08333333	-81.91666667	48.3	5311.753903	109.9742009	Combined Ash	None	--
468	Cameo	316	SI	Process Water Retention Pond	--	--	--	2	--	Combined Ash	--	Excluded

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
468	Cameo	317	SI	Ash Silo Storm Water Retention Pond	--	--	--	1	--	Combined Ash	--	Excluded
3280	Canadys Steam	107	SI	Inactive Ash Pond	33.07416667	-80.62194444	80	1000	12.5	Combined Ash	None	--
3280	Canadys Steam	108	SI	Polishing Pond	33.075	-80.61722222	3.5	--	--	--	None	--
3280	Canadys Steam	109	SI	Ash Pond	33.07083333	-80.61527778	95	1407	14.81052632	Combined Ash	None	--
1363	Cane Run	869	LF	Cane Run Special Waste Landfill	38.175	-85.89444444	--	--	--	Combined Ash	None	--
1363	Cane Run	538	SI	Main Ash Pond/E-Pond	38.1775	-85.8875	40	868	21.7	Combined Ash	None	--
1363	Cane Run	541	SI	Dead Storage Pond	38.18345556	-85.88604167	5	--	--	FGD Waste	None	--
1363	Cane Run	540	SI	Basin Pond	38.18305556	-85.88472222	5	--	--	FGD Waste	None	--
1363	Cane Run	539	SI	Clearwell Pond	--	--	1	--	--	FGD Waste	--	--
1363	Cane Run	542	SI	Emergency Pond	--	--	2	--	--	FGD Waste	--	--
2708	Cape Fear Steam Electric Plant	654	SI	1956 Ash Pond	35.59709167	-79.05053333	--	--	--	Combined Ash	None	Excluded
2708	Cape Fear Steam Electric Plant	652	SI	1963 Ash Pond	35.58801667	-79.05015	--	--	--	Combined Ash	None	Excluded
2708	Cape Fear Steam Electric Plant	655	SI	1970 Ash Pond	35.582975	-79.04858333	50	--	--	Combined Ash	None	Excluded
2708	Cape Fear Steam Electric Plant	651	SI	1978 Ash Pond	35.58784167	-79.04622222	43	1161	27	Combined Ash	None	--
2708	Cape Fear Steam Electric Plant	653	SI	1985 Ash Pond	35.59012778	-79.04109444	65	1764	27.13846154	Combined Ash	None	--
3644	Carbon Plant	905	LF	Original Landfill	39.71293056	-110.8653556	--	--	--	Combined Ash	None	Excluded
3644	Carbon Plant	1387	SI	South Settling Pond	39.72472222	-110.8638889	1.12759412	14.40082645	12.77128548	Combined Ash	None	--
3644	Carbon Plant	1388	SI	North Settling Pond	39.72472222	-110.8638889	0.55151515	2.829017447	5.12953713	Combined Ash	None	--
3644	Carbon Plant	876	LF	Ash Landfill	39.708785	-110.861003	11.7739066	--	--	Combined Ash	None	--
2828	Cardinal	694	SI	Bottom Ash Complex	40.237992	-80.659561	19	350	18.42105263	Combined Ash	None	--
2828	Cardinal	899	LF	FAR 1 Residual Waste Landfill	40.27202634	-80.65446374	--	--	--	Combined Ash	Yes	--
2828	Cardinal	693	SI	Fly Ash Reservoir 2	40.266333	-80.646583	139	11350	81.65467626	Combined Ash	None	--
1001	Cayuga	838	LF	Cayuga RWS 1 Landfill	39.91472222	-87.43388889	80	7376.28942	92.20361775	Combined Ash	Composite	--
1001	Cayuga	454	SI	Lined Ash Disposal Pond - Cell #1	39.91916667	-87.42388889	40	1400	35	Combined Ash	Composite	--
1001	Cayuga	457	SI	Ash Disposal Area #1	39.91472222	-87.42083333	26	260	10	Combined Ash	None	--
1001	Cayuga	455	SI	Primary Ash Settling Basin	39.91416667	-87.41666667	15	225	15	Combined Ash	None	--
1001	Cayuga	456	SI	Secondary Ash Settling Basin	39.91361111	-87.41416667	3	36	12	Combined Ash	None	--
1571	Chalk Point LLC	836	LF	brandywine	38.70583333	-76.80277778	596	2872.31405	4.819318875	Combined Ash	Yes	--
1571	Chalk Point LLC	1104	LF	controlled storage area	38.559166	-76.688333	--	--	--	Combined Ash	Yes	--
2169	Chamois Power Plant	1288	SI	Ash Pond #002	38.68194444	-91.75861111	2.75482094	24.79338843	9	Combined Ash	None	--
56	Charles R. Lowman	273	SI	Units 2-3 Pond	31.48694444	-87.91611111	29	629	21.68965517	Combined Ash	None	--
56	Charles R. Lowman	270	SI	Scrubber Waste Pond	31.48972222	-87.91416667	36	760	21.11111111	FGD Waste	None	--
56	Charles R. Lowman	272	SI	#1 Bottom Ash Pond	31.485	-87.91305556	16.5	330	20	Combined Ash	None	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
56	Charles R. Lowman	271	SI	Process Waste Pond	31.49166667	-87.91222222	6	--	--	Combined Ash	None	--
56	Charles R. Lowman	900	LF	--	--	--	--	--	--	Combined Ash	--	--
469	Cherokee	318	SI	Center Ash Pond	--	--	1	10	10	Combined Ash	--	--
469	Cherokee	319	SI	West Polishing Pond	--	--	1	16	16	Combined Ash	--	--
469	Cherokee	320	SI	West Ash Pond	--	--	--	8	--	Combined Ash	--	--
469	Cherokee	321	SI	Emergency Spill Pond	--	--	--	5	--	--	--	--
469	Cherokee	322	SI	East Ash Pond	--	--	--	8	--	Combined Ash	--	--
469	Cherokee	323	SI	East Polishing Pond	--	--	1	16	16	Combined Ash	--	--
3803	Chesapeake Energy Center	152	SI	Bottom Ash/Sedimentation Pond	36.76205833	-76.30375	9.7	77	7.93814433	Combined Ash	None	--
3803	Chesapeake Energy Center	865	LF	ash landfill	36.76444444	-76.3025	--	--	--	Combined Ash	Yes	--
3797	Chesterfield	150	SI	Lower (Old) Ash Pond	37.37277778	-77.38055556	49	740	15.10204082	Combined Ash	None	--
3797	Chesterfield	151	SI	Upper (New) Ash Pond	37.37277778	-77.36472222	112	10240	91.42857143	Combined Ash	None	--
8226	Cheswick Power Plant	1099	LF	Lefever	40.581433	-79.832236	--	--	--	Combined Ash	Yes	--
8226	Cheswick Power Plant	1165	SI	Bottom Ash Emergency Pond	40.54361111	-79.79416667	0.57392103	4.965794307	8.6524	Combined Ash	Clay	--
8226	Cheswick Power Plant	1166	SI	Bottom Ash Recycle Pond	40.54444444	-79.79416667	0.65206612	3.208425161	4.920398535	Combined Ash	Clay	--
113	Cholla	280	SI	Bottom Ash Pond	34.955225	-110.2884306	80	2300	28.75	Combined Ash	None	--
113	Cholla	863	LF	Bottom Ash Monofill	34.96388889	-110.2861111	--	--	--	Combined Ash	None	--
113	Cholla	279	SI	Fly Ash Pond	34.93276389	-110.2648361	420	18000	42.85714286	Combined Ash	None	--
2721	Cliffside	675	SI	Active Ash Pond	35.21333333	-81.74972222	84	5025	59.82142857	Combined Ash	None	--
2721	Cliffside	674	SI	Retired Unit 1-4 Basin	--	--	14	--	--	Combined Ash	--	Excluded
2721	Cliffside	676	SI	Retired Unit 5 Basin	--	--	46	--	--	Combined Ash	--	Excluded
983	Clifty Creek	848	LF	Type I Fly Ash Landfill	38.733774	-85.437397	--	--	--	Combined Ash	Yes	--
983	Clifty Creek	847	LF	Type III Fly Ash Landfill	38.73565	-85.434455	--	--	--	Combined Ash	None	--
983	Clifty Creek	414	SI	South Fly Ash Runoff Pond Site 16	38.73379722	-85.43019722	40	--	--	Combined Ash	None	--
983	Clifty Creek	413	SI	West Bottom Ash Pond Site 16 (Regn 5)	38.74023611	-85.41523611	58	3600	62.06896552	Combined Ash	None	--
3775	Clinch River	849	LF	Clinch River Industrial Waste Landfill, Permit 223	36.924744	-82.203874	--	--	--	Combined Ash	Yes	--
3775	Clinch River	144	SI	Bottom Ash Pond 1A/1B	36.93722222	-82.19752778	12.8	1240	96.875	Combined Ash	None	--
3775	Clinch River	145	SI	Bottom Ash Pond 2	36.9385	-82.19083333	--	1332	--	Combined Ash	None	Excluded
7213	Clover	851	LF	Stage 1&2	36.87027778	-78.72083333	33	1441.115702	43.6701728	Combined Ash	Composite	Excluded
7213	Clover	850	LF	Stage 3	36.869618	-78.720416	80.5	4958.677686	61.59848057	Combined Ash	Composite	--
7213	Clover	1280	SI	North Sludge	36.87	-78.70166667	1.80153811	4.304132231	2.389143039	FGD Waste	Composite	--
7213	Clover	1281	SI	South Sludge	36.87	-78.70166667	1.80153811	10.76033058	5.972857598	FGD Waste	Composite	--
7213	Clover	1283	SI	Leachate 1	36.87194444	-78.69777778	38.22	--	--	Combined Ash	Yes	Excluded
7213	Clover	1284	SI	Leachate 2	36.87194444	-78.69777778	38.22	--	--	Combined Ash	Yes	Excluded

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
7213	Clover	1282	SI	Coal/Limestone	36.86861111	-78.69444444	38.22	--	--	Ash & Coal Refuse	Yes	Excluded
6030	Coal Creek	854	LF	Section 26	47.44116472	-101.2160697	--	--	--	Combined Ash	Yes	--
6030	Coal Creek	868	LF	Section 31	47.42348333	-101.1640528	--	--	--	Combined Ash	Yes	Excluded
6030	Coal Creek	855	LF	Section 5	47.41005833	-101.1603578	--	--	--	Combined Ash	None	Excluded
6030	Coal Creek	1119	LF	Section 32	47.42028056	-101.1581611	220	14256.1983	64.80090136	Combined Ash	Yes	--
6030	Coal Creek	29	SI	Ash Pond 91	47.37609	-101.143559	72	249	3.458333333	Combined Ash	--	--
6030	Coal Creek	857	LF	SW Section 16	47.37834778	-101.1317489	--	--	--	Combined Ash	Yes	Excluded
6030	Coal Creek	30	SI	Upstream Raise/Ash Pond 92/SW Section 16	47.380215	-101.129303	90	769	8.544444444	Combined Ash	--	--
6030	Coal Creek	852	LF	SE Section 16	47.37575556	-101.1258111	70	2913.22314	41.61747343	Combined Ash	Yes	--
861	Coffeen	846	LF	Landfill	39.06930556	-89.40025	--	--	--	Combined Ash	Yes	--
861	Coffeen	380	SI	Gypsum Management Facility Recycle Pond	39.06624722	-89.39559722	17	243	14.29411765	FGD Waste	Composite	--
861	Coffeen	379	SI	Recycle Pond	39.05831667	-89.39442222	23	500	21.73913043	Combined Ash	None	Excluded
47	Colbert	859	LF	#5 Dry Stack (fly ash)	34.73305556	-87.83408333	--	--	--	Combined Ash	None	--
47	Colbert	258	SI	Disposal Area 5 Basin	--	--	12	372	31	Combined Ash	--	--
47	Colbert	259	SI	Disposal Area 5	--	--	75	5455	72.73333333	Combined Ash	--	--
47	Colbert	260	SI	Ash Pond 4	--	--	52	1364	26.23076923	Combined Ash	--	--
6178	Coleto Creek	182	SI	Primary Ash Pond	28.72472222	-97.20916667	190	2700	14.21052632	Combined Ash	Clay	--
6178	Coleto Creek	181	SI	Secondary Settling Pond	28.72861111	-97.20638889	10	300	30	Combined Ash	Clay	--
6076	Colstrip	49	SI	Units 1 & 2 Stage Two Evaporation Ponds (STEP)	45.9055	-106.6442222	176	4370	24.82954545	Combined Ash	Composite	--
6076	Colstrip	50	SI	Units 1 & 2 A Pond	45.87916667	-106.6188889	14	245	17.5	Combined Ash	None	--
6076	Colstrip	52	SI	Units 1 & 2 Bottom Ash Pond	45.88138889	-106.61875	7	73	10.42857143	Combined Ash	Composite	--
6076	Colstrip	51	SI	Units 3 & 4 Effluent Holding Pond (EHP)	45.87027778	-106.5482222	367	17000	46.32152589	Combined Ash	None	--
6076	Colstrip	46	SI	Units 3 & 4 Scrubber Drain Collection Pond	--	--	6	72	12	Combined Ash	--	Excluded
6076	Colstrip	47	SI	Units 3 & 4 Bottom Ash Pond	--	--	8	38	4.75	Combined Ash	--	--
6076	Colstrip	48	SI	Units 1 & 2 B Fly Ash Pond	--	--	10	196	19.6	Combined Ash	--	--
6076	Colstrip	53	SI	Units 3 & 4 Scrubber Wash Tray Pond	--	--	8	85	10.625	Combined Ash	--	Excluded
10784	Colstrip Energy LP	860	LF	CELP	45.97886111	-106.6635	--	--	--	Combined Ash	None	--
10784	Colstrip Energy LP	861	LF	CELP	45.97533333	-106.6594444	--	--	--	Combined Ash	None	Excluded
2123	Columbia	1213	SI	Ash Settling Pond	38.96584333	-92.31849028	8.5	45	5.294117647	Combined Ash	None	--
8023	Columbia	1136	LF	Ash Pond Disposal Facility	43.48969444	-89.42175	--	--	--	Combined Ash	None	Excluded
8023	Columbia	1135	LF	Dry Ash Disposal Facility	43.48727778	-89.41205556	--	--	--	Combined Ash	Yes	--
8023	Columbia	239	SI	Landfill Storm Water Pond	--	--	11	11	1	Combined Ash	Composite	Excluded
8023	Columbia	240	SI	Secondary Ash Pond	--	--	16	204	12.75	Combined Ash	None	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
8023	Columbia	241	SI	Polishing Pond	--	--	1	5	5	Combined Ash	None	--
8023	Columbia	242	SI	Primary Ash Pond	--	--	9	72	8	Combined Ash	None	--
470	Comanche	1137	LF	Comanche ADF	38.20170556	-104.5825083	280	18882.02479	67.43580283	Combined Ash	None	--
470	Comanche	324	SI	Ash Pond #2	--	--	2	12	6	FGD Waste	--	--
470	Comanche	325	SI	Polishing Pond (#4)	--	--	2	12	6	Combined Ash	--	--
470	Comanche	326	SI	Ash Pond #3	--	--	2	12	6	Combined Ash	--	--
470	Comanche	327	SI	Ash Pond #1	--	--	2	12	6	FGD Waste	--	--
470	Comanche	328	SI	Ash Disposal Facility (ADF) Stormwater Retention Pond	--	--	1	8	8	Combined Ash	--	--
3118	Conemaugh	1138	LF	Stage I	40.41111111	-79.07166667	--	--	--	Combined Ash	None	Excluded
3118	Conemaugh	864	LF	Stage II	40.40666667	-79.07027778	434	50826.44628	117.1116274	Combined Ash	Yes	--
3118	Conemaugh	1338	SI	Bottom Ash Final Settling Pond - D	40.38277778	-79.06333333	0.83677686	6.198347107	7.407407407	Combined Ash	Clay	--
3118	Conemaugh	1337	SI	Bottom Ash Final Settling Pond - C	40.38305556	-79.06333333	0.83677686	6.198347107	7.407407407	Combined Ash	Clay	--
3118	Conemaugh	1336	SI	Bottom Ash Final Settling Pond - B	40.38361111	-79.06333333	0.83677686	6.198347107	7.407407407	Combined Ash	Clay	--
3118	Conemaugh	1335	SI	Bottom Ash Sluice Recycle Pond - A	40.38388889	-79.06333333	0.83677686	6.198347107	7.407407407	Combined Ash	Clay	--
3118	Conemaugh	1334	SI	Cooling Tower Desilting Basin	40.38555556	-79.05777778	9.524	--	--	Combined Ash	Yes	Excluded
2840	Conesville	701	SI	Ash Pond Complex	40.18833333	-81.86972222	82	865	10.54878049	Combined Ash	None	--
2840	Conesville	1005	LF	--	--	--	52	2252.066116	43.30896376	Combined Ash	Composite	--
2840	Conesville	1006	LF	--	--	--	50	2835.743802	56.71487603	Combined Ash	--	Excluded
1710	Consumers Energy - J.H. Campbell	572	SI	EPRI 4	--	--	267	4276.859504	16.01820039	Ash & Coal Refuse	--	Excluded
1710	Consumers Energy - J.H. Campbell	967	LF	--	--	--	17.96	620.298967	34.5378044	Combined Ash	Composite	--
1710	Consumers Energy - J.H. Campbell	985	LF	--	--	--	18	657.1338843	36.50743802	Combined Ash	Composite	--
1710	Consumers Energy - J.H. Campbell	998	LF	--	--	--	17.4	783.1828512	45.01050869	Combined Ash	Composite	--
1710	Consumers Energy - J.H. Campbell	999	LF	--	--	--	17	1266.432645	74.49603792	Combined Ash	Composite	--
1384	Cooper Station.	973	LF	--	--	--	--	--	--	Combined Ash	--	--
7210	Cope	866	LF	Cope Landfill	33.37005556	-81.04075	340	14876.03306	43.75303841	Combined Ash	None	--
6177	Coronado Generating Station	180	SI	Evaporation Pond/Dam	34.55833333	-109.2952778	290	5900	20.34482759	Combined Ash	None	--
6177	Coronado Generating Station	867	LF	Ash Disposal	34.54766667	-109.28325	230	34435.26171	149.7185292	Combined Ash	None	--
6177	Coronado Generating Station	835	LF	N/A	--	--	--	--	--	Combined Ash	--	Excluded
8222	Coyote	250	SI	Ash Pond	47.218595	-101.814109	4	40	10	Combined Ash	--	--
8222	Coyote	248	SI	Nelson Pond	47.217021	-101.80979	5	92	18.4	Combined Ash	--	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
8222	Coyote	249	SI	Sluice Pond	47.217006	-101.805935	1	5	5	Combined Ash	--	--
8222	Coyote	826	LF	Black Pit	47.22230278	-101.7959417	43	1285.53719	29.89621372	Combined Ash	Clay	Excluded
8222	Coyote	833	LF	Blue Pit	47.21148889	-101.7883222	224	5224.416322	23.32328715	Combined Ash	Clay	--
8222	Coyote	825	LF	Green Pit	47.22711667	-101.7874778	98.3	607.4380165	6.179430484	Combined Ash	Clay	Excluded
8222	Coyote	856	LF	Purple Pit	47.22349722	-101.7578444	155.7	1548.370064	9.944573309	Combined Ash	None	--
2549	CR Huntley Generating Station	1100	LF	Huntley Ash Landfill	42.98833333	-78.92805556	--	--	--	Combined Ash	Yes	--
2549	CR Huntley Generating Station	645	SI	North Equalization Basin	42.96678611	-78.92686111	2	9	4.5	Combined Ash	--	--
2549	CR Huntley Generating Station	644	SI	South Equalization Basin	42.966509	-78.926638	2	6	3	Combined Ash	--	--
2549	CR Huntley Generating Station	643	SI	South Settling Pond System	42.96695	-78.925467	7	48	6.857142857	Combined Ash	--	--
6021	Craig	27	SI	Concentrator Decant Basin #1	--	--	--	1	--	Combined Ash	--	Excluded
6021	Craig	28	SI	Concentrator Decant Basin #2	--	--	--	1	--	FGD Waste	--	Excluded
6021	Craig	974	LF	--	--	--	18	--	--	Combined Ash	Clay	Excluded
867	Crawford	387	SI	EPRI 2	--	--	--	--	--	--	--	Excluded
753	Crisp Plant	1265	SI	Crisp Plant	31.84490556	-83.94425	6.82	--	--	Combined Ash	None	--
641	Crist	1276	SI	Interim Landfill Pond	30.568	-87.23752778	2.24517906	8.980716253	4	Combined Ash	None	--
641	Crist	1139	LF	Ash Landfill	30.56383333	-87.23536111	68	2364.554637	34.77286231	Combined Ash	Yes	--
641	Crist	1275	SI	Ash Landfill Pond	30.568	-87.23527778	2.68365473	40.25482094	15	Combined Ash	None	Excluded
641	Crist	1278	SI	Gypsum Area 1 SedimentationPond	30.57	-87.2325	4.75206612	95.04132231	20	FGD Waste	Composite	Excluded
641	Crist	1277	SI	Gypsum Area 1 Cell 2	30.56833333	-87.232	15.610652	402.5799128	25.78879559	FGD Waste	Composite	--
641	Crist	1279	SI	Gypsum Area 1 Return Water Pond	30.56888889	-87.23055556	3.52157943	52.82369146	15	FGD Waste	Composite	Excluded
641	Crist	1273	SI	Governor's Island Ash Pond	30.56413056	-87.22170556	13.51	--	--	Ash & Coal Refuse	None	Excluded
641	Crist	1274	SI	Ash Pond	30.56216667	-87.22011111	16.3	240.9142562	14.78001572	Ash & Coal Refuse	None	--
130	Cross	827	LF	Poz-O-Tec	33.38416667	-80.1175	91	2727.272727	29.97002997	Combined Ash	None	--
130	Cross	285	SI	Gypsum Pond	33.36791667	-80.10877778	1	6	6	FGD Waste	Clay	--
130	Cross	284	SI	Bottom Ash 1	33.37088889	-80.10466667	12.8	230	17.96875	Combined Ash	Clay	--
130	Cross	286	SI	Bottom Ash 2	33.37361111	-80.10072222	79	1158	14.65822785	Combined Ash	Clay	--
130	Cross	828	LF	-999	--	--	--	--	--	Combined Ash	--	--
130	Cross	829	LF	-999	--	--	--	--	--	Combined Ash	--	--
130	Cross	830	LF	-999	--	--	--	--	--	Combined Ash	--	--
628	Crystal River Power Plant	831	LF	Landfill-1	28.96666667	-82.68722222	--	--	--	Combined Ash	None	--
3399	Cumberland	125	SI	Gypsum Storage Area (North/South)	--	--	170	12397	72.92352941	FGD Waste	--	--
3399	Cumberland	126	SI	Dry Ash Stack	--	--	110	7810	71	Combined Ash	--	--
3399	Cumberland	127	SI	Ash Pond	--	--	50	1240	24.8	Combined Ash	--	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
3399	Cumberland	978	LF	--	--	--	--	--	--	Combined Ash	--	--
6823	D B Wilson	845	LF	Phase II Landfill	37.46083333	-87.08888889	--	--	--	Combined Ash	None	--
6823	D B Wilson	832	LF	Phase I Landfill	37.46027778	-87.085	--	--	--	Combined Ash	None	--
1702	D.E. Karn	571	SI	DE Karn 1 and 2 Solid Waste Disposal Area	43.64583333	-83.8325	--	--	--	--	None	--
1702	D.E. Karn	570	SI	Pond A	--	--	174	4423	25.41954023	Combined Ash	None	--
1702	D.E. Karn	1004	LF	--	--	--	40	1022.727273	25.56818182	Combined Ash	--	--
1385	Dale Station	558	SI	Dale Ash Pond #3	37.885	-84.26333333	1.6	--	--	Combined Ash	--	--
1385	Dale Station	560	SI	Dale Ash Pond #2	37.88388889	-84.26222222	8	112	14	Combined Ash	None	--
1385	Dale Station	559	SI	Dale Ash Pond #4	37.87777778	-84.26166667	10.7	143	13.36448598	Combined Ash	None	--
963	Dallman	399	SI	Dallman Ash Pond	39.76722222	-89.6	34	682	20.05882353	Combined Ash	None	--
963	Dallman	834	LF	Unit 2	39.769459	-89.597701	22	1115.702479	50.71374906	Combined Ash	Yes	--
963	Dallman	823	LF	Unit 1	39.766279	-89.596662	--	--	--	Combined Ash	None	Excluded
2723	Dan River	678	SI	Primary Pond	36.489167	-79.716111	27	477	17.66666667	Combined Ash	None	Excluded
2723	Dan River	679	SI	Dry Storage Basin, Dredge Pond Dike	36.48946389	-79.71566944	--	--	--	--	--	Excluded
2723	Dan River	677	SI	Secondary Pond	36.491944	-79.713056	12	187	15.58333333	Combined Ash	None	Excluded
2480	Danskammer Generating Station	1140	LF	Danskammer Solid Waste Management Facility	41.57666667	-73.96944444	21.8	1167.84045	53.57066284	Combined Ash	Composite	Excluded
4158	Dave Johnston Plant	4	SI	Blowdown Canal	42.84222222	-105.7805556	1	3	3	Combined Ash	None	Excluded
4158	Dave Johnston Plant	5	SI	4B Ash Pond	42.84222222	-105.7805556	20	145	7.25	Combined Ash	Composite	--
4158	Dave Johnston Plant	6	SI	4A Ash Pond	42.84222222	-105.7805556	20	145	7.25	Combined Ash	Composite	--
4158	Dave Johnston Plant	7	SI	1A Ash Pond	42.84222222	-105.7805556	13	115	8.846153846	Combined Ash	Composite	Excluded
4158	Dave Johnston Plant	8	SI	4 Clear Pond	42.84222222	-105.7805556	6.4	50	7.8125	Combined Ash	None	--
4158	Dave Johnston Plant	9	SI	1B Clear Pond	42.84222222	-105.7805556	2	20	10	Combined Ash	None	--
4158	Dave Johnston Plant	10	SI	1B Ash Pond	42.84222222	-105.7805556	13	112	8.615384615	Combined Ash	Composite	--
4158	Dave Johnston Plant	11	SI	1A Clear Pond	42.84222222	-105.7805556	2	16	8	Combined Ash	None	--
4158	Dave Johnston Plant	837	LF	Dave Johnston Plant Industrial Landfill	42.84611111	-105.7630556	555	20661.15702	37.22730995	Combined Ash	None	--
996	Dean H Mitchell	446	SI	Secondary 2	41.638407	-87.410366	0.48	2	4.166666667	Combined Ash	--	Excluded
996	Dean H Mitchell	445	SI	Secondary 1	41.64043	-87.406511	0.52	3	5.769230769	Combined Ash	--	Excluded
996	Dean H Mitchell	443	SI	Primary 2	41.639964	-87.406162	1.7	31	18.23529412	Combined Ash	--	Excluded
996	Dean H Mitchell	444	SI	Primary 3	41.639408	-87.405385	1.9	31	16.31578947	Combined Ash	--	Excluded
996	Dean H Mitchell	447	SI	Primary 4	41.638818	-87.403168	2.3	34	14.7826087	Combined Ash	--	Excluded
996	Dean H Mitchell	442	SI	Primary 1	41.634588	-87.395399	1.4	22	15.71428571	Combined Ash	--	Excluded
996	Dean H Mitchell	440	SI	Bottom Ash Complex	--	--	--	--	--	Combined Ash	None	Excluded
996	Dean H Mitchell	441	SI	Fly Ash Pond	--	--	--	--	--	Combined Ash	None	Excluded
663	Deerhaven Generating Station	1141	LF	Fly Ash Landfill	29.764712	-82.397978	--	--	--	Combined Ash	Yes	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
663	Deerhaven Generating Station	1331	SI	CoolingTowerBlowdown&BottomAshPond	29.76472222	-82.39222222	2.81221304	52.8953168	18.80914286	Combined Ash	None	--
1572	Dickerson	839	LF	Westland Ash Storage Site	39.19222222	-77.4575	206	7809.917355	37.91222017	Combined Ash	Yes	--
51	Dolet Hills	265	SI	Surge Pond No. 1	32.02997222	-93.57208333	2.25	29	12.88888889	Combined Ash	Clay	--
51	Dolet Hills	840	LF	Flyash/FGD Landfill	32.0125	-93.57083333	109	5268.595041	48.33573432	Combined Ash	Yes	--
51	Dolet Hills	269	SI	Auxiliary Surge Pond	32.02963889	-93.57052778	1.54	2	1.298701299	Combined Ash	Clay	--
51	Dolet Hills	267	SI	Surge Pond No. 2	32.02875	-93.56772222	4.8	18	3.75	Combined Ash	Clay	--
51	Dolet Hills	263	SI	Landfill Storm Water/Leachate	32.02041667	-93.56661111	1.32	--	--	Combined Ash	Clay	--
51	Dolet Hills	264	SI	Ash Basin No. 1	32.03044444	-93.56211111	30	578	19.26666667	Combined Ash	Clay	--
51	Dolet Hills	266	SI	Secondary Basin	32.03277778	-93.56208333	6.5	75	11.53846154	Combined Ash	None	--
51	Dolet Hills	268	SI	Ash Basin No. 2	32.0355	-93.56080556	31	501	16.16129032	Combined Ash	Clay	--
3317	Dolphus M Grainger	116	SI	Ash Pond 1	33.82709722	-79.04948889	42.5	298	7.011764706	Combined Ash	None	Excluded
3317	Dolphus M Grainger	115	SI	Ash Pond 2	33.82227778	-79.04708611	39	429	11	Combined Ash	None	Excluded
1046	Dubuque	476	SI	Ash Channel	--	--	--	10	--	Combined Ash	--	--
6016	Duck Creek	842	LF	Landfill	40.52027778	-89.98833333	169	--	--	Combined Ash	Composite	--
6016	Duck Creek	18	SI	Recycle Pond	--	--	--	--	--	--	Clay	--
6016	Duck Creek	19	SI	Ash Pond 1	--	--	58	1900	32.75862069	Combined Ash	None	Excluded
6016	Duck Creek	20	SI	Ash Pond 2	--	--	85	1000	11.76470588	Combined Ash	None	Excluded
2554	Dunkirk Generating Plant	843	LF	SWMF	42.497091	-79.305372	55.96	1660	29.66404575	Combined Ash	Composite	--
2554	Dunkirk Generating Plant	646	SI	Northwest Pump House	--	--	--	--	--	Combined Ash	--	Excluded
2554	Dunkirk Generating Plant	647	SI	Equalization Basin	--	--	--	2	--	Combined Ash	--	--
2554	Dunkirk Generating Plant	648	SI	Settling Pond System	--	--	2	12	6	Combined Ash	--	--
26	E. C. Gaston	257	SI	Ash Pond Dam	--	--	339	18888	55.71681416	Combined Ash	None	--
1355	E.W. Brown	524	SI	Ash Pond	37.7875	-84.71888889	75.12	--	--	Combined Ash	Composite	--
1355	E.W. Brown	525	SI	Auxiliary Pond	37.78109167	-84.71879167	25.7	515	20.03891051	Combined Ash	Composite	--
991	Eagle Valley	426	SI	C Pond	39.48408611	-86.42719444	8	102	12.75	Combined Ash	None	--
991	Eagle Valley	428	SI	B Pond	39.48254167	-86.42694444	13	177	13.61538462	Combined Ash	None	--
991	Eagle Valley	427	SI	A Pond	39.48098611	-86.42684444	19	400	21.05263158	Combined Ash	None	--
991	Eagle Valley	425	SI	E Pond	39.48441944	-86.4231	4	45	11.25	Combined Ash	None	Excluded
991	Eagle Valley	429	SI	D Pond	39.48308889	-86.42246389	16	370	23.125	Combined Ash	None	--
1217	Earl F Wisdom	844	LF	Ash Landfill	43.16133333	-95.25288889	--	--	--	Combined Ash	None	--
6018	East Bend Station	24	SI	East Bend Station Unit 1	38.90194444	-84.84111111	53.4	1277	23.91385768	Combined Ash	None	--
6018	East Bend Station	879	LF	East Landfill	38.90916667	-84.84027778	--	--	--	Combined Ash	Yes	--
6018	East Bend Station	23	SI	FGD Pond East	--	--	4	51	12.75	FGD Waste	--	--
6018	East Bend Station	25	SI	FGD Pond West	--	--	4	45	11.25	FGD Waste	--	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
2837	Eastlake	1262	SI	Combined Treatment Basin	41.67305556	-81.44305556	0.58539945	2.869605142	4.901960784	Combined Ash	None	--
2837	Eastlake	914	LF	North Park	--	--	--	--	--	Combined Ash	Yes	--
856	ED Edwards	378	SI	Pond 2 - Ash Pond Settling	40.59277778	-89.66722222	32	--	--	Combined Ash	None	--
856	ED Edwards	377	SI	Pond 3 - Clarification Pond	40.58972222	-89.66527778	23	--	--	Combined Ash	None	--
856	ED Edwards	376	SI	Ash Pond	--	--	89	1800	20.2247191	Combined Ash	None	--
4050	Edgewater	858	LF	I-43 ADF	43.69333333	-87.76416667	25	1026.260331	41.05041322	Combined Ash	Yes	--
4050	Edgewater	894	LF	Edgewater 1-4 Closed ADF	43.71138889	-87.71305556	--	--	--	Combined Ash	None	Excluded
4050	Edgewater	168	SI	B Pond	43.710917	-87.711869	1.93	19	9.844559585	Combined Ash	--	--
4050	Edgewater	165	SI	A Ponds (Two)	43.712168	-87.711684	4.4	44	10	Combined Ash	--	--
4050	Edgewater	164	SI	C Pond	43.71111	-87.711003	0.65	3	4.615384615	Combined Ash	--	--
4050	Edgewater	166	SI	I43 Coal Combustion landfill Contact Pond	43.717171	-87.710875	1.11	8	7.207207207	Combined Ash	--	Excluded
4050	Edgewater	169	SI	F Pond	43.710195	-87.704069	0.9	9	10	Combined Ash	--	--
4050	Edgewater	167	SI	Slag Pond	43.709357	-87.703924	1.8	10	5.555555556	Combined Ash	--	--
1004	Edwardsport	459	SI	Primary Ash Pond	38.80080556	-87.24330556	8	170	21.25	Combined Ash	None	--
1004	Edwardsport	458	SI	Secondary Ash Pond	38.80072222	-87.24302778	1	7	7	Combined Ash	None	--
1004	Edwardsport	971	LF	--	--	--	--	--	--	Combined Ash	--	--
1374	Elmer Smith Station	1234	SI	Pond #1	37.79491667	-87.06419444	1.60697888	24.1046832	15	Combined Ash	None	--
1374	Elmer Smith Station	1235	SI	Pond #2	37.79344444	-87.06313889	13.7741047	24.79338843	1.8	Combined Ash	None	--
1374	Elmer Smith Station	1237	SI	FGD Scrubber Purge basin	37.79722222	-87.06145	0.13774105	0.20661157	1.5	FGD Waste	None	--
1374	Elmer Smith Station	1236	SI	FGD Emergency Pond	37.79572222	-87.05869444	0.68870523	8.26446281	12	FGD Waste	Composite	--
3098	Elrama Power Plant	1342	SI	Ash Settling Pond 1	40.25333333	-79.92027778	2.13269054	29.34421488	13.7592465	Combined Ash	Yes	--
3098	Elrama Power Plant	1343	SI	Ash Settling Pond 2	40.25388889	-79.92027778	2.224	--	--	Combined Ash	Yes	--
3098	Elrama Power Plant	1344	SI	Ash Polishing Pond 4	40.25472222	-79.92027778	0.3902663	6.634527089	17	Combined Ash	Yes	--
3098	Elrama Power Plant	1345	SI	Scrubber Emergency Pond 5	40.25527778	-79.91972222	0.20661157	3.512396694	17	FGD Waste	Yes	Excluded
3098	Elrama Power Plant	895	LF	Fern Valley	40.28111111	-79.88972222	--	--	--	Combined Ash	Yes	Excluded
1832	Erickson Station	587	SI	Unit 1	42.687523	-84.653971	33	198	6	Combined Ash	--	--
87	Escalante	274	SI	Management Units 3 & 4 Bottom Ash	--	--	13	96	7.384615385	Combined Ash	--	--
87	Escalante	276	SI	Evaporation Pond 1a + 1b	--	--	2.3	14	6.086956522	FGD Waste	--	--
87	Escalante	277	SI	Emergency Scrubber Pond	--	--	0.8	3	3.75	FGD Waste	--	--
87	Escalante	278	SI	Evaporation Ponds 2-5	--	--	--	--	--	--	--	--
87	Escalante	275	SI	N/A	--	--	--	--	--	--	--	Excluded
87	Escalante	992	LF	--	--	--	97	573.9210285	5.916711634	Combined Ash	Clay	--
1012	F. B. Culley	466	SI	West Ash Pond	37.91198222	-87.32948472	18	620	34.44444444	Combined Ash	None	Excluded
1012	F. B. Culley	467	SI	East Pond	37.90922778	-87.32296111	7	372	53.14285714	Combined Ash	None	--
1218	Fair Station	896	LF	CIPCO landfill	41.46194444	-90.85888889	--	--	--	Combined Ash	Yes	Excluded

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
1218	Fair Station	1184	SI	#2 ash pond	41.45833333	-90.825	1.20523416	13.25757576	11	Combined Ash	Clay	Excluded
1218	Fair Station	1183	SI	#1 ash pond	41.45833333	-90.82444444	2.26280992	24.89090909	11	Combined Ash	Clay	Excluded
6179	Fayette Power Project	183	SI	Management Unit 009	29.90944444	-96.75111111	30	600	20	Combined Ash	Clay	--
6179	Fayette Power Project	184	SI	Management Unit 002	29.91472222	-96.74055556	84	2293	27.29761905	Combined Ash	Clay	--
6179	Fayette Power Project	897	LF	CCB Landfill	--	--	23	552	24	Combined Ash	Yes	--
886	Fisk	1238	SI	Dewatering Pad	41.84916667	-87.65666667	0.25482094	0.126262626	0.495495495	Ash & Coal Refuse	None	Excluded
886	Fisk	1239	SI	Dewatering Bin Sump	41.84888889	-87.65638889	0.09182736	0.183654729	2	Ash & Coal Refuse	None	Excluded
886	Fisk	1240	SI	Equalization Basin (Flume)	41.84861111	-87.65472222	0.04820937	0.482093664	10	Ash & Coal Refuse	None	Excluded
6138	Flint Creek	898	LF	Ash landfill	36.259077	-94.514209	40	934.8657025	23.37164256	Combined Ash	Yes	--
6138	Flint Creek	173	SI	Secondary Bottom Ash Pond	--	--	4	24	6	Ash & Coal Refuse	--	--
6138	Flint Creek	174	SI	Primary Bottom Ash Pond	--	--	43	484	11.25581395	Ash & Coal Refuse	--	--
3943	Fort Martin Power Station	1143	LF	Gypsum Phase I Landfill	39.717275	-79.95	99.5	2169.421489	21.80323104	Combined Ash	Yes	--
3943	Fort Martin Power Station	1142	LF	Ash Landfill	39.71277778	-79.9425	99.5	2169.421489	21.80323104	Combined Ash	None	--
3943	Fort Martin Power Station	1181	SI	Wastewater Treatment Lagoon 1	39.709222	-79.930731	1.26262626	10.19283747	8.072727273	Combined Ash	None	Excluded
3943	Fort Martin Power Station	1182	SI	Wastewater Treatment Lagoon 2	39.709222	-79.930731	1.26262626	10.19283747	8.072727273	Combined Ash	None	Excluded
10343	Foster Wheeler Mt Carmel Cogen	901	LF	-999	--	--	--	--	--	Combined Ash	--	--
2442	Four Corners	638	SI	Low Volume Waste Water System Decant Cells	36.6831	-108.5124	45.1	435	9.645232816	Combined Ash	--	--
2442	Four Corners	915	LF	Dry Flyash Disposal Area	36.68583333	-108.5080556	--	--	--	Combined Ash	Yes	--
2442	Four Corners	639	SI	Lined Ash Impoundment	36.6849	-108.5066	75	2399	31.98666667	Combined Ash	Composite	--
2442	Four Corners	903	LF	Plant Disposal (Gridded)	36.68833333	-108.5063889	--	--	--	Combined Ash	None	--
2442	Four Corners	640	SI	Lined Water Impoundment	--	--	45	435	9.666666667	FGD Waste	Composite	--
2442	Four Corners	641	SI	Low Volume Waste Water Pond	--	--	14	137	9.785714286	Combined Ash	--	--
2442	Four Corners	642	SI	Upper Retention Sump	--	--	1	11	11	FGD Waste	--	--
1043	Frank E. Ratts	469	SI	Pond 4	38.51630556	-87.27	25	--	--	Combined Ash	--	--
1043	Frank E. Ratts	470	SI	Pond 3	38.51636111	-87.26682778	10	--	--	Combined Ash	--	--
1043	Frank E. Ratts	475	SI	Pond 2	38.51716667	-87.26455556	10	--	--	Combined Ash	--	--
1043	Frank E. Ratts	472	SI	Pond 1	38.51955556	-87.26347222	6	--	--	Combined Ash	None	--
1043	Frank E. Ratts	468	SI	Fly Ash Pond 3	--	--	25	--	--	Combined Ash	None	--
1043	Frank E. Ratts	471	SI	Bottom Ash Pond	--	--	6	40	6.666666667	Combined Ash	None	--
1043	Frank E. Ratts	473	SI	Fly Ash Pond 2	--	--	16	--	--	Combined Ash	None	--
1043	Frank E. Ratts	474	SI	Fly Ash Pond 1	--	--	10	--	--	Combined Ash	None	--
2718	G G Allen	670	SI	Active Ash Basin	35.17741389	-81.01114722	160	5915	36.96875	Combined Ash	None	--
2718	G G Allen	668	SI	North Dike - Active Ash Basin	35.18098611	-81.01024722	--	--	--	Combined Ash	None	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
2718	G G Allen	892	LF	Ash/Gypsum Landfill	35.18388889	-81.01	--	--	--	Combined Ash	Yes	--
2718	G G Allen	669	SI	East Dike - Active Ash Basin	35.17736944	-81.00711944	--	--	--	Combined Ash	None	--
7	Gadsden	253	SI	Ash Pond (NID #1428)	--	--	68	753	11.07352941	Combined Ash	--	--
3403	Gallatin	128	SI	Bottom Ash Pond A	--	--	269	4390	16.3197026	Combined Ash	--	--
3403	Gallatin	129	SI	Fly Ash Pond E	--	--	157	4401	28.03184713	Combined Ash	--	--
3403	Gallatin	130	SI	Stilling Pond B, C, D	--	--	55	372	6.763636364	Combined Ash	--	--
8102	General James M. Gavin	246	SI	Stingy Run Ash Disposal Pond	38.96430833	-82.14427222	324.5	23365	72.00308166	Ash & Coal Refuse	None	--
8102	General James M. Gavin	1144	LF	FGD Landfill	38.95555556	-82.14111111	225	1118.204775	4.969799	Combined Ash	Composite	--
8102	General James M. Gavin	247	SI	Bottom Ash Pond	38.93055556	-82.12083333	85	1530	18	Ash & Coal Refuse	None	--
4143	Genoa	1007	LF	--	--	--	--	--	--	Combined Ash	--	Excluded
4143	Genoa	1131	LF	--	--	--	100	--	--	Combined Ash	--	--
1091	George Neal North	909	LF	Neal North Landfill West	42.31888889	-96.37055556	--	--	--	Combined Ash	None	Excluded
1091	George Neal North	910	LF	Neal North Landfill East	42.31944444	-96.36638889	--	--	--	Combined Ash	None	Excluded
1091	George Neal North	906	LF	Neal North Landfill Active	42.31555556	-96.36611111	200	--	--	Combined Ash	Yes	--
1091	George Neal North	907	LF	--	--	--	--	--	--	Combined Ash	--	--
1091	George Neal North	908	LF	--	--	--	--	--	--	Combined Ash	--	--
1091	George Neal North	504	SI	Surface Impoundment 1	--	--	12	137	11.41666667	Combined Ash	None	--
1091	George Neal North	505	SI	Surface Impoundment 3	--	--	76	837	11.01315789	Combined Ash	None	--
1091	George Neal North	506	SI	Surface Impoundment 2	--	--	27	296	10.96296296	Combined Ash	None	--
7343	George Neal South	1332	SI	Air Heater Wash Pond	42.29722222	-96.35888889	2.8238292	16.94297521	6	Combined Ash	Composite	Excluded
7343	George Neal South	911	LF	Neal 4 Landfill	42.29916667	-96.34722222	32	521.546281	16.29832128	Combined Ash	None	--
6077	Gerald Gentleman	912	LF	Fossil Fuels Combustion Ash Landfill	41.07222222	-101.1497222	--	--	--	Combined Ash	Yes	--
1356	Ghent	528	SI	Gypsum Stacking Facility	38.75166667	-85.02777778	46	2758	59.95652174	FGD Waste	None	--
1356	Ghent	527	SI	Ash Treatment Basin #1	38.74861111	-85.02722222	120	4339	36.15833333	Combined Ash	None	--
1356	Ghent	529	SI	Ash Treatment Basin #2	38.73972222	-85.02305556	146	7190	49.24657534	Combined Ash	None	--
1356	Ghent	526	SI	Secondary Ash Treatment Basin	--	--	4	--	--	Combined Ash	--	--
1356	Ghent	530	SI	Gypsum Stack Surge/Reclaim Pond	--	--	8	--	--	FGD Waste	Clay	--
6136	Gibbons Creek Steam Electric Station	913	LF	Site A	30.63444444	-96.09305556	--	--	--	Combined Ash	Yes	--
6136	Gibbons Creek Steam Electric Station	1244	SI	Scrubber Sludge Pond	30.61136111	-96.07977778	7.64038108	122.0256198	15.97114313	FGD Waste	Composite	--
6136	Gibbons Creek Steam Electric Station	1241	SI	Ash Pond A	30.61680556	-96.07602778	10.617539	212.3507805	20	Combined Ash	Clay	--
6136	Gibbons Creek Steam Electric Station	1242	SI	Ash Pond B	30.61680556	-96.07602778	10.617539	212.3507805	20	Combined Ash	Clay	--
6136	Gibbons Creek Steam Electric Station	1243	SI	Ash Pond C	30.61680556	-96.07602778	10.617539	212.3507805	20	Combined Ash	Clay	--
6136	Gibbons Creek Steam Electric Station	881	LF	Site F	30.63833333	-96.06666667	--	--	--	Combined Ash	Yes	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
6113	Gibson	902	LF	S Aggregate Landfill (26-06)	38.33638889	-87.78444444	378	52189.51871	138.0675098	Combined Ash	Composite	--
6113	Gibson	86	SI	North Settling Basin	38.37916667	-87.76333333	15	150	10	--	None	--
6113	Gibson	84	SI	North Ash Pond	38.37722222	-87.75805556	25	350	14	Combined Ash	None	--
6113	Gibson	904	LF	Aggregate Landfill (26-02)	38.37222222	-87.75194444	131.3	11968.00413	91.15006955	Combined Ash	Composite	--
6113	Gibson	83	SI	East Pond #2	38.37666667	-87.74277778	105	1733	16.5047619	Combined Ash	None	--
6113	Gibson	82	SI	East Settling Basin	38.37166667	-87.74083333	45	743	16.51111111	--	None	--
6113	Gibson	85	SI	East Pond #3	38.3825	-87.73972222	133	3325	25	Combined Ash	None	--
6113	Gibson	81	SI	East Pond #1	38.37666667	-87.73722222	105	1733	16.5047619	Combined Ash	None	--
3776	Glen Lyn	146	SI	Auxiliary Fly Ash Pond	37.37855556	-80.87558333	44.3	185	4.176072235	Combined Ash	None	--
3776	Glen Lyn	870	LF	Glen Lyn Industrial Waste Landfill, Permit 222	37.37805556	-80.875	--	--	--	Combined Ash	Yes	--
3776	Glen Lyn	147	SI	Bottom Ash Pond	37.37261111	-80.86544444	1.44	90	62.5	Combined Ash	None	--
8	Gorgas	254	SI	Gypsum Storage Facility	33.655278	-87.217222	21	983	46.80952381	FGD Waste	Composite	--
8	Gorgas	255	SI	Ash Pond (NID #1198) Rattlesnake Dam	33.639722	-87.185556	420	10750	25.5952381	Combined Ash	None	--
8	Gorgas	963	LF	--	--	--	--	--	--	Combined Ash	--	--
1825	Grand Haven City of J.B. Sims	1309	SI	West Ash Pond	43.07180556	-86.23280556	0.29660239	2.076216713	7	Combined Ash	Clay	--
1825	Grand Haven City of J.B. Sims	1310	SI	East Ash Pond	43.07180556	-86.23280556	0.29660239	2.076216713	7	Combined Ash	Clay	--
10151	Grant Town Power Plant	873	LF	Farmington	39.50555556	-80.25111111	--	--	--	Combined Ash	None	--
10151	Grant Town Power Plant	872	LF	Barrackville	39.501641	-80.179709	--	--	--	Combined Ash	None	--
10151	Grant Town Power Plant	871	LF	Grant Town	39.5575	-80.16972222	--	--	--	Combined Ash	None	--
10151	Grant Town Power Plant	1168	SI	Pond 3	39.5584	-80.16638889	1.83654729	14.69237833	8	Combined Ash	None	--
10151	Grant Town Power Plant	1167	SI	Pond 10	39.55972222	-80.16611111	0.12626263	1.01010101	8	Combined Ash	None	--
10151	Grant Town Power Plant	1170	SI	Sedimentation Pond 5	39.56305556	-80.16583333	0.17217631	1.377410468	8	Combined Ash	None	--
10151	Grant Town Power Plant	1169	SI	Sedimentation Pond 9	39.56	-80.16555556	0.54407713	4.35261708	8	Combined Ash	None	--
10151	Grant Town Power Plant	1171	SI	Sedimentation Pond 6	39.5625	-80.16527778	0.03673095	0.293847567	8	Combined Ash	None	--
165	GRDA	1210	SI	SS1	36.18555556	-95.29194444	0.05034435	0.528673095	10.50113999	FGD Waste	None	--
165	GRDA	874	LF	ash landfill	36.18555556	-95.28833333	--	--	--	Combined Ash	Yes	--
1357	Green River	531	SI	Main Ash Pond	37.36974722	-87.12181667	32	775	24.21875	Combined Ash	None	--
1357	Green River	532	SI	Former Ash Pond	37.36556944	-87.11969444	6	--	--	Combined Ash	None	--
1357	Green River	533	SI	Ash Pond Number 2	37.36809444	-87.11804167	23	--	--	Combined Ash	None	--
1357	Green River	534	SI	Finishing Pond Number 3	37.04961944	-87.11576667	2	--	--	Combined Ash	None	--
1357	Green River	535	SI	Scrubber Pond	37.36812778	-87.11523056	10	150	15	FGD Waste	None	--
10	Greene County	256	SI	Ash Pond	--	--	474	5331	11.24683544	Combined Ash	None	--
6041	H L Spurlock Station	34	SI	Spurlock Ash Pond	38.70044883	-83.80169383	61.4	1085	17.67100977	Combined Ash	Clay	--
6041	H L Spurlock Station	972	LF	--	--	--	33.42	1907.73905	57.08375373	Combined Ash	Clay	--
2709	H.F. Lee Plant	658	SI	Ash Pond 1	35.38168333	-78.10723611	33	--	--	Combined Ash	None	Excluded

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
2709	H.F. Lee Plant	656	SI	Ash Pond 3	35.37596944	-78.10719722	85	--	--	Combined Ash	None	Excluded
2709	H.F. Lee Plant	657	SI	Ash Pond 2	35.38053056	-78.1038	53	--	--	Combined Ash	None	Excluded
2709	H.F. Lee Plant	659	SI	Active Ash Pond	35.3791	-78.069	143	1980	13.84615385	Combined Ash	None	--
2709	H.F. Lee Plant	660	SI	1980 Pond	--	--	--	--	--	Combined Ash	--	--
708	Hammond	1145	LF	Huffaker CCB	34.296139	-85.30457	--	--	--	Combined Ash	Yes	--
708	Hammond	351	SI	Ash Pond 2	--	--	21	509	24.23809524	Combined Ash	None	--
708	Hammond	352	SI	Ash Pond 1	--	--	35	800	22.85714286	Combined Ash	None	--
708	Hammond	353	SI	Ash Pond 4	--	--	54	1242	23	Combined Ash	None	--
708	Hammond	354	SI	Ash Pond 3	--	--	25	687	27.48	Combined Ash	None	Excluded
1731	Harbor Beach Power Plant	581	SI	Pond	--	--	--	--	--	Combined Ash	--	--
990	Harding Street	420	SI	Pond 2	39.706656	-86.202417	30	505	16.83333333	Combined Ash	None	--
990	Harding Street	423	SI	Pond 1	39.708192	-86.199089	7	92	13.14285714	Combined Ash	None	--
990	Harding Street	422	SI	Ponds 2A/2B	39.70665	-86.197319	4	43	10.75	Combined Ash	None	--
990	Harding Street	424	SI	Pond 3	39.707464	-86.196203	9.5	8	0.842105263	Combined Ash	None	--
990	Harding Street	421	SI	Pond 4	39.7042	-86.194464	26	304	11.69230769	Combined Ash	None	--
709	Harllee Branch	355	SI	Ash Pond E	33.204167	-83.326389	311	4665	15	Ash & Coal Refuse	None	--
709	Harllee Branch	358	SI	Ash Pond D	33.1869	-83.3055	45	675	15	Ash & Coal Refuse	None	--
709	Harllee Branch	359	SI	Ash Pond C	33.1869	-83.3055	70	1050	15	Ash & Coal Refuse	None	--
709	Harllee Branch	357	SI	Ash Pond B	33.1915	-83.3033	75	750	10	Ash & Coal Refuse	None	--
709	Harllee Branch	356	SI	A	--	--	1	14	14	Ash & Coal Refuse	--	Excluded
6193	Harrington	878	LF	001	35.305659	-101.754015	--	--	--	Combined Ash	Yes	--
6193	Harrington	877	LF	117	35.30305556	-101.7508333	--	--	--	Combined Ash	Yes	--
3944	Harrison Power Station	891	LF	CCB Landfill	39.40444444	-80.33222222	200	45862.80992	229.3140496	Combined Ash	Clay	--
3944	Harrison Power Station	158	SI	EPRI 6	--	--	300	17355.3719	57.85123967	Combined Ash	--	Excluded
3179	Hatfield's Ferry Power Station	880	LF	Ash Disposal Site	39.851828	-79.945337	32	1542.235537	48.19486054	Combined Ash	None	--
3179	Hatfield's Ferry Power Station	1217	SI	Limestone Runoff Basin	39.86000556	-79.93233611	1.464	--	--	FGD Waste	Yes	Excluded
3179	Hatfield's Ferry Power Station	1218	SI	Gypsum Runoff Basin	39.86061667	-79.9311	1.464	--	--	FGD Waste	Yes	Excluded
3179	Hatfield's Ferry Power Station	1216	SI	West Lagoon	39.86256111	-79.93094444	1.51515152	15.3454775	10.12801515	Combined Ash	None	--
3179	Hatfield's Ferry Power Station	1215	SI	East Lagoon	39.86278333	-79.93034722	1.51515152	15.3454775	10.12801515	Combined Ash	None	--
3179	Hatfield's Ferry Power Station	1219	SI	Gypsum Storage Area Basin	39.86116111	-79.93009444	1.464	--	--	FGD Waste	Yes	Excluded
891	Havana	392	SI	North Ash Pond System	40.27676389	-90.07905278	6	25	4.166666667	Combined Ash	--	--
891	Havana	393	SI	East Ash Pond	40.2801	-90.07119722	90	2625	29.16666667	Combined Ash	Composite	--
2079	Hawthorn	599	SI	Scrubber Waste Settling Pond	--	--	1	2	2	FGD Waste	--	--
2079	Hawthorn	962	LF	--	--	--	--	--	--	Combined Ash	--	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
525	Hayden	1146	LF	Hayden Coal Ash Disposal Facility	40.47387222	-107.1611361	--	--	--	Combined Ash	None	--
525	Hayden	882	LF	Ash Disposal Facility	40.45109722	-107.1319972	--	--	--	Combined Ash	None	Excluded
525	Hayden	332	SI	Intermediate Quality Pond	--	--	20	274	13.7	Combined Ash	--	--
525	Hayden	333	SI	High Quality Skimmer Pond	--	--	1	6	6	Combined Ash	--	Excluded
525	Hayden	334	SI	High Quality Pond	--	--	4	40	10	Combined Ash	--	Excluded
525	Hayden	335	SI	Fly Ash Decant Basin	--	--	--	--	--	Combined Ash	--	--
525	Hayden	336	SI	Common Wet Ash Settling Basin	--	--	--	--	--	Combined Ash	--	--
525	Hayden	337	SI	Ash Disposal Facility (ADF) Contact Storm Water Pond	--	--	1	4	4	Combined Ash	--	--
3251	HB Robinson / Darlington Electric Power Plant	104	SI	Pond	34.41411111	-80.16222222	55	410	7.454545455	Combined Ash	None	--
892	Hennepin Power Station	394	SI	Ash Pond System (2 cells)	41.300222	-89.323988	21	563	26.80952381	Combined Ash	--	--
892	Hennepin Power Station	883	LF	-999	--	--	--	--	--	Combined Ash	Yes	--
1382	HMP&L Station Two Henderson	556	SI	Ash Pond No. 0855	37.647739	-87.505317	12.4	--	--	Combined Ash	None	--
1382	HMP&L Station Two Henderson	557	SI	Green Ash Pond	37.64612	-87.501376	21.3	--	--	Combined Ash	None	--
1382	HMP&L Station Two Henderson	984	LF	--	--	--	--	--	--	Combined Ash	--	--
108	HOLCOMB	1147	LF	HCF	37.945852	-100.965669	8	--	--	Combined Ash	None	--
3122	Homer City Station	725	SI	Coal Refuse Disposal Site - Leachate Pump Pond	40.518625	-79.212578	0.26	1	3.846153846	Combined Ash	--	Excluded
3122	Homer City Station	719	SI	Ash Disposal Site - Polishing Pond	40.518299	-79.212487	0.13	--	--	Combined Ash	--	--
3122	Homer City Station	92	SI	Coal Refuse Disposal Site - Small Sediment Trap	40.518566	-79.212215	0.18	1	5.555555556	Combined Ash	--	Excluded
3122	Homer City Station	884	LF	Ash Disposal Site	40.52638889	-79.21194444	145	3629.209711	25.02903249	Combined Ash	None	--
3122	Homer City Station	721	SI	Ash Disposal Site - Stormwater Surge Pond	40.526794	-79.20486	1.22	17	13.93442623	Combined Ash	--	Excluded
3122	Homer City Station	723	SI	Ash Disposal Site - Treatment Pond #2	40.516075	-79.199559	0.28	1	3.571428571	Combined Ash	--	--
3122	Homer City Station	90	SI	Coal Refuse Disposal Site - Stage I & II Pond	40.520906	-79.19929	1	13	13	Combined Ash	--	--
3122	Homer City Station	724	SI	Ash Disposal Site - Treatment Pond #1	40.515623	-79.199137	0.25	1	4	Combined Ash	--	--
3122	Homer City Station	726	SI	Ash Recycle Pond #2	40.514744	-79.198884	0.59	5	8.474576271	Combined Ash	--	--
3122	Homer City Station	722	SI	Ash Recycle Pond #1	40.514863	-79.198504	0.58	4	6.896551724	Combined Ash	--	--
3122	Homer City Station	91	SI	Ash Recycle Pond #4	40.513697	-79.198352	0.56	5	8.928571429	Combined Ash	--	--

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Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
3122	Homer City Station	727	SI	Ash Recycle Pond #3	40.51378	-79.197979	0.57	5	8.771929825	Combined Ash	--	--
3122	Homer City Station	720	SI	Coal Refuse Disposal Site - Storage Pond #2	40.509042	-79.197338	0.84	11	13.0952381	Combined Ash	--	--
3122	Homer City Station	886	LF	Emergency Strike Landfill	40.5175	-79.18888889	27	--	--	Combined Ash	None	Excluded
3122	Homer City Station	1134	LF	Coal Refuse Disposal Site	40.52777778	-79.18888889	165	16178.12213	98.04922503	Combined Ash	Composite	--
3122	Homer City Station	729	SI	Coal Refuse Disposal Site - Storage Pond #1	40.521757	-79.188655	1.26	2	1.587301587	Combined Ash	--	--
3122	Homer City Station	728	SI	Coal Refuse Disposal Site - Stage III & IV Pond	40.522143	-79.186773	1.54	26	16.88311688	Combined Ash	--	--
1943	Hoot Lake	1148	LF	Area 4	46.289375	-96.0384	--	--	--	Combined Ash	None	Excluded
1943	Hoot Lake	1158	LF	Area 1	46.28971389	-96.03636944	--	--	--	Combined Ash	None	Excluded
1943	Hoot Lake	1157	LF	Area 2	46.29038333	-96.0339	--	--	--	Combined Ash	None	Excluded
1943	Hoot Lake	1159	LF	IL002-Phase 1	46.28746667	-96.03198056	--	--	--	Combined Ash	Yes	--
1943	Hoot Lake	1160	LF	IL001-II	46.28780278	-96.03071667	--	--	--	Combined Ash	None	--
1943	Hoot Lake	887	LF	IL001-I	46.28873611	-96.030075	72	495.8677686	6.887052342	Combined Ash	None	--
1943	Hoot Lake	1156	LF	Area 3	46.29062	-96.013039	--	--	--	Combined Ash	None	Excluded
10771	Hopewell	1362	SI	Coal Pile Runoff Pond	37.298131	-77.284872	0.78739669	9.448760331	12	Ash & Coal Refuse	Composite	--
6772	Hugo	755	LF	Fly Ash Landfill	34.008487	-95.32962872	35.3	675.3991736	19.13312106	Combined Ash	Clay	--
6772	Hugo	230	SI	South Bottom Ash	34.00915278	-95.316675	34	344	10.11764706	Combined Ash	Clay	--
6772	Hugo	229	SI	North Bottom Ash Unit	34.01064722	-95.31594444	34	344	10.11764706	Combined Ash	Clay	--
6772	Hugo	231	SI	North Fly Ash	--	--	18	332	18.44444444	Combined Ash	Clay	--
6772	Hugo	232	SI	South Fly Ash Unit	--	--	18	332	18.44444444	Combined Ash	Clay	--
3176	Hunlock Power Station	103	SI	West Basin (005)	41.200563	-76.072583	5	90	18	Combined Ash	--	Excluded
3176	Hunlock Power Station	102	SI	East Basin (003)	41.199839	-76.072148	5	90	18	Combined Ash	--	Excluded
6165	Hunter Plant	756	LF	FGD Cell	39.00262778	-111.0102056	280	7438.016529	26.56434475	Combined Ash	None	--
6165	Hunter Plant	1258	SI	Landfill FGD Cell	39.15262778	-111.0102056	104.1	--	--	Combined Ash	Yes	Excluded
8069	Huntington Plant	757	LF	class III-b Industrial Waste Landfill	39.36940833	-111.0823778	70	7066.115703	100.94451	Combined Ash	None	--
8069	Huntington Plant	1364	SI	Scrubber Pond	39.37793333	-111.0813056	1.03305785	4	3.872	FGD Waste	Composite	--
8069	Huntington Plant	759	LF	Old Landfill	39.36836111	-111.0802111	--	--	--	Combined Ash	None	Excluded
8069	Huntington Plant	1363	SI	Lacey's lake	39.37630833	-111.0784278	1	4	4	Combined Ash	None	Excluded
8069	Huntington Plant	758	LF	Conditionally Exempt Combustion Waste Landfill	39.36466389	-111.0718639	--	--	--	Combined Ash	None	--
863	Hutsonville	383	SI	Ash Pond B	39.129551	-87.659345	4	70	17.5	Combined Ash	--	Excluded
863	Hutsonville	381	SI	Bottom Ash Pond	39.133223	-87.658424	1	6	6	Combined Ash	--	Excluded
863	Hutsonville	382	SI	Ash Pond C	39.131165	-87.658387	2	20	10	Combined Ash	--	Excluded
863	Hutsonville	384	SI	Ash Pond A	39.130078	-87.656369	14	250	17.85714286	Combined Ash	--	Excluded
6065	Iatan	1154	LF	Utility Waste Landfill	39.44972222	-94.96388889	--	--	--	Combined Ash	Yes	--
6065	Iatan	40	SI	Ash Pond	--	--	89	2328	26.15730337	Combined Ash	--	Excluded

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Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
6641	Independence	1153	LF	ISES Landfill	35.679507	-91.391202	221	8069.008264	36.51134961	Combined Ash	Clay	--
2132	Independence Power & Light - Blue Valley Station	618	SI	Bottom Ash Pond	39.09584722	-94.32355278	9.3	133	14.30107527	Combined Ash	None	--
2132	Independence Power & Light - Blue Valley Station	617	SI	South Fly Ash Pond	39.09617222	-94.322075	15.1	271	17.94701987	Combined Ash	None	Excluded
2132	Independence Power & Light - Blue Valley Station	616	SI	North Fly Ash Pond	39.09873056	-94.32163611	16.8	252	15	Combined Ash	None	--
594	Indian River Generating Station	775	LF	Burton Island Landfill	38.585207	-75.241928	--	--	--	Combined Ash	None	Excluded
594	Indian River Generating Station	762	LF	Solid Waste Landfill	38.579359	-75.232033	--	--	--	Combined Ash	Yes	--
594	Indian River Generating Station	339	SI	Sedimentation Pond	--	--	--	--	--	Combined Ash	--	--
594	Indian River Generating Station	340	SI	Ash Silo Area Sump System	--	--	--	--	--	Combined Ash	--	Excluded
6481	Intermountain Power Project	214	SI	Settling Basin	--	--	14	145	10.35714286	FGD Waste	Composite	--
6481	Intermountain Power Project	215	SI	Ash Water Recycle	--	--	27	590	21.85185185	Combined Ash	Composite	--
6481	Intermountain Power Project	216	SI	Land Fill Run-Off	--	--	5	30	6	--	Composite	--
6481	Intermountain Power Project	217	SI	Evaporation Ponds (6 Ponds)	--	--	180	3225	17.91666667	FGD Waste	Composite	--
6481	Intermountain Power Project	218	SI	Bottom Ash Basin	--	--	105	3000	28.57142857	Combined Ash	Composite	--
6481	Intermountain Power Project	219	SI	Wastewater Holding Basin	--	--	53	650	12.26415094	FGD Waste	Composite	--
7097	J K Spruce	1369	SI	NOR 001a	29.32041667	-98.31666667	2.006	--	--	Combined Ash	Yes	Excluded
7097	J K Spruce	1368	SI	NOR 001	29.31905556	-98.31597222	2.006	--	--	Combined Ash	Yes	Excluded
7097	J K Spruce	1372	SI	SRH	29.323975	-98.31481944	1.60697888	9.400826446	5.85	FGD Waste	Composite	--
7097	J K Spruce	1373	SI	NOR (021)	29.33138889	-98.31477778	4.98852158	47.28191001	9.478140819	Combined Ash	Composite	--
7097	J K Spruce	1370	SI	NOR 002	29.32005556	-98.31452778	2.006	--	--	Combined Ash	Yes	Excluded
7097	J K Spruce	1371	SI	NOR 008	29.31813889	-98.31416667	2.006	--	--	Combined Ash	Yes	Excluded
7097	J K Spruce	753	LF	Landfill (NOR 010)	29.32397222	-98.31369444	--	--	--	Combined Ash	Yes	--
2850	J M Stuart	706	SI	Ash Pond No. 5	38.64138889	-83.70388889	34	1426	41.94117647	Combined Ash	None	Excluded
2850	J M Stuart	711	SI	Ash Pond No. 10	38.63944444	-83.685	29	930	32.06896552	Combined Ash	Clay	--
2850	J M Stuart	710	SI	Ash Pond No. 3A	38.63416667	-83.68361111	50	1302	26.04	Combined Ash	Clay	--
2850	J M Stuart	767	LF	Landfill 11	38.637	-83.67811111	--	--	--	Combined Ash	Yes	--
2850	J M Stuart	708	SI	Pond #7A	38.631111	-83.678056	3	38	12.66666667	--	--	Excluded
2850	J M Stuart	709	SI	Ash Pond No. 7	38.63111111	-83.67805556	37	1550	41.89189189	Combined Ash	Clay	Excluded
2850	J M Stuart	707	SI	Ash Pond No. 6	38.63277778	-83.67611111	37	1550	41.89189189	Combined Ash	Clay	Excluded
2850	J M Stuart	766	LF	Landfill 9	38.63433333	-83.66205556	--	--	--	Combined Ash	Yes	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
6181	J T Deely	1295	SI	bottom ash	29.30684444	-98.32140278	6.68503214	54.19306703	8.106627747	Combined Ash	None	--
6181	J T Deely	1296	SI	bottom ash	29.30891667	-98.31782222	6.28099174	50.27892562	8.004934211	Combined Ash	None	--
6181	J T Deely	1292	SI	NOR 001a	29.32041667	-98.31666667	2.006	--	--	Combined Ash	Yes	Excluded
6181	J T Deely	1291	SI	NOR 001	29.31905556	-98.31597222	2.006	--	--	Combined Ash	Yes	Excluded
6181	J T Deely	768	LF	JTD / Evaporation Pond #021	29.323972	-98.3148	--	--	--	Combined Ash	Yes	--
6181	J T Deely	1293	SI	NOR 002	29.32005556	-98.31452778	2.006	--	--	Combined Ash	Yes	Excluded
6181	J T Deely	1294	SI	NOR 008	29.31813889	-98.31416667	2.006	--	--	Combined Ash	Yes	Excluded
6181	J T Deely	1002	LF	--	--	--	--	--	--	Combined Ash	--	--
1720	J.C. Weadock	573	SI	J.C. Weadock Fly Ash Dam	--	--	--	--	--	--	Clay	--
1720	J.C. Weadock	574	SI	East 7 & 8 Ponds	--	--	136	--	--	Combined Ash	--	--
1720	J.C. Weadock	575	SI	West A - E Ponds	--	--	156	--	--	Combined Ash	--	--
1720	J.C. Weadock	576	SI	Weadock Landfill Embankment	--	--	--	--	--	--	Clay	--
1720	J.C. Weadock	1003	LF	--	--	--	--	--	--	Combined Ash	--	--
1723	J.R Whiting	577	SI	Ponds 3-5	--	--	82	1489	18.15853659	Combined Ash	--	--
1723	J.R Whiting	578	SI	Pond 1	--	--	8	148	18.5	Combined Ash	None	--
1723	J.R Whiting	579	SI	Pond 2	--	--	7	135	19.28571429	Combined Ash	None	--
1723	J.R Whiting	580	SI	Pond 6	--	--	32	1054	32.9375	Combined Ash	None	--
1723	J.R Whiting	965	LF	--	--	--	11.87	--	--	Combined Ash	--	Excluded
1723	J.R Whiting	1000	LF	--	--	--	5.44	--	--	Combined Ash	--	Excluded
710	Jack McDonough	360	SI	Ash Pond 4	--	--	41	1996	48.68292683	Combined Ash	None	--
710	Jack McDonough	361	SI	Ash Pond 3	--	--	23	642	27.91304348	Combined Ash	None	--
710	Jack McDonough	362	SI	Ash Pond 1	--	--	25	546	21.84	Combined Ash	None	Excluded
710	Jack McDonough	363	SI	Ash Pond 2	--	--	6	118	19.66666667	Combined Ash	None	--
710	Jack McDonough	968	LF	--	--	--	--	--	--	Combined Ash	--	--
2049	Jack Watson	769	LF	Dry Ash Monofill	30.43333333	-89.02611111	--	--	--	Combined Ash	Yes	--
2049	Jack Watson	595	SI	Ash Pond	--	--	102	317	3.107843137	Combined Ash	None	--
1830	James De Young	1333	SI	Ash Settling Ponds	42.79388889	-86.11361111	1.49219467	6.014692378	4.030769231	Combined Ash	None	--
1830	James De Young	770	LF	Zeeland Township Landfill	42.78944444	-85.91888889	--	--	--	Combined Ash	None	--
6002	James H. Miller Jr.	16	SI	Ash Pond (NID #1101)	--	--	341	13606	39.90029326	Combined Ash	--	--
2161	James River Power Station	771	LF	Ash Landfill	37.10277778	-93.26805556	17	163.0165289	9.589207584	Combined Ash	Composite	--
2161	James River Power Station	619	SI	Pond	--	--	--	--	--	Combined Ash	--	--
2187	JE Corette Plant	764	LF	Fly Ash Landfill	45.78	-108.4825	--	--	--	Combined Ash	None	Excluded
2187	JE Corette Plant	1249	SI	Bottom Ash Pond #1	45.78194444	-108.4811111	2.48	--	--	Combined Ash	None	--
2187	JE Corette Plant	1250	SI	Bottom Ash Pond #2	45.78305556	-108.4808333	2.48	--	--	Combined Ash	None	--
3319	Jefferies	117	SI	Ash Pond B	33.31872222	-79.35136111	63	245	3.888888889	Combined Ash	None	--
3319	Jefferies	118	SI	Ash Pond A	33.325525	-79.34736111	88	982	11.15909091	Combined Ash	None	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
6068	Jeffrey Energy Center	41	SI	Bottom Ash Pond Dam	39.28223333	-96.14759167	72	550	7.638888889	Combined Ash	None	--
6068	Jeffrey Energy Center	42	SI	Bottom Ash Lake Dam	39.24375	-96.14678611	120	3000	25	Combined Ash	None	--
6068	Jeffrey Energy Center	772	LF	Fly Ash Landfill	39.28722222	-96.14333333	--	--	--	Combined Ash	None	--
6068	Jeffrey Energy Center	773	LF	Gypsum Landfill	39.27916667	-96.13916667	--	--	--	Combined Ash	None	--
6068	Jeffrey Energy Center	43	SI	Bottom Ash Settling Pond	39.2667	-96.13587778	53	988	18.64150943	Combined Ash	--	--
8066	Jim Bridger Plant Units 1-4	244	SI	FGD Pond #1	41.75380556	-108.8074444	93	1340	14.40860215	Combined Ash	Clay	Excluded
8066	Jim Bridger Plant Units 1-4	774	LF	Landfill	41.77012778	-108.7938111	180.5	9899.051963	54.84239315	Combined Ash	None	--
8066	Jim Bridger Plant Units 1-4	245	SI	FGD Pond #2	41.75688889	-108.7879167	392	11534	29.42346939	Combined Ash	None	--
3935	John E. Amos	742	LF	Quarrier Landfill	38.509045	-81.868582	200	8677.68595	43.38842975	Combined Ash	Yes	--
3935	John E. Amos	740	LF	John E Amos FGD Landfill	38.485988	-81.856277	--	--	--	Combined Ash	Yes	--
3935	John E. Amos	153	SI	Fly Ash Pond	--	--	175	2687	15.35428571	Combined Ash	None	--
3935	John E. Amos	154	SI	Bottom Ash Complex	--	--	30	220	7.333333333	Combined Ash	None	--
4271	John P. Madgett	990	LF	--	--	--	--	--	--	Combined Ash	--	--
4271	John P. Madgett	991	LF	--	--	--	--	--	--	Combined Ash	--	Excluded
3405	John Sevier	763	LF	Dry Fly Ash Stack	36.372825	-82.974115	90	1206.148804	13.40165338	Combined Ash	Composite	--
3405	John Sevier	131	SI	Dry Ash Stack	--	--	84	2355	28.03571429	Combined Ash	--	--
3405	John Sevier	132	SI	Bottom Ash Pond	--	--	41	744	18.14634146	Combined Ash	--	--
3406	Johnsonville	732	LF	DuPont Dredge Cell	36.03440278	-87.97888889	20.2	514.4628099	25.46845594	Combined Ash	None	--
3406	Johnsonville	733	LF	South Rail Loop	36.02591667	-87.9775	22	814	37	Combined Ash	Clay	Excluded
3406	Johnsonville	133	SI	Ash Disposal Area 2	--	--	87	2702	31.05747126	Combined Ash	--	--
3406	Johnsonville	291	SI	DuPont Road Dredge Cell	--	--	22	--	--	--	None	--
384	Joliet 29	309	SI	EPRI 1	--	--	63.1	627.2727273	9.940930702	Ash & Coal Refuse	--	Excluded
384	Joliet 29	1098	LF	--	--	--	--	--	--	Combined Ash	--	--
874	Joliet 9	1328	SI	Lower Quarry	41.49416667	-88.10694444	1.60491276	27.28351699	17	Combined Ash	None	--
874	Joliet 9	1327	SI	Upper Quarry	41.49472222	-88.10638889	42.2038567	2887.066116	68.40763708	Combined Ash	None	--
887	Joppa Steam	390	SI	Ash Pond	37.21527778	-88.85	103	3833	37.21359223	Ash & Coal Refuse	None	--
887	Joppa Steam	734	LF	-999	--	--	--	--	--	Combined Ash	Yes	--
3947	Kammer	159	SI	Boiler Slag Pond	--	--	2	22	11	Combined Ash	--	--
3936	Kanawha River	155	SI	Bottom Ash Complex	--	--	6	116	19.33333333	Combined Ash	--	--
1381	Kenneth C Coleman	553	SI	Active Ash Pond A	37.96666667	-86.79580556	23	1180	51.30434783	Combined Ash	None	--
1381	Kenneth C Coleman	555	SI	Inactive Ash Pond C	37.95661111	-86.79488889	19.5	--	--	Combined Ash	None	--
1381	Kenneth C Coleman	554	SI	New Ash Pond	--	--	64	2417	37.765625	Combined Ash	--	--
3136	Keystone	1307	SI	Bottom Ash Settling Pond (C)	40.864258	-79.499139	0.73415978	4.296740129	5.852595372	Combined Ash	Clay	--
3136	Keystone	1306	SI	Bottom Ash Settling Pond (B)	40.864847	-79.497442	0.73415978	4.296740129	5.852595372	Combined Ash	Clay	--
3136	Keystone	1305	SI	Bottom Ash Settling Pond (A)	40.864306	-79.495056	0.73415978	3.837603306	5.227204503	Combined Ash	Clay	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
3136	Keystone	1301	SI	Low Volume Waste Inlet Pond (A)	40.76202222	-79.46743056	7.508	--	--	Combined Ash	Yes	Excluded
3136	Keystone	1302	SI	Low Volume Waste Inlet Pond (B)	40.761903	-79.466419	7.508	--	--	Combined Ash	Yes	Excluded
3136	Keystone	1303	SI	Low Volume Waste Outlet Pond (A)	40.765825	-79.465603	7.508	--	--	Combined Ash	Yes	Excluded
3136	Keystone	1304	SI	Low Volume Waste Outlet Pond (B)	40.766278	-79.465044	7.508	--	--	FGD Waste	Yes	Excluded
3136	Keystone	736	LF	Original Ash Site	40.66025	-79.35361111	--	--	--	Combined Ash	None	Excluded
3136	Keystone	1297	SI	Bottom Ash Thermal Pond	40.66408056	-79.351125	7.11662075	128.5583104	18.06451613	Combined Ash	Composite	--
3136	Keystone	1300	SI	East Valley Ash Site Storm Water Pond (B)	40.66461944	-79.34950556	7.508	--	--	Combined Ash	Yes	--
3136	Keystone	1299	SI	East Valley Ash Site Storm Water Pond (A)	40.66524167	-79.34615278	7.508	--	--	Combined Ash	Yes	--
3136	Keystone	1298	SI	West Valley Ash Site Contact Stormwater / Leachate Pond	40.66516944	-79.34444167	7.508	--	--	Combined Ash	Yes	Excluded
3136	Keystone	1151	LF	West Valley Ash Site	40.67577778	-79.33927778	--	--	--	Combined Ash	Yes	--
3136	Keystone	1152	LF	East Valley Ash Site	40.67580556	-79.33494444	155	14047.38843	90.62831245	Combined Ash	Yes	--
6031	Killen Station	32	SI	Bottom Ash Pond	38.689341	-83.471246	39	1903	48.79487179	Combined Ash	--	--
6031	Killen Station	31	SI	Fly Ash Pond	38.683126	-83.467549	191	11004	57.61256545	Combined Ash	--	--
876	Kincaid Generation LLC	388	SI	Slag Field	39.59563889	-89.49238889	178	3560	20	Combined Ash	None	--
876	Kincaid Generation LLC	969	LF	--	--	--	--	--	--	Combined Ash	--	--
3407	Kingston	134	SI	Stilling Pond	--	--	29	290	10	Combined Ash	--	--
3407	Kingston	135	SI	Main Ash Pond	--	--	92	8907	96.81521739	Combined Ash	--	--
733	Kraft	1150	LF	Grumman Road Dry Ash Monofill	32.14027778	-81.18361111	--	--	--	Combined Ash	None	--
733	Kraft	375	SI	Ash Pond	--	--	8	41	5.125	Ash & Coal Refuse	--	--
2876	Kyger Creek	738	LF	Type III landfill	38.92361111	-82.16472222	--	--	--	Combined Ash	Yes	--
2876	Kyger Creek	716	SI	Bottom Ash Pond	38.91027778	-82.13277778	34	1435	42.20588235	Combined Ash	None	--
2876	Kyger Creek	717	SI	South Fly Ash Pond	38.91888889	-82.13055556	66	2500	37.87878788	Combined Ash	None	--
2713	L.V. Sutton Electric Plant	665	SI	1971 Pond	34.29591944	-77.9899	53	921	17.37735849	Combined Ash	None	--
2713	L.V. Sutton Electric Plant	666	SI	1984 Pond	34.29224722	-77.98971389	82	1364	16.63414634	Combined Ash	Clay	--
1241	La Cygne	739	LF	Utility Waste Landfill	38.35722222	-94.62777778	--	--	--	Combined Ash	Yes	--
1241	La Cygne	513	SI	Scrubber Sludge Ponds	--	--	483	9298	19.2505176	Combined Ash	Clay	--
1241	La Cygne	514	SI	Bottom Ash Settling Pond	--	--	2	12	6	Combined Ash	Clay	--
2103	Labadie	607	SI	Bottom Ash Pond	--	--	154	12000	77.92207792	Combined Ash	None	--
2103	Labadie	608	SI	Fly Ash Pond	--	--	79	1900	24.05063291	Combined Ash	Composite	--
2098	Lake Road	752	LF	Fly Ash Landfill	39.71777778	-94.88666667	9.7	80.34894399	8.283396287	Combined Ash	Clay	Excluded
2098	Lake Road	605	SI	Slag/Coal Pile Run-off Pond	39.72277778	-94.87861111	1.8	7	3.888888889	Combined Ash	None	Excluded
2098	Lake Road	606	SI	Settling Pond	--	--	1	5	5	Combined Ash	--	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
2838	Lake Shore	1270	SI	Combined Treatment Basin	41.53333333	-81.64166667	0.50505051	2.525252525	5	Combined Ash	None	--
964	Lakeside	400	SI	Lakeside Ash Pond	39.76305556	-89.59722222	37	680	18.37837838	Combined Ash	None	Excluded
1047	Lansing	730	LF	Closed Ash Disposal Facility	43.329578	-91.16616	--	--	--	Combined Ash	None	Excluded
1047	Lansing	741	LF	Active Ash Disposal Facility	43.328369	-91.163119	--	--	--	Combined Ash	None	--
1047	Lansing	477	SI	Lower Ash Pond	--	--	--	2	--	Combined Ash	None	--
1047	Lansing	478	SI	Main Ash Pond	--	--	15	294	19.6	Combined Ash	None	--
643	Lansing Smith	743	LF	Ash Landfill	30.26802778	-85.68436111	--	--	--	Combined Ash	Yes	--
643	Lansing Smith	341	SI	Ash Pond	--	--	172	2611	15.18023256	Combined Ash	None	--
6204	Laramie River Station	744	LF	Landfill	42.11333333	-104.9022222	--	--	--	Combined Ash	None	--
6204	Laramie River Station	188	SI	Bottom Ash Ponds 1 & 2 (BAP1 & BAP2)	42.108251	-104.89733	105	2111	20.1047619	Combined Ash	Composite	--
6204	Laramie River Station	189	SI	Emergency Holding Pond	42.117535	-104.882691	54.1	916	16.93160813	FGD Waste	Composite	--
1891	Laskin Energy Center	588	SI	Cells A, B, C & D (retired)	--	--	73	730	10	Combined Ash	None	Excluded
1891	Laskin Energy Center	589	SI	Cell E	--	--	23	174	7.565217391	Combined Ash	Composite	--
1250	Lawrence Energy Center	745	LF	Landfill 600	39.005	-95.27333333	825	21260.3306	25.7700977	Combined Ash	None	--
1250	Lawrence Energy Center	747	LF	Landfill 0333	39.00611111	-95.26277778	30	619.834711	20.66115703	Combined Ash	None	Excluded
1250	Lawrence Energy Center	1149	LF	Landfill 0847	39.004994	-95.259549	22	842.975207	38.31705486	Combined Ash	Yes	--
1250	Lawrence Energy Center	515	SI	Area 4	--	--	14	185	13.21428571	Combined Ash	None	--
1250	Lawrence Energy Center	516	SI	Area 1	--	--	5	71	14.2	Combined Ash	None	--
1250	Lawrence Energy Center	517	SI	Area 3	--	--	18	273	15.16666667	Combined Ash	Clay	--
1250	Lawrence Energy Center	518	SI	Area 2	--	--	10	155	15.5	Combined Ash	None	--
2817	Leland Olds	749	LF	SP-143	47.24605833	-101.3635333	20	283.884298	14.1942149	Combined Ash	Yes	--
2817	Leland Olds	683	SI	Ash Pond #1	47.28069444	-101.3181944	27	744	27.55555556	Combined Ash	None	--
2817	Leland Olds	684	SI	Ash Pond #2	47.28069444	-101.3181944	38	924	24.31578947	Combined Ash	None	--
2817	Leland Olds	685	SI	Ash Pond #3	47.28069444	-101.3181944	3	12	4	Combined Ash	None	--
2817	Leland Olds	748	LF	SP-038	47.27644722	-101.3107889	37	1115.70248	30.15412108	Combined Ash	None	--
6089	Lewis & Clark	750	LF	Savage Mine	47.47905556	-104.4383611	--	--	--	Combined Ash	None	--
6089	Lewis & Clark	1374	SI	West Scrubber Pond Cell 1	47.68016667	-104.1579167	1.33149679	11.47842057	8.620689655	Combined Ash	Clay	--
6089	Lewis & Clark	1375	SI	West Scrubber Pond Cell 2	47.67975	-104.1572222	0.42699725	2.089072544	4.892473118	Combined Ash	Clay	--
6089	Lewis & Clark	1377	SI	East Scrubber Pond Cell 2	47.67975	-104.1572222	0.42699725	2.089072544	4.892473118	Combined Ash	Clay	--
6089	Lewis & Clark	1376	SI	East Scrubber Pond Cell 1	47.67936111	-104.1563889	1.33149679	11.47842057	8.620689655	Combined Ash	Clay	--
6089	Lewis & Clark	751	LF	Scrubber Sludge	47.68258333	-104.1521111	--	--	--	Combined Ash	None	Excluded
6089	Lewis & Clark	1378	SI	Ash Pond 1	47.68144444	-104.1517222	15.1905418	182.2773186	11.9993955	Combined Ash	Composite	--
6089	Lewis & Clark	786	LF	-999	--	--	--	--	--	Combined Ash	None	Excluded
298	Limestone	300	SI	ST 18	31.41888889	-96.25638611	--	--	--	--	Clay	Excluded
298	Limestone	308	SI	DSDA Unit No. 003	31.41888889	-96.25638611	20.84	--	--	Combined Ash	Clay	Excluded

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
298	Limestone	821	LF	Class II Landfill	31.43277778	-96.24138889	--	--	--	Combined Ash	Yes	--
298	Limestone	301	SI	FGD Emergency Pond E	--	--	1	31	31	FGD Waste	--	--
298	Limestone	302	SI	ST-10 Pump	--	--	--	1	--	Combined Ash	--	Excluded
298	Limestone	303	SI	ST-9 Pump	--	--	--	--	--	Combined Ash	--	Excluded
298	Limestone	304	SI	Bottom Ash Cooling Pond	--	--	3	50	16.66666667	Combined Ash	--	--
298	Limestone	305	SI	Dewatered Sludge Disposal Area	--	--	3	25	8.333333333	FGD Waste	--	Excluded
298	Limestone	306	SI	Stormwater Pond A	--	--	1	14	14	--	--	Excluded
298	Limestone	307	SI	Stormwater Pond B	--	--	1	14	14	--	--	Excluded
2240	Lon Wright	765	LF	Ash Monofill	--	--	--	105.3719008	--	Combined Ash	Yes	--
6664	Louisa	801	LF	CCR Landfill	41.33361111	-91.09555556	26	79.2271809	3.047199265	Combined Ash	None	--
6664	Louisa	223	SI	Bottom Ash Pond	41.48055556	-90.81611111	42	--	--	Ash & Coal Refuse	Clay	--
6664	Louisa	222	SI	Louisa Surface Impoundment	--	--	42	242	5.761904762	Combined Ash	Clay	--
976	Marion Generating Station	402	SI	Pond A-1	37.622483	-88.959618	32	--	--	Combined Ash	--	--
976	Marion Generating Station	401	SI	Fly Ash Disposal Pond	37.623085	-88.958022	45	--	--	Combined Ash	--	--
976	Marion Generating Station	411	SI	South Fly Ash Pond	37.614852	-88.957672	103	--	--	Combined Ash	--	--
976	Marion Generating Station	410	SI	Pond 4	37.622813	-88.955435	55	--	--	Combined Ash	--	--
976	Marion Generating Station	412	SI	Pond 2	37.623314	-88.953918	15	--	--	Combined Ash	--	--
976	Marion Generating Station	405	SI	Pond 1	37.62245	-88.953884	9	--	--	Combined Ash	--	--
976	Marion Generating Station	802	LF	1990555005	37.62472222	-88.95288889	143	1983.47107	13.87042706	Combined Ash	None	--
976	Marion Generating Station	409	SI	Pond S-3	37.62583	-88.952365	20	--	--	Combined Ash	--	--
976	Marion Generating Station	406	SI	Pond S-1	37.623553	-88.95221	71	--	--	Combined Ash	--	--
976	Marion Generating Station	408	SI	Pond S-2	37.625837	-88.951926	25	--	--	Combined Ash	--	--
976	Marion Generating Station	404	SI	Pond S-6	37.62782	-88.951541	16	--	--	Combined Ash	--	--
976	Marion Generating Station	403	SI	Pond 3	37.624879	-88.95028	20	--	--	Combined Ash	--	--
976	Marion Generating Station	407	SI	Pond 3A	37.624139	-88.949876	20	--	--	Combined Ash	--	--
2727	Marshall	803	LF	FGD Residue Landfill	35.60361111	-80.97833333	18	145.3512397	8.075068871	Combined Ash	Composite	--
2727	Marshall	804	LF	Ash Landfill	35.61611111	-80.96861111	58	3595.041322	61.98347107	Combined Ash	None	Excluded
2727	Marshall	680	SI	Active Ash Pond	35.605944	-80.959917	1188	6885	5.795454545	Combined Ash	None	--
492	Martin Drake	1254	SI	Drake Equalization Basin	38.82385	-104.8330528	0.03859045	0.491046832	12.72456871	Combined Ash	None	--
492	Martin Drake	1253	SI	Drake W. Bottom Ash Basin	38.82361111	-104.833025	0.0530303	0.265151515	5	Combined Ash	None	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
492	Martin Drake	1252	SI	Drake E. Bottom Ash Basin	38.82361944	-104.8328833	0.05050505	0.265151515	5.25	Combined Ash	None	--
492	Martin Drake	1251	SI	Drake Cooling Tower 4	38.82458333	-104.8326583	0.07889118	0.394444444	4.999854503	Combined Ash	None	--
492	Martin Drake	805	LF	-999	--	--	--	--	--	Combined Ash	None	--
6146	Martin Lake	822	LF	PDP #2	32.26124167	-94.58276111	--	--	--	Combined Ash	Yes	Excluded
6146	Martin Lake	810	LF	PDP #3	32.25926944	-94.58261944	--	--	--	Combined Ash	Yes	Excluded
6146	Martin Lake	808	LF	PDP #1	32.26230556	-94.5823	--	--	--	Combined Ash	Yes	Excluded
6146	Martin Lake	1226	SI	Permanent Disposal Pond #4	32.25824444	-94.57884444	15.339876	347.107438	22.62778638	Combined Ash	Composite	--
6146	Martin Lake	1225	SI	East Bottom Ash Pond	32.26187778	-94.56365278	14.5798898	306.177686	21	Combined Ash	None	--
6146	Martin Lake	1224	SI	West Bottom Ash Pond	32.26071667	-94.56348889	14.5798898	306.177686	21	Combined Ash	Composite	--
6146	Martin Lake	1223	SI	ESP	32.26076944	-94.56153889	12.0999082	211.0130854	17.43923031	FGD Waste	Composite	--
6146	Martin Lake	807	LF	Caney Branch	32.243539	-94.540761	--	--	--	Combined Ash	Yes	Excluded
6146	Martin Lake	806	LF	A-1 ash disposal	32.22916944	-94.52399167	290	18595.04132	64.12083214	Combined Ash	Yes	--
6250	Mayo Electric Generating Facility	204	SI	1982 Pond	36.5378	-78.8931	140	4100	29.28571429	Combined Ash	None	--
6124	McIntosh	87	SI	Ash Pond	--	--	27	342	12.66666667	Ash & Coal Refuse	--	--
3287	McMeekin	1155	LF	Ash Landfill	34.04633333	-81.21327778	--	--	--	Combined Ash	None	--
2104	Meramec	609	SI	Bottom Ash Pond (3)	--	--	14	280	20	Combined Ash	None	--
2104	Meramec	610	SI	Fly Ash Pond #494 (Pond 7), Fly Ash Pond #495 (Pond 8), Fly Ash Pond #490 (Pond 9), and Fly Ash Pond #491 (Pond 10)	--	--	--	--	--	Combined Ash	None	Excluded
2104	Meramec	611	SI	Old Fly Ash Pond	--	--	18	300	16.66666667	Combined Ash	Composite	--
2104	Meramec	612	SI	New Fly Ash Pond	--	--	14	230	16.42857143	Combined Ash	Composite	--
2104	Meramec	613	SI	Retention Pond	--	--	1	10	10	Combined Ash	None	Excluded
864	Meredosia	385	SI	Fly Ash Pond	--	--	186	700	3.76344086	Combined Ash	None	Excluded
864	Meredosia	386	SI	Bottom Ash Pond	--	--	34	186	5.470588235	Combined Ash	None	Excluded
6213	Merom	812	LF	Area 2	39.06638889	-87.50027778	65	5268.595041	81.05530833	Combined Ash	Yes	--
6213	Merom	813	LF	Area 1	39.07472222	-87.50027778	--	--	--	Combined Ash	None	Excluded
6213	Merom	190	SI	All	--	--	--	--	--	Combined Ash	--	Excluded
2364	Merrimack Station	754	LF	Coal Ash Landfill	43.13497222	-71.4765	--	--	--	Combined Ash	Yes	--
2364	Merrimack Station	1319	SI	WWT #3 Slag Sluice Settling Area	43.14125	-71.47186111	0.64538567	0.529476584	0.820403372	Combined Ash	None	--
2364	Merrimack Station	1320	SI	Waste Treatment #4 Slag Settling Pond	43.13983333	-71.47016667	1.73576676	10.0674472	5.8	Combined Ash	None	--
2832	Miami Fort	700	SI	Ash Basin B	39.11194444	-84.81277778	20	515	25.75	Ash & Coal Refuse	None	--
2832	Miami Fort	699	SI	Ash Basin A	39.1125	-84.81	20	803	40.15	Ash & Coal Refuse	None	--
2832	Miami Fort	1121	LF	Miamiview Road Ash Landfill	39.15388889	-84.78888889	--	--	--	Combined Ash	Yes	Excluded
2832	Miami Fort	1109	LF	Lawrenceberg Road Ash Landfill	--	--	80	2479.338843	30.99173554	Combined Ash	Yes	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
997	Michigan City	451	SI	Primary 2	41.716443	-86.915613	2.6	44	16.92307692	Combined Ash	--	--
997	Michigan City	450	SI	Secondary 2	41.71739	-86.914924	0.2	3	15	Combined Ash	--	--
997	Michigan City	453	SI	Primary 1	41.71814	-86.914534	2.2	36	16.36363636	Combined Ash	--	--
997	Michigan City	452	SI	Secondary 1	41.718947	-86.913976	0.2	3	15	Combined Ash	--	--
997	Michigan City	448	SI	Final Settling Pond	41.720692	-86.913242	5.7	85	14.9122807	Combined Ash	--	--
997	Michigan City	449	SI	Bottom Ash Area	41.719552	-86.912839	0.7	1	1.428571429	Combined Ash	--	--
1364	Mill Creek	543	SI	Ash Pond	33.204167	-85.909242	43	--	--	Combined Ash	None	--
1364	Mill Creek	817	LF	Mill Creek Special Waste Landfill-Site A	38.04222222	-85.90888889	--	--	--	Combined Ash	None	--
1364	Mill Creek	819	LF	Mill Creek Special Waste Landfill-Site B	38.05083333	-85.90555556	--	--	--	Combined Ash	None	--
1364	Mill Creek	818	LF	Mill Creek Special Waste Landfill-Site C	38.04444444	-85.90472222	--	--	--	Combined Ash	Yes	--
1364	Mill Creek	544	SI	Emergency Pond	--	--	1	--	--	FGD Waste	--	--
1364	Mill Creek	545	SI	Dead Storage Pond	--	--	2	--	--	FGD Waste	--	--
1364	Mill Creek	546	SI	Construction Run Off Pond	--	--	3	--	--	FGD Waste	--	--
1364	Mill Creek	547	SI	Clearwell Pond	--	--	2	--	--	FGD Waste	--	--
2823	Milton R. Young Station	777	LF	IT-197	47.07111111	-101.3134528	--	--	--	Combined Ash	None	Excluded
2823	Milton R. Young Station	788	LF	IT-205 Section 3	47.06308333	-101.3125278	--	--	--	Combined Ash	None	--
2823	Milton R. Young Station	809	LF	IT-068	47.07941389	-101.2864889	--	--	--	Combined Ash	None	Excluded
2823	Milton R. Young Station	811	LF	Horseshoe Pit	47.07838889	-101.2733833	--	--	--	Combined Ash	None	Excluded
2823	Milton R. Young Station	820	LF	Cell 1 30 Year Ponds	47.05989	-101.22055	80	4028.92562	50.36157025	Combined Ash	Yes	--
2823	Milton R. Young Station	686	SI	Cell 1	--	--	--	--	--	Combined Ash	Clay	--
2823	Milton R. Young Station	687	SI	Unit 1 Alternative Bottom Ash Pond	--	--	2	25	12.5	Combined Ash	Clay	--
2823	Milton R. Young Station	688	SI	30 Year Ponds (Cell 2)	--	--	27	1252	46.37037037	Combined Ash	Clay	--
2823	Milton R. Young Station	689	SI	Horseshoe Pit Evaporation Pond	--	--	4	34	8.5	Combined Ash	--	--
2171	Missouri City	1257	SI	Ash Pond	39.23212222	-94.30763611	0.331	--	--	Combined Ash	None	--
3948	Mitchell	160	SI	Bottom Ash Complex	39.825	-80.815556	10.2	262	25.68627451	Combined Ash	Composite	--
3948	Mitchell	161	SI	Fly Ash Pond	39.823611	-80.815	71	13500	190.1408451	Ash & Coal Refuse	--	--
727	Mitchell	364	SI	Ash Pond A	--	--	4	61	15.25	Combined Ash	None	--
727	Mitchell	365	SI	Ash Pond 2	--	--	43	644	14.97674419	Combined Ash	None	--
727	Mitchell	366	SI	Ash Pond 1	--	--	44	659	14.97727273	Combined Ash	None	--
3181	Mitchell Power Station	779	LF	Inactive coal combustion byproduct disposal site	40.226871	-79.978892	--	--	--	Combined Ash	None	Excluded
3181	Mitchell Power Station	778	LF	Active Coal Combustion byproduct disposal site	40.22611111	-79.97888889	70	3471.07438	49.58677686	Combined Ash	None	--
1048	ML Kapp	479	SI	Main Ash Secondary Settling Pond	--	--	2	1	0.5	Combined Ash	None	--
1048	ML Kapp	480	SI	Emergency Ash Primary Settling Pond	--	--	1	3	3	Combined Ash	None	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
1048	ML Kapp	481	SI	Emergency Ash Secondary Settling Pond	--	--	1	2	2	Combined Ash	None	--
1048	ML Kapp	482	SI	Main Ash Primary Settling Pond	--	--	7	4	0.571428571	Combined Ash	None	--
1733	Monroe Power Plant	582	SI	Fly Ash Basin	41.88416667	-83.37527778	410.576	18595	45.29003157	Combined Ash	none	--
1733	Monroe Power Plant	583	SI	Bottom Ash Basin	--	--	100	620	6.2	Combined Ash	--	--
6147	Monticello	781	LF	G Area	33.14444444	-95.03805556	--	--	--	Combined Ash	Yes	--
6147	Monticello	1204	SI	West Decant Basin(s)	33.08489722	-95.03458056	0.88699311	15.96434803	17.99827732	Combined Ash	Composite	Excluded
6147	Monticello	1203	SI	East Decant Basin(s)	33.08515	-95.03393056	0.88705234	15.96434803	17.99707557	Combined Ash	None	Excluded
6147	Monticello	1205	SI	Bottom Ash Pond(s)	33.08775556	-95.03381111	20.2298439	293.6139118	14.51389904	Combined Ash	None	--
6147	Monticello	1206	SI	New Operating Scrubber Pond 2	33.08592778	-95.03345556	1	12.00325987	12.00325987	FGD Waste	Composite	Excluded
6147	Monticello	782	LF	A Area	33.09211111	-95.02919444	--	--	--	Combined Ash	None	Excluded
6147	Monticello	780	LF	B Area	--	--	--	--	--	Combined Ash	None	--
2080	Montrose	783	LF	Utility Waste Landfill	38.31138889	-93.94388889	--	--	--	Combined Ash	Yes	--
2080	Montrose	601	SI	South Ash Pond	38.31053889	-93.93953611	2.7	--	--	Combined Ash	--	--
2080	Montrose	600	SI	North Ash Pond	38.31093889	-93.93916667	1.65	--	--	Combined Ash	--	--
2080	Montrose	602	SI	Ash Settling Pond	--	--	4	13	3.25	Combined Ash	--	--
1573	Morgantown Generating Plant	1108	LF	Controlled Storage	38.36138889	-76.96944444	212	4772.727273	22.51286449	Combined Ash	Yes	--
1573	Morgantown Generating Plant	785	LF	Faulkner Ash Site	38.439064	-76.961462	--	--	--	Combined Ash	Yes	--
1606	Mount Tom	563	SI	Equalization Tank	42.278607	-72.60317	0.014	--	--	Combined Ash	--	Excluded
1606	Mount Tom	798	LF	Former Bottom Ash Basin "A"	42.276003	-72.602229	--	--	--	Combined Ash	None	Excluded
1606	Mount Tom	564	SI	Special Basin	--	--	1	7	7	Combined Ash	--	Excluded
1606	Mount Tom	565	SI	Bottom Ash Basin	--	--	2	18	9	Combined Ash	--	Excluded
6264	Mountaineer	787	LF	Little Broad Run Landfill	38.94666667	-81.95166667	325	10289.2562	31.65924984	Combined Ash	Composite	--
6264	Mountaineer	211	SI	Bottom Ash Complex	38.97	-81.936667	29	508	17.51724138	Combined Ash	Clay	--
3954	Mt. Storm	1112	LF	Closed Ash Mtn	39.19111111	-79.29027778	54	--	--	Combined Ash	Clay	Excluded
3954	Mt. Storm	1110	LF	Phase B Landfill	39.18555556	-79.28388889	155	656.5656566	4.235907462	Combined Ash	None	--
3954	Mt. Storm	1111	LF	Phase A Landfill (ASH)	39.196095	-79.282034	71	505.0505051	7.113387395	Combined Ash	Clay	--
3954	Mt. Storm	789	LF	Phase A Landfill (FGD)	39.196262	-79.276722	71	491.2764004	6.919385921	Combined Ash	Composite	--
1167	Muscatine #1	792	LF	Coal Combustion Residue Landfill	41.38	-91.20722222	36	1239.669422	34.43526171	Combined Ash	Yes	--
1167	Muscatine #1	1361	SI	coal pile runoff pond	41.38861111	-91.05805556	0.45913682	4.591368228	10	Ash & Coal Refuse	Clay	Excluded
2872	Muskingum River	712	SI	Unit 1-4 Bottom Ash Pond Dam	39.58362778	-81.68921111	5	100	20	Combined Ash	None	--
2872	Muskingum River	714	SI	Middle Fly Ash Pond	39.58166667	-81.68833333	40	1370	34.25	Combined Ash	None	--
2872	Muskingum River	715	SI	Lower Fly Ash Dam	39.58583333	-81.68833333	16	660	41.25	Combined Ash	None	--
2872	Muskingum River	713	SI	Upper Fly Ash Pond	39.575	-81.685	116.8	5250	44.94863014	Combined Ash	None	--
2952	Muskogee	1174	SI	T01	35.76555556	-95.29222222	23.14	--	--	Combined Ash	None	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
2952	Muskogee	1173	SI	F03	35.75361111	-95.29027778	0.44977043	--	--	Combined Ash	None	--
2952	Muskogee	1172	SI	F01	35.76388889	-95.28111111	17.5298439	--	--	Combined Ash	Clay	--
4162	Naughton Plant	15	SI	FGD Pond #1	41.767492	-110.595608	40	1038	25.95	Combined Ash	Composite	--
4162	Naughton Plant	14	SI	South Ash Pond	41.748486	-110.594661	206	4057	19.69417476	Combined Ash	None	--
4162	Naughton Plant	13	SI	North Ash Pond	41.761525	-110.588586	151.5	3370	22.24422442	Combined Ash	None	--
4162	Naughton Plant	12	SI	FGD Pond #2	41.766639	-110.586917	40	671	16.775	Combined Ash	Composite	--
4162	Naughton Plant	980	LF	--	--	--	--	--	--	Combined Ash	--	--
4941	Navajo Generating Station	793	LF	Ash Disposal Area	36.90861111	-111.3569444	--	--	--	Combined Ash	None	--
6064	Nearman Creek	795	LF	Fly Ash Dry Deposition Area	39.10694444	-94.71773889	--	--	--	Combined Ash	None	--
6064	Nearman Creek	794	LF	Bottom Ash Pond	39.174112	-94.692221	--	--	--	Combined Ash	Yes	--
6064	Nearman Creek	39	SI	N/A	--	--	7	124	17.71428571	Combined Ash	Clay	--
6096	Nebraska City	797	LF	NC2 Landfill Cell 1	40.62561111	-95.78605556	--	--	--	Combined Ash	Yes	--
6096	Nebraska City	943	LF	NC1 landfill	40.61922222	-95.78602778	17	371.9008265	21.8765192	Combined Ash	None	--
6096	Nebraska City	1271	SI	Bottom Ash Pond 1	40.625103	-95.774172	11.359045	96.7637741	8.518654002	Combined Ash	None	--
6096	Nebraska City	1272	SI	Bottom Ash Pond 2	40.625103	-95.774172	12.2520661	111.1042241	9.06820311	Combined Ash	None	--
4054	Nelson Dewey	170	SI	WPDES Pond	42.725581	-91.013559	4	26	6.5	Combined Ash	--	Excluded
4054	Nelson Dewey	893	LF	Ash Disposal Facility	42.72680556	-91.01277778	17.8	381.818182	21.45045966	Combined Ash	None	Excluded
4054	Nelson Dewey	171	SI	Slag Pond	42.725413	-91.008642	5	20	4	Combined Ash	--	--
3138	New Castle Plant	1350	SI	South Bottom Ash Pond	40.94	-80.37138889	0.72084481	5.766758494	8	Combined Ash	None	--
3138	New Castle Plant	1349	SI	North Bottom Ash Pond	40.941817	-80.368153	2.0087236	16.0697888	8	Combined Ash	None	--
3138	New Castle Plant	941	LF	Fly Ash Landfill	40.94555556	-80.36805556	57	3548.347107	62.25170364	Combined Ash	Composite	--
2167	New Madrid	1032	LF	UCW landfill	36.48964306	-89.58599806	--	--	--	Combined Ash	Yes	--
2167	New Madrid	622	SI	Ash Pond 1	36.50611111	-89.57388889	31	570	18.38709677	Combined Ash	None	--
2167	New Madrid	621	SI	Slag Pond 2	36.51444444	-89.55944444	4	14	3.5	Combined Ash	None	--
2167	New Madrid	620	SI	Ash Pond 2	36.50166667	-89.5575	79	1351	17.10126582	Combined Ash	Composite	--
2167	New Madrid	623	SI	Slag Pond 1	36.5075	-89.55666667	62	1137	18.33870968	Combined Ash	None	--
6017	Newton	1034	LF	Landfill Phase I	38.93305556	-88.295	--	--	--	Combined Ash	None	Excluded
6017	Newton	1033	LF	Landfill Phase II	38.93083333	-88.29194444	309	--	--	Combined Ash	Yes	--
6017	Newton	21	SI	Secondary Ash Pond	38.92195556	-88.29063889	9	83	9.222222222	Combined Ash	None	--
6017	Newton	22	SI	Primary Ash Pond	38.92836667	-88.28351389	400	9250	23.125	Combined Ash	None	--
2291	North Omaha	1113	LF	North Omaha Ash Landfill	41.33294444	-95.95097778	13	65.08264463	5.006357279	Combined Ash	None	--
2291	North Omaha	1036	LF	North Omaha Ash Landfill closed area	41.32966667	-95.9505	--	--	--	Combined Ash	Yes	Excluded
2291	North Omaha	1222	SI	Coal Pile Runoff pond	41.33008333	-95.94894444	2.298	--	--	Ash & Coal Refuse	None	Excluded
2291	North Omaha	1220	SI	West Ash Pond (IAW-3A)	41.33063889	-95.94569444	15.9894399	14.66023875	0.916870065	Combined Ash	Composite	--
2291	North Omaha	1221	SI	East Ash Pond (IAW-3B)	41.33063889	-95.94569444	11.5909091	10.6359045	0.917607447	Combined Ash	Composite	--
8224	North Valmy	1037	LF	U1, U2 & U3 Ash Landfill	40.89145278	-117.1504278	--	--	--	Combined Ash	None	--
2963	Northeastern	1038	LF	Fly Ash Landfill	36.41583333	-95.69833333	69	1974.291322	28.61291771	Combined Ash	Yes	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
2963	Northeastern	718	SI	Bottom Ash Pond	--	--	69	700	10.14492754	Combined Ash	Clay	--
667	Northside Generating Station	1039	LF	Outdoor pile 1	30.42694444	-81.55666667	--	--	--	Combined Ash	Yes	--
10030	NRG Energy Center Dover	251	SI	Waste Water Pond	--	--	--	--	--	Combined Ash	--	--
527	Nucla	338	SI	Coal/Ash Settling Basin	--	--	--	--	--	Combined Ash	--	--
527	Nucla	964	LF	--	--	--	41.2	929.7520665	22.56679773	Combined Ash	--	--
2848	O H Hutchings	705	SI	West Primary Settling Pond	39.61163056	-84.29494167	7.88	--	--	Combined Ash	None	--
2848	O H Hutchings	703	SI	Secondary Settling Pond	39.613175	-84.29474722	1.75	6	3.428571429	Combined Ash	None	--
2848	O H Hutchings	704	SI	East Primary Settling Pond	39.61177778	-84.29355556	5.4	--	--	Combined Ash	None	--
6180	Oak Grove	1040	LF	Ash Landfill 1	31.17544167	-96.49919167	--	--	--	Combined Ash	Yes	--
6180	Oak Grove	1185	SI	FGD-A	31.18421944	-96.49215278	9.43526171	144.2470156	15.28807786	Combined Ash	Clay	--
6180	Oak Grove	1042	LF	-999	--	--	--	--	--	Combined Ash	None	--
6180	Oak Grove	1054	LF	-999	--	--	--	--	--	Combined Ash	None	--
127	Oklaunion	281	SI	Wastewater Evaporation Pond 6	34.07999722	-99.17916667	58	1044	18	Combined Ash	Clay	--
127	Oklaunion	282	SI	Sludge Pond	--	--	23	565	24.56521739	FGD Waste	--	--
127	Oklaunion	283	SI	Pond #23	--	--	13	333	25.61538462	Combined Ash	--	--
127	Oklaunion	841	LF	--	--	--	--	--	--	Combined Ash	Composite	--
4151	Osage	1044	LF	Historic Ash Dam	43.971173	-104.40813	--	--	--	Combined Ash	None	Excluded
4151	Osage	1031	LF	Old Ash Dam	43.96988889	-104.4077778	--	--	--	Combined Ash	None	Excluded
4151	Osage	1267	SI	West Dam	43.96516667	-104.4068056	45	--	--	Combined Ash	None	Excluded
4151	Osage	1266	SI	East Dam	43.96483333	-104.40625	2.671	--	--	Combined Ash	Clay	Excluded
1831	Otto E. Eckert Station	586	SI	EPRI 5	--	--	151	4462.809917	29.55503257	Combined Ash	--	Excluded
6254	Ottumwa	1045	LF	Ottumwa Midland Landfill	41.07772222	-92.45022222	--	--	--	Combined Ash	Yes	--
6254	Ottumwa	205	SI	Monofill Leachate Retention Pond	--	--	--	1	--	Combined Ash	--	Excluded
6254	Ottumwa	206	SI	Monofill Storm Water Retention Pond	--	--	2	18	9	--	--	Excluded
6254	Ottumwa	207	SI	Main Ash Pond	--	--	18	229	12.72222222	Combined Ash	None	--
6254	Ottumwa	208	SI	Zero Liquid Discharge Pond	--	--	17	319	18.76470588	Combined Ash	None	Excluded
1378	Paradise	548	SI	Fly Ash Extension Area Pond	--	--	203	3935	19.38423645	Combined Ash	--	--
1378	Paradise	549	SI	Scrubber Sludge Complex	--	--	255	532	2.08627451	Combined Ash	--	--
1378	Paradise	550	SI	Slag Areas 2A & 2B	--	--	27	600	22.22222222	Combined Ash	--	Excluded
6248	Pawnee	1046	LF	Pawnee Station Landfill	40.20954167	-103.6840472	--	--	--	Combined Ash	None	--
6248	Pawnee	191	SI	Evaporative Pond C	--	--	11	96	8.727272727	Combined Ash	--	--
6248	Pawnee	192	SI	Intermediate Quality (IQ) Water Pond	--	--	4	48	12	Combined Ash	--	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
6248	Pawnee	193	SI	New Bottom Ash Water Recovery Pond	--	--	6	52	8.666666667	Combined Ash	--	--
6248	Pawnee	194	SI	Ash Disposal Facility (ADF)	--	--	34	1349	39.67647059	Combined Ash	--	--
6248	Pawnee	195	SI	Ash Water Recovery Pond	--	--	1	5	5	Combined Ash	--	Excluded
6248	Pawnee	196	SI	Evaporative Pond B	--	--	15	138	9.2	Combined Ash	--	--
6248	Pawnee	197	SI	Bottom Ash Disposal Pond	--	--	13	250	19.23076923	Combined Ash	--	Excluded
6238	Pearl Station	1211	SI	AP	39.44888889	-90.61555556	12.7988981	127.9889807	10	Combined Ash	None	--
3938	Philip Sporn	157	SI	Unit 5 (Fly Ash Pond)	38.97361111	-81.93777778	70.3	1965	27.95163585	Combined Ash	None	--
3938	Philip Sporn	156	SI	Bottom Ash Pond	38.96888889	-81.92888889	9.5	256	26.94736842	Ash & Coal Refuse	None	--
3938	Philip Sporn	979	LF	--	--	--	--	--	--	Combined Ash	--	--
2843	Picway	702	SI	[blank]	39.792655	-83.007777	23	275	11.95652174	--	--	--
7902	Pirkey	236	SI	Scrubber Sludg Landfill Runoff Pond	32.45136111	-94.49844444	12.88	25	1.940993789	FGD Waste	None	Excluded
7902	Pirkey	233	SI	West Bottom Ash Pond	32.46736111	-94.49172222	30.85	188	6.094003241	Combined Ash	None	--
7902	Pirkey	235	SI	Secondary Bottom Ash Pond	32.46538889	-94.48772222	2.65	12	4.528301887	Combined Ash	None	--
7902	Pirkey	237	SI	Surge Pond	32.46297222	-94.48741667	4.7	19	4.042553191	FGD Waste	None	Excluded
7902	Pirkey	234	SI	East Bottom Ash Pond	32.46705556	-94.48675	30.85	188	6.094003241	Combined Ash	None	--
7902	Pirkey	238	SI	Auxilliary Surge Pond	32.46447222	-94.48580556	4.3	64	14.88372093	FGD Waste	None	--
7902	Pirkey	1132	LF	--	--	--	--	--	--	Combined Ash	Composite	--
59	Platte	1047	LF	Ash Disposal Phase II	40.85487778	-98.35371667	--	--	--	Combined Ash	None	--
59	Platte	1048	LF	Ash Disposal Phase I	40.85370833	-98.35303611	--	--	--	Combined Ash	None	Excluded
6170	Pleasant Prairie	1049	LF	Pleasant Prairie	42.56166667	-87.90111111	26	4028.92562	154.9586777	Combined Ash	Yes	--
6004	Pleasants Power Station	1050	LF	McElroy's Run	39.36819	-81.271275	--	--	--	Combined Ash	Yes	--
6004	Pleasants Power Station	17	SI	McElroy's Run Embankment	39.36666667	-81.27083333	219	20000	91.32420091	Combined Ash	None	--
7242	Polk	1051	LF	Slag Pile	27.72611111	-81.99138889	--	--	--	Combined Ash	Yes	--
3113	Portland	1020	LF	Quarry 1	40.87027778	-75.20027778	2.3	4.958448118	2.155847008	Combined Ash	None	Excluded
3113	Portland	1052	LF	Bangor Landfill	40.87194444	-75.19833333	16.6	954.5454545	57.50273823	Combined Ash	Composite	--
3113	Portland	1043	LF	Quarry 2 & 3	40.87027778	-75.19805556	12	25.45454545	2.121212121	Combined Ash	None	Excluded
3113	Portland	1201	SI	West Sedimentation Basin	40.90611111	-75.07777778	0.89990817	3.130257117	3.478418367	Combined Ash	None	--
3113	Portland	1200	SI	East Sedimentation Basin	40.90611111	-75.0775	0.89990817	3.130257117	3.478418367	Combined Ash	None	--
3113	Portland	1199	SI	IWT Sedimentation Basin	40.90638889	-75.0775	1.48	--	--	Combined Ash	Yes	Excluded
3113	Portland	1041	LF	-999	--	--	--	--	--	Combined Ash	None	Excluded
879	Powerton	1228	SI	East Yard Runoff Basin	40.53916667	-89.68027778	8.38	--	--	Combined Ash	None	Excluded
879	Powerton	1231	SI	Metal Cleaning Basin	40.54472222	-89.67777778	1.91000918	16.52892562	8.653846154	Combined Ash	None	Excluded
879	Powerton	1229	SI	Secondary Ash Settling Basin	40.54638889	-89.6775	1.78145087	23.15886134	13	Combined Ash	None	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
879	Powerton	1227	SI	Ash Surge Basin	40.54638889	-89.67638889	8.14049587	113.9669421	14	Combined Ash	None	--
879	Powerton	1230	SI	Ash Bypass Basin	40.54194444	-89.67611111	0.90679522	6.081267218	6.706329114	Combined Ash	None	--
879	Powerton	1233	SI	Limestone Runoff Basin	40.545	-89.675	8.38	--	--	Combined Ash	Yes	Excluded
879	Powerton	1232	SI	41	40.54722222	-89.67416667	12.855831	51.42332415	4	Combined Ash	None	Excluded
3140	PPL Brunner Island	1114	LF	Disposal Area 8	40.08666667	-76.68833333	--	--	--	Combined Ash	Yes	--
3140	PPL Brunner Island	95	SI	Ash Basin No.6	40.086838	-76.688102	70	2600	37.14285714	Combined Ash	--	--
3140	PPL Brunner Island	93	SI	Industrial Waste Treatment Basin	40.078064	-76.680176	7	20	2.857142857	--	--	Excluded
3140	PPL Brunner Island	94	SI	Equalizatipond	40.07666	-76.678687	1	5	5	Combined Ash	--	--
3149	PPL Montour	1115	LF	Ash Area No. 3	41.06305556	-76.66111111	--	--	--	Combined Ash	Yes	--
3149	PPL Montour	1011	LF	Ash Area No. 2	41.06416667	-76.65138889	--	--	--	Combined Ash	--	Excluded
3149	PPL Montour	96	SI	Silo Runoff Pond	--	--	--	1	--	Combined Ash	--	Excluded
3149	PPL Montour	97	SI	Ash Area 3 Leachate Runoff Basin	--	--	2	11	5.5	Combined Ash	--	Excluded
3149	PPL Montour	98	SI	Detention Basin	--	--	21	53	2.523809524	--	--	Excluded
3149	PPL Montour	99	SI	Stormwater Basin	--	--	2	13	6.5	--	--	Excluded
3149	PPL Montour	100	SI	Ash Basin No. 1	--	--	143	5070	35.45454545	Combined Ash	--	--
1073	Prairie Creek	487	SI	Ash Pond #10	--	--	--	1	--	Combined Ash	--	--
1073	Prairie Creek	488	SI	Ash Pond #5	--	--	1	12	12	Combined Ash	--	--
1073	Prairie Creek	489	SI	Ash Pond #6	--	--	1	14	14	Combined Ash	--	--
1073	Prairie Creek	490	SI	Ash Pond #7	--	--	--	1	--	Combined Ash	--	--
1073	Prairie Creek	491	SI	Ash Pond #3	--	--	1	7	7	Combined Ash	--	--
1073	Prairie Creek	492	SI	Ash Pond #2	--	--	1	8	8	Combined Ash	--	--
1073	Prairie Creek	493	SI	Ash Pond #4	--	--	1	8	8	Combined Ash	--	--
1073	Prairie Creek	494	SI	Ash Pond #1	--	--	--	4	--	Combined Ash	--	--
1073	Prairie Creek	495	SI	Ash Pond #8 - Plant Drains	--	--	--	--	--	Combined Ash	--	--
1073	Prairie Creek	496	SI	Ash Pond #9 - Dumper Building	--	--	--	1	--	Combined Ash	--	--
1769	Presque Isle	1014	LF	Presque Isle Power Plant Ash Landfill #2	46.587834	-87.476013	--	--	--	Combined Ash	Yes	Excluded
1769	Presque Isle	1012	LF	Presque Isle Power Plant Ash Landfill #3	46.584725	-87.473626	292	8801.652893	30.14264689	Combined Ash	Yes	--
1769	Presque Isle	1013	LF	Presque Isle Power Plant Ash Landfill #1	46.587875	-87.469134	--	--	--	Combined Ash	None	Excluded
2403	PSEG Hudson Generating Station	1015	LF	Landfill 1	40.754374	-74.079108	--	--	--	Combined Ash	None	--
2403	PSEG Hudson Generating Station	1352	SI	South Pond	40.755306	-74.078844	4.233	59.13682277	13.97042825	Combined Ash	Clay	Excluded
2403	PSEG Hudson Generating Station	1351	SI	North Pond	40.75180556	-74.07522222	4.306	52.93847567	12.29411883	Combined Ash	Clay	Excluded
2408	PSEG Mercer Generating Station	1197	SI	South Pond	40.18036111	-74.72963889	0.854	--	--	Combined Ash	None	Excluded

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
2408	PSEG Mercer Generating Station	1198	SI	North Pond	40.17874444	-74.72816667	0.854	--	--	Combined Ash	None	Excluded
2408	PSEG Mercer Generating Station	1016	LF	Landfill 1	40.18225	-74.71694444	--	--	--	Combined Ash	None	--
4072	Pulliam	1017	LF	Pulliam Landfill	44.54388889	-88.01666667	--	--	--	Combined Ash	None	Excluded
4072	Pulliam	1212	SI	Pulliam Waste Water Pond	44.54388889	-88.01305556	0.12454086	1.930394858	15.50009217	Ash & Coal Refuse	None	--
1295	Quindaro	1030	LF	Quindaro Ash Landfill	39.14894444	-94.64483333	--	--	--	Combined Ash	Yes	--
6639	R D Green	1019	LF	Green Station Landfill	37.63416667	-87.50444444	--	--	--	Combined Ash	None	--
6639	R D Green	220	SI	Ash Pond Dam #0980	37.63438889	-87.50400278	21.3	--	--	Combined Ash	None	--
2864	R. E. Burger	1381	SI	Bottom Ash Pond	39.91289722	-80.76889444	3.44352617	40.17447199	11.66666667	Combined Ash	None	Excluded
2864	R. E. Burger	1380	SI	Fly Ash Pond	39.910125	-80.76314444	9.50413223	109.0449954	11.47342995	Combined Ash	None	Excluded
2864	R. E. Burger	976	LF	--	--	--	--	--	--	Combined Ash	--	Excluded
1008	R. Gallagher	460	SI	Ash Pond A	38.25655833	-85.84235	37	936	25.2972973	Combined Ash	None	--
1008	R. Gallagher	461	SI	Secondary Ash Pond	38.25681111	-85.83926389	4.5	63	14	Combined Ash	None	--
1008	R. Gallagher	1023	LF	N/A	--	--	--	--	--	Combined Ash	--	--
1008	R. Gallagher	1024	LF	N/A	--	--	--	--	--	Combined Ash	--	--
1008	R. Gallagher	1025	LF	N/A	--	--	--	--	--	Combined Ash	--	--
1008	R. Gallagher	1026	LF	N/A	--	--	--	--	--	Combined Ash	--	--
1008	R. Gallagher	1027	LF	N/A	--	--	--	--	--	Combined Ash	--	Excluded
1008	R. Gallagher	1029	LF	N/A	--	--	--	--	--	Combined Ash	--	Excluded
1008	R. Gallagher	1053	LF	N/A	--	--	--	--	--	Combined Ash	--	Excluded
1008	R. Gallagher	1056	LF	N/A	--	--	--	--	--	Combined Ash	--	Excluded
1008	R. Gallagher	1001	LF	--	--	--	--	--	--	Combined Ash	--	--
1570	R. Paul Smith Power Station	1083	LF	CCB Landfill	39.58972222	-77.83666667	--	--	--	Combined Ash	Yes	--
1570	R. Paul Smith Power Station	562	SI	Ash Pond #4	39.58741944	-77.83118611	11	218	19.81818182	Combined Ash	Composite	--
1570	R. Paul Smith Power Station	561	SI	Ash Pond #3	39.59195556	-77.83095	6	104	17.33333333	Combined Ash	None	--
2790	R.M. Heskett Station	1080	LF	Ash Disposal Site	46.867451	-100.897253	58	960.7438017	16.5645483	Combined Ash	Yes	--
2790	R.M. Heskett Station	1081	LF	Old Ash Landfill	46.87	-100.8902778	--	--	--	Combined Ash	None	Excluded
6085	R.M. Schahfer	68	SI	Gypsum Storage (Units 14&15)A	41.21004722	-87.02274722	45	--	--	FGD Waste	None	--
6085	R.M. Schahfer	54	SI	Waste Disposal Area	41.20505	-87.02237778	75	1165	15.53333333	Combined Ash	None	Excluded
6085	R.M. Schahfer	56	SI	Material Storage Runoff Basin	41.21239444	-87.01941389	12	48	4	FGD Waste	None	--
6085	R.M. Schahfer	58	SI	Gypsum Storage (Units 14&15)B	41.20936944	-87.01741944	9.5	--	--	FGD Waste	None	--
6085	R.M. Schahfer	55	SI	Recycle Basin	41.20560556	-87.01729722	30	372	12.4	Combined Ash	None	--
6085	R.M. Schahfer	67	SI	Metal Cleaning Waste Basin	41.21192222	-87.01636389	12	48	4	FGD Waste	None	--
6085	R.M. Schahfer	57	SI	FGD Landfill Stormwater Runoff Pond	41.21859722	-87.00565556	5	12	2.4	Combined Ash	None	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
6085	R.M. Schahfer	1082	LF	RMSGS Landfill	41.21458333	-87.00162778	200	10661.15703	53.30578513	Combined Ash	Yes	--
6761	Rawhide	1086	LF	CCR Monofill	40.87283333	-105.0426944	150	3162.194674	21.08129783	Combined Ash	None	--
6761	Rawhide	225	SI	North Bottom Ash Transfer Pond	--	--	4	37	9.25	Combined Ash	--	--
6761	Rawhide	226	SI	South Bottom Ash Transfer Pond	--	--	4	37	9.25	Combined Ash	--	--
6761	Rawhide	996	LF	--	--	--	--	--	--	Combined Ash	--	--
8219	Ray D Nixon	1087	LF	Clear Spring Ranch Ash Landfill	38.60823	-104.7132283	--	--	--	Combined Ash	None	--
8219	Ray D Nixon	1255	SI	Nixon Equalization Basin	38.62931167	-104.6996264	3.71271809	40.9884068	11.03999975	Combined Ash	None	Excluded
55076	Red Hills Generating Facility	1256	SI	AMU Basin	33.3825	-89.21888889	2.62	--	--	Combined Ash	Yes	--
55076	Red Hills Generating Facility	1088	LF	AMU	33.37972222	-89.21583333	--	--	--	Combined Ash	Yes	--
2324	Reid Gardner	637	SI	Pond C2	36.65886111	-114.6510806	8.5	173	20.35294118	FGD Waste	Composite	Excluded
2324	Reid Gardner	632	SI	Pond C1	36.65701111	-114.649775	14	115	8.214285714	FGD Waste	Composite	Excluded
2324	Reid Gardner	631	SI	Pond B3	36.65356389	-114.649225	8.1	90	11.11111111	FGD Waste	Composite	--
2324	Reid Gardner	630	SI	Pond B2	36.65486111	-114.6482694	12.4	148	11.93548387	FGD Waste	Composite	--
2324	Reid Gardner	634	SI	Pond B1	36.65599444	-114.6467972	13.4	193	14.40298507	FGD Waste	Composite	--
2324	Reid Gardner	635	SI	Pond E2	36.65433889	-114.6403417	14.4	165	11.45833333	FGD Waste	Composite	--
2324	Reid Gardner	636	SI	Pond E1	36.65317778	-114.6386806	5.9	115	19.49152542	FGD Waste	Composite	--
2324	Reid Gardner	633	SI	Pond F	36.65478333	-114.6377	4	37	9.25	FGD Waste	Composite	--
2324	Reid Gardner	1090	LF	Landfill	--	--	112.5	2801.652893	24.90358127	Combined Ash	None	--
1740	River Rouge Power Plant	1186	SI	bottom ash pond	42.27247778	-83.11265556	1.83654729	18.36547291	10	Combined Ash	None	--
2732	Riverbend	682	SI	Primary Ash Disposal Pond	35.36520278	-80.96329444	37.2	1640	44.08602151	Combined Ash	None	--
2732	Riverbend	681	SI	Secondary Pond	35.36810556	-80.96187778	23.5	980	41.70212766	Combined Ash	None	--
1081	Riverside	501	SI	South Ash Pond	41.53555556	-90.45166667	12	140	11.66666667	Combined Ash	None	--
1081	Riverside	500	SI	North Ash Pond	41.54416667	-90.44611111	14.1	84	5.957446809	Combined Ash	None	--
1927	Riverside	594	SI	Triangle Pond	--	--	--	2	--	Combined Ash	--	Excluded
1239	Riverton	512	SI	Industrial Landfill-East and West Ponds	37.06895278	-94.70081389	28	992	35.42857143	Combined Ash	None	--
3945	Rivesville Power Station	1358	SI	Bottom ash basin	39.530214	-80.115744	0.4323	--	--	Combined Ash	None	--
3945	Rivesville Power Station	1356	SI	Lagoon 1	39.53027778	-80.11527778	0.46717172	4.671717172	10	Combined Ash	Yes	Excluded
3945	Rivesville Power Station	1355	SI	Lagoon 2	39.53055556	-80.11444444	0.40174472	4.017447199	10	Combined Ash	Yes	Excluded
3945	Rivesville Power Station	1095	LF	Closed ash site	39.53888889	-80.09916667	60	495.8677686	8.26446281	Combined Ash	None	Excluded
3945	Rivesville Power Station	1116	LF	Ash disposal	39.5392	-80.094436	40	780.5325987	19.51331497	Combined Ash	None	--
3945	Rivesville Power Station	1357	SI	Disposal Site Sedimentation Pond	39.54	-80.09055556	0.59917355	3.379935721	5.640996169	Combined Ash	Clay	Excluded
6166	Rockport	179	SI	Bottom Ash Complex	37.91877222	-87.03744444	137	1640	11.97080292	Combined Ash	None	--
6166	Rockport	1097	LF	Rockport Plant Ash Landfill	--	--	--	--	--	Combined Ash	Yes	--
6190	Rodemacher	186	SI	Fly Ash Pond	31.39273056	-92.704125	42	670	15.95238095	Combined Ash	Clay	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
6190	Rodemacher	187	SI	Bottom Ash Pond	31.39666667	-92.70138889	43	641	14.90697674	Combined Ash	Clay	--
6190	Rodemacher	185	SI	Leachate Pond	31.39035833	-92.70029722	8	--	--	Combined Ash	Composite	--
2712	Roxboro Steam Electric Plant	661	SI	FGD Flush Pond	36.47371944	-79.07788611	3.1	53	17.09677419	FGD Waste	Composite	--
2712	Roxboro Steam Electric Plant	664	SI	FGD Settling Pond	36.46875	-79.07121111	16.6	420	25.30120482	FGD Waste	Composite	--
2712	Roxboro Steam Electric Plant	1096	LF	Fly ash landfill	36.47888889	-79.06166667	55	2581.61157	46.93839219	Combined Ash	None	--
2712	Roxboro Steam Electric Plant	662	SI	West Ash Pond Dam & Dikes 1, 2,,& 4	36.51852222	-79.022475	2400	--	--	Combined Ash	--	--
2712	Roxboro Steam Electric Plant	663	SI	Ash Pond	--	--	240	4800	20	Combined Ash	None	--
1393	RS Nelson	1330	SI	Coal Ash Settling Pond Unit 6	30.28611111	-93.30166667	11.4784206	60.83562902	5.3	Ash & Coal Refuse	Composite	Excluded
1393	RS Nelson	1085	LF	Unit 6 Coal Ash	30.27666667	-93.29833333	--	--	--	Combined Ash	Yes	--
1393	RS Nelson	1329	SI	CFB Ash Landfill Retention Basin	30.27805556	-93.28722222	2.47546488	11.96787649	4.834597577	Combined Ash	Composite	Excluded
1393	RS Nelson	1084	LF	CFB Ash Landfill	30.2775	-93.28694444	--	--	--	Combined Ash	Yes	--
6155	Rush Island	1091	LF	-999	--	--	--	--	--	Combined Ash	None	Excluded
6155	Rush Island	178	SI	Ash Pond	--	--	104	7000	67.30769231	Combined Ash	None	--
2451	San Juan	1308	SI	Solids Waste Pit	36.79915833	-108.4354222	21.293	--	--	FGD Waste	Yes	Excluded
6183	San Miguel	1094	LF	Mine Pits	28.64166667	-98.48972222	--	--	--	Combined Ash	Yes	--
6183	San Miguel	1093	LF	Emergency Ash Pit	28.68027778	-98.48333333	--	--	--	Combined Ash	Yes	Excluded
6183	San Miguel	1366	SI	Ash Water Transport Pond 1B	28.69944444	-98.47527778	13	216	16.61538462	Combined Ash	Clay	--
6183	San Miguel	1367	SI	Ash Water Transport Pond 1A	28.70027778	-98.47527778	12.7704316	216	16.91407205	Combined Ash	Clay	--
6183	San Miguel	1365	SI	Equalization Pond	28.70138889	-98.46777778	25	410	16.4	FGD Waste	Clay	Excluded
6648	Sandow No 4	1067	LF	Bottom Ash Fines	30.5401	-97.07942	51	1606.97888	31.5093898	Combined Ash	None	--
6648	Sandow No 4	1065	LF	Class II Landfill	30.54527778	-97.07883333	45	459.136823	10.20304051	Combined Ash	None	--
6648	Sandow No 4	1092	LF	B Pit	30.54713889	-97.07233333	56	2800.734619	50.01311819	Combined Ash	Clay	--
6648	Sandow No 4	1089	LF	Comb Slag-Bot Ash Landfills	30.56044444	-97.06358333	237	2295.684114	9.68643086	Combined Ash	None	--
6648	Sandow No 4	1057	LF	-999	--	--	--	--	--	Combined Ash	--	Excluded
6648	Sandow No 4	221	SI	EPRI 8	--	--	45	837.9997934	18.62221763	Ash & Coal Refuse	--	--
6257	Scherer	209	SI	Settlement-Recycle Pond	--	--	--	--	--	--	None	--
6257	Scherer	210	SI	Ash Pond	--	--	553	15955	28.8517179	Ash & Coal Refuse	None	--
2367	SCHILLER	1058	LF	Closed Landfill	43.093	-70.78186111	--	--	--	Combined Ash	None	Excluded
642	Scholz	1348	SI	Lower Pond	30.66897222	-84.89230556	11.2	168	15	Ash & Coal Refuse	None	--
642	Scholz	1347	SI	Middle Pond	30.66911111	-84.89086111	9.7	145.5	15	Ash & Coal Refuse	None	--
642	Scholz	1346	SI	Upper Pond	30.66983333	-84.89033333	10.9	375.8088843	34.47787929	Ash & Coal Refuse	None	--
136	Seminole Generating Station	1059	LF	FGD Landfill	29.74237778	-81.62952778	--	--	--	Combined Ash	Yes	--
1379	Shawnee	1060	LF	AFBC Fly Ash &	37.144521	-88.780926	2.5	39.02662994	15.61065197	Combined Ash	None	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
1379	Shawnee	1061	LF	-999	--	--	--	--	--	Combined Ash	--	--
1379	Shawnee	551	SI	Ash Pond	--	--	180	3099	17.21666667	Combined Ash	--	--
1379	Shawnee	552	SI	Consolidated Waste Dry Stack	--	--	200	20575	102.875	Combined Ash	--	--
3131	Shawville	1248	SI	Pond B	41.06063889	-78.37491667	1.61193756	12.21303949	7.576620713	Combined Ash	Composite	--
3131	Shawville	1246	SI	Pond 2	41.06258333	-78.37202778	1.212	--	--	Combined Ash	None	Excluded
3131	Shawville	1247	SI	Pond A	41.06258333	-78.37202778	1.66083563	12.64921947	7.616177812	Combined Ash	Composite	--
3131	Shawville	1245	SI	Pond 1	41.06377778	-78.37033333	1.212	--	--	Combined Ash	None	Excluded
3131	Shawville	1063	LF	Original	41.057479	-78.366463	--	--	--	Combined Ash	None	Excluded
3131	Shawville	1062	LF	Current	41.05841	-78.363989	68	4958.677686	72.92173068	Combined Ash	Yes	--
2277	Sheldon Station	1064	LF	Ash Landfill No. 4	40.555094	-96.793041	9	232.4380165	25.82644628	Combined Ash	Yes	--
2277	Sheldon Station	1066	LF	Ash Landfill No. 2	40.55583333	-96.78833333	--	--	--	Combined Ash	None	Excluded
2277	Sheldon Station	1360	SI	PROCESS POND	40.56111111	-96.78805556	2.14150597	19.52167126	9.115861241	Combined Ash	Clay	Excluded
2277	Sheldon Station	1078	LF	Ash Landfill No. 3	40.55277778	-96.7875	--	--	--	Combined Ash	Yes	Excluded
2277	Sheldon Station	1055	LF	Ash Landfill No. 1	40.56527778	-96.78722222	--	--	--	Combined Ash	None	Excluded
6090	Sherburne County	1068	LF	Landfill	45.38972222	-93.90555556	--	--	--	Combined Ash	Yes	--
6090	Sherburne County	69	SI	Bottom Ash Pond	45.37458333	-93.89047222	18	620	34.44444444	Combined Ash	Clay	--
6090	Sherburne County	70	SI	Pond No. 1	45.37111111	-93.89011111	61	3099	50.80327869	Combined Ash	Clay	--
6090	Sherburne County	71	SI	Pond No. 2	45.36963889	-93.884	100	6198	61.98	Combined Ash	Clay	--
6090	Sherburne County	73	SI	Pond 3 N	45.37172222	-93.87838889	50	1860	37.2	Combined Ash	Composite	--
6090	Sherburne County	72	SI	Recycle Basin	--	--	7	--	--	Combined Ash	--	--
6090	Sherburne County	74	SI	Unit No. 3 Dry Ash Landfill Basin	--	--	3	--	--	Combined Ash	--	--
2094	Sibley	1069	LF	Utility Waste Landfill	39.17222222	-94.16333333	--	--	--	Combined Ash	Yes	--
2094	Sibley	603	SI	Slag Settling Pond	--	--	1	--	--	Combined Ash	None	--
2094	Sibley	604	SI	Fly Ash Settling Pond	--	--	15	224	14.93333333	Combined Ash	Clay	--
6768	Sikeston Power Station	227	SI	Fly Ash Pond	36.88083333	-89.61472222	30	560	18.66666667	Combined Ash	Clay	--
6768	Sikeston Power Station	228	SI	Bottom Ash Pond	36.8775	-89.61388889	54	891	16.5	Combined Ash	Clay	--
2107	Sioux	614	SI	Fly Ash Pond	--	--	60	960	16	Combined Ash	Composite	--
2107	Sioux	615	SI	Bottom Ash Pond	--	--	47	2100	44.68085106	Combined Ash	None	--
1058	Sixth Street	486	SI	Ash Pond 1	41.98642	-91.663308	0.45	7	15.55555556	Combined Ash	--	Excluded
1058	Sixth Street	483	SI	Ash Pond 2	41.98679	-91.662879	0.52	7	13.46153846	Combined Ash	--	Excluded
1058	Sixth Street	485	SI	Ash Pond 4	41.98631	-91.662258	3	32	10.66666667	Combined Ash	--	Excluded
1058	Sixth Street	484	SI	Ash Pond 3	41.987194	-91.661573	4	40	10	Combined Ash	--	Excluded
1613	Somerset Station	566	SI	North Lift Pit	--	--	--	--	--	Combined Ash	--	Excluded
1613	Somerset Station	567	SI	South Pond	--	--	--	2	--	Combined Ash	--	Excluded
1613	Somerset Station	568	SI	Coal Pile Run-Off Sump	--	--	--	--	--	Combined Ash	--	Excluded
1613	Somerset Station	569	SI	Equalization Basin	--	--	--	--	--	Combined Ash	--	Excluded
6095	Sooner	1260	SI	F07	36.45611111	-97.04583333	2.5	7.800022957	3.120009183	Combined Ash	Clay	Excluded

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
6095	Sooner	1259	SI	F04	36.46555556	-97.04305556	21	124.0005601	5.904788578	Combined Ash	Clay	--
6061	South Mississippi El Pwr Assn	1021	LF	West Active Landfill	31.21277778	-89.39944444	--	--	--	Combined Ash	--	--
6061	South Mississippi El Pwr Assn	1022	LF	Cells 1-6	31.20916667	-89.39833333	--	--	--	Combined Ash	Yes	--
6061	South Mississippi El Pwr Assn	1008	LF	East Inactive Landfill	31.21111111	-89.39777778	--	--	--	Combined Ash	--	--
6061	South Mississippi El Pwr Assn	1353	SI	Scrubber Supply Pond	31.21277778	-89.39555556	29.33	--	--	FGD Waste	Yes	--
6061	South Mississippi El Pwr Assn	1354	SI	Emergency Dump Pond	31.21527778	-89.39555556	29.33	--	--	FGD Waste	Yes	--
4041	South Oak Creek	1072	LF	Oak Creek South Ash Landfill	42.84580556	-87.84716667	--	--	--	Combined Ash	None	Excluded
4041	South Oak Creek	1070	LF	Caledonia Ash Landfill	42.83869444	-87.84177778	175	5361.57025	30.63754429	Combined Ash	Yes	--
4041	South Oak Creek	1071	LF	Oak Creek North Ash Landfill	42.85277778	-87.83872222	--	--	--	Combined Ash	None	Excluded
6195	Southwest Power Station	1074	LF	Demonstration	37.14555556	-93.38694444	--	--	--	Combined Ash	None	Excluded
6195	Southwest Power Station	1269	SI	West Ash Pond	37.1475	-93.38555556	5	--	--	Combined Ash	Clay	--
6195	Southwest Power Station	1268	SI	East Ash Pond	37.14777778	-93.38472222	3	--	--	Combined Ash	Clay	--
6195	Southwest Power Station	1073	LF	Landfill active	37.14805556	-93.38083333	--	--	--	Combined Ash	None	--
8223	Springerville	1384	SI	Process Water Collection pond	34.319558	-109.160581	0.61310836	2.301652893	3.754071966	Combined Ash	None	Excluded
8223	Springerville	1075	LF	Ash LandFill	34.311956	-109.155852	900	75757.57576	84.17508418	Combined Ash	None	--
1743	St Clair Power Plant	584	SI	Pond	--	--	--	--	--	Combined Ash	--	--
207	St Johns River Power Park	1076	LF	Area 2	30.43916667	-81.55222222	40	1794.600551	44.86501377	Combined Ash	None	--
207	St Johns River Power Park	1018	LF	Area 1	30.43833333	-81.54583333	72	4037.667585	56.07871646	Combined Ash	None	Excluded
207	St Johns River Power Park	1077	LF	Area B	30.443508	-81.538978	35	4032	115.2	Combined Ash	None	--
2824	Stanton	997	LF	Old Ash Landfill	47.24444444	-101.3377778	108	561.5702479	5.199724518	Combined Ash	Yes	Excluded
2824	Stanton	937	LF	Fly Ash Landfill	47.2425	-101.3344444	37.1	1137.396694	30.65759284	Combined Ash	Clay	--
2824	Stanton	940	LF	Bottom Ash Landfill	47.28277778	-101.3333333	10.5	283.8842975	27.03659976	Combined Ash	Clay	--
2824	Stanton	692	SI	South Bottom Ash Pond/Cell 2	47.281834	-101.331463	4	40	10	Combined Ash	--	Excluded
2824	Stanton	691	SI	North Bottom Ash Pond/Cell	47.283774	-101.33139	4	37	9.25	Combined Ash	--	--
2824	Stanton	690	SI	Middle Bottom Ash Pond/Retention Cell	47.28279	-101.331359	3	38	12.66666667	Combined Ash	--	--
564	Stanton Energy Center	942	LF	CWSA	28.48138889	-81.18027778	312	--	--	Combined Ash	None	--
1131	Streeter Station	1028	LF	Leversee Road	42.544536	-92.420248	--	--	--	Combined Ash	None	--
3152	Sunbury Generation LP	101	SI	Residual Waste Ash Basin No. 1	40.83027778	-76.83472222	62	1139	18.37096774	Combined Ash	None	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
50951	Sunnyside Cogen Associates	944	LF	Sunnyside Ash Landfill - Landfill 1	39.53888889	-110.4105556	--	--	--	Combined Ash	None	--
1077	Sutherland	499	SI	Unit 3 Initial Settling Pond	42.047092	-92.85607	0.13	1	7.692307692	Combined Ash	--	--
1077	Sutherland	498	SI	Unit 1 & 2 Initial Settling Pond	42.047729	-92.855957	0.3	2	6.666666667	Combined Ash	--	--
1077	Sutherland	497	SI	Main Ash Settling Pond	42.047192	-92.854642	5.75	52	9.043478261	Combined Ash	--	--
1077	Sutherland	1117	LF	Marshalltown West	42.0686	-92.843121	17	--	--	Combined Ash	None	Excluded
1077	Sutherland	1118	LF	Marshalltown East	42.068625	-92.836794	2.58	86.46694215	33.51431866	Combined Ash	Clay	Excluded
10075	Taconite Harbor Energy Center	948	LF	Cell 2	47.53688389	-90.95482778	--	--	--	Combined Ash	Yes	--
10075	Taconite Harbor Energy Center	961	LF	Cell 3	47.536917	-90.954561	--	--	--	Combined Ash	Yes	--
10075	Taconite Harbor Energy Center	947	LF	Cell 1	47.53689083	-90.95415556	--	--	--	Combined Ash	Yes	--
988	Tanners Creek	418	SI	Fly Ash Pond - Clear Pond and Original (Lower Pond) Dike	39.07356944	-84.88386111	12	--	--	Combined Ash	Composite	--
988	Tanners Creek	417	SI	Fly Ash Pond - Upper Pond	39.07691667	-84.88013611	47.7	--	--	Combined Ash	None	--
988	Tanners Creek	419	SI	Fly Ash Pond	39.076917	-84.880136	60	1076	17.93333333	Combined Ash	Composite	--
988	Tanners Creek	950	LF	Ash Landfill	39.07527778	-84.875	--	--	--	Combined Ash	Yes	--
988	Tanners Creek	416	SI	Bottom Ash Complex	39.077375	-84.86681111	63.3	1645	25.98736177	Combined Ash	None	--
988	Tanners Creek	415	SI	Boiler Slag Pond (U-4)	--	--	20	820	41	Combined Ash	--	--
1252	Tecumseh Energy Center	519	SI	Area 2	39.05311111	-95.57283333	1	12	12	Combined Ash	None	--
1252	Tecumseh Energy Center	520	SI	Area 1	39.05219444	-95.57238889	2	20	10	Combined Ash	None	--
1252	Tecumseh Energy Center	1120	LF	Old Landfill	39.05583333	-95.56277778	--	--	--	Combined Ash	None	Excluded
1252	Tecumseh Energy Center	1133	LF	Landfill 322	39.04805556	-95.5625	32.2	331.6115702	10.29849597	Combined Ash	None	--
1252	Tecumseh Energy Center	995	LF	--	--	--	4.12	--	--	Combined Ash	--	--
2168	Thomas Hill	953	LF	MO-717502	39.53902583	-92.64948111	--	--	--	Combined Ash	None	--
2168	Thomas Hill	624	SI	Ash Pond Cell 2 - Middle	39.54277778	-92.63805556	12	31	2.583333333	Combined Ash	None	--
2168	Thomas Hill	627	SI	Ash Pond Slag Dewatering	39.54277778	-92.63805556	3	10	3.333333333	Combined Ash	None	--
2168	Thomas Hill	625	SI	Ash Pond Cell 1 - Upper	--	--	7	--	--	Combined Ash	--	--
2168	Thomas Hill	626	SI	Ash -3 Landfill	--	--	24	1050	43.75	--	--	--
2168	Thomas Hill	628	SI	Ash - 2 Landfill	--	--	44	1446	32.86363636	Combined Ash	--	--
2168	Thomas Hill	629	SI	Ash Pond Cell 3 - Lowest	--	--	10	50	5	Combined Ash	--	--
3115	Titus	955	LF	Old Ash Site (Flyash)	40.31472222	-75.91694444	--	--	--	Combined Ash	None	Excluded
3115	Titus	956	LF	Old Ash Site (Bottom Ash)	40.30944444	-75.91083333	--	--	--	Combined Ash	None	Excluded
3115	Titus	957	LF	Eyler Station Ash Site	40.31111111	-75.91083333	--	--	--	Combined Ash	None	Excluded
3115	Titus	954	LF	Beagle Club Ash Disposal Site	40.30583333	-75.90361111	39	1859.504132	47.67959313	Combined Ash	None	--
6194	Tolk	1161	LF	116	34.200988	-102.569056	--	--	--	Combined Ash	None	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
3845	TransAlta Centralia Generation	959	LF	Limited Purpose Landfill	46.75694444	-122.8166667	--	--	--	Combined Ash	Yes	--
1745	Trenton Channel Power Plant	960	LF	Sibley Quarry	42.16305556	-83.17472222	--	--	--	Combined Ash	None	--
1745	Trenton Channel Power Plant	585	SI	Pond	--	--	--	--	--	Combined Ash	--	--
6071	Trimble Co.	44	SI	Coal Combustion Waste Pond	38.59333333	-85.41777778	82	4841	59.03658537	Combined Ash	Clay	--
56224	TS Power Plant	816	LF	--	--	--	--	--	--	Combined Ash	--	--
7030	Twin Oaks Power One	928	LF	Ash Landfill	31.097149	-96.684213	61	3807.317975	62.41504877	Combined Ash	Yes	--
1361	Tyrone	537	SI	Ash Pond	38.04972222	-84.84527778	13	--	--	Combined Ash	None	--
1361	Tyrone	536	SI	Secondary Ash Pond	38.05138889	-84.84361111	1.2	--	--	Combined Ash	None	--
3295	Urquhart	1107	LF	Urquhart Landfill 1	33.429539	-81.91508	--	--	--	Combined Ash	None	--
3295	Urquhart	111	SI	Ash Pond	33.43527778	-81.91166667	9	--	--	Combined Ash	None	--
3295	Urquhart	110	SI	Ash Pond 1	--	--	1	11	11	Combined Ash	--	--
3295	Urquhart	112	SI	Ash Pond 2	--	--	1	7	7	Combined Ash	--	--
4042	Valley	920	LF	System Control Center Ash Landfill	43.05555556	-88.21694444	--	--	--	Combined Ash	Yes	Excluded
4042	Valley	919	LF	Highway 59 Ash Landfill	43.01222222	-88.19583333	--	--	--	Combined Ash	None	Excluded
4042	Valley	918	LF	Highway 32 Ash Landfill	43.342715	-87.915031	--	--	--	Combined Ash	Yes	--
4042	Valley	949	LF	Caledonia Ash Landfill	42.83861111	-87.84166667	16.4	330.9917355	20.1824229	Combined Ash	Yes	--
477	Valmont	1122	LF	Valmont Station ADF	40.028601	-105.203106	--	--	--	Combined Ash	None	--
477	Valmont	1123	LF	Closed Valmont Station ADF	40.03193056	-105.1951417	--	--	--	Combined Ash	None	Excluded
477	Valmont	329	SI	West Ash Settling Pond	--	--	1	16	16	Combined Ash	--	--
477	Valmont	330	SI	East Ash Settling Pond	--	--	1	16	16	Combined Ash	--	--
477	Valmont	331	SI	Coal Pile Stormwater Runoff Pond	--	--	--	--	--	Combined Ash	--	Excluded
897	Vermilion	395	SI	North Ash Pond System	40.18636944	-87.74571944	80	2400	30	Combined Ash	None	Excluded
897	Vermilion	396	SI	New East Ash Pond System	40.17841944	-87.73732222	20.6	340	16.50485437	Combined Ash	None	Excluded
897	Vermilion	970	LF	--	--	--	--	--	--	Combined Ash	--	Excluded
6073	Victor J. Daniel Jr	924	LF	CAMU - Central Ash Mngt. Unit	30.54972222	-88.56111111	--	--	--	Combined Ash	Yes	--
6073	Victor J. Daniel Jr	1124	LF	NAMU - North Ash Mngt. Unit	30.54305556	-88.55833333	49.2016308	--	--	Combined Ash	Yes	--
6073	Victor J. Daniel Jr	925	LF	-999	--	--	--	--	--	Combined Ash	--	Excluded
6073	Victor J. Daniel Jr	938	LF	-999	--	--	--	--	--	Combined Ash	--	Excluded
6073	Victor J. Daniel Jr	45	SI	EPRI 7	--	--	20.0387942	--	--	Ash & Coal Refuse	--	--
6019	W H Zimmer	26	SI	Wastewater Pond Complex	38.878405	-84.22883	15	75	5	FGD Waste	Clay	--
6019	W H Zimmer	929	LF	Class III Residual	38.85611111	-84.16777778	--	--	--	Combined Ash	Yes	--
3470	W. A. Parish	1125	LF	WAP Landfill	29.50888889	-95.62805556	28.6832221	--	--	Combined Ash	Yes	--
3470	W. A. Parish	136	SI	Air Preheater Pond	--	--	1	4	4	Combined Ash	--	Excluded

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Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
3470	W. A. Parish	137	SI	Unit 5 Bottom Ash Overflow Basin	--	--	--	--	--	Combined Ash	--	--
3470	W. A. Parish	138	SI	Flue Gas Desulfurization Emergency Pond (E-Pond)	--	--	--	2	--	FGD Waste	--	--
3470	W. A. Parish	139	SI	Unit 8 Bottom Ash Overflow Basin	--	--	--	--	--	Combined Ash	--	--
3470	W. A. Parish	140	SI	Unit 7/8 Dewatering Bin Basin	--	--	--	--	--	Combined Ash	--	Excluded
3470	W. A. Parish	141	SI	Unit 7 Bottom Ash Overflow Basin	--	--	--	--	--	Combined Ash	--	--
3470	W. A. Parish	142	SI	Coal Pile Run Off Pond	--	--	24	110	4.583333333	Combined Ash	--	Excluded
3470	W. A. Parish	143	SI	Unit 6 Bottom Ash Overflow Basin	--	--	--	--	--	Combined Ash	--	--
2866	W. H. Sammis	916	LF	Hollow Rock	40.51166667	-80.68	141.6	624.0128558	4.406870451	Combined Ash	Composite	--
2866	W. H. Sammis	1383	SI	South Ash Pond	40.52722222	-80.63027778	4.61432507	64.60055096	14	Combined Ash	None	--
2866	W. H. Sammis	1382	SI	North Ash Pond	40.52805556	-80.63027778	5.09641873	71.16620753	13.96396396	Combined Ash	None	--
3264	W. S. Lee	105	SI	Secondary Ash Pond	34.60424722	-82.44513056	23	391	17	Combined Ash	None	--
3264	W. S. Lee	106	SI	Primary Active Ash Pond	34.60294167	-82.44166667	41	779	19	Combined Ash	None	--
2716	W.H. Weatherspoon Plant	667	SI	Ash Pond	34.59083333	-78.97	54.5	1375	25.2293578	Combined Ash	None	Excluded
1010	Wabash River	462	SI	South Ash Pond	39.51	-87.425	70	1450	20.71428571	Combined Ash	Composite	--
1010	Wabash River	465	SI	Primary Ash Pond Cell A	39.518056	-87.421389	69	1350	19.56521739	Combined Ash	None	--
1010	Wabash River	464	SI	Primary Ash Pond Cell B	39.51805556	-87.42138889	21	530	25.23809524	Combined Ash	None	--
1010	Wabash River	463	SI	Secondary Ash Pond	39.515	-87.42111111	7	73	10.42857143	Combined Ash	None	--
2830	Walter C Beckjord	698	SI	Ash Pond A	38.99916667	-84.29833333	83.2	--	--	Combined Ash	None	Excluded
2830	Walter C Beckjord	697	SI	Ash Pond B	38.99472222	-84.29527778	50	280	5.6	Combined Ash	None	--
2830	Walter C Beckjord	696	SI	Ash Pond C	38.98583333	-84.29416667	45	1400	31.11111111	Combined Ash	None	--
2830	Walter C Beckjord	695	SI	Ash Pond C ext.	38.97777778	-84.29305556	58	1300	22.4137931	Combined Ash	None	Excluded
2830	Walter C Beckjord	1127	LF	Beckjord Ash Landfill	39.003333	-84.281388	126	--	--	Combined Ash	None	Excluded
2830	Walter C Beckjord	1126	LF	Pond Run Ash Disposal	38.995	-84.27916667	99	3595.041322	36.31354871	Combined Ash	Clay	--
1082	Walter Scott Jr. Energy Center	932	LF	Monofill	41.1622	-95.83461111	66.9	5578.512397	83.38583553	Combined Ash	Composite	--
1082	Walter Scott Jr. Energy Center	502	SI	North Surface Impoundment	--	--	171	2046	11.96491228	Combined Ash	None	--
1082	Walter Scott Jr. Energy Center	503	SI	South Surface Impoundment	--	--	133	1326	9.969924812	Combined Ash	None	--
6052	Wansley	35	SI	Ash Pond	--	--	343	16920	49.32944606	Ash & Coal Refuse	None	--
6705	Warrick Power Plant	224	SI	EPRI 9	--	--	140	2789.256198	19.92325856	Ash & Coal Refuse	--	--
3297	Wateree	933	LF	Wateree	33.824072	-80.63195	--	--	--	Combined Ash	Yes	--
3297	Wateree	114	SI	Ash Pond No. 1	33.82061111	-80.62081944	80	1200	15	Combined Ash	None	--
3297	Wateree	113	SI	Ash Pond No. 2	33.81611111	-80.61638889	80	1200	15	Combined Ash	None	--
883	Waukegan	1311	SI	East Ash Pond	42.37888889	-87.81444444	10	110	11	Ash & Coal Refuse	Composite	--
883	Waukegan	1312	SI	West Ash Pond	42.37888889	-87.81444444	10.1	111.1	11	Ash & Coal Refuse	Composite	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
6139	Welsh	177	SI	Primary Ash Pond	33.04975	-94.84635833	98.1	307	3.129459735	Combined Ash	None	--
6139	Welsh	934	LF	Ash landfill	33.04794444	-94.84608333	--	--	--	Combined Ash	None	--
6139	Welsh	175	SI	Active Bottom Ash Storage	33.04425833	-94.84401389	20	270	13.5	Combined Ash	Composite	--
6139	Welsh	176	SI	Secondary Ash Pond	33.04848611	-94.84154444	4.2	37	8.80952381	Combined Ash	None	--
4078	Weston	1318	SI	Tertiary BAT W3&4	44.85388889	-89.65805556	1.04196511	4.784022039	4.59134573	Combined Ash	Clay	--
4078	Weston	936	LF	Weston Onsite Ash Landfill #2879	44.85611111	-89.65611111	--	--	--	Combined Ash	None	Excluded
4078	Weston	1317	SI	South Secondary BAT W3&4	44.85361111	-89.655	2.95748393	14.08613407	4.762877635	Combined Ash	Clay	--
4078	Weston	1316	SI	North Secondary BAT W3&4	44.85444444	-89.655	2.83133609	13.60479798	4.805080554	Combined Ash	Clay	--
4078	Weston	1314	SI	North Primary BAT W3&4	44.85416667	-89.65388889	0.19338843	0.096694215	0.5	Combined Ash	Clay	--
4078	Weston	1315	SI	South Primary BAT W3&4	44.85361111	-89.65361111	0.18728191	0.093640955	0.5	Combined Ash	Clay	--
4078	Weston	1313	SI	W1&2 Seepage Basin	44.86277778	-89.6525	6.51551882	38.99609734	5.985110071	Combined Ash	None	--
4078	Weston	935	LF	Weston Ash - Legner	44.72361111	-89.63694444	18	371.9008265	20.66115703	Combined Ash	Yes	--
60	Whelan Energy Center Unit 1 (WEC1)	1214	SI	Ash Pond	40.578403	-98.313878	22.9568411	183.6547291	8	Combined Ash	Yes	--
6009	White Bluff	1128	LF	Ash Landfill	34.41694444	-92.14888889	--	--	--	Combined Ash	Yes	--
1040	Whitewater Valley	1323	SI	Aux Settling Pond A3	39.804328	-84.896458	0.168	--	--	Combined Ash	None	Excluded
1040	Whitewater Valley	1321	SI	Aux Settling Pond A1	39.803906	-84.896317	0.259	--	--	Combined Ash	None	Excluded
1040	Whitewater Valley	1324	SI	Aux Settling Pond A4	39.803561	-84.896272	0.235	--	--	Combined Ash	None	Excluded
1040	Whitewater Valley	1325	SI	Bottom Ash Sluicing Pond	39.803561	-84.896272	0.18939394	1.147842057	6.060606061	Combined Ash	None	--
1040	Whitewater Valley	1322	SI	Aux Settling Pond A2	39.804125	-84.896206	0.17	--	--	Combined Ash	None	Excluded
4057	WI Power & Light Co -Rock River Generating	2	SI	Slag Pond	42.577814	-89.031436	3	29	9.666666667	Combined Ash	--	--
4057	WI Power & Light Co -Rock River Generating	3	SI	WPDES Pond 2	42.576967	-89.03059	1	14	14	Combined Ash	--	--
4057	WI Power & Light Co -Rock River Generating	1	SI	WPDES Pond 1	42.577944	-89.030346	2	17	8.5	Combined Ash	--	--
4057	WI Power & Light Co -Rock River Generating	172	SI	Final WPDES Pond	42.580952	-89.030247	4	29	7.25	Combined Ash	--	--
50	Widows Creek	59	SI	Bottom Ash Stack	--	--	32	--	--	Combined Ash	None	--
50	Widows Creek	60	SI	Dredge Cell	--	--	116	--	--	Combined Ash	None	--
50	Widows Creek	61	SI	Gypsum Stack Pond 1	--	--	10	--	--	FGD Waste	None	--
50	Widows Creek	62	SI	Gypsum Stack Pond 2A	--	--	12	--	--	FGD Waste	None	--
50	Widows Creek	63	SI	Gypsum Stack Pond 2B	--	--	14	--	--	FGD Waste	None	--
50	Widows Creek	64	SI	Gypsum Stack Pond 3	--	--	59	--	--	FGD Waste	None	--
50	Widows Creek	65	SI	Gypsum Stack Stilling Pond	--	--	9	--	--	FGD Waste	None	--
50	Widows Creek	66	SI	Pump Pond	--	--	0.25	--	--	FGD Waste	None	--
50	Widows Creek	261	SI	Ash Pond	--	--	156	11709	75.05769231	Combined Ash	--	--
50	Widows Creek	262	SI	Gypsum Stack (Wet Stacking Area)	--	--	110	10961	99.64545455	Combined Ash	--	--

Attachment A-2. WMU Information

Oris Code	Plant Name	WMU ID	WMU Type	Unit Name	Latitude	Longitude	WMU Area (acres)	WMU Capacity (acre-ft)	WMU Depth (ft)	WMU Waste Type	WMU Liner Type	Shown in Results?
50	Widows Creek	289	SI	Red Water Pond	--	--	32	--	--	Combined Ash	None	--
50	Widows Creek	290	SI	Upper/Lower Stilling Pond	--	--	8	--	--	FGD Waste	None	--
884	Will County	389	SI	EPRI 3	--	--	--	--	--	--	--	Excluded
3298	Williams	1130	LF	Hwy 17A	33.14988889	-80.05594444	--	--	--	Combined Ash	Yes	--
3298	Williams	1129	LF	Hwy 52	33.11430556	-80.04661111	--	--	--	Combined Ash	Yes	--
3946	Willow Island	917	LF	-999	--	--	--	--	--	Combined Ash	Yes	--
6249	Winyah	199	SI	West Ash Pond	33.33189167	-79.37042778	62	1178	19	Combined Ash	None	--
6249	Winyah	198	SI	Unit 3 & 4 Slurry Pond	33.33744722	-79.36841111	100	1700	17	FGD Waste	None	--
6249	Winyah	200	SI	South Ash Pond	33.32435278	-79.35452222	61	1129	18.50819672	Combined Ash	None	--
6249	Winyah	202	SI	Ash Pond B	33.31872222	-79.35136111	63	537	8.523809524	Combined Ash	None	--
6249	Winyah	203	SI	Unit 2 Slurry Pond	33.33065	-79.35086667	34	416	12.23529412	FGD Waste	None	--
6249	Winyah	201	SI	Ash Pond A	33.325525	-79.34736111	88	807	9.170454545	Combined Ash	None	--
6249	Winyah	982	LF	--	--	--	--	--	--	Combined Ash	--	--
898	Wood River	398	SI	West Ash Pond (2 cells) Cells 2E and 3	38.86955278	-90.14046111	19	210	11.05263158	Combined Ash	Clay	--
898	Wood River	397	SI	East Ash Pond (2 cells)	38.86821944	-90.13142778	38	435	11.44736842	Combined Ash	Composite	--
50611	WPS Westwood Generation, LLC	951	LF	Closed Ash Landfill	40.62305556	-76.45194444	--	--	--	Combined Ash	Yes	Excluded
6101	Wyodak Plant	80	SI	Wyodak	44.28888889	-105.3911111	15.5	320	20.64516129	Combined Ash	None	--
6101	Wyodak Plant	981	LF	--	--	--	68	2169.421489	31.90325718	Combined Ash	--	--
728	Yates	987	LF	Gypsum Solid Waste Facility	33.46638889	-84.9	--	--	--	Combined Ash	Yes	--
728	Yates	986	LF	R-6 Ash Monofill	33.453585	-84.895905	--	--	--	Combined Ash	None	--
728	Yates	367	SI	Ash Pond 3	--	--	69	434	6.289855072	Combined Ash	None	--
728	Yates	368	SI	Pond B	--	--	6	--	--	Combined Ash	None	Excluded
728	Yates	369	SI	Ash Pond 1	--	--	17	184	10.82352941	Combined Ash	None	--
728	Yates	370	SI	Ash Pond 2	--	--	50	1103	22.06	Combined Ash	None	--
728	Yates	371	SI	B' Pond	--	--	30	298	9.933333333	Combined Ash	None	--
728	Yates	372	SI	Gypsum Solid Waste Facility	--	--	16	135	8.4375	FGD Waste	Composite	--
728	Yates	373	SI	Pond A	--	--	19	--	--	Combined Ash	None	Excluded
728	Yates	374	SI	Pond C	--	--	12	--	--	Combined Ash	None	Excluded
3809	Yorktown	1359	SI	Finger Ponds	37.21638889	-76.45777778	4.775	--	--	Combined Ash	Yes	Excluded
3809	Yorktown	988	LF	Ash Landfill	37.215975	-76.442493	48	991.7355372	20.66115702	Combined Ash	Clay	--

Appendix B.

Environmental Parameter Data

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B.1 Introduction

The U.S. Environmental Protection Agency (EPA or the Agency) used the facility and waste management unit (WMU) locations discussed in **Appendix A** to identify site-specific data on soil type, hydrogeologic environment, climate and nearby surface water bodies. Where possible, environmental data were collected using geographic information system (GIS) software to associate geographic coordinates for each WMU to site-specific and region-specific data. However, because uncertainty remained about the precise location for some units, EPA pulled data from a two-kilometer radius around the facility centroid to effectively capture local variability. Regional data were collected by assigning each facility to the nearest reference point in national databases, such as the Hydrologic Evaluation of Landfill Performance (HELP) model climate stations and the U.S. Geological Survey (USGS) hydrological regions. Whenever environmental parameters could not be linked based on location, EPA relied on national distributions.

Information about the methods used to collected and analyze these data is provided below. **Attachment B-1** provides the specific soil texture, pH and organic carbon content associated with each facility. **Attachment B-2** provides hydrogeologic environments. **Attachment B-3** provides climate center, precipitation rate and infiltration rate. **Attachment B-4** provides USGS Hydrologic Region; distance to nearest water body; and water body mean recharge, area, length, mean annual flow and mean annual velocity.

B.2 Soil Data

The ground water model used in the revised risk assessment, EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP), requires the properties of the entire soil column to model leachate transport through both the unsaturated (vadose) and saturated (ground water table) zones. Soil data were collected using either the reported WMU location and footprint or, where WMU locations were not available, a two-kilometer radius around each facility centroid.

B.2.1 Data Sources

The primary data source for soil properties was the State Soil Geographic (STATSGO) database. STATSGO is a repository of nationwide soil properties compiled primarily by the U.S. Department of Agriculture (USDA) from county soil survey data (USDA, 1994). STATSGO includes 1:250,000-scale GIS coverage that delineates the conterminous United States into map units and an associated database that contains soil data for each map unit. The map units that overlap with either the WMU footprint or two-kilometer radius surrounding a facility, as appropriate, were used to spatially represent soils in the database. USSOILS (Schwarz and Alexander, 1995) and Conterminous United States Multilayer Soil Characteristics (CONUS-SOIL) (Miller and White, 1998) are simplified compilations of STATSGO data which were used to collect soil properties.

- **USSOILS.** The USSOILS data set averages STATSGO data vertically over the entire soil column for each map unit (Schwarz and Alexander, 1995). USSOILS aggregates the STATSGO layer and component information up to the level of a map unit by depth-

averaging median properties within a component over the entire soil column and then area-averaging component values across a map unit.[1]

- **CONUS-SOIL.** The CONUS-SOIL soil data set was compiled by the Earth System Science Center in the College of Earth and Mineral Sciences at Pennsylvania State University (Miller and White, 1998). CONUS contains STATSGO soil properties averaged to 11 standard layer depths from the STATSGO layers to a total depth of 2.5 m. Within each STATSGO map unit and CONUS standard layer, soil properties either represent the predominant property (as with soil texture) or are area-weighted averages of STATSGO component values.[2]

B.2.2 Methodology

EPA first collected soil pH and organic matter data from USSOILS and soil texture data from CONUS-SOIL for each map unit. Soil texture data were used to provide nationally correlated bulk density, saturated water content, saturated hydraulic conductivity, and the van Genuchten soil moisture retention parameters (alpha and beta) based on Carsel and Parrish (1988) and Carsel et al. (1988). GIS software was then used to overlay the WMU footprint or the two-kilometer radius onto the STATSGO map to determine which STATSGO map units fell within these boundaries. Using these overlays, EPA calculated the percent of that bounded area that fell within each map unit. These percentages were used to allow probabilistic sampling of the soil texture, pH, and organic matter data for each WMU.

Table B-1. Soil Texture Crosswalk

STATSGO SCS Soil Texture	EPACMTP Soil Megatexture
Sand	Sandy Loam
Loamy Sand	
Sandy Loam	
Silt Loam	Silt Loam
Silt	
Loam	
Sandy Clay Loam	
Clay Loam	
Silty Clay Loam	Silty Clay Loam
Sandy Clay	
Silty Clay	
Clay	

SCS = Soil Conservation Service

Table B-1 shows the crosswalk that was used to assign the SCS textures to the EPACMTP megatextures. Soil data used for modeling is presented in **Attachment B-1**. STATSGO soils are classified into 12 Soil Conservation Service (SCS) soil textures, but EPACMTP uses three soil megatextures to represent the variability of hydrologic soil properties. Therefore, each STATSGO soil texture was crosswalked in a database to the EPACMTP megatexture with the most similar hydrogeologic properties. When merging these soil texture entries, EPA aggregated the percentages of map units that fell within the same megatexture and averaged both the pH and organic matter proportionally.

[1] Metadata on USSOILS are available online at: water.usgs.gov/GIS/metadata/usgswrd/XML/ussoils.xml

[2] Additional information on CONUS is available online at: www.soilinfo.psu.edu/index.cgi?soil_data&conus

B.3 Hydrogeologic Environment Data

Each facility modeled in this analysis was assigned one or more hydrogeologic environment(s) from EPA's Hydrogeologic Database (HGDB) in order to characterize four subsurface parameters required by EPACMTP: depth to ground water, aquifer thickness, hydraulic gradient, and saturated hydraulic conductivity. The HGDB was developed by the American Petroleum Institute (Newell et al., 1989; 1990) to specify correlated empirical probability distributions of these four parameters for the 12 distinct hydrogeologic environments described in Newell et al. (1990). To assign the HGDB distributions to the CCR WMUs modeled in this assessment, EPA first developed a national geographic coverage of the 12 hydrogeologic environments, and then used GIS software to overlay the CCR WMU locations and dimensions, and assign the hydrogeologic environments to each WMU.

B.3.1 Data Sources

EPACMTP uses the HGDB for national and regional analyses. Therefore, it was necessary to assign each facility to one or more hydrogeologic environments corresponding to the HGDB data set. Given the national scale of the risk assessment, only national data sets were used to delineate hydrogeologic environments, defined by an approximate 1:7,500,000 map scale. The following individual map layers were combined using GIS software to develop a single map layer for assigning the 12 hydrogeologic environments across the United States:

- **Shallowest principal aquifers** from *Principal Aquifers of the Conterminous United States, Hawaii, Puerto Rico, and the U.S. Virgin Islands* [USGS map file: aquifrp025]. 1:2,500,000 map scale, was used as the base layer in the assessment and to delineate several of the 12 hydrogeologic environments.
- **Alluvial and glacial aquifers** from *Aquifers of Alluvial and Glacial Origin* [USGS map file: alvaqfp025]. 1:2,500,000 map scale, was used to represent alluvial and glacial aquifers for the 22 states north of the southernmost line of glaciation. Note that the alluvial aquifers in this coverage are identical to those in the Hunt (1979) surficial geology layer below.
- **Surficial geology** of the conterminous United States was taken from:
  - *Surficial Geology of the Conterminous United States* [map file: geol75m]. 1:7,500,000 map scale, provided by Hunt (1979), these data was used to characterize shallow soil lithology and alluvial aquifers.
  - *The Surficial Deposits and Materials in the Eastern and Central United States (East of 102 degrees West Longitude)* [map file: sfgeoep020]. 1:1,000,00 map scale, includes the line of maximum glacial advance and represents surficial materials that have accumulated or formed during the past two million years, including residual soils, alluvium, and glacial deposits.
- **Karst aquifers** from *Engineering Aspects of Karst* [map file: karst0p075], 1:7,500,000-map scale, showing karst and pseudokarst (i.e., karst-like terrain produced by processes other than the dissolution of rocks) across the United States.

- **Bedrock geology** from *Generalized Geologic Map of the United States* [map file: geolgyp075], 1:7,500,00 map scale, showing the bedrock geology at or near land surface (i.e., beneath surficial soils, alluvium and glacial deposits).
- **STATSGO soils,** 1:250,000 map scale, from the digital map and attribute data for soils described in **Section B.2**.

As described below, these data layers were used to develop a national GIS hydrogeologic environment layer for assigning an aquifer type to a point or area of interest.

B.3.2 Methodology

To create the hydrogeologic environment layer, each individual data layer described above was obtained as a GIS shapefile and processed as needed to ensure that coordinate systems matched and the layers could be overlain. **Table B-2** describes how the polygons comprising the 12 hydrogeologic environments were developed in the GIS using these layers.

Table B-2. GIS Procedures for Assembling National Coverage of Hydrogeologic Environments [map file name in square brackets].

Hydrogeologic Environment		Description
1)	Metamorphic and igneous rock	Select polygons where ROCK_NAME = "igneous and metamorphic-rock aquifers" from the principal aquifer layer [aquifrp025] AND "igneous" or "metamorphic" polygons from the bedrock geology layer [geolgyp075] AND polygons from the Hunt (1979) surficial geology layer [geol75m] derived from or directly overlaying igneous or metamorphic rock.
2)	Bedded sedimentary rock	Select polygons where the ROCK_NAME = "sandstone and carbonate-rock aquifers" OR AQ_NAME was "Other rocks" from the principal aquifer layer [aquifrp025] AND "sedimentary" polygons from the bedrock geology layer [geolgyp075].
3)	Till over sedimentary rock	Select polygons that had a surficial geology [geol75m] = "mg: deposits of mountain glaciers", "tg: till or ground moraine" "ts: ice-laid deposits, like tg but mostly sand and silt", OR "ts/K,T: thin ice-laid deposits, like ts but thin and discontinuous. . ..", AND overlaying "sedimentary" polygons from the bedrock geology layer [geolgyp075].
4)	Sand and gravel	Select polygons where AQ_NAME = "other rocks" OR "high plains aquifer" from the principal aquifer layer [aquifrp025] AND sand and gravel related names in SURFICIALG from the Hunt (1979) surficial geology layer [geol75m] (SURFICIALG contained many different types of sand and gravel deposits).
5)	Alluvial valleys, basins and fans	Select polygons where AQ_NAME = "Unconsolidated sand and gravel aquifers" from the principal aquifer layer [aquifrp025] name OR surficial geology type (SURFICIALG) was either "fg: fan gravels" or "fs: fan sands" in the Hunt (1979) surficial geology layer [geol75m].

(continued)

Table B-2. GIS Procedures for Assembling National Coverage of Hydrogeologic Environments [map file name in square brackets].

Hydrogeologic Environment		Description
6)	River valleys and floodplains with overbank deposits	Select polygons where SURFICIALG = "al: floodplain and alluvium gravel terraces" in Hunt (1979) surficial geology layer [geol75m] AND STATSGO soils with < 50% sand AND a low permeability (< 0.0147 inches per hour).
7)	River valleys and floodplains without overbank deposits	Select polygons where SURFICIALG = "al: floodplain and alluvium gravel terraces" in Hunt (1979) surficial geology layer [geol75m] AND STATSGO soils that do NOT have < 50% sand AND a low permeability (< 0.0147 inches per hour).
8)	Outwash	Select polygons where ORIGIN_AGE = "glaciofluvial (outwash) deposits" in the Surficial Deposits and Materials layer [sfgeomean020] AND where SURFICIALG = anything but "ts: ice-laid deposits, like tg but mostly sand and silt" in the Hunt (1979) surficial geology layer [geol75m].
9)	Till and till over outwash	Select polygons from Hunt (1979) surficial geology layer [geol75,] that were not already classified hydrogeologic environment 8 AND where SURFICIALG = "w: gravel, sand and clay deposited by glacial streams adjacent to or downstream from temporary ice fronts" OR "ts: ice-laid deposits, like tg but mostly sand and silt" OR "tg: till, or ground moraine".
10)	Unconsolidated and semi-consolidated shallow aquifers	Select polygons where AQ_NAME = "coastal lowlands aquifer system," "Mississippi embayment aquifer system," "Northern Atlantic Coastal Plain aquifer system," "Southeast Coastal Plain aquifer system," "Texas coastal uplands aquifer system," or "surficial aquifer system." from the principal aquifers layer [aquifrp025].
11)	Coastal beach	Select polygons where SURFICIALG = "si: sea islands" from the Hunt (1979) surficial geology layer [geol75m].
12)	Solution limestone	Select polygons where ROCK_NAME contains "carbonate-rock aquifers," "sandstone and carbonate-rock aquifers", "unconsolidated sand and gravel aquifers," OR "sandstone aquifers" from the principal aquifer layer [aquifrp025] AND, for the last two only, are defined as areas of karst in the Engineering Aspects of Karst layer [karst0p075]

B.3.3 Data Processing

One or more of the 12 hydrogeological environments was assigned to each WMU footprint or two-kilometer region surrounding a facility, as appropriate, and the percentages of each assigned environment within the data collection area was determined and included with the assignments. When there was more than one environment assigned to a WMU (in cases where the assignment or location was uncertain), the hydrogeological environment was varied probabilistically based on these percentages during each Monte Carlo iteration for a particular WMU. **Table B-3** summarizes these assignments, showing the number of CCR facilities, surface impoundments and landfills for each hydrogeologic environment sent to EPACMTP.

Table B-3. Number of Facilities and WMUs in Each Hydrogeologic Environment

Hydrogeologic Environment		Facilities (2-km radius)	Impoundments (Boundary)	Landfills (Boundary)
1)	Metamorphic and igneous	20	46	19
2)	Bedded sedimentary rock	85	198	93
3)	Till over sedimentary rock	18	48	28
4)	Sand and gravel	47	94	43
5)	Alluvial basins valleys and fans	7	27	5
6)	River valleys and floodplains with overbank deposits	141	335	86
7)	River valleys and floodplains without overbank deposits	119	259	70
8)	Outwash	17	44	16
9)	Till and till over outwash	16	31	13
10)	Unconsolidated and semi-consolidated shallow aquifers	43	100	64
11)	Coastal beaches	2	0	4
12)	Solution limestone	42	92	34

Once the hydrogeologic environments were assigned, a preprocessing run of EPACMTP was conducted to construct a set of randomly generated but correlated hydrogeologic parameter values (i.e., depth to ground water, aquifer thickness, hydraulic gradient, and saturated hydraulic conductivity) for each occurrence of the hydrogeologic environments in the source data files. Missing values in the HGDB data set were filled using correlations during EPACMTP execution, as described in U.S. EPA (1997).

B.4 Climate Data

EPACMTP uses the climate station, along with soil texture, to select both the HELP-modeled infiltration rates in the landfill source model and the recharge rates to use in EPACMTP. Thus, the CCR risk assessment selected HELP meteorological (or climate) stations for each CCR disposal site to collect the climatic data necessary for fate and transport modeling.

To assign the EPACMTP/HELP climate centers to each facility, GIS software was used to determine the three climate centers closest to the facility and to get the long-term (1961–1990) annual average precipitation rate at each facility from a USGS coverage for the contiguous U.S.

(www.nationalatlas.gov; **Figure B-1**). The long-term average precipitation for each of the three closest EPACMTP climate centers was then compared with the precipitation for each facility location to select the climate station with the closest precipitation to the facility. **Attachment B-3** lists the climate center assigned to each CCR disposal facility along with the five-year average precipitation and HELP soil-specific infiltration/recharge rates for each station.

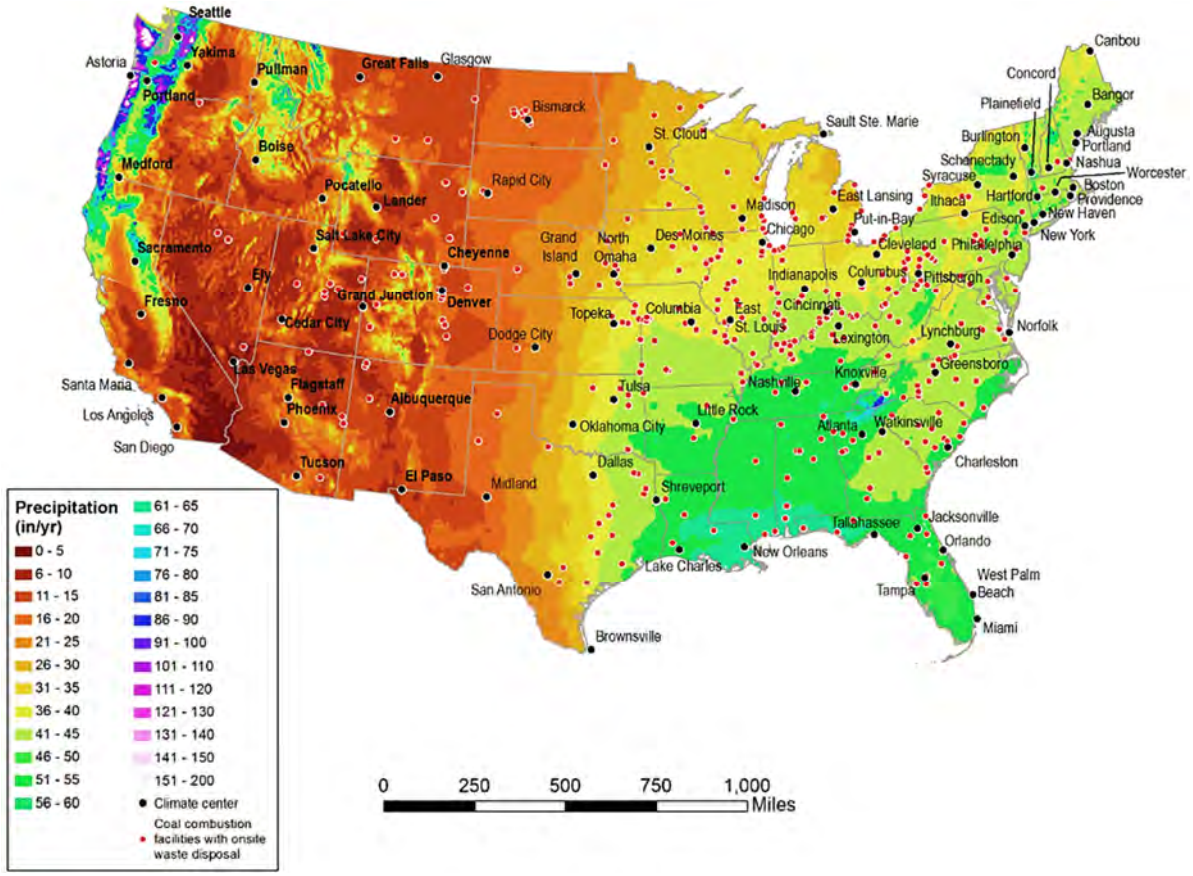

Figure B-1. EPACMTP climate centers, precipitation ranges and CCR disposal facilities.

B.5 Surface Water Data

The surface water model used in the revised risk assessment requires information on the water body type (stream or lake), flow conditions, dimensions and water quality for each surface water body. Data were collected on a site-based, regional or national basis depending on the specific parameter and data availability. Collection methods are discussed in the following subsections.

B.5.1 Data Sources

Data on surface water body characteristics and distances was necessary to calculate the fraction of the ground water plume intercepted by surface water bodies, as well as the resulting constituent concentrations in the surface water. Water body data were collected based on WMU location data, and consisted of the following sources:

- **NHDplus.** NHDplus is a geospatial, hydrologic framework data set that integrates the features of the National Hydrography Dataset (NHD), the Watershed Boundary Dataset (WBD), and the National Elevation Dataset (NED).[3] The NHD represents the drainage network with features such as rivers, streams, canals, lakes, ponds, coastline, dams and stream gauges. The WBD represents drainage basins as enclosed areas in eight different size categories. Both these data sets represent surface waters at a nominal scale of 1:24,000, and use an integer value as a common identifier (COMID) that uniquely identifies the occurrence of each NHD feature. The NED provides basic elevation information for earth science studies and mapping applications in the United States.
- **STORET.** The STORET (STOrage and RETrieval) Data Warehouse is EPA's repository of the water quality monitoring data including total suspended solids (TSS), surface water temperatures, and surface water pH. These data were collected by water resource management groups across the country including states, tribes, watershed groups, other federal agencies, volunteer groups and universities.[4]

B.5.2 Selection of Nearest Water Body

Prior to collecting data on surface water bodies, EPA identified the nearest water bodies and associated ComIDs for each WMU. This was done for the purpose of evaluating ground water flow direction for discharge into a surface water body. EPA notes that topography often controls general shallow ground water flow. Thus, EPA used surface topography as a proxy for the direction of ground water flow in the shallow aquifers modeled in the revised risk assessment. The NHD*Plus* Flow Direction Grid (U.S. EPA and USGS, 2007) provided the foundation for evaluating the probable topographical course of overland runoff. EPA utilized an application of this grid, known as the "Raindrop Tool," to trace the downhill path a hypothetical raindrop is likely to follow as it flows overland until it intersects with the nearest surface water body, as defined by NHD features.[5]

This tool is useful for evaluating the path of a raindrop from a single point. However, WMUs were often large enough that different points within a given WMU may result in runoff to different surface water bodies. Thus, water bodies and ComIDs were identified in the following steps:

- The area of the WMU was idealized as a circle centered at the WMU longitude/latitude.
- Eight points were placed around the circumference of each WMU at equally spaced angles of 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°.
- For each of the eight points, the Raindrop Tool selected the surface water body/ComID pair to which the runoff discharged. Each of the eight starting points were assigned an equal probability of occurrence.

[3] Further detail on NHDPlus is available online at: www.horizon-systems.com/nhdplus/

[4] Additional information on STORET is available online at: www.epa.gov/storet/

[5] Further discussion is available online at: www.epa.gov/waters/doc/rad/raindrop.html

- Where multiple points discharged to the same water body/ComID pair, the probabilities for that pair were aggregated.

For each surface water body/ComID pair identified, EPA collected the waterbody type, mean recharge rate, area, length, mean annual flow, and mean annual velocity from the NHDPlus.

Example results of this process are illustrated in **Figure B-2**. The dashed red lines represent the modeled raindrop pathlines, while the straight black lines represent the corresponding shortest straight-line distances from the WMUs to the surface water body. In cases where the projected rain drop flow path overlapped with the WMU footprint, an adjusted distance from where the straight-line distance exited the WMU footprint to the surface water body was used. In cases where the surface water body overlapped with the interior WMU footprint as a result of the idealized boundary, the distance from the water body to the WMU boundary was taken as representative. EPA notes that, since the actual boundary of the WMU already falls so close to the surface water body, the short distances resulting from this approach are believed to be representative. In addition to flow lines, the NHDPlus maintains a data set of polygons that represent larger water bodies, such as lakes and wide rivers. In some cases, the NHDPlus flow lines are located within the middle of the water body, while the polygon outlines the perimeter of the water body. In these cases, the distances to the NHDPlus polygons were used.

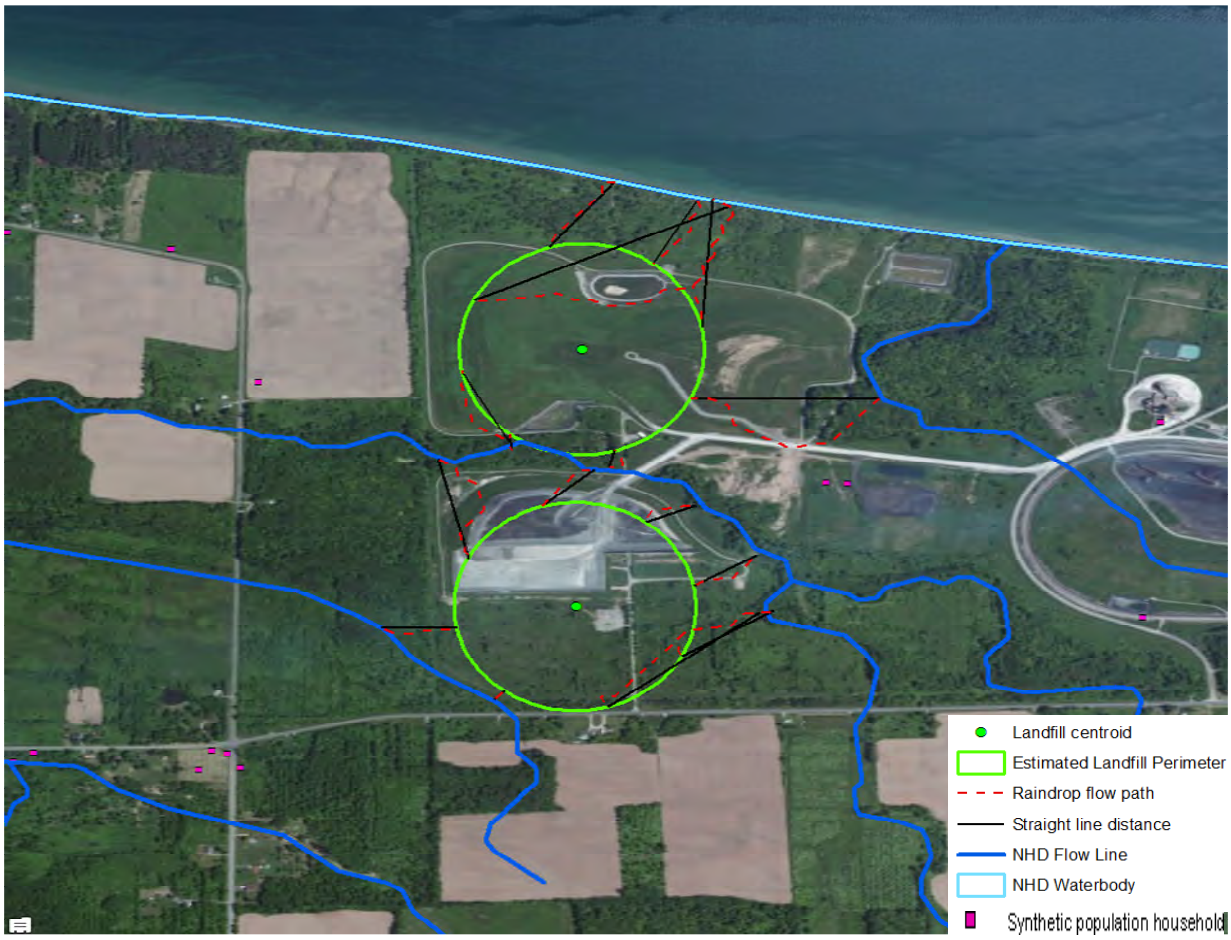

Figure B-2. Examples of surface water body identification results.

Some WMUs did not have location data to permit identification of the nearest water bodies. These units were probabilistically assigned distances and water bodies during the Monte Carlo analysis based on the distributions developed from data available for other impoundments or landfills. The resulting probability distributions are shown in **Figure B-3**. To minimize the potential for outliers at small distances to be selected for facilities without location data, minimum values were set at the first percentile for both surface impoundments (9.3 m) and landfills (19 m).

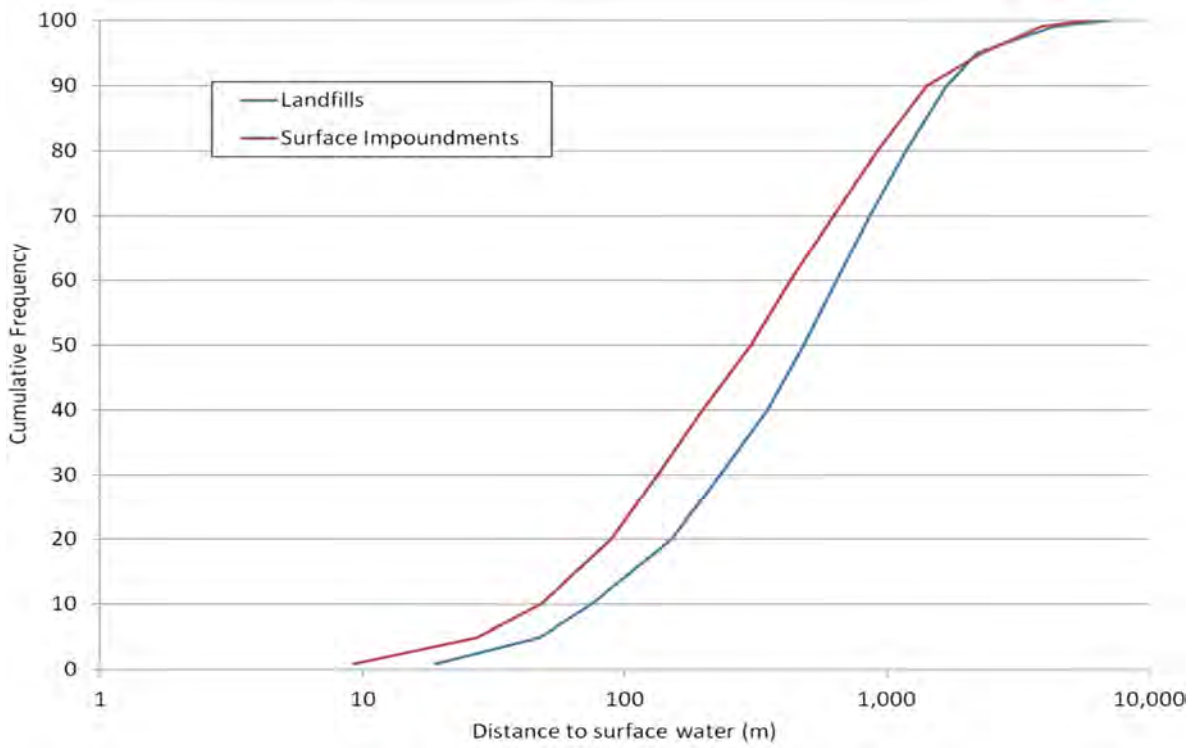

Figure B-3. Cumulative probability distributions for distance to surface water bodies.

B.5.3 Water Body Type

While there are several water body types in NHDplus, EPA only identified surface water models for streams and lakes. Thus, each of the NHDplus water body types needed to be designated as either a stream or a lake. Streams and rivers were designated as streams due to their measurable flow rates, while all other types were designated as lakes due to their negligible flow rates. **Table B-4** lists the NHDplus water body types identified near CCR WMUs and facilities, along with a crosswalk to the stream or lake designation assigned to that type.

Table B-4. NHDplus Water Body Types Assigned to CCR Disposal Facilities

NHDplus Water Body Type	Reach Model Type	Number of CCR Facilities	Surface Impoundments	Landfills
Connector	Stream	3	4	2
CanalDitch		11	11	6
ArtificialPath		173	372	148
Stream/River		264	540	416
Reservoir	Lake	3	2	2
Playa		2	11	0
Coastline		24	51	15
Lake/Pond		82	183	79

Stream Flow Conditions and Dimensions

NHDplus includes estimates of the mean annual stream flow rates for all flowing reaches, as well as the velocities that correspond to these mean flows. Stream dimensions were calculated from the NHDplus flow data as follows. First, the length of the modeled stream segment was set equal to the width of the ground water plume as it enters the water body, which was determined by EPACMTP. The stream width was then derived from the flow rate using an equation derived from empirical data by Kocher and Sartor (1997):

(B-1) $$W = 5.1867Q^{0.4559}$$

Where:

W = Stream width (L); and

Q = Mean annual stream flow rate (L^3/T)

The water column depth was then derived using the continuity equation, which assumes that a stream's flow rate is equal to the product of its cross-sectional area occupied by flow and mean flow velocity:

(B-2) $$Q = Av$$

Where:

A = Cross-sectional area occupied by flow (L^2); and

v = Mean annual stream flow velocity (L/T)

Rearranging and solving for water column depth (with dwc = A/W):

(B-3) $$dwc = \frac{Q}{vW}$$

Where:

dwc = Water column depth (L)

Lake Flow Conditions and Dimensions

Exact areas and depths were not readily available for many of the lakes located near facilities from either NHDplus or other sources. In addition, some facilities were located on very large water bodies (e.g., the Great Lakes) where applying the simple steady-state, single-compartment model used in this analysis to the entire water body would not be appropriate because contamination would be localized to a specific portion of that water body. Thus, a single, small lake (or model lake) was used to represent all lake water body types assigned to the CCR disposal facility. This was considered appropriate because it captures the impact of localized effects through a conservative approximation of much larger lakes. The model lake chosen was Shipman City Lake in Illinois, which is a well characterized 13-acre lake previously selected by EPA as the index reservoir for modeling drinking water exposures to pesticides (Jones et al., 1998). The parameter values for Shipman City Lake are shown in **Equation B-4**.

(B-4) $$V = \frac{A(dwc)}{HRT}$$

where:

V = Annual flow mixing volume (L3/T);
A = Area (13 acres);
dwc = Water column depth (9 ft); and
HRT = Hydraulic residence time [1 month (min), 6 months (mean), 24 months (max)].

B.5.4 Stream and Lake Water Quality Data

EPA's STORET system is the largest single source of water quality data in the country, containing over 275 million analyses performed on more than 45 million samples collected from 800,000 stations across the United States between the years of 1960 and 1998. Data on raw surface water temperature, TSS and pH were collected from the legacy STORET database based on the assigned USGS hydrologic region for use in the surface water model. However, the STORET website states:

> *"The EPA does not change or filter incoming data. This means that when pulling data out of the Warehouse, users must be aware that they are responsible for screening the data for their use."*[6]

EPA notes that there is a high degree of variability in the data due to differences in quality assurance/quality control testing , bias towards samples collected at site locations known to have contamination problems, and bias towards samples collected during critical periods (e.g., summer low flows). To account for these factors, EPA used the STORET data as discussed below.

Surface Water Temperature

Median surface water temperatures were collected for each hydrologic region and assigned to each facility centroid using GIS. Median values were selected in order to capture an appropriate annualized value while minimizing the impact of variability. These temperatures are provided for

[6] Available online at: www.epa.gov/storet/about.html

each hydrologic region in **Table B-5**, as well as the number of modeled facilities and WMUs assigned to each region.

Table B-5. Regional Surface Water Temperatures: CCR Disposal Facilities

Hydrologic Region	Median Surface Water Temperature (°C)	Number of CCR Facilities	Number of CCR Surface Impoundments	Number of CCR Landfills
1	14	5	19	8
2	16	25	36	32
3	21	60	130	51
4	14	36	71	40
5	17	81	244	87
6	18	8	29	7
7	15	51	119	38
8	20	5	13	4
9	10	1	0	7
10	13	49	118	78
11	17	22	50	21
12	21	15	56	30
13	16	1	5	1
14	9	14	31	18
15	17	5	22	5
16	9	3	6	2
17	11[a]	2	3	2

Data source: Legacy STORET database.

[a] Legacy STORET data were not available for Hydrologic Region 17 at the time of this CCR data collection effort. A median temperature of 11 was assigned to be representative of the cooler surface water temperatures anticipated in the mountainous Pacific northwest region.

Total Suspended Solids

Median annual TSS values were collected for each hydrologic region and assigned to each facility centroid using GIS. Medians were selected in order to capture an appropriate annualized value while minimizing the impact of variability. Data were collected separately for streams and lakes because the latter grouping tends to have lower TSS levels as a result of reduced sediment disturbance from moving water.

Minimum, maximum and weighted geometric means of these collected values were used to define log triangular distributions regionally for streams, but only nationally for lakes due to more limited data. The triangular distribution was selected because it is typically used to describe a population for which there is only limited sample data, but there is sufficient knowledge to determine that the

distribution is modal, rather than uniform, as was the case here. Geometric means weighted by the annual number of measurements were used because the actual distribution around the median is unknown. Once developed, these distributions were sampled during the preparation of the input data files. **Table B-6** provides the TSS values used to define the distribution for each region, along with the number of the modeled facilities assigned to that region.

Table B-6. Surface Water Total Suspended Solids (TSS) Distributions

Hydrologic Region	Number of CCR Facilities	Number of Samples	Number of Annual Median Values	Annual Median TSS (log-triangular distribution)		
				Minimum	Maximum	Weighted Geometric Mean
1	5	9,007	33	3.2	40	8
2	25	47,202	38	10	316	32
3	54	43,395	36	6.3	79	25
4	21	29,577	37	6.3	794	25
5	77	39,900	38	4	100	25
6	5	4,137	28	5	316	16
7	49	34,494	37	32	1,585	63
8	4	46,231	38	50	316	158
9	1	3,254	35	13	3,162	32
10	49	62,791	38	10	398	126
11	21	48,969	38	25	794	200
12	12	7,280	35	40	1,995	79
13	1	13,974	37	32	79,433	200
14	13	26,699	38	16	5,012	158
15	4	9,162	37	20	19,953	200
16	3	19,965	33	4	2,512	16
17	2	173,136	37	2	316	6
Lakes	109	4,360	99	1	398	25

Data source: Legacy STORET database.

Note: Because both lakes and streams can be modeled for the same facility, the total count of facilities in this table exceeds 383.

Surface Water pH

Median annual pH values were collected for each hydrologic region and assigned to each facility centroid using GIS. Median values were selected in order to capture an appropriate annualized value while minimizing the impact of variability. Because pH data are already log scale, the minimum, maximum and weighted averages of these collected values were used to define triangular distributions for each hydrologic region. The triangular distribution was selected

because it is typically used to describe a population for which there is only limited sample data, but there is sufficient knowledge to determine that the distribution is modal, rather than uniform, as was the case here. Once developed, these distributions were sampled during the preparation of the input data files. **Table B-7** provides the pH values used to define the distribution for each region, along with the number of the modeled facilities assigned to that region.

Table B-7. Regional Surface Water pH Distributions

Hydrologic Region	Number of CCR Facilities	Number of Samples	Number of Annual Median Values	Annual Median pH (triangular distribution)		
				Minimum	Maximum	Weighted Average
1	5	232,025	38	5.9	7.7	6.5
2	25	447,166	39	7.2	7.6	7.4
3	60	1,595,237	39	6.3	7.2	7.0
4	36	335,261	39	7.6	8.2	8.1
5	81	684,235	41	3.5	7.5	7.2
6	8	382,915	39	6.3	7.7	7.2
7	51	234,589	39	7.6	8.1	7.9
8	5	171,643	39	6.9	7.8	7.1
9	1	23,038	38	7.5	8.4	7.9
10	49	269,570	39	7.6	8.2	8.0
11	22	311,768	39	7.4	8.1	7.8
12	15	178,990	39	7.0	7.9	7.8
13	1	35,355	39	7.0	8.1	8.0
14	14	77,041	39	7.9	8.3	8.1
15	5	75,145	38	7.7	8.3	8.0
16	3	68,581	38	7.5	8.3	8.0
17	2	293,909	39	6.9	8.0	7.5

Data source: Legacy STORET database

B.6 National Drinking Water Well Distribution

Residents that use ground water from private wells as a source of potable water may be exposed to COPCs through the GW→DW pathway. Therefore, the location of these wells relative to the surface impoundments and landfills is an important parameter for the risk assessment. Since the human population is not evenly distributed across the landscape, EPA used synthetic population data to place each household and its occupants as discrete points. Synthetic populations are a

representation of households and individual residents in a given area based on methods to identify realistic locations.

Synthesized households and residents are placed to match the population distribution estimated by the LandScan USA 90-meter gridded population data set (Bhaduri, 2007), which distributes the U.S. population across a grid of 90-meter square cells using a combination of satellite imagery and other geographic data layers, including 2000 Census boundaries. The placement of synthesized households is constrained to match the population within a given 2000 Census block. Once a set of households is selected for a particular 90-meter grid cell, they are placed randomly within that 90-meter area. As a result, LandScan USA provides estimates of household locations at a finer resolution than is available from the 2000 Census data alone.

Figure B-4 provides an example CCR landfill and the corresponding synthetic household placement. The WMU centroid and estimated perimeter are shown, as well as a series of dashed-line buffers spaced at 0.2-mile (~ 300 meters) intervals from the WMU perimeter up to one mile away for an idea of scale. Synthetic population households are shown primarily along roadways. Although the household locations do not necessarily coincide with actual house locations, their locations are representative of typical dwelling location distributions as can be seen in the figure.

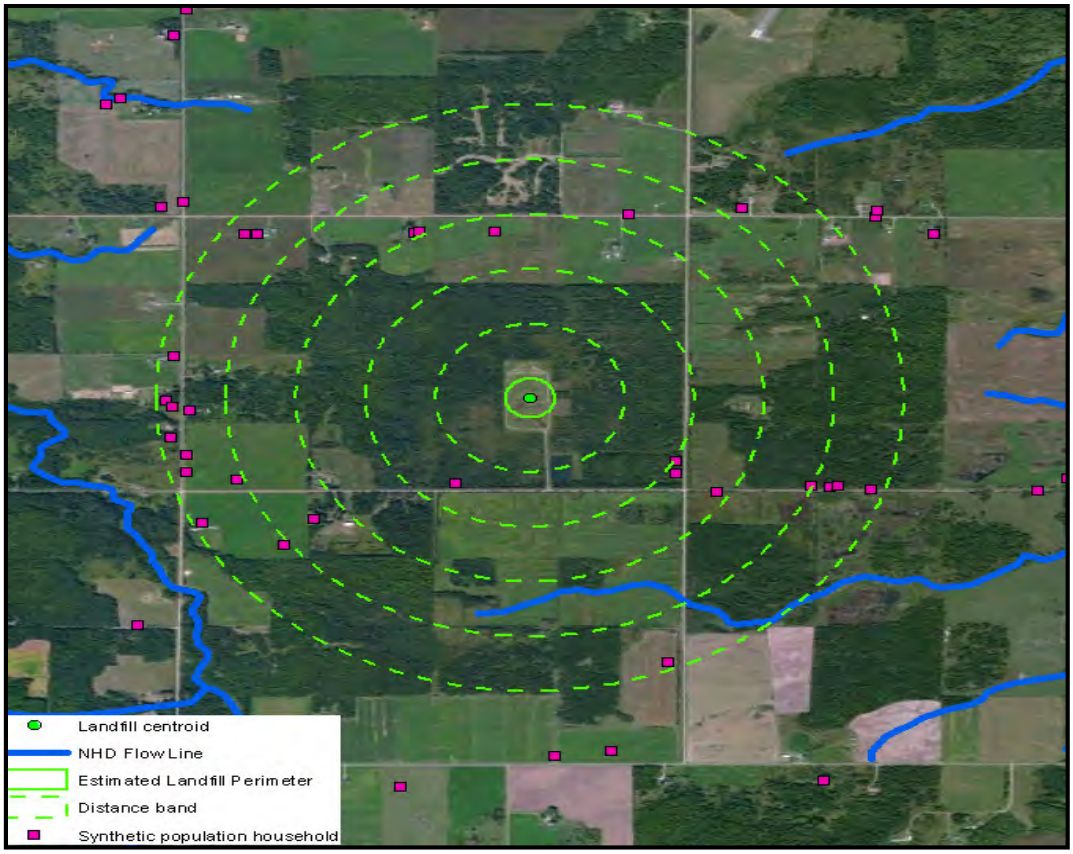

Figure B-4. Synthetic population locations in the vicinity of an example CCR landfill.

The GW→DW pathway considers residential exposure from the use of well water as a source of potable water. The revised risk assessment considered potential risks to highly exposed individuals, which are hypothetical receptors that represent an upper bound of the range of realistic exposures that may occur within the modeled population. Therefore, a GIS algorithm was applied to identify the nearest household from the edge of the WMU. Since houses were randomly placed within a 90 m grid, aerial photographs were visually inspected for all distances less than 150 m (approximately 1.5 grid lengths) to ensure that the location assigned aligned with the location of an actual residence. The associated receptor distances were corrected as necessary.

Figure B-5 shows the cumulative probability distributions for the distance to nearest receptors for CCR impoundments and landfills. Also included for comparison are the well distances used in the 2010 Risk Assessment, which were drawn from an earlier survey of municipal solid waste landfills (U.S. EPA, 1988). As these comparisons indicate, the three distributions are similar, but residents tend to be located somewhat further away from CCR WMUs. Among the CCR WMUs, residents tend to live closer to landfills (minimum of 20 m) than surface impoundments (minimum of 50 m), though much of the distinction between the two disappears at greater distances.

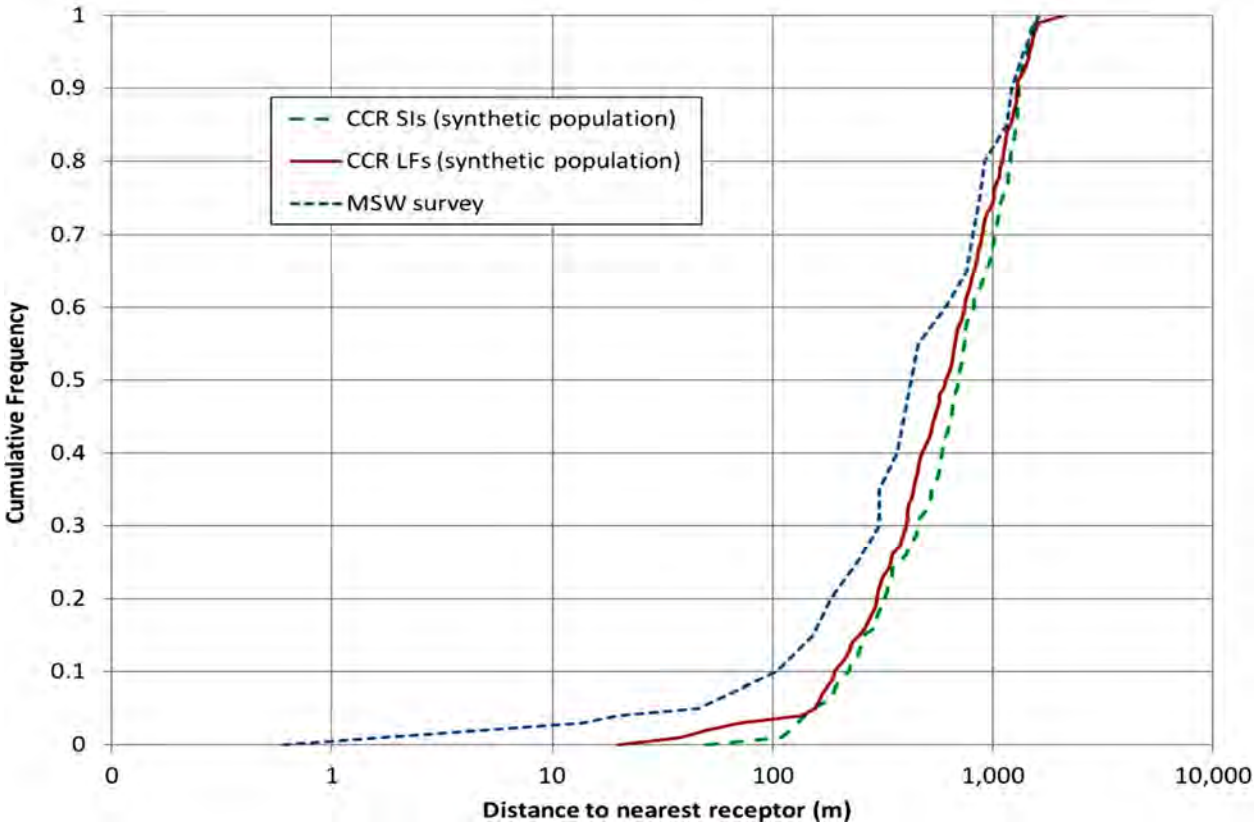

Figure B-5. Cumulative probability distributions for the distance to nearest receptor.

B.7 References

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Attachment B-1.

Soil Data

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
6137	A. B. Brown Generating Station	88	SI	100	SLT	7.9	0.4
6137	A. B. Brown Generating Station	89	SI	100	SCL	6.0	0.3
6137	A. B. Brown Generating Station	1163	LF	100	SCL	6.0	0.3
2535	AES Cayuga, LLC	1102	LF	100	SLT	7.1	1
2527	AES Greenidge	1101	LF	100	SLT	7.1	1
2527	AES Greenidge	1285	SI	100	SLT	7.1	1
2527	AES Greenidge	1286	SI	100	SLT	7.1	1
994	AES Petersburg	430	SI	100	SLT	6.7	0.98
994	AES Petersburg	431	SI	100	SLT	6.8	1
994	AES Petersburg	432	SI	100	SLT	6.8	1
994	AES Petersburg	433	SI	89	SLT	6.8	1
994	AES Petersburg	433	SI	11	SNL	6.4	0.6
994	AES Petersburg	989	LF	73	SLT	5.5	0.39
994	AES Petersburg	989	LF	27	SNL	6.4	0.6
6082	AES Somerset LLC	1105	LF	100	SLT	7.1	1
6082	AES Somerset LLC	1106	LF	100	SLT	7.1	1
6082	AES Somerset LLC	1287	SI	100	SLT	7.1	1
3942	Albright Power Station	930	LF	100	SLT	4.6	0.4
3942	Albright Power Station	931	LF	100	SLT	4.6	0.4
3942	Albright Power Station	1385	SI	100	SLT	4.6	0.4
3942	Albright Power Station	1386	SI	100	SLT	4.6	0.4
1915	Allen S King	927	LF	100	SNL	6.1	1.6
3393	Allen Steam Plant	119	SI	42	SCL	7.0	0.5
3393	Allen Steam Plant	119	SI	58	SLT	7.1	0.4
3393	Allen Steam Plant	120	SI	42	SCL	7.0	0.5
3393	Allen Steam Plant	120	SI	58	SLT	7.1	0.4
4140	Alma	993	LF	100	SLT	7.2	1.6
4140	Alma	994	LF	100	SLT	7.2	1.6
1122	Ames Electric Services Power Plant	1202	SI	100	SLT	7.0	2.4
6469	Antelope Valley Station	212	SI	100	SLT	7.7	1.4
6469	Antelope Valley Station	213	SI	100	SLT	7.6	1.2
6469	Antelope Valley Station	922	LF	100	SLT	7.6	1.1
6469	Antelope Valley Station	923	LF	100	SLT	7.6	1.2
160	Apache Station	287	SI	100	SCL	9.0	0.1
160	Apache Station	288	SI	100	SCL	9.0	0.1
160	Apache Station	292	SI	100	SCL	9.0	0.1
160	Apache Station	293	SI	100	SCL	9.0	0.1
160	Apache Station	294	SI	100	SCL	9.0	0.1
160	Apache Station	295	SI	100	SCL	9.0	0.1

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
160	Apache Station	296	SI	100	SCL	9.0	0.1
160	Apache Station	297	SI	100	SCL	9.0	0.1
160	Apache Station	298	SI	100	SCL	9.0	0.1
160	Apache Station	299	SI	100	SCL	9.0	0.1
465	Arapahoe	310	SI	47	SLT	7.5	0.3
465	Arapahoe	310	SI	53	SNL	7.3	0.4
465	Arapahoe	311	SI	47	SLT	7.5	0.3
465	Arapahoe	311	SI	53	SNL	7.3	0.4
465	Arapahoe	312	SI	47	SLT	7.5	0.3
465	Arapahoe	312	SI	53	SNL	7.3	0.4
465	Arapahoe	313	SI	47	SLT	7.5	0.3
465	Arapahoe	313	SI	53	SNL	7.3	0.4
465	Arapahoe	314	SI	47	SLT	7.5	0.3
465	Arapahoe	314	SI	53	SNL	7.3	0.4
465	Arapahoe	315	SI	47	SLT	7.5	0.3
465	Arapahoe	315	SI	53	SNL	7.3	0.4
3178	Armstrong Power Station	921	LF	100	SLT	5.0	0.6
3178	Armstrong Power Station	926	LF	100	SLT	5.0	0.6
2076	Asbury	596	SI	100	SLT	6.1	0.3
2076	Asbury	597	SI	100	SLT	6.1	0.3
2076	Asbury	598	SI	100	SLT	6.1	0.3
2706	Asheville Steam Electric Plant	649	SI	100	SLT	5.1	0.77
2706	Asheville Steam Electric Plant	650	SI	100	SLT	5.1	0.7
2835	Ashtabula	1263	SI	100	SNL	6.0	0.3
1961	Austin Northeast	958	LF	100	SLT	6.6	1.2
2836	Avon Lake	975	LF	100	SCL	5.3	1.00
2836	Avon Lake	1175	SI	100	SCL	5.0	1.1
2836	Avon Lake	1176	SI	100	SCL	5.0	1.1
995	Bailly	434	SI	100	SNL	6.2	0.4
995	Bailly	435	SI	100	SNL	6.2	0.4
995	Bailly	436	SI	100	SNL	6.2	0.4
995	Bailly	437	SI	100	SNL	6.2	0.4
995	Bailly	438	SI	100	SNL	6.2	0.4
995	Bailly	439	SI	100	SNL	6.2	0.4
995	Bailly	939	LF	100	SNL	6.2	0.4
995	Bailly	952	LF	100	SNL	6.2	0.4
889	Baldwin Energy Complex	391	SI	14	SCL	6.4	0.6
889	Baldwin Energy Complex	391	SI	86	SLT	5.5	0.4
3	Barry	252	SI	100	SCL	4.9	0.6
3982	Bay Front	162	SI	100	SCL	7.0	2
3982	Bay Front	163	SI	100	SCL	7.0	2

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
3982	Bay Front	945	LF	100	SCL	7.0	2
3982	Bay Front	946	LF	100	SCL	7.0	2
2878	Bay Shore	977	LF	100	SCL	7.1	0.7
2878	Bay Shore	1326	SI	100	SCL	7.1	0.7
8042	Belews Creek Steam Station	243	SI	100	SCL	5.1	0.36
8042	Belews Creek Steam Station	1009	LF	100	SCL	5.3	0.3
8042	Belews Creek Steam Station	1010	LF	100	SCL	5.3	0.3
8042	Belews Creek Steam Station	1079	LF	100	SCL	5.3	0.3
6034	Belle River	33	SI	100	SCL	7.0	0.6
6034	Belle River	1035	LF	100	SCL	7.0	0.6
3325	Ben French	1379	SI	100	SLT	7.9	0.4
645	Big Bend	342	SI	100	SNL	5.5	0.45
645	Big Bend	343	SI	100	SNL	5.6	0.7
645	Big Bend	344	SI	100	SNL	5.6	0.7
645	Big Bend	345	SI	100	SNL	5.6	0.66
645	Big Bend	346	SI	100	SNL	5.5	0.45
645	Big Bend	347	SI	100	SNL	5.6	0.68
645	Big Bend	348	SI	100	SNL	5.5	0.45
645	Big Bend	349	SI	100	SNL	5.5	0.45
645	Big Bend	1164	LF	100	SNL	5.6	0.7
3497	Big Brown	776	LF	100	SLT	6.2	0.7
3497	Big Brown	784	LF	100	SLT	6.2	0.7
3497	Big Brown	790	LF	100	SLT	6.2	0.7
3497	Big Brown	791	LF	100	SLT	6.2	0.7
3497	Big Brown	1177	SI	100	SLT	6.2	0.7
3497	Big Brown	1178	SI	100	SLT	6.2	0.7
3497	Big Brown	1179	SI	100	SLT	6.2	0.7
3497	Big Brown	1180	SI	100	SLT	6.2	0.7
6055	Big Cajun 2	36	SI	100	SCL	7.1	0.80
6055	Big Cajun 2	37	SI	100	SCL	7.1	0.80
6055	Big Cajun 2	38	SI	100	SCL	7.1	0.80
6055	Big Cajun 2	815	LF	100	SCL	7.0	0.65
1353	Big Sandy	521	SI	14	SCL	5.9	0.2
1353	Big Sandy	521	SI	86	SNL	4.9	0.8
1353	Big Sandy	522	SI	100	SCL	5.9	0.6
1353	Big Sandy	523	SI	2	SCL	5.9	0.2
1353	Big Sandy	523	SI	98	SNL	4.9	0.8
6098	Big Stone	814	LF	100	SNL	7.6	1.2
6098	Big Stone	1261	SI	100	SNL	7.6	1.2

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
1904	Black Dog	593	SI	86	SLT	7.2	1.6
1904	Black Dog	593	SI	14	SNL	6.9	2.4
1904	Black Dog	799	LF	100	SLT	7.3	1.7
6106	Boardman	746	LF	100	SNL	8.0	0.37
6106	Boardman	1339	SI	100	SNL	7.7	0.3
6106	Boardman	1340	SI	100	SNL	7.7	0.3
6106	Boardman	1341	SI	100	SNL	7.7	0.3
7790	Bonanza Power Plant	735	LF	100	SLT	8.6	0.6
7790	Bonanza Power Plant	737	LF	100	SLT	8.4	0.1
7790	Bonanza Power Plant	1207	SI	100	SLT	8.6	0.1
7790	Bonanza Power Plant	1208	SI	100	SLT	8.6	0.1
7790	Bonanza Power Plant	1209	SI	100	SLT	8.6	0.1
1893	Boswell Energy Center	590	SI	100	SNL	6.1	10
1893	Boswell Energy Center	591	SI	100	SNL	6.1	6.1
1893	Boswell Energy Center	592	SI	100	SNL	6.1	5.9
1893	Boswell Energy Center	796	LF	100	SNL	6.1	5.9
1893	Boswell Energy Center	853	LF	100	SNL	6.1	5.9
1893	Boswell Energy Center	862	LF	100	SNL	6.1	13.3
703	Bowen	350	SI	100	SLT	5.0	0.4
703	Bowen	1103	LF	100	SLT	5.0	0.4
602	Brandon Shores	1289	SI	100	SCL	4.6	0.4
602	Brandon Shores	1290	SI	100	SCL	4.6	0.4
1619	Brayton Point	731	LF	100	SNL	5.3	0.2
1619	Brayton Point	760	LF	11	SLT	5.2	2.3
1619	Brayton Point	760	LF	89	SNL	5.3	0.2
1619	Brayton Point	761	LF	8	SLT	5.2	2.3
1619	Brayton Point	761	LF	92	SNL	5.3	0.2
1619	Brayton Point	800	LF	100	SNL	5.3	0.2
1619	Brayton Point	824	LF	100	SNL	5.3	0.2
1619	Brayton Point	1187	SI	100	SNL	5.3	0.2
1619	Brayton Point	1188	SI	100	SNL	5.3	0.2
1619	Brayton Point	1189	SI	100	SNL	5.3	0.2
1619	Brayton Point	1190	SI	100	SNL	5.3	0.2
1619	Brayton Point	1191	SI	100	SNL	5.3	0.2
1619	Brayton Point	1192	SI	100	SNL	5.3	0.2
1619	Brayton Point	1193	SI	100	SNL	5.3	0.2
1619	Brayton Point	1194	SI	100	SNL	5.3	0.2
1619	Brayton Point	1195	SI	100	SNL	5.3	0.2
1619	Brayton Point	1196	SI	100	SNL	5.3	0.2
3796	Bremo Bluff	148	SI	93	SCL	5.1	0.3
3796	Bremo Bluff	148	SI	7	SLT	5.6	1
3796	Bremo Bluff	149	SI	95	SCL	5.1	0.3
3796	Bremo Bluff	149	SI	5	SLT	5.6	1

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
6094	Bruce Mansfield	75	SI	100	SLT	5.2	0.3
6094	Bruce Mansfield	76	SI	100	SLT	4.7	0.5
6094	Bruce Mansfield	77	SI	100	SLT	5.0	0.39
6094	Bruce Mansfield	78	SI	100	SLT	5.2	0.31
6094	Bruce Mansfield	79	SI	100	SLT	4.8	0.48
2720	Buck	671	SI	100	SCL	5.3	0.3
2720	Buck	672	SI	100	SCL	5.3	0.3
2720	Buck	673	SI	100	SCL	5.3	0.3
3396	Bull Run	121	SI	89	SCL	5.4	0.40
3396	Bull Run	121	SI	11	SNL	5.1	0.5
3396	Bull Run	122	SI	89	SCL	5.4	0.40
3396	Bull Run	122	SI	11	SNL	5.1	0.5
3396	Bull Run	123	SI	89	SCL	5.4	0.40
3396	Bull Run	123	SI	11	SNL	5.1	0.5
3396	Bull Run	124	SI	89	SCL	5.4	0.40
3396	Bull Run	124	SI	11	SNL	5.1	0.5
3396	Bull Run	889	LF	100	SCL	6.5	0.3
3396	Bull Run	890	LF	100	SCL	5.5	0.6
1104	Burlington	507	SI	100	SCL	6.3	2.4
1104	Burlington	508	SI	100	SCL	6.3	2.4
1104	Burlington	509	SI	100	SCL	6.3	2.4
1104	Burlington	510	SI	100	SCL	6.3	2.4
1104	Burlington	511	SI	100	SCL	6.3	2.4
676	C D McIntosh Jr	885	LF	100	SNL	5.2	0.40
676	C D McIntosh Jr	888	LF	100	SNL	6.0	0.35
468	Cameo	316	SI	11	SLT	8.1	0.1
468	Cameo	316	SI	89	SNL	8.3	0.2
468	Cameo	317	SI	11	SLT	8.1	0.1
468	Cameo	317	SI	89	SNL	8.3	0.2
3280	Canadys Steam	107	SI	100	SNL	5.3	0.9
3280	Canadys Steam	108	SI	100	SNL	5.3	0.9
3280	Canadys Steam	109	SI	100	SNL	5.3	0.9
1363	Cane Run	538	SI	100	SCL	5.9	0.5
1363	Cane Run	539	SI	98	SCL	5.9	0.58
1363	Cane Run	539	SI	2	SLT	5.1	0.4
1363	Cane Run	540	SI	100	SCL	5.9	0.5
1363	Cane Run	541	SI	100	SCL	5.9	0.5
1363	Cane Run	542	SI	98	SCL	5.9	0.58
1363	Cane Run	542	SI	2	SLT	5.1	0.4
1363	Cane Run	869	LF	100	SCL	5.9	0.5
2708	Cape Fear Steam Electric Plant	651	SI	100	SLT	5.8	1

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
2708	Cape Fear Steam Electric Plant	652	SI	69	SCL	4.9	0.35
2708	Cape Fear Steam Electric Plant	652	SI	31	SLT	5.8	1
2708	Cape Fear Steam Electric Plant	653	SI	95	SCL	4.9	0.3
2708	Cape Fear Steam Electric Plant	653	SI	5	SLT	5.8	1
2708	Cape Fear Steam Electric Plant	654	SI	69	SCL	4.9	0.35
2708	Cape Fear Steam Electric Plant	654	SI	31	SLT	5.8	1
2708	Cape Fear Steam Electric Plant	655	SI	100	SLT	5.8	1
3644	Carbon Plant	876	LF	100	SLT	7.8	0.3
3644	Carbon Plant	905	LF	100	SLT	7.8	0.3
3644	Carbon Plant	1387	SI	100	SLT	7.8	0.3
3644	Carbon Plant	1388	SI	100	SLT	7.8	0.3
2828	Cardinal	693	SI	100	SCL	5.9	0.5
2828	Cardinal	694	SI	100	SCL	5.9	0.5
2828	Cardinal	899	LF	100	SCL	6.1	0.44
1001	Cayuga	454	SI	100	SLT	7.1	1.9
1001	Cayuga	455	SI	100	SLT	7.1	1.9
1001	Cayuga	456	SI	100	SLT	7.1	1.9
1001	Cayuga	457	SI	100	SLT	7.1	1.9
1001	Cayuga	838	LF	100	SNL	6.5	2
1571	Chalk Point LLC	836	LF	100	SNL	4.8	0.4
1571	Chalk Point LLC	1104	LF	100	SNL	4.7	0.9
2169	Chamois Power Plant	1288	SI	100	SLT	7.7	0.8
56	Charles R. Lowman	270	SI	100	SLT	5.1	0.2
56	Charles R. Lowman	271	SI	100	SLT	5.1	0.2
56	Charles R. Lowman	272	SI	100	SLT	5.1	0.2
56	Charles R. Lowman	273	SI	100	SLT	5.1	0.2
56	Charles R. Lowman	900	LF	44	SCL	5.0	0.3
56	Charles R. Lowman	900	LF	56	SLT	5.1	0.2
469	Cherokee	318	SI	4	SCL	8.2	0.4
469	Cherokee	318	SI	29	SLT	7.8	0.7
469	Cherokee	318	SI	67	SNL	7.3	0.4
469	Cherokee	319	SI	4	SCL	8.2	0.4
469	Cherokee	319	SI	29	SLT	7.8	0.7
469	Cherokee	319	SI	67	SNL	7.3	0.4
469	Cherokee	320	SI	4	SCL	8.2	0.4
469	Cherokee	320	SI	29	SLT	7.8	0.7

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
469	Cherokee	320	SI	67	SNL	7.3	0.4
469	Cherokee	321	SI	4	SCL	8.2	0.4
469	Cherokee	321	SI	29	SLT	7.8	0.7
469	Cherokee	321	SI	67	SNL	7.3	0.4
469	Cherokee	322	SI	4	SCL	8.2	0.4
469	Cherokee	322	SI	29	SLT	7.8	0.7
469	Cherokee	322	SI	67	SNL	7.3	0.4
469	Cherokee	323	SI	4	SCL	8.2	0.4
469	Cherokee	323	SI	29	SLT	7.8	0.7
469	Cherokee	323	SI	67	SNL	7.3	0.4
3803	Chesapeake Energy Center	152	SI	100	SNL	6.4	5.3
3803	Chesapeake Energy Center	865	LF	100	SNL	6.4	5.3
3797	Chesterfield	150	SI	100	SNL	5.2	0.1
3797	Chesterfield	151	SI	100	SNL	5.2	0.1
8226	Cheswick Power Plant	1099	LF	100	SLT	5.1	0.5
8226	Cheswick Power Plant	1165	SI	100	SLT	5.2	0.3
8226	Cheswick Power Plant	1166	SI	100	SLT	5.2	0.3
113	Cholla	279	SI	100	SLT	8.1	0.20
113	Cholla	280	SI	100	SLT	7.9	0
113	Cholla	863	LF	100	SLT	7.9	0
2721	Cliffside	674	SI	100	SCL	5.3	0.3
2721	Cliffside	675	SI	100	SCL	5.3	0.3
2721	Cliffside	676	SI	100	SCL	5.3	0.3
983	Clifty Creek	413	SI	4	SCL	6.5	0.4
983	Clifty Creek	413	SI	96	SLT	6.5	0.6
983	Clifty Creek	414	SI	100	SCL	6.5	0.4
983	Clifty Creek	847	LF	100	SCL	6.5	0.4
983	Clifty Creek	848	LF	100	SCL	6.5	0.4
3775	Clinch River	144	SI	100	SCL	4.7	0.4
3775	Clinch River	145	SI	100	SCL	4.7	0.4
3775	Clinch River	849	LF	100	SCL	4.7	0.4
7213	Clover	850	LF	100	SCL	4.9	0.4
7213	Clover	851	LF	100	SCL	4.9	0.4
7213	Clover	1280	SI	100	SCL	5.2	0.2
7213	Clover	1281	SI	100	SCL	5.2	0.2
7213	Clover	1282	SI	47	SCL	5.2	0.2
7213	Clover	1282	SI	53	SLT	5.6	1
7213	Clover	1283	SI	88	SCL	5.2	0.2
7213	Clover	1283	SI	12	SLT	5.6	1
7213	Clover	1284	SI	88	SCL	5.2	0.2
7213	Clover	1284	SI	12	SLT	5.6	1
6030	Coal Creek	29	SI	16	SLT	7.6	1.5
6030	Coal Creek	29	SI	84	SNL	7.7	1

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
6030	Coal Creek	30	SI	100	SNL	7.7	1
6030	Coal Creek	852	LF	100	SNL	7.7	1
6030	Coal Creek	854	LF	100	SLT	7.6	1.5
6030	Coal Creek	855	LF	100	SLT	7.6	1.5
6030	Coal Creek	857	LF	100	SNL	7.7	1
6030	Coal Creek	868	LF	100	SLT	7.6	1.5
6030	Coal Creek	1119	LF	100	SLT	7.6	1.5
861	Coffeen	379	SI	100	SLT	5.5	0.4
861	Coffeen	380	SI	100	SCL	6.3	0.6
861	Coffeen	846	LF	83	SCL	6.3	0.6
861	Coffeen	846	LF	17	SLT	5.5	0.4
47	Colbert	258	SI	100	SCL	5.3	0.30
47	Colbert	259	SI	100	SCL	5.3	0.30
47	Colbert	260	SI	100	SCL	5.3	0.30
47	Colbert	859	LF	100	SCL	5.2	0.2
6178	Coleto Creek	181	SI	100	SCL	7.5	0.6
6178	Coleto Creek	182	SI	100	SCL	7.5	0.6
6076	Colstrip	46	SI	100	SLT	8.2	0.41
6076	Colstrip	47	SI	100	SLT	8.2	0.41
6076	Colstrip	48	SI	100	SLT	8.2	0.41
6076	Colstrip	49	SI	100	SLT	8.2	0.5
6076	Colstrip	50	SI	100	SLT	8.2	0.4
6076	Colstrip	51	SI	100	SLT	8.2	0.5
6076	Colstrip	52	SI	100	SLT	8.2	0.4
6076	Colstrip	53	SI	100	SLT	8.2	0.41
10784	Colstrip Energy LP	860	LF	100	SLT	8.2	0.40
10784	Colstrip Energy LP	861	LF	100	SLT	8.2	0.40
8023	Columbia	239	SI	40	SLT	7.2	4.7
8023	Columbia	239	SI	60	SNL	6.9	2.7
8023	Columbia	240	SI	40	SLT	7.2	4.7
8023	Columbia	240	SI	60	SNL	6.9	2.7
8023	Columbia	241	SI	40	SLT	7.2	4.7
8023	Columbia	241	SI	60	SNL	6.9	2.7
8023	Columbia	242	SI	40	SLT	7.2	4.7
8023	Columbia	242	SI	60	SNL	6.9	2.7
8023	Columbia	1135	LF	100	SLT	7.2	4.7
8023	Columbia	1136	LF	100	SNL	6.9	2.7
2123	Columbia	1213	SI	36	SCL	6.0	0.5
2123	Columbia	1213	SI	64	SLT	5.9	0.5
470	Comanche	324	SI	87	SLT	8.1	0.52
470	Comanche	324	SI	13	SNL	8.1	0.3
470	Comanche	325	SI	87	SLT	8.1	0.52
470	Comanche	325	SI	13	SNL	8.1	0.3

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
470	Comanche	326	SI	87	SLT	8.1	0.52
470	Comanche	326	SI	13	SNL	8.1	0.3
470	Comanche	327	SI	87	SLT	8.1	0.52
470	Comanche	327	SI	13	SNL	8.1	0.3
470	Comanche	328	SI	87	SLT	8.1	0.52
470	Comanche	328	SI	13	SNL	8.1	0.3
470	Comanche	1137	LF	100	SLT	8.2	0.4
3118	Conemaugh	864	LF	100	SLT	4.8	0.5
3118	Conemaugh	1138	LF	100	SLT	4.8	0.5
3118	Conemaugh	1334	SI	100	SLT	5.0	0.6
3118	Conemaugh	1335	SI	100	SLT	5.0	0.6
3118	Conemaugh	1336	SI	100	SLT	5.0	0.6
3118	Conemaugh	1337	SI	100	SLT	5.0	0.6
3118	Conemaugh	1338	SI	100	SLT	5.0	0.6
2840	Conesville	701	SI	100	SLT	5.6	0.38
2840	Conesville	1005	LF	100	SLT	5.8	0.3
2840	Conesville	1006	LF	100	SLT	5.8	0.3
1710	Consumers Energy - J.H. Campbell	572	SI	100	SNL	5.9	0.7
1710	Consumers Energy - J.H. Campbell	967	LF	100	SNL	5.9	0.7
1710	Consumers Energy - J.H. Campbell	985	LF	100	SNL	5.9	0.7
1710	Consumers Energy - J.H. Campbell	998	LF	100	SNL	5.9	0.7
1710	Consumers Energy - J.H. Campbell	999	LF	100	SNL	5.9	0.7
1384	Cooper Station.	973	LF	100	SCL	6.0	0.50
7210	Cope	866	LF	100	SLT	5.3	1.6
6177	Coronado Generating Station	180	SI	67	SLT	8.3	0.4
6177	Coronado Generating Station	180	SI	33	SNL	7.9	0.2
6177	Coronado Generating Station	835	LF	100	SNL	7.9	0.2
6177	Coronado Generating Station	867	LF	100	SNL	7.9	0.2
8222	Coyote	248	SI	100	SLT	7.6	0.9
8222	Coyote	249	SI	100	SLT	7.6	0.9
8222	Coyote	250	SI	100	SLT	7.6	0.9
8222	Coyote	825	LF	100	SLT	7.6	0.9
8222	Coyote	826	LF	100	SLT	7.6	0.9
8222	Coyote	833	LF	100	SLT	7.6	0.9

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
8222	Coyote	856	LF	100	SLT	7.6	0.9
2549	CR Huntley Generating Station	643	SI	100	SNL	6.7	0.3
2549	CR Huntley Generating Station	644	SI	100	SNL	6.7	0.3
2549	CR Huntley Generating Station	645	SI	100	SNL	6.7	0.3
2549	CR Huntley Generating Station	1100	LF	100	SNL	6.7	0.3
6021	Craig	27	SI	100	SLT	8.0	0.5
6021	Craig	28	SI	100	SLT	8.0	0.5
6021	Craig	974	LF	100	SLT	8.0	0.5
867	Crawford	387	SI	100	SNL	6.8	0.60
753	Crisp Plant	1265	SI	50	SLT	5.0	0.3
753	Crisp Plant	1265	SI	50	SNL	6.1	1.2
641	Crist	1139	LF	100	SLT	5.0	0.4
641	Crist	1273	SI	100	SLT	5.1	0.59
641	Crist	1274	SI	100	SLT	5.2	0.67
641	Crist	1275	SI	100	SLT	5.0	0.4
641	Crist	1276	SI	100	SLT	5.0	0.4
641	Crist	1277	SI	100	SLT	5.0	0.4
641	Crist	1278	SI	100	SLT	5.0	0.4
641	Crist	1279	SI	100	SLT	5.0	0.4
130	Cross	284	SI	100	SLT	4.8	0.7
130	Cross	285	SI	100	SLT	4.8	0.7
130	Cross	286	SI	100	SLT	4.8	0.7
130	Cross	827	LF	100	SLT	4.8	0.7
130	Cross	828	LF	100	SLT	4.8	0.7
130	Cross	829	LF	100	SLT	4.8	0.7
130	Cross	830	LF	100	SLT	4.8	0.7
628	Crystal River Power Plant	831	LF	100	SNL	6.1	0.5
3399	Cumberland	125	SI	12	SCL	5.1	0.4
3399	Cumberland	125	SI	88	SLT	5.8	0.60
3399	Cumberland	126	SI	12	SCL	5.1	0.4
3399	Cumberland	126	SI	88	SLT	5.8	0.60
3399	Cumberland	127	SI	12	SCL	5.1	0.4
3399	Cumberland	127	SI	88	SLT	5.8	0.60
3399	Cumberland	978	LF	12	SCL	5.1	0.4
3399	Cumberland	978	LF	88	SLT	5.8	0.60
6823	D B Wilson	832	LF	100	SLT	5.2	0.6
6823	D B Wilson	845	LF	100	SLT	5.2	0.6
1702	D.E. Karn	570	SI	95	SLT	7.9	1
1702	D.E. Karn	570	SI	5	SNL	6.3	1.1

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ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
1702	D.E. Karn	571	SI	100	SLT	7.9	1
1702	D.E. Karn	1004	LF	100	SLT	7.9	1
1385	Dale Station	558	SI	100	SCL	6.4	0.6
1385	Dale Station	559	SI	100	SCL	6.4	0.6
1385	Dale Station	560	SI	100	SCL	6.4	0.6
963	Dallman	399	SI	100	SLT	7.1	1.9
963	Dallman	823	LF	100	SLT	7.1	1.9
963	Dallman	834	LF	100	SLT	7.1	1.9
2723	Dan River	677	SI	100	SCL	5.0	0.4
2723	Dan River	678	SI	100	SCL	5.0	0.4
2723	Dan River	679	SI	100	SCL	5.0	0.39
2480	Danskammer Generating Station	1140	LF	100	SLT	6.7	1.1
4158	Dave Johnston Plant	4	SI	100	SLT	8.2	0.3
4158	Dave Johnston Plant	5	SI	100	SLT	8.2	0.3
4158	Dave Johnston Plant	6	SI	100	SLT	8.2	0.3
4158	Dave Johnston Plant	7	SI	100	SLT	8.2	0.3
4158	Dave Johnston Plant	8	SI	100	SLT	8.2	0.3
4158	Dave Johnston Plant	9	SI	100	SLT	8.2	0.3
4158	Dave Johnston Plant	10	SI	100	SLT	8.2	0.3
4158	Dave Johnston Plant	11	SI	100	SLT	8.2	0.3
4158	Dave Johnston Plant	837	LF	100	SLT	8.2	0.31
996	Dean H Mitchell	440	SI	100	SNL	6.2	0.4
996	Dean H Mitchell	441	SI	100	SNL	6.2	0.4
996	Dean H Mitchell	442	SI	100	SNL	6.2	0.4
996	Dean H Mitchell	443	SI	100	SNL	6.2	0.4
996	Dean H Mitchell	444	SI	100	SNL	6.2	0.4
996	Dean H Mitchell	445	SI	100	SNL	6.2	0.4
996	Dean H Mitchell	446	SI	100	SNL	6.2	0.4
996	Dean H Mitchell	447	SI	100	SNL	6.2	0.4
663	Deerhaven Generating Station	1141	LF	100	SNL	5.6	0.7
663	Deerhaven Generating Station	1331	SI	100	SNL	5.6	0.7
1572	Dickerson	839	LF	100	SLT	5.1	0.6
51	Dolet Hills	263	SI	100	SCL	4.7	0.9
51	Dolet Hills	264	SI	100	SCL	4.7	0.9
51	Dolet Hills	265	SI	100	SCL	5.1	0.71
51	Dolet Hills	266	SI	100	SCL	4.7	0.9
51	Dolet Hills	267	SI	100	SCL	4.7	0.9
51	Dolet Hills	268	SI	100	SCL	4.7	0.9
51	Dolet Hills	269	SI	100	SCL	4.7	0.9
51	Dolet Hills	840	LF	100	SCL	4.7	0.9

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ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
3317	Dolphus M Grainger	115	SI	100	SNL	6.1	0.8
3317	Dolphus M Grainger	116	SI	100	SNL	6.1	0.8
1046	Dubuque	476	SI	32	SCL	6.2	0.65
1046	Dubuque	476	SI	68	SLT	6.8	1.3
6016	Duck Creek	18	SI	48	SCL	7.7	0.6
6016	Duck Creek	18	SI	52	SLT	5.9	0.5
6016	Duck Creek	19	SI	48	SCL	7.7	0.6
6016	Duck Creek	19	SI	52	SLT	5.9	0.5
6016	Duck Creek	20	SI	48	SCL	7.7	0.6
6016	Duck Creek	20	SI	52	SLT	5.9	0.5
6016	Duck Creek	842	LF	100	SCL	6.2	0.44
2554	Dunkirk Generating Plant	646	SI	10	SLT	7.1	1
2554	Dunkirk Generating Plant	646	SI	90	SNL	6.7	0.3
2554	Dunkirk Generating Plant	647	SI	10	SLT	7.1	1
2554	Dunkirk Generating Plant	647	SI	90	SNL	6.7	0.3
2554	Dunkirk Generating Plant	648	SI	10	SLT	7.1	1
2554	Dunkirk Generating Plant	648	SI	90	SNL	6.7	0.3
2554	Dunkirk Generating Plant	843	LF	98	SLT	7.1	1
2554	Dunkirk Generating Plant	843	LF	2	SNL	6.7	0.3
26	E. C. Gaston	257	SI	51	SCL	4.9	0.29
26	E. C. Gaston	257	SI	49	SLT	5.1	0.36
1355	E.W. Brown	524	SI	100	SCL	6.6	1.1
1355	E.W. Brown	525	SI	100	SCL	6.6	1.1
991	Eagle Valley	425	SI	100	SLT	7.1	1.9
991	Eagle Valley	426	SI	100	SLT	7.1	1.9
991	Eagle Valley	427	SI	100	SLT	7.1	1.9
991	Eagle Valley	428	SI	100	SLT	7.1	1.9
991	Eagle Valley	429	SI	100	SLT	6.9	1.8
1217	Earl F Wisdom	844	LF	100	SCL	7.1	2.9
6018	East Bend Station	23	SI	80	SCL	6.2	0.47
6018	East Bend Station	23	SI	20	SLT	6.5	0.6
6018	East Bend Station	24	SI	100	SCL	6.0	0.5
6018	East Bend Station	25	SI	80	SCL	6.2	0.47
6018	East Bend Station	25	SI	20	SLT	6.5	0.6
6018	East Bend Station	879	LF	100	SCL	6.0	0.5
2837	Eastlake	914	LF	100	SNL	6.0	0.3
2837	Eastlake	1262	SI	100	SNL	6.0	0.3
856	ED Edwards	376	SI	74	SCL	6.6	1.3
856	ED Edwards	376	SI	20	SLT	5.9	0.5
856	ED Edwards	376	SI	5	SNL	6.5	1
856	ED Edwards	377	SI	100	SCL	6.8	1.6
856	ED Edwards	378	SI	100	SCL	6.8	1.6
4050	Edgewater	164	SI	100	SNL	6.2	0.4

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ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
4050	Edgewater	165	SI	100	SNL	6.2	0.4
4050	Edgewater	166	SI	100	SNL	6.2	0.4
4050	Edgewater	167	SI	100	SNL	6.2	0.4
4050	Edgewater	168	SI	100	SNL	6.2	0.4
4050	Edgewater	169	SI	100	SNL	6.2	0.4
4050	Edgewater	858	LF	100	SCL	7.3	4.6
4050	Edgewater	894	LF	100	SNL	6.2	0.4
1004	Edwardsport	458	SI	100	SLT	6.8	1
1004	Edwardsport	459	SI	100	SLT	6.8	1
1004	Edwardsport	971	LF	18	SCL	6.0	0.3
1004	Edwardsport	971	LF	77	SLT	6.2	0.70
1004	Edwardsport	971	LF	5	SNL	6.7	1.3
1374	Elmer Smith Station	1234	SI	100	SCL	5.8	0.5
1374	Elmer Smith Station	1235	SI	100	SCL	5.8	0.5
1374	Elmer Smith Station	1236	SI	100	SCL	5.8	0.5
1374	Elmer Smith Station	1237	SI	100	SCL	5.8	0.5
3098	Elrama Power Plant	895	LF	38	SLT	5.2	0.3
3098	Elrama Power Plant	895	LF	62	SNL	5.5	0.2
3098	Elrama Power Plant	1342	SI	100	SLT	5.6	0.5
3098	Elrama Power Plant	1343	SI	100	SLT	5.6	0.5
3098	Elrama Power Plant	1344	SI	100	SLT	5.6	0.5
3098	Elrama Power Plant	1345	SI	100	SLT	5.5	0.5
1832	Erickson Station	587	SI	100	SLT	7.2	2.1
87	Escalante	274	SI	5	SLT	8.1	0.2
87	Escalante	274	SI	95	SNL	7.8	0.2
87	Escalante	275	SI	5	SLT	8.1	0.2
87	Escalante	275	SI	95	SNL	7.8	0.2
87	Escalante	276	SI	5	SLT	8.1	0.2
87	Escalante	276	SI	95	SNL	7.8	0.2
87	Escalante	277	SI	5	SLT	8.1	0.2
87	Escalante	277	SI	95	SNL	7.8	0.2
87	Escalante	278	SI	5	SLT	8.1	0.2
87	Escalante	278	SI	95	SNL	7.8	0.2
87	Escalante	992	LF	100	SNL	7.8	0.2
1012	F. B. Culley	466	SI	1	SCL	6.0	0.3
1012	F. B. Culley	466	SI	99	SLT	6.5	0.6
1012	F. B. Culley	467	SI	100	SLT	6.5	0.6
1218	Fair Station	896	LF	100	SCL	6.0	0.6
1218	Fair Station	1183	SI	100	SCL	6.4	2.8
1218	Fair Station	1184	SI	100	SCL	6.4	2.8
6179	Fayette Power Project	183	SI	100	SCL	7.9	3
6179	Fayette Power Project	184	SI	100	SCL	7.9	3
6179	Fayette Power Project	897	LF	100	SCL	7.9	3

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ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
886	Fisk	1238	SI	100	SNL	6.8	0.6
886	Fisk	1239	SI	100	SNL	6.8	0.6
886	Fisk	1240	SI	100	SNL	6.8	0.6
6138	Flint Creek	173	SI	100	SCL	5.0	0.5
6138	Flint Creek	174	SI	100	SCL	5.0	0.5
6138	Flint Creek	898	LF	100	SCL	5.1	0.5
3943	Fort Martin Power Station	1142	LF	100	SLT	5.6	0.5
3943	Fort Martin Power Station	1143	LF	100	SLT	5.6	0.42
3943	Fort Martin Power Station	1181	SI	100	SCL	5.3	0.5
3943	Fort Martin Power Station	1182	SI	100	SCL	5.3	0.5
10343	Foster Wheeler Mt Carmel Cogen	901	LF	100	SLT	5.6	0.4
2442	Four Corners	638	SI	100	SLT	8.3	0.2
2442	Four Corners	639	SI	100	SLT	8.3	0.2
2442	Four Corners	640	SI	100	SLT	8.3	0.2
2442	Four Corners	641	SI	100	SLT	8.3	0.2
2442	Four Corners	642	SI	100	SLT	8.3	0.2
2442	Four Corners	903	LF	100	SLT	8.3	0.2
2442	Four Corners	915	LF	100	SLT	8.3	0.2
1043	Frank E. Ratts	468	SI	34	SCL	6.0	0.3
1043	Frank E. Ratts	468	SI	58	SLT	6.4	0.79
1043	Frank E. Ratts	468	SI	8	SNL	6.4	0.6
1043	Frank E. Ratts	469	SI	100	SLT	6.8	1
1043	Frank E. Ratts	470	SI	100	SLT	6.7	0.96
1043	Frank E. Ratts	471	SI	34	SCL	6.0	0.3
1043	Frank E. Ratts	471	SI	58	SLT	6.4	0.79
1043	Frank E. Ratts	471	SI	8	SNL	6.4	0.6
1043	Frank E. Ratts	472	SI	100	SLT	6.4	0.84
1043	Frank E. Ratts	473	SI	34	SCL	6.0	0.3
1043	Frank E. Ratts	473	SI	58	SLT	6.4	0.79
1043	Frank E. Ratts	473	SI	8	SNL	6.4	0.6
1043	Frank E. Ratts	474	SI	34	SCL	6.0	0.3
1043	Frank E. Ratts	474	SI	58	SLT	6.4	0.79
1043	Frank E. Ratts	474	SI	8	SNL	6.4	0.6
1043	Frank E. Ratts	475	SI	100	SLT	5.9	0.57
2718	G G Allen	668	SI	100	SCL	5.3	0.3
2718	G G Allen	669	SI	100	SCL	5.3	0.3
2718	G G Allen	670	SI	100	SCL	5.3	0.3
2718	G G Allen	892	LF	100	SCL	5.3	0.3
7	Gadsden	253	SI	24	SCL	5.0	0.3
7	Gadsden	253	SI	76	SLT	5.2	0.46
7	Gadsden	253	SI	0	SNL	4.7	0.4
3403	Gallatin	128	SI	48	SCL	6.0	0.6

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ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
3403	Gallatin	128	SI	52	SLT	5.3	0.8
3403	Gallatin	129	SI	48	SCL	6.0	0.6
3403	Gallatin	129	SI	52	SLT	5.3	0.8
3403	Gallatin	130	SI	48	SCL	6.0	0.6
3403	Gallatin	130	SI	52	SLT	5.3	0.8
8102	General James M. Gavin	246	SI	100	SNL	5.1	0.3
8102	General James M. Gavin	247	SI	100	SCL	5.7	0.6
8102	General James M. Gavin	1144	LF	100	SNL	5.1	0.3
4143	Genoa	1007	LF	100	SLT	6.8	1.4
4143	Genoa	1131	LF	100	SLT	6.8	1.4
1091	George Neal North	504	SI	100	SLT	7.9	0.8
1091	George Neal North	505	SI	100	SLT	7.9	0.8
1091	George Neal North	506	SI	100	SLT	7.9	0.8
1091	George Neal North	906	LF	100	SLT	7.9	0.8
1091	George Neal North	907	LF	100	SLT	7.9	0.8
1091	George Neal North	908	LF	100	SLT	7.9	0.8
1091	George Neal North	909	LF	100	SLT	7.9	0.8
1091	George Neal North	910	LF	100	SLT	7.9	0.8
7343	George Neal South	911	LF	100	SLT	7.9	0.8
7343	George Neal South	1332	SI	100	SLT	7.9	0.8
6077	Gerald Gentleman	912	LF	100	SLT	7.3	0.6
1356	Ghent	526	SI	60	SCL	6.4	0.81
1356	Ghent	526	SI	40	SLT	6.5	0.6
1356	Ghent	527	SI	100	SCL	6.0	0.5
1356	Ghent	528	SI	100	SCL	6.0	0.5
1356	Ghent	529	SI	100	SCL	7.1	1.3
1356	Ghent	530	SI	60	SCL	6.4	0.81
1356	Ghent	530	SI	40	SLT	6.5	0.6
6136	Gibbons Creek Steam Electric Station	881	LF	100	SCL	5.4	0.6
6136	Gibbons Creek Steam Electric Station	913	LF	100	SCL	5.4	0.6
6136	Gibbons Creek Steam Electric Station	1241	SI	100	SCL	5.4	0.6
6136	Gibbons Creek Steam Electric Station	1242	SI	100	SCL	5.4	0.6
6136	Gibbons Creek Steam Electric Station	1243	SI	100	SCL	5.4	0.6
6136	Gibbons Creek Steam Electric Station	1244	SI	100	SCL	5.4	0.6
6113	Gibson	81	SI	100	SCL	6.6	0.8
6113	Gibson	82	SI	100	SCL	6.6	0.8
6113	Gibson	83	SI	82	SCL	6.6	0.8

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ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
6113	Gibson	83	SI	18	SLT	6.8	1
6113	Gibson	84	SI	100	SLT	6.8	1
6113	Gibson	85	SI	100	SCL	6.6	0.8
6113	Gibson	86	SI	100	SLT	6.8	1
6113	Gibson	902	LF	62	SCL	6.6	0.8
6113	Gibson	902	LF	38	SLT	6.8	1
6113	Gibson	904	LF	100	SLT	6.8	1
3776	Glen Lyn	146	SI	100	SCL	5.1	0.6
3776	Glen Lyn	147	SI	100	SCL	5.1	0.6
3776	Glen Lyn	870	LF	100	SCL	5.1	0.6
8	Gorgas	254	SI	100	SLT	5.1	0.3
8	Gorgas	255	SI	100	SLT	5.1	0.3
8	Gorgas	963	LF	100	SLT	5.1	0.3
1825	Grand Haven City of J.B. Sims	1309	SI	100	SNL	5.9	0.7
1825	Grand Haven City of J.B. Sims	1310	SI	100	SNL	5.9	0.7
10151	Grant Town Power Plant	871	LF	100	SCL	5.3	0.5
10151	Grant Town Power Plant	872	LF	100	SCL	5.3	0.5
10151	Grant Town Power Plant	873	LF	100	SCL	5.3	0.5
10151	Grant Town Power Plant	1167	SI	100	SCL	5.3	0.5
10151	Grant Town Power Plant	1168	SI	100	SCL	5.3	0.5
10151	Grant Town Power Plant	1169	SI	100	SCL	5.3	0.5
10151	Grant Town Power Plant	1170	SI	100	SCL	5.3	0.5
10151	Grant Town Power Plant	1171	SI	100	SCL	5.3	0.5
165	GRDA	874	LF	100	SCL	4.9	0.5
165	GRDA	1210	SI	100	SCL	4.9	0.5
1357	Green River	531	SI	100	SLT	5.2	0.6
1357	Green River	532	SI	56	SCL	6.5	0.6
1357	Green River	532	SI	44	SLT	5.2	0.6
1357	Green River	533	SI	40	SCL	6.5	0.6
1357	Green River	533	SI	60	SLT	5.2	0.6
1357	Green River	534	SI	100	SLT	5.2	0.6
1357	Green River	535	SI	100	SCL	6.5	0.6
10	Greene County	256	SI	100	SLT	5.0	0.2
6041	H L Spurlock Station	34	SI	100	SCL	5.9	0.5
6041	H L Spurlock Station	972	LF	100	SCL	5.9	0.5
2709	H.F. Lee Plant	656	SI	100	SCL	5.0	0.5
2709	H.F. Lee Plant	657	SI	85	SCL	5.0	0.5
2709	H.F. Lee Plant	657	SI	15	SLT	4.7	0.5
2709	H.F. Lee Plant	658	SI	92	SCL	5.0	0.5
2709	H.F. Lee Plant	658	SI	8	SLT	4.7	0.5
2709	H.F. Lee Plant	659	SI	41	SCL	5.0	0.5

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
2709	H.F. Lee Plant	659	SI	59	SLT	5.8	1
2709	H.F. Lee Plant	660	SI	46	SCL	5.0	0.5
2709	H.F. Lee Plant	660	SI	30	SLT	5.7	0.93
2709	H.F. Lee Plant	660	SI	24	SNL	4.9	0.4
708	Hammond	351	SI	89	SCL	5.1	0.4
708	Hammond	351	SI	11	SNL	5.1	0.4
708	Hammond	352	SI	89	SCL	5.1	0.4
708	Hammond	352	SI	11	SNL	5.1	0.4
708	Hammond	353	SI	89	SCL	5.1	0.4
708	Hammond	353	SI	11	SNL	5.1	0.4
708	Hammond	354	SI	89	SCL	5.1	0.4
708	Hammond	354	SI	11	SNL	5.1	0.4
708	Hammond	1145	LF	100	SCL	5.0	0.4
1731	Harbor Beach Power Plant	581	SI	38	SLT	7.8	0.4
1731	Harbor Beach Power Plant	581	SI	62	SNL	6.3	1.1
990	Harding Street	420	SI	100	SLT	7.1	1.9
990	Harding Street	421	SI	100	SLT	7.1	1.9
990	Harding Street	422	SI	100	SLT	7.1	1.9
990	Harding Street	423	SI	100	SLT	7.1	1.9
990	Harding Street	424	SI	100	SLT	7.1	1.9
709	Harllee Branch	355	SI	100	SNL	5.1	0.2
709	Harllee Branch	356	SI	45	SCL	5.3	0.3
709	Harllee Branch	356	SI	55	SNL	5.1	0.2
709	Harllee Branch	357	SI	21	SCL	5.3	0.3
709	Harllee Branch	357	SI	79	SNL	5.1	0.2
709	Harllee Branch	358	SI	99	SCL	5.3	0.3
709	Harllee Branch	358	SI	1	SNL	5.1	0.2
709	Harllee Branch	359	SI	94	SCL	5.3	0.3
709	Harllee Branch	359	SI	6	SNL	5.1	0.2
6193	Harrington	877	LF	100	SLT	8.1	0.7
6193	Harrington	878	LF	100	SLT	8.1	0.85
3944	Harrison Power Station	158	SI	53	SCL	5.3	0.5
3944	Harrison Power Station	158	SI	47	SLT	5.1	0.4
3944	Harrison Power Station	891	LF	100	SCL	5.3	0.5
3179	Hatfield's Ferry Power Station	880	LF	100	SCL	5.8	0.4
3179	Hatfield's Ferry Power Station	1215	SI	100	SLT	5.6	0.5
3179	Hatfield's Ferry Power Station	1216	SI	100	SLT	5.6	0.5
3179	Hatfield's Ferry Power Station	1217	SI	100	SLT	5.6	0.5

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
3179	Hatfield's Ferry Power Station	1218	SI	100	SLT	5.6	0.5
3179	Hatfield's Ferry Power Station	1219	SI	100	SLT	5.6	0.5
891	Havana	392	SI	100	SCL	6.8	1.6
891	Havana	393	SI	15	SCL	6.8	1.6
891	Havana	393	SI	85	SNL	6.0	0.4
2079	Hawthorn	599	SI	100	SLT	7.7	0.9
2079	Hawthorn	962	LF	100	SLT	7.7	0.9
525	Hayden	332	SI	100	SLT	7.7	0.9
525	Hayden	333	SI	100	SLT	7.7	0.9
525	Hayden	334	SI	100	SLT	7.7	0.9
525	Hayden	335	SI	100	SLT	7.7	0.9
525	Hayden	336	SI	100	SLT	7.7	0.9
525	Hayden	337	SI	100	SLT	7.7	0.9
525	Hayden	882	LF	100	SNL	7.1	1
525	Hayden	1146	LF	100	SLT	7.7	0.9
3251	HB Robinson / Darlington Electric Power Plant	104	SI	100	SNL	5.2	0.4
892	Hennepin Power Station	394	SI	100	SLT	7.1	1.9
892	Hennepin Power Station	883	LF	100	SLT	7.1	1.9
1382	HMP&L Station Two Henderson	556	SI	100	SLT	5.3	0.3
1382	HMP&L Station Two Henderson	557	SI	100	SLT	5.3	0.3
1382	HMP&L Station Two Henderson	984	LF	39	SCL	6.5	0.6
1382	HMP&L Station Two Henderson	984	LF	61	SLT	5.3	0.33
108	HOLCOMB	1147	LF	100	SNL	7.3	0.1
3122	Homer City Station	90	SI	100	SLT	4.8	0.5
3122	Homer City Station	91	SI	100	SLT	4.8	0.5
3122	Homer City Station	92	SI	100	SLT	4.8	0.5
3122	Homer City Station	719	SI	100	SLT	4.8	0.5
3122	Homer City Station	720	SI	100	SLT	4.8	0.5
3122	Homer City Station	721	SI	100	SLT	4.8	0.5
3122	Homer City Station	722	SI	100	SLT	4.8	0.5
3122	Homer City Station	723	SI	100	SLT	4.8	0.5
3122	Homer City Station	724	SI	100	SLT	4.8	0.5
3122	Homer City Station	725	SI	100	SLT	4.8	0.5
3122	Homer City Station	726	SI	100	SLT	4.8	0.5
3122	Homer City Station	727	SI	100	SLT	4.8	0.5
3122	Homer City Station	728	SI	100	SLT	4.8	0.5

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
3122	Homer City Station	729	SI	100	SLT	4.8	0.5
3122	Homer City Station	884	LF	100	SLT	4.8	0.5
3122	Homer City Station	886	LF	100	SLT	4.9	0.53
3122	Homer City Station	1134	LF	100	SLT	4.8	0.50
1943	Hoot Lake	887	LF	100	SNL	7.5	2.5
1943	Hoot Lake	1148	LF	100	SNL	7.4	3.3
1943	Hoot Lake	1156	LF	100	SNL	7.4	3.3
1943	Hoot Lake	1157	LF	100	SNL	7.4	3.3
1943	Hoot Lake	1158	LF	100	SNL	7.4	3.3
1943	Hoot Lake	1159	LF	100	SNL	7.6	1.6
1943	Hoot Lake	1160	LF	100	SNL	7.5	1.8
10771	Hopewell	1362	SI	100	SLT	4.9	0.5
6772	Hugo	229	SI	100	SCL	7.4	1.4
6772	Hugo	230	SI	100	SCL	7.4	1.4
6772	Hugo	231	SI	100	SCL	7.3	1.4
6772	Hugo	232	SI	100	SCL	7.3	1.4
6772	Hugo	755	LF	100	SCL	7.4	1.4
3176	Hunlock Power Station	102	SI	100	SLT	5.4	0.6
3176	Hunlock Power Station	103	SI	100	SLT	5.4	0.6
6165	Hunter Plant	756	LF	100	SNL	8.3	0.3
6165	Hunter Plant	1258	SI	100	SCL	8.2	0.5
8069	Huntington Plant	757	LF	100	SLT	8.3	0.38
8069	Huntington Plant	758	LF	100	SLT	8.4	0.4
8069	Huntington Plant	759	LF	100	SLT	8.4	0.4
8069	Huntington Plant	1363	SI	100	SLT	8.4	0.4
8069	Huntington Plant	1364	SI	100	SLT	8.4	0.4
863	Hutsonville	381	SI	100	SLT	7.1	1.9
863	Hutsonville	382	SI	100	SLT	7.1	1.9
863	Hutsonville	383	SI	100	SLT	7.1	1.9
863	Hutsonville	384	SI	100	SLT	7.1	1.9
6065	Iatan	40	SI	100	SLT	7.7	0.90
6065	Iatan	1154	LF	100	SLT	7.7	0.9
6641	Independence	1153	LF	56	SCL	6.4	0.6
6641	Independence	1153	LF	44	SLT	6.2	0.6
2132	Independence Power & Light - Blue Valley Station	616	SI	100	SLT	6.4	1
2132	Independence Power & Light - Blue Valley Station	617	SI	100	SLT	6.4	1
2132	Independence Power & Light - Blue Valley Station	618	SI	100	SLT	6.4	1
594	Indian River Generating Station	339	SI	100	SNL	4.6	0.6

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
594	Indian River Generating Station	340	SI	100	SNL	4.6	0.6
594	Indian River Generating Station	762	LF	100	SNL	4.6	0.6
594	Indian River Generating Station	775	LF	100	SNL	4.6	0.6
6481	Intermountain Power Project	214	SI	35	SCL	8.8	0.5
6481	Intermountain Power Project	214	SI	65	SNL	8.7	0.4
6481	Intermountain Power Project	215	SI	35	SCL	8.8	0.5
6481	Intermountain Power Project	215	SI	65	SNL	8.7	0.4
6481	Intermountain Power Project	216	SI	35	SCL	8.8	0.5
6481	Intermountain Power Project	216	SI	65	SNL	8.7	0.4
6481	Intermountain Power Project	217	SI	35	SCL	8.8	0.5
6481	Intermountain Power Project	217	SI	65	SNL	8.7	0.4
6481	Intermountain Power Project	218	SI	35	SCL	8.8	0.5
6481	Intermountain Power Project	218	SI	65	SNL	8.7	0.4
6481	Intermountain Power Project	219	SI	35	SCL	8.8	0.5
6481	Intermountain Power Project	219	SI	65	SNL	8.7	0.4
7097	J K Spruce	753	LF	100	SCL	6.7	0.5
7097	J K Spruce	1368	SI	100	SCL	6.7	0.5
7097	J K Spruce	1369	SI	100	SCL	6.7	0.5
7097	J K Spruce	1370	SI	100	SCL	6.7	0.5
7097	J K Spruce	1371	SI	100	SCL	6.7	0.5
7097	J K Spruce	1372	SI	100	SCL	6.7	0.5
7097	J K Spruce	1373	SI	100	SCL	6.7	0.5
2850	J M Stuart	706	SI	100	SCL	5.7	0.6
2850	J M Stuart	707	SI	100	SCL	5.7	0.6
2850	J M Stuart	708	SI	100	SCL	5.7	0.6
2850	J M Stuart	709	SI	100	SCL	5.7	0.6
2850	J M Stuart	710	SI	100	SCL	5.7	0.6
2850	J M Stuart	711	SI	100	SCL	5.7	0.6

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
2850	J M Stuart	766	LF	100	SCL	5.7	0.6
2850	J M Stuart	767	LF	100	SCL	5.7	0.6
6181	J T Deely	768	LF	100	SCL	6.7	0.5
6181	J T Deely	1002	LF	100	SCL	6.7	0.5
6181	J T Deely	1291	SI	100	SCL	6.7	0.5
6181	J T Deely	1292	SI	100	SCL	6.7	0.5
6181	J T Deely	1293	SI	100	SCL	6.7	0.5
6181	J T Deely	1294	SI	100	SCL	6.7	0.5
6181	J T Deely	1295	SI	100	SCL	6.7	0.5
6181	J T Deely	1296	SI	100	SCL	6.7	0.5
1720	J.C. Weadock	573	SI	96	SLT	7.9	1
1720	J.C. Weadock	573	SI	4	SNL	6.3	1.1
1720	J.C. Weadock	574	SI	96	SLT	7.9	1
1720	J.C. Weadock	574	SI	4	SNL	6.3	1.1
1720	J.C. Weadock	575	SI	96	SLT	7.9	1
1720	J.C. Weadock	575	SI	4	SNL	6.3	1.1
1720	J.C. Weadock	576	SI	96	SLT	7.9	1
1720	J.C. Weadock	576	SI	4	SNL	6.3	1.1
1720	J.C. Weadock	1003	LF	100	SLT	7.9	1
1723	J.R Whiting	577	SI	100	SCL	7.1	0.9
1723	J.R Whiting	578	SI	100	SCL	7.1	0.9
1723	J.R Whiting	579	SI	100	SCL	7.1	0.9
1723	J.R Whiting	580	SI	100	SCL	7.1	0.9
1723	J.R Whiting	965	LF	100	SCL	7.1	0.9
1723	J.R Whiting	1000	LF	100	SCL	7.1	0.9
710	Jack McDonough	360	SI	100	SNL	5.3	0.1
710	Jack McDonough	361	SI	100	SNL	5.3	0.1
710	Jack McDonough	362	SI	100	SNL	5.3	0.1
710	Jack McDonough	363	SI	100	SNL	5.3	0.1
710	Jack McDonough	968	LF	100	SNL	5.3	0.1
2049	Jack Watson	595	SI	100	SLT	4.9	1.4
2049	Jack Watson	769	LF	100	SLT	4.7	1.9
1830	James De Young	770	LF	100	SCL	6.9	2.5
1830	James De Young	1333	SI	100	SNL	5.9	0.7
6002	James H. Miller Jr.	16	SI	100	SLT	5.1	0.3
2161	James River Power Station	619	SI	74	SCL	5.2	0.42
2161	James River Power Station	619	SI	26	SLT	6.2	0.8
2161	James River Power Station	771	LF	4	SCL	5.1	0.4
2161	James River Power Station	771	LF	96	SLT	6.2	0.8
2187	JE Corette Plant	764	LF	100	SLT	8.0	0.7
2187	JE Corette Plant	1249	SI	100	SLT	8.0	0.7
2187	JE Corette Plant	1250	SI	100	SLT	8.0	0.7
3319	Jefferies	117	SI	100	SLT	5.4	0.68

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
3319	Jefferies	118	SI	100	SLT	5.4	0.68
6068	Jeffrey Energy Center	41	SI	100	SCL	7.2	2.1
6068	Jeffrey Energy Center	42	SI	100	SCL	7.2	2.1
6068	Jeffrey Energy Center	43	SI	100	SCL	7.2	2.1
6068	Jeffrey Energy Center	772	LF	100	SCL	7.2	2.1
6068	Jeffrey Energy Center	773	LF	100	SCL	7.2	2.1
8066	Jim Bridger Plant Units 1-4	244	SI	100	SNL	8.3	0.2
8066	Jim Bridger Plant Units 1-4	245	SI	100	SNL	8.3	0.2
8066	Jim Bridger Plant Units 1-4	774	LF	100	SNL	8.3	0.2
3935	John E. Amos	153	SI	100	SLT	6.0	0.46
3935	John E. Amos	154	SI	100	SLT	6.0	0.46
3935	John E. Amos	740	LF	100	SLT	5.3	0.4
3935	John E. Amos	742	LF	100	SLT	5.3	0.4
4271	John P. Madgett	990	LF	100	SLT	7.2	1.6
4271	John P. Madgett	991	LF	100	SLT	7.2	1.6
3405	John Sevier	131	SI	11	SCL	5.1	0.2
3405	John Sevier	131	SI	89	SLT	6.0	0.5
3405	John Sevier	132	SI	11	SCL	5.1	0.2
3405	John Sevier	132	SI	89	SLT	6.0	0.5
3405	John Sevier	763	LF	100	SLT	6.4	0.5
3406	Johnsonville	133	SI	2	SCL	4.9	0.5
3406	Johnsonville	133	SI	98	SLT	5.2	0.40
3406	Johnsonville	291	SI	2	SCL	4.9	0.5
3406	Johnsonville	291	SI	98	SLT	5.2	0.40
3406	Johnsonville	732	LF	100	SLT	5.2	0.4
3406	Johnsonville	733	LF	100	SLT	5.2	0.4
384	Joliet 29	309	SI	13	SCL	7.1	1.4
384	Joliet 29	309	SI	87	SLT	6.9	1.7
384	Joliet 29	1098	LF	13	SCL	7.1	1.4
384	Joliet 29	1098	LF	87	SLT	6.9	1.7
874	Joliet 9	1327	SI	100	SLT	6.9	1.9
874	Joliet 9	1328	SI	100	SLT	6.9	1.9
887	Joppa Steam	390	SI	100	SLT	5.2	0.3
887	Joppa Steam	734	LF	100	SLT	5.2	0.3
3947	Kammer	159	SI	35	SCL	5.5	0.55
3947	Kammer	159	SI	65	SLT	5.7	0.41
3936	Kanawha River	155	SI	100	SNL	5.1	0.40
1381	Kenneth C Coleman	553	SI	100	SCL	5.8	0.5
1381	Kenneth C Coleman	554	SI	95	SCL	5.9	0.53
1381	Kenneth C Coleman	554	SI	5	SLT	5.4	0.4
1381	Kenneth C Coleman	555	SI	100	SCL	5.8	0.5
3136	Keystone	736	LF	100	SLT	5.0	0.6
3136	Keystone	1151	LF	100	SLT	4.9	0.7

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
3136	Keystone	1152	LF	100	SLT	5.0	0.65
3136	Keystone	1297	SI	100	SLT	5.0	0.63
3136	Keystone	1298	SI	100	SLT	5.0	0.6
3136	Keystone	1299	SI	100	SLT	5.0	0.61
3136	Keystone	1300	SI	100	SLT	5.0	0.64
3136	Keystone	1301	SI	100	SLT	4.7	0.64
3136	Keystone	1302	SI	100	SLT	4.6	0.61
3136	Keystone	1303	SI	100	SLT	4.9	0.7
3136	Keystone	1304	SI	100	SLT	4.9	0.7
3136	Keystone	1305	SI	100	SLT	5.0	0.6
3136	Keystone	1306	SI	100	SLT	5.0	0.6
3136	Keystone	1307	SI	100	SLT	5.0	0.6
6031	Killen Station	31	SI	100	SCL	5.7	0.6
6031	Killen Station	32	SI	100	SCL	5.7	0.6
876	Kincaid Generation LLC	388	SI	100	SCL	6.6	1.3
876	Kincaid Generation LLC	969	LF	100	SCL	6.6	1.3
3407	Kingston	134	SI	54	SCL	5.2	0.3
3407	Kingston	134	SI	19	SLT	5.1	0.3
3407	Kingston	134	SI	27	SNL	5.1	0.5
3407	Kingston	135	SI	54	SCL	5.2	0.3
3407	Kingston	135	SI	19	SLT	5.1	0.3
3407	Kingston	135	SI	27	SNL	5.1	0.5
733	Kraft	375	SI	43	SLT	5.1	1
733	Kraft	375	SI	57	SNL	7.2	7.1
733	Kraft	1150	LF	100	SNL	5.3	1.1
2876	Kyger Creek	716	SI	100	SCL	5.7	0.6
2876	Kyger Creek	717	SI	100	SCL	5.7	0.6
2876	Kyger Creek	738	LF	100	SNL	5.1	0.3
2713	L.V. Sutton Electric Plant	665	SI	16	SLT	5.3	1.7
2713	L.V. Sutton Electric Plant	665	SI	84	SNL	5.4	1
2713	L.V. Sutton Electric Plant	666	SI	48	SLT	5.3	1.7
2713	L.V. Sutton Electric Plant	666	SI	52	SNL	5.4	1
1241	La Cygne	513	SI	100	SCL	6.4	0.98
1241	La Cygne	514	SI	100	SCL	6.4	0.98
1241	La Cygne	739	LF	100	SCL	6.3	1
2103	Labadie	607	SI	5	SCL	6.1	0.57
2103	Labadie	607	SI	95	SLT	7.7	0.8
2103	Labadie	608	SI	5	SCL	6.1	0.57
2103	Labadie	608	SI	95	SLT	7.7	0.8
2098	Lake Road	605	SI	100	SLT	7.7	0.9
2098	Lake Road	606	SI	100	SLT	7.6	0.91
2098	Lake Road	752	LF	100	SLT	7.7	0.9
2838	Lake Shore	1270	SI	100	SNL	6.3	0.2

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
964	Lakeside	400	SI	8	SCL	5.8	0.4
964	Lakeside	400	SI	92	SLT	7.1	1.9
1047	Lansing	477	SI	100	SLT	6.7	0.88
1047	Lansing	478	SI	100	SLT	6.7	0.88
1047	Lansing	730	LF	100	SLT	6.7	0.7
1047	Lansing	741	LF	100	SLT	6.7	0.7
643	Lansing Smith	341	SI	100	SNL	4.9	3.4
643	Lansing Smith	743	LF	100	SNL	4.9	3.3
6204	Laramie River Station	188	SI	100	SLT	7.9	0.4
6204	Laramie River Station	189	SI	100	SLT	7.9	0.4
6204	Laramie River Station	744	LF	100	SLT	7.9	0.4
1891	Laskin Energy Center	588	SI	0	SCL	6.3	11.5
1891	Laskin Energy Center	588	SI	100	SNL	5.8	13
1891	Laskin Energy Center	589	SI	0	SCL	6.3	11.5
1891	Laskin Energy Center	589	SI	100	SNL	5.8	13
1250	Lawrence Energy Center	515	SI	44	SCL	6.6	1.3
1250	Lawrence Energy Center	515	SI	56	SLT	7.3	1.3
1250	Lawrence Energy Center	516	SI	44	SCL	6.6	1.3
1250	Lawrence Energy Center	516	SI	56	SLT	7.3	1.3
1250	Lawrence Energy Center	517	SI	44	SCL	6.6	1.3
1250	Lawrence Energy Center	517	SI	56	SLT	7.3	1.3
1250	Lawrence Energy Center	518	SI	44	SCL	6.6	1.3
1250	Lawrence Energy Center	518	SI	56	SLT	7.3	1.3
1250	Lawrence Energy Center	745	LF	44	SCL	6.6	1
1250	Lawrence Energy Center	745	LF	56	SLT	7.3	1.3
1250	Lawrence Energy Center	747	LF	48	SCL	6.6	1
1250	Lawrence Energy Center	747	LF	52	SLT	7.3	1.3
1250	Lawrence Energy Center	1149	LF	83	SCL	6.6	1
1250	Lawrence Energy Center	1149	LF	17	SLT	7.3	1.3
2817	Leland Olds	683	SI	100	SCL	7.8	0.2
2817	Leland Olds	684	SI	100	SCL	7.8	0.2
2817	Leland Olds	685	SI	100	SCL	7.8	0.2
2817	Leland Olds	748	LF	98	SCL	7.8	0.2
2817	Leland Olds	748	LF	2	SLT	7.8	0.9
2817	Leland Olds	749	LF	100	SLT	7.8	0.9
6089	Lewis & Clark	750	LF	100	SLT	8.0	0.8
6089	Lewis & Clark	751	LF	100	SLT	8.0	0.45
6089	Lewis & Clark	786	LF	100	SLT	7.9	0.54
6089	Lewis & Clark	1374	SI	100	SLT	7.9	0.6
6089	Lewis & Clark	1375	SI	100	SLT	7.9	0.6
6089	Lewis & Clark	1376	SI	100	SLT	7.9	0.6
6089	Lewis & Clark	1377	SI	100	SLT	7.9	0.6
6089	Lewis & Clark	1378	SI	100	SLT	8.0	0.34

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
298	Limestone	300	SI	100	SLT	6.2	0.70
298	Limestone	301	SI	100	SLT	6.2	0.70
298	Limestone	302	SI	100	SLT	6.2	0.70
298	Limestone	303	SI	100	SLT	6.2	0.70
298	Limestone	304	SI	100	SLT	6.2	0.70
298	Limestone	305	SI	100	SLT	6.2	0.70
298	Limestone	306	SI	100	SLT	6.2	0.70
298	Limestone	307	SI	100	SLT	6.2	0.70
298	Limestone	308	SI	100	SLT	6.2	0.7
298	Limestone	821	LF	100	SLT	6.2	0.7
2240	Lon Wright	765	LF	100	SCL	7.8	1.3
6664	Louisa	222	SI	37	SCL	6.4	2.8
6664	Louisa	222	SI	63	SNL	6.3	1
6664	Louisa	223	SI	100	SCL	6.0	0.6
6664	Louisa	801	LF	100	SNL	6.3	1
976	Marion Generating Station	401	SI	50	SCL	5.0	0.4
976	Marion Generating Station	401	SI	50	SLT	5.2	0.3
976	Marion Generating Station	402	SI	34	SCL	5.0	0.4
976	Marion Generating Station	402	SI	66	SLT	5.2	0.30
976	Marion Generating Station	403	SI	100	SCL	5.0	0.4
976	Marion Generating Station	404	SI	100	SCL	5.0	0.4
976	Marion Generating Station	405	SI	18	SCL	5.0	0.4
976	Marion Generating Station	405	SI	82	SLT	5.2	0.3
976	Marion Generating Station	406	SI	77	SCL	5.0	0.4
976	Marion Generating Station	406	SI	23	SLT	5.2	0.3
976	Marion Generating Station	407	SI	100	SCL	5.0	0.4
976	Marion Generating Station	408	SI	100	SCL	5.0	0.4
976	Marion Generating Station	409	SI	100	SCL	5.0	0.4
976	Marion Generating Station	410	SI	42	SCL	5.0	0.4
976	Marion Generating Station	410	SI	58	SLT	5.2	0.3
976	Marion Generating Station	411	SI	100	SLT	5.2	0.3
976	Marion Generating Station	412	SI	66	SCL	5.0	0.4
976	Marion Generating Station	412	SI	34	SLT	5.2	0.3
976	Marion Generating Station	802	LF	100	SCL	5.0	0.4
2727	Marshall	680	SI	100	SCL	5.3	0.3
2727	Marshall	803	LF	100	SCL	5.3	0.3
2727	Marshall	804	LF	100	SCL	5.3	0.3
492	Martin Drake	805	LF	100	SNL	6.9	0.9
492	Martin Drake	1251	SI	100	SNL	6.9	0.9
492	Martin Drake	1252	SI	100	SNL	6.9	0.9
492	Martin Drake	1253	SI	100	SNL	6.9	0.9
492	Martin Drake	1254	SI	100	SNL	6.9	0.9
6146	Martin Lake	806	LF	100	SNL	5.1	0.6

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
6146	Martin Lake	807	LF	100	SNL	5.1	0.6
6146	Martin Lake	808	LF	100	SCL	5.1	0.6
6146	Martin Lake	810	LF	100	SCL	5.1	0.6
6146	Martin Lake	822	LF	100	SCL	5.1	0.6
6146	Martin Lake	1223	SI	100	SCL	5.1	0.6
6146	Martin Lake	1224	SI	100	SCL	5.1	0.6
6146	Martin Lake	1225	SI	100	SCL	5.1	0.6
6146	Martin Lake	1226	SI	100	SCL	5.1	0.6
6250	Mayo Electric Generating Facility	204	SI	100	SNL	6.1	0.3
6124	McIntosh	87	SI	56	SCL	5.4	2.5
6124	McIntosh	87	SI	44	SNL	4.9	1.9
3287	McMeekin	1155	LF	100	SCL	5.0	0.3
2104	Meramec	609	SI	63	SCL	6.4	0.93
2104	Meramec	609	SI	37	SLT	6.4	1
2104	Meramec	610	SI	63	SCL	6.4	0.93
2104	Meramec	610	SI	37	SLT	6.4	1
2104	Meramec	611	SI	63	SCL	6.4	0.93
2104	Meramec	611	SI	37	SLT	6.4	1
2104	Meramec	612	SI	63	SCL	6.4	0.93
2104	Meramec	612	SI	37	SLT	6.4	1
2104	Meramec	613	SI	63	SCL	6.4	0.93
2104	Meramec	613	SI	37	SLT	6.4	1
864	Meredosia	385	SI	48	SCL	6.8	1.6
864	Meredosia	385	SI	52	SNL	6.0	0.4
864	Meredosia	386	SI	48	SCL	6.8	1.6
864	Meredosia	386	SI	52	SNL	6.0	0.4
6213	Merom	190	SI	64	SCL	5.6	0.4
6213	Merom	190	SI	36	SLT	5.5	0.4
6213	Merom	812	LF	100	SLT	5.5	0.4
6213	Merom	813	LF	100	SLT	5.5	0.4
2364	Merrimack Station	754	LF	100	SNL	5.1	3
2364	Merrimack Station	1319	SI	100	SNL	5.3	0.5
2364	Merrimack Station	1320	SI	100	SNL	5.3	0.5
2832	Miami Fort	699	SI	100	SLT	7.1	1.9
2832	Miami Fort	700	SI	100	SLT	7.1	1.9
2832	Miami Fort	1109	LF	100	SLT	7.1	1.9
2832	Miami Fort	1121	LF	99	SCL	6.5	0.4
2832	Miami Fort	1121	LF	1	SLT	7.1	1.9
997	Michigan City	448	SI	100	SNL	6.2	0.4
997	Michigan City	449	SI	100	SNL	6.2	0.4
997	Michigan City	450	SI	100	SNL	6.2	0.4
997	Michigan City	451	SI	100	SNL	6.2	0.4

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
997	Michigan City	452	SI	100	SNL	6.2	0.4
997	Michigan City	453	SI	100	SNL	6.2	0.4
1364	Mill Creek	543	SI	100	SCL	5.2	0.3
1364	Mill Creek	544	SI	85	SCL	6.0	0.67
1364	Mill Creek	544	SI	15	SLT	6.5	0.6
1364	Mill Creek	545	SI	85	SCL	6.0	0.67
1364	Mill Creek	545	SI	15	SLT	6.5	0.6
1364	Mill Creek	546	SI	85	SCL	6.0	0.67
1364	Mill Creek	546	SI	15	SLT	6.5	0.6
1364	Mill Creek	547	SI	85	SCL	6.0	0.67
1364	Mill Creek	547	SI	15	SLT	6.5	0.6
1364	Mill Creek	817	LF	100	SCL	5.9	0.5
1364	Mill Creek	818	LF	100	SCL	5.9	0.5
1364	Mill Creek	819	LF	100	SCL	5.9	0.5
2823	Milton R. Young Station	686	SI	100	SLT	7.7	0.92
2823	Milton R. Young Station	687	SI	100	SLT	7.7	0.92
2823	Milton R. Young Station	688	SI	100	SLT	7.7	0.92
2823	Milton R. Young Station	689	SI	100	SLT	7.7	0.92
2823	Milton R. Young Station	777	LF	100	SLT	7.6	0.9
2823	Milton R. Young Station	788	LF	100	SLT	7.6	0.9
2823	Milton R. Young Station	809	LF	100	SLT	7.6	0.9
2823	Milton R. Young Station	811	LF	100	SLT	7.7	0.9
2823	Milton R. Young Station	820	LF	100	SLT	7.8	0.9
2171	Missouri City	1257	SI	100	SLT	7.7	0.9
3948	Mitchell	160	SI	6	SCL	5.3	0.5
3948	Mitchell	160	SI	94	SLT	6.2	0.4
3948	Mitchell	161	SI	36	SCL	5.3	0.5
3948	Mitchell	161	SI	64	SLT	6.2	0.4
727	Mitchell	364	SI	100	SLT	5.2	0.37
727	Mitchell	365	SI	100	SLT	5.2	0.37
727	Mitchell	366	SI	100	SLT	5.2	0.37
3181	Mitchell Power Station	778	LF	100	SLT	5.6	0.5
3181	Mitchell Power Station	779	LF	100	SLT	5.6	0.5
1048	ML Kapp	479	SI	70	SCL	6.4	1.8
1048	ML Kapp	479	SI	30	SLT	6.8	1.4
1048	ML Kapp	480	SI	70	SCL	6.4	1.8
1048	ML Kapp	480	SI	30	SLT	6.8	1.4
1048	ML Kapp	481	SI	70	SCL	6.4	1.8
1048	ML Kapp	481	SI	30	SLT	6.8	1.4
1048	ML Kapp	482	SI	70	SCL	6.4	1.8
1048	ML Kapp	482	SI	30	SLT	6.8	1.4
1733	Monroe Power Plant	582	SI	100	SCL	7.1	0.9
1733	Monroe Power Plant	583	SI	8	SCL	7.1	0.9

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
1733	Monroe Power Plant	583	SI	92	SLT	7.1	0.6
6147	Monticello	780	LF	100	SCL	5.6	0.6
6147	Monticello	781	LF	100	SCL	5.6	0.6
6147	Monticello	782	LF	100	SCL	5.6	0.6
6147	Monticello	1203	SI	100	SCL	5.6	0.6
6147	Monticello	1204	SI	100	SCL	5.6	0.6
6147	Monticello	1205	SI	100	SCL	5.6	0.6
6147	Monticello	1206	SI	100	SCL	5.6	0.6
2080	Montrose	600	SI	100	SCL	6.4	1
2080	Montrose	601	SI	100	SCL	6.4	1
2080	Montrose	602	SI	100	SCL	6.4	1
2080	Montrose	783	LF	100	SCL	6.4	1
1573	Morgantown Generating Plant	785	LF	100	SNL	4.8	0.4
1573	Morgantown Generating Plant	1108	LF	100	SNL	4.6	0.7
1606	Mount Tom	563	SI	100	SLT	5.0	0
1606	Mount Tom	564	SI	74	SLT	5.4	0.22
1606	Mount Tom	564	SI	26	SNL	5.0	0.9
1606	Mount Tom	565	SI	74	SLT	5.4	0.22
1606	Mount Tom	565	SI	26	SNL	5.0	0.9
1606	Mount Tom	798	LF	100	SLT	5.0	0
6264	Mountaineer	211	SI	100	SLT	6.0	0.4
6264	Mountaineer	787	LF	100	SLT	5.3	0.4
3954	Mt. Storm	789	LF	100	SLT	4.6	0.4
3954	Mt. Storm	1110	LF	94	SLT	4.6	0.4
3954	Mt. Storm	1110	LF	6	SNL	4.5	0.5
3954	Mt. Storm	1111	LF	100	SLT	4.6	0.4
3954	Mt. Storm	1112	LF	100	SNL	4.5	0.5
1167	Muscatine #1	792	LF	100	SCL	6.3	1.6
1167	Muscatine #1	1361	SI	100	SNL	6.3	1
2872	Muskingum River	712	SI	100	SCL	6.0	0.4
2872	Muskingum River	713	SI	100	SCL	6.0	0.2
2872	Muskingum River	714	SI	100	SCL	6.0	0.32
2872	Muskingum River	715	SI	100	SCL	6.0	0.4
2952	Muskogee	1172	SI	100	SLT	7.3	0.5
2952	Muskogee	1173	SI	100	SLT	7.3	0.5
2952	Muskogee	1174	SI	100	SLT	7.3	0.5
4162	Naughton Plant	12	SI	100	SLT	8.2	0.5
4162	Naughton Plant	13	SI	100	SLT	8.2	0.5
4162	Naughton Plant	14	SI	100	SLT	8.2	0.5
4162	Naughton Plant	15	SI	100	SLT	8.2	0.5
4162	Naughton Plant	980	LF	100	SLT	8.2	0.5

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
4941	Navajo Generating Station	793	LF	100	SNL	8.0	0.5
6064	Nearman Creek	39	SI	100	SLT	7.3	0.94
6064	Nearman Creek	794	LF	100	SLT	7.7	0.9
6064	Nearman Creek	795	LF	100	SLT	6.5	1.0
6096	Nebraska City	797	LF	100	SLT	7.9	0.8
6096	Nebraska City	943	LF	100	SLT	7.9	0.8
6096	Nebraska City	1271	SI	100	SLT	7.9	0.8
6096	Nebraska City	1272	SI	100	SLT	7.9	0.8
4054	Nelson Dewey	170	SI	100	SLT	6.8	1.4
4054	Nelson Dewey	171	SI	100	SLT	6.8	1.4
4054	Nelson Dewey	893	LF	100	SLT	6.8	1.4
3138	New Castle Plant	941	LF	100	SLT	6.2	0.6
3138	New Castle Plant	1349	SI	100	SLT	6.2	0.6
3138	New Castle Plant	1350	SI	100	SLT	6.2	0.6
2167	New Madrid	620	SI	80	SCL	6.9	0.4
2167	New Madrid	620	SI	20	SNL	5.9	0.6
2167	New Madrid	621	SI	100	SCL	6.9	0.4
2167	New Madrid	622	SI	99	SLT	6.2	0.6
2167	New Madrid	622	SI	1	SNL	5.9	0.6
2167	New Madrid	623	SI	97	SCL	6.9	0.4
2167	New Madrid	623	SI	3	SNL	5.9	0.6
2167	New Madrid	1032	LF	100	SLT	6.2	0.6
6017	Newton	21	SI	100	SLT	5.3	0.5
6017	Newton	22	SI	100	SLT	5.3	0.5
6017	Newton	1033	LF	100	SLT	5.3	0.5
6017	Newton	1034	LF	100	SLT	5.3	0.5
2291	North Omaha	1036	LF	100	SLT	7.9	0.8
2291	North Omaha	1113	LF	100	SLT	7.9	0.8
2291	North Omaha	1220	SI	100	SLT	7.9	0.8
2291	North Omaha	1221	SI	100	SLT	7.9	0.8
2291	North Omaha	1222	SI	100	SLT	7.9	0.8
8224	North Valmy	1037	LF	100	SNL	8.6	0.3
2963	Northeastern	718	SI	100	SCL	6.8	1.1
2963	Northeastern	1038	LF	100	SCL	6.5	1.0
667	Northside Generating Station	1039	LF	100	SNL	5.6	0.6
10030	NRG Energy Center Dover	251	SI	100	SLT	4.6	0.5
527	Nucla	338	SI	36	SLT	8.1	0.1
527	Nucla	338	SI	64	SNL	8.0	0.5
527	Nucla	964	LF	36	SLT	8.1	0.1
527	Nucla	964	LF	64	SNL	8.0	0.5
2848	O H Hutchings	703	SI	100	SLT	7.1	1.9
2848	O H Hutchings	704	SI	100	SLT	7.1	1.9

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
2848	O H Hutchings	705	SI	100	SLT	7.1	1.9
6180	Oak Grove	1040	LF	100	SLT	6.2	0.7
6180	Oak Grove	1042	LF	100	SLT	6.2	0.7
6180	Oak Grove	1054	LF	100	SLT	6.2	0.7
6180	Oak Grove	1185	SI	100	SLT	6.2	0.7
127	Oklaunion	281	SI	100	SLT	8.0	0.2
127	Oklaunion	282	SI	100	SLT	8.0	0.2
127	Oklaunion	283	SI	100	SLT	8.0	0.2
127	Oklaunion	841	LF	100	SLT	8.0	0.2
4151	Osage	1031	LF	100	SCL	6.0	0.3
4151	Osage	1044	LF	100	SCL	6.0	0.3
4151	Osage	1266	SI	100	SCL	6.0	0.3
4151	Osage	1267	SI	100	SCL	6.0	0.3
1831	Otto E. Eckert Station	586	SI	100	SNL	6.9	1
6254	Ottumwa	205	SI	6	SCL	5.9	0.64
6254	Ottumwa	205	SI	94	SLT	6.2	1.2
6254	Ottumwa	206	SI	6	SCL	5.9	0.64
6254	Ottumwa	206	SI	94	SLT	6.2	1.2
6254	Ottumwa	207	SI	6	SCL	5.9	0.64
6254	Ottumwa	207	SI	94	SLT	6.2	1.2
6254	Ottumwa	208	SI	6	SCL	5.9	0.64
6254	Ottumwa	208	SI	94	SLT	6.2	1.2
6254	Ottumwa	1045	LF	79	SCL	6.0	0.73
6254	Ottumwa	1045	LF	21	SLT	6.0	0.7
1378	Paradise	548	SI	100	SLT	6.1	0.47
1378	Paradise	549	SI	100	SLT	6.1	0.47
1378	Paradise	550	SI	100	SLT	6.1	0.47
6248	Pawnee	191	SI	100	SNL	7.5	0.41
6248	Pawnee	192	SI	100	SNL	7.5	0.41
6248	Pawnee	193	SI	100	SNL	7.5	0.41
6248	Pawnee	194	SI	100	SNL	7.5	0.41
6248	Pawnee	195	SI	100	SNL	7.5	0.41
6248	Pawnee	196	SI	100	SNL	7.5	0.41
6248	Pawnee	197	SI	100	SNL	7.5	0.41
6248	Pawnee	1046	LF	100	SNL	7.3	0.3
6238	Pearl Station	1211	SI	100	SCL	6.8	1.6
3938	Philip Sporn	156	SI	100	SLT	6.0	0.4
3938	Philip Sporn	157	SI	100	SLT	6.0	0.4
3938	Philip Sporn	979	LF	24	SCL	5.5	0.27
3938	Philip Sporn	979	LF	57	SLT	6.0	0.4
3938	Philip Sporn	979	LF	19	SNL	5.4	0.3
2843	Picway	702	SI	100	SLT	7.1	0.6
7902	Pirkey	233	SI	100	SLT	4.9	0.6

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
7902	Pirkey	234	SI	100	SLT	4.9	0.6
7902	Pirkey	235	SI	100	SLT	4.9	0.6
7902	Pirkey	236	SI	100	SLT	4.9	0.6
7902	Pirkey	237	SI	100	SLT	4.9	0.6
7902	Pirkey	238	SI	100	SLT	4.9	0.6
7902	Pirkey	1132	LF	100	SLT	4.9	0.6
59	Platte	1047	LF	100	SNL	6.6	0.4
59	Platte	1048	LF	100	SNL	6.6	0.4
6170	Pleasant Prairie	1049	LF	100	SCL	7.3	10.3
6004	Pleasants Power Station	17	SI	100	SLT	5.3	0.4
6004	Pleasants Power Station	1050	LF	100	SLT	5.3	0.4
7242	Polk	1051	LF	100	SNL	5.6	0.7
3113	Portland	1020	LF	100	SNL	5.3	0.5
3113	Portland	1041	LF	100	SNL	6.2	0.3
3113	Portland	1043	LF	100	SNL	5.3	0.5
3113	Portland	1052	LF	100	SNL	5.3	0.5
3113	Portland	1199	SI	100	SNL	6.2	0.3
3113	Portland	1200	SI	100	SNL	6.2	0.3
3113	Portland	1201	SI	100	SNL	6.2	0.3
879	Powerton	1227	SI	100	SNL	6.5	1
879	Powerton	1228	SI	100	SNL	6.5	1
879	Powerton	1229	SI	100	SNL	6.5	1
879	Powerton	1230	SI	100	SNL	6.5	1
879	Powerton	1231	SI	100	SNL	6.5	1
879	Powerton	1232	SI	100	SNL	6.5	1
879	Powerton	1233	SI	100	SNL	6.5	1
3140	PPL Brunner Island	93	SI	100	SLT	5.1	0.5
3140	PPL Brunner Island	94	SI	100	SLT	5.1	0.5
3140	PPL Brunner Island	95	SI	100	SLT	5.1	0.5
3140	PPL Brunner Island	1114	LF	100	SLT	5.1	0.5
3149	PPL Montour	96	SI	7	SCL	6.0	0.5
3149	PPL Montour	96	SI	93	SLT	5.3	0.53
3149	PPL Montour	97	SI	7	SCL	6.0	0.5
3149	PPL Montour	97	SI	93	SLT	5.3	0.53
3149	PPL Montour	98	SI	7	SCL	6.0	0.5
3149	PPL Montour	98	SI	93	SLT	5.3	0.53
3149	PPL Montour	99	SI	7	SCL	6.0	0.5
3149	PPL Montour	99	SI	93	SLT	5.3	0.53
3149	PPL Montour	100	SI	7	SCL	6.0	0.5
3149	PPL Montour	100	SI	93	SLT	5.3	0.53
3149	PPL Montour	1011	LF	100	SLT	5.4	0.56
3149	PPL Montour	1115	LF	100	SLT	5.2	0.5
1073	Prairie Creek	487	SI	100	SCL	6.4	1.9

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
1073	Prairie Creek	488	SI	100	SCL	6.4	1.9
1073	Prairie Creek	489	SI	100	SCL	6.4	1.9
1073	Prairie Creek	490	SI	100	SCL	6.4	1.9
1073	Prairie Creek	491	SI	100	SCL	6.4	1.9
1073	Prairie Creek	492	SI	100	SCL	6.4	1.9
1073	Prairie Creek	493	SI	100	SCL	6.4	1.9
1073	Prairie Creek	494	SI	100	SCL	6.4	1.9
1073	Prairie Creek	495	SI	100	SCL	6.4	1.9
1073	Prairie Creek	496	SI	100	SCL	6.4	1.9
1769	Presque Isle	1012	LF	100	SNL	5.5	2.4
1769	Presque Isle	1013	LF	100	SNL	5.5	2.4
1769	Presque Isle	1014	LF	100	SNL	5.5	2.4
2403	PSEG Hudson Generating Station	1015	LF	100	SLT	6.2	7.1
2403	PSEG Hudson Generating Station	1351	SI	100	SLT	6.2	7.1
2403	PSEG Hudson Generating Station	1352	SI	100	SLT	6.2	7.1
2408	PSEG Mercer Generating Station	1016	LF	100	SNL	4.9	7.1
2408	PSEG Mercer Generating Station	1197	SI	100	SNL	4.9	7.1
2408	PSEG Mercer Generating Station	1198	SI	100	SNL	4.9	7.1
4072	Pulliam	1017	LF	100	SCL	7.3	4.6
4072	Pulliam	1212	SI	100	SCL	7.3	4.6
1295	Quindaro	1030	LF	100	SLT	6.6	0.99
6639	R D Green	220	SI	100	SLT	5.3	0.3
6639	R D Green	1019	LF	8	SCL	6.5	0.6
6639	R D Green	1019	LF	92	SLT	5.3	0.3
2864	R. E. Burger	976	LF	68	SCL	5.5	0.54
2864	R. E. Burger	976	LF	32	SLT	6.2	0.4
2864	R. E. Burger	1380	SI	100	SCL	5.7	0.6
2864	R. E. Burger	1381	SI	100	SCL	5.7	0.6
1008	R. Gallagher	460	SI	100	SCL	5.9	0.6
1008	R. Gallagher	461	SI	100	SCL	5.9	0.6
1008	R. Gallagher	1001	LF	100	SCL	5.9	0.6
1008	R. Gallagher	1023	LF	100	SCL	5.9	0.6
1008	R. Gallagher	1024	LF	100	SCL	5.9	0.6
1008	R. Gallagher	1025	LF	100	SCL	5.9	0.6
1008	R. Gallagher	1026	LF	100	SCL	5.9	0.6
1008	R. Gallagher	1027	LF	100	SCL	5.9	0.6
1008	R. Gallagher	1029	LF	100	SCL	5.9	0.6

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
1008	R. Gallagher	1053	LF	100	SCL	5.9	0.6
1008	R. Gallagher	1056	LF	100	SCL	5.9	0.6
1570	R. Paul Smith Power Station	561	SI	100	SLT	5.2	0.8
1570	R. Paul Smith Power Station	562	SI	100	SLT	5.2	0.8
1570	R. Paul Smith Power Station	1083	LF	100	SLT	5.2	0.8
2790	R.M. Heskett Station	1080	LF	100	SNL	7.7	1
2790	R.M. Heskett Station	1081	LF	100	SNL	7.7	1
6085	R.M. Schahfer	54	SI	100	SNL	7.0	0.80
6085	R.M. Schahfer	55	SI	100	SNL	6.9	0.75
6085	R.M. Schahfer	56	SI	100	SNL	6.8	0.68
6085	R.M. Schahfer	57	SI	100	SNL	6.8	9.3
6085	R.M. Schahfer	58	SI	100	SNL	7.0	0.79
6085	R.M. Schahfer	67	SI	100	SNL	6.2	0.4
6085	R.M. Schahfer	68	SI	100	SNL	7.0	0.8
6085	R.M. Schahfer	1082	LF	100	SNL	6.8	9.3
6761	Rawhide	225	SI	100	SLT	8.0	0.4
6761	Rawhide	226	SI	100	SLT	8.0	0.4
6761	Rawhide	996	LF	100	SLT	8.0	0.4
6761	Rawhide	1086	LF	100	SLT	8.0	0.4
8219	Ray D Nixon	1087	LF	100	SLT	8.0	0.6
8219	Ray D Nixon	1255	SI	100	SLT	8.0	0.6
55076	Red Hills Generating Facility	1088	LF	100	SLT	5.0	0.2
55076	Red Hills Generating Facility	1256	SI	100	SLT	5.0	0.2
2324	Reid Gardner	630	SI	100	SLT	8.3	0.3
2324	Reid Gardner	631	SI	100	SLT	8.3	0.3
2324	Reid Gardner	632	SI	100	SLT	8.3	0.3
2324	Reid Gardner	633	SI	100	SLT	8.3	0.3
2324	Reid Gardner	634	SI	100	SLT	8.3	0.3
2324	Reid Gardner	635	SI	100	SLT	8.3	0.3
2324	Reid Gardner	636	SI	100	SLT	8.3	0.3
2324	Reid Gardner	637	SI	100	SLT	8.3	0.3
2324	Reid Gardner	1090	LF	100	SLT	8.3	0.3
1740	River Rouge Power Plant	1186	SI	100	SLT	6.8	0.8
2732	Riverbend	681	SI	100	SCL	5.3	0.3
2732	Riverbend	682	SI	100	SCL	5.3	0.3
1081	Riverside	500	SI	100	SCL	6.4	2.8
1081	Riverside	501	SI	100	SCL	6.4	2.8
1927	Riverside	594	SI	32	SLT	6.8	5.3

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
1927	Riverside	594	SI	68	SNL	6.4	1.3
1239	Riverton	512	SI	100	SLT	6.2	0.8
3945	Rivesville Power Station	1095	LF	100	SCL	5.3	0.5
3945	Rivesville Power Station	1116	LF	100	SCL	5.3	0.5
3945	Rivesville Power Station	1355	SI	100	SLT	5.1	0.4
3945	Rivesville Power Station	1356	SI	100	SLT	5.1	0.4
3945	Rivesville Power Station	1357	SI	100	SCL	5.3	0.5
3945	Rivesville Power Station	1358	SI	100	SLT	5.1	0.4
6166	Rockport	179	SI	100	SCL	5.9	0.6
6166	Rockport	1097	LF	100	SCL	5.9	0.6
6190	Rodemacher	185	SI	16	SCL	7.4	1
6190	Rodemacher	185	SI	84	SLT	7.8	0.8
6190	Rodemacher	186	SI	100	SCL	7.4	1
6190	Rodemacher	187	SI	100	SCL	7.4	1
6190	Rodemacher	187	SI	0	SLT	5.1	0.3
2712	Roxboro Steam Electric Plant	661	SI	100	SNL	5.8	0.3
2712	Roxboro Steam Electric Plant	662	SI	100	SNL	5.9	0.28
2712	Roxboro Steam Electric Plant	663	SI	4	SCL	5.1	0.2
2712	Roxboro Steam Electric Plant	663	SI	96	SNL	5.8	0.29
2712	Roxboro Steam Electric Plant	664	SI	100	SNL	5.8	0.3
2712	Roxboro Steam Electric Plant	1096	LF	100	SNL	5.8	0.3
1393	RS Nelson	1084	LF	100	SCL	5.6	0.7
1393	RS Nelson	1085	LF	100	SCL	5.6	0.7
1393	RS Nelson	1329	SI	100	SCL	5.6	0.7
1393	RS Nelson	1330	SI	100	SCL	6.2	2.4
6155	Rush Island	178	SI	42	SCL	5.8	0.73
6155	Rush Island	178	SI	58	SLT	7.0	0.68
6155	Rush Island	1091	LF	100	SLT	5.6	0.4
2451	San Juan	1308	SI	100	SLT	8.4	0
6183	San Miguel	1093	LF	100	SCL	7.8	1.1
6183	San Miguel	1094	LF	100	SCL	7.8	1.1
6183	San Miguel	1365	SI	0	SCL	7.8	1.1
6183	San Miguel	1365	SI	100	SLT	7.5	0.9
6183	San Miguel	1366	SI	100	SLT	7.5	0.9
6183	San Miguel	1367	SI	100	SLT	7.5	0.9
6648	Sandow No 4	221	SI	100	SLT	6.5	0.41
6648	Sandow No 4	1057	LF	100	SLT	6.2	0.7

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
6648	Sandow No 4	1065	LF	100	SLT	6.9	0.02
6648	Sandow No 4	1067	LF	100	SLT	6.9	0
6648	Sandow No 4	1089	LF	100	SLT	6.6	0.27
6648	Sandow No 4	1092	LF	100	SLT	6.9	0
6257	Scherer	209	SI	16	SCL	5.3	0.3
6257	Scherer	209	SI	84	SNL	5.2	0.2
6257	Scherer	210	SI	16	SCL	5.3	0.3
6257	Scherer	210	SI	84	SNL	5.2	0.2
2367	SCHILLER	1058	LF	100	SNL	5.5	0.5
642	Scholz	1346	SI	71	SLT	5.1	0.3
642	Scholz	1346	SI	29	SNL	5.0	0.4
642	Scholz	1347	SI	56	SLT	5.1	0.3
642	Scholz	1347	SI	44	SNL	5.0	0.4
642	Scholz	1348	SI	83	SLT	5.1	0.3
642	Scholz	1348	SI	17	SNL	5.0	0.4
136	Seminole Generating Station	1059	LF	100	SNL	5.0	0.2
1379	Shawnee	551	SI	100	SLT	6.0	0.53
1379	Shawnee	552	SI	100	SLT	6.0	0.53
1379	Shawnee	1060	LF	100	SLT	5.4	0.4
1379	Shawnee	1061	LF	100	SLT	6.7	0.7
3131	Shawville	1062	LF	100	SLT	4.5	0.6
3131	Shawville	1063	LF	100	SLT	4.5	0.6
3131	Shawville	1245	SI	100	SLT	4.5	0.6
3131	Shawville	1246	SI	100	SLT	4.5	0.6
3131	Shawville	1247	SI	100	SLT	4.5	0.6
3131	Shawville	1248	SI	100	SLT	4.5	0.6
2277	Sheldon Station	1055	LF	65	SCL	6.7	0.4
2277	Sheldon Station	1055	LF	35	SLT	7.2	1.3
2277	Sheldon Station	1064	LF	100	SLT	7.2	1.3
2277	Sheldon Station	1066	LF	78	SCL	6.7	0.4
2277	Sheldon Station	1066	LF	22	SLT	7.2	1.3
2277	Sheldon Station	1078	LF	100	SCL	6.7	0.4
2277	Sheldon Station	1360	SI	61	SCL	6.7	0.4
2277	Sheldon Station	1360	SI	39	SLT	7.2	1.3
6090	Sherburne County	69	SI	100	SNL	6.4	1.3
6090	Sherburne County	70	SI	100	SNL	6.4	1.3
6090	Sherburne County	71	SI	100	SNL	6.4	1.3
6090	Sherburne County	72	SI	100	SNL	6.4	1.3
6090	Sherburne County	73	SI	100	SNL	6.4	1.3
6090	Sherburne County	74	SI	100	SNL	6.4	1.3
6090	Sherburne County	1068	LF	100	SNL	6.4	1.3
2094	Sibley	603	SI	100	SLT	6.7	0.98

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
2094	Sibley	604	SI	100	SLT	6.7	0.98
2094	Sibley	1069	LF	100	SLT	6.4	1
6768	Sikeston Power Station	227	SI	4	SLT	6.7	0.7
6768	Sikeston Power Station	227	SI	96	SNL	6.0	0.4
6768	Sikeston Power Station	228	SI	100	SNL	6.0	0.4
2107	Sioux	614	SI	46	SCL	5.7	1.1
2107	Sioux	614	SI	54	SLT	7.7	0.8
2107	Sioux	615	SI	46	SCL	5.7	1.1
2107	Sioux	615	SI	54	SLT	7.7	0.8
1058	Sixth Street	483	SI	100	SCL	6.4	2.8
1058	Sixth Street	484	SI	90	SCL	6.4	2.8
1058	Sixth Street	484	SI	10	SLT	6.7	2.1
1058	Sixth Street	485	SI	100	SCL	6.4	2.8
1058	Sixth Street	486	SI	100	SCL	6.4	2.8
1613	Somerset Station	566	SI	21	SLT	5.2	2.3
1613	Somerset Station	566	SI	79	SNL	5.3	0.23
1613	Somerset Station	567	SI	21	SLT	5.2	2.3
1613	Somerset Station	567	SI	79	SNL	5.3	0.23
1613	Somerset Station	568	SI	21	SLT	5.2	2.3
1613	Somerset Station	568	SI	79	SNL	5.3	0.23
1613	Somerset Station	569	SI	21	SLT	5.2	2.3
1613	Somerset Station	569	SI	79	SNL	5.3	0.23
6095	Sooner	1259	SI	100	SLT	7.0	0.8
6095	Sooner	1260	SI	100	SCL	7.4	0.8
6061	South Mississippi El Pwr Assn	1008	LF	100	SNL	5.0	0.30
6061	South Mississippi El Pwr Assn	1021	LF	100	SNL	5.0	0.3
6061	South Mississippi El Pwr Assn	1022	LF	100	SNL	5.0	0.24
6061	South Mississippi El Pwr Assn	1353	SI	100	SNL	5.0	0.3
6061	South Mississippi El Pwr Assn	1354	SI	100	SNL	5.0	0.3
4041	South Oak Creek	1070	LF	100	SCL	6.9	4.3
4041	South Oak Creek	1071	LF	100	SCL	6.9	4.3
4041	South Oak Creek	1072	LF	100	SCL	6.9	4.3
6195	Southwest Power Station	1073	LF	100	SCL	5.5	0.47
6195	Southwest Power Station	1074	LF	100	SCL	5.6	0.5
6195	Southwest Power Station	1268	SI	100	SCL	5.6	0.5
6195	Southwest Power Station	1269	SI	100	SCL	5.6	0.5
8223	Springerville	1075	LF	100	SNL	7.9	0.2
8223	Springerville	1384	SI	100	SNL	7.9	0.2

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ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
1743	St Clair Power Plant	584	SI	100	SCL	7.0	0.6
207	St Johns River Power Park	1018	LF	100	SNL	5.1	0.86
207	St Johns River Power Park	1076	LF	100	SNL	5.0	0.89
207	St Johns River Power Park	1077	LF	100	SNL	5.0	0.9
2824	Stanton	690	SI	1	SCL	7.8	0.2
2824	Stanton	690	SI	99	SLT	7.8	0.9
2824	Stanton	691	SI	83	SCL	7.8	0.2
2824	Stanton	691	SI	17	SLT	7.8	0.9
2824	Stanton	692	SI	100	SLT	7.8	0.9
2824	Stanton	937	LF	100	SLT	7.8	0.9
2824	Stanton	940	LF	100	SLT	7.8	0.9
2824	Stanton	997	LF	100	SLT	7.8	0.9
564	Stanton Energy Center	942	LF	100	SNL	5.2	0.4
1131	Streeter Station	1028	LF	100	SLT	6.3	2.4
3152	Sunbury Generation LP	101	SI	100	SLT	5.4	0.6
50951	Sunnyside Cogen Associates	944	LF	100	SLT	8.5	0.1
1077	Sutherland	497	SI	100	SCL	6.4	2.8
1077	Sutherland	498	SI	100	SCL	6.4	2.8
1077	Sutherland	499	SI	100	SCL	6.4	2.8
1077	Sutherland	1117	LF	100	SCL	6.3	2.2
1077	Sutherland	1118	LF	100	SCL	6.3	1.6
10075	Taconite Harbor Energy Center	947	LF	100	SLT	5.8	4.1
10075	Taconite Harbor Energy Center	948	LF	100	SLT	5.8	4.1
10075	Taconite Harbor Energy Center	961	LF	100	SLT	5.8	4.1
988	Tanners Creek	415	SI	51	SCL	6.3	0.48
988	Tanners Creek	415	SI	49	SLT	6.5	0.6
988	Tanners Creek	416	SI	100	SLT	6.5	0.6
988	Tanners Creek	417	SI	100	SLT	6.5	0.6
988	Tanners Creek	418	SI	100	SLT	6.5	0.6
988	Tanners Creek	419	SI	100	SLT	6.5	0.6
988	Tanners Creek	950	LF	100	SLT	6.5	0.6
1252	Tecumseh Energy Center	519	SI	100	SLT	7.3	1.3
1252	Tecumseh Energy Center	520	SI	100	SLT	7.3	1.3
1252	Tecumseh Energy Center	995	LF	100	SLT	7.3	1.3
1252	Tecumseh Energy Center	1120	LF	100	SLT	7.3	1.3
1252	Tecumseh Energy Center	1133	LF	100	SCL	6.3	1
2168	Thomas Hill	624	SI	100	SLT	5.9	0.5
2168	Thomas Hill	625	SI	100	SLT	5.9	0.61
2168	Thomas Hill	626	SI	100	SLT	5.9	0.61

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
2168	Thomas Hill	627	SI	100	SLT	5.9	0.5
2168	Thomas Hill	628	SI	100	SLT	5.9	0.61
2168	Thomas Hill	629	SI	100	SLT	5.9	0.61
2168	Thomas Hill	953	LF	100	SLT	6.1	1.3
3115	Titus	954	LF	100	SLT	5.7	0.5
3115	Titus	955	LF	100	SLT	5.8	0.5
3115	Titus	956	LF	100	SLT	5.8	0.5
3115	Titus	957	LF	100	SLT	5.8	0.5
6194	Tolk	1161	LF	100	SNL	7.5	0.1
3845	TransAlta Centralia Generation	959	LF	100	SLT	6.1	1.5
1745	Trenton Channel Power Plant	585	SI	100	SCL	7.1	0.7
1745	Trenton Channel Power Plant	960	LF	100	SCL	7.1	0.7
6071	Trimble Co.	44	SI	100	SCL	6.2	0.63
56224	TS Power Plant	816	LF	18	SCL	7.7	0.3
56224	TS Power Plant	816	LF	82	SLT	8.7	0.48
7030	Twin Oaks Power One	928	LF	100	SLT	6.2	0.7
1361	Tyrone	536	SI	100	SCL	6.6	1.1
1361	Tyrone	537	SI	100	SCL	6.6	1.1
3295	Urquhart	110	SI	100	SLT	5.4	1.0
3295	Urquhart	111	SI	100	SLT	5.5	1.2
3295	Urquhart	112	SI	100	SLT	5.4	1.0
3295	Urquhart	1107	LF	100	SLT	5.5	1.2
4042	Valley	918	LF	100	SCL	7.3	4.6
4042	Valley	919	LF	100	SLT	7.3	2.2
4042	Valley	920	LF	100	SLT	7.3	2.2
4042	Valley	949	LF	100	SCL	6.9	4.3
477	Valmont	329	SI	100	SNL	7.8	0.58
477	Valmont	330	SI	100	SNL	7.8	0.58
477	Valmont	331	SI	100	SNL	7.8	0.58
477	Valmont	1122	LF	100	SNL	7.8	0.6
477	Valmont	1123	LF	100	SNL	7.8	0.6
897	Vermilion	395	SI	13	SCL	6.9	4.3
897	Vermilion	395	SI	87	SLT	7.1	1.9
897	Vermilion	396	SI	100	SLT	7.1	1.9
897	Vermilion	970	LF	75	SCL	7.0	3.7
897	Vermilion	970	LF	25	SLT	7.1	1.9
6073	Victor J. Daniel Jr	45	SI	70	SCL	4.6	2.1
6073	Victor J. Daniel Jr	45	SI	30	SLT	4.9	1.1
6073	Victor J. Daniel Jr	924	LF	66	SCL	4.6	0.8
6073	Victor J. Daniel Jr	924	LF	34	SLT	4.9	1.1

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
6073	Victor J. Daniel Jr	925	LF	100	SLT	4.9	1.1
6073	Victor J. Daniel Jr	938	LF	100	SLT	4.9	1.1
6073	Victor J. Daniel Jr	1124	LF	7	SCL	4.6	0.8
6073	Victor J. Daniel Jr	1124	LF	93	SLT	4.9	1.1
6019	W H Zimmer	26	SI	100	SLT	6.6	0.4
6019	W H Zimmer	929	LF	67	SCL	6.5	0.4
6019	W H Zimmer	929	LF	33	SLT	6.1	0.3
3470	W. A. Parish	136	SI	100	SCL	7.0	1.2
3470	W. A. Parish	137	SI	100	SCL	7.0	1.2
3470	W. A. Parish	138	SI	100	SCL	7.0	1.2
3470	W. A. Parish	139	SI	100	SCL	7.0	1.2
3470	W. A. Parish	140	SI	100	SCL	7.0	1.2
3470	W. A. Parish	141	SI	100	SCL	7.0	1.2
3470	W. A. Parish	142	SI	100	SCL	7.0	1.2
3470	W. A. Parish	143	SI	100	SCL	7.0	1.2
3470	W. A. Parish	1125	LF	100	SCL	7.9	1.6
2866	W. H. Sammis	916	LF	100	SCL	6.2	0.4
2866	W. H. Sammis	1382	SI	100	SLT	4.9	0.7
2866	W. H. Sammis	1383	SI	100	SLT	4.9	0.7
3264	W. S. Lee	105	SI	100	SCL	5.2	0.22
3264	W. S. Lee	106	SI	100	SCL	5.3	0.30
2716	W.H. Weatherspoon Plant	667	SI	100	SLT	4.8	0.66
1010	Wabash River	462	SI	100	SLT	7.1	1.9
1010	Wabash River	463	SI	100	SLT	7.1	1.9
1010	Wabash River	464	SI	100	SLT	7.1	1.9
1010	Wabash River	465	SI	100	SLT	7.1	1.9
2830	Walter C Beckjord	695	SI	100	SLT	6.6	0.4
2830	Walter C Beckjord	696	SI	100	SLT	6.6	0.4
2830	Walter C Beckjord	697	SI	100	SLT	6.6	0.4
2830	Walter C Beckjord	698	SI	100	SLT	6.6	0.4
2830	Walter C Beckjord	1126	LF	100	SCL	6.5	0.4
2830	Walter C Beckjord	1127	LF	100	SCL	6.5	0.4
1082	Walter Scott Jr. Energy Center	502	SI	17	SCL	7.4	1.4
1082	Walter Scott Jr. Energy Center	502	SI	83	SLT	7.9	0.8
1082	Walter Scott Jr. Energy Center	503	SI	17	SCL	7.4	1.4
1082	Walter Scott Jr. Energy Center	503	SI	83	SLT	7.9	0.8
1082	Walter Scott Jr. Energy Center	932	LF	58	SCL	7.4	1.4

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
1082	Walter Scott Jr. Energy Center	932	LF	42	SLT	7.9	0.8
6052	Wansley	35	SI	62	SCL	5.3	0.3
6052	Wansley	35	SI	33	SLT	5.6	0.7
6052	Wansley	35	SI	6	SNL	5.1	0.2
6705	Warrick Power Plant	224	SI	22	SCL	6.0	0.3
6705	Warrick Power Plant	224	SI	78	SLT	6.4	0.65
3297	Wateree	113	SI	100	SCL	5.4	2.5
3297	Wateree	114	SI	94	SCL	5.3	2.4
3297	Wateree	114	SI	6	SLT	4.8	0.3
3297	Wateree	933	LF	100	SLT	4.8	0.3
883	Waukegan	1311	SI	100	SNL	6.2	0.4
883	Waukegan	1312	SI	100	SNL	6.2	0.4
6139	Welsh	175	SI	100	SLT	4.9	0.6
6139	Welsh	176	SI	100	SLT	4.9	0.6
6139	Welsh	177	SI	100	SLT	4.9	0.6
6139	Welsh	934	LF	100	SLT	4.9	0.6
4078	Weston	935	LF	100	SLT	5.6	2.9
4078	Weston	936	LF	100	SNL	6.1	3
4078	Weston	1313	SI	100	SNL	6.1	3
4078	Weston	1314	SI	100	SNL	6.1	3
4078	Weston	1315	SI	100	SNL	6.1	3
4078	Weston	1316	SI	100	SNL	6.1	3
4078	Weston	1317	SI	100	SNL	6.1	3
4078	Weston	1318	SI	100	SNL	6.1	3
60	Whelan Energy Center Unit 1 (WEC1)	1214	SI	100	SCL	6.9	1.1
6009	White Bluff	1128	LF	100	SCL	4.8	0.7
1040	Whitewater Valley	1321	SI	100	SLT	7.0	0.5
1040	Whitewater Valley	1322	SI	100	SLT	7.0	0.5
1040	Whitewater Valley	1323	SI	100	SLT	7.0	0.5
1040	Whitewater Valley	1324	SI	100	SLT	7.0	0.5
1040	Whitewater Valley	1325	SI	100	SLT	7.0	0.5
4057	WI Power & Light Co -Rock River Generating	1	SI	100	SLT	7.0	1.3
4057	WI Power & Light Co -Rock River Generating	2	SI	100	SLT	7.0	1.3
4057	WI Power & Light Co -Rock River Generating	3	SI	100	SLT	7.0	1.3
4057	WI Power & Light Co -Rock River Generating	172	SI	100	SLT	7.0	1.3
50	Widows Creek	59	SI	100	SCL	5.7	0.57
50	Widows Creek	60	SI	100	SCL	5.7	0.57

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
50	Widows Creek	61	SI	100	SCL	5.7	0.57
50	Widows Creek	62	SI	100	SCL	5.7	0.57
50	Widows Creek	63	SI	100	SCL	5.7	0.57
50	Widows Creek	64	SI	100	SCL	5.7	0.57
50	Widows Creek	65	SI	100	SCL	5.7	0.57
50	Widows Creek	66	SI	100	SCL	5.7	0.57
50	Widows Creek	261	SI	100	SCL	5.7	0.57
50	Widows Creek	262	SI	100	SCL	5.7	0.57
50	Widows Creek	289	SI	100	SCL	5.7	0.57
50	Widows Creek	290	SI	100	SCL	5.7	0.57
884	Will County	389	SI	33	SCL	6.9	4.3
884	Will County	389	SI	67	SLT	6.9	1.9
3298	Williams	1129	LF	100	SCL	4.9	1.1
3298	Williams	1130	LF	100	SLT	5.1	0.6
3946	Willow Island	917	LF	100	SLT	6.2	0.4
6249	Winyah	198	SI	3	SCL	4.9	1.1
6249	Winyah	198	SI	97	SLT	5.1	0.6
6249	Winyah	199	SI	66	SCL	4.9	1.1
6249	Winyah	199	SI	34	SLT	5.1	0.6
6249	Winyah	200	SI	100	SLT	5.1	0.6
6249	Winyah	201	SI	35	SLT	5.1	0.6
6249	Winyah	201	SI	65	SNL	5.3	1.3
6249	Winyah	202	SI	0	SCL	4.9	1.1
6249	Winyah	202	SI	55	SLT	5.1	0.6
6249	Winyah	202	SI	45	SNL	5.3	1.3
6249	Winyah	203	SI	100	SLT	5.1	0.6
6249	Winyah	982	LF	27	SCL	4.9	1.1
6249	Winyah	982	LF	50	SLT	5.1	0.6
6249	Winyah	982	LF	23	SNL	5.3	1.3
898	Wood River	397	SI	100	SCL	6.8	1.6
898	Wood River	398	SI	60	SCL	6.8	1.6
898	Wood River	398	SI	40	SLT	6.4	1.2
50611	WPS Westwood Generation, LLC	951	LF	100	SLT	5.6	0.4
6101	Wyodak Plant	80	SI	100	SNL	7.9	0.4
6101	Wyodak Plant	981	LF	100	SNL	7.9	0.4
728	Yates	367	SI	27	SCL	5.3	0.3
728	Yates	367	SI	34	SLT	5.6	0.7
728	Yates	367	SI	39	SNL	5.1	0.2
728	Yates	368	SI	27	SCL	5.3	0.3
728	Yates	368	SI	34	SLT	5.6	0.7
728	Yates	368	SI	39	SNL	5.1	0.2
728	Yates	369	SI	27	SCL	5.3	0.3

Attachment B-1. Soil Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percent Comp-osition	Mega-texture Code	Average pH	Average % Organic Material
728	Yates	369	SI	34	SLT	5.6	0.7
728	Yates	369	SI	39	SNL	5.1	0.2
728	Yates	370	SI	27	SCL	5.3	0.3
728	Yates	370	SI	34	SLT	5.6	0.7
728	Yates	370	SI	39	SNL	5.1	0.2
728	Yates	371	SI	27	SCL	5.3	0.3
728	Yates	371	SI	34	SLT	5.6	0.7
728	Yates	371	SI	39	SNL	5.1	0.2
728	Yates	372	SI	27	SCL	5.3	0.3
728	Yates	372	SI	34	SLT	5.6	0.7
728	Yates	372	SI	39	SNL	5.1	0.2
728	Yates	373	SI	27	SCL	5.3	0.3
728	Yates	373	SI	34	SLT	5.6	0.7
728	Yates	373	SI	39	SNL	5.1	0.2
728	Yates	374	SI	27	SCL	5.3	0.3
728	Yates	374	SI	34	SLT	5.6	0.7
728	Yates	374	SI	39	SNL	5.1	0.2
728	Yates	986	LF	86	SCL	5.3	0.3
728	Yates	986	LF	14	SNL	5.1	0.2
728	Yates	987	LF	46	SLT	5.6	0.7
728	Yates	987	LF	54	SNL	5.1	0.2
3809	Yorktown	988	LF	100	SCL	4.7	0.7
3809	Yorktown	1359	SI	100	SCL	4.7	0.7

Attachment B-2.
Hydrogeologic Data

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
6137	A. B. Brown Generating Station	88	SI	100	4	Sand and Gravel
6137	A. B. Brown Generating Station	89	SI	10	2	Bedded Sedimentary Rock
6137	A. B. Brown Generating Station	89	SI	44	4	Sand and Gravel
6137	A. B. Brown Generating Station	89	SI	46	8	Outwash
6137	A. B. Brown Generating Station	1163	LF	100	4	Sand and Gravel
2535	AES Cayuga, LLC	1102	LF	100	4	Sand and Gravel
2527	AES Greenidge	1101	LF	100	12	Solution Limestone
2527	AES Greenidge	1285	SI	100	12	Solution Limestone
2527	AES Greenidge	1286	SI	100	12	Solution Limestone
994	AES Petersburg	430	SI	100	2	Bedded Sedimentary Rock
994	AES Petersburg	431	SI	100	2	Bedded Sedimentary Rock
994	AES Petersburg	432	SI	100	2	Bedded Sedimentary Rock
994	AES Petersburg	433	SI	100	2	Bedded Sedimentary Rock
994	AES Petersburg	989	LF	100	2	Bedded Sedimentary Rock
6082	AES Somerset LLC	1105	LF	100	4	Sand and Gravel
6082	AES Somerset LLC	1106	LF	100	4	Sand and Gravel
6082	AES Somerset LLC	1287	SI	100	4	Sand and Gravel
3942	Albright Power Station	930	LF	100	2	Bedded Sedimentary Rock
3942	Albright Power Station	931	LF	100	2	Bedded Sedimentary Rock
3942	Albright Power Station	1385	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3942	Albright Power Station	1386	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1915	Allen S King	927	LF	54	2	Bedded Sedimentary Rock
1915	Allen S King	927	LF	46	9	Till and Till Over Outwash
3393	Allen Steam Plant	119	SI	35	6	River Valleys and Floodplains With Overbank Deposits
3393	Allen Steam Plant	119	SI	65	7	River Valleys and Floodplains Without Overbank Deposits
3393	Allen Steam Plant	120	SI	35	6	River Valleys and Floodplains With Overbank Deposits
3393	Allen Steam Plant	120	SI	65	7	River Valleys and Floodplains Without Overbank Deposits
4140	Alma	993	LF	100	6	River Valleys and Floodplains With Overbank Deposits
4140	Alma	994	LF	100	6	River Valleys and Floodplains With Overbank Deposits
1122	Ames Electric Services Power Plant	1202	SI	100	9	Till and Till Over Outwash
6469	Antelope Valley Station	212	SI	100	3	Till Over Sedimentary Rock
6469	Antelope Valley Station	213	SI	100	3	Till Over Sedimentary Rock
6469	Antelope Valley Station	922	LF	100	3	Till Over Sedimentary Rock

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
6469	Antelope Valley Station	923	LF	100	3	Till Over Sedimentary Rock
160	Apache Station	287	SI	100	5	Alluvial Basins Valleys and Fans
160	Apache Station	288	SI	100	5	Alluvial Basins Valleys and Fans
160	Apache Station	292	SI	100	5	Alluvial Basins Valleys and Fans
160	Apache Station	293	SI	100	5	Alluvial Basins Valleys and Fans
160	Apache Station	294	SI	100	5	Alluvial Basins Valleys and Fans
160	Apache Station	295	SI	100	5	Alluvial Basins Valleys and Fans
160	Apache Station	296	SI	100	5	Alluvial Basins Valleys and Fans
160	Apache Station	297	SI	100	5	Alluvial Basins Valleys and Fans
160	Apache Station	298	SI	100	5	Alluvial Basins Valleys and Fans
160	Apache Station	299	SI	100	5	Alluvial Basins Valleys and Fans
465	Arapahoe	310	SI	15	2	Bedded Sedimentary Rock
465	Arapahoe	310	SI	32	6	River Valleys and Floodplains With Overbank Deposits
465	Arapahoe	310	SI	53	7	River Valleys and Floodplains Without Overbank Deposits
465	Arapahoe	311	SI	15	2	Bedded Sedimentary Rock
465	Arapahoe	311	SI	32	6	River Valleys and Floodplains With Overbank Deposits
465	Arapahoe	311	SI	53	7	River Valleys and Floodplains Without Overbank Deposits
465	Arapahoe	312	SI	15	2	Bedded Sedimentary Rock
465	Arapahoe	312	SI	32	6	River Valleys and Floodplains With Overbank Deposits
465	Arapahoe	312	SI	53	7	River Valleys and Floodplains Without Overbank Deposits
465	Arapahoe	313	SI	15	2	Bedded Sedimentary Rock
465	Arapahoe	313	SI	32	6	River Valleys and Floodplains With Overbank Deposits
465	Arapahoe	313	SI	53	7	River Valleys and Floodplains Without Overbank Deposits
465	Arapahoe	314	SI	15	2	Bedded Sedimentary Rock
465	Arapahoe	314	SI	32	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
465	Arapahoe	314	SI	53	7	River Valleys and Floodplains Without Overbank Deposits
465	Arapahoe	315	SI	15	2	Bedded Sedimentary Rock
465	Arapahoe	315	SI	32	6	River Valleys and Floodplains With Overbank Deposits
465	Arapahoe	315	SI	53	7	River Valleys and Floodplains Without Overbank Deposits
3178	Armstrong Power Station	921	LF	100	6	River Valleys and Floodplains With Overbank Deposits
3178	Armstrong Power Station	926	LF	100	6	River Valleys and Floodplains With Overbank Deposits
2076	Asbury	596	SI	100	4	Sand and Gravel
2076	Asbury	597	SI	100	4	Sand and Gravel
2076	Asbury	598	SI	100	4	Sand and Gravel
2706	Asheville Steam Electric Plant	649	SI	100	1	Metamorphic and Igneous
2706	Asheville Steam Electric Plant	650	SI	100	1	Metamorphic and Igneous
2835	Ashtabula	1263	SI	100	4	Sand and Gravel
1961	Austin Northeast	958	LF	85	12	Solution Limestone
1961	Austin Northeast	958	LF	15	8	Outwash
2836	Avon Lake	975	LF	100	4	Sand and Gravel
2836	Avon Lake	1175	SI	100	4	Sand and Gravel
2836	Avon Lake	1176	SI	100	4	Sand and Gravel
995	Bailly	434	SI	53	3	Till Over Sedimentary Rock
995	Bailly	434	SI	47	9	Till and Till Over Outwash
995	Bailly	435	SI	100	3	Till Over Sedimentary Rock
995	Bailly	436	SI	100	3	Till Over Sedimentary Rock
995	Bailly	437	SI	100	3	Till Over Sedimentary Rock
995	Bailly	438	SI	100	3	Till Over Sedimentary Rock
995	Bailly	439	SI	100	3	Till Over Sedimentary Rock
995	Bailly	939	LF	100	3	Till Over Sedimentary Rock
995	Bailly	952	LF	100	3	Till Over Sedimentary Rock
889	Baldwin Energy Complex	391	SI	94	6	River Valleys and Floodplains With Overbank Deposits
889	Baldwin Energy Complex	391	SI	1	7	River Valleys and Floodplains Without Overbank Deposits
889	Baldwin Energy Complex	391	SI	5	8	Outwash
3	Barry	252	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
3982	Bay Front	162	SI	100	2	Bedded Sedimentary Rock
3982	Bay Front	163	SI	100	2	Bedded Sedimentary Rock
3982	Bay Front	945	LF	100	4	Sand and Gravel
3982	Bay Front	946	LF	100	4	Sand and Gravel
2878	Bay Shore	977	LF	100	12	Solution Limestone
2878	Bay Shore	1326	SI	100	12	Solution Limestone
8042	Belews Creek Steam Station	243	SI	88	1	Metamorphic and Igneous

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
8042	Belews Creek Steam Station	243	SI	12	2	Bedded Sedimentary Rock
8042	Belews Creek Steam Station	1009	LF	100	1	Metamorphic and Igneous
8042	Belews Creek Steam Station	1010	LF	100	1	Metamorphic and Igneous
8042	Belews Creek Steam Station	1079	LF	100	1	Metamorphic and Igneous
6034	Belle River	33	SI	100	4	Sand and Gravel
6034	Belle River	1035	LF	100	4	Sand and Gravel
3325	Ben French	1379	SI	100	12	Solution Limestone
645	Big Bend	342	SI	100	12	Solution Limestone
645	Big Bend	343	SI	100	12	Solution Limestone
645	Big Bend	344	SI	100	12	Solution Limestone
645	Big Bend	345	SI	100	12	Solution Limestone
645	Big Bend	346	SI	100	12	Solution Limestone
645	Big Bend	347	SI	100	12	Solution Limestone
645	Big Bend	348	SI	100	12	Solution Limestone
645	Big Bend	349	SI	100	12	Solution Limestone
645	Big Bend	1164	LF	100	12	Solution Limestone
3497	Big Brown	776	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3497	Big Brown	784	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3497	Big Brown	790	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3497	Big Brown	791	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3497	Big Brown	1177	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3497	Big Brown	1178	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3497	Big Brown	1179	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3497	Big Brown	1180	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6055	Big Cajun 2	36	SI	82	6	River Valleys and Floodplains With Overbank Deposits
6055	Big Cajun 2	36	SI	18	7	River Valleys and Floodplains Without Overbank Deposits
6055	Big Cajun 2	37	SI	82	6	River Valleys and Floodplains With Overbank Deposits
6055	Big Cajun 2	37	SI	18	7	River Valleys and Floodplains Without Overbank Deposits
6055	Big Cajun 2	38	SI	82	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
6055	Big Cajun 2	38	SI	18	7	River Valleys and Floodplains Without Overbank Deposits
6055	Big Cajun 2	815	LF	100	6	River Valleys and Floodplains With Overbank Deposits
1353	Big Sandy	521	SI	14	6	River Valleys and Floodplains With Overbank Deposits
1353	Big Sandy	521	SI	86	7	River Valleys and Floodplains Without Overbank Deposits
1353	Big Sandy	522	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1353	Big Sandy	523	SI	2	6	River Valleys and Floodplains With Overbank Deposits
1353	Big Sandy	523	SI	98	7	River Valleys and Floodplains Without Overbank Deposits
6098	Big Stone	814	LF	100	9	Till and Till Over Outwash
6098	Big Stone	1261	SI	100	9	Till and Till Over Outwash
1904	Black Dog	593	SI	52	2	Bedded Sedimentary Rock
1904	Black Dog	593	SI	48	8	Outwash
1904	Black Dog	799	LF	11	2	Bedded Sedimentary Rock
1904	Black Dog	799	LF	89	8	Outwash
6106	Boardman	746	LF	100	5	Alluvial Basins Valleys and Fans
6106	Boardman	1339	SI	100	5	Alluvial Basins Valleys and Fans
6106	Boardman	1340	SI	100	5	Alluvial Basins Valleys and Fans
6106	Boardman	1341	SI	100	5	Alluvial Basins Valleys and Fans
7790	Bonanza Power Plant	735	LF	74	6	River Valleys and Floodplains With Overbank Deposits
7790	Bonanza Power Plant	735	LF	26	7	River Valleys and Floodplains Without Overbank Deposits
7790	Bonanza Power Plant	737	LF	100	5	Alluvial Basins Valleys and Fans
7790	Bonanza Power Plant	1207	SI	100	2	Bedded Sedimentary Rock
7790	Bonanza Power Plant	1208	SI	100	2	Bedded Sedimentary Rock
7790	Bonanza Power Plant	1209	SI	100	2	Bedded Sedimentary Rock
1893	Boswell Energy Center	590	SI	100	1	Metamorphic and Igneous
1893	Boswell Energy Center	591	SI	100	1	Metamorphic and Igneous
1893	Boswell Energy Center	592	SI	100	1	Metamorphic and Igneous
1893	Boswell Energy Center	796	LF	100	1	Metamorphic and Igneous
1893	Boswell Energy Center	853	LF	100	1	Metamorphic and Igneous
1893	Boswell Energy Center	862	LF	100	1	Metamorphic and Igneous
703	Bowen	350	SI	100	12	Solution Limestone
703	Bowen	1103	LF	100	12	Solution Limestone

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
602	Brandon Shores	1289	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
602	Brandon Shores	1290	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
1619	Brayton Point	731	LF	100	3	Till Over Sedimentary Rock
1619	Brayton Point	760	LF	100	3	Till Over Sedimentary Rock
1619	Brayton Point	761	LF	100	3	Till Over Sedimentary Rock
1619	Brayton Point	800	LF	100	3	Till Over Sedimentary Rock
1619	Brayton Point	824	LF	100	3	Till Over Sedimentary Rock
1619	Brayton Point	1187	SI	100	3	Till Over Sedimentary Rock
1619	Brayton Point	1188	SI	100	3	Till Over Sedimentary Rock
1619	Brayton Point	1189	SI	100	3	Till Over Sedimentary Rock
1619	Brayton Point	1190	SI	100	3	Till Over Sedimentary Rock
1619	Brayton Point	1191	SI	100	3	Till Over Sedimentary Rock
1619	Brayton Point	1192	SI	100	3	Till Over Sedimentary Rock
1619	Brayton Point	1193	SI	100	3	Till Over Sedimentary Rock
1619	Brayton Point	1194	SI	100	3	Till Over Sedimentary Rock
1619	Brayton Point	1195	SI	100	3	Till Over Sedimentary Rock
1619	Brayton Point	1196	SI	100	3	Till Over Sedimentary Rock
3796	Bremo Bluff	148	SI	7	6	River Valleys and Floodplains With Overbank Deposits
3796	Bremo Bluff	148	SI	93	7	River Valleys and Floodplains Without Overbank Deposits
3796	Bremo Bluff	149	SI	5	6	River Valleys and Floodplains With Overbank Deposits
3796	Bremo Bluff	149	SI	95	7	River Valleys and Floodplains Without Overbank Deposits
6094	Bruce Mansfield	75	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6094	Bruce Mansfield	76	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6094	Bruce Mansfield	77	SI	24	2	Bedded Sedimentary Rock
6094	Bruce Mansfield	77	SI	69	6	River Valleys and Floodplains With Overbank Deposits
6094	Bruce Mansfield	77	SI	7	7	River Valleys and Floodplains Without Overbank Deposits
6094	Bruce Mansfield	78	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6094	Bruce Mansfield	79	SI	1	2	Bedded Sedimentary Rock
6094	Bruce Mansfield	79	SI	99	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
6094	Bruce Mansfield	79	SI	0	7	River Valleys and Floodplains Without Overbank Deposits
2720	Buck	671	SI	100	1	Metamorphic and Igneous
2720	Buck	672	SI	100	1	Metamorphic and Igneous
2720	Buck	673	SI	100	1	Metamorphic and Igneous
3396	Bull Run	121	SI	78	2	Bedded Sedimentary Rock
3396	Bull Run	121	SI	11	6	River Valleys and Floodplains With Overbank Deposits
3396	Bull Run	121	SI	11	7	River Valleys and Floodplains Without Overbank Deposits
3396	Bull Run	122	SI	78	2	Bedded Sedimentary Rock
3396	Bull Run	122	SI	11	6	River Valleys and Floodplains With Overbank Deposits
3396	Bull Run	122	SI	11	7	River Valleys and Floodplains Without Overbank Deposits
3396	Bull Run	123	SI	78	2	Bedded Sedimentary Rock
3396	Bull Run	123	SI	11	6	River Valleys and Floodplains With Overbank Deposits
3396	Bull Run	123	SI	11	7	River Valleys and Floodplains Without Overbank Deposits
3396	Bull Run	124	SI	78	2	Bedded Sedimentary Rock
3396	Bull Run	124	SI	11	6	River Valleys and Floodplains With Overbank Deposits
3396	Bull Run	124	SI	11	7	River Valleys and Floodplains Without Overbank Deposits
3396	Bull Run	889	LF	100	2	Bedded Sedimentary Rock
3396	Bull Run	890	LF	100	2	Bedded Sedimentary Rock
1104	Burlington	507	SI	56	6	River Valleys and Floodplains With Overbank Deposits
1104	Burlington	507	SI	44	7	River Valleys and Floodplains Without Overbank Deposits
1104	Burlington	508	SI	56	6	River Valleys and Floodplains With Overbank Deposits
1104	Burlington	508	SI	44	7	River Valleys and Floodplains Without Overbank Deposits
1104	Burlington	509	SI	56	6	River Valleys and Floodplains With Overbank Deposits
1104	Burlington	509	SI	44	7	River Valleys and Floodplains Without Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
1104	Burlington	510	SI	56	6	River Valleys and Floodplains With Overbank Deposits
1104	Burlington	510	SI	44	7	River Valleys and Floodplains Without Overbank Deposits
1104	Burlington	511	SI	56	6	River Valleys and Floodplains With Overbank Deposits
1104	Burlington	511	SI	44	7	River Valleys and Floodplains Without Overbank Deposits
676	C D McIntosh Jr	885	LF	100	4	Sand and Gravel
676	C D McIntosh Jr	888	LF	100	4	Sand and Gravel
468	Cameo	316	SI	8	2	Bedded Sedimentary Rock
468	Cameo	316	SI	11	6	River Valleys and Floodplains With Overbank Deposits
468	Cameo	316	SI	81	7	River Valleys and Floodplains Without Overbank Deposits
468	Cameo	317	SI	8	2	Bedded Sedimentary Rock
468	Cameo	317	SI	11	6	River Valleys and Floodplains With Overbank Deposits
468	Cameo	317	SI	81	7	River Valleys and Floodplains Without Overbank Deposits
3280	Canadys Steam	107	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
3280	Canadys Steam	108	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
3280	Canadys Steam	109	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
1363	Cane Run	538	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1363	Cane Run	539	SI	60	6	River Valleys and Floodplains With Overbank Deposits
1363	Cane Run	539	SI	40	7	River Valleys and Floodplains Without Overbank Deposits
1363	Cane Run	540	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1363	Cane Run	541	SI	100	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
1363	Cane Run	542	SI	60	6	River Valleys and Floodplains With Overbank Deposits
1363	Cane Run	542	SI	40	7	River Valleys and Floodplains Without Overbank Deposits
1363	Cane Run	869	LF	89	6	River Valleys and Floodplains With Overbank Deposits
1363	Cane Run	869	LF	11	7	River Valleys and Floodplains Without Overbank Deposits
2708	Cape Fear Steam Electric Plant	651	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2708	Cape Fear Steam Electric Plant	652	SI	18	1	Metamorphic and Igneous
2708	Cape Fear Steam Electric Plant	652	SI	68	6	River Valleys and Floodplains With Overbank Deposits
2708	Cape Fear Steam Electric Plant	652	SI	14	7	River Valleys and Floodplains Without Overbank Deposits
2708	Cape Fear Steam Electric Plant	653	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2708	Cape Fear Steam Electric Plant	654	SI	18	1	Metamorphic and Igneous
2708	Cape Fear Steam Electric Plant	654	SI	68	6	River Valleys and Floodplains With Overbank Deposits
2708	Cape Fear Steam Electric Plant	654	SI	14	7	River Valleys and Floodplains Without Overbank Deposits
2708	Cape Fear Steam Electric Plant	655	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3644	Carbon Plant	876	LF	100	2	Bedded Sedimentary Rock
3644	Carbon Plant	905	LF	100	2	Bedded Sedimentary Rock
3644	Carbon Plant	1387	SI	100	2	Bedded Sedimentary Rock
3644	Carbon Plant	1388	SI	100	2	Bedded Sedimentary Rock
2828	Cardinal	693	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2828	Cardinal	694	SI	93	6	River Valleys and Floodplains With Overbank Deposits
2828	Cardinal	694	SI	7	7	River Valleys and Floodplains Without Overbank Deposits
2828	Cardinal	899	LF	100	6	River Valleys and Floodplains With Overbank Deposits
1001	Cayuga	454	SI	99	8	Outwash

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
1001	Cayuga	454	SI	1	9	Till and Till Over Outwash
1001	Cayuga	455	SI	100	8	Outwash
1001	Cayuga	456	SI	100	8	Outwash
1001	Cayuga	457	SI	100	8	Outwash
1001	Cayuga	838	LF	100	8	Outwash
1571	Chalk Point LLC	836	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
1571	Chalk Point LLC	1104	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
2169	Chamois Power Plant	1288	SI	100	6	River Valleys and Floodplains With Overbank Deposits
56	Charles R. Lowman	270	SI	57	10	Unconsolidated and Semiconsolidated Shallow Aquifers
56	Charles R. Lowman	270	SI	43	7	River Valleys and Floodplains Without Overbank Deposits
56	Charles R. Lowman	271	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
56	Charles R. Lowman	272	SI	22	10	Unconsolidated and Semiconsolidated Shallow Aquifers
56	Charles R. Lowman	272	SI	78	7	River Valleys and Floodplains Without Overbank Deposits
56	Charles R. Lowman	273	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
56	Charles R. Lowman	900	LF	44	10	Unconsolidated and Semiconsolidated Shallow Aquifers
56	Charles R. Lowman	900	LF	8	6	River Valleys and Floodplains With Overbank Deposits
56	Charles R. Lowman	900	LF	48	7	River Valleys and Floodplains Without Overbank Deposits
469	Cherokee	318	SI	22	2	Bedded Sedimentary Rock
469	Cherokee	318	SI	27	6	River Valleys and Floodplains With Overbank Deposits
469	Cherokee	318	SI	51	7	River Valleys and Floodplains Without Overbank Deposits
469	Cherokee	319	SI	22	2	Bedded Sedimentary Rock
469	Cherokee	319	SI	27	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
469	Cherokee	319	SI	51	7	River Valleys and Floodplains Without Overbank Deposits
469	Cherokee	320	SI	22	2	Bedded Sedimentary Rock
469	Cherokee	320	SI	27	6	River Valleys and Floodplains With Overbank Deposits
469	Cherokee	320	SI	51	7	River Valleys and Floodplains Without Overbank Deposits
469	Cherokee	321	SI	22	2	Bedded Sedimentary Rock
469	Cherokee	321	SI	27	6	River Valleys and Floodplains With Overbank Deposits
469	Cherokee	321	SI	51	7	River Valleys and Floodplains Without Overbank Deposits
469	Cherokee	322	SI	22	2	Bedded Sedimentary Rock
469	Cherokee	322	SI	27	6	River Valleys and Floodplains With Overbank Deposits
469	Cherokee	322	SI	51	7	River Valleys and Floodplains Without Overbank Deposits
469	Cherokee	323	SI	22	2	Bedded Sedimentary Rock
469	Cherokee	323	SI	27	6	River Valleys and Floodplains With Overbank Deposits
469	Cherokee	323	SI	51	7	River Valleys and Floodplains Without Overbank Deposits
3803	Chesapeake Energy Center	152	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3803	Chesapeake Energy Center	865	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3797	Chesterfield	150	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
3797	Chesterfield	151	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
8226	Cheswick Power Plant	1099	LF	100	2	Bedded Sedimentary Rock
8226	Cheswick Power Plant	1165	SI	100	6	River Valleys and Floodplains With Overbank Deposits
8226	Cheswick Power Plant	1166	SI	100	6	River Valleys and Floodplains With Overbank Deposits
113	Cholla	279	SI	100	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
113	Cholla	280	SI	100	6	River Valleys and Floodplains With Overbank Deposits
113	Cholla	863	LF	56	2	Bedded Sedimentary Rock
113	Cholla	863	LF	44	6	River Valleys and Floodplains With Overbank Deposits
2721	Cliffside	674	SI	100	1	Metamorphic and Igneous
2721	Cliffside	675	SI	100	1	Metamorphic and Igneous
2721	Cliffside	676	SI	100	1	Metamorphic and Igneous
983	Clifty Creek	413	SI	100	6	River Valleys and Floodplains With Overbank Deposits
983	Clifty Creek	414	SI	100	6	River Valleys and Floodplains With Overbank Deposits
983	Clifty Creek	847	LF	100	6	River Valleys and Floodplains With Overbank Deposits
983	Clifty Creek	848	LF	100	6	River Valleys and Floodplains With Overbank Deposits
3775	Clinch River	144	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3775	Clinch River	145	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3775	Clinch River	849	LF	100	6	River Valleys and Floodplains With Overbank Deposits
7213	Clover	850	LF	100	6	River Valleys and Floodplains With Overbank Deposits
7213	Clover	851	LF	100	6	River Valleys and Floodplains With Overbank Deposits
7213	Clover	1280	SI	100	6	River Valleys and Floodplains With Overbank Deposits
7213	Clover	1281	SI	100	6	River Valleys and Floodplains With Overbank Deposits
7213	Clover	1282	SI	100	6	River Valleys and Floodplains With Overbank Deposits
7213	Clover	1283	SI	100	6	River Valleys and Floodplains With Overbank Deposits
7213	Clover	1284	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6030	Coal Creek	29	SI	100	3	Till Over Sedimentary Rock
6030	Coal Creek	30	SI	100	3	Till Over Sedimentary Rock

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
6030	Coal Creek	852	LF	100	3	Till Over Sedimentary Rock
6030	Coal Creek	854	LF	100	3	Till Over Sedimentary Rock
6030	Coal Creek	855	LF	100	3	Till Over Sedimentary Rock
6030	Coal Creek	857	LF	100	3	Till Over Sedimentary Rock
6030	Coal Creek	868	LF	100	3	Till Over Sedimentary Rock
6030	Coal Creek	1119	LF	100	3	Till Over Sedimentary Rock
861	Coffeen	379	SI	100	4	Sand and Gravel
861	Coffeen	380	SI	100	4	Sand and Gravel
861	Coffeen	846	LF	100	4	Sand and Gravel
47	Colbert	258	SI	1	12	Solution Limestone
47	Colbert	258	SI	65	6	River Valleys and Floodplains With Overbank Deposits
47	Colbert	258	SI	34	7	River Valleys and Floodplains Without Overbank Deposits
47	Colbert	259	SI	1	12	Solution Limestone
47	Colbert	259	SI	65	6	River Valleys and Floodplains With Overbank Deposits
47	Colbert	259	SI	34	7	River Valleys and Floodplains Without Overbank Deposits
47	Colbert	260	SI	1	12	Solution Limestone
47	Colbert	260	SI	65	6	River Valleys and Floodplains With Overbank Deposits
47	Colbert	260	SI	34	7	River Valleys and Floodplains Without Overbank Deposits
47	Colbert	859	LF	100	6	River Valleys and Floodplains With Overbank Deposits
6178	Coleto Creek	181	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6178	Coleto Creek	182	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6076	Colstrip	46	SI	100	2	Bedded Sedimentary Rock
6076	Colstrip	47	SI	100	2	Bedded Sedimentary Rock
6076	Colstrip	48	SI	100	2	Bedded Sedimentary Rock
6076	Colstrip	49	SI	100	2	Bedded Sedimentary Rock
6076	Colstrip	50	SI	100	2	Bedded Sedimentary Rock
6076	Colstrip	51	SI	100	2	Bedded Sedimentary Rock
6076	Colstrip	52	SI	100	2	Bedded Sedimentary Rock
6076	Colstrip	53	SI	100	2	Bedded Sedimentary Rock
10784	Colstrip Energy LP	860	LF	100	2	Bedded Sedimentary Rock
10784	Colstrip Energy LP	861	LF	100	2	Bedded Sedimentary Rock
8023	Columbia	239	SI	100	2	Bedded Sedimentary Rock
8023	Columbia	240	SI	100	2	Bedded Sedimentary Rock
8023	Columbia	241	SI	100	2	Bedded Sedimentary Rock
8023	Columbia	242	SI	100	2	Bedded Sedimentary Rock
8023	Columbia	1135	LF	100	2	Bedded Sedimentary Rock
8023	Columbia	1136	LF	100	2	Bedded Sedimentary Rock

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
2123	Columbia	1213	SI	31	12	Solution Limestone
2123	Columbia	1213	SI	69	4	Sand and Gravel
470	Comanche	324	SI	92	2	Bedded Sedimentary Rock
470	Comanche	324	SI	8	6	River Valleys and Floodplains With Overbank Deposits
470	Comanche	325	SI	92	2	Bedded Sedimentary Rock
470	Comanche	325	SI	8	6	River Valleys and Floodplains With Overbank Deposits
470	Comanche	326	SI	92	2	Bedded Sedimentary Rock
470	Comanche	326	SI	8	6	River Valleys and Floodplains With Overbank Deposits
470	Comanche	327	SI	92	2	Bedded Sedimentary Rock
470	Comanche	327	SI	8	6	River Valleys and Floodplains With Overbank Deposits
470	Comanche	328	SI	92	2	Bedded Sedimentary Rock
470	Comanche	328	SI	8	6	River Valleys and Floodplains With Overbank Deposits
470	Comanche	1137	LF	100	2	Bedded Sedimentary Rock
3118	Conemaugh	864	LF	100	2	Bedded Sedimentary Rock
3118	Conemaugh	1138	LF	100	2	Bedded Sedimentary Rock
3118	Conemaugh	1334	SI	100	2	Bedded Sedimentary Rock
3118	Conemaugh	1335	SI	100	2	Bedded Sedimentary Rock
3118	Conemaugh	1336	SI	100	2	Bedded Sedimentary Rock
3118	Conemaugh	1337	SI	100	2	Bedded Sedimentary Rock
3118	Conemaugh	1338	SI	100	2	Bedded Sedimentary Rock
2840	Conesville	701	SI	15	6	River Valleys and Floodplains With Overbank Deposits
2840	Conesville	701	SI	85	7	River Valleys and Floodplains Without Overbank Deposits
2840	Conesville	1005	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
2840	Conesville	1006	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
1710	Consumers Energy - J.H. Campbell	572	SI	100	4	Sand and Gravel
1710	Consumers Energy - J.H. Campbell	967	LF	100	4	Sand and Gravel
1710	Consumers Energy - J.H. Campbell	985	LF	100	4	Sand and Gravel
1710	Consumers Energy - J.H. Campbell	998	LF	100	4	Sand and Gravel
1710	Consumers Energy - J.H. Campbell	999	LF	100	4	Sand and Gravel
1384	Cooper Station.	973	LF	89	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
1384	Cooper Station.	973	LF	11	7	River Valleys and Floodplains Without Overbank Deposits
7210	Cope	866	LF	46	10	Unconsolidated and Semiconsolidated Shallow Aquifers
7210	Cope	866	LF	54	7	River Valleys and Floodplains Without Overbank Deposits
6177	Coronado Generating Station	180	SI	100	2	Bedded Sedimentary Rock
6177	Coronado Generating Station	835	LF	100	2	Bedded Sedimentary Rock
6177	Coronado Generating Station	867	LF	100	2	Bedded Sedimentary Rock
8222	Coyote	248	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
8222	Coyote	249	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
8222	Coyote	250	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
8222	Coyote	825	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
8222	Coyote	826	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
8222	Coyote	833	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
8222	Coyote	856	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
2549	CR Huntley Generating Station	643	SI	100	12	Solution Limestone
2549	CR Huntley Generating Station	644	SI	100	12	Solution Limestone
2549	CR Huntley Generating Station	645	SI	100	12	Solution Limestone
2549	CR Huntley Generating Station	1100	LF	100	4	Sand and Gravel
6021	Craig	27	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6021	Craig	28	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6021	Craig	974	LF	100	6	River Valleys and Floodplains With Overbank Deposits
867	Crawford	387	SI	100	12	Solution Limestone
753	Crisp Plant	1265	SI	100	7	River Valleys and Floodplains Without Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
641	Crist	1139	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
641	Crist	1273	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
641	Crist	1274	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
641	Crist	1275	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
641	Crist	1276	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
641	Crist	1277	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
641	Crist	1278	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
641	Crist	1279	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
130	Cross	284	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
130	Cross	285	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
130	Cross	286	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
130	Cross	827	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
130	Cross	828	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
130	Cross	829	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
130	Cross	830	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
628	Crystal River Power Plant	831	LF	100	12	Solution Limestone
3399	Cumberland	125	SI	79	6	River Valleys and Floodplains With Overbank Deposits
3399	Cumberland	125	SI	21	7	River Valleys and Floodplains Without Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
3399	Cumberland	126	SI	79	6	River Valleys and Floodplains With Overbank Deposits
3399	Cumberland	126	SI	21	7	River Valleys and Floodplains Without Overbank Deposits
3399	Cumberland	127	SI	79	6	River Valleys and Floodplains With Overbank Deposits
3399	Cumberland	127	SI	21	7	River Valleys and Floodplains Without Overbank Deposits
3399	Cumberland	978	LF	79	6	River Valleys and Floodplains With Overbank Deposits
3399	Cumberland	978	LF	21	7	River Valleys and Floodplains Without Overbank Deposits
6823	D B Wilson	832	LF	100	6	River Valleys and Floodplains With Overbank Deposits
6823	D B Wilson	845	LF	100	6	River Valleys and Floodplains With Overbank Deposits
1702	D.E. Karn	570	SI	100	2	Bedded Sedimentary Rock
1702	D.E. Karn	571	SI	100	2	Bedded Sedimentary Rock
1702	D.E. Karn	1004	LF	100	2	Bedded Sedimentary Rock
1385	Dale Station	558	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1385	Dale Station	559	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1385	Dale Station	560	SI	100	6	River Valleys and Floodplains With Overbank Deposits
963	Dallman	399	SI	100	4	Sand and Gravel
963	Dallman	823	LF	100	4	Sand and Gravel
963	Dallman	834	LF	100	4	Sand and Gravel
2723	Dan River	677	SI	100	2	Bedded Sedimentary Rock
2723	Dan River	678	SI	100	2	Bedded Sedimentary Rock
2723	Dan River	679	SI	100	2	Bedded Sedimentary Rock
2480	Danskammer Generating Station	1140	LF	100	12	Solution Limestone
4158	Dave Johnston Plant	4	SI	100	6	River Valleys and Floodplains With Overbank Deposits
4158	Dave Johnston Plant	5	SI	100	6	River Valleys and Floodplains With Overbank Deposits
4158	Dave Johnston Plant	6	SI	100	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
4158	Dave Johnston Plant	7	SI	100	6	River Valleys and Floodplains With Overbank Deposits
4158	Dave Johnston Plant	8	SI	100	6	River Valleys and Floodplains With Overbank Deposits
4158	Dave Johnston Plant	9	SI	100	6	River Valleys and Floodplains With Overbank Deposits
4158	Dave Johnston Plant	10	SI	100	6	River Valleys and Floodplains With Overbank Deposits
4158	Dave Johnston Plant	11	SI	100	6	River Valleys and Floodplains With Overbank Deposits
4158	Dave Johnston Plant	837	LF	93	6	River Valleys and Floodplains With Overbank Deposits
4158	Dave Johnston Plant	837	LF	7	7	River Valleys and Floodplains Without Overbank Deposits
996	Dean H Mitchell	440	SI	100	12	Solution Limestone
996	Dean H Mitchell	441	SI	100	12	Solution Limestone
996	Dean H Mitchell	442	SI	100	12	Solution Limestone
996	Dean H Mitchell	443	SI	100	12	Solution Limestone
996	Dean H Mitchell	444	SI	100	12	Solution Limestone
996	Dean H Mitchell	445	SI	100	12	Solution Limestone
996	Dean H Mitchell	446	SI	100	12	Solution Limestone
996	Dean H Mitchell	447	SI	100	12	Solution Limestone
663	Deerhaven Generating Station	1141	LF	100	4	Sand and Gravel
663	Deerhaven Generating Station	1331	SI	100	4	Sand and Gravel
1572	Dickerson	839	LF	47	12	Solution Limestone
1572	Dickerson	839	LF	53	6	River Valleys and Floodplains With Overbank Deposits
51	Dolet Hills	263	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
51	Dolet Hills	264	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
51	Dolet Hills	265	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
51	Dolet Hills	266	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
51	Dolet Hills	267	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
51	Dolet Hills	268	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
51	Dolet Hills	269	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
51	Dolet Hills	840	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3317	Dolphus M Grainger	115	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
3317	Dolphus M Grainger	116	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
1046	Dubuque	476	SI	36	6	River Valleys and Floodplains With Overbank Deposits
1046	Dubuque	476	SI	64	7	River Valleys and Floodplains Without Overbank Deposits
6016	Duck Creek	18	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6016	Duck Creek	19	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6016	Duck Creek	20	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6016	Duck Creek	842	LF	100	6	River Valleys and Floodplains With Overbank Deposits
2554	Dunkirk Generating Plant	646	SI	100	4	Sand and Gravel
2554	Dunkirk Generating Plant	647	SI	100	4	Sand and Gravel
2554	Dunkirk Generating Plant	648	SI	100	4	Sand and Gravel
2554	Dunkirk Generating Plant	843	LF	100	4	Sand and Gravel
26	E. C. Gaston	257	SI	93	6	River Valleys and Floodplains With Overbank Deposits
26	E. C. Gaston	257	SI	7	7	River Valleys and Floodplains Without Overbank Deposits
1355	E.W. Brown	524	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1355	E.W. Brown	525	SI	100	6	River Valleys and Floodplains With Overbank Deposits
991	Eagle Valley	425	SI	100	4	Sand and Gravel
991	Eagle Valley	426	SI	100	4	Sand and Gravel
991	Eagle Valley	427	SI	100	4	Sand and Gravel
991	Eagle Valley	428	SI	100	4	Sand and Gravel
991	Eagle Valley	429	SI	100	4	Sand and Gravel

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
1217	Earl F Wisdom	844	LF	100	2	Bedded Sedimentary Rock
6018	East Bend Station	23	SI	47	6	River Valleys and Floodplains With Overbank Deposits
6018	East Bend Station	23	SI	53	7	River Valleys and Floodplains Without Overbank Deposits
6018	East Bend Station	24	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
6018	East Bend Station	25	SI	47	6	River Valleys and Floodplains With Overbank Deposits
6018	East Bend Station	25	SI	53	7	River Valleys and Floodplains Without Overbank Deposits
6018	East Bend Station	879	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
2837	Eastlake	914	LF	100	4	Sand and Gravel
2837	Eastlake	1262	SI	100	4	Sand and Gravel
856	ED Edwards	376	SI	95	6	River Valleys and Floodplains With Overbank Deposits
856	ED Edwards	376	SI	4	7	River Valleys and Floodplains Without Overbank Deposits
856	ED Edwards	376	SI	2	8	Outwash
856	ED Edwards	377	SI	100	6	River Valleys and Floodplains With Overbank Deposits
856	ED Edwards	378	SI	100	6	River Valleys and Floodplains With Overbank Deposits
4050	Edgewater	164	SI	100	12	Solution Limestone
4050	Edgewater	165	SI	100	12	Solution Limestone
4050	Edgewater	166	SI	100	12	Solution Limestone
4050	Edgewater	167	SI	100	12	Solution Limestone
4050	Edgewater	168	SI	100	12	Solution Limestone
4050	Edgewater	169	SI	100	12	Solution Limestone
4050	Edgewater	858	LF	100	12	Solution Limestone
4050	Edgewater	894	LF	100	12	Solution Limestone
1004	Edwardsport	458	SI	100	2	Bedded Sedimentary Rock
1004	Edwardsport	459	SI	100	2	Bedded Sedimentary Rock
1004	Edwardsport	971	LF	100	2	Bedded Sedimentary Rock
1374	Elmer Smith Station	1234	SI	100	8	Outwash
1374	Elmer Smith Station	1235	SI	100	8	Outwash
1374	Elmer Smith Station	1236	SI	100	8	Outwash
1374	Elmer Smith Station	1237	SI	100	8	Outwash
3098	Elrama Power Plant	895	LF	38	6	River Valleys and Floodplains With Overbank Deposits
3098	Elrama Power Plant	895	LF	62	7	River Valleys and Floodplains Without Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
3098	Elrama Power Plant	1342	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3098	Elrama Power Plant	1343	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3098	Elrama Power Plant	1344	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3098	Elrama Power Plant	1345	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
1832	Erickson Station	587	SI	100	2	Bedded Sedimentary Rock
87	Escalante	274	SI	100	2	Bedded Sedimentary Rock
87	Escalante	275	SI	100	2	Bedded Sedimentary Rock
87	Escalante	276	SI	100	2	Bedded Sedimentary Rock
87	Escalante	277	SI	100	2	Bedded Sedimentary Rock
87	Escalante	278	SI	100	2	Bedded Sedimentary Rock
87	Escalante	992	LF	100	2	Bedded Sedimentary Rock
1012	F. B. Culley	466	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1012	F. B. Culley	467	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1218	Fair Station	896	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
1218	Fair Station	1183	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1218	Fair Station	1184	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6179	Fayette Power Project	183	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6179	Fayette Power Project	184	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6179	Fayette Power Project	897	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
886	Fisk	1238	SI	100	12	Solution Limestone
886	Fisk	1239	SI	100	12	Solution Limestone
886	Fisk	1240	SI	100	12	Solution Limestone
6138	Flint Creek	173	SI	100	12	Solution Limestone
6138	Flint Creek	174	SI	100	12	Solution Limestone
6138	Flint Creek	898	LF	100	12	Solution Limestone
3943	Fort Martin Power Station	1142	LF	100	6	River Valleys and Floodplains With Overbank Deposits
3943	Fort Martin Power Station	1143	LF	100	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
3943	Fort Martin Power Station	1181	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3943	Fort Martin Power Station	1182	SI	100	6	River Valleys and Floodplains With Overbank Deposits
10343	Foster Wheeler Mt Carmel Cogen	901	LF	100	2	Bedded Sedimentary Rock
2442	Four Corners	638	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
2442	Four Corners	639	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
2442	Four Corners	640	SI	2	2	Bedded Sedimentary Rock
2442	Four Corners	640	SI	98	7	River Valleys and Floodplains Without Overbank Deposits
2442	Four Corners	641	SI	2	2	Bedded Sedimentary Rock
2442	Four Corners	641	SI	98	7	River Valleys and Floodplains Without Overbank Deposits
2442	Four Corners	642	SI	2	2	Bedded Sedimentary Rock
2442	Four Corners	642	SI	98	7	River Valleys and Floodplains Without Overbank Deposits
2442	Four Corners	903	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
2442	Four Corners	915	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
1043	Frank E. Ratts	468	SI	100	2	Bedded Sedimentary Rock
1043	Frank E. Ratts	469	SI	100	2	Bedded Sedimentary Rock
1043	Frank E. Ratts	470	SI	100	2	Bedded Sedimentary Rock
1043	Frank E. Ratts	471	SI	100	2	Bedded Sedimentary Rock
1043	Frank E. Ratts	472	SI	100	2	Bedded Sedimentary Rock
1043	Frank E. Ratts	473	SI	100	2	Bedded Sedimentary Rock
1043	Frank E. Ratts	474	SI	100	2	Bedded Sedimentary Rock
1043	Frank E. Ratts	475	SI	100	2	Bedded Sedimentary Rock
2718	G G Allen	668	SI	100	1	Metamorphic and Igneous
2718	G G Allen	669	SI	100	1	Metamorphic and Igneous
2718	G G Allen	670	SI	100	1	Metamorphic and Igneous
2718	G G Allen	892	LF	100	1	Metamorphic and Igneous
7	Gadsden	253	SI	100	12	Solution Limestone
3403	Gallatin	128	SI	65	6	River Valleys and Floodplains With Overbank Deposits
3403	Gallatin	128	SI	35	7	River Valleys and Floodplains Without Overbank Deposits
3403	Gallatin	129	SI	65	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
3403	Gallatin	129	SI	35	7	River Valleys and Floodplains Without Overbank Deposits
3403	Gallatin	130	SI	65	6	River Valleys and Floodplains With Overbank Deposits
3403	Gallatin	130	SI	35	7	River Valleys and Floodplains Without Overbank Deposits
8102	General James M. Gavin	246	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
8102	General James M. Gavin	247	SI	100	6	River Valleys and Floodplains With Overbank Deposits
8102	General James M. Gavin	1144	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
4143	Genoa	1007	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
4143	Genoa	1131	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
1091	George Neal North	504	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
1091	George Neal North	505	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
1091	George Neal North	506	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
1091	George Neal North	906	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
1091	George Neal North	907	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
1091	George Neal North	908	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
1091	George Neal North	909	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
1091	George Neal North	910	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
7343	George Neal South	911	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
7343	George Neal South	1332	SI	100	7	River Valleys and Floodplains Without Overbank Deposits

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ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
6077	Gerald Gentleman	912	LF	100	4	Sand and Gravel
1356	Ghent	526	SI	55	6	River Valleys and Floodplains With Overbank Deposits
1356	Ghent	526	SI	45	7	River Valleys and Floodplains Without Overbank Deposits
1356	Ghent	527	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
1356	Ghent	528	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
1356	Ghent	529	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1356	Ghent	530	SI	55	6	River Valleys and Floodplains With Overbank Deposits
1356	Ghent	530	SI	45	7	River Valleys and Floodplains Without Overbank Deposits
6136	Gibbons Creek Steam Electric Station	881	LF	100	4	Sand and Gravel
6136	Gibbons Creek Steam Electric Station	913	LF	100	4	Sand and Gravel
6136	Gibbons Creek Steam Electric Station	1241	SI	100	4	Sand and Gravel
6136	Gibbons Creek Steam Electric Station	1242	SI	100	4	Sand and Gravel
6136	Gibbons Creek Steam Electric Station	1243	SI	100	4	Sand and Gravel
6136	Gibbons Creek Steam Electric Station	1244	SI	100	4	Sand and Gravel
6113	Gibson	81	SI	11	2	Bedded Sedimentary Rock
6113	Gibson	81	SI	89	6	River Valleys and Floodplains With Overbank Deposits
6113	Gibson	82	SI	8	2	Bedded Sedimentary Rock
6113	Gibson	82	SI	92	6	River Valleys and Floodplains With Overbank Deposits
6113	Gibson	83	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6113	Gibson	84	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6113	Gibson	85	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6113	Gibson	86	SI	100	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
6113	Gibson	902	LF	100	6	River Valleys and Floodplains With Overbank Deposits
6113	Gibson	904	LF	100	6	River Valleys and Floodplains With Overbank Deposits
3776	Glen Lyn	146	SI	70	6	River Valleys and Floodplains With Overbank Deposits
3776	Glen Lyn	146	SI	30	7	River Valleys and Floodplains Without Overbank Deposits
3776	Glen Lyn	147	SI	82	6	River Valleys and Floodplains With Overbank Deposits
3776	Glen Lyn	147	SI	18	7	River Valleys and Floodplains Without Overbank Deposits
3776	Glen Lyn	870	LF	78	6	River Valleys and Floodplains With Overbank Deposits
3776	Glen Lyn	870	LF	22	7	River Valleys and Floodplains Without Overbank Deposits
8	Gorgas	254	SI	100	6	River Valleys and Floodplains With Overbank Deposits
8	Gorgas	255	SI	88	6	River Valleys and Floodplains With Overbank Deposits
8	Gorgas	255	SI	12	7	River Valleys and Floodplains Without Overbank Deposits
8	Gorgas	963	LF	94	6	River Valleys and Floodplains With Overbank Deposits
8	Gorgas	963	LF	6	7	River Valleys and Floodplains Without Overbank Deposits
1825	Grand Haven City of J.B. Sims	1309	SI	100	2	Bedded Sedimentary Rock
1825	Grand Haven City of J.B. Sims	1310	SI	100	2	Bedded Sedimentary Rock
10151	Grant Town Power Plant	871	LF	100	2	Bedded Sedimentary Rock
10151	Grant Town Power Plant	872	LF	100	6	River Valleys and Floodplains With Overbank Deposits
10151	Grant Town Power Plant	873	LF	34	2	Bedded Sedimentary Rock
10151	Grant Town Power Plant	873	LF	66	6	River Valleys and Floodplains With Overbank Deposits
10151	Grant Town Power Plant	1167	SI	100	2	Bedded Sedimentary Rock
10151	Grant Town Power Plant	1168	SI	100	2	Bedded Sedimentary Rock
10151	Grant Town Power Plant	1169	SI	100	2	Bedded Sedimentary Rock
10151	Grant Town Power Plant	1170	SI	100	2	Bedded Sedimentary Rock
10151	Grant Town Power Plant	1171	SI	100	2	Bedded Sedimentary Rock

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
165	GRDA	874	LF	100	6	River Valleys and Floodplains With Overbank Deposits
165	GRDA	1210	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1357	Green River	531	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1357	Green River	532	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1357	Green River	533	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1357	Green River	534	SI	100	2	Bedded Sedimentary Rock
1357	Green River	535	SI	100	6	River Valleys and Floodplains With Overbank Deposits
10	Greene County	256	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
6041	H L Spurlock Station	34	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
6041	H L Spurlock Station	972	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
2709	H.F. Lee Plant	656	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
2709	H.F. Lee Plant	657	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
2709	H.F. Lee Plant	658	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
2709	H.F. Lee Plant	659	SI	59	6	River Valleys and Floodplains With Overbank Deposits
2709	H.F. Lee Plant	659	SI	41	7	River Valleys and Floodplains Without Overbank Deposits
2709	H.F. Lee Plant	660	SI	5	10	Unconsolidated and Semiconsolidated Shallow Aquifers
2709	H.F. Lee Plant	660	SI	26	6	River Valleys and Floodplains With Overbank Deposits
2709	H.F. Lee Plant	660	SI	70	7	River Valleys and Floodplains Without Overbank Deposits
708	Hammond	351	SI	100	2	Bedded Sedimentary Rock
708	Hammond	352	SI	100	2	Bedded Sedimentary Rock

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
708	Hammond	353	SI	100	2	Bedded Sedimentary Rock
708	Hammond	354	SI	100	2	Bedded Sedimentary Rock
708	Hammond	1145	LF	100	2	Bedded Sedimentary Rock
1731	Harbor Beach Power Plant	581	SI	100	4	Sand and Gravel
990	Harding Street	420	SI	100	3	Till Over Sedimentary Rock
990	Harding Street	421	SI	100	3	Till Over Sedimentary Rock
990	Harding Street	422	SI	100	3	Till Over Sedimentary Rock
990	Harding Street	423	SI	100	3	Till Over Sedimentary Rock
990	Harding Street	424	SI	100	3	Till Over Sedimentary Rock
709	Harllee Branch	355	SI	100	6	River Valleys and Floodplains With Overbank Deposits
709	Harllee Branch	356	SI	43	6	River Valleys and Floodplains With Overbank Deposits
709	Harllee Branch	356	SI	57	7	River Valleys and Floodplains Without Overbank Deposits
709	Harllee Branch	357	SI	79	6	River Valleys and Floodplains With Overbank Deposits
709	Harllee Branch	357	SI	21	7	River Valleys and Floodplains Without Overbank Deposits
709	Harllee Branch	358	SI	1	6	River Valleys and Floodplains With Overbank Deposits
709	Harllee Branch	358	SI	99	7	River Valleys and Floodplains Without Overbank Deposits
709	Harllee Branch	359	SI	6	6	River Valleys and Floodplains With Overbank Deposits
709	Harllee Branch	359	SI	94	7	River Valleys and Floodplains Without Overbank Deposits
6193	Harrington	877	LF	100	4	Sand and Gravel
6193	Harrington	878	LF	100	4	Sand and Gravel
3944	Harrison Power Station	158	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3944	Harrison Power Station	891	LF	100	6	River Valleys and Floodplains With Overbank Deposits
3179	Hatfield's Ferry Power Station	880	LF	16	2	Bedded Sedimentary Rock
3179	Hatfield's Ferry Power Station	880	LF	84	6	River Valleys and Floodplains With Overbank Deposits
3179	Hatfield's Ferry Power Station	1215	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3179	Hatfield's Ferry Power Station	1216	SI	100	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
3179	Hatfield's Ferry Power Station	1217	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3179	Hatfield's Ferry Power Station	1218	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3179	Hatfield's Ferry Power Station	1219	SI	100	6	River Valleys and Floodplains With Overbank Deposits
891	Havana	392	SI	100	6	River Valleys and Floodplains With Overbank Deposits
891	Havana	393	SI	15	6	River Valleys and Floodplains With Overbank Deposits
891	Havana	393	SI	85	7	River Valleys and Floodplains Without Overbank Deposits
2079	Hawthorn	599	SI	87	6	River Valleys and Floodplains With Overbank Deposits
2079	Hawthorn	599	SI	13	7	River Valleys and Floodplains Without Overbank Deposits
2079	Hawthorn	962	LF	87	6	River Valleys and Floodplains With Overbank Deposits
2079	Hawthorn	962	LF	13	7	River Valleys and Floodplains Without Overbank Deposits
525	Hayden	332	SI	1	2	Bedded Sedimentary Rock
525	Hayden	332	SI	99	6	River Valleys and Floodplains With Overbank Deposits
525	Hayden	333	SI	1	2	Bedded Sedimentary Rock
525	Hayden	333	SI	99	6	River Valleys and Floodplains With Overbank Deposits
525	Hayden	334	SI	1	2	Bedded Sedimentary Rock
525	Hayden	334	SI	99	6	River Valleys and Floodplains With Overbank Deposits
525	Hayden	335	SI	1	2	Bedded Sedimentary Rock
525	Hayden	335	SI	99	6	River Valleys and Floodplains With Overbank Deposits
525	Hayden	336	SI	1	2	Bedded Sedimentary Rock
525	Hayden	336	SI	99	6	River Valleys and Floodplains With Overbank Deposits
525	Hayden	337	SI	1	2	Bedded Sedimentary Rock
525	Hayden	337	SI	99	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
525	Hayden	882	LF	100	2	Bedded Sedimentary Rock
525	Hayden	1146	LF	12	2	Bedded Sedimentary Rock
525	Hayden	1146	LF	88	6	River Valleys and Floodplains With Overbank Deposits
3251	HB Robinson / Darlington Electric Power Plant	104	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
892	Hennepin Power Station	394	SI	100	4	Sand and Gravel
892	Hennepin Power Station	883	LF	100	4	Sand and Gravel
1382	HMP&L Station Two Henderson	556	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1382	HMP&L Station Two Henderson	557	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1382	HMP&L Station Two Henderson	984	LF	100	6	River Valleys and Floodplains With Overbank Deposits
108	HOLCOMB	1147	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
3122	Homer City Station	90	SI	100	2	Bedded Sedimentary Rock
3122	Homer City Station	91	SI	100	2	Bedded Sedimentary Rock
3122	Homer City Station	92	SI	100	2	Bedded Sedimentary Rock
3122	Homer City Station	719	SI	100	2	Bedded Sedimentary Rock
3122	Homer City Station	720	SI	100	2	Bedded Sedimentary Rock
3122	Homer City Station	721	SI	100	2	Bedded Sedimentary Rock
3122	Homer City Station	722	SI	100	2	Bedded Sedimentary Rock
3122	Homer City Station	723	SI	100	2	Bedded Sedimentary Rock
3122	Homer City Station	724	SI	100	2	Bedded Sedimentary Rock
3122	Homer City Station	725	SI	100	2	Bedded Sedimentary Rock
3122	Homer City Station	726	SI	100	2	Bedded Sedimentary Rock
3122	Homer City Station	727	SI	100	2	Bedded Sedimentary Rock
3122	Homer City Station	728	SI	100	2	Bedded Sedimentary Rock
3122	Homer City Station	729	SI	100	2	Bedded Sedimentary Rock
3122	Homer City Station	884	LF	100	2	Bedded Sedimentary Rock
3122	Homer City Station	886	LF	100	2	Bedded Sedimentary Rock
3122	Homer City Station	1134	LF	100	2	Bedded Sedimentary Rock
1943	Hoot Lake	887	LF	100	9	Till and Till Over Outwash
1943	Hoot Lake	1148	LF	100	9	Till and Till Over Outwash
1943	Hoot Lake	1156	LF	79	1	Metamorphic and Igneous
1943	Hoot Lake	1156	LF	21	9	Till and Till Over Outwash
1943	Hoot Lake	1157	LF	100	9	Till and Till Over Outwash
1943	Hoot Lake	1158	LF	100	9	Till and Till Over Outwash
1943	Hoot Lake	1159	LF	100	9	Till and Till Over Outwash
1943	Hoot Lake	1160	LF	100	9	Till and Till Over Outwash
10771	Hopewell	1362	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6772	Hugo	229	SI	100	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
6772	Hugo	230	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6772	Hugo	231	SI	4	12	Solution Limestone
6772	Hugo	231	SI	2	2	Bedded Sedimentary Rock
6772	Hugo	231	SI	95	6	River Valleys and Floodplains With Overbank Deposits
6772	Hugo	232	SI	4	12	Solution Limestone
6772	Hugo	232	SI	2	2	Bedded Sedimentary Rock
6772	Hugo	232	SI	95	6	River Valleys and Floodplains With Overbank Deposits
6772	Hugo	755	LF	100	6	River Valleys and Floodplains With Overbank Deposits
3176	Hunlock Power Station	102	SI	100	2	Bedded Sedimentary Rock
3176	Hunlock Power Station	103	SI	100	2	Bedded Sedimentary Rock
6165	Hunter Plant	756	LF	100	2	Bedded Sedimentary Rock
6165	Hunter Plant	1258	SI	100	2	Bedded Sedimentary Rock
8069	Huntington Plant	757	LF	100	2	Bedded Sedimentary Rock
8069	Huntington Plant	758	LF	100	2	Bedded Sedimentary Rock
8069	Huntington Plant	759	LF	100	2	Bedded Sedimentary Rock
8069	Huntington Plant	1363	SI	100	2	Bedded Sedimentary Rock
8069	Huntington Plant	1364	SI	100	2	Bedded Sedimentary Rock
863	Hutsonville	381	SI	100	9	Till and Till Over Outwash
863	Hutsonville	382	SI	100	9	Till and Till Over Outwash
863	Hutsonville	383	SI	100	9	Till and Till Over Outwash
863	Hutsonville	384	SI	100	9	Till and Till Over Outwash
6065	Iatan	40	SI	87	6	River Valleys and Floodplains With Overbank Deposits
6065	Iatan	40	SI	13	7	River Valleys and Floodplains Without Overbank Deposits
6065	Iatan	1154	LF	100	6	River Valleys and Floodplains With Overbank Deposits
6641	Independence	1153	LF	100	6	River Valleys and Floodplains With Overbank Deposits
2132	Independence Power & Light - Blue Valley Station	616	SI	100	4	Sand and Gravel
2132	Independence Power & Light - Blue Valley Station	617	SI	100	4	Sand and Gravel
2132	Independence Power & Light - Blue Valley Station	618	SI	100	4	Sand and Gravel
594	Indian River Generating Station	339	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
594	Indian River Generating Station	340	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
594	Indian River Generating Station	762	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
594	Indian River Generating Station	775	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6481	Intermountain Power Project	214	SI	100	5	Alluvial Basins Valleys and Fans
6481	Intermountain Power Project	215	SI	100	5	Alluvial Basins Valleys and Fans
6481	Intermountain Power Project	216	SI	100	5	Alluvial Basins Valleys and Fans
6481	Intermountain Power Project	217	SI	100	5	Alluvial Basins Valleys and Fans
6481	Intermountain Power Project	218	SI	100	5	Alluvial Basins Valleys and Fans
6481	Intermountain Power Project	219	SI	100	5	Alluvial Basins Valleys and Fans
7097	J K Spruce	753	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
7097	J K Spruce	1368	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
7097	J K Spruce	1369	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
7097	J K Spruce	1370	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
7097	J K Spruce	1371	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
7097	J K Spruce	1372	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
7097	J K Spruce	1373	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
2850	J M Stuart	706	SI	85	6	River Valleys and Floodplains With Overbank Deposits
2850	J M Stuart	706	SI	15	7	River Valleys and Floodplains Without Overbank Deposits
2850	J M Stuart	707	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2850	J M Stuart	708	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2850	J M Stuart	709	SI	81	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
2850	J M Stuart	709	SI	19	7	River Valleys and Floodplains Without Overbank Deposits
2850	J M Stuart	710	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2850	J M Stuart	710	SI	0	7	River Valleys and Floodplains Without Overbank Deposits
2850	J M Stuart	711	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2850	J M Stuart	766	LF	100	6	River Valleys and Floodplains With Overbank Deposits
2850	J M Stuart	767	LF	100	6	River Valleys and Floodplains With Overbank Deposits
6181	J T Deely	768	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6181	J T Deely	1002	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6181	J T Deely	1291	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6181	J T Deely	1292	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6181	J T Deely	1293	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6181	J T Deely	1294	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6181	J T Deely	1295	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6181	J T Deely	1296	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
1720	J.C. Weadock	573	SI	100	2	Bedded Sedimentary Rock
1720	J.C. Weadock	574	SI	100	2	Bedded Sedimentary Rock
1720	J.C. Weadock	575	SI	100	2	Bedded Sedimentary Rock
1720	J.C. Weadock	576	SI	100	2	Bedded Sedimentary Rock
1720	J.C. Weadock	1003	LF	100	2	Bedded Sedimentary Rock
1723	J.R Whiting	577	SI	100	12	Solution Limestone
1723	J.R Whiting	578	SI	100	12	Solution Limestone
1723	J.R Whiting	579	SI	100	12	Solution Limestone
1723	J.R Whiting	580	SI	100	12	Solution Limestone
1723	J.R Whiting	965	LF	100	12	Solution Limestone
1723	J.R Whiting	1000	LF	100	12	Solution Limestone
710	Jack McDonough	360	SI	100	1	Metamorphic and Igneous
710	Jack McDonough	361	SI	100	1	Metamorphic and Igneous

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
710	Jack McDonough	362	SI	100	1	Metamorphic and Igneous
710	Jack McDonough	363	SI	100	1	Metamorphic and Igneous
710	Jack McDonough	968	LF	100	1	Metamorphic and Igneous
2049	Jack Watson	595	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
2049	Jack Watson	769	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
1830	James De Young	770	LF	100	3	Till Over Sedimentary Rock
1830	James De Young	1333	SI	100	4	Sand and Gravel
6002	James H. Miller Jr.	16	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2161	James River Power Station	619	SI	100	12	Solution Limestone
2161	James River Power Station	771	LF	100	12	Solution Limestone
2187	JE Corette Plant	764	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
2187	JE Corette Plant	1249	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
2187	JE Corette Plant	1250	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
3319	Jefferies	117	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3319	Jefferies	118	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6068	Jeffrey Energy Center	41	SI	100	4	Sand and Gravel
6068	Jeffrey Energy Center	42	SI	100	4	Sand and Gravel
6068	Jeffrey Energy Center	43	SI	100	4	Sand and Gravel
6068	Jeffrey Energy Center	772	LF	100	4	Sand and Gravel
6068	Jeffrey Energy Center	773	LF	100	4	Sand and Gravel
8066	Jim Bridger Plant Units 1-4	244	SI	100	2	Bedded Sedimentary Rock
8066	Jim Bridger Plant Units 1-4	245	SI	100	2	Bedded Sedimentary Rock
8066	Jim Bridger Plant Units 1-4	774	LF	100	2	Bedded Sedimentary Rock
3935	John E. Amos	153	SI	16	2	Bedded Sedimentary Rock
3935	John E. Amos	153	SI	74	6	River Valleys and Floodplains With Overbank Deposits
3935	John E. Amos	153	SI	10	7	River Valleys and Floodplains Without Overbank Deposits
3935	John E. Amos	154	SI	16	2	Bedded Sedimentary Rock
3935	John E. Amos	154	SI	74	6	River Valleys and Floodplains With Overbank Deposits
3935	John E. Amos	154	SI	10	7	River Valleys and Floodplains Without Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
3935	John E. Amos	740	LF	100	6	River Valleys and Floodplains With Overbank Deposits
3935	John E. Amos	742	LF	100	6	River Valleys and Floodplains With Overbank Deposits
4271	John P. Madgett	990	LF	100	6	River Valleys and Floodplains With Overbank Deposits
4271	John P. Madgett	991	LF	100	6	River Valleys and Floodplains With Overbank Deposits
3405	John Sevier	131	SI	58	12	Solution Limestone
3405	John Sevier	131	SI	34	6	River Valleys and Floodplains With Overbank Deposits
3405	John Sevier	131	SI	9	7	River Valleys and Floodplains Without Overbank Deposits
3405	John Sevier	132	SI	58	12	Solution Limestone
3405	John Sevier	132	SI	34	6	River Valleys and Floodplains With Overbank Deposits
3405	John Sevier	132	SI	9	7	River Valleys and Floodplains Without Overbank Deposits
3405	John Sevier	763	LF	91	12	Solution Limestone
3405	John Sevier	763	LF	9	7	River Valleys and Floodplains Without Overbank Deposits
3406	Johnsonville	133	SI	16	4	Sand and Gravel
3406	Johnsonville	133	SI	2	6	River Valleys and Floodplains With Overbank Deposits
3406	Johnsonville	133	SI	82	7	River Valleys and Floodplains Without Overbank Deposits
3406	Johnsonville	291	SI	16	4	Sand and Gravel
3406	Johnsonville	291	SI	2	6	River Valleys and Floodplains With Overbank Deposits
3406	Johnsonville	291	SI	82	7	River Valleys and Floodplains Without Overbank Deposits
3406	Johnsonville	732	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
3406	Johnsonville	733	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
384	Joliet 29	309	SI	100	12	Solution Limestone
384	Joliet 29	1098	LF	100	12	Solution Limestone
874	Joliet 9	1327	SI	100	12	Solution Limestone
874	Joliet 9	1328	SI	100	12	Solution Limestone

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
887	Joppa Steam	390	SI	100	6	River Valleys and Floodplains With Overbank Deposits
887	Joppa Steam	734	LF	100	6	River Valleys and Floodplains With Overbank Deposits
3947	Kammer	159	SI	88	6	River Valleys and Floodplains With Overbank Deposits
3947	Kammer	159	SI	12	7	River Valleys and Floodplains Without Overbank Deposits
3936	Kanawha River	155	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
1381	Kenneth C Coleman	553	SI	2	6	River Valleys and Floodplains With Overbank Deposits
1381	Kenneth C Coleman	553	SI	98	8	Outwash
1381	Kenneth C Coleman	554	SI	1	2	Bedded Sedimentary Rock
1381	Kenneth C Coleman	554	SI	9	4	Sand and Gravel
1381	Kenneth C Coleman	554	SI	9	6	River Valleys and Floodplains With Overbank Deposits
1381	Kenneth C Coleman	554	SI	31	7	River Valleys and Floodplains Without Overbank Deposits
1381	Kenneth C Coleman	554	SI	50	8	Outwash
1381	Kenneth C Coleman	555	SI	100	8	Outwash
3136	Keystone	736	LF	100	2	Bedded Sedimentary Rock
3136	Keystone	1151	LF	100	2	Bedded Sedimentary Rock
3136	Keystone	1152	LF	100	2	Bedded Sedimentary Rock
3136	Keystone	1297	SI	100	2	Bedded Sedimentary Rock
3136	Keystone	1298	SI	100	2	Bedded Sedimentary Rock
3136	Keystone	1299	SI	100	2	Bedded Sedimentary Rock
3136	Keystone	1300	SI	100	2	Bedded Sedimentary Rock
3136	Keystone	1301	SI	100	2	Bedded Sedimentary Rock
3136	Keystone	1302	SI	100	2	Bedded Sedimentary Rock
3136	Keystone	1303	SI	100	2	Bedded Sedimentary Rock
3136	Keystone	1304	SI	100	2	Bedded Sedimentary Rock
3136	Keystone	1305	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3136	Keystone	1306	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3136	Keystone	1307	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6031	Killen Station	31	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6031	Killen Station	32	SI	100	6	River Valleys and Floodplains With Overbank Deposits

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ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
876	Kincaid Generation LLC	388	SI	100	4	Sand and Gravel
876	Kincaid Generation LLC	969	LF	3	2	Bedded Sedimentary Rock
876	Kincaid Generation LLC	969	LF	97	4	Sand and Gravel
3407	Kingston	134	SI	44	6	River Valleys and Floodplains With Overbank Deposits
3407	Kingston	134	SI	56	7	River Valleys and Floodplains Without Overbank Deposits
3407	Kingston	135	SI	44	6	River Valleys and Floodplains With Overbank Deposits
3407	Kingston	135	SI	56	7	River Valleys and Floodplains Without Overbank Deposits
733	Kraft	375	SI	48	6	River Valleys and Floodplains With Overbank Deposits
733	Kraft	375	SI	52	7	River Valleys and Floodplains Without Overbank Deposits
733	Kraft	1150	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
2876	Kyger Creek	716	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2876	Kyger Creek	717	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2876	Kyger Creek	738	LF	67	2	Bedded Sedimentary Rock
2876	Kyger Creek	738	LF	33	7	River Valleys and Floodplains Without Overbank Deposits
2713	L.V. Sutton Electric Plant	665	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
2713	L.V. Sutton Electric Plant	666	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
1241	La Cygne	513	SI	100	4	Sand and Gravel
1241	La Cygne	514	SI	100	4	Sand and Gravel
1241	La Cygne	739	LF	100	4	Sand and Gravel
2103	Labadie	607	SI	88	6	River Valleys and Floodplains With Overbank Deposits
2103	Labadie	607	SI	12	7	River Valleys and Floodplains Without Overbank Deposits
2103	Labadie	608	SI	88	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
2103	Labadie	608	SI	12	7	River Valleys and Floodplains Without Overbank Deposits
2098	Lake Road	605	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2098	Lake Road	606	SI	7	2	Bedded Sedimentary Rock
2098	Lake Road	606	SI	84	6	River Valleys and Floodplains With Overbank Deposits
2098	Lake Road	606	SI	9	7	River Valleys and Floodplains Without Overbank Deposits
2098	Lake Road	752	LF	100	6	River Valleys and Floodplains With Overbank Deposits
2838	Lake Shore	1270	SI	100	4	Sand and Gravel
964	Lakeside	400	SI	100	4	Sand and Gravel
1047	Lansing	477	SI	43	2	Bedded Sedimentary Rock
1047	Lansing	477	SI	11	6	River Valleys and Floodplains With Overbank Deposits
1047	Lansing	477	SI	46	7	River Valleys and Floodplains Without Overbank Deposits
1047	Lansing	478	SI	43	2	Bedded Sedimentary Rock
1047	Lansing	478	SI	11	6	River Valleys and Floodplains With Overbank Deposits
1047	Lansing	478	SI	46	7	River Valleys and Floodplains Without Overbank Deposits
1047	Lansing	730	LF	100	2	Bedded Sedimentary Rock
1047	Lansing	741	LF	100	2	Bedded Sedimentary Rock
643	Lansing Smith	341	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
643	Lansing Smith	743	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6204	Laramie River Station	188	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
6204	Laramie River Station	189	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
6204	Laramie River Station	744	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
1891	Laskin Energy Center	588	SI	100	3	Till Over Sedimentary Rock
1891	Laskin Energy Center	589	SI	100	3	Till Over Sedimentary Rock
1250	Lawrence Energy Center	515	SI	16	4	Sand and Gravel

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
1250	Lawrence Energy Center	515	SI	84	6	River Valleys and Floodplains With Overbank Deposits
1250	Lawrence Energy Center	516	SI	16	4	Sand and Gravel
1250	Lawrence Energy Center	516	SI	84	6	River Valleys and Floodplains With Overbank Deposits
1250	Lawrence Energy Center	517	SI	16	4	Sand and Gravel
1250	Lawrence Energy Center	517	SI	84	6	River Valleys and Floodplains With Overbank Deposits
1250	Lawrence Energy Center	518	SI	16	4	Sand and Gravel
1250	Lawrence Energy Center	518	SI	84	6	River Valleys and Floodplains With Overbank Deposits
1250	Lawrence Energy Center	745	LF	100	6	River Valleys and Floodplains With Overbank Deposits
1250	Lawrence Energy Center	747	LF	100	6	River Valleys and Floodplains With Overbank Deposits
1250	Lawrence Energy Center	1149	LF	100	6	River Valleys and Floodplains With Overbank Deposits
2817	Leland Olds	683	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2817	Leland Olds	684	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2817	Leland Olds	685	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2817	Leland Olds	748	LF	100	6	River Valleys and Floodplains With Overbank Deposits
2817	Leland Olds	749	LF	100	3	Till Over Sedimentary Rock
6089	Lewis & Clark	750	LF	100	3	Till Over Sedimentary Rock
6089	Lewis & Clark	751	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
6089	Lewis & Clark	786	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
6089	Lewis & Clark	1374	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
6089	Lewis & Clark	1375	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
6089	Lewis & Clark	1376	SI	100	7	River Valleys and Floodplains Without Overbank Deposits

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ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
6089	Lewis & Clark	1377	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
6089	Lewis & Clark	1378	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
298	Limestone	300	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
298	Limestone	301	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
298	Limestone	302	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
298	Limestone	303	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
298	Limestone	304	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
298	Limestone	305	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
298	Limestone	306	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
298	Limestone	307	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
298	Limestone	308	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
298	Limestone	821	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
2240	Lon Wright	765	LF	100	2	Bedded Sedimentary Rock
6664	Louisa	222	SI	30	6	River Valleys and Floodplains With Overbank Deposits
6664	Louisa	222	SI	70	7	River Valleys and Floodplains Without Overbank Deposits
6664	Louisa	223	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
6664	Louisa	801	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
976	Marion Generating Station	401	SI	100	4	Sand and Gravel
976	Marion Generating Station	402	SI	100	4	Sand and Gravel
976	Marion Generating Station	403	SI	100	4	Sand and Gravel
976	Marion Generating Station	404	SI	100	4	Sand and Gravel
976	Marion Generating Station	405	SI	100	4	Sand and Gravel

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
976	Marion Generating Station	406	SI	100	4	Sand and Gravel
976	Marion Generating Station	407	SI	100	4	Sand and Gravel
976	Marion Generating Station	408	SI	100	4	Sand and Gravel
976	Marion Generating Station	409	SI	100	4	Sand and Gravel
976	Marion Generating Station	410	SI	100	4	Sand and Gravel
976	Marion Generating Station	411	SI	100	4	Sand and Gravel
976	Marion Generating Station	412	SI	100	4	Sand and Gravel
976	Marion Generating Station	802	LF	100	4	Sand and Gravel
2727	Marshall	680	SI	100	1	Metamorphic and Igneous
2727	Marshall	803	LF	100	1	Metamorphic and Igneous
2727	Marshall	804	LF	100	1	Metamorphic and Igneous
492	Martin Drake	805	LF	100	2	Bedded Sedimentary Rock
492	Martin Drake	1251	SI	100	2	Bedded Sedimentary Rock
492	Martin Drake	1252	SI	100	2	Bedded Sedimentary Rock
492	Martin Drake	1253	SI	100	2	Bedded Sedimentary Rock
492	Martin Drake	1254	SI	100	2	Bedded Sedimentary Rock
6146	Martin Lake	806	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6146	Martin Lake	807	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6146	Martin Lake	808	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6146	Martin Lake	810	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6146	Martin Lake	822	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6146	Martin Lake	1223	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6146	Martin Lake	1224	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6146	Martin Lake	1225	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6146	Martin Lake	1226	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6250	Mayo Electric Generating Facility	204	SI	100	1	Metamorphic and Igneous
6124	McIntosh	87	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
3287	McMeekin	1155	LF	100	6	River Valleys and Floodplains With Overbank Deposits
2104	Meramec	609	SI	77	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
2104	Meramec	609	SI	23	7	River Valleys and Floodplains Without Overbank Deposits
2104	Meramec	610	SI	77	6	River Valleys and Floodplains With Overbank Deposits
2104	Meramec	610	SI	23	7	River Valleys and Floodplains Without Overbank Deposits
2104	Meramec	611	SI	77	6	River Valleys and Floodplains With Overbank Deposits
2104	Meramec	611	SI	23	7	River Valleys and Floodplains Without Overbank Deposits
2104	Meramec	612	SI	77	6	River Valleys and Floodplains With Overbank Deposits
2104	Meramec	612	SI	23	7	River Valleys and Floodplains Without Overbank Deposits
2104	Meramec	613	SI	77	6	River Valleys and Floodplains With Overbank Deposits
2104	Meramec	613	SI	23	7	River Valleys and Floodplains Without Overbank Deposits
864	Meredosia	385	SI	48	6	River Valleys and Floodplains With Overbank Deposits
864	Meredosia	385	SI	52	7	River Valleys and Floodplains Without Overbank Deposits
864	Meredosia	386	SI	48	6	River Valleys and Floodplains With Overbank Deposits
864	Meredosia	386	SI	52	7	River Valleys and Floodplains Without Overbank Deposits
6213	Merom	190	SI	100	2	Bedded Sedimentary Rock
6213	Merom	812	LF	100	2	Bedded Sedimentary Rock
6213	Merom	813	LF	100	2	Bedded Sedimentary Rock
2364	Merrimack Station	754	LF	100	9	Till and Till Over Outwash
2364	Merrimack Station	1319	SI	32	3	Till Over Sedimentary Rock
2364	Merrimack Station	1319	SI	68	9	Till and Till Over Outwash
2364	Merrimack Station	1320	SI	96	3	Till Over Sedimentary Rock
2364	Merrimack Station	1320	SI	4	9	Till and Till Over Outwash
2832	Miami Fort	699	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2832	Miami Fort	700	SI	100	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
2832	Miami Fort	1109	LF	100	6	River Valleys and Floodplains With Overbank Deposits
2832	Miami Fort	1121	LF	100	6	River Valleys and Floodplains With Overbank Deposits
997	Michigan City	448	SI	90	3	Till Over Sedimentary Rock
997	Michigan City	448	SI	10	9	Till and Till Over Outwash
997	Michigan City	449	SI	100	3	Till Over Sedimentary Rock
997	Michigan City	450	SI	100	3	Till Over Sedimentary Rock
997	Michigan City	451	SI	98	3	Till Over Sedimentary Rock
997	Michigan City	451	SI	2	9	Till and Till Over Outwash
997	Michigan City	452	SI	100	3	Till Over Sedimentary Rock
997	Michigan City	453	SI	100	3	Till Over Sedimentary Rock
1364	Mill Creek	543	SI	100	1	Metamorphic and Igneous
1364	Mill Creek	544	SI	40	2	Bedded Sedimentary Rock
1364	Mill Creek	544	SI	48	6	River Valleys and Floodplains With Overbank Deposits
1364	Mill Creek	544	SI	11	7	River Valleys and Floodplains Without Overbank Deposits
1364	Mill Creek	545	SI	40	2	Bedded Sedimentary Rock
1364	Mill Creek	545	SI	48	6	River Valleys and Floodplains With Overbank Deposits
1364	Mill Creek	545	SI	11	7	River Valleys and Floodplains Without Overbank Deposits
1364	Mill Creek	546	SI	40	2	Bedded Sedimentary Rock
1364	Mill Creek	546	SI	48	6	River Valleys and Floodplains With Overbank Deposits
1364	Mill Creek	546	SI	11	7	River Valleys and Floodplains Without Overbank Deposits
1364	Mill Creek	547	SI	40	2	Bedded Sedimentary Rock
1364	Mill Creek	547	SI	48	6	River Valleys and Floodplains With Overbank Deposits
1364	Mill Creek	547	SI	11	7	River Valleys and Floodplains Without Overbank Deposits
1364	Mill Creek	817	LF	100	2	Bedded Sedimentary Rock
1364	Mill Creek	817	LF	0	6	River Valleys and Floodplains With Overbank Deposits
1364	Mill Creek	818	LF	100	2	Bedded Sedimentary Rock
1364	Mill Creek	819	LF	88	2	Bedded Sedimentary Rock
1364	Mill Creek	819	LF	12	6	River Valleys and Floodplains With Overbank Deposits
2823	Milton R. Young Station	686	SI	100	3	Till Over Sedimentary Rock
2823	Milton R. Young Station	687	SI	100	3	Till Over Sedimentary Rock
2823	Milton R. Young Station	688	SI	100	3	Till Over Sedimentary Rock

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
2823	Milton R. Young Station	689	SI	100	3	Till Over Sedimentary Rock
2823	Milton R. Young Station	777	LF	100	3	Till Over Sedimentary Rock
2823	Milton R. Young Station	788	LF	100	3	Till Over Sedimentary Rock
2823	Milton R. Young Station	809	LF	100	3	Till Over Sedimentary Rock
2823	Milton R. Young Station	811	LF	100	3	Till Over Sedimentary Rock
2823	Milton R. Young Station	820	LF	100	3	Till Over Sedimentary Rock
2171	Missouri City	1257	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3948	Mitchell	160	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3948	Mitchell	161	SI	100	6	River Valleys and Floodplains With Overbank Deposits
727	Mitchell	364	SI	56	12	Solution Limestone
727	Mitchell	364	SI	44	7	River Valleys and Floodplains Without Overbank Deposits
727	Mitchell	365	SI	56	12	Solution Limestone
727	Mitchell	365	SI	44	7	River Valleys and Floodplains Without Overbank Deposits
727	Mitchell	366	SI	56	12	Solution Limestone
727	Mitchell	366	SI	44	7	River Valleys and Floodplains Without Overbank Deposits
3181	Mitchell Power Station	778	LF	100	2	Bedded Sedimentary Rock
3181	Mitchell Power Station	779	LF	100	2	Bedded Sedimentary Rock
1048	ML Kapp	479	SI	28	6	River Valleys and Floodplains With Overbank Deposits
1048	ML Kapp	479	SI	72	7	River Valleys and Floodplains Without Overbank Deposits
1048	ML Kapp	479	SI	0	8	Outwash
1048	ML Kapp	480	SI	28	6	River Valleys and Floodplains With Overbank Deposits
1048	ML Kapp	480	SI	72	7	River Valleys and Floodplains Without Overbank Deposits
1048	ML Kapp	480	SI	0	8	Outwash
1048	ML Kapp	481	SI	28	6	River Valleys and Floodplains With Overbank Deposits
1048	ML Kapp	481	SI	72	7	River Valleys and Floodplains Without Overbank Deposits
1048	ML Kapp	481	SI	0	8	Outwash
1048	ML Kapp	482	SI	28	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
1048	ML Kapp	482	SI	72	7	River Valleys and Floodplains Without Overbank Deposits
1048	ML Kapp	482	SI	0	8	Outwash
1733	Monroe Power Plant	582	SI	100	12	Solution Limestone
1733	Monroe Power Plant	583	SI	100	12	Solution Limestone
6147	Monticello	780	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6147	Monticello	781	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6147	Monticello	782	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6147	Monticello	1203	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6147	Monticello	1204	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6147	Monticello	1205	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6147	Monticello	1206	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
2080	Montrose	600	SI	100	4	Sand and Gravel
2080	Montrose	601	SI	100	4	Sand and Gravel
2080	Montrose	602	SI	39	2	Bedded Sedimentary Rock
2080	Montrose	602	SI	47	4	Sand and Gravel
2080	Montrose	602	SI	14	6	River Valleys and Floodplains With Overbank Deposits
2080	Montrose	602	SI	0	7	River Valleys and Floodplains Without Overbank Deposits
2080	Montrose	783	LF	100	4	Sand and Gravel
1573	Morgantown Generating Plant	785	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
1573	Morgantown Generating Plant	1108	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
1606	Mount Tom	563	SI	100	2	Bedded Sedimentary Rock
1606	Mount Tom	564	SI	100	2	Bedded Sedimentary Rock
1606	Mount Tom	565	SI	100	2	Bedded Sedimentary Rock
1606	Mount Tom	798	LF	100	2	Bedded Sedimentary Rock
6264	Mountaineer	211	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
6264	Mountaineer	787	LF	100	6	River Valleys and Floodplains With Overbank Deposits
3954	Mt. Storm	789	LF	100	2	Bedded Sedimentary Rock

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ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
3954	Mt. Storm	1110	LF	100	2	Bedded Sedimentary Rock
3954	Mt. Storm	1111	LF	100	2	Bedded Sedimentary Rock
3954	Mt. Storm	1112	LF	100	2	Bedded Sedimentary Rock
1167	Muscatine #1	792	LF	100	12	Solution Limestone
1167	Muscatine #1	1361	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
2872	Muskingum River	712	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
2872	Muskingum River	713	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2872	Muskingum River	714	SI	41	6	River Valleys and Floodplains With Overbank Deposits
2872	Muskingum River	714	SI	59	7	River Valleys and Floodplains Without Overbank Deposits
2872	Muskingum River	715	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
2952	Muskogee	1172	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
2952	Muskogee	1173	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
2952	Muskogee	1174	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
4162	Naughton Plant	12	SI	100	2	Bedded Sedimentary Rock
4162	Naughton Plant	13	SI	100	2	Bedded Sedimentary Rock
4162	Naughton Plant	14	SI	100	2	Bedded Sedimentary Rock
4162	Naughton Plant	15	SI	100	2	Bedded Sedimentary Rock
4162	Naughton Plant	980	LF	97	2	Bedded Sedimentary Rock
4162	Naughton Plant	980	LF	3	6	River Valleys and Floodplains With Overbank Deposits
4941	Navajo Generating Station	793	LF	100	2	Bedded Sedimentary Rock
6064	Nearman Creek	39	SI	89	6	River Valleys and Floodplains With Overbank Deposits
6064	Nearman Creek	39	SI	11	7	River Valleys and Floodplains Without Overbank Deposits
6064	Nearman Creek	794	LF	100	6	River Valleys and Floodplains With Overbank Deposits
6064	Nearman Creek	795	LF	100	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
6096	Nebraska City	797	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
6096	Nebraska City	943	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
6096	Nebraska City	1271	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
6096	Nebraska City	1272	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
4054	Nelson Dewey	170	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
4054	Nelson Dewey	171	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
4054	Nelson Dewey	893	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
3138	New Castle Plant	941	LF	100	2	Bedded Sedimentary Rock
3138	New Castle Plant	1349	SI	100	2	Bedded Sedimentary Rock
3138	New Castle Plant	1350	SI	100	2	Bedded Sedimentary Rock
2167	New Madrid	620	SI	80	6	River Valleys and Floodplains With Overbank Deposits
2167	New Madrid	620	SI	20	7	River Valleys and Floodplains Without Overbank Deposits
2167	New Madrid	621	SI	34	6	River Valleys and Floodplains With Overbank Deposits
2167	New Madrid	621	SI	66	7	River Valleys and Floodplains Without Overbank Deposits
2167	New Madrid	622	SI	99	6	River Valleys and Floodplains With Overbank Deposits
2167	New Madrid	622	SI	1	7	River Valleys and Floodplains Without Overbank Deposits
2167	New Madrid	623	SI	90	6	River Valleys and Floodplains With Overbank Deposits
2167	New Madrid	623	SI	10	7	River Valleys and Floodplains Without Overbank Deposits
2167	New Madrid	1032	LF	100	6	River Valleys and Floodplains With Overbank Deposits
6017	Newton	21	SI	100	2	Bedded Sedimentary Rock
6017	Newton	22	SI	100	2	Bedded Sedimentary Rock
6017	Newton	1033	LF	100	2	Bedded Sedimentary Rock

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
6017	Newton	1034	LF	100	2	Bedded Sedimentary Rock
2291	North Omaha	1036	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
2291	North Omaha	1113	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
2291	North Omaha	1220	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
2291	North Omaha	1221	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
2291	North Omaha	1222	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
8224	North Valmy	1037	LF	100	5	Alluvial Basins Valleys and Fans
2963	Northeastern	718	SI	21	4	Sand and Gravel
2963	Northeastern	718	SI	79	6	River Valleys and Floodplains With Overbank Deposits
2963	Northeastern	718	SI	0	7	River Valleys and Floodplains Without Overbank Deposits
2963	Northeastern	1038	LF	100	6	River Valleys and Floodplains With Overbank Deposits
667	Northside Generating Station	1039	LF	100	11	Coastal Beaches
10030	NRG Energy Center Dover	251	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
527	Nucla	338	SI	100	2	Bedded Sedimentary Rock
527	Nucla	964	LF	100	2	Bedded Sedimentary Rock
2848	O H Hutchings	703	SI	100	9	Till and Till Over Outwash
2848	O H Hutchings	704	SI	100	9	Till and Till Over Outwash
2848	O H Hutchings	705	SI	100	9	Till and Till Over Outwash
6180	Oak Grove	1040	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6180	Oak Grove	1042	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6180	Oak Grove	1054	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6180	Oak Grove	1185	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
127	Oklaunion	281	SI	100	2	Bedded Sedimentary Rock
127	Oklaunion	282	SI	100	2	Bedded Sedimentary Rock
127	Oklaunion	283	SI	100	2	Bedded Sedimentary Rock
127	Oklaunion	841	LF	100	2	Bedded Sedimentary Rock
4151	Osage	1031	LF	100	12	Solution Limestone

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
4151	Osage	1044	LF	100	12	Solution Limestone
4151	Osage	1266	SI	100	12	Solution Limestone
4151	Osage	1267	SI	100	12	Solution Limestone
1831	Otto E. Eckert Station	586	SI	100	2	Bedded Sedimentary Rock
6254	Ottumwa	205	SI	50	12	Solution Limestone
6254	Ottumwa	205	SI	23	2	Bedded Sedimentary Rock
6254	Ottumwa	205	SI	26	6	River Valleys and Floodplains With Overbank Deposits
6254	Ottumwa	206	SI	50	12	Solution Limestone
6254	Ottumwa	206	SI	23	2	Bedded Sedimentary Rock
6254	Ottumwa	206	SI	26	6	River Valleys and Floodplains With Overbank Deposits
6254	Ottumwa	207	SI	50	12	Solution Limestone
6254	Ottumwa	207	SI	23	2	Bedded Sedimentary Rock
6254	Ottumwa	207	SI	26	6	River Valleys and Floodplains With Overbank Deposits
6254	Ottumwa	208	SI	50	12	Solution Limestone
6254	Ottumwa	208	SI	23	2	Bedded Sedimentary Rock
6254	Ottumwa	208	SI	26	6	River Valleys and Floodplains With Overbank Deposits
6254	Ottumwa	1045	LF	100	6	River Valleys and Floodplains With Overbank Deposits
1378	Paradise	548	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1378	Paradise	549	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1378	Paradise	550	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6248	Pawnee	191	SI	100	4	Sand and Gravel
6248	Pawnee	192	SI	100	4	Sand and Gravel
6248	Pawnee	193	SI	100	4	Sand and Gravel
6248	Pawnee	194	SI	100	4	Sand and Gravel
6248	Pawnee	195	SI	100	4	Sand and Gravel
6248	Pawnee	196	SI	100	4	Sand and Gravel
6248	Pawnee	197	SI	100	4	Sand and Gravel
6248	Pawnee	1046	LF	100	4	Sand and Gravel
6238	Pearl Station	1211	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3938	Philip Sporn	156	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
3938	Philip Sporn	157	SI	100	7	River Valleys and Floodplains Without Overbank Deposits

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ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
3938	Philip Sporn	979	LF	24	6	River Valleys and Floodplains With Overbank Deposits
3938	Philip Sporn	979	LF	76	7	River Valleys and Floodplains Without Overbank Deposits
2843	Picway	702	SI	100	3	Till Over Sedimentary Rock
7902	Pirkey	233	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
7902	Pirkey	234	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
7902	Pirkey	235	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
7902	Pirkey	236	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
7902	Pirkey	237	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
7902	Pirkey	238	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
7902	Pirkey	1132	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
59	Platte	1047	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
59	Platte	1048	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
6170	Pleasant Prairie	1049	LF	100	12	Solution Limestone
6004	Pleasants Power Station	17	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6004	Pleasants Power Station	1050	LF	100	6	River Valleys and Floodplains With Overbank Deposits
7242	Polk	1051	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3113	Portland	1020	LF	100	2	Bedded Sedimentary Rock
3113	Portland	1041	LF	100	2	Bedded Sedimentary Rock
3113	Portland	1043	LF	100	2	Bedded Sedimentary Rock
3113	Portland	1052	LF	100	2	Bedded Sedimentary Rock
3113	Portland	1199	SI	100	2	Bedded Sedimentary Rock
3113	Portland	1200	SI	100	2	Bedded Sedimentary Rock
3113	Portland	1201	SI	100	2	Bedded Sedimentary Rock
879	Powerton	1227	SI	96	4	Sand and Gravel

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
879	Powerton	1227	SI	4	7	River Valleys and Floodplains Without Overbank Deposits
879	Powerton	1228	SI	100	4	Sand and Gravel
879	Powerton	1229	SI	71	4	Sand and Gravel
879	Powerton	1229	SI	29	7	River Valleys and Floodplains Without Overbank Deposits
879	Powerton	1230	SI	100	4	Sand and Gravel
879	Powerton	1231	SI	100	4	Sand and Gravel
879	Powerton	1232	SI	100	4	Sand and Gravel
879	Powerton	1233	SI	100	4	Sand and Gravel
3140	PPL Brunner Island	93	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3140	PPL Brunner Island	94	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3140	PPL Brunner Island	95	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3140	PPL Brunner Island	1114	LF	100	6	River Valleys and Floodplains With Overbank Deposits
3149	PPL Montour	96	SI	100	12	Solution Limestone
3149	PPL Montour	97	SI	100	12	Solution Limestone
3149	PPL Montour	98	SI	100	12	Solution Limestone
3149	PPL Montour	99	SI	100	12	Solution Limestone
3149	PPL Montour	100	SI	100	12	Solution Limestone
3149	PPL Montour	1011	LF	100	12	Solution Limestone
3149	PPL Montour	1115	LF	100	12	Solution Limestone
1073	Prairie Creek	487	SI	35	12	Solution Limestone
1073	Prairie Creek	487	SI	45	6	River Valleys and Floodplains With Overbank Deposits
1073	Prairie Creek	487	SI	21	7	River Valleys and Floodplains Without Overbank Deposits
1073	Prairie Creek	488	SI	35	12	Solution Limestone
1073	Prairie Creek	488	SI	45	6	River Valleys and Floodplains With Overbank Deposits
1073	Prairie Creek	488	SI	21	7	River Valleys and Floodplains Without Overbank Deposits
1073	Prairie Creek	489	SI	35	12	Solution Limestone
1073	Prairie Creek	489	SI	45	6	River Valleys and Floodplains With Overbank Deposits
1073	Prairie Creek	489	SI	21	7	River Valleys and Floodplains Without Overbank Deposits
1073	Prairie Creek	490	SI	35	12	Solution Limestone

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
1073	Prairie Creek	490	SI	45	6	River Valleys and Floodplains With Overbank Deposits
1073	Prairie Creek	490	SI	21	7	River Valleys and Floodplains Without Overbank Deposits
1073	Prairie Creek	491	SI	35	12	Solution Limestone
1073	Prairie Creek	491	SI	45	6	River Valleys and Floodplains With Overbank Deposits
1073	Prairie Creek	491	SI	21	7	River Valleys and Floodplains Without Overbank Deposits
1073	Prairie Creek	492	SI	35	12	Solution Limestone
1073	Prairie Creek	492	SI	45	6	River Valleys and Floodplains With Overbank Deposits
1073	Prairie Creek	492	SI	21	7	River Valleys and Floodplains Without Overbank Deposits
1073	Prairie Creek	493	SI	35	12	Solution Limestone
1073	Prairie Creek	493	SI	45	6	River Valleys and Floodplains With Overbank Deposits
1073	Prairie Creek	493	SI	21	7	River Valleys and Floodplains Without Overbank Deposits
1073	Prairie Creek	494	SI	35	12	Solution Limestone
1073	Prairie Creek	494	SI	45	6	River Valleys and Floodplains With Overbank Deposits
1073	Prairie Creek	494	SI	21	7	River Valleys and Floodplains Without Overbank Deposits
1073	Prairie Creek	495	SI	35	12	Solution Limestone
1073	Prairie Creek	495	SI	45	6	River Valleys and Floodplains With Overbank Deposits
1073	Prairie Creek	495	SI	21	7	River Valleys and Floodplains Without Overbank Deposits
1073	Prairie Creek	496	SI	35	12	Solution Limestone
1073	Prairie Creek	496	SI	45	6	River Valleys and Floodplains With Overbank Deposits
1073	Prairie Creek	496	SI	21	7	River Valleys and Floodplains Without Overbank Deposits
1769	Presque Isle	1012	LF	100	1	Metamorphic and Igneous
1769	Presque Isle	1013	LF	100	1	Metamorphic and Igneous
1769	Presque Isle	1014	LF	100	1	Metamorphic and Igneous
2403	PSEG Hudson Generating Station	1015	LF	100	3	Till Over Sedimentary Rock

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
2403	PSEG Hudson Generating Station	1351	SI	100	3	Till Over Sedimentary Rock
2403	PSEG Hudson Generating Station	1352	SI	100	3	Till Over Sedimentary Rock
2408	PSEG Mercer Generating Station	1016	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
2408	PSEG Mercer Generating Station	1197	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
2408	PSEG Mercer Generating Station	1198	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
4072	Pulliam	1017	LF	100	2	Bedded Sedimentary Rock
4072	Pulliam	1212	SI	100	2	Bedded Sedimentary Rock
1295	Quindaro	1030	LF	100	6	River Valleys and Floodplains With Overbank Deposits
6639	R D Green	220	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6639	R D Green	1019	LF	100	6	River Valleys and Floodplains With Overbank Deposits
2864	R. E. Burger	976	LF	90	6	River Valleys and Floodplains With Overbank Deposits
2864	R. E. Burger	976	LF	10	7	River Valleys and Floodplains Without Overbank Deposits
2864	R. E. Burger	1380	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2864	R. E. Burger	1381	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1008	R. Gallagher	460	SI	100	8	Outwash
1008	R. Gallagher	461	SI	34	7	River Valleys and Floodplains Without Overbank Deposits
1008	R. Gallagher	461	SI	66	8	Outwash
1008	R. Gallagher	1001	LF	40	7	River Valleys and Floodplains Without Overbank Deposits
1008	R. Gallagher	1001	LF	60	8	Outwash
1008	R. Gallagher	1023	LF	40	7	River Valleys and Floodplains Without Overbank Deposits
1008	R. Gallagher	1023	LF	60	8	Outwash
1008	R. Gallagher	1024	LF	40	7	River Valleys and Floodplains Without Overbank Deposits
1008	R. Gallagher	1024	LF	60	8	Outwash

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
1008	R. Gallagher	1025	LF	40	7	River Valleys and Floodplains Without Overbank Deposits
1008	R. Gallagher	1025	LF	60	8	Outwash
1008	R. Gallagher	1026	LF	40	7	River Valleys and Floodplains Without Overbank Deposits
1008	R. Gallagher	1026	LF	60	8	Outwash
1008	R. Gallagher	1027	LF	40	7	River Valleys and Floodplains Without Overbank Deposits
1008	R. Gallagher	1027	LF	60	8	Outwash
1008	R. Gallagher	1029	LF	40	7	River Valleys and Floodplains Without Overbank Deposits
1008	R. Gallagher	1029	LF	60	8	Outwash
1008	R. Gallagher	1053	LF	40	7	River Valleys and Floodplains Without Overbank Deposits
1008	R. Gallagher	1053	LF	60	8	Outwash
1008	R. Gallagher	1056	LF	40	7	River Valleys and Floodplains Without Overbank Deposits
1008	R. Gallagher	1056	LF	60	8	Outwash
1570	R. Paul Smith Power Station	561	SI	81	6	River Valleys and Floodplains With Overbank Deposits
1570	R. Paul Smith Power Station	561	SI	19	7	River Valleys and Floodplains Without Overbank Deposits
1570	R. Paul Smith Power Station	562	SI	83	6	River Valleys and Floodplains With Overbank Deposits
1570	R. Paul Smith Power Station	562	SI	17	7	River Valleys and Floodplains Without Overbank Deposits
1570	R. Paul Smith Power Station	1083	LF	100	6	River Valleys and Floodplains With Overbank Deposits
2790	R.M. Heskett Station	1080	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
2790	R.M. Heskett Station	1081	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
6085	R.M. Schahfer	54	SI	100	8	Outwash
6085	R.M. Schahfer	55	SI	100	8	Outwash
6085	R.M. Schahfer	56	SI	100	8	Outwash
6085	R.M. Schahfer	57	SI	100	8	Outwash
6085	R.M. Schahfer	58	SI	100	8	Outwash
6085	R.M. Schahfer	67	SI	100	8	Outwash
6085	R.M. Schahfer	68	SI	100	8	Outwash
6085	R.M. Schahfer	1082	LF	100	8	Outwash
6761	Rawhide	225	SI	100	2	Bedded Sedimentary Rock
6761	Rawhide	226	SI	100	2	Bedded Sedimentary Rock

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
6761	Rawhide	996	LF	100	2	Bedded Sedimentary Rock
6761	Rawhide	1086	LF	100	2	Bedded Sedimentary Rock
8219	Ray D Nixon	1087	LF	100	2	Bedded Sedimentary Rock
8219	Ray D Nixon	1255	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
55076	Red Hills Generating Facility	1088	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
55076	Red Hills Generating Facility	1256	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
2324	Reid Gardner	630	SI	100	5	Alluvial Basins Valleys and Fans
2324	Reid Gardner	631	SI	100	5	Alluvial Basins Valleys and Fans
2324	Reid Gardner	632	SI	100	5	Alluvial Basins Valleys and Fans
2324	Reid Gardner	633	SI	100	5	Alluvial Basins Valleys and Fans
2324	Reid Gardner	634	SI	100	5	Alluvial Basins Valleys and Fans
2324	Reid Gardner	635	SI	100	5	Alluvial Basins Valleys and Fans
2324	Reid Gardner	636	SI	100	5	Alluvial Basins Valleys and Fans
2324	Reid Gardner	637	SI	100	5	Alluvial Basins Valleys and Fans
2324	Reid Gardner	1090	LF	100	5	Alluvial Basins Valleys and Fans
1740	River Rouge Power Plant	1186	SI	100	12	Solution Limestone
2732	Riverbend	681	SI	100	1	Metamorphic and Igneous
2732	Riverbend	682	SI	100	1	Metamorphic and Igneous
1081	Riverside	500	SI	84	6	River Valleys and Floodplains With Overbank Deposits
1081	Riverside	500	SI	16	7	River Valleys and Floodplains Without Overbank Deposits
1081	Riverside	501	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
1927	Riverside	594	SI	93	2	Bedded Sedimentary Rock
1927	Riverside	594	SI	7	8	Outwash
1239	Riverton	512	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3945	Rivesville Power Station	1095	LF	100	6	River Valleys and Floodplains With Overbank Deposits
3945	Rivesville Power Station	1116	LF	100	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
3945	Rivesville Power Station	1355	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3945	Rivesville Power Station	1356	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3945	Rivesville Power Station	1357	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3945	Rivesville Power Station	1358	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6166	Rockport	179	SI	100	8	Outwash
6166	Rockport	1097	LF	100	8	Outwash
6190	Rodemacher	185	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6190	Rodemacher	186	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6190	Rodemacher	187	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6190	Rodemacher	187	SI	0	7	River Valleys and Floodplains Without Overbank Deposits
2712	Roxboro Steam Electric Plant	661	SI	100	1	Metamorphic and Igneous
2712	Roxboro Steam Electric Plant	662	SI	100	1	Metamorphic and Igneous
2712	Roxboro Steam Electric Plant	663	SI	100	1	Metamorphic and Igneous
2712	Roxboro Steam Electric Plant	664	SI	100	1	Metamorphic and Igneous
2712	Roxboro Steam Electric Plant	1096	LF	100	1	Metamorphic and Igneous
1393	RS Nelson	1084	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
1393	RS Nelson	1085	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
1393	RS Nelson	1329	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
1393	RS Nelson	1330	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6155	Rush Island	178	SI	63	6	River Valleys and Floodplains With Overbank Deposits
6155	Rush Island	178	SI	37	7	River Valleys and Floodplains Without Overbank Deposits
6155	Rush Island	1091	LF	100	6	River Valleys and Floodplains With Overbank Deposits
2451	San Juan	1308	SI	100	2	Bedded Sedimentary Rock
6183	San Miguel	1093	LF	100	2	Bedded Sedimentary Rock

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
6183	San Miguel	1094	LF	100	2	Bedded Sedimentary Rock
6183	San Miguel	1365	SI	100	2	Bedded Sedimentary Rock
6183	San Miguel	1366	SI	100	2	Bedded Sedimentary Rock
6183	San Miguel	1367	SI	100	2	Bedded Sedimentary Rock
6648	Sandow No 4	221	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6648	Sandow No 4	1057	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6648	Sandow No 4	1065	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6648	Sandow No 4	1067	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6648	Sandow No 4	1089	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6648	Sandow No 4	1092	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6257	Scherer	209	SI	100	1	Metamorphic and Igneous
6257	Scherer	210	SI	100	1	Metamorphic and Igneous
2367	SCHILLER	1058	LF	86	3	Till Over Sedimentary Rock
2367	SCHILLER	1058	LF	14	9	Till and Till Over Outwash
642	Scholz	1346	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
642	Scholz	1347	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
642	Scholz	1348	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
136	Seminole Generating Station	1059	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
1379	Shawnee	551	SI	38	6	River Valleys and Floodplains With Overbank Deposits
1379	Shawnee	551	SI	62	7	River Valleys and Floodplains Without Overbank Deposits
1379	Shawnee	552	SI	38	6	River Valleys and Floodplains With Overbank Deposits
1379	Shawnee	552	SI	62	7	River Valleys and Floodplains Without Overbank Deposits
1379	Shawnee	1060	LF	100	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
1379	Shawnee	1061	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
3131	Shawville	1062	LF	100	2	Bedded Sedimentary Rock
3131	Shawville	1063	LF	100	2	Bedded Sedimentary Rock
3131	Shawville	1245	SI	100	2	Bedded Sedimentary Rock
3131	Shawville	1246	SI	100	2	Bedded Sedimentary Rock
3131	Shawville	1247	SI	100	2	Bedded Sedimentary Rock
3131	Shawville	1248	SI	100	2	Bedded Sedimentary Rock
2277	Sheldon Station	1055	LF	100	4	Sand and Gravel
2277	Sheldon Station	1064	LF	100	4	Sand and Gravel
2277	Sheldon Station	1066	LF	100	4	Sand and Gravel
2277	Sheldon Station	1078	LF	100	4	Sand and Gravel
2277	Sheldon Station	1360	SI	100	4	Sand and Gravel
6090	Sherburne County	69	SI	100	8	Outwash
6090	Sherburne County	70	SI	100	8	Outwash
6090	Sherburne County	71	SI	100	8	Outwash
6090	Sherburne County	72	SI	74	8	Outwash
6090	Sherburne County	72	SI	26	9	Till and Till Over Outwash
6090	Sherburne County	73	SI	100	8	Outwash
6090	Sherburne County	74	SI	74	8	Outwash
6090	Sherburne County	74	SI	26	9	Till and Till Over Outwash
6090	Sherburne County	1068	LF	100	8	Outwash
2094	Sibley	603	SI	87	6	River Valleys and Floodplains With Overbank Deposits
2094	Sibley	603	SI	13	7	River Valleys and Floodplains Without Overbank Deposits
2094	Sibley	604	SI	87	6	River Valleys and Floodplains With Overbank Deposits
2094	Sibley	604	SI	13	7	River Valleys and Floodplains Without Overbank Deposits
2094	Sibley	1069	LF	100	6	River Valleys and Floodplains With Overbank Deposits
6768	Sikeston Power Station	227	SI	100	8	Outwash
6768	Sikeston Power Station	228	SI	100	8	Outwash
2107	Sioux	614	SI	66	6	River Valleys and Floodplains With Overbank Deposits
2107	Sioux	614	SI	34	7	River Valleys and Floodplains Without Overbank Deposits
2107	Sioux	615	SI	66	6	River Valleys and Floodplains With Overbank Deposits
2107	Sioux	615	SI	34	7	River Valleys and Floodplains Without Overbank Deposits
1058	Sixth Street	483	SI	100	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
1058	Sixth Street	484	SI	90	6	River Valleys and Floodplains With Overbank Deposits
1058	Sixth Street	484	SI	10	7	River Valleys and Floodplains Without Overbank Deposits
1058	Sixth Street	485	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1058	Sixth Street	486	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1613	Somerset Station	566	SI	15	1	Metamorphic and Igneous
1613	Somerset Station	566	SI	84	3	Till Over Sedimentary Rock
1613	Somerset Station	566	SI	1	9	Till and Till Over Outwash
1613	Somerset Station	567	SI	15	1	Metamorphic and Igneous
1613	Somerset Station	567	SI	84	3	Till Over Sedimentary Rock
1613	Somerset Station	567	SI	1	9	Till and Till Over Outwash
1613	Somerset Station	568	SI	15	1	Metamorphic and Igneous
1613	Somerset Station	568	SI	84	3	Till Over Sedimentary Rock
1613	Somerset Station	568	SI	1	9	Till and Till Over Outwash
1613	Somerset Station	569	SI	15	1	Metamorphic and Igneous
1613	Somerset Station	569	SI	84	3	Till Over Sedimentary Rock
1613	Somerset Station	569	SI	1	9	Till and Till Over Outwash
6095	Sooner	1259	SI	1	4	Sand and Gravel
6095	Sooner	1259	SI	99	6	River Valleys and Floodplains With Overbank Deposits
6095	Sooner	1260	SI	100	4	Sand and Gravel
6061	South Mississippi El Pwr Assn	1008	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6061	South Mississippi El Pwr Assn	1021	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6061	South Mississippi El Pwr Assn	1022	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6061	South Mississippi El Pwr Assn	1353	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6061	South Mississippi El Pwr Assn	1354	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
4041	South Oak Creek	1070	LF	100	12	Solution Limestone
4041	South Oak Creek	1071	LF	100	12	Solution Limestone
4041	South Oak Creek	1072	LF	100	12	Solution Limestone
6195	Southwest Power Station	1073	LF	100	12	Solution Limestone
6195	Southwest Power Station	1074	LF	100	12	Solution Limestone
6195	Southwest Power Station	1268	SI	100	12	Solution Limestone
6195	Southwest Power Station	1269	SI	100	12	Solution Limestone
8223	Springerville	1075	LF	100	2	Bedded Sedimentary Rock
8223	Springerville	1384	SI	100	2	Bedded Sedimentary Rock
1743	St Clair Power Plant	584	SI	100	4	Sand and Gravel
207	St Johns River Power Park	1018	LF	100	11	Coastal Beaches

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
207	St Johns River Power Park	1076	LF	100	11	Coastal Beaches
207	St Johns River Power Park	1077	LF	100	11	Coastal Beaches
2824	Stanton	690	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2824	Stanton	691	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2824	Stanton	692	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2824	Stanton	937	LF	100	3	Till Over Sedimentary Rock
2824	Stanton	940	LF	100	6	River Valleys and Floodplains With Overbank Deposits
2824	Stanton	997	LF	100	3	Till Over Sedimentary Rock
564	Stanton Energy Center	942	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
1131	Streeter Station	1028	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
3152	Sunbury Generation LP	101	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
50951	Sunnyside Cogen Associates	944	LF	100	2	Bedded Sedimentary Rock
1077	Sutherland	497	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1077	Sutherland	498	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1077	Sutherland	499	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1077	Sutherland	1117	LF	100	12	Solution Limestone
1077	Sutherland	1118	LF	100	12	Solution Limestone
10075	Taconite Harbor Energy Center	947	LF	100	1	Metamorphic and Igneous
10075	Taconite Harbor Energy Center	948	LF	100	1	Metamorphic and Igneous
10075	Taconite Harbor Energy Center	961	LF	100	1	Metamorphic and Igneous
988	Tanners Creek	415	SI	68	6	River Valleys and Floodplains With Overbank Deposits
988	Tanners Creek	415	SI	32	7	River Valleys and Floodplains Without Overbank Deposits
988	Tanners Creek	416	SI	75	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
988	Tanners Creek	416	SI	25	7	River Valleys and Floodplains Without Overbank Deposits
988	Tanners Creek	417	SI	100	6	River Valleys and Floodplains With Overbank Deposits
988	Tanners Creek	418	SI	100	6	River Valleys and Floodplains With Overbank Deposits
988	Tanners Creek	419	SI	100	6	River Valleys and Floodplains With Overbank Deposits
988	Tanners Creek	950	LF	100	6	River Valleys and Floodplains With Overbank Deposits
988	Tanners Creek	950	LF	0	7	River Valleys and Floodplains Without Overbank Deposits
1252	Tecumseh Energy Center	519	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
1252	Tecumseh Energy Center	520	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
1252	Tecumseh Energy Center	995	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
1252	Tecumseh Energy Center	1120	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
1252	Tecumseh Energy Center	1133	LF	100	6	River Valleys and Floodplains With Overbank Deposits
2168	Thomas Hill	624	SI	100	2	Bedded Sedimentary Rock
2168	Thomas Hill	625	SI	94	2	Bedded Sedimentary Rock
2168	Thomas Hill	625	SI	6	4	Sand and Gravel
2168	Thomas Hill	626	SI	94	2	Bedded Sedimentary Rock
2168	Thomas Hill	626	SI	6	4	Sand and Gravel
2168	Thomas Hill	627	SI	100	2	Bedded Sedimentary Rock
2168	Thomas Hill	628	SI	94	2	Bedded Sedimentary Rock
2168	Thomas Hill	628	SI	6	4	Sand and Gravel
2168	Thomas Hill	629	SI	94	2	Bedded Sedimentary Rock
2168	Thomas Hill	629	SI	6	4	Sand and Gravel
2168	Thomas Hill	953	LF	100	2	Bedded Sedimentary Rock
3115	Titus	954	LF	100	2	Bedded Sedimentary Rock
3115	Titus	955	LF	100	2	Bedded Sedimentary Rock
3115	Titus	956	LF	100	2	Bedded Sedimentary Rock
3115	Titus	957	LF	100	2	Bedded Sedimentary Rock
6194	Tolk	1161	LF	100	4	Sand and Gravel
3845	TransAlta Centralia Generation	959	LF	100	2	Bedded Sedimentary Rock
1745	Trenton Channel Power Plant	585	SI	100	12	Solution Limestone
1745	Trenton Channel Power Plant	960	LF	100	12	Solution Limestone

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
6071	Trimble Co.	44	SI	16	6	River Valleys and Floodplains With Overbank Deposits
6071	Trimble Co.	44	SI	84	7	River Valleys and Floodplains Without Overbank Deposits
56224	TS Power Plant	816	LF	1	5	Alluvial Basins Valleys and Fans
56224	TS Power Plant	816	LF	99	6	River Valleys and Floodplains With Overbank Deposits
7030	Twin Oaks Power One	928	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
1361	Tyrone	536	SI	100	6	River Valleys and Floodplains With Overbank Deposits
1361	Tyrone	537	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3295	Urquhart	110	SI	75	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3295	Urquhart	110	SI	25	7	River Valleys and Floodplains Without Overbank Deposits
3295	Urquhart	111	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3295	Urquhart	112	SI	75	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3295	Urquhart	112	SI	25	7	River Valleys and Floodplains Without Overbank Deposits
3295	Urquhart	1107	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
4042	Valley	918	LF	100	12	Solution Limestone
4042	Valley	919	LF	100	12	Solution Limestone
4042	Valley	920	LF	100	12	Solution Limestone
4042	Valley	949	LF	100	12	Solution Limestone
477	Valmont	329	SI	100	2	Bedded Sedimentary Rock
477	Valmont	330	SI	100	2	Bedded Sedimentary Rock
477	Valmont	331	SI	100	2	Bedded Sedimentary Rock
477	Valmont	1122	LF	100	2	Bedded Sedimentary Rock
477	Valmont	1123	LF	100	2	Bedded Sedimentary Rock
897	Vermilion	395	SI	100	3	Till Over Sedimentary Rock
897	Vermilion	396	SI	100	3	Till Over Sedimentary Rock
897	Vermilion	970	LF	100	3	Till Over Sedimentary Rock
6073	Victor J. Daniel Jr	45	SI	84	10	Unconsolidated and Semiconsolidated Shallow Aquifers

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
6073	Victor J. Daniel Jr	45	SI	16	6	River Valleys and Floodplains With Overbank Deposits
6073	Victor J. Daniel Jr	924	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6073	Victor J. Daniel Jr	925	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6073	Victor J. Daniel Jr	938	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6073	Victor J. Daniel Jr	1124	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6019	W H Zimmer	26	SI	100	6	River Valleys and Floodplains With Overbank Deposits
6019	W H Zimmer	929	LF	100	4	Sand and Gravel
3470	W. A. Parish	136	SI	0	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3470	W. A. Parish	136	SI	64	6	River Valleys and Floodplains With Overbank Deposits
3470	W. A. Parish	136	SI	36	7	River Valleys and Floodplains Without Overbank Deposits
3470	W. A. Parish	137	SI	0	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3470	W. A. Parish	137	SI	64	6	River Valleys and Floodplains With Overbank Deposits
3470	W. A. Parish	137	SI	36	7	River Valleys and Floodplains Without Overbank Deposits
3470	W. A. Parish	138	SI	0	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3470	W. A. Parish	138	SI	64	6	River Valleys and Floodplains With Overbank Deposits
3470	W. A. Parish	138	SI	36	7	River Valleys and Floodplains Without Overbank Deposits
3470	W. A. Parish	139	SI	0	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3470	W. A. Parish	139	SI	64	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
3470	W. A. Parish	139	SI	36	7	River Valleys and Floodplains Without Overbank Deposits
3470	W. A. Parish	140	SI	0	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3470	W. A. Parish	140	SI	64	6	River Valleys and Floodplains With Overbank Deposits
3470	W. A. Parish	140	SI	36	7	River Valleys and Floodplains Without Overbank Deposits
3470	W. A. Parish	141	SI	0	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3470	W. A. Parish	141	SI	64	6	River Valleys and Floodplains With Overbank Deposits
3470	W. A. Parish	141	SI	36	7	River Valleys and Floodplains Without Overbank Deposits
3470	W. A. Parish	142	SI	0	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3470	W. A. Parish	142	SI	64	6	River Valleys and Floodplains With Overbank Deposits
3470	W. A. Parish	142	SI	36	7	River Valleys and Floodplains Without Overbank Deposits
3470	W. A. Parish	143	SI	0	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3470	W. A. Parish	143	SI	64	6	River Valleys and Floodplains With Overbank Deposits
3470	W. A. Parish	143	SI	36	7	River Valleys and Floodplains Without Overbank Deposits
3470	W. A. Parish	1125	LF	100	6	River Valleys and Floodplains With Overbank Deposits
2866	W. H. Sammis	916	LF	100	2	Bedded Sedimentary Rock
2866	W. H. Sammis	1382	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2866	W. H. Sammis	1383	SI	100	6	River Valleys and Floodplains With Overbank Deposits
3264	W. S. Lee	105	SI	100	1	Metamorphic and Igneous
3264	W. S. Lee	106	SI	100	1	Metamorphic and Igneous
2716	W.H. Weatherspoon Plant	667	SI	100	7	River Valleys and Floodplains Without Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
1010	Wabash River	462	SI	100	9	Till and Till Over Outwash
1010	Wabash River	463	SI	100	9	Till and Till Over Outwash
1010	Wabash River	464	SI	100	9	Till and Till Over Outwash
1010	Wabash River	465	SI	100	9	Till and Till Over Outwash
2830	Walter C Beckjord	695	SI	100	6	River Valleys and Floodplains With Overbank Deposits
2830	Walter C Beckjord	696	SI	88	4	Sand and Gravel
2830	Walter C Beckjord	696	SI	12	6	River Valleys and Floodplains With Overbank Deposits
2830	Walter C Beckjord	697	SI	100	4	Sand and Gravel
2830	Walter C Beckjord	698	SI	100	4	Sand and Gravel
2830	Walter C Beckjord	1126	LF	100	4	Sand and Gravel
2830	Walter C Beckjord	1127	LF	100	4	Sand and Gravel
1082	Walter Scott Jr. Energy Center	502	SI	60	4	Sand and Gravel
1082	Walter Scott Jr. Energy Center	502	SI	40	7	River Valleys and Floodplains Without Overbank Deposits
1082	Walter Scott Jr. Energy Center	503	SI	60	4	Sand and Gravel
1082	Walter Scott Jr. Energy Center	503	SI	40	7	River Valleys and Floodplains Without Overbank Deposits
1082	Walter Scott Jr. Energy Center	932	LF	100	4	Sand and Gravel
6052	Wansley	35	SI	6	6	River Valleys and Floodplains With Overbank Deposits
6052	Wansley	35	SI	94	7	River Valleys and Floodplains Without Overbank Deposits
6705	Warrick Power Plant	224	SI	21	4	Sand and Gravel
6705	Warrick Power Plant	224	SI	49	6	River Valleys and Floodplains With Overbank Deposits
6705	Warrick Power Plant	224	SI	16	7	River Valleys and Floodplains Without Overbank Deposits
6705	Warrick Power Plant	224	SI	15	8	Outwash
3297	Wateree	113	SI	100	7	River Valleys and Floodplains Without Overbank Deposits
3297	Wateree	114	SI	7	6	River Valleys and Floodplains With Overbank Deposits
3297	Wateree	114	SI	93	7	River Valleys and Floodplains Without Overbank Deposits
3297	Wateree	933	LF	100	7	River Valleys and Floodplains Without Overbank Deposits
883	Waukegan	1311	SI	100	12	Solution Limestone
883	Waukegan	1312	SI	100	12	Solution Limestone
6139	Welsh	175	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
6139	Welsh	176	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6139	Welsh	177	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6139	Welsh	934	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
4078	Weston	935	LF	100	9	Till and Till Over Outwash
4078	Weston	936	LF	12	8	Outwash
4078	Weston	936	LF	88	9	Till and Till Over Outwash
4078	Weston	1313	SI	100	9	Till and Till Over Outwash
4078	Weston	1314	SI	100	8	Outwash
4078	Weston	1315	SI	100	8	Outwash
4078	Weston	1316	SI	93	8	Outwash
4078	Weston	1316	SI	7	9	Till and Till Over Outwash
4078	Weston	1317	SI	100	8	Outwash
4078	Weston	1318	SI	100	8	Outwash
60	Whelan Energy Center Unit 1 (WEC1)	1214	SI	100	12	Solution Limestone
6009	White Bluff	1128	LF	100	6	River Valleys and Floodplains With Overbank Deposits
1040	Whitewater Valley	1321	SI	100	12	Solution Limestone
1040	Whitewater Valley	1322	SI	100	12	Solution Limestone
1040	Whitewater Valley	1323	SI	100	12	Solution Limestone
1040	Whitewater Valley	1324	SI	100	12	Solution Limestone
1040	Whitewater Valley	1325	SI	100	12	Solution Limestone
4057	WI Power & Light Co -Rock River Generating	1	SI	100	9	Till and Till Over Outwash
4057	WI Power & Light Co -Rock River Generating	2	SI	100	9	Till and Till Over Outwash
4057	WI Power & Light Co -Rock River Generating	3	SI	100	9	Till and Till Over Outwash
4057	WI Power & Light Co -Rock River Generating	172	SI	100	9	Till and Till Over Outwash
50	Widows Creek	59	SI	15	6	River Valleys and Floodplains With Overbank Deposits
50	Widows Creek	59	SI	85	7	River Valleys and Floodplains Without Overbank Deposits
50	Widows Creek	60	SI	15	6	River Valleys and Floodplains With Overbank Deposits
50	Widows Creek	60	SI	85	7	River Valleys and Floodplains Without Overbank Deposits
50	Widows Creek	61	SI	15	6	River Valleys and Floodplains With Overbank Deposits
50	Widows Creek	61	SI	85	7	River Valleys and Floodplains Without Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
50	Widows Creek	62	SI	15	6	River Valleys and Floodplains With Overbank Deposits
50	Widows Creek	62	SI	85	7	River Valleys and Floodplains Without Overbank Deposits
50	Widows Creek	63	SI	15	6	River Valleys and Floodplains With Overbank Deposits
50	Widows Creek	63	SI	85	7	River Valleys and Floodplains Without Overbank Deposits
50	Widows Creek	64	SI	15	6	River Valleys and Floodplains With Overbank Deposits
50	Widows Creek	64	SI	85	7	River Valleys and Floodplains Without Overbank Deposits
50	Widows Creek	65	SI	15	6	River Valleys and Floodplains With Overbank Deposits
50	Widows Creek	65	SI	85	7	River Valleys and Floodplains Without Overbank Deposits
50	Widows Creek	66	SI	15	6	River Valleys and Floodplains With Overbank Deposits
50	Widows Creek	66	SI	85	7	River Valleys and Floodplains Without Overbank Deposits
50	Widows Creek	261	SI	15	6	River Valleys and Floodplains With Overbank Deposits
50	Widows Creek	261	SI	85	7	River Valleys and Floodplains Without Overbank Deposits
50	Widows Creek	262	SI	15	6	River Valleys and Floodplains With Overbank Deposits
50	Widows Creek	262	SI	85	7	River Valleys and Floodplains Without Overbank Deposits
50	Widows Creek	289	SI	15	6	River Valleys and Floodplains With Overbank Deposits
50	Widows Creek	289	SI	85	7	River Valleys and Floodplains Without Overbank Deposits
50	Widows Creek	290	SI	15	6	River Valleys and Floodplains With Overbank Deposits
50	Widows Creek	290	SI	85	7	River Valleys and Floodplains Without Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
884	Will County	389	SI	100	12	Solution Limestone
3298	Williams	1129	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3298	Williams	1130	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3946	Willow Island	917	LF	70	6	River Valleys and Floodplains With Overbank Deposits
3946	Willow Island	917	LF	30	7	River Valleys and Floodplains Without Overbank Deposits
6249	Winyah	198	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6249	Winyah	199	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6249	Winyah	200	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6249	Winyah	201	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6249	Winyah	202	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6249	Winyah	203	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
6249	Winyah	982	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
898	Wood River	397	SI	100	6	River Valleys and Floodplains With Overbank Deposits
898	Wood River	398	SI	100	6	River Valleys and Floodplains With Overbank Deposits
50611	WPS Westwood Generation, LLC	951	LF	100	2	Bedded Sedimentary Rock
6101	Wyodak Plant	80	SI	100	2	Bedded Sedimentary Rock
6101	Wyodak Plant	981	LF	100	2	Bedded Sedimentary Rock
728	Yates	367	SI	46	1	Metamorphic and Igneous
728	Yates	367	SI	10	6	River Valleys and Floodplains With Overbank Deposits
728	Yates	367	SI	44	7	River Valleys and Floodplains Without Overbank Deposits
728	Yates	368	SI	46	1	Metamorphic and Igneous

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
728	Yates	368	SI	10	6	River Valleys and Floodplains With Overbank Deposits
728	Yates	368	SI	44	7	River Valleys and Floodplains Without Overbank Deposits
728	Yates	369	SI	46	1	Metamorphic and Igneous
728	Yates	369	SI	10	6	River Valleys and Floodplains With Overbank Deposits
728	Yates	369	SI	44	7	River Valleys and Floodplains Without Overbank Deposits
728	Yates	370	SI	46	1	Metamorphic and Igneous
728	Yates	370	SI	10	6	River Valleys and Floodplains With Overbank Deposits
728	Yates	370	SI	44	7	River Valleys and Floodplains Without Overbank Deposits
728	Yates	371	SI	46	1	Metamorphic and Igneous
728	Yates	371	SI	10	6	River Valleys and Floodplains With Overbank Deposits
728	Yates	371	SI	44	7	River Valleys and Floodplains Without Overbank Deposits
728	Yates	372	SI	46	1	Metamorphic and Igneous
728	Yates	372	SI	10	6	River Valleys and Floodplains With Overbank Deposits
728	Yates	372	SI	44	7	River Valleys and Floodplains Without Overbank Deposits
728	Yates	373	SI	46	1	Metamorphic and Igneous
728	Yates	373	SI	10	6	River Valleys and Floodplains With Overbank Deposits
728	Yates	373	SI	44	7	River Valleys and Floodplains Without Overbank Deposits
728	Yates	374	SI	46	1	Metamorphic and Igneous
728	Yates	374	SI	10	6	River Valleys and Floodplains With Overbank Deposits
728	Yates	374	SI	44	7	River Valleys and Floodplains Without Overbank Deposits
728	Yates	986	LF	100	1	Metamorphic and Igneous
728	Yates	987	LF	54	6	River Valleys and Floodplains With Overbank Deposits

Attachment B-2. Hydrogeologic Data

ORIS Code	ORIS Plant Name	WMU ID	Unit Type	Percentage	HE Code	Hydrogeologic Environment (HE) Description
728	Yates	987	LF	46	7	River Valleys and Floodplains Without Overbank Deposits
3809	Yorktown	988	LF	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers
3809	Yorktown	1359	SI	100	10	Unconsolidated and Semiconsolidated Shallow Aquifers

Attachment B-3.

Climate Data

Attachment B-3. Climate Data

Oris Code	ORIS Plant Name	EPACMTP Climate Center	Precip 5-yr Avg (in/yr)	Recharge Rate Silty Loam	Recharge Rate Sandy Loam	Recharge Rate SiltyClay Loam	IWAIR Met Station	Mean Annual Windspeed (m/s)
6137	A. B. Brown Generating Station	East St. Louis, IL	36.2	0.144	0.168	0.070	St Louis	4.3
2535	AES Cayuga, LLC	Ithaca, NY	40.2	0.168	0.214	0.139	Williamsport-Lycoming	3.4
2527	AES Greenidge	Ithaca, NY	40.2	0.168	0.214	0.139	Williamsport-Lycoming	3.4
994	AES Petersburg	Cincinnati, OH	40.6	0.155	0.221	0.154	St Louis	4.3
6082	AES Somerset LLC	Ithaca, NY	40.2	0.168	0.214	0.139	Cleveland	4.7
3942	Albright Power Station	Pittsburgh, PA	38.1	0.089	0.131	0.079	Huntington	2.9
1915	Allen S King	Des Moines, IA	33.1	0.114	0.164	0.116	Minneapolis	4.7
3393	Allen Steam Plant	Nashville, TN	54.8	0.467	0.540	0.377	Meridian	2.8
4140	Alma	Madison, WI	32.1	0.091	0.140	0.069	Minneapolis	4.7
1122	Ames Electric Services Power Plant	Des Moines, IA	33.1	0.114	0.164	0.116	Waterloo	4.7
6469	Antelope Valley Station	Bismarck, ND	15.8	0.024	0.030	0.020	Bismarck	4.6
160	Apache Station	Tucson, AZ	10.1	0.000	0.000	0.001	Phoenix	2.8
465	Arapahoe	Cheyenne, WY	11.2	0.001	0.001	0.009	Denver	3.9
3178	Armstrong Power Station	Pittsburgh, PA	38.1	0.089	0.131	0.079	Williamsport-Lycoming	3.4
2076	Asbury	Tulsa, OK	30.4	0.069	0.101	0.047	Tulsa	4.6
2706	Asheville Steam Electric Plant	Watkinsville, GA	42.7	0.289	0.356	0.233	Asheville	3.3
2835	Ashtabula	Cleveland, OH	36.7	0.078	0.121	0.082	Cleveland	4.7
1961	Austin Northeast	Des Moines, IA	33.1	0.114	0.164	0.116	Minneapolis	4.7
2836	Avon Lake	Cleveland, OH	36.7	0.078	0.121	0.082	Cleveland	4.7
995	Bailly	Chicago, IL	34.1	0.080	0.114	0.062	Muskegon	4.8
889	Baldwin Energy Complex	East St. Louis, IL	36.2	0.144	0.168	0.070	St Louis	4.3
3	Barry	New Orleans, LA	70.1	0.589	0.745	0.450	New Orleans	3.7
3982	Bay Front	Madison, WI	32.1	0.091	0.140	0.069	Minneapolis	4.7
2878	Bay Shore	Put-in-Bay, OH	36.1	0.051	0.100	0.050	Detroit	4.6
8042	Belews Creek Steam Station	Greensboro, NC	45.4	0.326	0.390	0.271	Raleigh-Durham	3.4
6034	Belle River	Put-in-Bay, OH	36.1	0.051	0.100	0.050	Detroit	4.6

Attachment B-3. Climate Data

Oris Code	ORIS Plant Name	EPACMTP Climate Center	Precip 5-yr Avg (in/yr)	Recharge Rate Silty Loam	Recharge Rate Sandy Loam	Recharge Rate SiltyClay Loam	IWAIR Met Station	Mean Annual Windspeed (m/s)
3325	Ben French	Rapid City, SD	15.4	0.001	0.007	0.003	Casper	5.7
645	Big Bend	Tampa, FL	38.2	0.066	0.103	0.048	Tampa	3.7
3497	Big Brown	Shreveport, LA	44.2	0.230	0.294	0.184	Dallas	4.8
6055	Big Cajun 2	New Orleans, LA	70.1	0.589	0.745	0.450	New Orleans	3.7
1353	Big Sandy	Lexington, KY	50.8	0.329	0.397	0.270	Huntington	2.9
6098	Big Stone	St. Cloud, MN	25.8	0.060	0.083	0.055	Minneapolis	4.7
1904	Black Dog	St. Cloud, MN	25.8	0.060	0.083	0.055	Minneapolis	4.7
6106	Boardman	Pullman, WA	12.1	0.007	0.013	0.008	Spokane	4
7790	Bonanza Power Plant	Grand Junction, CO	7.2	0.000	0.000	0.000	Salt Lake City	4
1893	Boswell Energy Center	St. Cloud, MN	25.8	0.060	0.083	0.055	Minneapolis	4.7
703	Bowen	Atlanta, GA	49.5	0.342	0.399	0.282	Atlanta	4.1
602	Brandon Shores	Philadelphia, PA	43.7	0.201	0.261	0.164	Philadelphia	4.3
1619	Brayton Point	Providence, RI	46.7	0.213	0.286	0.175	Hartford	3.8
3796	Bremo Bluff	Lynchburg, VA	44.7	0.308	0.361	0.257	Raleigh-Durham	3.4
6094	Bruce Mansfield	Pittsburgh, PA	38.1	0.089	0.131	0.079	Dayton	4.5
2720	Buck	Greensboro, NC	45.4	0.326	0.390	0.271	Raleigh-Durham	3.4
3396	Bull Run	Knoxville, TN	48.1	0.411	0.446	0.354	Bristol	2.4
1104	Burlington	Columbia, MO	37.1	0.153	0.199	0.122	Waterloo	4.7
676	C D McIntosh Jr	Tampa, FL	38.2	0.066	0.103	0.048	Tampa	3.7
468	Cameo	Grand Junction, CO	7.2	0.000	0.000	0.000	Denver	3.9
3280	Canadys Steam	Watkinsville, GA	42.7	0.289	0.356	0.233	Charleston, SC	3.9
1363	Cane Run	Cincinnati, OH	40.6	0.155	0.221	0.154	St Louis	4.3
2708	Cape Fear Steam Electric Plant	Greensboro, NC	45.4	0.326	0.390	0.271	Raleigh-Durham	3.4
3644	Carbon Plant	Grand Junction, CO	7.2	0.000	0.000	0.000	Salt Lake City	4
2828	Cardinal	Pittsburgh, PA	38.1	0.089	0.131	0.079	Dayton	4.5
1001	Cayuga	Cincinnati, OH	40.6	0.155	0.221	0.154	Waterloo	4.7
1571	Chalk Point LLC	Norfolk, VA	44.4	0.312	0.000	0.269	Philadelphia	4.3

Attachment B-3. Climate Data

Oris Code	ORIS Plant Name	EPACMTP Climate Center	Precip 5-yr Avg (in/yr)	Recharge Rate Silty Loam	Recharge Rate Sandy Loam	Recharge Rate SiltyClay Loam	IWAIR Met Station	Mean Annual Windspeed (m/s)
2169	Chamois Power Plant	Columbia, MO	37.1	0.153	0.199	0.122	St Louis	4.3
56	Charles R. Lowman	New Orleans, LA	70.1	0.589	0.745	0.450	Meridian	2.8
469	Cherokee	Denver, CO	13.0	0.001	0.001	0.004	Denver	3.9
3803	Chesapeake Energy Center	Norfolk, VA	44.4	0.312	0.000	0.269	Norfolk	4.7
3797	Chesterfield	Norfolk, VA	44.4	0.312	0.000	0.269	Norfolk	4.7
8226	Cheswick Power Plant	Pittsburgh, PA	38.1	0.089	0.131	0.079	Dayton	4.5
113	Cholla	Albuquerque, NM	8.4	0.000	0.000	0.000	Las Vegas	4.1
2721	Cliffside	Knoxville, TN	48.1	0.411	0.446	0.354	Raleigh-Durham	3.4
983	Clifty Creek	Cincinnati, OH	40.6	0.155	0.221	0.154	St Louis	4.3
3775	Clinch River	Greensboro, NC	45.4	0.326	0.390	0.271	Bristol	2.4
7213	Clover	Lynchburg, VA	44.7	0.308	0.361	0.257	Raleigh-Durham	3.4
6030	Coal Creek	Bismarck, ND	15.8	0.024	0.030	0.020	Bismarck	4.6
861	Coffeen	East St. Louis, IL	36.2	0.144	0.168	0.070	St Louis	4.3
47	Colbert	Nashville, TN	54.8	0.467	0.540	0.377	Meridian	2.8
6178	Coleto Creek	San Antonio, TX	33.3	0.110	0.165	0.082	Houston	3.4
6076	Colstrip	Rapid City, SD	15.4	0.001	0.007	0.003	Bismarck	4.6
10784	Colstrip Energy LP	Rapid City, SD	15.4	0.001	0.007	0.003	Bismarck	4.6
2123	Columbia	Columbia, MO	37.1	0.153	0.199	0.122	St Louis	4.3
8023	Columbia	Madison, WI	32.1	0.091	0.140	0.069	Minneapolis	4.7
470	Comanche	Denver, CO	13.0	0.001	0.001	0.004	Denver	3.9
3118	Conemaugh	Pittsburgh, PA	38.1	0.089	0.131	0.079	Williamsport-Lycoming	3.4
2840	Conesville	Cleveland, OH	36.7	0.078	0.121	0.082	Dayton	4.5
1710	Consumers Energy - J.H. Campbell	East Lansing, MI	30.0	0.109	0.145	0.110	Muskegon	4.8
1384	Cooper Station.	Knoxville, TN	48.1	0.411	0.446	0.354	Huntington	2.9
7210	Cope	Watkinsville, GA	42.7	0.289	0.356	0.233	Macon	3.3
6177	Coronado Generating Station	Albuquerque, NM	8.4	0.000	0.000	0.000	Albuquerque	4
8222	Coyote	Bismarck, ND	15.8	0.024	0.030	0.020	Bismarck	4.6
2549	CR Huntley Generating Station	Cleveland, OH	36.7	0.078	0.121	0.082	Cleveland	4.7

Attachment B-3. Climate Data

Oris Code	ORIS Plant Name	EPACMTP Climate Center	Precip 5-yr Avg (in/yr)	Recharge Rate Silty Loam	Recharge Rate Sandy Loam	Recharge Rate SiltyClay Loam	IWAIR Met Station	Mean Annual Windspeed (m/s)
6021	Craig	Denver, CO	13.0	0.001	0.001	0.004	Denver	3.9
867	Crawford	Chicago, IL	34.1	0.080	0.114	0.062	Chicago	4.6
753	Crisp Plant	Watkinsville, GA	42.7	0.289	0.356	0.233	Macon	3.3
641	Crist	New Orleans, LA	70.1	0.589	0.745	0.450	New Orleans	3.7
130	Cross	Watkinsville, GA	42.7	0.289	0.356	0.233	Charleston, SC	3.9
628	Crystal River Power Plant	Jacksonville, FL	46.4	0.151	0.211	0.110	Tampa	3.7
3399	Cumberland	Nashville, TN	54.8	0.467	0.540	0.377	Nashville	3.6
6823	D B Wilson	Lexington, KY	50.8	0.329	0.397	0.270	Nashville	3.6
1702	D.E. Karn	East Lansing, MI	30.0	0.109	0.145	0.110	Detroit	4.6
1385	Dale Station	Lexington, KY	50.8	0.329	0.397	0.270	Huntington	2.9
963	Dallman	East St. Louis, IL	36.2	0.144	0.168	0.070	Waterloo	4.7
2723	Dan River	Greensboro, NC	45.4	0.326	0.390	0.271	Raleigh-Durham	3.4
2480	Danskammer Generating Station	New York, NY	44.8	0.244	0.294	0.197	Hartford	3.8
4158	Dave Johnston Plant	Lander, WY	12.3	0.003	0.005	0.009	Casper	5.7
996	Dean H Mitchell	Chicago, IL	34.1	0.080	0.114	0.062	Chicago	4.6
663	Deerhaven Generating Station	Jacksonville, FL	46.4	0.151	0.211	0.110	Charleston, SC	3.9
1572	Dickerson	Philadelphia, PA	43.7	0.201	0.261	0.164	Harrisburg	3.4
51	Dolet Hills	Shreveport, LA	44.2	0.230	0.294	0.184	Shreveport	3.7
3317	Dolphus M Grainger	Charleston, SC	48.3	0.261	0.329	0.212	Charleston, SC	3.9
1046	Dubuque	Madison, WI	32.1	0.091	0.140	0.069	Waterloo	4.7
6016	Duck Creek	East St. Louis, IL	36.2	0.144	0.168	0.070	Waterloo	4.7
2554	Dunkirk Generating Plant	Cleveland, OH	36.7	0.078	0.121	0.082	Cleveland	4.7
26	E. C. Gaston	Atlanta, GA	49.5	0.342	0.399	0.282	Meridian	2.8
1355	E.W. Brown	Lexington, KY	50.8	0.329	0.397	0.270	Nashville	3.6
991	Eagle Valley	Cincinnati, OH	40.6	0.155	0.221	0.154	Dayton	4.5
1217	Earl F Wisdom	Grand Island, NE	22.2	0.044	0.063	0.032	Waterloo	4.7
6018	East Bend Station	Cincinnati, OH	40.6	0.155	0.221	0.154	Huntington	2.9
2837	Eastlake	Cleveland, OH	36.7	0.078	0.121	0.082	Cleveland	4.7
856	ED Edwards	East St. Louis, IL	36.2	0.144	0.168	0.070	Waterloo	4.7
4050	Edgewater	Madison, WI	32.1	0.091	0.140	0.069	Chicago	4.6

Attachment B-3. Climate Data

Oris Code	ORIS Plant Name	EPACMTP Climate Center	Precip 5-yr Avg (in/yr)	Recharge Rate Silty Loam	Recharge Rate Sandy Loam	Recharge Rate SiltyClay Loam	IWAIR Met Station	Mean Annual Windspeed (m/s)
1004	Edwardsport	Cincinnati, OH	40.6	0.155	0.221	0.154	St Louis	4.3
1374	Elmer Smith Station	Cincinnati, OH	40.6	0.155	0.221	0.154	St Louis	4.3
3098	Elrama Power Plant	Pittsburgh, PA	38.1	0.089	0.131	0.079	Dayton	4.5
1832	Erickson Station	East Lansing, MI	30.0	0.109	0.145	0.110	Detroit	4.6
87	Escalante	Albuquerque, NM	8.4	0.000	0.000	0.000	Albuquerque	4
1012	F. B. Culley	Cincinnati, OH	40.6	0.155	0.221	0.154	St Louis	4.3
1218	Fair Station	Chicago, IL	34.1	0.080	0.114	0.062	Waterloo	4.7
6179	Fayette Power Project	Dallas, TX	31.1	0.060	0.107	0.053	Austin	4
886	Fisk	Chicago, IL	34.1	0.080	0.114	0.062	Chicago	4.6
6138	Flint Creek	Little Rock, AR	51.2	0.353	0.434	0.282	Tulsa	4.6
3943	Fort Martin Power Station	Pittsburgh, PA	38.1	0.089	0.131	0.079	Huntington	2.9
10343	Foster Wheeler Mt Carmel Cogen	Philadelphia, PA	43.7	0.201	0.261	0.164	Harrisburg	3.4
2442	Four Corners	Albuquerque, NM	8.4	0.000	0.000	0.000	Albuquerque	4
1043	Frank E. Ratts	Cincinnati, OH	40.6	0.155	0.221	0.154	St Louis	4.3
2718	G G Allen	Greensboro, NC	45.4	0.326	0.390	0.271	Raleigh-Durham	3.4
7	Gadsden	Atlanta, GA	49.5	0.342	0.399	0.282	Meridian	2.8
3403	Gallatin	Nashville, TN	54.8	0.467	0.540	0.377	Nashville	3.6
8102	General James M. Gavin	Lexington, KY	50.8	0.329	0.397	0.270	Huntington	2.9
4143	Genoa	Madison, WI	32.1	0.091	0.140	0.069	Minneapolis	4.7
1091	George Neal North	Grand Island, NE	22.2	0.044	0.063	0.032	Grand Island	5.3
7343	George Neal South	Grand Island, NE	22.2	0.044	0.063	0.032	Grand Island	5.3
6077	Gerald Gentleman	Cheyenne, WY	11.2	0.001	0.001	0.009	Grand Island	5.3
1356	Ghent	Cincinnati, OH	40.6	0.155	0.221	0.154	Huntington	2.9
6136	Gibbons Creek Steam Electric Station	Shreveport, LA	44.2	0.230	0.294	0.184	Austin	4
6113	Gibson	East St. Louis, IL	36.2	0.144	0.168	0.070	St Louis	4.3
3776	Glen Lyn	Pittsburgh, PA	38.1	0.089	0.131	0.079	Huntington	2.9
8	Gorgas	Nashville, TN	54.8	0.467	0.540	0.377	Meridian	2.8
1825	Grand Haven City of J.B. Sims	East Lansing, MI	30.0	0.109	0.145	0.110	Muskegon	4.8

Attachment B-3. Climate Data

Oris Code	ORIS Plant Name	EPACMTP Climate Center	Precip 5-yr Avg (in/yr)	Recharge Rate Silty Loam	Recharge Rate Sandy Loam	Recharge Rate SiltyClay Loam	IWAIR Met Station	Mean Annual Windspeed (m/s)
10151	Grant Town Power Plant	Pittsburgh, PA	38.1	0.089	0.131	0.079	Huntington	2.9
165	GRDA	Little Rock, AR	51.2	0.353	0.434	0.282	Tulsa	4.6
1357	Green River	Lexington, KY	50.8	0.329	0.397	0.270	Nashville	3.6
10	Greene County	Atlanta, GA	49.5	0.342	0.399	0.282	Meridian	2.8
6041	H L Spurlock Station	Lexington, KY	50.8	0.329	0.397	0.270	Huntington	2.9
2709	H.F. Lee Plant	Greensboro, NC	45.4	0.326	0.390	0.271	Norfolk	4.7
708	Hammond	Atlanta, GA	49.5	0.342	0.399	0.282	Bristol	2.4
1731	Harbor Beach Power Plant	East Lansing, MI	30.0	0.109	0.145	0.110	Detroit	4.6
990	Harding Street	Indianapolis, IN	40.3	0.130	0.186	0.106	Dayton	4.5
709	Harllee Branch	Watkinsville, GA	42.7	0.289	0.356	0.233	Macon	3.3
6193	Harrington	Midland, TX	16.3	0.018	0.025	0.014	Amarillo	6.1
3944	Harrison Power Station	Pittsburgh, PA	38.1	0.089	0.131	0.079	Huntington	2.9
3179	Hatfield's Ferry Power Station	Pittsburgh, PA	38.1	0.089	0.131	0.079	Huntington	2.9
891	Havana	East St. Louis, IL	36.2	0.144	0.168	0.070	Waterloo	4.7
2079	Hawthorn	Topeka, KS	32.2	0.105	0.148	0.076	Grand Island	5.3
525	Hayden	Cheyenne, WY	11.2	0.001	0.001	0.009	Denver	3.9
3251	HB Robinson / Darlington Electric Power Plant	Greensboro, NC	45.4	0.326	0.390	0.271	Macon	3.3
892	Hennepin Power Station	Chicago, IL	34.1	0.080	0.114	0.062	Waterloo	4.7
1382	HMP&L Station Two Henderson	East St. Louis, IL	36.2	0.144	0.168	0.070	St Louis	4.3
108	HOLCOMB	Denver, CO	13.0	0.001	0.001	0.004	Denver	3.9
3122	Homer City Station	Pittsburgh, PA	38.1	0.089	0.131	0.079	Williamsport-Lycoming	3.4
1943	Hoot Lake	St. Cloud, MN	25.8	0.060	0.083	0.055	Minneapolis	4.7
10771	Hopewell	Norfolk, VA	44.4	0.312	0.000	0.269	Norfolk	4.7
6772	Hugo	Shreveport, LA	44.2	0.230	0.294	0.184	Dallas	4.8
3176	Hunlock Power Station	Ithaca, NY	40.2	0.168	0.214	0.139	Williamsport-Lycoming	3.4
6165	Hunter Plant	Grand Junction, CO	7.2	0.000	0.000	0.000	Salt Lake City	4

Attachment B-3. Climate Data

Oris Code	ORIS Plant Name	EPACMTP Climate Center	Precip 5-yr Avg (in/yr)	Recharge Rate Silty Loam	Recharge Rate Sandy Loam	Recharge Rate SiltyClay Loam	IWAIR Met Station	Mean Annual Windspeed (m/s)
8069	Huntington Plant	Grand Junction, CO	7.2	0.000	0.000	0.000	Salt Lake City	4
863	Hutsonville	Cincinnati, OH	40.6	0.155	0.221	0.154	St Louis	4.3
6065	Iatan	Topeka, KS	32.2	0.105	0.148	0.076	Grand Island	5.3
6641	Independence	Little Rock, AR	51.2	0.353	0.434	0.282	Little Rock	3.5
2132	Independence Power & Light - Blue Valley Station	Topeka, KS	32.2	0.105	0.148	0.076	Grand Island	5.3
594	Indian River Generating Station	Philadelphia, PA	43.7	0.201	0.261	0.164	Philadelphia	4.3
6481	Intermountain Power Project	Cedar City, UT	9.8	0.000	0.001	0.000	Salt Lake City	4
7097	J K Spruce	San Antonio, TX	33.3	0.110	0.165	0.082	Austin	4
2850	J M Stuart	Lexington, KY	50.8	0.329	0.397	0.270	Huntington	2.9
6181	J T Deely	San Antonio, TX	33.3	0.110	0.165	0.082	Austin	4
1720	J.C. Weadock	East Lansing, MI	30.0	0.109	0.145	0.110	Detroit	4.6
1723	J.R Whiting	Put-in-Bay, OH	36.1	0.051	0.100	0.050	Detroit	4.6
710	Jack McDonough	Atlanta, GA	49.5	0.342	0.399	0.282	Atlanta	4.1
2049	Jack Watson	New Orleans, LA	70.1	0.589	0.745	0.450	New Orleans	3.7
1830	James De Young	Chicago, IL	34.1	0.080	0.114	0.062	Muskegon	4.8
6002	James H. Miller Jr.	Nashville, TN	54.8	0.467	0.540	0.377	Meridian	2.8
2161	James River Power Station	Little Rock, AR	51.2	0.353	0.434	0.282	Tulsa	4.6
2187	JE Corette Plant	Great Falls, MT	17.9	0.004	0.007	0.007	Billings	5
3319	Jefferies	Charleston, SC	48.3	0.261	0.329	0.212	Charleston, SC	3.9
6068	Jeffrey Energy Center	Topeka, KS	32.2	0.105	0.148	0.076	Grand Island	5.3
8066	Jim Bridger Plant Units 1-4	Lander, WY	12.3	0.003	0.005	0.009	Salt Lake City	4
3935	John E. Amos	Lexington, KY	50.8	0.329	0.397	0.270	Huntington	2.9
4271	John P. Madgett	Madison, WI	32.1	0.091	0.140	0.069	Minneapolis	4.7
3405	John Sevier	Lexington, KY	50.8	0.329	0.397	0.270	Bristol	2.4
3406	Johnsonville	Nashville, TN	54.8	0.467	0.540	0.377	Nashville	3.6
384	Joliet 29	Chicago, IL	34.1	0.080	0.114	0.062	Waterloo	4.7
874	Joliet 9	Chicago, IL	34.1	0.080	0.114	0.062	Waterloo	4.7
887	Joppa Steam	East St. Louis, IL	36.2	0.144	0.168	0.070	Nashville	3.6

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3947	Kammer	Pittsburgh, PA	38.1	0.089	0.131	0.079	Huntington	2.9
3936	Kanawha River	Lynchburg, VA	44.7	0.308	0.361	0.257	Huntington	2.9
1381	Kenneth C Coleman	Cincinnati, OH	40.6	0.155	0.221	0.154	St Louis	4.3
3136	Keystone	Pittsburgh, PA	38.1	0.089	0.131	0.079	Williamsport-Lycoming	3.4
6031	Killen Station	Lexington, KY	50.8	0.329	0.397	0.270	Huntington	2.9
876	Kincaid Generation LLC	East St. Louis, IL	36.2	0.144	0.168	0.070	Waterloo	4.7
3407	Kingston	Knoxville, TN	48.1	0.411	0.446	0.354	Bristol	2.4
733	Kraft	Watkinsville, GA	42.7	0.289	0.356	0.233	Charleston, SC	3.9
2876	Kyger Creek	Lexington, KY	50.8	0.329	0.397	0.270	Huntington	2.9
2713	L.V. Sutton Electric Plant	Charleston, SC	48.3	0.261	0.329	0.212	Norfolk	4.7
1241	La Cygne	Topeka, KS	32.2	0.105	0.148	0.076	Tulsa	4.6
2103	Labadie	East St. Louis, IL	36.2	0.144	0.168	0.070	St Louis	4.3
2098	Lake Road	Topeka, KS	32.2	0.105	0.148	0.076	Grand Island	5.3
2838	Lake Shore	Cleveland, OH	36.7	0.078	0.121	0.082	Cleveland	4.7
964	Lakeside	East St. Louis, IL	36.2	0.144	0.168	0.070	Waterloo	4.7
1047	Lansing	Madison, WI	32.1	0.091	0.140	0.069	Minneapolis	4.7
643	Lansing Smith	New Orleans, LA	70.1	0.589	0.745	0.450	New Orleans	3.7
6204	Laramie River Station	Denver, CO	13.0	0.001	0.001	0.004	Casper	5.7
1891	Laskin Energy Center	St. Cloud, MN	25.8	0.060	0.083	0.055	Minneapolis	4.7
1250	Lawrence Energy Center	Topeka, KS	32.2	0.105	0.148	0.076	Grand Island	5.3
2817	Leland Olds	Bismarck, ND	15.8	0.024	0.030	0.020	Bismarck	4.6
6089	Lewis & Clark	Great Falls, MT	17.9	0.004	0.007	0.007	Bismarck	4.6
298	Limestone	Dallas, TX	31.1	0.060	0.107	0.053	Dallas	4.8
2240	Lon Wright	North Omaha, NE	27.5	0.067	0.080	0.054	Grand Island	5.3
6664	Louisa	Chicago, IL	34.1	0.080	0.114	0.062	Waterloo	4.7
976	Marion Generating Station	East St. Louis, IL	36.2	0.144	0.168	0.070	St Louis	4.3
2727	Marshall	Greensboro, NC	45.4	0.326	0.390	0.271	Raleigh-Durham	3.4
492	Martin Drake	Denver, CO	13.0	0.001	0.001	0.004	Denver	3.9
6146	Martin Lake	Shreveport, LA	44.2	0.230	0.294	0.184	Shreveport	3.7

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6250	Mayo Electric Generating Facility	Lynchburg, VA	44.7	0.308	0.361	0.257	Raleigh-Durham	3.4
6124	McIntosh	Watkinsville, GA	42.7	0.289	0.356	0.233	Charleston, SC	3.9
3287	McMeekin	Watkinsville, GA	42.7	0.289	0.356	0.233	Macon	3.3
2104	Meramec	East St. Louis, IL	36.2	0.144	0.168	0.070	St Louis	4.3
864	Meredosia	East St. Louis, IL	36.2	0.144	0.168	0.070	Waterloo	4.7
6213	Merom	Cincinnati, OH	40.6	0.155	0.221	0.154	St Louis	4.3
2364	Merrimack Station	Nashua, NH	49.4	0.227	0.281	0.194	Portland, ME	3.9
2832	Miami Fort	Cincinnati, OH	40.6	0.155	0.221	0.154	Huntington	2.9
997	Michigan City	Chicago, IL	34.1	0.080	0.114	0.062	Muskegon	4.8
1364	Mill Creek	Lexington, KY	50.8	0.329	0.397	0.270	St Louis	4.3
2823	Milton R. Young Station	Bismarck, ND	15.8	0.024	0.030	0.020	Bismarck	4.6
2171	Missouri City	Topeka, KS	32.2	0.105	0.148	0.076	Grand Island	5.3
727	Mitchell	Tallahassee, FL	68.4	0.591	0.731	0.456	Macon	3.3
3948	Mitchell	Pittsburgh, PA	38.1	0.089	0.131	0.079	Huntington	2.9
3181	Mitchell Power Station	Pittsburgh, PA	38.1	0.089	0.131	0.079	Huntington	2.9
1048	ML Kapp	Chicago, IL	34.1	0.080	0.114	0.062	Waterloo	4.7
1733	Monroe Power Plant	Put-in-Bay, OH	36.1	0.051	0.100	0.050	Detroit	4.6
6147	Monticello	Shreveport, LA	44.2	0.230	0.294	0.184	Shreveport	3.7
2080	Montrose	Columbia, MO	37.1	0.153	0.199	0.122	Tulsa	4.6
1573	Morgantown Generating Plant	Norfolk, VA	44.4	0.312	0.000	0.269	Philadelphia	4.3
1606	Mount Tom	Worcester, MA	46.5	0.202	0.259	0.170	Hartford	3.8
6264	Mountaineer	Lexington, KY	50.8	0.329	0.397	0.270	Huntington	2.9
3954	Mt. Storm	Lynchburg, VA	44.7	0.308	0.361	0.257	Huntington	2.9
1167	Muscatine #1	Chicago, IL	34.1	0.080	0.114	0.062	Waterloo	4.7
2872	Muskingum River	Columbus, OH	36.1	0.077	0.116	0.066	Huntington	2.9
2952	Muskogee	Little Rock, AR	51.2	0.353	0.434	0.282	Tulsa	4.6
4162	Naughton Plant	Lander, WY	12.3	0.003	0.005	0.009	Salt Lake City	4
4941	Navajo Generating Station	Cedar City, UT	9.8	0.000	0.001	0.000	Las Vegas	4.1
6064	Nearman Creek	Topeka, KS	32.2	0.105	0.148	0.076	Grand Island	5.3
6096	Nebraska City	North Omaha, NE	27.5	0.067	0.080	0.054	Grand Island	5.3

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4054	Nelson Dewey	Madison, WI	32.1	0.091	0.140	0.069	Waterloo	4.7
3138	New Castle Plant	Pittsburgh, PA	38.1	0.089	0.131	0.079	Dayton	4.5
2167	New Madrid	Little Rock, AR	51.2	0.353	0.434	0.282	Nashville	3.6
6017	Newton	Cincinnati, OH	40.6	0.155	0.221	0.154	St Louis	4.3
2291	North Omaha	Grand Island, NE	22.2	0.044	0.063	0.032	Grand Island	5.3
8224	North Valmy	Ely, NV	8.8	0.000	0.000	0.000	Winnemucca	3.6
2963	Northeastern	Tulsa, OK	30.4	0.069	0.101	0.047	Tulsa	4.6
667	Northside Generating Station	Jacksonville, FL	46.4	0.151	0.211	0.110	Charleston, SC	3.9
10030	NRG Energy Center Dover	Philadelphia, PA	43.7	0.201	0.261	0.164	Philadelphia	4.3
527	Nucla	Grand Junction, CO	7.2	0.000	0.000	0.000	Denver	3.9
2848	O H Hutchings	Columbus, OH	36.1	0.077	0.116	0.066	Dayton	4.5
6180	Oak Grove	Dallas, TX	31.1	0.060	0.107	0.053	Dallas	4.8
127	Oklaunion	Oklahoma City, OK	30.4	0.061	0.094	0.039	Amarillo	6.1
4151	Osage	Lander, WY	12.3	0.003	0.005	0.009	Casper	5.7
1831	Otto E. Eckert Station	East Lansing, MI	30.0	0.109	0.145	0.110	Detroit	4.6
6254	Ottumwa	Columbia, MO	37.1	0.153	0.199	0.122	Waterloo	4.7
1378	Paradise	Lexington, KY	50.8	0.329	0.397	0.270	Nashville	3.6
6248	Pawnee	Denver, CO	13.0	0.001	0.001	0.004	Denver	3.9
6238	Pearl Station	East St. Louis, IL	36.2	0.144	0.168	0.070	St Louis	4.3
3938	Philip Sporn	Lexington, KY	50.8	0.329	0.397	0.270	Huntington	2.9
2843	Picway	Columbus, OH	36.1	0.077	0.116	0.066	Dayton	4.5
7902	Pirkey	Shreveport, LA	44.2	0.230	0.294	0.184	Shreveport	3.7
59	Platte	Grand Island, NE	22.2	0.044	0.063	0.032	Grand Island	5.3
6170	Pleasant Prairie	Madison, WI	32.1	0.091	0.140	0.069	Chicago	4.6
6004	Pleasants Power Station	Pittsburgh, PA	38.1	0.089	0.131	0.079	Huntington	2.9
7242	Polk	Tampa, FL	38.2	0.066	0.103	0.048	Tampa	3.7
3113	Portland	New York, NY	44.8	0.244	0.294	0.197	Harrisburg	3.4
879	Powerton	East St. Louis, IL	36.2	0.144	0.168	0.070	Waterloo	4.7

Attachment B-3. Climate Data

Oris Code	ORIS Plant Name	EPACMTP Climate Center	Precip 5-yr Avg (in/yr)	Recharge Rate Silty Loam	Recharge Rate Sandy Loam	Recharge Rate SiltyClay Loam	IWAIR Met Station	Mean Annual Windspeed (m/s)
3140	PPL Brunner Island	Philadelphia, PA	43.7	0.201	0.261	0.164	Harrisburg	3.4
3149	PPL Montour	Philadelphia, PA	43.7	0.201	0.261	0.164	Williamsport-Lycoming	3.4
1073	Prairie Creek	Des Moines, IA	33.1	0.114	0.164	0.116	Waterloo	4.7
1769	Presque Isle	Madison, WI	32.1	0.091	0.140	0.069	Minneapolis	4.7
2403	PSEG Hudson Generating Station	New York, NY	44.8	0.244	0.294	0.197	Philadelphia	4.3
2408	PSEG Mercer Generating Station	Philadelphia, PA	43.7	0.201	0.261	0.164	Philadelphia	4.3
4072	Pulliam	Sault Ste. Marie, MI	35.2	0.165	0.210	0.144	Chicago	4.6
1295	Quindaro	Topeka, KS	32.2	0.105	0.148	0.076	Grand Island	5.3
6639	R D Green	East St. Louis, IL	36.2	0.144	0.168	0.070	St Louis	4.3
2864	R. E. Burger	Pittsburgh, PA	38.1	0.089	0.131	0.079	Huntington	2.9
1008	R. Gallagher	Cincinnati, OH	40.6	0.155	0.221	0.154	St Louis	4.3
1570	R. Paul Smith Power Station	Pittsburgh, PA	38.1	0.089	0.131	0.079	Harrisburg	3.4
2790	R.M. Heskett Station	Bismarck, ND	15.8	0.024	0.030	0.020	Bismarck	4.6
6085	R.M. Schahfer	Chicago, IL	34.1	0.080	0.114	0.062	Waterloo	4.7
6761	Rawhide	Denver, CO	13.0	0.001	0.001	0.004	Denver	3.9
8219	Ray D Nixon	Cheyenne, WY	11.2	0.001	0.001	0.009	Denver	3.9
55076	Red Hills Generating Facility	Nashville, TN	54.8	0.467	0.540	0.377	Meridian	2.8
2324	Reid Gardner	Las Vegas, NV	5.3	0.000	0.000	0.002	Las Vegas	4.1
1740	River Rouge Power Plant	Put-in-Bay, OH	36.1	0.051	0.100	0.050	Detroit	4.6
2732	Riverbend	Greensboro, NC	45.4	0.326	0.390	0.271	Raleigh-Durham	3.4
1081	Riverside	Chicago, IL	34.1	0.080	0.114	0.062	Waterloo	4.7
1927	Riverside	St. Cloud, MN	25.8	0.060	0.083	0.055	Minneapolis	4.7
1239	Riverton	Tulsa, OK	30.4	0.069	0.101	0.047	Tulsa	4.6
3945	Rivesville Power Station	Pittsburgh, PA	38.1	0.089	0.131	0.079	Huntington	2.9
6166	Rockport	Cincinnati, OH	40.6	0.155	0.221	0.154	St Louis	4.3
6190	Rodemacher	Lake Charles, LA	52.2	0.365	0.464	0.282	Shreveport	3.7
2712	Roxboro Steam Electric Plant	Lynchburg, VA	44.7	0.308	0.361	0.257	Raleigh-Durham	3.4
1393	RS Nelson	Lake Charles, LA	52.2	0.365	0.464	0.282	Lake Charles	3.8

Attachment B-3. Climate Data

Oris Code	ORIS Plant Name	EPACMTP Climate Center	Precip 5-yr Avg (in/yr)	Recharge Rate Silty Loam	Recharge Rate Sandy Loam	Recharge Rate SiltyClay Loam	IWAIR Met Station	Mean Annual Windspeed (m/s)
6155	Rush Island	East St. Louis, IL	36.2	0.144	0.168	0.070	St Louis	4.3
2451	San Juan	Albuquerque, NM	8.4	0.000	0.000	0.000	Albuquerque	4
6183	San Miguel	San Antonio, TX	33.3	0.110	0.165	0.082	Austin	4
6648	Sandow No 4	Dallas, TX	31.1	0.060	0.107	0.053	Austin	4
6257	Scherer	Watkinsville, GA	42.7	0.289	0.356	0.233	Atlanta	4.1
2367	SCHILLER	Nashua, NH	49.4	0.227	0.281	0.194	Portland, ME	3.9
642	Scholz	Tallahassee, FL	68.4	0.591	0.731	0.456	Tampa	3.7
136	Seminole Generating Station	Jacksonville, FL	46.4	0.151	0.211	0.110	Charleston, SC	3.9
1379	Shawnee	East St. Louis, IL	36.2	0.144	0.168	0.070	Nashville	3.6
3131	Shawville	Syracuse, NY	48.0	0.255	0.325	0.212	Williamsport-Lycoming	3.4
2277	Sheldon Station	Grand Island, NE	22.2	0.044	0.063	0.032	Grand Island	5.3
6090	Sherburne County	St. Cloud, MN	25.8	0.060	0.083	0.055	Minneapolis	4.7
2094	Sibley	Topeka, KS	32.2	0.105	0.148	0.076	Grand Island	5.3
6768	Sikeston Power Station	Little Rock, AR	51.2	0.353	0.434	0.282	Nashville	3.6
2107	Sioux	East St. Louis, IL	36.2	0.144	0.168	0.070	St Louis	4.3
1058	Sixth Street	Chicago, IL	34.1	0.080	0.114	0.062	Waterloo	4.7
1613	Somerset Station	Providence, RI	46.7	0.213	0.286	0.175	Hartford	3.8
6095	Sooner	Oklahoma City, OK	30.4	0.061	0.094	0.039	Tulsa	4.6
6061	South Mississippi El Pwr Assn	New Orleans, LA	70.1	0.589	0.745	0.450	New Orleans	3.7
4041	South Oak Creek	Madison, WI	32.1	0.091	0.140	0.069	Chicago	4.6
6195	Southwest Power Station	Little Rock, AR	51.2	0.353	0.434	0.282	Tulsa	4.6
8223	Springerville	Albuquerque, NM	8.4	0.000	0.000	0.000	Albuquerque	4
1743	St Clair Power Plant	Put-in-Bay, OH	36.1	0.051	0.100	0.050	Detroit	4.6
207	St Johns River Power Park	Jacksonville, FL	46.4	0.151	0.211	0.110	Charleston, SC	3.9
2824	Stanton	Bismarck, ND	15.8	0.024	0.030	0.020	Bismarck	4.6
564	Stanton Energy Center	Orlando, FL	44.6	0.102	0.170	0.081	Charleston, SC	3.9
1131	Streeter Station	Des Moines, IA	33.1	0.114	0.164	0.116	Waterloo	4.7

Attachment B-3. Climate Data

Oris Code	ORIS Plant Name	EPACMTP Climate Center	Precip 5-yr Avg (in/yr)	Recharge Rate Silty Loam	Recharge Rate Sandy Loam	Recharge Rate SiltyClay Loam	IWAIR Met Station	Mean Annual Windspeed (m/s)
3152	Sunbury Generation LP	Philadelphia, PA	43.7	0.201	0.261	0.164	Williamsport-Lycoming	3.4
50951	Sunnyside Cogen Associates	Grand Junction, CO	7.2	0.000	0.000	0.000	Salt Lake City	4
1077	Sutherland	Des Moines, IA	33.1	0.114	0.164	0.116	Waterloo	4.7
10075	Taconite Harbor Energy Center	St. Cloud, MN	25.8	0.060	0.083	0.055	Minneapolis	4.7
988	Tanners Creek	Cincinnati, OH	40.6	0.155	0.221	0.154	Huntington	2.9
1252	Tecumseh Energy Center	Topeka, KS	32.2	0.105	0.148	0.076	Grand Island	5.3
2168	Thomas Hill	Columbia, MO	37.1	0.153	0.199	0.122	St Louis	4.3
3115	Titus	Philadelphia, PA	43.7	0.201	0.261	0.164	Harrisburg	3.4
6194	Tolk	Midland, TX	16.3	0.018	0.025	0.014	Amarillo	6.1
3845	TransAlta Centralia Generation	PortlandO, OR	34.7	0.417	0.439	0.393	Seattle	4
1745	Trenton Channel Power Plant	Put-in-Bay, OH	36.1	0.051	0.100	0.050	Detroit	4.6
6071	Trimble Co.	Cincinnati, OH	40.6	0.155	0.221	0.154	St Louis	4.3
56224	TS Power Plant	Ely, NV	8.8	0.000	0.000	0.000	Winnemucca	3.6
7030	Twin Oaks Power One	Dallas, TX	31.1	0.060	0.107	0.053	Dallas	4.8
1361	Tyrone	Lexington, KY	50.8	0.329	0.397	0.270	Nashville	3.6
3295	Urquhart	Watkinsville, GA	42.7	0.289	0.356	0.233	Macon	3.3
4042	Valley	Madison, WI	32.1	0.091	0.140	0.069	Chicago	4.6
477	Valmont	Cheyenne, WY	11.2	0.001	0.001	0.009	Denver	3.9
897	Vermilion	Indianapolis, IN	40.3	0.130	0.186	0.106	Waterloo	4.7
6073	Victor J. Daniel Jr	New Orleans, LA	70.1	0.589	0.745	0.450	New Orleans	3.7
6019	W H Zimmer	Lexington, KY	50.8	0.329	0.397	0.270	Huntington	2.9
3470	W. A. Parish	Shreveport, LA	44.2	0.230	0.294	0.184	Houston	3.4
2866	W. H. Sammis	Pittsburgh, PA	38.1	0.089	0.131	0.079	Dayton	4.5
3264	W. S. Lee	Atlanta, GA	49.5	0.342	0.399	0.282	Atlanta	4.1
2716	W.H. Weatherspoon Plant	Greensboro, NC	45.4	0.326	0.390	0.271	Norfolk	4.7
1010	Wabash River	Cincinnati, OH	40.6	0.155	0.221	0.154	Waterloo	4.7
2830	Walter C Beckjord	Cincinnati, OH	40.6	0.155	0.221	0.154	Huntington	2.9
1082	Walter Scott Jr. Energy Center	North Omaha, NE	27.5	0.067	0.080	0.054	Grand Island	5.3

Attachment B-3. Climate Data

Oris Code	ORIS Plant Name	EPACMTP Climate Center	Precip 5-yr Avg (in/yr)	Recharge Rate Silty Loam	Recharge Rate Sandy Loam	Recharge Rate SiltyClay Loam	IWAIR Met Station	Mean Annual Windspeed (m/s)
6052	Wansley	Atlanta, GA	49.5	0.342	0.399	0.282	Atlanta	4.1
6705	Warrick Power Plant	Cincinnati, OH	40.6	0.155	0.221	0.154	St Louis	4.3
3297	Wateree	Watkinsville, GA	42.7	0.289	0.356	0.233	Macon	3.3
883	Waukegan	Madison, WI	32.1	0.091	0.140	0.069	Chicago	4.6
6139	Welsh	Shreveport, LA	44.2	0.230	0.294	0.184	Shreveport	3.7
4078	Weston	Madison, WI	32.1	0.091	0.140	0.069	Minneapolis	4.7
60	Whelan Energy Center Unit 1 (WEC1)	Grand Island, NE	22.2	0.044	0.063	0.032	Grand Island	5.3
6009	White Bluff	Little Rock, AR	51.2	0.353	0.434	0.282	Little Rock	3.5
1040	Whitewater Valley	Indianapolis, IN	40.3	0.130	0.186	0.106	Dayton	4.5
4057	WI Power & Light Co -Rock River Generating	Madison, WI	32.1	0.091	0.140	0.069	Minneapolis	4.7
50	Widows Creek	Nashville, TN	54.8	0.467	0.540	0.377	Bristol	2.4
884	Will County	Chicago, IL	34.1	0.080	0.114	0.062	Chicago	4.6
3298	Williams	Charleston, SC	48.3	0.261	0.329	0.212	Charleston, SC	3.9
3946	Willow Island	Pittsburgh, PA	38.1	0.089	0.131	0.079	Huntington	2.9
6249	Winyah	Charleston, SC	48.3	0.261	0.329	0.212	Charleston, SC	3.9
898	Wood River	East St. Louis, IL	36.2	0.144	0.168	0.070	St Louis	4.3
50611	WPS Westwood Generation, LLC	Philadelphia, PA	43.7	0.201	0.261	0.164	Harrisburg	3.4
6101	Wyodak Plant	Rapid City, SD	15.4	0.001	0.007	0.003	Casper	5.7
728	Yates	Atlanta, GA	49.5	0.342	0.399	0.282	Atlanta	4.1
3809	Yorktown	Norfolk, VA	44.4	0.312	0.000	0.269	Norfolk	4.7

Attachment B-4.
Water Body Data

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
6137	A. B. Brown Generating Station	88	SI	21250406		36	100	StreamRiver	2	10.2	4.561	0.25	0.81
6137	A. B. Brown Generating Station	89	SI	10157689	Ohio River	88	100	ArtificialPath	66.5	5.3	3.145	146,613	3.9
6137	A. B. Brown Generating Station	1163	LF	10157317		1225	63	StreamRiver	66	3.9	2.475	1.8	0.82
6137	A. B. Brown Generating Station	1163	LF	10157551	Bayou Creek	1514	13	StreamRiver	66.9	43.9	10.931	24	0.81
6137	A. B. Brown Generating Station	1163	LF	10157737		191	25	LakePond	66	0.9	1.281	0.34	0.60
2535	AES Cayuga, LLC	1102	LF	21978623		71	29	StreamRiver	224	7.0	6.422	3.7	0.99
2535	AES Cayuga, LLC	1102	LF	21980363	Cayuga Lake	1447	71	LakePond	215.6	3.4	2.614	5.5	0.61
2527	AES Greenidge	1101	LF	21980257	Seneca Lake	33	100	LakePond	144.1	2.3	1.352	277	0.79
2527	AES Greenidge	1285	SI	21980257	Seneca Lake	339	100	LakePond	144.1	2.3	1.352	277	0.79
2527	AES Greenidge	1286	SI	21978203	Keuka Lake Outlet	452	100	StreamRiver	141.8	1.0	1.418	275	1.9
994	AES Petersburg	430	SI	18470878	Lick Creek	124	100	StreamRiver	96	6.9	2.401	4.6	0.78
994	AES Petersburg	431	SI	18470878	Lick Creek	438	100	StreamRiver	96	6.9	2.401	4.6	0.78
994	AES Petersburg	432	SI	18470878	Lick Creek	665	100	StreamRiver	96	6.9	2.401	4.6	0.78
994	AES Petersburg	433	SI	18470878	Lick Creek	1087	100	StreamRiver	96	6.9	2.401	4.6	0.78
994	AES Petersburg	989	LF	18446060	East Fork White River	1303	13	ArtificialPath	96	2.8	1.901	6,796	2.1
994	AES Petersburg	989	LF	18470878	Lick Creek	391	88	StreamRiver	96	6.9	2.401	4.6	0.78
6082	AES Somerset LLC	1105	LF	15559445	Fish Creek	115	50	StreamRiver	118	2.6	2.187	8.4	0.85
6082	AES Somerset LLC	1105	LF	15559465		35	25	StreamRiver	118	2.6	2.187	0.40	0.58
6082	AES Somerset LLC	1105	LF	15559543		234	25	StreamRiver	118	2.6	2.187	1.4	0.68
6082	AES Somerset LLC	1106	LF	15559445	Fish Creek	48	29	StreamRiver	118	2.6	2.187	8.4	0.85
6082	AES Somerset LLC	1106	LF	15559505		379	14	StreamRiver	118	2.2	1.363	1.3	0.71
6082	AES Somerset LLC	1106	LF	15561361	Ontario, Lake	221	57	Coastline	118	2.6	2.187		
6082	AES Somerset LLC	1287	SI	15559451		295	63	StreamRiver	118	2.2	1.363	0.44	0.65
6082	AES Somerset LLC	1287	SI	15559505		158	38	StreamRiver	118	2.2	1.363	1.3	0.71
3942	Albright Power Station	930	LF	3774457	Daugherty Run	731	100	StreamRiver	268.7	6.8	3.049	21	1.3
3942	Albright Power Station	931	LF	3774457	Daugherty Run	906	100	StreamRiver	268.7	6.8	3.049	21	1.3
3942	Albright Power Station	1385	SI	3775649	Cheat River	12	100	ArtificialPath	255.2	3.0	1.973	2,330	2.2
3942	Albright Power Station	1386	SI	3775651	Cheat River	13	100	ArtificialPath	259.6	1.9	1.006	2,306	1.1
1915	Allen S King	927	LF	2649096		942	100	StreamRiver	83	19.0	2.882	4.3	0.93
3393	Allen Steam Plant	119	SI	7474836				LakePond	110.7	15.7	4.673	275	1.0
3393	Allen Steam Plant	120	SI	7474836				LakePond	110.7	15.7	4.673	275	1.0
4140	Alma	993	LF	2118222				ArtificialPath	92.1	1.8	1.336	27,963	2.8

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
4140	Alma	994	LF	2118222				ArtificialPath	92.1	1.8	1.336	27,963	2.8
1122	Ames Electric Services Power Plant	1202	SI	6979020	South Skunk River	357	100	StreamRiver	58.2	6.4	3.532	169	1.4
6469	Antelope Valley Station	212	SI	16248553		171	100	StreamRiver	3	27.1	6.218	0.047	0.79
6469	Antelope Valley Station	213	SI	16248553				StreamRiver	3	27.1	6.218	0.047	0.79
6469	Antelope Valley Station	922	LF	16248507		21	40	StreamRiver	3.2	8.1	5.536	0.014	0.67
6469	Antelope Valley Station	922	LF	16248553		2184	60	StreamRiver	3	27.1	6.218	0.047	0.79
6469	Antelope Valley Station	923	LF	16248553		1351	100	StreamRiver	3	27.1	6.218	0.047	0.79
160	Apache Station	287	SI	21263023				Playa	4.8	2055.9	14.545	66	1.1
160	Apache Station	288	SI	21263023				Playa	4.8	2055.9	14.545	66	1.1
160	Apache Station	292	SI	21263023				Playa	4.8	2055.9	14.545	66	1.1
160	Apache Station	293	SI	21263023		2162	100	Playa	4.8	2055.9	14.545	66	1.1
160	Apache Station	294	SI	21263023		2379	100	Playa	4.8	2055.9	14.545	66	1.1
160	Apache Station	295	SI	21263023		2395	100	Playa	4.8	2055.9	14.545	66	1.1
160	Apache Station	296	SI	21263023		2132	100	Playa	4.8	2055.9	14.545	66	1.1
160	Apache Station	297	SI	21263023		2682	100	Playa	4.8	2055.9	14.545	66	1.1
160	Apache Station	298	SI	21263023		1926	100	Playa	4.8	2055.9	14.545	66	1.1
160	Apache Station	299	SI	21263023		2909	100	Playa	4.8	2055.9	14.545	66	1.1
465	Arapahoe	310	SI	194423				StreamRiver	21.5	5.7	1.3	1,392	2.4
465	Arapahoe	311	SI	194423				StreamRiver	21.5	5.7	1.3	1,392	2.4
465	Arapahoe	312	SI	194423				StreamRiver	21.5	5.7	1.3	1,392	2.4
465	Arapahoe	313	SI	194423				StreamRiver	21.5	5.7	1.3	1,392	2.4
465	Arapahoe	314	SI	194423				StreamRiver	21.5	5.7	1.3	1,392	2.4
465	Arapahoe	315	SI	194423				StreamRiver	21.5	5.7	1.3	1,392	2.4
3178	Armstrong Power Station	921	LF	4740193		113	33	StreamRiver	205	1.4	2.253	0.93	0.83
3178	Armstrong Power Station	921	LF	4742105	Allegheny River	114	50	ArtificialPath	206.8	0.3	0.279	15,341	2.4
3178	Armstrong Power Station	921	LF	4742115	Allegheny River	252	17	ArtificialPath	203.1	5.5	3.297	15,347	1.5
3178	Armstrong Power Station	926	LF	4742115	Allegheny River	277	100	ArtificialPath	203.1	5.5	3.297	15,347	1.5
2076	Asbury	596	SI	7589885				StreamRiver	90	5.3	4.771	1.6	0.67

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
2076	Asbury	597	SI	7589885	Blackberry Creek	75	33	StreamRiver	90	5.3	4.771	1.6	0.67
2076	Asbury	597	SI	7589977	Blackberry Creek	137	67	StreamRiver	92.2	15.6	5.763	7.0	0.85
2076	Asbury	598	SI	7589885	Blackberry Creek	300	50	StreamRiver	90	5.3	4.771	1.6	0.67
2076	Asbury	598	SI	7589977	Blackberry Creek	563	50	StreamRiver	92.2	15.6	5.763	7.0	0.85
2706	Asheville Steam Electric Plant	649	SI	22165396	French Broad River	36	100	ArtificialPath	436.7	3.3	1.961	1,417	2.0
2706	Asheville Steam Electric Plant	650	SI	22165396	French Broad River	97	100	ArtificialPath	436.7	3.3	1.961	1,417	2.0
2835	Ashtabula	1263	SI	9842358	Erie, Lake	356	100	Coastline	119	3.3	6.095		
1961	Austin Northeast	958	LF	7014355	Cedar River	10	100	StreamRiver	88.3	6.1	3.637	87	1.2
2836	Avon Lake	975	LF	28125104				Coastline	72.3	11.5	4.879		
2836	Avon Lake	1175	SI	28125104		80	100	Coastline	72.3	11.5	4.879		
2836	Avon Lake	1176	SI	28125104		68	100	Coastline	72.3	11.5	4.879		
995	Bailly	434	SI	3398586		25	100	Coastline	159	7.8	13.701		
995	Bailly	435	SI	3398156		3870	100	StreamRiver	161.8	6.7	0.766	2.7	0.47
995	Bailly	436	SI	3398156		3378	100	StreamRiver	161.8	6.7	0.766	2.7	0.47
995	Bailly	437	SI	3398156		3611	63	StreamRiver	161.8	6.7	0.766	2.7	0.47
995	Bailly	437	SI	3398586		974	38	Coastline	159	7.8	13.701		
995	Bailly	438	SI	3398156		3786	63	StreamRiver	161.8	6.7	0.766	2.7	0.47
995	Bailly	438	SI	3398586		1130	38	Coastline	159	7.8	13.701		
995	Bailly	439	SI	3398156		3276	100	StreamRiver	161.8	6.7	0.766	2.7	0.47
995	Bailly	939	LF	3398444	Dunes Creek	2195	100	StreamRiver	173.9	10.5	3.006	4.3	0.74
995	Bailly	952	LF	3398444	Dunes Creek	2060	100	StreamRiver	173.9	10.5	3.006	4.3	0.74
889	Baldwin Energy Complex	391	SI	13892052		25	100	StreamRiver	31.9	0.6	1.012	0.86	0.73
3	Barry	252	SI	18520589				StreamRiver	288.8	1.0	1.352	49	0.79
3982	Bay Front	162	SI	1797315	Superior, Lake	31	100	Coastline	220.1	6.3	9.68		
3982	Bay Front	163	SI	1797315	Superior, Lake	36	100	Coastline	220.1	6.3	9.68		
3982	Bay Front	945	LF	1814535	Rock Creek	343	63	StreamRiver	233.1	3.3	5.16	1.4	0.75
3982	Bay Front	945	LF	1814545		549	13	StreamRiver	232.9	1.7	4.204	0.67	0.69
3982	Bay Front	945	LF	1814559		513	25	StreamRiver	231.7	1.0	2.287	0.42	0.65
3982	Bay Front	946	LF	1797055		1397	100	StreamRiver	222.3	4.8	3.999	5.5	0.89
2878	Bay Shore	977	LF	30726962				Coastline	88.8	6.9	9.271		
2878	Bay Shore	1326	SI	30726962		128	100	Coastline	88.8	6.9	9.271		

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
8042	Belews Creek Steam Station	243	SI	8679473	Dan River	247	88	StreamRiver	187.1	12.9	6.58	581	1.4
8042	Belews Creek Steam Station	243	SI	8679535		956	13	StreamRiver	186.9	2.0	2.44	0.91	0.78
8042	Belews Creek Steam Station	1009	LF	8679473	Dan River	2046	50	StreamRiver	187.1	12.9	6.58	581	1.4
8042	Belews Creek Steam Station	1009	LF	8679535		178	25	StreamRiver	186.9	2.0	2.44	0.91	0.78
8042	Belews Creek Steam Station	1009	LF	8680029	West Belews Creek	601	25	LakePond	186.1	3.8	1.994	15	0.65
8042	Belews Creek Steam Station	1010	LF	8679999	Belews Lake	1941	25	LakePond	182.9	15.8	3.821	82	1.2
8042	Belews Creek Steam Station	1010	LF	8680025	Belews Lake	300	25	LakePond	178.6	1.2	1.098	66	1.0
8042	Belews Creek Steam Station	1010	LF	8680029	West Belews Creek	465	50	LakePond	186.1	3.8	1.994	15	0.65
8042	Belews Creek Steam Station	1079	LF	8680027	Belews Lake	199	38	LakePond	184.3	1.0	1.397	16	0.91
8042	Belews Creek Steam Station	1079	LF	8680029	West Belews Creek	109	63	LakePond	186.1	3.8	1.994	15	0.65
6034	Belle River	33	SI	13195966				StreamRiver	69.2	6.3	2.636	1.9	0.68
6034	Belle River	1035	LF	13195770		733	13	StreamRiver	68.1	3.6	3.889	3.1	0.77
6034	Belle River	1035	LF	13195966		1393	88	StreamRiver	69.2	6.3	2.636	1.9	0.68
3325	Ben French	1379	SI	17533087		180	100	StreamRiver	30.5	1.4	1.324	0.040	0.68
645	Big Bend	342	SI	16919198				Coastline	126	0.3	2.737		
645	Big Bend	343	SI	16918212		20	100	StreamRiver	128.8	5.2	1.635	2.2	0.69
645	Big Bend	344	SI	16918212		26	100	StreamRiver	128.8	5.2	1.635	2.2	0.69
645	Big Bend	345	SI	16918212		37	100	StreamRiver	128.8	5.2	1.635	2.2	0.69
645	Big Bend	346	SI	16919198				Coastline	126	0.3	2.737		
645	Big Bend	347	SI	16918212		16	100	StreamRiver	128.8	5.2	1.635	2.2	0.69
645	Big Bend	348	SI	16919198				Coastline	126	0.3	2.737		
645	Big Bend	349	SI	16919198				Coastline	126	0.3	2.737		
645	Big Bend	1164	LF	16918212		585	50	StreamRiver	128.8	5.2	1.635	2.2	0.69
645	Big Bend	1164	LF	16918614		212	50	StreamRiver	127	1.8	2.239	0.75	0.58
3497	Big Brown	776	LF	1454945	Bear Creek	1158	100	StreamRiver	24	12.0	5.823	2.8	0.83
3497	Big Brown	784	LF	1455469	Fairfield Lake	514	100	LakePond	24	4.7	1.319	2.7	0.48
3497	Big Brown	790	LF	1454945	Bear Creek	865	100	StreamRiver	24	12.0	5.823	2.8	0.83
3497	Big Brown	791	LF	1454921	Tehuacana Creek	1857	75	StreamRiver	26.6	14.1	6.398	206	1.1

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
3497	Big Brown	791	LF	1454945	Bear Creek	1038	25	StreamRiver	24	12.0	5.823	2.8	0.83
3497	Big Brown	1177	SI	1454945	Bear Creek	1881	25	StreamRiver	24	12.0	5.823	2.8	0.83
3497	Big Brown	1177	SI	1455407	Fairfield Lake	335	75	LakePond	24	3.2	1.997	19	1.2
3497	Big Brown	1178	SI	1454945	Bear Creek	355	100	StreamRiver	24	12.0	5.823	2.8	0.83
3497	Big Brown	1179	SI	1454945	Bear Creek	976	38	StreamRiver	24	12.0	5.823	2.8	0.83
3497	Big Brown	1179	SI	1455469	Fairfield Lake	242	63	LakePond	24	4.7	1.319	2.7	0.48
3497	Big Brown	1180	SI	1455407	Fairfield Lake	58	100	LakePond	24	3.2	1.997	19	1.2
6055	Big Cajun 2	36	SI	18714658				StreamRiver	121.7	31.9	3.946	30	0.63
6055	Big Cajun 2	37	SI	18714658				StreamRiver	121.7	31.9	3.946	30	0.63
6055	Big Cajun 2	38	SI	18714658				StreamRiver	121.7	31.9	3.946	30	0.63
6055	Big Cajun 2	815	LF	18714658	Patin Dyke Slough	68	100	StreamRiver	121.7	31.9	3.946	30	0.63
1353	Big Sandy	521	SI	908539	Blaine Creek	98	67	StreamRiver	99	4.0	3.035	326	1.3
1353	Big Sandy	521	SI	909005		353	33	Reservoir	99	1.1	1.206	1.1	0.63
1353	Big Sandy	522	SI	909015	Big Sandy River	75	100	ArtificialPath	99.2	16.8	7.427	5,111	2.0
1353	Big Sandy	523	SI	908507	Blaine Creek	45	67	StreamRiver	99	7.3	4.679	323	1.4
1353	Big Sandy	523	SI	908539	Blaine Creek	272	33	StreamRiver	99	4.0	3.035	326	1.3
6098	Big Stone	814	LF	4085588	Whetstone River	1885	100	StreamRiver	8.7	14.7	6.339	53	1.4
6098	Big Stone	1261	SI	4084392		1065	25	StreamRiver	8	8.7	3.009	0.46	0.75
6098	Big Stone	1261	SI	4085588	Whetstone River	890	75	StreamRiver	8.7	14.7	6.339	53	1.4
1904	Black Dog	593	SI	2387042				ArtificialPath	73.6	15.0	5.192	3,499	1.7
1904	Black Dog	799	LF	2387042	Minnesota River	28	67	ArtificialPath	73.6	15.0	5.192	3,499	1.7
1904	Black Dog	799	LF	2387356		78	33	LakePond	73.5	6.5	0.778	0.98	0.41
6106	Boardman	746	LF	24233486		1286	38	StreamRiver	11.4	12.0	5.768	1.4	0.97
6106	Boardman	746	LF	24235620		1618	63	StreamRiver	11.2	36.6	8.78	1.6	0.92
6106	Boardman	1339	SI	24235618		4646	100	StreamRiver	11	22.6	5.997	2.9	1.0
6106	Boardman	1340	SI	24235618		1046	100	StreamRiver	11	22.6	5.997	2.9	1.0
6106	Boardman	1341	SI	24235618		5841	13	StreamRiver	11	22.6	5.997	2.9	1.0
6106	Boardman	1341	SI	24235620		5594	25	StreamRiver	11.2	36.6	8.78	1.6	0.92
6106	Boardman	1341	SI	24235792		7548	63	ArtificialPath	11	115.4	0.43	30	0.74
7790	Bonanza Power Plant	735	LF	1372922		37	57	StreamRiver	11	1.2	1.685	0.022	0.50
7790	Bonanza Power Plant	735	LF	1374446	Green River	54	43	ArtificialPath	11	1.7	1.507	7,722	2.2
7790	Bonanza Power Plant	737	LF	1373564		19	38	StreamRiver	12	1.8	4.033	0.032	0.68
7790	Bonanza Power Plant	737	LF	1373600		178	25	StreamRiver	12	2.5	3.431	0.046	0.73
7790	Bonanza Power Plant	737	LF	5305188		1416	38	StreamRiver	12	2.9	2.079	0.051	0.70
7790	Bonanza Power Plant	1207	SI	5306592		95	100	StreamRiver	13	1.8	3.794	1.4	0.96

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
7790	Bonanza Power Plant	1208	SI	5305828		34	100	StreamRiver	13.2	0.7	1.937	0.15	0.70
7790	Bonanza Power Plant	1209	SI	5305828		2	100	StreamRiver	13.2	0.7	1.937	0.15	0.70
1893	Boswell Energy Center	590	SI	22326305		323	63	StreamRiver	92.6	16.5	2.293	3.5	0.79
1893	Boswell Energy Center	590	SI	22326521		59	25	LakePond	92.5	2.3	1.893	4.0	0.51
1893	Boswell Energy Center	590	SI	22326529		747	13	LakePond	93.1	6.3	2.591	1,550	1.6
1893	Boswell Energy Center	591	SI	22326521		54	63	LakePond	92.5	2.3	1.893	4.0	0.51
1893	Boswell Energy Center	591	SI	22326529		123	38	LakePond	93.1	6.3	2.591	1,550	1.6
1893	Boswell Energy Center	592	SI	22326523		319	100	LakePond	92	0.2	0.447	1,599	1.6
1893	Boswell Energy Center	796	LF	22326521		221	100	LakePond	92.5	2.3	1.893	4.0	0.51
1893	Boswell Energy Center	853	LF	22326521		7	67	LakePond	92.5	2.3	1.893	4.0	0.51
1893	Boswell Energy Center	853	LF	22326529		43	33	LakePond	93.1	6.3	2.591	1,550	1.6
1893	Boswell Energy Center	862	LF	22326305		1931	100	StreamRiver	92.6	16.5	2.293	3.5	0.79
703	Bowen	350	SI	6499098				ArtificialPath	264	12.9	5.814	2,598	2.0
703	Bowen	1103	LF	6499098	Etowah River	296	100	ArtificialPath	264	12.9	5.814	2,598	2.0
602	Brandon Shores	1289	SI	11690244		617	100	ArtificialPath	168.9	2.8	2.561	2.7	0.57
602	Brandon Shores	1290	SI	11690244		617	100	ArtificialPath	168.9	2.8	2.561	2.7	0.57
1619	Brayton Point	731	LF	6130309		20	100	ArtificialPath	360.8	3.0	2.458	12	0.64
1619	Brayton Point	760	LF	6130309		203	63	ArtificialPath	360.8	3.0	2.458	12	0.64
1619	Brayton Point	760	LF	6130319	Taunton River	1005	38	ArtificialPath	361.5	11.3	4.667	969	0.87
1619	Brayton Point	761	LF	6130309		134	63	ArtificialPath	360.8	3.0	2.458	12	0.64
1619	Brayton Point	761	LF	6130319	Taunton River	1072	38	ArtificialPath	361.5	11.3	4.667	969	0.87
1619	Brayton Point	800	LF	6130309		39	75	ArtificialPath	360.8	3.0	2.458	12	0.64
1619	Brayton Point	800	LF	6130319	Taunton River	1185	25	ArtificialPath	361.5	11.3	4.667	969	0.87
1619	Brayton Point	824	LF	6130309		65	100	ArtificialPath	360.8	3.0	2.458	12	0.64
1619	Brayton Point	1187	SI	6130309		52	100	ArtificialPath	360.8	3.0	2.458	12	0.64
1619	Brayton Point	1188	SI	6130309		54	100	ArtificialPath	360.8	3.0	2.458	12	0.64
1619	Brayton Point	1189	SI	6130309		175	100	ArtificialPath	360.8	3.0	2.458	12	0.64
1619	Brayton Point	1190	SI	6130309		220	100	ArtificialPath	360.8	3.0	2.458	12	0.64
1619	Brayton Point	1191	SI	6130309		77	100	ArtificialPath	360.8	3.0	2.458	12	0.64
1619	Brayton Point	1192	SI	6130309		254	100	ArtificialPath	360.8	3.0	2.458	12	0.64
1619	Brayton Point	1193	SI	6130309		159	100	ArtificialPath	360.8	3.0	2.458	12	0.64
1619	Brayton Point	1194	SI	6130319	Taunton River	1048	100	ArtificialPath	361.5	11.3	4.667	969	0.87
1619	Brayton Point	1195	SI	6130319	Taunton River	948	100	ArtificialPath	361.5	11.3	4.667	969	0.87
1619	Brayton Point	1196	SI	6130319	Taunton River	952	100	ArtificialPath	361.5	11.3	4.667	969	0.87
3796	Bremo Bluff	148	SI	8545789	Holman Creek	94	17	StreamRiver	164	1.3	2.024	4.3	0.87
3796	Bremo Bluff	148	SI	8545819	Holman Creek	30	33	StreamRiver	163.8	1.0	0.373	5.8	0.54
3796	Bremo Bluff	148	SI	8548181	James River	70	33	ArtificialPath	164	0.5	0.624	5,608	2.0
3796	Bremo Bluff	148	SI	8557867	James River	36	17	ArtificialPath	164	0.1	0.284	5,625	2.0
3796	Bremo Bluff	149	SI	8545819	Holman Creek	692	63	StreamRiver	163.8	1.0	0.373	5.8	0.54

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
3796	Bremo Bluff	149	SI	8548185	James River	205	38	ArtificialPath	163.2	1.9	1.829	5,631	2.0
6094	Bruce Mansfield	75	SI	3819803	Haden Run	344	50	StreamRiver	137.8	2.1	2.035	2.5	0.92
6094	Bruce Mansfield	75	SI	3821085	Ohio River	285	50	ArtificialPath	134.8	3.3	1.75	39,266	2.9
6094	Bruce Mansfield	76	SI	3819803	Haden Run	171	100	StreamRiver	137.8	2.1	2.035	2.5	0.92
6094	Bruce Mansfield	77	SI	3821085				ArtificialPath	134.8	3.3	1.75	39,266	2.9
6094	Bruce Mansfield	78	SI	3819803	Haden Run	275	100	StreamRiver	137.8	2.1	2.035	2.5	0.92
6094	Bruce Mansfield	79	SI	3820879	Mill Creek	192	50	StreamRiver	136.8	5.0	5.158	14	1.1
6094	Bruce Mansfield	79	SI	3821105	Mill Creek	45	25	ArtificialPath	133	0.1	0.276	17	0.66
6094	Bruce Mansfield	79	SI	3821113	Ohio River	359	25	ArtificialPath	135	3.0	1.365	39,859	2.9
2720	Buck	671	SI	9223641	Yadkin River	566	63	LakePond	163.1	3.7	1.95	4,292	1.9
2720	Buck	671	SI	9223657		959	38	LakePond	162.9	2.3	0.557	2.9	0.48
2720	Buck	672	SI	9223657		442	100	LakePond	162.9	2.3	0.557	2.9	0.48
2720	Buck	673	SI	9223641	Yadkin River	140	100	LakePond	163.1	3.7	1.95	4,292	1.9
3396	Bull Run	121	SI	22124076				StreamRiver	270.8	2.1	1.998	4.7	0.78
3396	Bull Run	122	SI	22124076				StreamRiver	270.8	2.1	1.998	4.7	0.78
3396	Bull Run	123	SI	22124076				StreamRiver	270.8	2.1	1.998	4.7	0.78
3396	Bull Run	124	SI	22124076				StreamRiver	270.8	2.1	1.998	4.7	0.78
3396	Bull Run	889	LF	14643321	Clinch River	59	50	LakePond	270.5	4.5	2.839	213	1.0
3396	Bull Run	889	LF	14643323	Clinch River	535	50	LakePond	271.8	2.5	1.802	4,628	1.9
3396	Bull Run	890	LF	22124042		167	17	StreamRiver	271.3	1.7	2.232	1.3	0.79
3396	Bull Run	890	LF	22124076	Worthington Branch	16	83	StreamRiver	270.8	2.1	1.998	4.7	0.78
1104	Burlington	507	SI	6966239				ArtificialPath	71	7.0	2.87	62,652	3.3
1104	Burlington	508	SI	6966239				ArtificialPath	71	7.0	2.87	62,652	3.3
1104	Burlington	509	SI	6966239				ArtificialPath	71	7.0	2.87	62,652	3.3
1104	Burlington	510	SI	6966239				ArtificialPath	71	7.0	2.87	62,652	3.3
1104	Burlington	511	SI	6966239				ArtificialPath	71	7.0	2.87	62,652	3.3
676	C D McIntosh Jr	885	LF	16794835	Saddle Creek	2678	100	StreamRiver	129	164.6	5.003	58	0.96
676	C D McIntosh Jr	888	LF	16794835	Saddle Creek	2422	100	StreamRiver	129	164.6	5.003	58	0.96
468	Cameo	316	SI	3178228				StreamRiver	43.1	0.3	0.263	0.79	0.91
468	Cameo	317	SI	3178228				StreamRiver	43.1	0.3	0.263	0.79	0.91
3280	Canadys Steam	107	SI	9614169	Edisto River	635	13	StreamRiver	196	0.7	1.336	2,219	1.7
3280	Canadys Steam	107	SI	9614527	Edisto River	113	63	StreamRiver	197.6	3.8	3.3	2,219	1.8
3280	Canadys Steam	107	SI	9614577	Edisto River	1008	25	StreamRiver	196.7	26.4	5.15	2,239	1.7
3280	Canadys Steam	108	SI	9614577	Edisto River	1064	100	StreamRiver	196.7	26.4	5.15	2,239	1.7
3280	Canadys Steam	109	SI	9614169	Edisto River	321	25	StreamRiver	196	0.7	1.336	2,219	1.7
3280	Canadys Steam	109	SI	9614577	Edisto River	261	75	StreamRiver	196.7	26.4	5.15	2,239	1.7
1363	Cane Run	538	SI	10163768	Mill Creek Cutoff	677	13	StreamRiver	111.3	6.9	3.556	40	1.1

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
1363	Cane Run	538	SI	10163770	Mill Creek	2052	13	StreamRiver	112	1.5	0.622	0.71	0.62
1363	Cane Run	538	SI	10163782	Mill Creek	2202	75	StreamRiver	112.2	11.5	7.616	6.2	0.67
1363	Cane Run	539	SI	10163768				StreamRiver	111.3	6.9	3.556	40	1.1
1363	Cane Run	540	SI	10163768	Mill Creek Cutoff	127	100	StreamRiver	111.3	6.9	3.556	40	1.1
1363	Cane Run	541	SI	10163768	Mill Creek Cutoff	125	100	StreamRiver	111.3	6.9	3.556	40	1.1
1363	Cane Run	542	SI	10163768				StreamRiver	111.3	6.9	3.556	40	1.1
1363	Cane Run	869	LF	10163782	Mill Creek	2077	43	StreamRiver	112.2	11.5	7.616	6.2	0.67
1363	Cane Run	869	LF	10164018	Ohio River	13	57	ArtificialPath	111.9	1.3	1.817	123,554	3.7
2708	Cape Fear Steam Electric Plant	651	SI	8844487		121	40	StreamRiver	110.3	3.8	3.116	1.7	0.58
2708	Cape Fear Steam Electric Plant	651	SI	8844727	Cape Fear River	227	40	ArtificialPath	106.8	1.0	1.527	3,146	1.8
2708	Cape Fear Steam Electric Plant	651	SI	8844733	Cape Fear River	411	20	ArtificialPath	111	0.9	1.11	3,154	1.8
2708	Cape Fear Steam Electric Plant	652	SI	8844487		284	33	StreamRiver	110.3	3.8	3.116	1.7	0.58
2708	Cape Fear Steam Electric Plant	652	SI	8844727	Cape Fear River	25	67	ArtificialPath	106.8	1.0	1.527	3,146	1.8
2708	Cape Fear Steam Electric Plant	653	SI	8844487		62	88	StreamRiver	110.3	3.8	3.116	1.7	0.58
2708	Cape Fear Steam Electric Plant	653	SI	8897286	Shaddox Creek	504	13	StreamRiver	104.5	4.0	3.309	14	0.88
2708	Cape Fear Steam Electric Plant	654	SI	8844727	Cape Fear River	92	17	ArtificialPath	106.8	1.0	1.527	3,146	1.8
2708	Cape Fear Steam Electric Plant	654	SI	8897286	Shaddox Creek	45	67	StreamRiver	104.5	4.0	3.309	14	0.88
2708	Cape Fear Steam Electric Plant	654	SI	8898150	Haw River	26	17	ArtificialPath	103.8	0.1	0.373	1,602	1.6
2708	Cape Fear Steam Electric Plant	655	SI	8844727	Cape Fear River	83	25	ArtificialPath	106.8	1.0	1.527	3,146	1.8
2708	Cape Fear Steam Electric Plant	655	SI	8844733	Cape Fear River	110	75	ArtificialPath	111	0.9	1.11	3,154	1.8
3644	Carbon Plant	876	LF	3907885		3	100	StreamRiver	13.3	6.5	4.244	0.15	0.93
3644	Carbon Plant	905	LF	3907877	Price River	155	100	StreamRiver	13.7	3.5	2.347	225	2.0
3644	Carbon Plant	1387	SI	3907877	Price River	91	100	StreamRiver	13.7	3.5	2.347	225	2.0
3644	Carbon Plant	1388	SI	3907877	Price River	101	100	StreamRiver	13.7	3.5	2.347	225	2.0
2828	Cardinal	693	SI	19451557	Riddles Run	52	75	StreamRiver	156.8	2.1	2.148	2.6	0.91

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
2828	Cardinal	693	SI	19453103	Ohio River	911	25	ArtificialPath	153.3	11.2	2.976	40,860	3.0
2828	Cardinal	694	SI	19451565	Salt Run	678	20	StreamRiver	157	1.4	0.964	6.8	1.0
2828	Cardinal	694	SI	19453117	Ohio River	33	80	ArtificialPath	157.5	6.6	3.078	40,873	3.0
2828	Cardinal	899	LF	19451557	Riddles Run	342	100	StreamRiver	156.8	2.1	2.148	2.6	0.91
1001	Cayuga	454	SI	10209979	Wabash River	481	100	ArtificialPath	100.2	20.2	9.504	9,307	2.2
1001	Cayuga	455	SI	10209979	Wabash River	283	100	ArtificialPath	100.2	20.2	9.504	9,307	2.2
1001	Cayuga	456	SI	10209979	Wabash River	191	100	ArtificialPath	100.2	20.2	9.504	9,307	2.2
1001	Cayuga	457	SI	10209979	Wabash River	514	100	ArtificialPath	100.2	20.2	9.504	9,307	2.2
1001	Cayuga	838	LF	10208939		1145	25	StreamRiver	99.6	6.5	3.806	3.4	0.85
1001	Cayuga	838	LF	10209979	Wabash River	1656	75	ArtificialPath	100.2	20.2	9.504	9,307	2.2
1571	Chalk Point LLC	836	LF	11908022	Mataponi Creek	53	75	StreamRiver	155.9	10.1	3.969	4.7	0.85
1571	Chalk Point LLC	836	LF	11908042	Rock Creek	1028	25	StreamRiver	159.8	5.1	3.531	2.4	0.81
1571	Chalk Point LLC	1104	LF	11908782	Swanson Creek	1759	50	ArtificialPath	179	4.9	2.171	34	0.75
1571	Chalk Point LLC	1104	LF	11908816	Patuxent River	285	50	ArtificialPath	179.4	5.0	2.986	813	1.4
2169	Chamois Power Plant	1288	SI	5159567		39	33	StreamRiver	24	0.1	0.077	2.2	0.47
2169	Chamois Power Plant	1288	SI	5159635	Dooling Creek	38	33	StreamRiver	24	2.2	3.422	2.2	0.77
2169	Chamois Power Plant	1288	SI	5160215		20	33	StreamRiver	24	1.0	1.768	0.061	0.60
56	Charles R. Lowman	270	SI	21642176	Tombigbee River	366	13	ArtificialPath	199.8	2.3	3.261	28,775	2.8
56	Charles R. Lowman	270	SI	21642548		1148	88	Connector	198.5	1.6	1.163	9.7	0.62
56	Charles R. Lowman	271	SI	21642176	Tombigbee River	297	25	ArtificialPath	199.8	2.3	3.261	28,775	2.8
56	Charles R. Lowman	271	SI	21642548		1220	75	Connector	198.5	1.6	1.163	9.7	0.62
56	Charles R. Lowman	272	SI	21642176	Tombigbee River	115	75	ArtificialPath	199.8	2.3	3.261	28,775	2.8
56	Charles R. Lowman	272	SI	21642548		1729	25	Connector	198.5	1.6	1.163	9.7	0.62
56	Charles R. Lowman	273	SI	21641264		1246	13	StreamRiver	200.9	4.2	3.246	2.6	0.63
56	Charles R. Lowman	273	SI	21642548		1360	88	Connector	198.5	1.6	1.163	9.7	0.62
56	Charles R. Lowman	900	LF	21642176				ArtificialPath	199.8	2.3	3.261	28,775	2.8
469	Cherokee	318	SI	229709				StreamRiver	18.9	23.5	3.109	1,505	2.4
469	Cherokee	319	SI	229709				StreamRiver	18.9	23.5	3.109	1,505	2.4
469	Cherokee	320	SI	229709				StreamRiver	18.9	23.5	3.109	1,505	2.4
469	Cherokee	321	SI	229709				StreamRiver	18.9	23.5	3.109	1,505	2.4
469	Cherokee	322	SI	229709				StreamRiver	18.9	23.5	3.109	1,505	2.4
469	Cherokee	323	SI	229709				StreamRiver	18.9	23.5	3.109	1,505	2.4
3803	Chesapeake Energy Center	152	SI	10054854		26	50	ArtificialPath	152.9	1.3	1.092	61	0.84

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
3803	Chesapeake Energy Center	152	SI	10055988		39	50	Reservoir	156.2	0.1	0.343	0.31	0.57
3803	Chesapeake Energy Center	865	LF	10055726	Southern Branch Elizabeth River	89	33	ArtificialPath	159	0.5	1.003	97	0.92
3803	Chesapeake Energy Center	865	LF	10055988		93	17	Reservoir	156.2	0.1	0.343	0.31	0.57
3803	Chesapeake Energy Center	865	LF	10055992		22	50	LakePond	158.8	0.7	0.237	0.27	0.32
3797	Chesterfield	150	SI	10067647		5	100	LakePond	158	7.3	1.114	2.7	0.47
3797	Chesterfield	151	SI	10067405	James River	151	43	ArtificialPath	159	2.2	1.906	7,627	2.1
3797	Chesterfield	151	SI	10072915		17	57	ArtificialPath	158.9	3.4	2.033	4.2	0.51
8226	Cheswick Power Plant	1099	LF	11049576	Little Deer Creek	217	100	StreamRiver	162.5	2.2	1.983	16	1.0
8226	Cheswick Power Plant	1165	SI	11049676	Tawney Run	5	100	StreamRiver	158.8	2.6	2.618	3.7	0.90
8226	Cheswick Power Plant	1166	SI	11049676	Tawney Run	3	100	StreamRiver	158.8	2.6	2.618	3.7	0.90
113	Cholla	279	SI	21746307		27	50	CanalDitch	7	4.1	3.921	0.67	0.64
113	Cholla	279	SI	21746347		420	50	CanalDitch	7	4.5	3.01	0.34	0.65
113	Cholla	280	SI	21746275		217	100	StreamRiver	7	3.1	2.615	0.10	0.77
113	Cholla	863	LF	21746245		679	100	StreamRiver	7	4.3	2.719	0.016	0.66
2721	Cliffside	674	SI	12035539				ArtificialPath	271.2	0.5	0.71	1,461	2.1
2721	Cliffside	675	SI	12034795	Suck Creek	101	67	StreamRiver	271	10.3	6.814	24	1.1
2721	Cliffside	675	SI	12035537	Broad River	240	17	ArtificialPath	279	0.2	0.451	1,485	1.5
2721	Cliffside	675	SI	12035809		80	17	LakePond	276	0.4	0.413	0.27	0.64
2721	Cliffside	676	SI	12035539				ArtificialPath	271.2	0.5	0.71	1,461	2.1
983	Clifty Creek	413	SI	10161792	Crooked Creek	35	100	StreamRiver	59.3	24.6	8.802	12	1.1
983	Clifty Creek	414	SI	10161794	Big Clifty Creek	273	88	StreamRiver	59.4	5.1	3.282	14	1.1
983	Clifty Creek	414	SI	10161934	Ohio River	17	13	ArtificialPath	60	16.3	5.415	122,540	3.7
983	Clifty Creek	847	LF	10161794	Big Clifty Creek	668	50	StreamRiver	59.4	5.1	3.282	14	1.1
983	Clifty Creek	847	LF	10161934	Ohio River	1243	50	ArtificialPath	60	16.3	5.415	122,540	3.7
983	Clifty Creek	848	LF	10161794	Big Clifty Creek	909	25	StreamRiver	59.4	5.1	3.282	14	1.1
983	Clifty Creek	848	LF	10161934	Ohio River	935	75	ArtificialPath	60	16.3	5.415	122,540	3.7
3775	Clinch River	144	SI	14638941	Dumps Creek	33	75	StreamRiver	195.1	2.2	1.566	36	0.97
3775	Clinch River	144	SI	14640413	Clinch River	61	25	ArtificialPath	197.8	0.7	1.651	820	1.6
3775	Clinch River	145	SI	14638941	Dumps Creek	73	100	StreamRiver	195.1	2.2	1.566	36	0.97
3775	Clinch River	849	LF	14640413	Clinch River	130	29	ArtificialPath	197.8	0.7	1.651	820	1.6
3775	Clinch River	849	LF	14640417	Clinch River	69	71	ArtificialPath	199.1	1.3	1.963	823	1.4
7213	Clover	850	LF	8651510	Black Walnut Creek	383	100	StreamRiver	115	2.4	1.134	8.0	0.84

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
7213	Clover	851	LF	8651510	Black Walnut Creek	407	100	StreamRiver	115	2.4	1.134	8.0	0.84
7213	Clover	1280	SI	8653052		459	63	LakePond	116	0.2	0.299	0.39	0.65
7213	Clover	1280	SI	8653054	Roanoke River	758	13	ArtificialPath	116	0.7	0.905	2,965	1.8
7213	Clover	1280	SI	8653058		332	25	LakePond	116	0.5	0.703	1.1	0.79
7213	Clover	1281	SI	8653052		459	63	LakePond	116	0.2	0.299	0.39	0.65
7213	Clover	1281	SI	8653054	Roanoke River	758	13	ArtificialPath	116	0.7	0.905	2,965	1.8
7213	Clover	1281	SI	8653058		332	25	LakePond	116	0.5	0.703	1.1	0.79
7213	Clover	1282	SI	8651532		31	14	StreamRiver	116	0.1	0.208	1.1	0.41
7213	Clover	1282	SI	8653054	Roanoke River	11	71	ArtificialPath	116	0.7	0.905	2,965	1.8
7213	Clover	1282	SI	8653058		7	14	LakePond	116	0.5	0.703	1.1	0.79
7213	Clover	1283	SI	8653052		51	38	LakePond	116	0.2	0.299	0.39	0.65
7213	Clover	1283	SI	8653054	Roanoke River	207	63	ArtificialPath	116	0.7	0.905	2,965	1.8
7213	Clover	1284	SI	8653052		51	38	LakePond	116	0.2	0.299	0.39	0.65
7213	Clover	1284	SI	8653054	Roanoke River	207	63	ArtificialPath	116	0.7	0.905	2,965	1.8
6030	Coal Creek	29	SI	14518483		4497	13	StreamRiver	4	6.5	2.255	0.0058	0.49
6030	Coal Creek	29	SI	14518523		4418	88	StreamRiver	4	6.2	2.234	0.0056	0.62
6030	Coal Creek	30	SI	14518523		4934	100	StreamRiver	4	6.2	2.234	0.0056	0.62
6030	Coal Creek	852	LF	14518523		4854	100	StreamRiver	4	6.2	2.234	0.0056	0.62
6030	Coal Creek	854	LF	14518385		1910	25	StreamRiver	4	7.9	2.161	0.0071	0.63
6030	Coal Creek	854	LF	14518389		270	75	StreamRiver	4	4.2	2.35	0.0038	0.59
6030	Coal Creek	855	LF	14518439		609	25	StreamRiver	4	2.0	1.606	0.0018	0.46
6030	Coal Creek	855	LF	14518483		6656	75	StreamRiver	4	6.5	2.255	0.0058	0.49
6030	Coal Creek	857	LF	14518523		4878	100	StreamRiver	4	6.2	2.234	0.0056	0.62
6030	Coal Creek	868	LF	14518407		26	100	StreamRiver	4	5.4	4.198	0.0049	0.60
6030	Coal Creek	1119	LF	14518407		398	100	StreamRiver	4	5.4	4.198	0.0049	0.60
861	Coffeen	379	SI	13881662		284	13	StreamRiver	30	2.4	2.472	0.79	0.68
861	Coffeen	379	SI	13882010		124	88	LakePond	29	2.4	2.783	1.6	0.59
861	Coffeen	380	SI	13881662		127	100	StreamRiver	30	2.4	2.472	0.79	0.68
861	Coffeen	846	LF	13881662		499	50	StreamRiver	30	2.4	2.472	0.79	0.68
861	Coffeen	846	LF	13882002		546	50	LakePond	29.6	4.5	1.961	9.9	0.75
47	Colbert	258	SI	19623794				LakePond	276.1	4.0	5.396	60,949	3.2
47	Colbert	259	SI	19623794				LakePond	276.1	4.0	5.396	60,949	3.2
47	Colbert	260	SI	19623794				LakePond	276.1	4.0	5.396	60,949	3.2
47	Colbert	859	LF	19581379	Cane Creek	888	50	StreamRiver	270.8	8.2	5.692	88	0.89
47	Colbert	859	LF	19623794	White Lake (historical)	545	50	LakePond	276.1	4.0	5.396	60,949	3.2
6178	Coleto Creek	181	SI	1639289	Coleto Creek Cooling Pond	44	100	LakePond	13.2	4.9	2.869	1.6	0.54

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
6178	Coleto Creek	182	SI	1639289	Coleto Creek Cooling Pond	0	100	LakePond	13.2	4.9	2.869	1.6	0.54
6076	Colstrip	46	SI	13262665				StreamRiver	9.5	30.6	11.221	0.98	0.97
6076	Colstrip	47	SI	13262665				StreamRiver	9.5	30.6	11.221	0.98	0.97
6076	Colstrip	48	SI	13262665				StreamRiver	9.5	30.6	11.221	0.98	0.97
6076	Colstrip	49	SI	13262665	East Fork Armells Creek	165	100	StreamRiver	9.5	30.6	11.221	0.98	0.97
6076	Colstrip	50	SI	13262665	East Fork Armells Creek	166	100	StreamRiver	9.5	30.6	11.221	0.98	0.97
6076	Colstrip	51	SI	13236335	Cow Creek	46	100	StreamRiver	10.7	12.0	1.867	0.29	0.80
6076	Colstrip	52	SI	13262665	East Fork Armells Creek	71	100	StreamRiver	9.5	30.6	11.221	0.98	0.97
6076	Colstrip	53	SI	13262665				StreamRiver	9.5	30.6	11.221	0.98	0.97
10784	Colstrip Energy LP	860	LF	13262539	East Fork Armells Creek	835	100	StreamRiver	9	6.3	4.522	6.5	1.1
10784	Colstrip Energy LP	861	LF	13262539	East Fork Armells Creek	720	63	StreamRiver	9	6.3	4.522	6.5	1.1
10784	Colstrip Energy LP	861	LF	13262549	Corral Creek	145	38	StreamRiver	9	5.2	4.706	0.39	0.85
8023	Columbia	239	SI	13633689				StreamRiver	127.7	9.0	4.583	3.7	0.71
8023	Columbia	240	SI	13633689				StreamRiver	127.7	9.0	4.583	3.7	0.71
8023	Columbia	241	SI	13633689				StreamRiver	127.7	9.0	4.583	3.7	0.71
8023	Columbia	242	SI	13633689				StreamRiver	127.7	9.0	4.583	3.7	0.71
8023	Columbia	1135	LF	13631823		461	13	StreamRiver	128.8	0.7	1.019	0.17	0.30
8023	Columbia	1135	LF	13633689		894	88	StreamRiver	127.7	9.0	4.583	3.7	0.71
8023	Columbia	1136	LF	13631785	Duck Creek	516	63	StreamRiver	129	0.6	0.462	0.84	0.39
8023	Columbia	1136	LF	13633653	Duck Creek	411	25	StreamRiver	129.3	2.5	1.845	0.62	0.37
8023	Columbia	1136	LF	13633689		1345	13	StreamRiver	127.7	9.0	4.583	3.7	0.71
2123	Columbia	1213	SI	5161861		220	100	StreamRiver	20	2.2	1.36	0.030	0.66
470	Comanche	324	SI	951449				StreamRiver	8.9	12.5	6.802	93	1.6
470	Comanche	325	SI	951449				StreamRiver	8.9	12.5	6.802	93	1.6
470	Comanche	326	SI	951449				StreamRiver	8.9	12.5	6.802	93	1.6
470	Comanche	327	SI	951449				StreamRiver	8.9	12.5	6.802	93	1.6
470	Comanche	328	SI	951449				StreamRiver	8.9	12.5	6.802	93	1.6
470	Comanche	1137	LF	951449	Saint Charles River	942	100	StreamRiver	8.9	12.5	6.802	93	1.6
3118	Conemaugh	864	LF	4754190		6	50	StreamRiver	259	3.1	2.288	2.1	0.89
3118	Conemaugh	864	LF	4754214		383	50	StreamRiver	257.3	4.2	2.809	2.9	0.95
3118	Conemaugh	1138	LF	4754190		36	100	StreamRiver	259	3.1	2.288	2.1	0.89

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
3118	Conemaugh	1334	SI	4754980	Conemaugh River	14	100	ArtificialPath	260.4	3.6	2.327	1,311	1.5
3118	Conemaugh	1335	SI	4754980	Conemaugh River	469	88	ArtificialPath	260.4	3.6	2.327	1,311	1.5
3118	Conemaugh	1335	SI	4754982	Conemaugh River	496	13	ArtificialPath	259	1.0	1.279	1,326	1.5
3118	Conemaugh	1336	SI	4754980	Conemaugh River	435	100	ArtificialPath	260.4	3.6	2.327	1,311	1.5
3118	Conemaugh	1337	SI	4754980	Conemaugh River	373	100	ArtificialPath	260.4	3.6	2.327	1,311	1.5
3118	Conemaugh	1338	SI	4754980	Conemaugh River	342	100	ArtificialPath	260.4	3.6	2.327	1,311	1.5
2840	Conesville	701	SI	15379411	Muskingum River	815	100	ArtificialPath	131.5	18.1	6.036	4,329	2.3
2840	Conesville	1005	LF	15379411				ArtificialPath	131.5	18.1	6.036	4,329	2.3
2840	Conesville	1006	LF	15379411				ArtificialPath	131.5	18.1	6.036	4,329	2.3
1710	Consumers Energy - J.H. Campbell	572	SI	9017399				StreamRiver	245.1	3.7	1.794	66	0.86
1710	Consumers Energy - J.H. Campbell	967	LF	9017399				StreamRiver	245.1	3.7	1.794	66	0.86
1710	Consumers Energy - J.H. Campbell	985	LF	9017399				StreamRiver	245.1	3.7	1.794	66	0.86
1710	Consumers Energy - J.H. Campbell	998	LF	9017399				StreamRiver	245.1	3.7	1.794	66	0.86
1710	Consumers Energy - J.H. Campbell	999	LF	9017399				StreamRiver	245.1	3.7	1.794	66	0.86
1384	Cooper Station.	973	LF	3575676				LakePond	170.6	8.2	5.023	5,416	2.0
7210	Cope	866	LF	10553480	Roberts Swamp	74	100	StreamRiver	262	15.6	5.246	45	1.0
6177	Coronado Generating Station	180	SI	19895815		59	100	StreamRiver	10	11.9	7.041	0.056	0.74
6177	Coronado Generating Station	835	LF	19895759				StreamRiver	10	84.6	18.462	10	1.5
6177	Coronado Generating Station	867	LF	19895815		1604	60	StreamRiver	10	11.9	7.041	0.056	0.74
6177	Coronado Generating Station	867	LF	19896013		313	40	StreamRiver	10	8.4	6.608	0.010	0.68
8222	Coyote	248	SI	16249845		251	100	StreamRiver	4.4	12.5	8.055	0.022	0.71
8222	Coyote	249	SI	16249845		95	100	StreamRiver	4.4	12.5	8.055	0.022	0.71

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
8222	Coyote	250	SI	16249845		474	100	StreamRiver	4.4	12.5	8.055	0.022	0.71
8222	Coyote	825	LF	16249845		29	100	StreamRiver	4.4	12.5	8.055	0.022	0.71
8222	Coyote	826	LF	16249845		181	100	StreamRiver	4.4	12.5	8.055	0.022	0.71
8222	Coyote	833	LF	16249845		474	63	StreamRiver	4.4	12.5	8.055	0.022	0.71
8222	Coyote	833	LF	16249849		351	38	StreamRiver	5	2.6	2.8	0.0046	0.62
8222	Coyote	856	LF	16249841		326	25	StreamRiver	4	1.4	2.086	0.0024	0.58
8222	Coyote	856	LF	16249845		1544	75	StreamRiver	4.4	12.5	8.055	0.022	0.71
2549	CR Huntley Generating Station	643	SI	15569803	Niagara River	20	100	ArtificialPath	170	1.0	0.505	28	0.72
2549	CR Huntley Generating Station	644	SI	15569803	Niagara River	36	100	ArtificialPath	170	1.0	0.505	28	0.72
2549	CR Huntley Generating Station	645	SI	15569803	Niagara River	57	100	ArtificialPath	170	1.0	0.505	28	0.72
2549	CR Huntley Generating Station	1100	LF	15568803		603	38	StreamRiver	164	4.7	1.874	0.96	0.66
2549	CR Huntley Generating Station	1100	LF	15569791	Niagara River	765	50	ArtificialPath	172	21.7	3.244	39	0.80
2549	CR Huntley Generating Station	1100	LF	15569797	Niagara River	1149	13	ArtificialPath	172	21.7	3.244	31	0.66
6021	Craig	27	SI	1356794				LakePond	22.1	1.0	0.47	0.36	0.74
6021	Craig	28	SI	1356794				LakePond	22.1	1.0	0.47	0.36	0.74
6021	Craig	974	LF	1356794				LakePond	22.1	1.0	0.47	0.36	0.74
867	Crawford	387	SI	14786229				ArtificialPath	109.6	131.5	5.928	203	1.1
753	Crisp Plant	1265	SI	6445762	Flint River	224	100	ArtificialPath	207.9	6.0	3.338	4,758	2.6
641	Crist	1139	LF	448392	Clear Creek	524	100	StreamRiver	436.7	17.4	6.123	13	0.95
641	Crist	1273	SI	450574	Clear Creek	42	38	ArtificialPath	438.2	1.3	1.737	15	0.63
641	Crist	1273	SI	450576	Clear Creek	50	63	ArtificialPath	440	0.1	0.116	15	0.63
641	Crist	1274	SI	448630	Escambia River	56	33	ArtificialPath	440.1	1.4	1.565	6,840	2.1
641	Crist	1274	SI	448632	Thompson Bayou	77	33	ArtificialPath	442.5	4.9	2.313	20	1.0
641	Crist	1274	SI	450574	Clear Creek	263	17	ArtificialPath	438.2	1.3	1.737	15	0.63
641	Crist	1274	SI	450576	Clear Creek	318	17	ArtificialPath	440	0.1	0.116	15	0.63
641	Crist	1275	SI	448392	Clear Creek	380	100	StreamRiver	436.7	17.4	6.123	13	0.95
641	Crist	1276	SI	448392	Clear Creek	229	100	StreamRiver	436.7	17.4	6.123	13	0.95
641	Crist	1277	SI	448392	Clear Creek	569	38	StreamRiver	436.7	17.4	6.123	13	0.95
641	Crist	1277	SI	450574	Clear Creek	248	63	ArtificialPath	438.2	1.3	1.737	15	0.63
641	Crist	1278	SI	448392	Clear Creek	334	13	StreamRiver	436.7	17.4	6.123	13	0.95
641	Crist	1278	SI	450574	Clear Creek	174	88	ArtificialPath	438.2	1.3	1.737	15	0.63
641	Crist	1279	SI	450574	Clear Creek	115	100	ArtificialPath	438.2	1.3	1.737	15	0.63

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
130	Cross	284	SI	9644979	Lake Moultrie	1469	100	ArtificialPath	178.4	38.6	5.022	60	0.85
130	Cross	285	SI	9644979	Lake Moultrie	1060	100	ArtificialPath	178.4	38.6	5.022	60	0.85
130	Cross	286	SI	9644979	Lake Moultrie	1748	88	ArtificialPath	178.4	38.6	5.022	60	0.85
130	Cross	286	SI	9644981	Lake Moultrie	121	13	LakePond	179	0.0	0.033	60	0.83
130	Cross	827	LF	9644979	Lake Moultrie	1973	75	ArtificialPath	178.4	38.6	5.022	60	0.85
130	Cross	827	LF	9644981	Lake Moultrie	2818	25	LakePond	179	0.0	0.033	60	0.83
130	Cross	828	LF	9644979				ArtificialPath	178.4	38.6	5.022	60	0.85
130	Cross	829	LF	9644979				ArtificialPath	178.4	38.6	5.022	60	0.85
130	Cross	830	LF	9644979				ArtificialPath	178.4	38.6	5.022	60	0.85
628	Crystal River Power Plant	831	LF	16928218	Gulf of Mexico	1250	100	Coastline	121.6	5.9	1.024		
3399	Cumberland	125	SI	11884358				StreamRiver	191.3	2.0	1.81	80	0.87
3399	Cumberland	126	SI	11884358				StreamRiver	191.3	2.0	1.81	80	0.87
3399	Cumberland	127	SI	11884358				StreamRiver	191.3	2.0	1.81	80	0.87
3399	Cumberland	978	LF	11884358				StreamRiver	191.3	2.0	1.81	80	0.87
6823	D B Wilson	832	LF	11629499		1360	75	StreamRiver	105.9	11.5	4.61	6.3	0.75
6823	D B Wilson	832	LF	11629523		1134	13	StreamRiver	106	2.0	2.606	1.1	0.71
6823	D B Wilson	832	LF	11629529		765	13	StreamRiver	106	2.0	1.524	1.1	0.64
6823	D B Wilson	845	LF	11629499		1553	50	StreamRiver	105.9	11.5	4.61	6.3	0.75
6823	D B Wilson	845	LF	11629523		238	50	StreamRiver	106	2.0	2.606	1.1	0.71
1702	D.E. Karn	570	SI	12928873				Coastline	72	2.0	4.496		
1702	D.E. Karn	571	SI	12928873	Saginaw Bay	106	100	Coastline	72	2.0	4.496		
1702	D.E. Karn	1004	LF	12928873				Coastline	72	2.0	4.496		
1385	Dale Station	558	SI	1827714	Kentucky River	18	100	ArtificialPath	122.8	4.0	1.478	5,597	2.0
1385	Dale Station	559	SI	1827730	Kentucky River	14	100	ArtificialPath	123	5.2	3.322	5,508	1.8
1385	Dale Station	560	SI	1827714	Kentucky River	78	100	ArtificialPath	122.8	4.0	1.478	5,597	2.0
963	Dallman	399	SI	13564568	Sugar Creek	81	63	StreamRiver	63	0.5	0.954	183	1.4
963	Dallman	399	SI	13564578	Sugar Creek	44	38	StreamRiver	63	1.3	1.05	180	1.5
963	Dallman	823	LF	13564568	Sugar Creek	268	50	StreamRiver	63	0.5	0.954	183	1.4
963	Dallman	823	LF	13564576		245	38	StreamRiver	63	2.4	2.435	0.62	0.68
963	Dallman	823	LF	13564578	Sugar Creek	335	13	StreamRiver	63	1.3	1.05	180	1.5
963	Dallman	834	LF	13564568	Sugar Creek	35	75	StreamRiver	63	0.5	0.954	183	1.4
963	Dallman	834	LF	13564576		215	25	StreamRiver	63	2.4	2.435	0.62	0.68
2723	Dan River	677	SI	8677721	Dan River	2	100	ArtificialPath	170.5	8.4	1.912	2,001	1.6
2723	Dan River	678	SI	8677721	Dan River	1	100	ArtificialPath	170.5	8.4	1.912	2,001	1.6
2723	Dan River	679	SI	8677721	Dan River	20	100	ArtificialPath	170.5	8.4	1.912	2,001	1.6
2480	Danskammer Generating Station	1140	LF	6212808	Hudson River	300	100	ArtificialPath	273.4	7.2	2.609	22,244	2.6
4158	Dave Johnston Plant	4	SI	22109291	Sand Creek	749	100	StreamRiver	9	15.4	8.207	2.9	1.1

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
4158	Dave Johnston Plant	5	SI	22109291	Sand Creek	619	75	StreamRiver	9	15.4	8.207	2.9	1.1
4158	Dave Johnston Plant	5	SI	22109491	North Platte River	626	25	LakePond	10	1.9	1.315	6,033	2.1
4158	Dave Johnston Plant	6	SI	22109291	Sand Creek	619	75	StreamRiver	9	15.4	8.207	2.9	1.1
4158	Dave Johnston Plant	6	SI	22109491	North Platte River	626	25	LakePond	10	1.9	1.315	6,033	2.1
4158	Dave Johnston Plant	7	SI	22109291	Sand Creek	651	75	StreamRiver	9	15.4	8.207	2.9	1.1
4158	Dave Johnston Plant	7	SI	22109491	North Platte River	655	25	LakePond	10	1.9	1.315	6,033	2.1
4158	Dave Johnston Plant	8	SI	22109291	Sand Creek	692	100	StreamRiver	9	15.4	8.207	2.9	1.1
4158	Dave Johnston Plant	9	SI	22109291	Sand Creek	734	100	StreamRiver	9	15.4	8.207	2.9	1.1
4158	Dave Johnston Plant	10	SI	22109291	Sand Creek	651	75	StreamRiver	9	15.4	8.207	2.9	1.1
4158	Dave Johnston Plant	10	SI	22109491	North Platte River	655	25	LakePond	10	1.9	1.315	6,033	2.1
4158	Dave Johnston Plant	11	SI	22109291	Sand Creek	734	100	StreamRiver	9	15.4	8.207	2.9	1.1
4158	Dave Johnston Plant	837	LF	22109291	Sand Creek	307	25	StreamRiver	9	15.4	8.207	2.9	1.1
4158	Dave Johnston Plant	837	LF	22109475	North Platte River	558	75	ArtificialPath	9.6	32.3	6.533	6,045	2.9
996	Dean H Mitchell	440	SI	3398598				Coastline	117.6	15.7	20.517		
996	Dean H Mitchell	441	SI	3398598				Coastline	117.6	15.7	20.517		
996	Dean H Mitchell	442	SI	3398598		107	100	Coastline	117.6	15.7	20.517		
996	Dean H Mitchell	443	SI	3398598		92	100	Coastline	117.6	15.7	20.517		
996	Dean H Mitchell	444	SI	3398598		112	100	Coastline	117.6	15.7	20.517		
996	Dean H Mitchell	445	SI	3398598		99	100	Coastline	117.6	15.7	20.517		
996	Dean H Mitchell	446	SI	3398598		598	100	Coastline	117.6	15.7	20.517		
996	Dean H Mitchell	447	SI	3398598		61	100	Coastline	117.6	15.7	20.517		
663	Deerhaven Generating Station	1141	LF	2161584		2491	13	StreamRiver	115.1	16.3	6.467	5.2	0.85
663	Deerhaven Generating Station	1141	LF	2161594		629	38	StreamRiver	114.7	2.8	2.264	0.88	0.73
663	Deerhaven Generating Station	1141	LF	2161866	Turkey Creek	1912	50	StreamRiver	106	15.9	5.544	5.1	0.87
663	Deerhaven Generating Station	1331	SI	2161866	Turkey Creek	2453	100	StreamRiver	106	15.9	5.544	5.1	0.87
1572	Dickerson	839	LF	4505898		209	80	StreamRiver	163	2.6	0.971	2.7	0.88
1572	Dickerson	839	LF	4505932		122	20	StreamRiver	166.5	3.0	2.229	1.2	0.81
51	Dolet Hills	263	SI	8342665	Mundy Bayou	2190	100	StreamRiver	48	27.2	10.148	12	0.93
51	Dolet Hills	264	SI	8342665	Mundy Bayou	1951	100	StreamRiver	48	27.2	10.148	12	0.93
51	Dolet Hills	265	SI	8342665	Mundy Bayou	1027	100	StreamRiver	48	27.2	10.148	12	0.93

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
51	Dolet Hills	266	SI	8342665	Mundy Bayou	1801	100	StreamRiver	48	27.2	10.148	12	0.93
51	Dolet Hills	267	SI	8342665	Mundy Bayou	1417	100	StreamRiver	48	27.2	10.148	12	0.93
51	Dolet Hills	268	SI	8342665	Mundy Bayou	1489	100	StreamRiver	48	27.2	10.148	12	0.93
51	Dolet Hills	269	SI	8342665	Mundy Bayou	1182	100	StreamRiver	48	27.2	10.148	12	0.93
51	Dolet Hills	840	LF	8342665	Mundy Bayou	2512	63	StreamRiver	48	27.2	10.148	12	0.93
51	Dolet Hills	840	LF	8342675	Fraigeson Creek	554	38	StreamRiver	42	5.3	2.804	1.5	0.80
3317	Dolphus M Grainger	115	SI	9071958	Waccamaw River	123	100	ArtificialPath	163.9	4.8	2.786	1,536	1.6
3317	Dolphus M Grainger	116	SI	9071944		357	20	LakePond	163.6	2.9	1.535	1.2	0.41
3317	Dolphus M Grainger	116	SI	9071958	Waccamaw River	9	80	ArtificialPath	163.9	4.8	2.786	1,536	1.6
1046	Dubuque	476	SI	13357548				ArtificialPath	124	3.9	0.97	44,809	3.1
6016	Duck Creek	18	SI	13606866				LakePond	89.6	34.2	2.847	8.9	0.99
6016	Duck Creek	19	SI	13606866				LakePond	89.6	34.2	2.847	8.9	0.99
6016	Duck Creek	20	SI	13606866				LakePond	89.6	34.2	2.847	8.9	0.99
6016	Duck Creek	842	LF	13606302		1264	50	LakePond	88	0.3	0.33	0.073	0.26
6016	Duck Creek	842	LF	13606412	Buckheart Creek	49	50	StreamRiver	91.7	7.3	2.505	3.8	0.87
2554	Dunkirk Generating Plant	646	SI	9840316				Coastline	212	0.7	2.17		
2554	Dunkirk Generating Plant	647	SI	9840316				Coastline	212	0.7	2.17		
2554	Dunkirk Generating Plant	648	SI	9840316				Coastline	212	0.7	2.17		
2554	Dunkirk Generating Plant	843	LF	9840306	Erie, Lake	1087	100	Coastline	213.9	3.2	0.374		
26	E. C. Gaston	257	SI	22273418				LakePond	198.9	1.8	1.645	15,076	2.4
1355	E.W. Brown	524	SI	1827810	Herrington Lake	100	100	LakePond	112.4	0.7	0.768	0.76	0.65
1355	E.W. Brown	525	SI	1827810	Herrington Lake	327	100	LakePond	112.4	0.7	0.768	0.76	0.65
991	Eagle Valley	425	SI	18477247	White River	204	50	StreamRiver	83.8	3.3	2.817	2,402	2.2
991	Eagle Valley	425	SI	18477265	White River	1296	50	StreamRiver	84.2	7.2	1.511	2,430	1.7
991	Eagle Valley	426	SI	18477247	White River	194	50	StreamRiver	83.8	3.3	2.817	2,402	2.2
991	Eagle Valley	426	SI	18477265	White River	970	50	StreamRiver	84.2	7.2	1.511	2,430	1.7
991	Eagle Valley	427	SI	18477265	White River	760	100	StreamRiver	84.2	7.2	1.511	2,430	1.7
991	Eagle Valley	428	SI	18477265	White River	848	100	StreamRiver	84.2	7.2	1.511	2,430	1.7
991	Eagle Valley	429	SI	18477247	White River	307	13	StreamRiver	83.8	3.3	2.817	2,402	2.2

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
991	Eagle Valley	429	SI	18477265	White River	1239	88	StreamRiver	84.2	7.2	1.511	2,430	1.7
1217	Earl F Wisdom	844	LF	14621206	Stony Creek	51	100	StreamRiver	51.1	36.4	11.252	8.9	1.0
6018	East Bend Station	23	SI	3407479				ArtificialPath	57.5	10.1	3.572	112,068	3.7
6018	East Bend Station	24	SI	3407479	Ohio River	7	100	ArtificialPath	57.5	10.1	3.572	112,068	3.7
6018	East Bend Station	25	SI	3407479				ArtificialPath	57.5	10.1	3.572	112,068	3.7
6018	East Bend Station	879	LF	3407135	Lick Creek	318	38	StreamRiver	61.8	14.6	7.033	6.3	0.93
6018	East Bend Station	879	LF	3407479	Ohio River	961	63	ArtificialPath	57.5	10.1	3.572	112,068	3.7
2837	Eastlake	914	LF	28123876				Coastline	132.4	19.4	7.628		
2837	Eastlake	1262	SI	28123876		40	100	Coastline	132.4	19.4	7.628		
856	ED Edwards	376	SI	13605656				StreamRiver	75.2	2.3	1.028	0.57	0.37
856	ED Edwards	377	SI	13605656		27	88	StreamRiver	75.2	2.3	1.028	0.57	0.37
856	ED Edwards	377	SI	13606204	Illinois River	280	13	ArtificialPath	74.4	3.0	4.616	10,239	2.3
856	ED Edwards	378	SI	13605656		52	75	StreamRiver	75.2	2.3	1.028	0.57	0.37
856	ED Edwards	378	SI	13606204	Illinois River	325	25	ArtificialPath	74.4	3.0	4.616	10,239	2.3
4050	Edgewater	164	SI	12175600		419	100	StreamRiver	104.6	4.1	2.588	2.3	0.78
4050	Edgewater	165	SI	12175600		361	88	StreamRiver	104.6	4.1	2.588	2.3	0.78
4050	Edgewater	165	SI	12176006		627	13	Coastline	105	2.8	4.96		
4050	Edgewater	166	SI	12175600		958	100	StreamRiver	104.6	4.1	2.588	2.3	0.78
4050	Edgewater	167	SI	12176006		23	100	Coastline	105	2.8	4.96		
4050	Edgewater	168	SI	12175600		290	100	StreamRiver	104.6	4.1	2.588	2.3	0.78
4050	Edgewater	169	SI	12176006		4	100	Coastline	105	2.8	4.96		
4050	Edgewater	858	LF	12175618	Weedons Creek	918	50	StreamRiver	101.9	3.7	2.175	4.7	0.84
4050	Edgewater	858	LF	12175636	Weedons Creek	1121	50	StreamRiver	102	2.8	1.45	0.70	0.56
4050	Edgewater	894	LF	12175600		41	100	StreamRiver	104.6	4.1	2.588	2.3	0.78
1004	Edwardsport	458	SI	18471000	White River	131	100	ArtificialPath	93	16.8	9.517	5,153	1.7
1004	Edwardsport	459	SI	18471000	White River	83	100	ArtificialPath	93	16.8	9.517	5,153	1.7
1004	Edwardsport	971	LF	18471000				ArtificialPath	93	16.8	9.517	5,153	1.7
1374	Elmer Smith Station	1234	SI	10110377	Ohio River	2	100	ArtificialPath	103.3	22.8	9.88	131,885	3.8
1374	Elmer Smith Station	1235	SI	10110377	Ohio River	86	100	ArtificialPath	103.3	22.8	9.88	131,885	3.8
1374	Elmer Smith Station	1236	SI	10110377	Ohio River	381	100	ArtificialPath	103.3	22.8	9.88	131,885	3.8
1374	Elmer Smith Station	1237	SI	10110377	Ohio River	100	100	ArtificialPath	103.3	22.8	9.88	131,885	3.8
3098	Elrama Power Plant	895	LF	3785889	Monongahela River	140	88	ArtificialPath	153	1.4	0.943	10,419	2.2
3098	Elrama Power Plant	895	LF	3785893	Monongahela River	286	13	ArtificialPath	152.3	4.4	1.815	10,410	2.2
3098	Elrama Power Plant	1342	SI	3785905	Monongahela River	321	100	ArtificialPath	149.5	3.2	1.277	10,394	2.8

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
3098	Elrama Power Plant	1343	SI	3785905	Monongahela River	376	100	ArtificialPath	149.5	3.2	1.277	10,394	2.8
3098	Elrama Power Plant	1344	SI	3785905	Monongahela River	491	100	ArtificialPath	149.5	3.2	1.277	10,394	2.8
3098	Elrama Power Plant	1345	SI	3785905	Monongahela River	558	100	ArtificialPath	149.5	3.2	1.277	10,394	2.8
1832	Erickson Station	587	SI	12241814		499	100	StreamRiver	108	7.5	3.232	1.6	0.75
87	Escalante	274	SI	17771165				StreamRiver	9	10.0	6.024	0.19	0.80
87	Escalante	275	SI	17771165				StreamRiver	9	10.0	6.024	0.19	0.80
87	Escalante	276	SI	17771165				StreamRiver	9	10.0	6.024	0.19	0.80
87	Escalante	277	SI	17771165				StreamRiver	9	10.0	6.024	0.19	0.80
87	Escalante	278	SI	17771165				StreamRiver	9	10.0	6.024	0.19	0.80
87	Escalante	992	LF	17771165				StreamRiver	9	10.0	6.024	0.19	0.80
1012	F. B. Culley	466	SI	10110339	Ohio River	3	100	ArtificialPath	89	11.0	4.03	132,544	2.2
1012	F. B. Culley	467	SI	10110269		10	63	StreamRiver	97.3	9.2	7.937	559	1.3
1012	F. B. Culley	467	SI	10110337		60	38	ArtificialPath	92.6	0.3	0.554	559	1.3
1218	Fair Station	896	LF	14805213	Pine Creek	21	100	StreamRiver	79	6.9	4.51	25	1.1
1218	Fair Station	1183	SI	14805943	Mississippi River	119	100	ArtificialPath	79	0.5	0.711	54,904	3.2
1218	Fair Station	1184	SI	14805943	Mississippi River	125	100	ArtificialPath	79	0.5	0.711	54,904	3.2
6179	Fayette Power Project	183	SI	5791766	Cedar Creek	827	100	StreamRiver	15.8	35.8	10.694	4.5	0.91
6179	Fayette Power Project	184	SI	5791766	Cedar Creek	99	100	StreamRiver	15.8	35.8	10.694	4.5	0.91
6179	Fayette Power Project	897	LF	5791766				StreamRiver	15.8	35.8	10.694	4.5	0.91
886	Fisk	1238	SI	14789961	Chicago Sanitary And Ship Canal	9	100	ArtificialPath	112	25.6	5.83	165	1.0
886	Fisk	1239	SI	14789961	Chicago Sanitary And Ship Canal	1	100	ArtificialPath	112	25.6	5.83	165	1.0
886	Fisk	1240	SI	14789961	Chicago Sanitary And Ship Canal	9	100	ArtificialPath	112	25.6	5.83	165	1.0
6138	Flint Creek	173	SI	399464				StreamRiver	137	4.8	4.08	1.3	0.77
6138	Flint Creek	174	SI	399464				StreamRiver	137	4.8	4.08	1.3	0.77
6138	Flint Creek	898	LF	399464		50	100	StreamRiver	137	4.8	4.08	1.3	0.77
3943	Fort Martin Power Station	1142	LF	3768484		260	50	StreamRiver	160.4	3.3	3.197	2.5	0.83

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
3943	Fort Martin Power Station	1142	LF	3768832	Monongahela River	654	50	ArtificialPath	162.6	7.5	4.138	5,343	1.1
3943	Fort Martin Power Station	1143	LF	3768476	Crooked Run	90	100	StreamRiver	159.7	2.3	1.753	5.6	0.70
3943	Fort Martin Power Station	1181	SI	3768832	Monongahela River	35	100	ArtificialPath	162.6	7.5	4.138	5,343	1.1
3943	Fort Martin Power Station	1182	SI	3768832	Monongahela River	35	100	ArtificialPath	162.6	7.5	4.138	5,343	1.1
10343	Foster Wheeler Mt Carmel Cogen	901	LF	4517604				StreamRiver	267.2	30.8	7.184	20	1.1
2442	Four Corners	638	SI	16967534	Chaco River	661	100	StreamRiver	11	4.0	1.933	295	2.2
2442	Four Corners	639	SI	16967534	Chaco River	1142	100	StreamRiver	11	4.0	1.933	295	2.2
2442	Four Corners	640	SI	16968628				StreamRiver	11	22.1	0.57	0.36	0.80
2442	Four Corners	641	SI	16968628				StreamRiver	11	22.1	0.57	0.36	0.80
2442	Four Corners	642	SI	16968628				StreamRiver	11	22.1	0.57	0.36	0.80
2442	Four Corners	903	LF	16967534	Chaco River	1565	63	StreamRiver	11	4.0	1.933	295	2.2
2442	Four Corners	903	LF	16968630		76	38	StreamRiver	11	1.4	2.403	0.022	0.64
2442	Four Corners	915	LF	16967534	Chaco River	1139	100	StreamRiver	11	4.0	1.933	295	2.2
1043	Frank E. Ratts	468	SI	18472136				ArtificialPath	96.4	7.0	2.717	12,422	2.4
1043	Frank E. Ratts	469	SI	18472136	White River	228	100	ArtificialPath	96.4	7.0	2.717	12,422	2.4
1043	Frank E. Ratts	470	SI	18472136	White River	360	100	ArtificialPath	96.4	7.0	2.717	12,422	2.4
1043	Frank E. Ratts	471	SI	18472136				ArtificialPath	96.4	7.0	2.717	12,422	2.4
1043	Frank E. Ratts	472	SI	18472136	White River	237	100	ArtificialPath	96.4	7.0	2.717	12,422	2.4
1043	Frank E. Ratts	473	SI	18472136				ArtificialPath	96.4	7.0	2.717	12,422	2.4
1043	Frank E. Ratts	474	SI	18472136				ArtificialPath	96.4	7.0	2.717	12,422	2.4
1043	Frank E. Ratts	475	SI	18472136	White River	381	100	ArtificialPath	96.4	7.0	2.717	12,422	2.4
2718	G G Allen	668	SI	9756896	Catawba River	223	100	LakePond	123.8	12.9	5.276	3,884	1.8
2718	G G Allen	669	SI	9756896	Catawba River	18	100	LakePond	123.8	12.9	5.276	3,884	1.8
2718	G G Allen	670	SI	9756896	Catawba River	84	100	LakePond	123.8	12.9	5.276	3,884	1.8
2718	G G Allen	892	LF	9756896	Catawba River	163	100	LakePond	123.8	12.9	5.276	3,884	1.8
7	Gadsden	253	SI	22199835				ArtificialPath	246	2.7	3.254	10,374	2.3
3403	Gallatin	128	SI	18415917				LakePond	137.8	42.5	11.478	18,812	2.5
3403	Gallatin	129	SI	18415917				LakePond	137.8	42.5	11.478	18,812	2.5
3403	Gallatin	130	SI	18415917				LakePond	137.8	42.5	11.478	18,812	2.5
8102	General James M. Gavin	246	SI	19443209		155	25	StreamRiver	103	1.3	1.26	0.53	0.72
8102	General James M. Gavin	246	SI	19443217		187	25	StreamRiver	103	0.4	0.708	0.71	0.67

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
8102	General James M. Gavin	246	SI	19443421	Stingy Run	96	50	StreamRiver	103	0.9	1.959	1.9	0.73
8102	General James M. Gavin	247	SI	19443293	Kyger Creek	460	63	StreamRiver	106.4	6.1	3.804	26	0.90
8102	General James M. Gavin	247	SI	19443465	Ohio River	553	13	ArtificialPath	106.9	3.9	3.277	59,443	3.2
8102	General James M. Gavin	247	SI	19443471	Ohio River	139	25	ArtificialPath	107.9	6.3	3.367	59,450	3.2
8102	General James M. Gavin	1144	LF	19443209		637	40	StreamRiver	103	1.3	1.26	0.53	0.72
8102	General James M. Gavin	1144	LF	19443249	Turkey Run	696	60	StreamRiver	104.3	4.3	3.652	1.8	0.83
4143	Genoa	1007	LF	13208374				ArtificialPath	145.4	1.9	2.556	32,842	2.9
4143	Genoa	1131	LF	13208374				ArtificialPath	145.4	1.9	2.556	32,842	2.9
1091	George Neal North	504	SI	17244416				ArtificialPath	28.5	31.9	6.467	46,038	3.5
1091	George Neal North	505	SI	17244416				ArtificialPath	28.5	31.9	6.467	46,038	3.5
1091	George Neal North	506	SI	17244416				ArtificialPath	28.5	31.9	6.467	46,038	3.5
1091	George Neal North	906	LF	17244030		1893	38	StreamRiver	30.5	34.3	1.424	0.13	0.31
1091	George Neal North	906	LF	17244416	Missouri River	8	63	ArtificialPath	28.5	31.9	6.467	46,038	3.5
1091	George Neal North	907	LF	17244416				ArtificialPath	28.5	31.9	6.467	46,038	3.5
1091	George Neal North	908	LF	17244416				ArtificialPath	28.5	31.9	6.467	46,038	3.5
1091	George Neal North	909	LF	17244416	Missouri River	15	100	ArtificialPath	28.5	31.9	6.467	46,038	3.5
1091	George Neal North	910	LF	17244416	Missouri River	343	100	ArtificialPath	28.5	31.9	6.467	46,038	3.5
7343	George Neal South	911	LF	17244030		221	100	StreamRiver	30.5	34.3	1.424	0.13	0.31
7343	George Neal South	1332	SI	17244416	Missouri River	659	100	ArtificialPath	28.5	31.9	6.467	46,038	3.5
6077	Gerald Gentleman	912	LF	17432276		39	100	StreamRiver	14.5	160.9	5.16	1.4	0.46
1356	Ghent	526	SI	3408285				ArtificialPath	56	4.1	2.236	112,376	3.7
1356	Ghent	527	SI	3408285	Ohio River	165	100	ArtificialPath	56	4.1	2.236	112,376	3.7
1356	Ghent	528	SI	3408281	Ohio River	7	29	ArtificialPath	56	0.1	0.212	112,374	4.1
1356	Ghent	528	SI	3408285	Ohio River	51	71	ArtificialPath	56	4.1	2.236	112,376	3.7
1356	Ghent	529	SI	3408201	Black Creek	824	100	StreamRiver	56	7.0	3.389	2.7	0.92
1356	Ghent	530	SI	3408285				ArtificialPath	56	4.1	2.236	112,376	3.7
6136	Gibbons Creek Steam Electric Station	881	LF	5577597	Plum Creek	1260	50	StreamRiver	19.9	12.1	8.059	2.4	0.78
6136	Gibbons Creek Steam Electric Station	881	LF	5577627	Hog Creek	830	50	StreamRiver	18.7	9.3	5.079	6.9	0.73
6136	Gibbons Creek Steam Electric Station	913	LF	5577621		171	13	StreamRiver	19.1	2.8	2.038	0.55	0.70

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
6136	Gibbons Creek Steam Electric Station	913	LF	5577627	Hog Creek	423	88	StreamRiver	18.7	9.3	5.079	6.9	0.73
6136	Gibbons Creek Steam Electric Station	1241	SI	5577643	Gibbons Creek	740	100	StreamRiver	18.6	1.8	1.182	30	1.2
6136	Gibbons Creek Steam Electric Station	1242	SI	5577643	Gibbons Creek	740	100	StreamRiver	18.6	1.8	1.182	30	1.2
6136	Gibbons Creek Steam Electric Station	1243	SI	5577643	Gibbons Creek	740	100	StreamRiver	18.6	1.8	1.182	30	1.2
6136	Gibbons Creek Steam Electric Station	1244	SI	5577653	Big Branch	303	75	StreamRiver	19.5	4.0	2.998	1.0	0.72
6136	Gibbons Creek Steam Electric Station	1244	SI	5578305	Carlos Lake	445	25	LakePond	20	0.7	0.326	1.2	0.41
6113	Gibson	81	SI	10381539		569	100	StreamRiver	73.9	15.2	5.831	4.7	0.61
6113	Gibson	82	SI	10381539		290	100	StreamRiver	73.9	15.2	5.831	4.7	0.61
6113	Gibson	83	SI	10381539		20	100	StreamRiver	73.9	15.2	5.831	4.7	0.61
6113	Gibson	84	SI	10381539		2449	100	StreamRiver	73.9	15.2	5.831	4.7	0.61
6113	Gibson	85	SI	10381539		220	100	StreamRiver	73.9	15.2	5.831	4.7	0.61
6113	Gibson	86	SI	10382059	Wabash River	255	100	ArtificialPath	71.8	2.9	3.354	28,710	2.2
6113	Gibson	902	LF	10381975		40	40	CanalDitch	69.6	6.5	5.035	2.0	0.61
6113	Gibson	902	LF	10381977	Coffee Bayou	193	60	StreamRiver	70.5	21.6	9.114	45	1.0
6113	Gibson	904	LF	10381539		109	100	StreamRiver	73.9	15.2	5.831	4.7	0.61
3776	Glen Lyn	146	SI	6908685	New River	61	100	ArtificialPath	169	3.0	2.602	5,294	2.3
3776	Glen Lyn	147	SI	6907783	East River	113	38	StreamRiver	172.5	9.8	5.516	97	1.4
3776	Glen Lyn	147	SI	6908699	New River	39	63	ArtificialPath	170.8	3.8	0.827	5,186	2.0
3776	Glen Lyn	870	LF	6908685	New River	59	100	ArtificialPath	169	3.0	2.602	5,294	2.3
8	Gorgas	254	SI	18592152	Mulberry Fork	681	100	LakePond	231.3	12.2	10.193	3,543	1.8
8	Gorgas	255	SI	18592136	Mulberry Fork	86	50	LakePond	235.3	0.5	1.123	3,510	1.8
8	Gorgas	255	SI	18592152	Mulberry Fork	661	50	LakePond	231.3	12.2	10.193	3,543	1.8
8	Gorgas	963	LF	18591860				StreamRiver	231.6	5.3	3.953	25	0.83
1825	Grand Haven City of J.B. Sims	1309	SI	9005799	Grand River	418	100	ArtificialPath	251	11.7	4.315	3,605	1.5
1825	Grand Haven City of J.B. Sims	1310	SI	9005799	Grand River	418	100	ArtificialPath	251	11.7	4.315	3,605	1.5
10151	Grant Town Power Plant	871	LF	3769488	Paw Paw Creek	63	100	StreamRiver	142.2	6.1	3.947	59	1.2
10151	Grant Town Power Plant	872	LF	3769696	Moody Run	259	29	StreamRiver	141.2	0.9	1.297	2.8	0.85
10151	Grant Town Power Plant	872	LF	3771470	Buffalo Creek	41	57	StreamRiver	140.3	0.6	0.827	227	1.1

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
10151	Grant Town Power Plant	872	LF	3771476	Buffalo Creek	339	14	Connector	141	0.0	0.067	227	1.1
10151	Grant Town Power Plant	873	LF	3769768	Buffalo Creek	391	100	StreamRiver	142.1	7.3	3.549	195	1.0
10151	Grant Town Power Plant	1167	SI	3769488	Paw Paw Creek	751	100	StreamRiver	142.2	6.1	3.947	59	1.2
10151	Grant Town Power Plant	1168	SI	3769488	Paw Paw Creek	567	100	StreamRiver	142.2	6.1	3.947	59	1.2
10151	Grant Town Power Plant	1169	SI	3769488	Paw Paw Creek	779	100	StreamRiver	142.2	6.1	3.947	59	1.2
10151	Grant Town Power Plant	1170	SI	3769488	Paw Paw Creek	1148	100	StreamRiver	142.2	6.1	3.947	59	1.2
10151	Grant Town Power Plant	1171	SI	3769488	Paw Paw Creek	1044	100	StreamRiver	142.2	6.1	3.947	59	1.2
165	GRDA	874	LF	21773139	Chouteau Creek	1381	100	ArtificialPath	40	22.4	6.481	64	0.81
165	GRDA	1210	SI	21773139	Chouteau Creek	1575	100	ArtificialPath	40	22.4	6.481	64	0.81
1357	Green River	531	SI	11629601		555	13	StreamRiver	100	1.1	1.646	0.61	0.71
1357	Green River	531	SI	11630665	Green River	450	88	ArtificialPath	100	2.7	2.491	9,266	2.2
1357	Green River	532	SI	11630665	Green River	66	100	ArtificialPath	100	2.7	2.491	9,266	2.2
1357	Green River	533	SI	11630665	Green River	176	100	ArtificialPath	100	2.7	2.491	9,266	2.2
1357	Green River	534	SI	11630375		177	63	StreamRiver	143	2.0	1.789	1.9	0.83
1357	Green River	534	SI	11630393		208	38	StreamRiver	145.8	1.4	1.51	0.78	0.74
1357	Green River	535	SI	11629611		106	38	StreamRiver	100	0.5	0.829	1.1	0.65
1357	Green River	535	SI	11630665	Green River	143	63	ArtificialPath	100	2.7	2.491	9,266	2.2
10	Greene County	256	SI	18211194				LakePond	140.8	9.4	4.374	10,380	2.3
6041	H L Spurlock Station	34	SI	1922018	Ohio River	89	100	ArtificialPath	68	7.0	4.62	98,763	3.6
6041	H L Spurlock Station	972	LF	1922018				ArtificialPath	68	7.0	4.62	98,763	3.6
2709	H.F. Lee Plant	656	SI	8790567	Halfmile Branch	30	57	StreamRiver	158.4	8.3	2.364	4.2	0.80
2709	H.F. Lee Plant	656	SI	11239877	Neuse River	115	43	StreamRiver	159.7	1.9	1.63	2,009	1.8
2709	H.F. Lee Plant	657	SI	8790567	Halfmile Branch	60	43	StreamRiver	158.4	8.3	2.364	4.2	0.80
2709	H.F. Lee Plant	657	SI	11239863	Neuse River	93	57	StreamRiver	159.4	0.8	0.994	2,014	1.7
2709	H.F. Lee Plant	658	SI	8790567	Halfmile Branch	21	86	StreamRiver	158.4	8.3	2.364	4.2	0.80
2709	H.F. Lee Plant	658	SI	11239863	Neuse River	757	14	StreamRiver	159.4	0.8	0.994	2,014	1.7
2709	H.F. Lee Plant	659	SI	11239873		1217	33	StreamRiver	157.2	1.8	1.708	0.68	0.51

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
2709	H.F. Lee Plant	659	SI	11239875	Neuse River	56	67	StreamRiver	157.3	6.2	7.423	2,032	1.3
2709	H.F. Lee Plant	660	SI	11239875				StreamRiver	157.3	6.2	7.423	2,032	1.3
708	Hammond	351	SI	15821397				StreamRiver	244.9	1.0	0.739	26	0.83
708	Hammond	352	SI	15821397				StreamRiver	244.9	1.0	0.739	26	0.83
708	Hammond	353	SI	15821397				StreamRiver	244.9	1.0	0.739	26	0.83
708	Hammond	354	SI	15821397				StreamRiver	244.9	1.0	0.739	26	0.83
708	Hammond	1145	LF	15821107	Smith Creek	117	50	StreamRiver	252.7	1.5	1.406	1.5	0.73
708	Hammond	1145	LF	15821109		19	50	StreamRiver	256.6	1.9	3.311	1.2	0.85
1731	Harbor Beach Power Plant	581	SI	12919103				Coastline	67	0.4	1.427		
990	Harding Street	420	SI	18476899	White River	104	100	ArtificialPath	76.5	20.4	4.325	1,869	1.9
990	Harding Street	421	SI	18476899	White River	590	100	ArtificialPath	76.5	20.4	4.325	1,869	1.9
990	Harding Street	422	SI	18476493		161	88	StreamRiver	80.2	18.9	10.144	22	1.0
990	Harding Street	422	SI	18476899	White River	429	13	ArtificialPath	76.5	20.4	4.325	1,869	1.9
990	Harding Street	423	SI	18476493		13	100	StreamRiver	80.2	18.9	10.144	22	1.0
990	Harding Street	424	SI	18476493		29	100	StreamRiver	80.2	18.9	10.144	22	1.0
709	Harllee Branch	355	SI	1056813		160	33	StreamRiver	174.9	1.2	1.657	0.59	0.67
709	Harllee Branch	355	SI	1056825	Beaverdam Creek	384	33	StreamRiver	174	0.6	0.783	3.3	0.78
709	Harllee Branch	355	SI	1056829		21	33	StreamRiver	174.2	3.1	1.497	2.1	0.77
709	Harllee Branch	356	SI	1057729				LakePond	170.2	2.7	2.464	921	1.4
709	Harllee Branch	357	SI	1057729	Little River	256	50	LakePond	170.2	2.7	2.464	921	1.4
709	Harllee Branch	357	SI	1057741	Little River	231	50	LakePond	173.1	10.7	3.682	918	0.96
709	Harllee Branch	358	SI	1057741	Little River	41	100	LakePond	173.1	10.7	3.682	918	0.96
709	Harllee Branch	359	SI	1057741	Little River	5	100	LakePond	173.1	10.7	3.682	918	0.96
6193	Harrington	877	LF	19983982		238	100	StreamRiver	5	39.4	5.199	0.49	0.91
6193	Harrington	878	LF	19983982		23	100	StreamRiver	5	39.4	5.199	0.49	0.91
3944	Harrison Power Station	158	SI	3715706				StreamRiver	140.4	2.3	2.527	1,431	2.1
3944	Harrison Power Station	891	LF	3715680	Robinson Run	378	100	StreamRiver	139.9	11.4	6.605	9.7	0.98
3179	Hatfield's Ferry Power Station	880	LF	3787587	Little Whiteley Creek	638	100	StreamRiver	150.3	7.6	3.892	14	1.1
3179	Hatfield's Ferry Power Station	1215	SI	3787587	Little Whiteley Creek	49	100	StreamRiver	150.3	7.6	3.892	14	1.1
3179	Hatfield's Ferry Power Station	1216	SI	3787587	Little Whiteley Creek	25	100	StreamRiver	150.3	7.6	3.892	14	1.1
3179	Hatfield's Ferry Power Station	1217	SI	3787587	Little Whiteley Creek	43	100	StreamRiver	150.3	7.6	3.892	14	1.1
3179	Hatfield's Ferry Power Station	1218	SI	3787587	Little Whiteley Creek	58	100	StreamRiver	150.3	7.6	3.892	14	1.1

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
3179	Hatfield's Ferry Power Station	1219	SI	3787587	Little Whiteley Creek	34	100	StreamRiver	150.3	7.6	3.892	14	1.1
891	Havana	392	SI	13608610	Illinois River	271	100	ArtificialPath	98.7	8.7	5.527	12,540	2.4
891	Havana	393	SI	13608610	Illinois River	349	100	ArtificialPath	98.7	8.7	5.527	12,540	2.4
2079	Hawthorn	599	SI	4391195				StreamRiver	47	45.7	9.406	82	1.1
2079	Hawthorn	962	LF	4391195				StreamRiver	47	45.7	9.406	82	1.1
525	Hayden	332	SI	120299630				StreamRiver	24.7	4.3	4.247	0.23	0.33
525	Hayden	333	SI	120299630				StreamRiver	24.7	4.3	4.247	0.23	0.33
525	Hayden	334	SI	120299630				StreamRiver	24.7	4.3	4.247	0.23	0.33
525	Hayden	335	SI	120299630				StreamRiver	24.7	4.3	4.247	0.23	0.33
525	Hayden	336	SI	120299630				StreamRiver	24.7	4.3	4.247	0.23	0.33
525	Hayden	337	SI	120299630				StreamRiver	24.7	4.3	4.247	0.23	0.33
525	Hayden	882	LF	1355212	Grassy Creek	680	100	StreamRiver	29.4	4.4	0.962	5.8	1.0
525	Hayden	1146	LF	120299723	Sage Creek	229	88	StreamRiver	26.4	5.1	3.487	11	1.5
525	Hayden	1146	LF	120299725	Grassy Creek	489	13	StreamRiver	27.2	3.3	3.603	8.6	1.6
3251	HB Robinson / Darlington Electric Power Plant	104	SI	9176570		149	100	StreamRiver	239.8	0.1	0.392	0.85	0.71
892	Hennepin Power Station	394	SI	14837739	Illinois River	6	50	ArtificialPath	75	5.8	5.035	9,133	2.0
892	Hennepin Power Station	394	SI	14837757	Illinois River	232	50	ArtificialPath	75	3.5	1.557	9,137	2.2
892	Hennepin Power Station	883	LF	14837739				ArtificialPath	75	5.8	5.035	9,133	2.0
1382	HMP&L Station Two Henderson	556	SI	11617207	Grane Creek	1185	100	StreamRiver	84.1	16.3	6.565	9.4	0.90
1382	HMP&L Station Two Henderson	557	SI	11617207	Grane Creek	1495	13	StreamRiver	84.1	16.3	6.565	9.4	0.90
1382	HMP&L Station Two Henderson	557	SI	11617335	Green River	171	88	ArtificialPath	83.8	11.1	6.149	12,480	2.3
1382	HMP&L Station Two Henderson	984	LF	11617207				StreamRiver	84.1	16.3	6.565	9.4	0.90
108	HOLCOMB	1147	LF	21251510		4032	100	StreamRiver	2.1	10.0	2.77	0.12	0.63
3122	Homer City Station	90	SI	4752220		537	100	StreamRiver	243.2	3.6	3.492	2.5	0.87
3122	Homer City Station	91	SI	4752280		1284	100	StreamRiver	248.1	2.6	1.512	1.8	0.87
3122	Homer City Station	92	SI	4752260		25	100	StreamRiver	242	2.7	1.332	1.8	0.82
3122	Homer City Station	719	SI	4752260		6	100	StreamRiver	242	2.7	1.332	1.8	0.82
3122	Homer City Station	720	SI	4752280		848	100	StreamRiver	248.1	2.6	1.512	1.8	0.87
3122	Homer City Station	721	SI	4752220		447	100	StreamRiver	243.2	3.6	3.492	2.5	0.87

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
3122	Homer City Station	722	SI	4752280		1428	100	StreamRiver	248.1	2.6	1.512	1.8	0.87
3122	Homer City Station	723	SI	4752280		1633	100	StreamRiver	248.1	2.6	1.512	1.8	0.87
3122	Homer City Station	724	SI	4752280		1573	100	StreamRiver	248.1	2.6	1.512	1.8	0.87
3122	Homer City Station	725	SI	4752260		15	100	StreamRiver	242	2.7	1.332	1.8	0.82
3122	Homer City Station	726	SI	4752280		1406	100	StreamRiver	248.1	2.6	1.512	1.8	0.87
3122	Homer City Station	727	SI	4752280		1276	100	StreamRiver	248.1	2.6	1.512	1.8	0.87
3122	Homer City Station	728	SI	4752220		6	100	StreamRiver	243.2	3.6	3.492	2.5	0.87
3122	Homer City Station	729	SI	4752220		22	100	StreamRiver	243.2	3.6	3.492	2.5	0.87
3122	Homer City Station	884	LF	4752220		696	13	StreamRiver	243.2	3.6	3.492	2.5	0.87
3122	Homer City Station	884	LF	4752250	Muddy Run	804	25	StreamRiver	239.5	6.2	3.004	7.9	0.93
3122	Homer City Station	884	LF	4752260		313	63	StreamRiver	242	2.7	1.332	1.8	0.82
3122	Homer City Station	886	LF	4752220		211	63	StreamRiver	243.2	3.6	3.492	2.5	0.87
3122	Homer City Station	886	LF	4752244	Cherry Run	457	38	StreamRiver	249	1.0	1.488	28	1.0
3122	Homer City Station	1134	LF	4752176		380	38	StreamRiver	238.1	4.7	3.577	3.2	0.89
3122	Homer City Station	1134	LF	4752220		209	63	StreamRiver	243.2	3.6	3.492	2.5	0.87
1943	Hoot Lake	887	LF	6657971		114	100	StreamRiver	32.1	3.6	4.426	0.34	0.63
1943	Hoot Lake	1148	LF	6657951	Otter Tail River	128	33	StreamRiver	31.9	0.2	0.523	258	2.6
1943	Hoot Lake	1148	LF	6657971		94	33	StreamRiver	32.1	3.6	4.426	0.34	0.63
1943	Hoot Lake	1148	LF	6658359	Wright Lake	109	33	LakePond	32	0.9	1.391	258	1.9
1943	Hoot Lake	1156	LF	6657971		154	63	StreamRiver	32.1	3.6	4.426	0.34	0.63
1943	Hoot Lake	1156	LF	6659311		1960	38	StreamRiver	35.5	25.2	8.409	6.8	0.58
1943	Hoot Lake	1157	LF	6657971		48	50	StreamRiver	32.1	3.6	4.426	0.34	0.63
1943	Hoot Lake	1157	LF	6658359	Wright Lake	68	50	LakePond	32	0.9	1.391	258	1.9
1943	Hoot Lake	1158	LF	6657971		22	75	StreamRiver	32.1	3.6	4.426	0.34	0.63
1943	Hoot Lake	1158	LF	6658359	Wright Lake	155	25	LakePond	32	0.9	1.391	258	1.9
1943	Hoot Lake	1159	LF	6657971		22	100	StreamRiver	32.1	3.6	4.426	0.34	0.63
1943	Hoot Lake	1160	LF	6657971		35	100	StreamRiver	32.1	3.6	4.426	0.34	0.63
10771	Hopewell	1362	SI	10067517	James River	1996	100	ArtificialPath	161.1	7.1	3.305	9,218	2.2
6772	Hugo	229	SI	592548	Bird Creek	281	100	StreamRiver	45.1	9.9	4.384	9.1	0.92
6772	Hugo	230	SI	592548	Bird Creek	319	100	StreamRiver	45.1	9.9	4.384	9.1	0.92
6772	Hugo	231	SI	592548				StreamRiver	45.1	9.9	4.384	9.1	0.92
6772	Hugo	232	SI	592548				StreamRiver	45.1	9.9	4.384	9.1	0.92
6772	Hugo	755	LF	592548	Bird Creek	1562	38	StreamRiver	45.1	9.9	4.384	9.1	0.92
6772	Hugo	755	LF	593644	Bird Creek	2191	38	StreamRiver	45	2.7	0.604	10	0.94
6772	Hugo	755	LF	593682	Kiamichi River	3132	25	StreamRiver	44.2	18.0	6.629	2,069	1.7
3176	Hunlock Power Station	102	SI	2603121	Susquehanna River	3	100	ArtificialPath	246.7	14.7	9.45	14,712	2.5
3176	Hunlock Power Station	103	SI	2603121	Susquehanna River	76	100	ArtificialPath	246.7	14.7	9.45	14,712	2.5

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
6165	Hunter Plant	756	LF	4876935		2340	13	StreamRiver	24.7	4.0	0.909	0.10	0.79
6165	Hunter Plant	756	LF	4876945		1190	25	StreamRiver	24.9	2.7	1.736	0.024	0.66
6165	Hunter Plant	756	LF	4878793		293	63	StreamRiver	22.6	8.5	3.963	0.074	0.79
6165	Hunter Plant	1258	SI	4876749		89	50	StreamRiver	35.4	5.2	4.458	0.045	0.70
6165	Hunter Plant	1258	SI	4877929		910	50	StreamRiver	34	5.1	2.612	0.095	0.74
8069	Huntington Plant	757	LF	4876411	Huntington Creek	1031	100	StreamRiver	60.6	9.3	4.198	72	1.8
8069	Huntington Plant	758	LF	4876411	Huntington Creek	1041	100	StreamRiver	60.6	9.3	4.198	72	1.8
8069	Huntington Plant	759	LF	4876411	Huntington Creek	1057	100	StreamRiver	60.6	9.3	4.198	72	1.8
8069	Huntington Plant	1363	SI	4876411	Huntington Creek	534	100	StreamRiver	60.6	9.3	4.198	72	1.8
8069	Huntington Plant	1364	SI	4876411	Huntington Creek	743	100	StreamRiver	60.6	9.3	4.198	72	1.8
863	Hutsonville	381	SI	10286344	Wabash River	19	100	ArtificialPath	76	5.5	3.144	12,016	2.4
863	Hutsonville	382	SI	10285974	Raccoon Creek	610	13	StreamRiver	75.4	20.8	6.42	36	1.0
863	Hutsonville	382	SI	10286344	Wabash River	145	88	ArtificialPath	76	5.5	3.144	12,016	2.4
863	Hutsonville	383	SI	10285974	Raccoon Creek	684	38	StreamRiver	75.4	20.8	6.42	36	1.0
863	Hutsonville	383	SI	10286344	Wabash River	310	63	ArtificialPath	76	5.5	3.144	12,016	2.4
863	Hutsonville	384	SI	10286344	Wabash River	42	100	ArtificialPath	76	5.5	3.144	12,016	2.4
6065	Iatan	40	SI	2254745				StreamRiver	46	4.3	4.141	2.5	0.64
6065	Iatan	1154	LF	2254745		260	13	StreamRiver	46	4.3	4.141	2.5	0.64
6065	Iatan	1154	LF	2254749		519	88	StreamRiver	46	5.3	2.685	0.053	0.56
6641	Independence	1153	LF	7550633		69	20	StreamRiver	113	2.6	1.941	0.85	0.48
6641	Independence	1153	LF	11832646		745	80	StreamRiver	113	0.8	1.32	1.4	0.43
2132	Independence Power & Light - Blue Valley Station	616	SI	4390505		934	100	StreamRiver	51.4	4.6	2.874	0.19	0.73
2132	Independence Power & Light - Blue Valley Station	617	SI	4390505		1181	100	StreamRiver	51.4	4.6	2.874	0.19	0.73
2132	Independence Power & Light - Blue Valley Station	618	SI	4390505		1345	100	StreamRiver	51.4	4.6	2.874	0.19	0.73
594	Indian River Generating Station	339	SI	8409145				ArtificialPath	320	1.2	1.671	119	0.95
594	Indian River Generating Station	340	SI	8409145				ArtificialPath	320	1.2	1.671	119	0.95

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
594	Indian River Generating Station	762	LF	8409145	Indian River	89	100	ArtificialPath	320	1.2	1.671	119	0.95
594	Indian River Generating Station	775	LF	8409147	Indian River	77	88	ArtificialPath	331.4	3.4	1.42	118	0.95
594	Indian River Generating Station	775	LF	8409159	Indian River	452	13	ArtificialPath	331.4	3.4	1.42	103	0.92
6481	Intermountain Power Project	214	SI	1197680				StreamRiver	14.6	89.8	6.688	0.72	0.41
6481	Intermountain Power Project	215	SI	1197680				StreamRiver	14.6	89.8	6.688	0.72	0.41
6481	Intermountain Power Project	216	SI	1197680				StreamRiver	14.6	89.8	6.688	0.72	0.41
6481	Intermountain Power Project	217	SI	1197680				StreamRiver	14.6	89.8	6.688	0.72	0.41
6481	Intermountain Power Project	218	SI	1197680				StreamRiver	14.6	89.8	6.688	0.72	0.41
6481	Intermountain Power Project	219	SI	1197680				StreamRiver	14.6	89.8	6.688	0.72	0.41
7097	J K Spruce	753	LF	10840882	Calaveras Lake	293	100	LakePond	14.9	20.6	7.798	26	0.74
7097	J K Spruce	1368	SI	10840882	Calaveras Lake	819	100	LakePond	14.9	20.6	7.798	26	0.74
7097	J K Spruce	1369	SI	10840882	Calaveras Lake	844	100	LakePond	14.9	20.6	7.798	26	0.74
7097	J K Spruce	1370	SI	10840882	Calaveras Lake	654	100	LakePond	14.9	20.6	7.798	26	0.74
7097	J K Spruce	1371	SI	10840882	Calaveras Lake	347	100	LakePond	14.9	20.6	7.798	26	0.74
7097	J K Spruce	1372	SI	10840882	Calaveras Lake	621	100	LakePond	14.9	20.6	7.798	26	0.74
7097	J K Spruce	1373	SI	10840882	Calaveras Lake	894	100	LakePond	14.9	20.6	7.798	26	0.74
2850	J M Stuart	706	SI	1920658	Threemile Creek	44	29	StreamRiver	70.7	0.6	0.545	7.3	0.56
2850	J M Stuart	706	SI	1920666	Threemile Creek	74	43	StreamRiver	71.2	3.4	3.016	6.2	0.91
2850	J M Stuart	706	SI	1922204	Ohio River	219	29	ArtificialPath	72	0.5	0.708	98,702	3.6
2850	J M Stuart	707	SI	1920740	Buzzardroost Creek	210	50	StreamRiver	73	3.0	2.9	1.4	0.85
2850	J M Stuart	707	SI	1922224	Ohio River	158	50	ArtificialPath	72	4.3	2.962	98,699	3.6
2850	J M Stuart	708	SI	1922224	Ohio River	89	100	ArtificialPath	72	4.3	2.962	98,699	3.6
2850	J M Stuart	709	SI	1922224	Ohio River	15	100	ArtificialPath	72	4.3	2.962	98,699	3.6
2850	J M Stuart	710	SI	1922224	Ohio River	41	100	ArtificialPath	72	4.3	2.962	98,699	3.6
2850	J M Stuart	711	SI	1920666	Threemile Creek	76	38	StreamRiver	71.2	3.4	3.016	6.2	0.91

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
2850	J M Stuart	711	SI	1920740	Buzzardroost Creek	1018	13	StreamRiver	73	3.0	2.9	1.4	0.85
2850	J M Stuart	711	SI	1922224	Ohio River	563	50	ArtificialPath	72	4.3	2.962	98,699	3.6
2850	J M Stuart	766	LF	1920716	Elk Run	742	13	StreamRiver	75.9	0.7	0.645	1.9	0.74
2850	J M Stuart	766	LF	1920740	Buzzardroost Creek	408	38	StreamRiver	73	3.0	2.9	1.4	0.85
2850	J M Stuart	766	LF	1922226	Ohio River	434	50	ArtificialPath	75.7	1.2	1.023	98,620	3.6
2850	J M Stuart	767	LF	1920740	Buzzardroost Creek	315	75	StreamRiver	73	3.0	2.9	1.4	0.85
2850	J M Stuart	767	LF	1922224	Ohio River	564	25	ArtificialPath	72	4.3	2.962	98,699	3.6
6181	J T Deely	768	LF	10840882	Calaveras Lake	401	100	LakePond	14.9	20.6	7.798	26	0.74
6181	J T Deely	1002	LF	10840882				LakePond	14.9	20.6	7.798	26	0.74
6181	J T Deely	1291	SI	10840882	Calaveras Lake	819	100	LakePond	14.9	20.6	7.798	26	0.74
6181	J T Deely	1292	SI	10840882	Calaveras Lake	844	100	LakePond	14.9	20.6	7.798	26	0.74
6181	J T Deely	1293	SI	10840882	Calaveras Lake	654	100	LakePond	14.9	20.6	7.798	26	0.74
6181	J T Deely	1294	SI	10840882	Calaveras Lake	347	100	LakePond	14.9	20.6	7.798	26	0.74
6181	J T Deely	1295	SI	10840882	Calaveras Lake	353	100	LakePond	14.9	20.6	7.798	26	0.74
6181	J T Deely	1296	SI	10840882	Calaveras Lake	290	100	LakePond	14.9	20.6	7.798	26	0.74
1720	J.C. Weadock	573	SI	12928873				Coastline	72	2.0	4.496		
1720	J.C. Weadock	574	SI	12928873				Coastline	72	2.0	4.496		
1720	J.C. Weadock	575	SI	12928873				Coastline	72	2.0	4.496		
1720	J.C. Weadock	576	SI	12928873				Coastline	72	2.0	4.496		
1720	J.C. Weadock	1003	LF	12928873				Coastline	72	2.0	4.496		
1723	J.R Whiting	577	SI	25769231				Coastline	95	2.9	17.625		
1723	J.R Whiting	578	SI	25769231				Coastline	95	2.9	17.625		
1723	J.R Whiting	579	SI	25769231				Coastline	95	2.9	17.625		
1723	J.R Whiting	580	SI	25769231				Coastline	95	2.9	17.625		
1723	J.R Whiting	965	LF	25769231				Coastline	95	2.9	17.625		
1723	J.R Whiting	1000	LF	25769231				Coastline	95	2.9	17.625		
710	Jack McDonough	360	SI	3286334				ArtificialPath	236.4	9.3	2.507	3,781	1.8
710	Jack McDonough	361	SI	3286334				ArtificialPath	236.4	9.3	2.507	3,781	1.8
710	Jack McDonough	362	SI	3286334				ArtificialPath	236.4	9.3	2.507	3,781	1.8
710	Jack McDonough	363	SI	3286334				ArtificialPath	236.4	9.3	2.507	3,781	1.8
710	Jack McDonough	968	LF	3286334				ArtificialPath	236.4	9.3	2.507	3,781	1.8
2049	Jack Watson	595	SI	18076850				CanalDitch	243.4	1.6	1.07	1.0	0.39
2049	Jack Watson	769	LF	18076850		37	57	CanalDitch	243.4	1.6	1.07	1.0	0.39
2049	Jack Watson	769	LF	18077068		788	43	ArtificialPath	247.3	5.1	4.454	3.3	0.49
1830	James De Young	770	LF	9017139		600	63	StreamRiver	222.2	5.5	4.861	1.7	0.75
1830	James De Young	770	LF	9017145		86	38	StreamRiver	221.9	3.1	4.632	0.98	0.72

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
1830	James De Young	1333	SI	9017853	Macatawa, Lake	140	100	LakePond	235.9	15.6	3.908	109	0.94
6002	James H. Miller Jr.	16	SI	18567309				StreamRiver	287.9	15.2	10.511	173	1.2
2161	James River Power Station	619	SI	7608061				LakePond	103.8	2.6	0.83	232	1.7
2161	James River Power Station	771	LF	7607387	James River	286	25	StreamRiver	104	0.6	0.778	233	1.1
2161	James River Power Station	771	LF	7608001	James River	156	75	StreamRiver	104	1.0	1.355	233	1.4
2187	JE Corette Plant	764	LF	4342872		66	67	StreamRiver	65.4	33.3	5.094	0.81	0.78
2187	JE Corette Plant	764	LF	4343546	Yellowstone River	52	33	ArtificialPath	64.2	0.2	0.48	9,675	2.3
2187	JE Corette Plant	1249	SI	4343546	Yellowstone River	20	100	ArtificialPath	64.2	0.2	0.48	9,675	2.3
2187	JE Corette Plant	1250	SI	4342872		143	20	StreamRiver	65.4	33.3	5.094	0.81	0.78
2187	JE Corette Plant	1250	SI	4343004	Yellowstone River	7	40	ArtificialPath	64	0.0	0.062	9,675	2.3
2187	JE Corette Plant	1250	SI	4343546	Yellowstone River	8	40	ArtificialPath	64.2	0.2	0.48	9,675	2.3
3319	Jefferies	117	SI	11565234		76	33	StreamRiver	171.9	1.0	1.446	0.40	0.54
3319	Jefferies	117	SI	11566154		76	33	LakePond	170.2	1.2	2.977	3.9	0.50
3319	Jefferies	117	SI	11566156		22	33	LakePond	172	1.1	1.607	0.86	0.39
3319	Jefferies	118	SI	11565204		107	40	CanalDitch	169.2	0.6	0.953	4.2	0.51
3319	Jefferies	118	SI	11565234		212	40	StreamRiver	171.9	1.0	1.446	0.40	0.54
3319	Jefferies	118	SI	11566154		158	20	LakePond	170.2	1.2	2.977	3.9	0.50
6068	Jeffrey Energy Center	41	SI	3644400		76	100	LakePond	35	2.5	1.392	0.56	0.66
6068	Jeffrey Energy Center	42	SI	3643012		123	100	StreamRiver	35	7.6	6.861	0.41	0.74
6068	Jeffrey Energy Center	43	SI	3644572		31	100	LakePond	35	1.4	1.108	0.29	0.58
6068	Jeffrey Energy Center	772	LF	3644400		37	100	LakePond	35	2.5	1.392	0.56	0.66
6068	Jeffrey Energy Center	773	LF	3644400		92	100	LakePond	35	2.5	1.392	0.56	0.66
8066	Jim Bridger Plant Units 1-4	244	SI	3388381		20	100	StreamRiver	11	7.1	6.533	0.12	0.80
8066	Jim Bridger Plant Units 1-4	245	SI	3387697		226	33	StreamRiver	11	2.6	2.445	2.7	0.92
8066	Jim Bridger Plant Units 1-4	245	SI	3388445	Jim Bridger Project Evaporation Pond	88	33	LakePond	11	1.0	0.54	1.4	0.76

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
8066	Jim Bridger Plant Units 1-4	245	SI	3388465		28	33	Playa	11	0.1	0.319	1.4	0.87
8066	Jim Bridger Plant Units 1-4	774	LF	3387677		345	63	StreamRiver	11	3.2	2.276	1.3	1.0
8066	Jim Bridger Plant Units 1-4	774	LF	3387679		272	25	StreamRiver	11	5.2	2.734	0.65	0.89
8066	Jim Bridger Plant Units 1-4	774	LF	3388445	Jim Bridger Project Evaporation Pond	480	13	LakePond	11	1.0	0.54	1.4	0.76
3935	John E. Amos	153	SI	19315422				ArtificialPath	131.5	2.1	1.283	18,953	2.4
3935	John E. Amos	154	SI	19315422				ArtificialPath	131.5	2.1	1.283	18,953	2.4
3935	John E. Amos	740	LF	19314852		444	100	StreamRiver	124.3	5.8	3.446	4.3	0.89
3935	John E. Amos	742	LF	19314054		54	100	StreamRiver	120.5	3.0	1.905	1.6	0.81
4271	John P. Madgett	990	LF	2118222				ArtificialPath	92.1	1.8	1.336	27,963	2.8
4271	John P. Madgett	991	LF	2118222				ArtificialPath	92.1	1.8	1.336	27,963	2.8
3405	John Sevier	131	SI	22178442				LakePond	164.6	2.6	1.657	4,980	1.3
3405	John Sevier	132	SI	22178442				LakePond	164.6	2.6	1.657	4,980	1.3
3405	John Sevier	763	LF	22178184		50	50	StreamRiver	166.9	3.1	1.789	1.8	0.77
3405	John Sevier	763	LF	22178442		76	50	LakePond	164.6	2.6	1.657	4,980	1.3
3406	Johnsonville	133	SI	10582213				LakePond	189.9	6.1	1.25	73,013	3.3
3406	Johnsonville	291	SI	10582213				LakePond	189.9	6.1	1.25	73,013	3.3
3406	Johnsonville	732	LF	10579813		2058	100	LakePond	189.7	3.0	0.633	3.1	0.48
3406	Johnsonville	733	LF	10582213		2665	100	LakePond	189.9	6.1	1.25	73,013	3.3
384	Joliet 29	309	SI	14788089				ArtificialPath	101.4	9.1	4.652	1,019	1.5
384	Joliet 29	1098	LF	14788089				ArtificialPath	101.4	9.1	4.652	1,019	1.5
874	Joliet 9	1327	SI	14788089	Des Plaines River	43	100	ArtificialPath	101.4	9.1	4.652	1,019	1.5
874	Joliet 9	1328	SI	14788089	Des Plaines River	437	100	ArtificialPath	101.4	9.1	4.652	1,019	1.5
887	Joppa Steam	390	SI	1838869		34	25	StreamRiver	61	0.8	1.57	0.36	0.66
887	Joppa Steam	390	SI	1839963	Ohio River	954	75	ArtificialPath	61.2	9.1	2.863	287,115	4.4
887	Joppa Steam	734	LF	1839963				ArtificialPath	61.2	9.1	2.863	287,115	4.4
3947	Kammer	159	SI	19455337				ArtificialPath	141.5	2.5	1.894	42,109	3.0
3936	Kanawha River	155	SI	6925319				ArtificialPath	185.9	8.6	4.288	13,724	2.4
1381	Kenneth C Coleman	553	SI	10109049		242	50	StreamRiver	119.7	1.7	3.211	3.6	0.68
1381	Kenneth C Coleman	553	SI	10109549	Ohio River	236	50	ArtificialPath	121	19.6	9.095	130,878	3.8
1381	Kenneth C Coleman	554	SI	10109549				ArtificialPath	121	19.6	9.095	130,878	3.8
1381	Kenneth C Coleman	555	SI	10109087		200	100	StreamRiver	120.7	4.3	2.367	2.6	0.52

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
3136	Keystone	736	LF	4741479		140	25	StreamRiver	208.8	1.0	1.065	7.8	0.97
3136	Keystone	736	LF	4741511		109	38	StreamRiver	207	1.3	1.94	0.83	0.77
3136	Keystone	736	LF	4741521	Crooked Creek	343	13	StreamRiver	203	0.2	0.547	335	1.6
3136	Keystone	736	LF	4742313		74	25	LakePond	203.5	0.3	0.642	8.0	0.71
3136	Keystone	1151	LF	4741419		395	33	StreamRiver	210.2	2.6	2.543	1.7	0.81
3136	Keystone	1151	LF	4741433	Plum Creek	888	50	StreamRiver	210.4	2.0	1.306	136	0.96
3136	Keystone	1151	LF	4741471		66	17	StreamRiver	210	0.9	1.777	0.58	0.73
3136	Keystone	1152	LF	4741433	Plum Creek	401	75	StreamRiver	210.4	2.0	1.306	136	0.96
3136	Keystone	1152	LF	4741471		172	25	StreamRiver	210	0.9	1.777	0.58	0.73
3136	Keystone	1297	SI	4741479		6	100	StreamRiver	208.8	1.0	1.065	7.8	0.97
3136	Keystone	1298	SI	4741479		375	100	StreamRiver	208.8	1.0	1.065	7.8	0.97
3136	Keystone	1299	SI	4741479		236	100	StreamRiver	208.8	1.0	1.065	7.8	0.97
3136	Keystone	1300	SI	4741479		6	100	StreamRiver	208.8	1.0	1.065	7.8	0.97
3136	Keystone	1301	SI	4741053	Garretts Run	54	100	StreamRiver	200.3	2.2	1.739	1.5	0.81
3136	Keystone	1302	SI	4741053	Garretts Run	33	100	StreamRiver	200.3	2.2	1.739	1.5	0.81
3136	Keystone	1303	SI	4741031	Garretts Run	539	38	StreamRiver	200	0.8	1.082	2.0	0.77
3136	Keystone	1303	SI	4741053	Garretts Run	375	63	StreamRiver	200.3	2.2	1.739	1.5	0.81
3136	Keystone	1304	SI	4741031	Garretts Run	610	25	StreamRiver	200	0.8	1.082	2.0	0.77
3136	Keystone	1304	SI	4741053	Garretts Run	419	75	StreamRiver	200.3	2.2	1.739	1.5	0.81
3136	Keystone	1305	SI	4742139	Allegheny River	554	100	ArtificialPath	200	0.8	0.987	15,444	2.4
3136	Keystone	1306	SI	4741753		190	100	StreamRiver	200	3.3	3.15	2.5	0.91
3136	Keystone	1307	SI	4741753		66	100	StreamRiver	200	3.3	3.15	2.5	0.91
6031	Killen Station	31	SI	1921950	Ohio River	238	50	ArtificialPath	80.8	1.3	1.582	98,562	3.6
6031	Killen Station	31	SI	1921988	Ohio River	167	50	ArtificialPath	84	4.8	2.075	98,553	3.6
6031	Killen Station	32	SI	1920376	Spring Run	631	100	StreamRiver	84	0.0	0.201	0.0021	0.16
876	Kincaid Generation LLC	388	SI	13565478	Sangchris Lake	156	43	LakePond	49	1.2	0.962	20	0.69
876	Kincaid Generation LLC	388	SI	13565484	Sangchris Lake	55	43	LakePond	49.1	9.0	5.117	6.9	0.71
876	Kincaid Generation LLC	388	SI	13565486	Sangchris Lake	36	14	LakePond	49	1.2	0.951	5.0	0.53
876	Kincaid Generation LLC	969	LF	13565486				LakePond	49	1.2	0.951	5.0	0.53
3407	Kingston	134	SI	22125770				LakePond	252	2.1	0.779	5.4	0.53
3407	Kingston	135	SI	22125770				LakePond	252	2.1	0.779	5.4	0.53
733	Kraft	375	SI	20107245				ArtificialPath	119	4.9	3.406	53	0.64
733	Kraft	1150	LF	20106909	Saint Augustine Creek	3473	38	StreamRiver	119.6	33.3	9.191	49	0.98
733	Kraft	1150	LF	20107243	Savannah River	2226	63	ArtificialPath	118.6	45.5	7.722	15,010	2.4
2876	Kyger Creek	716	SI	19443313	Kyger Creek	64	71	StreamRiver	108	1.2	1.71	33	0.75
2876	Kyger Creek	716	SI	19443471	Ohio River	3	29	ArtificialPath	107.9	6.3	3.367	59,450	3.2

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
2876	Kyger Creek	717	SI	19443313	Kyger Creek	165	63	StreamRiver	108	1.2	1.71	33	0.75
2876	Kyger Creek	717	SI	19443471	Ohio River	279	38	ArtificialPath	107.9	6.3	3.367	59,450	3.2
2876	Kyger Creek	738	LF	19443295	Little Kyger Creek	774	88	StreamRiver	106.3	8.4	4.619	6.3	0.87
2876	Kyger Creek	738	LF	19443299	Little Campaign Creek	1054	13	StreamRiver	106.8	1.5	1.23	2.6	0.79
2713	L.V. Sutton Electric Plant	665	SI	8834990	Cape Fear River	1283	100	ArtificialPath	256.8	28.0	11.105	7,616	2.1
2713	L.V. Sutton Electric Plant	666	SI	8832596	Cape Fear River	530	25	ArtificialPath	258	0.7	1.075	7,630	2.1
2713	L.V. Sutton Electric Plant	666	SI	8834990	Cape Fear River	919	75	ArtificialPath	256.8	28.0	11.105	7,616	2.1
1241	La Cygne	513	SI	2998084				LakePond	32	6.2	2.221	12	0.64
1241	La Cygne	514	SI	2998084				LakePond	32	6.2	2.221	12	0.64
1241	La Cygne	739	LF	2996362		239	25	StreamRiver	32	3.1	2.792	0.038	0.63
1241	La Cygne	739	LF	2998084	La Cygnes Lake	1190	75	LakePond	32	6.2	2.221	12	0.64
2103	Labadie	607	SI	6009846				StreamRiver	57.3	6.3	2.399	0.092	0.72
2103	Labadie	608	SI	6009846				StreamRiver	57.3	6.3	2.399	0.092	0.72
2098	Lake Road	605	SI	2252949	Missouri River	425	100	ArtificialPath	41.9	114.2	13.223	61,092	3.4
2098	Lake Road	606	SI	2252949				ArtificialPath	41.9	114.2	13.223	61,092	3.4
2098	Lake Road	752	LF	2252747	Contrary Creek	1332	38	CanalDitch	43.9	26.2	9.576	15	0.92
2098	Lake Road	752	LF	2252949	Missouri River	638	63	ArtificialPath	41.9	114.2	13.223	61,092	3.4
2838	Lake Shore	1270	SI	28123868		246	100	Coastline	135.1	109.4	23.697		
964	Lakeside	400	SI	13564568	Sugar Creek	629	50	StreamRiver	63	0.5	0.954	183	1.4
964	Lakeside	400	SI	13564578	Sugar Creek	67	25	StreamRiver	63	1.3	1.05	180	1.5
964	Lakeside	400	SI	13565430	Lake Springfield	25	25	LakePond	59.8	6.2	2.311	180	1.5
1047	Lansing	477	SI	13211666				ArtificialPath	136	0.7	1.105	33,701	2.4
1047	Lansing	478	SI	13211666				ArtificialPath	136	0.7	1.105	33,701	2.4
1047	Lansing	730	LF	13210258		46	100	StreamRiver	134.1	1.5	1.214	2.7	0.83
1047	Lansing	741	LF	13210286		38	100	StreamRiver	136	1.5	1.381	1.1	0.86
643	Lansing Smith	341	SI	2178625				StreamRiver	646.4	1.8	1.236	28	0.80
643	Lansing Smith	743	LF	2179431	Saint Andrew Bay	213	100	Coastline	640.6	2.6	2.871		
6204	Laramie River Station	188	SI	17483575	Laramie River	1714	100	StreamRiver	12	18.1	3.609	2,035	2.3
6204	Laramie River Station	189	SI	17483575	Laramie River	506	50	StreamRiver	12	18.1	3.609	2,035	2.3
6204	Laramie River Station	189	SI	17483589	Laramie River	930	50	StreamRiver	12	8.6	3.327	2,037	2.0
6204	Laramie River Station	744	LF	17483575	Laramie River	1425	75	StreamRiver	12	18.1	3.609	2,035	2.3

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
6204	Laramie River Station	744	LF	17483631		558	25	StreamRiver	12	7.1	4.935	27	1.3
1891	Laskin Energy Center	588	SI	1767116				LakePond	140	1.3	1.82	0.50	0.35
1891	Laskin Energy Center	589	SI	1767116				LakePond	140	1.3	1.82	0.50	0.35
1250	Lawrence Energy Center	515	SI	3729567				ArtificialPath	36.9	3.0	2.917	2,611	2.4
1250	Lawrence Energy Center	516	SI	3729567				ArtificialPath	36.9	3.0	2.917	2,611	2.4
1250	Lawrence Energy Center	517	SI	3729567				ArtificialPath	36.9	3.0	2.917	2,611	2.4
1250	Lawrence Energy Center	518	SI	3729567				ArtificialPath	36.9	3.0	2.917	2,611	2.4
1250	Lawrence Energy Center	745	LF	3729357		26	17	StreamRiver	35.1	1.2	1.316	0.061	0.65
1250	Lawrence Energy Center	745	LF	3729559	Kansas River	44	17	ArtificialPath	36	3.8	4.346	2,606	1.9
1250	Lawrence Energy Center	745	LF	3729567	Kansas River	455	17	ArtificialPath	36.9	3.0	2.917	2,611	2.4
1250	Lawrence Energy Center	745	LF	3731689		175	33	StreamRiver	35	1.9	1.337	0.050	0.66
1250	Lawrence Energy Center	745	LF	3733255		914	17	StreamRiver	36.2	2.2	1.924	0.021	0.57
1250	Lawrence Energy Center	747	LF	3729567	Kansas River	72	100	ArtificialPath	36.9	3.0	2.917	2,611	2.4
1250	Lawrence Energy Center	1149	LF	3729567	Kansas River	122	100	ArtificialPath	36.9	3.0	2.917	2,611	2.4
2817	Leland Olds	683	SI	14519643	Missouri River	330	100	ArtificialPath	4	2.8	2.781	43,597	3.3
2817	Leland Olds	684	SI	14519643	Missouri River	106	100	ArtificialPath	4	2.8	2.781	43,597	3.3
2817	Leland Olds	685	SI	14519643	Missouri River	690	100	ArtificialPath	4	2.8	2.781	43,597	3.3
2817	Leland Olds	748	LF	14518609		352	25	CanalDitch	4	1.4	1.633	0.025	0.23
2817	Leland Olds	748	LF	14519643	Missouri River	761	75	ArtificialPath	4	2.8	2.781	43,597	3.3
2817	Leland Olds	749	LF	14519461	Alderin Creek	429	75	StreamRiver	4.1	6.5	5.777	0.0058	0.65
2817	Leland Olds	749	LF	14519463		496	25	StreamRiver	4.6	5.8	4.154	0.035	0.80
6089	Lewis & Clark	750	LF	21874629	Peabody Coulee	128	100	StreamRiver	5	14.0	8.038	0.019	0.73
6089	Lewis & Clark	751	LF	21870815	Lone Tree Creek	1379	13	StreamRiver	5	29.4	7.069	1.2	1.0
6089	Lewis & Clark	751	LF	21871785	Yellowstone River	6	88	ArtificialPath	4.9	33.2	4.922	22,379	3.5
6089	Lewis & Clark	786	LF	21871785				ArtificialPath	4.9	33.2	4.922	22,379	3.5
6089	Lewis & Clark	1374	SI	21871785	Yellowstone River	238	100	ArtificialPath	4.9	33.2	4.922	22,379	3.5
6089	Lewis & Clark	1375	SI	21871785	Yellowstone River	178	100	ArtificialPath	4.9	33.2	4.922	22,379	3.5
6089	Lewis & Clark	1376	SI	21871785	Yellowstone River	91	100	ArtificialPath	4.9	33.2	4.922	22,379	3.5
6089	Lewis & Clark	1377	SI	21871785	Yellowstone River	178	100	ArtificialPath	4.9	33.2	4.922	22,379	3.5
6089	Lewis & Clark	1378	SI	21871785	Yellowstone River	17	100	ArtificialPath	4.9	33.2	4.922	22,379	3.5
298	Limestone	300	SI	5575475	Lambs Creek	1886	50	StreamRiver	21	4.2	2.28	11	0.82

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
298	Limestone	300	SI	5576035	Lynn Creek	572	50	StreamRiver	21.6	12.8	7.431	2.6	0.84
298	Limestone	301	SI	5576035				StreamRiver	21.6	12.8	7.431	2.6	0.84
298	Limestone	302	SI	5576035				StreamRiver	21.6	12.8	7.431	2.6	0.84
298	Limestone	303	SI	5576035				StreamRiver	21.6	12.8	7.431	2.6	0.84
298	Limestone	304	SI	5576035				StreamRiver	21.6	12.8	7.431	2.6	0.84
298	Limestone	305	SI	5576035				StreamRiver	21.6	12.8	7.431	2.6	0.84
298	Limestone	306	SI	5576035				StreamRiver	21.6	12.8	7.431	2.6	0.84
298	Limestone	307	SI	5576035				StreamRiver	21.6	12.8	7.431	2.6	0.84
298	Limestone	308	SI	5575475	Lambs Creek	1883	50	StreamRiver	21	4.2	2.28	11	0.82
298	Limestone	308	SI	5576035	Lynn Creek	569	50	StreamRiver	21.6	12.8	7.431	2.6	0.84
298	Limestone	821	LF	5576035	Lynn Creek	307	100	StreamRiver	21.6	12.8	7.431	2.6	0.84
2240	Lon Wright	765	LF	17264353				CanalDitch	40.1	11.8	7.316	0.68	0.67
6664	Louisa	222	SI	14807047				ArtificialPath	75.1	2.5	2.24	55,000	3.2
6664	Louisa	223	SI	14805067		931	14	StreamRiver	80.3	4.7	2.908	1.1	0.79
6664	Louisa	223	SI	14805109		55	57	StreamRiver	79	1.2	0.8	0.30	0.71
6664	Louisa	223	SI	14805139		693	29	StreamRiver	79	1.3	1.555	0.53	0.73
6664	Louisa	801	LF	14806993		1267	100	StreamRiver	75.6	35.6	7.177	8.6	0.59
976	Marion Generating Station	401	SI	10147935	Lake of Egypt	377	100	LakePond	49.6	5.8	1.804	31	1.2
976	Marion Generating Station	402	SI	10147091	Little Saline Creek	10	88	StreamRiver	49.1	3.0	2.629	11	0.95
976	Marion Generating Station	402	SI	10147935	Lake of Egypt	517	13	LakePond	49.6	5.8	1.804	31	1.2
976	Marion Generating Station	403	SI	10147055	South Fork Saline River	1	100	StreamRiver	49	0.4	1.283	32	1.2
976	Marion Generating Station	404	SI	10147055	South Fork Saline River	69	100	StreamRiver	49	0.4	1.283	32	1.2
976	Marion Generating Station	405	SI	10147935	Lake of Egypt	147	100	LakePond	49.6	5.8	1.804	31	1.2
976	Marion Generating Station	406	SI	10147055	South Fork Saline River	41	50	StreamRiver	49	0.4	1.283	32	1.2
976	Marion Generating Station	406	SI	10147935	Lake of Egypt	50	50	LakePond	49.6	5.8	1.804	31	1.2
976	Marion Generating Station	407	SI	10147055	South Fork Saline River	26	100	StreamRiver	49	0.4	1.283	32	1.2
976	Marion Generating Station	408	SI	10147055	South Fork Saline River	8	43	StreamRiver	49	0.4	1.283	32	1.2
976	Marion Generating Station	408	SI	10147091	Little Saline Creek	67	29	StreamRiver	49.1	3.0	2.629	11	0.95

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
976	Marion Generating Station	408	SI	10147935	Lake of Egypt	315	29	LakePond	49.6	5.8	1.804	31	1.2
976	Marion Generating Station	409	SI	10147055	South Fork Saline River	71	50	StreamRiver	49	0.4	1.283	32	1.2
976	Marion Generating Station	409	SI	10147091	Little Saline Creek	69	38	StreamRiver	49.1	3.0	2.629	11	0.95
976	Marion Generating Station	409	SI	10147935	Lake of Egypt	349	13	LakePond	49.6	5.8	1.804	31	1.2
976	Marion Generating Station	410	SI	10147091	Little Saline Creek	11	38	StreamRiver	49.1	3.0	2.629	11	0.95
976	Marion Generating Station	410	SI	10147935	Lake of Egypt	162	63	LakePond	49.6	5.8	1.804	31	1.2
976	Marion Generating Station	411	SI	10147091	Little Saline Creek	759	25	StreamRiver	49.1	3.0	2.629	11	0.95
976	Marion Generating Station	411	SI	10147935	Lake of Egypt	127	75	LakePond	49.6	5.8	1.804	31	1.2
976	Marion Generating Station	412	SI	10147935	Lake of Egypt	183	100	LakePond	49.6	5.8	1.804	31	1.2
976	Marion Generating Station	802	LF	10147055	South Fork Saline River	72	20	StreamRiver	49	0.4	1.283	32	1.2
976	Marion Generating Station	802	LF	10147091	Little Saline Creek	33	20	StreamRiver	49.1	3.0	2.629	11	0.95
976	Marion Generating Station	802	LF	10147935	Lake of Egypt	27	60	LakePond	49.6	5.8	1.804	31	1.2
2727	Marshall	680	SI	9751108	Lake Norman	34	67	LakePond	202	14.8	4.317	3,088	1.5
2727	Marshall	680	SI	9751144	Lake Norman	158	33	LakePond	196.4	15.0	6.197	3,112	1.8
2727	Marshall	803	LF	9750934	Beaverdam Creek	241	25	StreamRiver	201.5	0.9	0.987	0.65	0.69
2727	Marshall	803	LF	9751108	Lake Norman	1704	75	LakePond	202	14.8	4.317	3,088	1.5
2727	Marshall	804	LF	9751108	Lake Norman	1325	100	LakePond	202	14.8	4.317	3,088	1.5
492	Martin Drake	805	LF	1529727				StreamRiver	11	0.5	0.721	179	1.9
492	Martin Drake	1251	SI	1529727	Fountain Creek	168	100	StreamRiver	11	0.5	0.721	179	1.9
492	Martin Drake	1252	SI	1529727	Fountain Creek	179	100	StreamRiver	11	0.5	0.721	179	1.9
492	Martin Drake	1253	SI	1529727	Fountain Creek	164	100	StreamRiver	11	0.5	0.721	179	1.9
492	Martin Drake	1254	SI	1529727	Fountain Creek	159	100	StreamRiver	11	0.5	0.721	179	1.9
6146	Martin Lake	806	LF	5279038	Caney Branch	1330	13	StreamRiver	53.5	2.6	1.269	1.4	0.70
6146	Martin Lake	806	LF	5279582	Caney Creek	1303	38	StreamRiver	49.6	21.1	7.207	7.3	0.89
6146	Martin Lake	806	LF	5279746	Martin Lake	1898	13	LakePond	54.8	7.6	2.618	3.6	0.50
6146	Martin Lake	806	LF	5279840	Caney Creek	1217	38	LakePond	49.6	3.9	0.175	1.1	0.75

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
6146	Martin Lake	807	LF	5279038	Caney Branch	55	100	StreamRiver	53.5	2.6	1.269	1.4	0.70
6146	Martin Lake	808	LF	5279740	Martin Lake	228	63	LakePond	66.9	28.7	4.214	10	0.70
6146	Martin Lake	808	LF	5279756	Martin Lake	1197	38	LakePond	58.7	12.5	5.061	81	0.89
6146	Martin Lake	810	LF	5279756	Martin Lake	869	100	LakePond	58.7	12.5	5.061	81	0.89
6146	Martin Lake	822	LF	5279740	Martin Lake	392	38	LakePond	66.9	28.7	4.214	10	0.70
6146	Martin Lake	822	LF	5279756	Martin Lake	1075	63	LakePond	58.7	12.5	5.061	81	0.89
6146	Martin Lake	1223	SI	5279740	Martin Lake	100	67	LakePond	66.9	28.7	4.214	10	0.70
6146	Martin Lake	1223	SI	5279756	Martin Lake	47	33	LakePond	58.7	12.5	5.061	81	0.89
6146	Martin Lake	1224	SI	5279740	Martin Lake	146	75	LakePond	66.9	28.7	4.214	10	0.70
6146	Martin Lake	1224	SI	5279756	Martin Lake	147	25	LakePond	58.7	12.5	5.061	81	0.89
6146	Martin Lake	1225	SI	5279740	Martin Lake	48	100	LakePond	66.9	28.7	4.214	10	0.70
6146	Martin Lake	1226	SI	5279756	Martin Lake	670	100	LakePond	58.7	12.5	5.061	81	0.89
6250	Mayo Electric Generating Facility	204	SI	8693539	Crutchfield Branch	22	100	StreamRiver	95.8	3.5	2.356	1.7	0.85
6124	McIntosh	87	SI	20107091				ArtificialPath	131.6	1.0	0.753	14,801	2.4
3287	McMeekin	1155	LF	9869858	Saluda River	266	100	ArtificialPath	211.4	10.7	3.386	3,480	1.8
2104	Meramec	609	SI	3629071				ArtificialPath	51.8	7.9	3.831	173,379	4.2
2104	Meramec	610	SI	3629071				ArtificialPath	51.8	7.9	3.831	173,379	4.2
2104	Meramec	611	SI	3629071				ArtificialPath	51.8	7.9	3.831	173,379	4.2
2104	Meramec	612	SI	3629071				ArtificialPath	51.8	7.9	3.831	173,379	4.2
2104	Meramec	613	SI	3629071				ArtificialPath	51.8	7.9	3.831	173,379	4.2
864	Meredosia	385	SI	3598258				ArtificialPath	40.3	7.7	6.926	17,544	2.6
864	Meredosia	386	SI	3598258				ArtificialPath	40.3	7.7	6.926	17,544	2.6
6213	Merom	190	SI	10286370				LakePond	80	24.6	4.535	24	0.92
6213	Merom	812	LF	10286196	Little Turtle Creek	2493	50	StreamRiver	79.7	18.5	8.824	7.1	0.85
6213	Merom	812	LF	10286370	Turtle Creek	1565	50	LakePond	80	24.6	4.535	24	0.92
6213	Merom	813	LF	10286370	Turtle Creek	2195	100	LakePond	80	24.6	4.535	24	0.92
2364	Merrimack Station	754	LF	6740568	Bow Bog Brook	528	13	StreamRiver	254	1.5	3.296	14	0.95
2364	Merrimack Station	754	LF	6742050	Merrimack River	884	63	ArtificialPath	254.4	3.4	1.03	4,730	1.7
2364	Merrimack Station	754	LF	6742472	Merrimack River	523	25	ArtificialPath	254	2.7	2.145	4,728	1.9
2364	Merrimack Station	1319	SI	6742472	Merrimack River	376	100	ArtificialPath	254	2.7	2.145	4,728	1.9
2364	Merrimack Station	1320	SI	6742472	Merrimack River	164	100	ArtificialPath	254	2.7	2.145	4,728	1.9
2832	Miami Fort	699	SI	3406069	Ohio River	141	13	ArtificialPath	70	0.4	0.614	106,377	3.6
2832	Miami Fort	699	SI	3410051	Ohio River	150	63	ArtificialPath	70	2.0	1.259	106,372	3.6

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
2832	Miami Fort	699	SI	3886058	Great Miami River	212	25	ArtificialPath	70	0.7	1.031	4,970	2.4
2832	Miami Fort	700	SI	3406069	Ohio River	123	13	ArtificialPath	70	0.4	0.614	106,377	3.6
2832	Miami Fort	700	SI	3886058	Great Miami River	84	88	ArtificialPath	70	0.7	1.031	4,970	2.4
2832	Miami Fort	1109	LF	3410051				ArtificialPath	70	2.0	1.259	106,372	3.6
2832	Miami Fort	1121	LF	3886028	Great Miami River	207	13	ArtificialPath	69	1.0	0.805	4,954	2.0
2832	Miami Fort	1121	LF	3886034	Great Miami River	40	88	ArtificialPath	69.3	0.8	0.576	4,954	2.0
997	Michigan City	448	SI	3397270		9	100	Coastline	205.6	2.1	2.365		
997	Michigan City	449	SI	3397270		145	100	Coastline	205.6	2.1	2.365		
997	Michigan City	450	SI	3397270		100	100	Coastline	205.6	2.1	2.365		
997	Michigan City	451	SI	3397270		35	100	Coastline	205.6	2.1	2.365		
997	Michigan City	452	SI	3397270		86	100	Coastline	205.6	2.1	2.365		
997	Michigan City	453	SI	3397270		26	100	Coastline	205.6	2.1	2.365		
1364	Mill Creek	543	SI	22034711		23	100	StreamRiver	270.4	6.7	4.644	3.8	0.93
1364	Mill Creek	544	SI	10163798				StreamRiver	111.6	7.6	6.297	19	0.95
1364	Mill Creek	545	SI	10163798				StreamRiver	111.6	7.6	6.297	19	0.95
1364	Mill Creek	546	SI	10163798				StreamRiver	111.6	7.6	6.297	19	0.95
1364	Mill Creek	547	SI	10163798				StreamRiver	111.6	7.6	6.297	19	0.95
1364	Mill Creek	817	LF	10164038	Ohio River	176	100	ArtificialPath	114.8	8.5	6.832	123,620	3.7
1364	Mill Creek	818	LF	10164038	Ohio River	907	63	ArtificialPath	114.8	8.5	6.832	123,620	3.7
1364	Mill Creek	818	LF	10264556	Pond Creek	1475	38	StreamRiver	114.5	5.8	2.98	123	1.1
1364	Mill Creek	819	LF	10163798	Mill Creek	1487	38	StreamRiver	111.6	7.6	6.297	19	0.95
1364	Mill Creek	819	LF	10164038	Ohio River	686	50	ArtificialPath	114.8	8.5	6.832	123,620	3.7
1364	Mill Creek	819	LF	10264556	Pond Creek	2393	13	StreamRiver	114.5	5.8	2.98	123	1.1
2823	Milton R. Young Station	686	SI	14519747				LakePond	5	0.9	0.671	1.8	0.87
2823	Milton R. Young Station	687	SI	14519747				LakePond	5	0.9	0.671	1.8	0.87
2823	Milton R. Young Station	688	SI	14519747				LakePond	5	0.9	0.671	1.8	0.87
2823	Milton R. Young Station	689	SI	14519747				LakePond	5	0.9	0.671	1.8	0.87
2823	Milton R. Young Station	777	LF	14519097		1021	100	StreamRiver	5	5.7	2.767	0.0051	0.62
2823	Milton R. Young Station	788	LF	14519203		1806	100	StreamRiver	5	3.9	1.753	0.14	0.63
2823	Milton R. Young Station	809	LF	14519143		361	100	StreamRiver	5	4.1	2.726	0.0037	0.60
2823	Milton R. Young Station	811	LF	14519065	Square Butte Creek	2604	38	StreamRiver	4.6	4.4	1.149	0.88	0.84
2823	Milton R. Young Station	811	LF	14519143		774	25	StreamRiver	5	4.1	2.726	0.0037	0.60
2823	Milton R. Young Station	811	LF	14519165		2011	38	StreamRiver	5	3.0	2.146	0.40	0.84
2823	Milton R. Young Station	820	LF	14519125		565	25	StreamRiver	5	0.6	1.214	0.66	0.41

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
2823	Milton R. Young Station	820	LF	14519219		547	38	StreamRiver	5	3.7	3.662	0.0033	0.61
2823	Milton R. Young Station	820	LF	14519747	Nelson Lake	675	38	LakePond	5	0.9	0.671	1.8	0.87
2171	Missouri City	1257	SI	4391111	Rose Branch	144	100	StreamRiver	45.9	7.5	5.977	0.10	0.73
3948	Mitchell	160	SI	19455355	Ohio River	170	100	ArtificialPath	136.5	5.0	2.617	42,118	3.0
3948	Mitchell	161	SI	19455355	Ohio River	3	100	ArtificialPath	136.5	5.0	2.617	42,118	3.0
727	Mitchell	364	SI	902770057				ArtificialPath	205.3	28.2	7.846	6,739	2.0
727	Mitchell	365	SI	902770057				ArtificialPath	205.3	28.2	7.846	6,739	2.0
727	Mitchell	366	SI	902770057				ArtificialPath	205.3	28.2	7.846	6,739	2.0
3181	Mitchell Power Station	778	LF	3785375	Froman Run	883	38	StreamRiver	145.3	4.1	2.957	3.8	0.92
3181	Mitchell Power Station	778	LF	3785919	Monongahela River	362	63	ArtificialPath	147.5	3.3	2.14	10,381	2.2
3181	Mitchell Power Station	779	LF	3785361	Huston Run	701	13	StreamRiver	146.5	2.1	1.728	1.3	0.88
3181	Mitchell Power Station	779	LF	3785375	Froman Run	1088	13	StreamRiver	145.3	4.1	2.957	3.8	0.92
3181	Mitchell Power Station	779	LF	3785919	Monongahela River	340	75	ArtificialPath	147.5	3.3	2.14	10,381	2.2
1048	ML Kapp	479	SI	14804357				ArtificialPath	104	2.6	2.109	29	0.74
1048	ML Kapp	480	SI	14804357				ArtificialPath	104	2.6	2.109	29	0.74
1048	ML Kapp	481	SI	14804357				ArtificialPath	104	2.6	2.109	29	0.74
1048	ML Kapp	482	SI	14804357				ArtificialPath	104	2.6	2.109	29	0.74
1733	Monroe Power Plant	582	SI	13167364	Davis Drain	409	13	StreamRiver	92	2.8	3.315	0.77	0.63
1733	Monroe Power Plant	582	SI	25769197		58	88	Coastline	93.8	3.9	6.272		
1733	Monroe Power Plant	583	SI	25769309				Coastline	93.2	2.5	11.147		
6147	Monticello	780	LF	1010606				LakePond	54	11.5	5.155	24	0.71
6147	Monticello	781	LF	1009014	Tankersley Creek	3741	63	StreamRiver	56.3	35.9	10.783	26	0.99
6147	Monticello	781	LF	1010484	Dragoo Creek	1811	38	StreamRiver	48.8	12.4	6.592	4.0	0.83
6147	Monticello	782	LF	1010610	Monticello Reservoir	541	100	LakePond	57.6	43.0	3.018	173	1.0
6147	Monticello	1203	SI	1010610	Monticello Reservoir	645	100	LakePond	57.6	43.0	3.018	173	1.0
6147	Monticello	1204	SI	1010610	Monticello Reservoir	618	100	LakePond	57.6	43.0	3.018	173	1.0
6147	Monticello	1205	SI	1010610	Monticello Reservoir	796	100	LakePond	57.6	43.0	3.018	173	1.0
6147	Monticello	1206	SI	1010610	Monticello Reservoir	729	100	LakePond	57.6	43.0	3.018	173	1.0
2080	Montrose	600	SI	2334415	Montrose Lake	149	100	LakePond	38.1	2.8	2.085	25	0.74
2080	Montrose	601	SI	2334415	Montrose Lake	113	100	LakePond	38.1	2.8	2.085	25	0.74
2080	Montrose	602	SI	2333733				StreamRiver	39.8	1.8	2.65	0.024	0.58

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
2080	Montrose	783	LF	2334415	Montrose Lake	139	100	LakePond	38.1	2.8	2.085	25	0.74
1573	Morgantown Generating Plant	785	LF	4530667		1385	13	StreamRiver	165	0.5	0.886	1.7	0.44
1573	Morgantown Generating Plant	785	LF	4531757	Scar Branch	50	50	StreamRiver	165	3.3	3.707	1.5	0.79
1573	Morgantown Generating Plant	785	LF	4531763	Bowling Creek	128	38	StreamRiver	165.1	1.4	2.193	0.61	0.68
1573	Morgantown Generating Plant	1108	LF	4530805		960	13	StreamRiver	159.9	6.7	1.291	3.1	0.48
1573	Morgantown Generating Plant	1108	LF	4530855		20	63	StreamRiver	171	5.8	4.441	2.1	0.72
1573	Morgantown Generating Plant	1108	LF	4532017		400	25	ArtificialPath	163	4.4	1.809	5.4	0.53
1606	Mount Tom	563	SI	6782121	Connecticut River	68	100	ArtificialPath	308.4	0.7	0.869	14,863	2.4
1606	Mount Tom	564	SI	6782113				ArtificialPath	308.7	2.1	1.471	14,861	2.4
1606	Mount Tom	565	SI	6782113				ArtificialPath	308.7	2.1	1.471	14,861	2.4
1606	Mount Tom	798	LF	6781171		117	20	StreamRiver	303.7	3.3	1.534	4.1	0.88
1606	Mount Tom	798	LF	6782121	Connecticut River	53	60	ArtificialPath	308.4	0.7	0.869	14,863	2.4
1606	Mount Tom	798	LF	6782123		23	20	ArtificialPath	307	0.0	0.156	4.2	0.90
6264	Mountaineer	211	SI	19441555	Little Broad Run	63	88	StreamRiver	100	5.3	5.431	2.9	0.80
6264	Mountaineer	211	SI	19442931	Ohio River	676	13	ArtificialPath	100	4.0	3.01	59,204	3.2
6264	Mountaineer	787	LF	19441577	Little Broad Run	162	20	StreamRiver	100	1.6	1.485	0.66	0.72
6264	Mountaineer	787	LF	19441623	Broad Run	1077	40	StreamRiver	100	9.4	6.254	6.7	0.85
6264	Mountaineer	787	LF	19441625		661	40	StreamRiver	100	0.9	0.673	0.39	0.72
3954	Mt. Storm	789	LF	14366062	Mount Storm Lake	545	100	LakePond	270.5	8.1	3.263	34	0.80
3954	Mt. Storm	1110	LF	14365768	Morgan Run	484	38	StreamRiver	269.7	3.8	2.569	1.8	0.93
3954	Mt. Storm	1110	LF	14366062	Mount Storm Lake	1095	38	LakePond	270.5	8.1	3.263	34	0.80
3954	Mt. Storm	1110	LF	14366064	Mount Storm Lake	839	25	LakePond	264.5	1.4	1.436	24	0.59
3954	Mt. Storm	1111	LF	14366062	Mount Storm Lake	1049	100	LakePond	270.5	8.1	3.263	34	0.80
3954	Mt. Storm	1112	LF	3775537	Beaver Creek	739	13	StreamRiver	277.3	6.4	3.832	5.6	0.94
3954	Mt. Storm	1112	LF	14365710	Fourmile Run	382	50	StreamRiver	280.6	3.1	2.633	1.4	0.91

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
3954	Mt. Storm	1112	LF	14365768	Morgan Run	1089	13	StreamRiver	269.7	3.8	2.569	1.8	0.93
3954	Mt. Storm	1112	LF	14366062	Mount Storm Lake	1930	25	LakePond	270.5	8.1	3.263	34	0.80
1167	Muscatine #1	792	LF	17557513		8	100	StreamRiver	70.2	3.3	2.812	0.80	0.74
1167	Muscatine #1	1361	SI	14806993		6124	100	StreamRiver	75.6	35.6	7.177	8.6	0.59
2872	Muskingum River	712	SI	15383195	Muskingum River	456	100	ArtificialPath	113.2	1.5	1.026	7,195	2.1
2872	Muskingum River	713	SI	15382427	Hayward Run	632	25	StreamRiver	108.8	3.3	1.96	1.4	0.80
2872	Muskingum River	713	SI	15383195	Muskingum River	1131	13	ArtificialPath	113.2	1.5	1.026	7,195	2.1
2872	Muskingum River	713	SI	15383255	Muskingum River	860	63	ArtificialPath	108.7	4.3	2.734	7,291	2.1
2872	Muskingum River	714	SI	15383195	Muskingum River	525	100	ArtificialPath	113.2	1.5	1.026	7,195	2.1
2872	Muskingum River	715	SI	15383195	Muskingum River	264	100	ArtificialPath	113.2	1.5	1.026	7,195	2.1
2952	Muskogee	1172	SI	381680	Arkansas River	1461	50	ArtificialPath	56.7	2.9	1.297	26,553	2.8
2952	Muskogee	1172	SI	381842		58	50	LakePond	57	0.9	1.002	0.34	0.33
2952	Muskogee	1173	SI	380530		89	100	StreamRiver	57	0.8	1.503	0.63	0.61
2952	Muskogee	1174	SI	381680	Arkansas River	426	100	ArtificialPath	56.7	2.9	1.297	26,553	2.8
4162	Naughton Plant	12	SI	3266034		108	88	StreamRiver	92.5	4.6	4.411	0.043	0.67
4162	Naughton Plant	12	SI	3266082		254	13	LakePond	86	0.0	0.166	0.031	0.68
4162	Naughton Plant	13	SI	3265276		38	50	StreamRiver	82.8	0.4	0.554	0.32	0.77
4162	Naughton Plant	13	SI	3266034		394	25	StreamRiver	92.5	4.6	4.411	0.043	0.67
4162	Naughton Plant	13	SI	3266084		26	25	LakePond	91.8	1.0	0.531	0.23	0.74
4162	Naughton Plant	14	SI	3265282		280	100	StreamRiver	75.7	4.6	3.156	0.36	0.74
4162	Naughton Plant	15	SI	3266084		590	100	LakePond	91.8	1.0	0.531	0.23	0.74
4162	Naughton Plant	980	LF	24712403				LakePond	84.1	1.7	0.39	0.32	0.70
4941	Navajo Generating Station	793	LF	3528413		679	100	StreamRiver	14	28.5	14.877	0.17	0.93
6064	Nearman Creek	39	SI	2255187				StreamRiver	47	2.6	2.305	0.052	0.66
6064	Nearman Creek	794	LF	2255187	Nearman Creek	57	38	StreamRiver	47	2.6	2.305	0.052	0.66
6064	Nearman Creek	794	LF	2255471	Missouri River	2459	63	ArtificialPath	47	6.1	1.645	62,045	3.2
6064	Nearman Creek	795	LF	3727463		432	25	StreamRiver	49	2.7	2.516	0.93	0.82
6064	Nearman Creek	795	LF	3727473	Muncie Creek	350	75	StreamRiver	49	2.9	3.05	0.58	0.74
6096	Nebraska City	797	LF	7312135	Fourmile Creek	475	38	StreamRiver	41.4	10.7	5.325	2.7	0.81
6096	Nebraska City	797	LF	7312407		767	63	LakePond	41	1.7	0.475	0.25	0.32
6096	Nebraska City	943	LF	7312407		568	100	LakePond	41	1.7	0.475	0.25	0.32
6096	Nebraska City	1271	SI	7312385	Missouri River	192	100	ArtificialPath	41	4.6	3.805	58,958	3.0

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
6096	Nebraska City	1272	SI	7312385	Missouri River	194	100	ArtificialPath	41	4.6	3.805	58,958	3.0
4054	Nelson Dewey	170	SI	13326790		105	100	ArtificialPath	119	1.1	1.07	7.4	0.57
4054	Nelson Dewey	171	SI	13326790		244	100	ArtificialPath	119	1.1	1.07	7.4	0.57
4054	Nelson Dewey	893	LF	13326790		187	100	ArtificialPath	119	1.1	1.07	7.4	0.57
3138	New Castle Plant	941	LF	19463874	McKee Run	400	100	StreamRiver	146.8	5.1	2.186	9.8	1.1
3138	New Castle Plant	1349	SI	19463874	McKee Run	185	100	StreamRiver	146.8	5.1	2.186	9.8	1.1
3138	New Castle Plant	1350	SI	19464182	Beaver River	17	100	ArtificialPath	146	0.2	0.662	2,559	2.3
2167	New Madrid	620	SI	7469410	Mississippi River	959	25	ArtificialPath	181.6	19.3	6.293	573,662	5.2
2167	New Madrid	620	SI	7470334	Point Pleasant Chute	3116	75	LakePond	177.8	17.9	2.74	10	0.75
2167	New Madrid	621	SI	7469410	Mississippi River	6	100	ArtificialPath	181.6	19.3	6.293	573,662	5.2
2167	New Madrid	622	SI	760280		171	88	StreamRiver	182.9	8.9	1.674	4.1	0.67
2167	New Madrid	622	SI	7469410	Mississippi River	1488	13	ArtificialPath	181.6	19.3	6.293	573,662	5.2
2167	New Madrid	623	SI	7469410	Mississippi River	31	43	ArtificialPath	181.6	19.3	6.293	573,662	5.2
2167	New Madrid	623	SI	7470334	Point Pleasant Chute	3773	57	LakePond	177.8	17.9	2.74	10	0.75
2167	New Madrid	1032	LF	762036		120	100	StreamRiver	181.8	0.6	1.058	0.28	0.55
6017	Newton	21	SI	10435494		72	100	LakePond	35	6.3	4.093	21	0.67
6017	Newton	22	SI	10435490		75	40	LakePond	37.7	14.1	5.767	19	0.72
6017	Newton	22	SI	10435492		1	20	LakePond	35	0.0	0.276	0.52	0.65
6017	Newton	22	SI	10435496		342	40	LakePond	34.8	10.5	6.462	13	0.57
6017	Newton	1033	LF	10435496		114	83	LakePond	34.8	10.5	6.462	13	0.57
6017	Newton	1033	LF	10435536		69	17	LakePond	35	1.6	0.939	0.50	0.49
6017	Newton	1034	LF	10435496		515	100	LakePond	34.8	10.5	6.462	13	0.57
2291	North Omaha	1036	LF	17219446	Missouri River	177	100	ArtificialPath	53.5	18.4	3.316	46,968	3.0
2291	North Omaha	1113	LF	17219446	Missouri River	71	100	ArtificialPath	53.5	18.4	3.316	46,968	3.0
2291	North Omaha	1220	SI	17219446	Missouri River	53	100	ArtificialPath	53.5	18.4	3.316	46,968	3.0
2291	North Omaha	1221	SI	17219446	Missouri River	15	100	ArtificialPath	53.5	18.4	3.316	46,968	3.0
2291	North Omaha	1222	SI	17219446	Missouri River	268	100	ArtificialPath	53.5	18.4	3.316	46,968	3.0
8224	North Valmy	1037	LF	11202824	Humboldt River	979	100	StreamRiver	12	7.7	3.828	2,800	2.4
2963	Northeastern	718	SI	832872				StreamRiver	22	66.8	14.196	30	1.0
2963	Northeastern	1038	LF	833360	Verdigris River	48	100	StreamRiver	22	4.4	2.513	2,288	3.0
667	Northside Generating Station	1039	LF	16658019	San Carlos Creek	128	50	StreamRiver	126.2	1.6	0.767	0.62	0.37

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
667	Northside Generating Station	1039	LF	16659871	San Carlos Creek	1057	50	ArtificialPath	126.1	1.3	0.211	2.4	0.53
10030	NRG Energy Center Dover	251	SI	8074674				StreamRiver	260.3	2.3	1.776	1.1	0.66
527	Nucla	338	SI	18375940				StreamRiver	11.8	8.8	4.975	330	2.1
527	Nucla	964	LF	18375940				StreamRiver	11.8	8.8	4.975	330	2.1
2848	O H Hutchings	703	SI	3883754	Great Miami River	30	100	ArtificialPath	121.8	4.5	2.654	2,347	1.7
2848	O H Hutchings	704	SI	3883754	Great Miami River	21	100	ArtificialPath	121.8	4.5	2.654	2,347	1.7
2848	O H Hutchings	705	SI	3883754	Great Miami River	111	100	ArtificialPath	121.8	4.5	2.654	2,347	1.7
6180	Oak Grove	1040	LF	5575759		281	75	StreamRiver	12.6	6.3	2.344	1.3	0.76
6180	Oak Grove	1040	LF	5576197	Oliver Branch	961	25	LakePond	13	0.8	0.485	1.3	0.74
6180	Oak Grove	1042	LF	5575759				StreamRiver	12.6	6.3	2.344	1.3	0.76
6180	Oak Grove	1054	LF	5575759				StreamRiver	12.6	6.3	2.344	1.3	0.76
6180	Oak Grove	1185	SI	5576195	Herds Branch	468	38	LakePond	13	1.2	1.186	3.2	0.49
6180	Oak Grove	1185	SI	5576197	Oliver Branch	346	63	LakePond	13	0.8	0.485	1.3	0.74
127	Oklaunion	281	SI	13727077	Boggy Creek	70	50	StreamRiver	3	1.2	1.475	0.076	0.62
127	Oklaunion	281	SI	13727091	Boggy Creek	1207	38	StreamRiver	3	6.0	3.319	0.52	0.69
127	Oklaunion	281	SI	13728375	Boggy Creek	23	13	LakePond	3	0.1	0.103	0.079	0.28
127	Oklaunion	282	SI	13727091				StreamRiver	3	6.0	3.319	0.52	0.69
127	Oklaunion	283	SI	13727091				StreamRiver	3	6.0	3.319	0.52	0.69
127	Oklaunion	841	LF	13727091				StreamRiver	3	6.0	3.319	0.52	0.69
4151	Osage	1031	LF	9386901		22	100	StreamRiver	14.8	1.1	1.999	0.12	0.67
4151	Osage	1044	LF	9386901		56	100	StreamRiver	14.8	1.1	1.999	0.12	0.67
4151	Osage	1266	SI	9386901		35	100	StreamRiver	14.8	1.1	1.999	0.12	0.67
4151	Osage	1267	SI	9386901		136	100	StreamRiver	14.8	1.1	1.999	0.12	0.67
1831	Otto E. Eckert Station	586	SI	12241730				StreamRiver	99	0.9	1.792	442	1.8
6254	Ottumwa	205	SI	4994571				StreamRiver	40	4.7	4.828	33	1.1
6254	Ottumwa	206	SI	4994571				StreamRiver	40	4.7	4.828	33	1.1
6254	Ottumwa	207	SI	4994571				StreamRiver	40	4.7	4.828	33	1.1
6254	Ottumwa	208	SI	4994571				StreamRiver	40	4.7	4.828	33	1.1
6254	Ottumwa	1045	LF	4994605		373	63	StreamRiver	41	2.5	1.774	0.58	0.76
6254	Ottumwa	1045	LF	4994609		90	38	StreamRiver	42.3	1.1	1.664	0.24	0.68
1378	Paradise	548	SI	11628855				ArtificialPath	115.2	5.8	4.113	8,970	2.2
1378	Paradise	549	SI	11628855				ArtificialPath	115.2	5.8	4.113	8,970	2.2
1378	Paradise	550	SI	11628855				ArtificialPath	115.2	5.8	4.113	8,970	2.2
6248	Pawnee	191	SI	215051				StreamRiver	10	117.9	11.707	44	1.5

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
6248	Pawnee	192	SI	215051				StreamRiver	10	117.9	11.707	44	1.5
6248	Pawnee	193	SI	215051				StreamRiver	10	117.9	11.707	44	1.5
6248	Pawnee	194	SI	215051				StreamRiver	10	117.9	11.707	44	1.5
6248	Pawnee	195	SI	215051				StreamRiver	10	117.9	11.707	44	1.5
6248	Pawnee	196	SI	215051				StreamRiver	10	117.9	11.707	44	1.5
6248	Pawnee	197	SI	215051				StreamRiver	10	117.9	11.707	44	1.5
6248	Pawnee	1046	LF	3561528	Badger Creek	611	100	StreamRiver	10	19.4	14.16	59	1.4
6238	Pearl Station	1211	SI	3601022	Illinois River	143	100	ArtificialPath	38	1.3	1.615	18,247	2.6
3938	Philip Sporn	156	SI	19442931	Ohio River	284	100	ArtificialPath	100	4.0	3.01	59,204	3.2
3938	Philip Sporn	157	SI	19441555	Little Broad Run	74	50	StreamRiver	100	5.3	5.431	2.9	0.80
3938	Philip Sporn	157	SI	19442931	Ohio River	449	50	ArtificialPath	100	4.0	3.01	59,204	3.2
3938	Philip Sporn	979	LF	19442931				ArtificialPath	100	4.0	3.01	59,204	3.2
2843	Picway	702	SI	5218205	Scioto River	89	100	ArtificialPath	96	2.0	1.526	1,915	1.6
7902	Pirkey	233	SI	5279492	Hatley Creek	2397	100	StreamRiver	66.7	45.2	13.335	27	1.0
7902	Pirkey	234	SI	5279492	Hatley Creek	2804	100	StreamRiver	66.7	45.2	13.335	27	1.0
7902	Pirkey	235	SI	5279492	Hatley Creek	2828	100	StreamRiver	66.7	45.2	13.335	27	1.0
7902	Pirkey	236	SI	5279492	Hatley Creek	1388	100	StreamRiver	66.7	45.2	13.335	27	1.0
7902	Pirkey	237	SI	5279492	Hatley Creek	2751	100	StreamRiver	66.7	45.2	13.335	27	1.0
7902	Pirkey	238	SI	5279492	Hatley Creek	2915	100	StreamRiver	66.7	45.2	13.335	27	1.0
7902	Pirkey	1132	LF	5278680				StreamRiver	65	0.0	0.062	0.084	0.27
59	Platte	1047	LF	7265233		55	100	StreamRiver	14.5	6.1	7.884	0.012	0.56
59	Platte	1048	LF	7265233		214	100	StreamRiver	14.5	6.1	7.884	0.012	0.56
6170	Pleasant Prairie	1049	LF	14783669		143	100	StreamRiver	89.3	4.3	2.753	1.2	0.64
6004	Pleasants Power Station	17	SI	15433660	McElroys Run	113	67	StreamRiver	87.8	4.6	4.474	2.5	0.85
6004	Pleasants Power Station	17	SI	15434036	Forest City Lake	1483	17	LakePond	87.3	2.3	1.085	38	0.76
6004	Pleasants Power Station	17	SI	15434040	Ohio River	735	17	ArtificialPath	87.5	2.2	2.502	43,994	3.0
6004	Pleasants Power Station	1050	LF	15433660	McElroys Run	210	88	StreamRiver	87.8	4.6	4.474	2.5	0.85
6004	Pleasants Power Station	1050	LF	15434040	Ohio River	794	13	ArtificialPath	87.5	2.2	2.502	43,994	3.0
7242	Polk	1051	LF	16801745	Little Payne Creek	636	100	StreamRiver	139.7	34.9	6.028	12	0.79
3113	Portland	1020	LF	2587865	Martins Creek	516	100	StreamRiver	316.8	15.4	6.508	32	1.2
3113	Portland	1041	LF	2588325				ArtificialPath	309.8	3.5	2.543	8,342	2.8
3113	Portland	1043	LF	2587865	Martins Creek	599	100	StreamRiver	316.8	15.4	6.508	32	1.2

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
3113	Portland	1052	LF	2587865	Martins Creek	678	100	StreamRiver	316.8	15.4	6.508	32	1.2
3113	Portland	1199	SI	2588325	Delaware River	48	100	ArtificialPath	309.8	3.5	2.543	8,342	2.8
3113	Portland	1200	SI	2588325	Delaware River	55	100	ArtificialPath	309.8	3.5	2.543	8,342	2.8
3113	Portland	1201	SI	2588325	Delaware River	78	100	ArtificialPath	309.8	3.5	2.543	8,342	2.8
879	Powerton	1227	SI	13605832		95	63	StreamRiver	78.8	1.1	0.925	0.27	0.53
879	Powerton	1227	SI	13605926	Lost Creek	225	38	StreamRiver	77.4	9.9	5.442	16	1.0
879	Powerton	1228	SI	13605832		373	100	StreamRiver	78.8	1.1	0.925	0.27	0.53
879	Powerton	1229	SI	13605832		33	100	StreamRiver	78.8	1.1	0.925	0.27	0.53
879	Powerton	1230	SI	13605832		183	75	StreamRiver	78.8	1.1	0.925	0.27	0.53
879	Powerton	1230	SI	13605926	Lost Creek	185	25	StreamRiver	77.4	9.9	5.442	16	1.0
879	Powerton	1231	SI	13605832		12	100	StreamRiver	78.8	1.1	0.925	0.27	0.53
879	Powerton	1232	SI	13605832		251	17	StreamRiver	78.8	1.1	0.925	0.27	0.53
879	Powerton	1232	SI	13605926	Lost Creek	70	83	StreamRiver	77.4	9.9	5.442	16	1.0
879	Powerton	1233	SI	13605832		195	25	StreamRiver	78.8	1.1	0.925	0.27	0.53
879	Powerton	1233	SI	13605926	Lost Creek	57	75	StreamRiver	77.4	9.9	5.442	16	1.0
3140	PPL Brunner Island	93	SI	4721375		100	75	StreamRiver	230.4	0.6	0.852	6.9	0.76
3140	PPL Brunner Island	93	SI	4722219		68	25	ArtificialPath	231.4	0.5	1.022	7.1	0.80
3140	PPL Brunner Island	94	SI	4721375		99	100	StreamRiver	230.4	0.6	0.852	6.9	0.76
3140	PPL Brunner Island	95	SI	4721427	Hartman Run	83	43	StreamRiver	226	4.3	4.589	6.1	0.93
3140	PPL Brunner Island	95	SI	4722211	Susquehanna River	7	57	ArtificialPath	231.9	9.2	3.642	37,472	2.9
3140	PPL Brunner Island	1114	LF	4721427	Hartman Run	122	38	StreamRiver	226	4.3	4.589	6.1	0.93
3140	PPL Brunner Island	1114	LF	4722211	Susquehanna River	95	63	ArtificialPath	231.9	9.2	3.642	37,472	2.9
3149	PPL Montour	96	SI	8151995				StreamRiver	216.8	3.2	2.792	28	0.94
3149	PPL Montour	97	SI	8151995				StreamRiver	216.8	3.2	2.792	28	0.94
3149	PPL Montour	98	SI	8151995				StreamRiver	216.8	3.2	2.792	28	0.94
3149	PPL Montour	99	SI	8151995				StreamRiver	216.8	3.2	2.792	28	0.94
3149	PPL Montour	100	SI	8151995				StreamRiver	216.8	3.2	2.792	28	0.94
3149	PPL Montour	1011	LF	8152033		9	100	StreamRiver	221.6	2.9	1.939	2.7	0.68
3149	PPL Montour	1115	LF	8152033		465	100	StreamRiver	221.6	2.9	1.939	2.7	0.68
1073	Prairie Creek	487	SI	22477477				StreamRiver	72	5.7	3.096	109	1.1
1073	Prairie Creek	488	SI	22477477				StreamRiver	72	5.7	3.096	109	1.1
1073	Prairie Creek	489	SI	22477477				StreamRiver	72	5.7	3.096	109	1.1
1073	Prairie Creek	490	SI	22477477				StreamRiver	72	5.7	3.096	109	1.1
1073	Prairie Creek	491	SI	22477477				StreamRiver	72	5.7	3.096	109	1.1
1073	Prairie Creek	492	SI	22477477				StreamRiver	72	5.7	3.096	109	1.1
1073	Prairie Creek	493	SI	22477477				StreamRiver	72	5.7	3.096	109	1.1
1073	Prairie Creek	494	SI	22477477				StreamRiver	72	5.7	3.096	109	1.1

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
1073	Prairie Creek	495	SI	22477477				StreamRiver	72	5.7	3.096	109	1.1
1073	Prairie Creek	496	SI	22477477				StreamRiver	72	5.7	3.096	109	1.1
1769	Presque Isle	1012	LF	12025972		453	13	StreamRiver	276.2	0.4	0.884	163	1.0
1769	Presque Isle	1012	LF	12026272	Compeau Creek	186	88	StreamRiver	275.9	18.4	9.277	8.1	0.57
1769	Presque Isle	1013	LF	12026272	Compeau Creek	62	100	StreamRiver	275.9	18.4	9.277	8.1	0.57
1769	Presque Isle	1014	LF	12026272	Compeau Creek	141	100	StreamRiver	275.9	18.4	9.277	8.1	0.57
2403	PSEG Hudson Generating Station	1015	LF	6250804		58	33	StreamRiver	220	6.5	3.41	5.9	0.70
2403	PSEG Hudson Generating Station	1015	LF	6251356	Hackensack River	50	33	ArtificialPath	214	2.6	1.839	358	1.2
2403	PSEG Hudson Generating Station	1015	LF	6254202		35	33	ArtificialPath	212.5	0.1	0.3	6.0	0.54
2403	PSEG Hudson Generating Station	1351	SI	6250804		8	100	StreamRiver	220	6.5	3.41	5.9	0.70
2403	PSEG Hudson Generating Station	1352	SI	6250804		125	38	StreamRiver	220	6.5	3.41	5.9	0.70
2403	PSEG Hudson Generating Station	1352	SI	6254202		256	63	ArtificialPath	212.5	0.1	0.3	6.0	0.54
2408	PSEG Mercer Generating Station	1016	LF	4480871		166	50	StreamRiver	231.9	0.3	0.539	2.0	0.44
2408	PSEG Mercer Generating Station	1016	LF	4481751	Crosswicks Creek	222	25	ArtificialPath	236	1.3	0.892	201	1.3
2408	PSEG Mercer Generating Station	1016	LF	4481951		12	25	LakePond	232.1	0.4	0.858	2.2	0.67
2408	PSEG Mercer Generating Station	1197	SI	4480891		83	100	CanalDitch	229.2	1.5	1.956	0.91	0.39
2408	PSEG Mercer Generating Station	1198	SI	4480891		135	100	CanalDitch	229.2	1.5	1.956	0.91	0.39
4072	Pulliam	1017	LF	6802232	Green Bay	115	25	Coastline	113	1.2	1.517		
4072	Pulliam	1017	LF	6802234	Green Bay	45	75	Coastline	113	0.3	0.685		
4072	Pulliam	1212	SI	6802234	Green Bay	115	100	Coastline	113	0.3	0.685		
1295	Quindaro	1030	LF	2255479	Missouri River	79	100	ArtificialPath	47	11.1	4.257	62,047	4.7
6639	R D Green	220	SI	11617021	Groves Creek	611	25	StreamRiver	84	0.9	1.184	41	1.1
6639	R D Green	220	SI	11617335	Green River	148	75	ArtificialPath	83.8	11.1	6.149	12,480	2.3
6639	R D Green	1019	LF	11617021	Groves Creek	437	50	StreamRiver	84	0.9	1.184	41	1.1
6639	R D Green	1019	LF	11617335	Green River	144	50	ArtificialPath	83.8	11.1	6.149	12,480	2.3

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
2864	R. E. Burger	976	LF	19455275				ArtificialPath	141.5	0.0	0.124	41,857	3.0
2864	R. E. Burger	1380	SI	19455277	Ohio River	34	100	ArtificialPath	143.9	4.3	2.693	41,859	3.0
2864	R. E. Burger	1381	SI	19455277	Ohio River	248	100	ArtificialPath	143.9	4.3	2.693	41,859	3.0
1008	R. Gallagher	460	SI	10163876		41	100	StreamRiver	109.6	3.4	3.554	1.6	0.62
1008	R. Gallagher	461	SI	10163876		406	50	StreamRiver	109.6	3.4	3.554	1.6	0.62
1008	R. Gallagher	461	SI	10164012	Ohio River	13	50	ArtificialPath	109.7	37.5	5.704	123,503	3.7
1008	R. Gallagher	1001	LF	10164012				ArtificialPath	109.7	37.5	5.704	123,503	3.7
1008	R. Gallagher	1023	LF	10164012				ArtificialPath	109.7	37.5	5.704	123,503	3.7
1008	R. Gallagher	1024	LF	10164012				ArtificialPath	109.7	37.5	5.704	123,503	3.7
1008	R. Gallagher	1025	LF	10164012				ArtificialPath	109.7	37.5	5.704	123,503	3.7
1008	R. Gallagher	1026	LF	10164012				ArtificialPath	109.7	37.5	5.704	123,503	3.7
1008	R. Gallagher	1027	LF	10164012				ArtificialPath	109.7	37.5	5.704	123,503	3.7
1008	R. Gallagher	1029	LF	10164012				ArtificialPath	109.7	37.5	5.704	123,503	3.7
1008	R. Gallagher	1053	LF	10164012				ArtificialPath	109.7	37.5	5.704	123,503	3.7
1008	R. Gallagher	1056	LF	10164012				ArtificialPath	109.7	37.5	5.704	123,503	3.7
1570	R. Paul Smith Power Station	561	SI	5891920	Potomac River	22	100	ArtificialPath	199.2	5.1	2.205	6,633	2.1
1570	R. Paul Smith Power Station	562	SI	5891920	Potomac River	5	100	ArtificialPath	199.2	5.1	2.205	6,633	2.1
1570	R. Paul Smith Power Station	1083	LF	5891548		304	25	StreamRiver	199.9	2.8	2.628	1.0	0.79
1570	R. Paul Smith Power Station	1083	LF	5891920	Potomac River	373	75	ArtificialPath	199.2	5.1	2.205	6,633	2.1
2790	R.M. Heskett Station	1080	LF	14523377	Rock Haven Creek	51	100	StreamRiver	5	7.1	4.211	0.0063	0.66
2790	R.M. Heskett Station	1081	LF	14523377	Rock Haven Creek	30	83	StreamRiver	5	7.1	4.211	0.0063	0.66
2790	R.M. Heskett Station	1081	LF	14523603	Rock Haven Creek	313	17	ArtificialPath	5	0.2	0.495	0.011	0.22
6085	R.M. Schahfer	54	SI	13436733		82	100	StreamRiver	157.2	0.4	0.453	15	0.64
6085	R.M. Schahfer	55	SI	13436733		631	100	StreamRiver	157.2	0.4	0.453	15	0.64
6085	R.M. Schahfer	56	SI	13436723		583	100	StreamRiver	151.4	42.1	3.1	28	0.90
6085	R.M. Schahfer	57	SI	13434629	Kankakee River	33	100	StreamRiver	170.1	31.7	2.012	1,127	1.5
6085	R.M. Schahfer	58	SI	13436723		759	100	StreamRiver	151.4	42.1	3.1	28	0.90
6085	R.M. Schahfer	67	SI	13434629	Kankakee River	849	25	StreamRiver	170.1	31.7	2.012	1,127	1.5
6085	R.M. Schahfer	67	SI	13436723		824	75	StreamRiver	151.4	42.1	3.1	28	0.90
6085	R.M. Schahfer	68	SI	13436723		168	75	StreamRiver	151.4	42.1	3.1	28	0.90
6085	R.M. Schahfer	68	SI	13436733		431	25	StreamRiver	157.2	0.4	0.453	15	0.64
6085	R.M. Schahfer	1082	LF	13434629	Kankakee River	91	100	StreamRiver	170.1	31.7	2.012	1,127	1.5

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
6761	Rawhide	225	SI	2898303				StreamRiver	13	2.9	4.417	1.1	0.96
6761	Rawhide	226	SI	2898303				StreamRiver	13	2.9	4.417	1.1	0.96
6761	Rawhide	996	LF	2898303				StreamRiver	13	2.9	4.417	1.1	0.96
6761	Rawhide	1086	LF	2898203		175	50	StreamRiver	13	1.5	2.801	0.032	0.63
6761	Rawhide	1086	LF	2898315		10	50	StreamRiver	13	4.8	4.998	0.11	0.71
8219	Ray D Nixon	1087	LF	1530503		31	50	StreamRiver	9.4	3.2	3.059	0.53	0.75
8219	Ray D Nixon	1087	LF	1531245		28	50	StreamRiver	9.3	3.7	4.761	2.4	0.93
8219	Ray D Nixon	1255	SI	1530449	Little Fountain Creek	45	100	StreamRiver	9.7	0.8	1.156	23	1.3
55076	Red Hills Generating Facility	1088	LF	15778976		723	13	StreamRiver	120	1.7	2.277	0.89	0.68
55076	Red Hills Generating Facility	1088	LF	19221367		97	88	StreamRiver	120	2.3	2.501	1.2	0.74
55076	Red Hills Generating Facility	1256	SI	19221367		20	100	StreamRiver	120	2.3	2.501	1.2	0.74
2324	Reid Gardner	630	SI	20624280		178	100	StreamRiver	4	70.0	13.352	193	2.2
2324	Reid Gardner	631	SI	20624280		370	100	StreamRiver	4	70.0	13.352	193	2.2
2324	Reid Gardner	632	SI	20624280		89	100	StreamRiver	4	70.0	13.352	193	2.2
2324	Reid Gardner	633	SI	20624280		27	100	StreamRiver	4	70.0	13.352	193	2.2
2324	Reid Gardner	634	SI	20624280		13	100	StreamRiver	4	70.0	13.352	193	2.2
2324	Reid Gardner	635	SI	20624280		50	100	StreamRiver	4	70.0	13.352	193	2.2
2324	Reid Gardner	636	SI	20624280		200	100	StreamRiver	4	70.0	13.352	193	2.2
2324	Reid Gardner	637	SI	20624280		99	100	StreamRiver	4	70.0	13.352	193	2.2
2324	Reid Gardner	1090	LF	20624280				StreamRiver	4	70.0	13.352	193	2.2
1740	River Rouge Power Plant	1186	SI	10850250	Detroit River	117	100	ArtificialPath	82.5	11.0	5.711	2,097	1.7
2732	Riverbend	681	SI	9755520	Catawba River	99	100	LakePond	143.4	4.4	3.335	3,383	1.8
2732	Riverbend	682	SI	9755520	Catawba River	291	75	LakePond	143.4	4.4	3.335	3,383	1.8
2732	Riverbend	682	SI	9755522	Catawba River	234	25	ArtificialPath	148.4	8.6	3.788	3,380	1.8
1081	Riverside	500	SI	14803985	Crow Creek	221	17	StreamRiver	92.3	1.6	1.281	12	1.0
1081	Riverside	500	SI	14804491	Crow Creek	36	33	ArtificialPath	91.4	0.4	0.663	12	0.89
1081	Riverside	500	SI	14804493	Mississippi River	32	50	ArtificialPath	91	2.3	1.371	48,707	3.2
1081	Riverside	501	SI	14804493	Mississippi River	45	100	ArtificialPath	91	2.3	1.371	48,707	3.2
1927	Riverside	594	SI	1100714				ArtificialPath	73	9.2	3.784	8,935	2.6
1239	Riverton	512	SI	7591065	Lowell Reservoir	4	75	LakePond	103.5	4.3	1.851	1,384	1.5
1239	Riverton	512	SI	7591153		442	25	LakePond	102.7	0.8	0.247	0.27	0.46

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
3945	Rivesville Power Station	1095	LF	3769538	Parker Run	162	100	StreamRiver	150	4.1	2.923	3.1	0.89
3945	Rivesville Power Station	1116	LF	3769538	Parker Run	683	38	StreamRiver	150	4.1	2.923	3.1	0.89
3945	Rivesville Power Station	1116	LF	3769820	Monongahela River	561	63	ArtificialPath	149.9	9.6	5.956	4,888	1.9
3945	Rivesville Power Station	1355	SI	3769828	Monongahela River	60	100	ArtificialPath	150	1.3	1.195	4,816	2.2
3945	Rivesville Power Station	1356	SI	3769828	Monongahela River	62	100	ArtificialPath	150	1.3	1.195	4,816	2.2
3945	Rivesville Power Station	1357	SI	3769820	Monongahela River	379	100	ArtificialPath	149.9	9.6	5.956	4,888	1.9
3945	Rivesville Power Station	1358	SI	3769542	Pharaoh Run	143	13	StreamRiver	150	4.5	3.55	6.7	0.96
3945	Rivesville Power Station	1358	SI	3769828	Monongahela River	75	88	ArtificialPath	150	1.3	1.195	4,816	2.2
6166	Rockport	179	SI	10110119		388	13	StreamRiver	114	3.6	3.783	2.2	0.56
6166	Rockport	179	SI	10110131		2420	88	StreamRiver	117.5	4.1	2.312	32	1.1
6166	Rockport	1097	LF	10110119				StreamRiver	114	3.6	3.783	2.2	0.56
6190	Rodemacher	185	SI	19918814	Jean De Jean Bayou	90	100	StreamRiver	164.1	2.5	4.824	96	0.91
6190	Rodemacher	186	SI	19918814	Jean De Jean Bayou	24	100	StreamRiver	164.1	2.5	4.824	96	0.91
6190	Rodemacher	187	SI	19919248	Red River	415	33	ArtificialPath	162.8	2.1	2.65	31,015	2.9
6190	Rodemacher	187	SI	19919336		7	67	LakePond	163.5	1.1	0.906	0.49	0.52
2712	Roxboro Steam Electric Plant	661	SI	8701445	Hyco Lake	43	100	LakePond	98.1	3.8	3.522	4.6	0.71
2712	Roxboro Steam Electric Plant	662	SI	8693605	Ghent Creek	409	50	StreamRiver	92.9	1.8	2.543	6.1	0.86
2712	Roxboro Steam Electric Plant	662	SI	8696103	Ghent Creek	174	50	StreamRiver	95.2	3.2	2.037	5.5	0.75
2712	Roxboro Steam Electric Plant	663	SI	8701445				LakePond	98.1	3.8	3.522	4.6	0.71
2712	Roxboro Steam Electric Plant	664	SI	8701445	Hyco Lake	9	100	LakePond	98.1	3.8	3.522	4.6	0.71
2712	Roxboro Steam Electric Plant	1096	LF	8701437	Hyco Lake	999	100	LakePond	97.7	6.2	1.241	167	1.0
1393	RS Nelson	1084	LF	3709730	Verdine, Bayou	106	63	StreamRiver	99.9	8.0	3.08	4.2	0.64

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
1393	RS Nelson	1084	LF	15075536	West Fork Calcasieu River	1698	38	ArtificialPath	100	5.5	2.87	943	1.4
1393	RS Nelson	1085	LF	3709730	Verdine, Bayou	310	88	StreamRiver	99.9	8.0	3.08	4.2	0.64
1393	RS Nelson	1085	LF	15075546	Houston River	1195	13	StreamRiver	99.7	18.1	13.086	484	0.82
1393	RS Nelson	1329	SI	15075536	West Fork Calcasieu River	1878	100	ArtificialPath	100	5.5	2.87	943	1.4
1393	RS Nelson	1330	SI	15075546	Houston River	268	100	StreamRiver	99.7	18.1	13.086	484	0.82
6155	Rush Island	178	SI	3629181				ArtificialPath	55	2.1	2.057	176,931	4.2
6155	Rush Island	1091	LF	3629181				ArtificialPath	55	2.1	2.057	176,931	4.2
2451	San Juan	1308	SI	17001804	Westwater Arroyo	404	50	StreamRiver	12	1.6	1.045	1.4	0.99
2451	San Juan	1308	SI	17001806		54	50	StreamRiver	12	1.1	2.423	0.016	0.62
6183	San Miguel	1093	LF	10828296		643	100	StreamRiver	6	5.3	3.651	0.52	0.72
6183	San Miguel	1094	LF	10671315		84	100	StreamRiver	6	2.6	1.689	0.15	0.64
6183	San Miguel	1365	SI	10828244		23	50	StreamRiver	6.9	2.5	1.967	2.5	0.83
6183	San Miguel	1365	SI	10828254		96	25	StreamRiver	6.4	2.6	3.669	1.6	0.76
6183	San Miguel	1365	SI	10828730	Souse Creek	59	25	LakePond	6	0.0	0.061	1.1	0.42
6183	San Miguel	1366	SI	10828642	Souse Creek	187	100	StreamRiver	6.1	10.3	6.166	1.1	0.79
6183	San Miguel	1367	SI	10828642	Souse Creek	280	100	StreamRiver	6.1	10.3	6.166	1.1	0.79
6648	Sandow No 4	221	SI	5566231				StreamRiver	29	2.6	0.559	0.23	0.72
6648	Sandow No 4	1057	LF	5566231				StreamRiver	29	2.6	0.559	0.23	0.72
6648	Sandow No 4	1065	LF	5566241	East Yegua Creek	657	100	StreamRiver	28	11.0	3.813	0.97	0.84
6648	Sandow No 4	1067	LF	5566241	East Yegua Creek	1217	100	StreamRiver	28	11.0	3.813	0.97	0.84
6648	Sandow No 4	1089	LF	5566231		1471	38	StreamRiver	29	2.6	0.559	0.23	0.72
6648	Sandow No 4	1089	LF	5566241	East Yegua Creek	292	25	StreamRiver	28	11.0	3.813	0.97	0.84
6648	Sandow No 4	1089	LF	5566547	East Yegua Creek	46	38	LakePond	28.3	1.1	0.992	1.1	0.73
6648	Sandow No 4	1092	LF	5566241	East Yegua Creek	551	100	StreamRiver	28	11.0	3.813	0.97	0.84
6257	Scherer	209	SI	6336802				LakePond	177	0.1	0.183	0.97	0.69
6257	Scherer	210	SI	6336802				LakePond	177	0.1	0.183	0.97	0.69
2367	SCHILLER	1058	LF	5845176		272	20	StreamRiver	267.1	8.8	3.414	1.3	0.67
2367	SCHILLER	1058	LF	5846414	Piscataqua River	21	80	ArtificialPath	268.2	3.4	2.169	1,484	1.5
642	Scholz	1346	SI	902800005	Apalachicola River	437	100	ArtificialPath	285.6	49.1	4.702	24,243	2.7

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
642	Scholz	1347	SI	902800005	Apalachicola River	416	100	ArtificialPath	285.6	49.1	4.702	24,243	2.7
642	Scholz	1348	SI	902800005	Apalachicola River	502	100	ArtificialPath	285.6	49.1	4.702	24,243	2.7
136	Seminole Generating Station	1059	LF	16664705		1860	100	StreamRiver	128.9	9.6	2.022	3.9	0.65
1379	Shawnee	551	SI	1840007				ArtificialPath	63.4	8.5	3.795	287,058	4.4
1379	Shawnee	552	SI	1840007				ArtificialPath	63.4	8.5	3.795	287,058	4.4
1379	Shawnee	1060	LF	1839881	Little Bayou Creek	635	100	StreamRiver	65.4	16.6	6.749	12	0.88
1379	Shawnee	1061	LF	1840007				ArtificialPath	63.4	8.5	3.795	287,058	4.4
3131	Shawville	1062	LF	4672489	West Branch Susquehanna River	580	13	ArtificialPath	257.8	0.9	1.196	1,482	1.4
3131	Shawville	1062	LF	4672491	Bloody Run	831	13	ArtificialPath	259	0.0	0.041	1.3	0.82
3131	Shawville	1062	LF	4672501	West Branch Susquehanna River	698	50	ArtificialPath	253.3	3.6	2.668	1,551	1.7
3131	Shawville	1062	LF	4672505	West Branch Susquehanna River	649	25	ArtificialPath	254.8	1.8	1.48	1,480	1.8
3131	Shawville	1063	LF	4672489	West Branch Susquehanna River	626	13	ArtificialPath	257.8	0.9	1.196	1,482	1.4
3131	Shawville	1063	LF	4672501	West Branch Susquehanna River	934	25	ArtificialPath	253.3	3.6	2.668	1,551	1.7
3131	Shawville	1063	LF	4672505	West Branch Susquehanna River	523	63	ArtificialPath	254.8	1.8	1.48	1,480	1.8
3131	Shawville	1245	SI	4672489	West Branch Susquehanna River	7	100	ArtificialPath	257.8	0.9	1.196	1,482	1.4
3131	Shawville	1246	SI	4672505	West Branch Susquehanna River	15	100	ArtificialPath	254.8	1.8	1.48	1,480	1.8
3131	Shawville	1247	SI	4672505	West Branch Susquehanna River	7	100	ArtificialPath	254.8	1.8	1.48	1,480	1.8

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
3131	Shawville	1248	SI	4672505	West Branch Susquehanna River	16	100	ArtificialPath	254.8	1.8	1.48	1,480	1.8
2277	Sheldon Station	1055	LF	17405763		494	88	StreamRiver	30.8	7.6	3.275	0.28	0.76
2277	Sheldon Station	1055	LF	17405987	Salt Creek Reservoir 13-A	268	13	LakePond	30.5	2.1	0.369	0.23	0.32
2277	Sheldon Station	1064	LF	17405763		810	38	StreamRiver	30.8	7.6	3.275	0.28	0.76
2277	Sheldon Station	1064	LF	17405987	Salt Creek Reservoir 13-A	313	63	LakePond	30.5	2.1	0.369	0.23	0.32
2277	Sheldon Station	1066	LF	17405987	Salt Creek Reservoir 13-A	124	100	LakePond	30.5	2.1	0.369	0.23	0.32
2277	Sheldon Station	1078	LF	17405987	Salt Creek Reservoir 13-A	436	100	LakePond	30.5	2.1	0.369	0.23	0.32
2277	Sheldon Station	1360	SI	17405987	Salt Creek Reservoir 13-A	188	100	LakePond	30.5	2.1	0.369	0.23	0.32
6090	Sherburne County	69	SI	2723115	Mississippi River	779	100	ArtificialPath	72	20.7	5.526	6,727	2.2
6090	Sherburne County	70	SI	2723115	Mississippi River	323	100	ArtificialPath	72	20.7	5.526	6,727	2.2
6090	Sherburne County	71	SI	2723115	Mississippi River	354	100	ArtificialPath	72	20.7	5.526	6,727	2.2
6090	Sherburne County	72	SI	2723115				ArtificialPath	72	20.7	5.526	6,727	2.2
6090	Sherburne County	73	SI	2723115	Mississippi River	920	63	ArtificialPath	72	20.7	5.526	6,727	2.2
6090	Sherburne County	73	SI	2723123	Mississippi River	1221	38	ArtificialPath	72.5	13.6	1.374	6,730	2.1
6090	Sherburne County	74	SI	2723115				ArtificialPath	72	20.7	5.526	6,727	2.2
6090	Sherburne County	1068	LF	2723105	Mississippi River	833	100	ArtificialPath	72.3	17.3	2.25	6,724	2.8
2094	Sibley	603	SI	4391311				ArtificialPath	45.7	21.9	2.416	65,158	3.5
2094	Sibley	604	SI	4391311				ArtificialPath	45.7	21.9	2.416	65,158	3.5
2094	Sibley	1069	LF	4391319	Missouri River	112	100	ArtificialPath	45.1	3.1	2.545	65,158	3.5
6768	Sikeston Power Station	227	SI	758572		131	100	StreamRiver	136.2	5.8	2.624	2.7	0.67
6768	Sikeston Power Station	228	SI	758572		194	63	StreamRiver	136.2	5.8	2.624	2.7	0.67
6768	Sikeston Power Station	228	SI	758654	Ash Slough Ditch	897	38	CanalDitch	150.2	7.4	4.378	29	0.84
2107	Sioux	614	SI	880570				LakePond	39.2	2.5	1.584	0.71	0.38
2107	Sioux	615	SI	880570				LakePond	39.2	2.5	1.584	0.71	0.38

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
1058	Sixth Street	483	SI	22477721	West Fork Cedar River	773	100	ArtificialPath	71.7	29.8	1.009	3,062	1.8
1058	Sixth Street	484	SI	22477721	West Fork Cedar River	838	100	ArtificialPath	71.7	29.8	1.009	3,062	1.8
1058	Sixth Street	485	SI	22477721	West Fork Cedar River	776	100	ArtificialPath	71.7	29.8	1.009	3,062	1.8
1058	Sixth Street	486	SI	22477721	West Fork Cedar River	733	100	ArtificialPath	71.7	29.8	1.009	3,062	1.8
1613	Somerset Station	566	SI	6130213				ArtificialPath	352.7	1.8	1.296	957	1.1
1613	Somerset Station	567	SI	6130213				ArtificialPath	352.7	1.8	1.296	957	1.1
1613	Somerset Station	568	SI	6130213				ArtificialPath	352.7	1.8	1.296	957	1.1
1613	Somerset Station	569	SI	6130213				ArtificialPath	352.7	1.8	1.296	957	1.1
6095	Sooner	1259	SI	20970046	Cat Creek	1680	63	StreamRiver	14	4.6	4.105	0.52	0.71
6095	Sooner	1259	SI	20970180	Coon Creek	1641	38	StreamRiver	16.7	11.6	9.029	1.3	0.79
6095	Sooner	1260	SI	20970156		883	100	StreamRiver	15.6	6.2	4.364	0.70	0.75
6061	South Mississippi El Pwr Assn	1008	LF	18104286	Spring Creek	571	13	StreamRiver	216.1	2.2	2.993	1.3	0.73
6061	South Mississippi El Pwr Assn	1008	LF	18104316	Black Creek	118	88	StreamRiver	217	3.5	2.641	230	1.4
6061	South Mississippi El Pwr Assn	1021	LF	18104286	Spring Creek	331	38	StreamRiver	216.1	2.2	2.993	1.3	0.73
6061	South Mississippi El Pwr Assn	1021	LF	18104316	Black Creek	278	63	StreamRiver	217	3.5	2.641	230	1.4
6061	South Mississippi El Pwr Assn	1022	LF	18104316	Black Creek	101	100	StreamRiver	217	3.5	2.641	230	1.4
6061	South Mississippi El Pwr Assn	1353	SI	18104286	Spring Creek	788	13	StreamRiver	216.1	2.2	2.993	1.3	0.73
6061	South Mississippi El Pwr Assn	1353	SI	18104316	Black Creek	554	88	StreamRiver	217	3.5	2.641	230	1.4
6061	South Mississippi El Pwr Assn	1354	SI	18104316	Black Creek	801	100	StreamRiver	217	3.5	2.641	230	1.4
4041	South Oak Creek	1070	LF	12169039		941	63	StreamRiver	76	4.0	2.427	0.95	0.77
4041	South Oak Creek	1070	LF	12169263		877	38	StreamRiver	77.8	6.5	3.303	1.5	0.67
4041	South Oak Creek	1071	LF	12169329		166	100	Coastline	75.5	9.3	7.337		
4041	South Oak Creek	1072	LF	12169263		899	100	StreamRiver	77.8	6.5	3.303	1.5	0.67
6195	Southwest Power Station	1073	LF	7607249	Wilsons Creek	201	50	StreamRiver	101.6	0.7	0.954	48	1.1
6195	Southwest Power Station	1073	LF	7607261	Wilsons Creek	563	50	StreamRiver	103	1.4	0.829	50	1.2

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
6195	Southwest Power Station	1074	LF	7607261	Wilsons Creek	805	63	StreamRiver	103	1.4	0.829	50	1.2
6195	Southwest Power Station	1074	LF	7607293		795	38	StreamRiver	104.5	3.6	2.656	1.1	0.78
6195	Southwest Power Station	1268	SI	7607261	Wilsons Creek	958	100	StreamRiver	103	1.4	0.829	50	1.2
6195	Southwest Power Station	1269	SI	7607261	Wilsons Creek	974	100	StreamRiver	103	1.4	0.829	50	1.2
8223	Springerville	1075	LF	20584624		893	50	StreamRiver	11	10.7	7.975	0.020	0.76
8223	Springerville	1075	LF	21762216		659	17	StreamRiver	11	11.6	3.809	0.014	0.68
8223	Springerville	1075	LF	21762258		146	33	StreamRiver	11	13.9	11.778	0.087	0.86
8223	Springerville	1384	SI	20584624		83	100	StreamRiver	11	10.7	7.975	0.020	0.76
1743	St Clair Power Plant	584	SI	13196020				ArtificialPath	69.1	13.0	13.448	721	1.4
207	St Johns River Power Park	1018	LF	16659333		59	100	StreamRiver	125.3	1.3	1.375	0.51	0.58
207	St Johns River Power Park	1076	LF	16659333		662	50	StreamRiver	125.3	1.3	1.375	0.51	0.58
207	St Johns River Power Park	1076	LF	16659871	San Carlos Creek	2410	50	ArtificialPath	126.1	1.3	0.211	2.4	0.53
207	St Johns River Power Park	1077	LF	16659331		201	50	StreamRiver	124.5	1.1	0.799	0.45	0.52
207	St Johns River Power Park	1077	LF	16659685		1305	50	ArtificialPath	124.2	1.2	0.675	0.51	0.35
2824	Stanton	690	SI	14519595	Missouri River	530	100	ArtificialPath	4	1.8	2.578	43,597	3.7
2824	Stanton	691	SI	14519595	Missouri River	400	100	ArtificialPath	4	1.8	2.578	43,597	3.7
2824	Stanton	692	SI	14519595	Missouri River	614	100	ArtificialPath	4	1.8	2.578	43,597	3.7
2824	Stanton	937	LF	14518731		456	38	StreamRiver	4.7	9.4	7.089	0.0084	0.67
2824	Stanton	937	LF	14519463		875	63	StreamRiver	4.6	5.8	4.154	0.035	0.80
2824	Stanton	940	LF	14519605		18	100	Reservoir	4	0.4	0.415	0.040	0.25
2824	Stanton	997	LF	14519463		556	100	StreamRiver	4.6	5.8	4.154	0.035	0.80
564	Stanton Energy Center	942	LF	10997353		2879	38	StreamRiver	134.3	14.8	2.531	5.3	0.79
564	Stanton Energy Center	942	LF	11008205	Cowpen Branch	2995	13	StreamRiver	142.8	10.9	1.347	3.9	0.77
564	Stanton Energy Center	942	LF	11008233		6449	25	StreamRiver	141.4	8.5	1.796	3.0	0.71
564	Stanton Energy Center	942	LF	11009165	Hart Branch	2609	25	StreamRiver	144.4	4.0	1.786	1.4	0.70
1131	Streeter Station	1028	LF	22472175	West Fork Cedar River	1334	100	ArtificialPath	81.4	26.5	4.878	2,184	1.9
3152	Sunbury Generation LP	101	SI	4517358	Rolling Green Run	90	100	StreamRiver	240.7	4.7	5.233	2.6	0.88

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
50951	Sunnyside Cogen Associates	944	LF	3908507	Grassy Trail Creek	40	100	StreamRiver	11.7	4.6	5.375	12	1.4
1077	Sutherland	497	SI	17538901	Iowa River	959	50	StreamRiver	73.1	4.7	3.928	805	1.7
1077	Sutherland	497	SI	17538959		959	50	StreamRiver	72.3	3.1	0.834	0.64	0.69
1077	Sutherland	498	SI	17538901	Iowa River	1148	88	StreamRiver	73.1	4.7	3.928	805	1.7
1077	Sutherland	498	SI	17538959		1082	13	StreamRiver	72.3	3.1	0.834	0.64	0.69
1077	Sutherland	499	SI	17538959		999	100	StreamRiver	72.3	3.1	0.834	0.64	0.69
1077	Sutherland	1117	LF	17538831	Nickolson Creek	85	100	StreamRiver	73.6	4.4	3.191	2.8	0.83
1077	Sutherland	1118	LF	17538831	Nickolson Creek	202	100	StreamRiver	73.6	4.4	3.191	2.8	0.83
10075	Taconite Harbor Energy Center	947	LF	4798258		178	100	StreamRiver	170.9	3.3	3.122	16	1.1
10075	Taconite Harbor Energy Center	948	LF	4798258		162	100	StreamRiver	170.9	3.3	3.122	16	1.1
10075	Taconite Harbor Energy Center	961	LF	4798258		170	100	StreamRiver	170.9	3.3	3.122	16	1.1
988	Tanners Creek	415	SI	3406123				ArtificialPath	70.4	1.8	1.929	111,358	3.6
988	Tanners Creek	416	SI	3405453	Tanners Creek	32	20	StreamRiver	70	0.2	0.355	107	0.93
988	Tanners Creek	416	SI	3406123	Ohio River	116	20	ArtificialPath	70.4	1.8	1.929	111,358	3.6
988	Tanners Creek	416	SI	3406125	Tanners Creek	23	60	ArtificialPath	70.1	0.3	0.569	107	0.93
988	Tanners Creek	417	SI	3405491		29	86	StreamRiver	70.2	1.9	2.174	0.74	0.76
988	Tanners Creek	417	SI	3406133	Ohio River	354	14	ArtificialPath	70.5	3.0	1.551	111,466	3.6
988	Tanners Creek	418	SI	3405491		33	100	StreamRiver	70.2	1.9	2.174	0.74	0.76
988	Tanners Creek	419	SI	3405491		21	86	StreamRiver	70.2	1.9	2.174	0.74	0.76
988	Tanners Creek	419	SI	3406133	Ohio River	324	14	ArtificialPath	70.5	3.0	1.551	111,466	3.6
988	Tanners Creek	950	LF	3405491		579	43	StreamRiver	70.2	1.9	2.174	0.74	0.76
988	Tanners Creek	950	LF	3406125	Tanners Creek	108	14	ArtificialPath	70.1	0.3	0.569	107	0.93
988	Tanners Creek	950	LF	3406133	Ohio River	11	43	ArtificialPath	70.5	3.0	1.551	111,466	3.6
1252	Tecumseh Energy Center	519	SI	3646684	Tecumseh Creek	6	100	StreamRiver	36.5	11.1	8.699	3.3	0.89
1252	Tecumseh Energy Center	520	SI	3646684	Tecumseh Creek	37	100	StreamRiver	36.5	11.1	8.699	3.3	0.89
1252	Tecumseh Energy Center	995	LF	3646866				ArtificialPath	38	0.1	0.41	2,337	1.8
1252	Tecumseh Energy Center	1120	LF	3646298		4	33	StreamRiver	38	0.6	1.595	0.11	0.64
1252	Tecumseh Energy Center	1120	LF	3646856	Kansas River	74	67	ArtificialPath	38	0.8	1.171	2,338	2.9

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
1252	Tecumseh Energy Center	1133	LF	3646298		47	100	StreamRiver	38	0.6	1.595	0.11	0.64
2168	Thomas Hill	624	SI	4461386	Middle Fork Little Chariton River	551	100	StreamRiver	38.3	7.2	3.155	48	1.1
2168	Thomas Hill	625	SI	4461582				LakePond	38.8	13.3	3.318	47	1.3
2168	Thomas Hill	626	SI	4461582				LakePond	38.8	13.3	3.318	47	1.3
2168	Thomas Hill	627	SI	4461386	Middle Fork Little Chariton River	636	100	StreamRiver	38.3	7.2	3.155	48	1.1
2168	Thomas Hill	628	SI	4461582				LakePond	38.8	13.3	3.318	47	1.3
2168	Thomas Hill	629	SI	4461582				LakePond	38.8	13.3	3.318	47	1.3
2168	Thomas Hill	953	LF	4461386	Middle Fork Little Chariton River	108	100	StreamRiver	38.3	7.2	3.155	48	1.1
3115	Titus	954	LF	4782753	Schuylkill River	21	100	ArtificialPath	300.1	8.7	6.204	1,353	2.0
3115	Titus	955	LF	4782323	Schuylkill River	77	50	ArtificialPath	297	11.8	3.234	1,331	1.5
3115	Titus	955	LF	4782753	Schuylkill River	842	50	ArtificialPath	300.1	8.7	6.204	1,353	2.0
3115	Titus	956	LF	4782753	Schuylkill River	139	100	ArtificialPath	300.1	8.7	6.204	1,353	2.0
3115	Titus	957	LF	4782753	Schuylkill River	135	100	ArtificialPath	300.1	8.7	6.204	1,353	2.0
6194	Tolk	1161	LF	13475965	Blackwater Draw	4296	100	Connector	2.2	598.2	13.555	36	1.5
3845	TransAlta Centralia Generation	959	LF	23850959	Hanaford Creek	395	38	StreamRiver	775.4	2.5	2.052	73	1.1
3845	TransAlta Centralia Generation	959	LF	23850961	Hanaford Creek	322	25	StreamRiver	824.4	8.7	6.586	59	1.1
3845	TransAlta Centralia Generation	959	LF	23851493	Packwood Creek	1185	38	StreamRiver	781	1.4	1.073	32	1.0
1745	Trenton Channel Power Plant	585	SI	10850286				ArtificialPath	88.1	1.4	0.872	2,144	1.7
1745	Trenton Channel Power Plant	960	LF	10849980	Huntington Creek	1127	63	StreamRiver	82.7	13.4	4.012	3.6	0.71
1745	Trenton Channel Power Plant	960	LF	10850316		878	38	ArtificialPath	87.7	4.3	1.85	2,142	1.7
6071	Trimble Co.	44	SI	10161564		437	63	StreamRiver	68.9	6.9	3.43	3.3	0.97
6071	Trimble Co.	44	SI	10161570	Corn Creek	623	38	StreamRiver	71.5	0.7	0.448	37	0.91
56224	TS Power Plant	816	LF	11206810				StreamRiver	12	18.7	10.928	2,438	2.2
7030	Twin Oaks Power One	928	LF	5555198	Bee Branch	123	100	StreamRiver	19.9	19.3	10.858	2.9	0.83
1361	Tyrone	536	SI	1825620	Kentucky River	49	100	ArtificialPath	108.8	7.5	3.874	7,293	2.2

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
1361	Tyrone	537	SI	1825620	Kentucky River	37	100	ArtificialPath	108.8	7.5	3.874	7,293	2.2
3295	Urquhart	110	SI	22724031				ArtificialPath	268	2.6	2.197	11,843	1.6
3295	Urquhart	111	SI	22724031	Savannah River	43	100	ArtificialPath	268	2.6	2.197	11,843	1.6
3295	Urquhart	112	SI	22724031				ArtificialPath	268	2.6	2.197	11,843	1.6
3295	Urquhart	1107	LF	22724031	Savannah River	26	100	ArtificialPath	268	2.6	2.197	11,843	1.6
4042	Valley	918	LF	12162414		827	100	StreamRiver	95	23.0	8.195	5.0	0.80
4042	Valley	919	LF	14767328	Fox River	2125	75	StreamRiver	86.8	5.2	1.028	74	1.1
4042	Valley	919	LF	14767352		1309	25	StreamRiver	83.8	1.7	0.842	1.6	0.79
4042	Valley	920	LF	14767308		40	100	StreamRiver	82.7	5.4	3.093	1.3	0.76
4042	Valley	949	LF	12169039		1133	100	StreamRiver	76	4.0	2.427	0.95	0.77
477	Valmont	329	SI	2889816				LakePond	29.1	3.9	3.048	173	1.0
477	Valmont	330	SI	2889816				LakePond	29.1	3.9	3.048	173	1.0
477	Valmont	331	SI	2889816				LakePond	29.1	3.9	3.048	173	1.0
477	Valmont	1122	LF	2889270		725	14	StreamRiver	31	0.6	0.989	0.33	0.58
477	Valmont	1122	LF	2889298		1932	29	StreamRiver	28.7	6.6	5.134	174	1.7
477	Valmont	1122	LF	2889816	Hillcrest Reservoir	15	57	LakePond	29.1	3.9	3.048	173	1.0
477	Valmont	1123	LF	2889298		1147	63	StreamRiver	28.7	6.6	5.134	174	1.7
477	Valmont	1123	LF	2889816	Hillcrest Reservoir	4	38	LakePond	29.1	3.9	3.048	173	1.0
897	Vermilion	395	SI	10080952	Middle Fork Vermilion River	84	100	StreamRiver	85	12.8	8.3	335	1.5
897	Vermilion	396	SI	10080952	Middle Fork Vermilion River	80	100	StreamRiver	85	12.8	8.3	335	1.5
897	Vermilion	970	LF	10080988				LakePond	85	1.6	1.93	1.1	0.69
6073	Victor J. Daniel Jr	45	SI	18094759				StreamRiver	268.9	18.8	3.31	13	0.62
6073	Victor J. Daniel Jr	924	LF	18120652		847	100	StreamRiver	261.1	3.3	2.639	3.1	0.58
6073	Victor J. Daniel Jr	925	LF	18094759				StreamRiver	268.9	18.8	3.31	13	0.62
6073	Victor J. Daniel Jr	938	LF	18094759				StreamRiver	268.9	18.8	3.31	13	0.62
6073	Victor J. Daniel Jr	1124	LF	18094759		124	50	StreamRiver	268.9	18.8	3.31	13	0.62
6073	Victor J. Daniel Jr	1124	LF	18120652		1991	13	StreamRiver	261.1	3.3	2.639	3.1	0.58
6073	Victor J. Daniel Jr	1124	LF	18120712		676	38	StreamRiver	265.5	4.1	2.007	2.9	0.67
6019	W H Zimmer	26	SI	1922898	Ohio River	94	100	ArtificialPath	59.6	4.6	2.331	99,680	3.6
6019	W H Zimmer	929	LF	1922624	Little Indian Creek	1362	100	StreamRiver	61.9	12.3	7.396	6.1	0.98
3470	W. A. Parish	136	SI	3126488				LakePond	49.8	19.7	6.332	11	0.75
3470	W. A. Parish	137	SI	3126488				LakePond	49.8	19.7	6.332	11	0.75

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
3470	W. A. Parish	138	SI	3126488				LakePond	49.8	19.7	6.332	11	0.75
3470	W. A. Parish	139	SI	3126488				LakePond	49.8	19.7	6.332	11	0.75
3470	W. A. Parish	140	SI	3126488				LakePond	49.8	19.7	6.332	11	0.75
3470	W. A. Parish	141	SI	3126488				LakePond	49.8	19.7	6.332	11	0.75
3470	W. A. Parish	142	SI	3126488				LakePond	49.8	19.7	6.332	11	0.75
3470	W. A. Parish	143	SI	3126488				LakePond	49.8	19.7	6.332	11	0.75
3470	W. A. Parish	1125	LF	3123354	Dry Bayou	199	75	StreamRiver	50.3	6.7	3.241	1.2	0.63
3470	W. A. Parish	1125	LF	3123360		328	25	StreamRiver	53.6	5.8	4.598	2.6	0.66
2866	W. H. Sammis	916	LF	3820585	Carter Run	170	38	StreamRiver	138.2	3.2	2.295	1.4	0.86
2866	W. H. Sammis	916	LF	3820671	Hollow Rock Run	570	25	StreamRiver	138.2	3.6	2.504	4.4	0.97
2866	W. H. Sammis	916	LF	3820723	Hollow Rock Run	403	38	StreamRiver	140.4	6.7	2.478	2.8	0.87
2866	W. H. Sammis	1382	SI	3821343	Ohio River	62	100	ArtificialPath	139.6	9.2	2.225	40,225	3.2
2866	W. H. Sammis	1383	SI	3821343	Ohio River	102	75	ArtificialPath	139.6	9.2	2.225	40,225	3.2
2866	W. H. Sammis	1383	SI	3821351	Ohio River	287	25	ArtificialPath	141.5	4.0	1.808	40,227	3.0
3264	W. S. Lee	105	SI	9867770		17	100	StreamRiver	295	0.0	0.192	0.25	0.73
3264	W. S. Lee	106	SI	9867770		59	25	StreamRiver	295	0.0	0.192	0.25	0.73
3264	W. S. Lee	106	SI	9867774		26	25	StreamRiver	295	0.0	0.185	0.24	0.72
3264	W. S. Lee	106	SI	9868670		43	25	LakePond	295.3	0.3	0.333	0.25	0.66
3264	W. S. Lee	106	SI	9868678	Saluda River	339	25	ArtificialPath	292.7	1.9	1.519	607	1.9
2716	W.H. Weatherspoon Plant	667	SI	9127156		583	13	StreamRiver	223.1	0.2	0.281	0.12	0.49
2716	W.H. Weatherspoon Plant	667	SI	9128006	Jacob Swamp	320	88	StreamRiver	222.6	3.4	3.167	10	0.79
1010	Wabash River	462	SI	10283910	Wabash River	622	83	ArtificialPath	96.1	6.2	1.799	11,390	2.3
1010	Wabash River	462	SI	10286204	Wabash River	817	17	ArtificialPath	95.6	4.9	1.23	11,391	2.3
1010	Wabash River	463	SI	10283906	Wabash River	289	100	ArtificialPath	95.5	5.1	2.676	11,382	2.9
1010	Wabash River	464	SI	10283906	Wabash River	82	100	ArtificialPath	95.5	5.1	2.676	11,382	2.9
1010	Wabash River	465	SI	10283906	Wabash River	91	100	ArtificialPath	95.5	5.1	2.676	11,382	2.9
2830	Walter C Beckjord	695	SI	1922510	Pond Run	167	86	StreamRiver	65	5.1	2.891	2.9	0.90
2830	Walter C Beckjord	695	SI	1922876	Ohio River	3	14	ArtificialPath	65	1.0	1.147	99,825	3.6
2830	Walter C Beckjord	696	SI	1922510	Pond Run	19	33	StreamRiver	65	5.1	2.891	2.9	0.90
2830	Walter C Beckjord	696	SI	1922872	Ohio River	74	33	ArtificialPath	65	4.0	2.053	99,830	3.6
2830	Walter C Beckjord	696	SI	1922874	Pond Run	144	33	ArtificialPath	65	0.1	0.314	2.9	0.48
2830	Walter C Beckjord	697	SI	1922872	Ohio River	53	100	ArtificialPath	65	4.0	2.053	99,830	3.6
2830	Walter C Beckjord	698	SI	1918228	Ohio River	124	20	ArtificialPath	65	0.2	0.387	99,830	3.6
2830	Walter C Beckjord	698	SI	1922872	Ohio River	71	80	ArtificialPath	65	4.0	2.053	99,830	3.6
2830	Walter C Beckjord	1126	LF	1922510	Pond Run	63	100	StreamRiver	65	5.1	2.891	2.9	0.90

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
2830	Walter C Beckjord	1127	LF	1918114	Tenmile Creek	495	63	StreamRiver	65	5.9	4.531	15	0.98
2830	Walter C Beckjord	1127	LF	1922510	Pond Run	1001	38	StreamRiver	65	5.1	2.891	2.9	0.90
1082	Walter Scott Jr. Energy Center	502	SI	17219106				CanalDitch	53.7	0.3	0.516	38	0.80
1082	Walter Scott Jr. Energy Center	503	SI	17219106				CanalDitch	53.7	0.3	0.516	38	0.80
1082	Walter Scott Jr. Energy Center	932	LF	17219100		1861	50	CanalDitch	52.8	4.9	1.627	2.5	0.74
1082	Walter Scott Jr. Energy Center	932	LF	17219200		1171	50	StreamRiver	52	6.0	4.956	0.033	0.55
6052	Wansley	35	SI	3291908				ArtificialPath	266.1	3.8	2.064	5,214	2.0
6705	Warrick Power Plant	224	SI	10110339				ArtificialPath	89	11.0	4.03	132,544	2.2
3297	Wateree	113	SI	9721753	Wateree River	2	100	ArtificialPath	216.2	6.3	3.062	8,073	2.2
3297	Wateree	114	SI	9721507		322	25	StreamRiver	217.1	2.8	2.977	1.2	0.72
3297	Wateree	114	SI	9721753	Wateree River	70	75	ArtificialPath	216.2	6.3	3.062	8,073	2.2
3297	Wateree	933	LF	9721507		15	50	StreamRiver	217.1	2.8	2.977	1.2	0.72
3297	Wateree	933	LF	9721753	Wateree River	1129	50	ArtificialPath	216.2	6.3	3.062	8,073	2.2
883	Waukegan	1311	SI	12170763		220	100	Coastline	88.1	10.8	5.042		
883	Waukegan	1312	SI	12170763		219	100	Coastline	88.1	10.8	5.042		
6139	Welsh	175	SI	1009152	Swauano Creek	868	100	StreamRiver	76.6	8.5	7.689	19	0.96
6139	Welsh	176	SI	1009160	Welsh Reservoir	462	100	LakePond	75.7	8.2	2.431	16	0.66
6139	Welsh	177	SI	1009152	Swauano Creek	1346	13	StreamRiver	76.6	8.5	7.689	19	0.96
6139	Welsh	177	SI	1009160	Welsh Reservoir	645	88	LakePond	75.7	8.2	2.431	16	0.66
6139	Welsh	934	LF	1009152	Swauano Creek	1172	38	StreamRiver	76.6	8.5	7.689	19	0.96
6139	Welsh	934	LF	1009160	Welsh Reservoir	704	63	LakePond	75.7	8.2	2.431	16	0.66
4078	Weston	935	LF	14731726	Johnson Creek	792	100	StreamRiver	150.7	3.7	2.451	23	0.95
4078	Weston	936	LF	14732378	Wisconsin River	72	100	ArtificialPath	140.8	6.3	3.668	3,564	1.9
4078	Weston	1313	SI	14732378	Wisconsin River	10	100	ArtificialPath	140.8	6.3	3.668	3,564	1.9
4078	Weston	1314	SI	14732378	Wisconsin River	656	100	ArtificialPath	140.8	6.3	3.668	3,564	1.9
4078	Weston	1315	SI	14732378	Wisconsin River	670	100	ArtificialPath	140.8	6.3	3.668	3,564	1.9
4078	Weston	1316	SI	14732378	Wisconsin River	380	100	ArtificialPath	140.8	6.3	3.668	3,564	1.9

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
4078	Weston	1317	SI	14732378	Wisconsin River	473	100	ArtificialPath	140.8	6.3	3.668	3,564	1.9
4078	Weston	1318	SI	14732378	Wisconsin River	218	100	ArtificialPath	140.8	6.3	3.668	3,564	1.9
60	Whelan Energy Center Unit 1 (WEC1)	1214	SI	18758724		2141	100	StreamRiver	19.4	5.5	3.717	0.050	0.63
6009	White Bluff	1128	LF	22850711		367	25	StreamRiver	119	2.4	3.827	0.91	0.72
6009	White Bluff	1128	LF	22850721	Lipscomb Branch	323	25	StreamRiver	119	1.6	1.847	0.61	0.66
6009	White Bluff	1128	LF	22851451	Surge Pond	921	50	LakePond	119	1.5	0.502	2.2	0.75
1040	Whitewater Valley	1321	SI	3922369	East Fork Whitewater River	1486	100	StreamRiver	119	11.5	5.936	124	1.4
1040	Whitewater Valley	1322	SI	3922369	East Fork Whitewater River	1510	100	StreamRiver	119	11.5	5.936	124	1.4
1040	Whitewater Valley	1323	SI	3922369	East Fork Whitewater River	1506	100	StreamRiver	119	11.5	5.936	124	1.4
1040	Whitewater Valley	1324	SI	3922369	East Fork Whitewater River	1469	100	StreamRiver	119	11.5	5.936	124	1.4
1040	Whitewater Valley	1325	SI	3922369	East Fork Whitewater River	1471	100	StreamRiver	119	11.5	5.936	124	1.4
4057	WI Power & Light Co -Rock River Generating	1	SI	13297306	Rock River	2	100	ArtificialPath	123.8	33.5	4.925	1,493	1.6
4057	WI Power & Light Co -Rock River Generating	2	SI	13297306	Rock River	59	100	ArtificialPath	123.8	33.5	4.925	1,493	1.6
4057	WI Power & Light Co -Rock River Generating	3	SI	13297306	Rock River	3	100	ArtificialPath	123.8	33.5	4.925	1,493	1.6
4057	WI Power & Light Co -Rock River Generating	172	SI	13297306	Rock River	58	100	ArtificialPath	123.8	33.5	4.925	1,493	1.6
50	Widows Creek	59	SI	19646344				LakePond	254.7	0.9	1.097	46,353	3.0
50	Widows Creek	60	SI	19646344				LakePond	254.7	0.9	1.097	46,353	3.0
50	Widows Creek	61	SI	19646344				LakePond	254.7	0.9	1.097	46,353	3.0
50	Widows Creek	62	SI	19646344				LakePond	254.7	0.9	1.097	46,353	3.0
50	Widows Creek	63	SI	19646344				LakePond	254.7	0.9	1.097	46,353	3.0
50	Widows Creek	64	SI	19646344				LakePond	254.7	0.9	1.097	46,353	3.0

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
50	Widows Creek	65	SI	19646344				LakePond	254.7	0.9	1.097	46,353	3.0
50	Widows Creek	66	SI	19646344				LakePond	254.7	0.9	1.097	46,353	3.0
50	Widows Creek	261	SI	19646344				LakePond	254.7	0.9	1.097	46,353	3.0
50	Widows Creek	262	SI	19646344				LakePond	254.7	0.9	1.097	46,353	3.0
50	Widows Creek	289	SI	19646344				LakePond	254.7	0.9	1.097	46,353	3.0
50	Widows Creek	290	SI	19646344				LakePond	254.7	0.9	1.097	46,353	3.0
884	Will County	389	SI	14787485				ArtificialPath	116.2	2.5	6.427	342	1.2
3298	Williams	1129	LF	9644721		709	100	StreamRiver	179	5.3	3.391	1.9	0.44
3298	Williams	1130	LF	9644711	Molly Branch	74	63	StreamRiver	179	1.1	1.289	0.58	0.65
3298	Williams	1130	LF	9644713	Stony Branch	215	38	StreamRiver	179	2.1	1.944	0.75	0.69
3946	Willow Island	917	LF	15438238				ArtificialPath	90.6	0.1	0.139	44,013	3.0
6249	Winyah	198	SI	11565178		113	50	StreamRiver	171.7	1.8	1.718	0.75	0.38
6249	Winyah	198	SI	11565200	Pennyroyal Creek	66	50	StreamRiver	172	1.0	1.165	7.1	0.56
6249	Winyah	199	SI	11565200	Pennyroyal Creek	148	75	StreamRiver	172	1.0	1.165	7.1	0.56
6249	Winyah	199	SI	11565228	Pennyroyal Creek	60	25	StreamRiver	172	1.6	1.429	5.1	0.53
6249	Winyah	200	SI	11565228	Pennyroyal Creek	700	50	StreamRiver	172	1.6	1.429	5.1	0.53
6249	Winyah	200	SI	11565234		45	50	StreamRiver	171.9	1.0	1.446	0.40	0.54
6249	Winyah	201	SI	11565204		107	40	CanalDitch	169.2	0.6	0.953	4.2	0.51
6249	Winyah	201	SI	11565234		212	40	StreamRiver	171.9	1.0	1.446	0.40	0.54
6249	Winyah	201	SI	11566154		158	20	LakePond	170.2	1.2	2.977	3.9	0.50
6249	Winyah	202	SI	11565234		76	33	StreamRiver	171.9	1.0	1.446	0.40	0.54
6249	Winyah	202	SI	11566154		76	33	LakePond	170.2	1.2	2.977	3.9	0.50
6249	Winyah	202	SI	11566156		22	33	LakePond	172	1.1	1.607	0.86	0.39
6249	Winyah	203	SI	11565204		26	100	CanalDitch	169.2	0.6	0.953	4.2	0.51
6249	Winyah	982	LF	11565228				StreamRiver	172	1.6	1.429	5.1	0.53
898	Wood River	397	SI	879884		217	88	StreamRiver	37	5.1	2.435	1.5	0.68
898	Wood River	397	SI	879898	Wood River	157	13	StreamRiver	37	0.3	1.326	92	0.98
898	Wood River	398	SI	879892		495	100	StreamRiver	37	0.7	0.239	0.62	0.48
50611	WPS Westwood Generation, LLC	951	LF	4707642	Good Spring Creek	208	33	StreamRiver	320.7	20.0	9.297	11	1.1
50611	WPS Westwood Generation, LLC	951	LF	4707680	Lower Rausch Creek	17	67	StreamRiver	328	10.5	6.365	5.8	1.0
6101	Wyodak Plant	80	SI	10902255	Donkey Creek	356	100	StreamRiver	9.2	29.5	4.496	0.42	0.90
6101	Wyodak Plant	981	LF	10902255				StreamRiver	9.2	29.5	4.496	0.42	0.90
728	Yates	367	SI	3288658				StreamRiver	255.1	2.1	1.429	3.1	0.72

Attachment B-4. Waterbody Data

Oris Code	ORIS Plant Name	WMU ID	Unit Type	COMID	Nearest Waterbody Name (if available)	Minimum Distance to Waterbody (m)	Percent-age	Waterbody Type	Mean Recharge (mm/yr)	Area (km^2)	Length (km)	Mean Annual Flow (cfs)	Mean Annual Velocity (fps)
728	Yates	368	SI	3288658				StreamRiver	255.1	2.1	1.429	3.1	0.72
728	Yates	369	SI	3288658				StreamRiver	255.1	2.1	1.429	3.1	0.72
728	Yates	370	SI	3288658				StreamRiver	255.1	2.1	1.429	3.1	0.72
728	Yates	371	SI	3288658				StreamRiver	255.1	2.1	1.429	3.1	0.72
728	Yates	372	SI	3288658				StreamRiver	255.1	2.1	1.429	3.1	0.72
728	Yates	373	SI	3288658				StreamRiver	255.1	2.1	1.429	3.1	0.72
728	Yates	374	SI	3288658				StreamRiver	255.1	2.1	1.429	3.1	0.72
728	Yates	986	LF	3288658		108	67	StreamRiver	255.1	2.1	1.429	3.1	0.72
728	Yates	986	LF	3288684		188	33	StreamRiver	254.5	0.9	0.814	1.7	0.75
728	Yates	987	LF	3288658		431	25	StreamRiver	255.1	2.1	1.429	3.1	0.72
728	Yates	987	LF	3290264	Chattahoochee River	590	50	ArtificialPath	257	2.0	0.729	5,008	1.9
728	Yates	987	LF	3290268	Chattahoochee River	567	25	ArtificialPath	256.3	2.5	1.696	5,011	1.6
3809	Yorktown	988	LF	9897200	West Branch Wormley Creek	376	25	ArtificialPath	182	5.6	2.495	6.2	0.55
3809	Yorktown	988	LF	9897296		1579	75	Coastline	182	3.0	3.071		
3809	Yorktown	1359	SI	9897200	West Branch Wormley Creek	135	100	ArtificialPath	182	5.6	2.495	6.2	0.55

Appendix C.

Constituent Data

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C.1 CCR Constituent Database

This risk assessment addresses metallic and other inorganic constituents identified as constituents of potential concern (COPCs) in coal combustion residuals (CCRs). The CCR constituent database contains data collected over a series of CCR-related regulatory activities from 1998 through 2010, as follows:

- CCR and CCR leachate data used in the 1998 Risk Assessment (U.S. EPA, 1998a,b) and documented in the 1999 Report to Congress ("1999 RTC") (U.S. EPA, 1999);
- Data submitted to EPA through public comments on the 1999 RTC;
- Data submitted to EPA through public comments on the 2000 Regulatory Determination;
- Data submitted to and collected by EPA after the close of the public comment period for the 2000 Regulatory Determination;
- Data submitted to EPA through public comments on the 2010 Proposed CCR Rule;
- Data developed by EPA's Office of Research and Development using the Leaching Evaluation Assessment Framework (LEAF) test methods (U.S. EPA, 2009); and

Attachment C-1 provides a complete list of the data sources contained in the updated 2014 database that were considered in this risk assessment. The data in the CCR constituent database characterizes the concentrations of COPCs present in and released from CCRs. In addition to COPC concentrations, this database also provides information, as available, on the coal burned at the facility and the type of CCR(s) analyzed. The CCR constituent database includes CCRs generated from the major coal ranks: bituminous, sub-bituminous, and, to a lesser degree, lignite and anthracite. In some cases, the coal rank associated with samples in the database is not specified, partly because many facilities mix coals from different sources over time based on a number of factors, such as fuel cost and the need to reduce sulfur levels. The CCR constituent database also includes data on all major types of CCRs, which include fly ash, bottom ash, boiler slag, and flue gas desulfurization (FGD) waste. Similar to coal type, many of the available samples reflect the practice of codisposal, such as fly ash with bottom ash or CCRs with coal refuse. Thus, the CCR constituent database provides a snapshot of current management practices across a broad cross-section of the regulated universe, with a large number of samples collected from sites in 30 states. **Table C-1** lists the data evaluated in this risk assessment, along with the number of sites representing each waste type in the CCR constituent database.

Table C-1. Waste Types in the 2014 CCR Database

CCR Type	Number of Sites by Waste Type		
	Impoundment Wastewater	Impoundment Pore Water	Total Waste
Combined Ash	9	18	67
Ash and Coal Refuse	0	5	1
FGD Waste	2	7	6

C.2 Intra-site Variability

The 2010 Risk Assessment (U.S. EPA, 2010) averaged all of the samples collected at each site for each constituent and waste stream (impoundment surface water, impoundment pore water and whole waste) to create a single concentration for each site, constituent, and waste stream. EPA initially chose this approach in order to avoid the potential to bias the evaluation results toward sites with more samples. However, that approach was found to not adequately account for intra-site variability. Therefore, in the revised risk assessment, EPA relied on a quartile approach to retain more of the intra-site variability lost through the use of site averages. To develop the site quartiles, EPA first separated the data for each site, constituent, and waste stream by waste type (i.e., combined ash, ash and coal waste, FGD waste). Combining the data for the different waste types into a single set of quartiles for a site might bias concentrations toward the most sampled waste types. Therefore, quartiles were calculated for each waste type at each sample site for each waste stream and constituent. Where only one sample was available for a waste type at a sample site, all of the quartiles were set to this value to ensure equal weighting.

Nondetect analytical results were included using a value of half the reported detection limit. For the screening analysis, the 90th percentile of these quartiles across all sites and waste streams was calculated and used. For the full-scale probabilistic analysis, the Monte Carlo simulation sampled from the site-specific quartiles for each constituent and waste stream. **Attachments C-2** through **C-4** provides the quartiles used (sampled) in the full-scale CCR risk assessment by waste type/WMU scenario for CCR impoundment wastewater, pore water and whole waste, respectively. **Attachment C-5** provides a list of the constituents that have concentration data and notes which types of concentration are available (pore water, impoundment wastewater or whole waste).

C.3 LEAF Data

For surface impoundments, the revised risk assessment applied the data from the CCR constituent database in the same way as the 2010 Risk Assessment. For landfills, the 2010 Risk Assessment relied on a hierarchy of dissolved concentration data, ranging from field leachate data to toxicity characteristic leaching procedure. Since that time, new data have been made available through a series of EPA reports (U.S. EPA 2006, 2008, 2009) that examined the effects of coal rank and changes in air pollution control technologies on CCR leaching behavior. The leaching test methods used to evaluate leaching behavior are from the EPA SW-846 LEAF methods. The interlaboratory validation for these methods are described in U.S. EPA (2012a,b), while Kosson et al. (2002) provides the detailed test methodology for Methods SR02 and SR03.[1] These data were collected with three of the LEAF test methods, specifically SW-846 Methods 1313, 1314 and 1316. The data from these three methods were used together to develop the source term to characterize leaching from landfills considering geographically distributed, site-specific conditions and uncertainties to form a set of disposal scenarios that were used in the risk assessment. All three of these methods are briefly summarized in the following text.

[1] Methods SR02 and SR03 are predecessor methods to SW-846 Methods 1313 and 1316.

C.3.1 Summary of LEAF Methods Used

Method 1313: Liquid-Solid Partitioning as a Function of Eluate pH using a Parallel Batch Extraction Procedure

Method 1313 is a leaching test designed to estimate constituent concentrations in eluate as a function of pH. This procedure consists of nine separate parallel batch extractions, which involve placing a given mass of ash in a container with a specific volume of eluent to achieve a L/S ratio of 10 mL/g-dry. Each eluent is buffered using a dilute acid or base to achieve different target pH values ranging between 2.8 and 13. One of these values is the natural pH of the material (also referred to as "own pH"), which is achieved by allowing the material to equilibrate with deionized water. The extraction contact time ranges somewhere between 24 and 72 hours, based on the grain size of the material "as tested." This may be distinct from the grain size of the material "as received," because particle size reduction or air drying may be required either to improve handling and to achieve equilibrium between the liquid eluent and solid sample within a reasonable extraction timeframe. Solid and liquid phases are separated by either vacuum- or pressure-assisted filtration and prepared for chemical analysis. The measured eluate concentrations are plotted as a function of final pH for each batch. Eluate concentrations may be interpolated between these measured concentrations to provide a uniform basis for comparison, as the final measured eluate pH values are likely to differ marginally from the target values. The data collected with Method 1313 were used to characterize the leaching behavior of different CCRs as a function of pH and total leachable content. **Figure C-1** compares example concentration profiles for four constituents as a function of pH for three duplicate samples of the same ash (Sample ID: EaFA). For this waste, the arsenic (As) leachate concentrations ranged over about two orders of magnitude, with peak concentrations at the highest and lowest pH, and a minimum concentration at a pH of approximately 5.6. Chromium (Cr) concentrations varied by over four orders of magnitude across the same range, with a minimum at a pH of 5.6, while molybdenum (Mo) and calcium (Ca) ranging over a little more than an order of magnitude. Additional information on this subject can be found at U.S. EPA (2009).

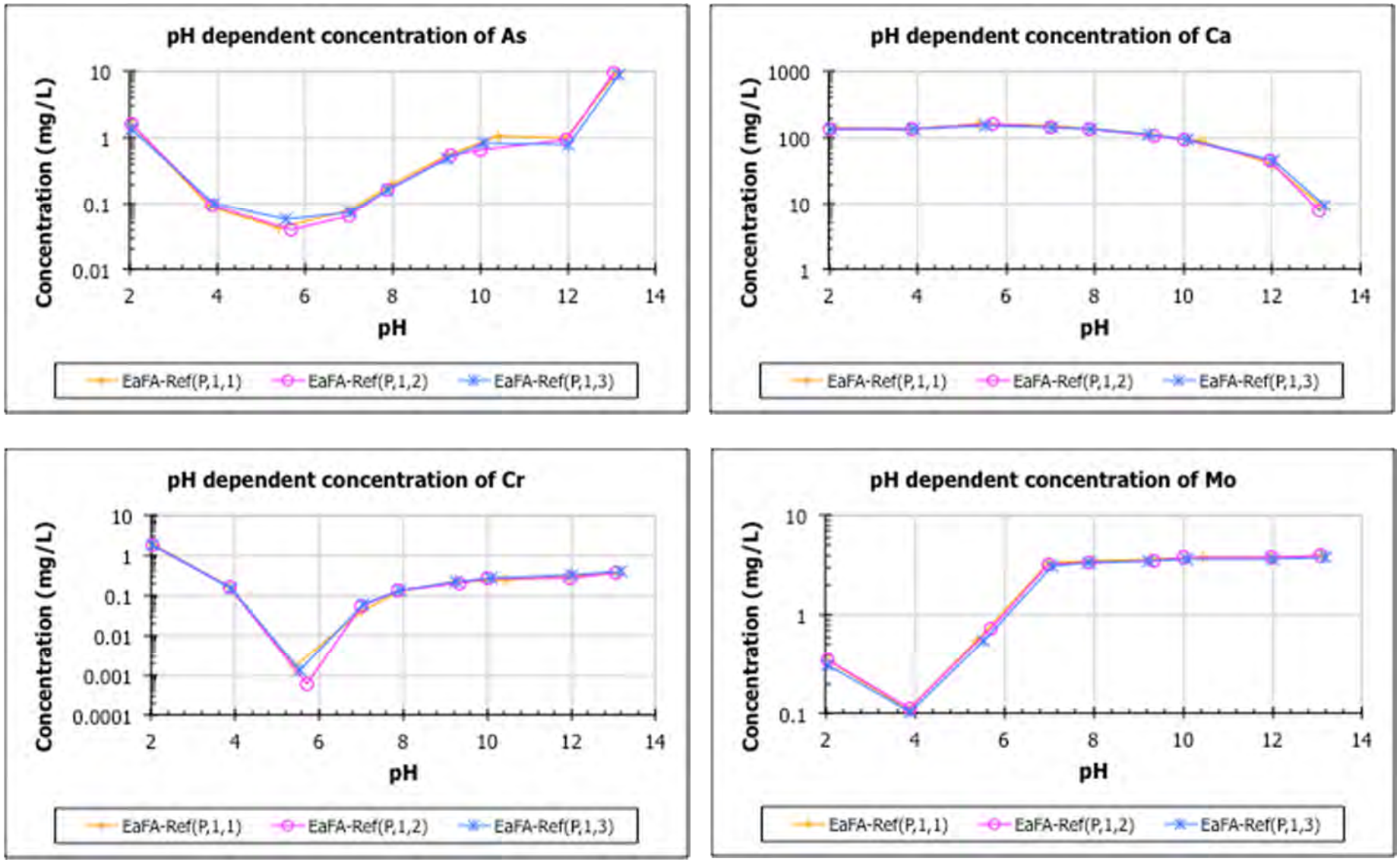

Figure C-1. Example eluate concentrations as a function of pH as obtained from Method 1313 on coal fly ash sample EaFA (Adapted from data in U.S. EPA, 2012a).

Method 1314: Liquid-Solid Partitioning as a Function of Liquid-to-Solid Ratio (L/S) for Constituents in Solid Materials Using an Up-Flow Percolation Column Procedure

Method 1314 is a leaching test designed to estimate constituent concentrations in eluate as a function of the cumulative L/S ratio. This procedure consists of five separate, parallel upflow percolation columns, which involves percolating deionized water through a given mass of moderately compacted ash against the force of gravity. The upflow percolation is intended to minimize air entrainment and preferential flow channeling. The flow rate is maintained at a level corresponding to in an increase of the L/S ratio between 0.5 and 1.0 mL/g-day in order to increase the likelihood of local equilibrium developing between the liquid eluate and solid ash. Samples are collected each time a specified cumulative L/S ratio has been reached. For the purposes of chemical speciation modeling, the entire eluent volume up to 10 mL/g of dry sample is collected in nine specific aliquots of varying volume. The data collected with Method 1314 were used together with those from Method 1316 to verify that the application of the Method 1313 data, which is collected at a single (10 mL/g) L/S ratio, provides a conservative estimate for peak leachate concentrations. **Figure C-2** shows example results of eluate concentrations as a function of the L/S ratio. Both arsenic and chromium show highest concentrations at the lowest and highest L/S ratio tested, while calcium and molybdenum leachate concentrations peak at just less than an L/S of 1 mL/g (L/kg).

Method 1316: Liquid-Solid Partitioning as a Function of Liquid-to-Solid Ratio using a Parallel Batch Extraction Procedure

Method 1316 is a leaching test designed to estimate constituent concentrations in eluate as a function of L/S ratio. This procedure consists of five separate parallel batch extractions, which involve placing a given mass of ash in a container with a specific volume of eluent. Each batch is set to a different, constant L/S ratio ranging between 0.5 and 10 mL/g-day. Particle size reduction of the solid material may be required in order to facilitate the approach to liquid-solid equilibrium. The extraction contact time ranges somewhere between 24 and 72 hours, based on the grain size of the material "as tested." This may be distinct from the grain size of the material "as received," because particle size reduction or air drying may be required either to improve handling and to achieve equilibrium between the liquid eluent and solid sample within a reasonable extraction timeframe. Solid and liquid phases are separated by either vacuum- or pressure-assisted filtration and prepared for chemical analysis. The measured eluate concentrations are plotted as a function of L/S ratio. This method provides data on the changes in equilibrium chemistry (i.e., ionic strength, constituent concentrations) as the L/S ratio value approaches values found within the solid phase pore solution. The data collected with Method 1316 were used together with those from Method 1314 to verify that the application of the Method 1313 data, which is collected at a single L/S ratio, provides a conservative estimate for peak leachate concentrations. **Figure C-3** shows example results of eluate concentrations as a function of the L/S ratio as obtained from parallel batch extractions using Method 1316.

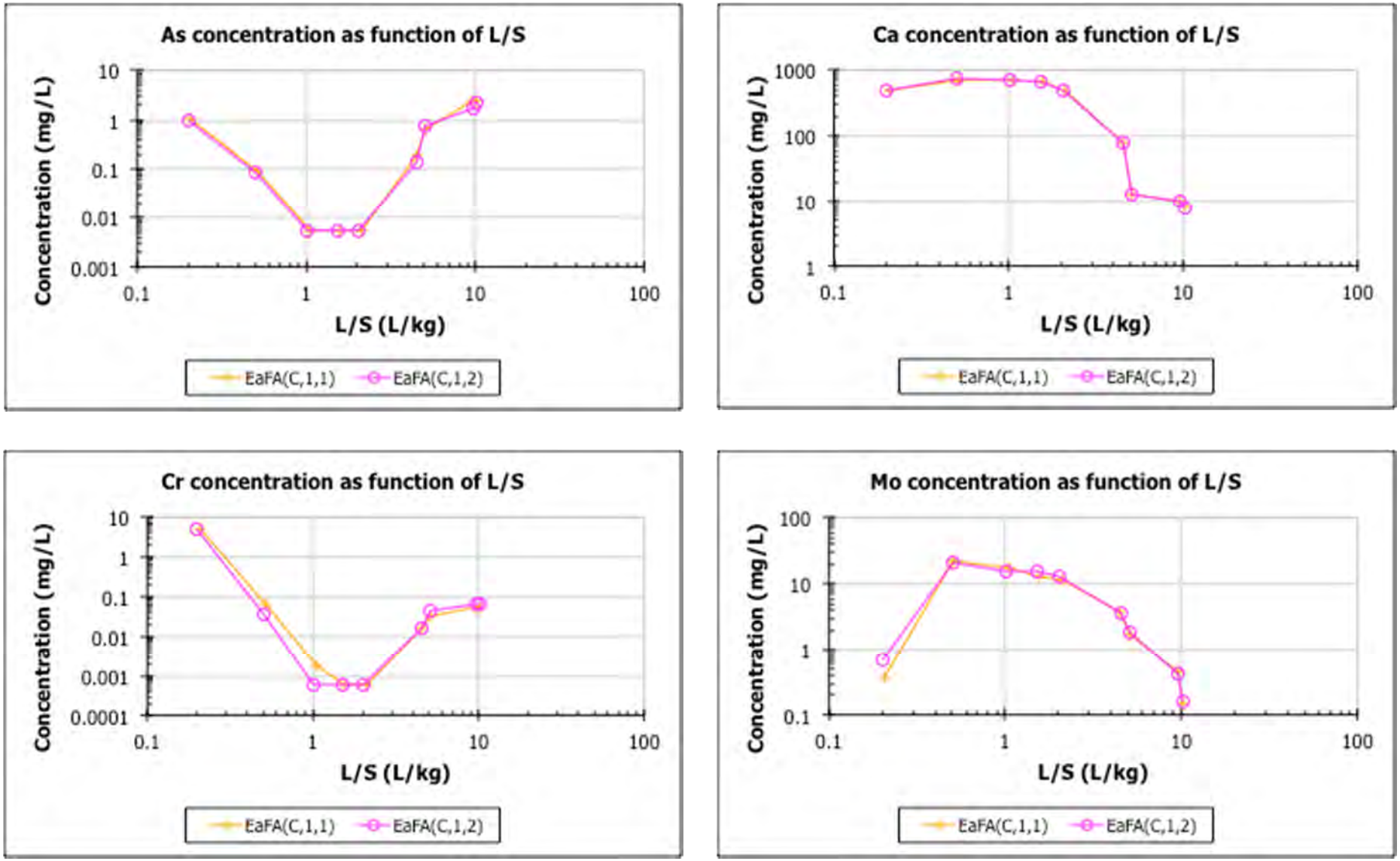

Figure C-2. Eluate concentrations as a function of L/S ratio as obtained from Method 1314 applied to coal fly ash sample EaFA (Adapted from data in U.S. EPA, 2012a).

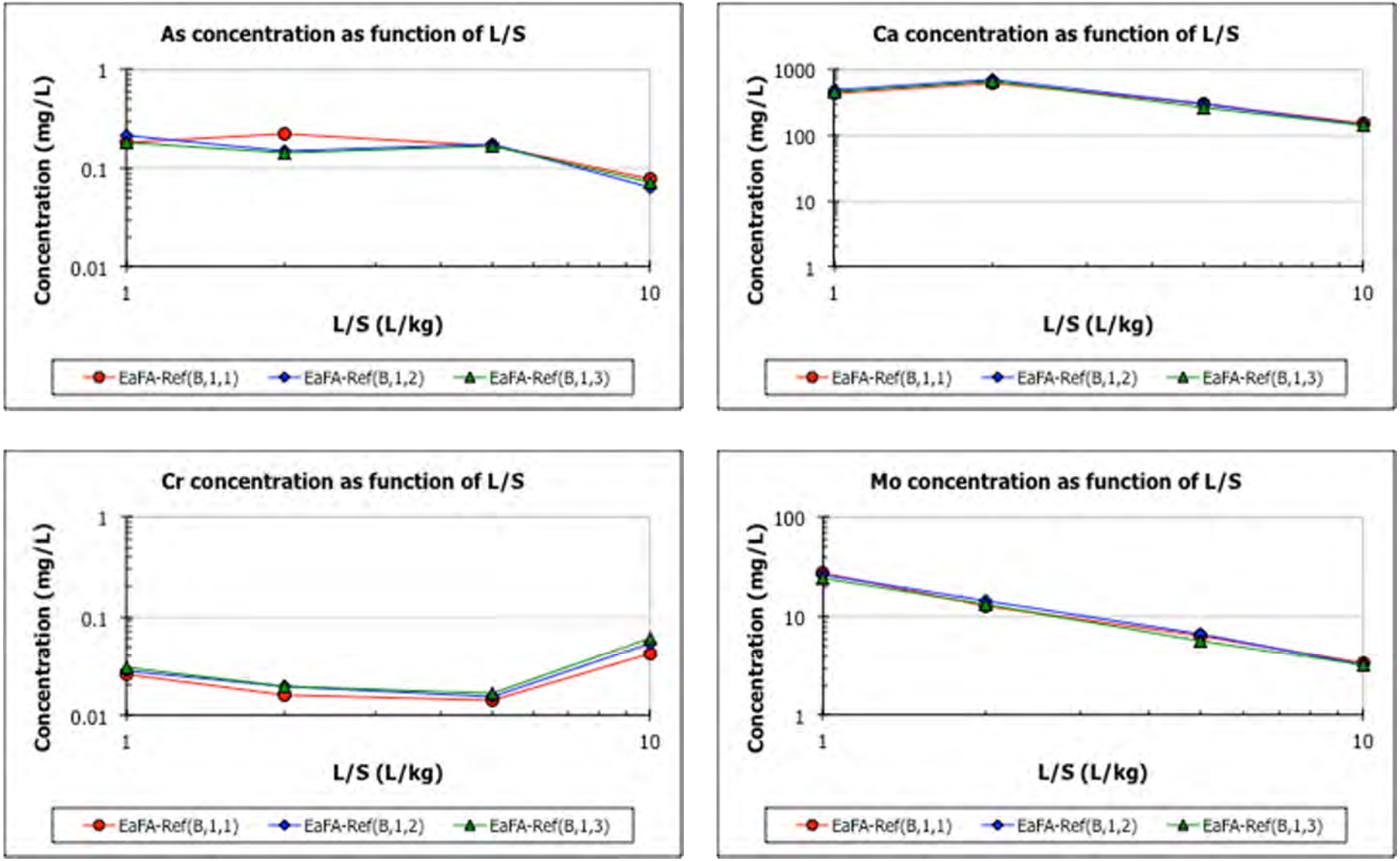

Figure C-3. Eluate concentrations as a function of L/S ratio as obtained from Method 1316 applied to coal fly ash sample EaFA (Adapted from data in U.S. EPA, 2012a).

C.3.2 Constituent Leaching Behavior

The leaching behavior of constituents, as defined by the Method 1313 data, can be divided into the following categories: washout-controlled and solubility-controlled. A single constituent may alternate between the two categories over the relevant pH range (e.g. some constituents may be washout-controlled at a low pH and solubility-controlled at a high pH, while other constituents display the opposite behavior). In addition, this behavior profile is not constant for a constituent across all CCR types. A given constituent may fall entirely into the washout-controlled zone when leached from ash generated by one combination of coal type and pollution control technology, but enter the solubility-controlled zone when leached from ash generated by a different combination. With these considerations in mind, the two leaching categories are briefly described below.

The washout-controlled zone is characterized by the quick dissolution and release of the more soluble species (e.g., sodium, potassium) from the ash into the pore water. In Method 1313 data, this behavior is characterized by a generally constant leachate concentration over a pH range. **Figure C-4** shows an example of an ash (Sample ID: AaFA) for which boron falls in the washout-controlled zone over the entire pH range evaluated and leachate concentrations are almost constant.

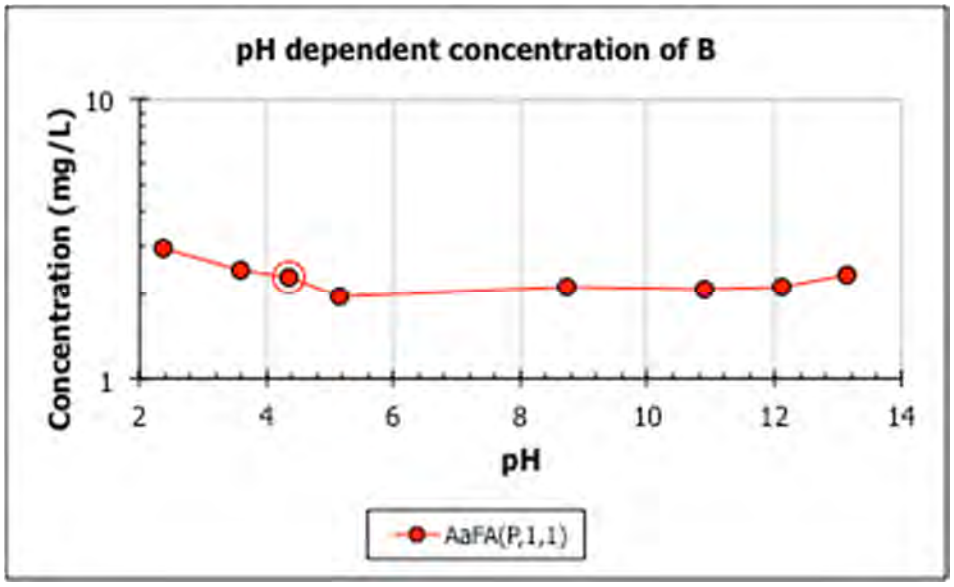

Figure C-4. Example of a washout-controlled species over the full experimental pH domain for sample AaFA (Adapted from data in U.S. EPA, 2009).

The solubility-controlled zone is characterized by a slower release of less soluble species (e.g., calcium, aluminum) where the leachate concentration is controlled by solubility of the species at a specific pH value. In Method 1313 data, this is characterized by variable leachate concentrations over the pH range. **Figure C-5** shows an example of an ash (Sample ID: AaFA) for which chromium falls within the solubility-controlled zone over the entire pH range. Note that concentrations vary by almost two orders of magnitude over the pH range evaluated.

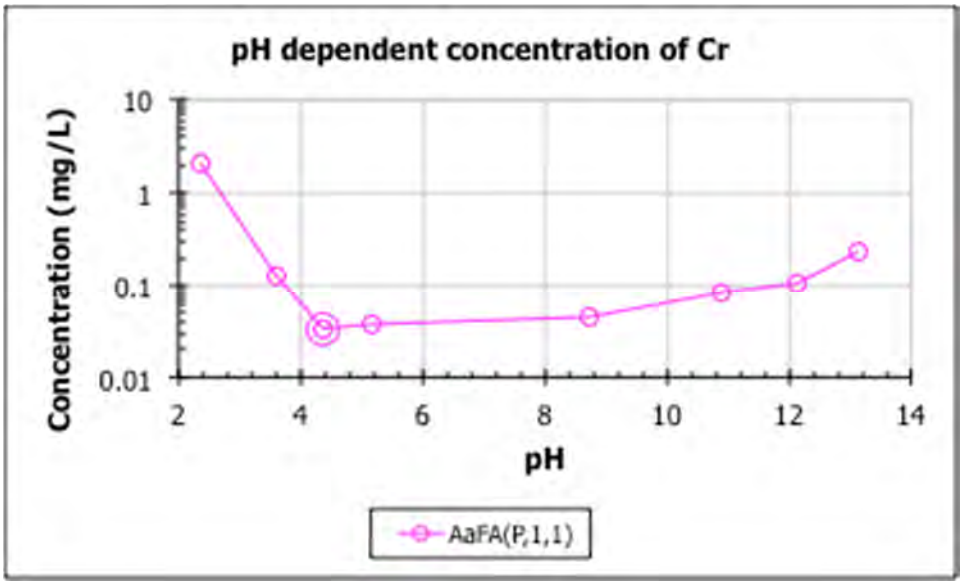

Figure C-5. Example of a solubility-controlled species over the full experimental pH domain for sample AaFA (Adapted from data in U.S. EPA, 2009).

In some cases, a constituent may be washout-controlled over one part of the pH range and solubility-controlled over another. **Figure C-6** shows an example of an ash (Sample ID: AFA) for which boron is washout-controlled, with an almost constant leachate concentration for pH values less than eight, and solubility-controlled for pH values above eight.

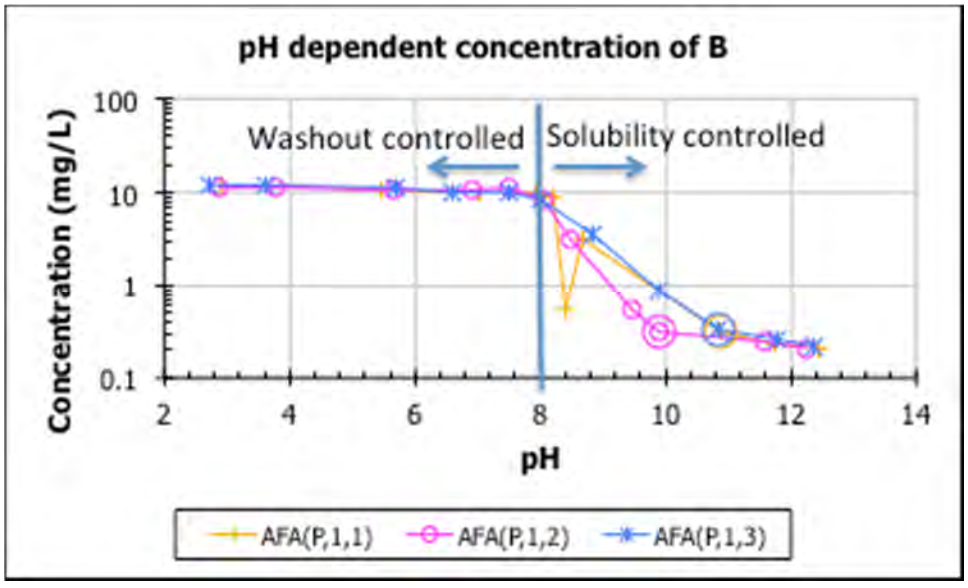

Figure C-6. Example of a part washout- and part solubility-controlled species triplicate measurements of sample AaFA (Adapted from data in U.S. EPA, 2009).

C.3.3 Data Preparation

During the waste sampling and LEAF analysis conducted to develop constituent concentrations for landfills, EPA determined that the range and variability of different waste chemistry was best represented by a single pH distribution for all waste types (U.S. EPA, 2009). Even though on a single distribution, it still effectively captures the different waste types. For example, low pH conditions were used to represent codisposal of CCR with coal refuse.

To accommodate this single distribution within the CCR Metal Speciation Equilibrium Model for Surface and Ground Water (MINTEQA2) modeling construct, the waste types for landfills were modeled using a single combined ash isotherm, and risk results were evaluated across all landfill waste types. To select a MINTEQA2 isotherm for each iteration of the Monte Carlo analysis for landfills, a leachate pH was randomly selected from the distribution, a combined ash waste type was assumed, and aquifer type was assigned based on the location of the landfill being modeled (see **Appendix B, Section B.3)**. Iron oxide, natural organic matter, and leachate ionic strength were then randomly selected based on the combined ash waste type to identify the unsaturated and saturated zone isotherms to be used for a particular model run. How these data were prepared for and used by EPA's Composite Model For Leachate Migration With Transformation Products (EPACMTP) is described in **Appendix I**.

The LEAF-generated landfill leachate data were consolidated into a single data set for the revised risk assessment. The Method 1313 data were organized into a series of tables, each containing the data collected for each ash sample, as described in U.S. EPA (2009). The landfill leachate data tables also included a measured availability (in mg/kg) for each constituent and waste that was used by the EPACMTP landfill model to provide a limit in the constituent mass that can be leached from a particular CCR waste at a particular leachate concentration. **Attachment C-7** provides each of these generated tables. Availability data, by constituent, are at the bottom of each table.

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Attachment C-1. Sources of Data

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Attachment C-2.

Quartile Data for CCR Impoundment Porewater

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
13115B	Combined ash	Aluminum	mg/L	0.075	0.075	0.0775	TRUE
14093	Fly Ash	Aluminum	mg/L	0.1575	0.3	0.415	TRUE
22346	Other	Aluminum	mg/L	0.011	0.021	0.031	TRUE
23223B	FGD waste	Aluminum	mg/L	0.68	0.75	0.82	TRUE
25410A	Combined ash	Aluminum	mg/L	44.4	44.4	44.4	TRUE
25410B	Fly Ash	Aluminum	mg/L	0.075	0.075	0.075	TRUE
33104	Fly Ash	Aluminum	mg/L	1.0185	1.979	2.9395	TRUE
33106	Fly Ash	Aluminum	mg/L	0.01	0.014	0.0145	TRUE
35015B	Fly Ash	Aluminum	mg/L	0.1525	0.165	0.1775	TRUE
40109	Fly Ash	Aluminum	mg/L	5.2825	8.555	11.8275	TRUE
43035	Combined ash	Aluminum	mg/L	5.6725	5.755	5.8375	TRUE
49003A	Fly Ash	Aluminum	mg/L	0.04875	0.0655	0.0825	TRUE
AP	Combined ash	Aluminum	mg/L	0.125	0.358	0.819	TRUE
BR	Ash & coal waste	Aluminum	mg/L	1.7	11.55	51.975	TRUE
C	Combined ash	Aluminum	mg/L	2.9	3.9	5.6	TRUE
CADK	FGD waste	Aluminum	mg/L	0.1625	0.165	0.1675	TRUE
CASJ	FGD waste	Aluminum	mg/L	0.054	0.15	0.15	TRUE
CATT	FGD waste	Aluminum	mg/L	0.275	0.28	0.285	TRUE
CL	Ash & coal waste	Aluminum	mg/L	0.22925	1.05125	3.78375	TRUE
CY	FGD waste	Aluminum	mg/L	4.2075	7.055	8.945	TRUE
FC	Ash & coal waste	Aluminum	mg/L	9.3725	10.5	13.45	TRUE
HA	Ash & coal waste	Aluminum	mg/L	0.65	0.65	0.65	TRUE
HA	Combined ash	Aluminum	mg/L	0.12875	0.28975	1.043	TRUE
L	Combined ash	Aluminum	mg/L	0.015	0.015	0.015	TRUE
MO	Ash & coal waste	Aluminum	mg/L	0.41	0.5775	352.375	TRUE
MO	Bottom ash	Aluminum	mg/L	0.2185	0.31525	1.6789375	TRUE
NA	Na FGD Sludge	Aluminum	mg/L	0.3	0.3	2.5	TRUE
OK	Bottom ash	Aluminum	mg/L	0.606125	0.92925	1.252375	TRUE
OK	Fly ash	Aluminum	mg/L	22.4025	42.11	66.8925	TRUE
SX	Bottom ash	Aluminum	mg/L	0.081792425	0.25028275	0.334547025	TRUE
SX	Fly ash	Aluminum	mg/L	8.06025	12.1525	12.36875	TRUE
AP	Combined ash	Ammonia	mg/L	0.05	0.05	0.05	TRUE
C	Combined ash	Ammonia	mg/L	1.4	2.55	3.2	TRUE
CL	Ash & coal waste	Ammonia	mg/L	0.29	0.55	0.88	TRUE
MO	Ash & coal waste	Ammonia	mg/L	1.135	3.69	6.3875	TRUE
MO	Bottom ash	Ammonia	mg/L	0.27	0.49	0.6	TRUE
SX	Bottom ash	Ammonia	mg/L	0.16	4.805	6.115	TRUE
13115B	Combined ash	Antimony	mg/L	0.0011	0.0016	0.0025	TRUE
14093	Fly Ash	Antimony	mg/L	0.00135	0.002	0.00435	TRUE
22346	Other	Antimony	mg/L	0.0003125	0.000575	0.0008375	TRUE
23223B	FGD waste	Antimony	mg/L	0.001225	0.00175	0.002275	TRUE
25410A	Combined ash	Antimony	mg/L	0.0024	0.0024	0.0024	TRUE
25410B	Fly Ash	Antimony	mg/L	0.0013	0.0013	0.0013	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
33104	Fly Ash	Antimony	mg/L	0.002575	0.00445	0.006325	TRUE
33106	Fly Ash	Antimony	mg/L	0.00135	0.0024	0.0035	TRUE
35015B	Fly Ash	Antimony	mg/L	0.003275	0.00385	0.004425	TRUE
40109	Fly Ash	Antimony	mg/L	0.00555	0.0085	0.01145	TRUE
43035	Combined ash	Antimony	mg/L	0.00025	0.0003	0.00035	TRUE
49003A	Fly Ash	Antimony	mg/L	0.02465	0.04495	0.05865	TRUE
AP	Combined ash	Antimony	mg/L	0.01	0.01	0.01	TRUE
C	Combined ash	Antimony	mg/L	0.05	0.05	0.1	TRUE
13115B	Combined ash	Arsenic	mg/L	0.022	0.023	0.0415	TRUE
14093	Fly Ash	Arsenic	mg/L	0.0925	0.163	0.2005	TRUE
22346	Other	Arsenic	mg/L	0.256	0.413	0.57	TRUE
23223B	FGD waste	Arsenic	mg/L	0.01775	0.0185	0.01925	TRUE
25410A	Combined ash	Arsenic	mg/L	0.069	0.069	0.069	TRUE
25410B	Fly Ash	Arsenic	mg/L	0.072	0.072	0.072	TRUE
33104	Fly Ash	Arsenic	mg/L	0.3915	0.721	1.0505	TRUE
33106	Fly Ash	Arsenic	mg/L	0.049	0.056	0.0895	TRUE
35015B	Fly Ash	Arsenic	mg/L	0.0875	0.132	0.1765	TRUE
40109	Fly Ash	Arsenic	mg/L	0.19275	0.2215	0.25025	TRUE
43035	Combined ash	Arsenic	mg/L	0.0055	0.0058	0.0061	TRUE
49003A	Fly Ash	Arsenic	mg/L	0.0825	0.148	0.2	TRUE
AP	Combined ash	Arsenic	mg/L	0.0325	0.041	0.059	TRUE
BR	Ash & coal waste	Arsenic	mg/L	0.004	0.022	0.9765	TRUE
C	Combined ash	Arsenic	mg/L	0.072	0.091	0.11	TRUE
CADK	FGD waste	Arsenic	mg/L	0.00625	0.0075	0.00875	TRUE
CASJ	FGD waste	Arsenic	mg/L	1.81725	2.855	6.41	TRUE
CATT	FGD waste	Arsenic	mg/L	0.139	0.206	0.273	TRUE
CL	Ash & coal waste	Arsenic	mg/L	0.082584687	0.404963334	0.66338875	TRUE
CY	FGD waste	Arsenic	mg/L	0.06405	0.0748	0.20825	TRUE
FC	Ash & coal waste	Arsenic	mg/L	0.0025	0.0025	0.0025	TRUE
HA	Ash & coal waste	Arsenic	mg/L	0.18	0.18	0.18	TRUE
HA	Combined ash	Arsenic	mg/L	0.005821	0.01933	0.1081	TRUE
MO	Ash & coal waste	Arsenic	mg/L	0.182282849	5.03	14.42148508	TRUE
MO	Bottom ash	Arsenic	mg/L	0.0025	0.0055785	0.014373468	TRUE
NA	Na FGD Sludge	Arsenic	mg/L	0.8	0.8	10	TRUE
O	FGD waste	Arsenic	mg/L	0.18025	0.3438	0.3438	TRUE
OK	Bottom ash	Arsenic	mg/L	0.025	0.025	0.025	TRUE
OK	Fly ash	Arsenic	mg/L	0.056195	0.0568	0.073125	TRUE
SX	Bottom ash	Arsenic	mg/L	0.008688875	0.02661935	0.105585375	TRUE
SX	Fly ash	Arsenic	mg/L	0.00836	0.0111	0.015	TRUE
13115B	Combined ash	Arsenic (III)	mg/L	0.00005	0.00005	0.000235	TRUE
14093	Fly Ash	Arsenic (III)	mg/L	0.0028	0.0037	0.05035	TRUE
22346	Other	Arsenic (III)	mg/L	0.024875	0.04025	0.055625	TRUE
23223B	FGD waste	Arsenic (III)	mg/L	0.0008125	0.000875	0.0009375	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
25410A	Combined ash	Arsenic (III)	mg/L	0.0003	0.0003	0.0003	TRUE
25410B	Fly Ash	Arsenic (III)	mg/L	0.00088	0.00088	0.00088	TRUE
33104	Fly Ash	Arsenic (III)	mg/L	0.214825	0.42955	0.644275	TRUE
33106	Fly Ash	Arsenic (III)	mg/L	0.00085	0.0014	0.002	TRUE
35015B	Fly Ash	Arsenic (III)	mg/L	0.052875	0.10225	0.151625	TRUE
40109	Fly Ash	Arsenic (III)	mg/L	0.04425	0.0655	0.08675	TRUE
43035	Combined ash	Arsenic (III)	mg/L	0.0000625	0.000075	0.0000875	TRUE
49003A	Fly Ash	Arsenic (III)	mg/L	0.000575	0.00077	0.0011175	TRUE
13115B	Combined ash	Arsenic (V)	mg/L	0.00605	0.0069	0.02045	TRUE
14093	Fly Ash	Arsenic (V)	mg/L	0.033125	0.066	0.076	TRUE
22346	Other	Arsenic (V)	mg/L	0.21175	0.3195	0.42725	TRUE
23223B	FGD waste	Arsenic (V)	mg/L	0.0004375	0.000625	0.0008125	TRUE
25410A	Combined ash	Arsenic (V)	mg/L	0.025	0.025	0.025	TRUE
25410B	Fly Ash	Arsenic (V)	mg/L	0.047	0.047	0.047	TRUE
33104	Fly Ash	Arsenic (V)	mg/L	0.1575	0.278	0.3985	TRUE
33106	Fly Ash	Arsenic (V)	mg/L	0.0435	0.053	0.053	TRUE
35015B	Fly Ash	Arsenic (V)	mg/L	0.02525	0.0265	0.02775	TRUE
40109	Fly Ash	Arsenic (V)	mg/L	0.026275	0.04485	0.063425	TRUE
43035	Combined ash	Arsenic (V)	mg/L	0.0037	0.0038	0.0039	TRUE
49003A	Fly Ash	Arsenic (V)	mg/L	0.0935	0.1535	0.19375	TRUE
13115B	Combined ash	rsenic, othe	mg/L	0.000085	0.00014	0.000185	TRUE
14093	Fly Ash	rsenic, othe	mg/L	0.000225	0.0003	0.00058	TRUE
23223B	FGD waste	rsenic, othe	mg/L	0.0003625	0.000575	0.0007875	TRUE
25410A	Combined ash	rsenic, othe	mg/L	0.0003	0.0003	0.0003	TRUE
25410B	Fly Ash	rsenic, othe	mg/L	0.00005	0.00005	0.00005	TRUE
35015B	Fly Ash	rsenic, othe	mg/L	0.000435	0.00052	0.000605	TRUE
40109	Fly Ash	rsenic, othe	mg/L	0.0007	0.0007	0.0007	TRUE
43035	Combined ash	rsenic, othe	mg/L	0.0000625	0.000075	0.0000875	TRUE
49003A	Fly Ash	rsenic, othe	mg/L	0.000125	0.00015	0.000155	TRUE
13115B	Combined ash	Barium	mg/L	0.07	0.08	0.09	TRUE
14093	Fly Ash	Barium	mg/L	0.0275	0.04	0.04	TRUE
22346	Other	Barium	mg/L	0.1184	0.1376	0.1568	TRUE
23223B	FGD waste	Barium	mg/L	0.02375	0.0325	0.04125	TRUE
25410A	Combined ash	Barium	mg/L	0.14	0.14	0.14	TRUE
25410B	Fly Ash	Barium	mg/L	0.08	0.08	0.08	TRUE
33104	Fly Ash	Barium	mg/L	0.202	0.21	0.218	TRUE
33106	Fly Ash	Barium	mg/L	0.101	0.125	0.147	TRUE
35015B	Fly Ash	Barium	mg/L	0.065	0.07	0.075	TRUE
40109	Fly Ash	Barium	mg/L	0.12775	0.1685	0.20925	TRUE
43035	Combined ash	Barium	mg/L	0.043	0.05	0.057	TRUE
49003A	Fly Ash	Barium	mg/L	0.09425	0.1075	0.1425	TRUE
AP	Combined ash	Barium	mg/L	0.0435	0.057	0.084	TRUE
BR	Ash & coal waste	Barium	mg/L	0.05	0.05	0.05	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
C	Combined ash	Barium	mg/L	0.06	0.079	0.19	TRUE
CADK	FGD waste	Barium	mg/L	0.02	0.02	0.02	TRUE
CASJ	FGD waste	Barium	mg/L	0.01	0.013	0.014	TRUE
CATT	FGD waste	Barium	mg/L	0.0825	0.085	0.0875	TRUE
CL	Ash & coal waste	Barium	mg/L	0.222633542	0.298316875	0.400052188	TRUE
CY	FGD waste	Barium	mg/L	0.121475	0.151	0.20925	TRUE
FC	Ash & coal waste	Barium	mg/L	0.11375	0.1315	0.1785	TRUE
HA	Ash & coal waste	Barium	mg/L	0.11	0.11	0.11	TRUE
HA	Combined ash	Barium	mg/L	0.08743	0.1761	0.2501	TRUE
L	Combined ash	Barium	mg/L	0.001	0.001	0.001	TRUE
MO	Ash & coal waste	Barium	mg/L	0.015126777	0.024100382	0.050431993	TRUE
MO	Bottom ash	Barium	mg/L	0.013491368	0.019940978	0.022872989	TRUE
NA	Na FGD Sludge	Barium	mg/L	0.02	0.14	0.25	TRUE
OK	Bottom ash	Barium	mg/L	0.10633	0.13262	0.15891	TRUE
OK	Fly ash	Barium	mg/L	0.087405	0.1958	0.22505	TRUE
SX	Bottom ash	Barium	mg/L	0.052247125	0.0673179	0.079726375	TRUE
SX	Fly ash	Barium	mg/L	0.0857	0.0947	0.0989	TRUE
13115B	Combined ash	Beryllium	mg/L	0.0004	0.0004	0.00045	TRUE
14093	Fly Ash	Beryllium	mg/L	0.0005	0.0005	0.0005	TRUE
22346	Other	Beryllium	mg/L	0.0001	0.0001	0.0001	TRUE
23223B	FGD waste	Beryllium	mg/L	0.0005	0.0005	0.0005	TRUE
25410A	Combined ash	Beryllium	mg/L	0.0005	0.0005	0.0005	TRUE
25410B	Fly Ash	Beryllium	mg/L	0.0004	0.0004	0.0004	TRUE
33104	Fly Ash	Beryllium	mg/L	0.0002	0.0002	0.0002	TRUE
33106	Fly Ash	Beryllium	mg/L	0.0002	0.0002	0.0002	TRUE
35015B	Fly Ash	Beryllium	mg/L	0.0004	0.0004	0.0004	TRUE
40109	Fly Ash	Beryllium	mg/L	0.0002	0.0002	0.0002	TRUE
43035	Combined ash	Beryllium	mg/L	0.000125	0.00015	0.000175	TRUE
49003A	Fly Ash	Beryllium	mg/L	0.0001	0.00025	0.0004	TRUE
AP	Combined ash	Beryllium	mg/L	0.0062	0.0062	0.0062	TRUE
C	Combined ash	Beryllium	mg/L	0.001	0.001	0.001	TRUE
13115B	Combined ash	Boron	mg/L	14.325	26.3	34.5	TRUE
14093	Fly Ash	Boron	mg/L	74.15	93.4	102.7	TRUE
22346	Other	Boron	mg/L	1.91	2.71	3.51	TRUE
23223B	FGD waste	Boron	mg/L	57.125	65.25	73.375	TRUE
25410A	Combined ash	Boron	mg/L	109	109	109	TRUE
25410B	Fly Ash	Boron	mg/L	24.2	24.2	24.2	TRUE
33104	Fly Ash	Boron	mg/L	1.0205	1.547	2.0735	TRUE
33106	Fly Ash	Boron	mg/L	1.0785	1.24	1.315	TRUE
35015B	Fly Ash	Boron	mg/L	4.3625	5.445	6.5275	TRUE
40109	Fly Ash	Boron	mg/L	5.3075	5.995	6.6825	TRUE
43035	Combined ash	Boron	mg/L	3.275	3.48	3.685	TRUE
49003A	Fly Ash	Boron	mg/L	0.91075	1.2055	1.6025	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
AP	Combined ash	Boron	mg/L	4.679	9.665	14.563	TRUE
BR	Ash & coal waste	Boron	mg/L	0.65	3.85	6.7	TRUE
C	Combined ash	Boron	mg/L	4.4	8.55	13.7	TRUE
CADK	FGD waste	Boron	mg/L	55.825	60.05	64.275	TRUE
CASJ	FGD waste	Boron	mg/L	18	18.1	29	TRUE
CATT	FGD waste	Boron	mg/L	102.25	110.5	118.75	TRUE
CL	Ash & coal waste	Boron	mg/L	0.5011875	0.78275	1.365	TRUE
CY	FGD waste	Boron	mg/L	0.025	0.025	0.025	TRUE
FC	Ash & coal waste	Boron	mg/L	0.155	0.35	1.3425	TRUE
HA	Ash & coal waste	Boron	mg/L	1.7	1.7	1.7	TRUE
HA	Combined ash	Boron	mg/L	0.544375	0.76825	2.393	TRUE
L	Combined ash	Boron	mg/L	0.61	0.62	0.63	TRUE
MO	Ash & coal waste	Boron	mg/L	0.77175	3.903333333	24.55	TRUE
MO	Bottom ash	Boron	mg/L	0.0341875	0.069	0.1323125	TRUE
NA	Na FGD Sludge	Boron	mg/L	123.5	170	492.5	TRUE
O	FGD waste	Boron	mg/L	4.895	8.71	8.71	TRUE
OK	Bottom ash	Boron	mg/L	2.0513125	3.966375	5.8814375	TRUE
OK	Fly ash	Boron	mg/L	1.5318125	2.626	4.1864375	TRUE
SX	Bottom ash	Boron	mg/L	0.5600625	38.575	72.89166667	TRUE
SX	Fly ash	Boron	mg/L	15.49	19.26375	20.5875	TRUE
AP	Combined ash	Bromide	mg/L	0.9175	1.285	2.18	FALSE
CADK	FGD waste	Bromide	mg/L	1.175	2.05	2.925	FALSE
CASJ	FGD waste	Bromide	mg/L	0.05	0.05	0.05	FALSE
CATT	FGD waste	Bromide	mg/L	48.325	50.75	53.175	FALSE
CL	Ash & coal waste	Bromide	mg/L	0.05225	0.078	0.0955	FALSE
CY	FGD waste	Bromide	mg/L	0.25	0.32	0.4175	FALSE
FC	Ash & coal waste	Bromide	mg/L	0.1	0.1	0.1	FALSE
HA	Combined ash	Bromide	mg/L	0.05	0.203	0.441	FALSE
MO	Ash & coal waste	Bromide	mg/L	0.25	0.5	2.5	FALSE
MO	Bottom ash	Bromide	mg/L	0.0425	0.05	0.08375	FALSE
NA	Na FGD Sludge	Bromide	mg/L	517	742	2750	FALSE
OK	Bottom ash	Bromide	mg/L	2.86575	3.1465	3.42725	FALSE
OK	Fly ash	Bromide	mg/L	10.384	13.003	16.5565	FALSE
SX	Bottom ash	Bromide	mg/L	0.08425	0.179	0.318	FALSE
SX	Fly ash	Bromide	mg/L	0.5	0.918	1.696	FALSE
13115B	Combined ash	Cadmium	mg/L	0.00095	0.0015	0.005	TRUE
14093	Fly Ash	Cadmium	mg/L	0.00095	0.0015	0.01135	TRUE
22346	Other	Cadmium	mg/L	0.00025	0.0004	0.00055	TRUE
23223B	FGD waste	Cadmium	mg/L	0.011925	0.01205	0.012175	TRUE
25410A	Combined ash	Cadmium	mg/L	0.0647	0.0647	0.0647	TRUE
25410B	Fly Ash	Cadmium	mg/L	0.014	0.014	0.014	TRUE
33104	Fly Ash	Cadmium	mg/L	0.000375	0.00045	0.000525	TRUE
33106	Fly Ash	Cadmium	mg/L	0.00265	0.0041	0.00435	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
35015B	Fly Ash	Cadmium	mg/L	0.0002375	0.000325	0.0004125	TRUE
40109	Fly Ash	Cadmium	mg/L	0.001175	0.00155	0.001925	TRUE
43035	Combined ash	Cadmium	mg/L	0.001275	0.00155	0.001825	TRUE
49003A	Fly Ash	Cadmium	mg/L	0.00115	0.0013	0.00245	TRUE
AP	Combined ash	Cadmium	mg/L	0.000725	0.001125	0.00125	TRUE
BR	Ash & coal waste	Cadmium	mg/L	0.05	0.075	0.375	TRUE
C	Combined ash	Cadmium	mg/L	0.0025	0.0025	0.0025	TRUE
CADK	FGD waste	Cadmium	mg/L	0.001	0.001	0.001	TRUE
CASJ	FGD waste	Cadmium	mg/L	0.009	0.02	0.02	TRUE
CATT	FGD waste	Cadmium	mg/L	0.0015	0.002	0.0025	TRUE
CL	Ash & coal waste	Cadmium	mg/L	0.00125	0.00125	0.00125	TRUE
CY	FGD waste	Cadmium	mg/L	0.00125	0.00125	0.0040625	TRUE
FC	Ash & coal waste	Cadmium	mg/L	0.00125	0.00125	0.00125	TRUE
HA	Ash & coal waste	Cadmium	mg/L	0.0025	0.0025	0.0025	TRUE
HA	Combined ash	Cadmium	mg/L	0.00125	0.00125	0.00125	TRUE
L	Combined ash	Cadmium	mg/L	0.001	0.001	0.001	TRUE
MO	Ash & coal waste	Cadmium	mg/L	0.013536534	0.075	0.092407083	TRUE
MO	Bottom ash	Cadmium	mg/L	0.00125	0.00125	0.00125	TRUE
NA	Na FGD Sludge	Cadmium	mg/L	0.25	0.25	0.25	TRUE
OK	Bottom ash	Cadmium	mg/L	0.0125	0.0125	0.0125	TRUE
OK	Fly ash	Cadmium	mg/L	0.006875	0.0125	0.0125	TRUE
SX	Bottom ash	Cadmium	mg/L	0.00125	0.01433105	0.032575025	TRUE
SX	Fly ash	Cadmium	mg/L	0.00602	0.00752	0.00909	TRUE
13115B	Combined ash	Calcium	mg/L	261	291	296.5	TRUE
14093	Fly Ash	Calcium	mg/L	587.5	591	636	TRUE
22346	Other	Calcium	mg/L	97.725	100.15	102.575	TRUE
23223B	FGD waste	Calcium	mg/L	533.75	543.5	553.25	TRUE
25410A	Combined ash	Calcium	mg/L	15	15	15	TRUE
25410B	Fly Ash	Calcium	mg/L	529	529	529	TRUE
33104	Fly Ash	Calcium	mg/L	60.45	65.8	71.15	TRUE
33106	Fly Ash	Calcium	mg/L	40.7	45.3	45.55	TRUE
35015B	Fly Ash	Calcium	mg/L	415.25	498.5	581.75	TRUE
40109	Fly Ash	Calcium	mg/L	61.175	63.95	66.725	TRUE
43035	Combined ash	Calcium	mg/L	4.1875	7.125	10.0625	TRUE
49003A	Fly Ash	Calcium	mg/L	48.75	51	59.5	TRUE
AP	Combined ash	Calcium	mg/L	158.9	343	524.8	TRUE
BR	Ash & coal waste	Calcium	mg/L	480.5	496	534.25	TRUE
C	Combined ash	Calcium	mg/L	76.525	144	156.5	TRUE
CADK	FGD waste	Calcium	mg/L	751.5	766	780.5	TRUE
CASJ	FGD waste	Calcium	mg/L	590	594	619	TRUE
CATT	FGD waste	Calcium	mg/L	834.25	873.5	912.75	TRUE
CL	Ash & coal waste	Calcium	mg/L	34.60958334	57.35125	91.99	TRUE
CY	FGD waste	Calcium	mg/L	28.425	38.55	76.225	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
FC	Ash & coal waste	Calcium	mg/L	28.9	76.35	101.275	TRUE
HA	Ash & coal waste	Calcium	mg/L	80	80	80	TRUE
HA	Combined ash	Calcium	mg/L	41.82	77.84	93.43	TRUE
L	Combined ash	Calcium	mg/L	406.775	471.85	536.925	TRUE
MO	Ash & coal waste	Calcium	mg/L	483.6875	541.9	574.2125	TRUE
MO	Bottom ash	Calcium	mg/L	93.25125	104.8566667	116.7833334	TRUE
NA	Na FGD Sludge	Calcium	mg/L	15.5	22	38	TRUE
O	FGD waste	Calcium	mg/L	543	592	592	TRUE
OK	Bottom ash	Calcium	mg/L	361.90625	440.3375	518.76875	TRUE
OK	Fly ash	Calcium	mg/L	37.86875	46.125	68.3825	TRUE
SX	Bottom ash	Calcium	mg/L	42.16708334	357.35	555.5	TRUE
SX	Fly ash	Calcium	mg/L	132.475	138.85	198.6375	TRUE
13115B	Combined ash	Chloride	mg/L	37.3	45.4	54.4	TRUE
14093	Fly Ash	Chloride	mg/L	18.15	27.3	30.05	TRUE
22346	Other	Chloride	mg/L	70.225	72.55	74.875	TRUE
23223B	FGD waste	Chloride	mg/L	421.25	471.5	521.75	TRUE
25410A	Combined ash	Chloride	mg/L	54.8	54.8	54.8	TRUE
25410B	Fly Ash	Chloride	mg/L	22.2	22.2	22.2	TRUE
33104	Fly Ash	Chloride	mg/L	9.275	11.45	13.625	TRUE
33106	Fly Ash	Chloride	mg/L	9.1	9.4	9.55	TRUE
35015B	Fly Ash	Chloride	mg/L	47.1	60.4	73.7	TRUE
40109	Fly Ash	Chloride	mg/L	7.725	7.85	7.975	TRUE
43035	Combined ash	Chloride	mg/L	33.875	36.75	39.625	TRUE
49003A	Fly Ash	Chloride	mg/L	16.85	18.8	21.8	TRUE
AP	Combined ash	Chloride	mg/L	131.4	262	326.65	TRUE
BR	Ash & coal waste	Chloride	mg/L	2.3025	3.555	5.09	TRUE
C	Combined ash	Chloride	mg/L	27.3	33	47	TRUE
CADK	FGD waste	Chloride	mg/L	460.5	603	745.5	TRUE
CASJ	FGD waste	Chloride	mg/L	4100	4220	4280	TRUE
CATT	FGD waste	Chloride	mg/L	738.25	791.5	844.75	TRUE
CL	Ash & coal waste	Chloride	mg/L	4.63625	6.183	6.95525	TRUE
CY	FGD waste	Chloride	mg/L	30.525	33.6	37.5	TRUE
FC	Ash & coal waste	Chloride	mg/L	13.25	14.85	17.125	TRUE
HA	Ash & coal waste	Chloride	mg/L	58	58	58	TRUE
HA	Combined ash	Chloride	mg/L	9.912	20.449	38.207	TRUE
L	Combined ash	Chloride	mg/L	19.13	24.07	29.01	TRUE
MO	Ash & coal waste	Chloride	mg/L	7.8725	20.245	27	TRUE
MO	Bottom ash	Chloride	mg/L	3.734	8.0155	16.515	TRUE
NA	Na FGD Sludge	Chloride	mg/L	5675	13400	52000	TRUE
O	FGD waste	Chloride	mg/L	1718	2023	2023	TRUE
OK	Bottom ash	Chloride	mg/L	1909.64025	1938.0885	1966.53675	TRUE
OK	Fly ash	Chloride	mg/L	10774.3275	12397.996	16202.1915	TRUE
SX	Bottom ash	Chloride	mg/L	17.00725	19.3245	22.68375	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
SX	Fly ash	Chloride	mg/L	29.371	36.057	39.896	TRUE
13115B	Combined ash	Chromium	mg/L	0.00025	0.00025	0.00025	TRUE
14093	Fly Ash	Chromium	mg/L	0.00025	0.00025	0.00025	TRUE
22346	Other	Chromium	mg/L	0.0001	0.0001	0.0001	TRUE
23223B	FGD waste	Chromium	mg/L	0.0006125	0.000975	0.0013375	TRUE
25410A	Combined ash	Chromium	mg/L	0.0038	0.0038	0.0038	TRUE
25410B	Fly Ash	Chromium	mg/L	0.00025	0.00025	0.00025	TRUE
33104	Fly Ash	Chromium	mg/L	0.00265	0.0051	0.00755	TRUE
33106	Fly Ash	Chromium	mg/L	0.0002	0.0002	0.0002	TRUE
35015B	Fly Ash	Chromium	mg/L	0.00025	0.00025	0.00025	TRUE
40109	Fly Ash	Chromium	mg/L	0.0002	0.0002	0.0002	TRUE
43035	Combined ash	Chromium	mg/L	0.045	0.066	0.087	TRUE
49003A	Fly Ash	Chromium	mg/L	0.0002125	0.00025	0.000265	TRUE
AP	Combined ash	Chromium	mg/L	0.0018	0.00459	0.020525	TRUE
BR	Ash & coal waste	Chromium	mg/L	0.05	0.05	0.05	TRUE
C	Combined ash	Chromium	mg/L	0.001	0.001	0.001	TRUE
CADK	FGD waste	Chromium	mg/L	0.1	0.1	0.1	TRUE
CASJ	FGD waste	Chromium	mg/L	0.1	0.1	0.5	TRUE
CATT	FGD waste	Chromium	mg/L	0.29	0.3	0.31	TRUE
CL	Ash & coal waste	Chromium	mg/L	0.00125	0.00125	0.00125	TRUE
CY	FGD waste	Chromium	mg/L	0.00125	0.00249	0.0059225	TRUE
FC	Ash & coal waste	Chromium	mg/L	0.00125	0.00125	0.00125	TRUE
HA	Ash & coal waste	Chromium	mg/L	0.005	0.005	0.005	TRUE
HA	Combined ash	Chromium	mg/L	0.00125	0.00125	0.00125	TRUE
L	Combined ash	Chromium	mg/L	0.005	0.005	0.005	TRUE
MO	Ash & coal waste	Chromium	mg/L	0.00125	0.223695848	0.68875	TRUE
MO	Bottom ash	Chromium	mg/L	0.00125	0.00125	0.00125	TRUE
NA	Na FGD Sludge	Chromium	mg/L	0.2	0.2	1	TRUE
O	FGD waste	Chromium	mg/L	0.012	0.012	0.012	TRUE
OK	Bottom ash	Chromium	mg/L	0.0125	0.0125	0.0125	TRUE
OK	Fly ash	Chromium	mg/L	0.0125	0.02927	0.034475	TRUE
SX	Bottom ash	Chromium	mg/L	0.00125	0.00125	0.00125	TRUE
SX	Fly ash	Chromium	mg/L	0.137	0.297	0.501	TRUE
22346	Other	hromium (II	mg/L	0.00001725	0.0000245	0.00003175	TRUE
23223B	FGD waste	hromium (II	mg/L	0.00005	0.00005	0.00005	TRUE
25410A	Combined ash	hromium (II	mg/L	0.00005	0.00005	0.00005	TRUE
33104	Fly Ash	hromium (II	mg/L	0.00044	0.00061	0.00078	TRUE
33106	Fly Ash	hromium (II	mg/L	0.000005	0.000005	0.000005	TRUE
40109	Fly Ash	hromium (II	mg/L	0.0000775	0.000105	0.0001325	TRUE
43035	Combined ash	hromium (II	mg/L	0.0014225	0.002315	0.0032075	TRUE
13115B	Combined ash	hromium (V	mg/L	0.0013	0.0013	0.0013	TRUE
14093	Fly Ash	hromium (V	mg/L	0.0006	0.0007	0.0013	TRUE
22346	Other	hromium (V	mg/L	0.000003	0.000003	0.000003	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
23223B	FGD waste	hromium (V	mg/L	0.0007625	0.001475	0.0021875	TRUE
25410A	Combined ash	hromium (V	mg/L	0.00025	0.00025	0.00025	TRUE
25410B	Fly Ash	hromium (V	mg/L	0.00005	0.00005	0.00005	TRUE
33104	Fly Ash	hromium (V	mg/L	0.00155375	0.0031025	0.00465125	TRUE
33106	Fly Ash	hromium (V	mg/L	0.000005	0.000005	0.000005	TRUE
35015B	Fly Ash	hromium (V	mg/L	0.00003125	0.0000375	0.00004375	TRUE
40109	Fly Ash	hromium (V	mg/L	0.00001975	0.0000345	0.00004925	TRUE
43035	Combined ash	hromium (V	mg/L	0.04975	0.0735	0.09725	TRUE
49003A	Fly Ash	hromium (V	mg/L	0.00008125	0.0001375	0.00019375	TRUE
13115B	Combined ash	Cobalt	mg/L	0.0005	0.0005	0.00125	TRUE
14093	Fly Ash	Cobalt	mg/L	0.0005	0.0005	0.00375	TRUE
22346	Other	Cobalt	mg/L	0.0003375	0.000495	0.0006525	TRUE
23223B	FGD waste	Cobalt	mg/L	0.001875	0.00325	0.004625	TRUE
25410A	Combined ash	Cobalt	mg/L	0.002	0.002	0.002	TRUE
25410B	Fly Ash	Cobalt	mg/L	0.0005	0.0005	0.0005	TRUE
33104	Fly Ash	Cobalt	mg/L	0.00015	0.0002	0.00025	TRUE
33106	Fly Ash	Cobalt	mg/L	0.0004	0.0007	0.0012	TRUE
35015B	Fly Ash	Cobalt	mg/L	0.000625	0.00075	0.000875	TRUE
40109	Fly Ash	Cobalt	mg/L	0.000125	0.00015	0.000175	TRUE
43035	Combined ash	Cobalt	mg/L	0.000065	0.00011	0.000155	TRUE
49003A	Fly Ash	Cobalt	mg/L	0.001445	0.00188	0.00284	TRUE
AP	Combined ash	Cobalt	mg/L	0.01	0.01	0.01	TRUE
BR	Ash & coal waste	Cobalt	mg/L	0.05	0.05	0.2225	TRUE
C	Combined ash	Cobalt	mg/L	0.005	0.005	0.005	TRUE
MO	Ash & coal waste	Cobalt	mg/L	0.155	1.7175	6.26125	TRUE
13115B	Combined ash	Copper	mg/L	0.006	0.007	0.021	TRUE
14093	Fly Ash	Copper	mg/L	0.0015	0.0015	0.0015	TRUE
22346	Other	Copper	mg/L	0.0001	0.0001	0.0001	TRUE
23223B	FGD waste	Copper	mg/L	0.0215	0.029	0.0365	TRUE
25410A	Combined ash	Copper	mg/L	0.021	0.021	0.021	TRUE
25410B	Fly Ash	Copper	mg/L	0.0015	0.0015	0.0015	TRUE
33104	Fly Ash	Copper	mg/L	0.00045	0.0007	0.00095	TRUE
33106	Fly Ash	Copper	mg/L	0.00035	0.0005	0.00075	TRUE
35015B	Fly Ash	Copper	mg/L	0.005125	0.00875	0.012375	TRUE
40109	Fly Ash	Copper	mg/L	0.00345	0.0051	0.00675	TRUE
43035	Combined ash	Copper	mg/L	0.00285	0.0033	0.00375	TRUE
49003A	Fly Ash	Copper	mg/L	0.0013	0.0038	0.0065	TRUE
AP	Combined ash	Copper	mg/L	0.005	0.005	0.005	TRUE
BR	Ash & coal waste	Copper	mg/L	0.05	0.1	0.6375	TRUE
C	Combined ash	Copper	mg/L	0.0005	0.0005	0.0005	TRUE
CADK	FGD waste	Copper	mg/L	0.03625	0.0475	0.05875	TRUE
CASJ	FGD waste	Copper	mg/L	0.02	0.02	0.125	TRUE
CATT	FGD waste	Copper	mg/L	0.125	0.125	0.125	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
CY	FGD waste	Copper	mg/L	0.054325	0.1085	0.20975	TRUE
FC	Ash & coal waste	Copper	mg/L	0.005	0.005	0.005	TRUE
HA	Ash & coal waste	Copper	mg/L	0.025	0.025	0.025	TRUE
HA	Combined ash	Copper	mg/L	0.005	0.01259	0.01706	TRUE
L	Combined ash	Copper	mg/L	0.0025	0.0025	0.0025	TRUE
MO	Ash & coal waste	Copper	mg/L	0.013778731	0.086168366	0.20363499	TRUE
MO	Bottom ash	Copper	mg/L	0.005	0.005	0.01307	TRUE
NA	Na FGD Sludge	Copper	mg/L	0.04	0.04	0.25	TRUE
OK	Bottom ash	Copper	mg/L	0.0799	0.1098	0.1397	TRUE
OK	Fly ash	Copper	mg/L	0.16695	0.2739	0.5153	TRUE
SX	Bottom ash	Copper	mg/L	0.005	0.005	0.01133445	TRUE
SX	Fly ash	Copper	mg/L	0.005	0.005	0.0104	TRUE
C	Combined ash	Organic Carl	mg/L	7.125	7.19	10.495	FALSE
CADK	FGD waste	Organic Carl	mg/L	45.35	55.6	65.85	FALSE
CASJ	FGD waste	Organic Carl	mg/L	51.7	59	90.4	FALSE
CATT	FGD waste	Organic Carl	mg/L	249.25	320.5	391.75	FALSE
CY	FGD waste	Organic Carl	mg/L	90.225	102.35	111.5	FALSE
FC	Ash & coal waste	Organic Carl	mg/L	2.015	3.725	5.8475	FALSE
HA	Combined ash	Organic Carl	mg/L	4.936707565	6.07919464	7.740028161	FALSE
MO	Ash & coal waste	Organic Carl	mg/L	4.199438087	7.1	16.72	FALSE
MO	Bottom ash	Organic Carl	mg/L	2.329383299	3.029477933	3.410523972	FALSE
NA	Na FGD Sludge	Organic Carl	mg/L	417	636	825	FALSE
OK	Bottom ash	Organic Carl	mg/L	22.66128815	22.66128815	22.66128815	FALSE
OK	Fly ash	Organic Carl	mg/L	47.93557138	51.16074497	73.13920452	FALSE
SX	Bottom ash	Organic Carl	mg/L	5.26756475	20.753413	32.318292	FALSE
SX	Fly ash	Organic Carl	mg/L	5.301197768	7.111551852	7.114545823	FALSE
SX	Bottom ash	rganic Carb	mg/L	5.90591625	22.1745605	33.76040725	FALSE
13115B	Combined ash	solved oxyg	%	2.9	2.9	2.9	FALSE
14093	Fly Ash	solved oxyg	%	4.5	5	5.25	FALSE
22346	Other	solved oxyg	%	31.175	34.35	37.525	FALSE
23223B	FGD waste	solved oxyg	%	0.225	0.25	0.275	FALSE
25410A	Combined ash	solved oxyg	%	2.9	2.9	2.9	FALSE
33104	Fly Ash	solved oxyg	%	44.75	51.6	58.45	FALSE
33106	Fly Ash	solved oxyg	%	30.55	33.5	34.25	FALSE
35015B	Fly Ash	solved oxyg	%	11.975	17.85	23.725	FALSE
40109	Fly Ash	solved oxyg	%	44.45	48.3	52.15	FALSE
43035	Combined ash	solved oxyg	%	18.575	24.05	29.525	FALSE
49003A	Fly Ash	solved oxyg	%	16.975	23	28.675	FALSE
AP	Combined ash	Ferric Iron	mg/L	0.03	0.03	0.03	FALSE
BR	Ash & coal waste	Ferric Iron	mg/L	1.9075	23.235	28.575	FALSE
L	Combined ash	Ferric Iron	mg/L	2.6	3.1	3.6	FALSE
MO	Ash & coal waste	Ferric Iron	mg/L	92.925	683.05	1040.09	FALSE
MO	Bottom ash	Ferric Iron	mg/L	0.8715	1.148	1.188	FALSE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
SX	Bottom ash	Ferric Iron	mg/L	0.0805	0.101	0.2125	FALSE
AP	Combined ash	Ferrous Iron	mg/L	0.035	0.035	0.035	FALSE
BR	Ash & coal waste	Ferrous Iron	mg/L	22.85	606.9	1439.75	FALSE
L	Combined ash	Ferrous Iron	mg/L	96.825	123.55	150.275	FALSE
MO	Ash & coal waste	Ferrous Iron	mg/L	643.0795	4382.885	17999	FALSE
MO	Bottom ash	Ferrous Iron	mg/L	7.057	11.781	14.72	FALSE
SX	Bottom ash	Ferrous Iron	mg/L	0.07	0.07	0.12375	FALSE
AP	Combined ash	Fluoride	mg/L	1.07	2.245	5.21	TRUE
C	Combined ash	Fluoride	mg/L	0.1	0.19	0.23	TRUE
CADK	FGD waste	Fluoride	mg/L	21.25	22.7	24.15	TRUE
CASJ	FGD waste	Fluoride	mg/L	10.47	12.55	15.75	TRUE
CATT	FGD waste	Fluoride	mg/L	6.455	6.49	6.525	TRUE
CL	Ash & coal waste	Fluoride	mg/L	0.37575	0.6205	0.854	TRUE
CY	FGD waste	Fluoride	mg/L	0.875	1.5	2	TRUE
FC	Ash & coal waste	Fluoride	mg/L	0.05	0.05	1.505	TRUE
HA	Combined ash	Fluoride	mg/L	0.05	0.095	0.14	TRUE
L	Combined ash	Fluoride	mg/L	0.3825	0.395	0.4075	TRUE
MO	Ash & coal waste	Fluoride	mg/L	0.1125	0.45	1	TRUE
MO	Bottom ash	Fluoride	mg/L	0.025	0.025	0.046	TRUE
NA	Na FGD Sludge	Fluoride	mg/L	337	376	404	TRUE
OK	Bottom ash	Fluoride	mg/L	0.25	0.25	0.25	TRUE
OK	Fly ash	Fluoride	mg/L	1.25	1.25	2.5	TRUE
SX	Bottom ash	Fluoride	mg/L	0.291	1.0595	1.466	TRUE
SX	Fly ash	Fluoride	mg/L	0.125	0.125	0.25	TRUE
C	Combined ash	nic Carbon,	mg/L	3.185	3.76	8.63	FALSE
CADK	FGD waste	nic Carbon,	mg/L	44.45	48.2	51.95	FALSE
CASJ	FGD waste	nic Carbon,	mg/L	12.8	14.1	33	FALSE
CATT	FGD waste	nic Carbon,	mg/L	3.2875	4.015	4.7425	FALSE
CY	FGD waste	nic Carbon,	mg/L	6.325	14.77	24.225	FALSE
FC	Ash & coal waste	nic Carbon,	mg/L	2.365	2.955	5.505	FALSE
HA	Combined ash	nic Carbon,	mg/L	3.775220912	40.1068722	44.58886074	FALSE
MO	Ash & coal waste	nic Carbon,	mg/L	1.135	8.135	20.57775997	FALSE
MO	Bottom ash	nic Carbon,	mg/L	12.67615104	16.83220219	17.53674564	FALSE
NA	Na FGD Sludge	nic Carbon,	mg/L	856.75	1114.5	1372.25	FALSE
OK	Bottom ash	nic Carbon,	mg/L	2.800281761	2.800281761	2.800281761	FALSE
OK	Fly ash	nic Carbon,	mg/L	1.678493618	1.722405184	2.148047972	FALSE
SX	Bottom ash	nic Carbon,	mg/L	5.00663275	9.952692	20.026531	FALSE
SX	Fly ash	nic Carbon,	mg/L	2.655525949	3.059711949	3.212404438	FALSE
SX	Bottom ash	ic Carbon, I	mg/L	6.59552225	11.0942695	21.23101175	FALSE
13115B	Combined ash	Iron	mg/L	0.025	0.025	1.6075	TRUE
14093	Fly Ash	Iron	mg/L	0.025	0.025	7.3625	TRUE
22346	Other	Iron	mg/L	6.4465	12.831	19.2155	TRUE
23223B	FGD waste	Iron	mg/L	0.31875	0.6125	0.90625	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
25410A	Combined ash	Iron	mg/L	1.53	1.53	1.53	TRUE
25410B	Fly Ash	Iron	mg/L	0.025	0.025	0.025	TRUE
33104	Fly Ash	Iron	mg/L	0.55525	1.0935	1.63175	TRUE
33106	Fly Ash	Iron	mg/L	0.9955	1.07	1.385	TRUE
35015B	Fly Ash	Iron	mg/L	0.025	0.025	0.025	TRUE
40109	Fly Ash	Iron	mg/L	0.0195	0.023	0.0265	TRUE
43035	Combined ash	Iron	mg/L	0.0125	0.0125	0.0125	TRUE
49003A	Fly Ash	Iron	mg/L	0.091625	0.21	0.31225	TRUE
AP	Combined ash	Iron	mg/L	0.036	0.0495	0.16525	TRUE
BR	Ash & coal waste	Iron	mg/L	31.525	610	1617.5	TRUE
C	Combined ash	Iron	mg/L	0.02	0.02	0.02	TRUE
CADK	FGD waste	Iron	mg/L	0.0125	0.015	0.0175	TRUE
CASJ	FGD waste	Iron	mg/L	0.025	0.025	0.125	TRUE
CATT	FGD waste	Iron	mg/L	0.02	0.02	0.02	TRUE
CL	Ash & coal waste	Iron	mg/L	0.025	0.025	0.212875	TRUE
CY	FGD waste	Iron	mg/L	0.19	0.445	1.045	TRUE
FC	Ash & coal waste	Iron	mg/L	0.0525	0.09	0.18	TRUE
HA	Ash & coal waste	Iron	mg/L	0.025	0.025	0.025	TRUE
HA	Combined ash	Iron	mg/L	0.025	0.025	0.07375	TRUE
MO	Ash & coal waste	Iron	mg/L	125.644375	2038.1	19170	TRUE
MO	Bottom ash	Iron	mg/L	8.04540625	17.7025	18.833125	TRUE
NA	Na FGD Sludge	Iron	mg/L	0.05	0.5	0.5	TRUE
O	FGD waste	Iron	mg/L	0.0566	0.0879	0.0879	TRUE
OK	Bottom ash	Iron	mg/L	0.0446875	0.064375	0.0840625	TRUE
OK	Fly ash	Iron	mg/L	0.025	0.025	0.047625	TRUE
SX	Bottom ash	Iron	mg/L	0.0484375	0.083725	0.2899375	TRUE
SX	Fly ash	Iron	mg/L	0.12475	0.4615	0.991	TRUE
13115B	Combined ash	Lead	mg/L	0.00025	0.0004	0.0004	TRUE
14093	Fly Ash	Lead	mg/L	0.0001	0.0001	0.0001	TRUE
22346	Other	Lead	mg/L	0.00005	0.00005	0.00005	TRUE
23223B	FGD waste	Lead	mg/L	0.0011	0.0019	0.0027	TRUE
25410A	Combined ash	Lead	mg/L	0.0046	0.0046	0.0046	TRUE
25410B	Fly Ash	Lead	mg/L	0.0008	0.0008	0.0008	TRUE
33104	Fly Ash	Lead	mg/L	0.00005	0.00005	0.00005	TRUE
33106	Fly Ash	Lead	mg/L	0.00005	0.00005	0.00005	TRUE
35015B	Fly Ash	Lead	mg/L	0.0001	0.0001	0.0001	TRUE
40109	Fly Ash	Lead	mg/L	0.0001625	0.000275	0.0003875	TRUE
43035	Combined ash	Lead	mg/L	0.00007	0.00007	0.00007	TRUE
49003A	Fly Ash	Lead	mg/L	0.00007	0.000085	0.0001	TRUE
AP	Combined ash	Lead	mg/L	0.00125	0.00125	0.00125	TRUE
C	Combined ash	Lead	mg/L	0.0015	0.0022	0.00305	TRUE
CADK	FGD waste	Lead	mg/L	0.1	0.1	0.1	TRUE
CASJ	FGD waste	Lead	mg/L	0.1	0.3	0.3	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
CATT	FGD waste	Lead	mg/L	0.21825	0.2275	0.23675	TRUE
CL	Ash & coal waste	Lead	mg/L	0.0025	0.0025	0.0025	TRUE
CY	FGD waste	Lead	mg/L	0.0025	0.0025	0.008125	TRUE
FC	Ash & coal waste	Lead	mg/L	0.0025	0.0025	0.0025	TRUE
HA	Ash & coal waste	Lead	mg/L	0.025	0.025	0.025	TRUE
HA	Combined ash	Lead	mg/L	0.0025	0.0025	0.0025	TRUE
MO	Ash & coal waste	Lead	mg/L	0.0025	0.0025	0.093	TRUE
MO	Bottom ash	Lead	mg/L	0.0025	0.0025	0.0025	TRUE
OK	Bottom ash	Lead	mg/L	0.025	0.025	0.025	TRUE
OK	Fly ash	Lead	mg/L	0.01375	0.025	0.025	TRUE
SX	Bottom ash	Lead	mg/L	0.0002351	0.0003696	0.0007448	TRUE
SX	Fly ash	Lead	mg/L	0.0025	0.0025	0.0025	TRUE
13115B	Combined ash	Lithium	mg/L	0.045	0.06	0.56	FALSE
14093	Fly Ash	Lithium	mg/L	0.09	0.1	0.105	FALSE
22346	Other	Lithium	mg/L	0.13525	0.1365	0.13775	FALSE
23223B	FGD waste	Lithium	mg/L	0.05	0.09	0.13	FALSE
25410A	Combined ash	Lithium	mg/L	0.06	0.06	0.06	FALSE
25410B	Fly Ash	Lithium	mg/L	0.05	0.05	0.05	FALSE
33104	Fly Ash	Lithium	mg/L	0.177	0.199	0.221	FALSE
33106	Fly Ash	Lithium	mg/L	0.0815	0.082	0.1035	FALSE
35015B	Fly Ash	Lithium	mg/L	0.1775	0.255	0.3325	FALSE
40109	Fly Ash	Lithium	mg/L	0.5695	0.578	0.5865	FALSE
43035	Combined ash	Lithium	mg/L	0.00925	0.0115	0.01375	FALSE
49003A	Fly Ash	Lithium	mg/L	0.17025	0.2485	0.31925	FALSE
13115B	Combined ash	Magnesium	mg/L	12	21	28.5	TRUE
14093	Fly Ash	Magnesium	mg/L	10	13	24.5	TRUE
22346	Other	Magnesium	mg/L	22.325	25.15	27.975	TRUE
23223B	FGD waste	Magnesium	mg/L	48.5	74	99.5	TRUE
25410A	Combined ash	Magnesium	mg/L	20	20	20	TRUE
25410B	Fly Ash	Magnesium	mg/L	7	7	7	TRUE
33104	Fly Ash	Magnesium	mg/L	1.325	2.54	3.755	TRUE
33106	Fly Ash	Magnesium	mg/L	4.845	6.61	6.76	TRUE
35015B	Fly Ash	Magnesium	mg/L	36	37	38	TRUE
40109	Fly Ash	Magnesium	mg/L	0.09	0.1	0.11	TRUE
43035	Combined ash	Magnesium	mg/L	0.025	0.025	0.025	TRUE
49003A	Fly Ash	Magnesium	mg/L	18.25	21	23.5	TRUE
AP	Combined ash	Magnesium	mg/L	4.2235	19.957	74.3665	TRUE
BR	Ash & coal waste	Magnesium	mg/L	13.4775	92	170	TRUE
C	Combined ash	Magnesium	mg/L	0.03	0.042	0.0865	TRUE
CADK	FGD waste	Magnesium	mg/L	303.5	329	354.5	TRUE
CASJ	FGD waste	Magnesium	mg/L	600	760	780	TRUE
CATT	FGD waste	Magnesium	mg/L	99.5	120	140.5	TRUE
CL	Ash & coal waste	Magnesium	mg/L	0.4920625	3.13	6.74	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
CY	FGD waste	Magnesium	mg/L	0.615	0.895	1.155	TRUE
FC	Ash & coal waste	Magnesium	mg/L	0.05	0.06	0.0775	TRUE
HA	Ash & coal waste	Magnesium	mg/L	5	5	5	TRUE
HA	Combined ash	Magnesium	mg/L	0.180375	5.44175	25.76125	TRUE
L	Combined ash	Magnesium	mg/L	17.85	18.87	19.89	TRUE
MO	Ash & coal waste	Magnesium	mg/L	47.40375	178	363.375	TRUE
MO	Bottom ash	Magnesium	mg/L	6.02790625	15.8325	18.0828125	TRUE
NA	Na FGD Sludge	Magnesium	mg/L	26.5	38	126	TRUE
O	FGD waste	Magnesium	mg/L	141	205	205	TRUE
OK	Bottom ash	Magnesium	mg/L	2.54325	4.7795	7.01575	TRUE
OK	Fly ash	Magnesium	mg/L	0.025	0.025	0.025	TRUE
SX	Bottom ash	Magnesium	mg/L	12.64166667	15.01666667	21.82916667	TRUE
SX	Fly ash	Magnesium	mg/L	0.714375	0.91225	2.949875	TRUE
13115B	Combined ash	Manganese	mg/L	0.002	0.002	2.086	TRUE
14093	Fly Ash	Manganese	mg/L	0.0235	0.025	1.2925	TRUE
22346	Other	Manganese	mg/L	0.115825	0.14055	0.165275	TRUE
23223B	FGD waste	Manganese	mg/L	0.26075	0.4085	0.55625	TRUE
25410A	Combined ash	Manganese	mg/L	0.008	0.008	0.008	TRUE
25410B	Fly Ash	Manganese	mg/L	0.052	0.052	0.052	TRUE
33104	Fly Ash	Manganese	mg/L	0.098825	0.19755	0.296275	TRUE
33106	Fly Ash	Manganese	mg/L	0.246	0.248	0.2545	TRUE
35015B	Fly Ash	Manganese	mg/L	0.098	0.155	0.212	TRUE
40109	Fly Ash	Manganese	mg/L	0.001775	0.00315	0.004525	TRUE
43035	Combined ash	Manganese	mg/L	0.000125	0.00015	0.000175	TRUE
49003A	Fly Ash	Manganese	mg/L	0.127	0.148	0.223	TRUE
AP	Combined ash	Manganese	mg/L	0.0045	0.0455	0.21975	TRUE
BR	Ash & coal waste	Manganese	mg/L	1.1	6.6	13.175	TRUE
C	Combined ash	Manganese	mg/L	0.005	0.005	0.005	TRUE
CADK	FGD waste	Manganese	mg/L	6.75	7.41	8.07	TRUE
CASJ	FGD waste	Manganese	mg/L	0.28	0.31	0.39	TRUE
CATT	FGD waste	Manganese	mg/L	0.105	0.16	0.215	TRUE
CL	Ash & coal waste	Manganese	mg/L	0.00125	0.00337045	0.099217063	TRUE
CY	FGD waste	Manganese	mg/L	0.00505	0.007465	0.0128775	TRUE
FC	Ash & coal waste	Manganese	mg/L	0.00125	0.00125	0.00125	TRUE
HA	Ash & coal waste	Manganese	mg/L	0.05	0.05	0.05	TRUE
HA	Combined ash	Manganese	mg/L	0.00125	0.00585	0.2501	TRUE
MO	Ash & coal waste	Manganese	mg/L	9.863572775	44.8	63.85	TRUE
MO	Bottom ash	Manganese	mg/L	0.650675	1.49234706	1.81367353	TRUE
NA	Na FGD Sludge	Manganese	mg/L	0.02	0.25	0.25	TRUE
OK	Bottom ash	Manganese	mg/L	0.0342	0.0559	0.0776	TRUE
OK	Fly ash	Manganese	mg/L	0.006875	0.0125	0.0125	TRUE
SX	Bottom ash	Manganese	mg/L	0.019177875	0.03458515	0.18725165	TRUE
SX	Fly ash	Manganese	mg/L	0.00125	0.00598	0.00737	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
22346	Other	Mercury	mg/L	3.325E-07	0.000000415	4.975E-07	TRUE
23223B	FGD waste	Mercury	mg/L	0.000002475	0.00000305	0.000003625	TRUE
35015B	Fly Ash	Mercury	mg/L	0.0000019	0.000003	0.0000041	TRUE
43035	Combined ash	Mercury	mg/L	0.0000064	0.0000074	0.0000084	TRUE
49003A	Fly Ash	Mercury	mg/L	0.0000014	0.0000014	0.0000014	TRUE
HA	Ash & coal waste	Mercury	mg/L	0.00025	0.00025	0.00025	TRUE
13115B	Combined ash	Molybdenum	mg/L	0.3	0.5	1.205	TRUE
14093	Fly Ash	Molybdenum	mg/L	0.42	0.74	3.385	TRUE
22346	Other	Molybdenum	mg/L	0.172	0.209	0.246	TRUE
23223B	FGD waste	Molybdenum	mg/L	15.6275	30.685	45.7425	TRUE
25410A	Combined ash	Molybdenum	mg/L	39.6	39.6	39.6	TRUE
25410B	Fly Ash	Molybdenum	mg/L	3.01	3.01	3.01	TRUE
33104	Fly Ash	Molybdenum	mg/L	0.1145	0.134	0.1535	TRUE
33106	Fly Ash	Molybdenum	mg/L	0.6735	1.06	1.085	TRUE
35015B	Fly Ash	Molybdenum	mg/L	0.1575	0.175	0.1925	TRUE
40109	Fly Ash	Molybdenum	mg/L	0.2745	0.303	0.3315	TRUE
43035	Combined ash	Molybdenum	mg/L	0.296	0.372	0.448	TRUE
49003A	Fly Ash	Molybdenum	mg/L	0.441	0.605	0.8525	TRUE
AP	Combined ash	Molybdenum	mg/L	0.18	0.365	0.557	TRUE
BR	Ash & coal waste	Molybdenum	mg/L	0.5	0.5	0.5	TRUE
C	Combined ash	Molybdenum	mg/L	0.46	0.53	0.74	TRUE
CADK	FGD waste	Molybdenum	mg/L	1.0725	1.165	1.2575	TRUE
CASJ	FGD waste	Molybdenum	mg/L	0.05	0.05	0.25	TRUE
CATT	FGD waste	Molybdenum	mg/L	0.4975	0.655	0.8125	TRUE
CL	Ash & coal waste	Molybdenum	mg/L	0.131375	0.342333334	0.570875	TRUE
CY	FGD waste	Molybdenum	mg/L	0.575	0.645	0.725	TRUE
FC	Ash & coal waste	Molybdenum	mg/L	0.25	0.25	0.25	TRUE
HA	Ash & coal waste	Molybdenum	mg/L	0.075	0.075	0.075	TRUE
HA	Combined ash	Molybdenum	mg/L	0.025	0.1475	0.153	TRUE
L	Combined ash	Molybdenum	mg/L	0.08625	0.1675	0.24875	TRUE
MO	Ash & coal waste	Molybdenum	mg/L	0.05	0.25	0.25	TRUE
MO	Bottom ash	Molybdenum	mg/L	0.25	0.25225	1.21815625	TRUE
NA	Na FGD Sludge	Molybdenum	mg/L	0.1	0.1	1	TRUE
O	FGD waste	Molybdenum	mg/L	0.0179	0.0179	0.0179	TRUE
OK	Bottom ash	Molybdenum	mg/L	0.2326875	0.269625	0.3065625	TRUE
OK	Fly ash	Molybdenum	mg/L	0.7425	0.8195	0.904625	TRUE
SX	Bottom ash	Molybdenum	mg/L	0.1643125	6.643333334	16.20833334	TRUE
SX	Fly ash	Molybdenum	mg/L	7.50225	9.25475	12.68125	TRUE
13115B	Combined ash	Nickel	mg/L	0.0075	0.008	0.009	TRUE
14093	Fly Ash	Nickel	mg/L	0.0045	0.005	0.01	TRUE
22346	Other	Nickel	mg/L	0.001375	0.00245	0.003525	TRUE
23223B	FGD waste	Nickel	mg/L	0.153	0.301	0.449	TRUE
25410A	Combined ash	Nickel	mg/L	0.128	0.128	0.128	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
25410B	Fly Ash	Nickel	mg/L	0.0015	0.0015	0.0015	TRUE
33104	Fly Ash	Nickel	mg/L	0.001225	0.00215	0.003075	TRUE
33106	Fly Ash	Nickel	mg/L	0.0033	0.0042	0.0057	TRUE
35015B	Fly Ash	Nickel	mg/L	0.00425	0.0055	0.00675	TRUE
40109	Fly Ash	Nickel	mg/L	0.0006	0.0009	0.0012	TRUE
43035	Combined ash	Nickel	mg/L	0.000475	0.00065	0.000825	TRUE
49003A	Fly Ash	Nickel	mg/L	0.00325	0.005	0.00675	TRUE
AP	Combined ash	Nickel	mg/L	0.016	0.039	0.051	TRUE
BR	Ash & coal waste	Nickel	mg/L	0.05	0.8	1.275	TRUE
C	Combined ash	Nickel	mg/L	0.01	0.028	0.04375	TRUE
CADK	FGD waste	Nickel	mg/L	0.1	0.1	0.1	TRUE
CASJ	FGD waste	Nickel	mg/L	0.1	0.3	0.3	TRUE
CATT	FGD waste	Nickel	mg/L	0.1	0.1	0.1	TRUE
CL	Ash & coal waste	Nickel	mg/L	0.0025	0.0025	0.0025	TRUE
CY	FGD waste	Nickel	mg/L	0.0803	0.095	0.2896	TRUE
FC	Ash & coal waste	Nickel	mg/L	0.0025	0.00575	0.0117	TRUE
HA	Combined ash	Nickel	mg/L	0.005076	0.005545	0.01094	TRUE
L	Combined ash	Nickel	mg/L	0.005	0.005	0.005	TRUE
MO	Ash & coal waste	Nickel	mg/L	0.421472482	5.6606893	14.21225123	TRUE
MO	Bottom ash	Nickel	mg/L	0.0136275	0.01733788	0.06515894	TRUE
NA	Na FGD Sludge	Nickel	mg/L	0.2	0.2	1.5	TRUE
O	FGD waste	Nickel	mg/L	0.0461	0.0461	0.0461	TRUE
OK	Bottom ash	Nickel	mg/L	0.03131	0.03762	0.04393	TRUE
OK	Fly ash	Nickel	mg/L	0.14345	0.2762	0.46435	TRUE
SX	Bottom ash	Nickel	mg/L	0.008434175	0.01259345	0.016400675	TRUE
SX	Fly ash	Nickel	mg/L	0.00552	0.00561	0.00985	TRUE
AP	Combined ash	trate nitrog	mg/L	0.025	0.05	0.19	TRUE
C	Combined ash	trate nitrog	mg/L	0.31	2.2	5.8	TRUE
CADK	FGD waste	trate nitrog	mg/L	6.5	11	15.5	TRUE
CASJ	FGD waste	trate nitrog	mg/L	0.125	0.125	4.5	TRUE
CL	Ash & coal waste	trate nitrog	mg/L	0.076	0.0995	0.13375	TRUE
CY	FGD waste	trate nitrog	mg/L	2.865	3.9	750.4225	TRUE
FC	Ash & coal waste	trate nitrog	mg/L	0.1	0.1	0.1	TRUE
HA	Combined ash	trate nitrog	mg/L	0.075	0.145	1.363	TRUE
MO	Ash & coal waste	trate nitrog	mg/L	0.20625	0.7	3.5	TRUE
MO	Bottom ash	trate nitrog	mg/L	0.075	0.075	0.09375	TRUE
NA	Na FGD Sludge	trate nitrog	mg/L	1310	1345	1372.5	TRUE
OK	Bottom ash	trate nitrog	mg/L	1.645	2.54	3.435	TRUE
OK	Fly ash	trate nitrog	mg/L	3.75	3.75	7.5	TRUE
SX	Bottom ash	trate nitrog	mg/L	0.0965	0.3465	1.367	TRUE
SX	Fly ash	trate nitrog	mg/L	0.598	0.75	0.75	TRUE
AP	Combined ash	trite nitrog	mg/L	0.075	0.075	0.15	TRUE
C	Combined ash	trite nitrog	mg/L	3.75	7.5	10.15	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
CADK	FGD waste	trite nitrog	mg/L	0.1025	0.135	0.1675	TRUE
CASJ	FGD waste	trite nitrog	mg/L	0.005	0.005	0.01	TRUE
CATT	FGD waste	trite nitrog	mg/L	0.01	0.01	0.01	TRUE
CL	Ash & coal waste	trite nitrog	mg/L	0.015	0.015	0.09775	TRUE
CY	FGD waste	trite nitrog	mg/L	0.25	0.375	1	TRUE
FC	Ash & coal waste	trite nitrog	mg/L	0.1	0.1	0.1	TRUE
HA	Combined ash	trite nitrog	mg/L	0.05	0.05	0.05	TRUE
MO	Ash & coal waste	trite nitrog	mg/L	0.375	1	2.5	TRUE
MO	Bottom ash	trite nitrog	mg/L	0.03	0.04	0.05	TRUE
NA	Na FGD Sludge	trite nitrog	mg/L	0.08	1.29	2.5	TRUE
O	FGD waste	trite nitrog	mg/L	461	461	461	TRUE
OK	Bottom ash	trite nitrog	mg/L	0.5	0.5	0.5	TRUE
OK	Fly ash	trite nitrog	mg/L	2.5	2.5	5	TRUE
SX	Bottom ash	trite nitrog	mg/L	0.01925	0.0545	0.1345	TRUE
SX	Fly ash	trite nitrog	mg/L	0.25	0.25	0.5	TRUE
CL	Ash & coal waste	Oxalate	mg/L	0.04	0.04	0.04	FALSE
SX	Bottom ash	Oxalate	mg/L	0.04	0.04	0.04	FALSE
13115B	Combined ash	n-reduction	mV	94	94	94	FALSE
14093	Fly Ash	n-reduction	mV	171	240	242.5	FALSE
22346	Other	n-reduction	mV	135	156	177	FALSE
23223B	FGD waste	n-reduction	mV	89.75	178.5	267.25	FALSE
25410A	Combined ash	n-reduction	mV	124	124	124	FALSE
33104	Fly Ash	n-reduction	mV	154	168	182	FALSE
33106	Fly Ash	n-reduction	mV	173.5	184	188	FALSE
35015B	Fly Ash	n-reduction	mV	46.25	133.5	220.75	FALSE
40109	Fly Ash	n-reduction	mV	211.25	211.5	211.75	FALSE
43035	Combined ash	n-reduction	mV	231	237	243	FALSE
49003A	Fly Ash	n-reduction	mV	228.25	238	255.5	FALSE
BR	Ash & coal waste	pH	pH	3.525	3.63	3.995	FALSE
MO	Ash & coal waste	pH	pH	2.005	3.4	3.68	FALSE
13115B	Combined ash	pH (field)	pH	7.4	7.4	7.4	FALSE
14093	Fly Ash	pH (field)	pH	8.75	9.3	9.35	FALSE
22346	Other	pH (field)	pH	7.0075	7.265	7.5225	FALSE
23223B	FGD waste	pH (field)	pH	6.75	7.3	7.85	FALSE
25410A	Combined ash	pH (field)	pH	11.7	11.7	11.7	FALSE
33104	Fly Ash	pH (field)	pH	8.175	9.1	10.025	FALSE
33106	Fly Ash	pH (field)	pH	7.01	7.04	7.045	FALSE
35015B	Fly Ash	pH (field)	pH	8.5	8.5	8.5	FALSE
40109	Fly Ash	pH (field)	pH	9.3375	9.755	10.1725	FALSE
43035	Combined ash	pH (field)	pH	11.7425	11.745	11.7475	FALSE
49003A	Fly Ash	pH (field)	pH	6.9975	7.37	7.78	FALSE
C	Combined ash	pH (field)	pH	11.2	11.3	11.7	FALSE
CL	Ash & coal waste	pH (field)	pH	9.355	9.79	10.235	FALSE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
HA	Combined ash	pH (field)	pH	7.44	7.97	10.32	FALSE
MO	Ash & coal waste	pH (field)	pH	2.78	3.755	5.6975	FALSE
MO	Bottom ash	pH (field)	pH	4.5225	5.85	6.12	FALSE
OK	Bottom ash	pH (field)	pH	10.84	10.84	10.84	FALSE
OK	Fly ash	pH (field)	pH	11.15	11.165	11.1975	FALSE
SX	Fly ash	pH (field)	pH	10.34	10.79	10.88	FALSE
AP	Combined ash	pH (lab)	pH	8.035	8.5	8.895	FALSE
CASJ	FGD waste	pH (lab)	pH	8.75	8.8	8.85	FALSE
CATT	FGD waste	pH (lab)	pH	9.265	9.3	9.335	FALSE
CL	Ash & coal waste	pH (lab)	pH	7.785	8.16	8.46	FALSE
CY	FGD waste	pH (lab)	pH	11.415	11.75	11.8725	FALSE
FC	Ash & coal waste	pH (lab)	pH	11.3525	11.485	11.605	FALSE
L	Combined ash	pH (lab)	pH	6.405	6.68	6.955	FALSE
MO	Ash & coal waste	pH (lab)	pH	6.855	6.91	8.255	FALSE
NA	Na FGD Sludge	pH (lab)	pH	4.25	5.4	6.275	FALSE
O	FGD waste	pH (lab)	pH	7.75	7.75	7.805	FALSE
OK	Bottom ash	pH (lab)	pH	10.84	10.84	10.84	FALSE
OK	Fly ash	pH (lab)	pH	11.025	11.16	11.19	FALSE
SX	Bottom ash	pH (lab)	pH	7.74375	8.212	8.60375	FALSE
AP	Combined ash	Phosphate	mg/L	0.175	0.175	0.325	FALSE
C	Combined ash	Phosphate	mg/L	0.025	0.057	0.088	FALSE
CADK	FGD waste	Phosphate	mg/L	0.05	0.05	0.05	FALSE
CASJ	FGD waste	Phosphate	mg/L	0.5	0.5	0.5	FALSE
CL	Ash & coal waste	Phosphate	mg/L	0.073	0.2135	0.47625	FALSE
CY	FGD waste	Phosphate	mg/L	0.25	0.4375	0.78125	FALSE
FC	Ash & coal waste	Phosphate	mg/L	0.125	0.125	0.125	FALSE
HA	Combined ash	Phosphate	mg/L	0.125	0.582	1.546	FALSE
MO	Ash & coal waste	Phosphate	mg/L	0.4375	1.425	5.55	FALSE
MO	Bottom ash	Phosphate	mg/L	0.125	0.1875	0.25	FALSE
NA	Na FGD Sludge	Phosphate	mg/L	2445	2580	2745	FALSE
OK	Bottom ash	Phosphate	mg/L	1.25	1.25	1.25	FALSE
OK	Fly ash	Phosphate	mg/L	6.25	6.25	12.5	FALSE
SX	Bottom ash	Phosphate	mg/L	0.045	0.045	0.12375	FALSE
SX	Fly ash	Phosphate	mg/L	0.625	0.625	1.25	FALSE
13115B	Combined ash	Potassium	mg/L	28.5	48	162.5	TRUE
14093	Fly Ash	Potassium	mg/L	18	26	50.5	TRUE
22346	Other	Potassium	mg/L	7.75	9.5	11.25	TRUE
23223B	FGD waste	Potassium	mg/L	35	50	65	TRUE
25410A	Combined ash	Potassium	mg/L	229	229	229	TRUE
25410B	Fly Ash	Potassium	mg/L	38	38	38	TRUE
33104	Fly Ash	Potassium	mg/L	7.2	8	8.8	TRUE
33106	Fly Ash	Potassium	mg/L	2.25	2.3	3.8	TRUE
35015B	Fly Ash	Potassium	mg/L	27.5	35	42.5	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
40109	Fly Ash	Potassium	mg/L	9.675	10.15	10.625	TRUE
43035	Combined ash	Potassium	mg/L	25	30	35	TRUE
49003A	Fly Ash	Potassium	mg/L	10.25	11	11	TRUE
AP	Combined ash	Potassium	mg/L	2.175	2.65	3.125	TRUE
BR	Ash & coal waste	Potassium	mg/L	8.95	30	70	TRUE
C	Combined ash	Potassium	mg/L	54.6	87.6	110	TRUE
CADK	FGD waste	Potassium	mg/L	200.725	353.15	505.575	TRUE
CASJ	FGD waste	Potassium	mg/L	200	220	280	TRUE
CATT	FGD waste	Potassium	mg/L	54.75	55.5	56.25	TRUE
CY	FGD waste	Potassium	mg/L	53.15	73.25	83.125	TRUE
FC	Ash & coal waste	Potassium	mg/L	8.265	12.095	43.35	TRUE
HA	Ash & coal waste	Potassium	mg/L	11	11	11	TRUE
HA	Combined ash	Potassium	mg/L	9.035	14.446	22.1725	TRUE
L	Combined ash	Potassium	mg/L	29.325	32.15	34.975	TRUE
MO	Ash & coal waste	Potassium	mg/L	15.055	34.45	44.95375	TRUE
MO	Bottom ash	Potassium	mg/L	3.0864375	5.1205	6.1205	TRUE
NA	Na FGD Sludge	Potassium	mg/L	420	636	940	TRUE
O	FGD waste	Potassium	mg/L	20.5	34	34	TRUE
OK	Bottom ash	Potassium	mg/L	12.9099375	21.919125	30.9283125	TRUE
OK	Fly ash	Potassium	mg/L	115.48	177.2	206.4625	TRUE
SX	Fly ash	Potassium	mg/L	93.3525	96.1425	109.4875	TRUE
SX	Bottom ash	geable Orga	mg/L	0.8806455	1.4025095	1.48405075	FALSE
AP	Combined ash	tential, EH (	mg/L	156	187.2	195	FALSE
C	Combined ash	tential, EH (	mg/L	87	167	284	FALSE
CASJ	FGD waste	tential, EH (	mg/L	-289	-280	-230	FALSE
CATT	FGD waste	tential, EH (	mg/L	-328.5	-289	-249.5	FALSE
CL	Ash & coal waste	tential, EH (	mg/L	181.65	247.85	290.425	FALSE
CY	FGD waste	tential, EH (	mg/L	48.5	128	142.25	FALSE
FC	Ash & coal waste	tential, EH (	mg/L	36.5	64.5	79	FALSE
HA	Combined ash	tential, EH (	mg/L	203	326.93	357.23	FALSE
L	Combined ash	tential, EH (	mg/L	-101	-29	43	FALSE
MO	Ash & coal waste	tential, EH (	mg/L	276.60625	395.5	519.825	FALSE
MO	Bottom ash	tential, EH (	mg/L	256.7	327.1	439.5	FALSE
NA	Na FGD Sludge	tential, EH (	mg/L	-58.25	-11.7	1.95	FALSE
O	FGD waste	tential, EH (	mg/L	204	293	293	FALSE
OK	Bottom ash	tential, EH (	mg/L	35.275	35.275	35.275	FALSE
OK	Fly ash	tential, EH (	mg/L	1.875	14.225	50.85	FALSE
SX	Bottom ash	tential, EH (	mg/L	204.61	230.955	246.32	FALSE
SX	Fly ash	tential, EH (	mg/L	71.7	74.03	117.93	FALSE
13115B	Combined ash	Selenium	mg/L	0.00485	0.0092	0.0156	TRUE
14093	Fly Ash	Selenium	mg/L	0.00104	0.0018	0.0025	TRUE
22346	Other	Selenium	mg/L	0.0002625	0.000365	0.0004675	TRUE
23223B	FGD waste	Selenium	mg/L	0.075025	0.14635	0.217675	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
25410A	Combined ash	Selenium	mg/L	0.193	0.193	0.193	TRUE
25410B	Fly Ash	Selenium	mg/L	0.0078	0.0078	0.0078	TRUE
33104	Fly Ash	Selenium	mg/L	0.031225	0.05815	0.085075	TRUE
33106	Fly Ash	Selenium	mg/L	0.00015	0.00017	0.001085	TRUE
35015B	Fly Ash	Selenium	mg/L	0.02075	0.0285	0.03625	TRUE
40109	Fly Ash	Selenium	mg/L	0.0034	0.0056	0.0078	TRUE
43035	Combined ash	Selenium	mg/L	0.112	0.135	0.158	TRUE
49003A	Fly Ash	Selenium	mg/L	0.00489275	0.01775	0.0925	TRUE
AP	Combined ash	Selenium	mg/L	0.00995	0.015	0.0575	TRUE
C	Combined ash	Selenium	mg/L	0.01325	0.017	0.0215	TRUE
CADK	FGD waste	Selenium	mg/L	0.0925	0.125	0.1575	TRUE
CASJ	FGD waste	Selenium	mg/L	0.23375	0.3615	0.5335	TRUE
CATT	FGD waste	Selenium	mg/L	0.9375	1.025	1.1125	TRUE
CL	Ash & coal waste	Selenium	mg/L	0.005	0.05648275	0.1203835	TRUE
CY	FGD waste	Selenium	mg/L	0.017725	0.06815	0.137	TRUE
FC	Ash & coal waste	Selenium	mg/L	0.01745	0.02185	0.0239	TRUE
HA	Ash & coal waste	Selenium	mg/L	0.0025	0.0025	0.0025	TRUE
HA	Combined ash	Selenium	mg/L	0.01	0.01	0.01	TRUE
MO	Ash & coal waste	Selenium	mg/L	0.005	0.035740303	0.10475	TRUE
MO	Bottom ash	Selenium	mg/L	0.005	0.005	0.005	TRUE
O	FGD waste	Selenium	mg/L	0.0022	0.0022	0.00325	TRUE
OK	Bottom ash	Selenium	mg/L	0.05	0.05	0.05	TRUE
OK	Fly ash	Selenium	mg/L	0.2929	0.3256	0.3922	TRUE
SX	Bottom ash	Selenium	mg/L	0.005	0.005	0.01512635	TRUE
SX	Fly ash	Selenium	mg/L	0.318	0.341	0.488	TRUE
13115B	Combined ash	elenium (IV	mg/L	0.000275	0.0005	0.00155	TRUE
14093	Fly Ash	elenium (IV	mg/L	0.00032	0.00059	0.000995	TRUE
22346	Other	elenium (IV	mg/L	0.000325	0.00055	0.000775	TRUE
23223B	FGD waste	elenium (IV	mg/L	0.0197875	0.039525	0.0592625	TRUE
25410A	Combined ash	elenium (IV	mg/L	0.101	0.101	0.101	TRUE
25410B	Fly Ash	elenium (IV	mg/L	0.0018	0.0018	0.0018	TRUE
33104	Fly Ash	elenium (IV	mg/L	0.02625	0.0475	0.06875	TRUE
33106	Fly Ash	elenium (IV	mg/L	0.000245	0.00025	0.001425	TRUE
35015B	Fly Ash	elenium (IV	mg/L	0.00744	0.01396	0.02048	TRUE
40109	Fly Ash	elenium (IV	mg/L	0.002425	0.00385	0.005275	TRUE
43035	Combined ash	elenium (IV	mg/L	0.01225	0.0125	0.01275	TRUE
49003A	Fly Ash	elenium (IV	mg/L	0.0040375	0.01215	0.0685	TRUE
13115B	Combined ash	elenium (VI	mg/L	0.00295	0.0058	0.0109	TRUE
14093	Fly Ash	elenium (VI	mg/L	0.000075	0.0001	0.0001	TRUE
22346	Other	elenium (VI	mg/L	0.0004875	0.000825	0.0011625	TRUE
23223B	FGD waste	elenium (VI	mg/L	0.0299525	0.059635	0.0893175	TRUE
25410A	Combined ash	elenium (VI	mg/L	0.014	0.014	0.014	TRUE
25410B	Fly Ash	elenium (VI	mg/L	0.0036	0.0036	0.0036	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
33104	Fly Ash	elenium (V	mg/L	0.0155	0.021	0.0265	TRUE
33106	Fly Ash	elenium (V	mg/L	0.00035	0.0005	0.0005	TRUE
35015B	Fly Ash	elenium (V	mg/L	0.007125	0.00875	0.010375	TRUE
40109	Fly Ash	elenium (V	mg/L	0.002	0.002	0.002	TRUE
43035	Combined ash	elenium (V	mg/L	0.1385	0.174	0.2095	TRUE
49003A	Fly Ash	elenium (V	mg/L	0.00045	0.001	0.001775	TRUE
43035	Combined ash	lenium, oth	mg/L	0.00015	0.00015	0.00015	FALSE
13115B	Combined ash	Silicon	mg/L	3.35	3.4	6.85	TRUE
14093	Fly Ash	Silicon	mg/L	1.5	1.5	10	TRUE
22346	Other	Silicon	mg/L	4.25	6.2	8.15	TRUE
23223B	FGD waste	Silicon	mg/L	2.925	5.45	7.975	TRUE
25410A	Combined ash	Silicon	mg/L	19	19	19	TRUE
25410B	Fly Ash	Silicon	mg/L	2.4	2.4	2.4	TRUE
33104	Fly Ash	Silicon	mg/L	7.9275	8.985	10.0425	TRUE
33106	Fly Ash	Silicon	mg/L	7.33	7.66	7.81	TRUE
35015B	Fly Ash	Silicon	mg/L	1.45	2.2	2.95	TRUE
40109	Fly Ash	Silicon	mg/L	1.245	1.46	1.675	TRUE
43035	Combined ash	Silicon	mg/L	9.6625	9.875	10.0875	TRUE
49003A	Fly Ash	Silicon	mg/L	3.26	4.4	7.05	TRUE
AP	Combined ash	Silicon	mg/L	1.535	3.19	5.84	TRUE
C	Combined ash	Silicon	mg/L	4.2	5.1	5.8	TRUE
CADK	FGD waste	Silicon	mg/L	11.175	11.25	11.325	TRUE
CASJ	FGD waste	Silicon	mg/L	9	10.3	10.8	TRUE
CATT	FGD waste	Silicon	mg/L	6.2125	6.595	6.9775	TRUE
CL	Ash & coal waste	Silicon	mg/L	2.707083333	3.94875	5.981666667	TRUE
CY	FGD waste	Silicon	mg/L	17.0775	21.15	23.6	TRUE
FC	Ash & coal waste	Silicon	mg/L	7.2575	10.955	21.65	TRUE
HA	Combined ash	Silicon	mg/L	1.83425	3.72025	5.53675	TRUE
L	Combined ash	Silicon	mg/L	10.355	11.73	13.105	TRUE
MO	Ash & coal waste	Silicon	mg/L	7.5415	17.1	52.86	TRUE
MO	Bottom ash	Silicon	mg/L	15.5253125	19.651875	21.893125	TRUE
NA	Na FGD Sludge	Silicon	mg/L	2.4	7	13.8	TRUE
OK	Bottom ash	Silicon	mg/L	16.33625	19.5275	22.71875	TRUE
OK	Fly ash	Silicon	mg/L	11.04125	11.9625	14.9675	TRUE
SX	Bottom ash	Silicon	mg/L	2.75875	6.62	9.40125	TRUE
SX	Fly ash	Silicon	mg/L	0.5	2.31175	5.5695	TRUE
13115B	Combined ash	Silver	mg/L	0.00045	0.0008	0.0014	TRUE
14093	Fly Ash	Silver	mg/L	0.0001	0.0001	0.00015	TRUE
22346	Other	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
23223B	FGD waste	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
25410A	Combined ash	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
25410B	Fly Ash	Silver	mg/L	0.0011	0.0011	0.0011	TRUE
33104	Fly Ash	Silver	mg/L	0.0001	0.0001	0.0001	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
33106	Fly Ash	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
35015B	Fly Ash	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
40109	Fly Ash	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
43035	Combined ash	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
49003A	Fly Ash	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
AP	Combined ash	Silver	mg/L	0.0025	0.0025	0.0025	TRUE
C	Combined ash	Silver	mg/L	0.005	0.005	0.005	TRUE
CY	FGD waste	Silver	mg/L	0.0005	0.0005	0.001625	TRUE
FC	Ash & coal waste	Silver	mg/L	0.00005	0.00005	0.00005	TRUE
HA	Ash & coal waste	Silver	mg/L	0.005	0.005	0.005	TRUE
HA	Combined ash	Silver	mg/L	0.0005	0.0005	0.0005	TRUE
OK	Bottom ash	Silver	mg/L	0.005	0.005	0.005	TRUE
OK	Fly ash	Silver	mg/L	0.00275	0.005	0.005	TRUE
SX	Fly ash	Silver	mg/L	0.0005	0.0005	0.0005	TRUE
13115B	Combined ash	Sodium	mg/L	55	57	64.5	TRUE
14093	Fly Ash	Sodium	mg/L	23.5	30	42.5	TRUE
22346	Other	Sodium	mg/L	44.25	50.5	56.75	TRUE
23223B	FGD waste	Sodium	mg/L	787	968	1149	TRUE
25410A	Combined ash	Sodium	mg/L	731	731	731	TRUE
25410B	Fly Ash	Sodium	mg/L	52	52	52	TRUE
33104	Fly Ash	Sodium	mg/L	9.975	10.45	10.925	TRUE
33106	Fly Ash	Sodium	mg/L	3.85	3.9	4.3	TRUE
35015B	Fly Ash	Sodium	mg/L	33.75	42.5	51.25	TRUE
40109	Fly Ash	Sodium	mg/L	5.9	6.2	6.5	TRUE
43035	Combined ash	Sodium	mg/L	458	523	588	TRUE
49003A	Fly Ash	Sodium	mg/L	26.25	29.5	31.5	TRUE
AP	Combined ash	Sodium	mg/L	195	200	205	TRUE
BR	Ash & coal waste	Sodium	mg/L	5.25	23	33.75	TRUE
C	Combined ash	Sodium	mg/L	39	42	115	TRUE
CADK	FGD waste	Sodium	mg/L	32.3	33.6	34.9	TRUE
CASJ	FGD waste	Sodium	mg/L	5960	6100	6270	TRUE
CATT	FGD waste	Sodium	mg/L	686.5	762	837.5	TRUE
CY	FGD waste	Sodium	mg/L	1843.25	2005	2062.5	TRUE
FC	Ash & coal waste	Sodium	mg/L	62.925	136	374.75	TRUE
HA	Ash & coal waste	Sodium	mg/L	53	53	53	TRUE
HA	Combined ash	Sodium	mg/L	13.5875	25.9475	60.095	TRUE
L	Combined ash	Sodium	mg/L	9.375	9.75	10.125	TRUE
MO	Ash & coal waste	Sodium	mg/L	12.65	19.2	25.385	TRUE
MO	Bottom ash	Sodium	mg/L	3.076916667	7.041583334	10.3523125	TRUE
NA	Na FGD Sludge	Sodium	mg/L	29650	64100	79500	TRUE
O	FGD waste	Sodium	mg/L	2325	2890	2991.5	TRUE
OK	Bottom ash	Sodium	mg/L	1286.875	1312.75	1338.625	TRUE
OK	Fly ash	Sodium	mg/L	7250	9266	11416.5	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
SX	Fly ash	Sodium	mg/L	282.2666667	317.0833333	319.6666667	TRUE
13115B	Combined ash	ductance @	mS/cm	1.6	1.6	1.6	FALSE
14093	Fly Ash	ductance @	mS/cm	2.65	2.7	2.8	FALSE
22346	Other	ductance @	mS/cm	0.96425	1.0015	1.03875	FALSE
23223B	FGD waste	ductance @	mS/cm	5.675	6.55	7.425	FALSE
25410A	Combined ash	ductance @	mS/cm	5.1	5.1	5.1	FALSE
33104	Fly Ash	ductance @	mS/cm	0.516	0.599	0.682	FALSE
33106	Fly Ash	ductance @	mS/cm	0.348	0.379	0.38	FALSE
35015B	Fly Ash	ductance @	mS/cm	2.1	2.4	2.7	FALSE
40109	Fly Ash	ductance @	mS/cm	0.498	0.528	0.558	FALSE
43035	Combined ash	ductance @	mS/cm	2.9325	3.295	3.6575	FALSE
49003A	Fly Ash	ductance @	mS/cm	0.63225	0.658	0.67975	FALSE
C	Combined ash	ductance @	mg/L	1159	1722	1821	FALSE
CL	Ash & coal waste	ductance @	mg/L	253.5	286	300.5	FALSE
HA	Combined ash	ductance @	mg/L	321.5	461	625.5	FALSE
MO	Ash & coal waste	ductance @	mg/L	3620.565929	14200	24300	FALSE
MO	Bottom ash	ductance @	mg/L	410.25	665.5	863.75	FALSE
SX	Fly ash	ductance @	mg/L	2160	2255	3549	FALSE
AP	Combined ash	nductance (	mg/L	3347.25	3966.5	5182.25	FALSE
CASJ	FGD waste	nductance (	mg/L	2.6775	2.705	2.7325	FALSE
CL	Ash & coal waste	nductance (	mg/L	345.5	533	710	FALSE
CY	FGD waste	nductance (	mg/L	8540	8540	8540	FALSE
FC	Ash & coal waste	nductance (	mg/L	1523.5	1864	4616.25	FALSE
OK	Bottom ash	nductance (	mg/L	11142.80327	11142.80327	11142.80327	FALSE
OK	Fly ash	nductance (	mg/L	41677.11925	44657.92752	59236.78978	FALSE
SX	Bottom ash	nductance (	mg/L	1440.75	2525	2800	FALSE
13115B	Combined ash	Strontium	mg/L	0.66	0.68	0.805	TRUE
14093	Fly Ash	Strontium	mg/L	1.755	2.25	2.695	TRUE
22346	Other	Strontium	mg/L	2.2725	2.355	2.4375	TRUE
23223B	FGD waste	Strontium	mg/L	15.4	15.9	16.4	TRUE
25410A	Combined ash	Strontium	mg/L	1.2	1.2	1.2	TRUE
25410B	Fly Ash	Strontium	mg/L	2.69	2.69	2.69	TRUE
33104	Fly Ash	Strontium	mg/L	1.2175	1.425	1.6325	TRUE
33106	Fly Ash	Strontium	mg/L	1.235	1.35	1.355	TRUE
35015B	Fly Ash	Strontium	mg/L	1.3625	1.735	2.1075	TRUE
40109	Fly Ash	Strontium	mg/L	5.265	5.38	5.495	TRUE
43035	Combined ash	Strontium	mg/L	0.94425	1.2395	1.53475	TRUE
49003A	Fly Ash	Strontium	mg/L	0.713	0.7505	1.07575	TRUE
AP	Combined ash	Strontium	mg/L	3.898	6.855	7.5	TRUE
BR	Ash & coal waste	Strontium	mg/L	7.2	7.8	9	TRUE
C	Combined ash	Strontium	mg/L	0.39	0.64	1.1	TRUE
CADK	FGD waste	Strontium	mg/L	6.92	7	7.08	TRUE
CASJ	FGD waste	Strontium	mg/L	6.85	9	11.2	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
CATT	FGD waste	Strontium	mg/L	15.45	16.1	16.75	TRUE
CL	Ash & coal waste	Strontium	mg/L	0.831375	1.731666667	2.8225	TRUE
CY	FGD waste	Strontium	mg/L	1.9675	3.34	6.455	TRUE
FC	Ash & coal waste	Strontium	mg/L	2.4675	2.9	3.6425	TRUE
HA	Ash & coal waste	Strontium	mg/L	2.1	2.1	2.1	TRUE
HA	Combined ash	Strontium	mg/L	0.64875	1.0155	5.56875	TRUE
L	Combined ash	Strontium	mg/L	2.0325	2.385	2.7375	TRUE
MO	Ash & coal waste	Strontium	mg/L	0.4	1.83025	2.81075	TRUE
MO	Bottom ash	Strontium	mg/L	0.31721875	0.4619375	0.53934375	TRUE
NA	Na FGD Sludge	Strontium	mg/L	0.7	0.86	2	TRUE
OK	Bottom ash	Strontium	mg/L	8.42703125	14.5834375	20.73984375	TRUE
OK	Fly ash	Strontium	mg/L	2.226541667	4.880625	9.105875	TRUE
SX	Bottom ash	Strontium	mg/L	0.26075	3.813333334	4.557916667	TRUE
SX	Fly ash	Strontium	mg/L	5.192	5.4515	6.624	TRUE
13115B	Combined ash	Sulfate	mg/L	574.5	810	1035	TRUE
14093	Fly Ash	Sulfate	mg/L	1510	1650	1675	TRUE
22346	Other	Sulfate	mg/L	180	225	270	TRUE
23223B	FGD waste	Sulfate	mg/L	2347.5	2615	2882.5	TRUE
25410A	Combined ash	Sulfate	mg/L	910	910	910	TRUE
25410B	Fly Ash	Sulfate	mg/L	1530	1530	1530	TRUE
33104	Fly Ash	Sulfate	mg/L	75	89	103	TRUE
33106	Fly Ash	Sulfate	mg/L	111	121	122	TRUE
35015B	Fly Ash	Sulfate	mg/L	1168.5	1389	1609.5	TRUE
40109	Fly Ash	Sulfate	mg/L	140	152	164	TRUE
43035	Combined ash	Sulfate	mg/L	660.25	813.5	966.75	TRUE
49003A	Fly Ash	Sulfate	mg/L	200.5	206.5	219.5	TRUE
AP	Combined ash	Sulfate	mg/L	833.5	1443	1765	TRUE
BR	Ash & coal waste	Sulfate	mg/L	1953.5	4404.5	5300.75	TRUE
C	Combined ash	Sulfate	mg/L	137.5	239	446.25	TRUE
CADK	FGD waste	Sulfate	mg/L	2072.5	2135	2197.5	TRUE
CASJ	FGD waste	Sulfate	mg/L	9260	10000	10700	TRUE
CATT	FGD waste	Sulfate	mg/L	1927.5	1965	2002.5	TRUE
CL	Ash & coal waste	Sulfate	mg/L	69.2195	93.672	139.3145	TRUE
CY	FGD waste	Sulfate	mg/L	3736.75	4040	4373.5	TRUE
FC	Ash & coal waste	Sulfate	mg/L	171	185	210	TRUE
HA	Ash & coal waste	Sulfate	mg/L	200	200	200	TRUE
HA	Combined ash	Sulfate	mg/L	55.145	107.353	297.187	TRUE
L	Combined ash	Sulfate	mg/L	1345.55	1412.8	1480.05	TRUE
MO	Ash & coal waste	Sulfate	mg/L	2106.025	15065.916	45435.009	TRUE
MO	Bottom ash	Sulfate	mg/L	287.7795	376.4425	411.002	TRUE
NA	Na FGD Sludge	Sulfate	mg/L	77025	120500	153500	TRUE
OK	Bottom ash	Sulfate	mg/L	1335.93025	1593.7315	1851.53275	TRUE
OK	Fly ash	Sulfate	mg/L	752.238	1027.231	1060.0815	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
SX	Bottom ash	Sulfate	mg/L	196.31	940.85	1530.96475	TRUE
SX	Fly ash	Sulfate	mg/L	936.377	958.914	2283.071	TRUE
AP	Combined ash	Sulfite	mg/L	2.5	2.5	10	FALSE
BR	Ash & coal waste	Sulfite	mg/L	0.395	0.5	0.5	FALSE
C	Combined ash	Sulfite	mg/L	0.2	0.2	0.2	FALSE
CADK	FGD waste	Sulfite	mg/L	1.4825	2.915	4.3475	FALSE
CASJ	FGD waste	Sulfite	mg/L	0.05	58.6	89.7	FALSE
CATT	FGD waste	Sulfite	mg/L	16.825	18.65	20.475	FALSE
CL	Ash & coal waste	Sulfite	mg/L	0.5	0.5	0.5	FALSE
CY	FGD waste	Sulfite	mg/L	2.1875	2.5	3.4375	FALSE
FC	Ash & coal waste	Sulfite	mg/L	0.125	0.125	0.30875	FALSE
HA	Combined ash	Sulfite	mg/L	0.125	0.125	0.125	FALSE
MO	Ash & coal waste	Sulfite	mg/L	2.1875	5	6.25	FALSE
MO	Bottom ash	Sulfite	mg/L	0.125	0.1875	0.625	FALSE
NA	Na FGD Sludge	Sulfite	mg/L	112	2085	4550	FALSE
OK	Bottom ash	Sulfite	mg/L	1.25	1.25	1.25	FALSE
OK	Fly ash	Sulfite	mg/L	6.25	6.25	12.5	FALSE
SX	Bottom ash	Sulfite	mg/L	0.75	2.5	5	FALSE
SX	Fly ash	Sulfite	mg/L	0.625	0.625	1.25	FALSE
AP	Combined ash	Sulfur	mg/L	330.54175	672.25	789.667	TRUE
CL	Ash & coal waste	Sulfur	mg/L	22.86666667	31.27083334	44.66666667	TRUE
CY	FGD waste	Sulfur	mg/L	1261.25	1372	1490.5	TRUE
FC	Ash & coal waste	Sulfur	mg/L	64.5	71.45	78.225	TRUE
HA	Combined ash	Sulfur	mg/L	17.53333333	34.9525	47.675	TRUE
MO	Ash & coal waste	Sulfur	mg/L	1129.246875	5742	17597.5	TRUE
MO	Bottom ash	Sulfur	mg/L	98.17	124.3	135.465625	TRUE
O	FGD waste	Sulfur	mg/L	3687	3997	4307	TRUE
OK	Bottom ash	Sulfur	mg/L	445.125	537.7	630.275	TRUE
OK	Fly ash	Sulfur	mg/L	236.675	344.2625	366.78125	TRUE
SX	Bottom ash	Sulfur	mg/L	68.99166668	323.9166667	520.2083334	TRUE
SX	Fly ash	Sulfur	mg/L	318.05	328.2625	754.425	TRUE
13115B	Combined ash	Temperatur	°C	18.3	18.3	18.3	FALSE
14093	Fly Ash	Temperatur	°C	20.9	21.3	21.95	FALSE
22346	Other	Temperatur	°C	19.275	19.35	19.425	FALSE
23223B	FGD waste	Temperatur	°C	19.925	22.25	24.575	FALSE
25410A	Combined ash	Temperatur	°C	30.6	30.6	30.6	FALSE
33104	Fly Ash	Temperatur	°C	27.95	28.3	28.65	FALSE
33106	Fly Ash	Temperatur	°C	22.35	22.7	23.45	FALSE
35015B	Fly Ash	Temperatur	°C	15.45	15.5	15.55	FALSE
40109	Fly Ash	Temperatur	°C	26.8	26.9	27	FALSE
43035	Combined ash	Temperatur	°C	16.4875	16.575	16.6625	FALSE
49003A	Fly Ash	Temperatur	°C	19.95	20.89	21.2425	FALSE
13115B	Combined ash	Thallium	mg/L	0.000175	0.00025	0.00025	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
14093	Fly Ash	Thallium	mg/L	0.00005	0.00005	0.000325	TRUE
22346	Other	Thallium	mg/L	0.0001375	0.000225	0.0003125	TRUE
23223B	FGD waste	Thallium	mg/L	0.0001	0.00015	0.0002	TRUE
25410A	Combined ash	Thallium	mg/L	0.0003	0.0003	0.0003	TRUE
25410B	Fly Ash	Thallium	mg/L	0.0031	0.0031	0.0031	TRUE
33104	Fly Ash	Thallium	mg/L	0.0002	0.0003	0.0004	TRUE
33106	Fly Ash	Thallium	mg/L	0.0001	0.0001	0.0001	TRUE
35015B	Fly Ash	Thallium	mg/L	0.0008875	0.001725	0.0025625	TRUE
40109	Fly Ash	Thallium	mg/L	0.000325	0.00035	0.000375	TRUE
43035	Combined ash	Thallium	mg/L	0.00005	0.00005	0.00005	TRUE
49003A	Fly Ash	Thallium	mg/L	0.000675	0.00105	0.00135	TRUE
AP	Combined ash	Thallium	mg/L	0.0025	0.0025	0.0025	TRUE
C	Combined ash	Thallium	mg/L	0.05	0.05	0.05	TRUE
AP	Combined ash	hiosulfate Ic	mg/L	0.225	0.225	1.43	FALSE
CADK	FGD waste	hiosulfate Ic	mg/L	0.51875	0.9125	1.30625	FALSE
CASJ	FGD waste	hiosulfate Ic	mg/L	0.125	0.125	22.5625	FALSE
CATT	FGD waste	hiosulfate Ic	mg/L	40.35	54.2	68.05	FALSE
CY	FGD waste	hiosulfate Ic	mg/L	0.21875	0.6715	2.2225	FALSE
FC	Ash & coal waste	hiosulfate Ic	mg/L	0.125	0.125	0.125	FALSE
HA	Combined ash	hiosulfate Ic	mg/L	0.125	0.125	0.125	FALSE
MO	Ash & coal waste	hiosulfate Ic	mg/L	0.18	0.18	0.9	FALSE
MO	Bottom ash	hiosulfate Ic	mg/L	0.18	0.18	0.18	FALSE
NA	Na FGD Sludge	hiosulfate Ic	mg/L	2150	4865	5007.5	FALSE
OK	Bottom ash	hiosulfate Ic	mg/L	1.8	1.8	1.8	FALSE
OK	Fly ash	hiosulfate Ic	mg/L	13.5	18	22.391	FALSE
SX	Fly ash	hiosulfate Ic	mg/L	0.9	0.9	1.8	FALSE
13115B	Combined ash	TOC	mg/L	17.85	21.5	22	FALSE
14093	Fly Ash	TOC	mg/L	2.9	3.9	5.1	FALSE
22346	Other	TOC	mg/L	0.10875	0.1725	0.23625	FALSE
23223B	FGD waste	TOC	mg/L	17.275	18.35	19.425	FALSE
25410A	Combined ash	TOC	mg/L	24	24	24	FALSE
25410B	Fly Ash	TOC	mg/L	16.6	16.6	16.6	FALSE
33104	Fly Ash	TOC	mg/L	0.045	0.045	0.045	FALSE
33106	Fly Ash	TOC	mg/L	0.045	0.045	0.045	FALSE
35015B	Fly Ash	TOC	mg/L	3.125	5.75	8.375	FALSE
40109	Fly Ash	TOC	mg/L	0.725	0.75	0.775	FALSE
43035	Combined ash	TOC	mg/L	6.475	6.95	7.425	FALSE
49003A	Fly Ash	TOC	mg/L	1.35	1.6	1.9	FALSE
C	Combined ash	TOC	mg/L	12.05	12.4	20.2	FALSE
SX	Bottom ash	TOC	mg/L	27.602878	33.9537765	38.94643075	FALSE
13115B	Combined ash	inorganic c	mg/L	2.71	2.94	58.97	FALSE
14093	Fly Ash	inorganic c	mg/L	9.3	16.6	25.85	FALSE
22346	Other	inorganic c	mg/L	30.575	40.55	50.525	FALSE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
23223B	FGD waste	inorganic c	mg/L	2.475	2.55	2.625	FALSE
25410A	Combined ash	inorganic c	mg/L	5.6	5.6	5.6	FALSE
25410B	Fly Ash	inorganic c	mg/L	11.3	11.3	11.3	FALSE
33104	Fly Ash	inorganic c	mg/L	12.56	21.14	29.72	FALSE
33106	Fly Ash	inorganic c	mg/L	8.53	10.4	10.45	FALSE
35015B	Fly Ash	inorganic c	mg/L	3.7475	5.965	8.1825	FALSE
40109	Fly Ash	inorganic c	mg/L	3.715	4.13	4.545	FALSE
43035	Combined ash	inorganic c	mg/L	6.275	6.65	7.025	FALSE
49003A	Fly Ash	inorganic c	mg/L	12.6575	15.45	19.35	FALSE
13115B	Combined ash	Uranium	mg/L	0.0004	0.0007	0.00265	TRUE
14093	Fly Ash	Uranium	mg/L	0.00145	0.0018	0.00255	TRUE
22346	Other	Uranium	mg/L	0.0081325	0.014355	0.0205775	TRUE
23223B	FGD waste	Uranium	mg/L	0.00025	0.0004	0.00055	TRUE
25410A	Combined ash	Uranium	mg/L	0.0007	0.0007	0.0007	TRUE
25410B	Fly Ash	Uranium	mg/L	0.0125	0.0125	0.0125	TRUE
33104	Fly Ash	Uranium	mg/L	0.0003875	0.000725	0.0010625	TRUE
33106	Fly Ash	Uranium	mg/L	0.000075	0.0001	0.00015	TRUE
35015B	Fly Ash	Uranium	mg/L	0.002825	0.00365	0.004475	TRUE
40109	Fly Ash	Uranium	mg/L	0.0005	0.0009	0.0013	TRUE
43035	Combined ash	Uranium	mg/L	0.00001	0.00001	0.00001	TRUE
49003A	Fly Ash	Uranium	mg/L	0.002075	0.005305	0.0211325	TRUE
AP	Combined ash	Uranium 23	mg/L	0.0072	0.0072	0.0072	FALSE
13115B	Combined ash	Vanadium	mg/L	0.0235	0.041	0.1235	TRUE
14093	Fly Ash	Vanadium	mg/L	0.02	0.036	0.1155	TRUE
22346	Other	Vanadium	mg/L	0.003175	0.00595	0.008725	TRUE
23223B	FGD waste	Vanadium	mg/L	0.0045	0.008	0.0115	TRUE
25410A	Combined ash	Vanadium	mg/L	1.23	1.23	1.23	TRUE
25410B	Fly Ash	Vanadium	mg/L	0.011	0.011	0.011	TRUE
33104	Fly Ash	Vanadium	mg/L	0.048425	0.09125	0.134075	TRUE
33106	Fly Ash	Vanadium	mg/L	0.00475	0.0069	0.01035	TRUE
35015B	Fly Ash	Vanadium	mg/L	0.0075	0.011	0.0145	TRUE
40109	Fly Ash	Vanadium	mg/L	0.2354	0.4084	0.5814	TRUE
43035	Combined ash	Vanadium	mg/L	0.1505	0.179	0.2075	TRUE
49003A	Fly Ash	Vanadium	mg/L	0.17405	0.3095	0.40825	TRUE
AP	Combined ash	Vanadium	mg/L	0.0245	0.063	0.104	TRUE
C	Combined ash	Vanadium	mg/L	0.295	0.37	0.5625	TRUE
CADK	FGD waste	Vanadium	mg/L	0.0195	0.022	0.0245	TRUE
CASJ	FGD waste	Vanadium	mg/L	0.04	0.05	0.05	TRUE
CATT	FGD waste	Vanadium	mg/L	0.02225	0.0235	0.02475	TRUE
CL	Ash & coal waste	Vanadium	mg/L	0.007971675	0.1095205	0.302844688	TRUE
CY	FGD waste	Vanadium	mg/L	0.2685	0.3805	0.658	TRUE
FC	Ash & coal waste	Vanadium	mg/L	0.069875	0.1	0.13375	TRUE
HA	Combined ash	Vanadium	mg/L	0.00921	0.04591	0.1941	TRUE

Attachment C-2. Quartile Data for CCR Impoundment Porewater

Site	New WasteType	Analyte	Units	25th %ile	50th %ile	75th %ile	Risk
MO	Ash & coal waste	Vanadium	mg/L	0.029925673	0.720771658	0.948465304	TRUE
MO	Bottom ash	Vanadium	mg/L	0.00125	0.00125	0.00125	TRUE
NA	Na FGD Sludge	Vanadium	mg/L	0.1	0.1	0.5	TRUE
O	FGD waste	Vanadium	mg/L	0.01195	0.0189	0.0189	TRUE
OK	Bottom ash	Vanadium	mg/L	0.10023	0.13822	0.17621	TRUE
OK	Fly ash	Vanadium	mg/L	0.24685	0.2794	0.3255	TRUE
SX	Bottom ash	Vanadium	mg/L	0.005928175	0.02463615	0.05692185	TRUE
SX	Fly ash	Vanadium	mg/L	0.267	0.288	0.54	TRUE
13115B	Combined ash	Zinc	mg/L	0.00475	0.007	0.0115	TRUE
14093	Fly Ash	Zinc	mg/L	0.026	0.04	0.0425	TRUE
22346	Other	Zinc	mg/L	0.001125	0.00125	0.001375	TRUE
23223B	FGD waste	Zinc	mg/L	0.007625	0.01275	0.017875	TRUE
25410A	Combined ash	Zinc	mg/L	0.13	0.13	0.13	TRUE
25410B	Fly Ash	Zinc	mg/L	0.025	0.025	0.025	TRUE
33104	Fly Ash	Zinc	mg/L	0.0015	0.0015	0.0015	TRUE
33106	Fly Ash	Zinc	mg/L	0.0015	0.0015	0.0015	TRUE
35015B	Fly Ash	Zinc	mg/L	0.03225	0.0515	0.07075	TRUE
40109	Fly Ash	Zinc	mg/L	0.00255	0.0036	0.00465	TRUE
43035	Combined ash	Zinc	mg/L	0.001	0.001	0.001	TRUE
49003A	Fly Ash	Zinc	mg/L	0.00475	0.006	0.00725	TRUE
AP	Combined ash	Zinc	mg/L	0.0072	0.0125	0.0125	TRUE
BR	Ash & coal waste	Zinc	mg/L	0.11	0.25	1.025	TRUE
C	Combined ash	Zinc	mg/L	0.01	0.029	0.048	TRUE
CADK	FGD waste	Zinc	mg/L	0.1	0.1	0.1	TRUE
CASJ	FGD waste	Zinc	mg/L	0.1	0.1	0.125	TRUE
CATT	FGD waste	Zinc	mg/L	0.21	0.21	0.21	TRUE
CL	Ash & coal waste	Zinc	mg/L	0.0125	0.0125	0.0125	TRUE
CY	FGD waste	Zinc	mg/L	0.09425	0.1122	0.13175	TRUE
FC	Ash & coal waste	Zinc	mg/L	0.0125	0.0125	0.0125	TRUE
HA	Combined ash	Zinc	mg/L	0.03215	0.04411	0.06253	TRUE
L	Combined ash	Zinc	mg/L	0.12	0.12	0.12	TRUE
MO	Ash & coal waste	Zinc	mg/L	0.05	2.1573	27.85	TRUE
MO	Bottom ash	Zinc	mg/L	0.0228	0.0829	0.1224425	TRUE
NA	Na FGD Sludge	Zinc	mg/L	0.2	0.2	1	TRUE
O	FGD waste	Zinc	mg/L	0.02405	0.0378	0.0378	TRUE
OK	Bottom ash	Zinc	mg/L	0.125	0.125	0.125	TRUE
OK	Fly ash	Zinc	mg/L	0.06875	0.125	0.125	TRUE
SX	Bottom ash	Zinc	mg/L	0.0125	0.0125	0.02940415	TRUE
SX	Fly ash	Zinc	mg/L	0.0714	0.0778	0.0929	TRUE

Attachment C-3.

Quartile Data for CCR Impoundment Surface Water

Attachment C-3. Quartile Data for CCR Impoundment Surface Water

Site	New_WasteType	Analyte	Units	25th	50th	75th	Risk
13115A	Combined ash	Aluminum	mg/L	1.0275	1.325	1.6225	TRUE
13115A	Fly Ash	Aluminum	mg/L	4.19	4.19	4.19	TRUE
22346	Other	Aluminum	mg/L	1.08	1.08	1.08	TRUE
22347	Fly Ash	Aluminum	mg/L	2.03	2.03	2.03	TRUE
23223B	FGD waste	Aluminum	mg/L	0.19	0.19	0.19	TRUE
25410A	Combined ash	Aluminum	mg/L	0.1	0.1	0.1	TRUE
33104	Combined ash	Aluminum	mg/L	0.13875	0.2485	0.35825	TRUE
33104	Fly Ash	Aluminum	mg/L	2.31	2.31	2.31	TRUE
33106	Combined ash	Aluminum	mg/L	0.014	0.014	0.014	TRUE
33106	Fly Ash	Aluminum	mg/L	0.107	0.148	1.939	TRUE
34186B	FGD waste	Aluminum	mg/L	0.20025	0.3695	0.53875	TRUE
35015B	Combined ash	Aluminum	mg/L	0.0165	0.018	0.023	TRUE
40109	Combined ash	Aluminum	mg/L	0.17225	0.2335	0.29475	TRUE
40109	Fly Ash	Aluminum	mg/L	2.15	2.15	2.15	TRUE
49003A	Fly Ash	Aluminum	mg/L	0.023	0.0325	0.04	TRUE
13115A	Combined ash	Antimony	mg/L	0.0005	0.0005	0.0005	TRUE
13115A	Fly Ash	Antimony	mg/L	0.0006	0.0006	0.0006	TRUE
22346	Other	Antimony	mg/L	0.0011	0.0011	0.0011	TRUE
22347	Fly Ash	Antimony	mg/L	0.0029	0.0029	0.0029	TRUE
23223B	FGD waste	Antimony	mg/L	0.0046	0.0046	0.0046	TRUE
25410A	Combined ash	Antimony	mg/L	0.0014	0.0014	0.0014	TRUE
33104	Combined ash	Antimony	mg/L	0.008075	0.00855	0.009025	TRUE
33104	Fly Ash	Antimony	mg/L	0.0274	0.0274	0.0274	TRUE
33106	Combined ash	Antimony	mg/L	0.0071	0.0071	0.0071	TRUE
33106	Fly Ash	Antimony	mg/L	0.0113	0.0139	0.01585	TRUE
34186B	FGD waste	Antimony	mg/L	0.012625	0.01585	0.019075	TRUE
35015B	Combined ash	Antimony	mg/L	0.0028	0.0031	0.00345	TRUE
40109	Combined ash	Antimony	mg/L	0.00575	0.0059	0.00605	TRUE
40109	Fly Ash	Antimony	mg/L	0.0059	0.0059	0.0059	TRUE
49003A	Fly Ash	Antimony	mg/L	0.020525	0.0221	0.0237	TRUE
13115A	Combined ash	Arsenic	mg/L	0.004125	0.00415	0.004175	TRUE
13115A	Fly Ash	Arsenic	mg/L	0.0051	0.0051	0.0051	TRUE
22346	Other	Arsenic	mg/L	0.023	0.023	0.023	TRUE
22347	Fly Ash	Arsenic	mg/L	0.0062	0.0062	0.0062	TRUE
23223B	FGD waste	Arsenic	mg/L	0.029	0.029	0.029	TRUE
25410A	Combined ash	Arsenic	mg/L	0.024	0.024	0.024	TRUE
33104	Combined ash	Arsenic	mg/L	0.11075	0.1215	0.13225	TRUE
33104	Fly Ash	Arsenic	mg/L	0.178	0.178	0.178	TRUE
33106	Combined ash	Arsenic	mg/L	0.0054	0.0054	0.0054	TRUE
33106	Fly Ash	Arsenic	mg/L	0.01455	0.024	0.0495	TRUE
34186B	FGD waste	Arsenic	mg/L	0.08075	0.1305	0.18025	TRUE
35015B	Combined ash	Arsenic	mg/L	0.0275	0.03	0.0355	TRUE
40109	Combined ash	Arsenic	mg/L	0.10525	0.1115	0.11775	TRUE
40109	Fly Ash	Arsenic	mg/L	0.038	0.038	0.038	TRUE
49003A	Fly Ash	Arsenic	mg/L	0.008275	0.00965	0.011	TRUE
13115A	Combined ash	Arsenic (III)	mg/L	0.00091	0.00094	0.00097	TRUE
13115A	Fly Ash	Arsenic (III)	mg/L	0.00057	0.00057	0.00057	TRUE
22346	Other	Arsenic (III)	mg/L	0.00021	0.00021	0.00021	TRUE
22347	Fly Ash	Arsenic (III)	mg/L	0.00023	0.00023	0.00023	TRUE
23223B	FGD waste	Arsenic (III)	mg/L	0.003	0.003	0.003	TRUE
25410A	Combined ash	Arsenic (III)	mg/L	0.0003	0.0003	0.0003	TRUE
33104	Combined ash	Arsenic (III)	mg/L	0.0001	0.0001	0.0001	TRUE
33104	Fly Ash	Arsenic (III)	mg/L	0.0002	0.0002	0.0002	TRUE
33106	Combined ash	Arsenic (III)	mg/L	0.00002	0.00002	0.00002	TRUE
33106	Fly Ash	Arsenic (III)	mg/L	0.0000375	0.00005	0.00022	TRUE
34186B	FGD waste	Arsenic (III)	mg/L	0.0499625	0.098975	0.1479875	TRUE

Attachment C-3. Quartile Data for CCR Impoundment Surface Water

Site	New_WasteType	Analyte	Units	25th	50th	75th	Risk
35015B	Combined ash	Arsenic (III)	mg/L	0.0003425	0.00066	0.00883	TRUE
40109	Combined ash	Arsenic (III)	mg/L	0.0001	0.0001	0.0001	TRUE
40109	Fly Ash	Arsenic (III)	mg/L	0.0007	0.0007	0.0007	TRUE
49003A	Fly Ash	Arsenic (III)	mg/L	0.002575	0.00705	0.0115	TRUE
13115A	Combined ash	Arsenic (V)	mg/L	0.0001625	0.000285	0.0004075	TRUE
13115A	Fly Ash	Arsenic (V)	mg/L	0.00004	0.00004	0.00004	TRUE
22346	Other	Arsenic (V)	mg/L	0.015	0.015	0.015	TRUE
22347	Fly Ash	Arsenic (V)	mg/L	0.0024	0.0024	0.0024	TRUE
23223B	FGD waste	Arsenic (V)	mg/L	0.005	0.005	0.005	TRUE
25410A	Combined ash	Arsenic (V)	mg/L	0.024	0.024	0.024	TRUE
33104	Combined ash	Arsenic (V)	mg/L	0.1045	0.115	0.1255	TRUE
33104	Fly Ash	Arsenic (V)	mg/L	0.15	0.15	0.15	TRUE
33106	Combined ash	Arsenic (V)	mg/L	0.0023	0.0023	0.0023	TRUE
33106	Fly Ash	Arsenic (V)	mg/L	0.01075	0.019	0.0235	TRUE
34186B	FGD waste	Arsenic (V)	mg/L	0.02375	0.0325	0.04125	TRUE
35015B	Combined ash	Arsenic (V)	mg/L	0.024	0.031	0.038	TRUE
40109	Combined ash	Arsenic (V)	mg/L	0.1015	0.11	0.1185	TRUE
40109	Fly Ash	Arsenic (V)	mg/L	0.015	0.015	0.015	TRUE
49003A	Fly Ash	Arsenic (V)	mg/L	0.0004675	0.002895	0.005825	TRUE
13115A	Combined ash	Arsenic, other	mg/L	0.00008925	0.0001095	0.00012975	TRUE
13115A	Fly Ash	Arsenic, other	mg/L	0.00003	0.00003	0.00003	TRUE
23223B	FGD waste	Arsenic, other	mg/L	0.003	0.003	0.003	TRUE
25410A	Combined ash	Arsenic, other	mg/L	0.0003	0.0003	0.0003	TRUE
33106	Combined ash	Arsenic, other	mg/L	0.00002	0.00002	0.00002	TRUE
34186B	FGD waste	Arsenic, other	mg/L	0.001025	0.00195	0.002875	TRUE
35015B	Combined ash	Arsenic, other	mg/L	0.000112	0.00015	0.00022	TRUE
49003A	Fly Ash	Arsenic, other	mg/L	0.00002875	0.0000565	0.00008725	TRUE
13115A	Combined ash	Barium	mg/L	0.16	0.18	0.2	TRUE
13115A	Fly Ash	Barium	mg/L	0.35	0.35	0.35	TRUE
22346	Other	Barium	mg/L	0.434	0.434	0.434	TRUE
22347	Fly Ash	Barium	mg/L	0.294	0.294	0.294	TRUE
23223B	FGD waste	Barium	mg/L	0.09	0.09	0.09	TRUE
25410A	Combined ash	Barium	mg/L	0.35	0.35	0.35	TRUE
33104	Combined ash	Barium	mg/L	0.132	0.14	0.148	TRUE
33104	Fly Ash	Barium	mg/L	0.319	0.319	0.319	TRUE
33106	Combined ash	Barium	mg/L	0.195	0.195	0.195	TRUE
33106	Fly Ash	Barium	mg/L	0.103	0.131	0.1555	TRUE
34186B	FGD waste	Barium	mg/L	0.09575	0.1165	0.13725	TRUE
35015B	Combined ash	Barium	mg/L	0.134	0.15	0.155	TRUE
40109	Combined ash	Barium	mg/L	0.17375	0.1765	0.17925	TRUE
40109	Fly Ash	Barium	mg/L	0.545	0.545	0.545	TRUE
49003A	Fly Ash	Barium	mg/L	0.18075	0.186	0.19	TRUE
13115A	Combined ash	Beryllium	mg/L	0.0005	0.0005	0.0005	TRUE
13115A	Fly Ash	Beryllium	mg/L	0.0005	0.0005	0.0005	TRUE
22346	Other	Beryllium	mg/L	0.0001	0.0001	0.0001	TRUE
22347	Fly Ash	Beryllium	mg/L	0.0001	0.0001	0.0001	TRUE
23223B	FGD waste	Beryllium	mg/L	0.0005	0.0005	0.0005	TRUE
25410A	Combined ash	Beryllium	mg/L	0.0005	0.0005	0.0005	TRUE
33104	Combined ash	Beryllium	mg/L	0.0002	0.0002	0.0002	TRUE
33104	Fly Ash	Beryllium	mg/L	0.0002	0.0002	0.0002	TRUE
33106	Combined ash	Beryllium	mg/L	0.0002	0.0002	0.0002	TRUE
33106	Fly Ash	Beryllium	mg/L	0.0012	0.0016	0.0051	TRUE
34186B	FGD waste	Beryllium	mg/L	0.000325	0.00055	0.000775	TRUE
35015B	Combined ash	Beryllium	mg/L	0.0001	0.0001	0.00025	TRUE
40109	Combined ash	Beryllium	mg/L	0.0002	0.0002	0.0002	TRUE
40109	Fly Ash	Beryllium	mg/L	0.0052	0.0052	0.0052	TRUE

Attachment C-3. Quartile Data for CCR Impoundment Surface Water

Site	New_WasteType	Analyte	Units	25th	50th	75th	Risk
49003A	Fly Ash	Beryllium	mg/L	0.0001	0.00025	0.0004	TRUE
13115A	Combined ash	Boron	mg/L	0.74	0.78	0.82	TRUE
13115A	Fly Ash	Boron	mg/L	0.47	0.47	0.47	TRUE
22346	Other	Boron	mg/L	0.442	0.442	0.442	TRUE
22347	Fly Ash	Boron	mg/L	1.02	1.02	1.02	TRUE
23223B	FGD waste	Boron	mg/L	98.5	98.5	98.5	TRUE
25410A	Combined ash	Boron	mg/L	3.89	3.89	3.89	TRUE
33104	Combined ash	Boron	mg/L	0.213	0.219	0.225	TRUE
33104	Fly Ash	Boron	mg/L	0.476	0.476	0.476	TRUE
33106	Combined ash	Boron	mg/L	0.265	0.265	0.265	TRUE
33106	Fly Ash	Boron	mg/L	0.4275	0.429	0.6335	TRUE
34186B	FGD waste	Boron	mg/L	32.65	38.5	44.35	TRUE
35015B	Combined ash	Boron	mg/L	1.95	2.2	2.205	TRUE
40109	Combined ash	Boron	mg/L	0.31275	0.3255	0.33825	TRUE
40109	Fly Ash	Boron	mg/L	0.272	0.272	0.272	TRUE
49003A	Fly Ash	Boron	mg/L	0.4275	0.437	0.4455	TRUE
13115A	Combined ash	Cadmium	mg/L	0.00015	0.00015	0.00015	TRUE
13115A	Fly Ash	Cadmium	mg/L	0.00015	0.00015	0.00015	TRUE
22346	Other	Cadmium	mg/L	0.0001	0.0001	0.0001	TRUE
22347	Fly Ash	Cadmium	mg/L	0.0003	0.0003	0.0003	TRUE
23223B	FGD waste	Cadmium	mg/L	0.0042	0.0042	0.0042	TRUE
25410A	Combined ash	Cadmium	mg/L	0.001	0.001	0.001	TRUE
33104	Combined ash	Cadmium	mg/L	0.00015	0.0002	0.00025	TRUE
33104	Fly Ash	Cadmium	mg/L	0.0006	0.0006	0.0006	TRUE
33106	Combined ash	Cadmium	mg/L	0.0005	0.0005	0.0005	TRUE
33106	Fly Ash	Cadmium	mg/L	0.001	0.0013	0.0016	TRUE
34186B	FGD waste	Cadmium	mg/L	0.002025	0.00355	0.005075	TRUE
35015B	Combined ash	Cadmium	mg/L	0.0009	0.0012	0.0013	TRUE
40109	Combined ash	Cadmium	mg/L	0.000175	0.00025	0.000325	TRUE
40109	Fly Ash	Cadmium	mg/L	0.0024	0.0024	0.0024	TRUE
49003A	Fly Ash	Cadmium	mg/L	0.001475	0.0018	0.002	TRUE
13115A	Combined ash	Calcium	mg/L	43.75	44.5	45.25	TRUE
13115A	Fly Ash	Calcium	mg/L	81	81	81	TRUE
22346	Other	Calcium	mg/L	79.1	79.1	79.1	TRUE
22347	Fly Ash	Calcium	mg/L	34.4	34.4	34.4	TRUE
23223B	FGD waste	Calcium	mg/L	577	577	577	TRUE
25410A	Combined ash	Calcium	mg/L	255	255	255	TRUE
33104	Combined ash	Calcium	mg/L	20.75	22.5	24.25	TRUE
33104	Fly Ash	Calcium	mg/L	58.1	58.1	58.1	TRUE
33106	Combined ash	Calcium	mg/L	13.2	13.2	13.2	TRUE
33106	Fly Ash	Calcium	mg/L	13.9	15.4	17.65	TRUE
34186B	FGD waste	Calcium	mg/L	577.5	585	592.5	TRUE
35015B	Combined ash	Calcium	mg/L	122	123	123.5	TRUE
40109	Combined ash	Calcium	mg/L	16.8	16.8	16.8	TRUE
40109	Fly Ash	Calcium	mg/L	14.4	14.4	14.4	TRUE
49003A	Fly Ash	Calcium	mg/L	41.75	43	43.5	TRUE
13115A	Combined ash	Chloride	mg/L	72.975	73.95	74.925	TRUE
13115A	Fly Ash	Chloride	mg/L	84.8	84.8	84.8	TRUE
22346	Other	Chloride	mg/L	72	72	72	TRUE
22347	Fly Ash	Chloride	mg/L	68.4	68.4	68.4	TRUE
23223B	FGD waste	Chloride	mg/L	345	345	345	TRUE
25410A	Combined ash	Chloride	mg/L	25.3	25.3	25.3	TRUE
33104	Combined ash	Chloride	mg/L	8.5	9.7	10.9	TRUE
33104	Fly Ash	Chloride	mg/L	5	5	5	TRUE
33106	Combined ash	Chloride	mg/L	9.8	9.8	9.8	TRUE
33106	Fly Ash	Chloride	mg/L	8.4	9.7	9.75	TRUE

Attachment C-3. Quartile Data for CCR Impoundment Surface Water

Site	New_WasteType	Analyte	Units	25th	50th	75th	Risk
34186B	FGD waste	Chloride	mg/L	1392.5	1705	2017.5	TRUE
35015B	Combined ash	Chloride	mg/L	60.35	64.8	65.5	TRUE
40109	Combined ash	Chloride	mg/L	4.775	5.05	5.325	TRUE
40109	Fly Ash	Chloride	mg/L	5.3	5.3	5.3	TRUE
49003A	Fly Ash	Chloride	mg/L	16.875	17.35	17.825	TRUE
13115A	Combined ash	Chromium	mg/L	0.001195	0.00173	0.002265	TRUE
13115A	Fly Ash	Chromium	mg/L	0.00096	0.00096	0.00096	TRUE
22346	Other	Chromium	mg/L	0.025	0.025	0.025	TRUE
22347	Fly Ash	Chromium	mg/L	0.02	0.02	0.02	TRUE
23223B	FGD waste	Chromium	mg/L	0.053	0.053	0.053	TRUE
25410A	Combined ash	Chromium	mg/L	0.013	0.013	0.013	TRUE
33104	Combined ash	Chromium	mg/L	0.003725	0.00425	0.004775	TRUE
33104	Fly Ash	Chromium	mg/L	0.022	0.022	0.022	TRUE
33106	Combined ash	Chromium	mg/L	0.0002	0.0002	0.0002	TRUE
33106	Fly Ash	Chromium	mg/L	0.0002	0.0002	0.0146	TRUE
34186B	FGD waste	Chromium	mg/L	0.0004	0.0006	0.0008	TRUE
35015B	Combined ash	Chromium	mg/L	0.000165	0.00023	0.000815	TRUE
40109	Combined ash	Chromium	mg/L	0.0021	0.0023	0.0025	TRUE
40109	Fly Ash	Chromium	mg/L	0.011	0.011	0.011	TRUE
49003A	Fly Ash	Chromium	mg/L	0.00107	0.0013	0.001575	TRUE
13115A	Combined ash	Chromium (III)	mg/L	0.00002	0.00002	0.00002	TRUE
13115A	Fly Ash	Chromium (III)	mg/L	0.00005	0.00005	0.00005	TRUE
22346	Other	Chromium (III)	mg/L	0.0012	0.0012	0.0012	TRUE
22347	Fly Ash	Chromium (III)	mg/L	0.0024	0.0024	0.0024	TRUE
23223B	FGD waste	Chromium (III)	mg/L	0.0013	0.0013	0.0013	TRUE
25410A	Combined ash	Chromium (III)	mg/L	0.0002	0.0002	0.0002	TRUE
33104	Combined ash	Chromium (III)	mg/L	0.0005025	0.000545	0.0005875	TRUE
33104	Fly Ash	Chromium (III)	mg/L	0.000044	0.000044	0.000044	TRUE
33106	Combined ash	Chromium (III)	mg/L	0.000074	0.000074	0.000074	TRUE
33106	Fly Ash	Chromium (III)	mg/L	0.00021	0.00025	0.013125	TRUE
35015B	Combined ash	Chromium (III)	mg/L	0.00005	0.00005	0.00005	TRUE
40109	Combined ash	Chromium (III)	mg/L	0.00028325	0.0005555	0.00082775	TRUE
40109	Fly Ash	Chromium (III)	mg/L	0.0099	0.0099	0.0099	TRUE
49003A	Fly Ash	Chromium (III)	mg/L	0.00002	0.00018	0.000355	TRUE
13115A	Combined ash	Chromium (VI)	mg/L	0.00071875	0.0014125	0.00210625	TRUE
13115A	Fly Ash	Chromium (VI)	mg/L	0.0009	0.0009	0.0009	TRUE
22346	Other	Chromium (VI)	mg/L	0.023	0.023	0.023	TRUE
22347	Fly Ash	Chromium (VI)	mg/L	0.015	0.015	0.015	TRUE
23223B	FGD waste	Chromium (VI)	mg/L	0.047	0.047	0.047	TRUE
25410A	Combined ash	Chromium (VI)	mg/L	0.013	0.013	0.013	TRUE
33104	Combined ash	Chromium (VI)	mg/L	0.003575	0.00415	0.004725	TRUE
33104	Fly Ash	Chromium (VI)	mg/L	0.023	0.023	0.023	TRUE
33106	Combined ash	Chromium (VI)	mg/L	0.000005	0.000005	0.000005	TRUE
33106	Fly Ash	Chromium (VI)	mg/L	0.000017	0.000029	0.0000395	TRUE
35015B	Combined ash	Chromium (VI)	mg/L	0.000025	0.000025	0.000025	TRUE
40109	Combined ash	Chromium (VI)	mg/L	0.0006325	0.000855	0.0010775	TRUE
40109	Fly Ash	Chromium (VI)	mg/L	0.000025	0.000025	0.000025	TRUE
49003A	Fly Ash	Chromium (VI)	mg/L	0.0002555	0.000605	0.0009	TRUE
13115A	Combined ash	Cobalt	mg/L	0.0005	0.0005	0.0005	TRUE
13115A	Fly Ash	Cobalt	mg/L	0.001	0.001	0.001	TRUE
22346	Other	Cobalt	mg/L	0.0008	0.0008	0.0008	TRUE
22347	Fly Ash	Cobalt	mg/L	0.00053	0.00053	0.00053	TRUE
23223B	FGD waste	Cobalt	mg/L	0.078	0.078	0.078	TRUE
25410A	Combined ash	Cobalt	mg/L	0.003	0.003	0.003	TRUE
33104	Combined ash	Cobalt	mg/L	0.0004	0.0007	0.001	TRUE
33104	Fly Ash	Cobalt	mg/L	0.0001	0.0001	0.0001	TRUE

Attachment C-3. Quartile Data for CCR Impoundment Surface Water

Site	New_WasteType	Analyte	Units	25th	50th	75th	Risk
33106	Combined ash	Cobalt	mg/L	0.0052	0.0052	0.0052	TRUE
33106	Fly Ash	Cobalt	mg/L	0.0101	0.0115	0.01655	TRUE
34186B	FGD waste	Cobalt	mg/L	0.0033175	0.006545	0.0097725	TRUE
35015B	Combined ash	Cobalt	mg/L	0.00229	0.003	0.00338	TRUE
40109	Combined ash	Cobalt	mg/L	0.0001	0.0001	0.0001	TRUE
40109	Fly Ash	Cobalt	mg/L	0.0189	0.0189	0.0189	TRUE
49003A	Fly Ash	Cobalt	mg/L	0.007125	0.007575	0.008	TRUE
13115A	Combined ash	Copper	mg/L	0.00825	0.0095	0.01075	TRUE
13115A	Fly Ash	Copper	mg/L	0.008	0.008	0.008	TRUE
22346	Other	Copper	mg/L	0.0038	0.0038	0.0038	TRUE
22347	Fly Ash	Copper	mg/L	0.0021	0.0021	0.0021	TRUE
23223B	FGD waste	Copper	mg/L	0.007	0.007	0.007	TRUE
25410A	Combined ash	Copper	mg/L	0.0015	0.0015	0.0015	TRUE
33104	Combined ash	Copper	mg/L	0.000975	0.00125	0.001525	TRUE
33104	Fly Ash	Copper	mg/L	0.0005	0.0005	0.0005	TRUE
33106	Combined ash	Copper	mg/L	0.0019	0.0019	0.0019	TRUE
33106	Fly Ash	Copper	mg/L	0.01035	0.012	0.082	TRUE
34186B	FGD waste	Copper	mg/L	0.0008	0.0012	0.0016	TRUE
35015B	Combined ash	Copper	mg/L	0.0022	0.0025	0.01325	TRUE
40109	Combined ash	Copper	mg/L	0.001475	0.00165	0.001825	TRUE
40109	Fly Ash	Copper	mg/L	0.452	0.452	0.452	TRUE
49003A	Fly Ash	Copper	mg/L	0.006375	0.0084	0.00905	TRUE
13115A	Combined ash	Dissolved oxygen	%	2.325	3.05	3.775	FALSE
13115A	Fly Ash	Dissolved oxygen	%	3.4	3.4	3.4	FALSE
22346	Other	Dissolved oxygen	%	65.1	65.1	65.1	FALSE
22347	Fly Ash	Dissolved oxygen	%	100	100	100	FALSE
23223B	FGD waste	Dissolved oxygen	%	0.3	0.3	0.3	FALSE
25410A	Combined ash	Dissolved oxygen	%	3.7	3.7	3.7	FALSE
33104	Combined ash	Dissolved oxygen	%	64.6	65.7	66.8	FALSE
33104	Fly Ash	Dissolved oxygen	%	67.7	67.7	67.7	FALSE
33106	Combined ash	Dissolved oxygen	%	77.6	77.6	77.6	FALSE
33106	Fly Ash	Dissolved oxygen	%	71.8	75.7	79.9	FALSE
34186B	FGD waste	Dissolved oxygen	%	10.5	19	27.5	FALSE
35015B	Combined ash	Dissolved oxygen	%	47.6	80.7	101.75	FALSE
40109	Combined ash	Dissolved oxygen	%	108.175	127.15	146.125	FALSE
40109	Fly Ash	Dissolved oxygen	%	82.4	82.4	82.4	FALSE
49003A	Fly Ash	Dissolved oxygen	%	34.925	63.05	89.85	FALSE
13115A	Combined ash	Iron	mg/L	0.025	0.025	0.025	TRUE
13115A	Fly Ash	Iron	mg/L	0.025	0.025	0.025	TRUE
22346	Other	Iron	mg/L	0.0015	0.0015	0.0015	TRUE
22347	Fly Ash	Iron	mg/L	0.0015	0.0015	0.0015	TRUE
23223B	FGD waste	Iron	mg/L	0.025	0.025	0.025	TRUE
25410A	Combined ash	Iron	mg/L	0.025	0.025	0.025	TRUE
33104	Combined ash	Iron	mg/L	0.008625	0.01475	0.020875	TRUE
33104	Fly Ash	Iron	mg/L	0.013	0.013	0.013	TRUE
33106	Combined ash	Iron	mg/L	0.007	0.007	0.007	TRUE
33106	Fly Ash	Iron	mg/L	0.012	0.018	0.37	TRUE
34186B	FGD waste	Iron	mg/L	0.016625	0.02855	0.040475	TRUE
35015B	Combined ash	Iron	mg/L	0.0065	0.0065	0.01575	TRUE
40109	Combined ash	Iron	mg/L	0.011	0.016	0.021	TRUE
40109	Fly Ash	Iron	mg/L	3.24	3.24	3.24	TRUE
49003A	Fly Ash	Iron	mg/L	0.0065	0.01575	0.025	TRUE
13115A	Combined ash	Lead	mg/L	0.0001	0.0001	0.0001	TRUE
13115A	Fly Ash	Lead	mg/L	0.00021	0.00021	0.00021	TRUE
22346	Other	Lead	mg/L	0.00005	0.00005	0.00005	TRUE
22347	Fly Ash	Lead	mg/L	0.0002	0.0002	0.0002	TRUE

Attachment C-3. Quartile Data for CCR Impoundment Surface Water

Site	New_WasteType	Analyte	Units	25th	50th	75th	Risk
23223B	FGD waste	Lead	mg/L	0.0001	0.0001	0.0001	TRUE
25410A	Combined ash	Lead	mg/L	0.0001	0.0001	0.0001	TRUE
33104	Combined ash	Lead	mg/L	0.00005	0.00005	0.00005	TRUE
33104	Fly Ash	Lead	mg/L	0.00005	0.00005	0.00005	TRUE
33106	Combined ash	Lead	mg/L	0.00005	0.00005	0.00005	TRUE
33106	Fly Ash	Lead	mg/L	0.0002	0.0002	0.00105	TRUE
34186B	FGD waste	Lead	mg/L	0.00035	0.0005	0.00065	TRUE
35015B	Combined ash	Lead	mg/L	0.00007	0.00007	0.000085	TRUE
40109	Combined ash	Lead	mg/L	0.00005	0.00005	0.00005	TRUE
40109	Fly Ash	Lead	mg/L	0.008	0.008	0.008	TRUE
49003A	Fly Ash	Lead	mg/L	0.00007	0.000085	0.0001	TRUE
13115A	Combined ash	Lithium	mg/L	0.01	0.01	0.01	FALSE
13115A	Fly Ash	Lithium	mg/L	0.01	0.01	0.01	FALSE
22346	Other	Lithium	mg/L	0.06	0.06	0.06	FALSE
22347	Fly Ash	Lithium	mg/L	0.027	0.027	0.027	FALSE
23223B	FGD waste	Lithium	mg/L	2.72	2.72	2.72	FALSE
25410A	Combined ash	Lithium	mg/L	0.1	0.1	0.1	FALSE
33104	Combined ash	Lithium	mg/L	0.145	0.15	0.155	FALSE
33104	Fly Ash	Lithium	mg/L	0.43	0.43	0.43	FALSE
33106	Combined ash	Lithium	mg/L	0.099	0.099	0.099	FALSE
33106	Fly Ash	Lithium	mg/L	0.1625	0.179	0.209	FALSE
34186B	FGD waste	Lithium	mg/L	1.635	2.22	2.805	FALSE
35015B	Combined ash	Lithium	mg/L	0.201	0.24	0.2465	FALSE
40109	Combined ash	Lithium	mg/L	0.2735	0.28	0.2865	FALSE
40109	Fly Ash	Lithium	mg/L	0.52	0.52	0.52	FALSE
49003A	Fly Ash	Lithium	mg/L	0.3165	0.319	0.33	FALSE
13115A	Combined ash	Magnesium	mg/L	21.5	22	22.5	TRUE
13115A	Fly Ash	Magnesium	mg/L	28	28	28	TRUE
22346	Other	Magnesium	mg/L	19.1	19.1	19.1	TRUE
22347	Fly Ash	Magnesium	mg/L	12.6	12.6	12.6	TRUE
23223B	FGD waste	Magnesium	mg/L	1990	1990	1990	TRUE
25410A	Combined ash	Magnesium	mg/L	33	33	33	TRUE
33104	Combined ash	Magnesium	mg/L	1.875	1.97	2.065	TRUE
33104	Fly Ash	Magnesium	mg/L	1.49	1.49	1.49	TRUE
33106	Combined ash	Magnesium	mg/L	2.53	2.53	2.53	TRUE
33106	Fly Ash	Magnesium	mg/L	2.32	2.58	2.62	TRUE
34186B	FGD waste	Magnesium	mg/L	2202.5	3405	4607.5	TRUE
35015B	Combined ash	Magnesium	mg/L	58.5	67	69.5	TRUE
40109	Combined ash	Magnesium	mg/L	1.41	1.45	1.49	TRUE
40109	Fly Ash	Magnesium	mg/L	1.81	1.81	1.81	TRUE
49003A	Fly Ash	Magnesium	mg/L	14	15	16.25	TRUE
13115A	Combined ash	Manganese	mg/L	0.002	0.002	0.002	TRUE
13115A	Fly Ash	Manganese	mg/L	0.014	0.014	0.014	TRUE
22346	Other	Manganese	mg/L	0.002	0.002	0.002	TRUE
22347	Fly Ash	Manganese	mg/L	0.001	0.001	0.001	TRUE
23223B	FGD waste	Manganese	mg/L	0.564	0.564	0.564	TRUE
25410A	Combined ash	Manganese	mg/L	0.002	0.002	0.002	TRUE
33104	Combined ash	Manganese	mg/L	0.0058	0.0112	0.0166	TRUE
33104	Fly Ash	Manganese	mg/L	0.0001	0.0001	0.0001	TRUE
33106	Combined ash	Manganese	mg/L	0.0794	0.0794	0.0794	TRUE
33106	Fly Ash	Manganese	mg/L	0.0601	0.0775	0.0818	TRUE
34186B	FGD waste	Manganese	mg/L	0.64725	0.8215	0.99575	TRUE
35015B	Combined ash	Manganese	mg/L	0.0758	0.092	0.1235	TRUE
40109	Combined ash	Manganese	mg/L	0.00085	0.0011	0.00135	TRUE
40109	Fly Ash	Manganese	mg/L	0.113	0.113	0.113	TRUE
49003A	Fly Ash	Manganese	mg/L	0.059	0.08165	0.104	TRUE

Attachment C-3. Quartile Data for CCR Impoundment Surface Water

Site	New_WasteType	Analyte	Units	25th	50th	75th	Risk
22346	Other	Mercury	mg/L	0.0000059	0.0000059	0.0000059	TRUE
22347	Fly Ash	Mercury	mg/L	0.0000021	0.0000021	0.0000021	TRUE
23223B	FGD waste	Mercury	mg/L	0.000028	0.000028	0.000028	TRUE
35015B	Combined ash	Mercury	mg/L	0.0000014	0.0000014	0.0000014	TRUE
49003A	Fly Ash	Mercury	mg/L	5.35E-07	0.00000069	8.45E-07	TRUE
13115A	Combined ash	Molybdenum	mg/L	0.03125	0.0475	0.06375	TRUE
13115A	Fly Ash	Molybdenum	mg/L	0.015	0.015	0.015	TRUE
22346	Other	Molybdenum	mg/L	0.0219	0.0219	0.0219	TRUE
22347	Fly Ash	Molybdenum	mg/L	0.0277	0.0277	0.0277	TRUE
23223B	FGD waste	Molybdenum	mg/L	0.32	0.32	0.32	TRUE
25410A	Combined ash	Molybdenum	mg/L	0.42	0.42	0.42	TRUE
33104	Combined ash	Molybdenum	mg/L	0.06525	0.0695	0.07375	TRUE
33104	Fly Ash	Molybdenum	mg/L	0.217	0.217	0.217	TRUE
33106	Combined ash	Molybdenum	mg/L	0.06	0.06	0.06	TRUE
33106	Fly Ash	Molybdenum	mg/L	0.0445	0.054	0.0905	TRUE
34186B	FGD waste	Molybdenum	mg/L	0.453	0.742	1.031	TRUE
35015B	Combined ash	Molybdenum	mg/L	0.10435	0.12	0.1255	TRUE
40109	Combined ash	Molybdenum	mg/L	0.06225	0.0625	0.06275	TRUE
40109	Fly Ash	Molybdenum	mg/L	0.008	0.008	0.008	TRUE
49003A	Fly Ash	Molybdenum	mg/L	0.339	0.37	0.4025	TRUE
13115A	Combined ash	Nickel	mg/L	0.00425	0.0045	0.00475	TRUE
13115A	Fly Ash	Nickel	mg/L	0.007	0.007	0.007	TRUE
22346	Other	Nickel	mg/L	0.0036	0.0036	0.0036	TRUE
22347	Fly Ash	Nickel	mg/L	0.0044	0.0044	0.0044	TRUE
23223B	FGD waste	Nickel	mg/L	0.463	0.463	0.463	TRUE
25410A	Combined ash	Nickel	mg/L	0.016	0.016	0.016	TRUE
33104	Combined ash	Nickel	mg/L	0.0018	0.003	0.0042	TRUE
33104	Fly Ash	Nickel	mg/L	0.0009	0.0009	0.0009	TRUE
33106	Combined ash	Nickel	mg/L	0.0136	0.0136	0.0136	TRUE
33106	Fly Ash	Nickel	mg/L	0.03225	0.0378	0.05485	TRUE
34186B	FGD waste	Nickel	mg/L	0.040725	0.07815	0.115575	TRUE
35015B	Combined ash	Nickel	mg/L	0.0115	0.015	0.016	TRUE
40109	Combined ash	Nickel	mg/L	0.00185	0.002	0.00215	TRUE
40109	Fly Ash	Nickel	mg/L	0.0582	0.0582	0.0582	TRUE
49003A	Fly Ash	Nickel	mg/L	0.014	0.0165	0.0195	TRUE
13115A	Combined ash	Oxidation-reduction potential	mV	292.5	296	299.5	FALSE
13115A	Fly Ash	Oxidation-reduction potential	mV	296	296	296	FALSE
22346	Other	Oxidation-reduction potential	mV	241	241	241	FALSE
22347	Fly Ash	Oxidation-reduction potential	mV	217	217	217	FALSE
23223B	FGD waste	Oxidation-reduction potential	mV	342	342	342	FALSE
25410A	Combined ash	Oxidation-reduction potential	mV	339	339	339	FALSE
33104	Combined ash	Oxidation-reduction potential	mV	220.75	221.5	222.25	FALSE
33104	Fly Ash	Oxidation-reduction potential	mV	214	214	214	FALSE
33106	Combined ash	Oxidation-reduction potential	mV	290	290	290	FALSE
33106	Fly Ash	Oxidation-reduction potential	mV	284	285	336.5	FALSE
34186B	FGD waste	Oxidation-reduction potential	mV	240.25	250.5	260.75	FALSE
35015B	Combined ash	Oxidation-reduction potential	mV	248.5	257	276	FALSE
40109	Combined ash	Oxidation-reduction potential	mV	409	409	409	FALSE
40109	Fly Ash	Oxidation-reduction potential	mV	387	387	387	FALSE
49003A	Fly Ash	Oxidation-reduction potential	mV	282	298	310	FALSE
13115A	Combined ash	pH (field)	pH	8.825	8.85	8.875	FALSE
13115A	Fly Ash	pH (field)	pH	8	8	8	FALSE
22346	Other	pH (field)	pH	8.64	8.64	8.64	FALSE
22347	Fly Ash	pH (field)	pH	9.36	9.36	9.36	FALSE
23223B	FGD waste	pH (field)	pH	7.4	7.4	7.4	FALSE
25410A	Combined ash	pH (field)	pH	9.3	9.3	9.3	FALSE

Attachment C-3. Quartile Data for CCR Impoundment Surface Water

Site	New_WasteType	Analyte	Units	25th	50th	75th	Risk
33104	Combined ash	pH (field)	pH	7.905	8.24	8.575	FALSE
33104	Fly Ash	pH (field)	pH	10.12	10.12	10.12	FALSE
33106	Combined ash	pH (field)	pH	5.97	5.97	5.97	FALSE
33106	Fly Ash	pH (field)	pH	5.025	5.79	5.88	FALSE
34186B	FGD waste	pH (field)	pH	7.37	7.91	8.45	FALSE
35015B	Combined ash	pH (field)	pH	7.7	7.8	8.2	FALSE
40109	Combined ash	pH (field)	pH	8.005	8.35	8.695	FALSE
40109	Fly Ash	pH (field)	pH	4.35	4.35	4.35	FALSE
49003A	Fly Ash	pH (field)	pH	7.175	7.24	7.3125	FALSE
13115A	Combined ash	Potassium	mg/L	6.5	7	7.5	TRUE
13115A	Fly Ash	Potassium	mg/L	6	6	6	TRUE
22346	Other	Potassium	mg/L	5	5	5	TRUE
22347	Fly Ash	Potassium	mg/L	4	4	4	TRUE
23223B	FGD waste	Potassium	mg/L	40	40	40	TRUE
25410A	Combined ash	Potassium	mg/L	20	20	20	TRUE
33104	Combined ash	Potassium	mg/L	3.95	4.3	4.65	TRUE
33104	Fly Ash	Potassium	mg/L	9.4	9.4	9.4	TRUE
33106	Combined ash	Potassium	mg/L	4	4	4	TRUE
33106	Fly Ash	Potassium	mg/L	5.1	5.2	6.1	TRUE
34186B	FGD waste	Potassium	mg/L	410	440	470	TRUE
35015B	Combined ash	Potassium	mg/L	9.5	10	11.5	TRUE
40109	Combined ash	Potassium	mg/L	5.95	6.1	6.25	TRUE
40109	Fly Ash	Potassium	mg/L	13.6	13.6	13.6	TRUE
49003A	Fly Ash	Potassium	mg/L	9	9	9.25	TRUE
13115A	Combined ash	Selenium	mg/L	0.002425	0.00245	0.002475	TRUE
13115A	Fly Ash	Selenium	mg/L	0.0018	0.0018	0.0018	TRUE
22346	Other	Selenium	mg/L	0.019	0.019	0.019	TRUE
22347	Fly Ash	Selenium	mg/L	0.013	0.013	0.013	TRUE
23223B	FGD waste	Selenium	mg/L	2.36	2.36	2.36	TRUE
25410A	Combined ash	Selenium	mg/L	0.022	0.022	0.022	TRUE
33104	Combined ash	Selenium	mg/L	0.03075	0.0325	0.03425	TRUE
33104	Fly Ash	Selenium	mg/L	0.103	0.103	0.103	TRUE
33106	Combined ash	Selenium	mg/L	0.01	0.01	0.01	TRUE
33106	Fly Ash	Selenium	mg/L	0.019	0.024	0.0335	TRUE
34186B	FGD waste	Selenium	mg/L	0.046125	0.08375	0.121375	TRUE
35015B	Combined ash	Selenium	mg/L	0.018	0.018	0.023	TRUE
40109	Combined ash	Selenium	mg/L	0.00245	0.0025	0.00255	TRUE
40109	Fly Ash	Selenium	mg/L	0.00045	0.00045	0.00045	TRUE
49003A	Fly Ash	Selenium	mg/L	0.03175	0.0335	0.03525	TRUE
13115A	Combined ash	Selenium (IV)	mg/L	0.00042	0.00058	0.00074	TRUE
13115A	Fly Ash	Selenium (IV)	mg/L	0.00014	0.00014	0.00014	TRUE
22346	Other	Selenium (IV)	mg/L	0.018	0.018	0.018	TRUE
22347	Fly Ash	Selenium (IV)	mg/L	0.0087	0.0087	0.0087	TRUE
23223B	FGD waste	Selenium (IV)	mg/L	0.001	0.001	0.001	TRUE
25410A	Combined ash	Selenium (IV)	mg/L	0.015	0.015	0.015	TRUE
33104	Combined ash	Selenium (IV)	mg/L	0.03	0.031	0.032	TRUE
33104	Fly Ash	Selenium (IV)	mg/L	0.097	0.097	0.097	TRUE
33106	Combined ash	Selenium (IV)	mg/L	0.0083	0.0083	0.0083	TRUE
33106	Fly Ash	Selenium (IV)	mg/L	0.0155	0.02	0.0295	TRUE
34186B	FGD waste	Selenium (IV)	mg/L	0.001	0.001	0.001	TRUE
35015B	Combined ash	Selenium (IV)	mg/L	0.0155	0.018	0.0205	TRUE
40109	Combined ash	Selenium (IV)	mg/L	0.002125	0.00225	0.002375	TRUE
40109	Fly Ash	Selenium (IV)	mg/L	0.00025	0.00025	0.00025	TRUE
49003A	Fly Ash	Selenium (IV)	mg/L	0.02	0.025	0.03025	TRUE
13115A	Combined ash	Selenium (VI)	mg/L	0.0008675	0.000945	0.0010225	TRUE
13115A	Fly Ash	Selenium (VI)	mg/L	0.0013	0.0013	0.0013	TRUE

Attachment C-3. Quartile Data for CCR Impoundment Surface Water

Site	New_WasteType	Analyte	Units	25th	50th	75th	Risk
22346	Other	Selenium (VI)	mg/L	0.00026	0.00026	0.00026	TRUE
22347	Fly Ash	Selenium (VI)	mg/L	0.0015	0.0015	0.0015	TRUE
23223B	FGD waste	Selenium (VI)	mg/L	1.66	1.66	1.66	TRUE
25410A	Combined ash	Selenium (VI)	mg/L	0.0034	0.0034	0.0034	TRUE
33104	Combined ash	Selenium (VI)	mg/L	0.001775	0.00185	0.001925	TRUE
33104	Fly Ash	Selenium (VI)	mg/L	0.002	0.002	0.002	TRUE
33106	Combined ash	Selenium (VI)	mg/L	0.00064	0.00064	0.00064	TRUE
33106	Fly Ash	Selenium (VI)	mg/L	0.0011	0.0017	0.0018	TRUE
34186B	FGD waste	Selenium (VI)	mg/L	0.0055	0.009	0.0125	TRUE
35015B	Combined ash	Selenium (VI)	mg/L	0.001025	0.0013	0.0015	TRUE
40109	Combined ash	Selenium (VI)	mg/L	0.0005	0.0005	0.0005	TRUE
40109	Fly Ash	Selenium (VI)	mg/L	0.0005	0.0005	0.0005	TRUE
49003A	Fly Ash	Selenium (VI)	mg/L	0.0022	0.00265	0.00315	TRUE
34186B	FGD waste	Selenium, other	mg/L	0.0135	0.026	0.0385	FALSE
13115A	Combined ash	Silicon	mg/L	2.4	2.6	2.8	TRUE
13115A	Fly Ash	Silicon	mg/L	3.4	3.4	3.4	TRUE
22346	Other	Silicon	mg/L	4.21	4.21	4.21	TRUE
22347	Fly Ash	Silicon	mg/L	1.05	1.05	1.05	TRUE
23223B	FGD waste	Silicon	mg/L	12.7	12.7	12.7	TRUE
25410A	Combined ash	Silicon	mg/L	8.8	8.8	8.8	TRUE
33104	Combined ash	Silicon	mg/L	7.255	7.32	7.385	TRUE
33104	Fly Ash	Silicon	mg/L	4.76	4.76	4.76	TRUE
33106	Combined ash	Silicon	mg/L	4.67	4.67	4.67	TRUE
33106	Fly Ash	Silicon	mg/L	4.715	4.73	5.255	TRUE
34186B	FGD waste	Silicon	mg/L	13.06	23.84	34.62	TRUE
35015B	Combined ash	Silicon	mg/L	3.29	3.71	4.555	TRUE
40109	Combined ash	Silicon	mg/L	5.0375	5.065	5.0925	TRUE
40109	Fly Ash	Silicon	mg/L	5.84	5.84	5.84	TRUE
49003A	Fly Ash	Silicon	mg/L	2.95	3.135	3.375	TRUE
13115A	Combined ash	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
13115A	Fly Ash	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
22346	Other	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
22347	Fly Ash	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
23223B	FGD waste	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
25410A	Combined ash	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
33104	Combined ash	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
33104	Fly Ash	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
33106	Combined ash	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
33106	Fly Ash	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
34186B	FGD waste	Silver	mg/L	0.0002	0.0003	0.0004	TRUE
35015B	Combined ash	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
40109	Combined ash	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
40109	Fly Ash	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
49003A	Fly Ash	Silver	mg/L	0.0001	0.0001	0.0001	TRUE
13115A	Combined ash	Sodium	mg/L	53.25	53.5	53.75	TRUE
13115A	Fly Ash	Sodium	mg/L	56	56	56	TRUE
22346	Other	Sodium	mg/L	68	68	68	TRUE
22347	Fly Ash	Sodium	mg/L	45	45	45	TRUE
23223B	FGD waste	Sodium	mg/L	743	743	743	TRUE
25410A	Combined ash	Sodium	mg/L	60	60	60	TRUE
33104	Combined ash	Sodium	mg/L	7.2	8.4	9.6	TRUE
33104	Fly Ash	Sodium	mg/L	7.3	7.3	7.3	TRUE
33106	Combined ash	Sodium	mg/L	7	7	7	TRUE
33106	Fly Ash	Sodium	mg/L	8.4	8.5	8.55	TRUE
34186B	FGD waste	Sodium	mg/L	3610	3950	4290	TRUE
35015B	Combined ash	Sodium	mg/L	34	36	36	TRUE

Attachment C-3. Quartile Data for CCR Impoundment Surface Water

Site	New_WasteType	Analyte	Units	25th	50th	75th	Risk
40109	Combined ash	Sodium	mg/L	8.2	8.3	8.4	TRUE
40109	Fly Ash	Sodium	mg/L	11.8	11.8	11.8	TRUE
49003A	Fly Ash	Sodium	mg/L	31.75	37	42.25	TRUE
13115A	Combined ash	Specific conductance @ 25C (field	mS/cm	0.7	0.7	0.7	FALSE
13115A	Fly Ash	Specific conductance @ 25C (field	mS/cm	1	1	1	FALSE
22346	Other	Specific conductance @ 25C (field	mS/cm	0.911	0.911	0.911	FALSE
22347	Fly Ash	Specific conductance @ 25C (field	mS/cm	0.547	0.547	0.547	FALSE
23223B	FGD waste	Specific conductance @ 25C (field	mS/cm	13	13	13	FALSE
25410A	Combined ash	Specific conductance @ 25C (field	mS/cm	1.6	1.6	1.6	FALSE
33104	Combined ash	Specific conductance @ 25C (field	mS/cm	0.1975	0.213	0.2285	FALSE
33104	Fly Ash	Specific conductance @ 25C (field	mS/cm	0.455	0.455	0.455	FALSE
33106	Combined ash	Specific conductance @ 25C (field	mS/cm	0.174	0.174	0.174	FALSE
33106	Fly Ash	Specific conductance @ 25C (field	mS/cm	0.1935	0.209	0.251	FALSE
34186B	FGD waste	Specific conductance @ 25C (field	mS/cm	20.6725	22.495	24.3175	FALSE
35015B	Combined ash	Specific conductance @ 25C (field	mS/cm	1.1595	1.319	1.3335	FALSE
40109	Combined ash	Specific conductance @ 25C (field	mS/cm	0.1905	0.192	0.1935	FALSE
40109	Fly Ash	Specific conductance @ 25C (field	mS/cm	0.287	0.287	0.287	FALSE
49003A	Fly Ash	Specific conductance @ 25C (field	mS/cm	0.56625	0.5835	0.6	FALSE
13115A	Combined ash	Strontium	mg/L	0.5775	0.625	0.6725	TRUE
13115A	Fly Ash	Strontium	mg/L	0.58	0.58	0.58	TRUE
22346	Other	Strontium	mg/L	0.828	0.828	0.828	TRUE
22347	Fly Ash	Strontium	mg/L	1.01	1.01	1.01	TRUE
23223B	FGD waste	Strontium	mg/L	11.7	11.7	11.7	TRUE
25410A	Combined ash	Strontium	mg/L	4.3	4.3	4.3	TRUE
33104	Combined ash	Strontium	mg/L	0.2785	0.299	0.3195	TRUE
33104	Fly Ash	Strontium	mg/L	0.478	0.478	0.478	TRUE
33106	Combined ash	Strontium	mg/L	0.209	0.209	0.209	TRUE
33106	Fly Ash	Strontium	mg/L	0.2085	0.247	0.2595	TRUE
34186B	FGD waste	Strontium	mg/L	2.87	4.24	5.61	TRUE
35015B	Combined ash	Strontium	mg/L	0.4125	0.465	0.486	TRUE
40109	Combined ash	Strontium	mg/L	0.5455	0.546	0.5465	TRUE
40109	Fly Ash	Strontium	mg/L	0.806	0.806	0.806	TRUE
49003A	Fly Ash	Strontium	mg/L	0.40375	0.408	0.41575	TRUE
13115A	Combined ash	Sulfate	mg/L	101.3	111.2	121.1	TRUE
13115A	Fly Ash	Sulfate	mg/L	124	124	124	TRUE
22346	Other	Sulfate	mg/L	174	174	174	TRUE
22347	Fly Ash	Sulfate	mg/L	92.8	92.8	92.8	TRUE
23223B	FGD waste	Sulfate	mg/L	10400	10400	10400	TRUE
25410A	Combined ash	Sulfate	mg/L	782	782	782	TRUE
33104	Combined ash	Sulfate	mg/L	46.25	47.5	48.75	TRUE
33104	Fly Ash	Sulfate	mg/L	150	150	150	TRUE
33106	Combined ash	Sulfate	mg/L	53	53	53	TRUE
33106	Fly Ash	Sulfate	mg/L	63.5	70	90.5	TRUE
34186B	FGD waste	Sulfate	mg/L	15275	20350	25425	TRUE
35015B	Combined ash	Sulfate	mg/L	413.5	441	451.5	TRUE
40109	Combined ash	Sulfate	mg/L	52.75	53.5	54.25	TRUE
40109	Fly Ash	Sulfate	mg/L	111	111	111	TRUE
49003A	Fly Ash	Sulfate	mg/L	165.25	191.5	217.5	TRUE
13115A	Combined ash	Temperature	°C	29.625	29.65	29.675	FALSE
13115A	Fly Ash	Temperature	°C	35.5	35.5	35.5	FALSE
22346	Other	Temperature	°C	30.2	30.2	30.2	FALSE
22347	Fly Ash	Temperature	°C	25.9	25.9	25.9	FALSE
23223B	FGD waste	Temperature	°C	25.6	25.6	25.6	FALSE
25410A	Combined ash	Temperature	°C	31.7	31.7	31.7	FALSE
33104	Combined ash	Temperature	°C	28.125	28.55	28.975	FALSE
33104	Fly Ash	Temperature	°C	30	30	30	FALSE

Attachment C-3. Quartile Data for CCR Impoundment Surface Water

Site	New_WasteType	Analyte	Units	25th	50th	75th	Risk
33106	Combined ash	Temperature	°C	25.8	25.8	25.8	FALSE
33106	Fly Ash	Temperature	°C	30.7	32	32	FALSE
34186B	FGD waste	Temperature	°C	12.25	14.56	16.87	FALSE
35015B	Combined ash	Temperature	°C	12.19	13.9	14.275	FALSE
40109	Combined ash	Temperature	°C	29.175	29.85	30.525	FALSE
40109	Fly Ash	Temperature	°C	26.5	26.5	26.5	FALSE
49003A	Fly Ash	Temperature	°C	15.875	18.8	21.75	FALSE
13115A	Combined ash	Thallium	mg/L	0.00005	0.00005	0.00005	TRUE
13115A	Fly Ash	Thallium	mg/L	0.00005	0.00005	0.00005	TRUE
22346	Other	Thallium	mg/L	0.0005	0.0005	0.0005	TRUE
22347	Fly Ash	Thallium	mg/L	0.00005	0.00005	0.00005	TRUE
23223B	FGD waste	Thallium	mg/L	0.0029	0.0029	0.0029	TRUE
25410A	Combined ash	Thallium	mg/L	0.0025	0.0025	0.0025	TRUE
33104	Combined ash	Thallium	mg/L	0.00055	0.0007	0.00085	TRUE
33104	Fly Ash	Thallium	mg/L	0.0003	0.0003	0.0003	TRUE
33106	Combined ash	Thallium	mg/L	0.0007	0.0007	0.0007	TRUE
33106	Fly Ash	Thallium	mg/L	0.00115	0.0016	0.0029	TRUE
34186B	FGD waste	Thallium	mg/L	0.0001	0.00015	0.0002	TRUE
35015B	Combined ash	Thallium	mg/L	0.0105	0.0142	0.0159	TRUE
40109	Combined ash	Thallium	mg/L	0.000925	0.00095	0.000975	TRUE
40109	Fly Ash	Thallium	mg/L	0.0063	0.0063	0.0063	TRUE
49003A	Fly Ash	Thallium	mg/L	0.007525	0.0098	0.012075	TRUE
13115A	Combined ash	TOC	mg/L	1.975	3.55	5.125	FALSE
13115A	Fly Ash	TOC	mg/L	6	6	6	FALSE
22346	Other	TOC	mg/L	2.6	2.6	2.6	FALSE
22347	Fly Ash	TOC	mg/L	4.7	4.7	4.7	FALSE
23223B	FGD waste	TOC	mg/L	9.9	9.9	9.9	FALSE
25410A	Combined ash	TOC	mg/L	5.3	5.3	5.3	FALSE
33104	Combined ash	TOC	mg/L	0.045	0.045	0.045	FALSE
33104	Fly Ash	TOC	mg/L	0.045	0.045	0.045	FALSE
33106	Combined ash	TOC	mg/L	0.045	0.045	0.045	FALSE
33106	Fly Ash	TOC	mg/L	0.045	0.045	0.045	FALSE
34186B	FGD waste	TOC	mg/L	37.35	41.6	45.85	FALSE
35015B	Combined ash	TOC	mg/L	2.25	3.9	4	FALSE
40109	Combined ash	TOC	mg/L	0.045	0.045	0.045	FALSE
40109	Fly Ash	TOC	mg/L	0.045	0.045	0.045	FALSE
49003A	Fly Ash	TOC	mg/L	0.8	1.15	1.425	FALSE
13115A	Combined ash	Total inorganic carbon	mg/L	23	23.6	24.2	FALSE
13115A	Fly Ash	Total inorganic carbon	mg/L	48.7	48.7	48.7	FALSE
22346	Other	Total inorganic carbon	mg/L	35.9	35.9	35.9	FALSE
22347	Fly Ash	Total inorganic carbon	mg/L	11.9	11.9	11.9	FALSE
23223B	FGD waste	Total inorganic carbon	mg/L	1.7	1.7	1.7	FALSE
25410A	Combined ash	Total inorganic carbon	mg/L	15.4	15.4	15.4	FALSE
33104	Combined ash	Total inorganic carbon	mg/L	6.89	7.74	8.59	FALSE
33104	Fly Ash	Total inorganic carbon	mg/L	3.92	3.92	3.92	FALSE
33106	Combined ash	Total inorganic carbon	mg/L	2.18	2.18	2.18	FALSE
33106	Fly Ash	Total inorganic carbon	mg/L	0.89	1.03	1.52	FALSE
34186B	FGD waste	Total inorganic carbon	mg/L	3.3575	4.865	6.3725	FALSE
35015B	Combined ash	Total inorganic carbon	mg/L	16.05	19.2	20.4	FALSE
40109	Combined ash	Total inorganic carbon	mg/L	5.3075	5.545	5.7825	FALSE
40109	Fly Ash	Total inorganic carbon	mg/L	0.92	0.92	0.92	FALSE
49003A	Fly Ash	Total inorganic carbon	mg/L	1.4375	2.025	2.4825	FALSE
13115A	Combined ash	Uranium	mg/L	0.001125	0.00115	0.001175	TRUE
13115A	Fly Ash	Uranium	mg/L	0.0012	0.0012	0.0012	TRUE
22346	Other	Uranium	mg/L	0.00266	0.00266	0.00266	TRUE
22347	Fly Ash	Uranium	mg/L	0.00123	0.00123	0.00123	TRUE

Attachment C-3. Quartile Data for CCR Impoundment Surface Water

Site	New_WasteType	Analyte	Units	25th	50th	75th	Risk
23223B	FGD waste	Uranium	mg/L	0.0007	0.0007	0.0007	TRUE
25410A	Combined ash	Uranium	mg/L	0.0037	0.0037	0.0037	TRUE
33104	Combined ash	Uranium	mg/L	0.000775	0.00125	0.001725	TRUE
33104	Fly Ash	Uranium	mg/L	0.0007	0.0007	0.0007	TRUE
33106	Combined ash	Uranium	mg/L	0.00005	0.00005	0.00005	TRUE
33106	Fly Ash	Uranium	mg/L	0.00005	0.00005	0.000275	TRUE
34186B	FGD waste	Uranium	mg/L	0.0088525	0.011235	0.0136175	TRUE
35015B	Combined ash	Uranium	mg/L	0.001375	0.00175	0.001885	TRUE
40109	Combined ash	Uranium	mg/L	0.000675	0.00085	0.001025	TRUE
40109	Fly Ash	Uranium	mg/L	0.001	0.001	0.001	TRUE
49003A	Fly Ash	Uranium	mg/L	0.0001	0.000125	0.000155	TRUE
13115A	Combined ash	Vanadium	mg/L	0.01625	0.0165	0.01675	TRUE
13115A	Fly Ash	Vanadium	mg/L	0.01	0.01	0.01	TRUE
22346	Other	Vanadium	mg/L	0.103	0.103	0.103	TRUE
22347	Fly Ash	Vanadium	mg/L	0.0493	0.0493	0.0493	TRUE
23223B	FGD waste	Vanadium	mg/L	0.018	0.018	0.018	TRUE
25410A	Combined ash	Vanadium	mg/L	0.55	0.55	0.55	TRUE
33104	Combined ash	Vanadium	mg/L	0.06925	0.0772	0.08515	TRUE
33104	Fly Ash	Vanadium	mg/L	0.2296	0.2296	0.2296	TRUE
33106	Combined ash	Vanadium	mg/L	0.0056	0.0056	0.0056	TRUE
33106	Fly Ash	Vanadium	mg/L	0.0226	0.0356	0.0532	TRUE
34186B	FGD waste	Vanadium	mg/L	0.0271	0.0524	0.0777	TRUE
35015B	Combined ash	Vanadium	mg/L	0.00515	0.0065	0.00925	TRUE
40109	Combined ash	Vanadium	mg/L	0.032075	0.03285	0.033625	TRUE
40109	Fly Ash	Vanadium	mg/L	0.0047	0.0047	0.0047	TRUE
49003A	Fly Ash	Vanadium	mg/L	0.054125	0.05865	0.06475	TRUE
13115A	Combined ash	Zinc	mg/L	0.00875	0.0095	0.01025	TRUE
13115A	Fly Ash	Zinc	mg/L	0.009	0.009	0.009	TRUE
22346	Other	Zinc	mg/L	0.001	0.001	0.001	TRUE
22347	Fly Ash	Zinc	mg/L	0.003	0.003	0.003	TRUE
23223B	FGD waste	Zinc	mg/L	0.034	0.034	0.034	TRUE
25410A	Combined ash	Zinc	mg/L	0.0025	0.0025	0.0025	TRUE
33104	Combined ash	Zinc	mg/L	0.0015	0.0015	0.0015	TRUE
33104	Fly Ash	Zinc	mg/L	0.0015	0.0015	0.0015	TRUE
33106	Combined ash	Zinc	mg/L	0.0183	0.0183	0.0183	TRUE
33106	Fly Ash	Zinc	mg/L	0.04685	0.0581	0.06925	TRUE
34186B	FGD waste	Zinc	mg/L	0.01775	0.0345	0.05125	TRUE
35015B	Combined ash	Zinc	mg/L	0.006	0.011	0.013	TRUE
40109	Combined ash	Zinc	mg/L	0.002125	0.00275	0.003375	TRUE
40109	Fly Ash	Zinc	mg/L	0.0746	0.0746	0.0746	TRUE
49003A	Fly Ash	Zinc	mg/L	0.01375	0.015	0.01725	TRUE

Attachment C-4.

Quartile Data for CCR Whole Waste

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Harrim 3019	Ash (NOS)	Acid Neutr. Potential	ppm	16.7	16.7	16.7	FALSE
Harrim 3019	Bottom ash	Acid Neutr. Potential	ppm	396.75	398.5	400.25	FALSE
Harrim 3019	Fly ash	Acid Neutr. Potential	ppm	170.75	198	246.7	FALSE
Tracy Vein Slope	Ash (NOS)	Acid Neutr. Potential	ppm	290	290	290	FALSE
Tracy Vein Slope	FBC	Acid Neutr. Potential	ppm	555000	555000	555000	FALSE
City Mine	FBC	Aluminum	ppm	89379	101000	101500	TRUE
Philadelphia Girard	Ash (NOS)	Aluminum	ppm	21870	21870	21870	TRUE
Cleveland	Fly ash	Aluminum	ppm	25.7	25.7	25.7	TRUE
CLSM	Combined ash	Aluminum	ppm	90472.3	90472.3	90472.3	TRUE
CLSM	FBC	Aluminum	ppm	11708.3	11708.3	11708.3	TRUE
Emerald Anthracite	Ash (NOS)	Aluminum	ppm	25981.95	28890	30842.5	TRUE
Freeport Mine	FGD waste	Aluminum	ppm	877	877	877	TRUE
Gale	Ash (NOS)	Aluminum	ppm	13630	13630	13630	TRUE
Girard Estate	Ash (NOS)	Aluminum	ppm	10900	10900	10900	TRUE
HA	Ash & coal waste	Aluminum	ppm	4500	5300	6650	TRUE
Harrim 3019	Bottom ash	Aluminum	ppm	30287.5	34475	38662.5	TRUE
Harrim 3019	Fly ash	Aluminum	ppm	28700	39050	60750	TRUE
an Coal Corporatio	Ash (NOS)	Aluminum	ppm	7515	12750	19552.5	TRUE
an Coal Corporatio	Bottom ash	Aluminum	ppm	2242.5	3720	9290	TRUE
an Coal Corporatio	Fly ash	Aluminum	ppm	63980	77960	91940	TRUE
Coal Corporation 5	Ash (NOS)	Aluminum	ppm	17800	17800	17800	TRUE
Coal Corporation 5	Bottom ash	Aluminum	ppm	22825	35250	47675	TRUE
Coal Corporation 5	Fly ash	Aluminum	ppm	41200	53200	65200	TRUE
ddo Highland Coal (	Ash (NOS)	Aluminum	ppm	5170	8330	19400	TRUE
ddo Highland Coal (	Bottom ash	Aluminum	ppm	17900	17900	17900	TRUE
Knickerbocker Pit	FBC	Aluminum	ppm	22025	23075	28357.5	TRUE
gh Coal and Naviga	Ash (NOS)	Aluminum	ppm	20100	22200	22700	TRUE
ttle Sandy #10 Min	Combined ash	Aluminum	ppm	5435	6100	6250	TRUE
ttle Sandy #10 Min	FGD waste	Aluminum	ppm	3000	3200	3590	TRUE
Martins Creek	Bottom ash	Aluminum	ppm	100600	104000	125901	TRUE
Martins Creek	Fly ash	Aluminum	ppm	110342	118000	125471	TRUE
McCloskey Site	FBC	Aluminum	ppm	19300	27450	35600	TRUE
McKay Site	FBC	Aluminum	ppm	22500	30000	37500	TRUE
Miller Creek Mine	Bottom ash	Aluminum	ppm	3038	7195.39	8360	TRUE
Miller Creek Mine	Combined ash	Aluminum	ppm	1385.25	2453	8020.75	TRUE
Miller Creek Mine	Fly ash	Aluminum	ppm	8580	10000	10590	TRUE
N & L Coal Co.	Ash (NOS)	Aluminum	ppm	17275	115190	146850	TRUE
N & L Coal Co.-2	Ash (NOS)	Aluminum	ppm	17200	122000	131000	TRUE
o. 1 Contracting Co	Ash (NOS)	Aluminum	ppm	24075	25050	26025	TRUE
el Supply Company	Ash (NOS)	Aluminum	ppm	18400	23400	24500	TRUE
el Supply Company	Ash (NOS)	Aluminum	ppm	17200	24100	29429.4	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
el Supply Company	Ash (NOS)	Aluminum	ppm	17850	22300	26750	TRUE
rthampton400002	Ash (NOS)	Aluminum	ppm	24500	24500	24500	TRUE
heast Energy Com	Ash (NOS)	Aluminum	ppm	11683.75	15950	20125	TRUE
heast Energy Com	Bottom ash	Aluminum	ppm	1600	1600	1600	TRUE
heast Energy Com	Fly ash	Aluminum	ppm	8800	8800	8800	TRUE
eastern Power Cor	Ash (NOS)	Aluminum	ppm	16950	18400	22650	TRUE
eastern Power Cor	Bottom ash	Aluminum	ppm	9950	12000	15000	TRUE
eastern Power Cor	Fly ash	Aluminum	ppm	19330	22400	28700	TRUE
Nucla	FBC	Aluminum	ppm	102075	110050	118025	TRUE
Nucla2	FBC	Aluminum	ppm	95000	97000	103500	TRUE
Oak Creek	Bottom ash	Aluminum	ppm	95220	95220	95220	TRUE
Pacton Corp	Ash (NOS)	Aluminum	ppm	27500	27500	27500	TRUE
Pacton Corp	Bottom ash	Aluminum	ppm	10000	10000	10000	TRUE
Pacton Corp	Fly ash	Aluminum	ppm	25912.5	70200	132150	TRUE
Pagnotti Coal Co.	Ash (NOS)	Aluminum	ppm	22900	32275	37287.5	TRUE
Pagnotti Coal Co.	Bottom ash	Aluminum	ppm	8000	8000	8000	TRUE
Pagnotti Coal Co.	Fly ash	Aluminum	ppm	41250	42500	43750	TRUE
Panther Creek	FBC	Aluminum	ppm	25728.75	27595	31700	TRUE
Pleasant Prairie	Bottom ash	Aluminum	ppm	50784	50784	50784	TRUE
Porter Associates	Ash (NOS)	Aluminum	ppm	7275	10500	14700	TRUE
Porter Associates	Bottom ash	Aluminum	ppm	3642.5	8300	19950	TRUE
ylkill Reclamation (	Ash (NOS)	Aluminum	ppm	1270	1270	1270	TRUE
Shawnee	FBC	Aluminum	ppm	16200	39800	62000	TRUE
Silverton	Ash (NOS)	Aluminum	ppm	15250	16870	18490	TRUE
ehanna Coal Comp	Ash (NOS)	Aluminum	ppm	19125	25100	30975	TRUE
hanna Coal Compa	Ash (NOS)	Aluminum	ppm	24375	35050	36500	TRUE
SW	Bottom ash	Aluminum	ppm	133000	139000	145000	TRUE
SW	Fly ash	Aluminum	ppm	117000	124000	141000	TRUE
Tracy Vein Slope	Ash (NOS)	Aluminum	ppm	9047.5	12825	16400	TRUE
Tracy Vein Slope	Bottom ash	Aluminum	ppm	7677.5	8025	8372.5	TRUE
Tracy Vein Slope	FBC	Aluminum	ppm	7240	7240	7240	TRUE
Universal	Combined ash	Aluminum	ppm	4600	5770	8400	TRUE
wood Energy Prop	Ash (NOS)	Aluminum	ppm	10639.75	16250	18452.5	TRUE
Wheelabrator	FBC	Aluminum	ppm	16575	20430	22512.5	TRUE
12	FBC	Aluminum	ppm	32600	35700	46700	TRUE
14	FBC	Aluminum	ppm	25200	25200	25200	TRUE
17	FBC	Aluminum	ppm	35100	46946	60984	TRUE
18	FBC	Aluminum	ppm	20123	29532	29895	TRUE
19	FBC	Aluminum	ppm	3910	3910	3910	TRUE
2	FBC	Aluminum	ppm	9	14.5	20	TRUE
20	FBC	Aluminum	ppm	25890	31090	36176	TRUE
21	FBC	Aluminum	ppm	527.175	13500	27045	TRUE
26	FBC	Aluminum	ppm	15800	15800	15800	TRUE
27	FBC	Aluminum	ppm	66029	66029	66029	TRUE
28	FBC	Aluminum	ppm	11292.5	41925	50087.5	TRUE
29	FBC	Aluminum	ppm	5904.45	16719.55	27490.33	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
30	FBC	Aluminum	ppm	10174.43	22367.8	34243.95	TRUE
31	FBC	Aluminum	ppm	26218.75	29437.5	32656.25	TRUE
38	FBC	Aluminum	ppm	18318.75	21025	25912.5	TRUE
39	FBC	Aluminum	ppm	73825	78850	83875	TRUE
4	FBC	Aluminum	ppm	11029.55	14435	16255	TRUE
6	FBC	Aluminum	ppm	35573.25	42736.5	49899.75	TRUE
7	FBC	Aluminum	ppm	24729.99	24729.99	24729.99	TRUE
8	FBC	Aluminum	ppm	39000	39000	39000	TRUE
A/C Fuels Company	Ash (NOS)	Aluminum	ppm	19400	19400	19400	TRUE
B-D Mining Co.	Ash (NOS)	Aluminum	ppm	21817.5	27950	30968.45	TRUE
B-D Mining Co.	Bottom ash	Aluminum	ppm	26651	34698	51294.25	TRUE
B-D Mining Co.	Fly ash	Aluminum	ppm	32755	40702.5	54691.25	TRUE
Deer Ridge Mine	Fly ash	Aluminum	ppm	1787.5	2278.68	114250	TRUE
DPC	Bottom ash	Aluminum	ppm	2630	2630	2630	TRUE
DPC	Fly ash	Aluminum	ppm	10400	10400	10400	TRUE
ern Analytical, ID: 5	Slag	Aluminum	ppm	18000	18000	18000	TRUE
City Mine	FBC	Antimony	ppm	2.5	2.5	2.5	TRUE
CLSM	Combined ash	Antimony	ppm	7.9	7.9	7.9	TRUE
CLSM	FBC	Antimony	ppm	2.9	2.9	2.9	TRUE
Emerald Anthracite	Ash (NOS)	Antimony	ppm	75.59	81.18	84.09	TRUE
Freeport Mine	FGD waste	Antimony	ppm	10	10	10	TRUE
Gale	Ash (NOS)	Antimony	ppm	3	3	3	TRUE
Harrim 3019	Bottom ash	Antimony	ppm	1775	1775	1775	TRUE
Harrim 3019	Fly ash	Antimony	ppm	20	33.5	377.75	TRUE
an Coal Corporatio	Ash (NOS)	Antimony	ppm	2.31	6.41	12.625	TRUE
an Coal Corporatio	Bottom ash	Antimony	ppm	1.04425	2.7	6.27	TRUE
an Coal Corporatio	Fly ash	Antimony	ppm	1370	1370	1370	TRUE
Coal Corporation 5	Ash (NOS)	Antimony	ppm	47	47	47	TRUE
Coal Corporation 5	Bottom ash	Antimony	ppm	12.5	15	17.5	TRUE
Coal Corporation 5	Fly ash	Antimony	ppm	12.5	15	17.5	TRUE
ddo Highland Coal (	Ash (NOS)	Antimony	ppm	5.4	10	10	TRUE
ddo Highland Coal (	Bottom ash	Antimony	ppm	35	35	35	TRUE
Knickerbocker Pit	FBC	Antimony	ppm	27.5	32	48.7675	TRUE
gh Coal and Naviga	Ash (NOS)	Antimony	ppm	20	20	20	TRUE
LIMB Site	Ash (NOS)	Antimony	ppm	25	25	25	TRUE
Martins Creek	Bottom ash	Antimony	ppm	5	5	12	TRUE
Martins Creek	Fly ash	Antimony	ppm	5	5	5	TRUE
McKay Site	FBC	Antimony	ppm	2.5	2.5	2.5	TRUE
N & L Coal Co.	Ash (NOS)	Antimony	ppm	4	87.4	123.75	TRUE
N & L Coal Co.-2	Ash (NOS)	Antimony	ppm	10	10	40.225	TRUE
o. 1 Contracting Co	Ash (NOS)	Antimony	ppm	0.8	1.2	1.6	TRUE
uel Supply Company	Ash (NOS)	Antimony	ppm	20	20	20	TRUE
uel Supply Company	Ash (NOS)	Antimony	ppm	13.75	17.5	21.25	TRUE
uel Supply Company	Ash (NOS)	Antimony	ppm	30.5	41	51.5	TRUE
orthampton400002	Ash (NOS)	Antimony	ppm	20	20	20	TRUE
heast Energy Com	Ash (NOS)	Antimony	ppm	10	10	12.5	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
heast Energy Com	Bottom ash	Antimony	ppm	0.5	0.5	0.5	TRUE
heast Energy Com	Fly ash	Antimony	ppm	0.4	0.4	0.4	TRUE
eastern Power Cor	Bottom ash	Antimony	ppm	0.2155	0.4345	1.44375	TRUE
eastern Power Cor	Fly ash	Antimony	ppm	0.373	0.851	3.48	TRUE
Nucla	FBC	Antimony	ppm	24	24	24	TRUE
Nucla2	FBC	Antimony	ppm	29	40	60	TRUE
aceAnalytical (201(	Slag	Antimony	ppm	0.245	0.245	0.245	TRUE
Pacton Corp	Ash (NOS)	Antimony	ppm	44	44	44	TRUE
Pacton Corp	Bottom ash	Antimony	ppm	33	33	33	TRUE
Pacton Corp	Fly ash	Antimony	ppm	12	38	45	TRUE
Pagnotti Coal Co.	Ash (NOS)	Antimony	ppm	37.5	37.5	37.5	TRUE
Pagnotti Coal Co.	Fly ash	Antimony	ppm	0.21	0.21	0.21	TRUE
Panther Creek	FBC	Antimony	ppm	2.4	4.78	67	TRUE
Porter Associates	Ash (NOS)	Antimony	ppm	5.6	10	22	TRUE
Porter Associates	Bottom ash	Antimony	ppm	10	10	32	TRUE
Shawnee	FBC	Antimony	ppm	12	13	18	TRUE
ehanna Coal Comp	Ash (NOS)	Antimony	ppm	17.5	41.5	67.25	TRUE
hanna Coal Compa	Ash (NOS)	Antimony	ppm	24	38	52	TRUE
Tracy Vein Slope	Ash (NOS)	Antimony	ppm	7.4725	8.035	33.785	TRUE
Tracy Vein Slope	Bottom ash	Antimony	ppm	6.13	6.2	6.27	TRUE
USGS	Fly ash	Antimony	ppm	4.05	4.9	9.6	TRUE
wood Energy Prop	Ash (NOS)	Antimony	ppm	0.65675	2.515	7.8875	TRUE
Wheelabrator	FBC	Antimony	ppm	2.4325	15.39	35.75	TRUE
Xcel/MSI	Fly ash	Antimony	ppm	2.475	2.6	3.7	TRUE
Zhang et al. (2001)	Fly Ash	Antimony	ppm	9	12	16	TRUE
1	FBC	Antimony	ppm	40.86	40.86	40.86	TRUE
10	FBC	Antimony	ppm	15.625	18.75	21.875	TRUE
12	FBC	Antimony	ppm	5	21	25	TRUE
14	FBC	Antimony	ppm	5	5	5	TRUE
17	FBC	Antimony	ppm	0.955	4.55	21.15	TRUE
18	FBC	Antimony	ppm	3.5	5	6.5	TRUE
19	FBC	Antimony	ppm	6.25	6.25	6.25	TRUE
2	FBC	Antimony	ppm	2.858	2.858	2.858	TRUE
20	FBC	Antimony	ppm	28.75	38	52	TRUE
21	FBC	Antimony	ppm	0.25	0.25	0.4375	TRUE
26	FBC	Antimony	ppm	2.5	4.875	8.5625	TRUE
27	FBC	Antimony	ppm	9	9	9	TRUE
28	FBC	Antimony	ppm	46	114	553.25	TRUE
29	FBC	Antimony	ppm	0.125	0.125	0.125	TRUE
3	FBC	Antimony	ppm	12.5	12.5	12.5	TRUE
30	FBC	Antimony	ppm	5	30	62.4125	TRUE
31	FBC	Antimony	ppm	2.54875	5.0325	7.51625	TRUE
38	FBC	Antimony	ppm	0.025	0.375	10.75	TRUE
39	FBC	Antimony	ppm	1	1	1	TRUE
4	FBC	Antimony	ppm	11.425	28	39.391	TRUE
5	FBC	Antimony	ppm	2.5	2.5	2.5	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
6	FBC	Antimony	ppm	10.625	16.25	21.875	TRUE
8	FBC	Antimony	ppm	1.25	1.25	1.25	TRUE
A/C Fuels Company	Ash (NOS)	Antimony	ppm	1	1	1	TRUE
B-D Mining Co.	Ash (NOS)	Antimony	ppm	21.25	36	63	TRUE
B-D Mining Co.	Bottom ash	Antimony	ppm	23.125	28.5	53.75	TRUE
B-D Mining Co.	Fly ash	Antimony	ppm	37.5	40.5	48.75	TRUE
DPC	Bottom ash	Antimony	ppm	0.18	0.18	0.18	TRUE
DPC	Fly ash	Antimony	ppm	0.77	0.77	0.77	TRUE
ern Analytical, ID: 5	Slag	Antimony	ppm	0.25	0.25	0.25	TRUE
Bowen	Fly ash	Arsenic	ppm	68	68	68	TRUE
CAER	Bottom ash	Arsenic	ppm	23.235	35.91	50.55	TRUE
CAER	FGD waste	Arsenic	ppm	5.02	5.02	5.02	TRUE
CAER	Fly ash	Arsenic	ppm	75.47	111.7	133.28	TRUE
Cardinal	Fly ash	Arsenic	ppm	108.25	131.5	154.75	TRUE
City Mine	FBC	Arsenic	ppm	26	27	28.5	TRUE
Philadelphia Girard	Ash (NOS)	Arsenic	ppm	39.18	39.18	39.18	TRUE
Cleveland	Fly ash	Arsenic	ppm	0.047	0.047	0.047	TRUE
Emerald Anthracite	Ash (NOS)	Arsenic	ppm	15.8575	28.33	36.575	TRUE
EORDC	FGD waste	Arsenic	ppm	54	54	54	TRUE
Fleming	FBC	Arsenic	ppm	75	75	75	TRUE
Freeport Mine	FGD waste	Arsenic	ppm	3.2	3.2	3.2	TRUE
Gale	Ash (NOS)	Arsenic	ppm	51.5	51.5	51.5	TRUE
Girard Estate	Ash (NOS)	Arsenic	ppm	11	11	11	TRUE
HA	Ash & coal waste	Arsenic	ppm	7	8	11.5	TRUE
Harrim 3019	Ash (NOS)	Arsenic	ppm	150.449	150.449	150.449	TRUE
Harrim 3019	Bottom ash	Arsenic	ppm	74.325	82.55	90.775	TRUE
Harrim 3019	Fly ash	Arsenic	ppm	12.075	25	43.8	TRUE
an Coal Corporatio	Ash (NOS)	Arsenic	ppm	23.3	37.9	76.15	TRUE
an Coal Corporatio	Bottom ash	Arsenic	ppm	2	4.07	10.75	TRUE
an Coal Corporatio	Fly ash	Arsenic	ppm	43.8	48.9	54	TRUE
Coal Corporation 5	Ash (NOS)	Arsenic	ppm	13	13	13	TRUE
Coal Corporation 5	Bottom ash	Arsenic	ppm	32.275	35.75	39.225	TRUE
Coal Corporation 5	Fly ash	Arsenic	ppm	18.95	20.4	21.85	TRUE
ddo Highland Coal (	Ash (NOS)	Arsenic	ppm	1.3	2.3	8.45	TRUE
ddo Highland Coal (	Bottom ash	Arsenic	ppm	35.9	35.9	35.9	TRUE
Kentucky	Bottom ash	Arsenic	ppm	17.25	25.5	33.75	TRUE
Kentucky	Fly ash	Arsenic	ppm	426.5	547.5	663.5	TRUE
Knickerbocker Pit	FBC	Arsenic	ppm	10.63	14.95	40.045	TRUE
KY	FGD waste	Arsenic	ppm	7.5	9.5	14.75	TRUE
gh Coal and Naviga	Ash (NOS)	Arsenic	ppm	16.7	18.4	22.125	TRUE
LIMB Site	Ash (NOS)	Arsenic	ppm	61.5	63	64.5	TRUE
ttle Sandy #10 Min	Bottom ash	Arsenic	ppm	14	14	14	TRUE
ttle Sandy #10 Min	Combined ash	Arsenic	ppm	7.23	11	14	TRUE
ttle Sandy #10 Min	FGD waste	Arsenic	ppm	31	33	33.35	TRUE
ttle Sandy #10 Min	Fly ash	Arsenic	ppm	220	220	220	TRUE
Lone Mtn	Fly ash	Arsenic	ppm	76	76	76	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Mandan	FBC	Arsenic	ppm	21.65	21.65	21.65	TRUE
Martins Creek	Bottom ash	Arsenic	ppm	4.285	5.25	8.196	TRUE
Martins Creek	Fly ash	Arsenic	ppm	60.36	75.71	123	TRUE
McCloskey Site	FBC	Arsenic	ppm	41.6325	45.355	49.0775	TRUE
McKay Site	FBC	Arsenic	ppm	40.25	51.5	62.75	TRUE
Miller	Fly ash	Arsenic	ppm	18	18	18	TRUE
Miller Creek Mine	Bottom ash	Arsenic	ppm	2.823	50.49	51.776	TRUE
Miller Creek Mine	Combined ash	Arsenic	ppm	6.465	19.965	45.25	TRUE
Miller Creek Mine	Fly ash	Arsenic	ppm	39.25	90.5	152.7175	TRUE
N & L Coal Co.	Ash (NOS)	Arsenic	ppm	15.7	20.95	113.0078	TRUE
N & L Coal Co.-2	Ash (NOS)	Arsenic	ppm	24.1	63.6	158	TRUE
Nepco	FBC	Arsenic	ppm	21	21	21	TRUE
NETL	Bottom ash	Arsenic	ppm	29	29	29	TRUE
NETL	FBC	Arsenic	ppm	65.5	79	92.5	TRUE
NETL	Fly ash	Arsenic	ppm	50	95.5	143.25	TRUE
NETL	Slag	Arsenic	ppm	20	20	20	TRUE
o. 1 Contracting Co	Ash (NOS)	Arsenic	ppm	18.275	18.85	19.425	TRUE
uel Supply Company	Ash (NOS)	Arsenic	ppm	11.4	26.4	40.6	TRUE
uel Supply Company	Ash (NOS)	Arsenic	ppm	15.7	24	30	TRUE
uel Supply Company	Ash (NOS)	Arsenic	ppm	19.725	25.75	31.775	TRUE
orthampton400002	Ash (NOS)	Arsenic	ppm	40.6	40.6	40.6	TRUE
heast Energy Com	Ash (NOS)	Arsenic	ppm	1.257	13.4	22.15	TRUE
heast Energy Com	Bottom ash	Arsenic	ppm	2.5	2.5	2.5	TRUE
heast Energy Com	Fly ash	Arsenic	ppm	12	12	12	TRUE
eastern Power Cor	Ash (NOS)	Arsenic	ppm	3.985	6	6.1375	TRUE
eastern Power Cor	Bottom ash	Arsenic	ppm	1.8725	2.645	3.1625	TRUE
eastern Power Cor	Fly ash	Arsenic	ppm	8.57	10	12.4	TRUE
Nucla	FBC	Arsenic	ppm	7.25	7.4	7.55	TRUE
Nucla2	FBC	Arsenic	ppm	16.9	31	40.5	TRUE
Oak Creek	Bottom ash	Arsenic	ppm	0.5	0.5	0.5	TRUE
aceAnalytical (201	Slag	Arsenic	ppm	0.245	0.245	0.245	TRUE
Pacton Corp	Ash (NOS)	Arsenic	ppm	24	24	24	TRUE
Pacton Corp	Bottom ash	Arsenic	ppm	133	133	133	TRUE
Pacton Corp	Fly ash	Arsenic	ppm	54.2	208	219	TRUE
Pagnotti Coal Co.	Ash (NOS)	Arsenic	ppm	4.158225	7.27	27.3325	TRUE
Pagnotti Coal Co.	Fly ash	Arsenic	ppm	250	250	250	TRUE
Panther Creek	FBC	Arsenic	ppm	11.25	17.85	19.15	TRUE
Paradise	Fly ash	Arsenic	ppm	75	75	75	TRUE
ett et al. (1993) Co	Fly Ash	Arsenic	ppm	30.75	52.5	76	TRUE
Plant 10	FBC	Arsenic	ppm	52.1	64.1	88.8	TRUE
Plant 12	FBC	Arsenic	ppm	84.3	112	118	TRUE
Plant 8	FBC	Arsenic	ppm	36.8	41	45.35	TRUE
Plant 9	FBC	Arsenic	ppm	1.6	2.2	3.7	TRUE
Pleasant Prairie	Bottom ash	Arsenic	ppm	0.5	0.5	0.5	TRUE
Pleasant Prairie	Fly ash	Arsenic	ppm	38	38	38	TRUE
Porter Associates	Ash (NOS)	Arsenic	ppm	13.325	20.47	47.425	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Porter Associates	Bottom ash	Arsenic	ppm	3.275	8.565	11.475	TRUE
ylkill Reclamation (	Ash (NOS)	Arsenic	ppm	2.1	2.1	2.1	TRUE
Scrubgrass	FBC	Arsenic	ppm	59	59	59	TRUE
SFA	Fly ash	Arsenic	ppm	180	180	180	TRUE
Shawnee	FBC	Arsenic	ppm	7.5	12	19	TRUE
Silverton	Ash (NOS)	Arsenic	ppm	47	48.5	50	TRUE
Sioux	Fly ash	Arsenic	ppm	79.25	84.5	89.75	TRUE
Stanton	Fly ash	Arsenic	ppm	63	63	63	TRUE
STK	Fly ash	Arsenic	ppm	115	120	125	TRUE
ehanna Coal Comp	Ash (NOS)	Arsenic	ppm	16.45	26.95	31.25	TRUE
hanna Coal Compa	Ash (NOS)	Arsenic	ppm	10.575	15.5	24.4175	TRUE
SW	Bottom ash	Arsenic	ppm	22.3	25.2	29.5	TRUE
SW	Fly ash	Arsenic	ppm	25.9	31.25	38.575	TRUE
Tracy Vein Slope	Ash (NOS)	Arsenic	ppm	60.4	75.75	98.225	TRUE
Tracy Vein Slope	Bottom ash	Arsenic	ppm	14.525	18.25	21.975	TRUE
Tracy Vein Slope	FBC	Arsenic	ppm	6.97	6.97	6.97	TRUE
Universal	Combined ash	Arsenic	ppm	35.5	48	54.5	TRUE
USGS	Fly ash	Arsenic	ppm	6.45	16.4	49.5	TRUE
wood Energy Prop	Ash (NOS)	Arsenic	ppm	8.7175	11.15	12.425	TRUE
Wheelabrator	FBC	Arsenic	ppm	10.435	13.6	15.32	TRUE
Xcel/MSI	Fly ash	Arsenic	ppm	14.675	15.45	17.1	TRUE
Yates	Fly ash	Arsenic	ppm	106	106	106	TRUE
Zhang et al. (2001)	Fly Ash	Arsenic	ppm	26	60	505	TRUE
1	FBC	Arsenic	ppm	1.1775	1.92	4.3875	TRUE
10	FBC	Arsenic	ppm	3.175	3.85	4.525	TRUE
11	FBC	Arsenic	ppm	48.5	51	53.5	TRUE
12	FBC	Arsenic	ppm	22.7025	44.73	97.2375	TRUE
14	FBC	Arsenic	ppm	26	26	26	TRUE
17	FBC	Arsenic	ppm	58.425	74.3	94.15	TRUE
18	FBC	Arsenic	ppm	40	44	62	TRUE
19	FBC	Arsenic	ppm	6.25	6.25	6.25	TRUE
2	FBC	Arsenic	ppm	9.017	9.017	9.017	TRUE
20	FBC	Arsenic	ppm	4.465	9.85	24.01	TRUE
21	FBC	Arsenic	ppm	8.75	11	11.75	TRUE
23	FBC	Arsenic	ppm	29.975	36.11	39.6375	TRUE
26	FBC	Arsenic	ppm	2.16875	2.6375	3.2	TRUE
27	FBC	Arsenic	ppm	12	12	12	TRUE
28	FBC	Arsenic	ppm	18.445	41.85	50.3	TRUE
29	FBC	Arsenic	ppm	13.25	17.4	86.05	TRUE
3	FBC	Arsenic	ppm	3.1	3.2	3.3	TRUE
30	FBC	Arsenic	ppm	25.56	36.2	63.05	TRUE
31	FBC	Arsenic	ppm	23.4125	26.825	30.2375	TRUE
37	FBC	Arsenic	ppm	3.795	5.79	7.785	TRUE
38	FBC	Arsenic	ppm	8.15875	14.3	16.375	TRUE
39	FBC	Arsenic	ppm	13.25	14.5	15.75	TRUE
4	FBC	Arsenic	ppm	8.925	12.5	27.982	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
5	FBC	Arsenic	ppm	3.125	4.25	4.4	TRUE
6	FBC	Arsenic	ppm	101.9	126.6	151.3	TRUE
7	FBC	Arsenic	ppm	81.26	81.26	81.26	TRUE
8	FBC	Arsenic	ppm	56	56	56	TRUE
A/C Fuels Company	Ash (NOS)	Arsenic	ppm	2	2	2	TRUE
Baldwin	Fly ash	Arsenic	ppm	50	50	50	TRUE
B-D Mining Co.	Ash (NOS)	Arsenic	ppm	9.23	18	22.3	TRUE
B-D Mining Co.	Bottom ash	Arsenic	ppm	3.14725	5.814	9.4625	TRUE
B-D Mining Co.	Fly ash	Arsenic	ppm	2.792	6.25	21	TRUE
CLSM	Combined ash	Arsenic	ppm	306	306	306	TRUE
CLSM	FBC	Arsenic	ppm	113.7	113.7	113.7	TRUE
Coal Creek	Bottom ash	Arsenic	ppm	0.04	0.04	0.04	TRUE
Coal Creek	Fly ash	Arsenic	ppm	0.132	0.132	0.132	TRUE
Deer Ridge Mine	Fly ash	Arsenic	ppm	9.35	22.82	27.00475	TRUE
DPC	Bottom ash	Arsenic	ppm	6.17	6.17	6.17	TRUE
DPC	Fly ash	Arsenic	ppm	104	104	104	TRUE
ern Analytical, ID: 5	Slag	Arsenic	ppm	1.1	1.1	1.1	TRUE
Edgewater	Bottom ash	Arsenic	ppm	13.95	13.95	13.95	TRUE
EERC?	Combined ash	Arsenic	ppm	16.675	18.65	20.625	TRUE
EERC?	FGD	Arsenic	ppm	0.5	21.8	53.4	TRUE
EERC?	FGD gypsum	Arsenic	ppm	0.5	0.75	1.1625	TRUE
EERC?	FGD gypsum liquids	Arsenic	mg/L	0.0828	0.0828	0.0828	TRUE
EERC?	FGD liquids	Arsenic	mg/L	0.049075	0.0842	0.11575	TRUE
EERC?	FGD liquids	Arsenic	ppm	0.5	0.5	0.5	TRUE
EERC?	Fly Ash	Arsenic	ppm	37.05	44.75	74.925	TRUE
Bowen	Fly ash	Barium	ppm	974	974	974	TRUE
CAER	Bottom ash	Barium	ppm	442.5	550	755	TRUE
CAER	FGD waste	Barium	ppm	123	123	123	TRUE
CAER	Fly ash	Barium	ppm	393	426	640	TRUE
Cardinal	Fly ash	Barium	ppm	375	375	375	TRUE
City Mine	FBC	Barium	ppm	293.5	341	342.5	TRUE
Philadelphia Girard	Ash (NOS)	Barium	ppm	172	172	172	TRUE
Emerald Anthracite	Ash (NOS)	Barium	ppm	147.65	207.5	266.125	TRUE
Fleming	FBC	Barium	ppm	150	150	150	TRUE
Freeport Mine	FGD waste	Barium	ppm	11	11	11	TRUE
Gale	Ash (NOS)	Barium	ppm	143	143	143	TRUE
Girard Estate	Ash (NOS)	Barium	ppm	100	100	100	TRUE
HA	Ash & coal waste	Barium	ppm	175	210	210	TRUE
Harrim 3019	Ash (NOS)	Barium	ppm	800	800	800	TRUE
Harrim 3019	Bottom ash	Barium	ppm	176.375	190.25	204.125	TRUE
Harrim 3019	Fly ash	Barium	ppm	251.5	298	321.2	TRUE
an Coal Corporatio	Ash (NOS)	Barium	ppm	97.45	166.5	286.25	TRUE
an Coal Corporatio	Bottom ash	Barium	ppm	19.75	33.1	65.25	TRUE
an Coal Corporatio	Fly ash	Barium	ppm	320.3	321.2	322.1	TRUE
Coal Corporation 5	Ash (NOS)	Barium	ppm	210	210	210	TRUE
Coal Corporation 5	Bottom ash	Barium	ppm	207.75	250.5	293.25	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Coal Corporation 5	Fly ash	Barium	ppm	414.5	453	491.5	TRUE
ddo Highland Coal (	Ash (NOS)	Barium	ppm	116	198	400	TRUE
ddo Highland Coal (	Bottom ash	Barium	ppm	144	144	144	TRUE
Knickerbocker Pit	FBC	Barium	ppm	165.025	218.4	289.25	TRUE
KY	FGD waste	Barium	ppm	95	97	103.5	TRUE
gh Coal and Naviga	Ash (NOS)	Barium	ppm	160	188	260	TRUE
LIMB Site	Ash (NOS)	Barium	ppm	252.5	255	257.5	TRUE
ttle Sandy #10 Min	Bottom ash	Barium	ppm	68	68	68	TRUE
ttle Sandy #10 Min	Combined ash	Barium	ppm	26	41	44	TRUE
ttle Sandy #10 Min	FGD waste	Barium	ppm	27.55	29	29.5	TRUE
ttle Sandy #10 Min	Fly ash	Barium	ppm	150	150	150	TRUE
Lone Mtn	Fly ash	Barium	ppm	1483.2	1483.2	1483.2	TRUE
Mandan	FBC	Barium	ppm	5100	5100	5100	TRUE
Martins Creek	Bottom ash	Barium	ppm	571	665	760	TRUE
Martins Creek	Fly ash	Barium	ppm	396	550	675	TRUE
McCloskey Site	FBC	Barium	ppm	16.325	32.55	48.775	TRUE
McKay Site	FBC	Barium	ppm	167.5	215	262.5	TRUE
Miller	Fly ash	Barium	ppm	7140	7140	7140	TRUE
Miller Creek Mine	Bottom ash	Barium	ppm	14	43.13	57	TRUE
Miller Creek Mine	Combined ash	Barium	ppm	24	36.5	82.4425	TRUE
Miller Creek Mine	Fly ash	Barium	ppm	41.75	64	108.25	TRUE
N & L Coal Co.	Ash (NOS)	Barium	ppm	155	200	446.175	TRUE
N & L Coal Co.-2	Ash (NOS)	Barium	ppm	232	786	971	TRUE
NETL	Bottom ash	Barium	ppm	1110	1110	1110	TRUE
NETL	FBC	Barium	ppm	362.75	457.5	552.25	TRUE
NETL	Fly ash	Barium	ppm	524.5	846.5	1016.75	TRUE
NETL	Slag	Barium	ppm	321	321	321	TRUE
o. 1 Contracting Co	Ash (NOS)	Barium	ppm	231.25	237.5	243.75	TRUE
el Supply Company	Ash (NOS)	Barium	ppm	170	177	242	TRUE
el Supply Company	Ash (NOS)	Barium	ppm	109.5	115.95	153.25	TRUE
el Supply Company	Ash (NOS)	Barium	ppm	142.75	161.5	180.25	TRUE
rthampton400002	Ash (NOS)	Barium	ppm	242	242	242	TRUE
heast Energy Com	Ash (NOS)	Barium	ppm	175.25	212.5	292.5	TRUE
heast Energy Com	Bottom ash	Barium	ppm	15	15	15	TRUE
heast Energy Com	Fly ash	Barium	ppm	160	160	160	TRUE
eastern Power Con	Ash (NOS)	Barium	ppm	172.5	176	199	TRUE
eastern Power Con	Bottom ash	Barium	ppm	92.125	105.5	132.75	TRUE
eastern Power Con	Fly ash	Barium	ppm	150	195	243	TRUE
Nucla	FBC	Barium	ppm	145	190	235	TRUE
Nucla2	FBC	Barium	ppm	199	330	335	TRUE
Pacton Corp	Ash (NOS)	Barium	ppm	174	174	174	TRUE
Pacton Corp	Bottom ash	Barium	ppm	75	75	75	TRUE
Pacton Corp	Fly ash	Barium	ppm	289	360	860	TRUE
Pagnotti Coal Co.	Ash (NOS)	Barium	ppm	217	226	297.4	TRUE
Pagnotti Coal Co.	Fly ash	Barium	ppm	800	800	800	TRUE
Panther Creek	FBC	Barium	ppm	182.525	227.5	277.5	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
ett et al. (1993) Co	Fly Ash	Barium	ppm	6050	6450	8875	TRUE
Pleasant Prairie	Fly ash	Barium	ppm	6220	6220	6220	TRUE
Porter Associates	Ash (NOS)	Barium	ppm	94.45	130	209.5	TRUE
Porter Associates	Bottom ash	Barium	ppm	42	104	207	TRUE
ylkill Reclamation (	Ash (NOS)	Barium	ppm	36	36	36	TRUE
SFA	Fly ash	Barium	ppm	1370	1370	1370	TRUE
Shawnee	FBC	Barium	ppm	57	190	1200	TRUE
Silverton	Ash (NOS)	Barium	ppm	162.25	181.5	200.75	TRUE
Sioux	Fly ash	Barium	ppm	420.2	420.2	420.2	TRUE
Stanton	Fly ash	Barium	ppm	1370	1370	1370	TRUE
STK	Fly ash	Barium	ppm	1047.5	1085	1122.5	TRUE
ehanna Coal Comp	Ash (NOS)	Barium	ppm	194.75	248	282.25	TRUE
hanna Coal Compa	Ash (NOS)	Barium	ppm	204.675	249.2	259.875	TRUE
SW	Bottom ash	Barium	ppm	1950	2590	3010	TRUE
SW	Fly ash	Barium	ppm	2230	2500	3040	TRUE
Tracy Vein Slope	Ash (NOS)	Barium	ppm	95.675	118.35	143.75	TRUE
Tracy Vein Slope	Bottom ash	Barium	ppm	48.7	55.8	62.9	TRUE
Tracy Vein Slope	FBC	Barium	ppm	68.9	68.9	68.9	TRUE
Universal	Combined ash	Barium	ppm	41.5	55	83	TRUE
wood Energy Prop	Ash (NOS)	Barium	ppm	91.025	137	189.075	TRUE
Wheelabrator	FBC	Barium	ppm	136.075	150.5	199.825	TRUE
Xcel/MSI	Fly ash	Barium	ppm	385.5	5071	6593.25	TRUE
Zhang et al. (2001)	Fly Ash	Barium	ppm	830	2900	4000	TRUE
1	FBC	Barium	ppm	103.825	281.05	420.55	TRUE
10	FBC	Barium	ppm	540.75	628.5	716.25	TRUE
11	FBC	Barium	ppm	162.25	174.5	186.75	TRUE
12	FBC	Barium	ppm	215.175	235.1	246.1	TRUE
14	FBC	Barium	ppm	46.75	46.75	46.75	TRUE
17	FBC	Barium	ppm	140.35	151.5	172.25	TRUE
18	FBC	Barium	ppm	171	276	284	TRUE
19	FBC	Barium	ppm	39.2	39.2	39.2	TRUE
2	FBC	Barium	ppm	88	204.165	320.33	TRUE
20	FBC	Barium	ppm	192.8	212	269.75	TRUE
21	FBC	Barium	ppm	109.4	158.8	225	TRUE
26	FBC	Barium	ppm	457	539	592.5	TRUE
27	FBC	Barium	ppm	2689	2689	2689	TRUE
28	FBC	Barium	ppm	154.775	169	296.5	TRUE
29	FBC	Barium	ppm	0.05	26.225	250.175	TRUE
3	FBC	Barium	ppm	645.75	860.5	1075.25	TRUE
30	FBC	Barium	ppm	61.625	85.34	190.325	TRUE
31	FBC	Barium	ppm	165.125	170.25	175.375	TRUE
38	FBC	Barium	ppm	132.275	153.5	225.225	TRUE
39	FBC	Barium	ppm	415	590	765	TRUE
4	FBC	Barium	ppm	92.1	110.15	170.84	TRUE
5	FBC	Barium	ppm	274	287	463.5	TRUE
6	FBC	Barium	ppm	182.25	221.5	260.75	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
7	FBC	Barium	ppm	450.69	450.69	450.69	TRUE
8	FBC	Barium	ppm	650	650	650	TRUE
A/C Fuels Company	Ash (NOS)	Barium	ppm	160	160	160	TRUE
Baldwin	Fly ash	Barium	ppm	416	416	416	TRUE
B-D Mining Co.	Ash (NOS)	Barium	ppm	149.25	217	270.575	TRUE
B-D Mining Co.	Bottom ash	Barium	ppm	194.2	204.05	213.9	TRUE
B-D Mining Co.	Fly ash	Barium	ppm	268.8	283.5	576	TRUE
CLSM	Combined ash	Barium	ppm	187.4	187.4	187.4	TRUE
CLSM	FBC	Barium	ppm	61.7	61.7	61.7	TRUE
Coal Creek	Bottom ash	Barium	ppm	4.3	4.3	4.3	TRUE
Coal Creek	Fly ash	Barium	ppm	5.22	5.22	5.22	TRUE
Deer Ridge Mine	Fly ash	Barium	ppm	36.1675	52	562.5	TRUE
DPC	Bottom ash	Barium	ppm	24	24	24	TRUE
DPC	Fly ash	Barium	ppm	51.4	51.4	51.4	TRUE
ern Analytical, ID: 5	Slag	Barium	ppm	230	230	230	TRUE
Bowen	Fly ash	Beryllium	ppm	22.1	22.1	22.1	TRUE
Cardinal	Fly ash	Beryllium	ppm	10.775	11.45	12.125	TRUE
City Mine	FBC	Beryllium	ppm	0.25	0.25	0.25	TRUE
Freeport Mine	FGD waste	Beryllium	ppm	0.25	0.25	0.25	TRUE
Lone Mtn	Fly ash	Beryllium	ppm	24	24	24	TRUE
Martins Creek	Bottom ash	Beryllium	ppm	0.5	2.5	6.25	TRUE
Martins Creek	Fly ash	Beryllium	ppm	2.975	4	5.25	TRUE
Miller	Fly ash	Beryllium	ppm	2.2	2.2	2.2	TRUE
NETL	Bottom ash	Beryllium	ppm	9	9	9	TRUE
NETL	FBC	Beryllium	ppm	6.75	9.5	12.25	TRUE
NETL	Fly ash	Beryllium	ppm	4.75	9	12.25	TRUE
NETL	Slag	Beryllium	ppm	1	1	1	TRUE
Nucla	FBC	Beryllium	ppm	3.05	4.1	5.15	TRUE
Nucla2	FBC	Beryllium	ppm	3.4	5.5	5.5	TRUE
aceAnalytical (201(	Slag	Beryllium	ppm	3.4	3.4	3.4	TRUE
Paradise	Fly ash	Beryllium	ppm	10	10	10	TRUE
Pleasant Prairie	Fly ash	Beryllium	ppm	3.2	3.2	3.2	TRUE
Shawnee	FBC	Beryllium	ppm	0.1	0.1	0.1	TRUE
Sioux	Fly ash	Beryllium	ppm	8.725	8.85	8.975	TRUE
Stanton	Fly ash	Beryllium	ppm	28.5	28.5	28.5	TRUE
USGS	Fly ash	Beryllium	ppm	13.5	16	18.25	TRUE
Xcel/MSI	Fly ash	Beryllium	ppm	2.625	3.7	4.625	TRUE
Yates	Fly ash	Beryllium	ppm	16.6	16.6	16.6	TRUE
Zhang et al. (2001)	Fly Ash	Beryllium	ppm	10	10	10	TRUE
1	FBC	Beryllium	ppm	0.9425	1.1	1.2725	TRUE
10	FBC	Beryllium	ppm	1.5625	1.875	2.1875	TRUE
17	FBC	Beryllium	ppm	1.95	2.7	2.775	TRUE
18	FBC	Beryllium	ppm	9.5	11	11.5	TRUE
19	FBC	Beryllium	ppm	2.5	2.5	2.5	TRUE
2	FBC	Beryllium	ppm	0.5	0.7875	1.075	TRUE
26	FBC	Beryllium	ppm	1.2125	1.725	2.275	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
28	FBC	Beryllium	ppm	7	7	7	TRUE
3	FBC	Beryllium	ppm	1.25	1.25	1.25	TRUE
30	FBC	Beryllium	ppm	1.2825	2.075	2.7625	TRUE
39	FBC	Beryllium	ppm	1.875	3.25	4.625	TRUE
5	FBC	Beryllium	ppm	1.025	1.1	1.925	TRUE
8	FBC	Beryllium	ppm	9.5	9.5	9.5	TRUE
Baldwin	Fly ash	Beryllium	ppm	15.8	15.8	15.8	TRUE
CLSM	Combined ash	Beryllium	ppm	3.7	3.7	3.7	TRUE
CLSM	FBC	Beryllium	ppm	19	19	19	TRUE
Cleveland	Fly ash	Boron	ppm	0.186	0.186	0.186	TRUE
Emerald Anthracite	Ash (NOS)	Boron	ppm	26.98	28.04	29.35	TRUE
Fleming	FBC	Boron	ppm	190	190	190	TRUE
Gale	Ash (NOS)	Boron	ppm	25	25	25	TRUE
HA	Ash & coal waste	Boron	ppm	12	12	15	TRUE
Harrim 3019	Ash (NOS)	Boron	ppm	85	85	85	TRUE
Harrim 3019	Bottom ash	Boron	ppm	76	89	102	TRUE
Harrim 3019	Fly ash	Boron	ppm	83.65	94.9	130	TRUE
an Coal Corporatio	Ash (NOS)	Boron	ppm	99.1	190	243	TRUE
an Coal Corporatio	Bottom ash	Boron	ppm	18.275	30.55	87.825	TRUE
an Coal Corporatio	Fly ash	Boron	ppm	95.25	108.5	121.75	TRUE
Coal Corporation 5	Bottom ash	Boron	ppm	114.35	125.7	137.05	TRUE
Coal Corporation 5	Fly ash	Boron	ppm	150.6	153.2	155.8	TRUE
ddo Highland Coal (	Ash (NOS)	Boron	ppm	28.3	39.6	329.3	TRUE
ddo Highland Coal (	Bottom ash	Boron	ppm	83.4	83.4	83.4	TRUE
Knickerbocker Pit	FBC	Boron	ppm	13.825	19.68	28.06	TRUE
gh Coal and Naviga	Ash (NOS)	Boron	ppm	21.1	26	55	TRUE
LIMB Site	Ash (NOS)	Boron	ppm	400	400	400	TRUE
ttle Sandy #10 Min	Bottom ash	Boron	ppm	300	300	300	TRUE
ttle Sandy #10 Min	Combined ash	Boron	ppm	5.1	68	76	TRUE
ttle Sandy #10 Min	FGD waste	Boron	ppm	128	146	153	TRUE
ttle Sandy #10 Min	Fly ash	Boron	ppm	530	530	530	TRUE
Martins Creek	Bottom ash	Boron	ppm	145	162	247.2	TRUE
Martins Creek	Fly ash	Boron	ppm	345	425	520	TRUE
McCloskey Site	FBC	Boron	ppm	0.083	0.092	0.101	TRUE
McKay Site	FBC	Boron	ppm	37.75	41.5	45.25	TRUE
Miller Creek Mine	Bottom ash	Boron	ppm	13	68	266	TRUE
Miller Creek Mine	Combined ash	Boron	ppm	32.75	68.5	110	TRUE
Miller Creek Mine	Fly ash	Boron	ppm	160.25	200	290.75	TRUE
N & L Coal Co.	Ash (NOS)	Boron	ppm	10.1	60	144	TRUE
N & L Coal Co.-2	Ash (NOS)	Boron	ppm	17	133	195	TRUE
o. 1 Contracting Co	Ash (NOS)	Boron	ppm	33	33	33	TRUE
el Supply Company	Ash (NOS)	Boron	ppm	18.8	54.4	55	TRUE
el Supply Company	Ash (NOS)	Boron	ppm	25.6	30.4	33.7	TRUE
el Supply Company	Ash (NOS)	Boron	ppm	58.55	58.6	58.65	TRUE
rthampton400002	Ash (NOS)	Boron	ppm	17.3	17.3	17.3	TRUE
heast Energy Com	Ash (NOS)	Boron	ppm	48.65	112.7	190.9	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
heast Energy Com	Bottom ash	Boron	ppm	50	50	50	TRUE
heast Energy Com	Fly ash	Boron	ppm	130	130	130	TRUE
eastern Power Cor	Ash (NOS)	Boron	ppm	19	19	19	TRUE
eastern Power Cor	Bottom ash	Boron	ppm	3.3	5	16.2	TRUE
eastern Power Cor	Fly ash	Boron	ppm	6.175	22.5	34.975	TRUE
Nucla	FBC	Boron	ppm	56.25	57.5	58.75	TRUE
Nucla2	FBC	Boron	ppm	58.75	90	90	TRUE
Oak Creek	Bottom ash	Boron	ppm	100	100	100	TRUE
Pacton Corp	Bottom ash	Boron	ppm	244	244	244	TRUE
Pacton Corp	Fly ash	Boron	ppm	84	237	239.5	TRUE
Pagnotti Coal Co.	Ash (NOS)	Boron	ppm	25.01	33.34	41.67	TRUE
Pagnotti Coal Co.	Fly ash	Boron	ppm	3	3	3	TRUE
Panther Creek	FBC	Boron	ppm	17.5	21.5	27.715	TRUE
ett et al. (1993) Co	Fly Ash	Boron	ppm	730	935	1125	TRUE
Pleasant Prairie	Bottom ash	Boron	ppm	340	340	340	TRUE
Porter Associates	Ash (NOS)	Boron	ppm	7.655	84.2	155.5	TRUE
Porter Associates	Bottom ash	Boron	ppm	15.775	27.3	74.475	TRUE
Shawnee	FBC	Boron	ppm	5	131	170	TRUE
Silverton	Ash (NOS)	Boron	ppm	18.25	20.5	22.75	TRUE
ehanna Coal Comp	Ash (NOS)	Boron	ppm	17.425	20.3	24.75	TRUE
hanna Coal Compa	Ash (NOS)	Boron	ppm	12.235	20.5	27.8375	TRUE
Tracy Vein Slope	Ash (NOS)	Boron	ppm	151.575	192	198.75	TRUE
Tracy Vein Slope	Bottom ash	Boron	ppm	44.375	50.65	56.925	TRUE
Tracy Vein Slope	FBC	Boron	ppm	7.43	7.43	7.43	TRUE
Universal	Combined ash	Boron	ppm	181	193	215	TRUE
wood Energy Prop	Ash (NOS)	Boron	ppm	7.2	10.4	17.3	TRUE
Wheelabrator	FBC	Boron	ppm	6.8	14.4	32.19	TRUE
Xcel/MSI	Fly ash	Boron	ppm	589.25	737.5	1304.25	TRUE
Zhang et al. (2001)	Fly Ash	Boron	ppm	140	360	860	TRUE
12	FBC	Boron	ppm	17	19.03	19.64	TRUE
14	FBC	Boron	ppm	20.8	20.8	20.8	TRUE
17	FBC	Boron	ppm	28.25	29.65	37.575	TRUE
18	FBC	Boron	ppm	472.5	641	646.5	TRUE
2	FBC	Boron	ppm	0.056	0.38385	0.7117	TRUE
20	FBC	Boron	ppm	20.145	24	45.375	TRUE
21	FBC	Boron	ppm	5.5	15	20	TRUE
22	FBC	Boron	ppm	49	49	49	TRUE
26	FBC	Boron	ppm	1.25	1.25	1.25	TRUE
27	FBC	Boron	ppm	571	571	571	TRUE
28	FBC	Boron	ppm	91.775	105.45	117.25	TRUE
29	FBC	Boron	ppm	0.025	0.025	0.025	TRUE
30	FBC	Boron	ppm	20.4625	32.25	43.495	TRUE
31	FBC	Boron	ppm	560	930	1300	TRUE
37	FBC	Boron	ppm	10.35	15.9	21.45	TRUE
38	FBC	Boron	ppm	15.585	31.9	38.1925	TRUE
4	FBC	Boron	ppm	8.026	14.65	19.65	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
6	FBC	Boron	ppm	56.7	73.8	90.9	TRUE
7	FBC	Boron	ppm	2473	2473	2473	TRUE
A/C Fuels Company	Ash (NOS)	Boron	ppm	28	28	28	TRUE
B-D Mining Co.	Ash (NOS)	Boron	ppm	20.445	25.975	35.5	TRUE
B-D Mining Co.	Bottom ash	Boron	ppm	6	6	8	TRUE
B-D Mining Co.	Fly ash	Boron	ppm	23.5	37.5	50	TRUE
CLSM	Combined ash	Boron	ppm	79	79	79	TRUE
CLSM	FBC	Boron	ppm	78	78	78	TRUE
Coal Creek	Bottom ash	Boron	ppm	0.901	0.901	0.901	TRUE
Coal Creek	Fly ash	Boron	ppm	1.32	1.32	1.32	TRUE
Deer Ridge Mine	Fly ash	Boron	ppm	35.5	53	125.5	TRUE
DPC	Bottom ash	Boron	ppm	54.1	54.1	54.1	TRUE
DPC	Fly ash	Boron	ppm	754	754	754	TRUE
ern Analytical, ID: 5	Slag	Boron	ppm	23	23	23	TRUE
Edgewater	Bottom ash	Boron	ppm	290	290	290	TRUE
Zhang et al. (2001)	Fly Ash	Bromine	ppm	10	10	10	FALSE
ern Analytical, ID: 5	Slag	CaCO3	ppm	21000	21000	21000	FALSE
Bowen	Fly ash	Cadmium	ppm	0.7	0.7	0.7	TRUE
Cardinal	Fly ash	Cadmium	ppm	1.085	1.17	1.255	TRUE
City Mine	FBC	Cadmium	ppm	2.5	2.5	2.5	TRUE
Cleveland	Fly ash	Cadmium	ppm	0.000165	0.000165	0.000165	TRUE
Emerald Anthracite	Ash (NOS)	Cadmium	ppm	1.144	1.188	2.394	TRUE
EORDC	FGD waste	Cadmium	ppm	0.1	0.1	0.1	TRUE
Fleming	FBC	Cadmium	ppm	1	1	1	TRUE
Freeport Mine	FGD waste	Cadmium	ppm	1	1	1	TRUE
Gale	Ash (NOS)	Cadmium	ppm	1	1	1	TRUE
HA	Ash & coal waste	Cadmium	ppm	0.25	0.25	0.25	TRUE
Harrim 3019	Ash (NOS)	Cadmium	ppm	2	2	2	TRUE
Harrim 3019	Fly ash	Cadmium	ppm	0.5	0.5	0.5	TRUE
an Coal Corporatio	Ash (NOS)	Cadmium	ppm	0.5375	1.335	3.0075	TRUE
an Coal Corporatio	Bottom ash	Cadmium	ppm	1.04	2.4	3.7	TRUE
an Coal Corporatio	Fly ash	Cadmium	ppm	2.5	2.5	2.5	TRUE
Coal Corporation 5	Bottom ash	Cadmium	ppm	1.7125	3.175	4.6375	TRUE
Coal Corporation 5	Fly ash	Cadmium	ppm	1.375	2.25	3.125	TRUE
ddo Highland Coal (	Ash (NOS)	Cadmium	ppm	0.5	0.5	1.245	TRUE
ddo Highland Coal (	Bottom ash	Cadmium	ppm	0.5	0.5	0.5	TRUE
Knickerbocker Pit	FBC	Cadmium	ppm	1	1.05	1.2	TRUE
gh Coal and Naviga	Ash (NOS)	Cadmium	ppm	0.5	0.5	0.5	TRUE
LIMB Site	Ash (NOS)	Cadmium	ppm	0.305	0.31	0.315	TRUE
ttle Sandy #10 Min	Bottom ash	Cadmium	ppm	2.5	2.5	2.5	TRUE
ttle Sandy #10 Min	Combined ash	Cadmium	ppm	0.65	1.02	1.25	TRUE
ttle Sandy #10 Min	FGD waste	Cadmium	ppm	0.73	0.96	1.03	TRUE
ttle Sandy #10 Min	Fly ash	Cadmium	ppm	2.2	2.2	2.2	TRUE
Lone Mtn	Fly ash	Cadmium	ppm	11.86	11.86	11.86	TRUE
Mandan	FBC	Cadmium	ppm	0.33	0.33	0.33	TRUE
Martins Creek	Bottom ash	Cadmium	ppm	1	2	4	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Martins Creek	Fly ash	Cadmium	ppm	1	1	2	TRUE
McCloskey Site	FBC	Cadmium	ppm	0.025	0.025	0.025	TRUE
McKay Site	FBC	Cadmium	ppm	2.5	2.5	2.5	TRUE
Miller	Fly ash	Cadmium	ppm	1.6	1.6	1.6	TRUE
Miller Creek Mine	Bottom ash	Cadmium	ppm	0.7	2.19	2.7	TRUE
Miller Creek Mine	Combined ash	Cadmium	ppm	0.09575	0.4	1.725	TRUE
Miller Creek Mine	Fly ash	Cadmium	ppm	0.65	0.65	2.475	TRUE
N & L Coal Co.	Ash (NOS)	Cadmium	ppm	1.42	2.7	5	TRUE
N & L Coal Co.-2	Ash (NOS)	Cadmium	ppm	2	2	3	TRUE
Nepco	FBC	Cadmium	ppm	0.5	0.5	0.5	TRUE
NETL	Bottom ash	Cadmium	ppm	0.2	0.2	0.2	TRUE
NETL	FBC	Cadmium	ppm	0.9	1.1	1.3	TRUE
NETL	Fly ash	Cadmium	ppm	0.5	3.75	8.125	TRUE
NETL	Slag	Cadmium	ppm	5	5	5	TRUE
o. 1 Contracting Co	Ash (NOS)	Cadmium	ppm	3.6	3.6	3.6	TRUE
uel Supply Company	Ash (NOS)	Cadmium	ppm	0.5	0.5	0.5	TRUE
uel Supply Company	Ash (NOS)	Cadmium	ppm	1.025975	2.05065	3.075325	TRUE
uel Supply Company	Ash (NOS)	Cadmium	ppm	0.5	0.5	0.5	TRUE
orthampton400002	Ash (NOS)	Cadmium	ppm	0.5	0.5	0.5	TRUE
heast Energy Comp	Ash (NOS)	Cadmium	ppm	0.3375	0.75	0.975	TRUE
heast Energy Comp	Bottom ash	Cadmium	ppm	0.05	0.05	0.05	TRUE
heast Energy Comp	Fly ash	Cadmium	ppm	0.4	0.4	0.4	TRUE
eastern Power Con	Bottom ash	Cadmium	ppm	0.52125	0.7175	0.8725	TRUE
eastern Power Con	Fly ash	Cadmium	ppm	0.64075	1	1.465	TRUE
Nucla	FBC	Cadmium	ppm	1.825	1.95	2.075	TRUE
Nucla2	FBC	Cadmium	ppm	0.22	0.34	0.345	TRUE
Oak Creek	Bottom ash	Cadmium	ppm	0.8	0.8	0.8	TRUE
aceAnalytical (201	Slag	Cadmium	ppm	0.0245	0.0245	0.0245	TRUE
Pacton Corp	Bottom ash	Cadmium	ppm	8	8	8	TRUE
Pacton Corp	Fly ash	Cadmium	ppm	8	10	20	TRUE
Pagnotti Coal Co.	Ash (NOS)	Cadmium	ppm	0.95	1.5	1.65	TRUE
Pagnotti Coal Co.	Fly ash	Cadmium	ppm	0.25	0.25	0.25	TRUE
Panther Creek	FBC	Cadmium	ppm	0.625	0.75	0.875	TRUE
Paradise	Fly ash	Cadmium	ppm	5.2	5.2	5.2	TRUE
ett et al. (1993) Co	Fly Ash	Cadmium	ppm	0.5	0.5	0.5	TRUE
Plant 10	FBC	Cadmium	ppm	1.1	1.6	2.275	TRUE
Plant 12	FBC	Cadmium	ppm	1.9	2.1	2.5	TRUE
Plant 8	FBC	Cadmium	ppm	0.75	2.49	3.5	TRUE
Plant 9	FBC	Cadmium	ppm	0.025	0.025	0.025	TRUE
Pleasant Prairie	Bottom ash	Cadmium	ppm	0.05	0.05	0.05	TRUE
Pleasant Prairie	Fly ash	Cadmium	ppm	1.8	1.8	1.8	TRUE
Porter Associates	Ash (NOS)	Cadmium	ppm	0.5	1.49	3.5075	TRUE
Porter Associates	Bottom ash	Cadmium	ppm	0.5	0.5	0.725	TRUE
Scrubgrass	FBC	Cadmium	ppm	0.7	0.7	0.7	TRUE
Shawnee	FBC	Cadmium	ppm	0.21	0.4	1.1	TRUE
Silverton	Ash (NOS)	Cadmium	ppm	2	2	2	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Sioux	Fly ash	Cadmium	ppm	2.85	3.3	3.75	TRUE
Stanton	Fly ash	Cadmium	ppm	0.9	0.9	0.9	TRUE
ehanna Coal Comp	Ash (NOS)	Cadmium	ppm	0.25	0.425	0.8	TRUE
hanna Coal Compa	Ash (NOS)	Cadmium	ppm	0.6	1.4	2.8	TRUE
SW	Bottom ash	Cadmium	ppm	0.1	0.1	0.1	TRUE
SW	Fly ash	Cadmium	ppm	1.05	1.05	1.05	TRUE
Tracy Vein Slope	Ash (NOS)	Cadmium	ppm	0.74725	0.8995	1.4475	TRUE
Tracy Vein Slope	Bottom ash	Cadmium	ppm	0.613	0.62	0.627	TRUE
Universal	Combined ash	Cadmium	ppm	0.925	1.6	2.25	TRUE
USGS	Fly ash	Cadmium	ppm	0.4	0.6	2.55	TRUE
wood Energy Prop	Ash (NOS)	Cadmium	ppm	0.632	0.7285	0.8525	TRUE
Wheelabrator	FBC	Cadmium	ppm	0.95	1.1	1.3	TRUE
Xcel/MSI	Fly ash	Cadmium	ppm	1.0725	1.22	1.735	TRUE
Yates	Fly ash	Cadmium	ppm	0.9	0.9	0.9	TRUE
Zhang et al. (2001)	Fly Ash	Cadmium	ppm	2.5	2.5	24	TRUE
1	FBC	Cadmium	ppm	1.34	1.75	2.29	TRUE
10	FBC	Cadmium	ppm	1.5625	1.875	2.1875	TRUE
11	FBC	Cadmium	ppm	0.34375	6.675	13.25	TRUE
12	FBC	Cadmium	ppm	0.125	0.125	0.40625	TRUE
14	FBC	Cadmium	ppm	0.125	0.125	0.125	TRUE
17	FBC	Cadmium	ppm	1.6	3.15	3.875	TRUE
18	FBC	Cadmium	ppm	1.75	3	3.5	TRUE
19	FBC	Cadmium	ppm	2.5	2.5	2.5	TRUE
2	FBC	Cadmium	ppm	0.458	0.458	0.458	TRUE
20	FBC	Cadmium	ppm	1.15	1.4	2.55	TRUE
21	FBC	Cadmium	ppm	0.125	0.125	0.125	TRUE
23	FBC	Cadmium	ppm	0.455	0.49	0.545	TRUE
26	FBC	Cadmium	ppm	0.25	0.75	1.5625	TRUE
27	FBC	Cadmium	ppm	1	1	1	TRUE
28	FBC	Cadmium	ppm	0.875	1.125	1.3625	TRUE
29	FBC	Cadmium	ppm	0.0125	0.0125	0.0125	TRUE
3	FBC	Cadmium	ppm	1.25	1.25	1.25	TRUE
30	FBC	Cadmium	ppm	0.625	1.35	2.275	TRUE
31	FBC	Cadmium	ppm	5.225	5.45	5.675	TRUE
37	FBC	Cadmium	ppm	2.775	4.3	5.65	TRUE
38	FBC	Cadmium	ppm	0.125	0.535	1.15	TRUE
39	FBC	Cadmium	ppm	0.5	0.5	0.5	TRUE
4	FBC	Cadmium	ppm	0.031875	0.7979	1.038	TRUE
5	FBC	Cadmium	ppm	0.25	0.25	0.25	TRUE
6	FBC	Cadmium	ppm	1.258125	1.29625	1.334375	TRUE
7	FBC	Cadmium	ppm	5.96	5.96	5.96	TRUE
8	FBC	Cadmium	ppm	0.9	0.9	0.9	TRUE
A/C Fuels Company	Ash (NOS)	Cadmium	ppm	0.5	0.5	0.5	TRUE
Baldwin	Fly ash	Cadmium	ppm	11.3	11.3	11.3	TRUE
B-D Mining Co.	Ash (NOS)	Cadmium	ppm	0.31	0.6	0.8	TRUE
B-D Mining Co.	Bottom ash	Cadmium	ppm	1.3	3	3.6	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
B-D Mining Co.	Fly ash	Cadmium	ppm	1.3	1.5	2	TRUE
CLSM	Combined ash	Cadmium	ppm	760.25	760.25	760.25	TRUE
CLSM	FBC	Cadmium	ppm	292.8	292.8	292.8	TRUE
Coal Creek	Bottom ash	Cadmium	ppm	0.0002	0.0002	0.0002	TRUE
Coal Creek	Fly ash	Cadmium	ppm	0.0007	0.0007	0.0007	TRUE
Deer Ridge Mine	Fly ash	Cadmium	ppm	0.0575	0.65	1	TRUE
DPC	Bottom ash	Cadmium	ppm	0.28	0.28	0.28	TRUE
DPC	Fly ash	Cadmium	ppm	0.84	0.84	0.84	TRUE
ern Analytical, ID: 5	Slag	Cadmium	ppm	0.25	0.25	0.25	TRUE
Edgewater	Bottom ash	Cadmium	ppm	0.5	0.5	0.5	TRUE
EERC?	Combined ash	Cadmium	ppm	0.5	0.5	0.5	TRUE
EERC?	FGD	Cadmium	ppm	0.5	0.5	1.08	TRUE
EERC?	FGD gypsum	Cadmium	ppm	0.5	0.5	0.8475	TRUE
EERC?	FGD gypsum liquids	Cadmium	mg/L	0.00479	0.00479	0.00479	TRUE
EERC?	FGD liquids	Cadmium	mg/L	0.001765	0.00249	0.003253	TRUE
EERC?	FGD liquids	Cadmium	ppm	0.5	0.5	0.5	TRUE
EERC?	Fly Ash	Cadmium	ppm	0.5	0.5	1.8625	TRUE
City Mine	FBC	Calcium	ppm	1534.5	2403	4515	TRUE
Cleveland	Fly ash	Calcium	ppm	15.4	15.4	15.4	TRUE
Freeport Mine	FGD waste	Calcium	ppm	207000	207000	207000	TRUE
HA	Ash & coal waste	Calcium	ppm	3000	3600	4550	TRUE
Martins Creek	Bottom ash	Calcium	ppm	10400	12426	21810	TRUE
Martins Creek	Fly ash	Calcium	ppm	14700	16439	19700	TRUE
McKay Site	FBC	Calcium	ppm	85250	103500	121750	TRUE
Miller Creek Mine	Bottom ash	Calcium	ppm	1385	2050	6348	TRUE
Miller Creek Mine	Combined ash	Calcium	ppm	979.75	2450	14250	TRUE
Miller Creek Mine	Fly ash	Calcium	ppm	3227	5089	6243.13	TRUE
Nucla	FBC	Calcium	ppm	87075	93050	99025	TRUE
Nucla2	FBC	Calcium	ppm	60500	64000	82000	TRUE
Oak Creek	Bottom ash	Calcium	ppm	12094	12094	12094	TRUE
Pagnotti Coal Co.	Ash (NOS)	Calcium	ppm	22280	22280	22280	TRUE
Pleasant Prairie	Bottom ash	Calcium	ppm	31360	31360	31360	TRUE
Shawnee	FBC	Calcium	ppm	260000	260000	279500	TRUE
CLSM	Combined ash	Calcium	ppm	594.6	594.6	594.6	TRUE
CLSM	FBC	Calcium	ppm	40581.5	40581.5	40581.5	TRUE
Deer Ridge Mine	Fly ash	Calcium	ppm	657.25	1210	3072.825	TRUE
DPC	Bottom ash	Calcium	ppm	5330	5330	5330	TRUE
DPC	Fly ash	Calcium	ppm	12700	12700	12700	TRUE
ern Analytical, ID: 5	Slag	Calcium	ppm	6200	6200	6200	TRUE
Edgewater	Bottom ash	Calcium	ppm	113000	113000	113000	TRUE
Bowen	Fly ash	Chloride	ppm	9	9	9	TRUE
Cardinal	Fly ash	Chloride	ppm	146.25	200.5	254.75	TRUE
ttle Sandy #10 Min	Bottom ash	Chloride	ppm	29	29	29	TRUE
ttle Sandy #10 Min	Combined ash	Chloride	ppm	10	17	63	TRUE
ttle Sandy #10 Min	FGD waste	Chloride	ppm	171.5	330	376.5	TRUE
ttle Sandy #10 Min	Fly ash	Chloride	ppm	10	10	10	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Lone Mtn	Fly ash	Chloride	ppm	333	333	333	TRUE
Miller	Fly ash	Chloride	ppm	9	9	9	TRUE
Miller Creek Mine	Bottom ash	Chloride	ppm	2.5	2.5	72	TRUE
Miller Creek Mine	Combined ash	Chloride	ppm	2.5	40	225	TRUE
Miller Creek Mine	Fly ash	Chloride	ppm	5	5	5	TRUE
Paradise	Fly ash	Chloride	ppm	94	94	94	TRUE
Pleasant Prairie	Fly ash	Chloride	ppm	18	18	18	TRUE
Sioux	Fly ash	Chloride	ppm	165	321	477	TRUE
Stanton	Fly ash	Chloride	ppm	216	216	216	TRUE
Universal	Combined ash	Chloride	ppm	10.5	14	20	TRUE
Yates	Fly ash	Chloride	ppm	108	108	108	TRUE
Baldwin	Fly ash	Chloride	ppm	415	415	415	TRUE
CLSM	Combined ash	Chloride	ppm	65.5	65.5	65.5	TRUE
CLSM	FBC	Chloride	ppm	1781	1781	1781	TRUE
Deer Ridge Mine	Fly ash	Chloride	ppm	6.9	150	180.75	TRUE
DPC	Bottom ash	Chloride	ppm	21.3	21.3	21.3	TRUE
DPC	Fly ash	Chloride	ppm	85.4	85.4	85.4	TRUE
Zhang et al. (2001)	Fly Ash	Chlorine	ppm	15	19	43	FALSE
Bowen	Fly ash	Chromium	ppm	168.1	168.1	168.1	TRUE
CAER	Bottom ash	Chromium	ppm	87.5	95	104	TRUE
CAER	Fly ash	Chromium	ppm	136	179	182	TRUE
Cardinal	Fly ash	Chromium	ppm	166.35	170.6	174.85	TRUE
City Mine	FBC	Chromium	ppm	156.5	181	181.5	TRUE
Philadelphia Girard	Ash (NOS)	Chromium	ppm	28.4	28.4	28.4	TRUE
Cleveland	Fly ash	Chromium	ppm	0.051	0.051	0.051	TRUE
Emerald Anthracite	Ash (NOS)	Chromium	ppm	31.075	40.067	50.875	TRUE
EORDC	FGD waste	Chromium	ppm	24	24	24	TRUE
Fleming	FBC	Chromium	ppm	37	37	37	TRUE
Freeport Mine	FGD waste	Chromium	ppm	2	2	2	TRUE
Gale	Ash (NOS)	Chromium	ppm	40	40	40	TRUE
Girard Estate	Ash (NOS)	Chromium	ppm	20	20	20	TRUE
HA	Ash & coal waste	Chromium	ppm	11.5	12	14	TRUE
Harrim 3019	Ash (NOS)	Chromium	ppm	294.991	294.991	294.991	TRUE
Harrim 3019	Bottom ash	Chromium	ppm	61.725	65.85	69.975	TRUE
Harrim 3019	Fly ash	Chromium	ppm	52.25	64.5	85.2	TRUE
an Coal Corporatio	Ash (NOS)	Chromium	ppm	21.325	32.55	48.175	TRUE
an Coal Corporatio	Bottom ash	Chromium	ppm	4.025	8.8	26	TRUE
an Coal Corporatio	Fly ash	Chromium	ppm	85.2	104	122.8	TRUE
Coal Corporation 5	Ash (NOS)	Chromium	ppm	26	26	26	TRUE
Coal Corporation 5	Bottom ash	Chromium	ppm	38.25	44.5	50.75	TRUE
Coal Corporation 5	Fly ash	Chromium	ppm	47.75	55.5	63.25	TRUE
ddo Highland Coal (	Ash (NOS)	Chromium	ppm	10.5	48	54.5	TRUE
ddo Highland Coal (	Bottom ash	Chromium	ppm	14.8	14.8	14.8	TRUE
Kentucky	Bottom ash	Chromium	ppm	102.5	125	142.5	TRUE
Kentucky	Fly ash	Chromium	ppm	198	216	235.75	TRUE
Knickerbocker Pit	FBC	Chromium	ppm	28.25	35.5	41.075	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
KY	FGD waste	Chromium	ppm	0.005	0.005	0.005	TRUE
gh Coal and Naviga	Ash (NOS)	Chromium	ppm	40	51	52	TRUE
LIMB Site	Ash (NOS)	Chromium	ppm	54.5	69	83.5	TRUE
ttle Sandy #10 Min	Bottom ash	Chromium	ppm	13	13	13	TRUE
ttle Sandy #10 Min	Combined ash	Chromium	ppm	5.1	5.9	7.6	TRUE
ttle Sandy #10 Min	FGD waste	Chromium	ppm	8.85	9.4	10.35	TRUE
ttle Sandy #10 Min	Fly ash	Chromium	ppm	63	63	63	TRUE
Lone Mtn	Fly ash	Chromium	ppm	148.7	148.7	148.7	TRUE
Mandan	FBC	Chromium	ppm	10.2	10.2	10.2	TRUE
Martins Creek	Bottom ash	Chromium	ppm	191	197	247	TRUE
Martins Creek	Fly ash	Chromium	ppm	173.1	196	213.52	TRUE
McCloskey Site	FBC	Chromium	ppm	33.21875	66.3125	99.40625	TRUE
McKay Site	FBC	Chromium	ppm	57.25	58.5	59.75	TRUE
Miller	Fly ash	Chromium	ppm	59.6	59.6	59.6	TRUE
Miller Creek Mine	Bottom ash	Chromium	ppm	0.38	14	20.37	TRUE
Miller Creek Mine	Combined ash	Chromium	ppm	4.925	9.9	22	TRUE
Miller Creek Mine	Fly ash	Chromium	ppm	21.25	26	34	TRUE
N & L Coal Co.	Ash (NOS)	Chromium	ppm	19.55	132.7	246.4695	TRUE
N & L Coal Co.-2	Ash (NOS)	Chromium	ppm	57	157	203	TRUE
Nepco	FBC	Chromium	ppm	1380	1380	1380	TRUE
NETL	Bottom ash	Chromium	ppm	119	119	119	TRUE
NETL	FBC	Chromium	ppm	97.5	108	118.5	TRUE
NETL	Fly ash	Chromium	ppm	95.75	167.5	176.75	TRUE
NETL	Slag	Chromium	ppm	5970	5970	5970	TRUE
o. 1 Contracting Co	Ash (NOS)	Chromium	ppm	15.15	24.3	33.45	TRUE
uel Supply Company	Ash (NOS)	Chromium	ppm	29	31	76	TRUE
uel Supply Company	Ash (NOS)	Chromium	ppm	27.5	41.5	72.875	TRUE
uel Supply Company	Ash (NOS)	Chromium	ppm	32.25	43.5	54.75	TRUE
orthampton400002	Ash (NOS)	Chromium	ppm	31	31	31	TRUE
heast Energy Com	Ash (NOS)	Chromium	ppm	29.75	36	40	TRUE
heast Energy Com	Bottom ash	Chromium	ppm	6.2	6.2	6.2	TRUE
heast Energy Com	Fly ash	Chromium	ppm	26	26	26	TRUE
eastern Power Con	Ash (NOS)	Chromium	ppm	18.35	22.5	25.5	TRUE
eastern Power Con	Bottom ash	Chromium	ppm	7.98	10.25	15.125	TRUE
eastern Power Con	Fly ash	Chromium	ppm	18.25	25.25	29.475	TRUE
Nucla	FBC	Chromium	ppm	27.5	29	30.5	TRUE
Nucla2	FBC	Chromium	ppm	9.2	13	13.5	TRUE
Oak Creek	Bottom ash	Chromium	ppm	140	140	140	TRUE
aceAnalytical (201	Slag	Chromium	ppm	45.1	45.1	45.1	TRUE
Pacton Corp	Ash (NOS)	Chromium	ppm	49	49	49	TRUE
Pacton Corp	Bottom ash	Chromium	ppm	40	40	40	TRUE
Pacton Corp	Fly ash	Chromium	ppm	66.5	84	160	TRUE
Pagnotti Coal Co.	Ash (NOS)	Chromium	ppm	27.5	29.4	45.5	TRUE
Pagnotti Coal Co.	Fly ash	Chromium	ppm	46	46	46	TRUE
Panther Creek	FBC	Chromium	ppm	40.5	44.8	49.075	TRUE
Paradise	Fly ash	Chromium	ppm	148.5	148.5	148.5	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
ett et al. (1993) Co	Fly Ash	Chromium	ppm	53.25	61.5	70.25	TRUE
Plant 10	FBC	Chromium	ppm	23.95	30.8	42.45	TRUE
Plant 12	FBC	Chromium	ppm	21.8	22.8	33.8	TRUE
Plant 8	FBC	Chromium	ppm	26.5	30	33.75	TRUE
Plant 9	FBC	Chromium	ppm	79.5	97.3	109.375	TRUE
Pleasant Prairie	Bottom ash	Chromium	ppm	37	37	37	TRUE
Pleasant Prairie	Fly ash	Chromium	ppm	114.3	114.3	114.3	TRUE
Porter Associates	Ash (NOS)	Chromium	ppm	18.5	27	46.7	TRUE
Porter Associates	Bottom ash	Chromium	ppm	8.975	29.5	58.25	TRUE
ylkill Reclamation (	Ash (NOS)	Chromium	ppm	23	23	23	TRUE
Scrubgrass	FBC	Chromium	ppm	95	95	95	TRUE
Shawnee	FBC	Chromium	ppm	0.9	9.7	76	TRUE
Silverton	Ash (NOS)	Chromium	ppm	46.375	52.75	59.125	TRUE
Sioux	Fly ash	Chromium	ppm	120.925	134.95	148.975	TRUE
Stanton	Fly ash	Chromium	ppm	170	170	170	TRUE
ehanna Coal Comp	Ash (NOS)	Chromium	ppm	33.9	43	48.5	TRUE
hanna Coal Compa	Ash (NOS)	Chromium	ppm	25.425	34.5	40.325	TRUE
SW	Bottom ash	Chromium	ppm	23.6	25.6	27.5	TRUE
SW	Fly ash	Chromium	ppm	15.4	18.6	28	TRUE
Tracy Vein Slope	Ash (NOS)	Chromium	ppm	30.175	41.45	52.325	TRUE
Tracy Vein Slope	Bottom ash	Chromium	ppm	15.9	21.7	27.5	TRUE
Tracy Vein Slope	FBC	Chromium	ppm	6.43	6.43	6.43	TRUE
Universal	Combined ash	Chromium	ppm	16	17	22.5	TRUE
USGS	Fly ash	Chromium	ppm	140	150	165	TRUE
wood Energy Prop	Ash (NOS)	Chromium	ppm	9.9375	15.6	19.4	TRUE
Wheelabrator	FBC	Chromium	ppm	15.175	18.15	27.3	TRUE
Xcel/MSI	Fly ash	Chromium	ppm	55.25	74.5	83	TRUE
Yates	Fly ash	Chromium	ppm	181	181	181	TRUE
Zhang et al. (2001)	Fly Ash	Chromium	ppm	31	60	81	TRUE
1	FBC	Chromium	ppm	14.96	16.39	19.6	TRUE
10	FBC	Chromium	ppm	33	37	41	TRUE
11	FBC	Chromium	ppm	59.25	63.5	67.75	TRUE
12	FBC	Chromium	ppm	38	44.05	51.3	TRUE
14	FBC	Chromium	ppm	48	48	48	TRUE
17	FBC	Chromium	ppm	27.5	37.5	50.5	TRUE
18	FBC	Chromium	ppm	25.5	30	30	TRUE
19	FBC	Chromium	ppm	12.9	12.9	12.9	TRUE
2	FBC	Chromium	ppm	4.1	12.715	21.33	TRUE
20	FBC	Chromium	ppm	36	47.3	52.19	TRUE
21	FBC	Chromium	ppm	30.5	40.5	47.575	TRUE
23	FBC	Chromium	ppm	26.9475	29.215	31.3325	TRUE
26	FBC	Chromium	ppm	18.5	21	23.5	TRUE
27	FBC	Chromium	ppm	37	37	37	TRUE
28	FBC	Chromium	ppm	56.125	72.75	99.5	TRUE
29	FBC	Chromium	ppm	45.625	52.85	72.75	TRUE
3	FBC	Chromium	ppm	28.75	29.5	30.25	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
30	FBC	Chromium	ppm	26.925	45.8	56.55	TRUE
31	FBC	Chromium	ppm	55.5	55.5	55.5	TRUE
37	FBC	Chromium	ppm	60	86	99.5	TRUE
38	FBC	Chromium	ppm	14.875	19.3	41.3	TRUE
39	FBC	Chromium	ppm	42.25	47.5	52.75	TRUE
4	FBC	Chromium	ppm	13.08	20.64	23.8	TRUE
5	FBC	Chromium	ppm	17.5	21	23	TRUE
6	FBC	Chromium	ppm	35.875	42.65	49.425	TRUE
7	FBC	Chromium	ppm	54.51	54.51	54.51	TRUE
8	FBC	Chromium	ppm	45	45	45	TRUE
A/C Fuels Company	Ash (NOS)	Chromium	ppm	4	4	4	TRUE
Baldwin	Fly ash	Chromium	ppm	448.8	448.8	448.8	TRUE
B-D Mining Co.	Ash (NOS)	Chromium	ppm	33.1	47.5	51.875	TRUE
B-D Mining Co.	Bottom ash	Chromium	ppm	30.5	38.5	44.775	TRUE
B-D Mining Co.	Fly ash	Chromium	ppm	61.85	73.2	86.725	TRUE
CLSM	Combined ash	Chromium	ppm	75.5	75.5	75.5	TRUE
CLSM	FBC	Chromium	ppm	26.7	26.7	26.7	TRUE
Coal Creek	Bottom ash	Chromium	ppm	0.045	0.045	0.045	TRUE
Coal Creek	Fly ash	Chromium	ppm	0.059	0.059	0.059	TRUE
Deer Ridge Mine	Fly ash	Chromium	ppm	8.575	11.12	38.6075	TRUE
DPC	Bottom ash	Chromium	ppm	9.8	9.8	9.8	TRUE
DPC	Fly ash	Chromium	ppm	50.2	50.2	50.2	TRUE
ern Analytical, ID: 5	Slag	Chromium	ppm	23	23	23	TRUE
Edgewater	Bottom ash	Chromium	ppm	54.4	54.4	54.4	TRUE
EERC?	Combined ash	Chromium	ppm	30.425	34.55	38.675	TRUE
EERC?	FGD	Chromium	ppm	10.4	37.3	51.6	TRUE
EERC?	FGD gypsum	Chromium	ppm	3.2675	3.67	3.995	TRUE
EERC?	FGD gypsum liquids	Chromium	mg/L	0.0099	0.0099	0.0099	TRUE
EERC?	FGD liquids	Chromium	mg/L	0.00395	0.005	0.0068	TRUE
EERC?	FGD liquids	Chromium	ppm	6.61	6.61	6.61	TRUE
EERC?	Fly Ash	Chromium	ppm	45.4	71.1	125	TRUE
Bowen	Fly ash	Cobalt	ppm	79.9	79.9	79.9	TRUE
CAER	Bottom ash	Cobalt	ppm	43	59	65.5	TRUE
CAER	Fly ash	Cobalt	ppm	71	72	76	TRUE
Cardinal	Fly ash	Cobalt	ppm	46.1	46.1	46.1	TRUE
Philadelphia Girard	Ash (NOS)	Cobalt	ppm	7.1	7.1	7.1	TRUE
Emerald Anthracite	Ash (NOS)	Cobalt	ppm	11.9	14.9	17.35	TRUE
Freeport Mine	FGD waste	Cobalt	ppm	2.5	2.5	2.5	TRUE
Girard Estate	Ash (NOS)	Cobalt	ppm	2	2	2	TRUE
Harrim 3019	Ash (NOS)	Cobalt	ppm	27	27	27	TRUE
Harrim 3019	Bottom ash	Cobalt	ppm	57.45	81.1	104.75	TRUE
Harrim 3019	Fly ash	Cobalt	ppm	24.5	29.7	36.5	TRUE
an Coal Corporatio	Ash (NOS)	Cobalt	ppm	4.6	8.1	10	TRUE
an Coal Corporatio	Bottom ash	Cobalt	ppm	1.37	3.37	19.06	TRUE
an Coal Corporatio	Fly ash	Cobalt	ppm	66.9	104.1	141.3	TRUE
Coal Corporation 5	Ash (NOS)	Cobalt	ppm	20	20	20	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Knickerbocker Pit	FBC	Cobalt	ppm	7.05	10	10.8	TRUE
KY	FGD waste	Cobalt	ppm	0.005	0.005	0.005	TRUE
gh Coal and Naviga	Ash (NOS)	Cobalt	ppm	9.7	12	17	TRUE
Lone Mtn	Fly ash	Cobalt	ppm	87.3	87.3	87.3	TRUE
Martins Creek	Bottom ash	Cobalt	ppm	53	55.5	64.35	TRUE
Martins Creek	Fly ash	Cobalt	ppm	24.83	27.4	35.415	TRUE
Miller	Fly ash	Cobalt	ppm	42.3	42.3	42.3	TRUE
N & L Coal Co.	Ash (NOS)	Cobalt	ppm	6.1675	27.75	47.2125	TRUE
N & L Coal Co.-2	Ash (NOS)	Cobalt	ppm	9	23.45	25.1	TRUE
NETL	Bottom ash	Cobalt	ppm	26	26	26	TRUE
NETL	FBC	Cobalt	ppm	28.75	29.5	30.25	TRUE
NETL	Fly ash	Cobalt	ppm	25	39.5	50	TRUE
NETL	Slag	Cobalt	ppm	10	10	10	TRUE
el Supply Company	Ash (NOS)	Cobalt	ppm	5.1	7	7.7	TRUE
heast Energy Com	Ash (NOS)	Cobalt	ppm	15	17	19	TRUE
eastern Power Con	Bottom ash	Cobalt	ppm	1.29	1.34	1.345	TRUE
eastern Power Con	Fly ash	Cobalt	ppm	3.15	3.22	3.41	TRUE
Nucla	FBC	Cobalt	ppm	10	10	10	TRUE
Nucla2	FBC	Cobalt	ppm	5	8.1	8.2	TRUE
aceAnalytical (201(	Slag	Cobalt	ppm	16.1	16.1	16.1	TRUE
Pacton Corp	Ash (NOS)	Cobalt	ppm	8	8	8	TRUE
Panther Creek	FBC	Cobalt	ppm	3.25	5.5	8.975	TRUE
ett et al. (1993) Co	Fly Ash	Cobalt	ppm	28.5	34.5	42	TRUE
Pleasant Prairie	Fly ash	Cobalt	ppm	54.1	54.1	54.1	TRUE
Porter Associates	Ash (NOS)	Cobalt	ppm	5.765	8.63	28.05	TRUE
Porter Associates	Bottom ash	Cobalt	ppm	2.45	14	28	TRUE
Shawnee	FBC	Cobalt	ppm	0.95	1	5.2	TRUE
Sioux	Fly ash	Cobalt	ppm	134.7	134.7	134.7	TRUE
Stanton	Fly ash	Cobalt	ppm	86.1	86.1	86.1	TRUE
ehanna Coal Comp	Ash (NOS)	Cobalt	ppm	16.325	18.4	19.875	TRUE
hanna Coal Compa	Ash (NOS)	Cobalt	ppm	6.3	9	9.65	TRUE
USGS	Fly ash	Cobalt	ppm	40.85	48.6	56.55	TRUE
wood Energy Prop	Ash (NOS)	Cobalt	ppm	1.86	2.01	3.3	TRUE
Wheelabrator	FBC	Cobalt	ppm	3.55	3.815	4.34	TRUE
Xcel/MSI	Fly ash	Cobalt	ppm	17.95	26.15	27.825	TRUE
Zhang et al. (2001)	Fly Ash	Cobalt	ppm	44	54	120	TRUE
1	FBC	Cobalt	ppm	4.3375	5.725	7.5	TRUE
10	FBC	Cobalt	ppm	7.8125	9.375	10.9375	TRUE
12	FBC	Cobalt	ppm	1.25	4.175	7.325	TRUE
14	FBC	Cobalt	ppm	5.1	5.1	5.1	TRUE
18	FBC	Cobalt	ppm	9.5	13	13.5	TRUE
19	FBC	Cobalt	ppm	18.7	18.7	18.7	TRUE
2	FBC	Cobalt	ppm	1.4	3.4835	5.567	TRUE
20	FBC	Cobalt	ppm	9.5	9.8	9.8	TRUE
21	FBC	Cobalt	ppm	3.25	4.5	7.25	TRUE
26	FBC	Cobalt	ppm	3.7625	9.3	15.25	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
28	FBC	Cobalt	ppm	34.9	49.55	111.6	TRUE
29	FBC	Cobalt	ppm	10.04688	45.7	69.325	TRUE
3	FBC	Cobalt	ppm	6.25	6.25	6.25	TRUE
30	FBC	Cobalt	ppm	16.4	21.05	23.6	TRUE
31	FBC	Cobalt	ppm	4.63	6.42	8.21	TRUE
38	FBC	Cobalt	ppm	3.58	4.29	5.225	TRUE
39	FBC	Cobalt	ppm	9.5	13	16.5	TRUE
4	FBC	Cobalt	ppm	2.0575	2.105	2.1525	TRUE
5	FBC	Cobalt	ppm	14	16.5	23.5	TRUE
6	FBC	Cobalt	ppm	2.725	2.725	2.725	TRUE
7	FBC	Cobalt	ppm	35.13	35.13	35.13	TRUE
Baldwin	Fly ash	Cobalt	ppm	59.2	59.2	59.2	TRUE
B-D Mining Co.	Ash (NOS)	Cobalt	ppm	9	9.8	11	TRUE
CLSM	Combined ash	Cobalt	ppm	46.4	46.4	46.4	TRUE
CLSM	FBC	Cobalt	ppm	7	7	7	TRUE
Bowen	Fly ash	Copper	ppm	220.6	220.6	220.6	TRUE
CAER	Bottom ash	Copper	ppm	81	81	81	TRUE
CAER	Fly ash	Copper	ppm	21	42	45	TRUE
Cardinal	Fly ash	Copper	ppm	71.625	79.05	86.475	TRUE
Philadelphia Girard	Ash (NOS)	Copper	ppm	22.3	22.3	22.3	TRUE
Cleveland	Fly ash	Copper	ppm	0.058	0.058	0.058	TRUE
Emerald Anthracite	Ash (NOS)	Copper	ppm	40.025	42.8835	50.85	TRUE
EORDC	FGD waste	Copper	ppm	19	19	19	TRUE
Freeport Mine	FGD waste	Copper	ppm	2	2	2	TRUE
Gale	Ash (NOS)	Copper	ppm	33	33	33	TRUE
Girard Estate	Ash (NOS)	Copper	ppm	17	17	17	TRUE
HA	Ash & coal waste	Copper	ppm	33.5	38	39	TRUE
Harrim 3019	Ash (NOS)	Copper	ppm	98.177	98.177	98.177	TRUE
Harrim 3019	Bottom ash	Copper	ppm	32.425	35.85	39.275	TRUE
Harrim 3019	Fly ash	Copper	ppm	41.25	49	50.45	TRUE
an Coal Corporatio	Ash (NOS)	Copper	ppm	18.65	27.35	43.45	TRUE
an Coal Corporatio	Bottom ash	Copper	ppm	6.635	10.8	25.6	TRUE
an Coal Corporatio	Fly ash	Copper	ppm	60.05	70.5	80.95	TRUE
Coal Corporation 5	Ash (NOS)	Copper	ppm	49	49	49	TRUE
Coal Corporation 5	Bottom ash	Copper	ppm	24	27	30	TRUE
Coal Corporation 5	Fly ash	Copper	ppm	60	65	70	TRUE
ddo Highland Coal (	Ash (NOS)	Copper	ppm	21.4	36	43	TRUE
ddo Highland Coal (	Bottom ash	Copper	ppm	14.9	14.9	14.9	TRUE
Kentucky	Bottom ash	Copper	ppm	45.5	52	60	TRUE
Kentucky	Fly ash	Copper	ppm	214	241	263.5	TRUE
Knickerbocker Pit	FBC	Copper	ppm	20.97	23.8	26.9	TRUE
KY	FGD waste	Copper	ppm	0.005	0.005	0.005	TRUE
gh Coal and Naviga	Ash (NOS)	Copper	ppm	19	29	33	TRUE
LIMB Site	Ash (NOS)	Copper	ppm	15.25	16.5	17.75	TRUE
ttle Sandy #10 Min	Bottom ash	Copper	ppm	28	28	28	TRUE
ttle Sandy #10 Min	Combined ash	Copper	ppm	10	15	15	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
ttle Sandy #10 Min	FGD waste	Copper	ppm	10	11	12.85	TRUE
ttle Sandy #10 Min	Fly ash	Copper	ppm	110	110	110	TRUE
Lone Mtn	Fly ash	Copper	ppm	220.8	220.8	220.8	TRUE
Martins Creek	Bottom ash	Copper	ppm	53.8	70.26	74.3	TRUE
Martins Creek	Fly ash	Copper	ppm	52.11	55.1	66.53	TRUE
McCloskey Site	FBC	Copper	ppm	58.75	60	61.25	TRUE
McKay Site	FBC	Copper	ppm	50.5	53	55.5	TRUE
Miller	Fly ash	Copper	ppm	348.7	348.7	348.7	TRUE
Miller Creek Mine	Bottom ash	Copper	ppm	42	54.16	84	TRUE
Miller Creek Mine	Combined ash	Copper	ppm	21	45.5	94.9675	TRUE
Miller Creek Mine	Fly ash	Copper	ppm	18	30.5	51.75	TRUE
N & L Coal Co.	Ash (NOS)	Copper	ppm	36.55	90.77	122.968	TRUE
N & L Coal Co.-2	Ash (NOS)	Copper	ppm	58.85	115.5	135.5	TRUE
NETL	Bottom ash	Copper	ppm	6130	6130	6130	TRUE
NETL	FBC	Copper	ppm	66.75	80.5	94.25	TRUE
NETL	Fly ash	Copper	ppm	71.75	99	142.25	TRUE
NETL	Slag	Copper	ppm	95	95	95	TRUE
ɔ. 1 Contracting Co	Ash (NOS)	Copper	ppm	226	424	622	TRUE
ıel Supply Compan	Ash (NOS)	Copper	ppm	27	35.1	60	TRUE
ıel Supply Compan	Ash (NOS)	Copper	ppm	19.25	22.7	26.625	TRUE
ıel Supply Compan	Ash (NOS)	Copper	ppm	43.75	67.5	91.25	TRUE
ɔrthampton400002	Ash (NOS)	Copper	ppm	35.1	35.1	35.1	TRUE
heast Energy Com	Ash (NOS)	Copper	ppm	33.675	37.9	48.75	TRUE
heast Energy Com	Bottom ash	Copper	ppm	11	11	11	TRUE
heast Energy Com	Fly ash	Copper	ppm	55	55	55	TRUE
eastern Power Cor	Ash (NOS)	Copper	ppm	12.3	12.6	12.9	TRUE
eastern Power Cor	Bottom ash	Copper	ppm	5.8925	7.16	9.405	TRUE
eastern Power Cor	Fly ash	Copper	ppm	17.9	20.35	25.8	TRUE
Nucla	FBC	Copper	ppm	26.25	29.5	32.75	TRUE
Nucla2	FBC	Copper	ppm	14.6	25	25.5	TRUE
Oak Creek	Bottom ash	Copper	ppm	84	84	84	TRUE
aceAnalytical (201(	Slag	Copper	ppm	22.5	22.5	22.5	TRUE
Pacton Corp	Ash (NOS)	Copper	ppm	25	25	25	TRUE
Pacton Corp	Bottom ash	Copper	ppm	18	18	18	TRUE
Pacton Corp	Fly ash	Copper	ppm	38	120	165	TRUE
Pagnotti Coal Co.	Ash (NOS)	Copper	ppm	15.6	23.9	26.2	TRUE
Pagnotti Coal Co.	Fly ash	Copper	ppm	53.5	53.5	53.5	TRUE
Panther Creek	FBC	Copper	ppm	35.025	37	40.75	TRUE
Paradise	Fly ash	Copper	ppm	288.9	288.9	288.9	TRUE
ett et al. (1993) Co	Fly Ash	Copper	ppm	147.5	192.5	227.5	TRUE
Pleasant Prairie	Bottom ash	Copper	ppm	69	69	69	TRUE
Pleasant Prairie	Fly ash	Copper	ppm	331.1	331.1	331.1	TRUE
Porter Associates	Ash (NOS)	Copper	ppm	18.125	27.3	47	TRUE
Porter Associates	Bottom ash	Copper	ppm	18	25.9	31.5	TRUE
ylkill Reclamation (	Ash (NOS)	Copper	ppm	9	9	9	TRUE
SFA	Fly ash	Copper	ppm	890	890	890	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Shawnee	FBC	Copper	ppm	12	19	28	TRUE
Silverton	Ash (NOS)	Copper	ppm	34.25	35.5	36.75	TRUE
Sioux	Fly ash	Copper	ppm	364.65	382.2	399.75	TRUE
Stanton	Fly ash	Copper	ppm	230.4	230.4	230.4	TRUE
STK	Fly ash	Copper	ppm	25	25	25	TRUE
ehanna Coal Comp	Ash (NOS)	Copper	ppm	43.25	46.65	53	TRUE
hanna Coal Compa	Ash (NOS)	Copper	ppm	18.525	22.25	26.1	TRUE
Tracy Vein Slope	Ash (NOS)	Copper	ppm	24.775	32.95	45.65	TRUE
Tracy Vein Slope	Bottom ash	Copper	ppm	39.9	57.6	75.3	TRUE
Tracy Vein Slope	FBC	Copper	ppm	5.52	5.52	5.52	TRUE
Universal	Combined ash	Copper	ppm	18.5	24	32.25	TRUE
wood Energy Prop	Ash (NOS)	Copper	ppm	10.775	11.7	18.175	TRUE
Wheelabrator	FBC	Copper	ppm	17.475	21.1	22.05	TRUE
Yates	Fly ash	Copper	ppm	229.7	229.7	229.7	TRUE
Zhang et al. (2001)	Fly Ash	Copper	ppm	57	81	120	TRUE
1	FBC	Copper	ppm	47.325	175.8	330	TRUE
10	FBC	Copper	ppm	33.5	38	42.5	TRUE
11	FBC	Copper	ppm	12.525	15.35	18.175	TRUE
12	FBC	Copper	ppm	21.8	23.6	28.6	TRUE
14	FBC	Copper	ppm	22.4	22.4	22.4	TRUE
17	FBC	Copper	ppm	31.2	35	47	TRUE
19	FBC	Copper	ppm	37.3	37.3	37.3	TRUE
2	FBC	Copper	ppm	5.1	39.225	73.35	TRUE
20	FBC	Copper	ppm	18	30.8	40.3	TRUE
21	FBC	Copper	ppm	28.5	38	42.625	TRUE
23	FBC	Copper	ppm	26.1925	26.67	27.05	TRUE
26	FBC	Copper	ppm	9.35	13	15.75	TRUE
27	FBC	Copper	ppm	99	99	99	TRUE
28	FBC	Copper	ppm	29.1	40.85	45.175	TRUE
29	FBC	Copper	ppm	40.125	45.65	60.55	TRUE
3	FBC	Copper	ppm	15.25	18.5	21.75	TRUE
30	FBC	Copper	ppm	19.125	28.342	41.15	TRUE
31	FBC	Copper	ppm	30.125	34.25	38.375	TRUE
37	FBC	Copper	ppm	44	44	44	TRUE
38	FBC	Copper	ppm	16.425	20.5	24.925	TRUE
39	FBC	Copper	ppm	45	53	61	TRUE
4	FBC	Copper	ppm	11.4	15.1	19.2	TRUE
5	FBC	Copper	ppm	5.05	8.4	10.7	TRUE
6	FBC	Copper	ppm	21.6	22.5	23.4	TRUE
7	FBC	Copper	ppm	31.29	31.29	31.29	TRUE
8	FBC	Copper	ppm	83	83	83	TRUE
A/C Fuels Company	Ash (NOS)	Copper	ppm	19	19	19	TRUE
Baldwin	Fly ash	Copper	ppm	226.4	226.4	226.4	TRUE
B-D Mining Co.	Ash (NOS)	Copper	ppm	23	33.05	41.55	TRUE
B-D Mining Co.	Bottom ash	Copper	ppm	12.925	16.85	17.85	TRUE
B-D Mining Co.	Fly ash	Copper	ppm	32.75	45.8	62.525	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
CLSM	Combined ash	Copper	ppm	233.1	233.1	233.1	TRUE
CLSM	FBC	Copper	ppm	282.1	282.1	282.1	TRUE
Deer Ridge Mine	Fly ash	Copper	ppm	67.725	82.095	129.08	TRUE
DPC	Bottom ash	Copper	ppm	22.4	22.4	22.4	TRUE
DPC	Fly ash	Copper	ppm	39.3	39.3	39.3	TRUE
ern Analytical, ID: 5	Slag	Copper	ppm	16	16	16	TRUE
Edgewater	Bottom ash	Copper	ppm	81.8	81.8	81.8	TRUE
KY	FGD waste	Fluoride	ppm	596	816	850.25	TRUE
ttle Sandy #10 Min	Bottom ash	Fluoride	ppm	0.375	0.375	0.375	TRUE
ttle Sandy #10 Min	Combined ash	Fluoride	ppm	1.4	2.2	5	TRUE
ttle Sandy #10 Min	FGD waste	Fluoride	ppm	6.2	7.4	9.2	TRUE
ttle Sandy #10 Min	Fly ash	Fluoride	ppm	25	25	25	TRUE
Miller Creek Mine	Bottom ash	Fluoride	ppm	1	3	4.9	TRUE
Miller Creek Mine	Combined ash	Fluoride	ppm	0.2	1	5	TRUE
Miller Creek Mine	Fly ash	Fluoride	ppm	3.65	6.95	8.05	TRUE
Universal	Combined ash	Fluoride	ppm	9	15	24.5	TRUE
CLSM	Combined ash	Fluoride	ppm	2.5	2.5	2.5	TRUE
CLSM	FBC	Fluoride	ppm	13	13	13	TRUE
Deer Ridge Mine	Fly ash	Fluoride	ppm	2.175	5.4	15	TRUE
Zhang et al. (2001)	Fly Ash	Gallium	ppm	17	21	25	FALSE
Zhang et al. (2001)	Fly Ash	Germanium	ppm	9	11	21	FALSE
City Mine	FBC	Iron	ppm	134000	138000	145500	TRUE
Philadelphia Girard	Ash (NOS)	Iron	ppm	17100	17100	17100	TRUE
Cleveland	Fly ash	Iron	ppm	69.4	69.4	69.4	TRUE
Emerald Anthracite	Ash (NOS)	Iron	ppm	14832.3	15700	21806.5	TRUE
Freeport Mine	FGD waste	Iron	ppm	957	957	957	TRUE
Gale	Ash (NOS)	Iron	ppm	10675	10675	10675	TRUE
Girard Estate	Ash (NOS)	Iron	ppm	10900	10900	10900	TRUE
HA	Ash & coal waste	Iron	ppm	3450	4000	4350	TRUE
Harrim 3019	Bottom ash	Iron	ppm	14335	14770	15205	TRUE
Harrim 3019	Fly ash	Iron	ppm	16375	23650	27450	TRUE
an Coal Corporatio	Ash (NOS)	Iron	ppm	7905	16800	33750	TRUE
an Coal Corporatio	Bottom ash	Iron	ppm	4890	9590	16830	TRUE
an Coal Corporatio	Fly ash	Iron	ppm	28950	31400	33850	TRUE
Coal Corporation 5	Ash (NOS)	Iron	ppm	11800	11800	11800	TRUE
Coal Corporation 5	Bottom ash	Iron	ppm	11450	12800	14150	TRUE
Coal Corporation 5	Fly ash	Iron	ppm	15200	16800	18400	TRUE
ddo Highland Coal (	Ash (NOS)	Iron	ppm	3300	4770	7060	TRUE
ddo Highland Coal (	Bottom ash	Iron	ppm	37400	37400	37400	TRUE
Knickerbocker Pit	FBC	Iron	ppm	12352.5	16085	17845	TRUE
gh Coal and Naviga	Ash (NOS)	Iron	ppm	930	12900	15000	TRUE
LIMB Site	Ash (NOS)	Iron	ppm	27450	47300	67150	TRUE
ttle Sandy #10 Min	Bottom ash	Iron	ppm	22000	22000	22000	TRUE
ttle Sandy #10 Min	Combined ash	Iron	ppm	14200	17000	25000	TRUE
ttle Sandy #10 Min	FGD waste	Iron	ppm	3150	3300	3500	TRUE
ttle Sandy #10 Min	Fly ash	Iron	ppm	40000	40000	40000	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Martins Creek	Bottom ash	Iron	ppm	119000	120459	129051	TRUE
Martins Creek	Fly ash	Iron	ppm	59000	67880	71500	TRUE
McCloskey Site	FBC	Iron	ppm	29125	36000	42875	TRUE
McKay Site	FBC	Iron	ppm	18750	19500	20250	TRUE
Miller Creek Mine	Bottom ash	Iron	ppm	10626	35210	85470.09	TRUE
Miller Creek Mine	Combined ash	Iron	ppm	7788.5	13780.5	78500	TRUE
Miller Creek Mine	Fly ash	Iron	ppm	18000	19000	32205	TRUE
N & L Coal Co.	Ash (NOS)	Iron	ppm	8922.5	46150	67972.5	TRUE
N & L Coal Co.-2	Ash (NOS)	Iron	ppm	9410	49400	66500	TRUE
o. 1 Contracting Co	Ash (NOS)	Iron	ppm	13675	13950	14225	TRUE
uel Supply Compan	Ash (NOS)	Iron	ppm	10200	13600	17900	TRUE
uel Supply Compan	Ash (NOS)	Iron	ppm	8895	9590	13306.55	TRUE
uel Supply Compan	Ash (NOS)	Iron	ppm	15975	16350	16725	TRUE
orthampton400002	Ash (NOS)	Iron	ppm	23100	23100	23100	TRUE
heast Energy Com	Ash (NOS)	Iron	ppm	3468.5	10187.5	22800	TRUE
heast Energy Com	Bottom ash	Iron	ppm	4200	4200	4200	TRUE
heast Energy Com	Fly ash	Iron	ppm	10000	10000	10000	TRUE
eastern Power Con	Ash (NOS)	Iron	ppm	4665	6280	8190	TRUE
eastern Power Con	Bottom ash	Iron	ppm	2015	2660	4090	TRUE
eastern Power Con	Fly ash	Iron	ppm	3860	5890	8210	TRUE
Nucla	FBC	Iron	ppm	25300	29500	33700	TRUE
Nucla2	FBC	Iron	ppm	14500	15000	16000	TRUE
Oak Creek	Bottom ash	Iron	ppm	154000	154000	154000	TRUE
Pacton Corp	Ash (NOS)	Iron	ppm	10800	10800	10800	TRUE
Pacton Corp	Bottom ash	Iron	ppm	8775	8775	8775	TRUE
Pacton Corp	Fly ash	Iron	ppm	21612.5	34200	43600	TRUE
Pagnotti Coal Co.	Ash (NOS)	Iron	ppm	10855	15325	19895	TRUE
Pagnotti Coal Co.	Bottom ash	Iron	ppm	625	625	625	TRUE
Pagnotti Coal Co.	Fly ash	Iron	ppm	6487.5	10825	15162.5	TRUE
Panther Creek	FBC	Iron	ppm	15500	16515	17530	TRUE
Pleasant Prairie	Bottom ash	Iron	ppm	28000	28000	28000	TRUE
Porter Associates	Ash (NOS)	Iron	ppm	6390	12000	16700	TRUE
Porter Associates	Bottom ash	Iron	ppm	6395	9960	25400	TRUE
ylkill Reclamation (	Ash (NOS)	Iron	ppm	1790	1790	1790	TRUE
Shawnee	FBC	Iron	ppm	16700	21000	59900	TRUE
Silverton	Ash (NOS)	Iron	ppm	11601.25	12527.5	13453.75	TRUE
ehanna Coal Comp	Ash (NOS)	Iron	ppm	14400	17250	18600	TRUE
hanna Coal Compa	Ash (NOS)	Iron	ppm	8420	11150	13195	TRUE
SW	Bottom ash	Iron	ppm	27000	29100	31500	TRUE
SW	Fly ash	Iron	ppm	23100	24200	24900	TRUE
Tracy Vein Slope	Ash (NOS)	Iron	ppm	10426.93	15100	16425	TRUE
Tracy Vein Slope	Bottom ash	Iron	ppm	32000	43600	55200	TRUE
Tracy Vein Slope	FBC	Iron	ppm	2600	2600	2600	TRUE
Universal	Combined ash	Iron	ppm	8610	13000	19350	TRUE
wood Energy Prop	Ash (NOS)	Iron	ppm	2815	4983	5625	TRUE
Wheelabrator	FBC	Iron	ppm	6177.5	10367.5	14586.25	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Xcel/MSI	Fly ash	Iron	ppm	30760	37008.5	41217	TRUE
Zhang et al. (2001)	Fly Ash	Iron	ppm	100	200	200	TRUE
12	FBC	Iron	ppm	8050	8680	11550	TRUE
14	FBC	Iron	ppm	9090	9090	9090	TRUE
17	FBC	Iron	ppm	14613	26741	28990	TRUE
18	FBC	Iron	ppm	40097	71721	76519.5	TRUE
19	FBC	Iron	ppm	5700	5700	5700	TRUE
2	FBC	Iron	ppm	6.2	14.185	22.17	TRUE
20	FBC	Iron	ppm	12210	17000	25740	TRUE
21	FBC	Iron	ppm	14775	18150	22575	TRUE
23	FBC	Iron	ppm	27375	28351.4	29815.92	TRUE
26	FBC	Iron	ppm	7430	7430	7430	TRUE
27	FBC	Iron	ppm	47961	47961	47961	TRUE
28	FBC	Iron	ppm	4422.5	14520	31135	TRUE
29	FBC	Iron	ppm	14348.8	17757.6	20488.33	TRUE
30	FBC	Iron	ppm	14337.49	18135	25340	TRUE
31	FBC	Iron	ppm	16775	16775	16775	TRUE
38	FBC	Iron	ppm	5775	10617.5	15512.5	TRUE
39	FBC	Iron	ppm	23025	26750	30475	TRUE
4	FBC	Iron	ppm	5011.75	8256	10110	TRUE
6	FBC	Iron	ppm	34660.5	41761	48861.5	TRUE
7	FBC	Iron	ppm	25335.62	25335.62	25335.62	TRUE
8	FBC	Iron	ppm	16000	16000	16000	TRUE
A/C Fuels Company	Ash (NOS)	Iron	ppm	8640	8640	8640	TRUE
B-D Mining Co.	Ash (NOS)	Iron	ppm	13433.75	20125	26050	TRUE
B-D Mining Co.	Bottom ash	Iron	ppm	11595	12210	12506.25	TRUE
B-D Mining Co.	Fly ash	Iron	ppm	25275	29030	32042.5	TRUE
CLSM	Combined ash	Iron	ppm	22610	22610	22610	TRUE
CLSM	FBC	Iron	ppm	13525	13525	13525	TRUE
Deer Ridge Mine	Fly ash	Iron	ppm	4645.355	6264.3	42500	TRUE
DPC	Bottom ash	Iron	ppm	4780	4780	4780	TRUE
DPC	Fly ash	Iron	ppm	10200	10200	10200	TRUE
ern Analytical, ID: 5	Slag	Iron	ppm	18000	18000	18000	TRUE
Zhang et al. (2001)	Fly Ash	Lanthanum	ppm	47	49	61	TRUE
Bowen	Fly ash	Lead	ppm	63.9	63.9	63.9	TRUE
CAER	Bottom ash	Lead	ppm	20.835	32.49	53.585	TRUE
CAER	Fly ash	Lead	ppm	76.51	88.68	109.04	TRUE
Cardinal	Fly ash	Lead	ppm	46.125	48.75	51.375	TRUE
City Mine	FBC	Lead	ppm	1335	1355	1404	TRUE
Philadelphia Girard	Ash (NOS)	Lead	ppm	21.6	21.6	21.6	TRUE
Cleveland	Fly ash	Lead	ppm	0.013	0.013	0.013	TRUE
Emerald Anthracite	Ash (NOS)	Lead	ppm	16.8	43.8	50.787	TRUE
EORDC	FGD waste	Lead	ppm	9.7	9.7	9.7	TRUE
Fleming	FBC	Lead	ppm	15	15	15	TRUE
Freeport Mine	FGD waste	Lead	ppm	0.5	0.5	0.5	TRUE
Gale	Ash (NOS)	Lead	ppm	21	21	21	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Girard Estate	Ash (NOS)	Lead	ppm	6	6	6	TRUE
HA	Ash & coal waste	Lead	ppm	8.05	9.6	9.8	TRUE
Harrim 3019	Ash (NOS)	Lead	ppm	26	26	26	TRUE
Harrim 3019	Bottom ash	Lead	ppm	18.025	25.55	33.075	TRUE
Harrim 3019	Fly ash	Lead	ppm	12.5	20.5	38.4	TRUE
an Coal Corporatio	Ash (NOS)	Lead	ppm	11	16.55	33.5	TRUE
an Coal Corporatio	Bottom ash	Lead	ppm	3.34	7.02	17.4	TRUE
an Coal Corporatio	Fly ash	Lead	ppm	44.8	45.4	46	TRUE
Coal Corporation 5	Bottom ash	Lead	ppm	6.25	7.5	8.75	TRUE
Coal Corporation 5	Fly ash	Lead	ppm	28.5	31	33.5	TRUE
ddo Highland Coal (	Ash (NOS)	Lead	ppm	7.5	18	19.5	TRUE
ddo Highland Coal (	Bottom ash	Lead	ppm	33	33	33	TRUE
Kentucky	Bottom ash	Lead	ppm	20	20	20	TRUE
Kentucky	Fly ash	Lead	ppm	330.75	334.5	338.25	TRUE
Knickerbocker Pit	FBC	Lead	ppm	14.5	22.3	32.0425	TRUE
gh Coal and Naviga	Ash (NOS)	Lead	ppm	12.5	16	20	TRUE
LIMB Site	Ash (NOS)	Lead	ppm	13.75	14.5	15.25	TRUE
ttle Sandy #10 Min	Bottom ash	Lead	ppm	120	120	120	TRUE
ttle Sandy #10 Min	Combined ash	Lead	ppm	4.7	7.2	24	TRUE
ttle Sandy #10 Min	FGD waste	Lead	ppm	12.5	13	13.5	TRUE
ttle Sandy #10 Min	Fly ash	Lead	ppm	240	240	240	TRUE
Lone Mtn	Fly ash	Lead	ppm	69.8	69.8	69.8	TRUE
Mandan	FBC	Lead	ppm	11.8	11.8	11.8	TRUE
McCloskey Site	FBC	Lead	ppm	48.75	50	51.25	TRUE
McKay Site	FBC	Lead	ppm	36	49	62	TRUE
Miller	Fly ash	Lead	ppm	38	38	38	TRUE
Miller Creek Mine	Bottom ash	Lead	ppm	5.7	15.4	63.5	TRUE
Miller Creek Mine	Combined ash	Lead	ppm	8.95	17	43.325	TRUE
Miller Creek Mine	Fly ash	Lead	ppm	35.5	48	93.625	TRUE
N & L Coal Co.	Ash (NOS)	Lead	ppm	29.475	45.75	103.75	TRUE
N & L Coal Co.-2	Ash (NOS)	Lead	ppm	20.7	22.9	41.3875	TRUE
Nepco	FBC	Lead	ppm	39	39	39	TRUE
NETL	Bottom ash	Lead	ppm	762	762	762	TRUE
NETL	FBC	Lead	ppm	46.25	52.5	58.75	TRUE
NETL	Fly ash	Lead	ppm	24.75	68	110.5	TRUE
NETL	Slag	Lead	ppm	29	29	29	TRUE
o. 1 Contracting Co	Ash (NOS)	Lead	ppm	29.125	38.75	48.375	TRUE
el Supply Company	Ash (NOS)	Lead	ppm	11	15	18	TRUE
el Supply Company	Ash (NOS)	Lead	ppm	12.025	21	26.55	TRUE
el Supply Company	Ash (NOS)	Lead	ppm	15.5	18	20.5	TRUE
rthampton400002	Ash (NOS)	Lead	ppm	18	18	18	TRUE
heast Energy Com	Ash (NOS)	Lead	ppm	21	25	33.5	TRUE
heast Energy Com	Bottom ash	Lead	ppm	2.2	2.2	2.2	TRUE
heast Energy Com	Fly ash	Lead	ppm	19	19	19	TRUE
eastern Power Cor	Ash (NOS)	Lead	ppm	11.525	14.05	16.575	TRUE
eastern Power Cor	Bottom ash	Lead	ppm	8.7	11.2	15.95	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
eastern Power Con	Fly ash	Lead	ppm	17.5	25.2	37.9	TRUE
Nucla	FBC	Lead	ppm	34.75	35.5	36.25	TRUE
Nucla2	FBC	Lead	ppm	0.945	1.8	12.4	TRUE
Oak Creek	Bottom ash	Lead	ppm	33	33	33	TRUE
aceAnalytical (2010	Slag	Lead	ppm	8.1	8.1	8.1	TRUE
Pacton Corp	Ash (NOS)	Lead	ppm	39	39	39	TRUE
Pacton Corp	Bottom ash	Lead	ppm	40	40	40	TRUE
Pacton Corp	Fly ash	Lead	ppm	56.5	63	101.5	TRUE
Pagnotti Coal Co.	Ash (NOS)	Lead	ppm	20	34	35.7	TRUE
Pagnotti Coal Co.	Fly ash	Lead	ppm	72.5	72.5	72.5	TRUE
Panther Creek	FBC	Lead	ppm	21.125	23.5	29.75	TRUE
Paradise	Fly ash	Lead	ppm	76	76	76	TRUE
ett et al. (1993) Cor	Fly Ash	Lead	ppm	16.7	19.5	20.75	TRUE
Plant 10	FBC	Lead	ppm	29.1	34.8	53.45	TRUE
Plant 12	FBC	Lead	ppm	39.2	50.5	58	TRUE
Plant 8	FBC	Lead	ppm	15.05	20	43.1	TRUE
Plant 9	FBC	Lead	ppm	46.625	52.5	66.875	TRUE
Pleasant Prairie	Bottom ash	Lead	ppm	0.5	0.5	0.5	TRUE
Pleasant Prairie	Fly ash	Lead	ppm	43.5	43.5	43.5	TRUE
Porter Associates	Ash (NOS)	Lead	ppm	12.3	19.15	27.5	TRUE
Porter Associates	Bottom ash	Lead	ppm	3.76	7.05	16	TRUE
Scrubgrass	FBC	Lead	ppm	50	50	50	TRUE
SFA	Fly ash	Lead	ppm	80	80	80	TRUE
Shawnee	FBC	Lead	ppm	4.8	6.6	7.3	TRUE
Silverton	Ash (NOS)	Lead	ppm	25.25	29.5	33.75	TRUE
Sioux	Fly ash	Lead	ppm	182.475	205.95	229.425	TRUE
Stanton	Fly ash	Lead	ppm	65.2	65.2	65.2	TRUE
STK	Fly ash	Lead	ppm	140	140	140	TRUE
ehanna Coal Comp	Ash (NOS)	Lead	ppm	28	41.5	53.925	TRUE
hanna Coal Compa	Ash (NOS)	Lead	ppm	23.15	26.5	34.9	TRUE
SW	Bottom ash	Lead	ppm	9.67	12.4	20	TRUE
SW	Fly ash	Lead	ppm	47.025	52.3	64.15	TRUE
Tracy Vein Slope	Ash (NOS)	Lead	ppm	13.5425	22.4	32.375	TRUE
Tracy Vein Slope	Bottom ash	Lead	ppm	6.435	9.69	12.945	TRUE
Tracy Vein Slope	FBC	Lead	ppm	4.23	4.23	4.23	TRUE
Universal	Combined ash	Lead	ppm	26	32	35	TRUE
USGS	Fly ash	Lead	ppm	45	75	125	TRUE
wood Energy Prop	Ash (NOS)	Lead	ppm	7.02	8.96	14.9	TRUE
Wheelabrator	FBC	Lead	ppm	13.65	20.45	21.5	TRUE
Xcel/MSI	Fly ash	Lead	ppm	41.5	49.55	50.85	TRUE
Yates	Fly ash	Lead	ppm	46	46	46	TRUE
Zhang et al. (2001)	Fly Ash	Lead	ppm	38	48	54	TRUE
1	FBC	Lead	ppm	2.975	10.835	14.0525	TRUE
10	FBC	Lead	ppm	7.8125	9.375	10.9375	TRUE
11	FBC	Lead	ppm	7.375	40.875	73	TRUE
12	FBC	Lead	ppm	39.175	46.9	54.625	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
14	FBC	Lead	ppm	31.2	31.2	31.2	TRUE
17	FBC	Lead	ppm	34.5	50.8	69.5	TRUE
18	FBC	Lead	ppm	16	30	32	TRUE
19	FBC	Lead	ppm	3.75	3.75	3.75	TRUE
2	FBC	Lead	ppm	2	3.1335	4.267	TRUE
20	FBC	Lead	ppm	25.4	28	44.35	TRUE
21	FBC	Lead	ppm	22.25	23.5	36.6	TRUE
23	FBC	Lead	ppm	13.475	14.955	16.295	TRUE
26	FBC	Lead	ppm	4.6625	6.025	7.9375	TRUE
27	FBC	Lead	ppm	16	16	16	TRUE
28	FBC	Lead	ppm	44.2	50.25	60.55	TRUE
29	FBC	Lead	ppm	23.025	35.85	39.675	TRUE
3	FBC	Lead	ppm	6.25	6.25	6.25	TRUE
30	FBC	Lead	ppm	24.7	31.945	46.825	TRUE
31	FBC	Lead	ppm	1.19	1.19	1.19	TRUE
37	FBC	Lead	ppm	44	58	67.5	TRUE
38	FBC	Lead	ppm	21.1	25.7	34.85	TRUE
39	FBC	Lead	ppm	10	15	20	TRUE
4	FBC	Lead	ppm	9.005	14.2	22.5185	TRUE
5	FBC	Lead	ppm	1.71875	4.4625	6.1375	TRUE
6	FBC	Lead	ppm	5.30625	8.1125	10.91875	TRUE
7	FBC	Lead	ppm	105.48	105.48	105.48	TRUE
8	FBC	Lead	ppm	67	67	67	TRUE
A/C Fuels Company	Ash (NOS)	Lead	ppm	13	13	13	TRUE
Baldwin	Fly ash	Lead	ppm	133.2	133.2	133.2	TRUE
B-D Mining Co.	Ash (NOS)	Lead	ppm	23	25	28	TRUE
B-D Mining Co.	Bottom ash	Lead	ppm	26	28	56	TRUE
B-D Mining Co.	Fly ash	Lead	ppm	40.8	44.35	62.375	TRUE
CLSM	Combined ash	Lead	ppm	33	33	33	TRUE
CLSM	FBC	Lead	ppm	18	18	18	TRUE
Coal Creek	Bottom ash	Lead	ppm	0.0087	0.0087	0.0087	TRUE
Coal Creek	Fly ash	Lead	ppm	0.0318	0.0318	0.0318	TRUE
Deer Ridge Mine	Fly ash	Lead	ppm	25	64.295	80.85	TRUE
DPC	Bottom ash	Lead	ppm	4.6	4.6	4.6	TRUE
DPC	Fly ash	Lead	ppm	52.8	52.8	52.8	TRUE
ern Analytical, ID: 5	Slag	Lead	ppm	6.7	6.7	6.7	TRUE
Edgewater	Bottom ash	Lead	ppm	19.9	19.9	19.9	TRUE
EERC?	Combined ash	Lead	ppm	23.2	27.8	32.4	TRUE
EERC?	FGD	Lead	ppm	4.4	20.9	80.3	TRUE
EERC?	FGD gypsum	Lead	ppm	1.5	1.5	1.5	TRUE
EERC?	FGD gypsum liquids	Lead	mg/L	0.001	0.001	0.001	TRUE
EERC?	FGD liquids	Lead	mg/L	0.001	0.001	0.001	TRUE
EERC?	FGD liquids	Lead	ppm	1.5	1.5	1.5	TRUE
EERC?	Fly Ash	Lead	ppm	38.75	63.75	82.5	TRUE
City Mine	FBC	Magnesium	ppm	1601.5	1779	1837	TRUE
Cleveland	Fly ash	Magnesium	ppm	2.26	2.26	2.26	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Freeport Mine	FGD waste	Magnesium	ppm	1470	1470	1470	TRUE
ttle Sandy #10 Mir	Combined ash	Magnesium	ppm	310.5	330	380	TRUE
ttle Sandy #10 Mir	FGD waste	Magnesium	ppm	1015	1160	1230	TRUE
Martins Creek	Bottom ash	Magnesium	ppm	2550	3513	4923	TRUE
Martins Creek	Fly ash	Magnesium	ppm	2140	3100	3166	TRUE
McKay Site	FBC	Magnesium	ppm	45750	57500	69250	TRUE
Miller Creek Mine	Bottom ash	Magnesium	ppm	199	623	1222.42	TRUE
Miller Creek Mine	Combined ash	Magnesium	ppm	171	264.35	2825	TRUE
Miller Creek Mine	Fly ash	Magnesium	ppm	842	977	992	TRUE
Nucla	FBC	Magnesium	ppm	4610	4960	5310	TRUE
Nucla2	FBC	Magnesium	ppm	3750	3900	4650	TRUE
Oak Creek	Bottom ash	Magnesium	ppm	6031	6031	6031	TRUE
Pagnotti Coal Co.	Ash (NOS)	Magnesium	ppm	2330	2330	2330	TRUE
Pleasant Prairie	Bottom ash	Magnesium	ppm	19899	19899	19899	TRUE
Shawnee	FBC	Magnesium	ppm	3240	3730	12000	TRUE
SW	Bottom ash	Magnesium	ppm	4190	4380	4690	TRUE
SW	Fly ash	Magnesium	ppm	4810	5110	5250	TRUE
Universal	Combined ash	Magnesium	ppm	530	633	730	TRUE
CLSM	Combined ash	Magnesium	ppm	6101.8	6101.8	6101.8	TRUE
CLSM	FBC	Magnesium	ppm	2098.2	2098.2	2098.2	TRUE
Deer Ridge Mine	Fly ash	Magnesium	ppm	199.1875	256.5	1963.75	TRUE
DPC	Bottom ash	Magnesium	ppm	899	899	899	TRUE
DPC	Fly ash	Magnesium	ppm	3360	3360	3360	TRUE
ern Analytical, ID: 5	Slag	Magnesium	ppm	1300	1300	1300	TRUE
Edgewater	Bottom ash	Magnesium	ppm	17550	17550	17550	TRUE
Bowen	Fly ash	Manganese	ppm	186.8	186.8	186.8	TRUE
CAER	Bottom ash	Manganese	ppm	211.5	220	254	TRUE
CAER	FGD waste	Manganese	ppm	95	95	95	TRUE
CAER	Fly ash	Manganese	ppm	75	224	242	TRUE
Cardinal	Fly ash	Manganese	ppm	271.85	303.2	334.55	TRUE
Philadelphia Girard	Ash (NOS)	Manganese	ppm	54.6	54.6	54.6	TRUE
Cleveland	Fly ash	Manganese	ppm	0.098	0.098	0.098	TRUE
Emerald Anthracite	Ash (NOS)	Manganese	ppm	74.81925	158.7	228.75	TRUE
Fleming	FBC	Manganese	ppm	50	50	50	TRUE
Freeport Mine	FGD waste	Manganese	ppm	12.3	12.3	12.3	TRUE
Gale	Ash (NOS)	Manganese	ppm	81	81	81	TRUE
Girard Estate	Ash (NOS)	Manganese	ppm	44	44	44	TRUE
HA	Ash & coal waste	Manganese	ppm	37.5	39	104.5	TRUE
Harrim 3019	Ash (NOS)	Manganese	ppm	230.427	230.427	230.427	TRUE
Harrim 3019	Bottom ash	Manganese	ppm	204.1	338.4	472.7	TRUE
Harrim 3019	Fly ash	Manganese	ppm	52.25	72.45	82.5	TRUE
an Coal Corporatio	Ash (NOS)	Manganese	ppm	51.3	85.45	135.75	TRUE
an Coal Corporatio	Bottom ash	Manganese	ppm	15.625	36	73.4	TRUE
an Coal Corporatio	Fly ash	Manganese	ppm	73.075	77.25	81.425	TRUE
Coal Corporation 5	Ash (NOS)	Manganese	ppm	7	7	7	TRUE
Coal Corporation 5	Bottom ash	Manganese	ppm	141.75	147.5	153.25	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Coal Corporation 5	Fly ash	Manganese	ppm	76	87	98	TRUE
ddo Highland Coal (	Ash (NOS)	Manganese	ppm	37.5	40	52	TRUE
ddo Highland Coal (	Bottom ash	Manganese	ppm	39	39	39	TRUE
Kentucky	Bottom ash	Manganese	ppm	230.5	262	291.5	TRUE
Kentucky	Fly ash	Manganese	ppm	126	150.5	169.25	TRUE
Knickerbocker Pit	FBC	Manganese	ppm	55.2	63.24	76.55	TRUE
KY	FGD waste	Manganese	ppm	64	82	96.5	TRUE
gh Coal and Naviga	Ash (NOS)	Manganese	ppm	54	85	103	TRUE
LIMB Site	Ash (NOS)	Manganese	ppm	1050	1100	1150	TRUE
ttle Sandy #10 Min	Bottom ash	Manganese	ppm	200	200	200	TRUE
ttle Sandy #10 Min	Combined ash	Manganese	ppm	36	51	76	TRUE
ttle Sandy #10 Min	FGD waste	Manganese	ppm	25.45	27.9	27.95	TRUE
ttle Sandy #10 Min	Fly ash	Manganese	ppm	86	86	86	TRUE
Lone Mtn	Fly ash	Manganese	ppm	228.4	228.4	228.4	TRUE
Martins Creek	Bottom ash	Manganese	ppm	101	108.15	147.83	TRUE
Martins Creek	Fly ash	Manganese	ppm	63.23	73.9	81.8	TRUE
McCloskey Site	FBC	Manganese	ppm	530	567.5	605	TRUE
McKay Site	FBC	Manganese	ppm	410	490	570	TRUE
Miller	Fly ash	Manganese	ppm	534.3	534.3	534.3	TRUE
Miller Creek Mine	Bottom ash	Manganese	ppm	56	61	120.25	TRUE
Miller Creek Mine	Combined ash	Manganese	ppm	13.695	26	92.5	TRUE
Miller Creek Mine	Fly ash	Manganese	ppm	57.5	72.5	95.4175	TRUE
N & L Coal Co.	Ash (NOS)	Manganese	ppm	91.48575	112.65	184.5	TRUE
N & L Coal Co.-2	Ash (NOS)	Manganese	ppm	99.2	138	200	TRUE
o. 1 Contracting Co	Ash (NOS)	Manganese	ppm	121	124	127	TRUE
el Supply Company	Ash (NOS)	Manganese	ppm	80.5	92	108	TRUE
el Supply Company	Ash (NOS)	Manganese	ppm	41.4	51	76.2	TRUE
el Supply Company	Ash (NOS)	Manganese	ppm	57.85	67.7	77.55	TRUE
rthampton400002	Ash (NOS)	Manganese	ppm	108	108	108	TRUE
heast Energy Com	Ash (NOS)	Manganese	ppm	49.25	79.5	88.625	TRUE
heast Energy Com	Bottom ash	Manganese	ppm	64	64	64	TRUE
heast Energy Com	Fly ash	Manganese	ppm	120	120	120	TRUE
eastern Power Con	Ash (NOS)	Manganese	ppm	21.9	28	41.1	TRUE
eastern Power Con	Bottom ash	Manganese	ppm	22	23.5	42.8	TRUE
eastern Power Con	Fly ash	Manganese	ppm	38.2	48	52.5	TRUE
Nucla	FBC	Manganese	ppm	99	106	113	TRUE
Nucla2	FBC	Manganese	ppm	115	120	140	TRUE
aceAnalytical (201(	Slag	Manganese	ppm	288	288	288	TRUE
Pacton Corp	Ash (NOS)	Manganese	ppm	43	43	43	TRUE
Pacton Corp	Bottom ash	Manganese	ppm	208	208	208	TRUE
Pacton Corp	Fly ash	Manganese	ppm	172.5	200	310	TRUE
Pagnotti Coal Co.	Ash (NOS)	Manganese	ppm	46.4875	66.5	76.65	TRUE
Pagnotti Coal Co.	Fly ash	Manganese	ppm	115	115	115	TRUE
Panther Creek	FBC	Manganese	ppm	73.2	86	97.175	TRUE
Paradise	Fly ash	Manganese	ppm	366.7	366.7	366.7	TRUE
ett et al. (1993) Co	Fly Ash	Manganese	ppm	300	370	480	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Pleasant Prairie	Fly ash	Manganese	ppm	312.7	312.7	312.7	TRUE
Porter Associates	Ash (NOS)	Manganese	ppm	38.5	52.1	81.5	TRUE
Porter Associates	Bottom ash	Manganese	ppm	28.4	48.9	57.75	TRUE
ylkill Reclamation (	Ash (NOS)	Manganese	ppm	47	47	47	TRUE
Shawnee	FBC	Manganese	ppm	110	160	540	TRUE
Silverton	Ash (NOS)	Manganese	ppm	86.25	91.5	96.75	TRUE
Sioux	Fly ash	Manganese	ppm	179.85	189.2	198.55	TRUE
Stanton	Fly ash	Manganese	ppm	284.9	284.9	284.9	TRUE
ehanna Coal Comp	Ash (NOS)	Manganese	ppm	123	147	167	TRUE
hanna Coal Compa	Ash (NOS)	Manganese	ppm	46.95	53.05	63	TRUE
SW	Bottom ash	Manganese	ppm	165	186	203	TRUE
SW	Fly ash	Manganese	ppm	159	175	187	TRUE
Tracy Vein Slope	Ash (NOS)	Manganese	ppm	61.175	80.15	325.1	TRUE
Tracy Vein Slope	Bottom ash	Manganese	ppm	78.275	89.85	101.425	TRUE
Tracy Vein Slope	FBC	Manganese	ppm	25.6	25.6	25.6	TRUE
Universal	Combined ash	Manganese	ppm	55	77	110	TRUE
USGS	Fly ash	Manganese	ppm	270	330	360	TRUE
wood Energy Prop	Ash (NOS)	Manganese	ppm	39.875	54.25	70.1	TRUE
Wheelabrator	FBC	Manganese	ppm	42.925	55.55	76.825	TRUE
Xcel/MSI	Fly ash	Manganese	ppm	135.75	146	343.75	TRUE
Yates	Fly ash	Manganese	ppm	339.4	339.4	339.4	TRUE
Zhang et al. (2001)	Fly Ash	Manganese	ppm	140	480	700	TRUE
12	FBC	Manganese	ppm	34.35	83.75	260	TRUE
14	FBC	Manganese	ppm	41.8	41.8	41.8	TRUE
17	FBC	Manganese	ppm	59.95	63.55	128.575	TRUE
18	FBC	Manganese	ppm	87.5	101	103.5	TRUE
19	FBC	Manganese	ppm	45.8	45.8	45.8	TRUE
2	FBC	Manganese	ppm	110	118.2	126.4	TRUE
20	FBC	Manganese	ppm	53.4	63	82.2	TRUE
21	FBC	Manganese	ppm	57.25	82	91.525	TRUE
27	FBC	Manganese	ppm	409	409	409	TRUE
28	FBC	Manganese	ppm	48.8	63.3	82.9	TRUE
29	FBC	Manganese	ppm	565.975	635.8	719.425	TRUE
3	FBC	Manganese	ppm	0.05	0.05	0.05	TRUE
30	FBC	Manganese	ppm	115.65	177.65	280.075	TRUE
31	FBC	Manganese	ppm	141	141	141	TRUE
37	FBC	Manganese	ppm	672	672	672	TRUE
38	FBC	Manganese	ppm	45.4	61.1	89.775	TRUE
39	FBC	Manganese	ppm	485	500	515	TRUE
4	FBC	Manganese	ppm	56.65	80.46	90.775	TRUE
6	FBC	Manganese	ppm	81.55	91.7	101.85	TRUE
7	FBC	Manganese	ppm	524.88	524.88	524.88	TRUE
8	FBC	Manganese	ppm	89	89	89	TRUE
A/C Fuels Company	Ash (NOS)	Manganese	ppm	64	64	64	TRUE
Baldwin	Fly ash	Manganese	ppm	414.3	414.3	414.3	TRUE
B-D Mining Co.	Ash (NOS)	Manganese	ppm	54.325	65.65	79.925	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
B-D Mining Co.	Bottom ash	Manganese	ppm	49.5	51.8	52.675	TRUE
B-D Mining Co.	Fly ash	Manganese	ppm	82.775	88.7	92.3	TRUE
CLSM	Combined ash	Manganese	ppm	607.8	607.8	607.8	TRUE
CLSM	FBC	Manganese	ppm	1561.8	1561.8	1561.8	TRUE
Deer Ridge Mine	Fly ash	Manganese	ppm	11.8675	17.45	88.5	TRUE
DPC	Bottom ash	Manganese	ppm	144	144	144	TRUE
DPC	Fly ash	Manganese	ppm	209	209	209	TRUE
ern Analytical, ID: 5	Slag	Manganese	ppm	46	46	46	TRUE
City Mine	FBC	Mercury	ppm	0.25	0.25	0.25	TRUE
Philadelphia Girard	Ash (NOS)	Mercury	ppm	0.22	0.22	0.22	TRUE
Emerald Anthracite	Ash (NOS)	Mercury	ppm	0.36875	0.445	0.5925	TRUE
EORDC	FGD waste	Mercury	ppm	0.5	0.5	0.5	TRUE
Freeport Mine	FGD waste	Mercury	ppm	1.1125	1.115	1.1175	TRUE
Gale	Ash (NOS)	Mercury	ppm	2.5	2.5	2.5	TRUE
Girard Estate	Ash (NOS)	Mercury	ppm	0.25	0.25	0.25	TRUE
HA	Ash & coal waste	Mercury	ppm	0.065	0.065	0.065	TRUE
Harrim 3019	Ash (NOS)	Mercury	ppm	8.5	8.5	8.5	TRUE
Harrim 3019	Bottom ash	Mercury	ppm	0.408	0.408	0.408	TRUE
Harrim 3019	Fly ash	Mercury	ppm	0.19	0.2	0.44	TRUE
an Coal Corporatio	Ash (NOS)	Mercury	ppm	0.23875	0.449	1.36	TRUE
an Coal Corporatio	Bottom ash	Mercury	ppm	0.22	0.285	0.342	TRUE
an Coal Corporatio	Fly ash	Mercury	ppm	1.98	3.77	5.56	TRUE
Coal Corporation 5	Ash (NOS)	Mercury	ppm	0.1	0.1	0.1	TRUE
Coal Corporation 5	Bottom ash	Mercury	ppm	0.017	0.024	0.031	TRUE
Coal Corporation 5	Fly ash	Mercury	ppm	0.08	0.15	0.22	TRUE
ddo Highland Coal (	Ash (NOS)	Mercury	ppm	0.02	0.0765	23.28325	TRUE
ddo Highland Coal (	Bottom ash	Mercury	ppm	0.02	0.02	0.02	TRUE
Knickerbocker Pit	FBC	Mercury	ppm	0.33	0.42	0.61	TRUE
gh Coal and Naviga	Ash (NOS)	Mercury	ppm	0.4425	0.5	0.538	TRUE
ttle Sandy #10 Min	Bottom ash	Mercury	ppm	0.0125	0.0125	0.0125	TRUE
ttle Sandy #10 Min	Combined ash	Mercury	ppm	0.0125	0.013	0.5	TRUE
ttle Sandy #10 Min	FGD waste	Mercury	ppm	0.425	0.5	0.5	TRUE
ttle Sandy #10 Min	Fly ash	Mercury	ppm	0.043	0.043	0.043	TRUE
Mandan	FBC	Mercury	ppm	0.6058	0.6058	0.6058	TRUE
McCloskey Site	FBC	Mercury	ppm	0.34825	0.4465	0.54475	TRUE
McKay Site	FBC	Mercury	ppm	0.3225	0.345	0.3675	TRUE
Miller Creek Mine	Bottom ash	Mercury	ppm	0.00037	0.00715	0.01	TRUE
Miller Creek Mine	Combined ash	Mercury	ppm	0.00015	0.01	0.1335	TRUE
Miller Creek Mine	Fly ash	Mercury	ppm	0.0125	0.02625	0.113	TRUE
N & L Coal Co.	Ash (NOS)	Mercury	ppm	0.48425	8.5	13.8875	TRUE
N & L Coal Co.-2	Ash (NOS)	Mercury	ppm	1.6625	5.425	7.5	TRUE
Nepco	FBC	Mercury	ppm	0.01	0.01	0.01	TRUE
o. 1 Contracting Co	Ash (NOS)	Mercury	ppm	0.3	0.3	0.3	TRUE
uel Supply Company	Ash (NOS)	Mercury	ppm	0.194	0.277	0.535	TRUE
uel Supply Company	Ash (NOS)	Mercury	ppm	0.1835	0.222	0.311	TRUE
uel Supply Company	Ash (NOS)	Mercury	ppm	0.25275	0.4485	0.64425	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
rthampton400002	Ash (NOS)	Mercury	ppm	0.535	0.535	0.535	TRUE
heast Energy Com	Ash (NOS)	Mercury	ppm	0.02	0.255	1	TRUE
heast Energy Com	Bottom ash	Mercury	ppm	0.05	0.05	0.05	TRUE
heast Energy Com	Fly ash	Mercury	ppm	0.13	0.13	0.13	TRUE
eastern Power Con	Ash (NOS)	Mercury	ppm	0.44	0.61	0.645	TRUE
eastern Power Con	Bottom ash	Mercury	ppm	0.03	0.05	0.05	TRUE
eastern Power Con	Fly ash	Mercury	ppm	0.4825	0.712	1.0025	TRUE
Nucla2	FBC	Mercury	ppm	0.15625	0.29	0.31	TRUE
Oak Creek	Bottom ash	Mercury	ppm	0.05	0.05	0.05	TRUE
Pacton Corp	Fly ash	Mercury	ppm	0.2	0.4	0.4	TRUE
Pagnotti Coal Co.	Ash (NOS)	Mercury	ppm	0.23225	0.425	0.61	TRUE
Pagnotti Coal Co.	Fly ash	Mercury	ppm	0.01	0.01	0.01	TRUE
Panther Creek	FBC	Mercury	ppm	0.4	0.6	0.6	TRUE
ett et al. (1993) Co	Fly Ash	Mercury	ppm	0.1975	0.275	0.3925	TRUE
Plant 10	FBC	Mercury	ppm	0.7325	0.93	1.4125	TRUE
Plant 12	FBC	Mercury	ppm	0.05	0.69	1.94	TRUE
Plant 8	FBC	Mercury	ppm	0.01	0.01	0.015	TRUE
Plant 9	FBC	Mercury	ppm	0.3425	0.56	0.7875	TRUE
Pleasant Prairie	Bottom ash	Mercury	ppm	0.05	0.05	0.05	TRUE
Porter Associates	Ash (NOS)	Mercury	ppm	0.2625	0.377	0.9985	TRUE
Porter Associates	Bottom ash	Mercury	ppm	0.19	0.32	0.42	TRUE
Scrubgrass	FBC	Mercury	ppm	0.01	0.01	0.01	TRUE
Shawnee	FBC	Mercury	ppm	0.05	0.16	0.19	TRUE
ehanna Coal Comp	Ash (NOS)	Mercury	ppm	0.142	0.2405	0.29625	TRUE
hanna Coal Compa	Ash (NOS)	Mercury	ppm	0.19625	0.2265	0.455	TRUE
SW	Bottom ash	Mercury	ppm	0.025	0.025	0.025	TRUE
SW	Fly ash	Mercury	ppm	0.01	0.025	0.05	TRUE
Tracy Vein Slope	Ash (NOS)	Mercury	ppm	0.9245	1.38	3.36	TRUE
Tracy Vein Slope	Bottom ash	Mercury	ppm	0.24925	0.3775	0.50575	TRUE
Tracy Vein Slope	FBC	Mercury	ppm	0.288	0.288	0.288	TRUE
Universal	Combined ash	Mercury	ppm	0.0625	0.15	0.2	TRUE
wood Energy Prop	Ash (NOS)	Mercury	ppm	0.157	0.266	0.3345	TRUE
Wheelabrator	FBC	Mercury	ppm	0.26	0.29	0.32	TRUE
Xcel/MSI	Fly ash	Mercury	ppm	0.1975	0.2585	0.345	TRUE
Zhang et al. (2001)	Fly Ash	Mercury	ppm	0.15	0.15	0.15	TRUE
1	FBC	Mercury	ppm	0.03	0.03	0.057	TRUE
10	FBC	Mercury	ppm	0.05	0.05	0.05	TRUE
11	FBC	Mercury	ppm	0.06875	0.1325	0.19625	TRUE
12	FBC	Mercury	ppm	0.34875	0.655	0.7775	TRUE
14	FBC	Mercury	ppm	0.222	0.222	0.222	TRUE
17	FBC	Mercury	ppm	1.2375	1.715	2.1775	TRUE
18	FBC	Mercury	ppm	0.1525	0.3	0.4	TRUE
19	FBC	Mercury	ppm	0.125	0.125	0.125	TRUE
2	FBC	Mercury	ppm	0.161	0.161	0.161	TRUE
20	FBC	Mercury	ppm	0.305	0.41	0.61	TRUE
21	FBC	Mercury	ppm	0.2725	0.375	0.5525	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
23	FBC	Mercury	ppm	0.36	0.385	0.4425	TRUE
26	FBC	Mercury	ppm	0.05	0.05	0.125	TRUE
27	FBC	Mercury	ppm	0.47	0.47	0.47	TRUE
28	FBC	Mercury	ppm	0.03125	0.474	1.1675	TRUE
29	FBC	Mercury	ppm	0.027669	0.4232	0.897125	TRUE
3	FBC	Mercury	ppm	0.05	0.05	0.05	TRUE
30	FBC	Mercury	ppm	0.01	0.44	1.475	TRUE
31	FBC	Mercury	ppm	0.61	0.61	0.61	TRUE
37	FBC	Mercury	ppm	0.006875	0.01125	0.015625	TRUE
38	FBC	Mercury	ppm	0.0081	0.1145	0.25875	TRUE
39	FBC	Mercury	ppm	0.095	0.17	0.245	TRUE
4	FBC	Mercury	ppm	0.00005	0.0002	0.13	TRUE
5	FBC	Mercury	ppm	0.05	0.05	0.05	TRUE
6	FBC	Mercury	ppm	0.9	1.16	1.42	TRUE
7	FBC	Mercury	ppm	0.05	0.05	0.05	TRUE
8	FBC	Mercury	ppm	0.45	0.45	0.45	TRUE
A/C Fuels Company	Ash (NOS)	Mercury	ppm	0.7	0.7	0.7	TRUE
B-D Mining Co.	Ash (NOS)	Mercury	ppm	0.28025	0.452	0.64075	TRUE
B-D Mining Co.	Fly ash	Mercury	ppm	0.27	0.34	0.365	TRUE
CLSM	Combined ash	Mercury	ppm	27.3	27.3	27.3	TRUE
CLSM	FBC	Mercury	ppm	4	4	4	TRUE
Coal Creek	Bottom ash	Mercury	ppm	0.0009	0.0009	0.0009	TRUE
Coal Creek	Fly ash	Mercury	ppm	0.0003	0.0003	0.0003	TRUE
Deer Ridge Mine	Fly ash	Mercury	ppm	0.02025	0.0735	0.1625	TRUE
DPC	Bottom ash	Mercury	ppm	0.007	0.007	0.007	TRUE
DPC	Fly ash	Mercury	ppm	0.247	0.247	0.247	TRUE
ern Analytical, ID: 5	Slag	Mercury	ppm	0.05	0.05	0.05	TRUE
EERC?	Combined ash	Mercury	ppm	0.03175	0.0585	0.08525	TRUE
EERC?	FGD	Mercury	ppm	0.1755	0.233	0.263	TRUE
EERC?	FGD gypsum	Mercury	ppm	0.04475	0.05	0.0845	TRUE
EERC?	FGD gypsum liquids	Mercury	mg/L	0.000005	0.000005	0.000005	TRUE
EERC?	FGD liquids	Mercury	mg/L	0.000075	0.000075	0.000075	TRUE
EERC?	FGD liquids	Mercury	ppm	0.085	0.12	0.158	TRUE
EERC?	Fly Ash	Mercury	ppm	0.157	0.48	1.00375	TRUE
CAER	Bottom ash	Molybdenum	ppm	20.5	22	24.5	TRUE
CAER	FGD waste	Molybdenum	ppm	28	28	28	TRUE
CAER	Fly ash	Molybdenum	ppm	38	91	92	TRUE
Emerald Anthracite	Ash (NOS)	Molybdenum	ppm	25.55	28	34	TRUE
EORDC	FGD waste	Molybdenum	ppm	3.8	3.8	3.8	TRUE
Gale	Ash (NOS)	Molybdenum	ppm	5	5	5	TRUE
HA	Ash & coal waste	Molybdenum	ppm	0.5	0.5	0.5	TRUE
Harrim 3019	Ash (NOS)	Molybdenum	ppm	10.5	10.5	10.5	TRUE
Harrim 3019	Bottom ash	Molybdenum	ppm	25	25	25	TRUE
Harrim 3019	Fly ash	Molybdenum	ppm	16	17	19	TRUE
an Coal Corporatio	Ash (NOS)	Molybdenum	ppm	6.1425	9.635	25.75	TRUE
an Coal Corporatio	Bottom ash	Molybdenum	ppm	5.15	10.8	20	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
an Coal Corporatio	Fly ash	Molybdenum	ppm	10.5875	12.325	14.0625	TRUE
Coal Corporation 5	Ash (NOS)	Molybdenum	ppm	19	19	19	TRUE
Coal Corporation 5	Bottom ash	Molybdenum	ppm	17.25	17.5	17.75	TRUE
Coal Corporation 5	Fly ash	Molybdenum	ppm	14	14	14	TRUE
ddo Highland Coal (	Ash (NOS)	Molybdenum	ppm	7.5	19	136	TRUE
ddo Highland Coal (	Bottom ash	Molybdenum	ppm	5	5	5	TRUE
Knickerbocker Pit	FBC	Molybdenum	ppm	3.3	13	46.97	TRUE
KY	FGD waste	Molybdenum	ppm	24.5	26	26.5	TRUE
gh Coal and Naviga	Ash (NOS)	Molybdenum	ppm	10	12	13	TRUE
LIMB Site	Ash (NOS)	Molybdenum	ppm	2.5	2.5	2.5	TRUE
ttle Sandy #10 Min	Bottom ash	Molybdenum	ppm	2.5	2.5	2.5	TRUE
ttle Sandy #10 Min	Combined ash	Molybdenum	ppm	2.5	2.54	3.6	TRUE
ttle Sandy #10 Min	FGD waste	Molybdenum	ppm	8.05	9.8	12.55	TRUE
ttle Sandy #10 Min	Fly ash	Molybdenum	ppm	15	15	15	TRUE
McCloskey Site	FBC	Molybdenum	ppm	0.15	0.15	0.15	TRUE
McKay Site	FBC	Molybdenum	ppm	4.375	6.25	8.125	TRUE
Miller Creek Mine	Bottom ash	Molybdenum	ppm	0.316	2.7	5.66	TRUE
Miller Creek Mine	Combined ash	Molybdenum	ppm	1.7625	3.795	16	TRUE
Miller Creek Mine	Fly ash	Molybdenum	ppm	3.075	4.55	13.7725	TRUE
N & L Coal Co.	Ash (NOS)	Molybdenum	ppm	10	15.715	30	TRUE
N & L Coal Co.-2	Ash (NOS)	Molybdenum	ppm	6.0625	7	10.1125	TRUE
o. 1 Contracting Co	Ash (NOS)	Molybdenum	ppm	4.725	9.15	13.575	TRUE
uel Supply Company	Ash (NOS)	Molybdenum	ppm	10	17	31	TRUE
uel Supply Company	Ash (NOS)	Molybdenum	ppm	0.0443	0.0443	0.0443	TRUE
uel Supply Company	Ash (NOS)	Molybdenum	ppm	36.25	52.5	68.75	TRUE
rthampton400002	Ash (NOS)	Molybdenum	ppm	10	10	10	TRUE
heast Energy Com	Ash (NOS)	Molybdenum	ppm	11	14	25	TRUE
heast Energy Com	Bottom ash	Molybdenum	ppm	0.5	0.5	0.5	TRUE
heast Energy Com	Fly ash	Molybdenum	ppm	1.2	1.2	1.2	TRUE
eastern Power Con	Ash (NOS)	Molybdenum	ppm	2.9	2.9	2.9	TRUE
eastern Power Con	Bottom ash	Molybdenum	ppm	0.4735	0.785	7.29	TRUE
eastern Power Con	Fly ash	Molybdenum	ppm	0.7625	3.135	17.525	TRUE
Nucla	FBC	Molybdenum	ppm	82	83	84	TRUE
Nucla2	FBC	Molybdenum	ppm	2.375	2.45	3.825	TRUE
aceAnalytical (201(	Slag	Molybdenum	ppm	2.3	2.3	2.3	TRUE
Pacton Corp	Ash (NOS)	Molybdenum	ppm	17	17	17	TRUE
Pacton Corp	Bottom ash	Molybdenum	ppm	15	15	15	TRUE
Pacton Corp	Fly ash	Molybdenum	ppm	9	18	20	TRUE
Pagnotti Coal Co.	Ash (NOS)	Molybdenum	ppm	12.625	13.25	13.875	TRUE
Pagnotti Coal Co.	Fly ash	Molybdenum	ppm	50	50	50	TRUE
Panther Creek	FBC	Molybdenum	ppm	1.3	3.3	16	TRUE
ett et al. (1993) Co	Fly Ash	Molybdenum	ppm	11	16	31	TRUE
Porter Associates	Ash (NOS)	Molybdenum	ppm	5	15.585	26.75	TRUE
Porter Associates	Bottom ash	Molybdenum	ppm	9	21	34	TRUE
Shawnee	FBC	Molybdenum	ppm	4.8	5	6	TRUE
Silverton	Ash (NOS)	Molybdenum	ppm	5	5	5	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
ehanna Coal Comp	Ash (NOS)	Molybdenum	ppm	17	31	33.25	TRUE
hanna Coal Compa	Ash (NOS)	Molybdenum	ppm	10.25	13	26.5	TRUE
Tracy Vein Slope	Ash (NOS)	Molybdenum	ppm	8.22	9.385	10.65	TRUE
Tracy Vein Slope	Bottom ash	Molybdenum	ppm	3.4025	4.195	4.9875	TRUE
Tracy Vein Slope	FBC	Molybdenum	ppm	0.84	0.84	0.84	TRUE
Universal	Combined ash	Molybdenum	ppm	2.73	3.3	3.97	TRUE
wood Energy Prop	Ash (NOS)	Molybdenum	ppm	0.83	0.92	1.37	TRUE
Wheelabrator	FBC	Molybdenum	ppm	1.5475	2.865	18.0475	TRUE
Xcel/MSI	Fly ash	Molybdenum	ppm	8.675	9.25	10.95	TRUE
Zhang et al. (2001)	Fly Ash	Molybdenum	ppm	160	170	200	TRUE
1	FBC	Molybdenum	ppm	9.48	15.1	16.14	TRUE
10	FBC	Molybdenum	ppm	15.625	18.75	21.875	TRUE
12	FBC	Molybdenum	ppm	10	13	18.5	TRUE
14	FBC	Molybdenum	ppm	2.5	2.5	2.5	TRUE
17	FBC	Molybdenum	ppm	1.25	2.3	5	TRUE
18	FBC	Molybdenum	ppm	7	8	8.5	TRUE
19	FBC	Molybdenum	ppm	24	24	24	TRUE
2	FBC	Molybdenum	ppm	3.1	3.1	3.1	TRUE
20	FBC	Molybdenum	ppm	7	12	19	TRUE
21	FBC	Molybdenum	ppm	1.25	1.25	1.25	TRUE
23	FBC	Molybdenum	ppm	2.19	2.345	2.5	TRUE
26	FBC	Molybdenum	ppm	4.9	6.025	8.6875	TRUE
27	FBC	Molybdenum	ppm	3	3	3	TRUE
28	FBC	Molybdenum	ppm	9.06875	35.5	57.75	TRUE
29	FBC	Molybdenum	ppm	0.075	0.075	107.7188	TRUE
3	FBC	Molybdenum	ppm	6.25	6.25	6.25	TRUE
30	FBC	Molybdenum	ppm	0.675	12.75	21.075	TRUE
31	FBC	Molybdenum	ppm	8	8	8	TRUE
37	FBC	Molybdenum	ppm	6.875	8.25	9.625	TRUE
38	FBC	Molybdenum	ppm	2.5	13.25	23.25	TRUE
39	FBC	Molybdenum	ppm	9.25	13.5	17.75	TRUE
4	FBC	Molybdenum	ppm	0.365	18.945	22.469	TRUE
5	FBC	Molybdenum	ppm	7.1	11.5	15	TRUE
6	FBC	Molybdenum	ppm	0.775	1.425	2.075	TRUE
7	FBC	Molybdenum	ppm	4.04	4.04	4.04	TRUE
A/C Fuels Company	Ash (NOS)	Molybdenum	ppm	5	5	5	TRUE
B-D Mining Co.	Ash (NOS)	Molybdenum	ppm	10.955	13.5	19.5	TRUE
B-D Mining Co.	Fly ash	Molybdenum	ppm	3.5	3.5	3.5	TRUE
CLSM	Combined ash	Molybdenum	ppm	33.15	33.15	33.15	TRUE
CLSM	FBC	Molybdenum	ppm	125.7	125.7	125.7	TRUE
Deer Ridge Mine	Fly ash	Molybdenum	ppm	1.825	2.55	4.02625	TRUE
DPC	Bottom ash	Molybdenum	ppm	2.38	2.38	2.38	TRUE
DPC	Fly ash	Molybdenum	ppm	14.3	14.3	14.3	TRUE
ern Analytical, ID: 5	Slag	Molybdenum	ppm	3	3	3	TRUE
Bowen	Fly ash	Nickel	ppm	130.1	130.1	130.1	TRUE
CAER	Bottom ash	Nickel	ppm	62.5	67	94	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
CAER	FGD waste	Nickel	ppm	5	5	5	TRUE
CAER	Fly ash	Nickel	ppm	127	151	156	TRUE
Cardinal	Fly ash	Nickel	ppm	138.425	140.25	142.075	TRUE
City Mine	FBC	Nickel	ppm	321.5	399	432.5	TRUE
Philadelphia Girard	Ash (NOS)	Nickel	ppm	12.2	12.2	12.2	TRUE
Cleveland	Fly ash	Nickel	ppm	0.049	0.049	0.049	TRUE
Emerald Anthracite	Ash (NOS)	Nickel	ppm	19.55	36.95	95.34225	TRUE
EORDC	FGD waste	Nickel	ppm	18	18	18	TRUE
Fleming	FBC	Nickel	ppm	23	23	23	TRUE
Freeport Mine	FGD waste	Nickel	ppm	2.5	2.5	2.5	TRUE
Gale	Ash (NOS)	Nickel	ppm	17	17	17	TRUE
HA	Ash & coal waste	Nickel	ppm	10.5	11	12.5	TRUE
Harrim 3019	Ash (NOS)	Nickel	ppm	112.5	112.5	112.5	TRUE
Harrim 3019	Bottom ash	Nickel	ppm	62.8	64.1	65.4	TRUE
Harrim 3019	Fly ash	Nickel	ppm	45.5	55.75	68.85	TRUE
an Coal Corporatio	Ash (NOS)	Nickel	ppm	15.95	26.5	42.15	TRUE
an Coal Corporatio	Bottom ash	Nickel	ppm	5.42	11.5	40.15	TRUE
an Coal Corporatio	Fly ash	Nickel	ppm	67.725	79.95	92.175	TRUE
Coal Corporation 5	Ash (NOS)	Nickel	ppm	34	34	34	TRUE
Coal Corporation 5	Bottom ash	Nickel	ppm	42.75	45.5	48.25	TRUE
Coal Corporation 5	Fly ash	Nickel	ppm	47	51	55	TRUE
ddo Highland Coal (	Ash (NOS)	Nickel	ppm	27.5	32	45	TRUE
ddo Highland Coal (	Bottom ash	Nickel	ppm	31.3	31.3	31.3	TRUE
Kentucky	Bottom ash	Nickel	ppm	64.5	67	137	TRUE
Kentucky	Fly ash	Nickel	ppm	241.25	320.5	500.25	TRUE
Knickerbocker Pit	FBC	Nickel	ppm	8.575	10.1	13.0825	TRUE
KY	FGD waste	Nickel	ppm	0.005	0.005	3.5	TRUE
gh Coal and Naviga	Ash (NOS)	Nickel	ppm	19	22	31	TRUE
LIMB Site	Ash (NOS)	Nickel	ppm	65.25	76.5	87.75	TRUE
ttle Sandy #10 Min	Bottom ash	Nickel	ppm	21	21	21	TRUE
ttle Sandy #10 Min	Combined ash	Nickel	ppm	12	13	13	TRUE
ttle Sandy #10 Min	FGD waste	Nickel	ppm	0.5	0.5	0.73	TRUE
ttle Sandy #10 Min	Fly ash	Nickel	ppm	270	270	270	TRUE
Lone Mtn	Fly ash	Nickel	ppm	195.6	195.6	195.6	TRUE
Martins Creek	Bottom ash	Nickel	ppm	65.19	77.2	127.86	TRUE
Martins Creek	Fly ash	Nickel	ppm	66.3	77.06	80.97	TRUE
McCloskey Site	FBC	Nickel	ppm	156.25	165	173.75	TRUE
McKay Site	FBC	Nickel	ppm	43.75	47.5	51.25	TRUE
Miller	Fly ash	Nickel	ppm	130.1	130.1	130.1	TRUE
Miller Creek Mine	Bottom ash	Nickel	ppm	75.6	130	145.1	TRUE
Miller Creek Mine	Combined ash	Nickel	ppm	40.5	66.46	138.5	TRUE
Miller Creek Mine	Fly ash	Nickel	ppm	19.5	34	131.25	TRUE
N & L Coal Co.	Ash (NOS)	Nickel	ppm	75.205	116	148.5	TRUE
N & L Coal Co.-2	Ash (NOS)	Nickel	ppm	61.5	92.6	132	TRUE
Nepco	FBC	Nickel	ppm	545	545	545	TRUE
NETL	Bottom ash	Nickel	ppm	199	199	199	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
NETL	FBC	Nickel	ppm	427	728	1029	TRUE
NETL	Fly ash	Nickel	ppm	50	106.5	124.25	TRUE
NETL	Slag	Nickel	ppm	710	710	710	TRUE
ɔ. 1 Contracting Co	Ash (NOS)	Nickel	ppm	356.75	694.5	1032.25	TRUE
ıel Supply Compan	Ash (NOS)	Nickel	ppm	24	27	28	TRUE
ıel Supply Compan	Ash (NOS)	Nickel	ppm	10.55	18.5	39.15	TRUE
ıel Supply Compan	Ash (NOS)	Nickel	ppm	18.75	20.5	22.25	TRUE
ɔrthampton400002	Ash (NOS)	Nickel	ppm	28	28	28	TRUE
heast Energy Com	Ash (NOS)	Nickel	ppm	16.5	29	39.5	TRUE
heast Energy Com	Bottom ash	Nickel	ppm	6.4	6.4	6.4	TRUE
heast Energy Com	Fly ash	Nickel	ppm	31	31	31	TRUE
eastern Power Con	Ash (NOS)	Nickel	ppm	10.8	10.8	10.8	TRUE
eastern Power Con	Bottom ash	Nickel	ppm	4.23	4.41	5.23	TRUE
eastern Power Con	Fly ash	Nickel	ppm	7.95	10.03	10.75	TRUE
Nucla	FBC	Nickel	ppm	26.25	27.5	28.75	TRUE
Nucla2	FBC	Nickel	ppm	12.4	18	18	TRUE
Oak Creek	Bottom ash	Nickel	ppm	140	140	140	TRUE
aceAnalytical (201(	Slag	Nickel	ppm	24.8	24.8	24.8	TRUE
Pacton Corp	Ash (NOS)	Nickel	ppm	18	18	18	TRUE
Pacton Corp	Bottom ash	Nickel	ppm	23	23	23	TRUE
Pacton Corp	Fly ash	Nickel	ppm	45	58	145	TRUE
Pagnotti Coal Co.	Ash (NOS)	Nickel	ppm	10	10.5	16.4	TRUE
Pagnotti Coal Co.	Fly ash	Nickel	ppm	2	2	2	TRUE
Panther Creek	FBC	Nickel	ppm	14.5	19	23.775	TRUE
Paradise	Fly ash	Nickel	ppm	162.2	162.2	162.2	TRUE
ett et al. (1993) Co	Fly Ash	Nickel	ppm	30.25	32.5	265.5	TRUE
Plant 10	FBC	Nickel	ppm	21.35	26.8	39.75	TRUE
Plant 12	FBC	Nickel	ppm	30	38.4	43.5	TRUE
Plant 8	FBC	Nickel	ppm	24	25	28	TRUE
Plant 9	FBC	Nickel	ppm	87.95	121.55	145	TRUE
Pleasant Prairie	Bottom ash	Nickel	ppm	48	48	48	TRUE
Pleasant Prairie	Fly ash	Nickel	ppm	93.8	93.8	93.8	TRUE
Porter Associates	Ash (NOS)	Nickel	ppm	16.7	38.25	66.85	TRUE
Porter Associates	Bottom ash	Nickel	ppm	17	31	41	TRUE
ylkill Reclamation (	Ash (NOS)	Nickel	ppm	9	9	9	TRUE
Scrubgrass	FBC	Nickel	ppm	45	45	45	TRUE
SFA	Fly ash	Nickel	ppm	130	130	130	TRUE
Shawnee	FBC	Nickel	ppm	2	33	80	TRUE
Silverton	Ash (NOS)	Nickel	ppm	17.75	18.5	19.25	TRUE
Sioux	Fly ash	Nickel	ppm	178.4	187.9	197.4	TRUE
Stanton	Fly ash	Nickel	ppm	70.2	70.2	70.2	TRUE
STK	Fly ash	Nickel	ppm	10	10	10	TRUE
ehanna Coal Comp	Ash (NOS)	Nickel	ppm	178.5	192.5	199	TRUE
hanna Coal Compa	Ash (NOS)	Nickel	ppm	11.05	14	16.85	TRUE
Tracy Vein Slope	Ash (NOS)	Nickel	ppm	28.225	36.75	48.375	TRUE
Tracy Vein Slope	Bottom ash	Nickel	ppm	43.8	59	74.2	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Tracy Vein Slope	FBC	Nickel	ppm	2.87	2.87	2.87	TRUE
Universal	Combined ash	Nickel	ppm	31	38.25	65	TRUE
USGS	Fly ash	Nickel	ppm	145.5	200	340	TRUE
wood Energy Prop	Ash (NOS)	Nickel	ppm	5.7375	7.165	8.425	TRUE
Wheelabrator	FBC	Nickel	ppm	9.5	11.2	15.4	TRUE
Xcel/MSI	Fly ash	Nickel	ppm	39	59	75.5	TRUE
Yates	Fly ash	Nickel	ppm	147.1	147.1	147.1	TRUE
Zhang et al. (2001)	Fly Ash	Nickel	ppm	33	39	100	TRUE
1	FBC	Nickel	ppm	13.85	14.56	14.955	TRUE
10	FBC	Nickel	ppm	7.8125	9.375	10.9375	TRUE
11	FBC	Nickel	ppm	28.5	31	33.5	TRUE
12	FBC	Nickel	ppm	14.2	18	19.9	TRUE
14	FBC	Nickel	ppm	23	23	23	TRUE
17	FBC	Nickel	ppm	19.925	27.75	37.075	TRUE
18	FBC	Nickel	ppm	19.5	21	31.5	TRUE
19	FBC	Nickel	ppm	593.5	724	854.5	TRUE
2	FBC	Nickel	ppm	3.1	9.6835	16.267	TRUE
20	FBC	Nickel	ppm	12	20.2	31.95	TRUE
21	FBC	Nickel	ppm	11	12.5	26.75	TRUE
23	FBC	Nickel	ppm	29.785	31.54	33.9475	TRUE
26	FBC	Nickel	ppm	525.75	761	846.5	TRUE
27	FBC	Nickel	ppm	43	43	43	TRUE
28	FBC	Nickel	ppm	51.5	58.95	66.4	TRUE
29	FBC	Nickel	ppm	54.725	57.45	65.65	TRUE
3	FBC	Nickel	ppm	6.25	6.25	6.25	TRUE
30	FBC	Nickel	ppm	30.1395	34.6	41.225	TRUE
31	FBC	Nickel	ppm	0.77	0.77	0.77	TRUE
37	FBC	Nickel	ppm	65	71	77	TRUE
38	FBC	Nickel	ppm	8.34	13.375	19.8	TRUE
39	FBC	Nickel	ppm	4.25	7.5	10.75	TRUE
4	FBC	Nickel	ppm	9.084	13.76	15.35	TRUE
5	FBC	Nickel	ppm	697	761	971.25	TRUE
6	FBC	Nickel	ppm	18.8	21.4	24	TRUE
7	FBC	Nickel	ppm	46.43	46.43	46.43	TRUE
8	FBC	Nickel	ppm	44	44	44	TRUE
A/C Fuels Company	Ash (NOS)	Nickel	ppm	7	7	7	TRUE
Baldwin	Fly ash	Nickel	ppm	275.1	275.1	275.1	TRUE
B-D Mining Co.	Ash (NOS)	Nickel	ppm	14.85	20.6	30.5	TRUE
B-D Mining Co.	Bottom ash	Nickel	ppm	10.05	10.7	12	TRUE
B-D Mining Co.	Fly ash	Nickel	ppm	23.05	25.8	45.275	TRUE
CLSM	Combined ash	Nickel	ppm	2097	2097	2097	TRUE
CLSM	FBC	Nickel	ppm	54055	54055	54055	TRUE
Deer Ridge Mine	Fly ash	Nickel	ppm	98.0575	158.115	409	TRUE
DPC	Bottom ash	Nickel	ppm	6.88	6.88	6.88	TRUE
DPC	Fly ash	Nickel	ppm	32.7	32.7	32.7	TRUE
ern Analytical, ID: 5	Slag	Nickel	ppm	23	23	23	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Edgewater	Bottom ash	Nickel	ppm	29.9	29.9	29.9	TRUE
EERC?	Combined ash	Nickel	ppm	17.1	21.3	25.5	TRUE
EERC?	FGD	Nickel	ppm	3.98	25.3	87.2	TRUE
EERC?	FGD gypsum	Nickel	ppm	0.5	3.655	6.815	TRUE
EERC?	FGD gypsum liquids	Nickel	mg/L	0.338	0.338	0.338	TRUE
EERC?	FGD liquids	Nickel	mg/L	0.11445	0.1905	0.27675	TRUE
EERC?	FGD liquids	Nickel	ppm	2.87	2.87	2.87	TRUE
EERC?	Fly Ash	Nickel	ppm	23.675	51	74.85	TRUE
DPC	Bottom ash	Nitrate Nitrogen	ppm	0.235	0.235	0.235	TRUE
DPC	Fly ash	Nitrate Nitrogen	ppm	0.25	0.25	0.25	TRUE
Cleveland	Fly ash	Nitrogen	ppm	1.9	1.9	1.9	FALSE
Philadelphia Girard	Ash (NOS)	pH	pH	10.72	10.72	10.72	FALSE
Emerald Anthracite	Ash (NOS)	pH	pH	10.6025	11.685	11.8	FALSE
Gale	Ash (NOS)	pH	pH	9.02	9.02	9.02	FALSE
Girard Estate	Ash (NOS)	pH	pH	12.51	12.51	12.51	FALSE
HA	Ash & coal waste	pH	pH	8.55	9.1	9.1	FALSE
Harrim 3019	Ash (NOS)	pH	pH	11.56	11.56	11.56	FALSE
Harrim 3019	Bottom ash	pH	pH	11.94	12.06	12.18	FALSE
Harrim 3019	Fly ash	pH	pH	11.7075	11.825	12.0525	FALSE
an Coal Corporatio	Ash (NOS)	pH	pH	9.0675	10.38	11.2225	FALSE
an Coal Corporatio	Bottom ash	pH	pH	8.3225	8.715	9.11	FALSE
an Coal Corporatio	Fly ash	pH	pH	11.9775	12.085	12.1925	FALSE
Coal Corporation 5	Ash (NOS)	pH	pH	12.05	12.05	12.05	FALSE
Coal Corporation 5	Bottom ash	pH	pH	11.1125	11.365	11.6175	FALSE
Coal Corporation 5	Fly ash	pH	pH	11.1775	11.395	11.6125	FALSE
ddo Highland Coal (	Ash (NOS)	pH	pH	7.5	7.82	9.975	FALSE
ddo Highland Coal (	Bottom ash	pH	pH	8.64	8.64	8.64	FALSE
Knickerbocker Pit	FBC	pH	pH	9.735	10.435	10.84	FALSE
gh Coal and Naviga	Ash (NOS)	pH	pH	10.44	10.45	11.06	FALSE
ttle Sandy #10 Min	Bottom ash	pH	pH	11.3	11.3	11.3	FALSE
ttle Sandy #10 Min	Combined ash	pH	pH	9.34	9.63	9.7	FALSE
ttle Sandy #10 Min	FGD waste	pH	pH	12	12.2	12.3	FALSE
ttle Sandy #10 Min	Fly ash	pH	pH	4.01	4.01	4.01	FALSE
Martins Creek	Bottom ash	pH	pH	6.82	7.4	7.99	FALSE
Martins Creek	Fly ash	pH	pH	10.1	11.6	12.1	FALSE
McCloskey Site	FBC	pH	pH	12.1	12.2	12.3	FALSE
McKay Site	FBC	pH	pH	11.7	11.8	11.9	FALSE
Miller Creek Mine	Bottom ash	pH	pH	4.475	6.9	9.55	FALSE
Miller Creek Mine	Combined ash	pH	pH	6.825	7.75	9.8	FALSE
Miller Creek Mine	Fly ash	pH	pH	7.75	9.1	9.485	FALSE
N & L Coal Co.	Ash (NOS)	pH	pH	9.355	11.1	12.285	FALSE
N & L Coal Co.-2	Ash (NOS)	pH	pH	4.54	11.75	12.3	FALSE
o. 1 Contracting Co	Ash (NOS)	pH	pH	11.1	11.4	11.7	FALSE
el Supply Company	Ash (NOS)	pH	pH	11.41	11.65	12.27	FALSE
el Supply Company	Ash (NOS)	pH	pH	10.68	10.86	11.735	FALSE
el Supply Company	Ash (NOS)	pH	pH	12.005	12.13	12.255	FALSE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
rthampton400002	Ash (NOS)	pH	pH	11.41	11.41	11.41	FALSE
heast Energy Com	Ash (NOS)	pH	pH	8.3725	9.15	9.6925	FALSE
heast Energy Com	Bottom ash	pH	pH	8	8	8	FALSE
heast Energy Com	Fly ash	pH	pH	9.7	9.7	9.7	FALSE
eastern Power Con	Ash (NOS)	pH	pH	10.005	10.01	10.24	FALSE
eastern Power Con	Bottom ash	pH	pH	11	11.2	11.56	FALSE
eastern Power Con	Fly ash	pH	pH	10.6	10.6	10.8	FALSE
Pacton Corp	Ash (NOS)	pH	pH	10.46	10.54	10.62	FALSE
Pacton Corp	Bottom ash	pH	pH	11.7	11.7	11.7	FALSE
Pacton Corp	Fly ash	pH	pH	10.175	10.95	11.65	FALSE
Pagnotti Coal Co.	Ash (NOS)	pH	pH	10.1	10.45	11.1	FALSE
Pagnotti Coal Co.	Fly ash	pH	pH	11.75	11.75	11.75	FALSE
Panther Creek	FBC	pH	pH	10.45	11.17	11.5075	FALSE
nther Creek Partne	Ash (NOS)	pH	pH	10.6725	11	11.4025	FALSE
Porter Associates	Ash (NOS)	pH	pH	10.6325	11.83	12.2225	FALSE
Porter Associates	Bottom ash	pH	pH	8.28	9.21	11.465	FALSE
ading Anthracite C	Ash (NOS)	pH	pH	9.64	10.22	10.56	FALSE
ading Anthracite C	Bottom ash	pH	pH	11.31	11.31	11.31	FALSE
ading Anthracite C	Fly ash	pH	pH	10.995	11.11	11.225	FALSE
ylkill Reclamation C	Ash (NOS)	pH	pH	8.07	8.07	8.07	FALSE
Silverton	Ash (NOS)	pH	pH	8.495	8.67	8.845	FALSE
ehanna Coal Comp	Ash (NOS)	pH	pH	11.1875	11.93	12.195	FALSE
hanna Coal Compa	Ash (NOS)	pH	pH	10.5925	11.135	11.4775	FALSE
Tracy Vein Slope	Ash (NOS)	pH	pH	8.775	9.72	11.04	FALSE
Tracy Vein Slope	Bottom ash	pH	pH	7.5775	7.685	7.7925	FALSE
Tracy Vein Slope	FBC	pH	pH	10.5	10.5	10.5	FALSE
Universal	Combined ash	pH	pH	8.4	9.04	9.58	FALSE
wood Energy Prop	Ash (NOS)	pH	pH	10.75	11.685	11.7925	FALSE
Wheelabrator	FBC	pH	pH	10.9	10.995	11.2425	FALSE
brator Culm Servic	Ash (NOS)	pH	pH	10.59	10.95	11.18	FALSE
A/C Fuels Company	Ash (NOS)	pH	pH	11.85	11.85	11.85	FALSE
B-D Mining Co.	Ash (NOS)	pH	pH	10.0925	10.185	10.5325	FALSE
B-D Mining Co.	Bottom ash	pH	pH	7.545	11.045	11.53	FALSE
B-D Mining Co.	Fly ash	pH	pH	11.3475	11.815	11.9075	FALSE
Deer Ridge Mine	Fly ash	pH	pH	4.75	6.1	6.4375	FALSE
DPC	Bottom ash	pH	pH	11.78	11.78	11.78	FALSE
DPC	Fly ash	pH	pH	10.7	10.7	10.7	FALSE
EERC?	FGD gypsum liquids	pH (lab)	pH	5.3	5.4	5.42	FALSE
EERC?	FGD liquids	pH (lab)	pH	6.73	6.75	7.2	FALSE
Cleveland	Fly ash	Phosphorus	ppm	0.464	0.464	0.464	FALSE
Miller Creek Mine	Combined ash	Phosphorus	ppm	3.265	26.645	56.125	FALSE
Oak Creek	Bottom ash	Phosphorus	ppm	2640	2640	2640	FALSE
Pleasant Prairie	Bottom ash	Phosphorus	ppm	2288	2288	2288	FALSE
Deer Ridge Mine	Fly ash	Phosphorus	ppm	16.13	340	680	FALSE
DPC	Bottom ash	Phosphorus	ppm	0.05	0.05	0.05	FALSE
DPC	Fly ash	Phosphorus	ppm	0.05	0.05	0.05	FALSE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
ern Analytical, ID: 5	Slag	Phosphorus	ppm	200	200	200	FALSE
Edgewater	Bottom ash	Phosphorus	ppm	1750	1750	1750	FALSE
Philadelphia Girard	Ash (NOS)	Potassium	ppm	6600	6600	6600	TRUE
Cleveland	Fly ash	Potassium	ppm	3.06	3.06	3.06	TRUE
Emerald Anthracite	Ash (NOS)	Potassium	ppm	5100	6400	7700	TRUE
Freeport Mine	FGD waste	Potassium	ppm	215	215	215	TRUE
Girard Estate	Ash (NOS)	Potassium	ppm	2800	2800	2800	TRUE
Harrim 3019	Bottom ash	Potassium	ppm	1890	2370	2850	TRUE
Harrim 3019	Fly ash	Potassium	ppm	2030	3860	6060	TRUE
an Coal Corporatio	Ash (NOS)	Potassium	ppm	726.25	1175	1792.5	TRUE
an Coal Corporatio	Bottom ash	Potassium	ppm	111	143	974.5	TRUE
an Coal Corporatio	Fly ash	Potassium	ppm	7735	10050	12365	TRUE
Coal Corporation 5	Ash (NOS)	Potassium	ppm	1510	1510	1510	TRUE
Knickerbocker Pit	FBC	Potassium	ppm	6300	7155	8312.5	TRUE
gh Coal and Naviga	Ash (NOS)	Potassium	ppm	4075	4100	4750	TRUE
ttle Sandy #10 Min	Combined ash	Potassium	ppm	608	656	748	TRUE
ttle Sandy #10 Min	FGD waste	Potassium	ppm	625	730	791	TRUE
Martins Creek	Bottom ash	Potassium	ppm	9620	10550	11500	TRUE
Martins Creek	Fly ash	Potassium	ppm	9059	10200	11544	TRUE
Miller Creek Mine	Bottom ash	Potassium	ppm	232	477	1580	TRUE
Miller Creek Mine	Combined ash	Potassium	ppm	262.5	438	978.25	TRUE
Miller Creek Mine	Fly ash	Potassium	ppm	1790	2640	3640	TRUE
N & L Coal Co.	Ash (NOS)	Potassium	ppm	4525	15771	19270	TRUE
N & L Coal Co.-2	Ash (NOS)	Potassium	ppm	15335	21500	23650	TRUE
el Supply Company	Ash (NOS)	Potassium	ppm	2895	4710	29027.9	TRUE
heast Energy Comp	Ash (NOS)	Potassium	ppm	1200	1200	2170	TRUE
eastern Power Con	Bottom ash	Potassium	ppm	4175	5390	5895	TRUE
eastern Power Con	Fly ash	Potassium	ppm	5885	7530	7575	TRUE
Nucla	FBC	Potassium	ppm	7875	8750	9625	TRUE
Nucla2	FBC	Potassium	ppm	6400	6700	7850	TRUE
Oak Creek	Bottom ash	Potassium	ppm	2075	2075	2075	TRUE
Pacton Corp	Ash (NOS)	Potassium	ppm	4900	4900	4900	TRUE
Panther Creek	FBC	Potassium	ppm	3692.5	5650	6150	TRUE
Pleasant Prairie	Bottom ash	Potassium	ppm	1660	1660	1660	TRUE
Porter Associates	Ash (NOS)	Potassium	ppm	827	1200	2220	TRUE
Porter Associates	Bottom ash	Potassium	ppm	344.5	477.5	1162.5	TRUE
ylkill Reclamation C	Ash (NOS)	Potassium	ppm	370	370	370	TRUE
Shawnee	FBC	Potassium	ppm	3010	6000	8020	TRUE
ehanna Coal Comp	Ash (NOS)	Potassium	ppm	1922.5	4035	5075	TRUE
hanna Coal Compa	Ash (NOS)	Potassium	ppm	5230	5745	7127.5	TRUE
Universal	Combined ash	Potassium	ppm	880	1200	1300	TRUE
wood Energy Prop	Ash (NOS)	Potassium	ppm	1860	2200	2560	TRUE
Wheelabrator	FBC	Potassium	ppm	3987.5	4560	5007.5	TRUE
1	FBC	Potassium	ppm	2.82	2.82	2.82	TRUE
11	FBC	Potassium	ppm	755	1270	1785	TRUE
12	FBC	Potassium	ppm	4750	5400	5881	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
14	FBC	Potassium	ppm	4710	4710	4710	TRUE
18	FBC	Potassium	ppm	1397.5	2211	2287.5	TRUE
19	FBC	Potassium	ppm	637	637	637	TRUE
2	FBC	Potassium	ppm	1.125	1.2125	1.3	TRUE
20	FBC	Potassium	ppm	3580	3845	4575	TRUE
21	FBC	Potassium	ppm	3692.5	5200	5725	TRUE
26	FBC	Potassium	ppm	1340	1340	1340	TRUE
27	FBC	Potassium	ppm	1543	1543	1543	TRUE
28	FBC	Potassium	ppm	448.5	2010	4230	TRUE
29	FBC	Potassium	ppm	6947.7	10876.9	11547.95	TRUE
30	FBC	Potassium	ppm	1182.5	2865	4697.5	TRUE
31	FBC	Potassium	ppm	9163	9163	9163	TRUE
38	FBC	Potassium	ppm	3987.5	4180	4330	TRUE
4	FBC	Potassium	ppm	2220	2580	2940	TRUE
6	FBC	Potassium	ppm	10239	10239	10239	TRUE
7	FBC	Potassium	ppm	8332.49	8332.49	8332.49	TRUE
8	FBC	Potassium	ppm	5000	5000	5000	TRUE
B-D Mining Co.	Ash (NOS)	Potassium	ppm	2775	3740	5250	TRUE
CLSM	Combined ash	Potassium	ppm	14385	14385	14385	TRUE
CLSM	FBC	Potassium	ppm	2894.5	2894.5	2894.5	TRUE
Deer Ridge Mine	Fly ash	Potassium	ppm	138.825	570	759	TRUE
DPC	Bottom ash	Potassium	ppm	374	374	374	TRUE
DPC	Fly ash	Potassium	ppm	2120	2120	2120	TRUE
ern Analytical, ID: 5	Slag	Potassium	ppm	1900	1900	1900	TRUE
Edgewater	Bottom ash	Potassium	ppm	650	650	650	TRUE
Zhang et al. (2001)	Fly Ash	Scandium	ppm	23	28	35	FALSE
City Mine	FBC	Selenium	ppm	12.5	12.5	12.5	TRUE
Cleveland	Fly ash	Selenium	ppm	0.01	0.01	0.01	TRUE
EERC?	FGD gypsum	Selenium	ppm	1	1.78	2.59	TRUE
EERC?	FGD gypsum liquids	Selenium	mg/L	0.684	0.684	0.684	TRUE
EERC?	FGD liquids	Selenium	mg/L	0.26725	0.532	0.85425	TRUE
EERC?	FGD liquids	Selenium	ppm	3.01	3.01	3.01	TRUE
EERC?	Fly Ash	Selenium	ppm	10.6	14.8	29.1	TRUE
Emerald Anthracite	Ash (NOS)	Selenium	ppm	2.0475	5.915	17.1775	TRUE
EORDC	FGD waste	Selenium	ppm	4.2	4.2	4.2	TRUE
Fleming	FBC	Selenium	ppm	1.3	1.3	1.3	TRUE
Freeport Mine	FGD waste	Selenium	ppm	10.85	11.8	12.75	TRUE
Gale	Ash (NOS)	Selenium	ppm	4.4	4.4	4.4	TRUE
Girard Estate	Ash (NOS)	Selenium	ppm	5	5	5	TRUE
HA	Ash & coal waste	Selenium	ppm	0.25125	0.5	0.8	TRUE
Harrim 3019	Ash (NOS)	Selenium	ppm	3.5	3.5	3.5	TRUE
Harrim 3019	Bottom ash	Selenium	ppm	1	1	1	TRUE
Harrim 3019	Fly ash	Selenium	ppm	0.9	1	1.1	TRUE
an Coal Corporatio	Ash (NOS)	Selenium	ppm	2.29	4.875	8.03	TRUE
an Coal Corporatio	Bottom ash	Selenium	ppm	0.5	0.907	1.2275	TRUE
an Coal Corporatio	Fly ash	Selenium	ppm	2.3425	2.845	3.3475	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Coal Corporation 5	Ash (NOS)	Selenium	ppm	0.9	0.9	0.9	TRUE
Coal Corporation 5	Bottom ash	Selenium	ppm	0.89	1.28	1.67	TRUE
Coal Corporation 5	Fly ash	Selenium	ppm	22.575	26.05	29.525	TRUE
ldo Highland Coal (	Ash (NOS)	Selenium	ppm	1.1	2.56	9.4	TRUE
ldo Highland Coal (	Bottom ash	Selenium	ppm	0.5	0.5	0.5	TRUE
Knickerbocker Pit	FBC	Selenium	ppm	1.905	2.385	4.8775	TRUE
gh Coal and Naviga	Ash (NOS)	Selenium	ppm	1.9	3.3	3.3	TRUE
LIMB Site	Ash (NOS)	Selenium	ppm	0.25	0.25	0.25	TRUE
ttle Sandy #10 Min	Bottom ash	Selenium	ppm	0.125	0.125	0.125	TRUE
ttle Sandy #10 Min	Combined ash	Selenium	ppm	0.5	1.02	1.8	TRUE
ttle Sandy #10 Min	FGD waste	Selenium	ppm	2.65	2.8	2.87	TRUE
ttle Sandy #10 Min	Fly ash	Selenium	ppm	41	41	41	TRUE
Mandan	FBC	Selenium	ppm	1.78	1.78	1.78	TRUE
Martins Creek	Bottom ash	Selenium	ppm	2.8915	3.0485	4.895	TRUE
Martins Creek	Fly ash	Selenium	ppm	2.415	3.12	3.85	TRUE
McCloskey Site	FBC	Selenium	ppm	44.6525	52.315	59.9775	TRUE
McKay Site	FBC	Selenium	ppm	1	1	1	TRUE
Miller Creek Mine	Bottom ash	Selenium	ppm	0.25	1.39	2.005	TRUE
Miller Creek Mine	Combined ash	Selenium	ppm	0.665	1.725	5.12	TRUE
Miller Creek Mine	Fly ash	Selenium	ppm	9.1725	12.5	12.5	TRUE
N & L Coal Co.	Ash (NOS)	Selenium	ppm	4.2875	6.785	12.475	TRUE
N & L Coal Co.-2	Ash (NOS)	Selenium	ppm	2.795	7.13	7.3	TRUE
Nepco	FBC	Selenium	ppm	12.6	12.6	12.6	TRUE
NETL	Bottom ash	Selenium	ppm	0.4	0.4	0.4	TRUE
NETL	FBC	Selenium	ppm	7.475	11.65	15.825	TRUE
NETL	Fly ash	Selenium	ppm	3.1	7.45	11.15	TRUE
NETL	Slag	Selenium	ppm	2.1	2.1	2.1	TRUE
o. 1 Contracting Co	Ash (NOS)	Selenium	ppm	16.6	22.4	28.2	TRUE
uel Supply Company	Ash (NOS)	Selenium	ppm	0.5	2.2	8.9	TRUE
uel Supply Company	Ash (NOS)	Selenium	ppm	1.9	2.7	5.535	TRUE
uel Supply Company	Ash (NOS)	Selenium	ppm	0.9	1.3	1.7	TRUE
rthampton400002	Ash (NOS)	Selenium	ppm	8.9	8.9	8.9	TRUE
heast Energy Com	Ash (NOS)	Selenium	ppm	4.5	7.8	8.56	TRUE
heast Energy Com	Bottom ash	Selenium	ppm	3.9	3.9	3.9	TRUE
heast Energy Com	Fly ash	Selenium	ppm	21	21	21	TRUE
eastern Power Con	Ash (NOS)	Selenium	ppm	3.8925	6.275	6.3875	TRUE
eastern Power Con	Bottom ash	Selenium	ppm	0.65875	0.965	7.2375	TRUE
eastern Power Con	Fly ash	Selenium	ppm	4.93	12.165	13.9125	TRUE
Nucla	FBC	Selenium	ppm	8.025	9.35	10.675	TRUE
Nucla2	FBC	Selenium	ppm	0.9925	1.9	2.05	TRUE
Oak Creek	Bottom ash	Selenium	ppm	0.05	0.05	0.05	TRUE
Pacton Corp	Ash (NOS)	Selenium	ppm	2.6	2.6	2.6	TRUE
Pacton Corp	Fly ash	Selenium	ppm	4	4	4	TRUE
Pagnotti Coal Co.	Ash (NOS)	Selenium	ppm	2.92554	6.0965	9.36475	TRUE
Pagnotti Coal Co.	Fly ash	Selenium	ppm	0.1	0.1	0.1	TRUE
Panther Creek	FBC	Selenium	ppm	7.1	11	16	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
ett et al. (1993) Co	Fly Ash	Selenium	ppm	7.4	13.4	17.75	TRUE
Plant 10	FBC	Selenium	ppm	0.735	2	3.75	TRUE
Plant 12	FBC	Selenium	ppm	0.295	1.25	3.79	TRUE
Plant 8	FBC	Selenium	ppm	1.15	2.7	92.3	TRUE
Plant 9	FBC	Selenium	ppm	1.3475	2.485	2.8175	TRUE
Pleasant Prairie	Bottom ash	Selenium	ppm	0.05	0.05	0.05	TRUE
Porter Associates	Ash (NOS)	Selenium	ppm	1.875	4.085	6.845	TRUE
Porter Associates	Bottom ash	Selenium	ppm	1.29	1.76	5.15	TRUE
Scrubgrass	FBC	Selenium	ppm	21.7	21.7	21.7	TRUE
Shawnee	FBC	Selenium	ppm	0.2	0.35	1	TRUE
Silverton	Ash (NOS)	Selenium	ppm	5.55	6.7	7.85	TRUE
ehanna Coal Comp	Ash (NOS)	Selenium	ppm	2.1575	3.765	12.25	TRUE
hanna Coal Compa	Ash (NOS)	Selenium	ppm	1.2405	2.43	4.12	TRUE
SW	Bottom ash	Selenium	ppm	0.6	0.6	0.6	TRUE
SW	Fly ash	Selenium	ppm	0.6	0.6	0.6	TRUE
Tracy Vein Slope	Ash (NOS)	Selenium	ppm	9.14	11.3	12.25	TRUE
Tracy Vein Slope	Bottom ash	Selenium	ppm	5.255	5.78	6.305	TRUE
Tracy Vein Slope	FBC	Selenium	ppm	3.22	3.22	3.22	TRUE
Universal	Combined ash	Selenium	ppm	5.285	7.2	8.6	TRUE
USGS	Fly ash	Selenium	ppm	2	2.75	4.7	TRUE
wood Energy Prop	Ash (NOS)	Selenium	ppm	3.615	5.02	5.665	TRUE
Wheelabrator	FBC	Selenium	ppm	3.04	3.45	8.7	TRUE
Xcel/MSI	Fly ash	Selenium	ppm	19.7	20.9	22.1	TRUE
Zhang et al. (2001)	Fly Ash	Selenium	ppm	3.6	8.1	9.9	TRUE
1	FBC	Selenium	ppm	0.64	1.5	2.45	TRUE
10	FBC	Selenium	ppm	4.625	6.75	8.875	TRUE
11	FBC	Selenium	ppm	45.25	45.5	45.75	TRUE
12	FBC	Selenium	ppm	0.89	5.29	9.645	TRUE
14	FBC	Selenium	ppm	3.68	3.68	3.68	TRUE
17	FBC	Selenium	ppm	0.915	3.4	5.075	TRUE
18	FBC	Selenium	ppm	0.5	0.5	0.5	TRUE
19	FBC	Selenium	ppm	6.25	6.25	6.25	TRUE
2	FBC	Selenium	ppm	4.767	4.767	4.767	TRUE
20	FBC	Selenium	ppm	0.59	2.48	6.155	TRUE
21	FBC	Selenium	ppm	6.5	12.2	15.35	TRUE
23	FBC	Selenium	ppm	1.065	1.39	2.145	TRUE
26	FBC	Selenium	ppm	3.325	4.75	6.05	TRUE
27	FBC	Selenium	ppm	9	9	9	TRUE
28	FBC	Selenium	ppm	0.5	1.4925	2.075	TRUE
29	FBC	Selenium	ppm	3.485	10.895	17.825	TRUE
3	FBC	Selenium	ppm	2.6875	5.125	7.5625	TRUE
30	FBC	Selenium	ppm	0.044375	0.96	2.885	TRUE
31	FBC	Selenium	ppm	7.54	7.54	7.54	TRUE
37	FBC	Selenium	ppm	2.565	3.42	4.275	TRUE
38	FBC	Selenium	ppm	0.625	1.4565	13.76	TRUE
39	FBC	Selenium	ppm	12.75	21.5	30.25	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
4	FBC	Selenium	ppm	0.201	0.4117	0.6795	TRUE
5	FBC	Selenium	ppm	1	2.15	3.9	TRUE
6	FBC	Selenium	ppm	43.84375	84.5625	125.2813	TRUE
7	FBC	Selenium	ppm	32.7	32.7	32.7	TRUE
8	FBC	Selenium	ppm	18	18	18	TRUE
A/C Fuels Company	Ash (NOS)	Selenium	ppm	1	1	1	TRUE
B-D Mining Co.	Ash (NOS)	Selenium	ppm	0.742	3.11	6.995	TRUE
B-D Mining Co.	Bottom ash	Selenium	ppm	0.57225	0.5925	0.61275	TRUE
B-D Mining Co.	Fly ash	Selenium	ppm	0.457	0.472	0.487	TRUE
CLSM	Combined ash	Selenium	ppm	673	673	673	TRUE
CLSM	FBC	Selenium	ppm	223.3	223.3	223.3	TRUE
Coal Creek	Bottom ash	Selenium	ppm	0.0002	0.0002	0.0002	TRUE
Coal Creek	Fly ash	Selenium	ppm	0.0099	0.0099	0.0099	TRUE
Deer Ridge Mine	Fly ash	Selenium	ppm	6.45	13.0175	17.8345	TRUE
DPC	Bottom ash	Selenium	ppm	0.159	0.159	0.159	TRUE
DPC	Fly ash	Selenium	ppm	6.73	6.73	6.73	TRUE
ern Analytical, ID: 5	Slag	Selenium	ppm	0.25	0.25	0.25	TRUE
Edgewater	Bottom ash	Selenium	ppm	9.5	9.5	9.5	TRUE
EERC?	Combined ash	Selenium	ppm	9.3425	9.535	9.7275	TRUE
EERC?	FGD	Selenium	ppm	1.41	3.175	4.2725	TRUE
City Mine	FBC	Silicon	ppm	174500	183000	187000	TRUE
Martins Creek	Bottom ash	Silicon	ppm	190000	199000	256500	TRUE
Martins Creek	Fly ash	Silicon	ppm	167464	183000	210219	TRUE
Miller Creek Mine	Bottom ash	Silicon	ppm	266.25	332.5	372	TRUE
Miller Creek Mine	Combined ash	Silicon	ppm	201.75	297.5	587.55	TRUE
Miller Creek Mine	Fly ash	Silicon	ppm	187.195	293	1725.25	TRUE
Nucla	FBC	Silicon	ppm	206250	209500	212750	TRUE
Nucla2	FBC	Silicon	ppm	185000	200000	200000	TRUE
Oak Creek	Bottom ash	Silicon	ppm	288000	288000	288000	TRUE
Pleasant Prairie	Bottom ash	Silicon	ppm	172800	172800	172800	TRUE
Shawnee	FBC	Silicon	ppm	28200	71200	120000	TRUE
SW	Bottom ash	Silicon	ppm	256000	262000	280000	TRUE
SW	Fly ash	Silicon	ppm	253250	263000	279750	TRUE
CLSM	Combined ash	Silicon	ppm	3900	3900	3900	TRUE
CLSM	FBC	Silicon	ppm	9300	9300	9300	TRUE
Deer Ridge Mine	Fly ash	Silicon	ppm	19.75	39	216.5	TRUE
DPC	Bottom ash	Silicon	ppm	577	577	577	TRUE
DPC	Fly ash	Silicon	ppm	586	586	586	TRUE
B-D Mining Co.	Ash (NOS)	Silver	ppm	1.65	1.9	4.25	TRUE
B-D Mining Co.	Bottom ash	Silver	ppm	1	1	1	TRUE
B-D Mining Co.	Fly ash	Silver	ppm	1.25	1.5	1.75	TRUE
City Mine	FBC	Silver	ppm	12.5	12.5	12.5	TRUE
Emerald Anthracite	Ash (NOS)	Silver	ppm	2.45	2.7	2.95	TRUE
Freeport Mine	FGD waste	Silver	ppm	1	1	1	TRUE
HA	Ash & coal waste	Silver	ppm	0.5	0.5	0.5	TRUE
Harrim 3019	Ash (NOS)	Silver	ppm	6.5	6.5	6.5	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Harrim 3019	Bottom ash	Silver	ppm	87.575	171.05	254.525	TRUE
Harrim 3019	Fly ash	Silver	ppm	2	2	2.3	TRUE
an Coal Corporatio	Ash (NOS)	Silver	ppm	3.9	6.5	9.18	TRUE
an Coal Corporatio	Bottom ash	Silver	ppm	10.3	16.5	177.25	TRUE
an Coal Corporatio	Fly ash	Silver	ppm	6.5375	10.775	15.0125	TRUE
Coal Corporation 5	Ash (NOS)	Silver	ppm	2	2	2	TRUE
Knickerbocker Pit	FBC	Silver	ppm	0.55	1.4	1.95	TRUE
LIMB Site	Ash (NOS)	Silver	ppm	950.9375	1900.625	2850.313	TRUE
ttle Sandy #10 Min	Bottom ash	Silver	ppm	5	5	5	TRUE
ttle Sandy #10 Min	Combined ash	Silver	ppm	0.5	1.02	1.25	TRUE
ttle Sandy #10 Min	FGD waste	Silver	ppm	0.5	0.5	0.73	TRUE
ttle Sandy #10 Min	Fly ash	Silver	ppm	1.25	1.25	1.25	TRUE
Mandan	FBC	Silver	ppm	0.25	0.25	0.25	TRUE
McKay Site	FBC	Silver	ppm	2.5	2.5	2.5	TRUE
Miller Creek Mine	Bottom ash	Silver	ppm	0.06	0.1	0.3	TRUE
Miller Creek Mine	Combined ash	Silver	ppm	0.1275	0.25	1.25	TRUE
Miller Creek Mine	Fly ash	Silver	ppm	1.25	1.25	4.025	TRUE
N & L Coal Co.	Ash (NOS)	Silver	ppm	3	28.25	40.6375	TRUE
N & L Coal Co.-2	Ash (NOS)	Silver	ppm	22.225	25.7	26.15	TRUE
el Supply Company	Ash (NOS)	Silver	ppm	1.15	1.3	1.45	TRUE
heast Energy Comp	Ash (NOS)	Silver	ppm	5	5	5	TRUE
eastern Power Con	Bottom ash	Silver	ppm	3.805	6.11	16.555	TRUE
eastern Power Con	Fly ash	Silver	ppm	0.5	2.26	3.94	TRUE
Nucla	FBC	Silver	ppm	1.2	1.2	1.2	TRUE
Nucla2	FBC	Silver	ppm	0.47025	0.49	0.49	TRUE
Oak Creek	Bottom ash	Silver	ppm	2.5	2.5	2.5	TRUE
Pacton Corp	Ash (NOS)	Silver	ppm	1	1	1	TRUE
Pacton Corp	Bottom ash	Silver	ppm	5	5	5	TRUE
Pacton Corp	Fly ash	Silver	ppm	2.5	2.5	3.25	TRUE
Pagnotti Coal Co.	Ash (NOS)	Silver	ppm	1	1	1	TRUE
Pagnotti Coal Co.	Fly ash	Silver	ppm	0.5	0.5	0.5	TRUE
Panther Creek	FBC	Silver	ppm	1.6	7.6	8	TRUE
ett et al. (1993) Co	Fly Ash	Silver	ppm	0.1	0.1	0.1	TRUE
Pleasant Prairie	Bottom ash	Silver	ppm	2.5	2.5	2.5	TRUE
Porter Associates	Ash (NOS)	Silver	ppm	1.22	2	3.475	TRUE
Porter Associates	Bottom ash	Silver	ppm	2.75	3.5	4.25	TRUE
Shawnee	FBC	Silver	ppm	0.9	1.1	2	TRUE
ehanna Coal Comp	Ash (NOS)	Silver	ppm	1.75	2.15	2.65	TRUE
hanna Coal Compa	Ash (NOS)	Silver	ppm	1.1	1.8	2.575	TRUE
SW	Bottom ash	Silver	ppm	0.25	0.25	0.25	TRUE
SW	Fly ash	Silver	ppm	0.25	0.25	0.25	TRUE
Universal	Combined ash	Silver	ppm	0.25	0.33	1.2	TRUE
wood Energy Prop	Ash (NOS)	Silver	ppm	3.3	3.3	3.3	TRUE
Wheelabrator	FBC	Silver	ppm	0.58	0.58	0.58	TRUE
Xcel/MSI	Fly ash	Silver	ppm	1.42	1.585	1.78	TRUE
Zhang et al. (2001)	Fly Ash	Silver	ppm	0.25	0.25	0.5	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
1	FBC	Silver	ppm	0.43	0.82	2	TRUE
10	FBC	Silver	ppm	6.25	7.5	8.75	TRUE
11	FBC	Silver	ppm	1	1	1	TRUE
12	FBC	Silver	ppm	0.5	1.1	2	TRUE
14	FBC	Silver	ppm	1.6	1.6	1.6	TRUE
17	FBC	Silver	ppm	1.5	1.85	2.8	TRUE
18	FBC	Silver	ppm	1	1	1	TRUE
19	FBC	Silver	ppm	21.8	21.8	21.8	TRUE
2	FBC	Silver	ppm	0.288	0.288	0.288	TRUE
20	FBC	Silver	ppm	1	1.6	1.9	TRUE
21	FBC	Silver	ppm	0.25	0.25	0.4375	TRUE
26	FBC	Silver	ppm	1	1.725	3.0875	TRUE
27	FBC	Silver	ppm	0.5	0.5	0.5	TRUE
28	FBC	Silver	ppm	2.6	4.05	13.675	TRUE
29	FBC	Silver	ppm	0.05	0.05	0.05	TRUE
3	FBC	Silver	ppm	5	5	5	TRUE
30	FBC	Silver	ppm	0.005	0.5	2.5	TRUE
31	FBC	Silver	ppm	0.67	0.67	0.67	TRUE
38	FBC	Silver	ppm	0.25	0.5	0.685	TRUE
39	FBC	Silver	ppm	1	1	1	TRUE
4	FBC	Silver	ppm	0.065	0.693	1.88795	TRUE
5	FBC	Silver	ppm	1	1	1	TRUE
6	FBC	Silver	ppm	2.1125	3.225	4.3375	TRUE
7	FBC	Silver	ppm	0.51	0.51	0.51	TRUE
8	FBC	Silver	ppm	0.5	0.5	0.5	TRUE
CLSM	Combined ash	Silver	ppm	18.5	18.5	18.5	TRUE
CLSM	FBC	Silver	ppm	3.3	3.3	3.3	TRUE
Deer Ridge Mine	Fly ash	Silver	ppm	0.0575	0.225	1	TRUE
ern Analytical, ID: 5	Slag	Silver	ppm	0.25	0.25	0.25	TRUE
City Mine	FBC	Sodium	ppm	2465.5	3143	3793	TRUE
ttle Sandy #10 Min	Bottom ash	Sodium	ppm	970	970	970	TRUE
ttle Sandy #10 Min	Combined ash	Sodium	ppm	164	200	200	TRUE
ttle Sandy #10 Min	FGD waste	Sodium	ppm	250	250	253	TRUE
ttle Sandy #10 Min	Fly ash	Sodium	ppm	790	790	790	TRUE
Martins Creek	Bottom ash	Sodium	ppm	575	2739	4684	TRUE
Martins Creek	Fly ash	Sodium	ppm	650	3279	4250	TRUE
Miller Creek Mine	Bottom ash	Sodium	ppm	226	258	340	TRUE
Miller Creek Mine	Combined ash	Sodium	ppm	275	387	1016.075	TRUE
Miller Creek Mine	Fly ash	Sodium	ppm	465	520.5	781.5	TRUE
Nucla	FBC	Sodium	ppm	2650	2850	3050	TRUE
Nucla2	FBC	Sodium	ppm	1325	1400	1450	TRUE
Oak Creek	Bottom ash	Sodium	ppm	444	444	444	TRUE
Pleasant Prairie	Bottom ash	Sodium	ppm	518	518	518	TRUE
Shawnee	FBC	Sodium	ppm	1070	1260	15000	TRUE
Universal	Combined ash	Sodium	ppm	191.5	230	415.5	TRUE
CLSM	Combined ash	Sodium	ppm	1166.5	1166.5	1166.5	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
CLSM	FBC	Sodium	ppm	4552.5	4552.5	4552.5	TRUE
Deer Ridge Mine	Fly ash	Sodium	ppm	181.5	285	783.25	TRUE
DPC	Bottom ash	Sodium	ppm	262	262	262	TRUE
DPC	Fly ash	Sodium	ppm	1840	1840	1840	TRUE
ern Analytical, ID: 5	Slag	Sodium	ppm	900	900	900	TRUE
Edgewater	Bottom ash	Sodium	ppm	3498	3498	3498	TRUE
CAER	Bottom ash	Strontium	ppm	644	900	1870	TRUE
CAER	FGD waste	Strontium	ppm	680	680	680	TRUE
CAER	Fly ash	Strontium	ppm	481	540	1290	TRUE
Fleming	FBC	Strontium	ppm	160	160	160	TRUE
HA	Ash & coal waste	Strontium	ppm	91	96	158	TRUE
Kentucky	Bottom ash	Strontium	ppm	170.5	195	227	TRUE
Kentucky	Fly ash	Strontium	ppm	175.25	210.5	247.25	TRUE
KY	FGD waste	Strontium	ppm	115.5	118	374	TRUE
LIMB Site	Ash (NOS)	Strontium	ppm	57	88	119	TRUE
Martins Creek	Bottom ash	Strontium	ppm	606	631.57	765	TRUE
Martins Creek	Fly ash	Strontium	ppm	711	781	914.55	TRUE
Nucla	FBC	Strontium	ppm	210	210	210	TRUE
Nucla2	FBC	Strontium	ppm	265	270	275	TRUE
SFA	Fly ash	Strontium	ppm	810	810	810	TRUE
Shawnee	FBC	Strontium	ppm	220	250	2600	TRUE
STK	Fly ash	Strontium	ppm	815	850	885	TRUE
Zhang et al. (2001)	Fly Ash	Strontium	ppm	580	790	1400	TRUE
CLSM	Combined ash	Strontium	ppm	123.3	123.3	123.3	TRUE
CLSM	FBC	Strontium	ppm	5.6	5.6	5.6	TRUE
ttle Sandy #10 Mir	Bottom ash	Sulfate	ppm	200	200	200	TRUE
ttle Sandy #10 Mir	Combined ash	Sulfate	ppm	79	660	3500	TRUE
ttle Sandy #10 Mir	FGD waste	Sulfate	ppm	633.5	1100	1200	TRUE
ttle Sandy #10 Mir	Fly ash	Sulfate	ppm	7300	7300	7300	TRUE
Miller Creek Mine	Bottom ash	Sulfate	ppm	36.005	72	1006	TRUE
Miller Creek Mine	Combined ash	Sulfate	ppm	257.5	753	2600	TRUE
Miller Creek Mine	Fly ash	Sulfate	ppm	210	380	3680	TRUE
Pagnotti Coal Co.	Ash (NOS)	Sulfate	ppm	4150	4150	4150	TRUE
Pagnotti Coal Co.	Bottom ash	Sulfate	ppm	900	900	900	TRUE
Pagnotti Coal Co.	Fly ash	Sulfate	ppm	13500	16500	19500	TRUE
Universal	Combined ash	Sulfate	ppm	340	420	670	TRUE
Deer Ridge Mine	Fly ash	Sulfate	ppm	204.5	209	394.5	TRUE
DPC	Bottom ash	Sulfate	ppm	2750	2750	2750	TRUE
DPC	Fly ash	Sulfate	ppm	9630	9630	9630	TRUE
ttle Sandy #10 Mir	Bottom ash	Sulfide	ppm	12	12	12	TRUE
ttle Sandy #10 Mir	Combined ash	Sulfide	ppm	11	25	25	TRUE
ttle Sandy #10 Mir	FGD waste	Sulfide	ppm	25	25	62	TRUE
ttle Sandy #10 Mir	Fly ash	Sulfide	ppm	0.05	0.05	0.05	TRUE
Miller Creek Mine	Bottom ash	Sulfide	ppm	5.5	10	14.5	TRUE
Miller Creek Mine	Combined ash	Sulfide	ppm	0.1	1	32.5	TRUE
Miller Creek Mine	Fly ash	Sulfide	ppm	0.15	14	28	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Universal	Combined ash	Sulfide	ppm	0.5	2.8	5.85	TRUE
Deer Ridge Mine	Fly ash	Sulfide	ppm	0.025	0.025	0.025	TRUE
HA	Ash & coal waste	Sulfur	ppm	0.01	0.01	0.01	TRUE
Martins Creek	Bottom ash	Sulfur	ppm	851	1434	1944	TRUE
Martins Creek	Fly ash	Sulfur	ppm	6300	7089	7342	TRUE
Nucla2	FBC	Sulfur	ppm	20850	21700	35850	TRUE
Shawnee	FBC	Sulfur	ppm	36000	36000	48000	TRUE
City Mine	FBC	Thallium	ppm	0.25	0.25	0.25	TRUE
Freeport Mine	FGD waste	Thallium	ppm	1	1	1	TRUE
Nucla	FBC	Thallium	ppm	100	100	100	TRUE
Nucla2	FBC	Thallium	ppm	4.725	4.9	7.35	TRUE
Shawnee	FBC	Thallium	ppm	9	9	9	TRUE
Xcel/MSI	Fly ash	Thallium	ppm	0.4075	0.475	0.5025	TRUE
1	FBC	Thallium	ppm	8.7	9.83	10.96	TRUE
10	FBC	Thallium	ppm	15.625	18.75	21.875	TRUE
18	FBC	Thallium	ppm	0.5	0.5	1.25	TRUE
19	FBC	Thallium	ppm	12.5	12.5	12.5	TRUE
2	FBC	Thallium	ppm	2.792	2.792	2.792	TRUE
26	FBC	Thallium	ppm	2.5	2.5	5	TRUE
3	FBC	Thallium	ppm	12.5	12.5	12.5	TRUE
4	FBC	Thallium	ppm	39.011	39.011	39.011	TRUE
5	FBC	Thallium	ppm	0.34375	1.5625	2.5	TRUE
8	FBC	Thallium	ppm	2.8	2.8	2.8	TRUE
CLSM	Combined ash	Thallium	ppm	1.3	1.3	1.3	TRUE
CLSM	FBC	Thallium	ppm	0.15	0.15	0.15	TRUE
Zhang et al. (2001)	Fly Ash	Tin	ppm	10	10	10	FALSE
ern Analytical, ID: 5	Slag	Tin	ppm	1	1	1	FALSE
ern Analytical, ID: 5	Slag	Titanium	ppm	630	630	630	FALSE
ttle Sandy #10 Min	Bottom ash	TOC	ppm	6200	6200	6200	FALSE
ttle Sandy #10 Min	Combined ash	TOC	ppm	4800	12000	18000	FALSE
ttle Sandy #10 Min	FGD waste	TOC	ppm	5925	6650	6775	FALSE
ttle Sandy #10 Min	Fly ash	TOC	ppm	12000	12000	12000	FALSE
Miller Creek Mine	Bottom ash	TOC	ppm	807.5	3379.5	8540	FALSE
Miller Creek Mine	Combined ash	TOC	ppm	859.5	5600	17500	FALSE
Miller Creek Mine	Fly ash	TOC	ppm	9625	13000	26400	FALSE
Nepco	FBC	TOC	ppm	48600	48600	48600	FALSE
Scrubgrass	FBC	TOC	ppm	21200	21200	21200	FALSE
Universal	Combined ash	TOC	ppm	6340	45700	69800	FALSE
DPC	Bottom ash	TOC	ppm	41400	41400	41400	FALSE
DPC	Fly ash	TOC	ppm	92700	92700	92700	FALSE
Zhang et al. (2001)	Fly Ash	Uranium	ppm	5	5	5	TRUE
Bowen	Fly ash	Vanadium	ppm	307.4	307.4	307.4	TRUE
CAER	Bottom ash	Vanadium	ppm	194	197	211.5	TRUE
CAER	FGD waste	Vanadium	ppm	49	49	49	TRUE
CAER	Fly ash	Vanadium	ppm	241	367	429	TRUE
Cardinal	Fly ash	Vanadium	ppm	276.375	285.45	294.525	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
City Mine	FBC	Vanadium	ppm	12.5	12.5	12.5	TRUE
Freeport Mine	FGD waste	Vanadium	ppm	3.3	3.3	3.3	TRUE
Kentucky	Bottom ash	Vanadium	ppm	213	252	399.5	TRUE
Kentucky	Fly ash	Vanadium	ppm	365.75	556	876.5	TRUE
KY	FGD waste	Vanadium	ppm	20	24	28	TRUE
LIMB Site	Ash (NOS)	Vanadium	ppm	24.825	29.65	34.475	TRUE
ttle Sandy #10 Min	Combined ash	Vanadium	ppm	16.2	17	19.5	TRUE
ttle Sandy #10 Min	FGD waste	Vanadium	ppm	18	20	22.5	TRUE
Lone Mtn	Fly ash	Vanadium	ppm	561.9	561.9	561.9	TRUE
Martins Creek	Bottom ash	Vanadium	ppm	34.1	128.3	197.37	TRUE
Martins Creek	Fly ash	Vanadium	ppm	24.95	114.3	165	TRUE
Miller	Fly ash	Vanadium	ppm	308.8	308.8	308.8	TRUE
Miller Creek Mine	Bottom ash	Vanadium	ppm	29.75	42.5	55.25	TRUE
Miller Creek Mine	Combined ash	Vanadium	ppm	19	36	360	TRUE
Miller Creek Mine	Fly ash	Vanadium	ppm	61.5	70	73.5	TRUE
Nucla	FBC	Vanadium	ppm	25.325	30.65	35.975	TRUE
Nucla2	FBC	Vanadium	ppm	34.5	50	51	TRUE
aceAnalytical (2010	Slag	Vanadium	ppm	121	121	121	TRUE
Paradise	Fly ash	Vanadium	ppm	470.7	470.7	470.7	TRUE
ett et al. (1993) Co	Fly Ash	Vanadium	ppm	165	195	607.5	TRUE
Pleasant Prairie	Fly ash	Vanadium	ppm	330.8	330.8	330.8	TRUE
SFA	Fly ash	Vanadium	ppm	300	300	300	TRUE
Shawnee	FBC	Vanadium	ppm	110	120	150	TRUE
Sioux	Fly ash	Vanadium	ppm	327	344.3	361.6	TRUE
Stanton	Fly ash	Vanadium	ppm	316	316	316	TRUE
STK	Fly ash	Vanadium	ppm	325	330	335	TRUE
Universal	Combined ash	Vanadium	ppm	38	40	64	TRUE
Xcel/MSI	Fly ash	Vanadium	ppm	163.75	181.5	197.5	TRUE
Yates	Fly ash	Vanadium	ppm	351.4	351.4	351.4	TRUE
Zhang et al. (2001)	Fly Ash	Vanadium	ppm	75	150	190	TRUE
1	FBC	Vanadium	ppm	20.8025	24.2	30.1775	TRUE
10	FBC	Vanadium	ppm	43	49	55	TRUE
18	FBC	Vanadium	ppm	54	61	61.5	TRUE
19	FBC	Vanadium	ppm	2441.75	3294.5	4147.25	TRUE
2	FBC	Vanadium	ppm	12	36.333	36.333	TRUE
26	FBC	Vanadium	ppm	593.75	808	916	TRUE
3	FBC	Vanadium	ppm	38	39	40	TRUE
39	FBC	Vanadium	ppm	97.75	118.5	139.25	TRUE
4	FBC	Vanadium	ppm	36.43	36.43	36.43	TRUE
5	FBC	Vanadium	ppm	863.5	1135	1150	TRUE
Baldwin	Fly ash	Vanadium	ppm	517.4	517.4	517.4	TRUE
CLSM	Combined ash	Vanadium	ppm	200.8	200.8	200.8	TRUE
CLSM	FBC	Vanadium	ppm	3086.8	3086.8	3086.8	TRUE
Deer Ridge Mine	Fly ash	Vanadium	ppm	18.25	22.385	135.21	TRUE
rn Analytical, ID: 5	Slag	Vanadium	ppm	40	40	40	TRUE
Zhang et al. (2001)	Fly Ash	Ytterbium	ppm	2.5	2.5	2.5	FALSE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
ett et al. (1993) Co	Fly Ash	Yttrium	ppm	37.75	42	46.25	FALSE
Zhang et al. (2001)	Fly Ash	Yttrium	ppm	31	33	37	FALSE
B-D Mining Co.	Ash (NOS)	Zinc	ppm	15.05	20.7	24.725	TRUE
B-D Mining Co.	Bottom ash	Zinc	ppm	11.725	17	20.625	TRUE
B-D Mining Co.	Fly ash	Zinc	ppm	20.175	24.5	33.25	TRUE
Bowen	Fly ash	Zinc	ppm	141.4	141.4	141.4	TRUE
CAER	Bottom ash	Zinc	ppm	29.5	37	64.5	TRUE
CAER	FGD waste	Zinc	ppm	38	38	38	TRUE
CAER	Fly ash	Zinc	ppm	179	495	570	TRUE
Cardinal	Fly ash	Zinc	ppm	172.5	184.6	196.7	TRUE
City Mine	FBC	Zinc	ppm	571	669	707	TRUE
Philadelphia Girard	Ash (NOS)	Zinc	ppm	15	15	15	TRUE
Cleveland	Fly ash	Zinc	ppm	0.034	0.034	0.034	TRUE
Emerald Anthracite	Ash (NOS)	Zinc	ppm	24.275	27.7	36.875	TRUE
EORDC	FGD waste	Zinc	ppm	44	44	44	TRUE
Freeport Mine	FGD waste	Zinc	ppm	5	5	5	TRUE
Gale	Ash (NOS)	Zinc	ppm	29	29	29	TRUE
Girard Estate	Ash (NOS)	Zinc	ppm	14	14	14	TRUE
HA	Ash & coal waste	Zinc	ppm	17.5	21	21.5	TRUE
Harrim 3019	Ash (NOS)	Zinc	ppm	124.323	124.323	124.323	TRUE
Harrim 3019	Bottom ash	Zinc	ppm	53.175	59.15	65.125	TRUE
Harrim 3019	Fly ash	Zinc	ppm	39.3	45.3	54.725	TRUE
an Coal Corporatio	Ash (NOS)	Zinc	ppm	22.75	35	71	TRUE
an Coal Corporatio	Bottom ash	Zinc	ppm	5.05	11	41	TRUE
an Coal Corporatio	Fly ash	Zinc	ppm	75	79.9	84.8	TRUE
Coal Corporation 5	Ash (NOS)	Zinc	ppm	31	31	31	TRUE
Coal Corporation 5	Bottom ash	Zinc	ppm	21.05	21.7	22.35	TRUE
Coal Corporation 5	Fly ash	Zinc	ppm	34.8	36.2	37.6	TRUE
ddo Highland Coal (	Ash (NOS)	Zinc	ppm	18.15	24.9	44.2	TRUE
ddo Highland Coal (	Bottom ash	Zinc	ppm	12.8	12.8	12.8	TRUE
Kentucky	Bottom ash	Zinc	ppm	171	252	263.5	TRUE
Kentucky	Fly ash	Zinc	ppm	2275	4085	5867.5	TRUE
Knickerbocker Pit	FBC	Zinc	ppm	17.2675	19.85	23	TRUE
KY	FGD waste	Zinc	ppm	7.25	10	17	TRUE
gh Coal and Naviga	Ash (NOS)	Zinc	ppm	28.4	33	46.5	TRUE
LIMB Site	Ash (NOS)	Zinc	ppm	137.5	145	152.5	TRUE
ttle Sandy #10 Min	Bottom ash	Zinc	ppm	33	33	33	TRUE
ttle Sandy #10 Min	Combined ash	Zinc	ppm	20	22.5	48	TRUE
ttle Sandy #10 Min	FGD waste	Zinc	ppm	35	35	38.1	TRUE
ttle Sandy #10 Min	Fly ash	Zinc	ppm	600	600	600	TRUE
Lone Mtn	Fly ash	Zinc	ppm	168.5	168.5	168.5	TRUE
Martins Creek	Bottom ash	Zinc	ppm	45.76	57.5	65.3	TRUE
Martins Creek	Fly ash	Zinc	ppm	86	93.46	114.1	TRUE
McCloskey Site	FBC	Zinc	ppm	205.625	248.75	291.875	TRUE
McKay Site	FBC	Zinc	ppm	220	230	240	TRUE
Miller	Fly ash	Zinc	ppm	90.5	90.5	90.5	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Miller Creek Mine	Bottom ash	Zinc	ppm	131	248.46	319	TRUE
Miller Creek Mine	Combined ash	Zinc	ppm	40	83.75	167.75	TRUE
Miller Creek Mine	Fly ash	Zinc	ppm	63	131.5	223.2025	TRUE
N & L Coal Co.	Ash (NOS)	Zinc	ppm	23.6	37.9	185.7765	TRUE
N & L Coal Co.-2	Ash (NOS)	Zinc	ppm	47	113	142	TRUE
NETL	Bottom ash	Zinc	ppm	600	600	600	TRUE
NETL	FBC	Zinc	ppm	8499.75	16666.5	24833.25	TRUE
NETL	Fly ash	Zinc	ppm	100.25	137.5	201.25	TRUE
NETL	Slag	Zinc	ppm	75	75	75	TRUE
o. 1 Contracting Co	Ash (NOS)	Zinc	ppm	18.55	21.7	24.85	TRUE
uel Supply Company	Ash (NOS)	Zinc	ppm	17.7	19.8	23.7	TRUE
uel Supply Company	Ash (NOS)	Zinc	ppm	11.25	12.95	31.675	TRUE
uel Supply Company	Ash (NOS)	Zinc	ppm	15.1	17.9	20.7	TRUE
orthampton400002	Ash (NOS)	Zinc	ppm	23.87	23.87	23.87	TRUE
heast Energy Com	Ash (NOS)	Zinc	ppm	21.8	30.85	40.5	TRUE
heast Energy Com	Bottom ash	Zinc	ppm	24	24	24	TRUE
heast Energy Com	Fly ash	Zinc	ppm	54	54	54	TRUE
eastern Power Con	Ash (NOS)	Zinc	ppm	7.05	8	8.95	TRUE
eastern Power Con	Bottom ash	Zinc	ppm	5.1025	6.14	8.92	TRUE
eastern Power Con	Fly ash	Zinc	ppm	10.575	14.15	17.1	TRUE
Nucla	FBC	Zinc	ppm	322.5	355	387.5	TRUE
Nucla2	FBC	Zinc	ppm	25	37	38	TRUE
Oak Creek	Bottom ash	Zinc	ppm	250	250	250	TRUE
aceAnalytical (201	Slag	Zinc	ppm	10.7	10.7	10.7	TRUE
Pacton Corp	Ash (NOS)	Zinc	ppm	15	15	15	TRUE
Pacton Corp	Bottom ash	Zinc	ppm	23	23	23	TRUE
Pacton Corp	Fly ash	Zinc	ppm	73.5	120	184	TRUE
Pagnotti Coal Co.	Ash (NOS)	Zinc	ppm	17.2	19.9	29.25	TRUE
Pagnotti Coal Co.	Fly ash	Zinc	ppm	125	125	125	TRUE
Panther Creek	FBC	Zinc	ppm	16.5	21.5	23.75	TRUE
Paradise	Fly ash	Zinc	ppm	582.5	582.5	582.5	TRUE
ett et al. (1993) Co	Fly Ash	Zinc	ppm	67	87.5	147.5	TRUE
Pleasant Prairie	Bottom ash	Zinc	ppm	46	46	46	TRUE
Pleasant Prairie	Fly ash	Zinc	ppm	158.8	158.8	158.8	TRUE
Porter Associates	Ash (NOS)	Zinc	ppm	22.2	32.5	43.35	TRUE
Porter Associates	Bottom ash	Zinc	ppm	19.6	31.8	40	TRUE
ylkill Reclamation C	Ash (NOS)	Zinc	ppm	4.4	4.4	4.4	TRUE
SFA	Fly ash	Zinc	ppm	210	210	210	TRUE
Shawnee	FBC	Zinc	ppm	17	62	69	TRUE
Silverton	Ash (NOS)	Zinc	ppm	34.125	39.25	44.375	TRUE
Sioux	Fly ash	Zinc	ppm	3330.625	3999.25	4667.875	TRUE
Stanton	Fly ash	Zinc	ppm	153.2	153.2	153.2	TRUE
STK	Fly ash	Zinc	ppm	300	310	320	TRUE
ehanna Coal Comp	Ash (NOS)	Zinc	ppm	37.225	42	52.675	TRUE
hanna Coal Compa	Ash (NOS)	Zinc	ppm	13.675	15	20.225	TRUE
Tracy Vein Slope	Ash (NOS)	Zinc	ppm	28.1	38.4	68.05	TRUE

Attachment C-4. Quartile Data for CCR Whole Waste

Site	New WasteType	Analyte	Units	25th	50th	75th	Risk
Tracy Vein Slope	Bottom ash	Zinc	ppm	22.035	38.99	55.945	TRUE
Tracy Vein Slope	FBC	Zinc	ppm	2.48	2.48	2.48	TRUE
Universal	Combined ash	Zinc	ppm	69	110	133	TRUE
wood Energy Prop	Ash (NOS)	Zinc	ppm	7.92	12.2	13.975	TRUE
Wheelabrator	FBC	Zinc	ppm	12.2	14.925	18.125	TRUE
Xcel/MSI	Fly ash	Zinc	ppm	60.5	96	160	TRUE
Yates	Fly ash	Zinc	ppm	153.9	153.9	153.9	TRUE
Zhang et al. (2001)	Fly Ash	Zinc	ppm	47	57	170	TRUE
1	FBC	Zinc	ppm	19.9	20.6	20.71	TRUE
10	FBC	Zinc	ppm	32	32	32	TRUE
11	FBC	Zinc	ppm	52.5	65	77.5	TRUE
12	FBC	Zinc	ppm	12.025	13.7	14.7	TRUE
17	FBC	Zinc	ppm	27.3	50	54.5	TRUE
18	FBC	Zinc	ppm	52.5	72	74	TRUE
19	FBC	Zinc	ppm	1440	1440	1440	TRUE
2	FBC	Zinc	ppm	28	28.5	29	TRUE
20	FBC	Zinc	ppm	15.7	19.9	24.05	TRUE
21	FBC	Zinc	ppm	16.5	20	23.5	TRUE
23	FBC	Zinc	ppm	55.675	69.485	80.255	TRUE
26	FBC	Zinc	ppm	24.5	28.5	31.5	TRUE
27	FBC	Zinc	ppm	105	105	105	TRUE
28	FBC	Zinc	ppm	43.175	52.95	65.875	TRUE
29	FBC	Zinc	ppm	122.675	149.2	154.95	TRUE
3	FBC	Zinc	ppm	29.75	31.5	33.25	TRUE
30	FBC	Zinc	ppm	25.6775	45.05	55.625	TRUE
31	FBC	Zinc	ppm	48.1	48.1	48.1	TRUE
37	FBC	Zinc	ppm	192	257	328	TRUE
38	FBC	Zinc	ppm	11.27	14.925	19.225	TRUE
39	FBC	Zinc	ppm	26.75	29.5	32.25	TRUE
4	FBC	Zinc	ppm	12.225	18.65	23.824	TRUE
5	FBC	Zinc	ppm	21.5	28.5	31	TRUE
6	FBC	Zinc	ppm	36.075	39.05	42.025	TRUE
7	FBC	Zinc	ppm	51.48	51.48	51.48	TRUE
8	FBC	Zinc	ppm	56	56	56	TRUE
A/C Fuels Company	Ash (NOS)	Zinc	ppm	11	11	11	TRUE
Baldwin	Fly ash	Zinc	ppm	1432.9	1432.9	1432.9	TRUE
CLSM	Combined ash	Zinc	ppm	12.9	12.9	12.9	TRUE
CLSM	FBC	Zinc	ppm	10.1	10.1	10.1	TRUE
Deer Ridge Mine	Fly ash	Zinc	ppm	193.185	323.495	415	TRUE
DPC	Bottom ash	Zinc	ppm	66.4	66.4	66.4	TRUE
DPC	Fly ash	Zinc	ppm	102	102	102	TRUE
ern Analytical, ID: 5	Slag	Zinc	ppm	23	23	23	TRUE
Edgewater	Bottom ash	Zinc	ppm	67.7	67.7	67.7	TRUE
ett et al. (1993) Co	Fly Ash	Zirconium	ppm	187.5	210	222.5	FALSE
Zhang et al. (2001)	Fly Ash	Zirconium	ppm	157	306	349	FALSE

Attachment C-5.

LEAF Leachate Data

Table C-5-1. Leachate Concentrations for Bituminous Fly Ash, Waste ID AaFA Med

	Concentration (mg/L)							
pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	2.88E-01	S	2.73E+00	W	3.19E-02	W	2.95E-01	S
3	2.46E-01	S	2.65E+00	W	3.12E-02	W	2.66E-01	S
3.2	2.12E-01	S	2.57E+00	W	3.05E-02	W	2.42E-01	S
3.4	1.85E-01	S	2.51E+00	W	2.98E-02	W	2.22E-01	S
3.6	1.62E-01	S	2.44E+00	W	2.92E-02	W	2.04E-01	S
3.8	1.64E-01	S	2.41E+00	W	2.95E-02	W	2.00E-01	S
4	1.65E-01	S	2.38E+00	W	2.97E-02	W	1.96E-01	S
4.2	1.67E-01	S	2.36E+00	W	2.99E-02	W	1.92E-01	S
4.4	1.75E-01	S	2.31E+00	W	2.66E-02	W	1.48E-01	S
4.6	2.13E-01	S	2.21E+00	W	1.48E-02	S	4.42E-02	S
4.8	2.58E-01	S	2.12E+00	W	8.39E-03	S	1.39E-02	S
5	3.09E-01	S	2.03E+00	W	4.88E-03	S	4.60E-03	S
5.2	3.53E-01	S	1.97E+00	W	3.31E-03	S	2.06E-03	S
5.4	3.55E-01	S	1.98E+00	W	3.34E-03	S	2.06E-03	S
5.6	3.56E-01	S	1.99E+00	W	3.37E-03	S	2.06E-03	S
5.8	3.58E-01	S	2.00E+00	W	3.41E-03	S	2.06E-03	S
6	3.59E-01	S	2.01E+00	W	3.44E-03	S	2.06E-03	S
6.2	3.60E-01	S	2.02E+00	W	3.47E-03	S	2.06E-03	S
6.4	3.61E-01	S	2.03E+00	W	3.50E-03	S	2.06E-03	S
6.6	3.63E-01	S	2.04E+00	W	3.53E-03	S	2.06E-03	S
6.8	3.64E-01	S	2.05E+00	W	3.56E-03	S	2.06E-03	S
7	3.65E-01	S	2.06E+00	W	3.59E-03	S	2.06E-03	S
7.2	3.66E-01	S	2.06E+00	W	3.61E-03	S	2.06E-03	S
7.4	3.67E-01	S	2.07E+00	W	3.64E-03	S	2.06E-03	S
7.6	3.68E-01	S	2.08E+00	W	3.67E-03	S	2.06E-03	S
7.8	3.69E-01	S	2.09E+00	W	3.69E-03	S	2.06E-03	S
8	3.70E-01	S	2.09E+00	W	3.72E-03	S	2.06E-03	S
8.2	3.71E-01	S	2.10E+00	W	3.74E-03	W	2.06E-03	S
8.4	3.72E-01	S	2.11E+00	W	3.77E-03	W	2.06E-03	S
8.6	3.73E-01	S	2.11E+00	W	3.79E-03	W	2.06E-03	S

Table C-5-1. Leachate Concentrations for Bituminous Fly Ash, Waste ID AaFA Med

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.8	3.91E-01	S	2.12E+00	W	3.81E-03	W	2.06E-03	S
9	4.38E-01	S	2.12E+00	W	3.81E-03	W	2.06E-03	S
9.2	4.89E-01	S	2.11E+00	W	3.82E-03	W	2.06E-03	S
9.4	5.44E-01	S	2.11E+00	W	3.82E-03	W	2.06E-03	S
9.6	6.05E-01	S	2.11E+00	W	3.82E-03	W	2.06E-03	S
9.8	6.71E-01	S	2.11E+00	W	3.83E-03	W	2.06E-03	S
10	7.42E-01	S	2.11E+00	W	3.83E-03	W	2.06E-03	S
10.2	8.19E-01	S	2.11E+00	W	3.83E-03	W	2.06E-03	S
10.4	9.03E-01	S	2.10E+00	W	3.84E-03	W	2.06E-03	S
10.6	9.93E-01	S	2.10E+00	W	3.84E-03	W	2.06E-03	S
10.8	1.09E+00	S	2.10E+00	W	3.84E-03	W	2.06E-03	S
11	1.13E+00	S	2.10E+00	W	3.86E-03	W	2.06E-03	S
11.2	1.14E+00	S	2.11E+00	W	3.87E-03	W	2.06E-03	S
11.4	1.14E+00	S	2.11E+00	W	3.89E-03	W	2.06E-03	S
11.6	1.14E+00	S	2.12E+00	W	3.91E-03	W	2.06E-03	S
11.8	1.15E+00	S	2.13E+00	W	3.93E-03	W	2.06E-03	S
12	1.15E+00	S	2.13E+00	W	3.95E-03	W	2.06E-03	S
12.2	1.25E+00	S	2.15E+00	W	4.03E-03	W	2.06E-03	S
12.4	1.60E+00	S	2.20E+00	W	4.22E-03	W	2.06E-03	S
12.6	2.02E+00	S	2.25E+00	W	4.42E-03	W	2.06E-03	S
12.8	2.55E+00	S	2.30E+00	W	4.63E-03	W	2.06E-03	S
13	3.21E+00	S	2.35E+00	W	4.85E-03	W	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	3.37E+01		3.03E+01		3.19E-01		2.95E+00	

Table C-5-1. Leachate Concentrations for Bituminous Fly Ash, Waste ID AaFA Med

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
2.8	6.73E-01	S	3.00E-06	S	3.27E-01	S	3.06E-02	S
3	4.23E-01	S	3.00E-06	S	2.73E-01	S	3.42E-02	S
3.2	2.74E-01	S	3.00E-06	S	2.31E-01	S	3.79E-02	S
3.4	1.82E-01	S	3.00E-06	S	1.97E-01	S	4.17E-02	S
3.6	1.24E-01	S	3.00E-06	S	1.70E-01	S	4.57E-02	S
3.8	8.60E-02	S	3.00E-06	S	1.59E-01	S	4.73E-02	S
4	6.08E-02	S	3.00E-06	S	1.50E-01	S	4.89E-02	S
4.2	4.37E-02	S	3.00E-06	S	1.42E-01	S	5.04E-02	S
4.4	3.41E-02	S	3.00E-06	S	1.60E-01	S	5.45E-02	S
4.6	3.50E-02	S	3.00E-06	S	3.50E-01	S	7.15E-02	S
4.8	3.59E-02	S	3.00E-06	S	7.44E-01	S	9.28E-02	S
5	3.67E-02	S	3.00E-06	S	1.53E+00	S	1.19E-01	S
5.2	3.75E-02	S	3.00E-06	S	2.59E+00	W	1.43E-01	W
5.4	3.79E-02	S	3.00E-06	S	2.60E+00	W	1.43E-01	W
5.6	3.84E-02	S	3.00E-06	S	2.61E+00	W	1.43E-01	W
5.8	3.88E-02	S	3.00E-06	S	2.62E+00	W	1.43E-01	W
6	3.92E-02	S	3.00E-06	S	2.63E+00	W	1.43E-01	W
6.2	3.96E-02	S	3.00E-06	S	2.64E+00	W	1.44E-01	W
6.4	4.00E-02	S	3.00E-06	S	2.65E+00	W	1.44E-01	W
6.6	4.04E-02	S	3.00E-06	S	2.65E+00	W	1.44E-01	W
6.8	4.08E-02	S	3.00E-06	S	2.66E+00	W	1.44E-01	W
7	4.11E-02	S	3.00E-06	S	2.67E+00	W	1.44E-01	W
7.2	4.15E-02	S	2.32E-06	S	2.68E+00	W	1.44E-01	W
7.4	4.19E-02	S	3.00E-06	S	2.69E+00	W	1.44E-01	W
7.6	4.22E-02	S	3.00E-06	S	2.69E+00	W	1.44E-01	W
7.8	4.26E-02	S	3.00E-06	S	2.70E+00	W	1.45E-01	W
8	4.29E-02	S	3.00E-06	S	2.71E+00	W	1.45E-01	W
8.2	4.32E-02	S	3.00E-06	S	2.71E+00	W	1.45E-01	W
8.4	4.36E-02	S	3.00E-06	S	2.72E+00	W	1.45E-01	W
8.6	4.39E-02	S	3.00E-06	S	2.73E+00	W	1.45E-01	W

Table C-5-1. Leachate Concentrations for Bituminous Fly Ash, Waste ID AaFA Med

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
8.8	4.52E-02	S	3.00E-06	S	2.73E+00	W	1.45E-01	W
9	4.82E-02	S	3.00E-06	S	2.74E+00	W	1.43E-01	W
9.2	5.12E-02	S	3.00E-06	S	2.75E+00	W	1.42E-01	W
9.4	5.44E-02	S	3.00E-06	S	2.76E+00	W	1.41E-01	W
9.6	5.77E-02	S	3.00E-06	S	2.76E+00	W	1.40E-01	W
9.8	6.12E-02	S	3.00E-06	S	2.77E+00	W	1.39E-01	W
10	6.48E-02	S	3.00E-06	S	2.78E+00	W	1.38E-01	W
10.2	6.85E-02	S	3.00E-06	S	2.79E+00	W	1.37E-01	W
10.4	7.23E-02	S	3.00E-06	S	2.79E+00	W	1.36E-01	W
10.6	7.63E-02	S	3.00E-06	S	2.80E+00	W	1.35E-01	W
10.8	8.04E-02	S	3.00E-06	S	2.81E+00	W	1.35E-01	W
11	8.45E-02	S	3.00E-06	S	2.81E+00	W	1.35E-01	W
11.2	8.85E-02	S	3.00E-06	S	2.82E+00	W	1.35E-01	W
11.4	9.26E-02	S	3.00E-06	S	2.82E+00	W	1.35E-01	W
11.6	9.69E-02	S	3.00E-06	S	2.83E+00	W	1.36E-01	W
11.8	1.01E-01	S	3.00E-06	S	2.83E+00	W	1.36E-01	W
12	1.06E-01	S	3.00E-06	S	2.84E+00	W	1.37E-01	W
12.2	1.15E-01	S	3.00E-06	S	2.83E+00	W	1.38E-01	W
12.4	1.34E-01	S	3.00E-06	S	2.79E+00	W	1.40E-01	W
12.6	1.56E-01	S	3.00E-06	S	2.76E+00	W	1.42E-01	W
12.8	1.80E-01	S	3.00E-06	S	2.73E+00	W	1.44E-01	W
13	2.09E-01	S	3.00E-06	S	2.69E+00	W	1.47E-01	W
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	6.73E+00		3.26E-05		3.60E+01		1.91E+00	

Table C-5-1. Leachate Concentrations for Bituminous Fly Ash, Waste ID AaFA Med

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	5.09E-01	S	6.75E-02	S	8.13E-01	S
3	4.00E-01	S	5.59E-02	S	3.67E-01	S
3.2	3.19E-01	S	4.68E-02	S	1.75E-01	S
3.4	2.58E-01	S	3.96E-02	S	8.69E-02	S
3.6	2.11E-01	S	3.39E-02	S	4.50E-02	S
3.8	2.12E-01	S	3.38E-02	S	4.40E-02	S
4	2.13E-01	S	3.38E-02	S	4.30E-02	S
4.2	2.13E-01	S	3.38E-02	S	4.22E-02	S
4.4	2.43E-01	S	3.05E-02	S	4.83E-02	S
4.6	4.55E-01	S	1.86E-02	S	1.01E-01	S
4.8	8.30E-01	S	1.16E-02	S	2.04E-01	S
5	1.48E+00	S	7.37E-03	S	4.02E-01	S
5.2	2.24E+00	W	5.24E-03	S	6.57E-01	S
5.4	2.26E+00	W	4.97E-03	S	6.63E-01	S
5.6	2.27E+00	W	4.72E-03	S	6.68E-01	S
5.8	2.28E+00	W	4.49E-03	S	6.73E-01	S
6	2.30E+00	W	4.28E-03	S	6.77E-01	S
6.2	2.31E+00	W	4.09E-03	S	6.82E-01	S
6.4	2.32E+00	W	3.91E-03	S	6.87E-01	S
6.6	2.33E+00	W	3.75E-03	S	6.91E-01	S
6.8	2.35E+00	W	3.59E-03	S	6.95E-01	S
7	2.36E+00	W	3.45E-03	S	6.99E-01	S
7.2	2.37E+00	W	3.31E-03	S	7.04E-01	S
7.4	2.38E+00	W	3.19E-03	S	7.08E-01	S
7.6	2.39E+00	W	3.07E-03	S	7.11E-01	S
7.8	2.40E+00	W	2.96E-03	S	7.15E-01	S
8	2.41E+00	W	2.86E-03	S	7.19E-01	S
8.2	2.42E+00	W	2.76E-03	S	7.23E-01	S
8.4	2.43E+00	W	2.67E-03	S	7.26E-01	S
8.6	2.44E+00	W	2.58E-03	S	7.30E-01	S

Table C-5-1. Leachate Concentrations for Bituminous Fly Ash, Waste ID AaFA Med

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.8	2.48E+00	W	2.53E-03	S	7.78E-01	S
9	2.59E+00	W	2.53E-03	S	9.03E-01	S
9.2	2.69E+00	W	2.53E-03	S	1.04E+00	S
9.4	2.80E+00	W	2.53E-03	S	1.20E+00	S
9.6	2.91E+00	W	2.53E-03	S	1.38E+00	S
9.8	3.02E+00	W	2.53E-03	S	1.59E+00	S
10	3.13E+00	W	2.53E-03	S	1.81E+00	S
10.2	3.24E+00	W	2.53E-03	S	2.07E+00	S
10.4	3.36E+00	W	2.53E-03	S	2.35E+00	S
10.6	3.47E+00	W	2.53E-03	S	2.67E+00	S
10.8	3.59E+00	W	2.53E-03	S	3.02E+00	S
11	3.64E+00	W	2.53E-03	S	3.21E+00	S
11.2	3.63E+00	W	2.53E-03	S	3.27E+00	W
11.4	3.62E+00	W	2.53E-03	S	3.33E+00	W
11.6	3.62E+00	W	2.53E-03	S	3.40E+00	W
11.8	3.61E+00	W	2.53E-03	S	3.46E+00	W
12	3.60E+00	W	2.53E-03	S	3.52E+00	W
12.2	3.57E+00	W	2.53E-03	S	3.65E+00	W
12.4	3.50E+00	W	2.53E-03	S	3.91E+00	W
12.6	3.44E+00	W	2.53E-03	S	4.18E+00	W
12.8	3.37E+00	W	2.53E-03	S	4.47E+00	W
13	3.31E+00	W	2.53E-03	S	4.77E+00	W
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	4.45E+01		6.75E-01		5.90E+01	

Table C-5-2. Leachate Concentrations for Bituminous Fly Ash, Waste ID AaFB Med

	Concentration (mg/L)							
pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	1.27E+00	S	3.22E+00	W	5.48E-02	S	4.21E-01	S
3	1.15E+00	S	3.12E+00	W	5.36E-02	S	3.78E-01	S
3.2	1.04E+00	S	3.02E+00	W	5.25E-02	S	3.42E-01	S
3.4	9.44E-01	S	2.93E+00	W	5.15E-02	S	3.11E-01	S
3.6	8.64E-01	S	2.85E+00	W	5.05E-02	S	2.84E-01	S
3.8	7.95E-01	S	2.77E+00	W	4.96E-02	S	2.61E-01	S
4	6.79E-01	S	2.71E+00	W	4.50E-02	S	2.34E-01	S
4.2	5.22E-01	S	2.66E+00	W	3.65E-02	S	2.01E-01	S
4.4	4.06E-01	S	2.62E+00	W	2.99E-02	S	1.73E-01	S
4.6	3.19E-01	S	2.57E+00	W	2.46E-02	S	1.51E-01	S
4.8	2.53E-01	S	2.53E+00	W	2.05E-02	S	1.32E-01	S
5	2.03E-01	S	2.50E+00	W	1.72E-02	S	1.16E-01	S
5.2	1.64E-01	S	2.46E+00	W	1.45E-02	S	1.03E-01	S
5.4	1.34E-01	S	2.43E+00	W	1.23E-02	S	9.15E-02	S
5.6	1.10E-01	S	2.39E+00	W	1.06E-02	S	8.16E-02	S
5.8	9.73E-02	S	2.37E+00	W	9.42E-03	S	6.97E-02	S
6	9.74E-02	S	2.36E+00	W	9.05E-03	S	5.48E-02	S
6.2	9.75E-02	S	2.34E+00	W	8.71E-03	S	4.35E-02	S
6.4	9.76E-02	S	2.33E+00	W	8.39E-03	S	3.47E-02	S
6.6	9.77E-02	S	2.32E+00	W	8.09E-03	S	2.79E-02	S
6.8	9.78E-02	S	2.31E+00	W	7.81E-03	S	2.26E-02	S
7	9.80E-02	S	2.29E+00	W	7.54E-03	S	1.84E-02	S
7.2	9.81E-02	S	2.28E+00	W	7.30E-03	S	1.51E-02	S
7.4	1.18E-01	S	2.27E+00	W	7.19E-03	S	1.21E-02	S
7.6	1.42E-01	S	2.27E+00	W	7.09E-03	S	9.71E-03	S
7.8	1.71E-01	S	2.26E+00	W	6.99E-03	S	7.86E-03	S
8	2.05E-01	S	2.25E+00	W	6.90E-03	S	6.39E-03	S
8.2	2.44E-01	S	2.25E+00	W	6.81E-03	W	5.23E-03	S
8.4	2.89E-01	S	2.24E+00	W	6.73E-03	W	4.29E-03	S

Table C-5-2. Leachate Concentrations for Bituminous Fly Ash, Waste ID AaFB Med

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.6	3.41E-01	S	2.23E+00	W	6.64E-03	W	3.54E-03	S
8.8	4.02E-01	S	2.23E+00	W	6.56E-03	W	2.94E-03	S
9	4.71E-01	S	2.22E+00	W	6.49E-03	W	2.45E-03	S
9.2	5.48E-01	S	2.21E+00	W	6.41E-03	W	2.06E-03	S
9.4	5.98E-01	S	2.22E+00	W	6.32E-03	W	2.06E-03	S
9.6	6.52E-01	S	2.23E+00	W	6.24E-03	W	2.06E-03	S
9.8	7.09E-01	S	2.24E+00	W	6.16E-03	W	2.06E-03	S
10	7.70E-01	S	2.24E+00	W	6.08E-03	W	2.06E-03	S
10.2	8.34E-01	S	2.25E+00	W	6.00E-03	W	2.06E-03	S
10.4	9.03E-01	S	2.26E+00	W	5.92E-03	W	2.06E-03	S
10.6	9.35E-01	S	2.27E+00	W	5.94E-03	W	2.06E-03	S
10.8	9.65E-01	S	2.28E+00	W	5.96E-03	W	2.06E-03	S
11	9.96E-01	S	2.29E+00	W	5.98E-03	W	2.06E-03	S
11.2	1.03E+00	S	2.30E+00	W	6.00E-03	W	2.06E-03	S
11.4	1.06E+00	S	2.31E+00	W	6.02E-03	W	2.06E-03	S
11.6	1.09E+00	S	2.32E+00	W	6.04E-03	W	2.06E-03	S
11.8	1.12E+00	S	2.33E+00	W	6.06E-03	W	2.06E-03	S
12	1.16E+00	S	2.34E+00	W	6.08E-03	W	2.06E-03	S
12.2	1.20E+00	S	2.35E+00	W	6.12E-03	W	2.06E-03	S
12.4	1.57E+00	S	2.42E+00	W	6.53E-03	W	2.06E-03	S
12.6	2.04E+00	S	2.48E+00	W	6.96E-03	W	2.06E-03	S
12.8	2.63E+00	S	2.55E+00	W	7.42E-03	W	2.06E-03	S
13	3.39E+00	S	2.62E+00	W	7.89E-03	W	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	3.68E+01		3.57E+01		5.48E-01		4.21E+00	

Table C-5-2. Leachate Concentrations for Bituminous Fly Ash, Waste ID AaFB Med

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
2.8	1.05E+00	S	3.00E-06	S	1.86E-01	S	2.91E-02	S
3	7.64E-01	S	3.00E-06	S	1.52E-01	S	3.37E-02	S
3.2	5.69E-01	S	3.00E-06	S	1.25E-01	S	3.88E-02	S
3.4	4.31E-01	S	3.00E-06	S	1.05E-01	S	4.41E-02	S
3.6	3.32E-01	S	3.00E-06	S	8.85E-02	S	4.99E-02	S
3.8	2.60E-01	S	3.00E-06	S	7.54E-02	S	5.61E-02	S
4	1.93E-01	S	3.00E-06	S	8.29E-02	S	6.31E-02	S
4.2	1.33E-01	S	3.00E-06	S	1.30E-01	S	7.16E-02	S
4.4	9.34E-02	S	3.00E-06	S	2.00E-01	S	8.08E-02	S
4.6	6.66E-02	S	3.00E-06	S	3.02E-01	S	9.06E-02	S
4.8	4.81E-02	S	3.00E-06	S	4.47E-01	S	1.01E-01	S
5	3.53E-02	S	3.00E-06	S	6.53E-01	S	1.12E-01	S
5.2	2.61E-02	S	3.00E-06	S	9.38E-01	S	1.24E-01	S
5.4	1.96E-02	S	3.00E-06	S	1.33E+00	S	1.37E-01	S
5.6	1.49E-02	S	3.00E-06	S	1.86E+00	S	1.51E-01	S
5.8	1.37E-02	S	3.00E-06	S	2.33E+00	S	1.60E-01	S
6	1.80E-02	S	3.00E-06	S	2.40E+00	S	1.62E-01	S
6.2	2.33E-02	S	3.00E-06	S	2.47E+00	S	1.63E-01	W
6.4	3.00E-02	S	3.00E-06	S	2.54E+00	S	1.64E-01	W
6.6	3.83E-02	S	3.00E-06	S	2.62E+00	S	1.65E-01	W
6.8	4.86E-02	S	3.00E-06	S	2.69E+00	S	1.66E-01	W
7	6.11E-02	S	3.00E-06	S	2.76E+00	S	1.67E-01	W
7.2	7.65E-02	S	3.00E-06	S	2.83E+00	W	1.68E-01	W
7.4	8.86E-02	S	3.00E-06	S	2.85E+00	W	1.67E-01	W
7.6	1.02E-01	S	3.00E-06	S	2.87E+00	W	1.66E-01	W
7.8	1.17E-01	S	3.00E-06	S	2.89E+00	W	1.65E-01	W
8	1.34E-01	S	3.00E-06	S	2.90E+00	W	1.64E-01	W
8.2	1.52E-01	S	3.00E-06	S	2.92E+00	W	1.63E-01	W
8.4	1.73E-01	S	3.00E-06	S	2.94E+00	W	1.62E-01	W

Table C-5-2. Leachate Concentrations for Bituminous Fly Ash, Waste ID AaFB Med

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
8.6	1.95E-01	S	3.00E-06	S	2.96E+00	W	1.61E-01	W
8.8	2.20E-01	S	3.00E-06	S	2.97E+00	W	1.60E-01	W
9	2.48E-01	S	3.00E-06	S	2.99E+00	W	1.59E-01	W
9.2	2.78E-01	S	3.00E-06	S	3.00E+00	W	1.58E-01	W
9.4	2.95E-01	S	3.00E-06	S	3.03E+00	W	1.58E-01	W
9.6	3.13E-01	S	3.00E-06	S	3.05E+00	W	1.58E-01	W
9.8	3.32E-01	S	3.00E-06	S	3.07E+00	W	1.58E-01	W
10	3.51E-01	S	3.00E-06	S	3.09E+00	W	1.58E-01	W
10.2	3.71E-01	S	3.00E-06	S	3.11E+00	W	1.59E-01	W
10.4	3.92E-01	S	3.00E-06	S	3.13E+00	W	1.59E-01	W
10.6	4.10E-01	S	3.00E-06	S	3.14E+00	W	1.60E-01	W
10.8	4.27E-01	S	3.00E-06	S	3.15E+00	W	1.61E-01	W
11	4.45E-01	S	3.00E-06	S	3.16E+00	W	1.62E-01	W
11.2	4.64E-01	S	3.00E-06	S	3.17E+00	W	1.62E-01	W
11.4	4.83E-01	S	3.00E-06	S	3.18E+00	W	1.63E-01	W
11.6	5.02E-01	S	3.00E-06	S	3.19E+00	W	1.64E-01	W
11.8	5.22E-01	S	3.00E-06	S	3.19E+00	W	1.65E-01	W
12	5.42E-01	S	3.00E-06	S	3.20E+00	W	1.66E-01	W
12.2	5.66E-01	S	3.00E-06	S	3.22E+00	W	1.67E-01	W
12.4	6.54E-01	S	3.00E-06	S	3.29E+00	W	1.70E-01	W
12.6	7.55E-01	S	3.00E-06	S	3.37E+00	W	1.72E-01	W
12.8	8.69E-01	S	3.00E-06	S	3.44E+00	W	1.75E-01	W
13	9.99E-01	S	3.00E-06	S	3.52E+00	W	1.78E-01	S
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	1.22E+01		4.20E-05		4.82E+01		2.45E+00	

Table C-5-2. Leachate Concentrations for Bituminous Fly Ash, Waste ID AaFB Med

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	1.48E+00	S	7.85E-02	S	8.27E-01	S
3	1.18E+00	S	6.77E-02	S	4.89E-01	S
3.2	9.58E-01	S	5.90E-02	S	2.99E-01	S
3.4	7.87E-01	S	5.19E-02	S	1.88E-01	S
3.6	6.54E-01	S	4.59E-02	S	1.22E-01	S
3.8	5.49E-01	S	4.09E-02	S	8.06E-02	S
4	5.22E-01	S	3.63E-02	S	6.71E-02	S
4.2	5.91E-01	S	3.19E-02	S	7.65E-02	S
4.4	6.65E-01	S	2.83E-02	S	8.67E-02	S
4.6	7.44E-01	S	2.52E-02	S	9.76E-02	S
4.8	8.29E-01	S	2.25E-02	S	1.09E-01	S
5	9.20E-01	S	2.02E-02	S	1.22E-01	S
5.2	1.02E+00	S	1.83E-02	S	1.36E-01	S
5.4	1.12E+00	S	1.65E-02	S	1.50E-01	S
5.6	1.23E+00	S	1.50E-02	S	1.65E-01	S
5.8	1.33E+00	S	1.38E-02	S	1.79E-01	S
6	1.42E+00	S	1.28E-02	S	1.88E-01	S
6.2	1.51E+00	S	1.20E-02	S	1.97E-01	S
6.4	1.60E+00	S	1.12E-02	S	2.07E-01	S
6.6	1.69E+00	S	1.05E-02	S	2.16E-01	S
6.8	1.79E+00	S	9.86E-03	S	2.26E-01	S
7	1.89E+00	S	9.27E-03	S	2.35E-01	S
7.2	1.99E+00	S	8.74E-03	S	2.45E-01	S
7.4	2.22E+00	S	7.63E-03	S	2.88E-01	S
7.6	2.48E+00	S	6.66E-03	S	3.39E-01	S
7.8	2.77E+00	S	5.84E-03	S	3.98E-01	S
8	3.07E+00	S	5.13E-03	S	4.65E-01	S
8.2	3.41E+00	S	4.52E-03	S	5.41E-01	S
8.4	3.77E+00	S	4.00E-03	S	6.27E-01	S

Table C-5-2. Leachate Concentrations for Bituminous Fly Ash, Waste ID AaFB Med

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.6	4.15E+00	S	3.55E-03	S	7.25E-01	S
8.8	4.57E+00	S	3.16E-03	S	8.35E-01	S
9	5.01E+00	S	2.81E-03	S	9.58E-01	S
9.2	5.48E+00	S	2.53E-03	S	1.10E+00	S
9.4	5.78E+00	S	2.53E-03	S	1.29E+00	S
9.6	6.08E+00	S	2.53E-03	S	1.51E+00	S
9.8	6.39E+00	S	2.53E-03	S	1.75E+00	S
10	6.70E+00	S	2.53E-03	S	2.04E+00	S
10.2	7.03E+00	S	2.53E-03	S	2.36E+00	S
10.4	7.37E+00	S	2.53E-03	S	2.73E+00	S
10.6	7.38E+00	S	2.53E-03	S	2.88E+00	S
10.8	7.38E+00	S	2.53E-03	S	3.02E+00	S
11	7.37E+00	S	2.53E-03	S	3.17E+00	S
11.2	7.36E+00	S	2.53E-03	S	3.32E+00	S
11.4	7.36E+00	S	2.53E-03	S	3.48E+00	S
11.6	7.35E+00	S	2.53E-03	S	3.64E+00	S
11.8	7.35E+00	S	2.53E-03	S	3.81E+00	S
12	7.34E+00	S	2.53E-03	S	3.98E+00	S
12.2	7.33E+00	S	2.53E-03	S	4.17E+00	S
12.4	7.11E+00	S	2.53E-03	S	4.70E+00	S
12.6	6.90E+00	S	2.53E-03	S	5.29E+00	S
12.8	6.70E+00	S	2.53E-03	S	5.95E+00	S
13	6.51E+00	S	2.53E-03	S	6.67E+00	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	9.38E+01		7.85E-01		8.32E+01	

Table C-5-3. Leachate Concentrations for Bituminous Fly Ash, Waste ID AaFC Med

Sample ID	AaFC-[Med] (P,1,1)
Date Exported	8/27/2011, 6:47 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term moc
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	9.32E-01	S	1.18E+01	W	5.82E-02	S	4.81E-01	S
3	6.19E-01	S	1.13E+01	W	5.43E-02	S	4.12E-01	S
3.2	4.22E-01	S	1.09E+01	W	5.09E-02	S	3.57E-01	S
3.4	2.94E-01	S	1.06E+01	W	4.79E-02	S	3.12E-01	S
3.6	2.10E-01	S	1.02E+01	W	4.53E-02	S	2.75E-01	S
3.8	1.52E-01	S	9.91E+00	W	4.29E-02	S	2.43E-01	S
4	1.29E-01	S	9.89E+00	W	4.01E-02	S	2.32E-01	S
4.2	1.18E-01	S	9.98E+00	W	3.73E-02	S	2.27E-01	S
4.4	1.08E-01	S	1.01E+01	W	3.48E-02	S	2.23E-01	S
4.6	9.91E-02	S	1.01E+01	W	3.26E-02	S	2.19E-01	S
4.8	9.13E-02	S	1.02E+01	W	3.06E-02	S	2.15E-01	S
5	8.45E-02	S	1.03E+01	W	2.88E-02	S	2.11E-01	S
5.2	7.84E-02	S	1.04E+01	W	2.72E-02	S	2.08E-01	S
5.4	7.94E-02	S	1.03E+01	W	2.08E-02	S	1.69E-01	S
5.6	8.03E-02	S	1.02E+01	W	1.61E-02	S	1.38E-01	S
5.8	8.13E-02	S	1.02E+01	W	1.26E-02	S	1.14E-01	S
6	8.22E-02	S	1.01E+01	W	9.90E-03	S	9.45E-02	S
6.2	8.32E-02	S	1.01E+01	W	7.85E-03	S	7.89E-02	S
6.4	8.40E-02	S	9.99E+00	W	6.28E-03	S	6.63E-02	S
6.6	8.75E-02	S	9.92E+00	W	5.30E-03	S	5.39E-02	S
6.8	9.96E-02	S	9.80E+00	W	5.17E-03	S	3.95E-02	S
7	1.13E-01	S	9.69E+00	W	5.04E-03	S	2.93E-02	S
7.2	1.28E-01	S	9.58E+00	W	4.93E-03	S	2.19E-02	S
7.4	1.44E-01	S	9.48E+00	W	4.82E-03	S	1.64E-02	S
7.6	1.61E-01	S	9.38E+00	W	4.71E-03	S	1.25E-02	S

Table C-5-3. Leachate Concentrations for Bituminous Fly Ash, Waste ID AaFC Med

Sample ID	AaFC-[Med] (P,1,1)
Date Exported	8/27/2011, 6:47 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
7.8	1.80E-01	S	9.28E+00	W	4.61E-03	S	9.53E-03	S
8	2.01E-01	S	9.19E+00	W	4.51E-03	S	7.33E-03	S
8.2	2.24E-01	S	9.10E+00	W	4.42E-03	W	5.67E-03	S
8.4	2.49E-01	S	9.01E+00	W	4.34E-03	W	4.42E-03	S
8.6	2.75E-01	S	8.92E+00	W	4.25E-03	W	3.46E-03	S
8.8	3.04E-01	S	8.84E+00	W	4.17E-03	W	2.73E-03	S
9	3.35E-01	S	8.76E+00	W	4.09E-03	W	2.16E-03	S
9.2	3.34E-01	S	8.64E+00	W	4.12E-03	W	2.06E-03	S
9.4	3.26E-01	S	8.51E+00	W	4.17E-03	W	2.06E-03	S
9.6	3.18E-01	S	8.39E+00	W	4.22E-03	W	2.06E-03	S
9.8	3.10E-01	S	8.27E+00	W	4.27E-03	W	2.06E-03	S
10	3.02E-01	S	8.15E+00	W	4.32E-03	W	2.06E-03	S
10.2	2.95E-01	S	8.04E+00	W	4.37E-03	W	2.06E-03	S
10.4	2.88E-01	S	7.93E+00	W	4.42E-03	W	2.06E-03	S
10.6	2.82E-01	S	7.83E+00	W	4.47E-03	W	2.06E-03	S
10.8	2.75E-01	S	7.73E+00	W	4.52E-03	W	2.06E-03	S
11	2.69E-01	S	7.63E+00	W	4.57E-03	W	2.06E-03	S
11.2	2.63E-01	S	7.53E+00	W	4.61E-03	W	2.06E-03	S
11.4	2.58E-01	S	7.44E+00	W	4.66E-03	W	2.06E-03	S
11.6	2.68E-01	S	7.14E+00	W	4.65E-03	W	2.06E-03	S
11.8	3.06E-01	S	6.58E+00	W	4.57E-03	W	2.06E-03	S
12	3.48E-01	S	6.07E+00	W	4.49E-03	W	2.06E-03	S
12.2	3.95E-01	S	5.60E+00	W	4.42E-03	W	2.06E-03	S
12.4	5.08E-01	S	5.45E+00	W	4.54E-03	W	2.06E-03	S
12.6	7.90E-01	S	5.73E+00	W	4.98E-03	W	2.06E-03	S
12.8	1.22E+00	S	6.01E+00	W	5.46E-03	W	2.06E-03	S
13	1.87E+00	S	6.31E+00	W	5.98E-03	W	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	1.70E+01		1.18E+02		5.82E-01		4.81E+00	

Table C-5-3. Leachate Concentrations for Bituminous Fly Ash, Waste ID AaFC Med

Sample ID
Date Exported
Database Name deling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	1.35E-01	S	3.00E-06	S	1.47E+00	S	7.88E-02	S
3	6.29E-02	S	3.00E-06	S	1.37E+00	S	8.05E-02	S
3.2	3.07E-02	S	3.00E-06	S	1.29E+00	S	8.21E-02	S
3.4	1.56E-02	S	3.00E-06	S	1.22E+00	S	8.36E-02	S
3.6	8.29E-03	S	3.00E-06	S	1.15E+00	S	8.51E-02	S
3.8	4.54E-03	S	3.00E-06	S	1.09E+00	S	8.65E-02	S
4	3.51E-03	S	3.00E-06	S	1.14E+00	S	8.89E-02	S
4.2	3.13E-03	S	3.00E-06	S	1.24E+00	S	9.18E-02	S
4.4	2.81E-03	S	3.00E-06	S	1.35E+00	S	9.45E-02	S
4.6	2.53E-03	S	3.00E-06	S	1.46E+00	S	9.73E-02	S
4.8	2.29E-03	S	3.00E-06	S	1.57E+00	S	1.00E-01	S
5	2.08E-03	S	3.00E-06	S	1.68E+00	S	1.03E-01	S
5.2	1.90E-03	S	1.80E-06	S	1.80E+00	S	1.05E-01	S
5.4	2.35E-03	S	3.00E-06	S	1.95E+00	S	1.10E-01	S
5.6	2.89E-03	S	3.00E-06	S	2.11E+00	S	1.15E-01	S
5.8	3.53E-03	S	3.00E-06	S	2.27E+00	S	1.20E-01	S
6	4.28E-03	S	3.00E-06	S	2.44E+00	S	1.25E-01	S
6.2	5.16E-03	S	3.00E-06	S	2.61E+00	S	1.30E-01	S
6.4	6.18E-03	S	3.00E-06	S	2.79E+00	S	1.35E-01	S
6.6	7.34E-03	S	3.00E-06	S	2.94E+00	S	1.39E-01	S
6.8	8.59E-03	S	3.00E-06	S	2.99E+00	S	1.39E-01	S
7	1.00E-02	S	3.00E-06	S	3.03E+00	S	1.40E-01	S
7.2	1.16E-02	S	3.00E-06	S	3.07E+00	W	1.40E-01	S
7.4	1.34E-02	S	3.00E-06	S	3.11E+00	W	1.41E-01	S
7.6	1.55E-02	S	3.00E-06	S	3.15E+00	W	1.41E-01	S

Table C-5-3. Leachate Concentrations for Bituminous Fly Ash, Waste ID AaFC Med

Sample ID
Date Exported
Database Name deling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
7.8	1.77E-02	S	3.00E-06	S	3.19E+00	W	1.42E-01	S
8	2.03E-02	S	3.00E-06	S	3.23E+00	W	1.43E-01	S
8.2	2.31E-02	S	3.00E-06	S	3.27E+00	W	1.43E-01	S
8.4	2.62E-02	S	3.00E-06	S	3.31E+00	W	1.43E-01	S
8.6	2.97E-02	S	3.00E-06	S	3.35E+00	W	1.44E-01	S
8.8	3.36E-02	S	3.00E-06	S	3.39E+00	W	1.44E-01	S
9	3.78E-02	S	3.00E-06	S	3.42E+00	W	1.45E-01	S
9.2	4.41E-02	S	3.00E-06	S	3.46E+00	W	1.38E-01	S
9.4	5.17E-02	S	3.00E-06	S	3.49E+00	W	1.30E-01	S
9.6	6.04E-02	S	3.00E-06	S	3.53E+00	W	1.23E-01	S
9.8	7.04E-02	S	3.00E-06	S	3.57E+00	W	1.16E-01	S
10	8.17E-02	S	3.00E-06	S	3.60E+00	W	1.09E-01	S
10.2	9.46E-02	S	3.00E-06	S	3.63E+00	W	1.03E-01	S
10.4	1.09E-01	S	3.00E-06	S	3.67E+00	W	9.80E-02	S
10.6	1.26E-01	S	3.00E-06	S	3.70E+00	W	9.29E-02	S
10.8	1.45E-01	S	3.00E-06	S	3.74E+00	W	8.81E-02	S
11	1.66E-01	S	3.00E-06	S	3.77E+00	W	8.37E-02	S
11.2	1.89E-01	S	3.00E-06	S	3.80E+00	W	7.96E-02	S
11.4	2.16E-01	S	3.00E-06	S	3.83E+00	W	7.58E-02	S
11.6	2.34E-01	S	3.00E-06	S	3.84E+00	W	6.40E-02	S
11.8	2.37E-01	S	3.00E-06	S	3.81E+00	W	4.53E-02	S
12	2.39E-01	S	3.00E-06	S	3.78E+00	W	3.23E-02	S
12.2	2.41E-01	S	3.00E-06	S	3.74E+00	W	2.31E-02	S
12.4	2.52E-01	S	3.00E-06	S	3.78E+00	W	2.23E-02	S
12.6	2.77E-01	S	3.00E-06	S	3.92E+00	W	3.31E-02	S
12.8	3.05E-01	S	3.00E-06	S	4.06E+00	W	4.90E-02	S
13	3.35E-01	S	3.00E-06	S	4.20E+00	W	7.19E-02	S
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	4.24E+00		4.17E-05		5.64E+01		1.45E+00	

Table C-5-3. Leachate Concentrations for Bituminous Fly Ash, Waste ID AaFC Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	2.92E-01	S	1.38E-01	S	1.15E+00	S
3	2.19E-01	S	1.19E-01	S	6.22E-01	S
3.2	1.67E-01	S	1.03E-01	S	3.50E-01	S
3.4	1.29E-01	S	9.05E-02	S	2.04E-01	S
3.6	1.02E-01	S	8.00E-02	S	1.22E-01	S
3.8	8.10E-02	S	7.12E-02	S	7.56E-02	S
4	7.26E-02	S	6.67E-02	S	6.59E-02	S
4.2	6.84E-02	S	6.40E-02	S	6.61E-02	S
4.4	6.46E-02	S	6.15E-02	S	6.62E-02	S
4.6	6.11E-02	S	5.92E-02	S	6.64E-02	S
4.8	5.80E-02	S	5.71E-02	S	6.66E-02	S
5	5.51E-02	S	5.51E-02	S	6.67E-02	S
5.2	5.25E-02	S	5.33E-02	S	6.69E-02	S
5.4	6.07E-02	S	4.84E-02	S	7.58E-02	S
5.6	6.97E-02	S	4.41E-02	S	8.54E-02	S
5.8	7.97E-02	S	4.03E-02	S	9.59E-02	S
6	9.08E-02	S	3.70E-02	S	1.07E-01	S
6.2	1.03E-01	S	3.40E-02	S	1.19E-01	S
6.4	1.16E-01	S	3.14E-02	S	1.33E-01	S
6.6	1.24E-01	S	2.91E-02	S	1.47E-01	S
6.8	1.12E-01	S	2.72E-02	S	1.65E-01	S
7	1.01E-01	S	2.55E-02	S	1.83E-01	S
7.2	9.22E-02	S	2.40E-02	S	2.03E-01	S
7.4	8.41E-02	S	2.26E-02	S	2.25E-01	S
7.6	7.68E-02	S	2.13E-02	S	2.49E-01	S

Table C-5-3. Leachate Concentrations for Bituminous Fly Ash, Waste ID AaFC Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
7.8	7.04E-02	S	2.01E-02	S	2.74E-01	S
8	6.46E-02	S	1.90E-02	S	3.01E-01	S
8.2	5.94E-02	S	1.80E-02	S	3.30E-01	S
8.4	5.48E-02	S	1.70E-02	S	3.60E-01	S
8.6	5.06E-02	S	1.62E-02	S	3.93E-01	S
8.8	4.68E-02	S	1.54E-02	S	4.28E-01	S
9	4.34E-02	S	1.46E-02	S	4.66E-01	S
9.2	4.31E-02	S	1.28E-02	S	4.93E-01	S
9.4	4.35E-02	S	1.09E-02	S	5.18E-01	S
9.6	4.40E-02	S	9.39E-03	S	5.44E-01	S
9.8	4.44E-02	S	8.09E-03	S	5.71E-01	S
10	4.48E-02	S	7.00E-03	S	5.99E-01	S
10.2	4.52E-02	S	6.07E-03	S	6.27E-01	S
10.4	4.56E-02	S	5.28E-03	S	6.56E-01	S
10.6	4.60E-02	S	4.60E-03	S	6.86E-01	S
10.8	4.64E-02	S	4.02E-03	S	7.16E-01	S
11	4.68E-02	S	3.53E-03	S	7.47E-01	S
11.2	4.72E-02	S	3.10E-03	S	7.79E-01	S
11.4	4.76E-02	S	2.73E-03	S	8.12E-01	S
11.6	4.86E-02	S	2.53E-03	S	8.39E-01	S
11.8	5.07E-02	S	2.53E-03	S	8.54E-01	S
12	5.28E-02	S	2.53E-03	S	8.70E-01	S
12.2	5.49E-02	S	2.53E-03	S	8.86E-01	S
12.4	5.75E-02	S	2.53E-03	S	9.91E-01	S
12.6	6.07E-02	S	2.53E-03	S	1.28E+00	S
12.8	6.39E-02	S	2.53E-03	S	1.64E+00	S
13	6.73E-02	S	2.53E-03	S	2.09E+00	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	2.92E+00		1.38E+00		2.27E+01	

Table C-5-4. Leachate Concentrations for Bituminous Fly Ash, Waste ID AFA Med

Sample ID	AFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:47 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	6.16E-01	S	1.24E+01	W	2.25E-02	S	4.84E-01	S
3	5.51E-01	S	1.23E+01	W	2.34E-02	S	4.48E-01	S
3.2	4.72E-01	S	1.22E+01	W	2.43E-02	S	3.83E-01	S
3.4	4.08E-01	S	1.21E+01	W	2.43E-02	S	3.26E-01	S
3.6	3.37E-01	S	1.20E+01	W	2.44E-02	S	2.86E-01	S
3.8	3.02E-01	S	1.20E+01	W	2.56E-02	S	2.67E-01	S
4	2.75E-01	S	1.19E+01	W	2.53E-02	S	2.49E-01	S
4.2	2.58E-01	S	1.18E+01	W	2.50E-02	S	2.34E-01	S
4.4	2.43E-01	S	1.16E+01	W	2.47E-02	S	2.20E-01	S
4.6	2.29E-01	S	1.14E+01	W	2.44E-02	S	2.07E-01	S
4.8	2.15E-01	S	1.13E+01	W	2.40E-02	S	1.96E-01	S
5	2.01E-01	S	1.11E+01	W	2.37E-02	S	1.85E-01	S
5.2	1.89E-01	S	1.11E+01	W	2.34E-02	S	1.74E-01	S
5.4	1.78E-01	S	1.10E+01	W	2.32E-02	S	1.64E-01	S
5.6	1.67E-01	S	1.10E+01	W	2.29E-02	S	1.55E-01	S
5.8	1.63E-01	S	1.09E+01	W	2.13E-02	S	1.46E-01	S
6	1.62E-01	S	1.08E+01	W	1.85E-02	S	1.36E-01	S
6.2	1.60E-01	S	1.07E+01	W	1.62E-02	S	1.29E-01	S
6.4	1.59E-01	S	1.05E+01	W	1.42E-02	S	1.22E-01	S
6.6	1.58E-01	S	1.04E+01	W	1.25E-02	S	1.15E-01	S
6.8	1.51E-01	S	1.03E+01	W	1.06E-02	S	1.09E-01	S
7	1.44E-01	S	1.03E+01	W	8.95E-03	S	9.03E-02	S
7.2	1.37E-01	S	1.03E+01	W	7.60E-03	S	6.08E-02	S
7.4	1.31E-01	S	1.02E+01	W	5.94E-03	S	4.13E-02	S
7.6	1.30E-01	S	1.02E+01	W	4.42E-03	S	3.07E-02	S
7.8	1.33E-01	S	9.48E+00	W	3.11E-03	S	2.57E-02	S
8	1.35E-01	S	8.60E+00	S	2.00E-03	S	2.14E-02	S

Table C-5-4. Leachate Concentrations for Bituminous Fly Ash, Waste ID AFA Med

Sample ID	AFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:47 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	1.35E-01	S	6.90E+00	S	1.93E-03	S	1.68E-02	S
8.4	1.10E-01	S	5.56E+00	S	1.87E-03	S	1.34E-02	S
8.6	9.70E-02	S	3.78E+00	S	1.62E-03	S	1.12E-02	S
8.8	1.03E-01	S	2.79E+00	S	1.35E-03	S	1.07E-02	S
9	9.28E-02	S	2.21E+00	S	1.13E-03	S	1.03E-02	S
9.2	8.39E-02	S	1.76E+00	S	9.48E-04	S	9.97E-03	S
9.4	7.59E-02	S	1.41E+00	S	7.98E-04	S	9.65E-03	S
9.6	6.89E-02	S	1.14E+00	S	7.46E-04	S	8.96E-03	S
9.8	6.27E-02	S	9.18E-01	S	7.46E-04	S	8.69E-03	S
10	5.71E-02	S	7.45E-01	S	7.46E-04	S	8.43E-03	S
10.2	5.08E-02	S	6.07E-01	S	7.46E-04	S	8.18E-03	S
10.4	4.50E-02	S	4.97E-01	S	7.46E-04	S	7.95E-03	S
10.6	4.02E-02	S	4.08E-01	S	7.46E-04	S	7.73E-03	S
10.8	3.89E-02	S	3.36E-01	S	7.46E-04	S	7.51E-03	S
11	3.76E-02	S	3.00E-01	S	7.46E-04	S	7.57E-03	S
11.2	3.63E-02	S	2.80E-01	S	7.46E-04	S	7.76E-03	S
11.4	3.49E-02	S	2.62E-01	S	7.46E-04	S	7.76E-03	S
11.6	3.36E-02	S	2.45E-01	S	7.46E-04	S	7.61E-03	S
11.8	3.25E-02	S	2.31E-01	S	7.46E-04	S	7.25E-03	S
12	3.37E-02	S	2.23E-01	S	7.46E-04	S	4.57E-03	S
12.2	3.49E-02	S	2.16E-01	S	7.46E-04	S	2.90E-03	S
12.4	3.62E-02	S	2.09E-01	S	7.46E-04	S	1.85E-03	S
12.6	3.75E-02	S	2.02E-01	S	7.46E-04	S	1.19E-03	S
12.8	3.88E-02	S	1.95E-01	S	7.46E-04	S	8.06E-04	S
13	4.02E-02	S	1.86E-01	S	7.46E-04	S	5.81E-04	S
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	6.16E+00		1.24E+02		2.56E-01		4.84E+00	

Table C-5-4. Leachate Concentrations for Bituminous Fly Ash, Waste ID AFA Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	2.97E+00	S	2.20E-05	S	1.48E-01	S	3.80E-01	S
3	2.65E+00	S	2.10E-05	S	1.30E-01	S	2.59E-01	S
3.2	2.16E+00	S	2.01E-05	S	1.12E-01	S	1.34E-01	S
3.4	1.68E+00	S	1.93E-05	S	9.53E-02	S	6.58E-02	S
3.6	1.32E+00	S	1.85E-05	S	8.40E-02	S	3.36E-02	S
3.8	1.22E+00	S	1.81E-05	S	9.22E-02	S	3.27E-02	S
4	1.16E+00	S	1.95E-05	S	1.05E-01	S	3.43E-02	S
4.2	1.11E+00	S	2.09E-05	S	1.18E-01	S	3.58E-02	S
4.4	1.07E+00	S	2.24E-05	S	1.31E-01	S	3.74E-02	S
4.6	1.03E+00	S	2.38E-05	S	1.44E-01	S	3.89E-02	S
4.8	1.00E+00	S	2.54E-05	S	1.58E-01	S	4.04E-02	S
5	9.70E-01	S	2.69E-05	S	1.73E-01	S	4.19E-02	S
5.2	9.41E-01	S	2.85E-05	S	1.89E-01	S	4.34E-02	S
5.4	9.14E-01	S	2.88E-05	S	2.06E-01	S	4.48E-02	S
5.6	8.89E-01	S	3.17E-05	S	2.25E-01	S	4.65E-02	S
5.8	8.83E-01	S	3.60E-05	S	2.96E-01	S	5.17E-02	S
6	9.01E-01	S	4.06E-05	S	4.54E-01	S	5.99E-02	S
6.2	9.15E-01	S	4.84E-05	S	6.07E-01	S	6.59E-02	S
6.4	9.29E-01	S	6.15E-05	S	7.66E-01	S	7.23E-02	S
6.6	9.43E-01	S	7.76E-05	S	9.94E-01	S	8.12E-02	S
6.8	9.90E-01	S	1.02E-04	S	1.32E+00	S	9.08E-02	S
7	1.04E+00	S	1.31E-04	S	1.99E+00	S	1.03E-01	S
7.2	1.07E+00	S	1.83E-04	S	3.62E+00	S	1.20E-01	S
7.4	1.15E+00	S	2.53E-04	S	6.50E+00	S	1.38E-01	S
7.6	1.20E+00	S	3.25E-04	S	7.95E+00	S	1.53E-01	S
7.8	1.25E+00	S	3.68E-04	S	6.87E+00	S	1.59E-01	S
8	1.26E+00	S	4.16E-04	S	6.58E+00	S	1.65E-01	S

Table C-5-4. Leachate Concentrations for Bituminous Fly Ash, Waste ID AFA Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	1.26E+00	S	4.13E-04	S	3.98E+00	S	1.41E-01	S
8.4	1.31E+00	S	3.98E-04	S	2.70E+00	S	9.81E-02	S
8.6	1.25E+00	S	3.52E-04	S	2.16E+00	S	7.64E-02	S
8.8	1.25E+00	S	3.84E-04	S	1.58E+00	S	7.64E-02	S
9	1.26E+00	S	3.54E-04	S	1.42E+00	S	6.30E-02	S
9.2	1.26E+00	S	3.25E-04	S	1.29E+00	S	5.22E-02	S
9.4	1.26E+00	S	2.89E-04	S	1.17E+00	S	4.34E-02	S
9.6	1.23E+00	S	2.57E-04	S	1.05E+00	S	3.62E-02	S
9.8	1.19E+00	S	2.29E-04	S	9.32E-01	S	3.03E-02	S
10	1.18E+00	S	1.94E-04	S	8.37E-01	S	2.55E-02	S
10.2	1.17E+00	S	1.53E-04	S	7.60E-01	S	2.15E-02	S
10.4	1.17E+00	S	1.21E-04	S	6.92E-01	S	1.82E-02	S
10.6	1.17E+00	S	9.64E-05	S	6.31E-01	S	1.55E-02	S
10.8	1.16E+00	S	7.74E-05	S	5.76E-01	S	1.32E-02	S
11	1.16E+00	S	7.39E-05	S	5.66E-01	S	9.94E-03	S
11.2	1.16E+00	S	7.06E-05	S	5.61E-01	S	7.04E-03	S
11.4	1.14E+00	S	6.75E-05	S	5.57E-01	S	6.35E-03	S
11.6	1.13E+00	S	6.45E-05	S	5.51E-01	S	5.85E-03	S
11.8	1.12E+00	S	5.68E-05	S	5.50E-01	S	5.77E-03	S
12	1.15E+00	S	5.01E-05	S	5.71E-01	S	5.69E-03	S
12.2	1.17E+00	S	4.43E-05	S	5.94E-01	S	5.62E-03	S
12.4	1.20E+00	S	3.92E-05	S	6.17E-01	S	5.54E-03	S
12.6	1.22E+00	S	3.48E-05	S	6.40E-01	S	5.47E-03	S
12.8	1.25E+00	S	3.09E-05	S	6.64E-01	S	5.40E-03	S
13	1.27E+00	S	2.76E-05	S	6.88E-01	S	5.33E-03	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	2.97E+01		4.16E-03		7.95E+01		3.80E+00	

Table C-5-4. Leachate Concentrations for Bituminous Fly Ash, Waste ID AFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	1.57E-01	S	1.39E-01	S	2.19E-01	S
3	1.37E-01	S	1.29E-01	S	1.55E-01	S
3.2	1.20E-01	S	1.11E-01	S	1.10E-01	S
3.4	1.01E-01	S	9.51E-02	S	7.51E-02	S
3.6	8.57E-02	S	8.54E-02	S	5.24E-02	S
3.8	8.63E-02	S	7.86E-02	S	5.06E-02	S
4	8.78E-02	S	7.27E-02	S	5.10E-02	S
4.2	8.93E-02	S	6.75E-02	S	5.14E-02	S
4.4	9.08E-02	S	6.28E-02	S	5.17E-02	S
4.6	9.29E-02	S	5.87E-02	S	5.21E-02	S
4.8	9.50E-02	S	5.50E-02	S	5.24E-02	S
5	9.71E-02	S	5.17E-02	S	5.27E-02	S
5.2	9.90E-02	S	4.86E-02	S	5.31E-02	S
5.4	1.01E-01	S	4.59E-02	S	5.34E-02	S
5.6	1.03E-01	S	4.34E-02	S	5.37E-02	S
5.8	1.07E-01	S	3.89E-02	S	5.89E-02	S
6	1.10E-01	S	3.34E-02	S	6.89E-02	S
6.2	1.14E-01	S	3.03E-02	S	8.01E-02	S
6.4	1.18E-01	S	2.79E-02	S	9.27E-02	S
6.6	1.23E-01	S	2.57E-02	S	1.07E-01	S
6.8	1.29E-01	S	2.32E-02	S	1.20E-01	S
7	1.38E-01	S	2.01E-02	S	1.35E-01	S
7.2	1.56E-01	S	1.63E-02	S	1.50E-01	S
7.4	1.75E-01	S	1.32E-02	S	1.60E-01	S
7.6	1.90E-01	S	1.10E-02	S	1.68E-01	S
7.8	2.05E-01	S	9.37E-03	S	1.88E-01	S
8	2.19E-01	S	8.01E-03	S	2.07E-01	S

Table C-5-4. Leachate Concentrations for Bituminous Fly Ash, Waste ID AFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	2.39E-01	S	5.46E-03	S	2.04E-01	S
8.4	2.13E-01	S	3.19E-03	S	1.95E-01	S
8.6	1.93E-01	S	2.53E-03	S	1.85E-01	S
8.8	1.83E-01	S	2.53E-03	S	1.79E-01	S
9	1.49E-01	S	2.53E-03	S	1.74E-01	S
9.2	1.21E-01	S	2.53E-03	S	1.69E-01	S
9.4	9.94E-02	S	2.53E-03	S	1.64E-01	S
9.6	8.18E-02	S	2.53E-03	S	1.61E-01	S
9.8	6.76E-02	S	2.53E-03	S	1.60E-01	S
10	5.61E-02	S	2.53E-03	S	1.55E-01	S
10.2	4.67E-02	S	2.53E-03	S	1.48E-01	S
10.4	3.90E-02	S	2.53E-03	S	1.42E-01	S
10.6	3.27E-02	S	2.53E-03	S	1.36E-01	S
10.8	2.75E-02	S	2.53E-03	S	1.31E-01	S
11	2.90E-02	S	2.53E-03	S	1.26E-01	S
11.2	3.41E-02	S	2.53E-03	S	1.36E-01	S
11.4	4.00E-02	S	2.53E-03	S	1.28E-01	S
11.6	4.22E-02	S	2.53E-03	S	1.20E-01	S
11.8	4.53E-02	S	2.53E-03	S	1.25E-01	S
12	3.83E-02	S	2.53E-03	S	1.39E-01	S
12.2	3.30E-02	S	2.53E-03	S	1.54E-01	S
12.4	3.05E-02	S	2.53E-03	S	1.41E-01	S
12.6	2.66E-02	S	2.53E-03	S	1.50E-01	S
12.8	2.28E-02	S	2.53E-03	S	1.61E-01	S
13	1.95E-02	S	2.53E-03	S	1.72E-01	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	2.39E+00		1.39E+00		2.19E+00	

Table C-5-5. Leachate Concentrations for Bituminous Fly Ash, Waste ID BFA Med

Sample ID BFA-[Med] (P,1,1)
Date Exported 8/27/2011, 6:48 PM
Database Name C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version 1.2.12.11227

	Concentration (mg/L)							
pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	5.37E-01	S	3.46E+01	W	2.25E-02	W	1.61E-01	S
3	4.68E-01	S	3.39E+01	W	2.21E-02	W	1.43E-01	S
3.2	4.13E-01	S	3.36E+01	W	2.16E-02	W	1.27E-01	S
3.4	3.67E-01	S	3.32E+01	W	2.12E-02	W	1.13E-01	S
3.6	3.29E-01	S	3.29E+01	W	2.08E-02	W	1.02E-01	S
3.8	2.34E-01	S	3.05E+01	W	1.97E-02	W	8.87E-02	S
4	2.08E-01	S	2.97E+01	W	1.82E-02	S	8.27E-02	S
4.2	1.97E-01	S	2.95E+01	W	1.65E-02	S	7.91E-02	S
4.4	1.87E-01	S	2.93E+01	W	1.54E-02	S	7.59E-02	S
4.6	1.78E-01	S	2.91E+01	W	1.43E-02	S	7.29E-02	S
4.8	1.69E-01	S	2.90E+01	W	1.33E-02	S	7.02E-02	S
5	1.62E-01	S	2.88E+01	W	1.24E-02	S	6.77E-02	S
5.2	1.55E-01	S	2.86E+01	W	1.03E-02	S	5.89E-02	S
5.4	1.49E-01	S	2.83E+01	W	8.19E-03	S	5.09E-02	S
5.6	1.43E-01	S	2.80E+01	W	6.55E-03	S	4.42E-02	S
5.8	1.38E-01	S	2.77E+01	W	5.27E-03	S	3.86E-02	S
6	1.33E-01	S	2.74E+01	W	4.28E-03	S	3.39E-02	S
6.2	1.29E-01	S	2.72E+01	W	3.50E-03	S	2.98E-02	S
6.4	1.25E-01	S	2.69E+01	W	2.88E-03	S	2.64E-02	S
6.6	1.21E-01	S	2.67E+01	W	2.38E-03	S	2.34E-02	S
6.8	1.16E-01	S	2.65E+01	W	1.98E-03	S	2.09E-02	S
7	1.12E-01	S	2.63E+01	W	1.66E-03	S	1.87E-02	S
7.2	1.09E-01	S	2.61E+01	W	1.39E-03	S	1.67E-02	S
7.4	1.07E-01	S	2.59E+01	W	1.21E-03	S	1.50E-02	S
7.6	1.05E-01	S	2.57E+01	W	1.07E-03	S	1.36E-02	S
7.8	1.02E-01	S	2.55E+01	W	9.55E-04	S	1.23E-02	S
8	9.96E-02	S	2.53E+01	W	8.51E-04	S	1.12E-02	S

Table C-5-5. Leachate Concentrations for Bituminous Fly Ash, Waste ID BFA Med

Sample ID	BFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:48 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	9.71E-02	S	2.52E+01	S	7.61E-04	W	1.08E-02	S
8.4	8.82E-02	S	2.21E+01	S	7.46E-04	W	1.04E-02	S
8.6	7.65E-02	S	1.64E+01	S	7.46E-04	W	1.01E-02	S
8.8	6.94E-02	S	1.21E+01	S	7.46E-04	W	9.59E-03	S
9	6.39E-02	S	8.98E+00	S	7.46E-04	W	9.05E-03	S
9.2	5.89E-02	S	7.26E+00	S	7.46E-04	W	8.55E-03	S
9.4	5.24E-02	S	7.29E+00	S	7.46E-04	W	8.02E-03	S
9.6	4.33E-02	S	7.32E+00	S	7.46E-04	W	7.54E-03	S
9.8	3.59E-02	S	7.35E+00	S	7.46E-04	W	7.09E-03	S
10	3.08E-02	S	7.11E+00	S	7.46E-04	W	6.67E-03	S
10.2	4.02E-02	S	6.73E+00	S	7.46E-04	W	5.84E-03	S
10.4	3.74E-02	S	6.11E+00	S	7.46E-04	W	4.79E-03	S
10.6	3.49E-02	S	5.56E+00	S	7.46E-04	W	3.94E-03	S
10.8	3.26E-02	S	5.07E+00	S	7.46E-04	W	3.26E-03	S
11	3.04E-02	S	4.65E+00	S	7.46E-04	W	2.70E-03	S
11.2	2.86E-02	S	4.31E+00	S	7.46E-04	W	2.25E-03	S
11.4	2.63E-02	S	3.83E+00	S	7.46E-04	W	2.06E-03	S
11.6	2.54E-02	S	3.31E+00	S	7.46E-04	W	2.06E-03	S
11.8	2.53E-02	S	2.89E+00	S	7.46E-04	W	2.06E-03	S
12	2.52E-02	S	2.56E+00	S	7.46E-04	W	2.06E-03	S
12.2	2.52E-02	S	2.30E+00	S	7.46E-04	W	2.06E-03	S
12.4	2.54E-02	S	2.18E+00	S	7.46E-04	W	2.06E-03	S
12.6	2.56E-02	S	2.07E+00	S	7.46E-04	W	2.06E-03	S
12.8	2.57E-02	S	1.97E+00	S	7.46E-04	W	2.06E-03	S
13	2.57E-02	S	1.88E+00	S	7.46E-04	W	2.06E-03	S
tection Limit (min, mg/	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
tection Limit (max, mg/	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	5.37E+00		3.46E+02		2.25E-01		1.61E+00	

Table C-5-5. Leachate Concentrations for Bituminous Fly Ash, Waste ID BFA Med

Sample ID
Date Exported
Database Name ing\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	4.62E+00	S	4.71E-05	S	8.61E-02	S	9.00E-02	S
3	3.84E+00	S	5.56E-05	S	7.03E-02	S	6.04E-02	S
3.2	3.04E+00	S	6.18E-05	S	6.26E-02	S	3.98E-02	S
3.4	2.43E+00	S	6.88E-05	S	5.61E-02	S	2.58E-02	S
3.6	1.98E+00	S	7.88E-05	S	5.15E-02	S	1.69E-02	S
3.8	1.11E+00	S	1.48E-04	S	6.01E-02	S	9.19E-03	S
4	9.43E-01	S	1.39E-04	S	6.68E-02	S	9.06E-03	S
4.2	8.77E-01	S	1.31E-04	S	7.17E-02	S	1.00E-02	S
4.4	8.12E-01	S	1.23E-04	S	7.67E-02	S	1.10E-02	S
4.6	7.54E-01	S	1.16E-04	S	8.19E-02	S	1.21E-02	S
4.8	7.03E-01	S	1.10E-04	S	8.72E-02	S	1.32E-02	S
5	6.87E-01	S	1.05E-04	S	9.25E-02	S	1.44E-02	S
5.2	6.72E-01	W	8.52E-05	S	1.18E-01	S	1.59E-02	S
5.4	6.70E-01	W	7.12E-05	S	1.53E-01	S	1.76E-02	S
5.6	6.80E-01	W	6.34E-05	S	1.97E-01	S	1.94E-02	S
5.8	6.89E-01	W	5.67E-05	S	2.51E-01	S	2.12E-02	S
6	6.98E-01	W	5.09E-05	S	3.16E-01	S	2.32E-02	S
6.2	7.07E-01	W	4.58E-05	S	3.97E-01	S	2.53E-02	S
6.4	7.16E-01	W	4.14E-05	S	4.93E-01	S	2.75E-02	S
6.6	7.24E-01	W	3.76E-05	S	6.09E-01	S	2.99E-02	S
6.8	7.29E-01	W	3.41E-05	S	7.48E-01	S	3.23E-02	S
7	7.34E-01	W	3.11E-05	S	9.13E-01	S	3.49E-02	S
7.2	7.38E-01	W	2.85E-05	S	1.11E+00	S	3.76E-02	S
7.4	7.41E-01	W	2.61E-05	S	1.34E+00	S	4.01E-02	S
7.6	7.45E-01	W	2.39E-05	S	1.58E+00	S	4.22E-02	S
7.8	7.49E-01	W	2.20E-05	S	1.79E+00	S	4.43E-02	S
8	7.53E-01	W	2.03E-05	S	2.01E+00	S	4.36E-02	S

Table C-5-5. Leachate Concentrations for Bituminous Fly Ash, Waste ID BFA Med

Sample ID
Date Exported
Database Name ing\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	7.57E-01	W	1.88E-05	S	2.10E+00	W	4.69E-02	S
8.4	7.66E-01	W	1.85E-05	S	2.25E+00	W	3.95E-02	S
8.6	7.77E-01	W	2.02E-05	S	2.15E+00	W	2.42E-02	S
8.8	7.88E-01	W	2.19E-05	S	2.03E+00	W	1.48E-02	S
9	7.98E-01	W	2.37E-05	S	1.91E+00	W	9.14E-03	S
9.2	8.09E-01	W	2.39E-05	S	1.83E+00	W	6.42E-03	S
9.4	8.19E-01	W	1.99E-05	S	1.84E+00	W	6.27E-03	S
9.6	8.30E-01	W	1.66E-05	S	1.84E+00	W	6.12E-03	S
9.8	8.40E-01	W	1.39E-05	S	1.84E+00	W	5.98E-03	S
10	8.50E-01	W	1.35E-05	S	1.80E+00	W	5.74E-03	S
10.2	8.49E-01	W	1.47E-05	S	1.80E+00	W	5.40E-03	S
10.4	8.48E-01	W	1.60E-05	S	1.81E+00	W	4.76E-03	S
10.6	8.47E-01	W	1.74E-05	S	1.81E+00	W	4.21E-03	S
10.8	8.46E-01	W	1.89E-05	S	1.82E+00	W	3.73E-03	S
11	8.45E-01	W	2.04E-05	S	1.82E+00	W	3.21E-03	S
11.2	8.44E-01	W	2.11E-05	S	1.81E+00	W	2.78E-03	S
11.4	8.47E-01	W	1.97E-05	S	1.84E+00	W	2.78E-03	S
11.6	8.54E-01	W	1.84E-05	S	1.86E+00	W	2.78E-03	S
11.8	8.61E-01	W	2.03E-05	S	1.86E+00	W	2.78E-03	S
12	8.65E-01	W	5.72E-05	S	1.84E+00	W	2.78E-03	S
12.2	8.68E-01	W	6.48E-05	S	1.83E+00	W	2.78E-03	S
12.4	8.72E-01	W	7.33E-05	S	1.81E+00	W	2.78E-03	S
12.6	8.76E-01	W	8.28E-05	S	1.79E+00	W	2.78E-03	S
12.8	8.80E-01	W	9.33E-05	S	1.77E+00	W	2.78E-03	S
13	8.84E-01	W	1.05E-04	S	1.76E+00	W	2.78E-03	S
tection Limit (min, mg/	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
tection Limit (max, mg/	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	4.62E+01		1.48E-03		2.25E+01		9.00E-01	

Table C-5-5. Leachate Concentrations for Bituminous Fly Ash, Waste ID BFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	8.41E-02	S	3.17E-01	S	2.84E-01	S
3	7.20E-02	S	2.89E-01	S	1.51E-01	S
3.2	6.24E-02	S	2.67E-01	S	8.33E-02	S
3.4	5.45E-02	S	2.47E-01	S	4.65E-02	S
3.6	4.82E-02	S	2.29E-01	S	2.69E-02	S
3.8	4.40E-02	S	2.09E-01	S	2.22E-02	S
4	4.12E-02	S	1.93E-01	S	2.20E-02	S
4.2	3.91E-02	S	1.83E-01	S	2.27E-02	S
4.4	3.71E-02	S	1.73E-01	S	2.27E-02	S
4.6	3.54E-02	S	1.64E-01	S	2.27E-02	S
4.8	3.37E-02	S	1.56E-01	S	2.27E-02	S
5	3.31E-02	S	1.48E-01	S	2.37E-02	S
5.2	3.35E-02	S	1.23E-01	S	2.60E-02	S
5.4	3.39E-02	S	1.01E-01	S	2.69E-02	S
5.6	3.37E-02	S	8.32E-02	S	2.93E-02	S
5.8	3.35E-02	S	6.92E-02	S	3.18E-02	S
6	3.34E-02	S	5.79E-02	S	3.44E-02	S
6.2	3.32E-02	S	4.87E-02	S	3.71E-02	S
6.4	3.30E-02	S	4.12E-02	S	4.00E-02	S
6.6	3.29E-02	S	3.51E-02	S	4.30E-02	S
6.8	3.27E-02	S	3.00E-02	S	4.61E-02	S
7	3.26E-02	S	2.57E-02	S	4.93E-02	S
7.2	3.24E-02	S	2.26E-02	S	5.27E-02	S
7.4	3.26E-02	S	2.06E-02	S	5.62E-02	S
7.6	3.28E-02	S	1.89E-02	S	5.98E-02	S
7.8	3.31E-02	S	1.73E-02	S	6.35E-02	S
8	3.33E-02	S	1.59E-02	S	7.04E-02	S

Table C-5-5. Leachate Concentrations for Bituminous Fly Ash, Waste ID BFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	3.36E-02	S	1.46E-02	S	7.71E-02	S
8.4	3.33E-02	S	1.21E-02	S	8.13E-02	S
8.6	3.20E-02	S	7.98E-03	S	8.56E-02	S
8.8	2.94E-02	S	5.20E-03	S	8.16E-02	S
9	2.75E-02	S	3.42E-03	S	8.67E-02	S
9.2	2.58E-02	S	2.53E-03	S	9.21E-02	S
9.4	2.37E-02	S	2.53E-03	S	9.76E-02	S
9.6	2.04E-02	S	2.53E-03	S	1.03E-01	S
9.8	1.87E-02	S	2.53E-03	S	1.12E-01	S
10	1.72E-02	S	2.53E-03	S	1.19E-01	S
10.2	1.89E-02	S	2.53E-03	S	1.22E-01	S
10.4	1.79E-02	S	2.53E-03	S	1.29E-01	S
10.6	1.69E-02	S	2.53E-03	S	1.34E-01	S
10.8	1.60E-02	S	2.53E-03	S	1.41E-01	S
11	1.51E-02	S	2.53E-03	S	1.48E-01	S
11.2	1.42E-02	S	2.53E-03	S	1.52E-01	S
11.4	1.27E-02	S	2.53E-03	S	1.44E-01	S
11.6	1.22E-02	S	2.53E-03	S	1.36E-01	S
11.8	1.21E-02	S	2.53E-03	S	1.24E-01	S
12	1.25E-02	S	2.53E-03	S	1.10E-01	S
12.2	1.28E-02	S	2.53E-03	S	9.89E-02	S
12.4	1.32E-02	S	2.53E-03	S	8.87E-02	S
12.6	1.35E-02	S	2.53E-03	S	7.97E-02	S
12.8	1.39E-02	S	2.53E-03	S	7.17E-02	S
13	1.42E-02	S	2.53E-03	S	6.46E-02	S
tection Limit (min, mg/	5.20E-04		5.10E-04		3.10E-04	
tection Limit (max, mg/	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	8.41E-01		3.17E+00		2.84E+00	

Table C-5-6. Leachate Concentrations for Bituminous Fly Ash, Waste ID BPB Med

Sample ID	BPB-[Med] (P,1,1)
Date Exported	8/27/2011, 6:48 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	3.09E-02	S	7.11E+01	S	2.82E-02	S	5.60E-01	S
3	4.70E-02	S	7.11E+01	S	2.66E-02	S	5.60E-01	S
3.2	6.96E-02	S	7.11E+01	S	2.52E-02	S	5.60E-01	S
3.4	1.01E-01	S	6.40E+01	S	2.39E-02	S	4.76E-01	S
3.6	1.05E-01	S	5.36E+01	S	2.41E-02	S	4.43E-01	S
3.8	8.17E-02	S	4.88E+01	S	2.48E-02	S	4.53E-01	S
4	6.76E-02	S	4.46E+01	S	2.56E-02	S	3.94E-01	S
4.2	5.65E-02	S	4.10E+01	S	2.64E-02	S	3.50E-01	S
4.4	4.83E-02	S	3.82E+01	S	2.71E-02	S	3.12E-01	S
4.6	4.43E-02	S	3.75E+01	S	2.78E-02	S	2.80E-01	S
4.8	4.09E-02	S	3.67E+01	S	2.85E-02	S	2.53E-01	S
5	3.78E-02	S	3.60E+01	S	2.92E-02	S	2.29E-01	S
5.2	3.51E-02	S	3.54E+01	S	2.99E-02	S	2.09E-01	S
5.4	3.26E-02	S	3.48E+01	S	3.11E-02	S	2.01E-01	S
5.6	3.04E-02	S	3.42E+01	S	3.24E-02	S	1.93E-01	S
5.8	2.84E-02	S	3.36E+01	S	3.37E-02	S	1.86E-01	S
6	2.67E-02	S	3.31E+01	S	3.50E-02	S	1.80E-01	S
6.2	2.50E-02	S	3.26E+01	S	3.63E-02	S	1.71E-01	S
6.4	2.36E-02	S	3.21E+01	S	3.76E-02	S	1.55E-01	S
6.6	2.22E-02	S	3.16E+01	S	3.90E-02	S	1.42E-01	S
6.8	2.10E-02	S	3.12E+01	S	4.03E-02	S	1.30E-01	S
7	1.98E-02	S	3.08E+01	S	3.99E-02	S	1.19E-01	S
7.2	1.90E-02	S	2.69E+01	S	3.88E-02	S	9.62E-02	W
7.4	1.82E-02	S	2.35E+01	S	3.77E-02	S	7.75E-02	W
7.6	1.75E-02	S	2.06E+01	S	3.75E-02	S	6.28E-02	W
7.8	1.68E-02	S	1.82E+01	S	3.72E-02	S	5.12E-02	W
8	1.61E-02	S	1.60E+01	S	3.64E-02	S	4.20E-02	W

Table C-5-6. Leachate Concentrations for Bituminous Fly Ash, Waste ID BPB Med

Sample ID	BPB-[Med] (P,1,1)
Date Exported	8/27/2011, 6:48 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	1.55E-02	S	1.42E+01	S	3.55E-02	W	3.45E-02	W
8.4	1.50E-02	S	1.26E+01	S	3.47E-02	W	2.86E-02	W
8.6	1.44E-02	S	1.12E+01	S	3.40E-02	W	2.37E-02	W
8.8	1.39E-02	S	1.00E+01	S	3.33E-02	W	1.98E-02	W
9	1.35E-02	S	8.97E+00	S	3.26E-02	W	1.66E-02	W
9.2	1.30E-02	S	8.05E+00	S	3.19E-02	W	1.40E-02	W
9.4	1.26E-02	S	7.24E+00	S	3.13E-02	W	1.21E-02	W
9.6	1.22E-02	S	6.52E+00	S	3.07E-02	W	1.04E-02	W
9.8	1.18E-02	S	5.89E+00	S	3.01E-02	W	9.04E-03	W
10	1.14E-02	S	5.34E+00	S	2.96E-02	W	7.86E-03	W
10.2	1.11E-02	S	4.84E+00	S	2.90E-02	W	6.86E-03	W
10.4	1.08E-02	S	4.40E+00	S	2.85E-02	W	5.99E-03	W
10.6	1.05E-02	S	4.00E+00	S	2.80E-02	W	5.25E-03	W
10.8	1.02E-02	S	3.65E+00	S	2.75E-02	W	4.62E-03	W
11	9.88E-03	S	3.34E+00	S	2.71E-02	W	4.07E-03	W
11.2	9.61E-03	S	3.05E+00	S	2.66E-02	W	3.59E-03	W
11.4	9.35E-03	S	2.80E+00	S	2.62E-02	W	3.18E-03	W
11.6	8.51E-03	S	2.57E+00	S	2.58E-02	W	2.46E-03	W
11.8	8.17E-03	S	2.63E+00	S	2.55E-02	W	2.06E-03	W
12	8.44E-03	S	3.29E+00	S	2.54E-02	W	2.06E-03	W
12.2	8.71E-03	S	4.09E+00	S	2.53E-02	W	2.06E-03	W
12.4	8.99E-03	S	5.08E+00	S	2.51E-02	W	2.06E-03	W
12.6	9.27E-03	S	6.28E+00	S	2.66E-02	W	2.06E-03	W
12.8	9.55E-03	S	7.74E+00	S	2.84E-02	W	2.06E-03	W
13	2.00E-02	S	3.40E+00	S	2.63E-02	W	2.06E-03	W
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	1.05E+00		7.11E+02		4.03E-01		5.60E+00	

Table C-5-6. Leachate Concentrations for Bituminous Fly Ash, Waste ID BPB Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	4.73E-01	S	2.07E-06	S	2.24E-01	S	4.01E-01	W
3	4.73E-01	S	2.07E-06	S	1.36E-01	S	5.81E-01	W
3.2	4.73E-01	S	2.07E-06	S	8.49E-02	S	8.20E-01	W
3.4	4.31E-01	S	2.07E-06	S	5.46E-02	S	1.13E+00	W
3.6	3.80E-01	S	2.07E-06	S	3.96E-02	S	1.17E+00	W
3.8	3.65E-01	S	2.07E-06	S	3.08E-02	S	1.04E+00	W
4	3.15E-01	S	2.07E-06	S	2.42E-02	S	9.34E-01	W
4.2	2.59E-01	S	2.07E-06	S	1.92E-02	S	8.41E-01	W
4.4	2.14E-01	S	2.07E-06	S	1.72E-02	S	7.93E-01	W
4.6	1.79E-01	S	2.07E-06	S	2.55E-02	S	9.09E-01	W
4.8	1.51E-01	S	2.07E-06	S	3.73E-02	S	1.04E+00	W
5	1.28E-01	S	2.07E-06	S	5.35E-02	S	1.18E+00	W
5.2	1.10E-01	S	2.07E-06	S	7.57E-02	S	1.33E+00	W
5.4	9.65E-02	S	2.07E-06	S	1.06E-01	S	1.49E+00	W
5.6	8.60E-02	S	2.07E-06	S	1.46E-01	S	1.67E+00	W
5.8	7.69E-02	S	2.07E-06	S	1.99E-01	S	1.86E+00	W
6	6.90E-02	S	2.07E-06	S	2.69E-01	S	2.06E+00	W
6.2	6.22E-02	S	2.07E-06	S	3.60E-01	S	2.28E+00	W
6.4	5.54E-02	S	2.07E-06	S	4.77E-01	S	2.52E+00	W
6.6	4.80E-02	S	2.07E-06	S	6.26E-01	S	2.77E+00	W
6.8	4.18E-02	S	2.07E-06	S	8.16E-01	S	3.03E+00	W
7	3.65E-02	S	2.07E-06	S	1.06E+00	S	3.32E+00	S
7.2	3.56E-02	W	2.07E-06	S	1.05E+00	W	2.29E+00	S
7.4	3.50E-02	W	2.07E-06	S	1.04E+00	W	1.57E+00	S
7.6	3.42E-02	W	2.07E-06	S	1.03E+00	W	1.09E+00	S
7.8	3.38E-02	W	2.07E-06	S	1.02E+00	W	7.63E-01	S
8	3.32E-02	W	2.07E-06	S	1.01E+00	W	5.39E-01	S

Table C-5-6. Leachate Concentrations for Bituminous Fly Ash, Waste ID BPB Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	3.27E-02	W	2.07E-06	S	9.98E-01	W	3.83E-01	S
8.4	3.22E-02	W	2.07E-06	S	9.88E-01	W	2.75E-01	S
8.6	3.23E-02	W	2.07E-06	S	9.78E-01	W	1.99E-01	S
8.8	3.19E-02	W	2.07E-06	S	9.69E-01	W	1.45E-01	S
9	3.16E-02	W	2.07E-06	S	9.60E-01	W	1.07E-01	S
9.2	3.12E-02	W	2.07E-06	S	9.51E-01	W	7.87E-02	S
9.4	3.09E-02	W	2.07E-06	S	9.43E-01	W	5.86E-02	S
9.6	3.06E-02	W	2.07E-06	S	9.34E-01	W	4.38E-02	S
9.8	3.03E-02	W	2.07E-06	S	9.26E-01	W	3.30E-02	S
10	3.00E-02	W	2.07E-06	S	9.18E-01	W	2.50E-02	S
10.2	2.97E-02	W	2.07E-06	S	9.11E-01	W	1.90E-02	S
10.4	2.95E-02	W	2.07E-06	S	9.03E-01	W	1.46E-02	S
10.6	2.92E-02	W	2.07E-06	S	8.96E-01	W	1.12E-02	S
10.8	2.89E-02	W	2.07E-06	S	8.89E-01	W	8.67E-03	S
11	2.87E-02	W	2.07E-06	S	8.82E-01	W	6.74E-03	S
11.2	2.84E-02	W	2.07E-06	S	8.76E-01	W	5.26E-03	S
11.4	2.82E-02	W	2.07E-06	S	8.69E-01	W	4.12E-03	S
11.6	2.80E-02	W	2.07E-06	S	8.63E-01	W	3.24E-03	S
11.8	2.77E-02	W	2.07E-06	S	8.64E-01	W	3.91E-03	S
12	2.71E-02	W	2.07E-06	S	8.78E-01	W	1.02E-02	S
12.2	2.68E-02	W	2.07E-06	S	8.92E-01	W	2.62E-02	S
12.4	2.62E-02	W	2.07E-06	S	9.06E-01	W	6.63E-02	S
12.6	2.53E-02	W	2.07E-06	S	9.20E-01	W	1.65E-01	S
12.8	2.45E-02	W	2.07E-06	S	9.33E-01	W	4.06E-01	S
13	2.51E-02	W	2.07E-06	S	8.25E-01	W	2.46E-02	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		1.00E-03		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		1.00E-03		8.00E-05	
Availability (mg/kg)	4.73E+00		2.18E-05		1.06E+01		3.32E+01	

Table C-5-6. Leachate Concentrations for Bituminous Fly Ash, Waste ID BPB Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	6.28E-02	S	1.46E-02	S	2.42E-02	S
3	7.13E-02	S	1.13E-01	S	2.92E-02	S
3.2	8.04E-02	S	7.62E-01	S	3.48E-02	S
3.4	8.99E-02	S	4.59E+00	S	4.10E-02	S
3.6	1.04E-01	S	7.45E+00	S	4.36E-02	S
3.8	1.23E-01	S	6.16E+00	S	4.44E-02	S
4	1.43E-01	S	5.15E+00	S	4.51E-02	S
4.2	1.53E-01	S	4.34E+00	S	4.59E-02	S
4.4	1.51E-01	S	3.69E+00	S	4.69E-02	S
4.6	1.50E-01	S	3.19E+00	S	4.94E-02	S
4.8	1.48E-01	S	2.77E+00	S	5.19E-02	S
5	1.47E-01	S	2.42E+00	S	5.27E-02	S
5.2	1.45E-01	S	2.12E+00	S	4.93E-02	S
5.4	1.44E-01	S	1.87E+00	S	4.99E-02	S
5.6	1.43E-01	S	1.66E+00	S	5.05E-02	S
5.8	1.42E-01	S	1.48E+00	S	5.11E-02	S
6	1.40E-01	S	1.32E+00	S	5.17E-02	S
6.2	1.39E-01	S	1.18E+00	S	5.23E-02	S
6.4	1.44E-01	S	1.06E+00	S	5.28E-02	S
6.6	1.50E-01	S	9.60E-01	S	5.34E-02	S
6.8	1.50E-01	S	8.70E-01	S	5.39E-02	S
7	1.48E-01	S	7.90E-01	S	5.45E-02	S
7.2	1.42E-01	S	6.33E-01	S	5.50E-02	S
7.4	1.34E-01	S	5.08E-01	S	5.55E-02	S
7.6	1.33E-01	S	4.10E-01	S	5.60E-02	S
7.8	1.32E-01	S	3.32E-01	S	5.65E-02	S
8	1.31E-01	S	2.71E-01	S	5.49E-02	S

Table C-5-6. Leachate Concentrations for Bituminous Fly Ash, Waste ID BPB Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	1.38E-01	S	2.22E-01	S	5.19E-02	S
8.4	1.47E-01	S	1.83E-01	S	4.90E-02	S
8.6	1.56E-01	S	1.51E-01	S	4.64E-02	S
8.8	1.65E-01	S	1.26E-01	S	4.36E-02	S
9	1.75E-01	S	1.05E-01	S	4.09E-02	S
9.2	1.83E-01	S	8.79E-02	S	3.85E-02	S
9.4	1.69E-01	S	7.40E-02	S	3.77E-02	S
9.6	1.57E-01	S	6.24E-02	S	3.59E-02	S
9.8	1.46E-01	S	5.29E-02	S	3.42E-02	S
10	1.36E-01	S	4.49E-02	S	3.27E-02	S
10.2	1.26E-01	S	3.83E-02	S	3.12E-02	S
10.4	1.18E-01	S	3.28E-02	S	2.98E-02	S
10.6	1.10E-01	S	2.81E-02	S	2.85E-02	S
10.8	1.03E-01	S	2.42E-02	S	2.73E-02	S
11	9.62E-02	S	2.09E-02	S	2.62E-02	S
11.2	9.02E-02	S	1.80E-02	S	2.60E-02	S
11.4	8.46E-02	S	1.56E-02	S	2.62E-02	S
11.6	7.95E-02	S	1.36E-02	S	2.63E-02	S
11.8	8.98E-02	S	1.36E-02	S	2.98E-02	S
12	1.25E-01	S	1.77E-02	S	3.15E-02	S
12.2	1.73E-01	S	2.30E-02	S	3.18E-02	S
12.4	2.38E-01	S	2.96E-02	S	3.21E-02	S
12.6	3.26E-01	S	3.80E-02	S	3.24E-02	S
12.8	4.44E-01	S	4.86E-02	S	3.80E-02	S
13	7.08E-01	S	2.07E-02	S	6.03E-02	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	4.68E+00		7.45E+01		5.65E-01	

Table C-5-7. Leachate Concentrations for Bituminous Fly Ash, Waste ID BPT Med

Sample ID	BPT-[Med] (P,1,1)
Date Exported	8/27/2011, 6:48 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	1.40E-01	S	2.70E+01	W	1.08E-02	S	1.19E-01	S
3	1.17E-01	S	2.74E+01	W	1.00E-02	S	1.16E-01	S
3.2	9.97E-02	S	2.77E+01	W	9.27E-03	S	1.14E-01	S
3.4	8.46E-02	S	2.80E+01	W	8.62E-03	S	1.12E-01	S
3.6	7.07E-02	S	2.83E+01	W	8.04E-03	S	1.12E-01	S
3.8	5.96E-02	S	2.86E+01	W	7.47E-03	S	1.11E-01	S
4	4.19E-02	S	2.81E+01	W	6.25E-03	S	1.08E-01	S
4.2	2.77E-02	S	2.73E+01	W	5.27E-03	S	1.05E-01	S
4.4	1.95E-02	S	2.66E+01	W	4.61E-03	S	1.02E-01	S
4.6	1.40E-02	S	2.60E+01	W	4.40E-03	S	9.91E-02	S
4.8	1.01E-02	S	2.53E+01	W	4.20E-03	S	9.63E-02	S
5	7.46E-03	S	2.48E+01	W	3.88E-03	S	9.37E-02	S
5.2	5.29E-03	S	2.42E+01	W	3.57E-03	S	9.12E-02	S
5.4	3.77E-03	S	2.37E+01	W	3.44E-03	S	8.89E-02	S
5.6	3.20E-03	S	2.36E+01	W	3.74E-03	S	7.94E-02	S
5.8	3.20E-03	S	2.36E+01	W	4.79E-03	S	6.53E-02	S
6	3.20E-03	S	2.37E+01	W	6.09E-03	S	5.41E-02	S
6.2	3.20E-03	S	2.38E+01	W	7.68E-03	S	4.51E-02	S
6.4	3.20E-03	S	2.39E+01	W	9.60E-03	S	3.78E-02	S
6.6	3.20E-03	S	2.40E+01	W	1.19E-02	S	3.19E-02	S
6.8	3.20E-03	S	2.41E+01	W	1.47E-02	S	2.60E-02	S
7	3.20E-03	S	2.41E+01	W	1.81E-02	S	2.11E-02	S
7.2	3.20E-03	S	2.42E+01	W	2.24E-02	S	1.72E-02	S
7.4	3.20E-03	S	2.43E+01	W	2.75E-02	S	1.42E-02	S
7.6	3.20E-03	S	2.48E+01	W	3.36E-02	S	1.17E-02	S
7.8	3.20E-03	S	2.65E+01	W	3.62E-02	S	9.27E-03	S
8	3.20E-03	S	2.84E+01	W	3.70E-02	S	7.28E-03	S

Table C-5-7. Leachate Concentrations for Bituminous Fly Ash, Waste ID BPT Med

Sample ID	BPT-[Med] (P,1,1)
Date Exported	8/27/2011, 6:48 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	3.20E-03	S	3.03E+01	W	3.79E-02	W	5.75E-03	S
8.4	3.20E-03	S	3.23E+01	W	3.88E-02	W	4.57E-03	S
8.6	3.20E-03	S	3.43E+01	W	3.97E-02	W	3.65E-03	S
8.8	3.20E-03	S	3.65E+01	W	4.06E-02	W	2.93E-03	S
9	3.20E-03	S	3.87E+01	W	4.15E-02	W	2.37E-03	S
9.2	3.20E-03	S	3.90E+01	W	4.26E-02	W	2.06E-03	S
9.4	3.20E-03	S	3.86E+01	W	4.33E-02	W	2.06E-03	S
9.6	3.20E-03	S	3.07E+01	W	4.37E-02	W	2.06E-03	S
9.8	3.20E-03	S	2.46E+01	W	4.40E-02	W	2.06E-03	S
10	3.20E-03	S	2.32E+01	W	4.44E-02	W	2.06E-03	S
10.2	4.05E-03	S	2.28E+01	W	4.42E-02	W	2.06E-03	S
10.4	5.17E-03	S	2.25E+01	W	4.41E-02	W	2.06E-03	S
10.6	6.55E-03	S	2.21E+01	W	4.39E-02	W	2.06E-03	S
10.8	8.27E-03	S	2.18E+01	W	4.37E-02	W	2.06E-03	S
11	1.20E-02	S	2.14E+01	W	4.36E-02	W	2.06E-03	S
11.2	1.86E-02	S	2.11E+01	W	4.34E-02	W	2.06E-03	S
11.4	2.24E-02	S	2.16E+01	W	4.34E-02	W	2.06E-03	S
11.6	2.57E-02	S	2.27E+01	W	4.36E-02	W	2.06E-03	S
11.8	2.93E-02	S	2.39E+01	W	4.39E-02	W	2.06E-03	S
12	3.33E-02	S	2.51E+01	W	4.42E-02	W	2.06E-03	S
12.2	3.78E-02	S	2.64E+01	W	4.44E-02	W	2.06E-03	S
12.4	5.41E-02	S	2.71E+01	W	4.30E-02	W	2.06E-03	S
12.6	1.25E-01	S	2.62E+01	W	4.07E-02	W	2.06E-03	S
12.8	1.85E-01	S	2.53E+01	W	4.12E-02	W	2.06E-03	S
13	1.85E-01	S	2.45E+01	W	4.12E-02	W	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	2.37E+00		3.90E+02		5.27E-01		1.19E+00	

Table C-5-7. Leachate Concentrations for Bituminous Fly Ash, Waste ID BPT Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
2.8	9.94E-01	S	2.07E-06	S	6.10E-02	S	7.45E-02	S
3	7.73E-01	S	2.07E-06	S	4.80E-02	S	9.75E-02	S
3.2	6.59E-01	S	2.07E-06	S	3.84E-02	S	1.26E-01	S
3.4	5.73E-01	S	2.07E-06	S	3.11E-02	S	1.59E-01	S
3.6	5.02E-01	S	2.07E-06	S	2.55E-02	S	1.99E-01	S
3.8	4.10E-01	S	2.07E-06	S	2.12E-02	S	2.46E-01	S
4	1.22E-01	S	2.07E-06	S	1.94E-02	S	2.22E-01	S
4.2	3.73E-02	S	2.07E-06	S	1.85E-02	S	1.77E-01	S
4.4	1.60E-02	S	2.07E-06	S	1.77E-02	S	1.43E-01	S
4.6	1.09E-02	S	2.07E-06	S	1.70E-02	S	1.17E-01	S
4.8	7.13E-03	S	2.07E-06	S	1.63E-02	S	9.58E-02	S
5	4.73E-03	S	2.07E-06	S	1.57E-02	S	7.94E-02	S
5.2	3.30E-03	S	2.07E-06	S	1.51E-02	S	6.63E-02	S
5.4	2.48E-03	S	2.07E-06	S	1.46E-02	S	5.57E-02	S
5.6	2.09E-03	S	2.07E-06	S	1.94E-02	S	6.40E-02	S
5.8	2.45E-03	S	2.07E-06	S	3.09E-02	S	8.84E-02	S
6	2.84E-03	S	2.07E-06	S	4.87E-02	S	1.21E-01	S
6.2	3.29E-03	S	2.07E-06	S	7.54E-02	S	1.63E-01	S
6.4	3.38E-03	S	2.07E-06	S	1.15E-01	S	2.18E-01	S
6.6	3.07E-03	S	2.07E-06	S	1.74E-01	S	2.90E-01	S
6.8	2.80E-03	S	2.07E-06	S	2.59E-01	S	3.81E-01	S
7	2.56E-03	S	2.07E-06	S	3.82E-01	S	4.98E-01	S
7.2	2.34E-03	W	2.07E-06	S	5.56E-01	W	6.45E-01	S
7.4	2.15E-03	W	2.07E-06	S	8.02E-01	W	8.29E-01	S
7.6	1.98E-03	W	2.07E-06	S	1.08E+00	W	1.05E+00	S
7.8	2.33E-03	W	2.07E-06	S	1.22E+00	W	1.30E+00	S
8	3.06E-03	W	2.07E-06	S	1.37E+00	W	1.60E+00	S

Table C-5-7. Leachate Concentrations for Bituminous Fly Ash, Waste ID BPT Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
8.2	3.99E-03	W	2.07E-06	S	1.54E+00	W	1.95E+00	S
8.4	5.17E-03	W	2.07E-06	S	1.73E+00	W	2.38E+00	S
8.6	6.66E-03	W	2.07E-06	S	1.93E+00	W	2.88E+00	S
8.8	8.53E-03	W	2.07E-06	S	2.15E+00	W	3.47E+00	S
9	8.70E-03	W	2.07E-06	S	2.39E+00	W	4.17E+00	S
9.2	1.14E-02	W	2.07E-06	S	2.49E+00	W	1.67E+00	S
9.4	1.48E-02	W	2.07E-06	S	2.52E+00	W	5.35E-01	S
9.6	1.85E-02	W	2.07E-06	S	1.90E+00	W	2.68E-01	S
9.8	3.64E-02	W	2.07E-06	S	1.45E+00	W	1.36E-01	S
10	6.41E-02	W	2.07E-06	S	1.44E+00	W	1.38E-01	S
10.2	6.21E-02	W	2.07E-06	S	1.53E+00	W	1.66E-01	S
10.4	6.02E-02	W	2.07E-06	S	1.62E+00	W	1.98E-01	S
10.6	5.83E-02	W	2.07E-06	S	1.71E+00	W	2.36E-01	S
10.8	5.75E-02	W	2.07E-06	S	1.81E+00	W	2.80E-01	S
11	5.74E-02	W	2.07E-06	S	1.92E+00	W	3.31E-01	S
11.2	5.73E-02	W	2.07E-06	S	2.02E+00	W	3.91E-01	S
11.4	5.17E-02	W	2.07E-06	S	2.01E+00	W	3.86E-01	S
11.6	4.58E-02	W	2.07E-06	S	1.91E+00	W	3.34E-01	S
11.8	4.06E-02	W	2.07E-06	S	1.82E+00	W	2.90E-01	S
12	3.61E-02	W	2.07E-06	S	1.74E+00	W	2.52E-01	S
12.2	3.22E-02	W	2.07E-06	S	1.66E+00	W	2.19E-01	S
12.4	2.96E-02	W	2.07E-06	S	1.60E+00	W	1.95E-01	S
12.6	3.33E-02	W	2.07E-06	S	1.60E+00	W	1.83E-01	S
12.8	3.97E-02	W	2.07E-06	S	1.60E+00	W	1.72E-01	S
13	4.72E-02	W	2.07E-06	S	1.60E+00	W	1.61E-01	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		1.00E-03		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		1.00E-03		8.00E-05	
Availability (mg/kg)	9.94E+00		2.65E-05		2.52E+01		4.17E+01	

Table C-5-7. Leachate Concentrations for Bituminous Fly Ash, Waste ID BPT Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	1.75E-01	S	9.24E-02	S	7.72E-01	S
3	1.55E-01	S	1.01E-01	S	3.74E-01	S
3.2	1.38E-01	S	1.10E-01	S	2.35E-01	S
3.4	1.24E-01	S	1.19E-01	S	1.52E-01	S
3.6	1.13E-01	S	1.28E-01	S	9.65E-02	S
3.8	1.03E-01	S	1.38E-01	S	6.11E-02	S
4	9.56E-02	S	1.28E-01	S	2.16E-02	S
4.2	8.93E-02	S	1.12E-01	S	6.21E-03	S
4.4	8.84E-02	S	9.91E-02	S	4.45E-03	S
4.6	9.31E-02	S	8.80E-02	S	4.71E-03	S
4.8	9.97E-02	S	7.85E-02	S	4.97E-03	S
5	1.08E-01	S	7.04E-02	S	5.23E-03	S
5.2	1.16E-01	S	6.33E-02	S	5.50E-03	S
5.4	1.25E-01	S	5.72E-02	S	6.06E-03	S
5.6	1.39E-01	S	5.86E-02	S	6.80E-03	S
5.8	1.55E-01	S	6.45E-02	S	7.57E-03	S
6	1.68E-01	S	7.08E-02	S	8.41E-03	S
6.2	1.83E-01	S	7.75E-02	S	9.30E-03	S
6.4	1.99E-01	S	8.46E-02	S	1.03E-02	S
6.6	2.24E-01	S	9.21E-02	S	1.13E-02	S
6.8	2.52E-01	S	9.99E-02	S	1.24E-02	S
7	2.83E-01	S	1.08E-01	S	1.35E-02	S
7.2	3.16E-01	S	1.17E-01	S	1.47E-02	S
7.4	3.52E-01	S	1.26E-01	S	1.60E-02	S
7.6	3.91E-01	S	1.35E-01	S	1.74E-02	S
7.8	3.29E-01	S	1.41E-01	S	1.97E-02	S
8	2.69E-01	S	1.48E-01	S	2.16E-02	S

Table C-5-7. Leachate Concentrations for Bituminous Fly Ash, Waste ID BPT Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	2.22E-01	S	1.55E-01	S	2.35E-02	S
8.4	1.91E-01	S	1.62E-01	S	2.56E-02	S
8.6	1.66E-01	S	1.69E-01	S	2.79E-02	S
8.8	1.45E-01	S	1.76E-01	S	3.06E-02	S
9	1.26E-01	S	1.83E-01	S	3.38E-02	S
9.2	1.27E-01	S	1.05E-01	S	4.64E-02	S
9.4	1.65E-01	S	5.37E-02	S	6.58E-02	S
9.6	1.97E-01	S	3.69E-02	S	6.83E-02	S
9.8	2.19E-01	S	2.56E-02	S	7.08E-02	S
10	2.64E-01	S	2.96E-02	S	7.97E-02	S
10.2	3.19E-01	S	3.87E-02	S	9.12E-02	S
10.4	3.82E-01	S	5.02E-02	S	1.04E-01	S
10.6	4.57E-01	S	6.48E-02	S	1.19E-01	S
10.8	5.44E-01	S	8.33E-02	S	1.35E-01	S
11	7.09E-01	S	1.07E-01	S	1.53E-01	S
11.2	9.46E-01	S	1.36E-01	S	1.73E-01	S
11.4	1.15E+00	S	1.46E-01	S	1.86E-01	S
11.6	1.36E+00	S	1.40E-01	S	1.94E-01	S
11.8	1.61E+00	S	1.33E-01	S	2.01E-01	S
12	1.90E+00	S	1.27E-01	S	2.09E-01	S
12.2	2.23E+00	S	1.21E-01	S	2.17E-01	S
12.4	2.82E+00	S	9.93E-02	S	2.77E-01	S
12.6	4.18E+00	S	5.47E-02	S	5.44E-01	S
12.8	4.18E+00	S	3.04E-02	S	9.29E-01	S
13	4.18E+00	S	1.71E-02	S	1.57E+00	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	5.35E+01		1.83E+00		1.19E+01	

Table C-5-8. Leachate Concentrations for Bituminous Fly Ash, Waste ID CFA Med

Sample ID	CFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:48 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	8.37E-02	S	1.22E+01	W	1.65E-02	S	1.96E-01	S
3	8.37E-02	S	1.22E+01	W	1.65E-02	S	1.96E-01	S
3.2	7.79E-02	S	1.22E+01	W	1.63E-02	S	1.94E-01	S
3.4	6.80E-02	S	1.21E+01	W	1.60E-02	S	1.88E-01	S
3.6	6.04E-02	S	1.19E+01	W	1.58E-02	S	1.83E-01	S
3.8	5.52E-02	S	1.17E+01	W	1.55E-02	S	1.78E-01	S
4	5.07E-02	S	1.15E+01	W	1.53E-02	S	1.74E-01	S
4.2	4.67E-02	S	1.13E+01	W	1.51E-02	S	1.70E-01	S
4.4	4.32E-02	S	1.13E+01	W	1.49E-02	S	1.63E-01	S
4.6	4.12E-02	S	1.13E+01	W	1.47E-02	S	1.61E-01	S
4.8	4.09E-02	S	1.13E+01	W	1.43E-02	S	1.58E-01	S
5	4.07E-02	S	1.13E+01	W	1.37E-02	S	1.55E-01	S
5.2	4.09E-02	S	1.13E+01	W	1.32E-02	S	1.53E-01	S
5.4	4.11E-02	S	1.13E+01	W	1.27E-02	S	1.50E-01	S
5.6	4.23E-02	S	1.11E+01	W	1.16E-02	S	1.48E-01	S
5.8	4.43E-02	S	1.10E+01	W	1.07E-02	S	1.46E-01	S
6	4.63E-02	S	1.10E+01	W	9.82E-03	S	1.38E-01	S
6.2	4.79E-02	S	1.10E+01	W	8.78E-03	S	1.30E-01	S
6.4	5.07E-02	S	1.10E+01	W	7.76E-03	S	1.23E-01	S
6.6	5.49E-02	S	1.12E+01	W	6.42E-03	S	1.09E-01	S
6.8	6.24E-02	S	1.15E+01	W	5.03E-03	S	9.44E-02	S
7	6.96E-02	S	1.08E+01	W	3.84E-03	S	6.97E-02	S
7.2	7.51E-02	S	8.45E+00	W	2.64E-03	S	4.05E-02	S
7.4	8.08E-02	S	5.64E+00	W	1.87E-03	S	2.39E-02	S
7.6	8.28E-02	S	6.28E+00	W	1.36E-03	S	1.25E-02	S
7.8	8.33E-02	S	7.05E+00	W	9.68E-04	S	5.81E-03	S
8	8.22E-02	S	7.89E+00	S	7.46E-04	S	2.75E-03	S

Table C-5-8. Leachate Concentrations for Bituminous Fly Ash, Waste ID CFA Med

Sample ID	CFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:48 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	7.73E-02	S	8.61E+00	S	7.46E-04	S	2.06E-03	S
8.4	6.97E-02	S	8.99E+00	S	7.46E-04	S	2.06E-03	S
8.6	5.94E-02	S	8.19E+00	S	7.46E-04	S	2.06E-03	S
8.8	5.01E-02	S	6.78E+00	S	7.46E-04	S	2.06E-03	S
9	4.24E-02	S	5.63E+00	S	7.46E-04	S	2.06E-03	S
9.2	3.61E-02	S	4.70E+00	S	7.46E-04	S	2.06E-03	S
9.4	3.08E-02	S	3.93E+00	S	7.46E-04	S	2.06E-03	S
9.6	2.64E-02	S	3.29E+00	S	7.46E-04	S	2.06E-03	S
9.8	2.27E-02	S	2.39E+00	S	7.46E-04	S	2.06E-03	S
10	1.87E-02	S	1.79E+00	S	7.46E-04	S	2.06E-03	S
10.2	1.43E-02	S	1.48E+00	S	7.46E-04	S	2.06E-03	S
10.4	1.32E-02	S	1.19E+00	S	7.46E-04	S	2.06E-03	S
10.6	1.26E-02	S	1.06E+00	S	7.46E-04	S	2.06E-03	S
10.8	1.22E-02	S	9.16E-01	S	7.46E-04	S	2.06E-03	S
11	1.30E-02	S	8.58E-01	S	7.46E-04	S	2.06E-03	S
11.2	1.39E-02	S	7.73E-01	S	7.46E-04	S	2.06E-03	S
11.4	1.48E-02	S	7.64E-01	S	7.46E-04	S	2.06E-03	S
11.6	1.57E-02	S	7.60E-01	S	7.46E-04	S	2.06E-03	S
11.8	1.67E-02	S	7.56E-01	S	7.46E-04	S	2.06E-03	S
12	1.77E-02	S	7.52E-01	S	7.46E-04	S	2.06E-03	S
12.2	1.82E-02	S	7.47E-01	S	7.46E-04	S	2.06E-03	S
12.4	1.84E-02	S	7.44E-01	S	7.46E-04	S	2.06E-03	S
12.6	1.87E-02	S	7.40E-01	S	7.46E-04	S	2.06E-03	S
12.8	1.89E-02	S	7.36E-01	S	7.46E-04	S	2.06E-03	S
13	1.92E-02	S	7.32E-01	S	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	8.37E-01		1.22E+02		1.65E-01		1.96E+00	

Table C-5-8. Leachate Concentrations for Bituminous Fly Ash, Waste ID CFA Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
2.8	8.31E-01	S	4.09E-05	S	3.65E-02	S	2.19E-01	S
3	8.31E-01	S	3.96E-05	S	4.62E-02	S	2.19E-01	S
3.2	6.66E-01	S	3.75E-05	S	5.77E-02	S	1.81E-01	S
3.4	3.47E-01	S	3.49E-05	S	7.11E-02	S	1.34E-01	S
3.6	2.19E-01	S	3.26E-05	S	8.42E-02	S	1.07E-01	S
3.8	1.45E-01	S	3.06E-05	S	9.60E-02	S	8.92E-02	S
4	9.83E-02	S	2.88E-05	S	1.09E-01	S	7.50E-02	S
4.2	6.79E-02	S	2.87E-05	S	1.23E-01	S	6.32E-02	S
4.4	4.76E-02	S	2.80E-05	S	1.37E-01	S	5.43E-02	S
4.6	4.65E-02	S	2.72E-05	S	1.72E-01	S	4.86E-02	S
4.8	6.27E-02	S	2.76E-05	S	2.28E-01	S	5.46E-02	S
5	8.35E-02	S	2.91E-05	S	3.30E-01	S	6.25E-02	S
5.2	1.08E-01	S	3.07E-05	S	4.69E-01	S	7.10E-02	S
5.4	1.28E-01	S	3.23E-05	S	6.59E-01	S	8.04E-02	S
5.6	1.49E-01	S	3.04E-05	S	9.14E-01	S	9.06E-02	S
5.8	1.73E-01	S	2.88E-05	S	8.23E-01	S	8.73E-02	S
6	2.08E-01	S	2.72E-05	S	9.82E-01	S	9.19E-02	S
6.2	2.49E-01	S	2.58E-05	S	7.31E-01	S	8.34E-02	S
6.4	2.96E-01	S	2.45E-05	S	5.29E-01	S	7.41E-02	S
6.6	3.12E-01	S	2.33E-05	S	8.21E-01	S	1.06E-01	S
6.8	3.71E-01	S	2.21E-05	S	1.47E+00	S	1.64E-01	S
7	3.81E-01	S	2.27E-05	S	2.02E+00	S	1.96E-01	S
7.2	3.72E-01	W	3.20E-05	S	1.75E+00	S	1.52E-01	S
7.4	4.49E-01	W	4.64E-05	S	1.46E+00	S	1.06E-01	S
7.6	4.40E-01	W	4.42E-05	S	1.54E+00	S	1.15E-01	S
7.8	4.31E-01	W	4.21E-05	S	1.69E+00	S	1.35E-01	S
8	4.22E-01	W	4.02E-05	S	1.85E+00	S	1.57E-01	S

Table C-5-8. Leachate Concentrations for Bituminous Fly Ash, Waste ID CFA Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
8.2	3.91E-01	W	3.95E-05	S	1.97E+00	S	1.60E-01	S
8.4	3.87E-01	W	3.95E-05	S	2.05E+00	S	1.58E-01	S
8.6	3.58E-01	W	4.13E-05	S	1.87E+00	S	1.32E-01	S
8.8	3.31E-01	W	3.96E-05	S	1.60E+00	S	1.05E-01	S
9	3.06E-01	W	3.60E-05	S	1.37E+00	S	8.38E-02	S
9.2	2.83E-01	W	3.71E-05	S	1.18E+00	S	6.73E-02	S
9.4	2.63E-01	W	3.83E-05	S	1.02E+00	S	5.43E-02	S
9.6	2.44E-01	W	3.95E-05	S	8.85E-01	S	4.40E-02	S
9.8	2.27E-01	W	4.08E-05	S	7.69E-01	S	3.58E-02	S
10	2.12E-01	W	4.20E-05	S	6.40E-01	S	2.81E-02	S
10.2	1.98E-01	W	4.27E-05	S	5.45E-01	S	2.23E-02	S
10.4	1.92E-01	W	4.03E-05	S	5.14E-01	S	1.93E-02	S
10.6	1.87E-01	W	3.81E-05	S	4.94E-01	S	1.69E-02	S
10.8	1.81E-01	W	4.26E-05	S	4.84E-01	S	1.44E-02	S
11	1.84E-01	W	3.89E-05	S	4.93E-01	S	1.25E-02	S
11.2	1.84E-01	W	3.55E-05	S	5.20E-01	S	1.08E-02	S
11.4	1.82E-01	W	3.42E-05	S	5.48E-01	S	9.44E-03	S
11.6	1.80E-01	W	3.63E-05	S	5.77E-01	S	8.23E-03	S
11.8	1.78E-01	W	3.85E-05	S	6.07E-01	S	7.19E-03	S
12	1.77E-01	W	4.08E-05	S	6.38E-01	S	6.30E-03	S
12.2	1.85E-01	W	4.32E-05	S	6.70E-01	S	5.53E-03	S
12.4	2.00E-01	W	4.56E-05	S	7.03E-01	S	4.87E-03	S
12.6	2.02E-01	W	4.82E-05	S	7.38E-01	S	4.29E-03	S
12.8	2.05E-01	W	5.03E-05	S	7.73E-01	S	3.79E-03	S
13	2.07E-01	W	5.03E-05	S	8.09E-01	S	3.36E-03	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	8.31E+00		5.10E-04		2.05E+01		2.19E+00	

Table C-5-8. Leachate Concentrations for Bituminous Fly Ash, Waste ID CFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	2.69E-01	S	1.43E-01	S	6.44E-02	S
3	2.42E-01	S	1.43E-01	S	6.15E-02	S
3.2	2.19E-01	S	1.37E-01	S	5.89E-02	S
3.4	1.99E-01	S	1.22E-01	S	5.66E-02	S
3.6	1.82E-01	S	1.12E-01	S	5.45E-02	S
3.8	1.67E-01	S	1.03E-01	S	5.25E-02	S
4	1.54E-01	S	9.58E-02	S	5.08E-02	S
4.2	1.43E-01	S	8.81E-02	S	4.91E-02	S
4.4	1.33E-01	S	8.04E-02	S	4.76E-02	S
4.6	1.25E-01	S	7.37E-02	S	4.83E-02	S
4.8	1.28E-01	S	6.68E-02	S	5.47E-02	S
5	1.31E-01	S	5.79E-02	S	6.17E-02	S
5.2	1.35E-01	S	5.04E-02	S	6.93E-02	S
5.4	1.38E-01	S	4.41E-02	S	7.72E-02	S
5.6	1.45E-01	S	4.12E-02	S	8.55E-02	S
5.8	1.56E-01	S	4.43E-02	S	9.43E-02	S
6	1.66E-01	S	4.03E-02	S	1.04E-01	S
6.2	1.80E-01	S	4.46E-02	S	1.17E-01	S
6.4	2.01E-01	S	5.20E-02	S	1.35E-01	S
6.6	2.13E-01	S	4.44E-02	S	1.46E-01	S
6.8	2.45E-01	S	3.46E-02	S	1.68E-01	S
7	2.72E-01	S	2.58E-02	S	1.82E-01	S
7.2	2.77E-01	S	1.52E-02	S	1.72E-01	S
7.4	2.70E-01	S	8.92E-03	S	1.63E-01	S
7.6	2.77E-01	S	8.38E-03	S	1.45E-01	S
7.8	2.83E-01	S	9.13E-03	S	1.27E-01	S
8	2.90E-01	S	9.47E-03	S	1.13E-01	S

Table C-5-8. Leachate Concentrations for Bituminous Fly Ash, Waste ID CFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	2.93E-01	S	1.04E-02	S	1.06E-01	S
8.4	2.79E-01	S	1.10E-02	S	9.90E-02	S
8.6	2.24E-01	S	1.02E-02	S	9.95E-02	S
8.8	1.68E-01	S	8.68E-03	S	1.03E-01	S
9	1.30E-01	S	7.37E-03	S	1.07E-01	S
9.2	1.02E-01	S	6.28E-03	S	1.11E-01	S
9.4	8.06E-02	S	5.37E-03	S	1.15E-01	S
9.6	6.39E-02	S	4.60E-03	S	1.19E-01	S
9.8	4.44E-02	S	3.96E-03	S	1.22E-01	S
10	3.40E-02	S	3.10E-03	S	1.26E-01	S
10.2	2.65E-02	S	2.63E-03	S	1.27E-01	S
10.4	2.36E-02	S	2.53E-03	S	1.28E-01	S
10.6	2.20E-02	S	2.53E-03	S	1.44E-01	S
10.8	2.08E-02	S	2.53E-03	S	1.56E-01	S
11	2.18E-02	S	2.53E-03	S	1.63E-01	S
11.2	2.28E-02	S	2.53E-03	S	1.70E-01	S
11.4	2.38E-02	S	2.53E-03	S	1.77E-01	S
11.6	2.48E-02	S	2.53E-03	S	1.85E-01	S
11.8	2.58E-02	S	2.53E-03	S	1.85E-01	S
12	2.69E-02	S	2.53E-03	S	1.85E-01	S
12.2	2.80E-02	S	2.53E-03	S	1.85E-01	S
12.4	2.87E-02	S	2.53E-03	S	1.85E-01	S
12.6	2.96E-02	S	2.53E-03	S	1.90E-01	S
12.8	3.15E-02	S	2.53E-03	S	1.90E-01	S
13	3.27E-02	S	2.53E-03	S	1.90E-01	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	2.93E+00		1.43E+00		1.93E+00	

Table C-5-9. Leachate Concentrations for Bituminous Fly Ash, Waste ID DaFA Med

Sample ID	DaFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:48 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	1.27E+00	S	2.20E+00	W	5.20E-02	S	2.66E-01	S
3	1.02E+00	S	2.07E+00	W	4.96E-02	S	2.31E-01	S
3.2	8.38E-01	S	1.97E+00	W	4.74E-02	S	2.02E-01	S
3.4	6.95E-01	S	1.87E+00	W	4.55E-02	S	1.79E-01	S
3.6	5.82E-01	S	1.78E+00	W	4.37E-02	S	1.59E-01	S
3.8	4.92E-01	S	1.70E+00	W	4.21E-02	S	1.43E-01	S
4	4.20E-01	S	1.63E+00	W	4.07E-02	S	1.29E-01	S
4.2	3.61E-01	S	1.57E+00	W	3.93E-02	S	1.16E-01	S
4.4	3.22E-01	S	1.53E+00	W	3.76E-02	S	1.09E-01	S
4.6	3.01E-01	S	1.54E+00	W	3.55E-02	S	1.07E-01	S
4.8	2.83E-01	S	1.54E+00	W	3.35E-02	S	1.06E-01	S
5	2.66E-01	S	1.54E+00	W	3.17E-02	S	1.04E-01	S
5.2	2.50E-01	S	1.55E+00	W	3.01E-02	S	1.02E-01	S
5.4	2.37E-01	S	1.55E+00	W	2.86E-02	S	1.01E-01	S
5.6	2.34E-01	S	1.55E+00	W	2.53E-02	S	9.31E-02	S
5.8	2.46E-01	S	1.54E+00	W	2.01E-02	S	7.79E-02	S
6	2.58E-01	S	1.53E+00	W	1.61E-02	S	6.56E-02	S
6.2	2.70E-01	S	1.52E+00	W	1.30E-02	S	5.55E-02	S
6.4	2.83E-01	S	1.51E+00	W	1.06E-02	S	4.72E-02	S
6.6	2.95E-01	S	1.50E+00	W	8.67E-03	S	4.04E-02	S
6.8	3.08E-01	S	1.50E+00	W	7.14E-03	S	3.47E-02	S
7	3.21E-01	S	1.49E+00	W	5.91E-03	S	2.99E-02	S
7.2	3.48E-01	S	1.48E+00	W	5.25E-03	S	2.45E-02	S
7.4	3.95E-01	S	1.48E+00	W	5.05E-03	S	1.87E-02	S
7.6	4.47E-01	S	1.48E+00	W	4.87E-03	S	1.44E-02	S
7.8	5.04E-01	S	1.47E+00	W	4.71E-03	S	1.12E-02	S
8	5.66E-01	S	1.47E+00	W	4.55E-03	S	8.76E-03	S

Table C-5-9. Leachate Concentrations for Bituminous Fly Ash, Waste ID DaFA Med

Sample ID	DaFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:48 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	6.35E-01	S	1.46E+00	W	4.40E-03	W	6.89E-03	S
8.4	7.09E-01	S	1.46E+00	W	4.25E-03	W	5.44E-03	S
8.6	7.91E-01	S	1.46E+00	W	4.12E-03	W	4.33E-03	S
8.8	8.79E-01	S	1.46E+00	W	3.99E-03	W	3.46E-03	S
9	9.75E-01	S	1.45E+00	W	3.87E-03	W	2.78E-03	S
9.2	1.08E+00	S	1.45E+00	W	3.76E-03	W	2.24E-03	S
9.4	1.17E+00	S	1.45E+00	W	3.74E-03	W	2.06E-03	S
9.6	1.25E+00	S	1.44E+00	W	3.78E-03	W	2.06E-03	S
9.8	1.34E+00	S	1.44E+00	W	3.83E-03	W	2.06E-03	S
10	1.43E+00	S	1.43E+00	W	3.87E-03	W	2.06E-03	S
10.2	1.52E+00	S	1.43E+00	W	3.91E-03	W	2.06E-03	S
10.4	1.62E+00	S	1.43E+00	W	3.95E-03	W	2.06E-03	S
10.6	1.72E+00	S	1.42E+00	W	3.99E-03	W	2.06E-03	S
10.8	1.82E+00	S	1.42E+00	W	4.03E-03	W	2.06E-03	S
11	1.90E+00	S	1.42E+00	W	4.06E-03	W	2.06E-03	S
11.2	1.87E+00	S	1.43E+00	W	4.04E-03	W	2.06E-03	S
11.4	1.85E+00	S	1.43E+00	W	4.03E-03	W	2.06E-03	S
11.6	1.82E+00	S	1.44E+00	W	4.01E-03	W	2.06E-03	S
11.8	1.79E+00	S	1.45E+00	W	4.00E-03	W	2.06E-03	S
12	1.98E+00	S	1.47E+00	W	4.08E-03	W	2.06E-03	S
12.2	2.51E+00	S	1.52E+00	W	4.27E-03	W	2.06E-03	S
12.4	3.16E+00	S	1.57E+00	W	4.47E-03	W	2.06E-03	S
12.6	3.97E+00	S	1.63E+00	W	4.67E-03	W	2.06E-03	S
12.8	4.97E+00	S	1.68E+00	W	4.89E-03	W	2.06E-03	S
13	6.21E+00	S	1.73E+00	W	5.10E-03	W	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	6.14E+01		2.20E+01		5.20E-01		2.66E+00	

Table C-5-9. Leachate Concentrations for Bituminous Fly Ash, Waste ID DaFA Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	1.52E+00	S	3.00E-06	S	6.42E-01	S	4.51E-02	S
3	8.24E-01	S	3.00E-06	S	5.84E-01	S	5.34E-02	S
3.2	4.64E-01	S	3.00E-06	S	5.35E-01	S	6.25E-02	S
3.4	2.71E-01	S	3.00E-06	S	4.93E-01	S	7.25E-02	S
3.6	1.63E-01	S	3.00E-06	S	4.56E-01	S	8.34E-02	S
3.8	1.01E-01	S	3.00E-06	S	4.24E-01	S	9.51E-02	S
4	6.40E-02	S	3.00E-06	S	3.96E-01	S	1.08E-01	S
4.2	4.15E-02	S	3.00E-06	S	3.70E-01	S	1.21E-01	S
4.4	2.61E-02	S	3.00E-06	S	4.01E-01	S	1.33E-01	S
4.6	1.56E-02	S	3.00E-06	S	5.35E-01	S	1.40E-01	S
4.8	9.55E-03	S	3.00E-06	S	7.04E-01	S	1.47E-01	S
5	5.96E-03	S	3.00E-06	S	9.16E-01	S	1.54E-01	S
5.2	3.79E-03	S	3.00E-06	S	1.18E+00	S	1.61E-01	S
5.4	2.45E-03	S	3.00E-06	S	1.51E+00	S	1.69E-01	S
5.6	2.02E-03	S	3.00E-06	S	1.80E+00	S	1.76E-01	S
5.8	2.34E-03	S	3.00E-06	S	1.95E+00	S	1.85E-01	S
6	2.70E-03	S	3.00E-06	S	2.11E+00	S	1.94E-01	S
6.2	3.10E-03	S	3.00E-06	S	2.28E+00	S	2.03E-01	S
6.4	3.54E-03	S	3.00E-06	S	2.46E+00	S	2.11E-01	S
6.6	4.03E-03	S	3.00E-06	S	2.65E+00	S	2.20E-01	S
6.8	4.57E-03	S	3.00E-06	S	2.84E+00	S	2.29E-01	S
7	5.16E-03	S	3.00E-06	S	3.04E+00	S	2.39E-01	S
7.2	6.00E-03	S	3.00E-06	S	3.16E+00	W	2.42E-01	W
7.4	7.22E-03	S	3.00E-06	S	3.18E+00	W	2.39E-01	W
7.6	8.65E-03	S	3.00E-06	S	3.19E+00	W	2.35E-01	W
7.8	1.03E-02	S	3.00E-06	S	3.21E+00	W	2.32E-01	W
8	1.22E-02	S	3.00E-06	S	3.23E+00	W	2.29E-01	W

Table C-5-9. Leachate Concentrations for Bituminous Fly Ash, Waste ID DaFA Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
8.2	1.44E-02	S	3.00E-06	S	3.24E+00	W	2.26E-01	W
8.4	1.70E-02	S	3.00E-06	S	3.26E+00	W	2.23E-01	W
8.6	1.99E-02	S	3.00E-06	S	3.27E+00	W	2.20E-01	W
8.8	2.33E-02	S	3.00E-06	S	3.29E+00	W	2.18E-01	W
9	2.71E-02	S	3.00E-06	S	3.30E+00	W	2.15E-01	W
9.2	3.14E-02	S	3.00E-06	S	3.32E+00	W	2.13E-01	W
9.4	3.55E-02	S	3.00E-06	S	3.34E+00	W	2.12E-01	W
9.6	3.95E-02	S	3.00E-06	S	3.35E+00	W	2.13E-01	W
9.8	4.38E-02	S	3.00E-06	S	3.37E+00	W	2.13E-01	W
10	4.85E-02	S	3.00E-06	S	3.39E+00	W	2.14E-01	W
10.2	5.36E-02	S	3.00E-06	S	3.40E+00	W	2.15E-01	W
10.4	5.92E-02	S	3.00E-06	S	3.42E+00	W	2.15E-01	W
10.6	6.51E-02	S	3.00E-06	S	3.43E+00	W	2.16E-01	W
10.8	7.16E-02	S	3.00E-06	S	3.45E+00	W	2.17E-01	W
11	7.82E-02	S	3.00E-06	S	3.46E+00	W	2.18E-01	W
11.2	8.41E-02	S	3.00E-06	S	3.48E+00	W	2.20E-01	W
11.4	9.02E-02	S	3.00E-06	S	3.50E+00	W	2.23E-01	W
11.6	9.67E-02	S	3.00E-06	S	3.51E+00	W	2.25E-01	W
11.8	1.04E-01	S	3.00E-06	S	3.53E+00	W	2.28E-01	W
12	1.12E-01	S	3.00E-06	S	3.55E+00	W	2.30E-01	W
12.2	1.24E-01	S	3.00E-06	S	3.56E+00	W	2.33E-01	W
12.4	1.37E-01	S	3.00E-06	S	3.58E+00	W	2.36E-01	W
12.6	1.51E-01	S	3.00E-06	S	3.59E+00	W	2.39E-01	W
12.8	1.67E-01	S	3.00E-06	S	3.60E+00	W	2.41E-01	W
13	1.83E-01	S	3.00E-06	S	3.62E+00	W	2.44E-01	W
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	1.52E+01		3.70E-05		4.45E+01		2.98E+00	

Table C-5-9. Leachate Concentrations for Bituminous Fly Ash, Waste ID DaFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	5.61E-01	S	3.04E-01	S	3.75E+00	S
3	4.94E-01	S	2.83E-01	S	2.38E+00	S
3.2	4.38E-01	S	2.65E-01	S	1.55E+00	S
3.4	3.91E-01	S	2.48E-01	S	1.04E+00	S
3.6	3.52E-01	S	2.34E-01	S	7.14E-01	S
3.8	3.18E-01	S	2.21E-01	S	4.99E-01	S
4	2.89E-01	S	2.09E-01	S	3.56E-01	S
4.2	2.64E-01	S	1.99E-01	S	2.58E-01	S
4.4	2.58E-01	S	1.89E-01	S	2.21E-01	S
4.6	2.77E-01	S	1.79E-01	S	2.37E-01	S
4.8	2.97E-01	S	1.70E-01	S	2.54E-01	S
5	3.17E-01	S	1.62E-01	S	2.72E-01	S
5.2	3.37E-01	S	1.55E-01	S	2.89E-01	S
5.4	3.58E-01	S	1.48E-01	S	3.08E-01	S
5.6	3.90E-01	S	1.40E-01	S	3.36E-01	S
5.8	4.42E-01	S	1.31E-01	S	3.81E-01	S
6	4.98E-01	S	1.22E-01	S	4.30E-01	S
6.2	5.59E-01	S	1.14E-01	S	4.84E-01	S
6.4	6.26E-01	S	1.07E-01	S	5.42E-01	S
6.6	6.98E-01	S	1.01E-01	S	6.06E-01	S
6.8	7.75E-01	S	9.46E-02	S	6.74E-01	S
7	8.59E-01	S	8.92E-02	S	7.48E-01	S
7.2	9.34E-01	S	8.21E-02	S	8.21E-01	S
7.4	9.94E-01	S	7.34E-02	S	8.90E-01	S
7.6	1.06E+00	S	6.58E-02	S	9.63E-01	S
7.8	1.12E+00	S	5.92E-02	S	1.04E+00	S
8	1.19E+00	S	5.33E-02	S	1.12E+00	S

Table C-5-9. Leachate Concentrations for Bituminous Fly Ash, Waste ID DaFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	1.26E+00	S	4.82E-02	S	1.20E+00	S
8.4	1.33E+00	S	4.37E-02	S	1.29E+00	S
8.6	1.40E+00	S	3.97E-02	S	1.38E+00	S
8.8	1.48E+00	S	3.61E-02	S	1.48E+00	S
9	1.56E+00	S	3.29E-02	S	1.58E+00	S
9.2	1.64E+00	S	3.01E-02	S	1.69E+00	S
9.4	1.70E+00	S	2.59E-02	S	1.85E+00	S
9.6	1.76E+00	S	2.15E-02	S	2.06E+00	S
9.8	1.82E+00	S	1.79E-02	S	2.28E+00	S
10	1.87E+00	S	1.50E-02	S	2.53E+00	S
10.2	1.93E+00	S	1.26E-02	S	2.80E+00	S
10.4	1.99E+00	S	1.06E-02	S	3.09E+00	S
10.6	2.05E+00	S	8.96E-03	S	3.40E+00	S
10.8	2.11E+00	S	7.59E-03	S	3.74E+00	S
11	2.17E+00	S	6.59E-03	S	4.05E+00	S
11.2	2.22E+00	S	6.24E-03	S	4.16E+00	S
11.4	2.28E+00	S	5.91E-03	S	4.28E+00	S
11.6	2.34E+00	S	5.60E-03	S	4.40E+00	S
11.8	2.40E+00	S	5.31E-03	S	4.52E+00	S
12	2.44E+00	S	5.54E-03	S	4.69E+00	S
12.2	2.46E+00	S	6.47E-03	S	4.93E+00	S
12.4	2.48E+00	S	7.53E-03	S	5.18E+00	S
12.6	2.49E+00	S	8.75E-03	S	5.44E+00	S
12.8	2.51E+00	S	1.01E-02	S	5.70E+00	S
13	2.53E+00	S	1.17E-02	S	5.97E+00	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	3.10E+01		3.04E+00		7.03E+01	

Table C-5-10. Leachate Concentrations for Bituminous Fly Ash, Waste ID DFA Med

Sample ID	DFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:48 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	5.41E-01	S	3.07E+01	W	2.46E-02	S	5.44E-02	S
3	4.17E-01	S	3.00E+01	W	2.38E-02	S	5.20E-02	S
3.2	3.56E-01	S	2.92E+01	W	2.28E-02	S	4.89E-02	S
3.4	2.95E-01	S	2.82E+01	W	2.19E-02	S	4.61E-02	S
3.6	2.46E-01	S	2.74E+01	W	2.10E-02	S	4.36E-02	S
3.8	2.07E-01	S	2.66E+01	W	2.04E-02	S	4.10E-02	S
4	1.75E-01	S	2.58E+01	W	1.97E-02	S	3.85E-02	S
4.2	1.50E-01	S	2.51E+01	W	1.90E-02	S	3.63E-02	S
4.4	1.46E-01	S	2.52E+01	W	1.82E-02	S	3.54E-02	S
4.6	1.43E-01	S	2.54E+01	W	1.75E-02	S	3.49E-02	S
4.8	1.41E-01	S	2.56E+01	W	1.68E-02	S	3.45E-02	S
5	1.38E-01	S	2.56E+01	W	1.62E-02	S	3.39E-02	S
5.2	1.36E-01	S	2.56E+01	W	1.56E-02	S	3.23E-02	S
5.4	1.41E-01	S	2.56E+01	W	1.47E-02	S	3.08E-02	S
5.6	1.47E-01	S	2.56E+01	W	1.22E-02	S	2.63E-02	S
5.8	1.55E-01	S	2.56E+01	W	1.14E-02	S	2.55E-02	S
6	1.66E-01	S	2.57E+01	W	1.07E-02	S	2.47E-02	S
6.2	1.68E-01	S	2.56E+01	W	9.97E-03	S	2.36E-02	S
6.4	1.74E-01	S	2.56E+01	W	7.15E-03	S	1.74E-02	S
6.6	1.80E-01	S	2.54E+01	W	5.18E-03	S	1.29E-02	S
6.8	1.86E-01	S	2.51E+01	W	3.79E-03	S	9.69E-03	S
7	1.92E-01	S	2.49E+01	S	2.79E-03	S	7.32E-03	S
7.2	1.99E-01	S	2.46E+01	S	2.20E-03	S	5.84E-03	S
7.4	1.95E-01	S	2.36E+01	S	1.82E-03	S	4.87E-03	S
7.6	2.17E-01	S	2.09E+01	S	1.51E-03	S	4.07E-03	S
7.8	2.25E-01	S	1.97E+01	S	1.26E-03	S	3.43E-03	S
8	2.34E-01	S	1.88E+01	S	1.06E-03	S	2.90E-03	S

Table C-5-10. Leachate Concentrations for Bituminous Fly Ash, Waste ID DFA Med

Sample ID	DFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:48 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	2.28E-01	S	1.78E+01	S	8.95E-04	W	2.46E-03	S
8.4	2.27E-01	S	1.70E+01	S	7.57E-04	W	2.09E-03	S
8.6	2.27E-01	S	1.51E+01	S	7.46E-04	W	2.06E-03	S
8.8	2.01E-01	S	1.35E+01	S	7.46E-04	W	2.06E-03	S
9	1.79E-01	S	1.20E+01	S	7.46E-04	W	2.06E-03	S
9.2	1.60E-01	S	9.88E+00	S	7.46E-04	W	2.06E-03	S
9.4	1.34E-01	S	8.81E+00	S	7.46E-04	W	2.06E-03	S
9.6	1.13E-01	S	8.10E+00	S	7.46E-04	W	2.06E-03	S
9.8	8.93E-02	S	6.82E+00	S	7.46E-04	W	2.06E-03	S
10	6.57E-02	S	5.46E+00	S	7.46E-04	W	2.06E-03	S
10.2	5.83E-02	S	4.39E+00	S	7.46E-04	W	2.06E-03	S
10.4	4.91E-02	S	3.55E+00	S	7.46E-04	W	2.06E-03	S
10.6	3.90E-02	S	2.89E+00	S	7.46E-04	W	2.06E-03	S
10.8	3.86E-02	S	2.36E+00	S	7.46E-04	W	2.06E-03	S
11	3.82E-02	S	1.94E+00	S	7.46E-04	W	2.06E-03	S
11.2	3.78E-02	S	1.52E+00	S	7.46E-04	W	2.06E-03	S
11.4	3.99E-02	S	1.23E+00	S	7.46E-04	W	2.06E-03	S
11.6	4.83E-02	S	1.12E+00	S	7.46E-04	W	2.06E-03	S
11.8	5.84E-02	S	1.01E+00	S	7.46E-04	W	2.06E-03	S
12	7.03E-02	S	9.24E-01	S	7.46E-04	W	2.06E-03	S
12.2	8.44E-02	S	8.20E-01	S	7.46E-04	W	2.06E-03	S
12.4	1.01E-01	S	7.28E-01	S	7.46E-04	W	2.06E-03	S
12.6	1.21E-01	S	6.48E-01	S	7.46E-04	W	2.06E-03	S
12.8	1.43E-01	S	5.78E-01	S	7.46E-04	W	2.06E-03	S
13	1.70E-01	S	5.16E-01	S	7.46E-04	W	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	5.41E+00		3.07E+02		2.46E-01		5.44E-01	

Table C-5-10. Leachate Concentrations for Bituminous Fly Ash, Waste ID DFA Med

Sample ID
Date Exported
Database Name ing\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	1.34E+00	S	2.22E-05	S	7.68E-02	S	7.66E-02	S
3	1.06E+00	S	2.31E-05	S	5.95E-02	S	6.74E-02	S
3.2	6.16E-01	S	2.65E-05	S	5.95E-02	S	4.89E-02	S
3.4	3.72E-01	S	3.00E-05	S	6.16E-02	S	3.62E-02	S
3.6	2.32E-01	S	3.38E-05	S	6.42E-02	S	2.73E-02	S
3.8	1.49E-01	S	3.79E-05	S	6.69E-02	S	2.09E-02	S
4	9.77E-02	S	4.22E-05	S	6.96E-02	S	1.62E-02	S
4.2	6.55E-02	S	4.67E-05	S	7.23E-02	S	1.38E-02	S
4.4	5.44E-02	S	4.45E-05	S	8.38E-02	S	1.48E-02	S
4.6	4.15E-02	S	4.25E-05	S	1.01E-01	S	1.66E-02	S
4.8	3.08E-02	S	4.07E-05	S	1.20E-01	S	1.85E-02	S
5	2.36E-02	S	3.91E-05	S	1.44E-01	S	2.06E-02	S
5.2	2.21E-02	S	3.75E-05	S	1.91E-01	S	2.30E-02	S
5.4	2.08E-02	S	3.61E-05	S	2.50E-01	S	2.55E-02	S
5.6	1.96E-02	S	3.49E-05	S	3.24E-01	S	2.82E-02	S
5.8	1.85E-02	S	3.38E-05	S	4.17E-01	S	3.11E-02	S
6	1.75E-02	S	3.27E-05	S	5.32E-01	S	3.41E-02	S
6.2	1.66E-02	S	3.17E-05	S	6.72E-01	S	3.74E-02	S
6.4	1.57E-02	S	3.11E-05	S	8.44E-01	S	4.08E-02	S
6.6	1.60E-02	S	3.34E-05	S	9.76E-01	S	4.33E-02	S
6.8	1.50E-02	S	3.58E-05	S	1.09E+00	S	4.53E-02	S
7	1.47E-02	S	3.63E-05	S	1.21E+00	S	4.73E-02	S
7.2	1.45E-02	S	3.58E-05	S	1.45E+00	W	5.22E-02	S
7.4	1.68E-02	S	3.59E-05	S	1.78E+00	W	5.45E-02	S
7.6	2.96E-02	S	3.04E-05	S	1.77E+00	W	5.23E-02	S
7.8	3.59E-02	S	2.88E-05	S	1.78E+00	W	5.01E-02	S
8	4.33E-02	S	3.20E-05	S	1.79E+00	W	4.81E-02	S

Table C-5-10. Leachate Concentrations for Bituminous Fly Ash, Waste ID DFA Med

Sample ID
Date Exported
Database Name ing\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	5.20E-02	S	3.55E-05	S	1.77E+00	W	4.62E-02	S
8.4	6.23E-02	S	3.92E-05	S	1.76E+00	W	4.45E-02	S
8.6	6.84E-02	S	4.33E-05	S	1.73E+00	W	3.85E-02	S
8.8	7.45E-02	S	4.14E-05	S	1.71E+00	W	3.31E-02	S
9	9.45E-02	S	3.36E-05	S	1.69E+00	W	2.85E-02	S
9.2	1.08E-01	W	2.74E-05	S	1.66E+00	W	2.34E-02	S
9.4	1.11E-01	W	2.24E-05	S	1.64E+00	W	1.80E-02	S
9.6	1.14E-01	W	2.26E-05	S	1.62E+00	W	1.60E-02	S
9.8	1.17E-01	W	2.73E-05	S	1.62E+00	W	1.32E-02	S
10	1.19E-01	W	2.87E-05	S	1.73E+00	W	1.05E-02	S
10.2	1.22E-01	W	2.49E-05	S	1.85E+00	W	8.31E-03	S
10.4	1.24E-01	W	2.14E-05	S	1.86E+00	W	6.66E-03	S
10.6	1.24E-01	W	2.06E-05	S	1.85E+00	W	5.50E-03	S
10.8	1.23E-01	W	1.99E-05	S	1.76E+00	W	4.56E-03	S
11	1.22E-01	W	1.91E-05	S	1.67E+00	W	3.80E-03	S
11.2	1.22E-01	W	1.84E-05	S	1.59E+00	W	3.17E-03	S
11.4	1.21E-01	W	1.88E-05	S	1.54E+00	W	2.78E-03	S
11.6	1.20E-01	W	2.21E-05	S	1.55E+00	W	2.78E-03	S
11.8	1.18E-01	W	2.60E-05	S	1.56E+00	W	2.78E-03	S
12	1.17E-01	W	2.55E-05	S	1.58E+00	W	2.78E-03	S
12.2	1.16E-01	W	2.48E-05	S	1.61E+00	W	2.78E-03	S
12.4	1.15E-01	W	2.41E-05	S	1.63E+00	W	2.78E-03	S
12.6	1.14E-01	W	2.39E-05	S	1.65E+00	W	2.78E-03	S
12.8	1.13E-01	W	2.58E-05	S	1.66E+00	W	2.78E-03	S
13	1.13E-01	W	2.77E-05	S	1.66E+00	W	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	1.34E+01		4.67E-04		1.86E+01		7.66E-01	

Table C-5-10. Leachate Concentrations for Bituminous Fly Ash, Waste ID DFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	3.32E-02	S	3.40E-01	S	2.09E-01	S
3	2.98E-02	S	3.04E-01	S	1.03E-01	S
3.2	2.80E-02	S	2.66E-01	S	6.48E-02	S
3.4	2.65E-02	S	2.34E-01	S	4.63E-02	S
3.6	2.51E-02	S	2.07E-01	S	3.37E-02	S
3.8	2.39E-02	S	1.85E-01	S	2.50E-02	S
4	2.27E-02	S	1.66E-01	S	1.87E-02	S
4.2	2.20E-02	S	1.50E-01	S	1.44E-02	S
4.4	2.35E-02	S	1.46E-01	S	1.54E-02	S
4.6	2.53E-02	S	1.40E-01	S	1.66E-02	S
4.8	2.62E-02	S	1.34E-01	S	1.88E-02	S
5	2.67E-02	S	1.28E-01	S	2.13E-02	S
5.2	2.65E-02	S	1.15E-01	S	2.40E-02	S
5.4	2.64E-02	S	1.04E-01	S	2.69E-02	S
5.6	2.63E-02	S	9.36E-02	S	3.04E-02	S
5.8	2.62E-02	S	8.49E-02	S	3.49E-02	S
6	2.63E-02	S	7.72E-02	S	3.99E-02	S
6.2	2.70E-02	S	7.05E-02	S	4.53E-02	S
6.4	2.59E-02	S	6.45E-02	S	5.13E-02	S
6.6	2.82E-02	S	5.80E-02	S	5.65E-02	S
6.8	3.19E-02	S	5.17E-02	S	6.46E-02	S
7	3.60E-02	S	4.63E-02	S	7.45E-02	S
7.2	4.05E-02	S	3.83E-02	S	8.09E-02	S
7.4	5.19E-02	S	2.40E-02	S	8.38E-02	S
7.6	5.76E-02	S	1.13E-02	S	8.67E-02	S
7.8	6.05E-02	S	7.71E-03	S	8.97E-02	S
8	6.35E-02	S	5.33E-03	S	9.30E-02	S

Table C-5-10. Leachate Concentrations for Bituminous Fly Ash, Waste ID DFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	6.27E-02	S	3.71E-03	S	9.68E-02	S
8.4	6.59E-02	S	2.61E-03	S	1.01E-01	S
8.6	6.09E-02	S	2.53E-03	S	1.04E-01	S
8.8	5.24E-02	S	2.53E-03	S	1.06E-01	S
9	4.53E-02	S	2.53E-03	S	1.10E-01	S
9.2	3.93E-02	S	2.53E-03	S	1.14E-01	S
9.4	3.16E-02	S	2.53E-03	S	1.18E-01	S
9.6	2.84E-02	S	2.53E-03	S	1.22E-01	S
9.8	2.17E-02	S	2.53E-03	S	1.26E-01	S
10	1.51E-02	S	2.53E-03	S	1.21E-01	S
10.2	1.14E-02	S	2.53E-03	S	1.15E-01	S
10.4	9.62E-03	S	2.53E-03	S	1.14E-01	S
10.6	7.59E-03	S	2.53E-03	S	1.13E-01	S
10.8	7.43E-03	S	2.53E-03	S	1.12E-01	S
11	7.48E-03	S	2.53E-03	S	1.11E-01	S
11.2	7.53E-03	S	2.53E-03	S	1.11E-01	S
11.4	7.66E-03	S	2.53E-03	S	1.13E-01	S
11.6	7.98E-03	S	2.53E-03	S	1.24E-01	S
11.8	8.31E-03	S	2.53E-03	S	1.26E-01	S
12	8.65E-03	S	2.53E-03	S	1.35E-01	S
12.2	8.99E-03	S	2.53E-03	S	1.44E-01	S
12.4	9.34E-03	S	2.53E-03	S	1.54E-01	S
12.6	9.70E-03	S	2.53E-03	S	1.63E-01	S
12.8	1.01E-02	S	2.53E-03	S	1.74E-01	S
13	1.04E-02	S	2.53E-03	S	1.85E-01	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	6.59E-01		3.40E+00		2.09E+00	

Table C-5-11. Leachate Concentrations for Bituminous Fly Ash, Waste ID EaFa-Ref Med

Sample ID	EaFA-Ref-[Med] (P,1,1)
Date Exported	8/27/2011, 6:48 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	3.84E-01	S	3.50E+00	W	2.81E-02	S	2.99E-01	S
3	2.86E-01	S	3.57E+00	W	2.78E-02	S	2.78E-01	S
3.2	2.15E-01	S	3.63E+00	W	2.76E-02	S	2.61E-01	S
3.4	1.66E-01	S	3.69E+00	W	2.74E-02	S	2.45E-01	S
3.6	1.30E-01	S	3.75E+00	W	2.72E-02	S	2.31E-01	S
3.8	1.03E-01	S	3.80E+00	W	2.70E-02	S	2.18E-01	S
4	8.68E-02	S	3.89E+00	W	2.71E-02	S	2.13E-01	S
4.2	7.93E-02	S	4.02E+00	W	2.71E-02	S	2.16E-01	S
4.4	7.17E-02	S	4.15E+00	W	2.75E-02	S	2.20E-01	S
4.6	6.52E-02	S	4.28E+00	W	2.79E-02	S	2.23E-01	S
4.8	5.94E-02	S	4.41E+00	W	2.82E-02	S	2.26E-01	S
5	5.44E-02	S	4.54E+00	W	2.84E-02	S	2.29E-01	S
5.2	5.01E-02	S	4.67E+00	W	2.86E-02	S	2.32E-01	S
5.4	4.64E-02	S	4.80E+00	W	2.88E-02	S	2.35E-01	S
5.6	4.68E-02	S	4.82E+00	W	2.28E-02	S	2.01E-01	S
5.8	4.94E-02	S	4.80E+00	W	1.56E-02	S	1.46E-01	S
6	5.20E-02	S	4.77E+00	W	1.05E-02	S	1.08E-01	S
6.2	5.46E-02	S	4.72E+00	W	6.87E-03	S	8.21E-02	S
6.4	5.73E-02	S	4.66E+00	W	4.33E-03	S	6.14E-02	S
6.6	6.12E-02	S	4.61E+00	W	2.77E-03	S	4.73E-02	S
6.8	6.44E-02	S	4.55E+00	W	1.80E-03	S	3.70E-02	S
7	6.85E-02	S	4.50E+00	W	1.23E-03	S	2.87E-02	S
7.2	8.05E-02	S	4.47E+00	W	1.10E-03	S	1.64E-02	S
7.4	9.24E-02	S	4.43E+00	W	1.10E-03	S	9.83E-03	S
7.6	1.12E-01	S	4.42E+00	W	1.10E-03	S	6.30E-03	S
7.8	1.38E-01	S	4.39E+00	W	1.10E-03	S	4.16E-03	S
8	1.78E-01	S	4.36E+00	W	1.10E-03	S	2.60E-03	S

Table C-5-11. Leachate Concentrations for Bituminous Fly Ash, Waste ID EaFa-Ref Med

Sample ID	EaFA-Ref-[Med] (P,1,1)
Date Exported	8/27/2011, 6:48 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	2.11E-01	S	4.35E+00	W	1.10E-03	W	2.17E-03	S
8.4	2.49E-01	S	4.35E+00	W	1.10E-03	W	1.82E-03	S
8.6	2.93E-01	S	4.35E+00	W	1.10E-03	W	1.52E-03	S
8.8	3.44E-01	S	4.34E+00	W	1.10E-03	W	1.25E-03	S
9	4.08E-01	S	4.33E+00	W	1.10E-03	W	1.03E-03	S
9.2	4.76E-01	S	4.31E+00	W	1.10E-03	W	9.02E-04	S
9.4	5.44E-01	S	4.32E+00	W	1.10E-03	W	9.00E-04	S
9.6	6.28E-01	S	4.33E+00	W	1.10E-03	W	9.00E-04	S
9.8	7.31E-01	S	4.32E+00	W	1.10E-03	W	9.00E-04	S
10	8.31E-01	S	4.32E+00	W	1.10E-03	W	9.00E-04	S
10.2	8.73E-01	S	4.32E+00	W	1.10E-03	W	9.00E-04	S
10.4	8.63E-01	S	4.33E+00	W	1.10E-03	W	9.00E-04	S
10.6	8.53E-01	S	4.33E+00	W	1.10E-03	W	9.00E-04	S
10.8	8.45E-01	S	4.33E+00	W	1.10E-03	W	9.00E-04	S
11	8.38E-01	S	4.34E+00	W	1.10E-03	W	9.00E-04	S
11.2	8.32E-01	S	4.34E+00	W	1.10E-03	W	9.00E-04	S
11.4	8.33E-01	S	4.34E+00	W	1.10E-03	W	9.00E-04	S
11.6	8.29E-01	S	4.35E+00	W	1.10E-03	W	9.00E-04	S
11.8	8.25E-01	S	4.36E+00	W	1.10E-03	W	9.00E-04	S
12	9.89E-01	S	4.39E+00	W	1.10E-03	W	9.00E-04	S
12.2	1.55E+00	S	4.69E+00	W	1.10E-03	W	9.00E-04	S
12.4	2.38E+00	S	5.05E+00	W	1.10E-03	W	9.00E-04	S
12.6	3.61E+00	S	5.43E+00	W	1.10E-03	W	9.00E-04	S
12.8	5.40E+00	S	5.82E+00	W	1.10E-03	W	9.00E-04	S
13	8.00E+00	S	6.24E+00	W	1.10E-03	W	9.00E-04	S
Detection Limit (min, mg/L)	1.10E-02		1.00E-03		2.20E-03		1.80E-03	
Detection Limit (max, mg/L)	1.10E-02		1.00E-03		2.20E-03		1.80E-03	
Availability (mg/kg)	5.40E+01		5.82E+01		2.88E-01		2.99E+00	

Table C-5-11. Leachate Concentrations for Bituminous Fly Ash, Waste ID EaFa-Ref Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
2.8	5.80E-01	S	NA	1.83E-01	S	8.61E-03	S
3	4.49E-01	S	NA	1.63E-01	S	1.03E-02	S
3.2	3.53E-01	S	NA	1.46E-01	S	1.21E-02	S
3.4	2.82E-01	S	NA	1.31E-01	S	1.42E-02	S
3.6	2.27E-01	S	NA	1.19E-01	S	1.64E-02	S
3.8	1.85E-01	S	NA	1.08E-01	S	1.88E-02	S
4	1.14E-01	S	NA	1.18E-01	S	2.18E-02	S
4.2	5.66E-02	S	NA	1.51E-01	S	2.55E-02	S
4.4	2.92E-02	S	NA	1.92E-01	S	2.97E-02	S
4.6	1.56E-02	S	NA	2.42E-01	S	3.43E-02	S
4.8	8.68E-03	S	NA	3.02E-01	S	3.94E-02	S
5	4.93E-03	S	NA	3.73E-01	S	4.50E-02	S
5.2	2.87E-03	S	NA	4.58E-01	S	4.99E-02	S
5.4	1.70E-03	S	NA	5.52E-01	S	5.66E-02	S
5.6	1.91E-03	S	NA	6.83E-01	S	6.36E-02	S
5.8	2.62E-03	S	NA	8.49E-01	S	6.94E-02	S
6	3.90E-03	S	NA	1.04E+00	S	7.66E-02	S
6.2	6.73E-03	S	NA	1.26E+00	S	8.46E-02	S
6.4	1.14E-02	S	NA	1.59E+00	S	9.31E-02	S
6.6	1.77E-02	S	NA	1.97E+00	S	1.02E-01	S
6.8	2.88E-02	S	NA	2.42E+00	S	1.11E-01	S
7	4.56E-02	S	NA	2.96E+00	S	1.21E-01	S
7.2	6.01E-02	S	NA	3.19E+00	W	1.25E-01	S
7.4	7.57E-02	S	NA	3.26E+00	W	1.28E-01	S
7.6	9.57E-02	S	NA	3.34E+00	W	1.30E-01	S
7.8	1.20E-01	S	NA	3.40E+00	W	1.32E-01	S
8	1.44E-01	S	NA	3.44E+00	W	1.32E-01	S

Table C-5-11. Leachate Concentrations for Bituminous Fly Ash, Waste ID EaFa-Ref Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
8.2	1.55E-01	S	NA	3.46E+00	W	1.32E-01	S
8.4	1.65E-01	S	NA	3.48E+00	W	1.32E-01	S
8.6	1.76E-01	S	NA	3.50E+00	W	1.32E-01	S
8.8	1.88E-01	S	NA	3.51E+00	W	1.32E-01	S
9	2.02E-01	S	NA	3.52E+00	W	1.32E-01	S
9.2	2.16E-01	S	NA	3.54E+00	W	1.31E-01	S
9.4	2.26E-01	S	NA	3.57E+00	W	1.28E-01	S
9.6	2.37E-01	S	NA	3.62E+00	W	1.26E-01	S
9.8	2.47E-01	S	NA	3.65E+00	W	1.29E-01	S
10	2.57E-01	S	NA	3.68E+00	W	1.30E-01	S
10.2	2.64E-01	S	NA	3.70E+00	W	1.28E-01	S
10.4	2.71E-01	S	NA	3.70E+00	W	1.26E-01	S
10.6	2.78E-01	S	NA	3.71E+00	W	1.26E-01	S
10.8	2.84E-01	S	NA	3.71E+00	W	1.27E-01	S
11	2.88E-01	S	NA	3.72E+00	W	1.27E-01	S
11.2	2.95E-01	S	NA	3.72E+00	W	1.27E-01	S
11.4	3.01E-01	S	NA	3.72E+00	W	1.27E-01	S
11.6	3.08E-01	S	NA	3.73E+00	W	1.28E-01	S
11.8	3.15E-01	S	NA	3.73E+00	W	1.28E-01	S
12	3.25E-01	S	NA	3.74E+00	W	1.31E-01	S
12.2	3.44E-01	S	NA	3.78E+00	W	1.40E-01	S
12.4	3.65E-01	S	NA	3.82E+00	W	1.49E-01	S
12.6	3.86E-01	S	NA	3.86E+00	W	1.57E-01	S
12.8	4.08E-01	S	NA	3.91E+00	W	1.69E-01	S
13	4.31E-01	S	NA	3.94E+00	W	1.81E-01	S
Detection Limit (min, mg/L)	1.20E-03		NA	1.20E-03		7.50E-03	
Detection Limit (max, mg/L)	1.20E-03		NA	1.20E-03		7.50E-03	
Availability (mg/kg)	5.80E+00		NA	3.91E+01		1.69E+00	

Table C-5-11. Leachate Concentrations for Bituminous Fly Ash, Waste ID EaFa-Ref Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	2.14E-01	S	5.56E-02	S	7.69E-01	S
3	1.73E-01	S	5.26E-02	S	4.82E-01	S
3.2	1.42E-01	S	4.94E-02	S	3.09E-01	S
3.4	1.18E-01	S	4.66E-02	S	2.06E-01	S
3.6	9.95E-02	S	4.42E-02	S	1.40E-01	S
3.8	8.44E-02	S	4.23E-02	S	9.73E-02	S
4	9.01E-02	S	3.79E-02	S	8.16E-02	S
4.2	1.05E-01	S	3.08E-02	S	8.10E-02	S
4.4	1.22E-01	S	2.52E-02	S	8.04E-02	S
4.6	1.40E-01	S	2.08E-02	S	7.99E-02	S
4.8	1.61E-01	S	1.72E-02	S	7.94E-02	S
5	1.82E-01	S	1.42E-02	S	7.92E-02	S
5.2	2.02E-01	S	1.18E-02	S	7.90E-02	S
5.4	2.23E-01	S	9.90E-03	S	7.88E-02	S
5.6	2.55E-01	S	8.27E-03	S	8.14E-02	S
5.8	2.98E-01	S	6.96E-03	S	8.70E-02	S
6	3.51E-01	S	5.89E-03	S	9.45E-02	S
6.2	4.10E-01	S	5.02E-03	S	1.03E-01	S
6.4	4.90E-01	S	4.29E-03	S	1.12E-01	S
6.6	5.91E-01	S	3.64E-03	S	1.22E-01	S
6.8	6.99E-01	S	2.93E-03	S	1.32E-01	S
7	8.16E-01	S	2.37E-03	S	1.42E-01	S
7.2	9.51E-01	S	2.30E-03	S	1.55E-01	S
7.4	1.11E+00	S	2.30E-03	S	1.70E-01	S
7.6	1.28E+00	S	2.30E-03	S	1.85E-01	S
7.8	1.47E+00	S	2.30E-03	S	2.00E-01	S
8	1.68E+00	S	2.30E-03	S	2.27E-01	S

Table C-5-11. Leachate Concentrations for Bituminous Fly Ash, Waste ID EaFa-Ref Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	1.93E+00	S	2.30E-03	S	2.75E-01	S
8.4	2.21E+00	S	2.30E-03	S	3.35E-01	S
8.6	2.53E+00	S	2.30E-03	S	4.02E-01	S
8.8	2.89E+00	S	2.30E-03	S	4.79E-01	S
9	3.30E+00	S	2.30E-03	S	5.74E-01	S
9.2	3.70E+00	S	2.30E-03	S	6.90E-01	S
9.4	3.93E+00	S	2.30E-03	S	8.33E-01	S
9.6	4.17E+00	S	2.30E-03	S	1.01E+00	S
9.8	4.42E+00	S	2.30E-03	S	1.22E+00	S
10	4.66E+00	S	2.30E-03	S	1.46E+00	S
10.2	4.78E+00	S	2.30E-03	S	1.59E+00	S
10.4	4.89E+00	S	2.30E-03	S	1.67E+00	S
10.6	4.98E+00	S	2.30E-03	S	1.74E+00	S
10.8	5.05E+00	S	2.30E-03	S	1.82E+00	S
11	5.12E+00	S	2.30E-03	S	1.92E+00	S
11.2	5.19E+00	S	2.30E-03	S	2.00E+00	S
11.4	5.26E+00	S	2.30E-03	S	2.09E+00	S
11.6	5.32E+00	S	2.30E-03	S	2.18E+00	S
11.8	5.39E+00	S	2.30E-03	S	2.27E+00	S
12	5.50E+00	S	2.30E-03	S	2.48E+00	S
12.2	5.78E+00	S	2.30E-03	S	2.83E+00	S
12.4	6.03E+00	S	2.30E-03	S	3.22E+00	S
12.6	6.28E+00	S	2.30E-03	S	3.65E+00	S
12.8	6.54E+00	S	2.30E-03	S	4.14E+00	S
13	6.80E+00	S	2.30E-03	S	4.68E+00	S
Detection Limit (min, mg/L)	1.50E-02		4.60E-03		1.50E-03	
Detection Limit (max, mg/L)	1.50E-02		4.60E-03		1.50E-03	
Availability (mg/kg)	6.54E+01		5.56E-01		4.14E+01	

Table C-5-12. Leachate Concentrations for Bituminous Fly Ash, Waste ID EFA Med

Sample ID	EFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:49 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	2.51E-01	S	3.43E+00	W	7.21E-03	S	2.59E-01	S
3	1.77E-01	S	3.41E+00	W	7.05E-03	S	2.58E-01	S
3.2	1.28E-01	S	3.40E+00	W	6.90E-03	S	2.57E-01	S
3.4	9.38E-02	S	3.39E+00	W	6.76E-03	S	2.57E-01	S
3.6	7.01E-02	S	3.38E+00	W	6.64E-03	S	2.56E-01	S
3.8	5.33E-02	S	3.37E+00	W	6.52E-03	S	2.55E-01	S
4	4.42E-02	S	3.27E+00	W	6.43E-03	S	2.67E-01	S
4.2	1.86E-02	S	2.99E+00	W	5.37E-03	S	3.02E-01	S
4.4	1.91E-02	S	2.89E+00	W	4.33E-03	S	2.78E-01	S
4.6	1.96E-02	S	2.80E+00	W	3.52E-03	S	2.58E-01	S
4.8	2.01E-02	S	2.71E+00	W	2.89E-03	S	2.39E-01	S
5	2.06E-02	S	2.63E+00	W	2.39E-03	S	2.23E-01	S
5.2	2.11E-02	S	2.56E+00	W	2.00E-03	S	2.08E-01	S
5.4	2.01E-02	S	2.49E+00	W	1.81E-03	S	1.88E-01	S
5.6	1.68E-02	S	2.47E+00	W	1.49E-03	S	1.59E-01	S
5.8	1.42E-02	S	2.45E+00	W	1.25E-03	S	1.36E-01	S
6	1.20E-02	S	2.43E+00	W	1.04E-03	S	1.16E-01	S
6.2	1.02E-02	S	2.41E+00	W	8.80E-04	S	1.00E-01	S
6.4	8.73E-03	S	2.40E+00	W	7.46E-04	S	8.69E-02	S
6.6	6.95E-03	S	2.54E+00	W	7.46E-04	S	6.17E-02	S
6.8	9.67E-03	S	2.56E+00	W	7.46E-04	S	3.32E-02	S
7	1.33E-02	S	2.53E+00	W	7.46E-04	S	1.79E-02	S
7.2	1.82E-02	S	2.50E+00	W	7.46E-04	S	9.80E-03	S
7.4	2.46E-02	S	2.47E+00	W	7.46E-04	S	5.46E-03	S
7.6	3.30E-02	S	2.44E+00	W	7.46E-04	S	3.09E-03	S
7.8	4.57E-02	S	2.41E+00	W	7.46E-04	S	2.06E-03	S
8	6.61E-02	S	2.35E+00	W	7.46E-04	S	2.06E-03	S

Table C-5-12. Leachate Concentrations for Bituminous Fly Ash, Waste ID EFA Med

Sample ID	EFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:49 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	8.48E-02	S	2.29E+00	W	7.46E-04	S	2.06E-03	S
8.4	9.68E-02	S	2.24E+00	W	7.46E-04	S	2.06E-03	S
8.6	1.02E-01	S	2.22E+00	W	7.46E-04	S	2.06E-03	S
8.8	9.84E-02	S	2.25E+00	W	7.46E-04	S	2.06E-03	S
9	9.53E-02	S	2.27E+00	W	7.46E-04	S	2.06E-03	S
9.2	9.23E-02	S	2.29E+00	W	7.46E-04	S	2.06E-03	S
9.4	8.96E-02	S	2.31E+00	W	7.46E-04	S	2.06E-03	S
9.6	8.69E-02	S	2.33E+00	W	7.46E-04	S	2.06E-03	S
9.8	8.44E-02	S	2.36E+00	W	7.46E-04	S	2.06E-03	S
10	8.20E-02	S	2.38E+00	W	7.46E-04	S	2.06E-03	S
10.2	7.97E-02	S	2.40E+00	W	7.46E-04	S	2.06E-03	S
10.4	7.75E-02	S	2.42E+00	W	7.46E-04	S	2.06E-03	S
10.6	7.55E-02	S	2.44E+00	W	7.46E-04	S	2.06E-03	S
10.8	7.35E-02	S	2.46E+00	W	7.46E-04	S	2.06E-03	S
11	7.14E-02	S	2.46E+00	W	7.46E-04	S	2.06E-03	S
11.2	6.92E-02	S	2.47E+00	W	7.46E-04	S	2.06E-03	S
11.4	6.71E-02	S	2.49E+00	W	7.46E-04	S	2.06E-03	S
11.6	6.51E-02	S	2.50E+00	W	7.46E-04	S	2.06E-03	S
11.8	6.32E-02	S	2.51E+00	W	7.46E-04	S	2.06E-03	S
12	6.13E-02	S	2.52E+00	W	7.46E-04	S	2.06E-03	S
12.2	5.86E-02	S	2.54E+00	W	7.46E-04	S	2.06E-03	S
12.4	5.52E-02	S	2.55E+00	W	7.46E-04	S	2.06E-03	S
12.6	5.20E-02	S	2.56E+00	W	7.46E-04	S	2.06E-03	S
12.8	4.90E-02	S	2.57E+00	W	7.46E-04	S	2.06E-03	S
13	4.63E-02	S	2.58E+00	W	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	2.51E+00		3.43E+01		7.21E-02		3.02E+00	

Table C-5-12. Leachate Concentrations for Bituminous Fly Ash, Waste ID EFA Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	4.10E-01	S	1.05E-05	S	2.51E-02	S	1.59E-02	S
3	2.34E-01	S	1.06E-05	S	1.66E-02	S	1.36E-02	S
3.2	1.39E-01	S	1.07E-05	S	1.13E-02	S	1.19E-02	S
3.4	8.47E-02	S	1.07E-05	S	7.88E-03	S	1.04E-02	S
3.6	5.32E-02	S	1.08E-05	S	5.60E-03	S	9.16E-03	S
3.8	3.43E-02	S	9.02E-06	S	4.06E-03	S	8.14E-03	S
4	1.99E-02	S	1.12E-05	S	3.80E-03	S	9.62E-03	S
4.2	5.40E-03	S	9.83E-06	S	1.29E-02	S	1.31E-02	S
4.4	4.85E-03	S	1.17E-05	S	2.33E-02	S	1.63E-02	S
4.6	4.37E-03	S	1.15E-05	S	4.10E-02	S	2.00E-02	S
4.8	3.96E-03	S	1.13E-05	S	7.05E-02	S	2.43E-02	S
5	3.60E-03	S	1.12E-05	S	1.18E-01	S	2.94E-02	S
5.2	3.28E-03	S	1.10E-05	S	1.95E-01	S	3.52E-02	S
5.4	2.78E-03	S	1.09E-05	S	2.68E-01	S	3.91E-02	S
5.6	2.57E-03	S	1.09E-05	S	3.46E-01	S	4.02E-02	S
5.8	2.37E-03	S	1.09E-05	S	4.44E-01	S	4.12E-02	S
6	2.20E-03	S	1.09E-05	S	5.65E-01	S	4.22E-02	S
6.2	2.04E-03	S	1.09E-05	S	7.13E-01	S	4.31E-02	S
6.4	1.90E-03	S	9.04E-06	S	8.93E-01	S	4.41E-02	S
6.6	1.90E-03	S	1.09E-05	S	1.12E+00	S	4.85E-02	S
6.8	1.90E-03	S	1.09E-05	S	1.30E+00	S	5.41E-02	S
7	2.26E-03	S	1.09E-05	S	1.37E+00	S	5.73E-02	S
7.2	2.67E-03	S	1.09E-05	S	1.44E+00	W	6.05E-02	S
7.4	3.15E-03	S	1.09E-05	S	1.51E+00	W	6.38E-02	S
7.6	3.69E-03	S	1.09E-05	S	1.58E+00	W	6.73E-02	S
7.8	4.61E-03	S	1.09E-05	S	1.63E+00	W	6.93E-02	S
8	5.61E-03	S	1.21E-05	S	1.62E+00	W	6.90E-02	S

Table C-5-12. Leachate Concentrations for Bituminous Fly Ash, Waste ID EFA Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
8.2	5.22E-03	S	1.19E-05	S	1.61E+00	W	6.72E-02	W
8.4	3.76E-03	S	1.05E-05	S	1.61E+00	W	6.41E-02	W
8.6	3.37E-03	S	9.85E-06	S	1.61E+00	W	6.31E-02	W
8.8	3.71E-03	S	9.85E-06	S	1.61E+00	W	6.38E-02	W
9	4.09E-03	S	9.85E-06	S	1.62E+00	W	6.45E-02	W
9.2	4.50E-03	S	9.85E-06	S	1.62E+00	W	6.52E-02	W
9.4	4.93E-03	S	9.85E-06	S	1.63E+00	W	6.60E-02	W
9.6	5.40E-03	S	9.85E-06	S	1.63E+00	W	6.67E-02	W
9.8	5.90E-03	S	9.85E-06	S	1.64E+00	W	6.74E-02	W
10	6.43E-03	S	9.85E-06	S	1.64E+00	W	6.81E-02	W
10.2	7.01E-03	S	9.85E-06	S	1.65E+00	W	6.87E-02	W
10.4	7.62E-03	S	9.85E-06	S	1.65E+00	W	6.94E-02	W
10.6	8.27E-03	S	9.85E-06	S	1.66E+00	W	7.01E-02	W
10.8	8.96E-03	S	9.85E-06	S	1.66E+00	W	7.08E-02	W
11	1.02E-02	S	9.85E-06	S	1.68E+00	W	7.18E-02	W
11.2	1.35E-02	S	1.05E-05	S	1.70E+00	W	7.33E-02	W
11.4	1.77E-02	S	1.11E-05	S	1.73E+00	W	7.48E-02	W
11.6	2.32E-02	S	1.18E-05	S	1.75E+00	W	7.62E-02	W
11.8	3.03E-02	S	1.24E-05	S	1.78E+00	W	7.77E-02	W
12	3.93E-02	S	1.32E-05	S	1.81E+00	W	7.92E-02	W
12.2	5.08E-02	S	1.35E-05	S	1.82E+00	W	7.99E-02	W
12.4	6.54E-02	S	1.35E-05	S	1.82E+00	W	7.99E-02	W
12.6	8.39E-02	S	1.35E-05	S	1.82E+00	W	7.99E-02	W
12.8	1.07E-01	S	1.35E-05	S	1.82E+00	W	7.99E-02	W
13	1.36E-01	S	1.35E-05	S	1.82E+00	W	7.99E-02	W
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	4.10E+00		1.42E-04		1.91E+01		8.39E-01	

Table C-5-12. Leachate Concentrations for Bituminous Fly Ash, Waste ID EFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	2.64E-01	S	9.63E-02	S	2.63E-01	S
3	1.92E-01	S	8.23E-02	S	8.46E-02	S
3.2	1.42E-01	S	7.10E-02	S	2.93E-02	S
3.4	1.08E-01	S	6.19E-02	S	1.08E-02	S
3.6	8.27E-02	S	5.43E-02	S	4.23E-03	S
3.8	6.44E-02	S	4.80E-02	S	1.74E-03	S
4	5.90E-02	S	4.25E-02	S	1.43E-03	S
4.2	8.16E-02	S	2.19E-02	S	1.43E-03	S
4.4	8.91E-02	S	1.73E-02	S	1.80E-03	S
4.6	9.69E-02	S	1.38E-02	S	2.25E-03	S
4.8	1.05E-01	S	1.11E-02	S	2.79E-03	S
5	1.13E-01	S	9.02E-03	S	3.42E-03	S
5.2	1.22E-01	S	7.38E-03	S	4.16E-03	S
5.4	1.16E-01	S	6.79E-03	S	4.37E-03	S
5.6	1.08E-01	S	6.75E-03	S	4.61E-03	S
5.8	1.01E-01	S	6.72E-03	S	4.85E-03	S
6	9.51E-02	S	6.69E-03	S	5.10E-03	S
6.2	8.94E-02	S	6.66E-03	S	5.35E-03	S
6.4	8.42E-02	S	6.63E-03	S	5.61E-03	S
6.6	1.03E-01	S	4.73E-03	S	7.82E-03	S
6.8	1.39E-01	S	3.40E-03	S	1.14E-02	S
7	1.73E-01	S	3.17E-03	S	1.35E-02	S
7.2	2.13E-01	S	2.97E-03	S	1.58E-02	S
7.4	2.62E-01	S	2.78E-03	S	1.85E-02	S
7.6	3.20E-01	S	2.61E-03	S	2.15E-02	S
7.8	4.00E-01	S	2.53E-03	S	2.70E-02	S
8	5.03E-01	S	2.53E-03	S	3.92E-02	S

Table C-5-12. Leachate Concentrations for Bituminous Fly Ash, Waste ID EFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	6.07E-01	S	2.53E-03	S	5.03E-02	S
8.4	7.04E-01	S	2.53E-03	S	5.70E-02	S
8.6	7.72E-01	S	2.53E-03	S	6.67E-02	S
8.8	8.03E-01	S	2.53E-03	S	8.05E-02	S
9	8.34E-01	S	2.53E-03	S	9.67E-02	S
9.2	8.67E-01	S	2.53E-03	S	1.16E-01	S
9.4	8.99E-01	S	2.53E-03	S	1.38E-01	S
9.6	9.32E-01	S	2.53E-03	S	1.64E-01	S
9.8	9.66E-01	S	2.53E-03	S	1.94E-01	S
10	1.00E+00	S	2.53E-03	S	2.28E-01	S
10.2	1.03E+00	S	2.53E-03	S	2.68E-01	S
10.4	1.07E+00	S	2.53E-03	S	3.14E-01	S
10.6	1.11E+00	S	2.53E-03	S	3.67E-01	S
10.8	1.14E+00	S	2.53E-03	S	4.28E-01	S
11	1.18E+00	S	2.53E-03	S	4.90E-01	S
11.2	1.23E+00	S	2.53E-03	S	5.19E-01	S
11.4	1.27E+00	S	2.53E-03	S	5.49E-01	S
11.6	1.31E+00	S	2.53E-03	S	5.81E-01	S
11.8	1.35E+00	S	2.53E-03	S	6.13E-01	S
12	1.39E+00	S	2.53E-03	S	6.47E-01	S
12.2	1.42E+00	S	2.53E-03	S	6.82E-01	S
12.4	1.42E+00	S	2.53E-03	S	7.19E-01	S
12.6	1.42E+00	S	2.53E-03	S	7.56E-01	S
12.8	1.42E+00	S	2.53E-03	S	7.95E-01	S
13	1.42E+00	S	2.53E-03	S	8.36E-01	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	1.49E+01		9.63E-01		8.35E+00	

Table C-5-13. Leachate Concentrations for Bituminous Fly Ash, Waste ID EFB Med

Sample ID	EFB-[Med] (P,1,1)
Date Exported	8/27/2011, 6:49 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	2.34E-01	S	3.19E+00	W	1.22E-02	S	1.25E-01	S
3	1.82E-01	S	3.20E+00	W	1.20E-02	S	1.25E-01	S
3.2	1.53E-01	S	3.16E+00	W	1.16E-02	S	1.25E-01	S
3.4	1.30E-01	S	3.12E+00	W	1.12E-02	S	1.24E-01	S
3.6	1.12E-01	S	3.08E+00	W	1.10E-02	S	1.23E-01	S
3.8	9.02E-02	S	2.91E+00	W	1.08E-02	S	1.18E-01	S
4	7.32E-02	S	2.76E+00	W	1.06E-02	S	1.14E-01	S
4.2	6.00E-02	S	2.62E+00	W	1.05E-02	S	1.10E-01	S
4.4	5.30E-02	S	2.53E+00	W	1.03E-02	S	1.07E-01	S
4.6	4.18E-02	S	2.44E+00	W	7.40E-03	S	6.59E-02	S
4.8	3.32E-02	S	2.35E+00	W	5.40E-03	S	4.15E-02	S
5	2.67E-02	S	2.28E+00	W	4.00E-03	S	2.66E-02	S
5.2	2.11E-02	S	2.21E+00	W	2.68E-03	S	1.46E-02	S
5.4	1.83E-02	S	2.21E+00	W	2.17E-03	S	1.23E-02	S
5.6	1.76E-02	S	2.27E+00	W	2.34E-03	S	1.81E-02	S
5.8	1.70E-02	S	2.29E+00	W	2.13E-03	S	1.75E-02	S
6	1.65E-02	S	2.25E+00	W	1.66E-03	S	1.14E-02	S
6.2	1.59E-02	S	2.22E+00	W	1.30E-03	S	7.48E-03	S
6.4	1.66E-02	S	2.21E+00	W	1.13E-03	S	5.76E-03	S
6.6	1.86E-02	S	2.21E+00	W	1.08E-03	S	5.15E-03	S
6.8	2.08E-02	S	2.22E+00	W	1.03E-03	S	4.63E-03	S
7	2.32E-02	S	2.23E+00	W	9.91E-04	S	4.16E-03	S
7.2	2.57E-02	S	2.24E+00	W	9.51E-04	S	3.76E-03	S
7.4	2.85E-02	S	2.24E+00	W	9.13E-04	S	3.41E-03	S
7.6	3.14E-02	S	2.25E+00	W	8.79E-04	S	3.09E-03	S
7.8	3.46E-02	S	2.26E+00	W	8.46E-04	S	2.81E-03	S
8	3.80E-02	S	2.26E+00	W	8.15E-04	S	2.57E-03	S

Table C-5-13. Leachate Concentrations for Bituminous Fly Ash, Waste ID EFB Med

Sample ID	EFB-[Med] (P,1,1)
Date Exported	8/27/2011, 6:49 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	4.17E-02	S	2.27E+00	W	7.86E-04	S	2.35E-03	S
8.4	4.85E-02	S	2.26E+00	W	7.59E-04	S	2.15E-03	S
8.6	5.87E-02	S	2.25E+00	W	7.46E-04	S	2.06E-03	S
8.8	7.40E-02	S	2.24E+00	W	7.46E-04	S	2.06E-03	S
9	9.29E-02	S	2.23E+00	W	7.46E-04	S	2.06E-03	S
9.2	1.16E-01	S	2.22E+00	W	7.46E-04	S	2.06E-03	S
9.4	1.39E-01	S	2.31E+00	W	7.46E-04	S	2.06E-03	S
9.6	1.66E-01	S	2.44E+00	W	7.46E-04	S	2.06E-03	S
9.8	1.98E-01	S	2.58E+00	W	7.46E-04	S	2.06E-03	S
10	2.56E-01	S	2.57E+00	W	7.46E-04	S	2.06E-03	S
10.2	3.27E-01	S	2.51E+00	W	7.46E-04	S	2.06E-03	S
10.4	4.16E-01	S	2.44E+00	W	7.46E-04	S	2.06E-03	S
10.6	5.02E-01	S	2.46E+00	W	7.46E-04	S	2.06E-03	S
10.8	5.73E-01	S	2.56E+00	W	7.46E-04	S	2.06E-03	S
11	6.53E-01	S	2.66E+00	W	7.46E-04	S	2.06E-03	S
11.2	7.43E-01	S	2.76E+00	W	7.46E-04	S	2.06E-03	S
11.4	8.42E-01	S	2.86E+00	W	7.46E-04	S	2.06E-03	S
11.6	9.53E-01	S	2.97E+00	W	7.46E-04	S	2.06E-03	S
11.8	1.08E+00	S	3.08E+00	W	7.46E-04	S	2.06E-03	S
12	1.21E+00	S	3.19E+00	W	7.46E-04	S	2.06E-03	S
12.2	1.24E+00	S	3.23E+00	W	7.46E-04	S	2.06E-03	S
12.4	1.24E+00	S	3.27E+00	W	7.46E-04	S	2.06E-03	S
12.6	1.24E+00	S	3.31E+00	W	7.46E-04	S	2.06E-03	S
12.8	1.24E+00	S	3.35E+00	W	7.46E-04	S	2.06E-03	S
13	1.24E+00	S	3.40E+00	W	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	1.32E+01		3.57E+01		1.22E-01		1.25E+00	

Table C-5-13. Leachate Concentrations for Bituminous Fly Ash, Waste ID EFB Med

Sample ID
Date Exported
Database Name :ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	3.38E-01	S	1.99E-05	S	3.85E-02	S	3.11E-02	S
3	3.16E-01	S	2.18E-05	S	2.89E-02	S	3.27E-02	S
3.2	2.90E-01	S	2.57E-05	S	2.25E-02	S	3.41E-02	S
3.4	2.68E-01	S	3.00E-05	S	1.77E-02	S	3.54E-02	S
3.6	2.15E-01	S	3.12E-05	S	1.45E-02	S	3.60E-02	S
3.8	1.01E-01	S	2.06E-05	S	1.27E-02	S	3.37E-02	S
4	4.89E-02	S	1.39E-05	S	1.12E-02	S	3.17E-02	S
4.2	2.46E-02	S	9.59E-06	S	9.87E-03	S	2.99E-02	S
4.4	1.43E-02	S	1.13E-05	S	1.10E-02	S	2.96E-02	S
4.6	1.10E-02	S	1.46E-05	S	2.38E-02	S	3.32E-02	S
4.8	8.48E-03	S	1.86E-05	S	4.99E-02	S	3.71E-02	S
5	6.63E-03	S	2.36E-05	S	1.01E-01	S	4.14E-02	S
5.2	6.39E-03	S	2.67E-05	S	2.20E-01	S	4.73E-02	S
5.4	6.59E-03	S	2.57E-05	S	3.32E-01	S	5.04E-02	S
5.6	6.00E-03	S	2.37E-05	S	3.19E-01	S	4.90E-02	S
5.8	6.40E-03	S	2.30E-05	S	3.78E-01	S	5.04E-02	S
6	7.94E-03	S	2.34E-05	S	5.46E-01	S	5.48E-02	S
6.2	9.78E-03	S	2.39E-05	S	7.77E-01	S	5.94E-02	S
6.4	1.15E-02	S	2.43E-05	S	9.62E-01	S	6.26E-02	S
6.6	1.30E-02	S	2.48E-05	S	1.04E+00	S	6.41E-02	S
6.8	1.46E-02	S	2.52E-05	S	1.12E+00	S	6.57E-02	S
7	1.64E-02	S	2.56E-05	S	1.21E+00	S	6.72E-02	S
7.2	1.83E-02	S	2.61E-05	S	1.30E+00	W	6.88E-02	S
7.4	2.04E-02	S	2.65E-05	S	1.40E+00	W	7.03E-02	S
7.6	2.26E-02	S	2.69E-05	S	1.50E+00	W	7.19E-02	S
7.8	2.50E-02	S	2.73E-05	S	1.60E+00	W	7.34E-02	S
8	2.77E-02	S	2.77E-05	S	1.71E+00	W	7.49E-02	S

Table C-5-13. Leachate Concentrations for Bituminous Fly Ash, Waste ID EFB Med

Sample ID
Date Exported
Database Name :ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
8.2	3.05E-02	S	2.81E-05	S	1.82E+00	W	7.64E-02	W
8.4	3.12E-02	S	2.95E-05	S	1.95E+00	W	7.93E-02	W
8.6	3.13E-02	S	3.04E-05	S	2.03E+00	W	8.18E-02	W
8.8	3.08E-02	S	3.09E-05	S	2.06E+00	W	8.39E-02	W
9	3.02E-02	S	3.13E-05	S	2.10E+00	W	8.60E-02	W
9.2	2.97E-02	S	3.18E-05	S	2.14E+00	W	8.80E-02	W
9.4	3.04E-02	S	2.89E-05	S	2.15E+00	W	8.80E-02	W
9.6	3.13E-02	S	2.77E-05	S	2.16E+00	W	8.78E-02	W
9.8	3.22E-02	S	2.66E-05	S	2.17E+00	W	8.77E-02	W
10	3.41E-02	S	2.36E-05	S	2.24E+00	W	9.00E-02	W
10.2	3.60E-02	S	1.63E-05	S	2.33E+00	W	9.32E-02	W
10.4	3.78E-02	S	1.14E-05	S	2.42E+00	W	9.64E-02	W
10.6	3.93E-02	S	1.03E-05	S	2.48E+00	W	9.86E-02	W
10.8	4.04E-02	S	1.21E-05	S	2.49E+00	W	9.99E-02	W
11	4.15E-02	S	1.42E-05	S	2.51E+00	W	1.01E-01	W
11.2	4.26E-02	S	1.66E-05	S	2.52E+00	W	1.03E-01	W
11.4	4.37E-02	S	1.93E-05	S	2.54E+00	W	1.04E-01	W
11.6	4.48E-02	S	2.24E-05	S	2.55E+00	W	1.05E-01	W
11.8	4.59E-02	S	2.60E-05	S	2.57E+00	W	1.06E-01	W
12	4.71E-02	S	3.01E-05	S	2.58E+00	W	1.08E-01	W
12.2	4.82E-02	S	3.47E-05	S	2.58E+00	W	1.08E-01	W
12.4	4.93E-02	S	3.99E-05	S	2.58E+00	W	1.08E-01	W
12.6	5.05E-02	S	4.46E-05	S	2.58E+00	W	1.08E-01	W
12.8	5.17E-02	S	4.46E-05	S	2.58E+00	W	1.08E-01	W
13	5.28E-02	S	4.46E-05	S	2.58E+00	W	1.08E-01	W
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	3.38E+00		4.75E-04		2.75E+01		1.15E+00	

Table C-5-13. Leachate Concentrations for Bituminous Fly Ash, Waste ID EFB Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	1.07E-01	S	2.43E-01	S	7.82E-01	S
3	9.44E-02	S	2.11E-01	S	3.63E-01	S
3.2	8.36E-02	S	1.74E-01	S	1.68E-01	S
3.4	7.46E-02	S	1.45E-01	S	8.18E-02	S
3.6	6.70E-02	S	1.27E-01	S	4.40E-02	S
3.8	5.54E-02	S	1.15E-01	S	2.57E-02	S
4	4.62E-02	S	1.04E-01	S	1.54E-02	S
4.2	3.89E-02	S	9.53E-02	S	9.44E-03	S
4.4	3.66E-02	S	9.57E-02	S	7.35E-03	S
4.6	3.72E-02	S	8.57E-02	S	7.07E-03	S
4.8	3.77E-02	S	7.72E-02	S	6.82E-03	S
5	3.83E-02	S	6.98E-02	S	6.58E-03	S
5.2	3.85E-02	S	5.83E-02	S	6.54E-03	S
5.4	3.60E-02	S	5.43E-02	S	6.26E-03	S
5.6	3.16E-02	S	6.07E-02	S	5.63E-03	S
5.8	3.05E-02	S	5.85E-02	S	5.57E-03	S
6	3.21E-02	S	4.91E-02	S	6.02E-03	S
6.2	3.37E-02	S	4.14E-02	S	6.50E-03	S
6.4	3.65E-02	S	3.65E-02	S	7.16E-03	S
6.6	4.06E-02	S	3.35E-02	S	8.04E-03	S
6.8	4.50E-02	S	3.09E-02	S	8.99E-03	S
7	4.98E-02	S	2.85E-02	S	1.00E-02	S
7.2	5.49E-02	S	2.64E-02	S	1.12E-02	S
7.4	6.03E-02	S	2.45E-02	S	1.24E-02	S
7.6	6.61E-02	S	2.27E-02	S	1.37E-02	S
7.8	7.23E-02	S	2.12E-02	S	1.51E-02	S
8	7.89E-02	S	1.98E-02	S	1.66E-02	S

Table C-5-13. Leachate Concentrations for Bituminous Fly Ash, Waste ID EFB Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	8.60E-02	S	1.85E-02	S	1.82E-02	S
8.4	1.00E-01	S	1.69E-02	S	2.15E-02	S
8.6	1.23E-01	S	1.52E-02	S	2.66E-02	S
8.8	1.57E-01	S	1.35E-02	S	3.43E-02	S
9	1.99E-01	S	1.20E-02	S	4.40E-02	S
9.2	2.52E-01	S	1.06E-02	S	5.61E-02	S
9.4	3.04E-01	S	9.45E-03	S	7.65E-02	S
9.6	3.60E-01	S	8.43E-03	S	1.08E-01	S
9.8	4.25E-01	S	7.54E-03	S	1.50E-01	S
10	4.91E-01	S	6.31E-03	S	2.09E-01	S
10.2	5.53E-01	S	5.07E-03	S	2.82E-01	S
10.4	6.21E-01	S	4.09E-03	S	3.77E-01	S
10.6	6.69E-01	S	3.58E-03	S	4.61E-01	S
10.8	6.91E-01	S	3.40E-03	S	5.15E-01	S
11	7.14E-01	S	3.23E-03	S	5.73E-01	S
11.2	7.37E-01	S	3.07E-03	S	6.37E-01	S
11.4	7.61E-01	S	2.92E-03	S	7.07E-01	S
11.6	7.85E-01	S	2.78E-03	S	7.83E-01	S
11.8	8.09E-01	S	2.65E-03	S	8.66E-01	S
12	8.34E-01	S	2.53E-03	S	9.56E-01	S
12.2	8.34E-01	S	2.42E-03	S	1.00E+00	S
12.4	8.34E-01	S	2.31E-03	S	1.05E+00	S
12.6	8.34E-01	S	2.21E-03	S	1.10E+00	S
12.8	8.34E-01	S	2.11E-03	S	1.15E+00	S
13	8.34E-01	S	2.02E-03	S	1.20E+00	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	8.88E+00		2.43E+00		1.22E+01	

Table C-5-14. Leachate Concentrations for Bituminous Fly Ash, Waste ID EFC Med

Sample ID	EFC-[Med] (P,1,1)
Date Exported	8/27/2011, 6:49 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	2.11E-01	S	5.40E+00	W	1.71E-02	S	1.49E-01	S
3	1.50E-01	S	5.27E+00	W	1.67E-02	S	1.43E-01	S
3.2	1.09E-01	S	5.16E+00	W	1.64E-02	S	1.39E-01	S
3.4	8.12E-02	S	5.05E+00	W	1.61E-02	S	1.36E-01	S
3.6	6.14E-02	S	4.95E+00	W	1.59E-02	S	1.33E-01	S
3.8	4.71E-02	S	4.86E+00	W	1.55E-02	S	1.30E-01	S
4	3.66E-02	S	4.75E+00	W	1.48E-02	S	1.27E-01	S
4.2	2.77E-02	S	4.46E+00	W	1.33E-02	S	1.20E-01	S
4.4	1.52E-02	S	4.18E+00	W	1.12E-02	S	9.85E-02	S
4.6	1.30E-02	S	3.93E+00	W	9.58E-03	S	8.17E-02	S
4.8	9.84E-03	S	3.70E+00	W	8.21E-03	S	6.84E-02	S
5	8.43E-03	S	3.60E+00	W	7.09E-03	S	5.91E-02	S
5.2	4.68E-03	S	3.58E+00	W	6.15E-03	S	5.08E-02	S
5.4	3.79E-03	S	3.56E+00	W	5.15E-03	S	3.43E-02	S
5.6	3.31E-03	S	3.55E+00	W	3.97E-03	S	2.35E-02	S
5.8	4.11E-03	S	3.53E+00	W	3.09E-03	S	1.23E-02	S
6	5.06E-03	S	3.51E+00	W	2.42E-03	S	6.14E-03	S
6.2	6.19E-03	S	3.50E+00	W	1.91E-03	S	3.13E-03	S
6.4	7.36E-03	S	3.48E+00	W	1.52E-03	S	2.06E-03	S
6.6	7.24E-03	S	3.47E+00	W	1.22E-03	S	2.06E-03	S
6.8	7.12E-03	S	3.45E+00	W	9.86E-04	S	2.06E-03	S
7	8.97E-03	S	3.44E+00	W	8.01E-04	S	2.06E-03	S
7.2	1.20E-02	S	3.44E+00	W	7.46E-04	S	2.06E-03	S
7.4	1.58E-02	S	3.45E+00	W	7.46E-04	S	2.06E-03	S
7.6	2.08E-02	S	3.45E+00	W	7.46E-04	S	2.06E-03	S
7.8	2.54E-02	S	3.46E+00	W	7.46E-04	S	2.06E-03	S

Table C-5-14. Leachate Concentrations for Bituminous Fly Ash, Waste ID EFC Med

Sample ID	EFC-[Med] (P,1,1)
Date Exported	8/27/2011, 6:49 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8	2.96E-02	S	3.47E+00	W	7.46E-04	S	2.06E-03	S
8.2	3.45E-02	S	3.48E+00	W	7.46E-04	S	2.06E-03	S
8.4	4.14E-02	S	3.55E+00	W	7.46E-04	S	2.06E-03	S
8.6	5.11E-02	S	3.70E+00	W	7.46E-04	S	2.06E-03	S
8.8	6.73E-02	S	3.69E+00	W	7.46E-04	S	2.06E-03	S
9	8.81E-02	S	3.54E+00	W	7.46E-04	S	2.06E-03	S
9.2	1.15E-01	S	3.45E+00	W	7.46E-04	S	2.06E-03	S
9.4	1.48E-01	S	3.62E+00	W	7.46E-04	S	2.06E-03	S
9.6	1.81E-01	S	3.66E+00	W	7.46E-04	S	2.06E-03	S
9.8	2.13E-01	S	3.73E+00	W	7.46E-04	S	2.06E-03	S
10	2.50E-01	S	3.81E+00	W	7.46E-04	S	2.06E-03	S
10.2	2.92E-01	S	3.88E+00	W	7.46E-04	S	2.06E-03	S
10.4	3.12E-01	S	3.90E+00	W	7.46E-04	S	2.06E-03	S
10.6	3.34E-01	S	3.86E+00	W	7.46E-04	S	2.06E-03	S
10.8	3.56E-01	S	3.84E+00	W	7.46E-04	S	2.06E-03	S
11	3.79E-01	S	3.86E+00	W	7.46E-04	S	2.06E-03	S
11.2	4.04E-01	S	3.88E+00	W	7.46E-04	S	2.06E-03	S
11.4	4.30E-01	S	3.90E+00	W	7.46E-04	S	2.06E-03	S
11.6	4.52E-01	S	4.02E+00	W	7.46E-04	S	2.06E-03	S
11.8	5.01E-01	S	4.34E+00	W	7.46E-04	S	2.06E-03	S
12	5.50E-01	S	4.49E+00	W	7.46E-04	S	2.06E-03	S
12.2	6.03E-01	S	4.65E+00	W	7.46E-04	S	2.06E-03	S
12.4	6.60E-01	S	4.81E+00	W	7.46E-04	S	2.06E-03	S
12.6	7.22E-01	S	4.97E+00	W	7.46E-04	S	2.06E-03	S
12.8	7.88E-01	S	5.21E+00	W	7.46E-04	S	2.06E-03	S
13	8.60E-01	S	5.38E+00	W	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	8.44E+00		5.58E+01		1.71E-01		1.49E+00	

Table C-5-14. Leachate Concentrations for Bituminous Fly Ash, Waste ID EFC Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	4.71E-01	S	1.49E-05	S	3.80E-01	S	2.96E-02	S
3	3.38E-01	S	1.44E-05	S	3.80E-01	S	2.96E-02	S
3.2	2.48E-01	S	1.40E-05	S	3.80E-01	S	2.90E-02	S
3.4	1.85E-01	S	1.43E-05	S	3.80E-01	S	2.98E-02	S
3.6	1.30E-01	S	1.44E-05	S	3.80E-01	S	3.06E-02	S
3.8	9.45E-02	S	1.36E-05	S	3.80E-01	S	3.14E-02	S
4	7.24E-02	S	1.28E-05	S	3.80E-01	S	3.22E-02	S
4.2	4.26E-02	S	1.25E-05	S	3.80E-01	S	3.23E-02	S
4.4	3.29E-02	S	1.25E-05	S	3.80E-01	S	3.16E-02	S
4.6	1.82E-02	S	1.25E-05	S	3.80E-01	S	3.57E-02	S
4.8	1.04E-02	S	1.25E-05	S	3.80E-01	S	4.13E-02	S
5	8.79E-03	S	1.25E-05	S	4.05E-01	S	4.75E-02	S
5.2	9.24E-03	S	1.25E-05	S	4.54E-01	S	4.97E-02	S
5.4	9.69E-03	S	1.32E-05	S	5.07E-01	S	3.99E-02	S
5.6	1.02E-02	S	1.57E-05	S	5.63E-01	S	4.05E-02	S
5.8	1.11E-02	S	1.66E-05	S	6.24E-01	S	4.39E-02	S
6	1.20E-02	S	1.85E-05	S	6.96E-01	S	4.82E-02	S
6.2	1.30E-02	S	1.73E-05	S	8.18E-01	S	5.28E-02	S
6.4	1.40E-02	S	1.67E-05	S	9.17E-01	S	5.77E-02	S
6.6	1.51E-02	S	1.69E-05	S	9.53E-01	S	6.28E-02	S
6.8	1.62E-02	S	1.70E-05	S	9.90E-01	S	6.82E-02	S
7	1.74E-02	S	1.53E-05	S	1.04E+00	S	7.39E-02	S
7.2	1.86E-02	S	1.39E-05	S	1.06E+00	W	7.63E-02	S
7.4	1.98E-02	S	1.56E-05	S	1.10E+00	W	7.69E-02	S
7.6	2.11E-02	S	1.78E-05	S	1.14E+00	W	7.84E-02	S
7.8	2.24E-02	S	1.82E-05	S	1.15E+00	W	7.93E-02	S

Table C-5-14. Leachate Concentrations for Bituminous Fly Ash, Waste ID EFC Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8	2.38E-02	S	1.84E-05	S	1.16E+00	W	8.01E-02	S
8.2	2.53E-02	S	1.87E-05	S	1.18E+00	W	8.09E-02	W
8.4	2.62E-02	S	1.59E-05	S	1.26E+00	W	8.89E-02	W
8.6	3.02E-02	S	1.10E-05	S	1.32E+00	W	9.72E-02	W
8.8	3.45E-02	S	9.38E-06	S	1.36E+00	W	9.61E-02	W
9	3.47E-02	S	9.38E-06	S	1.39E+00	W	9.51E-02	W
9.2	3.49E-02	S	9.38E-06	S	1.43E+00	W	9.41E-02	W
9.4	4.45E-02	S	9.38E-06	S	1.46E+00	W	9.31E-02	W
9.6	5.85E-02	S	9.93E-06	S	1.50E+00	W	9.48E-02	W
9.8	5.97E-02	S	1.08E-05	S	1.53E+00	W	9.64E-02	W
10	6.08E-02	S	1.16E-05	S	1.56E+00	W	9.71E-02	W
10.2	6.19E-02	S	1.39E-05	S	1.59E+00	W	9.92E-02	W
10.4	6.31E-02	S	1.78E-05	S	1.59E+00	W	1.01E-01	W
10.6	6.55E-02	S	1.83E-05	S	1.60E+00	W	1.03E-01	W
10.8	7.25E-02	S	1.83E-05	S	1.62E+00	W	1.04E-01	W
11	7.82E-02	S	1.65E-05	S	1.64E+00	W	1.04E-01	W
11.2	8.42E-02	S	1.50E-05	S	1.67E+00	W	1.04E-01	W
11.4	9.05E-02	S	1.36E-05	S	1.70E+00	W	1.04E-01	W
11.6	9.72E-02	S	1.25E-05	S	1.73E+00	W	1.03E-01	W
11.8	1.10E-01	S	1.25E-05	S	1.79E+00	W	1.03E-01	W
12	1.27E-01	S	1.25E-05	S	1.77E+00	W	1.02E-01	W
12.2	1.28E-01	S	1.25E-05	S	1.78E+00	W	9.67E-02	W
12.4	1.29E-01	S	1.25E-05	S	1.78E+00	W	9.15E-02	W
12.6	1.31E-01	S	1.25E-05	S	1.78E+00	W	8.66E-02	W
12.8	1.32E-01	S	1.25E-05	S	1.78E+00	W	8.21E-02	W
13	1.37E-01	S	1.25E-05	S	1.78E+00	W	7.79E-02	W
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	4.71E+00		1.88E-04		1.90E+01		1.10E+00	

Table C-5-14. Leachate Concentrations for Bituminous Fly Ash, Waste ID EFC Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	1.91E-01	S	1.36E-01	S	8.59E-01	S
3	1.58E-01	S	1.16E-01	S	4.52E-01	S
3.2	1.33E-01	S	1.00E-01	S	2.48E-01	S
3.4	1.12E-01	S	8.72E-02	S	9.67E-02	S
3.6	9.60E-02	S	7.66E-02	S	4.92E-02	S
3.8	8.28E-02	S	6.77E-02	S	2.83E-02	S
4	7.07E-02	S	6.03E-02	S	1.67E-02	S
4.2	6.20E-02	S	5.32E-02	S	1.11E-02	S
4.4	5.83E-02	S	4.00E-02	S	9.35E-03	S
4.6	6.01E-02	S	3.05E-02	S	8.54E-03	S
4.8	6.08E-02	S	2.35E-02	S	8.10E-03	S
5	6.49E-02	S	1.93E-02	S	9.35E-03	S
5.2	7.32E-02	S	2.69E-02	S	1.03E-02	S
5.4	8.21E-02	S	2.40E-02	S	9.02E-03	S
5.6	9.18E-02	S	2.15E-02	S	9.81E-03	S
5.8	1.02E-01	S	1.94E-02	S	1.06E-02	S
6	1.13E-01	S	1.75E-02	S	1.15E-02	S
6.2	1.25E-01	S	1.59E-02	S	1.24E-02	S
6.4	1.38E-01	S	1.44E-02	S	1.33E-02	S
6.6	1.52E-01	S	1.31E-02	S	1.43E-02	S
6.8	1.66E-01	S	1.20E-02	S	1.53E-02	S
7	1.81E-01	S	1.10E-02	S	1.64E-02	S
7.2	2.01E-01	S	1.03E-02	S	2.09E-02	S
7.4	2.24E-01	S	9.80E-03	S	2.71E-02	S
7.6	2.49E-01	S	9.32E-03	S	3.47E-02	S
7.8	2.76E-01	S	8.87E-03	S	3.88E-02	S

Table C-5-14. Leachate Concentrations for Bituminous Fly Ash, Waste ID EFC Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8	3.05E-01	S	8.45E-03	S	4.19E-02	S
8.2	3.56E-01	S	8.06E-03	S	4.53E-02	S
8.4	4.23E-01	S	6.86E-03	S	5.34E-02	S
8.6	5.59E-01	S	5.63E-03	S	6.81E-02	S
8.8	7.35E-01	S	4.64E-03	S	8.65E-02	S
9	9.60E-01	S	3.84E-03	S	1.09E-01	S
9.2	1.16E+00	S	3.19E-03	S	1.45E-01	S
9.4	1.34E+00	S	2.66E-03	S	1.98E-01	S
9.6	1.55E+00	S	2.53E-03	S	2.67E-01	S
9.8	1.87E+00	S	2.53E-03	S	3.24E-01	S
10	2.04E+00	S	2.53E-03	S	3.91E-01	S
10.2	2.22E+00	S	2.53E-03	S	4.70E-01	S
10.4	2.30E+00	S	2.53E-03	S	5.63E-01	S
10.6	2.38E+00	S	2.53E-03	S	6.72E-01	S
10.8	2.47E+00	S	2.53E-03	S	7.73E-01	S
11	2.55E+00	S	2.53E-03	S	8.06E-01	S
11.2	2.64E+00	S	2.53E-03	S	8.66E-01	S
11.4	2.72E+00	S	2.53E-03	S	9.39E-01	S
11.6	2.81E+00	S	2.53E-03	S	1.02E+00	S
11.8	2.74E+00	S	2.53E-03	S	1.08E+00	S
12	2.67E+00	S	2.53E-03	S	1.15E+00	S
12.2	2.59E+00	S	2.53E-03	S	1.22E+00	S
12.4	2.52E+00	S	2.53E-03	S	1.30E+00	S
12.6	2.45E+00	S	2.53E-03	S	1.36E+00	S
12.8	2.39E+00	S	2.53E-03	S	1.43E+00	S
13	2.32E+00	S	2.53E-03	S	1.51E+00	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	2.92E+01		1.36E+00		1.53E+01	

Table C-5-15. Leachate Concentrations for Bituminous Fly Ash, Waste ID FFA Med

Sample ID	FFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:49 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	2.94E-01	S	3.53E+00	W	1.23E-02	W	1.31E-01	W
3	2.04E-01	S	3.45E+00	W	1.19E-02	W	1.26E-01	W
3.2	1.58E-01	S	3.34E+00	W	1.16E-02	W	1.20E-01	W
3.4	1.25E-01	S	3.24E+00	W	1.13E-02	W	1.14E-01	W
3.6	1.00E-01	S	3.15E+00	W	1.10E-02	W	1.10E-01	W
3.8	8.10E-02	S	3.07E+00	W	1.07E-02	W	1.05E-01	W
4	6.63E-02	S	3.00E+00	W	1.05E-02	S	1.01E-01	S
4.2	5.48E-02	S	2.93E+00	W	1.02E-02	S	9.76E-02	S
4.4	4.92E-02	S	2.84E+00	W	9.29E-03	S	8.97E-02	S
4.6	4.42E-02	S	2.77E+00	W	8.28E-03	S	8.22E-02	S
4.8	4.01E-02	S	2.71E+00	W	7.06E-03	S	7.45E-02	S
5	3.67E-02	S	2.66E+00	W	5.77E-03	S	6.69E-02	S
5.2	3.37E-02	S	2.62E+00	W	4.75E-03	S	6.03E-02	S
5.4	3.11E-02	S	2.57E+00	W	3.94E-03	S	5.46E-02	S
5.6	3.00E-02	S	2.54E+00	W	3.31E-03	S	4.65E-02	S
5.8	3.03E-02	S	2.51E+00	W	2.82E-03	S	3.74E-02	S
6	3.09E-02	S	2.48E+00	W	2.31E-03	S	2.91E-02	S
6.2	3.19E-02	S	2.44E+00	W	1.82E-03	S	2.20E-02	S
6.4	3.29E-02	S	2.40E+00	W	1.44E-03	S	1.68E-02	S
6.6	3.53E-02	S	2.39E+00	W	1.22E-03	S	1.28E-02	S
6.8	4.77E-02	S	2.39E+00	W	9.94E-04	S	6.48E-03	S
7	7.74E-02	S	2.38E+00	W	7.46E-04	S	2.25E-03	S
7.2	9.91E-02	S	2.42E+00	W	7.46E-04	S	2.06E-03	S
7.4	1.25E-01	S	2.43E+00	W	7.46E-04	S	2.06E-03	S
7.6	1.40E-01	S	2.37E+00	W	7.46E-04	S	2.06E-03	S
7.8	1.57E-01	S	2.32E+00	W	7.46E-04	S	2.06E-03	S
8	1.84E-01	S	2.29E+00	W	7.46E-04	S	2.06E-03	S

Table C-5-15. Leachate Concentrations for Bituminous Fly Ash, Waste ID FFA Med

Sample ID	FFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:49 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	2.15E-01	S	2.26E+00	W	7.46E-04	W	2.06E-03	S
8.4	2.69E-01	S	2.22E+00	W	7.46E-04	W	2.06E-03	S
8.6	3.73E-01	S	2.29E+00	W	7.46E-04	W	2.06E-03	S
8.8	5.14E-01	S	2.35E+00	W	7.46E-04	W	2.06E-03	S
9	7.03E-01	S	2.42E+00	W	7.46E-04	W	2.06E-03	S
9.2	9.55E-01	S	2.49E+00	W	7.46E-04	W	2.06E-03	S
9.4	1.09E+00	S	2.49E+00	W	7.46E-04	W	2.06E-03	S
9.6	1.19E+00	S	2.49E+00	W	7.46E-04	W	2.06E-03	S
9.8	1.26E+00	S	2.49E+00	W	7.46E-04	W	2.06E-03	S
10	1.33E+00	S	2.49E+00	W	7.46E-04	W	2.06E-03	S
10.2	1.40E+00	S	2.49E+00	W	7.46E-04	W	2.06E-03	S
10.4	1.48E+00	S	2.49E+00	W	7.46E-04	W	2.06E-03	S
10.6	1.56E+00	S	2.49E+00	W	7.46E-04	W	2.06E-03	S
10.8	1.64E+00	S	2.49E+00	W	7.46E-04	W	2.06E-03	S
11	1.72E+00	S	2.49E+00	W	7.46E-04	W	2.06E-03	S
11.2	1.80E+00	S	2.49E+00	W	7.46E-04	W	2.06E-03	S
11.4	1.89E+00	S	2.49E+00	W	7.46E-04	W	2.06E-03	S
11.6	1.98E+00	S	2.49E+00	W	7.46E-04	W	2.06E-03	S
11.8	2.00E+00	S	2.49E+00	W	7.46E-04	W	2.06E-03	S
12	2.00E+00	S	2.49E+00	W	7.46E-04	W	2.06E-03	S
12.2	2.00E+00	S	2.49E+00	W	7.46E-04	W	2.06E-03	S
12.4	2.00E+00	S	2.49E+00	W	7.46E-04	W	2.06E-03	S
12.6	2.00E+00	S	2.49E+00	W	7.46E-04	W	2.06E-03	S
12.8	2.00E+00	S	2.49E+00	W	7.46E-04	W	2.06E-03	S
13	2.00E+00	S	2.49E+00	W	7.46E-04	W	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	2.08E+01		3.53E+01		1.23E-01		1.31E+00	

Table C-5-15. Leachate Concentrations for Bituminous Fly Ash, Waste ID FFA Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	3.68E-01	S	3.56E-05	S	3.80E-01	S	2.34E-02	S
3	2.64E-01	S	3.84E-05	S	3.80E-01	S	2.64E-02	S
3.2	1.74E-01	S	4.15E-05	S	3.80E-01	S	2.98E-02	S
3.4	1.17E-01	S	4.46E-05	S	3.80E-01	S	3.33E-02	S
3.6	8.09E-02	S	4.77E-05	S	3.80E-01	S	3.70E-02	S
3.8	5.70E-02	S	5.08E-05	S	3.80E-01	S	4.09E-02	S
4	4.08E-02	S	5.40E-05	S	3.80E-01	S	4.50E-02	S
4.2	2.98E-02	S	5.72E-05	S	3.80E-01	S	4.92E-02	S
4.4	1.49E-02	S	5.99E-05	S	3.80E-01	S	5.44E-02	S
4.6	7.72E-03	S	6.45E-05	S	3.80E-01	S	6.03E-02	S
4.8	5.58E-03	S	6.73E-05	S	4.08E-01	S	6.80E-02	S
5	5.50E-03	S	6.81E-05	S	4.69E-01	S	7.78E-02	S
5.2	5.43E-03	S	6.89E-05	S	5.36E-01	S	8.86E-02	S
5.4	5.36E-03	S	6.96E-05	S	6.09E-01	S	1.00E-01	S
5.6	5.37E-03	S	7.24E-05	S	6.65E-01	S	1.10E-01	S
5.8	5.47E-03	S	7.72E-05	S	6.98E-01	S	1.17E-01	S
6	6.19E-03	S	7.65E-05	S	7.87E-01	S	1.23E-01	S
6.2	7.75E-03	S	7.08E-05	S	9.51E-01	S	1.29E-01	S
6.4	9.62E-03	S	6.57E-05	S	1.14E+00	S	1.36E-01	S
6.6	1.20E-02	S	5.62E-05	S	1.34E+00	S	1.40E-01	S
6.8	1.66E-02	S	4.96E-05	S	1.56E+00	S	1.44E-01	S
7	2.49E-02	S	4.86E-05	S	1.82E+00	S	1.49E-01	S
7.2	2.97E-02	S	4.15E-05	S	1.81E+00	W	1.49E-01	S
7.4	3.39E-02	S	3.80E-05	S	1.79E+00	W	1.49E-01	S
7.6	3.71E-02	S	3.80E-05	S	1.81E+00	W	1.50E-01	S
7.8	4.04E-02	S	3.80E-05	S	1.82E+00	W	1.51E-01	S
8	4.37E-02	S	4.71E-05	S	1.80E+00	W	1.55E-01	S

Table C-5-15. Leachate Concentrations for Bituminous Fly Ash, Waste ID FFA Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
8.2	4.72E-02	S	5.81E-05	S	1.78E+00	W	1.59E-01	W
8.4	5.23E-02	S	6.00E-05	S	1.74E+00	W	1.61E-01	W
8.6	5.58E-02	S	6.31E-05	S	1.77E+00	W	1.61E-01	W
8.8	5.95E-02	S	6.62E-05	S	1.80E+00	W	1.61E-01	W
9	6.32E-02	S	6.94E-05	S	1.83E+00	W	1.61E-01	W
9.2	6.72E-02	S	7.26E-05	S	1.86E+00	W	1.61E-01	W
9.4	6.96E-02	S	7.30E-05	S	1.87E+00	W	1.61E-01	W
9.6	7.18E-02	S	7.24E-05	S	1.88E+00	W	1.62E-01	W
9.8	7.39E-02	S	7.10E-05	S	1.87E+00	W	1.65E-01	W
10	7.59E-02	S	6.96E-05	S	1.87E+00	W	1.68E-01	W
10.2	7.80E-02	S	6.83E-05	S	1.87E+00	W	1.71E-01	W
10.4	8.01E-02	S	6.71E-05	S	1.87E+00	W	1.74E-01	W
10.6	8.21E-02	S	6.59E-05	S	1.86E+00	W	1.76E-01	W
10.8	8.43E-02	S	6.47E-05	S	1.86E+00	W	1.79E-01	W
11	8.64E-02	S	6.36E-05	S	1.86E+00	W	1.82E-01	W
11.2	8.85E-02	S	6.25E-05	S	1.86E+00	W	1.85E-01	W
11.4	9.07E-02	S	6.15E-05	S	1.85E+00	W	1.88E-01	W
11.6	9.28E-02	S	6.04E-05	S	1.85E+00	W	1.91E-01	W
11.8	9.50E-02	S	5.95E-05	S	1.85E+00	W	1.92E-01	W
12	9.72E-02	S	5.85E-05	S	1.85E+00	W	1.92E-01	W
12.2	9.94E-02	S	5.76E-05	S	1.84E+00	W	1.92E-01	W
12.4	1.02E-01	S	5.67E-05	S	1.84E+00	W	1.92E-01	W
12.6	1.04E-01	S	5.59E-05	S	1.84E+00	W	1.92E-01	W
12.8	1.06E-01	S	5.50E-05	S	1.84E+00	W	1.92E-01	W
13	1.08E-01	S	5.42E-05	S	1.83E+00	W	1.92E-01	W
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	3.68E+00		7.79E-04		1.94E+01		1.99E+00	

Table C-5-15. Leachate Concentrations for Bituminous Fly Ash, Waste ID FFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	2.71E-01	S	5.39E-02	S	2.35E+00	S
3	1.97E-01	S	4.02E-02	S	1.06E+00	S
3.2	1.53E-01	S	3.03E-02	S	4.73E-01	S
3.4	1.20E-01	S	2.32E-02	S	2.22E-01	S
3.6	9.58E-02	S	1.81E-02	S	1.09E-01	S
3.8	7.73E-02	S	1.43E-02	S	5.53E-02	S
4	6.31E-02	S	1.14E-02	S	2.91E-02	S
4.2	5.20E-02	S	9.19E-03	S	1.58E-02	S
4.4	5.55E-02	S	8.48E-03	S	1.48E-02	S
4.6	6.27E-02	S	8.03E-03	S	1.58E-02	S
4.8	7.43E-02	S	7.15E-03	S	1.79E-02	S
5	9.22E-02	S	6.01E-03	S	2.13E-02	S
5.2	1.13E-01	S	5.08E-03	S	2.53E-02	S
5.4	1.38E-01	S	4.33E-03	S	2.97E-02	S
5.6	1.61E-01	S	3.95E-03	S	3.35E-02	S
5.8	1.79E-01	S	3.85E-03	S	3.63E-02	S
6	2.02E-01	S	3.60E-03	S	4.01E-02	S
6.2	2.29E-01	S	3.24E-03	S	4.50E-02	S
6.4	2.60E-01	S	2.93E-03	S	5.04E-02	S
6.6	2.97E-01	S	2.65E-03	S	5.57E-02	S
6.8	3.79E-01	S	2.53E-03	S	6.64E-02	S
7	5.32E-01	S	2.53E-03	S	8.58E-02	S
7.2	6.16E-01	S	2.53E-03	S	9.73E-02	S
7.4	7.00E-01	S	2.53E-03	S	1.12E-01	S
7.6	7.43E-01	S	2.53E-03	S	1.18E-01	S
7.8	7.88E-01	S	2.53E-03	S	1.24E-01	S
8	8.45E-01	S	2.53E-03	S	1.41E-01	S

Table C-5-15. Leachate Concentrations for Bituminous Fly Ash, Waste ID FFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	9.04E-01	S	2.53E-03	S	1.59E-01	S
8.4	1.03E+00	S	2.53E-03	S	1.97E-01	S
8.6	1.12E+00	S	2.53E-03	S	2.72E-01	S
8.8	1.23E+00	S	2.53E-03	S	3.74E-01	S
9	1.34E+00	S	2.53E-03	S	5.09E-01	S
9.2	1.46E+00	W	2.53E-03	S	6.89E-01	S
9.4	1.51E+00	W	2.53E-03	S	7.81E-01	S
9.6	1.54E+00	W	2.53E-03	S	8.49E-01	S
9.8	1.55E+00	W	2.53E-03	S	8.88E-01	S
10	1.56E+00	W	2.53E-03	S	9.27E-01	S
10.2	1.57E+00	W	2.53E-03	S	9.67E-01	S
10.4	1.58E+00	W	2.53E-03	S	1.01E+00	S
10.6	1.59E+00	W	2.53E-03	S	1.05E+00	S
10.8	1.60E+00	W	2.53E-03	S	1.09E+00	S
11	1.61E+00	W	2.53E-03	S	1.14E+00	S
11.2	1.62E+00	W	2.53E-03	S	1.18E+00	S
11.4	1.63E+00	W	2.53E-03	S	1.23E+00	S
11.6	1.64E+00	W	2.53E-03	S	1.27E+00	S
11.8	1.64E+00	W	2.53E-03	S	1.32E+00	S
12	1.64E+00	W	2.53E-03	S	1.37E+00	S
12.2	1.64E+00	W	2.53E-03	S	1.42E+00	S
12.4	1.64E+00	W	2.53E-03	S	1.47E+00	S
12.6	1.64E+00	W	2.53E-03	S	1.52E+00	S
12.8	1.64E+00	W	2.53E-03	S	1.57E+00	S
13	1.64E+00	W	2.53E-03	S	1.62E+00	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	1.71E+01		5.39E-01		2.35E+01	

Table C-5-16. Leachate Concentrations for Bituminous Fly Ash, Waste ID GAB Med

Sample ID	GAB-[Med] (P,1,1)
Date Exported	8/27/2011, 6:49 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	3.58E-01	S	5.06E+00	S	4.53E-02	S	1.97E-01	S
3	3.73E-01	S	5.43E+00	S	4.43E-02	S	1.80E-01	S
3.2	3.87E-01	S	5.80E+00	S	4.34E-02	S	1.66E-01	S
3.4	4.01E-01	S	6.17E+00	S	4.25E-02	S	1.54E-01	S
3.6	4.14E-01	S	6.54E+00	S	4.17E-02	W	1.43E-01	S
3.8	4.28E-01	S	6.91E+00	S	4.10E-02	W	1.34E-01	S
4	3.16E-01	S	7.73E+00	S	3.95E-02	W	1.25E-01	S
4.2	2.35E-01	S	8.61E+00	S	3.75E-02	W	1.17E-01	S
4.4	1.80E-01	S	9.54E+00	S	3.56E-02	W	1.12E-01	S
4.6	1.94E-01	S	9.66E+00	W	2.21E-02	S	1.05E-01	S
4.8	2.08E-01	S	9.78E+00	W	1.41E-02	S	9.82E-02	S
5	2.22E-01	S	9.89E+00	W	9.98E-03	S	9.24E-02	S
5.2	2.51E-01	S	1.00E+01	W	7.17E-03	S	8.72E-02	S
5.4	2.82E-01	S	1.01E+01	W	5.21E-03	S	8.25E-02	S
5.6	3.16E-01	S	1.02E+01	W	3.84E-03	S	7.82E-02	S
5.8	3.38E-01	S	1.03E+01	W	2.85E-03	S	6.95E-02	S
6	3.59E-01	S	1.04E+01	W	2.14E-03	S	6.21E-02	S
6.2	3.81E-01	S	1.05E+01	W	1.63E-03	S	5.56E-02	S
6.4	4.04E-01	S	1.06E+01	W	1.24E-03	S	5.00E-02	S
6.6	4.48E-01	S	1.05E+01	W	9.60E-04	S	4.51E-02	S
6.8	5.57E-01	S	1.06E+01	W	7.46E-04	S	4.07E-02	S
7	5.82E-01	S	1.08E+01	W	7.46E-04	S	2.95E-02	S
7.2	6.06E-01	S	1.09E+01	W	7.46E-04	S	2.15E-02	S
7.4	6.56E-01	S	1.11E+01	W	7.46E-04	S	1.58E-02	S
7.6	7.37E-01	S	1.07E+01	W	7.46E-04	S	1.03E-02	S
7.8	9.84E-01	S	9.96E+00	W	7.46E-04	S	6.54E-03	S
8	8.47E-01	S	9.59E+00	W	7.46E-04	S	5.47E-03	S

Table C-5-16. Leachate Concentrations for Bituminous Fly Ash, Waste ID GAB Med

Sample ID	GAB-[Med] (P,1,1)
Date Exported	8/27/2011, 6:49 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	8.01E-01	S	9.54E+00	W	7.46E-04	W	4.66E-03	S
8.4	7.57E-01	S	9.51E+00	W	7.46E-04	W	3.76E-03	S
8.6	7.17E-01	S	9.48E+00	W	7.46E-04	W	3.15E-03	S
8.8	5.97E-01	S	9.45E+00	W	7.46E-04	W	2.65E-03	S
9	5.12E-01	S	9.24E+00	S	7.46E-04	W	2.24E-03	S
9.2	4.40E-01	S	8.91E+00	S	7.46E-04	W	2.06E-03	S
9.4	3.80E-01	S	8.59E+00	S	7.46E-04	W	2.06E-03	S
9.6	3.36E-01	S	8.30E+00	S	7.46E-04	W	2.06E-03	S
9.8	3.17E-01	S	7.86E+00	S	7.46E-04	W	2.06E-03	S
10	3.02E-01	S	7.82E+00	S	7.46E-04	W	2.06E-03	S
10.2	2.91E-01	S	7.63E+00	S	7.46E-04	W	2.06E-03	S
10.4	2.80E-01	S	7.19E+00	S	7.46E-04	W	2.06E-03	S
10.6	2.70E-01	S	6.79E+00	S	7.46E-04	W	2.06E-03	S
10.8	2.60E-01	S	6.41E+00	S	7.46E-04	W	2.06E-03	S
11	2.49E-01	S	6.07E+00	S	7.46E-04	W	2.06E-03	S
11.2	2.43E-01	S	5.74E+00	S	7.46E-04	W	2.06E-03	S
11.4	2.47E-01	S	4.77E+00	S	7.46E-04	W	2.06E-03	S
11.6	2.52E-01	S	3.97E+00	S	7.46E-04	W	2.06E-03	S
11.8	2.56E-01	S	3.32E+00	S	7.46E-04	W	2.06E-03	S
12	2.61E-01	S	2.79E+00	S	7.46E-04	W	2.06E-03	S
12.2	2.65E-01	S	2.34E+00	S	7.46E-04	W	2.06E-03	S
12.4	2.70E-01	S	1.97E+00	S	7.46E-04	W	2.06E-03	S
12.6	2.74E-01	S	1.67E+00	S	7.46E-04	W	2.06E-03	S
12.8	2.79E-01	S	1.42E+00	S	7.46E-04	W	2.06E-03	S
13	2.83E-01	S	1.20E+00	S	7.46E-04	W	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	9.85E+00		1.11E+02		4.53E-01		1.97E+00	

Table C-5-16. Leachate Concentrations for Bituminous Fly Ash, Waste ID GAB Med

Sample ID
Date Exported
Database Name ing\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	9.63E-01	S	4.81E-05	S	1.79E-02	S	1.84E-02	S
3	6.24E-01	S	7.24E-05	S	2.05E-02	S	2.00E-02	S
3.2	4.15E-01	S	1.11E-04	S	2.32E-02	S	2.17E-02	S
3.4	2.83E-01	S	1.66E-04	S	2.62E-02	S	2.33E-02	S
3.6	1.97E-01	S	2.06E-04	S	2.93E-02	S	2.50E-02	S
3.8	1.40E-01	S	2.51E-04	S	3.28E-02	S	2.68E-02	S
4	3.11E-02	S	2.32E-04	S	3.85E-02	S	3.14E-02	S
4.2	7.43E-03	S	1.70E-04	S	4.51E-02	S	3.86E-02	S
4.4	1.90E-03	S	1.26E-04	S	5.71E-02	S	4.37E-02	S
4.6	1.90E-03	S	1.03E-04	S	8.28E-02	S	4.80E-02	S
4.8	1.90E-03	S	8.54E-05	S	1.16E-01	S	5.31E-02	S
5	1.90E-03	S	7.13E-05	S	1.59E-01	S	5.86E-02	S
5.2	1.90E-03	S	5.99E-05	S	2.17E-01	S	6.45E-02	S
5.4	1.90E-03	S	5.07E-05	S	2.92E-01	S	7.08E-02	S
5.6	1.90E-03	S	4.31E-05	S	3.99E-01	S	7.73E-02	S
5.8	1.90E-03	S	4.12E-05	S	5.46E-01	S	8.43E-02	S
6	1.90E-03	S	3.71E-05	S	7.40E-01	S	9.15E-02	S
6.2	1.90E-03	S	3.35E-05	S	9.92E-01	S	9.92E-02	S
6.4	1.90E-03	S	3.03E-05	S	1.32E+00	S	1.07E-01	S
6.6	1.90E-03	S	2.76E-05	S	1.47E+00	S	1.11E-01	S
6.8	1.90E-03	S	2.51E-05	S	1.78E+00	S	1.12E-01	S
7	1.90E-03	S	2.28E-05	S	1.87E+00	S	1.12E-01	S
7.2	1.90E-03	S	2.07E-05	S	1.96E+00	W	1.12E-01	S
7.4	1.90E-03	S	1.88E-05	S	2.05E+00	W	1.14E-01	S
7.6	1.90E-03	S	1.80E-05	S	2.11E+00	W	1.17E-01	S
7.8	1.90E-03	S	1.80E-05	S	2.12E+00	W	1.21E-01	S
8	1.90E-03	S	2.51E-05	S	2.06E+00	W	1.21E-01	S

Table C-5-16. Leachate Concentrations for Bituminous Fly Ash, Waste ID GAB Med

Sample ID
Date Exported
Database Name ing\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
8.2	1.90E-03	S	2.64E-05	S	2.09E+00	W	1.19E-01	S
8.4	1.90E-03	S	2.77E-05	S	2.15E+00	W	1.16E-01	S
8.6	1.90E-03	S	2.90E-05	S	2.22E+00	W	1.14E-01	S
8.8	1.90E-03	S	3.03E-05	S	2.29E+00	W	1.12E-01	S
9	1.90E-03	S	3.16E-05	S	2.32E+00	W	1.07E-01	S
9.2	1.90E-03	S	3.13E-05	S	2.31E+00	W	9.64E-02	S
9.4	1.90E-03	S	2.93E-05	S	2.30E+00	W	8.72E-02	S
9.6	1.90E-03	S	2.76E-05	S	2.29E+00	W	8.43E-02	S
9.8	1.90E-03	S	2.59E-05	S	2.28E+00	W	8.55E-02	S
10	1.90E-03	S	2.51E-05	S	2.34E+00	W	7.94E-02	S
10.2	1.90E-03	S	2.51E-05	S	2.48E+00	W	6.94E-02	S
10.4	1.90E-03	S	2.51E-05	S	2.56E+00	W	6.03E-02	S
10.6	1.90E-03	S	2.51E-05	S	2.64E+00	W	5.25E-02	S
10.8	1.90E-03	S	2.51E-05	S	2.72E+00	W	4.59E-02	S
11	1.90E-03	S	2.32E-05	S	2.80E+00	W	4.01E-02	S
11.2	1.90E-03	S	2.32E-05	S	2.88E+00	W	3.44E-02	S
11.4	1.90E-03	S	1.64E-05	S	2.57E+00	W	1.82E-02	S
11.6	1.90E-03	S	1.08E-05	S	2.10E+00	W	1.06E-02	S
11.8	1.90E-03	S	7.13E-06	S	1.72E+00	W	5.90E-03	S
12	1.90E-03	S	4.75E-06	S	1.42E+00	W	4.00E-03	S
12.2	1.90E-03	S	3.19E-06	S	1.17E+00	W	4.00E-03	S
12.4	1.90E-03	S	2.15E-06	S	9.68E-01	W	4.00E-03	S
12.6	1.90E-03	S	2.07E-06	S	8.04E-01	W	4.00E-03	S
12.8	1.90E-03	S	2.07E-06	S	6.70E-01	W	4.00E-03	S
13	1.90E-03	S	2.07E-06	S	5.60E-01	W	4.00E-03	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		1.00E-03		8.00E-03	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		1.00E-03		8.00E-03	
Availability (mg/kg)	9.63E+00		2.52E-03		2.88E+01		1.21E+00	

Table C-5-16. Leachate Concentrations for Bituminous Fly Ash, Waste ID GAB Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	6.84E-01	S	2.68E-02	S	3.14E+00	S
3	6.39E-01	S	3.22E-02	S	1.60E+00	S
3.2	5.99E-01	S	3.80E-02	S	8.48E-01	S
3.4	5.64E-01	S	4.45E-02	S	4.68E-01	S
3.6	5.32E-01	S	5.16E-02	S	2.67E-01	S
3.8	5.04E-01	S	6.05E-02	S	1.67E-01	S
4	5.09E-01	S	6.84E-02	S	1.19E-01	S
4.2	5.50E-01	S	7.68E-02	S	9.13E-02	S
4.4	5.50E-01	S	8.58E-02	S	7.13E-02	S
4.6	6.20E-01	S	9.44E-02	S	8.60E-02	S
4.8	6.94E-01	S	1.02E-01	S	1.01E-01	S
5	7.43E-01	S	1.10E-01	S	1.10E-01	S
5.2	7.91E-01	S	1.19E-01	S	1.19E-01	S
5.4	8.40E-01	S	1.28E-01	S	1.28E-01	S
5.6	8.91E-01	S	1.37E-01	S	1.38E-01	S
5.8	9.43E-01	S	1.46E-01	S	1.51E-01	S
6	9.95E-01	S	1.57E-01	S	1.66E-01	S
6.2	1.07E+00	S	1.72E-01	S	1.81E-01	S
6.4	1.14E+00	S	1.89E-01	S	1.98E-01	S
6.6	1.22E+00	S	2.06E-01	S	2.19E-01	S
6.8	1.27E+00	S	1.97E-01	S	2.20E-01	S
7	1.27E+00	S	1.95E-01	S	2.07E-01	S
7.2	1.27E+00	S	1.94E-01	S	1.95E-01	S
7.4	1.33E+00	S	1.93E-01	S	1.98E-01	S
7.6	1.46E+00	S	1.71E-01	S	2.16E-01	S
7.8	1.64E+00	S	1.53E-01	S	2.86E-01	S
8	1.70E+00	S	1.54E-01	S	2.50E-01	S

Table C-5-16. Leachate Concentrations for Bituminous Fly Ash, Waste ID GAB Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	1.76E+00	S	1.64E-01	S	2.61E-01	S
8.4	1.86E+00	S	1.75E-01	S	2.71E-01	S
8.6	2.01E+00	S	1.86E-01	S	2.81E-01	S
8.8	2.12E+00	S	1.98E-01	S	2.38E-01	S
9	2.24E+00	S	1.80E-01	S	2.29E-01	S
9.2	2.35E+00	S	1.47E-01	S	2.20E-01	S
9.4	2.45E+00	S	1.21E-01	S	2.15E-01	S
9.6	2.55E+00	S	9.94E-02	S	2.30E-01	S
9.8	2.66E+00	S	6.69E-02	S	2.46E-01	S
10	2.68E+00	S	5.39E-02	S	2.36E-01	S
10.2	2.77E+00	S	5.39E-02	S	2.05E-01	S
10.4	2.87E+00	S	5.47E-02	S	1.78E-01	S
10.6	2.96E+00	S	5.55E-02	S	1.55E-01	S
10.8	3.06E+00	S	5.63E-02	S	1.35E-01	S
11	3.15E+00	S	5.70E-02	S	1.18E-01	S
11.2	3.32E+00	S	5.07E-02	S	1.09E-01	S
11.4	3.33E+00	S	4.44E-02	S	1.15E-01	S
11.6	3.40E+00	S	3.88E-02	S	1.27E-01	S
11.8	3.40E+00	S	2.46E-02	S	1.41E-01	S
12	3.40E+00	S	1.95E-02	S	1.55E-01	S
12.2	3.40E+00	S	1.55E-02	S	1.71E-01	S
12.4	3.40E+00	S	1.24E-02	S	1.88E-01	S
12.6	3.40E+00	S	9.89E-03	S	2.07E-01	S
12.8	3.40E+00	S	7.95E-03	S	2.27E-01	S
13	3.40E+00	S	6.41E-03	S	2.48E-01	S
Detection Limit (min, mg/L)	5.20E-04		5.00E-03		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.00E-03		3.10E-04	
Availability (mg/kg)	3.49E+01		2.06E+00		3.14E+01	

Table C-5-17. Leachate Concentrations for Bituminous Fly Ash, Waste ID GAT Med

Sample ID	GAT-[Med] (P,1,1)
Date Exported	8/27/2011, 6:49 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	1.67E-01	S	5.54E+00	S	3.23E-02	S	1.86E-01	S
3	1.15E-01	S	5.66E+00	S	3.26E-02	S	1.88E-01	S
3.2	1.00E-01	S	6.15E+00	S	2.81E-02	S	1.78E-01	S
3.4	8.69E-02	S	6.85E+00	S	2.19E-02	S	1.63E-01	S
3.6	7.62E-02	S	7.60E+00	S	1.73E-02	S	1.50E-01	S
3.8	6.72E-02	S	8.37E+00	S	1.39E-02	S	1.38E-01	S
4	6.81E-02	S	8.94E+00	S	1.24E-02	S	1.33E-01	S
4.2	7.84E-02	S	9.29E+00	S	1.24E-02	S	1.32E-01	S
4.4	8.96E-02	S	9.63E+00	S	1.24E-02	S	1.32E-01	S
4.6	1.02E-01	S	9.96E+00	W	1.24E-02	S	1.31E-01	S
4.8	1.15E-01	S	1.03E+01	W	1.24E-02	S	1.31E-01	S
5	1.29E-01	S	1.06E+01	W	1.24E-02	S	1.30E-01	S
5.2	1.44E-01	S	1.09E+01	W	1.26E-02	S	1.30E-01	S
5.4	1.59E-01	S	1.10E+01	W	1.30E-02	S	1.29E-01	S
5.6	1.65E-01	S	1.11E+01	W	1.29E-02	S	1.26E-01	S
5.8	1.62E-01	S	1.12E+01	W	1.26E-02	S	1.21E-01	S
6	1.72E-01	S	1.10E+01	W	9.55E-03	S	1.17E-01	S
6.2	1.67E-01	S	1.07E+01	W	7.66E-03	S	8.34E-02	S
6.4	1.58E-01	S	1.02E+01	W	5.77E-03	S	5.31E-02	S
6.6	1.51E-01	S	9.75E+00	W	4.39E-03	S	3.43E-02	S
6.8	1.44E-01	S	9.33E+00	W	3.36E-03	S	2.25E-02	S
7	1.37E-01	S	8.95E+00	W	2.59E-03	S	1.49E-02	S
7.2	1.31E-01	S	8.59E+00	W	2.02E-03	S	9.98E-03	S
7.4	1.26E-01	S	8.26E+00	W	1.58E-03	S	6.77E-03	S
7.6	1.20E-01	S	7.95E+00	W	1.25E-03	S	4.63E-03	S
7.8	1.15E-01	S	7.65E+00	W	9.88E-04	S	3.21E-03	S
8	1.18E-01	S	7.45E+00	W	8.98E-04	S	2.76E-03	S

Table C-5-17. Leachate Concentrations for Bituminous Fly Ash, Waste ID GAT Med

Sample ID	GAT-[Med] (P,1,1)
Date Exported	8/27/2011, 6:49 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	1.21E-01	S	7.25E+00	W	8.18E-04	W	2.38E-03	S
8.4	1.24E-01	S	7.14E+00	W	7.46E-04	W	2.06E-03	S
8.6	1.29E-01	S	7.27E+00	W	7.46E-04	W	2.06E-03	S
8.8	1.31E-01	S	7.29E+00	W	7.46E-04	W	2.06E-03	S
9	1.36E-01	S	7.49E+00	S	7.46E-04	W	2.06E-03	S
9.2	1.41E-01	S	7.74E+00	S	7.46E-04	W	2.06E-03	S
9.4	1.46E-01	S	8.00E+00	S	7.46E-04	W	2.06E-03	S
9.6	1.51E-01	S	8.26E+00	S	7.46E-04	W	2.06E-03	S
9.8	1.33E-01	S	6.74E+00	S	7.46E-04	W	2.06E-03	S
10	1.38E-01	S	6.52E+00	S	7.46E-04	W	2.06E-03	S
10.2	1.42E-01	S	6.31E+00	S	7.46E-04	W	2.06E-03	S
10.4	1.60E-01	S	6.34E+00	S	7.46E-04	W	2.06E-03	S
10.6	1.77E-01	S	5.99E+00	S	7.46E-04	W	2.06E-03	S
10.8	1.93E-01	S	5.34E+00	S	7.46E-04	W	2.06E-03	S
11	2.11E-01	S	4.77E+00	S	7.46E-04	W	2.06E-03	S
11.2	2.30E-01	S	4.27E+00	S	7.46E-04	W	2.06E-03	S
11.4	2.50E-01	S	3.83E+00	S	7.46E-04	W	2.06E-03	S
11.6	2.72E-01	S	3.44E+00	S	7.46E-04	W	2.06E-03	S
11.8	2.95E-01	S	3.10E+00	S	7.46E-04	W	2.06E-03	S
12	3.20E-01	S	2.80E+00	S	7.46E-04	W	2.06E-03	S
12.2	3.46E-01	S	2.53E+00	S	7.46E-04	W	2.06E-03	S
12.4	3.75E-01	S	2.29E+00	S	7.46E-04	W	2.06E-03	S
12.6	4.04E-01	S	2.07E+00	S	7.46E-04	W	2.06E-03	S
12.8	4.36E-01	S	1.88E+00	S	7.46E-04	W	2.06E-03	S
13	4.62E-01	S	1.71E+00	S	7.46E-04	W	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	4.80E+00		1.12E+02		3.26E-01		1.88E+00	

Table C-5-17. Leachate Concentrations for Bituminous Fly Ash, Waste ID GAT Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	4.01E-01	S	1.33E-05	S	1.11E-02	S	1.20E-02	S
3	4.13E-01	S	6.78E-06	S	9.35E-03	S	1.41E-02	S
3.2	2.07E-01	S	6.30E-06	S	1.31E-02	S	1.73E-02	S
3.4	7.49E-02	S	8.44E-06	S	2.26E-02	S	2.07E-02	S
3.6	2.87E-02	S	1.11E-05	S	3.77E-02	S	2.45E-02	S
3.8	1.16E-02	S	1.45E-05	S	6.11E-02	S	2.87E-02	S
4	6.58E-03	S	1.52E-05	S	8.39E-02	S	3.33E-02	S
4.2	5.12E-03	S	1.32E-05	S	9.86E-02	S	3.84E-02	S
4.4	4.04E-03	S	1.16E-05	S	1.15E-01	S	4.40E-02	S
4.6	3.22E-03	S	1.02E-05	S	1.33E-01	S	5.01E-02	S
4.8	2.59E-03	S	9.02E-06	S	1.53E-01	S	5.68E-02	S
5	2.10E-03	S	8.02E-06	S	1.76E-01	S	6.39E-02	S
5.2	1.90E-03	S	7.36E-06	S	2.11E-01	S	7.14E-02	S
5.4	1.90E-03	S	6.96E-06	S	2.66E-01	S	7.90E-02	S
5.6	1.90E-03	S	6.58E-06	S	3.39E-01	S	8.52E-02	S
5.8	1.90E-03	S	6.24E-06	S	4.37E-01	S	8.96E-02	S
6	1.90E-03	S	5.70E-06	S	5.04E-01	S	9.27E-02	S
6.2	2.30E-03	S	5.89E-06	S	5.65E-01	S	8.88E-02	S
6.4	3.07E-03	S	6.85E-06	S	6.30E-01	S	8.16E-02	S
6.6	4.07E-03	S	7.94E-06	S	7.00E-01	S	7.51E-02	S
6.8	5.34E-03	S	9.15E-06	S	7.75E-01	S	6.94E-02	S
7	6.96E-03	S	1.05E-05	S	8.55E-01	S	6.42E-02	S
7.2	9.01E-03	S	1.20E-05	S	9.41E-01	W	5.96E-02	S
7.4	1.16E-02	S	1.37E-05	S	1.03E+00	W	5.54E-02	S
7.6	1.48E-02	S	1.55E-05	S	1.13E+00	W	5.15E-02	S
7.8	1.87E-02	S	1.76E-05	S	1.24E+00	W	4.81E-02	S
8	2.04E-02	S	1.82E-05	S	1.26E+00	W	4.70E-02	S

Table C-5-17. Leachate Concentrations for Bituminous Fly Ash, Waste ID GAT Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
8.2	2.21E-02	W	1.87E-05	S	1.29E+00	W	4.60E-02	S
8.4	2.40E-02	W	2.03E-05	S	1.35E+00	W	4.56E-02	S
8.6	2.66E-02	W	2.29E-05	S	1.43E+00	W	4.59E-02	S
8.8	3.08E-02	W	2.59E-05	S	1.55E+00	W	4.46E-02	S
9	3.20E-02	W	1.68E-05	S	1.67E+00	W	4.54E-02	S
9.2	3.09E-02	W	1.07E-05	S	1.74E+00	W	4.69E-02	S
9.4	2.99E-02	W	6.92E-06	S	1.81E+00	W	4.84E-02	S
9.6	2.89E-02	W	4.50E-06	S	1.88E+00	W	4.99E-02	S
9.8	3.90E-02	W	1.38E-05	S	1.55E+00	W	3.27E-02	S
10	3.94E-02	W	1.13E-05	S	1.58E+00	W	3.03E-02	S
10.2	3.97E-02	W	9.28E-06	S	1.61E+00	W	2.81E-02	S
10.4	4.26E-02	W	1.80E-05	S	1.75E+00	W	2.75E-02	S
10.6	4.43E-02	W	2.03E-05	S	1.82E+00	W	2.50E-02	S
10.8	4.48E-02	W	1.35E-05	S	1.85E+00	W	2.11E-02	S
11	4.52E-02	W	9.11E-06	S	1.87E+00	W	1.78E-02	S
11.2	4.57E-02	W	6.17E-06	S	1.89E+00	W	1.51E-02	S
11.4	4.62E-02	W	4.21E-06	S	1.91E+00	W	1.29E-02	S
11.6	4.66E-02	W	2.89E-06	S	1.91E+00	W	1.10E-02	S
11.8	4.71E-02	W	2.25E-06	S	1.89E+00	W	9.41E-03	S
12	4.75E-02	W	1.80E-06	S	1.87E+00	W	8.07E-03	S
12.2	4.80E-02	W	1.80E-06	S	1.86E+00	W	6.95E-03	S
12.4	4.84E-02	W	1.80E-06	S	1.84E+00	W	6.36E-03	S
12.6	4.88E-02	W	1.80E-06	S	1.82E+00	W	6.18E-03	S
12.8	4.93E-02	W	1.80E-06	S	1.81E+00	W	6.01E-03	S
13	4.97E-02	W	1.80E-06	S	1.79E+00	W	5.85E-03	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		1.00E-03		8.00E-03	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		1.00E-03		8.00E-03	
Availability (mg/kg)	4.13E+00		2.63E-04		2.10E+01		9.27E-01	

Table C-5-17. Leachate Concentrations for Bituminous Fly Ash, Waste ID GAT Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	4.81E-01	S	2.49E-02	S	6.81E-01	S
3	3.98E-01	S	2.42E-02	S	3.76E-01	S
3.2	4.16E-01	S	2.88E-02	S	2.49E-01	S
3.4	4.80E-01	S	3.71E-02	S	1.67E-01	S
3.6	5.49E-01	S	4.70E-02	S	1.15E-01	S
3.8	6.23E-01	S	5.90E-02	S	8.04E-02	S
4	6.74E-01	S	6.75E-02	S	6.60E-02	S
4.2	6.99E-01	S	7.09E-02	S	6.27E-02	S
4.4	7.23E-01	S	7.44E-02	S	5.98E-02	S
4.6	7.46E-01	S	7.79E-02	S	5.71E-02	S
4.8	7.69E-01	S	8.13E-02	S	5.46E-02	S
5	7.93E-01	S	8.48E-02	S	5.23E-02	S
5.2	8.40E-01	S	8.96E-02	S	4.92E-02	S
5.4	9.15E-01	S	9.59E-02	S	4.55E-02	S
5.6	9.90E-01	S	1.00E-01	S	4.13E-02	S
5.8	1.06E+00	S	1.03E-01	S	3.68E-02	S
6	1.21E+00	S	8.52E-02	S	6.51E-02	S
6.2	1.32E+00	S	8.43E-02	S	6.38E-02	S
6.4	1.47E+00	S	8.61E-02	S	6.07E-02	S
6.6	1.64E+00	S	8.79E-02	S	5.79E-02	S
6.8	1.82E+00	S	8.96E-02	S	5.53E-02	S
7	2.01E+00	S	9.13E-02	S	5.29E-02	S
7.2	2.21E+00	S	9.31E-02	S	5.06E-02	S
7.4	2.43E+00	S	9.48E-02	S	4.85E-02	S
7.6	2.67E+00	S	9.65E-02	S	4.66E-02	S
7.8	2.92E+00	S	9.81E-02	S	4.47E-02	S
8	3.23E+00	S	1.01E-01	S	4.82E-02	S

Table C-5-17. Leachate Concentrations for Bituminous Fly Ash, Waste ID GAT Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	3.56E+00	S	1.04E-01	S	5.19E-02	S
8.4	3.81E+00	S	1.12E-01	S	5.50E-02	S
8.6	4.09E+00	S	1.14E-01	S	5.90E-02	S
8.8	4.35E+00	S	1.85E-01	S	6.17E-02	S
9	4.75E+00	S	2.15E-01	S	7.69E-02	S
9.2	5.04E+00	S	1.55E-01	S	9.82E-02	S
9.4	5.35E+00	S	1.13E-01	S	1.25E-01	S
9.6	5.67E+00	S	8.26E-02	S	1.58E-01	S
9.8	5.02E+00	S	8.73E-02	S	1.12E-01	S
10	5.31E+00	S	7.42E-02	S	1.27E-01	S
10.2	5.60E+00	S	6.34E-02	S	1.44E-01	S
10.4	6.57E+00	S	5.66E-02	S	1.65E-01	S
10.6	7.44E+00	S	5.25E-02	S	1.87E-01	S
10.8	8.15E+00	S	5.06E-02	S	2.06E-01	S
11	8.92E+00	S	4.87E-02	S	2.27E-01	S
11.2	9.74E+00	S	4.70E-02	S	2.50E-01	S
11.4	1.06E+01	S	4.53E-02	S	2.75E-01	S
11.6	1.13E+01	S	4.38E-02	S	3.02E-01	S
11.8	1.15E+01	S	4.23E-02	S	3.30E-01	S
12	1.15E+01	S	4.09E-02	S	3.61E-01	S
12.2	1.15E+01	S	3.95E-02	S	3.95E-01	S
12.4	1.15E+01	S	3.83E-02	S	4.30E-01	S
12.6	1.15E+01	S	3.70E-02	S	4.69E-01	S
12.8	1.15E+01	S	3.59E-02	S	5.10E-01	S
13	1.15E+01	S	3.48E-02	S	5.53E-01	S
Detection Limit (min, mg/L)	5.20E-04		5.00E-03		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.00E-03		3.10E-04	
Availability (mg/kg)	1.27E+02		2.18E+00		6.81E+00	

Table C-5-18. Leachate Concentrations for Bituminous Fly Ash, Waste ID GFA Med

Sample ID	GFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:50 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	2.08E-01	S	3.03E+00	W	7.30E-03	S	1.11E-01	S
3	1.33E-01	S	2.97E+00	W	7.20E-03	S	1.09E-01	S
3.2	8.76E-02	S	2.85E+00	W	6.95E-03	S	1.05E-01	S
3.4	5.92E-02	S	2.68E+00	W	6.57E-03	S	9.86E-02	S
3.6	4.55E-02	S	2.54E+00	W	6.29E-03	S	9.29E-02	S
3.8	4.21E-02	S	2.37E+00	W	6.00E-03	S	8.41E-02	S
4	3.90E-02	S	2.22E+00	W	5.74E-03	S	7.65E-02	S
4.2	3.63E-02	S	2.08E+00	W	5.51E-03	S	7.00E-02	S
4.4	3.42E-02	S	1.98E+00	W	5.25E-03	S	6.48E-02	S
4.6	3.28E-02	S	1.94E+00	W	4.83E-03	S	6.19E-02	S
4.8	3.15E-02	S	1.91E+00	W	4.45E-03	S	5.91E-02	S
5	3.04E-02	S	1.87E+00	W	4.12E-03	S	5.66E-02	S
5.2	2.93E-02	S	1.84E+00	W	3.82E-03	S	5.43E-02	S
5.4	2.83E-02	S	1.82E+00	W	3.48E-03	S	5.02E-02	S
5.6	2.74E-02	S	1.81E+00	W	3.12E-03	S	4.48E-02	S
5.8	2.72E-02	S	1.80E+00	W	2.61E-03	S	3.59E-02	S
6	2.78E-02	S	1.77E+00	W	2.05E-03	S	2.60E-02	S
6.2	2.83E-02	S	1.75E+00	W	1.63E-03	S	1.90E-02	S
6.4	3.25E-02	S	1.70E+00	W	1.14E-03	S	1.01E-02	S
6.6	3.71E-02	S	1.65E+00	W	8.02E-04	S	5.48E-03	S
6.8	3.46E-02	S	1.67E+00	W	9.00E-04	S	6.40E-03	S
7	4.60E-02	S	1.67E+00	W	8.98E-04	S	4.58E-03	S
7.2	7.54E-02	S	1.64E+00	W	7.46E-04	S	2.38E-03	S
7.4	8.89E-02	S	1.64E+00	W	7.46E-04	S	2.21E-03	S
7.6	1.04E-01	S	1.64E+00	W	7.46E-04	S	2.06E-03	S
7.8	1.29E-01	S	1.64E+00	W	7.46E-04	S	2.06E-03	S
8	1.58E-01	S	1.64E+00	W	7.46E-04	S	2.06E-03	S

Table C-5-18. Leachate Concentrations for Bituminous Fly Ash, Waste ID GFA Med

Sample ID	GFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:50 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	1.92E-01	S	1.65E+00	W	7.46E-04	W	2.06E-03	S
8.4	2.34E-01	S	1.65E+00	W	7.46E-04	W	2.06E-03	S
8.6	2.96E-01	S	1.65E+00	W	7.46E-04	W	2.06E-03	S
8.8	4.07E-01	S	1.66E+00	W	7.46E-04	W	2.06E-03	S
9	5.54E-01	S	1.68E+00	W	7.46E-04	W	2.06E-03	S
9.2	7.49E-01	S	1.69E+00	W	7.46E-04	W	2.06E-03	S
9.4	8.50E-01	S	1.73E+00	W	7.87E-04	W	2.06E-03	S
9.6	9.62E-01	S	1.76E+00	W	8.28E-04	W	2.06E-03	S
9.8	1.09E+00	S	1.79E+00	W	8.71E-04	W	2.06E-03	S
10	1.14E+00	S	1.83E+00	W	9.60E-04	W	2.06E-03	S
10.2	1.21E+00	S	1.86E+00	W	1.06E-03	W	2.06E-03	S
10.4	1.27E+00	S	1.90E+00	W	1.16E-03	W	2.06E-03	S
10.6	1.33E+00	S	1.94E+00	W	1.27E-03	W	2.06E-03	S
10.8	1.40E+00	S	1.97E+00	W	1.39E-03	W	2.06E-03	S
11	1.47E+00	S	2.01E+00	W	1.52E-03	W	2.06E-03	S
11.2	1.54E+00	S	2.01E+00	W	1.59E-03	W	2.06E-03	S
11.4	1.62E+00	S	2.02E+00	W	1.66E-03	W	2.06E-03	S
11.6	1.70E+00	S	2.02E+00	W	1.69E-03	W	2.06E-03	S
11.8	1.77E+00	S	2.04E+00	W	1.67E-03	W	2.06E-03	S
12	1.77E+00	S	2.05E+00	W	1.66E-03	W	2.06E-03	S
12.2	1.77E+00	S	2.06E+00	W	1.64E-03	W	2.06E-03	S
12.4	1.77E+00	S	2.07E+00	W	1.62E-03	W	2.06E-03	S
12.6	1.77E+00	S	2.08E+00	W	1.61E-03	W	2.06E-03	S
12.8	1.77E+00	S	2.09E+00	W	1.59E-03	W	2.06E-03	S
13	1.77E+00	S	2.10E+00	W	1.58E-03	W	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	1.81E+01		3.03E+01		7.30E-02		1.11E+00	

Table C-5-18. Leachate Concentrations for Bituminous Fly Ash, Waste ID GFA Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	3.17E-01	S	1.76E-05	S	3.80E-01	S	2.74E-02	S
3	3.06E-01	S	1.36E-05	S	3.80E-01	S	1.54E-02	S
3.2	2.83E-01	S	1.07E-05	S	3.80E-01	S	8.97E-03	S
3.4	2.53E-01	S	9.41E-06	S	3.80E-01	S	5.40E-03	S
3.6	1.88E-01	S	7.06E-06	S	3.80E-01	S	4.73E-03	S
3.8	7.83E-02	S	8.97E-06	S	3.80E-01	S	7.99E-03	S
4	3.41E-02	S	1.06E-05	S	3.80E-01	S	1.32E-02	S
4.2	1.55E-02	S	1.27E-05	S	3.80E-01	S	2.11E-02	S
4.4	8.62E-03	S	1.56E-05	S	3.80E-01	S	3.03E-02	S
4.6	6.90E-03	S	2.13E-05	S	3.80E-01	S	3.32E-02	S
4.8	5.59E-03	S	2.88E-05	S	3.80E-01	S	3.62E-02	S
5	4.56E-03	S	3.85E-05	S	3.80E-01	S	3.94E-02	S
5.2	3.75E-03	S	5.08E-05	S	3.80E-01	S	4.28E-02	S
5.4	3.36E-03	S	5.20E-05	S	4.01E-01	S	4.37E-02	S
5.6	3.27E-03	S	4.20E-05	S	4.47E-01	S	4.21E-02	S
5.8	3.37E-03	S	3.32E-05	S	5.25E-01	S	3.82E-02	S
6	3.65E-03	S	2.57E-05	S	6.48E-01	S	3.26E-02	S
6.2	3.95E-03	S	2.01E-05	S	7.95E-01	S	2.80E-02	S
6.4	7.18E-03	S	2.25E-05	S	8.95E-01	S	2.52E-02	S
6.6	1.28E-02	S	2.51E-05	S	1.00E+00	S	2.27E-02	S
6.8	1.25E-02	S	2.99E-05	S	1.02E+00	S	2.17E-02	S
7	1.65E-02	S	3.06E-05	S	1.03E+00	S	2.07E-02	S
7.2	2.54E-02	S	2.71E-05	S	1.09E+00	W	2.10E-02	S
7.4	2.84E-02	S	2.83E-05	S	1.10E+00	W	2.27E-02	S
7.6	3.16E-02	S	2.96E-05	S	1.11E+00	W	2.44E-02	S
7.8	3.29E-02	S	2.53E-05	S	1.12E+00	W	2.91E-02	S
8	3.43E-02	S	2.18E-05	S	1.13E+00	W	3.47E-02	S

Table C-5-18. Leachate Concentrations for Bituminous Fly Ash, Waste ID GFA Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
8.2	3.56E-02	S	1.88E-05	S	1.15E+00	W	4.11E-02	S
8.4	3.70E-02	S	1.63E-05	S	1.16E+00	W	4.85E-02	S
8.6	3.96E-02	S	1.61E-05	S	1.17E+00	W	5.45E-02	S
8.8	4.34E-02	S	1.72E-05	S	1.16E+00	W	5.82E-02	S
9	4.75E-02	S	1.83E-05	S	1.16E+00	W	6.21E-02	S
9.2	5.19E-02	S	1.95E-05	S	1.16E+00	W	6.61E-02	S
9.4	5.37E-02	S	2.07E-05	S	1.17E+00	W	7.03E-02	S
9.6	5.56E-02	S	2.20E-05	S	1.17E+00	W	7.47E-02	S
9.8	5.75E-02	S	2.33E-05	S	1.17E+00	W	7.93E-02	S
10	5.92E-02	S	2.50E-05	S	1.17E+00	W	8.14E-02	S
10.2	6.09E-02	S	2.67E-05	S	1.18E+00	W	8.36E-02	S
10.4	6.26E-02	S	2.86E-05	S	1.18E+00	W	8.58E-02	S
10.6	6.44E-02	S	3.05E-05	S	1.18E+00	W	8.80E-02	S
10.8	6.61E-02	S	3.26E-05	S	1.19E+00	W	9.03E-02	S
11	6.79E-02	S	3.47E-05	S	1.19E+00	W	9.25E-02	S
11.2	7.09E-02	S	2.87E-05	S	1.19E+00	W	9.41E-02	S
11.4	7.40E-02	S	2.38E-05	S	1.19E+00	W	9.58E-02	S
11.6	8.07E-02	S	2.27E-05	S	1.20E+00	W	9.71E-02	S
11.8	9.20E-02	S	2.48E-05	S	1.23E+00	W	9.81E-02	S
12	1.05E-01	S	2.41E-05	S	1.22E+00	W	9.81E-02	S
12.2	1.19E-01	S	2.05E-05	S	1.22E+00	W	9.81E-02	S
12.4	1.34E-01	S	1.75E-05	S	1.22E+00	W	9.81E-02	S
12.6	1.52E-01	S	1.50E-05	S	1.22E+00	W	9.81E-02	S
12.8	1.71E-01	S	1.29E-05	S	1.22E+00	W	9.81E-02	S
13	1.93E-01	S	1.26E-05	S	1.21E+00	W	9.81E-02	S
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	3.17E+00		5.22E-04		1.26E+01		1.01E+00	

Table C-5-18. Leachate Concentrations for Bituminous Fly Ash, Waste ID GFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	2.50E-01	S	5.92E-02	S	9.73E-01	S
3	1.54E-01	S	4.85E-02	S	6.90E-01	S
3.2	9.81E-02	S	3.20E-02	S	3.14E-01	S
3.4	6.41E-02	S	1.73E-02	S	1.10E-01	S
3.6	5.02E-02	S	1.27E-02	S	5.34E-02	S
3.8	5.32E-02	S	1.66E-02	S	3.77E-02	S
4	5.61E-02	S	2.15E-02	S	2.70E-02	S
4.2	5.90E-02	S	2.75E-02	S	1.97E-02	S
4.4	6.28E-02	S	3.24E-02	S	1.61E-02	S
4.6	7.11E-02	S	2.84E-02	S	1.83E-02	S
4.8	8.02E-02	S	2.50E-02	S	2.07E-02	S
5	8.99E-02	S	2.22E-02	S	2.32E-02	S
5.2	1.00E-01	S	1.97E-02	S	2.60E-02	S
5.4	1.13E-01	S	1.66E-02	S	2.92E-02	S
5.6	1.28E-01	S	1.32E-02	S	3.29E-02	S
5.8	1.50E-01	S	9.52E-03	S	3.84E-02	S
6	1.81E-01	S	6.27E-03	S	4.65E-02	S
6.2	2.18E-01	S	4.19E-03	S	5.59E-02	S
6.4	2.72E-01	S	3.41E-03	S	6.44E-02	S
6.6	3.36E-01	S	2.79E-03	S	7.39E-02	S
6.8	3.31E-01	S	2.53E-03	S	7.21E-02	S
7	3.77E-01	S	2.53E-03	S	7.91E-02	S
7.2	4.82E-01	S	2.53E-03	S	9.96E-02	S
7.4	5.15E-01	S	2.53E-03	S	1.09E-01	S
7.6	5.51E-01	S	2.53E-03	S	1.19E-01	S
7.8	5.90E-01	S	2.53E-03	S	1.39E-01	S
8	6.32E-01	S	2.53E-03	S	1.62E-01	S

Table C-5-18. Leachate Concentrations for Bituminous Fly Ash, Waste ID GFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	6.75E-01	S	2.53E-03	S	1.88E-01	S
8.4	7.20E-01	S	2.53E-03	S	2.17E-01	S
8.6	7.73E-01	S	2.53E-03	S	2.62E-01	S
8.8	8.32E-01	S	2.53E-03	S	3.45E-01	S
9	8.94E-01	S	2.53E-03	S	4.51E-01	S
9.2	9.59E-01	W	2.53E-03	S	5.86E-01	S
9.4	9.85E-01	W	2.53E-03	S	6.56E-01	S
9.6	1.01E+00	W	2.53E-03	S	7.32E-01	S
9.8	1.04E+00	W	2.53E-03	S	8.16E-01	S
10	1.05E+00	W	2.53E-03	S	8.60E-01	S
10.2	1.06E+00	W	2.53E-03	S	9.05E-01	S
10.4	1.07E+00	W	2.53E-03	S	9.52E-01	S
10.6	1.08E+00	W	2.53E-03	S	1.00E+00	S
10.8	1.09E+00	W	2.53E-03	S	1.05E+00	S
11	1.10E+00	W	2.53E-03	S	1.10E+00	S
11.2	1.11E+00	W	2.53E-03	S	1.14E+00	S
11.4	1.13E+00	W	2.53E-03	S	1.17E+00	S
11.6	1.17E+00	W	2.53E-03	S	1.20E+00	S
11.8	1.24E+00	W	2.53E-03	S	1.22E+00	S
12	1.24E+00	W	2.53E-03	S	1.22E+00	S
12.2	1.24E+00	W	2.53E-03	S	1.22E+00	S
12.4	1.24E+00	W	2.53E-03	S	1.22E+00	S
12.6	1.24E+00	W	2.53E-03	S	1.22E+00	S
12.8	1.24E+00	W	2.53E-03	S	1.22E+00	S
13	1.24E+00	W	2.53E-03	S	1.22E+00	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	1.27E+01		5.92E-01		1.25E+01	

Table C-5-19. Leachate Concentrations for Bituminous Fly Ash, Waste ID HFA Med

Sample ID	HFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:50 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	1.10E+00	S	3.22E+01	W	2.53E-01	W	8.37E-02	W
3	1.04E+00	S	3.15E+01	W	2.51E-01	W	8.24E-02	W
3.2	9.77E-01	S	3.08E+01	W	2.49E-01	W	8.11E-02	W
3.4	9.24E-01	S	3.02E+01	W	2.47E-01	W	8.00E-02	W
3.6	8.78E-01	S	2.97E+01	W	2.45E-01	W	7.90E-02	W
3.8	8.36E-01	S	2.91E+01	W	2.44E-01	W	7.80E-02	W
4	7.98E-01	S	2.87E+01	W	2.42E-01	S	7.71E-02	W
4.2	4.90E-01	S	2.71E+01	W	2.33E-01	S	7.20E-02	W
4.4	3.65E-01	S	2.60E+01	W	2.28E-01	S	6.85E-02	W
4.6	3.33E-01	S	2.57E+01	W	2.26E-01	S	6.68E-02	W
4.8	3.02E-01	S	2.60E+01	W	2.06E-01	S	6.08E-02	W
5	2.61E-01	S	2.61E+01	W	1.60E-01	S	4.72E-02	S
5.2	2.23E-01	S	2.59E+01	W	1.16E-01	S	3.41E-02	S
5.4	1.91E-01	S	2.57E+01	W	8.52E-02	S	2.50E-02	S
5.6	1.65E-01	S	2.55E+01	W	6.32E-02	S	1.85E-02	S
5.8	1.43E-01	S	2.53E+01	W	4.74E-02	S	1.38E-02	S
6	1.25E-01	S	2.52E+01	W	3.59E-02	S	1.04E-02	S
6.2	1.09E-01	S	2.50E+01	W	2.74E-02	S	7.97E-03	S
6.4	9.60E-02	S	2.48E+01	W	2.11E-02	S	6.12E-03	S
6.6	8.48E-02	S	2.47E+01	W	1.64E-02	S	4.75E-03	S
6.8	7.51E-02	S	2.45E+01	W	1.28E-02	S	3.71E-03	S
7	6.68E-02	S	2.44E+01	W	1.01E-02	S	2.92E-03	S
7.2	5.96E-02	S	2.43E+01	W	8.03E-03	S	2.31E-03	S
7.4	5.43E-02	S	2.39E+01	W	7.10E-03	S	2.06E-03	S
7.6	5.04E-02	S	2.32E+01	W	6.96E-03	S	2.06E-03	S
7.8	4.69E-02	S	2.27E+01	W	6.82E-03	S	2.06E-03	S
8	4.38E-02	S	2.21E+01	W	6.69E-03	S	2.06E-03	S

Table C-5-19. Leachate Concentrations for Bituminous Fly Ash, Waste ID HFA Med

Sample ID	HFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:50 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

8.2	4.09E-02	S	2.16E+01	W	6.57E-03	W	2.06E-03	S
8.4	3.83E-02	S	2.11E+01	W	6.45E-03	W	2.06E-03	S
8.6	3.62E-02	S	2.05E+01	W	6.37E-03	W	2.06E-03	S
8.8	3.55E-02	S	1.99E+01	W	6.55E-03	W	2.06E-03	S
9	3.48E-02	S	1.92E+01	W	6.73E-03	W	2.06E-03	S
9.2	3.41E-02	S	1.85E+01	W	6.84E-03	W	2.06E-03	S
9.4	3.42E-02	S	1.80E+01	W	6.87E-03	W	2.06E-03	S
9.6	3.49E-02	S	1.77E+01	W	6.91E-03	W	2.06E-03	S
9.8	3.79E-02	S	1.80E+01	W	6.96E-03	W	2.06E-03	S
10	4.21E-02	S	1.81E+01	W	7.09E-03	W	2.06E-03	S
10.2	4.66E-02	S	1.83E+01	W	7.22E-03	W	2.06E-03	S
10.4	4.97E-02	S	1.80E+01	W	7.24E-03	W	2.06E-03	S
10.6	5.30E-02	S	1.75E+01	W	7.31E-03	W	2.06E-03	S
10.8	5.63E-02	S	1.71E+01	W	7.38E-03	W	2.06E-03	S
11	5.98E-02	S	1.66E+01	W	7.45E-03	W	2.06E-03	S
11.2	6.35E-02	S	1.62E+01	W	7.52E-03	W	2.06E-03	S
11.4	6.73E-02	S	1.58E+01	W	7.58E-03	W	2.06E-03	S
11.6	7.13E-02	S	1.55E+01	W	7.65E-03	W	2.06E-03	S
11.8	7.54E-02	S	1.51E+01	W	7.71E-03	W	2.06E-03	S
12	7.97E-02	S	1.48E+01	W	7.78E-03	W	2.06E-03	S
12.2	8.42E-02	S	1.44E+01	W	7.84E-03	W	2.06E-03	S
12.4	8.89E-02	S	1.41E+01	W	7.91E-03	W	2.06E-03	S
12.6	9.37E-02	S	1.38E+01	W	7.97E-03	W	2.06E-03	S
12.8	9.87E-02	S	1.35E+01	W	8.03E-03	W	2.06E-03	S
13	1.04E-01	S	1.32E+01	W	8.10E-03	W	2.06E-03	S
tection Limit (min, mg/	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
tection Limit (max, mg/	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	1.10E+01		3.22E+02		2.53E+00		8.37E-01	

Table C-5-19. Leachate Concentrations for Bituminous Fly Ash, Waste ID HFA Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	9.47E-01	S	9.85E-06	S	3.57E-01	S	1.69E-02	S
3	7.23E-01	S	9.74E-06	S	2.82E-01	S	1.81E-02	S
3.2	5.61E-01	S	9.63E-06	S	2.26E-01	S	1.93E-02	S
3.4	4.43E-01	S	9.54E-06	S	1.83E-01	S	2.06E-02	S
3.6	3.54E-01	S	9.45E-06	S	1.50E-01	S	2.18E-02	S
3.8	2.87E-01	S	9.36E-06	S	1.25E-01	S	2.30E-02	S
4	2.34E-01	S	7.71E-06	S	1.05E-01	S	2.43E-02	S
4.2	3.40E-02	S	8.88E-06	S	7.86E-02	S	2.33E-02	S
4.4	9.11E-03	S	8.84E-06	S	7.01E-02	S	2.32E-02	S
4.6	5.74E-03	S	9.14E-06	S	8.26E-02	S	2.32E-02	S
4.8	5.07E-03	S	9.31E-06	S	1.05E-01	S	2.22E-02	S
5	4.98E-03	S	9.36E-06	S	1.22E-01	S	2.19E-02	S
5.2	5.24E-03	S	9.41E-06	S	1.37E-01	S	2.23E-02	S
5.4	5.50E-03	S	9.46E-06	S	1.54E-01	S	2.26E-02	S
5.6	5.77E-03	S	9.50E-06	S	1.72E-01	S	2.30E-02	S
5.8	6.03E-03	S	9.55E-06	S	1.91E-01	S	2.33E-02	S
6	6.30E-03	S	9.59E-06	S	2.11E-01	S	2.36E-02	S
6.2	6.58E-03	S	9.64E-06	S	2.33E-01	S	2.39E-02	S
6.4	6.85E-03	S	9.68E-06	S	2.56E-01	S	2.42E-02	S
6.6	7.13E-03	S	9.72E-06	S	2.81E-01	S	2.45E-02	S
6.8	7.41E-03	S	9.75E-06	S	3.07E-01	S	2.48E-02	S
7	7.69E-03	S	9.79E-06	S	3.35E-01	S	2.51E-02	S
7.2	7.97E-03	S	9.83E-06	S	3.64E-01	W	2.54E-02	S
7.4	8.79E-03	S	9.89E-06	S	3.80E-01	W	2.63E-02	S
7.6	1.03E-02	S	9.98E-06	S	3.80E-01	W	2.79E-02	S
7.8	1.19E-02	S	1.01E-05	S	3.80E-01	W	2.95E-02	S
8	1.38E-02	S	1.01E-05	S	3.80E-01	W	3.12E-02	S

Table C-5-19. Leachate Concentrations for Bituminous Fly Ash, Waste ID HFA Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

8.2	1.60E-02	S	1.02E-05	S	3.80E-01	W	3.29E-02	S
8.4	1.84E-02	S	1.03E-05	S	3.80E-01	W	3.47E-02	S
8.6	2.14E-02	S	1.04E-05	S	3.80E-01	W	3.45E-02	S
8.8	2.67E-02	S	9.65E-06	S	3.80E-01	W	3.40E-02	S
9	3.31E-02	S	8.99E-06	S	3.80E-01	W	3.36E-02	S
9.2	3.91E-02	S	8.80E-06	S	3.80E-01	W	3.74E-02	S
9.4	4.31E-02	S	9.04E-06	S	3.80E-01	W	3.94E-02	S
9.6	4.67E-02	S	9.28E-06	S	3.80E-01	W	3.51E-02	S
9.8	5.21E-02	S	9.28E-06	S	3.80E-01	W	3.33E-02	S
10	5.84E-02	S	9.28E-06	S	3.80E-01	W	4.22E-02	S
10.2	6.54E-02	S	7.71E-06	S	3.80E-01	W	5.33E-02	S
10.4	6.97E-02	S	9.41E-06	S	3.80E-01	W	4.88E-02	S
10.6	7.33E-02	S	9.65E-06	S	3.80E-01	W	4.35E-02	S
10.8	7.70E-02	S	9.89E-06	S	3.80E-01	W	3.89E-02	S
11	8.08E-02	S	1.01E-05	S	3.80E-01	W	3.49E-02	S
11.2	8.48E-02	S	1.04E-05	S	3.80E-01	W	3.13E-02	S
11.4	8.88E-02	S	1.06E-05	S	3.80E-01	W	2.82E-02	S
11.6	9.30E-02	S	9.04E-06	S	3.80E-01	W	2.54E-02	S
11.8	9.72E-02	S	1.11E-05	S	3.80E-01	W	2.29E-02	S
12	1.02E-01	S	1.14E-05	S	3.80E-01	W	2.07E-02	S
12.2	1.06E-01	S	1.14E-05	S	3.80E-01	W	1.88E-02	S
12.4	1.11E-01	S	1.14E-05	S	3.80E-01	W	1.71E-02	S
12.6	1.16E-01	S	1.14E-05	S	3.80E-01	W	1.55E-02	S
12.8	1.20E-01	S	1.14E-05	S	3.80E-01	W	1.41E-02	S
13	1.25E-01	S	1.14E-05	S	3.80E-01	W	1.29E-02	S
tection Limit (min, mg/	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
tection Limit (max, mg/	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	9.47E+00		1.19E-04		3.98E+00		5.47E-01	

Table C-5-19. Leachate Concentrations for Bituminous Fly Ash, Waste ID HFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	2.01E-02	S	3.89E-02	S	1.12E+00	S
3	2.08E-02	S	6.07E-02	S	5.91E-01	S
3.2	2.14E-02	S	9.20E-02	S	3.26E-01	S
3.4	2.20E-02	S	1.36E-01	S	1.87E-01	S
3.6	2.25E-02	S	1.97E-01	S	1.10E-01	S
3.8	2.31E-02	S	2.79E-01	S	6.70E-02	S
4	2.36E-02	S	3.88E-01	S	4.18E-02	S
4.2	1.69E-02	S	3.31E-01	S	9.80E-03	S
4.4	1.39E-02	S	2.91E-01	S	4.84E-03	S
4.6	1.33E-02	S	2.52E-01	S	4.92E-03	S
4.8	1.31E-02	S	2.12E-01	S	4.60E-03	S
5	1.29E-02	S	1.77E-01	S	4.61E-03	S
5.2	1.24E-02	S	1.47E-01	S	5.50E-03	S
5.4	1.20E-02	S	1.23E-01	S	6.50E-03	S
5.6	1.16E-02	S	1.03E-01	S	7.65E-03	S
5.8	1.13E-02	S	8.76E-02	S	8.94E-03	S
6	1.09E-02	S	7.46E-02	S	1.04E-02	S
6.2	1.06E-02	S	6.38E-02	S	1.20E-02	S
6.4	1.03E-02	S	5.49E-02	S	1.39E-02	S
6.6	1.00E-02	S	4.75E-02	S	1.59E-02	S
6.8	9.74E-03	S	4.12E-02	S	1.82E-02	S
7	9.49E-03	S	3.59E-02	S	2.07E-02	S
7.2	9.25E-03	S	3.14E-02	S	2.35E-02	S
7.4	9.67E-03	S	2.94E-02	S	2.57E-02	S
7.6	1.08E-02	S	2.92E-02	S	2.71E-02	S
7.8	1.21E-02	S	2.91E-02	S	2.87E-02	S
8	1.34E-02	S	2.90E-02	S	3.02E-02	S

Table C-5-19. Leachate Concentrations for Bituminous Fly Ash, Waste ID HFA Med

Sample ID						
Date Exported						
Database Name						
LeachXS Version						
8.2	1.49E-02	S	2.88E-02	S	3.18E-02	S
8.4	1.65E-02	S	2.87E-02	S	3.35E-02	S
8.6	1.88E-02	S	2.69E-02	S	3.55E-02	S
8.8	2.40E-02	S	2.61E-02	S	3.88E-02	S
9	3.06E-02	S	2.53E-02	S	4.23E-02	S
9.2	3.75E-02	S	2.78E-02	S	4.56E-02	S
9.4	4.38E-02	S	2.96E-02	S	5.01E-02	S
9.6	5.06E-02	S	2.72E-02	S	5.65E-02	S
9.8	5.79E-02	S	2.52E-02	S	6.68E-02	S
10	6.61E-02	S	3.08E-02	S	7.93E-02	S
10.2	7.52E-02	S	3.75E-02	S	9.37E-02	S
10.4	8.11E-02	S	3.61E-02	S	1.06E-01	S
10.6	8.65E-02	S	3.52E-02	S	1.19E-01	S
10.8	9.22E-02	S	3.43E-02	S	1.33E-01	S
11	9.82E-02	S	3.35E-02	S	1.48E-01	S
11.2	1.04E-01	S	3.27E-02	S	1.65E-01	S
11.4	1.11E-01	S	3.19E-02	S	1.84E-01	S
11.6	1.18E-01	S	3.12E-02	S	2.04E-01	S
11.8	1.18E-01	S	3.05E-02	S	2.26E-01	S
12	1.18E-01	S	2.98E-02	S	2.51E-01	S
12.2	1.18E-01	S	2.91E-02	S	2.77E-01	S
12.4	1.18E-01	S	2.85E-02	S	3.05E-01	S
12.6	1.18E-01	S	2.79E-02	S	3.36E-01	S
12.8	1.18E-01	S	2.73E-02	S	3.70E-01	S
13	1.18E-01	S	2.67E-02	S	4.06E-01	S
tection Limit (min, mg/	5.20E-04		5.10E-04		3.10E-04	
tection Limit (max, mg/	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	1.24E+00		3.88E+00		1.12E+01	

Table C-5-20. Leachate Concentrations for Bituminous Fly Ash, Waste ID KFA Med

Sample ID	KFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:50 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	1.34E+00	S	5.62E+01	W	2.65E-02	W	7.84E-02	S
3	1.19E+00	S	5.45E+01	W	2.58E-02	W	7.25E-02	S
3.2	1.06E+00	S	5.29E+01	W	2.52E-02	W	6.74E-02	S
3.4	9.53E-01	S	5.15E+01	W	2.46E-02	W	6.29E-02	S
3.6	8.61E-01	S	5.02E+01	W	2.41E-02	W	5.89E-02	S
3.8	7.82E-01	S	4.90E+01	W	2.36E-02	W	5.54E-02	S
4	6.16E-01	S	4.71E+01	W	2.33E-02	S	5.23E-02	S
4.2	4.31E-01	S	4.47E+01	W	2.25E-02	S	4.91E-02	S
4.4	3.06E-01	S	4.27E+01	W	2.12E-02	S	4.62E-02	S
4.6	2.32E-01	S	4.16E+01	W	1.76E-02	S	4.20E-02	S
4.8	1.89E-01	S	4.12E+01	W	1.44E-02	S	3.49E-02	S
5	1.64E-01	S	4.10E+01	W	1.22E-02	S	1.07E-02	S
5.2	1.52E-01	S	4.08E+01	W	1.05E-02	S	5.88E-03	S
5.4	1.41E-01	S	4.07E+01	W	9.10E-03	S	5.13E-03	S
5.6	1.32E-01	S	4.05E+01	W	7.93E-03	S	4.50E-03	S
5.8	1.24E-01	S	4.04E+01	W	6.94E-03	S	3.96E-03	S
6	1.17E-01	S	4.03E+01	W	6.10E-03	S	3.51E-03	S
6.2	1.13E-01	W	3.99E+01	W	4.65E-03	S	3.11E-03	S
6.4	1.14E-01	W	3.93E+01	W	3.10E-03	S	2.78E-03	S
6.6	1.14E-01	W	3.87E+01	W	2.09E-03	S	2.49E-03	S
6.8	1.14E-01	W	3.81E+01	W	1.43E-03	S	2.23E-03	S
7	1.13E-01	W	3.76E+01	W	1.06E-03	S	2.06E-03	S
7.2	1.11E-01	W	3.73E+01	W	9.86E-04	S	2.06E-03	S
7.4	1.09E-01	W	3.70E+01	W	9.18E-04	S	2.06E-03	S
7.6	1.07E-01	W	3.67E+01	W	8.56E-04	S	2.06E-03	S
7.8	1.05E-01	W	3.64E+01	W	8.00E-04	S	2.06E-03	S
8	1.03E-01	W	3.62E+01	W	7.49E-04	S	2.06E-03	S

Table C-5-20. Leachate Concentrations for Bituminous Fly Ash, Waste ID KFA Med

Sample ID	KFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:50 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	9.83E-02	W	3.57E+01	W	7.46E-04	W	2.06E-03	S
8.4	9.08E-02	W	3.49E+01	W	7.46E-04	W	2.06E-03	S
8.6	8.40E-02	W	3.42E+01	W	7.46E-04	W	2.06E-03	S
8.8	7.79E-02	W	3.36E+01	W	7.46E-04	W	2.06E-03	S
9	7.24E-02	W	3.29E+01	W	7.46E-04	W	2.06E-03	S
9.2	6.83E-02	W	3.25E+01	W	7.46E-04	W	2.06E-03	S
9.4	6.80E-02	W	3.28E+01	W	7.46E-04	W	2.06E-03	S
9.6	6.91E-02	W	3.32E+01	W	7.46E-04	W	2.06E-03	S
9.8	7.27E-02	W	3.31E+01	W	7.46E-04	W	2.06E-03	S
10	7.76E-02	W	3.28E+01	W	7.46E-04	W	2.06E-03	S
10.2	8.09E-02	W	3.28E+01	W	7.46E-04	W	2.06E-03	S
10.4	8.16E-02	W	3.30E+01	W	7.46E-04	W	2.06E-03	S
10.6	8.09E-02	W	3.27E+01	W	7.46E-04	W	2.06E-03	S
10.8	8.06E-02	W	3.20E+01	W	7.46E-04	W	2.06E-03	S
11	8.03E-02	W	3.14E+01	W	7.46E-04	W	2.06E-03	S
11.2	8.00E-02	W	3.09E+01	W	7.46E-04	W	2.06E-03	S
11.4	7.97E-02	W	3.03E+01	W	7.46E-04	W	2.06E-03	S
11.6	7.94E-02	W	2.97E+01	W	7.46E-04	W	2.06E-03	S
11.8	7.91E-02	W	2.92E+01	W	7.46E-04	W	2.06E-03	S
12	7.89E-02	W	2.87E+01	W	7.46E-04	W	2.06E-03	S
12.2	7.86E-02	W	2.82E+01	W	7.46E-04	W	2.06E-03	S
12.4	7.84E-02	W	2.77E+01	W	7.46E-04	W	2.06E-03	S
12.6	7.81E-02	W	2.73E+01	W	7.46E-04	W	2.06E-03	S
12.8	7.79E-02	W	2.68E+01	W	7.46E-04	W	2.06E-03	S
13	7.76E-02	W	2.64E+01	W	7.46E-04	W	2.06E-03	S
tection Limit (min, mg	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
tection Limit (max, mg	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	1.34E+01		5.62E+02		2.65E-01		7.84E-01	

Table C-5-20. Leachate Concentrations for Bituminous Fly Ash, Waste ID KFA Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	1.14E+00	S	9.11E-05	S	9.45E-02	S	1.81E-02	S
3	6.93E-01	S	6.74E-05	S	8.78E-02	S	1.59E-02	S
3.2	4.36E-01	S	5.08E-05	S	8.20E-02	S	1.40E-02	S
3.4	2.82E-01	S	3.90E-05	S	7.68E-02	S	1.25E-02	S
3.6	1.87E-01	S	3.04E-05	S	7.23E-02	S	1.12E-02	S
3.8	1.27E-01	S	2.40E-05	S	6.83E-02	S	1.01E-02	S
4	5.09E-02	S	2.33E-05	S	6.46E-02	S	1.02E-02	S
4.2	1.17E-02	S	2.60E-05	S	6.08E-02	S	1.13E-02	S
4.4	3.22E-03	S	2.87E-05	S	6.52E-02	S	1.27E-02	S
4.6	1.90E-03	S	2.89E-05	S	1.23E-01	S	1.52E-02	S
4.8	1.90E-03	S	2.63E-05	S	2.75E-01	S	1.82E-02	S
5	2.86E-03	S	2.48E-05	S	4.45E-01	S	2.25E-02	S
5.2	3.51E-03	S	2.43E-05	S	5.62E-01	S	2.47E-02	S
5.4	3.61E-03	S	2.39E-05	S	7.03E-01	S	2.59E-02	S
5.6	3.72E-03	S	2.36E-05	S	8.72E-01	S	2.70E-02	S
5.8	3.82E-03	S	2.32E-05	S	1.07E+00	S	2.81E-02	S
6	3.92E-03	S	2.29E-05	S	1.31E+00	S	2.92E-02	S
6.2	4.28E-03	S	2.31E-05	S	1.51E+00	S	3.04E-02	S
6.4	4.97E-03	S	2.37E-05	S	1.65E+00	S	3.17E-02	S
6.6	5.73E-03	S	2.44E-05	S	1.80E+00	S	3.30E-02	S
6.8	6.59E-03	S	2.50E-05	S	1.96E+00	S	3.43E-02	S
7	7.47E-03	S	2.54E-05	S	2.09E+00	S	3.53E-02	S
7.2	8.20E-03	S	2.51E-05	S	2.14E+00	W	3.53E-02	S
7.4	8.98E-03	S	2.47E-05	S	2.18E+00	W	3.52E-02	S
7.6	9.81E-03	S	2.44E-05	S	2.23E+00	W	3.52E-02	S
7.8	1.07E-02	S	2.40E-05	S	2.28E+00	W	3.52E-02	S
8	1.16E-02	S	2.37E-05	S	2.32E+00	W	3.52E-02	S

Table C-5-20. Leachate Concentrations for Bituminous Fly Ash, Waste ID KFA Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	1.30E-02	S	2.33E-05	S	2.34E+00	W	3.47E-02	S
8.4	1.46E-02	S	2.33E-05	S	2.33E+00	W	3.37E-02	S
8.6	1.62E-02	S	2.33E-05	S	2.32E+00	W	3.26E-02	S
8.8	1.80E-02	S	2.33E-05	S	2.31E+00	W	3.17E-02	S
9	1.99E-02	S	2.33E-05	S	2.30E+00	W	3.08E-02	S
9.2	2.19E-02	W	2.62E-05	S	2.30E+00	W	3.01E-02	S
9.4	2.39E-02	W	3.63E-05	S	2.33E+00	W	3.00E-02	S
9.6	2.30E-02	W	3.03E-05	S	2.40E+00	W	2.98E-02	S
9.8	2.00E-02	W	2.30E-05	S	2.45E+00	W	2.90E-02	S
10	2.08E-02	W	2.51E-05	S	2.47E+00	W	2.79E-02	S
10.2	2.30E-02	W	2.85E-05	S	2.51E+00	W	2.68E-02	S
10.4	2.67E-02	W	3.36E-05	S	2.56E+00	W	2.55E-02	S
10.6	2.82E-02	W	3.80E-05	S	2.58E+00	W	2.37E-02	S
10.8	2.80E-02	W	3.61E-05	S	2.58E+00	W	2.17E-02	S
11	2.78E-02	W	3.43E-05	S	2.57E+00	W	1.99E-02	S
11.2	2.76E-02	W	3.26E-05	S	2.56E+00	W	1.83E-02	S
11.4	2.74E-02	W	3.11E-05	S	2.56E+00	W	1.68E-02	S
11.6	2.72E-02	W	2.96E-05	S	2.55E+00	W	1.55E-02	S
11.8	2.70E-02	W	2.83E-05	S	2.54E+00	W	1.43E-02	S
12	2.69E-02	W	2.70E-05	S	2.54E+00	W	1.32E-02	S
12.2	2.67E-02	W	2.58E-05	S	2.53E+00	W	1.22E-02	S
12.4	2.65E-02	W	2.47E-05	S	2.52E+00	W	1.13E-02	S
12.6	2.64E-02	W	2.36E-05	S	2.52E+00	W	1.05E-02	S
12.8	2.62E-02	W	2.26E-05	S	2.51E+00	W	9.78E-03	S
13	2.60E-02	W	2.17E-05	S	2.51E+00	W	9.09E-03	S
tection Limit (min, mg	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
tection Limit (max, mg	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	1.14E+01		9.11E-04		2.68E+01		3.53E-01	

Table C-5-20. Leachate Concentrations for Bituminous Fly Ash, Waste ID KFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	2.22E-02	S	1.03E+00	S	1.27E-01	S
3	2.00E-02	S	9.51E-01	S	8.96E-02	S
3.2	1.82E-02	S	8.85E-01	S	6.46E-02	S
3.4	1.67E-02	S	8.27E-01	S	4.75E-02	S
3.6	1.53E-02	S	7.76E-01	S	3.56E-02	S
3.8	1.41E-02	S	7.31E-01	S	2.71E-02	S
4	1.32E-02	S	6.83E-01	S	1.70E-02	S
4.2	1.23E-02	S	6.25E-01	S	9.79E-03	S
4.4	1.18E-02	S	5.59E-01	S	6.32E-03	S
4.6	1.27E-02	S	4.52E-01	S	6.37E-03	S
4.8	1.42E-02	S	3.65E-01	S	7.83E-03	S
5	2.03E-02	S	2.27E-01	S	1.34E-02	S
5.2	2.43E-02	S	1.81E-01	S	1.72E-02	S
5.4	2.56E-02	S	1.69E-01	S	1.84E-02	S
5.6	2.69E-02	S	1.58E-01	S	1.96E-02	S
5.8	2.82E-02	S	1.48E-01	S	2.08E-02	S
6	2.95E-02	S	1.39E-01	S	2.21E-02	S
6.2	3.22E-02	S	1.24E-01	S	2.44E-02	S
6.4	3.66E-02	S	1.07E-01	S	2.81E-02	S
6.6	4.14E-02	S	9.20E-02	S	3.22E-02	S
6.8	4.67E-02	S	7.97E-02	S	3.67E-02	S
7	5.20E-02	S	7.08E-02	S	4.08E-02	S
7.2	5.61E-02	S	6.73E-02	S	4.22E-02	S
7.4	6.05E-02	S	6.41E-02	S	4.36E-02	S
7.6	6.51E-02	S	6.12E-02	S	4.50E-02	S
7.8	6.99E-02	S	5.84E-02	S	4.64E-02	S
8	7.49E-02	S	5.58E-02	S	4.78E-02	S

Table C-5-20. Leachate Concentrations for Bituminous Fly Ash, Waste ID KFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	8.28E-02	S	5.27E-02	S	5.03E-02	S
8.4	9.02E-02	S	4.90E-02	S	5.28E-02	S
8.6	9.82E-02	S	4.57E-02	S	5.54E-02	S
8.8	1.07E-01	S	4.26E-02	S	5.81E-02	S
9	1.16E-01	S	3.99E-02	S	6.08E-02	S
9.2	1.25E-01	S	3.96E-02	S	6.35E-02	S
9.4	1.34E-01	S	4.65E-02	S	6.75E-02	S
9.6	1.42E-01	S	5.21E-02	S	7.23E-02	S
9.8	1.51E-01	S	5.68E-02	S	7.68E-02	S
10	1.57E-01	S	6.07E-02	S	9.18E-02	S
10.2	1.64E-01	W	6.37E-02	S	1.14E-01	S
10.4	1.71E-01	W	6.57E-02	S	1.43E-01	S
10.6	1.76E-01	W	6.87E-02	S	1.56E-01	S
10.8	1.82E-01	W	7.38E-02	S	1.55E-01	S
11	1.87E-01	W	7.92E-02	S	1.54E-01	S
11.2	1.93E-01	W	8.48E-02	S	1.53E-01	S
11.4	1.99E-01	W	9.07E-02	S	1.51E-01	S
11.6	2.05E-01	W	9.70E-02	S	1.50E-01	S
11.8	2.11E-01	W	1.04E-01	S	1.49E-01	S
12	2.13E-01	W	1.10E-01	S	1.48E-01	S
12.2	2.13E-01	W	1.18E-01	S	1.47E-01	S
12.4	2.13E-01	W	1.25E-01	S	1.46E-01	S
12.6	2.13E-01	W	1.33E-01	S	1.45E-01	S
12.8	2.13E-01	W	1.41E-01	S	1.44E-01	S
13	2.13E-01	W	1.50E-01	S	1.43E-01	S
tection Limit (min, mg	5.20E-04		5.10E-04		3.10E-04	
tection Limit (max, mg	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	2.24E+00		1.03E+01		1.59E+00	

Table C-5-21. Leachate Concentrations for Bituminous Fly Ash, Waste ID LAB Med

Sample ID	LAB-[Med] (P,1,1)
Date Exported	8/27/2011, 6:50 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	1.03E-01	S	1.27E+00	S	3.88E-03	S	2.31E-02	W
3	7.13E-02	S	1.22E+00	S	3.72E-03	S	2.21E-02	W
3.2	5.07E-02	S	1.17E+00	S	3.58E-03	S	2.13E-02	W
3.4	3.67E-02	S	1.12E+00	S	3.45E-03	S	2.05E-02	W
3.6	2.71E-02	S	1.08E+00	S	3.33E-03	S	1.99E-02	W
3.8	2.04E-02	S	1.05E+00	S	3.22E-03	S	1.92E-02	W
4	1.76E-02	S	9.65E-01	S	2.79E-03	S	1.90E-02	W
4.2	1.60E-02	S	8.79E-01	S	2.30E-03	S	1.87E-02	W
4.4	1.45E-02	S	8.05E-01	S	1.91E-03	S	1.85E-02	W
4.6	1.33E-02	S	7.40E-01	S	1.60E-03	S	1.82E-02	W
4.8	1.21E-02	S	6.82E-01	S	1.36E-03	S	1.80E-02	W
5	1.43E-02	S	6.24E-01	S	1.00E-03	S	1.35E-02	S
5.2	1.67E-02	S	5.74E-01	S	7.46E-04	S	1.03E-02	S
5.4	2.27E-02	S	5.68E-01	S	7.46E-04	S	7.33E-03	S
5.6	3.07E-02	S	5.63E-01	S	7.46E-04	S	5.28E-03	S
5.8	4.03E-02	S	5.59E-01	S	7.46E-04	S	4.30E-03	S
6	5.16E-02	S	5.57E-01	S	7.46E-04	S	3.94E-03	S
6.2	6.56E-02	S	5.55E-01	S	7.46E-04	S	3.62E-03	S
6.4	9.06E-02	S	5.44E-01	S	7.46E-04	S	3.12E-03	S
6.6	1.36E-01	S	5.24E-01	S	7.46E-04	S	2.53E-03	S
6.8	1.81E-01	S	5.18E-01	S	7.46E-04	S	2.06E-03	S
7	2.29E-01	S	5.20E-01	S	7.46E-04	S	2.06E-03	S
7.2	2.88E-01	S	5.22E-01	S	7.46E-04	S	2.06E-03	S
7.4	3.59E-01	S	5.24E-01	S	7.46E-04	S	2.06E-03	S
7.6	4.46E-01	S	5.26E-01	S	7.46E-04	S	2.06E-03	S
7.8	4.97E-01	S	5.36E-01	S	7.46E-04	S	2.06E-03	S
8	5.54E-01	S	5.46E-01	S	7.46E-04	S	2.06E-03	S

Table C-5-21. Leachate Concentrations for Bituminous Fly Ash, Waste ID LAB Med

Sample ID	LAB-[Med] (P,1,1)
Date Exported	8/27/2011, 6:50 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	6.15E-01	S	5.57E-01	S	7.46E-04	W	2.06E-03	S
8.4	6.65E-01	S	5.58E-01	S	7.46E-04	W	2.06E-03	S
8.6	7.17E-01	S	5.59E-01	S	7.46E-04	W	2.06E-03	S
8.8	7.73E-01	S	5.60E-01	S	7.46E-04	W	2.06E-03	S
9	8.02E-01	S	5.68E-01	S	7.46E-04	W	2.06E-03	S
9.2	8.33E-01	S	5.75E-01	S	7.46E-04	W	2.06E-03	S
9.4	8.63E-01	S	5.83E-01	S	7.46E-04	W	2.06E-03	S
9.6	8.98E-01	S	5.95E-01	S	7.46E-04	W	2.06E-03	S
9.8	9.38E-01	S	6.10E-01	S	7.46E-04	W	2.06E-03	S
10	9.79E-01	S	6.26E-01	S	7.46E-04	W	2.06E-03	S
10.2	1.02E+00	S	6.41E-01	S	7.46E-04	W	2.06E-03	S
10.4	1.06E+00	S	6.72E-01	S	7.46E-04	W	2.06E-03	S
10.6	1.12E+00	S	7.59E-01	S	7.46E-04	W	2.06E-03	S
10.8	1.17E+00	S	8.55E-01	S	7.46E-04	W	2.06E-03	S
11	1.23E+00	S	9.62E-01	S	7.46E-04	W	2.06E-03	S
11.2	1.28E+00	S	1.08E+00	S	7.46E-04	W	2.06E-03	S
11.4	1.34E+00	S	1.21E+00	S	7.46E-04	W	2.06E-03	S
11.6	1.40E+00	S	1.35E+00	S	7.46E-04	W	2.06E-03	S
11.8	1.46E+00	S	1.51E+00	S	7.46E-04	W	2.06E-03	S
12	1.53E+00	S	1.68E+00	S	7.46E-04	W	2.06E-03	S
12.2	1.57E+00	S	1.82E+00	S	7.46E-04	W	2.06E-03	S
12.4	1.57E+00	S	1.82E+00	S	7.46E-04	W	2.06E-03	S
12.6	1.57E+00	S	1.82E+00	S	7.46E-04	W	2.06E-03	S
12.8	1.57E+00	S	1.82E+00	S	7.46E-04	W	2.06E-03	S
13	1.57E+00	S	1.82E+00	S	7.46E-04	W	2.06E-03	S
tection Limit (min, mg	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
tection Limit (max, mg	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	1.67E+01		1.92E+01		3.88E-02		2.31E-01	

Table C-5-21. Leachate Concentrations for Bituminous Fly Ash, Waste ID LAB Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	4.04E-02	S	9.68E-06	S	1.80E-02	S	1.46E-02	S
3	2.92E-02	S	7.90E-06	S	1.60E-02	S	1.63E-02	S
3.2	2.15E-02	S	6.53E-06	S	1.44E-02	S	1.81E-02	S
3.4	1.61E-02	S	5.46E-06	S	1.30E-02	S	2.00E-02	S
3.6	1.23E-02	S	4.61E-06	S	1.18E-02	S	2.20E-02	S
3.8	9.54E-03	S	3.93E-06	S	1.07E-02	S	2.40E-02	S
4	7.05E-03	S	4.73E-06	S	1.33E-02	S	2.66E-02	S
4.2	5.25E-03	S	5.76E-06	S	1.80E-02	S	2.87E-02	S
4.4	3.96E-03	S	6.94E-06	S	2.39E-02	S	3.09E-02	S
4.6	3.02E-03	S	8.29E-06	S	3.15E-02	S	3.31E-02	S
4.8	2.34E-03	S	9.83E-06	S	4.09E-02	S	3.53E-02	S
5	2.10E-03	S	8.07E-06	S	6.52E-02	S	3.74E-02	S
5.2	1.90E-03	S	6.68E-06	S	1.02E-01	S	3.95E-02	S
5.4	1.90E-03	S	7.66E-06	S	1.28E-01	S	4.24E-02	S
5.6	1.90E-03	S	8.75E-06	S	1.59E-01	S	4.55E-02	S
5.8	1.90E-03	S	8.13E-06	S	1.93E-01	S	4.89E-02	S
6	1.90E-03	S	6.21E-06	S	2.29E-01	S	5.28E-02	S
6.2	1.90E-03	S	4.79E-06	S	2.70E-01	W	5.69E-02	S
6.4	1.90E-03	S	3.64E-06	S	3.01E-01	W	5.83E-02	S
6.6	1.90E-03	S	2.73E-06	S	3.20E-01	W	5.68E-02	S
6.8	2.08E-03	S	3.24E-06	S	3.39E-01	W	5.53E-02	S
7	2.27E-03	S	5.29E-06	S	3.49E-01	W	5.92E-02	S
7.2	2.48E-03	S	8.52E-06	S	3.60E-01	W	6.31E-02	S
7.4	2.69E-03	S	1.35E-05	S	3.70E-01	W	6.72E-02	S
7.6	2.92E-03	S	2.13E-05	S	3.80E-01	W	7.15E-02	S
7.8	3.60E-03	S	1.98E-05	S	3.88E-01	W	7.07E-02	S
8	4.41E-03	S	1.85E-05	S	3.95E-01	W	6.99E-02	S

Table C-5-21. Leachate Concentrations for Bituminous Fly Ash, Waste ID LAB Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
8.2	5.37E-03	S	1.73E-05	S	4.02E-01	W	6.91E-02	S
8.4	6.09E-03	S	1.35E-05	S	3.97E-01	W	6.77E-02	S
8.6	6.89E-03	S	1.05E-05	S	3.92E-01	W	6.64E-02	S
8.8	7.77E-03	S	8.31E-06	S	3.88E-01	W	6.52E-02	S
9	7.93E-03	S	7.47E-06	S	3.82E-01	W	7.06E-02	S
9.2	8.09E-03	S	6.73E-06	S	3.77E-01	W	7.63E-02	S
9.4	8.25E-03	S	6.08E-06	S	3.71E-01	W	8.23E-02	S
9.6	8.48E-03	S	6.32E-06	S	3.70E-01	W	8.86E-02	S
9.8	8.82E-03	S	7.75E-06	S	3.72E-01	W	8.90E-02	S
10	9.22E-03	S	9.74E-06	S	3.72E-01	W	8.35E-02	S
10.2	9.62E-03	S	1.22E-05	S	3.73E-01	W	7.84E-02	S
10.4	1.01E-02	S	1.57E-05	S	3.74E-01	W	7.64E-02	S
10.6	1.09E-02	S	1.51E-05	S	3.76E-01	W	7.97E-02	S
10.8	1.17E-02	S	1.45E-05	S	3.78E-01	W	8.31E-02	S
11	1.26E-02	S	1.39E-05	S	3.80E-01	W	8.66E-02	S
11.2	1.35E-02	S	1.33E-05	S	3.82E-01	W	9.01E-02	S
11.4	1.45E-02	S	1.28E-05	S	3.83E-01	W	9.37E-02	S
11.6	1.55E-02	S	1.23E-05	S	3.85E-01	W	9.74E-02	S
11.8	1.66E-02	S	1.19E-05	S	3.87E-01	W	1.01E-01	S
12	1.77E-02	S	1.14E-05	S	3.89E-01	W	1.05E-01	S
12.2	1.89E-02	S	1.10E-05	S	3.91E-01	W	1.07E-01	S
12.4	2.02E-02	S	1.06E-05	S	3.92E-01	W	1.08E-01	S
12.6	2.15E-02	S	1.03E-05	S	3.94E-01	W	1.09E-01	S
12.8	2.29E-02	S	9.90E-06	S	3.96E-01	W	1.10E-01	S
13	2.43E-02	S	9.57E-06	S	3.97E-01	W	1.11E-01	S
tection Limit (min, mg/	5.00E-04		3.60E-06		1.00E-03		8.00E-05	
tection Limit (max, mg	5.00E-04		3.60E-06		1.00E-03		8.00E-05	
Availability (mg/kg)	4.04E-01		2.13E-04		4.19E+00		1.17E+00	

Table C-5-21. Leachate Concentrations for Bituminous Fly Ash, Waste ID LAB Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	4.93E-02	S	5.48E-02	S	1.87E-01	S
3	4.34E-02	S	4.87E-02	S	9.62E-02	S
3.2	3.86E-02	S	4.37E-02	S	5.17E-02	S
3.4	3.45E-02	S	3.95E-02	S	2.89E-02	S
3.6	3.10E-02	S	3.58E-02	S	1.67E-02	S
3.8	2.81E-02	S	3.27E-02	S	9.90E-03	S
4	2.30E-02	S	2.78E-02	S	9.81E-03	S
4.2	1.85E-02	S	2.30E-02	S	1.12E-02	S
4.4	1.50E-02	S	1.92E-02	S	1.28E-02	S
4.6	1.23E-02	S	1.62E-02	S	1.45E-02	S
4.8	1.02E-02	S	1.37E-02	S	1.63E-02	S
5	8.99E-03	S	1.11E-02	S	2.25E-02	S
5.2	7.97E-03	S	9.10E-03	S	3.06E-02	S
5.4	8.42E-03	S	8.30E-03	S	3.68E-02	S
5.6	8.87E-03	S	7.59E-03	S	4.39E-02	S
5.8	9.50E-03	S	6.88E-03	S	5.18E-02	S
6	1.03E-02	S	6.18E-03	S	6.02E-02	S
6.2	1.12E-02	S	5.57E-03	S	6.97E-02	S
6.4	1.25E-02	S	4.77E-03	S	8.30E-02	S
6.6	1.41E-02	S	3.89E-03	S	1.02E-01	S
6.8	1.53E-02	S	3.18E-03	S	1.20E-01	S
7	1.69E-02	S	3.07E-03	S	1.38E-01	S
7.2	1.86E-02	S	2.97E-03	S	1.58E-01	S
7.4	2.04E-02	S	2.87E-03	S	1.80E-01	S
7.6	2.24E-02	S	2.78E-03	S	2.04E-01	S
7.8	2.36E-02	S	2.69E-03	S	2.27E-01	S
8	2.49E-02	S	2.61E-03	S	2.52E-01	S

Table C-5-21. Leachate Concentrations for Bituminous Fly Ash, Waste ID LAB Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	2.62E-02	S	2.53E-03	S	2.80E-01	S
8.4	2.72E-02	S	2.53E-03	S	3.03E-01	S
8.6	2.83E-02	S	2.53E-03	S	3.28E-01	S
8.8	2.93E-02	S	2.53E-03	S	3.54E-01	S
9	3.00E-02	S	2.53E-03	S	3.74E-01	S
9.2	3.06E-02	S	2.53E-03	S	3.95E-01	S
9.4	3.13E-02	S	2.53E-03	S	4.17E-01	S
9.6	3.19E-02	S	2.53E-03	S	4.41E-01	S
9.8	3.25E-02	S	2.53E-03	S	4.65E-01	S
10	3.32E-02	S	2.53E-03	S	4.86E-01	S
10.2	3.39E-02	S	2.53E-03	S	5.08E-01	S
10.4	3.45E-02	S	2.62E-03	S	5.29E-01	S
10.6	3.55E-02	S	3.13E-03	S	5.51E-01	S
10.8	3.66E-02	S	3.74E-03	S	5.72E-01	S
11	3.77E-02	S	4.44E-03	S	5.94E-01	S
11.2	3.88E-02	S	5.26E-03	S	6.16E-01	S
11.4	3.99E-02	S	6.22E-03	S	6.39E-01	S
11.6	4.10E-02	S	7.33E-03	S	6.62E-01	S
11.8	4.22E-02	S	8.61E-03	S	6.86E-01	S
12	4.33E-02	S	1.01E-02	S	7.10E-01	S
12.2	4.45E-02	S	1.18E-02	S	7.27E-01	S
12.4	4.56E-02	S	1.37E-02	S	7.27E-01	S
12.6	4.68E-02	S	1.60E-02	S	7.27E-01	S
12.8	4.80E-02	S	1.85E-02	S	7.27E-01	S
13	4.92E-02	S	2.15E-02	S	7.27E-01	S
tection Limit (min, mg/	5.20E-04		5.10E-04		3.10E-04	
tection Limit (max, mg	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	5.09E-01		5.48E-01		7.71E+00	

Table C-5-22. Leachate Concentrations for Bituminous Fly Ash, Waste ID LAT Med

Sample ID LAT-[Med] (P,1,1)
Date Exported 8/27/2011, 6:50 PM
Database Name C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version 1.2.12.11227

	Concentration (mg/L)							
pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	6.29E-02	S	1.18E+00	S	3.64E-03	S	2.33E-02	S
3	4.47E-02	S	1.14E+00	S	3.49E-03	S	2.24E-02	S
3.2	3.25E-02	S	1.10E+00	S	3.35E-03	S	2.16E-02	S
3.4	2.41E-02	S	1.06E+00	S	3.23E-03	S	2.08E-02	S
3.6	1.82E-02	S	1.02E+00	S	3.11E-03	S	2.02E-02	S
3.8	1.44E-02	S	9.42E-01	S	2.87E-03	S	1.92E-02	S
4	1.80E-02	S	7.50E-01	S	1.82E-03	S	1.18E-02	S
4.2	2.32E-02	S	6.44E-01	S	1.44E-03	S	8.41E-03	S
4.4	3.27E-02	S	5.90E-01	S	1.31E-03	S	6.30E-03	S
4.6	3.98E-02	S	5.58E-01	S	1.21E-03	S	5.27E-03	S
4.8	4.21E-02	S	5.44E-01	S	1.11E-03	S	4.88E-03	S
5	4.45E-02	S	5.31E-01	S	1.03E-03	S	4.53E-03	S
5.2	4.70E-02	S	5.19E-01	S	9.52E-04	S	4.22E-03	S
5.4	4.95E-02	S	5.07E-01	S	8.85E-04	S	3.95E-03	S
5.6	5.20E-02	S	4.96E-01	S	8.25E-04	S	3.70E-03	S
5.8	5.45E-02	S	4.86E-01	S	7.71E-04	S	3.47E-03	S
6	6.42E-02	S	4.76E-01	S	7.46E-04	S	3.15E-03	S
6.2	8.80E-02	S	4.64E-01	S	7.46E-04	S	2.78E-03	S
6.4	1.24E-01	S	4.51E-01	S	7.46E-04	S	2.46E-03	S
6.6	1.74E-01	S	4.39E-01	S	7.46E-04	S	2.18E-03	S
6.8	2.27E-01	S	4.30E-01	S	7.46E-04	S	2.06E-03	S
7	2.76E-01	S	4.24E-01	S	7.46E-04	S	2.06E-03	S
7.2	3.35E-01	S	4.18E-01	S	7.46E-04	S	2.06E-03	S
7.4	3.94E-01	S	4.15E-01	S	7.46E-04	S	2.06E-03	S
7.6	4.41E-01	S	4.20E-01	S	7.46E-04	S	2.06E-03	S
7.8	4.81E-01	S	4.28E-01	S	7.46E-04	S	2.06E-03	S

Table C-5-22. Leachate Concentrations for Bituminous Fly Ash, Waste ID LAT Med

Sample ID	LAT-[Med] (P,1,1)
Date Exported	8/27/2011, 6:50 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8	5.23E-01	S	4.37E-01	S	7.46E-04	S	2.06E-03	S
8.2	5.69E-01	S	4.45E-01	S	7.46E-04	W	2.06E-03	S
8.4	6.17E-01	S	4.53E-01	S	7.46E-04	W	2.06E-03	S
8.6	6.58E-01	S	4.62E-01	S	7.46E-04	W	2.06E-03	S
8.8	6.84E-01	S	4.71E-01	S	7.46E-04	W	2.06E-03	S
9	7.10E-01	S	4.79E-01	S	7.46E-04	W	2.06E-03	S
9.2	7.36E-01	S	4.88E-01	S	7.46E-04	W	2.06E-03	S
9.4	7.63E-01	S	4.96E-01	S	7.46E-04	W	2.06E-03	S
9.6	7.84E-01	S	5.09E-01	S	7.46E-04	W	2.06E-03	S
9.8	8.06E-01	S	5.39E-01	S	7.46E-04	W	2.06E-03	S
10	8.34E-01	S	5.84E-01	S	7.46E-04	W	2.06E-03	S
10.2	8.62E-01	S	6.31E-01	S	7.46E-04	W	2.06E-03	S
10.4	8.91E-01	S	6.81E-01	S	7.46E-04	W	2.06E-03	S
10.6	9.33E-01	S	7.67E-01	S	7.46E-04	W	2.06E-03	S
10.8	9.77E-01	S	8.62E-01	S	7.46E-04	W	2.06E-03	S
11	1.02E+00	S	9.66E-01	S	7.46E-04	W	2.06E-03	S
11.2	1.07E+00	S	1.08E+00	S	7.46E-04	W	2.06E-03	S
11.4	1.11E+00	S	1.21E+00	S	7.46E-04	W	2.06E-03	S
11.6	1.16E+00	S	1.35E+00	S	7.46E-04	W	2.06E-03	S
11.8	1.21E+00	S	1.50E+00	S	7.46E-04	W	2.06E-03	S
12	1.26E+00	S	1.66E+00	S	7.46E-04	W	2.06E-03	S
12.2	1.30E+00	S	1.80E+00	S	7.46E-04	W	2.06E-03	S
12.4	1.30E+00	S	1.80E+00	S	7.46E-04	W	2.06E-03	S
12.6	1.30E+00	S	1.80E+00	S	7.46E-04	W	2.06E-03	S
12.8	1.30E+00	S	1.80E+00	S	7.46E-04	W	2.06E-03	S
13	1.30E+00	S	1.80E+00	S	7.46E-04	W	2.06E-03	S
tection Limit (min, mg	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
tection Limit (max, mg	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	1.38E+01		1.91E+01		3.64E-02		2.33E-01	

Table C-5-22. Leachate Concentrations for Bituminous Fly Ash, Waste ID LAT Med

Sample ID
Date Exported
Database Name :ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
2.8	4.21E-02	S	5.45E-06	S	8.74E-03	S	9.05E-03	S
3	2.89E-02	S	5.45E-06	S	8.18E-03	S	1.05E-02	S
3.2	2.03E-02	S	5.45E-06	S	7.69E-03	S	1.21E-02	S
3.4	1.46E-02	S	5.45E-06	S	7.26E-03	S	1.39E-02	S
3.6	1.07E-02	S	5.45E-06	S	6.87E-03	S	1.57E-02	S
3.8	4.27E-03	S	5.45E-06	S	6.21E-03	S	1.75E-02	S
4	2.82E-03	S	7.22E-06	S	2.10E-02	S	2.71E-02	S
4.2	1.90E-03	S	9.44E-06	S	3.92E-02	S	3.55E-02	S
4.4	1.90E-03	S	8.89E-06	S	5.57E-02	S	3.93E-02	S
4.6	1.90E-03	S	8.40E-06	S	7.36E-02	S	4.24E-02	S
4.8	1.90E-03	S	7.95E-06	S	9.07E-02	S	4.46E-02	S
5	1.90E-03	S	7.54E-06	S	1.11E-01	S	4.67E-02	S
5.2	1.90E-03	S	7.17E-06	S	1.34E-01	S	4.89E-02	S
5.4	1.90E-03	S	6.83E-06	S	1.62E-01	S	5.11E-02	S
5.6	1.90E-03	S	6.52E-06	S	1.93E-01	S	5.33E-02	S
5.8	1.90E-03	S	6.23E-06	S	2.30E-01	S	5.55E-02	S
6	1.90E-03	S	6.01E-06	S	2.56E-01	S	5.63E-02	S
6.2	2.02E-03	S	5.84E-06	S	2.71E-01	W	5.60E-02	S
6.4	2.29E-03	S	5.68E-06	S	2.87E-01	W	5.61E-02	S
6.6	2.59E-03	S	5.52E-06	S	3.05E-01	W	5.61E-02	S
6.8	2.92E-03	S	5.45E-06	S	3.17E-01	W	5.67E-02	S
7	3.27E-03	S	5.45E-06	S	3.24E-01	W	5.79E-02	S
7.2	3.65E-03	S	5.45E-06	S	3.31E-01	W	5.90E-02	S
7.4	4.34E-03	S	5.71E-06	S	3.38E-01	W	6.01E-02	S
7.6	5.25E-03	S	6.24E-06	S	3.44E-01	W	6.08E-02	S
7.8	6.08E-03	S	6.81E-06	S	3.50E-01	W	6.14E-02	S

Table C-5-22. Leachate Concentrations for Bituminous Fly Ash, Waste ID LAT Med

Sample ID
Date Exported
Database Name :ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
8	7.01E-03	S	7.41E-06	S	3.55E-01	W	6.20E-02	S
8.2	8.07E-03	S	8.05E-06	S	3.60E-01	W	6.26E-02	S
8.4	9.25E-03	S	8.73E-06	S	3.66E-01	W	6.31E-02	S
8.6	1.04E-02	S	9.44E-06	S	3.71E-01	W	6.42E-02	S
8.8	1.06E-02	S	6.65E-06	S	3.67E-01	W	6.30E-02	S
9	1.08E-02	S	4.72E-06	S	3.64E-01	W	6.19E-02	S
9.2	1.10E-02	S	3.38E-06	S	3.60E-01	W	6.09E-02	S
9.4	1.13E-02	S	2.43E-06	S	3.57E-01	W	5.98E-02	S
9.6	1.13E-02	S	2.66E-06	S	3.56E-01	W	6.12E-02	S
9.8	1.16E-02	S	4.37E-06	S	3.59E-01	W	6.57E-02	S
10	1.20E-02	S	7.11E-06	S	3.62E-01	W	7.12E-02	S
10.2	1.25E-02	S	1.15E-05	S	3.64E-01	W	7.70E-02	S
10.4	1.30E-02	S	1.83E-05	S	3.67E-01	W	8.32E-02	S
10.6	1.40E-02	S	1.60E-05	S	3.68E-01	W	8.82E-02	S
10.8	1.51E-02	S	1.41E-05	S	3.69E-01	W	9.33E-02	S
11	1.63E-02	S	1.24E-05	S	3.70E-01	W	9.86E-02	S
11.2	1.75E-02	S	1.10E-05	S	3.71E-01	W	1.04E-01	S
11.4	1.87E-02	S	9.72E-06	S	3.72E-01	W	1.10E-01	S
11.6	2.01E-02	S	8.63E-06	S	3.73E-01	W	1.16E-01	S
11.8	2.15E-02	S	7.67E-06	S	3.73E-01	W	1.22E-01	S
12	2.30E-02	S	6.83E-06	S	3.74E-01	W	1.28E-01	S
12.2	2.45E-02	S	6.10E-06	S	3.75E-01	W	1.33E-01	S
12.4	2.61E-02	S	5.45E-06	S	3.76E-01	W	1.33E-01	S
12.6	2.78E-02	S	4.88E-06	S	3.76E-01	W	1.33E-01	S
12.8	2.96E-02	S	4.38E-06	S	3.77E-01	W	1.33E-01	S
13	3.15E-02	S	3.94E-06	S	3.77E-01	W	1.33E-01	S
:tection Limit (min, mg/	5.00E-04		3.60E-06		1.00E-03		8.00E-05	
tection Limit (max, mg/	5.00E-04		3.60E-06		1.00E-03		8.00E-05	
Availability (mg/kg)	4.21E-01		1.84E-04		3.99E+00		1.41E+00	

Table C-5-22. Leachate Concentrations for Bituminous Fly Ash, Waste ID LAT Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	4.93E-02	S	3.86E-02	S	1.10E-01	S
3	4.33E-02	S	3.54E-02	S	5.55E-02	S
3.2	3.84E-02	S	3.27E-02	S	2.92E-02	S
3.4	3.43E-02	S	3.03E-02	S	1.60E-02	S
3.6	3.08E-02	S	2.82E-02	S	9.06E-03	S
3.8	2.56E-02	S	2.17E-02	S	6.18E-03	S
4	1.47E-02	S	1.45E-02	S	1.13E-02	S
4.2	1.25E-02	S	1.03E-02	S	1.72E-02	S
4.4	1.53E-02	S	7.69E-03	S	2.63E-02	S
4.6	1.60E-02	S	6.45E-03	S	3.40E-02	S
4.8	1.44E-02	S	6.04E-03	S	3.75E-02	S
5	1.30E-02	S	5.66E-03	S	4.11E-02	S
5.2	1.18E-02	S	5.33E-03	S	4.49E-02	S
5.4	1.08E-02	S	5.03E-03	S	4.89E-02	S
5.6	9.87E-03	S	4.75E-03	S	5.32E-02	S
5.8	9.05E-03	S	4.50E-03	S	5.76E-02	S
6	9.02E-03	S	4.30E-03	S	6.30E-02	S
6.2	1.01E-02	S	4.16E-03	S	7.34E-02	S
6.4	1.16E-02	S	4.02E-03	S	8.98E-02	S
6.6	1.33E-02	S	3.90E-03	S	1.09E-01	S
6.8	1.50E-02	S	3.82E-03	S	1.30E-01	S
7	1.68E-02	S	3.77E-03	S	1.51E-01	S
7.2	1.87E-02	S	3.73E-03	S	1.74E-01	S
7.4	2.04E-02	S	3.60E-03	S	2.00E-01	S
7.6	2.17E-02	S	3.38E-03	S	2.25E-01	S
7.8	2.28E-02	S	3.18E-03	S	2.47E-01	S

Table C-5-22. Leachate Concentrations for Bituminous Fly Ash, Waste ID LAT Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8	2.39E-02	S	3.00E-03	S	2.72E-01	S
8.2	2.51E-02	S	2.83E-03	S	2.98E-01	S
8.4	2.62E-02	S	2.67E-03	S	3.26E-01	S
8.6	2.72E-02	S	2.53E-03	S	3.51E-01	S
8.8	2.80E-02	S	2.76E-03	S	3.68E-01	S
9	2.87E-02	S	3.00E-03	S	3.84E-01	S
9.2	2.95E-02	S	3.26E-03	S	4.02E-01	S
9.4	3.02E-02	S	3.54E-03	S	4.19E-01	S
9.6	3.06E-02	S	3.79E-03	S	4.35E-01	S
9.8	3.08E-02	S	4.17E-03	S	4.50E-01	S
10	3.12E-02	S	4.75E-03	S	4.68E-01	S
10.2	3.15E-02	S	5.40E-03	S	4.87E-01	S
10.4	3.18E-02	S	6.12E-03	S	5.05E-01	S
10.6	3.28E-02	S	6.87E-03	S	5.24E-01	S
10.8	3.37E-02	S	7.71E-03	S	5.44E-01	S
11	3.47E-02	S	8.62E-03	S	5.64E-01	S
11.2	3.57E-02	S	9.62E-03	S	5.84E-01	S
11.4	3.67E-02	S	1.07E-02	S	6.04E-01	S
11.6	3.78E-02	S	1.19E-02	S	6.25E-01	S
11.8	3.88E-02	S	1.32E-02	S	6.46E-01	S
12	3.98E-02	S	1.47E-02	S	6.67E-01	S
12.2	4.09E-02	S	1.62E-02	S	6.84E-01	S
12.4	4.19E-02	S	1.79E-02	S	6.84E-01	S
12.6	4.30E-02	S	1.97E-02	S	6.84E-01	S
12.8	4.41E-02	S	2.17E-02	S	6.84E-01	S
13	4.52E-02	S	2.39E-02	S	6.84E-01	S
tection Limit (min, mg	5.20E-04		5.10E-04		3.10E-04	
tection Limit (max, mg	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	4.93E-01		3.86E-01		7.25E+00	

Table C-5-23. Leachate Concentrations for Bituminous Fly Ash, Waste ID SHB Med

Sample ID	SHB-[Med] (P,1,1)
Date Exported	8/27/2011, 6:50 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term modeling\EPA Rpt 4 (5
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	0.209397476	S	15.91046042	S	0.0815702	W	0.078701556	W
3	1.88E-01	S	1.53E+01	S	8.07E-02	W	7.91E-02	W
3.2	1.70E-01	S	1.47E+01	S	8.00E-02	W	7.80E-02	W
3.4	1.54E-01	S	1.44E+01	S	7.82E-02	W	7.69E-02	W
3.6	1.47E-01	S	1.44E+01	S	7.58E-02	W	7.26E-02	W
3.8	1.41E-01	S	1.43E+01	S	7.36E-02	W	6.87E-02	W
4	1.36E-01	S	1.61E+01	S	6.64E-02	S	6.42E-02	S
4.2	1.20E-01	S	1.58E+01	S	6.02E-02	S	6.02E-02	S
4.4	1.07E-01	S	1.55E+01	S	5.48E-02	S	5.66E-02	S
4.6	9.64E-02	S	1.52E+01	S	5.02E-02	S	5.34E-02	S
4.8	9.03E-02	S	1.49E+01	S	4.62E-02	S	5.09E-02	S
5	9.06E-02	S	1.47E+01	S	4.31E-02	S	4.95E-02	S
5.2	9.08E-02	S	1.44E+01	S	4.03E-02	S	4.82E-02	S
5.4	9.10E-02	S	1.42E+01	S	3.77E-02	S	4.69E-02	S
5.6	9.13E-02	S	1.39E+01	S	3.54E-02	S	4.57E-02	S
5.8	9.15E-02	S	1.37E+01	S	3.33E-02	S	4.46E-02	S
6	9.08E-02	S	1.35E+01	S	3.14E-02	S	4.35E-02	S
6.2	8.78E-02	S	1.33E+01	S	2.97E-02	S	4.25E-02	S
6.4	8.51E-02	S	1.31E+01	S	2.81E-02	S	4.16E-02	S
6.6	8.25E-02	S	1.29E+01	S	2.66E-02	S	4.07E-02	S
6.8	8.00E-02	S	1.28E+01	S	2.53E-02	S	3.99E-02	S
7	7.77E-02	S	1.26E+01	S	2.41E-02	S	3.91E-02	S
7.2	7.90E-02	S	1.25E+01	S	1.85E-02	S	2.50E-02	S
7.4	8.04E-02	S	1.24E+01	S	1.18E-02	S	1.50E-02	S
7.6	8.18E-02	S	1.24E+01	S	7.59E-03	S	8.68E-03	S
7.8	8.37E-02	S	1.24E+01	S	5.64E-03	S	5.36E-03	S
8	8.80E-02	S	1.24E+01	S	5.72E-03	S	3.55E-03	S

Table C-5-23. Leachate Concentrations for Bituminous Fly Ash, Waste ID SHB Med

Sample ID	SHB-[Med] (P,1,1)
Date Exported	8/27/2011, 6:50 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term modeling\EPA Rpt 4 (5
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	8.99E-02	S	1.09E+01	S	5.61E-03	W	2.37E-03	S
8.4	8.46E-02	S	1.07E+01	S	5.51E-03	W	2.06E-03	S
8.6	7.57E-02	S	1.05E+01	S	5.42E-03	W	2.06E-03	S
8.8	6.80E-02	S	1.09E+01	S	5.34E-03	W	2.06E-03	S
9	6.11E-02	S	1.13E+01	S	5.25E-03	W	2.06E-03	S
9.2	5.51E-02	S	1.16E+01	S	5.17E-03	W	2.06E-03	S
9.4	4.98E-02	S	1.20E+01	S	5.09E-03	W	2.06E-03	S
9.6	4.52E-02	S	1.13E+01	S	5.02E-03	W	2.06E-03	S
9.8	4.12E-02	S	1.03E+01	S	4.95E-03	W	2.06E-03	S
10	3.76E-02	S	9.38E+00	S	4.88E-03	W	2.06E-03	S
10.2	3.43E-02	S	8.59E+00	S	4.81E-03	W	2.06E-03	S
10.4	3.14E-02	S	7.87E+00	S	4.75E-03	W	2.06E-03	S
10.6	2.88E-02	S	7.23E+00	S	4.68E-03	W	2.06E-03	S
10.8	2.65E-02	S	6.65E+00	S	4.62E-03	W	2.06E-03	S
11	2.44E-02	S	6.13E+00	S	4.56E-03	W	2.06E-03	S
11.2	2.26E-02	S	5.65E+00	S	4.51E-03	W	2.06E-03	S
11.4	2.08E-02	S	5.22E+00	S	4.45E-03	W	2.06E-03	S
11.6	2.08E-02	S	5.15E+00	S	4.40E-03	W	2.06E-03	S
11.8	2.09E-02	S	5.58E+00	S	4.39E-03	W	2.06E-03	S
12	2.33E-02	S	5.05E+00	S	4.48E-03	W	2.06E-03	S
12.2	2.64E-02	S	4.68E+00	S	4.60E-03	W	2.06E-03	S
12.4	2.96E-02	S	4.35E+00	S	4.72E-03	W	2.06E-03	S
12.6	3.02E-02	S	4.05E+00	S	4.84E-03	W	2.06E-03	S
12.8	3.21E-02	S	3.77E+00	S	4.97E-03	W	2.06E-03	S
13	3.47E-02	S	3.51E+00	S	5.09E-03	W	2.06E-03	S
tection Limit (min, mg/	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
tection Limit (max, mg	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	2.09E+00		1.61E+02		8.16E-01		7.91E-01	

Table C-5-23. Leachate Concentrations for Bituminous Fly Ash, Waste ID SHB Med

Sample ID
Date Exported
Database Name 5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	1.7169583	S	4.50116E-05	S	0.040655719	S	0.032823	S
3	1.68E+00	S	4.43E-05	S	2.96E-02	S	3.51E-02	S
3.2	1.47E+00	S	4.37E-05	S	2.50E-02	S	3.72E-02	S
3.4	1.07E+00	S	4.32E-05	S	2.75E-02	S	4.05E-02	S
3.6	5.04E-01	S	4.51E-05	S	3.44E-02	S	4.51E-02	S
3.8	2.45E-01	S	4.73E-05	S	4.26E-02	S	5.00E-02	S
4	7.81E-02	S	4.94E-05	S	3.07E-01	S	7.74E-02	S
4.2	2.63E-02	S	4.95E-05	S	4.16E-01	S	8.11E-02	S
4.4	9.34E-03	S	4.81E-05	S	5.57E-01	S	8.49E-02	S
4.6	3.47E-03	S	4.68E-05	S	7.35E-01	S	8.87E-02	S
4.8	3.08E-03	S	4.55E-05	S	8.83E-01	S	9.17E-02	S
5	3.39E-03	S	4.44E-05	S	9.20E-01	S	9.34E-02	S
5.2	3.72E-03	S	4.33E-05	S	9.57E-01	S	9.51E-02	S
5.4	4.06E-03	S	4.23E-05	S	9.94E-01	S	9.68E-02	S
5.6	4.42E-03	S	4.14E-05	S	1.03E+00	S	9.84E-02	S
5.8	4.79E-03	S	4.05E-05	S	1.07E+00	S	1.00E-01	S
6	5.19E-03	S	3.96E-05	S	1.11E+00	S	1.02E-01	S
6.2	5.24E-03	S	3.88E-05	S	1.14E+00	S	1.03E-01	S
6.4	4.03E-03	S	3.81E-05	S	1.18E+00	S	1.05E-01	S
6.6	3.79E-03	S	3.73E-05	S	1.22E+00	S	1.06E-01	S
6.8	4.03E-03	S	3.67E-05	S	1.25E+00	S	1.08E-01	S
7	4.28E-03	S	3.60E-05	S	1.29E+00	S	1.09E-01	S
7.2	5.54E-03	S	3.86E-05	S	1.35E+00	S	1.12E-01	S
7.4	8.53E-03	S	4.15E-05	S	1.45E+00	S	1.17E-01	S
7.6	1.18E-02	S	4.45E-05	S	1.57E+00	S	1.22E-01	S
7.8	1.81E-02	S	4.77E-05	S	1.69E+00	S	1.26E-01	S
8	2.91E-02	S	5.09E-05	S	1.81E+00	S	1.31E-01	S

Table C-5-23. Leachate Concentrations for Bituminous Fly Ash, Waste ID SHB Med

Sample ID
Date Exported
Database Name 5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	6.29E-02	S	5.42E-05	S	1.83E+00	W	1.01E-01	S
8.4	8.82E-02	S	5.76E-05	S	1.87E+00	W	9.40E-02	S
8.6	1.07E-01	S	6.10E-05	S	1.92E+00	W	8.76E-02	S
8.8	1.28E-01	S	5.82E-05	S	2.09E+00	W	8.47E-02	S
9	1.54E-01	S	5.21E-05	S	2.28E+00	W	8.20E-02	S
9.2	1.83E-01	S	4.68E-05	S	2.47E+00	W	7.94E-02	S
9.4	2.18E-01	S	4.20E-05	S	2.68E+00	W	7.70E-02	S
9.6	2.47E-01	S	3.97E-05	S	2.64E+00	W	6.65E-02	S
9.8	2.63E-01	S	4.00E-05	S	2.53E+00	W	5.55E-02	S
10	2.81E-01	S	4.03E-05	S	2.43E+00	W	4.65E-02	S
10.2	3.01E-01	W	4.07E-05	S	2.33E+00	W	3.91E-02	S
10.4	3.22E-01	W	4.10E-05	S	2.24E+00	W	3.29E-02	S
10.6	3.44E-01	W	4.13E-05	S	2.16E+00	W	2.79E-02	S
10.8	3.66E-01	W	4.16E-05	S	2.08E+00	W	2.37E-02	S
11	3.90E-01	W	4.19E-05	S	2.00E+00	W	2.01E-02	S
11.2	4.12E-01	W	4.23E-05	S	1.93E+00	W	1.72E-02	S
11.4	4.25E-01	W	4.26E-05	S	1.86E+00	W	1.47E-02	S
11.6	4.32E-01	W	4.29E-05	S	1.90E+00	W	1.73E-02	S
11.8	4.48E-01	W	4.19E-05	S	2.16E+00	W	3.48E-02	S
12	4.42E-01	W	3.65E-05	S	2.12E+00	W	2.87E-02	S
12.2	4.23E-01	W	3.72E-05	S	1.96E+00	W	1.85E-02	S
12.4	4.03E-01	W	3.86E-05	S	1.81E+00	W	1.20E-02	S
12.6	3.85E-01	W	3.83E-05	S	1.68E+00	W	7.88E-03	S
12.8	3.68E-01	W	3.58E-05	S	1.56E+00	W	5.19E-03	S
13	3.52E-01	W	3.36E-05	S	1.45E+00	W	3.44E-03	S
tection Limit (min, mg/	5.00E-04		3.60E-06		1.00E-03		8.00E-05	
tection Limit (max, mg/	5.00E-04		3.60E-06		1.00E-03		8.00E-05	
Availability (mg/kg)	1.72E+01		6.10E-04		2.68E+01		1.31E+00	

Table C-5-23. Leachate Concentrations for Bituminous Fly Ash, Waste ID SHB Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	0.10652918	S	0.07857581	S	0.20440248	S
3	9.76E-02	S	7.06E-02	S	1.29E-01	S
3.2	9.13E-02	S	6.36E-02	S	8.42E-02	S
3.4	9.17E-02	S	5.65E-02	S	5.63E-02	S
3.6	9.21E-02	S	4.99E-02	S	3.38E-02	S
3.8	9.25E-02	S	4.44E-02	S	1.72E-02	S
4	1.14E-01	S	2.30E-02	S	1.95E-02	S
4.2	1.34E-01	S	1.96E-02	S	2.03E-02	S
4.4	1.55E-01	S	1.69E-02	S	2.10E-02	S
4.6	1.78E-01	S	1.47E-02	S	2.27E-02	S
4.8	2.02E-01	S	1.32E-02	S	2.46E-02	S
5	2.26E-01	S	1.24E-02	S	2.66E-02	S
5.2	2.51E-01	S	1.18E-02	S	2.87E-02	S
5.4	2.78E-01	S	1.12E-02	S	3.09E-02	S
5.6	3.07E-01	S	1.06E-02	S	3.31E-02	S
5.8	3.37E-01	S	1.01E-02	S	3.54E-02	S
6	3.63E-01	S	9.68E-03	S	3.78E-02	S
6.2	3.88E-01	S	9.25E-03	S	4.03E-02	S
6.4	4.13E-01	S	8.85E-03	S	4.29E-02	S
6.6	4.40E-01	S	8.49E-03	S	4.55E-02	S
6.8	4.67E-01	S	8.14E-03	S	4.82E-02	S
7	4.94E-01	S	7.83E-03	S	5.10E-02	S
7.2	5.23E-01	S	7.07E-03	S	5.84E-02	S
7.4	5.77E-01	S	5.81E-03	S	6.68E-02	S
7.6	6.42E-01	S	4.74E-03	S	7.62E-02	S
7.8	7.13E-01	S	3.89E-03	S	8.86E-02	S
8	7.89E-01	S	3.21E-03	S	1.08E-01	S

Table C-5-23. Leachate Concentrations for Bituminous Fly Ash, Waste ID SHB Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	9.30E-01	S	2.86E-03	S	1.31E-01	S
8.4	1.07E+00	S	2.68E-03	S	1.27E-01	S
8.6	1.16E+00	S	2.53E-03	S	1.20E-01	S
8.8	1.25E+00	S	2.53E-03	S	1.14E-01	S
9	1.35E+00	S	2.53E-03	S	1.08E-01	S
9.2	1.45E+00	S	2.53E-03	S	1.02E-01	S
9.4	1.50E+00	S	2.53E-03	S	9.73E-02	S
9.6	1.52E+00	S	2.53E-03	S	9.26E-02	S
9.8	1.54E+00	S	2.53E-03	S	8.82E-02	S
10	1.57E+00	S	2.53E-03	S	8.41E-02	S
10.2	1.60E+00	S	2.53E-03	S	8.03E-02	S
10.4	1.62E+00	S	2.53E-03	S	7.67E-02	S
10.6	1.65E+00	S	2.53E-03	S	7.34E-02	S
10.8	1.65E+00	S	2.53E-03	S	7.02E-02	S
11	1.65E+00	S	2.53E-03	S	6.73E-02	S
11.2	1.67E+00	S	2.53E-03	S	6.45E-02	S
11.4	1.69E+00	S	2.53E-03	S	6.19E-02	S
11.6	1.71E+00	S	2.53E-03	S	5.94E-02	S
11.8	1.79E+00	S	2.53E-03	S	6.79E-02	S
12	2.05E+00	S	2.53E-03	S	5.80E-02	S
12.2	2.09E+00	S	2.53E-03	S	4.79E-02	S
12.4	2.17E+00	S	2.53E-03	S	3.90E-02	S
12.6	2.21E+00	S	2.53E-03	S	3.32E-02	S
12.8	2.21E+00	S	2.53E-03	S	2.84E-02	S
13	2.21E+00	S	2.53E-03	S	2.44E-02	S
tection Limit (min, mg/	5.20E-04		5.10E-04		3.10E-04	
tection Limit (max, mg	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	2.45E+01		7.86E-01		2.04E+00	

Table C-5-24. Leachate Concentrations for Bituminous Fly Ash, Waste ID SHT Med

Sample ID	SHT-[Med] (P,1,1)
Date Exported	8/27/2011, 6:50 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	2.85E-01	S	1.29E+01	W	6.83E-02	S	8.20E-02	S
3	2.58E-01	S	1.29E+01	W	6.60E-02	S	7.82E-02	S
3.2	2.34E-01	S	1.29E+01	W	6.39E-02	S	7.58E-02	S
3.4	2.14E-01	S	1.29E+01	W	6.21E-02	S	7.11E-02	S
3.6	1.81E-01	S	1.28E+01	W	5.75E-02	S	6.65E-02	S
3.8	1.44E-01	S	1.24E+01	W	5.30E-02	S	5.96E-02	S
4	1.34E-01	S	1.24E+01	W	5.19E-02	S	5.48E-02	S
4.2	1.26E-01	S	1.28E+01	W	5.24E-02	S	5.16E-02	S
4.4	1.18E-01	S	1.31E+01	W	5.27E-02	S	4.88E-02	S
4.6	1.12E-01	S	1.35E+01	W	5.35E-02	S	4.62E-02	S
4.8	1.05E-01	S	1.38E+01	W	5.47E-02	S	4.38E-02	S
5	9.98E-02	S	1.41E+01	W	5.53E-02	S	4.09E-02	S
5.2	9.47E-02	S	1.45E+01	W	5.59E-02	S	3.83E-02	S
5.4	9.00E-02	S	1.48E+01	W	5.65E-02	S	3.55E-02	S
5.6	8.58E-02	S	1.51E+01	W	5.71E-02	S	3.21E-02	S
5.8	8.58E-02	S	1.51E+01	W	5.80E-02	S	2.74E-02	S
6	8.91E-02	S	1.47E+01	W	5.96E-02	S	1.99E-02	S
6.2	9.25E-02	S	1.43E+01	W	6.12E-02	S	1.46E-02	S
6.4	9.58E-02	S	1.39E+01	W	6.27E-02	S	1.08E-02	S
6.6	9.92E-02	S	1.34E+01	W	6.43E-02	S	8.07E-03	S
6.8	1.03E-01	S	1.30E+01	W	6.58E-02	S	6.08E-03	S
7	1.06E-01	S	1.27E+01	W	6.74E-02	S	4.62E-03	S
7.2	1.09E-01	S	1.23E+01	W	6.89E-02	S	3.54E-03	S
7.4	1.13E-01	S	1.20E+01	W	7.04E-02	S	2.73E-03	S
7.6	1.18E-01	S	1.17E+01	W	7.19E-02	S	2.12E-03	S
7.8	1.27E-01	S	1.14E+01	W	7.34E-02	S	2.06E-03	S
8	1.39E-01	S	1.11E+01	W	7.48E-02	S	2.06E-03	S

Table C-5-24. Leachate Concentrations for Bituminous Fly Ash, Waste ID SHT Med

Sample ID	SHT-[Med] (P,1,1)
Date Exported	8/27/2011, 6:50 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	1.45E-01	S	1.08E+01	W	7.62E-02	W	2.06E-03	S
8.4	1.51E-01	S	1.06E+01	W	7.75E-02	W	2.06E-03	S
8.6	1.59E-01	S	1.07E+01	W	7.73E-02	W	2.06E-03	S
8.8	1.63E-01	S	1.07E+01	W	7.72E-02	W	2.06E-03	S
9	1.62E-01	S	1.07E+01	W	7.71E-02	W	2.06E-03	S
9.2	1.65E-01	S	1.07E+01	W	7.69E-02	W	2.06E-03	S
9.4	1.72E-01	S	1.06E+01	W	7.68E-02	W	2.06E-03	S
9.6	1.72E-01	S	1.03E+01	W	7.67E-02	W	2.06E-03	S
9.8	1.67E-01	S	9.96E+00	W	7.65E-02	W	2.06E-03	S
10	1.63E-01	S	9.64E+00	S	7.62E-02	W	2.06E-03	S
10.2	1.58E-01	S	9.33E+00	S	7.55E-02	W	2.06E-03	S
10.4	1.54E-01	S	9.03E+00	S	7.56E-02	W	2.06E-03	S
10.6	1.44E-01	S	8.75E+00	S	7.58E-02	W	2.06E-03	S
10.8	1.34E-01	S	8.48E+00	S	7.61E-02	W	2.06E-03	S
11	1.26E-01	S	8.23E+00	S	7.64E-02	W	2.06E-03	S
11.2	1.18E-01	S	7.99E+00	S	7.67E-02	W	2.06E-03	S
11.4	1.11E-01	S	7.76E+00	S	7.70E-02	W	2.06E-03	S
11.6	1.06E-01	S	7.54E+00	S	7.73E-02	W	2.06E-03	S
11.8	1.02E-01	S	7.32E+00	S	7.77E-02	W	2.06E-03	S
12	1.12E-01	S	7.15E+00	S	7.79E-02	W	2.06E-03	S
12.2	1.32E-01	S	7.01E+00	S	7.84E-02	W	2.06E-03	S
12.4	1.55E-01	S	6.87E+00	S	7.89E-02	W	2.06E-03	S
12.6	2.64E-01	S	7.04E+00	S	7.87E-02	W	2.06E-03	S
12.8	4.37E-01	S	7.40E+00	S	7.81E-02	W	2.06E-03	S
13	7.17E-01	S	7.77E+00	S	7.77E-02	W	2.06E-03	S
tection Limit (min, mg	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
tection Limit (max, mg	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	5.81E+00		1.51E+02		1.04E+00		8.20E-01	

Table C-5-24. Leachate Concentrations for Bituminous Fly Ash, Waste ID SHT Med

Sample ID
Date Exported
Database Name leling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	3.28E-01	S	3.49E-06	S	1.62E-01	S	1.23E-01	S
3	2.39E-01	S	2.98E-06	S	1.10E-01	S	1.26E-01	S
3.2	1.78E-01	S	2.57E-06	S	7.71E-02	S	1.28E-01	S
3.4	1.35E-01	S	2.24E-06	S	5.51E-02	S	1.31E-01	S
3.6	3.86E-02	S	2.07E-06	S	4.74E-02	S	1.42E-01	S
3.8	1.22E-02	S	2.07E-06	S	5.05E-02	S	1.64E-01	S
4	5.01E-03	S	2.25E-06	S	7.23E-02	S	1.71E-01	S
4.2	4.92E-03	S	2.68E-06	S	1.10E-01	S	1.78E-01	S
4.4	4.39E-03	S	3.17E-06	S	1.64E-01	S	1.84E-01	S
4.6	3.65E-03	S	3.73E-06	S	2.41E-01	S	1.91E-01	S
4.8	3.06E-03	S	4.36E-06	S	3.48E-01	S	1.97E-01	S
5	2.59E-03	S	5.05E-06	S	4.94E-01	S	2.04E-01	S
5.2	2.36E-03	S	5.83E-06	S	6.92E-01	S	2.10E-01	S
5.4	2.17E-03	S	6.68E-06	S	9.58E-01	S	2.17E-01	S
5.6	2.14E-03	S	7.63E-06	S	1.31E+00	S	2.23E-01	S
5.8	2.39E-03	S	8.67E-06	S	1.65E+00	S	2.30E-01	S
6	2.66E-03	S	9.80E-06	S	1.86E+00	S	2.37E-01	S
6.2	2.95E-03	S	1.10E-05	S	2.08E+00	W	2.44E-01	S
6.4	3.25E-03	S	1.24E-05	S	2.32E+00	W	2.50E-01	S
6.6	3.59E-03	S	1.05E-05	S	2.43E+00	W	2.61E-01	S
6.8	3.94E-03	S	8.51E-06	S	2.50E+00	W	2.71E-01	S
7	4.31E-03	S	6.91E-06	S	2.57E+00	W	2.82E-01	S
7.2	4.71E-03	S	5.65E-06	S	2.65E+00	W	2.93E-01	S
7.4	4.85E-03	S	4.64E-06	S	2.72E+00	W	3.05E-01	S
7.6	4.98E-03	S	3.83E-06	S	2.80E+00	W	3.16E-01	S
7.8	5.12E-03	S	3.18E-06	S	2.87E+00	W	3.27E-01	S
8	5.26E-03	S	2.65E-06	S	2.95E+00	W	3.39E-01	S

Table C-5-24. Leachate Concentrations for Bituminous Fly Ash, Waste ID SHT Med

Sample ID
Date Exported
Database Name leling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
8.2	6.33E-03	S	2.22E-06	S	3.02E+00	W	3.50E-01	S
8.4	9.34E-03	S	2.07E-06	S	3.10E+00	W	3.54E-01	S
8.6	1.28E-02	S	2.07E-06	S	3.18E+00	W	3.61E-01	S
8.8	1.73E-02	S	2.07E-06	S	3.27E+00	W	3.68E-01	S
9	2.33E-02	S	2.07E-06	S	3.35E+00	W	3.75E-01	S
9.2	2.92E-02	S	2.07E-06	S	3.44E+00	W	3.82E-01	S
9.4	3.83E-02	S	2.07E-06	S	3.47E+00	W	3.88E-01	S
9.6	4.32E-02	S	2.07E-06	S	3.41E+00	W	3.89E-01	S
9.8	4.87E-02	S	2.07E-06	S	3.34E+00	W	3.91E-01	S
10	5.48E-02	S	2.07E-06	S	3.27E+00	W	3.75E-01	S
10.2	6.23E-02	W	2.07E-06	S	3.20E+00	W	3.52E-01	S
10.4	7.13E-02	W	2.07E-06	S	3.12E+00	W	3.31E-01	S
10.6	7.68E-02	W	2.07E-06	S	3.06E+00	W	3.11E-01	S
10.8	8.05E-02	W	2.57E-06	S	3.01E+00	W	2.89E-01	S
11	8.19E-02	W	3.49E-06	S	2.97E+00	W	2.66E-01	S
11.2	8.33E-02	W	4.73E-06	S	2.93E+00	W	2.46E-01	S
11.4	8.47E-02	W	6.38E-06	S	2.89E+00	W	2.27E-01	S
11.6	8.68E-02	W	8.55E-06	S	2.85E+00	W	2.11E-01	S
11.8	8.95E-02	W	1.14E-05	S	2.82E+00	W	1.95E-01	S
12	9.20E-02	W	1.33E-05	S	2.79E+00	W	1.82E-01	S
12.2	9.45E-02	W	1.44E-05	S	2.76E+00	W	1.78E-01	S
12.4	9.68E-02	W	1.56E-05	S	2.72E+00	W	1.74E-01	S
12.6	9.28E-02	W	1.61E-05	S	2.75E+00	W	1.92E-01	S
12.8	8.35E-02	W	1.61E-05	S	2.81E+00	W	2.28E-01	S
13	7.52E-02	W	1.61E-05	S	2.87E+00	W	2.69E-01	S
tection Limit (min, mg/	5.00E-04		3.60E-06		1.00E-03		8.00E-05	
tection Limit (max, mg	5.00E-04		3.60E-06		1.00E-03		8.00E-05	
Availability (mg/kg)	3.28E+00		2.14E-04		3.74E+01		3.91E+00	

Table C-5-24. Leachate Concentrations for Bituminous Fly Ash, Waste ID SHT Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	1.28E-01	S	1.83E-01	S	1.38E+00	S
3	1.15E-01	S	1.51E-01	S	5.01E-01	S
3.2	1.04E-01	S	1.26E-01	S	1.94E-01	S
3.4	9.49E-02	S	1.06E-01	S	7.93E-02	S
3.6	9.13E-02	S	8.45E-02	S	4.30E-02	S
3.8	9.21E-02	S	6.37E-02	S	2.72E-02	S
4	9.46E-02	S	5.12E-02	S	3.06E-02	S
4.2	9.94E-02	S	4.36E-02	S	3.51E-02	S
4.4	1.10E-01	S	3.74E-02	S	3.99E-02	S
4.6	1.23E-01	S	3.24E-02	S	4.52E-02	S
4.8	1.38E-01	S	2.82E-02	S	5.14E-02	S
5	1.53E-01	S	2.46E-02	S	6.56E-02	S
5.2	1.65E-01	S	2.17E-02	S	8.20E-02	S
5.4	1.76E-01	S	1.92E-02	S	9.37E-02	S
5.6	1.87E-01	S	1.70E-02	S	1.07E-01	S
5.8	2.04E-01	S	1.50E-02	S	1.20E-01	S
6	2.32E-01	S	1.30E-02	S	1.35E-01	S
6.2	2.64E-01	S	1.13E-02	S	1.51E-01	S
6.4	2.98E-01	S	9.90E-03	S	1.69E-01	S
6.6	3.35E-01	S	8.48E-03	S	1.87E-01	S
6.8	3.75E-01	S	7.27E-03	S	2.08E-01	S
7	4.09E-01	S	6.25E-03	S	2.29E-01	S
7.2	4.46E-01	S	5.40E-03	S	2.52E-01	S
7.4	4.84E-01	S	4.69E-03	S	2.77E-01	S
7.6	5.24E-01	S	4.08E-03	S	3.04E-01	S
7.8	5.67E-01	S	3.57E-03	S	3.42E-01	S
8	6.11E-01	S	3.13E-03	S	3.84E-01	S

Table C-5-24. Leachate Concentrations for Bituminous Fly Ash, Waste ID SHT Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	6.58E-01	S	2.75E-03	S	4.31E-01	S
8.4	7.07E-01	S	2.53E-03	S	4.83E-01	S
8.6	7.58E-01	S	2.53E-03	S	5.43E-01	S
8.8	8.12E-01	S	2.53E-03	S	5.88E-01	S
9	8.68E-01	S	2.53E-03	S	6.36E-01	S
9.2	9.68E-01	S	2.53E-03	S	7.24E-01	S
9.4	1.07E+00	S	2.53E-03	S	8.08E-01	S
9.6	1.13E+00	S	2.53E-03	S	8.61E-01	S
9.8	1.20E+00	S	2.53E-03	S	9.16E-01	S
10	1.33E+00	S	2.53E-03	S	9.73E-01	S
10.2	1.43E+00	S	2.53E-03	S	1.03E+00	S
10.4	1.46E+00	S	2.53E-03	S	1.09E+00	S
10.6	1.49E+00	S	2.53E-03	S	1.06E+00	S
10.8	1.53E+00	S	2.53E-03	S	1.03E+00	S
11	1.57E+00	S	2.53E-03	S	1.00E+00	S
11.2	1.61E+00	S	2.53E-03	S	9.73E-01	S
11.4	1.66E+00	S	2.53E-03	S	9.47E-01	S
11.6	1.66E+00	S	2.53E-03	S	9.21E-01	S
11.8	1.70E+00	S	2.53E-03	S	8.98E-01	S
12	1.77E+00	S	2.53E-03	S	8.89E-01	S
12.2	1.89E+00	S	2.53E-03	S	8.95E-01	S
12.4	2.01E+00	S	2.53E-03	S	9.06E-01	S
12.6	2.12E+00	S	2.53E-03	S	1.08E+00	S
12.8	2.21E+00	S	2.53E-03	S	1.30E+00	S
13	2.21E+00	S	2.53E-03	S	1.55E+00	S
tection Limit (min, mg/	5.20E-04		5.10E-04		3.10E-04	
tection Limit (max, mg	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	2.94E+01		1.83E+00		1.72E+01	

Table C-5-25. Leachate Concentrations for Bituminous Fly Ash, Waste ID TFA Med

Sample ID	TFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:51 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	2.23E+00	S	1.25E+01	W	8.07E-02	W	2.47E-01	S
3	1.57E+00	S	1.22E+01	W	7.86E-02	W	2.24E-01	S
3.2	9.19E-01	S	1.18E+01	W	7.62E-02	W	1.99E-01	S
3.4	5.54E-01	S	1.14E+01	W	7.39E-02	W	1.79E-01	S
3.6	3.43E-01	S	1.10E+01	W	7.19E-02	W	1.61E-01	S
3.8	2.19E-01	S	1.07E+01	W	7.00E-02	W	1.47E-01	S
4	2.14E-01	S	1.04E+01	W	3.43E-02	S	9.25E-02	S
4.2	2.41E-01	S	1.01E+01	W	1.54E-02	S	5.57E-02	S
4.4	2.59E-01	S	1.00E+01	W	1.11E-02	S	3.96E-02	S
4.6	2.75E-01	S	9.91E+00	W	8.65E-03	S	2.94E-02	S
4.8	2.91E-01	S	9.81E+00	W	6.83E-03	S	2.20E-02	S
5	3.07E-01	S	9.72E+00	W	5.51E-03	S	1.67E-02	S
5.2	3.21E-01	S	9.65E+00	W	5.37E-03	S	1.28E-02	S
5.4	3.34E-01	S	9.58E+00	W	5.24E-03	S	9.90E-03	S
5.6	3.47E-01	S	9.51E+00	W	5.12E-03	S	7.73E-03	S
5.8	3.40E-01	S	8.91E+00	W	5.21E-03	S	8.33E-03	S
6	3.59E-01	S	8.87E+00	W	5.16E-03	S	6.41E-03	S
6.2	3.72E-01	S	8.87E+00	W	5.10E-03	S	5.06E-03	S
6.4	3.85E-01	S	8.87E+00	W	5.03E-03	S	4.03E-03	S
6.6	3.98E-01	S	8.88E+00	W	4.98E-03	S	3.23E-03	S
6.8	4.11E-01	S	8.88E+00	W	4.92E-03	S	2.60E-03	S
7	4.24E-01	S	8.87E+00	W	4.87E-03	S	2.14E-03	S
7.2	4.39E-01	S	8.77E+00	W	4.90E-03	S	2.06E-03	S
7.4	4.52E-01	S	8.67E+00	W	4.95E-03	S	2.06E-03	S
7.6	4.65E-01	S	8.57E+00	W	4.99E-03	S	2.06E-03	S
7.8	4.77E-01	S	8.47E+00	W	5.03E-03	S	2.06E-03	S

Table C-5-25. Leachate Concentrations for Bituminous Fly Ash, Waste ID TFA Med

Sample ID	TFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:51 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8	4.90E-01	S	8.38E+00	W	5.07E-03	S	2.06E-03	S
8.2	4.95E-01	S	8.34E+00	W	5.07E-03	W	2.06E-03	S
8.4	4.98E-01	S	8.31E+00	W	5.05E-03	W	2.06E-03	S
8.6	5.01E-01	S	8.28E+00	W	5.03E-03	W	2.06E-03	S
8.8	5.06E-01	S	8.23E+00	W	4.99E-03	W	2.06E-03	S
9	5.15E-01	S	8.13E+00	W	4.90E-03	W	2.06E-03	S
9.2	5.43E-01	S	8.00E+00	W	4.84E-03	W	2.06E-03	S
9.4	5.76E-01	S	7.88E+00	W	4.79E-03	W	2.06E-03	S
9.6	6.11E-01	S	7.76E+00	W	4.74E-03	W	2.06E-03	S
9.8	6.45E-01	S	7.70E+00	W	4.75E-03	W	2.06E-03	S
10	6.78E-01	S	7.71E+00	W	4.80E-03	W	2.06E-03	S
10.2	6.88E-01	S	7.76E+00	W	4.87E-03	W	2.06E-03	S
10.4	6.91E-01	S	7.82E+00	W	4.95E-03	W	2.06E-03	S
10.6	7.16E-01	S	7.85E+00	W	4.99E-03	W	2.06E-03	S
10.8	7.79E-01	S	7.86E+00	W	5.02E-03	W	2.06E-03	S
11	8.78E-01	S	7.86E+00	W	5.07E-03	W	2.06E-03	S
11.2	9.88E-01	S	7.86E+00	W	5.11E-03	W	2.06E-03	S
11.4	1.11E+00	S	7.86E+00	W	5.16E-03	W	2.06E-03	S
11.6	1.24E+00	S	7.86E+00	W	5.20E-03	W	2.06E-03	S
11.8	1.39E+00	S	7.86E+00	W	5.25E-03	W	2.06E-03	S
12	1.55E+00	S	7.86E+00	W	5.29E-03	W	2.06E-03	S
12.2	1.73E+00	S	7.86E+00	W	5.33E-03	W	2.06E-03	S
12.4	1.92E+00	S	7.86E+00	W	5.37E-03	W	2.06E-03	S
12.6	2.13E+00	S	7.86E+00	W	5.42E-03	W	2.06E-03	S
12.8	2.36E+00	S	7.86E+00	W	5.46E-03	W	2.06E-03	S
13	2.61E+00	S	7.86E+00	W	5.50E-03	W	2.06E-03	S
tection Limit (min, mg	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
tection Limit (max, mg	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	2.67E+01		1.25E+02		8.07E-01		2.47E+00	

Table C-5-25. Leachate Concentrations for Bituminous Fly Ash, Waste ID TFA Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	2.53E+00	S	3.00E-06	S	1.17E-01	S	3.07E-02	S
3	1.59E+00	S	3.00E-06	S	1.00E-01	S	3.11E-02	S
3.2	6.48E-01	S	3.00E-06	S	9.72E-02	S	2.98E-02	S
3.4	2.78E-01	S	3.00E-06	S	9.45E-02	S	2.87E-02	S
3.6	1.25E-01	S	3.00E-06	S	9.20E-02	S	2.76E-02	S
3.8	5.90E-02	S	2.32E-06	S	8.97E-02	S	2.67E-02	S
4	3.11E-02	S	3.00E-06	S	1.43E-01	S	3.50E-02	S
4.2	2.01E-02	S	3.00E-06	S	2.51E-01	S	4.82E-02	S
4.4	1.87E-02	S	3.00E-06	S	3.48E-01	S	5.53E-02	S
4.6	1.86E-02	S	3.00E-06	S	4.59E-01	S	6.12E-02	S
4.8	1.85E-02	S	3.00E-06	S	5.99E-01	S	6.75E-02	S
5	1.85E-02	S	3.00E-06	S	7.65E-01	S	7.38E-02	S
5.2	1.99E-02	S	3.00E-06	S	8.26E-01	W	7.49E-02	S
5.4	2.14E-02	S	3.00E-06	S	8.89E-01	W	7.59E-02	S
5.6	2.30E-02	S	3.00E-06	S	9.55E-01	W	7.69E-02	S
5.8	2.40E-02	S	3.00E-06	S	9.87E-01	W	7.92E-02	S
6	2.55E-02	S	3.00E-06	S	1.01E+00	W	7.98E-02	S
6.2	2.60E-02	S	3.00E-06	S	9.91E-01	W	8.01E-02	S
6.4	2.65E-02	S	3.00E-06	S	9.73E-01	W	8.04E-02	S
6.6	2.69E-02	S	3.00E-06	S	9.55E-01	W	8.07E-02	S
6.8	2.74E-02	S	3.00E-06	S	9.39E-01	W	8.10E-02	S
7	2.80E-02	S	3.00E-06	S	9.26E-01	W	8.13E-02	S
7.2	3.02E-02	S	3.00E-06	S	9.39E-01	W	8.11E-02	S
7.4	3.27E-02	S	3.00E-06	S	9.52E-01	W	8.07E-02	S
7.6	3.53E-02	S	3.00E-06	S	9.65E-01	W	8.02E-02	S
7.8	3.80E-02	S	3.00E-06	S	9.78E-01	W	7.98E-02	S

Table C-5-25. Leachate Concentrations for Bituminous Fly Ash, Waste ID TFA Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8	4.09E-02	S	3.00E-06	S	9.91E-01	W	7.94E-02	S
8.2	4.48E-02	S	3.00E-06	S	1.00E+00	W	7.77E-02	S
8.4	4.92E-02	S	3.00E-06	S	1.01E+00	W	7.57E-02	S
8.6	5.40E-02	S	3.00E-06	S	1.02E+00	W	7.39E-02	S
8.8	5.93E-02	S	3.00E-06	S	1.02E+00	W	7.19E-02	S
9	6.55E-02	S	3.00E-06	S	1.03E+00	W	6.96E-02	S
9.2	7.16E-02	S	3.00E-06	S	1.04E+00	W	6.71E-02	S
9.4	7.79E-02	S	3.00E-06	S	1.05E+00	W	6.48E-02	S
9.6	8.47E-02	S	3.00E-06	S	1.06E+00	W	6.26E-02	S
9.8	9.09E-02	S	3.00E-06	S	1.07E+00	W	5.99E-02	S
10	9.64E-02	S	3.00E-06	S	1.07E+00	W	5.68E-02	S
10.2	1.01E-01	S	3.00E-06	S	1.08E+00	W	5.34E-02	S
10.4	1.04E-01	S	3.00E-06	S	1.09E+00	W	5.01E-02	S
10.6	1.08E-01	S	3.00E-06	S	1.11E+00	W	4.79E-02	S
10.8	1.13E-01	S	3.00E-06	S	1.12E+00	W	4.66E-02	S
11	1.18E-01	S	3.00E-06	S	1.14E+00	W	4.60E-02	S
11.2	1.23E-01	S	3.00E-06	S	1.15E+00	W	4.54E-02	S
11.4	1.28E-01	S	3.00E-06	S	1.16E+00	W	4.48E-02	S
11.6	1.33E-01	S	3.00E-06	S	1.18E+00	W	4.42E-02	S
11.8	1.38E-01	S	3.00E-06	S	1.19E+00	W	4.36E-02	S
12	1.44E-01	S	3.00E-06	S	1.20E+00	W	4.31E-02	S
12.2	1.49E-01	S	3.00E-06	S	1.22E+00	W	4.25E-02	S
12.4	1.55E-01	S	3.00E-06	S	1.22E+00	W	4.20E-02	S
12.6	1.61E-01	S	3.00E-06	S	1.22E+00	W	4.15E-02	S
12.8	1.66E-01	S	3.00E-06	S	1.22E+00	W	4.10E-02	S
13	1.72E-01	S	3.00E-06	S	1.22E+00	W	4.05E-02	S
tection Limit (min, mg	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
tection Limit (max, mg	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	2.53E+01		3.40E-05		1.38E+01		8.13E-01	

Table C-5-25. Leachate Concentrations for Bituminous Fly Ash, Waste ID TFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	3.69E-01	S	2.57E-01	S	1.64E+00	S
3	3.22E-01	S	2.23E-01	S	7.94E-01	S
3.2	2.68E-01	S	1.89E-01	S	3.05E-01	S
3.4	2.26E-01	S	1.62E-01	S	1.24E-01	S
3.6	1.92E-01	S	1.40E-01	S	5.31E-02	S
3.8	1.65E-01	S	1.21E-01	S	2.38E-02	S
4	1.38E-01	S	6.79E-02	S	2.59E-02	S
4.2	1.19E-01	S	3.67E-02	S	3.62E-02	S
4.4	1.18E-01	S	2.73E-02	S	4.34E-02	S
4.6	1.20E-01	S	2.17E-02	S	5.04E-02	S
4.8	1.22E-01	S	1.73E-02	S	5.82E-02	S
5	1.24E-01	S	1.41E-02	S	6.66E-02	S
5.2	1.38E-01	S	1.29E-02	S	7.11E-02	S
5.4	1.52E-01	S	1.18E-02	S	7.57E-02	S
5.6	1.67E-01	S	1.09E-02	S	8.05E-02	S
5.8	1.72E-01	S	1.07E-02	S	7.57E-02	S
6	1.91E-01	S	1.00E-02	S	8.10E-02	S
6.2	2.02E-01	S	9.57E-03	S	8.46E-02	S
6.4	2.14E-01	S	9.16E-03	S	8.82E-02	S
6.6	2.25E-01	S	8.79E-03	S	9.18E-02	S
6.8	2.37E-01	S	8.44E-03	S	9.55E-02	S
7	2.50E-01	S	8.10E-03	S	9.94E-02	S
7.2	2.70E-01	S	7.42E-03	S	1.05E-01	S
7.4	2.91E-01	S	6.70E-03	S	1.11E-01	S
7.6	3.13E-01	S	6.07E-03	S	1.17E-01	S
7.8	3.35E-01	S	5.51E-03	S	1.24E-01	S

Table C-5-25. Leachate Concentrations for Bituminous Fly Ash, Waste ID TFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8	3.59E-01	S	5.01E-03	S	1.31E-01	S
8.2	3.93E-01	S	4.64E-03	S	1.42E-01	S
8.4	4.30E-01	S	4.32E-03	S	1.55E-01	S
8.6	4.71E-01	S	4.03E-03	S	1.69E-01	S
8.8	5.20E-01	S	3.84E-03	S	1.89E-01	S
9	5.85E-01	S	3.82E-03	S	2.18E-01	S
9.2	6.59E-01	S	3.55E-03	S	2.60E-01	S
9.4	7.42E-01	S	3.27E-03	S	3.11E-01	S
9.6	8.32E-01	S	3.01E-03	S	3.71E-01	S
9.8	9.11E-01	S	2.78E-03	S	4.31E-01	S
10	9.74E-01	S	2.57E-03	S	4.89E-01	S
10.2	1.01E+00	S	2.53E-03	S	5.34E-01	S
10.4	1.04E+00	S	2.53E-03	S	5.76E-01	S
10.6	1.08E+00	S	2.53E-03	S	6.19E-01	S
10.8	1.13E+00	S	2.53E-03	S	6.60E-01	S
11	1.18E+00	S	2.53E-03	S	7.00E-01	S
11.2	1.23E+00	S	2.53E-03	S	7.42E-01	S
11.4	1.29E+00	S	2.53E-03	S	7.85E-01	S
11.6	1.34E+00	S	2.53E-03	S	8.30E-01	S
11.8	1.40E+00	S	2.53E-03	S	8.77E-01	S
12	1.46E+00	S	2.53E-03	S	9.26E-01	S
12.2	1.51E+00	S	2.53E-03	S	9.76E-01	S
12.4	1.51E+00	S	2.53E-03	S	1.03E+00	S
12.6	1.51E+00	S	2.53E-03	S	1.08E+00	S
12.8	1.51E+00	S	2.53E-03	S	1.14E+00	S
13	1.51E+00	S	2.53E-03	S	1.20E+00	S
tection Limit (min, mg	5.20E-04		5.10E-04		3.10E-04	
tection Limit (max, mg	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	1.71E+01		2.57E+00		1.64E+01	

Table C-5-26. Leachate Concentrations for Bituminous Fly Ash, Waste ID UFA Med

Sample ID UFA-[Med] (P,1,1)
Date Exported 8/27/2011, 6:51 PM
Database Name C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version 1.2.12.11227

	Concentration (mg/L)							
pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	1.57E+00	S	4.69E+01	W	1.52E+00	S	3.32E-01	S
3	1.46E+00	S	4.66E+01	W	1.49E+00	S	3.20E-01	S
3.2	1.30E+00	S	4.54E+01	W	1.16E+00	S	2.85E-01	S
3.4	1.16E+00	S	4.43E+01	W	9.13E-01	S	2.56E-01	S
3.6	1.05E+00	S	4.32E+01	W	7.29E-01	S	2.30E-01	S
3.8	9.54E-01	S	4.23E+01	W	5.90E-01	S	2.09E-01	S
4	8.74E-01	S	4.14E+01	W	4.74E-01	S	1.89E-01	S
4.2	8.75E-01	S	4.14E+01	W	2.80E-01	S	1.45E-01	S
4.4	8.75E-01	S	4.14E+01	W	1.69E-01	S	1.13E-01	S
4.6	8.75E-01	S	4.13E+01	W	1.05E-01	S	8.88E-02	S
4.8	8.75E-01	S	4.13E+01	W	6.63E-02	S	7.05E-02	S
5	8.73E-01	S	4.12E+01	W	4.47E-02	S	5.69E-02	S
5.2	8.56E-01	S	4.09E+01	W	3.98E-02	S	4.80E-02	S
5.4	8.40E-01	S	4.06E+01	W	3.57E-02	S	4.07E-02	S
5.6	8.25E-01	S	4.04E+01	W	3.20E-02	S	3.47E-02	S
5.8	8.10E-01	S	4.01E+01	W	2.89E-02	S	2.98E-02	S
6	7.97E-01	S	3.99E+01	W	2.61E-02	S	2.57E-02	S
6.2	7.84E-01	S	3.96E+01	W	2.37E-02	S	2.23E-02	S
6.4	7.71E-01	S	3.94E+01	W	2.20E-02	S	1.97E-02	S
6.6	7.60E-01	S	3.91E+01	W	2.19E-02	S	1.89E-02	S
6.8	7.49E-01	S	3.88E+01	W	2.18E-02	S	1.81E-02	S
7	7.39E-01	S	3.85E+01	W	2.18E-02	S	1.73E-02	S
7.2	7.29E-01	S	3.83E+01	W	2.17E-02	S	1.66E-02	S
7.4	7.19E-01	S	3.80E+01	W	2.16E-02	S	1.60E-02	S
7.6	7.10E-01	S	3.78E+01	W	2.15E-02	S	1.54E-02	S
7.8	7.02E-01	S	3.75E+01	W	2.15E-02	S	1.48E-02	S
8	6.16E-01	S	3.69E+01	W	2.09E-02	S	1.31E-02	S

Table C-5-26. Leachate Concentrations for Bituminous Fly Ash, Waste ID UFA Med

Sample ID UFA-[Med] (P,1,1)
Date Exported 8/27/2011, 6:51 PM
Database Name C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version 1.2.12.11227

	Concentration (mg/L)							
pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	5.32E-01	S	3.62E+01	W	2.03E-02	W	1.14E-02	S
8.4	4.61E-01	S	3.55E+01	W	1.97E-02	W	1.00E-02	S
8.6	4.01E-01	S	3.48E+01	W	1.91E-02	W	8.82E-03	S
8.8	3.23E-01	S	3.42E+01	W	1.88E-02	W	8.03E-03	S
9	2.53E-01	S	3.36E+01	S	1.87E-02	W	7.42E-03	S
9.2	1.99E-01	S	3.30E+01	S	1.85E-02	W	6.87E-03	S
9.4	1.57E-01	S	3.24E+01	S	1.83E-02	W	6.37E-03	S
9.6	1.22E-01	S	3.20E+01	S	1.89E-02	W	6.17E-03	S
9.8	9.42E-02	S	3.16E+01	S	1.96E-02	W	6.05E-03	S
10	7.33E-02	S	3.12E+01	S	2.04E-02	W	5.93E-03	S
10.2	5.73E-02	S	3.08E+01	S	2.12E-02	W	5.83E-03	S
10.4	4.50E-02	S	3.05E+01	S	2.20E-02	W	5.72E-03	S
10.6	3.83E-02	S	2.87E+01	S	2.26E-02	W	5.37E-03	S
10.8	3.87E-02	S	2.43E+01	S	2.28E-02	W	4.55E-03	S
11	3.92E-02	S	2.06E+01	S	2.29E-02	W	3.87E-03	S
11.2	3.96E-02	S	1.75E+01	S	2.31E-02	W	3.30E-03	S
11.4	4.01E-02	S	1.49E+01	S	2.32E-02	W	2.82E-03	S
11.6	4.05E-02	S	1.27E+01	S	2.33E-02	W	2.42E-03	S
11.8	4.09E-02	S	1.09E+01	S	2.35E-02	W	2.08E-03	S
12	4.26E-02	S	1.01E+01	S	2.39E-02	W	2.06E-03	S
12.2	4.43E-02	S	9.48E+00	S	2.43E-02	W	2.06E-03	S
12.4	4.61E-02	S	8.86E+00	S	2.47E-02	W	2.06E-03	S
12.6	4.80E-02	S	8.30E+00	S	2.51E-02	W	2.06E-03	S
12.8	4.99E-02	S	7.77E+00	S	2.55E-02	W	2.06E-03	S
13	5.18E-02	S	7.29E+00	S	2.59E-02	W	2.06E-03	S
tection Limit (min, mg	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
tection Limit (max, mg	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	1.57E+01		4.69E+02		1.52E+01		3.32E+00	

Table C-5-26. Leachate Concentrations for Bituminous Fly Ash, Waste ID UFA Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
2.8	1.43E+01	S	3.00E-06	S	6.06E-01	S	7.19E-02	W
3	1.43E+01	S	1.80E-06	S	4.70E-01	S	7.31E-02	W
3.2	6.50E+00	S	3.00E-06	S	8.59E-01	S	6.90E-02	W
3.4	3.11E+00	S	3.00E-06	S	1.51E+00	S	6.53E-02	W
3.6	1.55E+00	S	3.00E-06	S	2.58E+00	S	6.20E-02	W
3.8	8.02E-01	S	3.00E-06	S	4.28E+00	S	5.91E-02	W
4	4.34E-01	S	3.00E-06	S	6.78E+00	S	5.66E-02	W
4.2	2.98E-01	S	3.00E-06	S	7.32E+00	S	5.74E-02	W
4.4	2.08E-01	S	3.00E-06	S	7.88E+00	S	5.81E-02	W
4.6	1.47E-01	S	3.00E-06	S	8.45E+00	S	5.89E-02	W
4.8	1.06E-01	S	3.00E-06	S	9.04E+00	S	5.96E-02	W
5	8.18E-02	S	3.00E-06	S	9.56E+00	S	6.01E-02	W
5.2	8.68E-02	S	3.00E-06	S	9.65E+00	W	5.98E-02	W
5.4	9.18E-02	S	3.00E-06	S	9.73E+00	W	5.95E-02	W
5.6	9.70E-02	S	3.00E-06	S	9.81E+00	W	5.92E-02	W
5.8	1.02E-01	S	3.00E-06	S	9.89E+00	W	5.90E-02	W
6	1.08E-01	S	3.00E-06	S	9.96E+00	W	5.87E-02	W
6.2	1.13E-01	S	3.00E-06	S	1.00E+01	W	5.85E-02	W
6.4	1.26E-01	S	3.00E-06	S	1.01E+01	W	5.83E-02	W
6.6	1.80E-01	S	3.00E-06	S	1.02E+01	W	5.84E-02	W
6.8	2.54E-01	S	3.00E-06	S	1.03E+01	W	5.85E-02	W
7	3.54E-01	S	3.00E-06	S	1.03E+01	W	5.87E-02	W
7.2	4.90E-01	S	3.00E-06	S	1.04E+01	W	5.88E-02	W
7.4	6.71E-01	S	3.00E-06	S	1.05E+01	W	5.89E-02	W
7.6	9.13E-01	S	3.00E-06	S	1.05E+01	W	5.90E-02	W
7.8	1.23E+00	S	3.00E-06	S	1.06E+01	W	5.91E-02	W
8	1.23E+00	S	3.00E-06	S	1.07E+01	W	5.85E-02	W

Table C-5-26. Leachate Concentrations for Bituminous Fly Ash, Waste ID UFA Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
8.2	1.16E+00	W	3.00E-06	S	1.09E+01	W	5.77E-02	S
8.4	1.10E+00	W	3.00E-06	S	1.10E+01	W	5.70E-02	S
8.6	1.04E+00	W	3.00E-06	S	1.11E+01	W	5.64E-02	S
8.8	1.15E+00	W	3.00E-06	S	1.12E+01	W	5.34E-02	S
9	1.34E+00	W	6.05E-06	S	1.13E+01	W	4.97E-02	S
9.2	1.56E+00	W	1.21E-05	S	1.13E+01	W	4.64E-02	S
9.4	1.81E+00	W	2.38E-05	S	1.14E+01	W	4.34E-02	S
9.6	1.95E+00	W	1.89E-05	S	1.17E+01	W	3.71E-02	S
9.8	2.06E+00	W	1.13E-05	S	1.22E+01	W	3.09E-02	S
10	2.16E+00	W	6.77E-06	S	1.27E+01	W	2.58E-02	S
10.2	2.27E+00	W	4.11E-06	S	1.32E+01	W	2.16E-02	S
10.4	2.39E+00	W	3.00E-06	S	1.37E+01	W	1.82E-02	S
10.6	2.44E+00	W	3.00E-06	S	1.41E+01	W	1.48E-02	S
10.8	2.33E+00	W	3.00E-06	S	1.41E+01	W	1.11E-02	S
11	2.23E+00	W	3.00E-06	S	1.42E+01	W	8.35E-03	S
11.2	2.14E+00	W	3.00E-06	S	1.42E+01	W	6.32E-03	S
11.4	2.05E+00	W	3.00E-06	S	1.43E+01	W	4.80E-03	S
11.6	1.97E+00	W	3.00E-06	S	1.43E+01	W	3.67E-03	S
11.8	1.89E+00	W	3.00E-06	S	1.44E+01	W	2.82E-03	S
12	1.77E+00	W	5.88E-06	S	1.45E+01	W	2.78E-03	S
12.2	1.67E+00	W	2.00E-05	S	1.45E+01	W	2.78E-03	S
12.4	1.57E+00	W	3.75E-05	S	1.45E+01	W	2.78E-03	S
12.6	1.48E+00	W	3.75E-05	S	1.45E+01	W	2.78E-03	S
12.8	1.40E+00	W	3.75E-05	S	1.45E+01	W	2.78E-03	S
13	1.32E+00	W	3.75E-05	S	1.45E+01	W	2.78E-03	S
tection Limit (min, mg/	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
tection Limit (max, mg	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	1.43E+02		3.79E-04		1.47E+02		7.31E-01	

Table C-5-26. Leachate Concentrations for Bituminous Fly Ash, Waste ID UFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	4.39E-01	S	9.37E-01	S	1.21E+01	S
3	4.19E-01	S	8.96E-01	S	1.07E+01	S
3.2	3.23E-01	S	7.26E-01	S	8.20E+00	S
3.4	2.53E-01	S	5.96E-01	S	6.39E+00	S
3.6	2.02E-01	S	4.95E-01	S	5.05E+00	S
3.8	1.62E-01	S	4.15E-01	S	4.04E+00	S
4	1.33E-01	S	3.52E-01	S	3.31E+00	S
4.2	1.26E-01	S	3.22E-01	S	3.39E+00	W
4.4	1.20E-01	S	2.95E-01	S	3.46E+00	W
4.6	1.15E-01	S	2.72E-01	S	3.54E+00	W
4.8	1.10E-01	S	2.51E-01	S	3.61E+00	W
5	1.06E-01	S	2.35E-01	S	3.67E+00	W
5.2	1.07E-01	S	2.29E-01	S	3.63E+00	W
5.4	1.09E-01	S	2.23E-01	S	3.59E+00	W
5.6	1.10E-01	S	2.18E-01	S	3.55E+00	W
5.8	1.12E-01	S	2.13E-01	S	3.52E+00	W
6	1.13E-01	S	2.08E-01	S	3.48E+00	W
6.2	1.14E-01	S	2.03E-01	S	3.45E+00	W
6.4	1.15E-01	S	2.00E-01	S	3.42E+00	W
6.6	1.15E-01	S	2.01E-01	S	3.41E+00	W
6.8	1.15E-01	S	2.02E-01	S	3.40E+00	W
7	1.14E-01	S	2.04E-01	S	3.39E+00	W
7.2	1.14E-01	S	2.05E-01	S	3.38E+00	W
7.4	1.14E-01	S	2.06E-01	S	3.37E+00	W
7.6	1.13E-01	S	2.07E-01	S	3.36E+00	W
7.8	1.13E-01	S	2.08E-01	S	3.35E+00	W
8	1.15E-01	S	2.01E-01	S	3.30E+00	W

Table C-5-26. Leachate Concentrations for Bituminous Fly Ash, Waste ID UFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	1.18E-01	S	1.94E-01	S	3.24E+00	W
8.4	1.20E-01	S	1.87E-01	S	3.18E+00	W
8.6	1.23E-01	S	1.80E-01	S	3.13E+00	W
8.8	1.28E-01	S	1.72E-01	S	3.11E+00	W
9	1.34E-01	S	1.63E-01	S	3.12E+00	S
9.2	1.39E-01	S	1.56E-01	S	3.12E+00	S
9.4	1.46E-01	S	1.48E-01	S	3.12E+00	S
9.6	1.51E-01	S	1.46E-01	S	2.70E+00	S
9.8	1.56E-01	S	1.45E-01	S	2.23E+00	S
10	1.62E-01	S	1.43E-01	S	1.85E+00	S
10.2	1.67E-01	S	1.42E-01	S	1.54E+00	S
10.4	1.73E-01	S	1.42E-01	S	1.29E+00	S
10.6	1.66E-01	S	1.40E-01	S	1.09E+00	S
10.8	1.36E-01	S	1.36E-01	S	9.43E-01	S
11	1.12E-01	S	1.32E-01	S	8.18E-01	S
11.2	9.20E-02	S	1.29E-01	S	7.11E-01	S
11.4	7.60E-02	S	1.25E-01	S	6.19E-01	S
11.6	6.30E-02	S	1.22E-01	S	5.41E-01	S
11.8	5.24E-02	S	1.19E-01	S	4.74E-01	S
12	5.08E-02	S	1.82E-01	S	4.61E-01	S
12.2	4.96E-02	S	2.83E-01	S	4.51E-01	S
12.4	4.85E-02	S	4.38E-01	S	4.42E-01	S
12.6	4.74E-02	S	6.71E-01	S	4.33E-01	S
12.8	4.64E-02	S	1.02E+00	S	4.24E-01	S
13	4.54E-02	S	1.31E+00	S	4.16E-01	S
tection Limit (min, mg/	5.20E-04		5.10E-04		3.10E-04	
tection Limit (max, mg	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	4.39E+00		1.03E+01		1.21E+02	

Table C-5-27. Leachate Concentrations for Bituminous Fly Ash, Waste ID WFA Med

Sample ID	WFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:51 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	6.82E-01	S	5.00E+00	W	4.02E-02	S	2.43E-01	S
3	4.77E-01	S	4.97E+00	W	3.96E-02	S	2.30E-01	S
3.2	3.41E-01	S	4.94E+00	W	3.91E-02	S	2.18E-01	S
3.4	3.18E-01	S	4.81E+00	W	3.76E-02	S	1.92E-01	S
3.6	3.01E-01	S	4.69E+00	W	3.63E-02	S	1.70E-01	S
3.8	2.85E-01	S	4.57E+00	W	3.51E-02	S	1.51E-01	S
4	2.58E-01	S	4.48E+00	W	3.38E-02	S	1.39E-01	S
4.2	2.20E-01	S	4.38E+00	W	3.29E-02	S	1.29E-01	S
4.4	1.87E-01	S	4.29E+00	W	3.21E-02	S	1.21E-01	S
4.6	1.60E-01	S	4.21E+00	W	3.13E-02	S	1.13E-01	S
4.8	1.38E-01	S	4.13E+00	W	3.06E-02	S	1.07E-01	S
5	1.19E-01	S	4.06E+00	W	2.99E-02	S	1.01E-01	S
5.2	1.12E-01	S	4.00E+00	W	2.87E-02	S	9.53E-02	S
5.4	1.19E-01	S	3.96E+00	W	2.68E-02	S	9.18E-02	S
5.6	1.27E-01	S	3.93E+00	W	2.51E-02	S	8.86E-02	S
5.8	1.34E-01	S	3.90E+00	W	2.36E-02	S	8.56E-02	S
6	1.41E-01	S	3.87E+00	W	2.21E-02	S	8.28E-02	S
6.2	1.48E-01	S	3.84E+00	W	2.07E-02	S	8.01E-02	S
6.4	1.68E-01	S	3.79E+00	W	1.76E-02	S	7.38E-02	S
6.6	1.91E-01	S	3.74E+00	W	1.49E-02	S	6.80E-02	S
6.8	2.20E-01	S	3.69E+00	W	1.25E-02	S	6.05E-02	S
7	2.65E-01	S	3.64E+00	W	1.00E-02	S	4.85E-02	S
7.2	3.18E-01	S	3.59E+00	W	8.04E-03	S	3.91E-02	S
7.4	4.19E-01	S	3.53E+00	W	5.54E-03	S	2.54E-02	S
7.6	5.48E-01	S	3.46E+00	W	3.86E-03	S	1.67E-02	S
7.8	6.87E-01	S	3.41E+00	W	3.00E-03	S	1.13E-02	S
8	8.39E-01	S	3.38E+00	W	2.51E-03	S	7.89E-03	S

Table C-5-27. Leachate Concentrations for Bituminous Fly Ash, Waste ID WFA Med

Sample ID	WFA-[Med] (P,1,1)
Date Exported	8/27/2011, 6:51 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	1.01E+00	S	3.34E+00	W	2.37E-03	W	5.87E-03	S
8.4	1.20E+00	S	3.30E+00	W	2.25E-03	W	4.39E-03	S
8.6	1.43E+00	S	3.26E+00	W	2.14E-03	W	3.31E-03	S
8.8	1.70E+00	S	3.23E+00	W	2.03E-03	W	2.51E-03	S
9	1.98E+00	S	3.20E+00	W	1.94E-03	W	2.15E-03	S
9.2	2.19E+00	S	3.18E+00	W	1.95E-03	W	2.06E-03	S
9.4	2.37E+00	S	3.17E+00	W	2.00E-03	W	2.06E-03	S
9.6	2.56E+00	S	3.16E+00	W	2.04E-03	W	2.06E-03	S
9.8	2.77E+00	S	3.16E+00	W	2.09E-03	W	2.06E-03	S
10	2.98E+00	S	3.15E+00	W	2.13E-03	W	2.06E-03	S
10.2	3.20E+00	S	3.14E+00	W	2.19E-03	W	2.06E-03	S
10.4	3.30E+00	S	3.13E+00	W	2.26E-03	W	2.06E-03	S
10.6	3.41E+00	S	3.14E+00	W	2.30E-03	W	2.06E-03	S
10.8	3.52E+00	S	3.15E+00	W	2.33E-03	W	2.06E-03	S
11	3.63E+00	S	3.15E+00	W	2.36E-03	W	2.06E-03	S
11.2	3.73E+00	W	3.16E+00	W	2.36E-03	W	2.06E-03	S
11.4	3.89E+00	W	3.21E+00	W	2.34E-03	W	2.06E-03	S
11.6	4.07E+00	W	3.27E+00	W	2.33E-03	W	2.06E-03	S
11.8	4.24E+00	W	3.34E+00	W	2.32E-03	W	2.06E-03	S
12	4.42E+00	W	3.40E+00	W	2.32E-03	W	2.06E-03	S
12.2	4.47E+00	W	3.46E+00	W	2.31E-03	W	2.06E-03	S
12.4	4.48E+00	W	3.53E+00	W	2.30E-03	W	2.06E-03	S
12.6	4.49E+00	W	3.59E+00	W	2.30E-03	W	2.06E-03	S
12.8	4.49E+00	W	3.65E+00	W	2.29E-03	W	2.06E-03	S
13	4.50E+00	W	3.66E+00	W	2.28E-03	W	2.06E-03	S
tection Limit (min, mg	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
tection Limit (max, mg	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	4.87E+01		4.98E+01		4.01E-01		2.43E+00	

Table C-5-27. Leachate Concentrations for Bituminous Fly Ash, Waste ID WFA Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	2.81E+00	S	3.00E-06	S	2.84E-01	S	3.68E-02	S
3	2.72E+00	S	3.00E-06	S	2.19E-01	S	4.37E-02	S
3.2	2.65E+00	S	3.00E-06	S	1.72E-01	S	5.12E-02	S
3.4	2.14E+00	S	3.00E-06	S	1.82E-01	S	5.68E-02	S
3.6	1.74E+00	S	3.00E-06	S	1.95E-01	S	6.25E-02	S
3.8	1.41E+00	S	3.00E-06	S	2.09E-01	S	6.84E-02	S
4	9.32E-01	S	3.00E-06	S	2.37E-01	S	7.35E-02	S
4.2	5.24E-01	S	3.00E-06	S	2.82E-01	S	7.79E-02	S
4.4	2.89E-01	S	3.00E-06	S	3.37E-01	S	8.20E-02	S
4.6	1.64E-01	S	3.00E-06	S	4.00E-01	S	8.63E-02	S
4.8	9.50E-02	S	3.00E-06	S	4.72E-01	S	9.05E-02	S
5	5.64E-02	S	3.00E-06	S	5.53E-01	S	9.47E-02	S
5.2	3.45E-02	S	3.00E-06	S	6.56E-01	S	9.99E-02	S
5.4	2.44E-02	S	3.00E-06	S	7.75E-01	S	1.06E-01	S
5.6	1.77E-02	S	3.00E-06	S	9.10E-01	S	1.12E-01	S
5.8	1.29E-02	S	3.00E-06	S	1.06E+00	S	1.19E-01	S
6	9.96E-03	S	3.00E-06	S	1.21E+00	S	1.25E-01	S
6.2	9.23E-03	S	3.00E-06	S	1.30E+00	S	1.28E-01	W
6.4	1.00E-02	S	3.00E-06	S	1.38E+00	S	1.31E-01	W
6.6	1.10E-02	S	3.00E-06	S	1.46E+00	S	1.34E-01	W
6.8	1.26E-02	S	3.00E-06	S	1.53E+00	S	1.36E-01	W
7	1.65E-02	S	3.00E-06	S	1.59E+00	S	1.37E-01	W
7.2	2.15E-02	S	2.32E-06	S	1.65E+00	W	1.38E-01	W
7.4	3.83E-02	S	3.00E-06	S	1.72E+00	W	1.36E-01	W
7.6	6.73E-02	S	3.00E-06	S	1.80E+00	W	1.35E-01	W
7.8	1.04E-01	S	3.00E-06	S	1.86E+00	W	1.34E-01	W
8	1.48E-01	S	3.00E-06	S	1.91E+00	W	1.32E-01	W

Table C-5-27. Leachate Concentrations for Bituminous Fly Ash, Waste ID WFA Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	1.67E-01	S	3.00E-06	S	1.91E+00	W	1.31E-01	W
8.4	1.88E-01	S	3.00E-06	S	1.92E+00	W	1.30E-01	W
8.6	2.11E-01	S	3.00E-06	S	1.92E+00	W	1.28E-01	W
8.8	2.36E-01	S	3.00E-06	S	1.93E+00	W	1.27E-01	W
9	2.55E-01	S	3.00E-06	S	1.93E+00	W	1.27E-01	W
9.2	2.64E-01	W	3.00E-06	S	1.93E+00	W	1.27E-01	W
9.4	2.69E-01	W	3.00E-06	S	1.94E+00	W	1.28E-01	W
9.6	2.74E-01	W	3.00E-06	S	1.95E+00	W	1.29E-01	W
9.8	2.79E-01	W	3.00E-06	S	1.95E+00	W	1.30E-01	W
10	2.84E-01	W	3.00E-06	S	1.96E+00	W	1.31E-01	W
10.2	2.89E-01	W	3.00E-06	S	1.97E+00	W	1.32E-01	W
10.4	2.91E-01	W	3.00E-06	S	1.97E+00	W	1.34E-01	W
10.6	2.92E-01	W	3.00E-06	S	1.97E+00	W	1.37E-01	W
10.8	2.94E-01	W	3.00E-06	S	1.97E+00	W	1.40E-01	W
11	2.96E-01	W	3.00E-06	S	1.97E+00	W	1.42E-01	W
11.2	2.97E-01	W	3.00E-06	S	1.97E+00	W	1.45E-01	W
11.4	3.01E-01	W	3.00E-06	S	1.97E+00	W	1.49E-01	W
11.6	3.05E-01	W	3.00E-06	S	1.97E+00	W	1.53E-01	W
11.8	3.10E-01	W	3.00E-06	S	1.97E+00	W	1.58E-01	W
12	3.15E-01	W	3.00E-06	S	1.98E+00	W	1.62E-01	W
12.2	3.19E-01	W	3.00E-06	S	1.97E+00	W	1.63E-01	W
12.4	3.24E-01	W	3.00E-06	S	1.97E+00	W	1.62E-01	W
12.6	3.28E-01	W	3.00E-06	S	1.97E+00	W	1.62E-01	W
12.8	3.33E-01	W	3.00E-06	S	1.96E+00	W	1.61E-01	W
13	3.38E-01	W	3.00E-06	S	1.96E+00	W	1.60E-01	W
tection Limit (min, mg	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
tection Limit (max, mg	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	2.80E+01		3.26E-05		2.14E+01		1.77E+00	

Table C-5-27. Leachate Concentrations for Bituminous Fly Ash, Waste ID WFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	1.24E+00	S	1.32E-01	S	3.59E+00	S
3	1.10E+00	S	1.25E-01	S	3.11E+00	S
3.2	9.85E-01	S	1.19E-01	S	2.71E+00	S
3.4	9.65E-01	S	1.09E-01	S	1.91E+00	S
3.6	9.52E-01	S	9.95E-02	S	1.36E+00	S
3.8	9.40E-01	S	9.15E-02	S	9.86E-01	S
4	9.40E-01	S	8.35E-02	S	7.97E-01	S
4.2	9.49E-01	S	7.62E-02	S	7.03E-01	S
4.4	9.59E-01	S	6.97E-02	S	6.35E-01	S
4.6	9.68E-01	S	6.41E-02	S	5.77E-01	S
4.8	9.78E-01	S	5.91E-02	S	5.26E-01	S
5	9.87E-01	S	5.47E-02	S	4.81E-01	S
5.2	1.02E+00	S	5.05E-02	S	4.70E-01	S
5.4	1.09E+00	S	4.56E-02	S	5.13E-01	S
5.6	1.16E+00	S	4.12E-02	S	5.60E-01	S
5.8	1.23E+00	S	3.75E-02	S	6.10E-01	S
6	1.31E+00	S	3.44E-02	S	6.56E-01	S
6.2	1.36E+00	S	3.23E-02	S	6.76E-01	S
6.4	1.44E+00	S	3.11E-02	S	6.83E-01	S
6.6	1.53E+00	S	2.99E-02	S	6.89E-01	S
6.8	1.62E+00	S	2.83E-02	S	7.01E-01	S
7	1.70E+00	S	2.54E-02	S	7.36E-01	S
7.2	1.79E+00	S	2.28E-02	S	7.70E-01	S
7.4	1.90E+00	S	1.84E-02	S	8.23E-01	S
7.6	2.02E+00	S	1.50E-02	S	8.78E-01	S
7.8	2.13E+00	S	1.27E-02	S	9.34E-01	S
8	2.24E+00	S	1.10E-02	S	9.96E-01	S

Table C-5-27. Leachate Concentrations for Bituminous Fly Ash, Waste ID WFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	2.33E+00	S	9.99E-03	S	1.10E+00	S
8.4	2.41E+00	S	9.07E-03	S	1.20E+00	S
8.6	2.50E+00	S	8.25E-03	S	1.32E+00	S
8.8	2.60E+00	S	7.52E-03	S	1.44E+00	S
9	2.66E+00	S	6.68E-03	S	1.61E+00	S
9.2	2.70E+00	W	5.74E-03	S	1.78E+00	S
9.4	2.73E+00	W	4.88E-03	S	1.96E+00	S
9.6	2.76E+00	W	4.16E-03	S	2.16E+00	S
9.8	2.79E+00	W	3.57E-03	S	2.37E+00	S
10	2.82E+00	W	3.06E-03	S	2.60E+00	S
10.2	2.85E+00	W	2.65E-03	S	2.83E+00	S
10.4	2.88E+00	W	2.53E-03	S	2.97E+00	S
10.6	2.90E+00	W	2.53E-03	S	3.09E+00	S
10.8	2.92E+00	W	2.53E-03	S	3.20E+00	S
11	2.94E+00	W	2.53E-03	S	3.33E+00	S
11.2	2.96E+00	W	2.58E-03	S	3.43E+00	S
11.4	2.97E+00	W	3.04E-03	S	3.56E+00	S
11.6	2.98E+00	W	3.60E-03	S	3.69E+00	S
11.8	2.99E+00	W	4.26E-03	S	3.83E+00	S
12	3.00E+00	W	5.02E-03	S	3.97E+00	S
12.2	3.00E+00	W	5.90E-03	S	4.11E+00	S
12.4	3.00E+00	W	6.92E-03	S	4.26E+00	S
12.6	3.00E+00	W	8.09E-03	S	4.40E+00	S
12.8	3.00E+00	W	9.44E-03	S	4.55E+00	S
13	3.00E+00	W	1.10E-02	S	4.70E+00	S
tection Limit (min, mg	5.20E-04		5.10E-04		3.10E-04	
tection Limit (max, mg	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	3.26E+01		1.32E+00		4.94E+01	

Table C-5-28. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID CaFA Med

Sample ID	CaFA-[Med] (P,1,1)
Date Exported	8/27/2011, 2:09 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	2.11E+00	S	5.64E+01	W	1.85E-01	W	8.92E-01	S
3	1.77E+00	S	5.51E+01	W	1.80E-01	W	7.61E-01	S
3.2	1.50E+00	S	5.40E+01	W	1.76E-01	W	6.56E-01	S
3.4	1.29E+00	S	5.29E+01	W	1.72E-01	W	5.71E-01	S
3.6	1.12E+00	S	5.19E+01	W	1.68E-01	W	5.00E-01	S
3.8	9.72E-01	S	5.10E+01	W	1.65E-01	W	4.42E-01	S
4	8.08E-01	S	5.01E+01	W	1.60E-01	W	3.95E-01	S
4.2	5.48E-01	S	4.91E+01	W	1.51E-01	W	3.62E-01	S
4.4	3.78E-01	S	4.81E+01	W	1.42E-01	W	3.33E-01	S
4.6	2.65E-01	S	4.72E+01	W	1.34E-01	W	3.08E-01	S
4.8	1.89E-01	S	4.64E+01	W	1.27E-01	W	2.86E-01	S
5	1.36E-01	S	4.56E+01	W	1.21E-01	S	2.66E-01	S
5.2	9.99E-02	S	4.49E+01	W	1.15E-01	S	2.48E-01	S
5.4	7.39E-02	S	4.42E+01	W	1.09E-01	S	2.32E-01	S
5.6	5.93E-02	S	4.36E+01	W	1.05E-01	S	2.21E-01	S
5.8	5.62E-02	S	4.32E+01	W	1.03E-01	S	2.17E-01	S
6	5.33E-02	S	4.28E+01	W	1.01E-01	S	2.14E-01	S
6.2	5.07E-02	S	4.25E+01	W	9.84E-02	S	2.11E-01	S
6.4	4.83E-02	S	4.21E+01	W	9.64E-02	S	2.08E-01	S
6.6	4.60E-02	S	4.18E+01	W	9.44E-02	S	2.05E-01	S
6.8	4.84E-02	S	4.11E+01	W	7.35E-02	S	1.57E-01	S
7	5.20E-02	S	4.03E+01	W	5.44E-02	S	1.13E-01	S
7.2	5.58E-02	S	3.96E+01	W	4.06E-02	S	8.28E-02	S
7.4	5.98E-02	S	3.89E+01	W	3.06E-02	S	6.10E-02	S
7.6	6.39E-02	S	3.82E+01	W	2.32E-02	S	4.54E-02	S
7.8	6.81E-02	S	3.75E+01	W	1.77E-02	S	3.40E-02	S
8	7.26E-02	S	3.69E+01	W	1.36E-02	S	2.56E-02	S

Table C-5-28. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID CaFA Med

Sample ID	CaFA-[Med] (P,1,1)
Date Exported	8/27/2011, 2:09 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	7.72E-02	S	3.63E+01	W	1.06E-02	S	1.95E-02	S
8.4	8.20E-02	S	3.57E+01	W	8.23E-03	S	1.49E-02	S
8.6	8.69E-02	S	3.52E+01	W	6.45E-03	S	1.14E-02	S
8.8	9.21E-02	S	3.46E+01	W	5.08E-03	S	8.86E-03	S
9	9.74E-02	S	3.41E+01	W	4.03E-03	S	6.90E-03	S
9.2	1.00E-01	S	3.35E+01	W	3.40E-03	W	5.56E-03	S
9.4	9.43E-02	S	3.28E+01	W	3.40E-03	W	4.90E-03	S
9.6	8.90E-02	S	3.20E+01	W	3.40E-03	W	4.33E-03	S
9.8	8.42E-02	S	3.13E+01	W	3.40E-03	W	3.84E-03	S
10	7.97E-02	S	3.06E+01	W	3.40E-03	W	3.41E-03	S
10.2	7.55E-02	S	2.99E+01	W	3.40E-03	W	3.04E-03	S
10.4	7.16E-02	S	2.93E+01	W	3.40E-03	W	2.71E-03	S
10.6	6.80E-02	S	2.87E+01	W	3.40E-03	W	2.43E-03	S
10.8	6.46E-02	S	2.81E+01	W	3.41E-03	W	2.18E-03	S
11	5.94E-02	S	2.66E+01	S	3.41E-03	W	2.06E-03	S
11.2	5.28E-02	S	2.44E+01	S	3.41E-03	W	2.06E-03	S
11.4	4.70E-02	S	2.25E+01	S	3.42E-03	W	2.06E-03	S
11.6	4.20E-02	S	2.07E+01	S	3.42E-03	W	2.06E-03	S
11.8	3.76E-02	S	1.91E+01	S	3.43E-03	W	2.06E-03	S
12	3.37E-02	S	1.76E+01	S	3.43E-03	W	2.06E-03	S
12.2	4.37E-02	S	1.63E+01	S	3.54E-03	W	2.06E-03	S
12.4	5.64E-02	S	1.50E+01	S	3.65E-03	W	2.06E-03	S
12.6	7.25E-02	S	1.39E+01	S	3.77E-03	W	2.06E-03	S
12.8	9.29E-02	S	1.29E+01	S	3.88E-03	W	2.06E-03	S
13	1.19E-01	S	1.19E+01	S	4.00E-03	W	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	2.11E+01		5.64E+02		1.85E+00		8.92E+00	

Table C-5-28. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID CaFA Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	2.75E+00	S	2.53E-05	S	1.58E+00	S	2.58E-01	S
3	2.13E+00	S	2.68E-05	S	1.32E+00	S	2.11E-01	S
3.2	1.68E+00	S	2.83E-05	S	1.12E+00	S	1.75E-01	S
3.4	1.34E+00	S	2.98E-05	S	9.57E-01	S	1.47E-01	S
3.6	1.08E+00	S	3.13E-05	S	8.25E-01	S	1.24E-01	S
3.8	8.87E-01	S	3.28E-05	S	7.17E-01	S	1.06E-01	S
4	6.57E-01	S	3.11E-05	S	6.55E-01	S	9.06E-02	S
4.2	3.22E-01	S	2.03E-05	S	7.08E-01	S	7.54E-02	S
4.4	1.63E-01	S	1.35E-05	S	7.62E-01	S	6.33E-02	S
4.6	8.52E-02	S	9.16E-06	S	8.18E-01	S	5.36E-02	S
4.8	4.57E-02	S	6.31E-06	S	8.75E-01	S	4.57E-02	S
5	2.52E-02	S	4.42E-06	S	9.33E-01	S	3.92E-02	S
5.2	1.42E-02	S	3.13E-06	S	9.93E-01	S	3.38E-02	S
5.4	8.18E-03	S	3.00E-06	S	1.05E+00	S	2.93E-02	S
5.6	6.27E-03	S	3.00E-06	S	1.11E+00	S	2.68E-02	S
5.8	8.92E-03	S	3.00E-06	S	1.14E+00	S	2.73E-02	S
6	1.26E-02	S	3.66E-06	S	1.17E+00	S	2.78E-02	S
6.2	1.75E-02	S	4.89E-06	S	1.21E+00	S	2.83E-02	S
6.4	2.40E-02	S	6.49E-06	S	1.24E+00	S	2.88E-02	S
6.6	3.27E-02	S	8.53E-06	S	1.27E+00	S	2.93E-02	S
6.8	3.52E-02	S	7.99E-06	S	1.32E+00	S	3.07E-02	S
7	3.57E-02	S	6.90E-06	S	1.37E+00	S	3.24E-02	S
7.2	3.62E-02	S	5.99E-06	S	1.42E+00	S	3.41E-02	S
7.4	3.67E-02	S	5.22E-06	S	1.47E+00	S	3.59E-02	S
7.6	3.71E-02	S	4.57E-06	S	1.52E+00	S	3.77E-02	S
7.8	3.76E-02	S	4.01E-06	S	1.58E+00	S	3.96E-02	S
8	3.80E-02	S	3.53E-06	S	1.63E+00	S	4.15E-02	S

Table C-5-28. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID CaFA Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
8.2	3.85E-02	S	3.12E-06	S	1.68E+00	W	4.34E-02	S
8.4	3.89E-02	S	3.00E-06	S	1.73E+00	W	4.54E-02	S
8.6	3.94E-02	S	3.00E-06	S	1.79E+00	W	4.74E-02	S
8.8	3.98E-02	S	3.00E-06	S	1.84E+00	W	4.94E-02	S
9	4.03E-02	S	3.00E-06	S	1.89E+00	W	5.15E-02	S
9.2	4.09E-02	S	3.00E-06	S	1.93E+00	W	5.37E-02	S
9.4	4.21E-02	S	3.00E-06	S	1.93E+00	W	5.61E-02	S
9.6	4.32E-02	S	3.00E-06	S	1.92E+00	W	5.85E-02	S
9.8	4.44E-02	S	3.00E-06	S	1.91E+00	W	6.09E-02	S
10	4.56E-02	S	3.00E-06	S	1.90E+00	W	6.34E-02	S
10.2	4.69E-02	S	3.00E-06	S	1.89E+00	W	6.60E-02	S
10.4	4.81E-02	S	3.00E-06	S	1.89E+00	W	6.86E-02	S
10.6	4.93E-02	S	3.00E-06	S	1.88E+00	W	7.12E-02	S
10.8	5.05E-02	S	3.00E-06	S	1.87E+00	W	7.39E-02	S
11	6.49E-02	S	3.00E-06	S	1.88E+00	W	5.50E-02	S
11.2	1.04E-01	S	3.00E-06	S	1.90E+00	W	2.97E-02	S
11.4	1.64E-01	S	3.00E-06	S	1.92E+00	W	1.62E-02	S
11.6	2.59E-01	S	3.00E-06	S	1.94E+00	W	8.90E-03	S
11.8	4.04E-01	S	3.00E-06	S	1.96E+00	W	4.95E-03	S
12	6.26E-01	S	1.80E-06	S	1.99E+00	W	2.78E-03	S
12.2	6.63E-01	S	3.00E-06	S	2.03E+00	W	3.29E-03	S
12.4	7.02E-01	S	3.00E-06	S	2.07E+00	W	3.88E-03	S
12.6	7.42E-01	S	3.00E-06	S	2.11E+00	W	4.57E-03	S
12.8	7.84E-01	S	3.00E-06	S	2.15E+00	W	5.36E-03	S
13	8.28E-01	S	3.00E-06	S	2.19E+00	W	6.28E-03	S
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	2.75E+01		3.28E-04		3.06E+01		2.58E+00	

Table C-5-28. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID CaFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	2.07E+00	S	6.87E-02	S	1.14E+01	S
3	1.75E+00	S	6.34E-02	S	8.96E+00	S
3.2	1.50E+00	S	5.88E-02	S	7.14E+00	S
3.4	1.30E+00	S	5.48E-02	S	5.77E+00	S
3.6	1.13E+00	S	5.13E-02	S	4.72E+00	S
3.8	9.95E-01	S	4.82E-02	S	3.91E+00	S
4	8.53E-01	S	4.46E-02	S	3.10E+00	S
4.2	6.52E-01	S	3.83E-02	S	2.03E+00	S
4.4	5.04E-01	S	3.31E-02	S	1.36E+00	S
4.6	3.95E-01	S	2.88E-02	S	9.23E-01	S
4.8	3.12E-01	S	2.52E-02	S	6.38E-01	S
5	2.50E-01	S	2.22E-02	S	4.48E-01	S
5.2	2.01E-01	S	1.96E-02	S	3.19E-01	S
5.4	1.63E-01	S	1.74E-02	S	2.30E-01	S
5.6	1.42E-01	S	1.60E-02	S	1.85E-01	S
5.8	1.42E-01	S	1.58E-02	S	1.87E-01	S
6	1.42E-01	S	1.55E-02	S	1.89E-01	S
6.2	1.41E-01	S	1.53E-02	S	1.91E-01	S
6.4	1.41E-01	S	1.50E-02	S	1.93E-01	S
6.6	1.41E-01	S	1.48E-02	S	1.95E-01	S
6.8	1.51E-01	S	1.30E-02	S	2.16E-01	S
7	1.63E-01	S	1.10E-02	S	2.44E-01	S
7.2	1.76E-01	S	9.46E-03	S	2.75E-01	S
7.4	1.89E-01	S	8.14E-03	S	3.08E-01	S
7.6	2.03E-01	S	7.03E-03	S	3.44E-01	S
7.8	2.18E-01	S	6.09E-03	S	3.84E-01	S
8	2.34E-01	S	5.30E-03	S	4.27E-01	S

Table C-5-28. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID CaFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	2.50E-01	S	4.62E-03	S	4.73E-01	S
8.4	2.67E-01	S	4.05E-03	S	5.23E-01	S
8.6	2.84E-01	S	3.56E-03	S	5.77E-01	S
8.8	3.02E-01	S	3.14E-03	S	6.36E-01	S
9	3.21E-01	S	2.77E-03	S	6.98E-01	S
9.2	3.41E-01	S	2.53E-03	S	7.58E-01	S
9.4	3.62E-01	S	2.53E-03	S	7.96E-01	S
9.6	3.84E-01	S	2.53E-03	S	8.35E-01	S
9.8	4.07E-01	S	2.53E-03	S	8.76E-01	S
10	4.31E-01	S	2.53E-03	S	9.17E-01	S
10.2	4.55E-01	S	2.53E-03	S	9.60E-01	S
10.4	4.81E-01	S	2.53E-03	S	1.00E+00	S
10.6	5.07E-01	S	2.53E-03	S	1.05E+00	S
10.8	5.34E-01	S	2.53E-03	S	1.09E+00	S
11	5.24E-01	S	2.53E-03	S	1.00E+00	S
11.2	4.78E-01	S	2.53E-03	S	8.13E-01	S
11.4	4.38E-01	S	2.53E-03	S	6.61E-01	S
11.6	4.01E-01	S	2.53E-03	S	5.39E-01	S
11.8	3.68E-01	S	2.53E-03	S	4.42E-01	S
12	3.39E-01	S	2.53E-03	S	3.63E-01	S
12.2	3.94E-01	S	2.53E-03	S	3.82E-01	S
12.4	4.56E-01	S	2.53E-03	S	4.02E-01	S
12.6	5.28E-01	S	2.53E-03	S	4.22E-01	S
12.8	6.09E-01	S	2.53E-03	S	4.44E-01	S
13	7.01E-01	S	2.53E-03	S	4.66E-01	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	2.07E+01		6.87E-01		1.14E+02	

Table C-5-29. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID JAB Med

Sample ID	JAB-[Med] (P,1,1)
Date Exported	8/27/2011, 2:09 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	3.20E-03	S	1.70E+01	W	3.46E-02	S	9.28E-01	S
3	3.20E-03	S	1.70E+01	W	3.46E-02	S	9.28E-01	S
3.2	3.20E-03	S	1.65E+01	W	3.46E-02	S	9.28E-01	S
3.4	3.20E-03	S	1.51E+01	W	3.46E-02	S	9.28E-01	S
3.6	3.20E-03	S	1.39E+01	W	3.46E-02	S	9.28E-01	S
3.8	3.20E-03	S	1.11E+01	W	2.69E-02	S	7.59E-01	S
4	3.20E-03	S	7.72E+00	W	4.16E-03	S	1.74E-01	S
4.2	3.20E-03	S	7.13E+00	W	2.64E-03	S	1.17E-01	S
4.4	3.20E-03	S	6.77E+00	W	2.11E-03	S	9.40E-02	S
4.6	3.20E-03	S	6.60E+00	W	2.11E-03	S	8.95E-02	S
4.8	3.20E-03	S	6.44E+00	W	2.10E-03	S	8.55E-02	S
5	3.20E-03	S	6.73E+00	W	1.51E-03	S	7.12E-02	S
5.2	3.20E-03	S	6.69E+00	W	1.47E-03	S	6.30E-02	S
5.4	3.20E-03	S	6.65E+00	W	1.43E-03	S	5.61E-02	S
5.6	3.20E-03	S	6.61E+00	W	1.34E-03	S	4.81E-02	S
5.8	3.20E-03	S	6.57E+00	W	1.19E-03	S	4.00E-02	S
6	3.20E-03	S	6.53E+00	W	1.07E-03	S	3.34E-02	S
6.2	3.20E-03	S	6.48E+00	W	9.60E-04	S	2.81E-02	S
6.4	3.20E-03	S	6.44E+00	W	8.66E-04	S	2.37E-02	S
6.6	3.20E-03	S	6.74E+00	W	7.94E-04	S	1.89E-02	S
6.8	3.20E-03	S	7.05E+00	W	7.29E-04	S	1.51E-02	S
7	3.20E-03	S	7.60E+00	W	6.78E-04	S	1.16E-02	S
7.2	3.20E-03	S	8.44E+00	W	6.39E-04	S	8.48E-03	S
7.4	3.20E-03	S	9.35E+00	W	6.02E-04	S	6.27E-03	S
7.6	3.20E-03	S	1.05E+01	W	6.35E-04	S	4.52E-03	S
7.8	3.20E-03	S	1.18E+01	W	6.69E-04	S	3.29E-03	S
8	3.20E-03	S	1.32E+01	W	7.04E-04	S	2.41E-03	S

Table C-5-29. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID JAB Med

Sample ID	JAB-[Med] (P,1,1)
Date Exported	8/27/2011, 2:09 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	3.20E-03	S	1.43E+01	W	7.44E-04	S	2.06E-03	S
8.4	3.20E-03	S	1.49E+01	W	7.07E-04	S	2.06E-03	S
8.6	3.20E-03	S	1.55E+01	W	6.73E-04	S	2.06E-03	S
8.8	3.20E-03	S	1.62E+01	W	6.41E-04	S	2.06E-03	S
9	3.20E-03	S	1.60E+01	W	6.11E-04	S	2.06E-03	S
9.2	3.20E-03	S	1.51E+01	W	5.84E-04	W	2.06E-03	S
9.4	3.20E-03	S	1.31E+01	W	2.82E-04	W	2.06E-03	S
9.6	3.20E-03	S	1.14E+01	W	1.84E-04	W	2.06E-03	S
9.8	3.20E-03	S	8.59E+00	W	1.73E-04	W	2.06E-03	S
10	3.20E-03	S	6.16E+00	S	1.62E-04	W	2.06E-03	S
10.2	3.20E-03	S	4.45E+00	S	1.52E-04	W	2.06E-03	S
10.4	3.20E-03	S	3.23E+00	S	1.43E-04	W	2.06E-03	S
10.6	3.20E-03	S	2.36E+00	S	1.35E-04	W	2.06E-03	S
10.8	3.20E-03	S	1.74E+00	S	1.27E-04	W	2.06E-03	S
11	3.20E-03	S	1.29E+00	S	1.20E-04	W	2.06E-03	S
11.2	3.20E-03	S	9.56E-01	S	1.13E-04	W	2.06E-03	S
11.4	3.20E-03	S	7.15E-01	S	1.07E-04	W	2.06E-03	S
11.6	3.20E-03	S	5.37E-01	S	1.01E-04	W	2.06E-03	S
11.8	3.20E-03	S	4.17E-01	S	9.52E-05	W	2.06E-03	S
12	3.20E-03	S	3.27E-01	S	1.22E-04	W	2.06E-03	S
12.2	3.80E-03	S	3.44E-01	S	1.39E-04	W	2.06E-03	S
12.4	5.35E-03	S	4.83E-01	S	2.17E-04	W	2.06E-03	S
12.6	5.35E-03	S	6.73E-01	S	4.34E-04	W	2.06E-03	S
12.8	5.35E-03	S	9.35E-01	S	8.58E-04	W	2.06E-03	S
13	5.35E-03	S	1.29E+00	S	1.68E-03	W	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	5.75E-02		1.70E+02		3.46E-01		9.28E+00	

Table C-5-29. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID JAB Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	2.49E-03	S	5.70E-05	S	5.00E-04	S	4.09E-04	S
3	3.21E-03	S	5.70E-05	S	5.00E-04	S	6.86E-04	S
3.2	4.08E-03	S	5.70E-05	S	7.97E-04	S	1.11E-03	S
3.4	5.10E-03	S	5.70E-05	S	1.29E-03	S	1.75E-03	S
3.6	1.73E-02	S	5.70E-05	S	2.03E-03	S	2.69E-03	S
3.8	8.95E-02	S	5.36E-05	S	3.13E-03	S	4.03E-03	S
4	4.27E-01	S	2.21E-05	S	7.74E-02	S	5.92E-03	S
4.2	5.14E-01	S	2.20E-05	S	1.16E-01	S	7.02E-03	S
4.4	5.69E-01	S	2.14E-05	S	1.44E-01	S	7.56E-03	S
4.6	5.84E-01	S	2.01E-05	S	1.49E-01	S	7.44E-03	S
4.8	5.98E-01	S	1.89E-05	S	1.54E-01	S	7.33E-03	S
5	6.19E-01	S	2.34E-05	S	1.83E-01	S	7.61E-03	S
5.2	6.29E-01	W	2.59E-05	S	1.95E-01	S	7.82E-03	S
5.4	6.39E-01	W	2.85E-05	S	2.07E-01	S	8.03E-03	S
5.6	6.55E-01	W	2.87E-05	S	2.25E-01	S	8.13E-03	S
5.8	6.79E-01	W	2.65E-05	S	2.49E-01	S	8.13E-03	S
6	7.03E-01	W	2.45E-05	S	2.76E-01	S	8.13E-03	S
6.2	7.26E-01	W	2.27E-05	S	3.03E-01	S	8.14E-03	S
6.4	7.50E-01	W	2.11E-05	S	3.33E-01	S	8.14E-03	S
6.6	7.72E-01	W	1.98E-05	S	3.72E-01	S	8.34E-03	S
6.8	7.94E-01	W	1.86E-05	S	4.14E-01	S	8.54E-03	S
7	8.12E-01	W	1.74E-05	S	4.61E-01	S	8.91E-03	S
7.2	8.25E-01	W	1.63E-05	S	5.14E-01	S	9.48E-03	S
7.4	8.39E-01	W	1.52E-05	S	5.71E-01	S	1.01E-02	S
7.6	8.31E-01	W	1.52E-05	S	6.06E-01	S	1.07E-02	S
7.8	8.23E-01	W	1.52E-05	S	6.44E-01	S	1.13E-02	S
8	8.16E-01	W	1.52E-05	S	6.82E-01	S	1.19E-02	S

Table C-5-29. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID JAB Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
8.2	8.17E-01	W	1.50E-05	S	7.03E-01	W	1.15E-02	S
8.4	8.37E-01	W	1.74E-05	S	7.07E-01	W	1.05E-02	S
8.6	8.57E-01	W	2.00E-05	S	7.11E-01	W	9.68E-03	S
8.8	8.77E-01	W	2.30E-05	S	7.14E-01	W	8.91E-03	S
9	8.90E-01	S	2.30E-05	S	7.19E-01	W	7.59E-03	S
9.2	8.97E-01	S	2.02E-05	S	7.23E-01	W	6.00E-03	S
9.4	5.03E-01	S	1.80E-05	S	7.25E-01	W	4.81E-03	S
9.6	2.86E-01	S	1.61E-05	S	7.26E-01	W	3.88E-03	S
9.8	2.12E-01	S	1.63E-05	S	7.11E-01	W	3.74E-03	S
10	2.18E-01	S	1.67E-05	S	6.88E-01	W	3.62E-03	S
10.2	2.24E-01	S	1.71E-05	S	6.66E-01	W	3.50E-03	S
10.4	2.29E-01	S	1.74E-05	S	6.44E-01	W	3.39E-03	S
10.6	2.35E-01	S	1.78E-05	S	6.24E-01	W	3.28E-03	S
10.8	2.41E-01	S	1.81E-05	S	6.05E-01	W	3.18E-03	S
11	2.47E-01	S	1.85E-05	S	5.87E-01	W	3.09E-03	S
11.2	2.53E-01	S	1.89E-05	S	5.70E-01	W	2.99E-03	S
11.4	2.59E-01	S	1.92E-05	S	5.53E-01	W	2.91E-03	S
11.6	2.65E-01	S	1.96E-05	S	5.37E-01	W	2.82E-03	S
11.8	3.58E-01	S	2.19E-05	S	5.77E-01	W	3.86E-03	S
12	5.13E-01	S	2.71E-05	S	6.35E-01	W	5.99E-03	S
12.2	6.49E-01	S	2.54E-05	S	6.88E-01	W	9.03E-03	S
12.4	7.27E-01	S	1.83E-05	S	7.33E-01	W	1.32E-02	S
12.6	8.13E-01	S	1.33E-05	S	7.69E-01	W	1.32E-02	S
12.8	8.98E-01	S	9.64E-06	S	7.71E-01	W	1.32E-02	S
13	8.98E-01	S	8.54E-06	S	7.71E-01	W	1.32E-02	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		1.00E-03		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		1.00E-03		8.00E-05	
Availability (mg/kg)	9.65E+00		5.70E-04		8.29E+00		1.42E-01	

Table C-5-29. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID JAB Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	2.38E-01	S	5.02E-02	S	1.43E-03	S
3	2.38E-01	S	5.02E-02	S	1.43E-03	S
3.2	2.38E-01	S	5.02E-02	S	1.43E-03	S
3.4	2.38E-01	S	5.02E-02	S	1.43E-03	S
3.6	2.38E-01	S	5.02E-02	S	1.43E-03	S
3.8	2.32E-01	S	4.64E-02	S	1.43E-03	S
4	1.41E-01	S	2.41E-02	S	1.43E-03	S
4.2	1.35E-01	S	2.06E-02	S	1.54E-03	S
4.4	1.25E-01	S	1.90E-02	S	1.65E-03	S
4.6	1.11E-01	S	1.87E-02	S	1.76E-03	S
4.8	9.97E-02	S	1.85E-02	S	1.87E-03	S
5	9.27E-02	S	1.80E-02	S	2.06E-03	S
5.2	9.33E-02	W	1.76E-02	S	2.34E-03	S
5.4	9.38E-02	W	1.72E-02	S	2.63E-03	S
5.6	9.40E-02	W	1.68E-02	S	2.85E-03	S
5.8	9.39E-02	W	1.62E-02	S	2.96E-03	S
6	9.37E-02	W	1.56E-02	S	3.06E-03	S
6.2	9.36E-02	W	1.51E-02	S	3.17E-03	S
6.4	9.35E-02	W	1.47E-02	S	3.28E-03	S
6.6	9.42E-02	W	1.44E-02	S	4.02E-03	S
6.8	9.49E-02	W	1.42E-02	S	4.90E-03	S
7	9.56E-02	W	1.42E-02	S	6.10E-03	S
7.2	9.63E-02	W	1.42E-02	S	7.74E-03	S
7.4	9.70E-02	W	1.43E-02	S	9.77E-03	S
7.6	9.73E-02	W	1.43E-02	S	1.08E-02	S
7.8	9.76E-02	W	1.43E-02	S	1.19E-02	S
8	9.79E-02	W	1.44E-02	S	1.31E-02	S

Table C-5-29. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID JAB Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	9.95E-02	W	1.37E-02	S	1.37E-02	S
8.4	1.02E-01	W	1.26E-02	S	1.45E-02	S
8.6	1.05E-01	W	1.17E-02	S	1.52E-02	S
8.8	1.09E-01	W	1.08E-02	S	1.60E-02	S
9	1.11E-01	W	1.01E-02	S	1.71E-02	S
9.2	1.14E-01	W	9.47E-03	S	1.88E-02	S
9.4	1.21E-01	W	9.29E-03	S	2.07E-02	S
9.6	1.28E-01	W	9.12E-03	S	2.28E-02	S
9.8	1.22E-01	W	8.98E-03	S	2.24E-02	S
10	1.12E-01	S	8.84E-03	S	2.16E-02	S
10.2	1.02E-01	S	8.70E-03	S	2.08E-02	S
10.4	9.41E-02	S	8.57E-03	S	2.00E-02	S
10.6	8.66E-02	S	8.45E-03	S	1.93E-02	S
10.8	7.97E-02	S	8.33E-03	S	1.86E-02	S
11	7.36E-02	S	8.21E-03	S	1.80E-02	S
11.2	6.80E-02	S	8.10E-03	S	1.74E-02	S
11.4	6.29E-02	S	7.99E-03	S	1.68E-02	S
11.6	5.82E-02	S	7.88E-03	S	1.63E-02	S
11.8	5.68E-02	S	7.12E-03	S	3.31E-02	S
12	5.25E-02	S	6.22E-03	S	8.17E-02	S
12.2	5.37E-02	S	7.27E-03	S	1.79E-01	S
12.4	6.05E-02	S	1.13E-02	S	3.52E-01	S
12.6	6.80E-02	S	1.75E-02	S	3.52E-01	S
12.8	7.62E-02	S	2.68E-02	S	3.52E-01	S
13	8.53E-02	S	4.08E-02	S	3.52E-01	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	2.38E+00		5.02E-01		3.78E+00	

Table C-5-30. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID JAT Med

Sample ID	JAT-[Med] (P,1,1)
Date Exported	8/27/2011, 2:09 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	3.20E-03	S	1.61E+01	W	2.12E-02	S	5.53E-01	S
3	3.20E-03	S	1.54E+01	W	2.12E-02	S	5.53E-01	S
3.2	3.20E-03	S	1.48E+01	W	2.12E-02	S	5.53E-01	S
3.4	3.20E-03	S	1.42E+01	W	2.12E-02	S	5.53E-01	S
3.6	3.20E-03	S	1.37E+01	W	2.12E-02	S	5.53E-01	S
3.8	3.20E-03	S	1.32E+01	W	2.12E-02	S	5.53E-01	S
4	3.20E-03	S	1.20E+01	W	1.95E-02	S	5.29E-01	S
4.2	3.20E-03	S	1.05E+01	W	1.67E-02	S	4.85E-01	S
4.4	3.20E-03	S	9.28E+00	W	1.09E-02	S	4.02E-01	S
4.6	3.20E-03	S	8.52E+00	W	6.73E-03	S	3.11E-01	S
4.8	3.20E-03	S	8.21E+00	W	5.19E-03	S	2.34E-01	S
5	3.20E-03	S	7.91E+00	W	4.04E-03	S	1.78E-01	S
5.2	3.20E-03	S	7.64E+00	W	3.17E-03	S	1.37E-01	S
5.4	3.20E-03	S	7.45E+00	W	2.59E-03	S	1.05E-01	S
5.6	3.20E-03	S	7.33E+00	W	2.20E-03	S	8.01E-02	S
5.8	3.20E-03	S	7.21E+00	W	1.87E-03	S	6.16E-02	S
6	3.20E-03	S	7.29E+00	W	1.66E-03	S	4.76E-02	S
6.2	3.20E-03	S	7.36E+00	W	1.48E-03	S	3.71E-02	S
6.4	3.20E-03	S	7.43E+00	W	1.32E-03	S	2.91E-02	S
6.6	3.20E-03	S	7.51E+00	W	1.18E-03	S	2.31E-02	S
6.8	3.20E-03	S	7.58E+00	W	1.06E-03	S	1.84E-02	S
7	3.20E-03	S	7.64E+00	W	9.58E-04	S	1.47E-02	S
7.2	3.20E-03	S	7.93E+00	W	8.62E-04	S	1.20E-02	S
7.4	3.20E-03	S	8.44E+00	W	7.72E-04	S	1.00E-02	S
7.6	3.20E-03	S	8.98E+00	W	6.94E-04	S	8.36E-03	S
7.8	3.20E-03	S	9.61E+00	W	6.52E-04	S	6.55E-03	S
8	3.20E-03	S	1.03E+01	W	5.18E-04	S	4.68E-03	S

Table C-5-30. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID JAT Med

Sample ID	JAT-[Med] (P,1,1)
Date Exported	8/27/2011, 2:09 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	3.20E-03	S	1.12E+01	W	1.65E-04	S	3.44E-03	S
8.4	3.20E-03	S	1.23E+01	W	8.50E-05	S	2.55E-03	S
8.6	3.20E-03	S	1.31E+01	W	4.61E-05	S	2.06E-03	S
8.8	3.20E-03	S	1.37E+01	W	8.50E-05	S	2.06E-03	S
9	3.20E-03	S	1.44E+01	W	8.50E-05	S	2.06E-03	S
9.2	3.20E-03	S	1.50E+01	W	8.50E-05	W	2.06E-03	S
9.4	3.20E-03	S	1.56E+01	W	8.50E-05	W	2.06E-03	S
9.6	3.20E-03	S	1.60E+01	W	8.50E-05	W	2.06E-03	S
9.8	3.20E-03	S	1.41E+01	W	8.50E-05	W	2.06E-03	S
10	3.20E-03	S	9.31E+00	S	8.50E-05	W	2.06E-03	S
10.2	3.20E-03	S	5.35E+00	S	8.50E-05	W	2.06E-03	S
10.4	3.20E-03	S	3.11E+00	S	2.50E-05	W	2.06E-03	S
10.6	3.20E-03	S	2.31E+00	S	8.50E-05	W	2.06E-03	S
10.8	3.20E-03	S	1.72E+00	S	8.50E-05	W	2.06E-03	S
11	3.20E-03	S	1.29E+00	S	8.50E-05	W	2.06E-03	S
11.2	3.20E-03	S	9.75E-01	S	8.50E-05	W	2.06E-03	S
11.4	3.20E-03	S	7.39E-01	S	8.50E-05	W	2.06E-03	S
11.6	3.20E-03	S	5.63E-01	S	8.50E-05	W	2.06E-03	S
11.8	3.20E-03	S	4.31E-01	S	8.50E-05	W	2.06E-03	S
12	3.20E-03	S	3.31E-01	S	8.50E-05	W	2.06E-03	S
12.2	3.20E-03	S	2.56E-01	S	2.50E-05	W	2.06E-03	S
12.4	4.38E-03	S	3.05E-01	S	1.06E-04	W	2.06E-03	S
12.6	5.11E-03	S	3.63E-01	S	4.37E-04	W	2.06E-03	S
12.8	5.11E-03	S	4.31E-01	S	1.77E-03	W	2.06E-03	S
13	5.11E-03	S	5.10E-01	S	7.00E-03	W	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	5.37E-02		1.61E+02		2.12E-01		5.53E+00	

Table C-5-30. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID JAT Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	3.12E-04	S	3.30E-06	S	1.50E-03	S	1.16E-03	S
3	4.11E-04	S	3.50E-06	S	1.79E-03	S	1.39E-03	S
3.2	5.31E-04	S	3.71E-06	S	2.11E-03	S	1.65E-03	S
3.4	6.76E-04	S	3.91E-06	S	2.46E-03	S	1.94E-03	S
3.6	8.50E-04	S	4.11E-06	S	3.71E-03	S	2.25E-03	S
3.8	1.05E-03	S	4.31E-06	S	6.95E-03	S	2.60E-03	S
4	1.29E-03	S	4.50E-06	S	1.26E-02	S	2.98E-03	S
4.2	2.59E-03	S	4.70E-06	S	2.23E-02	S	3.39E-03	S
4.4	8.62E-03	S	6.03E-06	S	3.83E-02	S	3.83E-03	S
4.6	1.81E-02	S	7.53E-06	S	5.64E-02	S	4.58E-03	S
4.8	2.33E-02	S	8.24E-06	S	7.37E-02	S	5.13E-03	S
5	2.96E-02	S	8.98E-06	S	9.53E-02	S	5.72E-03	S
5.2	3.73E-02	S	9.76E-06	S	1.22E-01	S	6.35E-03	S
5.4	4.56E-02	S	9.76E-06	S	1.52E-01	S	6.66E-03	S
5.6	5.43E-02	S	9.04E-06	S	1.84E-01	S	6.61E-03	S
5.8	6.42E-02	S	8.39E-06	S	2.22E-01	S	6.57E-03	S
6	7.33E-02	S	7.67E-06	S	2.52E-01	S	6.61E-03	S
6.2	8.35E-02	S	7.03E-06	S	2.86E-01	S	6.64E-03	S
6.4	9.46E-02	S	6.47E-06	S	3.23E-01	S	6.68E-03	S
6.6	1.07E-01	S	5.96E-06	S	3.63E-01	S	6.71E-03	S
6.8	1.20E-01	S	5.51E-06	S	4.08E-01	S	6.74E-03	S
7	1.35E-01	S	5.11E-06	S	4.55E-01	S	6.77E-03	S
7.2	1.48E-01	S	5.30E-06	S	5.02E-01	S	6.91E-03	S
7.4	1.59E-01	S	6.13E-06	S	5.47E-01	S	7.15E-03	S
7.6	1.71E-01	S	7.07E-06	S	5.94E-01	S	7.40E-03	S
7.8	1.84E-01	S	9.42E-06	S	6.34E-01	S	7.63E-03	S
8	2.00E-01	S	1.28E-05	S	6.54E-01	S	7.75E-03	S

Table C-5-30. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID JAT Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
8.2	2.24E-01	S	1.24E-05	S	6.71E-01	W	7.87E-03	S
8.4	2.50E-01	S	1.21E-05	S	6.88E-01	W	7.99E-03	S
8.6	2.74E-01	S	1.15E-05	S	7.01E-01	W	8.09E-03	S
8.8	2.81E-01	S	1.61E-05	S	7.15E-01	W	8.29E-03	S
9	2.87E-01	S	2.17E-05	S	7.25E-01	W	8.36E-03	S
9.2	2.91E-01	S	2.84E-05	S	7.30E-01	W	8.32E-03	S
9.4	2.95E-01	S	3.68E-05	S	7.35E-01	W	8.28E-03	S
9.6	3.11E-01	S	1.82E-05	S	7.17E-01	W	6.03E-03	S
9.8	3.32E-01	S	8.58E-06	S	6.88E-01	W	4.38E-03	S
10	3.57E-01	S	1.01E-05	S	6.75E-01	W	3.97E-03	S
10.2	3.94E-01	S	1.21E-05	S	6.65E-01	W	3.32E-03	S
10.4	4.35E-01	S	1.44E-05	S	6.56E-01	W	2.78E-03	S
10.6	4.55E-01	S	1.46E-05	S	6.60E-01	W	2.95E-03	S
10.8	4.75E-01	S	1.49E-05	S	6.63E-01	W	3.13E-03	S
11	4.96E-01	S	1.52E-05	S	6.67E-01	W	3.32E-03	S
11.2	5.17E-01	S	1.55E-05	S	6.70E-01	W	3.51E-03	S
11.4	5.39E-01	S	1.57E-05	S	6.74E-01	W	3.71E-03	S
11.6	5.61E-01	S	1.60E-05	S	6.77E-01	W	3.92E-03	S
11.8	5.84E-01	S	1.63E-05	S	6.80E-01	W	4.14E-03	S
12	6.08E-01	S	1.66E-05	S	6.84E-01	W	4.36E-03	S
12.2	6.32E-01	W	1.68E-05	S	6.87E-01	W	4.59E-03	S
12.4	7.00E-01	W	2.89E-05	S	7.38E-01	W	7.25E-03	S
12.6	7.37E-01	W	4.33E-05	S	7.72E-01	W	1.01E-02	S
12.8	7.37E-01	W	4.20E-05	S	7.72E-01	W	1.01E-02	S
13	7.37E-01	W	4.07E-05	S	7.72E-01	W	1.01E-02	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		1.00E-03		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		1.00E-03		8.00E-05	
Availability (mg/kg)	7.74E+00		4.55E-04		8.10E+00		1.06E-01	

Table C-5-30. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID JAT Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	2.32E-01	S	1.04E-02	S	1.43E-03	S
3	2.32E-01	S	1.04E-02	S	1.43E-03	S
3.2	2.32E-01	S	1.04E-02	S	1.43E-03	S
3.4	2.32E-01	S	1.04E-02	S	1.43E-03	S
3.6	2.32E-01	S	1.04E-02	S	1.43E-03	S
3.8	2.28E-01	S	1.04E-02	S	1.43E-03	S
4	2.19E-01	S	1.00E-02	S	1.43E-03	S
4.2	2.11E-01	S	9.27E-03	S	1.43E-03	S
4.4	1.58E-01	S	6.98E-03	S	1.43E-03	S
4.6	1.19E-01	S	5.29E-03	S	1.43E-03	S
4.8	1.15E-01	S	5.03E-03	S	1.43E-03	S
5	1.11E-01	S	4.79E-03	S	1.43E-03	S
5.2	1.07E-01	W	4.57E-03	S	1.43E-03	S
5.4	1.04E-01	W	4.37E-03	S	1.49E-03	S
5.6	1.00E-01	W	4.19E-03	S	1.63E-03	S
5.8	9.74E-02	W	4.02E-03	S	1.77E-03	S
6	9.79E-02	W	3.80E-03	S	2.13E-03	S
6.2	9.85E-02	W	3.60E-03	S	2.55E-03	S
6.4	9.90E-02	W	3.42E-03	S	3.03E-03	S
6.6	9.95E-02	W	3.25E-03	S	3.59E-03	S
6.8	1.00E-01	W	3.10E-03	S	4.23E-03	S
7	1.01E-01	W	2.96E-03	S	4.96E-03	S
7.2	1.00E-01	W	2.82E-03	S	5.78E-03	S
7.4	9.96E-02	W	2.70E-03	S	6.70E-03	S
7.6	9.88E-02	W	2.58E-03	S	7.73E-03	S
7.8	9.82E-02	W	2.53E-03	S	8.56E-03	S
8	9.86E-02	W	2.53E-03	S	9.18E-03	S

Table C-5-30. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID JAT Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	1.01E-01	W	2.53E-03	S	1.06E-02	S
8.4	1.02E-01	W	2.53E-03	S	1.23E-02	S
8.6	1.06E-01	W	2.53E-03	S	1.39E-02	S
8.8	1.11E-01	W	2.53E-03	S	1.49E-02	S
9	1.17E-01	W	2.53E-03	S	1.62E-02	S
9.2	1.26E-01	W	2.53E-03	S	1.80E-02	S
9.4	1.34E-01	W	2.53E-03	S	2.00E-02	S
9.6	1.45E-01	W	2.53E-03	S	2.46E-02	S
9.8	1.45E-01	W	2.53E-03	S	3.03E-02	S
10	1.25E-01	S	2.53E-03	S	3.30E-02	S
10.2	1.00E-01	S	2.53E-03	S	3.53E-02	S
10.4	8.10E-02	S	2.53E-03	S	3.78E-02	S
10.6	7.78E-02	S	2.53E-03	S	4.36E-02	S
10.8	7.48E-02	S	2.53E-03	S	5.03E-02	S
11	7.20E-02	S	2.53E-03	S	5.78E-02	S
11.2	6.93E-02	S	2.53E-03	S	6.63E-02	S
11.4	6.68E-02	S	2.53E-03	S	7.59E-02	S
11.6	6.44E-02	S	2.53E-03	S	8.66E-02	S
11.8	6.21E-02	S	2.53E-03	S	9.86E-02	S
12	6.00E-02	S	2.53E-03	S	1.12E-01	S
12.2	5.79E-02	S	2.53E-03	S	1.27E-01	S
12.4	6.04E-02	S	2.53E-03	S	2.32E-01	S
12.6	6.30E-02	S	2.53E-03	S	3.11E-01	S
12.8	6.56E-02	S	2.53E-03	S	3.11E-01	S
13	6.83E-02	S	2.53E-03	S	3.11E-01	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	2.32E+00		1.04E-01		3.27E+00	

Table C-5-31. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID PPB Med

Sample ID	PPB-[Med] (P,1,1)
Date Exported	8/27/2011, 2:09 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	3.20E-03	S	6.75E+00	W	4.83E-02	S	8.55E-01	S
3	3.20E-03	S	6.84E+00	W	4.83E-02	S	8.55E-01	S
3.2	3.20E-03	S	6.92E+00	W	4.83E-02	S	8.55E-01	S
3.4	3.20E-03	S	7.00E+00	W	4.83E-02	S	8.55E-01	S
3.6	3.20E-03	S	7.08E+00	W	1.05E-02	S	3.56E-01	S
3.8	3.20E-03	S	7.16E+00	W	1.19E-02	S	2.81E-01	S
4	3.20E-03	S	7.23E+00	W	1.81E-02	S	5.16E-01	S
4.2	3.20E-03	S	7.30E+00	W	2.70E-02	S	6.13E-01	S
4.4	3.20E-03	S	7.36E+00	W	3.54E-02	S	5.75E-01	S
4.6	3.20E-03	S	7.42E+00	W	3.34E-02	S	4.27E-01	S
4.8	3.20E-03	S	7.49E+00	W	4.08E-02	S	6.51E-01	S
5	3.20E-03	S	7.54E+00	W	3.65E-02	S	7.11E-01	S
5.2	3.20E-03	S	7.39E+00	W	2.13E-02	S	2.86E-01	S
5.4	3.20E-03	S	7.09E+00	W	1.39E-02	S	1.46E-01	S
5.6	3.20E-03	S	6.81E+00	W	1.69E-02	S	1.37E-01	S
5.8	3.20E-03	S	7.60E+00	W	1.67E-02	S	3.42E-01	S
6	3.20E-03	S	8.61E+00	W	1.65E-02	S	2.53E-01	S
6.2	3.20E-03	S	9.72E+00	W	1.62E-02	S	1.78E-01	S
6.4	3.20E-03	S	1.09E+01	W	1.60E-02	S	1.25E-01	S
6.6	3.20E-03	S	1.22E+01	W	1.58E-02	S	8.80E-02	S
6.8	3.20E-03	S	1.37E+01	W	1.56E-02	S	6.28E-02	S
7	3.20E-03	S	1.52E+01	W	1.54E-02	S	4.52E-02	S
7.2	3.20E-03	S	1.68E+01	W	1.52E-02	S	3.29E-02	S
7.4	3.20E-03	S	1.86E+01	W	1.51E-02	S	2.41E-02	S
7.6	3.20E-03	S	2.06E+01	W	1.49E-02	S	1.79E-02	S
7.8	3.20E-03	S	2.26E+01	W	1.47E-02	S	1.33E-02	S
8	3.20E-03	S	2.48E+01	W	1.46E-02	S	1.04E-02	S

Table C-5-31. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID PPB Med

Sample ID	PPB-[Med] (P,1,1)
Date Exported	8/27/2011, 2:09 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	3.20E-03	S	2.72E+01	W	1.44E-02	S	8.84E-03	S
8.4	3.20E-03	S	2.72E+01	W	1.43E-02	S	7.52E-03	S
8.6	3.20E-03	S	1.85E+01	W	1.41E-02	S	6.43E-03	S
8.8	3.20E-03	S	1.27E+01	W	1.40E-02	S	5.90E-03	S
9	3.20E-03	S	9.54E+00	W	1.16E-02	S	5.33E-03	S
9.2	3.20E-03	S	9.26E+00	W	1.03E-02	S	4.07E-03	S
9.4	3.20E-03	S	8.99E+00	W	9.80E-03	S	3.51E-03	S
9.6	3.20E-03	S	8.87E+00	W	8.41E-03	S	3.04E-03	S
9.8	3.20E-03	S	8.94E+00	W	6.21E-03	S	2.63E-03	S
10	3.20E-03	S	9.02E+00	S	4.61E-03	S	2.29E-03	S
10.2	3.20E-03	S	9.09E+00	S	3.44E-03	S	2.06E-03	S
10.4	3.20E-03	S	9.17E+00	S	3.31E-03	S	2.06E-03	S
10.6	3.20E-03	S	9.24E+00	S	6.66E-03	S	4.03E-03	S
10.8	3.20E-03	S	9.31E+00	S	6.58E-03	S	3.66E-03	S
11	3.20E-03	S	9.38E+00	S	4.98E-03	S	3.33E-03	S
11.2	3.20E-03	S	9.46E+00	S	3.58E-03	S	3.04E-03	S
11.4	3.20E-03	S	8.60E+00	S	2.58E-03	S	2.78E-03	S
11.6	3.20E-03	S	6.80E+00	S	1.88E-03	S	2.54E-03	S
11.8	3.20E-03	S	5.40E+00	S	2.77E-03	S	2.33E-03	S
12	3.20E-03	S	4.31E+00	S	4.69E-03	S	2.14E-03	S
12.2	3.22E-03	S	3.45E+00	S	6.13E-03	S	2.06E-03	S
12.4	6.26E-03	S	2.77E+00	S	6.07E-03	S	2.06E-03	S
12.6	7.10E-03	S	2.24E+00	S	1.30E-02	S	2.06E-03	S
12.8	7.10E-03	S	1.81E+00	S	3.54E-02	S	2.06E-03	S
13	7.10E-03	S	1.47E+00	S	4.83E-02	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	8.09E-02		2.72E+02		4.83E-01		8.55E+00	

Table C-5-31. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID PPB Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	2.50E-04	S	6.21E-05	S	8.33E-02	S	4.42E-01	W
3	2.50E-04	S	6.21E-05	S	7.16E-02	S	4.42E-01	W
3.2	1.91E-03	S	6.21E-05	S	6.21E-02	S	4.42E-01	W
3.4	1.56E-02	S	6.21E-05	S	5.43E-02	S	4.42E-01	W
3.6	8.29E-01	S	3.48E-05	S	4.79E-02	S	4.08E-01	W
3.8	7.38E-01	S	2.88E-05	S	4.25E-02	S	3.24E-01	W
4	5.74E-01	S	4.42E-05	S	3.80E-02	S	2.61E-01	W
4.2	4.64E-01	S	4.93E-05	S	3.41E-02	S	2.12E-01	W
4.4	4.88E-01	S	5.48E-05	S	3.08E-02	S	1.74E-01	W
4.6	4.54E-01	S	6.07E-05	S	2.79E-02	S	1.44E-01	W
4.8	3.46E-01	S	5.91E-05	S	2.54E-02	S	1.20E-01	W
5	3.76E-01	S	5.55E-05	S	2.32E-02	S	1.01E-01	W
5.2	5.85E-01	S	3.49E-05	S	2.85E-02	S	1.09E-01	W
5.4	7.11E-01	S	1.62E-05	S	4.41E-02	S	1.44E-01	W
5.6	7.13E-01	S	5.29E-05	S	6.70E-02	S	1.88E-01	W
5.8	7.38E-01	S	4.84E-05	S	5.20E-02	S	2.22E-01	W
6	7.64E-01	S	4.44E-05	S	6.68E-02	S	2.34E-01	W
6.2	7.89E-01	W	4.08E-05	S	8.51E-02	S	2.47E-01	W
6.4	8.15E-01	W	3.77E-05	S	1.08E-01	S	2.60E-01	W
6.6	8.41E-01	W	3.48E-05	S	1.35E-01	S	2.73E-01	W
6.8	8.66E-01	W	3.23E-05	S	1.68E-01	S	2.87E-01	W
7	8.92E-01	W	3.00E-05	S	2.08E-01	S	3.00E-01	W
7.2	9.17E-01	W	2.79E-05	S	2.57E-01	W	3.14E-01	W
7.4	9.39E-01	W	2.60E-05	S	3.14E-01	W	3.28E-01	W
7.6	9.41E-01	W	2.43E-05	S	3.82E-01	W	3.43E-01	W
7.8	9.43E-01	W	2.28E-05	S	4.63E-01	W	3.57E-01	W
8	9.45E-01	W	2.14E-05	S	5.58E-01	W	3.72E-01	S

Table C-5-31. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID PPB Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
8.2	9.59E-01	W	2.01E-05	S	6.70E-01	W	3.87E-01	S
8.4	9.84E-01	W	1.89E-05	S	7.16E-01	W	2.90E-01	S
8.6	1.01E+00	W	1.77E-05	S	4.72E-01	W	5.18E-02	S
8.8	1.03E+00	W	1.67E-05	S	3.14E-01	W	9.65E-03	S
9	6.80E-01	S	1.47E-05	S	2.33E-01	S	3.65E-03	S
9.2	5.02E-01	S	1.41E-05	S	2.37E-01	S	1.09E-02	S
9.4	4.71E-01	S	1.53E-05	S	2.40E-01	S	3.19E-02	S
9.6	3.46E-01	S	1.59E-05	S	2.40E-01	S	5.77E-02	S
9.8	1.80E-01	S	1.55E-05	S	2.34E-01	S	5.39E-02	S
10	9.50E-02	S	1.50E-05	S	2.28E-01	S	5.05E-02	S
10.2	5.08E-02	S	1.46E-05	S	2.23E-01	S	4.74E-02	S
10.4	5.32E-02	S	1.42E-05	S	2.18E-01	S	4.45E-02	S
10.6	1.76E-01	S	1.38E-05	S	2.13E-01	S	4.18E-02	S
10.8	1.14E-01	S	1.35E-05	S	2.09E-01	S	3.93E-02	S
11	6.84E-02	S	1.32E-05	S	2.04E-01	S	3.70E-02	S
11.2	4.15E-02	S	1.28E-05	S	2.00E-01	S	3.49E-02	S
11.4	2.54E-02	S	1.33E-05	S	1.96E-01	S	3.30E-02	S
11.6	1.56E-02	S	1.52E-05	S	1.92E-01	S	3.12E-02	S
11.8	2.66E-02	S	1.72E-05	S	1.88E-01	S	2.95E-02	S
12	7.68E-02	S	1.94E-05	S	1.84E-01	S	2.79E-02	S
12.2	1.29E-01	S	2.08E-05	S	1.81E-01	S	2.65E-02	S
12.4	1.21E-01	S	2.47E-05	S	1.77E-01	S	2.51E-02	S
12.6	4.88E-01	S	2.78E-05	S	1.74E-01	S	2.38E-02	S
12.8	1.40E+00	S	3.12E-05	S	1.71E-01	S	2.26E-02	S
13	1.40E+00	S	3.50E-05	S	1.68E-01	S	2.15E-02	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		1.00E-03		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		1.00E-03		8.00E-05	
Availability (mg/kg)	1.60E+01		6.21E-04		7.16E+00		4.42E+00	

Table C-5-31. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID PPB Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	4.27E-02	S	1.82E-01	S	2.73E-04	S
3	5.35E-02	S	1.82E-01	S	4.85E-04	S
3.2	6.61E-02	S	1.82E-01	S	8.29E-04	S
3.4	8.07E-02	S	1.82E-01	S	1.37E-03	S
3.6	9.73E-02	S	1.75E-01	S	2.66E-03	S
3.8	1.16E-01	S	1.56E-01	S	3.45E-03	S
4	1.08E-01	S	1.39E-01	S	2.81E-03	S
4.2	1.27E-01	S	1.25E-01	S	2.82E-03	S
4.4	1.49E-01	S	1.13E-01	S	3.10E-03	S
4.6	1.74E-01	S	1.03E-01	S	3.11E-03	S
4.8	1.83E-01	S	9.40E-02	S	3.22E-03	S
5	1.40E-01	S	8.61E-02	S	4.02E-03	S
5.2	1.23E-01	S	9.59E-02	S	4.35E-03	S
5.4	9.82E-02	S	1.24E-01	S	3.37E-03	S
5.6	9.77E-02	S	1.59E-01	S	3.09E-03	S
5.8	9.83E-02	S	1.02E-01	S	2.80E-03	S
6	9.90E-02	S	9.89E-02	S	3.23E-03	S
6.2	9.96E-02	S	9.61E-02	S	3.72E-03	S
6.4	1.00E-01	S	9.35E-02	S	4.25E-03	S
6.6	1.01E-01	S	9.10E-02	S	4.85E-03	S
6.8	1.01E-01	S	8.86E-02	S	5.51E-03	S
7	1.02E-01	S	8.64E-02	S	6.23E-03	S
7.2	1.03E-01	S	8.43E-02	S	7.03E-03	S
7.4	1.03E-01	S	8.23E-02	S	7.90E-03	S
7.6	1.04E-01	S	8.04E-02	S	8.85E-03	S
7.8	1.04E-01	S	7.86E-02	S	9.88E-03	S
8	1.05E-01	S	7.69E-02	S	1.04E-02	S

Table C-5-31. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID PPB Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	1.05E-01	S	7.52E-02	S	1.10E-02	S
8.4	1.06E-01	S	5.94E-02	S	1.15E-02	S
8.6	1.06E-01	S	1.84E-02	S	1.24E-02	S
8.8	1.07E-01	S	5.89E-03	S	1.36E-02	S
9	1.07E-01	S	2.96E-03	S	1.38E-02	S
9.2	1.05E-01	S	5.53E-03	S	1.33E-02	S
9.4	1.04E-01	S	1.02E-02	S	1.29E-02	S
9.6	1.03E-01	S	1.39E-02	S	1.15E-02	S
9.8	1.02E-01	S	1.24E-02	S	9.12E-03	S
10	1.01E-01	S	1.11E-02	S	7.30E-03	S
10.2	1.01E-01	S	9.92E-03	S	5.86E-03	S
10.4	9.98E-02	S	8.91E-03	S	6.09E-03	S
10.6	9.90E-02	S	8.01E-03	S	1.01E-02	S
10.8	1.00E-01	S	7.22E-03	S	8.47E-03	S
11	1.03E-01	S	6.53E-03	S	6.80E-03	S
11.2	1.06E-01	S	5.91E-03	S	5.47E-03	S
11.4	1.08E-01	S	5.66E-03	S	4.42E-03	S
11.6	1.52E-01	S	5.87E-03	S	7.34E-03	S
11.8	2.14E-01	S	6.08E-03	S	1.89E-02	S
12	2.99E-01	S	6.29E-03	S	4.81E-02	S
12.2	3.54E-01	S	6.50E-03	S	7.68E-02	S
12.4	3.54E-01	S	6.72E-03	S	7.68E-02	S
12.6	3.54E-01	S	6.95E-03	S	8.04E-02	S
12.8	3.54E-01	S	7.17E-03	S	8.04E-02	S
13	3.54E-01	S	7.40E-03	S	8.04E-02	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	4.04E+00		1.82E+00		9.17E-01	

Table C-5-32. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID PPT Med

Sample ID	PPT-[Med] (P,1,1)
Date Exported	8/27/2011, 2:09 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	3.20E-03	S	7.37E+00	W	5.86E-02	S	2.05E-04	S
3	3.20E-03	S	7.96E+00	W	5.86E-02	S	2.05E-04	S
3.2	3.20E-03	S	8.55E+00	W	3.80E-02	S	2.05E-04	S
3.4	3.20E-03	S	9.14E+00	W	2.06E-02	S	1.71E-02	S
3.6	3.20E-03	S	9.73E+00	W	5.04E-02	S	8.88E-01	S
3.8	3.20E-03	S	1.03E+01	W	2.89E-02	S	3.94E-01	S
4	3.20E-03	S	1.09E+01	W	1.71E-02	S	2.59E-01	S
4.2	3.20E-03	S	1.15E+01	W	4.18E-02	S	9.19E-01	S
4.4	3.20E-03	S	8.15E+00	W	2.54E-02	S	6.71E-01	S
4.6	3.20E-03	S	8.10E+00	W	1.78E-02	S	4.36E-01	S
4.8	3.20E-03	S	8.06E+00	W	1.62E-02	S	2.88E-01	S
5	3.20E-03	S	8.02E+00	W	1.95E-02	S	2.90E-01	S
5.2	3.20E-03	S	7.53E+00	W	2.33E-02	S	2.16E-01	S
5.4	3.20E-03	S	6.47E+00	W	2.62E-02	S	1.62E-01	S
5.6	3.20E-03	S	5.81E+00	W	2.28E-02	S	1.47E-01	S
5.8	3.20E-03	S	6.24E+00	W	1.99E-02	S	1.18E-01	S
6	3.20E-03	S	6.69E+00	W	1.74E-02	S	9.49E-02	S
6.2	3.20E-03	S	7.16E+00	W	1.54E-02	S	7.71E-02	S
6.4	3.20E-03	S	7.70E+00	W	1.36E-02	S	6.07E-02	S
6.6	3.20E-03	S	8.34E+00	W	1.21E-02	S	4.56E-02	S
6.8	3.20E-03	S	9.01E+00	W	1.11E-02	S	3.45E-02	S
7	3.20E-03	S	9.72E+00	W	1.18E-02	S	2.63E-02	S
7.2	3.20E-03	S	1.05E+01	W	1.25E-02	S	2.02E-02	S
7.4	3.20E-03	S	1.12E+01	W	1.33E-02	S	1.57E-02	S
7.6	3.20E-03	S	1.20E+01	W	1.41E-02	S	1.22E-02	S
7.8	3.20E-03	S	1.29E+01	W	1.49E-02	S	1.00E-02	S
8	3.20E-03	S	1.30E+01	W	1.53E-02	S	8.29E-03	S

Table C-5-32. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID PPT Med

Sample ID	PPT-[Med] (P,1,1)
Date Exported	8/27/2011, 2:09 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	3.20E-03	S	1.23E+01	W	1.46E-02	S	6.98E-03	S
8.4	3.20E-03	S	1.17E+01	W	1.43E-02	S	6.17E-03	S
8.6	3.20E-03	S	1.11E+01	W	1.39E-02	S	5.48E-03	S
8.8	3.20E-03	S	1.05E+01	W	1.35E-02	S	4.86E-03	S
9	3.20E-03	S	9.99E+00	W	1.32E-02	S	3.84E-03	S
9.2	3.20E-03	S	9.51E+00	W	1.29E-02	S	3.14E-03	S
9.4	3.20E-03	S	9.05E+00	W	1.26E-02	S	2.71E-03	S
9.6	3.20E-03	S	8.63E+00	W	1.23E-02	S	2.34E-03	S
9.8	3.20E-03	S	8.24E+00	W	1.19E-02	S	2.06E-03	S
10	3.20E-03	S	7.87E+00	S	1.08E-02	S	2.06E-03	S
10.2	3.20E-03	S	7.53E+00	S	9.89E-03	S	2.06E-03	S
10.4	3.20E-03	S	7.20E+00	S	9.05E-03	S	2.06E-03	S
10.6	3.20E-03	S	5.20E+00	S	8.29E-03	S	2.06E-03	S
10.8	3.20E-03	S	3.69E+00	S	7.60E-03	S	2.06E-03	S
11	3.20E-03	S	2.63E+00	S	6.99E-03	S	2.06E-03	S
11.2	3.20E-03	S	1.89E+00	S	6.43E-03	S	2.06E-03	S
11.4	3.20E-03	S	1.37E+00	S	5.93E-03	S	2.06E-03	S
11.6	3.20E-03	S	9.93E-01	S	5.33E-03	S	2.06E-03	S
11.8	3.20E-03	S	7.25E-01	S	4.89E-03	S	2.06E-03	S
12	3.20E-03	S	5.38E-01	S	5.00E-03	S	2.06E-03	S
12.2	3.20E-03	S	4.18E-01	S	7.18E-03	S	2.06E-03	S
12.4	3.88E-03	S	4.11E-01	S	1.00E-02	S	2.06E-03	S
12.6	7.88E-03	S	7.56E-01	S	1.02E-02	S	2.06E-03	S
12.8	1.58E-02	S	1.38E+00	S	1.05E-02	S	2.06E-03	S
13	3.14E-02	S	2.48E+00	S	1.06E-02	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	2.50E-01		1.30E+02		5.86E-01		9.19E+00	

Table C-5-32. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID PPT Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	**Chromium**	**Solubility/ Washout**	**Mercury**	**Solubility/ Washout**	**Molybdenum**	**Solubility/ Washout**	**Antimony**	**Solubility/ Washout**
2.8	8.97E-02	S	2.07E-06	S	5.00E-04	S	6.53E-02	W
3	8.29E-02	S	2.07E-06	S	5.00E-04	S	8.80E-02	W
3.2	7.70E-02	S	2.07E-06	S	5.00E-04	S	1.16E-01	W
3.4	7.18E-02	S	2.07E-06	S	5.00E-04	S	1.51E-01	W
3.6	6.76E-03	S	2.07E-06	S	5.00E-04	S	1.94E-01	W
3.8	8.86E-03	S	2.07E-06	S	5.00E-04	S	2.45E-01	W
4	1.14E-02	S	3.23E-06	S	1.98E-03	S	3.06E-01	W
4.2	1.21E-02	S	2.18E-06	S	9.12E-03	S	3.78E-01	W
4.4	1.34E-02	S	3.35E-06	S	2.28E-03	S	2.46E-01	W
4.6	1.57E-02	S	6.13E-06	S	8.10E-03	S	2.97E-01	W
4.8	1.84E-02	S	7.02E-06	S	2.72E-02	S	3.56E-01	W
5	2.13E-02	S	1.18E-05	S	8.71E-02	S	4.22E-01	W
5.2	2.46E-02	S	1.11E-05	S	1.61E-01	S	4.47E-01	W
5.4	2.83E-02	S	4.92E-06	S	1.31E-01	S	3.97E-01	W
5.6	3.23E-02	S	4.55E-06	S	1.15E-01	S	3.59E-01	W
5.8	3.67E-02	S	4.23E-06	S	1.37E-01	S	3.46E-01	W
6	4.16E-02	S	4.69E-06	S	1.62E-01	S	3.33E-01	W
6.2	4.68E-02	W	6.70E-06	S	1.91E-01	S	3.21E-01	W
6.4	5.26E-02	W	5.04E-06	S	2.17E-01	S	3.13E-01	W
6.6	5.89E-02	W	3.39E-06	S	2.36E-01	S	3.09E-01	W
6.8	7.70E-02	W	3.02E-06	S	2.55E-01	S	3.05E-01	W
7	8.80E-02	W	2.84E-06	S	2.76E-01	S	3.01E-01	W
7.2	9.52E-02	W	2.67E-06	S	2.97E-01	W	2.97E-01	W
7.4	1.03E-01	W	2.52E-06	S	3.20E-01	W	2.94E-01	W
7.6	1.09E-01	W	2.44E-06	S	3.43E-01	W	2.91E-01	W
7.8	1.08E-01	W	5.15E-06	S	3.68E-01	W	2.87E-01	W
8	1.13E-01	W	1.06E-05	S	3.80E-01	W	2.59E-01	S

Table C-5-32. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID PPT Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	1.20E-01	W	2.16E-05	S	3.74E-01	W	2.07E-01	S
8.4	1.28E-01	W	2.39E-05	S	3.68E-01	W	1.66E-01	S
8.6	1.36E-01	W	2.22E-05	S	3.63E-01	W	1.34E-01	S
8.8	1.46E-01	W	2.07E-05	S	3.57E-01	W	1.09E-01	S
9	1.64E-01	S	1.93E-05	S	3.52E-01	W	8.87E-02	S
9.2	1.84E-01	S	1.80E-05	S	3.47E-01	W	7.26E-02	S
9.4	2.06E-01	S	1.69E-05	S	3.43E-01	W	5.97E-02	S
9.6	2.17E-01	S	1.61E-05	S	3.38E-01	W	4.93E-02	S
9.8	1.95E-01	S	1.61E-05	S	3.34E-01	W	4.09E-02	S
10	1.98E-01	S	1.61E-05	S	3.29E-01	S	3.40E-02	S
10.2	2.07E-01	S	1.61E-05	S	3.25E-01	S	2.84E-02	S
10.4	1.87E-01	S	1.61E-05	S	3.21E-01	S	2.38E-02	S
10.6	1.69E-01	S	1.61E-05	S	2.75E-01	S	1.96E-02	S
10.8	1.53E-01	S	1.61E-05	S	2.33E-01	S	1.62E-02	S
11	1.39E-01	S	1.61E-05	S	1.98E-01	S	1.34E-02	S
11.2	1.22E-01	S	1.61E-05	S	1.69E-01	S	1.12E-02	S
11.4	1.06E-01	S	1.61E-05	S	1.45E-01	S	9.33E-03	S
11.6	9.21E-02	S	1.61E-05	S	1.24E-01	S	7.81E-03	S
11.8	9.59E-02	S	1.72E-05	S	1.07E-01	S	6.55E-03	S
12	9.72E-02	S	1.63E-05	S	1.05E-01	S	5.79E-03	S
12.2	1.91E-01	S	4.91E-06	S	1.83E-01	S	6.25E-03	S
12.4	3.47E-01	S	2.49E-06	S	2.70E-01	S	8.43E-03	S
12.6	3.68E-01	S	4.92E-06	S	2.64E-01	S	2.06E-02	S
12.8	3.89E-01	S	9.60E-06	S	2.59E-01	S	4.97E-02	S
13	4.13E-01	S	1.86E-05	S	2.53E-01	S	1.18E-01	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		1.00E-03		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		1.00E-03		8.00E-05	
Availability (mg/kg)	6.15E+00		2.39E-04		4.09E+00		4.47E+00	

Table C-5-32. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID PPT Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	7.70E-03	S	1.95E-01	S	2.59E-02	S
3	1.28E-02	S	2.37E-01	S	1.69E-02	S
3.2	2.06E-02	S	2.83E-01	S	1.14E-02	S
3.4	3.22E-02	S	3.35E-01	S	7.83E-03	S
3.6	8.88E-02	S	3.93E-01	S	3.46E-03	S
3.8	8.34E-02	S	4.57E-01	S	3.75E-03	S
4	7.64E-02	S	5.27E-01	S	3.36E-03	S
4.2	7.69E-02	S	6.04E-01	S	2.55E-03	S
4.4	6.87E-02	S	5.46E-01	S	3.59E-03	S
4.6	6.83E-02	S	4.78E-01	S	3.33E-03	S
4.8	6.80E-02	S	4.21E-01	S	3.33E-03	S
5	6.77E-02	S	3.73E-01	S	3.69E-03	S
5.2	6.74E-02	S	3.57E-01	S	4.08E-03	S
5.4	6.74E-02	S	3.84E-01	S	4.32E-03	S
5.6	6.80E-02	S	3.92E-01	S	4.36E-03	S
5.8	6.88E-02	S	3.21E-01	S	4.54E-03	S
6	6.97E-02	S	2.65E-01	S	4.72E-03	S
6.2	7.05E-02	S	2.20E-01	S	4.90E-03	S
6.4	7.09E-02	S	1.92E-01	S	5.28E-03	S
6.6	7.06E-02	S	1.82E-01	S	6.01E-03	S
6.8	7.03E-02	S	1.73E-01	S	6.83E-03	S
7	7.00E-02	S	1.65E-01	S	7.72E-03	S
7.2	6.97E-02	S	1.57E-01	S	8.70E-03	S
7.4	6.94E-02	S	1.50E-01	S	9.78E-03	S
7.6	6.96E-02	S	1.43E-01	S	1.07E-02	S
7.8	6.89E-02	S	1.37E-01	S	1.14E-02	S
8	6.91E-02	S	1.27E-01	S	1.22E-02	S

Table C-5-32. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID PPT Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	6.97E-02	S	1.13E-01	S	1.30E-02	S
8.4	7.04E-02	S	1.01E-01	S	1.39E-02	S
8.6	7.25E-02	S	9.05E-02	S	1.54E-02	S
8.8	7.47E-02	S	8.13E-02	S	1.63E-02	S
9	7.69E-02	S	7.32E-02	S	1.71E-02	S
9.2	7.92E-02	S	6.61E-02	S	1.79E-02	S
9.4	8.14E-02	S	5.98E-02	S	1.88E-02	S
9.6	8.29E-02	S	5.42E-02	S	1.97E-02	S
9.8	7.44E-02	S	4.92E-02	S	2.05E-02	S
10	7.50E-02	S	4.48E-02	S	1.86E-02	S
10.2	6.76E-02	S	4.09E-02	S	1.66E-02	S
10.4	6.06E-02	S	3.73E-02	S	1.48E-02	S
10.6	5.44E-02	S	2.64E-02	S	1.33E-02	S
10.8	4.89E-02	S	1.84E-02	S	1.19E-02	S
11	4.41E-02	S	1.29E-02	S	1.08E-02	S
11.2	3.81E-02	S	9.06E-03	S	9.94E-03	S
11.4	3.22E-02	S	6.43E-03	S	9.13E-03	S
11.6	2.87E-02	S	4.59E-03	S	8.39E-03	S
11.8	2.97E-02	S	3.29E-03	S	8.32E-03	S
12	2.81E-02	S	2.53E-03	S	1.02E-02	S
12.2	3.45E-02	S	2.53E-03	S	5.00E-02	S
12.4	5.77E-02	S	2.95E-03	S	1.69E-01	S
12.6	1.20E-01	S	5.17E-03	S	2.21E-01	S
12.8	2.46E-01	S	8.98E-03	S	2.88E-01	S
13	4.98E-01	S	1.55E-02	S	3.73E-01	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	3.88E+00		6.04E+00		4.55E+00	

Table C-5-33. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID XFA Med

Sample ID	XFA-[Med] (P,1,1)
Date Exported	8/27/2011, 2:10 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	3.20E-03	S	8.64E+00	W	7.68E-02	S	1.76E+00	S
3	3.20E-03	S	7.47E+00	W	7.68E-02	S	1.76E+00	S
3.2	3.20E-03	S	6.52E+00	W	3.51E-02	S	9.64E-01	S
3.4	3.20E-03	S	5.73E+00	W	7.85E-03	S	3.05E-01	S
3.6	3.20E-03	S	5.08E+00	W	1.91E-03	S	1.03E-01	S
3.8	3.20E-03	S	4.74E+00	W	7.46E-04	S	5.12E-02	S
4	3.20E-03	S	4.91E+00	W	7.46E-04	S	5.60E-02	S
4.2	3.20E-03	S	5.07E+00	W	7.46E-04	S	6.08E-02	S
4.4	3.20E-03	S	5.17E+00	W	8.13E-04	S	6.29E-02	S
4.6	3.20E-03	S	5.14E+00	W	1.07E-03	S	5.85E-02	S
4.8	3.20E-03	S	5.11E+00	W	1.40E-03	S	5.45E-02	S
5	3.20E-03	S	5.07E+00	W	1.79E-03	S	4.61E-02	S
5.2	3.20E-03	S	5.10E+00	W	2.06E-03	W	3.97E-02	S
5.4	3.20E-03	S	5.23E+00	W	2.06E-03	W	3.69E-02	S
5.6	3.20E-03	S	5.36E+00	W	2.06E-03	W	3.44E-02	S
5.8	3.20E-03	S	5.49E+00	W	2.06E-03	W	3.21E-02	S
6	3.20E-03	S	5.62E+00	W	2.06E-03	W	3.01E-02	S
6.2	3.20E-03	S	5.74E+00	W	2.06E-03	W	2.82E-02	S
6.4	3.20E-03	S	5.86E+00	W	2.06E-03	W	2.65E-02	S
6.6	3.20E-03	S	5.99E+00	W	2.06E-03	W	2.50E-02	S
6.8	3.20E-03	S	6.11E+00	W	2.06E-03	W	2.36E-02	S
7	3.20E-03	S	6.96E+00	W	2.11E-03	W	2.10E-02	S
7.2	3.20E-03	S	7.90E+00	W	2.16E-03	W	1.88E-02	S
7.4	3.20E-03	S	8.94E+00	W	2.20E-03	W	1.69E-02	S
7.6	3.20E-03	S	1.01E+01	W	2.25E-03	W	1.52E-02	S
7.8	3.20E-03	S	1.02E+01	W	2.24E-03	W	1.41E-02	S
8	3.20E-03	S	1.04E+01	W	2.24E-03	W	1.32E-02	S

Table C-5-33. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID XFA Med

Sample ID	XFA-[Med] (P,1,1)
Date Exported	8/27/2011, 2:10 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	3.20E-03	S	1.05E+01	W	2.23E-03	W	1.23E-02	S
8.4	3.20E-03	S	1.07E+01	W	2.23E-03	W	1.15E-02	S
8.6	3.20E-03	S	1.08E+01	W	2.22E-03	W	1.07E-02	S
8.8	3.20E-03	S	1.10E+01	W	2.22E-03	W	1.00E-02	S
9	3.20E-03	S	1.11E+01	W	2.21E-03	W	9.42E-03	S
9.2	3.20E-03	S	1.07E+01	W	2.28E-03	W	8.43E-03	S
9.4	3.20E-03	S	1.00E+01	W	2.39E-03	W	7.40E-03	S
9.6	3.20E-03	S	9.46E+00	W	2.50E-03	W	6.51E-03	S
9.8	3.20E-03	S	8.92E+00	W	2.61E-03	W	5.75E-03	S
10	3.20E-03	S	7.36E+00	S	2.45E-03	S	5.07E-03	S
10.2	3.20E-03	S	5.34E+00	S	2.07E-03	S	4.46E-03	S
10.4	3.20E-03	S	3.90E+00	S	1.75E-03	S	3.94E-03	S
10.6	3.20E-03	S	2.86E+00	S	1.49E-03	S	3.48E-03	S
10.8	3.20E-03	S	2.11E+00	S	1.27E-03	S	3.09E-03	S
11	3.20E-03	S	1.57E+00	S	1.09E-03	S	2.74E-03	S
11.2	3.20E-03	S	1.17E+00	S	9.34E-04	S	2.44E-03	S
11.4	3.20E-03	S	8.78E-01	S	8.04E-04	S	2.18E-03	S
11.6	3.20E-03	S	1.03E+00	S	7.46E-04	S	2.06E-03	S
11.8	3.20E-03	S	1.89E+00	S	7.46E-04	S	2.06E-03	S
12	3.20E-03	S	3.43E+00	S	7.46E-04	S	2.06E-03	S
12.2	3.20E-03	S	6.16E+00	S	7.46E-04	S	2.06E-03	S
12.4	3.20E-03	S	1.10E+01	S	7.46E-04	S	2.06E-03	S
12.6	3.20E-03	S	1.11E+01	S	7.46E-04	S	2.06E-03	S
12.8	3.20E-03	S	1.11E+01	S	7.46E-04	S	2.06E-03	S
13	3.20E-03	S	1.11E+01	S	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	3.26E-02		1.14E+02		7.68E-01		1.76E+01	

Table C-5-33. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID XFA Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	4.13E-02	S	1.00E-04	S	1.07E-02	S	2.78E-03	S
3	1.00E-01	S	1.00E-04	S	3.45E-02	S	2.78E-03	S
3.2	2.30E-01	S	8.21E-05	S	1.03E-01	S	2.78E-03	S
3.4	5.01E-01	S	5.64E-05	S	2.89E-01	S	2.78E-03	S
3.6	1.04E+00	S	3.96E-05	S	7.62E-01	S	2.78E-03	S
3.8	1.67E+00	S	3.13E-05	S	1.44E+00	S	2.78E-03	S
4	1.57E+00	S	3.13E-05	S	1.40E+00	S	2.78E-03	S
4.2	1.48E+00	S	3.13E-05	S	1.36E+00	S	2.78E-03	S
4.4	1.48E+00	S	3.08E-05	S	1.36E+00	S	2.78E-03	S
4.6	1.67E+00	S	2.96E-05	S	1.47E+00	S	2.78E-03	S
4.8	1.87E+00	S	2.84E-05	S	1.58E+00	S	2.78E-03	S
5	2.03E+00	S	2.24E-05	S	1.75E+00	S	2.78E-03	S
5.2	2.12E+00	W	1.93E-05	S	1.88E+00	W	2.78E-03	S
5.4	2.16E+00	W	2.06E-05	S	1.92E+00	W	2.78E-03	S
5.6	2.19E+00	W	2.20E-05	S	1.96E+00	W	2.78E-03	S
5.8	2.23E+00	W	2.35E-05	S	1.99E+00	W	2.78E-03	S
6	2.26E+00	W	2.49E-05	S	2.03E+00	W	2.78E-03	S
6.2	2.29E+00	W	2.65E-05	S	2.06E+00	W	2.78E-03	S
6.4	2.32E+00	W	2.80E-05	S	2.10E+00	W	2.78E-03	S
6.6	2.35E+00	W	2.96E-05	S	2.13E+00	W	2.78E-03	S
6.8	2.38E+00	W	3.13E-05	S	2.16E+00	W	2.78E-03	S
7	2.54E+00	W	2.95E-05	S	2.20E+00	W	2.78E-03	S
7.2	2.69E+00	W	2.79E-05	S	2.23E+00	W	2.78E-03	S
7.4	2.86E+00	W	2.64E-05	S	2.26E+00	W	2.78E-03	S
7.6	3.03E+00	W	2.50E-05	S	2.29E+00	W	2.78E-03	S
7.8	3.08E+00	W	2.65E-05	S	2.28E+00	W	2.78E-03	S
8	3.14E+00	W	2.81E-05	S	2.28E+00	W	2.78E-03	S

Table C-5-33. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID XFA Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	3.20E+00	W	2.98E-05	S	2.27E+00	W	2.78E-03	S
8.4	3.26E+00	W	3.15E-05	S	2.27E+00	W	2.78E-03	S
8.6	3.31E+00	W	3.33E-05	S	2.26E+00	W	2.78E-03	S
8.8	3.37E+00	W	3.51E-05	S	2.26E+00	W	2.78E-03	S
9	3.43E+00	W	3.69E-05	S	2.25E+00	W	2.78E-03	S
9.2	3.40E+00	W	3.69E-05	S	2.28E+00	W	2.78E-03	S
9.4	3.35E+00	W	3.62E-05	S	2.31E+00	W	2.78E-03	S
9.6	3.29E+00	W	3.54E-05	S	2.35E+00	W	2.78E-03	S
9.8	3.24E+00	W	3.47E-05	S	2.39E+00	W	2.78E-03	S
10	2.66E+00	S	3.46E-05	S	2.18E+00	S	2.78E-03	S
10.2	1.83E+00	S	3.50E-05	S	1.79E+00	S	2.78E-03	S
10.4	1.26E+00	S	3.54E-05	S	1.48E+00	S	2.78E-03	S
10.6	8.80E-01	S	3.58E-05	S	1.22E+00	S	2.78E-03	S
10.8	6.17E-01	S	3.62E-05	S	1.02E+00	S	2.78E-03	S
11	4.35E-01	S	3.65E-05	S	8.48E-01	S	2.78E-03	S
11.2	3.09E-01	S	3.69E-05	S	7.09E-01	S	2.78E-03	S
11.4	2.21E-01	S	3.73E-05	S	5.95E-01	S	2.78E-03	S
11.6	1.10E-01	S	3.37E-05	S	3.15E-01	S	2.78E-03	S
11.8	3.85E-02	S	2.74E-05	S	1.06E-01	S	2.78E-03	S
12	1.37E-02	S	2.23E-05	S	3.64E-02	S	2.78E-03	S
12.2	4.98E-03	S	1.83E-05	S	1.27E-02	S	2.78E-03	S
12.4	1.84E-03	S	1.50E-05	S	4.52E-03	S	2.78E-03	S
12.6	6.89E-04	S	1.23E-05	S	1.63E-03	S	2.78E-03	S
12.8	2.62E-04	S	1.02E-05	S	6.00E-04	S	2.78E-03	S
13	2.50E-04	S	8.42E-06	S	3.80E-04	S	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	3.43E+01		1.00E-03		2.39E+01		2.84E-02	

Table C-5-33. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID XFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	5.04E-01	S	8.63E-03	S	1.73E-03	S
3	5.04E-01	S	8.63E-03	S	2.49E-03	S
3.2	4.11E-01	S	7.01E-03	S	3.51E-03	S
3.4	2.78E-01	S	4.72E-03	S	4.84E-03	S
3.6	1.93E-01	S	3.25E-03	S	6.55E-03	S
3.8	1.51E-01	S	2.53E-03	S	8.23E-03	S
4	1.52E-01	S	2.53E-03	S	8.98E-03	S
4.2	1.53E-01	S	2.53E-03	S	9.76E-03	S
4.4	1.54E-01	S	2.53E-03	S	1.07E-02	S
4.6	1.57E-01	S	2.53E-03	S	1.21E-02	S
4.8	1.59E-01	S	2.53E-03	S	1.36E-02	S
5	1.65E-01	S	2.53E-03	S	1.61E-02	S
5.2	1.70E-01	S	2.53E-03	S	1.83E-02	S
5.4	1.72E-01	S	2.53E-03	S	1.95E-02	S
5.6	1.74E-01	S	2.53E-03	S	2.07E-02	S
5.8	1.77E-01	S	2.53E-03	S	2.19E-02	S
6	1.79E-01	S	2.53E-03	S	2.32E-02	S
6.2	1.81E-01	S	2.53E-03	S	2.45E-02	S
6.4	1.84E-01	S	2.53E-03	S	2.58E-02	S
6.6	1.86E-01	S	2.53E-03	S	2.71E-02	S
6.8	1.88E-01	S	2.53E-03	S	2.85E-02	S
7	1.90E-01	S	2.53E-03	S	3.14E-02	S
7.2	1.93E-01	S	2.53E-03	S	3.45E-02	S
7.4	1.95E-01	S	2.53E-03	S	3.78E-02	S
7.6	1.97E-01	S	2.53E-03	S	4.13E-02	S
7.8	1.93E-01	S	2.53E-03	S	4.42E-02	S
8	1.90E-01	S	2.53E-03	S	4.72E-02	S

Table C-5-33. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID XFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	1.86E-01	S	2.53E-03	S	5.03E-02	S
8.4	1.83E-01	S	2.53E-03	S	5.36E-02	S
8.6	1.80E-01	S	2.53E-03	S	5.70E-02	S
8.8	1.77E-01	S	2.53E-03	S	6.05E-02	S
9	1.74E-01	S	2.53E-03	S	6.41E-02	S
9.2	1.73E-01	S	2.53E-03	S	6.49E-02	S
9.4	1.71E-01	S	2.53E-03	S	6.44E-02	S
9.6	1.70E-01	S	2.53E-03	S	6.40E-02	S
9.8	1.69E-01	S	2.53E-03	S	6.36E-02	S
10	1.47E-01	S	2.53E-03	S	6.22E-02	S
10.2	1.13E-01	S	2.53E-03	S	5.99E-02	S
10.4	8.68E-02	S	2.53E-03	S	5.77E-02	S
10.6	6.72E-02	S	2.53E-03	S	5.56E-02	S
10.8	5.22E-02	S	2.53E-03	S	5.37E-02	S
11	4.08E-02	S	2.53E-03	S	5.18E-02	S
11.2	3.20E-02	S	2.53E-03	S	5.01E-02	S
11.4	2.52E-02	S	2.53E-03	S	4.84E-02	S
11.6	2.12E-02	S	2.53E-03	S	3.33E-02	S
11.8	1.89E-02	S	2.53E-03	S	1.64E-02	S
12	1.69E-02	S	2.53E-03	S	8.15E-03	S
12.2	1.52E-02	S	2.53E-03	S	4.11E-03	S
12.4	1.36E-02	S	2.53E-03	S	2.09E-03	S
12.6	1.22E-02	S	2.53E-03	S	1.08E-03	S
12.8	1.10E-02	S	2.53E-03	S	5.61E-04	S
13	9.94E-03	S	2.53E-03	S	2.95E-04	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	5.04E+00		8.63E-02		6.49E-01	

Table C-5-34. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID ZFA Med

Sample ID	ZFA-[Med] (P,1,1)
Date Exported	8/27/2011, 2:10 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
2.8	3.20E-03	S	7.19E+00	S	1.83E-01	S	2.83E+00	S
3	3.20E-03	S	6.32E+00	S	1.83E-01	S	3.06E+00	S
3.2	3.20E-03	S	5.60E+00	S	1.83E-01	S	3.28E+00	S
3.4	3.20E-03	S	5.00E+00	S	1.83E-01	S	3.50E+00	S
3.6	3.20E-03	S	4.50E+00	S	1.80E-01	S	3.73E+00	S
3.8	3.20E-03	S	4.06E+00	S	1.29E-01	S	3.96E+00	S
4	3.20E-03	S	3.69E+00	S	9.36E-02	S	4.19E+00	S
4.2	3.20E-03	S	3.37E+00	S	6.92E-02	S	4.42E+00	S
4.4	3.20E-03	S	3.27E+00	S	5.63E-02	S	4.15E+00	S
4.6	3.20E-03	S	3.19E+00	S	4.66E-02	S	3.86E+00	S
4.8	3.20E-03	S	3.12E+00	S	3.89E-02	S	3.60E+00	S
5	3.20E-03	S	3.05E+00	S	3.27E-02	S	3.37E+00	S
5.2	3.20E-03	S	3.00E+00	S	2.26E-02	S	2.77E+00	S
5.4	3.20E-03	S	2.96E+00	S	1.18E-02	S	1.89E+00	S
5.6	3.20E-03	S	2.93E+00	S	6.32E-03	S	1.31E+00	S
5.8	3.20E-03	S	2.89E+00	S	3.46E-03	S	9.21E-01	S
6	3.20E-03	S	2.86E+00	S	1.93E-03	S	6.54E-01	S
6.2	3.20E-03	S	2.83E+00	S	1.10E-03	S	4.70E-01	S
6.4	3.20E-03	S	2.86E+00	S	7.46E-04	S	3.18E-01	S
6.6	3.20E-03	S	3.00E+00	S	7.46E-04	S	1.86E-01	S
6.8	3.20E-03	S	3.15E+00	S	7.46E-04	S	1.11E-01	S
7	3.20E-03	S	3.30E+00	S	7.46E-04	S	6.67E-02	S
7.2	3.20E-03	S	3.45E+00	S	7.46E-04	S	4.08E-02	S
7.4	3.20E-03	S	3.71E+00	S	7.46E-04	S	2.86E-02	S
7.6	3.20E-03	S	4.26E+00	S	7.46E-04	S	2.68E-02	S
7.8	3.20E-03	S	4.87E+00	S	7.46E-04	S	2.52E-02	S
8	3.20E-03	S	5.54E+00	S	7.46E-04	S	2.36E-02	S

Table C-5-34. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID ZFA Med

Sample ID	ZFA-[Med] (P,1,1)
Date Exported	8/27/2011, 2:10 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

	Concentration (mg/L)							
pH	**Arsenic**	**Solubility/ Washout**	**Boron**	**Solubility/ Washout**	**Cadmium**	**Solubility/ Washout**	**Cobalt**	**Solubility/ Washout**
8.2	3.20E-03	S	6.22E+00	W	7.46E-04	S	2.01E-02	S
8.4	3.20E-03	S	6.96E+00	W	7.46E-04	S	1.73E-02	S
8.6	3.20E-03	S	7.76E+00	W	7.46E-04	S	1.49E-02	S
8.8	3.20E-03	S	8.04E+00	W	7.46E-04	S	1.38E-02	S
9	3.20E-03	S	8.21E+00	W	7.46E-04	S	1.29E-02	S
9.2	3.20E-03	S	8.37E+00	W	7.46E-04	S	1.22E-02	S
9.4	3.20E-03	S	8.54E+00	W	7.46E-04	S	1.15E-02	S
9.6	3.20E-03	S	6.65E+00	W	7.46E-04	S	1.07E-02	S
9.8	3.20E-03	S	4.50E+00	W	7.46E-04	S	9.94E-03	S
10	3.20E-03	S	3.07E+00	S	7.46E-04	S	9.25E-03	S
10.2	3.20E-03	S	2.11E+00	S	7.46E-04	S	8.61E-03	S
10.4	3.20E-03	S	1.46E+00	S	7.46E-04	S	8.03E-03	S
10.6	3.20E-03	S	1.02E+00	S	7.46E-04	S	7.50E-03	S
10.8	3.20E-03	S	7.17E-01	S	7.46E-04	S	7.01E-03	S
11	3.20E-03	S	5.45E-01	S	7.46E-04	S	6.45E-03	S
11.2	3.20E-03	S	8.01E-01	S	7.46E-04	S	5.07E-03	S
11.4	3.20E-03	S	1.17E+00	S	7.46E-04	S	4.00E-03	S
11.6	3.20E-03	S	1.69E+00	S	7.46E-04	S	3.17E-03	S
11.8	3.20E-03	S	2.43E+00	S	7.46E-04	S	2.52E-03	S
12	3.20E-03	S	3.42E+00	S	7.46E-04	S	2.06E-03	S
12.2	3.20E-03	S	4.12E+00	S	7.46E-04	S	2.06E-03	S
12.4	3.20E-03	S	4.94E+00	S	7.46E-04	S	2.06E-03	S
12.6	3.20E-03	S	5.91E+00	S	7.46E-04	S	2.06E-03	S
12.8	3.20E-03	S	7.05E+00	S	7.46E-04	S	2.06E-03	S
13	3.20E-03	S	8.38E+00	S	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	3.37E-02		8.54E+01		1.83E+00		4.42E+01	

Table C-5-34. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID ZFA Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	2.50E-04	S	3.00E-06	S	3.80E-04	S	2.78E-03	S
3	2.50E-04	S	3.00E-06	S	3.80E-04	S	2.78E-03	S
3.2	2.58E-04	S	3.00E-06	S	7.10E-04	S	2.78E-03	S
3.4	7.39E-04	S	3.00E-06	S	1.72E-03	S	2.78E-03	S
3.6	1.99E-03	S	3.00E-06	S	3.95E-03	S	2.78E-03	S
3.8	5.08E-03	S	3.00E-06	S	8.69E-03	S	2.78E-03	S
4	1.24E-02	S	3.00E-06	S	1.84E-02	S	2.78E-03	S
4.2	2.88E-02	S	3.00E-06	S	3.74E-02	S	2.78E-03	S
4.4	3.57E-02	S	3.00E-06	S	4.66E-02	S	2.78E-03	S
4.6	4.12E-02	S	3.00E-06	S	5.46E-02	S	2.78E-03	S
4.8	4.71E-02	S	3.00E-06	S	6.37E-02	S	2.78E-03	S
5	5.36E-02	S	3.00E-06	S	7.37E-02	S	2.78E-03	S
5.2	6.43E-02	S	3.00E-06	S	9.18E-02	S	2.78E-03	S
5.4	8.32E-02	S	3.00E-06	S	1.27E-01	S	2.78E-03	S
5.6	1.07E-01	S	3.00E-06	S	1.75E-01	S	2.78E-03	S
5.8	1.36E-01	S	3.00E-06	S	2.37E-01	S	2.78E-03	S
6	1.71E-01	S	3.00E-06	S	3.19E-01	S	2.78E-03	S
6.2	2.14E-01	S	3.00E-06	S	4.24E-01	S	2.78E-03	S
6.4	2.66E-01	S	3.00E-06	S	5.22E-01	S	2.78E-03	S
6.6	3.29E-01	S	3.00E-06	S	5.50E-01	S	2.78E-03	S
6.8	4.03E-01	S	3.00E-06	S	5.78E-01	S	2.78E-03	S
7	4.91E-01	S	3.00E-06	S	6.06E-01	S	2.78E-03	S
7.2	5.95E-01	S	3.00E-06	S	6.35E-01	W	2.78E-03	S
7.4	7.01E-01	S	3.00E-06	S	6.61E-01	W	2.78E-03	S
7.6	7.80E-01	S	3.00E-06	S	6.76E-01	W	2.78E-03	S
7.8	8.65E-01	S	3.00E-06	S	6.91E-01	W	2.78E-03	S
8	9.61E-01	S	3.00E-06	S	7.04E-01	W	2.78E-03	S

Table C-5-34. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID ZFA Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	1.14E+00	S	3.00E-06	S	6.78E-01	W	2.78E-03	S
8.4	1.36E+00	S	3.00E-06	S	6.53E-01	W	2.78E-03	S
8.6	1.60E+00	S	3.00E-06	S	6.29E-01	W	2.78E-03	S
8.8	1.70E+00	S	3.00E-06	S	6.19E-01	W	2.78E-03	S
9	1.76E+00	S	3.00E-06	S	6.12E-01	W	2.78E-03	S
9.2	1.83E+00	S	3.00E-06	S	6.05E-01	W	2.78E-03	S
9.4	1.90E+00	S	3.00E-06	S	5.98E-01	W	2.78E-03	S
9.6	1.53E+00	S	3.00E-06	S	5.31E-01	W	2.78E-03	S
9.8	1.08E+00	S	3.00E-06	S	4.46E-01	W	2.78E-03	S
10	7.72E-01	S	3.00E-06	S	3.76E-01	S	2.78E-03	S
10.2	5.55E-01	S	3.00E-06	S	3.18E-01	S	2.78E-03	S
10.4	4.01E-01	S	3.00E-06	S	2.70E-01	S	2.78E-03	S
10.6	2.91E-01	S	3.00E-06	S	2.30E-01	S	2.78E-03	S
10.8	2.13E-01	S	3.00E-06	S	1.96E-01	S	2.78E-03	S
11	1.51E-01	S	3.00E-06	S	1.61E-01	S	2.78E-03	S
11.2	7.73E-02	S	3.00E-06	S	8.66E-02	S	2.78E-03	S
11.4	4.00E-02	S	3.00E-06	S	4.72E-02	S	2.78E-03	S
11.6	2.09E-02	S	3.00E-06	S	2.60E-02	S	2.78E-03	S
11.8	1.11E-02	S	3.00E-06	S	1.45E-02	S	2.78E-03	S
12	6.37E-03	S	3.00E-06	S	8.59E-03	S	2.78E-03	S
12.2	7.08E-03	S	3.00E-06	S	8.28E-03	S	2.78E-03	S
12.4	7.85E-03	S	3.00E-06	S	7.98E-03	S	2.78E-03	S
12.6	8.68E-03	S	3.00E-06	S	7.70E-03	S	2.78E-03	S
12.8	9.60E-03	S	3.00E-06	S	7.44E-03	S	2.78E-03	S
13	1.06E-02	S	3.00E-06	S	7.18E-03	S	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	1.90E+01		3.16E-05		7.04E+00		2.93E-02	

Table C-5-34. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID ZFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
2.8	1.58E+00	S	2.49E-02	S	2.67E-03	S
3	1.58E+00	S	2.49E-02	S	3.78E-03	S
3.2	1.58E+00	S	2.49E-02	S	5.23E-03	S
3.4	1.58E+00	S	2.49E-02	S	7.10E-03	S
3.6	1.57E+00	S	2.47E-02	S	9.47E-03	S
3.8	1.35E+00	S	2.10E-02	S	1.24E-02	S
4	1.17E+00	S	1.80E-02	S	1.61E-02	S
4.2	1.02E+00	S	1.56E-02	S	2.06E-02	S
4.4	9.82E-01	S	1.46E-02	S	2.15E-02	S
4.6	9.57E-01	S	1.38E-02	S	2.20E-02	S
4.8	9.33E-01	S	1.31E-02	S	2.24E-02	S
5	9.12E-01	S	1.24E-02	S	2.28E-02	S
5.2	8.53E-01	S	1.16E-02	S	2.29E-02	S
5.4	7.50E-01	S	1.06E-02	S	2.25E-02	S
5.6	6.63E-01	S	9.77E-03	S	2.21E-02	S
5.8	5.88E-01	S	9.00E-03	S	2.17E-02	S
6	5.24E-01	S	8.31E-03	S	2.14E-02	S
6.2	4.69E-01	S	7.70E-03	S	2.10E-02	S
6.4	4.24E-01	S	6.82E-03	S	2.14E-02	S
6.6	3.92E-01	S	5.46E-03	S	2.36E-02	S
6.8	3.64E-01	S	4.40E-03	S	2.59E-02	S
7	3.38E-01	S	3.57E-03	S	2.83E-02	S
7.2	3.14E-01	S	2.91E-03	S	3.09E-02	S
7.4	2.99E-01	S	2.53E-03	S	3.31E-02	S
7.6	2.98E-01	S	2.53E-03	S	3.43E-02	S
7.8	2.97E-01	S	2.53E-03	S	3.56E-02	S
8	2.97E-01	S	2.53E-03	S	3.70E-02	S

Table C-5-34. Leachate Concentrations for Sub bituminous lignite fly ash, Waste ID ZFA Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	**Selenium**	**Solubility/ Washout**	**Thallium**	**Solubility/ Washout**	**Vanadium**	**Solubility/ Washout**
8.2	3.04E-01	S	2.53E-03	S	4.32E-02	S
8.4	3.12E-01	S	2.53E-03	S	5.02E-02	S
8.6	3.19E-01	S	2.53E-03	S	5.82E-02	S
8.8	3.23E-01	S	2.53E-03	S	5.82E-02	S
9	3.25E-01	S	2.53E-03	S	5.67E-02	S
9.2	3.28E-01	S	2.53E-03	S	5.54E-02	S
9.4	3.31E-01	S	2.53E-03	S	5.40E-02	S
9.6	2.91E-01	S	2.53E-03	S	4.96E-02	S
9.8	2.39E-01	S	2.53E-03	S	4.42E-02	S
10	1.98E-01	S	2.53E-03	S	3.94E-02	S
10.2	1.64E-01	S	2.53E-03	S	3.53E-02	S
10.4	1.36E-01	S	2.53E-03	S	3.16E-02	S
10.6	1.13E-01	S	2.53E-03	S	2.84E-02	S
10.8	9.50E-02	S	2.53E-03	S	2.56E-02	S
11	7.85E-02	S	2.53E-03	S	2.25E-02	S
11.2	5.65E-02	S	2.53E-03	S	1.62E-02	S
11.4	4.09E-02	S	2.53E-03	S	1.17E-02	S
11.6	2.98E-02	S	2.53E-03	S	8.46E-03	S
11.8	2.18E-02	S	2.53E-03	S	6.18E-03	S
12	1.73E-02	S	2.53E-03	S	4.73E-03	S
12.2	2.70E-02	S	2.53E-03	S	5.27E-03	S
12.4	4.18E-02	S	2.53E-03	S	5.87E-03	S
12.6	6.44E-02	S	2.53E-03	S	6.52E-03	S
12.8	9.84E-02	S	2.53E-03	S	7.24E-03	S
13	1.49E-01	S	2.53E-03	S	8.02E-03	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	1.58E+01		2.49E-01		5.82E-01	

Table C-5-35. Leachate Concentrations for Gypsum Export, Waste ID AaAU Med

Sample ID	AaAU-[Med] (P,1,1)
Date Exported	9/20/2011, 7:36 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	4.45E-02	S	8.43E-01	W	7.46E-04	S	8.97E-03	S
3	3.14E-02	S	8.42E-01	W	7.46E-04	S	7.79E-03	S
3.2	2.27E-02	S	8.41E-01	W	7.46E-04	S	6.83E-03	S
3.4	1.67E-02	S	8.40E-01	W	7.46E-04	S	6.03E-03	S
3.6	1.25E-02	S	8.39E-01	W	7.46E-04	S	5.36E-03	S
3.8	9.54E-03	S	8.38E-01	W	7.46E-04	S	4.80E-03	S
4	7.91E-03	S	8.36E-01	W	7.46E-04	S	4.17E-03	S
4.2	6.64E-03	S	8.34E-01	W	7.46E-04	S	3.64E-03	S
4.4	5.62E-03	S	8.32E-01	W	7.46E-04	S	3.20E-03	S
4.6	4.80E-03	S	8.30E-01	W	7.46E-04	S	2.82E-03	S
4.8	4.12E-03	S	8.28E-01	W	7.46E-04	S	2.51E-03	S
5	3.56E-03	S	8.26E-01	W	7.46E-04	S	2.24E-03	S
5.2	3.20E-03	S	8.21E-01	W	7.46E-04	S	2.06E-03	S
5.4	3.20E-03	S	8.08E-01	W	7.46E-04	S	2.06E-03	S
5.6	3.20E-03	S	7.95E-01	W	7.46E-04	S	2.06E-03	S
5.8	3.20E-03	S	7.83E-01	W	7.46E-04	S	2.06E-03	S
6	3.20E-03	S	7.72E-01	W	7.46E-04	S	2.06E-03	S
6.2	3.20E-03	S	7.61E-01	W	7.46E-04	S	2.06E-03	S
6.4	3.20E-03	S	7.51E-01	W	7.46E-04	S	2.06E-03	S
6.6	3.20E-03	S	7.41E-01	W	7.46E-04	S	2.06E-03	S
6.8	3.20E-03	S	7.31E-01	W	7.46E-04	S	2.06E-03	S
7	3.20E-03	S	7.22E-01	W	7.46E-04	S	2.06E-03	S
7.2	3.20E-03	S	7.17E-01	W	7.46E-04	S	2.06E-03	S
7.4	3.20E-03	S	7.20E-01	W	7.46E-04	S	2.06E-03	S
7.6	3.20E-03	S	7.23E-01	W	7.46E-04	S	2.06E-03	S
7.8	3.20E-03	S	7.26E-01	W	7.46E-04	S	2.06E-03	S
8	3.20E-03	S	7.28E-01	W	7.46E-04	S	2.06E-03	S

Table C-5-35. Leachate Concentrations for Gypsum Export, Waste ID AaAU Med

Sample ID	AaAU-[Med] (P,1,1)
Date Exported	9/20/2011, 7:36 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	3.20E-03	S	7.31E-01	W	7.46E-04	S	2.06E-03	S
8.4	3.20E-03	S	7.34E-01	W	7.46E-04	S	2.06E-03	S
8.6	3.20E-03	S	7.36E-01	W	7.46E-04	S	2.06E-03	S
8.8	3.20E-03	S	7.39E-01	W	7.46E-04	S	2.06E-03	S
9	3.20E-03	S	7.41E-01	W	7.46E-04	S	2.06E-03	S
9.2	3.20E-03	S	7.45E-01	W	7.46E-04	S	2.06E-03	S
9.4	3.20E-03	S	7.51E-01	W	7.46E-04	S	2.06E-03	S
9.6	3.20E-03	S	7.57E-01	W	7.46E-04	S	2.06E-03	S
9.8	3.20E-03	S	7.63E-01	W	7.46E-04	S	2.06E-03	S
10	3.20E-03	S	7.68E-01	W	7.46E-04	S	2.06E-03	S
10.2	3.20E-03	S	7.74E-01	W	7.46E-04	S	2.06E-03	S
10.4	3.20E-03	S	7.66E-01	W	7.46E-04	S	2.06E-03	S
10.6	3.20E-03	S	7.56E-01	W	7.46E-04	S	2.06E-03	S
10.8	3.20E-03	S	7.46E-01	W	7.46E-04	S	2.06E-03	S
11	3.20E-03	S	7.37E-01	W	7.46E-04	S	2.06E-03	S
11.2	3.20E-03	S	7.27E-01	W	7.46E-04	S	2.06E-03	S
11.4	3.20E-03	S	7.19E-01	W	7.46E-04	S	2.06E-03	S
11.6	3.20E-03	S	7.10E-01	W	7.46E-04	S	2.06E-03	S
11.8	3.20E-03	S	7.01E-01	W	7.46E-04	S	2.06E-03	S
12	3.20E-03	S	7.32E-01	S	7.46E-04	S	2.06E-03	S
12.2	3.20E-03	S	8.99E-01	S	7.46E-04	S	2.06E-03	S
12.4	3.20E-03	S	1.10E+00	S	7.46E-04	S	2.06E-03	S
12.6	3.20E-03	S	1.34E+00	S	7.46E-04	S	2.06E-03	S
12.8	3.20E-03	S	1.63E+00	S	7.46E-04	S	2.06E-03	S
13	3.20E-03	S	1.98E+00	S	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	2.32E-01		1.90E+01		8.70E-03		5.76E-02	

Table C-5-35. Leachate Concentrations for Gypsum Export, Waste ID AaAU Med

Sample ID
Date Exported
Database Name leling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	3.74E-02	S	7.34E-05	S	1.13E-02	S	4.23E-03	S
3	3.07E-02	S	5.92E-05	S	8.84E-03	S	3.85E-03	S
3.2	2.55E-02	S	4.83E-05	S	7.04E-03	S	3.53E-03	S
3.4	2.15E-02	S	4.00E-05	S	5.68E-03	S	3.25E-03	S
3.6	1.82E-02	S	3.34E-05	S	4.64E-03	S	3.01E-03	S
3.8	1.56E-02	S	2.82E-05	S	3.83E-03	S	2.79E-03	S
4	1.10E-02	S	3.78E-05	S	3.80E-03	S	2.78E-03	S
4.2	7.86E-03	S	5.11E-05	S	3.80E-03	S	2.78E-03	S
4.4	5.69E-03	S	6.81E-05	S	3.80E-03	S	2.78E-03	S
4.6	4.17E-03	S	8.96E-05	S	3.80E-03	S	2.78E-03	S
4.8	3.10E-03	S	1.17E-04	S	3.80E-03	S	2.78E-03	S
5	2.33E-03	S	1.50E-04	S	3.80E-03	S	2.78E-03	S
5.2	1.96E-03	S	1.57E-04	S	3.80E-03	S	2.78E-03	S
5.4	2.23E-03	S	9.23E-05	S	3.80E-03	S	2.78E-03	S
5.6	2.51E-03	S	5.53E-05	S	3.80E-03	S	2.78E-03	S
5.8	2.83E-03	S	3.37E-05	S	3.80E-03	S	2.78E-03	S
6	3.17E-03	S	2.09E-05	S	3.80E-03	S	2.78E-03	S
6.2	3.54E-03	S	1.32E-05	S	3.80E-03	S	2.78E-03	S
6.4	3.94E-03	S	8.42E-06	S	3.80E-03	S	2.78E-03	S
6.6	4.37E-03	S	5.45E-06	S	3.80E-03	S	2.78E-03	S
6.8	4.83E-03	S	3.58E-06	S	3.80E-03	S	2.78E-03	S
7	5.32E-03	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
7.2	5.70E-03	S	3.00E-06	S	3.80E-03	W	2.78E-03	S
7.4	5.74E-03	S	3.00E-06	S	3.80E-03	W	2.78E-03	S
7.6	5.78E-03	S	3.00E-06	S	3.80E-03	W	2.78E-03	S
7.8	5.82E-03	S	3.00E-06	S	3.80E-03	W	2.78E-03	S
8	5.86E-03	S	3.00E-06	S	3.80E-03	W	2.78E-03	S

Table C-5-35. Leachate Concentrations for Gypsum Export, Waste ID AaAU Med

Sample ID
Date Exported
Database Name leling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	5.89E-03	S	3.00E-06	S	3.80E-03	W	2.78E-03	S
8.4	5.93E-03	S	3.00E-06	S	3.80E-03	W	2.78E-03	S
8.6	5.97E-03	S	3.00E-06	S	3.80E-03	W	2.78E-03	S
8.8	6.00E-03	S	3.00E-06	S	3.80E-03	W	2.78E-03	S
9	6.04E-03	S	3.00E-06	S	3.80E-03	W	2.78E-03	S
9.2	6.16E-03	S	3.00E-06	S	3.80E-03	W	2.78E-03	S
9.4	6.52E-03	S	3.00E-06	S	3.80E-03	W	2.78E-03	S
9.6	6.88E-03	S	3.04E-06	S	3.80E-03	W	2.78E-03	S
9.8	7.25E-03	S	3.79E-06	S	3.80E-03	W	2.78E-03	S
10	7.64E-03	S	4.71E-06	S	3.80E-03	S	2.78E-03	S
10.2	8.04E-03	S	5.81E-06	S	3.80E-03	S	2.78E-03	S
10.4	8.23E-03	S	5.28E-06	S	4.18E-03	S	2.78E-03	S
10.6	8.38E-03	S	4.56E-06	S	4.67E-03	S	2.78E-03	S
10.8	8.54E-03	S	3.94E-06	S	5.20E-03	S	2.78E-03	S
11	8.69E-03	S	3.42E-06	S	5.79E-03	S	2.78E-03	S
11.2	8.84E-03	S	3.00E-06	S	6.43E-03	S	2.78E-03	S
11.4	8.99E-03	S	3.00E-06	S	7.12E-03	S	2.78E-03	S
11.6	9.14E-03	S	3.00E-06	S	7.88E-03	S	2.78E-03	S
11.8	9.29E-03	S	3.00E-06	S	8.70E-03	S	2.78E-03	S
12	9.54E-03	S	3.00E-06	S	9.33E-03	S	2.78E-03	S
12.2	1.01E-02	S	3.00E-06	S	9.21E-03	S	2.78E-03	S
12.4	1.06E-02	S	4.39E-06	S	9.09E-03	S	2.78E-03	S
12.6	1.12E-02	S	6.47E-06	S	8.98E-03	S	2.78E-03	S
12.8	1.18E-02	S	9.46E-06	S	8.86E-03	S	2.78E-03	S
13	1.24E-02	S	1.38E-05	S	8.75E-03	S	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	2.27E-01		1.16E-03		1.05E-01		3.24E-02	

Table C-5-35. Leachate Concentrations for Gypsum Export, Waste ID AaAU Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	6.71E-01	S	7.65E-03	S	2.47E-02	S
3	5.80E-01	S	7.37E-03	S	1.90E-02	S
3.2	5.06E-01	S	7.11E-03	S	1.48E-02	S
3.4	4.45E-01	S	6.87E-03	S	1.18E-02	S
3.6	3.94E-01	S	6.66E-03	S	9.45E-03	S
3.8	3.51E-01	S	6.46E-03	S	7.69E-03	S
4	3.44E-01	S	6.41E-03	S	7.30E-03	S
4.2	3.39E-01	W	6.36E-03	S	7.00E-03	S
4.4	3.35E-01	W	6.32E-03	S	6.73E-03	S
4.6	3.30E-01	W	6.28E-03	S	6.47E-03	S
4.8	3.26E-01	W	6.24E-03	S	6.24E-03	S
5	3.22E-01	W	6.20E-03	S	6.03E-03	S
5.2	3.17E-01	W	6.15E-03	S	5.86E-03	S
5.4	3.09E-01	W	6.04E-03	S	5.81E-03	S
5.6	3.00E-01	W	5.95E-03	S	5.76E-03	S
5.8	2.93E-01	W	5.85E-03	S	5.71E-03	S
6	2.86E-01	W	5.76E-03	S	5.67E-03	S
6.2	2.79E-01	W	5.68E-03	S	5.62E-03	S
6.4	2.72E-01	W	5.60E-03	S	5.58E-03	S
6.6	2.66E-01	W	5.52E-03	S	5.54E-03	S
6.8	2.61E-01	W	5.45E-03	S	5.50E-03	S
7	2.55E-01	W	5.38E-03	S	5.47E-03	S
7.2	2.51E-01	W	5.36E-03	S	5.46E-03	S
7.4	2.51E-01	W	5.46E-03	S	5.52E-03	S
7.6	2.51E-01	W	5.57E-03	S	5.58E-03	S
7.8	2.50E-01	W	5.67E-03	S	5.64E-03	S
8	2.50E-01	W	5.77E-03	S	5.69E-03	S

Table C-5-35. Leachate Concentrations for Gypsum Export, Waste ID AaAU Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	2.50E-01	W	5.87E-03	S	5.75E-03	S
8.4	2.49E-01	W	5.97E-03	S	5.81E-03	S
8.6	2.49E-01	W	6.07E-03	S	5.86E-03	S
8.8	2.49E-01	W	6.17E-03	S	5.92E-03	S
9	2.49E-01	W	6.27E-03	S	5.97E-03	S
9.2	2.49E-01	W	6.34E-03	S	5.96E-03	S
9.4	2.53E-01	W	6.35E-03	S	5.81E-03	S
9.6	2.56E-01	W	6.36E-03	S	5.67E-03	S
9.8	2.60E-01	W	6.37E-03	S	5.54E-03	S
10	2.63E-01	W	6.37E-03	S	5.41E-03	S
10.2	2.67E-01	W	6.38E-03	S	5.29E-03	S
10.4	2.71E-01	W	6.28E-03	S	5.25E-03	S
10.6	2.75E-01	W	6.16E-03	S	5.23E-03	S
10.8	2.79E-01	W	6.05E-03	S	5.20E-03	S
11	2.83E-01	W	5.94E-03	S	5.18E-03	S
11.2	2.88E-01	W	5.84E-03	S	5.16E-03	S
11.4	2.92E-01	W	5.74E-03	S	5.14E-03	S
11.6	2.96E-01	W	5.64E-03	S	5.11E-03	S
11.8	3.00E-01	W	5.54E-03	S	5.09E-03	S
12	3.19E-01	S	5.31E-03	S	4.96E-03	S
12.2	3.87E-01	S	4.68E-03	S	4.53E-03	S
12.4	4.69E-01	S	4.14E-03	S	4.14E-03	S
12.6	5.66E-01	S	3.66E-03	S	3.79E-03	S
12.8	6.81E-01	S	3.25E-03	S	3.47E-03	S
13	8.17E-01	S	2.89E-03	S	3.19E-03	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	7.93E+00		5.45E-02		1.40E-01	

Table C-5-36. Leachate Concentrations for Gypsum Export, Waste ID AaAW Med

Sample ID	AaAW-[Med] (P,1,1)
Date Exported	9/20/2011, 7:36 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	4.49E-02	S	1.70E-01	S	7.46E-04	S	1.55E-02	S
3	3.12E-02	S	1.65E-01	S	7.46E-04	S	1.40E-02	S
3.2	2.22E-02	S	1.61E-01	S	7.46E-04	S	1.27E-02	S
3.4	1.61E-02	S	1.56E-01	S	7.46E-04	S	1.16E-02	S
3.6	1.19E-02	S	1.52E-01	S	7.46E-04	S	1.06E-02	S
3.8	8.96E-03	S	1.49E-01	S	7.46E-04	S	9.82E-03	S
4	7.63E-03	S	1.46E-01	S	7.46E-04	S	9.29E-03	S
4.2	6.68E-03	S	1.44E-01	S	7.46E-04	S	8.86E-03	S
4.4	5.88E-03	S	1.43E-01	S	7.46E-04	S	8.46E-03	S
4.6	5.21E-03	S	1.41E-01	S	7.46E-04	S	8.10E-03	S
4.8	4.64E-03	S	1.39E-01	S	7.46E-04	S	7.76E-03	S
5	4.15E-03	S	1.38E-01	S	7.46E-04	S	7.46E-03	S
5.2	3.73E-03	S	1.36E-01	S	7.46E-04	S	7.17E-03	S
5.4	3.36E-03	S	1.35E-01	S	7.46E-04	S	6.91E-03	S
5.6	3.20E-03	S	1.31E-01	S	7.46E-04	S	6.16E-03	S
5.8	3.20E-03	S	1.25E-01	S	7.46E-04	S	5.10E-03	S
6	3.20E-03	S	1.20E-01	S	7.46E-04	S	4.25E-03	S
6.2	3.20E-03	S	1.15E-01	S	7.46E-04	S	3.56E-03	S
6.4	3.20E-03	S	1.10E-01	S	7.46E-04	S	3.00E-03	S
6.6	3.20E-03	S	1.06E-01	S	7.46E-04	S	2.54E-03	S
6.8	3.20E-03	S	1.02E-01	S	7.46E-04	S	2.16E-03	S
7	3.20E-03	S	1.02E-01	S	7.46E-04	S	2.06E-03	S
7.2	3.20E-03	S	1.02E-01	S	7.46E-04	S	2.06E-03	S
7.4	3.20E-03	S	1.03E-01	S	7.46E-04	S	2.06E-03	S
7.6	3.20E-03	S	1.04E-01	S	7.46E-04	S	2.06E-03	S
7.8	3.20E-03	S	1.05E-01	S	7.46E-04	S	2.06E-03	S
8	3.20E-03	S	1.05E-01	S	7.46E-04	S	2.06E-03	S

Table C-5-36. Leachate Concentrations for Gypsum Export, Waste ID AaAW Med

Sample ID	AaAW-[Med] (P,1,1)
Date Exported	9/20/2011, 7:36 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	3.20E-03	S	1.06E-01	S	7.46E-04	S	2.06E-03	S
8.4	3.20E-03	S	1.07E-01	S	7.46E-04	S	2.06E-03	S
8.6	3.20E-03	S	1.08E-01	S	7.46E-04	S	2.06E-03	S
8.8	3.20E-03	S	1.08E-01	S	7.46E-04	S	2.06E-03	S
9	3.20E-03	S	1.09E-01	S	7.46E-04	S	2.06E-03	S
9.2	3.20E-03	S	1.10E-01	S	7.46E-04	S	2.06E-03	S
9.4	3.20E-03	S	1.11E-01	S	7.46E-04	S	2.06E-03	S
9.6	3.20E-03	S	1.13E-01	S	7.46E-04	S	2.06E-03	S
9.8	3.20E-03	S	1.14E-01	S	7.46E-04	S	2.06E-03	S
10	3.20E-03	S	1.15E-01	S	7.46E-04	S	2.06E-03	S
10.2	3.20E-03	S	1.16E-01	S	7.46E-04	S	2.06E-03	S
10.4	3.20E-03	S	1.18E-01	S	7.46E-04	S	2.06E-03	S
10.6	3.20E-03	S	1.19E-01	S	7.46E-04	S	2.06E-03	S
10.8	3.20E-03	S	1.20E-01	S	7.46E-04	S	2.06E-03	S
11	3.20E-03	S	1.20E-01	S	7.46E-04	S	2.06E-03	S
11.2	3.20E-03	S	1.20E-01	S	7.46E-04	S	2.06E-03	S
11.4	3.20E-03	S	1.19E-01	S	7.46E-04	S	2.06E-03	S
11.6	3.20E-03	S	1.18E-01	S	7.46E-04	S	2.06E-03	S
11.8	3.20E-03	S	1.18E-01	S	7.46E-04	S	2.06E-03	S
12	3.20E-03	S	1.17E-01	S	7.46E-04	S	2.06E-03	S
12.2	3.20E-03	S	1.75E-01	S	7.46E-04	S	2.06E-03	S
12.4	3.20E-03	S	2.60E-01	S	7.46E-04	S	2.06E-03	S
12.6	3.20E-03	S	3.83E-01	S	7.46E-04	S	2.06E-03	S
12.8	3.20E-03	S	5.62E-01	S	7.46E-04	S	2.06E-03	S
13	3.20E-03	S	8.20E-01	S	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	

Table C-5-36. Leachate Concentrations for Gypsum Export, Waste ID AaAW Med

Sample ID	AaAW-[Med] (P,1,1)
Date Exported	9/20/2011, 7:36 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
Availability (mg/kg)	2.31E-01		7.72E+00		1.02E-02		1.03E-01	

Table C-5-36. Leachate Concentrations for Gypsum Export, Waste ID AaAW Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	3.93E-02	S	4.54E-05	S	1.15E-02	S	4.30E-03	S
3	3.19E-02	S	3.45E-05	S	9.03E-03	S	3.91E-03	S
3.2	2.63E-02	S	2.67E-05	S	7.18E-03	S	3.57E-03	S
3.4	2.19E-02	S	2.09E-05	S	5.79E-03	S	3.28E-03	S
3.6	1.85E-02	S	1.66E-05	S	4.73E-03	S	3.03E-03	S
3.8	1.57E-02	S	1.34E-05	S	3.90E-03	S	2.81E-03	S
4	1.49E-02	S	1.33E-05	S	3.80E-03	S	2.78E-03	S
4.2	1.45E-02	S	1.37E-05	S	3.80E-03	S	2.78E-03	S
4.4	1.40E-02	S	1.41E-05	S	3.80E-03	S	2.78E-03	S
4.6	1.36E-02	S	1.44E-05	S	3.80E-03	S	2.78E-03	S
4.8	1.33E-02	S	1.48E-05	S	3.80E-03	S	2.78E-03	S
5	1.29E-02	S	1.51E-05	S	3.80E-03	S	2.78E-03	S
5.2	1.26E-02	S	1.55E-05	S	3.80E-03	S	2.78E-03	S
5.4	1.23E-02	S	1.58E-05	S	3.80E-03	S	2.78E-03	S
5.6	1.20E-02	S	1.57E-05	S	3.80E-03	S	2.78E-03	S
5.8	1.16E-02	S	1.52E-05	S	3.80E-03	S	2.78E-03	S
6	1.13E-02	S	1.47E-05	S	3.80E-03	S	2.78E-03	S
6.2	1.10E-02	S	1.43E-05	S	3.80E-03	S	2.78E-03	S
6.4	1.07E-02	S	1.39E-05	S	3.80E-03	S	2.78E-03	S
6.6	1.04E-02	S	1.35E-05	S	3.80E-03	S	2.78E-03	S
6.8	1.01E-02	S	1.31E-05	S	3.80E-03	S	2.78E-03	S
7	1.02E-02	S	1.30E-05	S	3.80E-03	S	2.78E-03	S
7.2	1.03E-02	S	1.30E-05	S	3.80E-03	W	2.78E-03	S
7.4	1.05E-02	S	1.30E-05	S	3.80E-03	W	2.78E-03	S
7.6	1.06E-02	S	1.30E-05	S	3.80E-03	W	2.78E-03	S
7.8	1.08E-02	S	1.30E-05	S	3.80E-03	W	2.78E-03	S
8	1.09E-02	S	1.30E-05	S	3.80E-03	W	2.78E-03	S

Table C-5-36. Leachate Concentrations for Gypsum Export, Waste ID AaAW Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	1.11E-02	S	1.30E-05	S	3.80E-03	W	2.78E-03	S
8.4	1.12E-02	S	1.30E-05	S	3.80E-03	W	2.78E-03	S
8.6	1.14E-02	S	1.30E-05	S	3.80E-03	W	2.78E-03	S
8.8	1.15E-02	S	1.30E-05	S	3.80E-03	W	2.78E-03	S
9	1.16E-02	S	1.30E-05	S	3.80E-03	W	2.78E-03	S
9.2	1.16E-02	S	1.30E-05	S	3.80E-03	W	2.78E-03	S
9.4	1.17E-02	S	1.30E-05	S	3.80E-03	W	2.78E-03	S
9.6	1.17E-02	S	1.30E-05	S	3.80E-03	W	2.78E-03	S
9.8	1.17E-02	S	1.30E-05	S	3.80E-03	W	2.78E-03	S
10	1.17E-02	S	1.30E-05	S	3.80E-03	S	2.78E-03	S
10.2	1.17E-02	S	1.30E-05	S	3.80E-03	S	2.78E-03	S
10.4	1.17E-02	S	1.30E-05	S	3.80E-03	S	2.78E-03	S
10.6	1.17E-02	S	1.30E-05	S	3.80E-03	S	2.78E-03	S
10.8	1.17E-02	S	1.30E-05	S	3.80E-03	S	2.78E-03	S
11	1.21E-02	S	1.26E-05	S	4.23E-03	S	2.78E-03	S
11.2	1.31E-02	S	1.17E-05	S	5.37E-03	S	2.78E-03	S
11.4	1.41E-02	S	1.10E-05	S	6.79E-03	S	2.78E-03	S
11.6	1.52E-02	S	1.03E-05	S	8.55E-03	S	2.78E-03	S
11.8	1.63E-02	S	9.60E-06	S	1.07E-02	S	2.78E-03	S
12	1.76E-02	S	9.00E-06	S	1.34E-02	S	2.78E-03	S
12.2	1.79E-02	S	1.07E-05	S	1.34E-02	S	2.78E-03	S
12.4	1.81E-02	S	1.27E-05	S	1.33E-02	S	2.78E-03	S
12.6	1.84E-02	S	1.50E-05	S	1.33E-02	S	2.78E-03	S
12.8	1.87E-02	S	1.77E-05	S	1.32E-02	S	2.78E-03	S
13	1.90E-02	S	2.09E-05	S	1.32E-02	S	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	

Table C-5-36. Leachate Concentrations for Gypsum Export, Waste ID AaAW Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
Availability (mg/kg)	2.56E-01		2.55E-04		1.81E-01		3.82E-02	

Table C-5-36. Leachate Concentrations for Gypsum Export, Waste ID AaAW Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	5.68E-01	S	2.53E-03	S	2.57E-02	S
3	4.83E-01	S	2.53E-03	S	1.95E-02	S
3.2	4.15E-01	S	2.53E-03	S	1.51E-02	S
3.4	3.60E-01	S	2.53E-03	S	1.18E-02	S
3.6	3.15E-01	S	2.53E-03	S	9.43E-03	S
3.8	2.77E-01	S	2.53E-03	S	7.61E-03	S
4	2.71E-01	S	2.53E-03	S	7.31E-03	S
4.2	2.69E-01	W	2.53E-03	S	7.24E-03	S
4.4	2.67E-01	W	2.53E-03	S	7.18E-03	S
4.6	2.66E-01	W	2.53E-03	S	7.12E-03	S
4.8	2.64E-01	W	2.53E-03	S	7.06E-03	S
5	2.63E-01	W	2.53E-03	S	7.00E-03	S
5.2	2.61E-01	W	2.53E-03	S	6.95E-03	S
5.4	2.60E-01	W	2.53E-03	S	6.90E-03	S
5.6	2.52E-01	W	2.53E-03	S	6.85E-03	S
5.8	2.39E-01	W	2.53E-03	S	6.81E-03	S
6	2.26E-01	W	2.53E-03	S	6.77E-03	S
6.2	2.15E-01	W	2.53E-03	S	6.73E-03	S
6.4	2.05E-01	W	2.53E-03	S	6.69E-03	S
6.6	1.95E-01	W	2.53E-03	S	6.66E-03	S
6.8	1.86E-01	W	2.53E-03	S	6.62E-03	S
7	1.84E-01	W	2.53E-03	S	6.60E-03	S
7.2	1.85E-01	W	2.53E-03	S	6.59E-03	S
7.4	1.85E-01	W	2.53E-03	S	6.58E-03	S
7.6	1.86E-01	W	2.53E-03	S	6.57E-03	S
7.8	1.87E-01	W	2.53E-03	S	6.55E-03	S
8	1.87E-01	W	2.53E-03	S	6.54E-03	S

Table C-5-36. Leachate Concentrations for Gypsum Export, Waste ID AaAW Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	1.88E-01	W	2.53E-03	S	6.53E-03	S
8.4	1.88E-01	W	2.53E-03	S	6.52E-03	S
8.6	1.89E-01	W	2.53E-03	S	6.51E-03	S
8.8	1.89E-01	W	2.53E-03	S	6.50E-03	S
9	1.90E-01	W	2.53E-03	S	6.49E-03	S
9.2	1.92E-01	W	2.53E-03	S	6.41E-03	S
9.4	1.94E-01	W	2.53E-03	S	6.33E-03	S
9.6	1.96E-01	W	2.53E-03	S	6.25E-03	S
9.8	1.98E-01	W	2.53E-03	S	6.17E-03	S
10	2.00E-01	W	2.53E-03	S	6.10E-03	S
10.2	2.02E-01	W	2.53E-03	S	6.03E-03	S
10.4	2.05E-01	W	2.53E-03	S	5.96E-03	S
10.6	2.07E-01	W	2.53E-03	S	5.89E-03	S
10.8	2.09E-01	W	2.53E-03	S	5.82E-03	S
11	2.49E-01	W	2.53E-03	S	5.73E-03	S
11.2	3.62E-01	W	2.53E-03	S	5.61E-03	S
11.4	5.22E-01	W	2.53E-03	S	5.49E-03	S
11.6	7.49E-01	W	2.53E-03	S	5.38E-03	S
11.8	1.07E+00	W	2.53E-03	S	5.27E-03	S
12	1.51E+00	S	2.53E-03	S	5.17E-03	S
12.2	1.52E+00	S	2.53E-03	S	5.09E-03	S
12.4	1.52E+00	S	2.53E-03	S	5.02E-03	S
12.6	1.52E+00	S	2.53E-03	S	4.94E-03	S
12.8	1.52E+00	S	2.53E-03	S	4.87E-03	S
13	1.52E+00	S	2.53E-03	S	4.80E-03	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	

Table C-5-36. Leachate Concentrations for Gypsum Export, Waste ID AaAW Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
Availability (mg/kg)	2.09E+01		3.47E-02		1.44E-01	

Table C-5-37. Leachate Concentrations for Gypsum Export, Waste ID CaAW Med

Sample ID	CaAW-[Med] (P,1,1)
Date Exported	9/20/2011, 7:36 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	3.14E-02	S	7.23E+00	W	6.28E-03	S	5.89E-02	S
3	2.74E-02	S	7.21E+00	W	6.25E-03	S	5.96E-02	S
3.2	2.42E-02	S	7.20E+00	W	6.22E-03	S	6.03E-02	S
3.4	2.15E-02	S	7.19E+00	W	6.19E-03	S	6.09E-02	S
3.6	1.92E-02	S	7.17E+00	W	6.16E-03	S	6.15E-02	S
3.8	1.73E-02	S	7.16E+00	W	6.13E-03	S	6.20E-02	S
4	1.56E-02	S	7.15E+00	W	6.11E-03	S	6.26E-02	S
4.2	1.42E-02	S	7.14E+00	W	6.09E-03	S	6.31E-02	S
4.4	1.31E-02	S	7.24E+00	W	6.04E-03	S	6.39E-02	S
4.6	1.21E-02	S	7.34E+00	W	5.99E-03	S	6.47E-02	S
4.8	1.12E-02	S	7.44E+00	W	5.95E-03	S	6.55E-02	S
5	1.04E-02	S	7.54E+00	W	5.91E-03	S	6.63E-02	S
5.2	9.67E-03	S	7.63E+00	W	5.87E-03	S	6.70E-02	S
5.4	9.04E-03	S	7.72E+00	W	5.84E-03	S	6.78E-02	S
5.6	8.47E-03	S	7.81E+00	W	5.80E-03	S	6.85E-02	S
5.8	7.95E-03	S	7.90E+00	W	5.77E-03	S	6.92E-02	S
6	6.98E-03	S	7.82E+00	W	4.34E-03	S	4.24E-02	S
6.2	6.14E-03	S	7.74E+00	W	3.25E-03	S	2.58E-02	S
6.4	5.42E-03	S	7.67E+00	W	2.45E-03	S	1.59E-02	S
6.6	4.80E-03	S	7.60E+00	W	1.87E-03	S	9.96E-03	S
6.8	4.27E-03	S	7.53E+00	W	1.43E-03	S	6.32E-03	S
7	3.81E-03	S	7.46E+00	W	1.11E-03	S	4.07E-03	S
7.2	3.41E-03	S	7.40E+00	W	8.64E-04	S	2.65E-03	S
7.4	3.20E-03	S	7.39E+00	W	7.46E-04	S	2.06E-03	S
7.6	3.20E-03	S	7.47E+00	W	7.46E-04	S	2.06E-03	S
7.8	3.20E-03	S	7.50E+00	W	7.46E-04	S	2.06E-03	S
8	3.20E-03	S	7.42E+00	W	7.46E-04	S	2.06E-03	S

Table C-5-37. Leachate Concentrations for Gypsum Export, Waste ID CaAW Med

Sample ID	CaAW-[Med] (P,1,1)
Date Exported	9/20/2011, 7:36 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	3.20E-03	S	7.34E+00	W	7.46E-04	S	2.06E-03	S
8.4	3.20E-03	S	7.26E+00	W	7.46E-04	S	2.06E-03	S
8.6	3.20E-03	S	7.19E+00	W	7.46E-04	S	2.06E-03	S
8.8	3.20E-03	S	7.12E+00	W	7.46E-04	S	2.06E-03	S
9	3.20E-03	S	7.05E+00	W	7.46E-04	S	2.06E-03	S
9.2	3.20E-03	S	7.04E+00	W	7.46E-04	S	2.06E-03	S
9.4	3.20E-03	S	7.06E+00	W	7.46E-04	S	2.06E-03	S
9.6	3.20E-03	S	7.07E+00	W	7.46E-04	S	2.06E-03	S
9.8	3.20E-03	S	7.08E+00	W	7.46E-04	S	2.06E-03	S
10	3.20E-03	S	7.10E+00	W	7.46E-04	S	2.06E-03	S
10.2	3.20E-03	S	7.11E+00	W	7.46E-04	S	2.06E-03	S
10.4	3.20E-03	S	7.12E+00	W	7.46E-04	S	2.06E-03	S
10.6	3.20E-03	S	7.13E+00	W	7.46E-04	S	2.06E-03	S
10.8	3.20E-03	S	7.14E+00	W	7.46E-04	S	2.06E-03	S
11	3.20E-03	S	7.16E+00	W	7.46E-04	S	2.06E-03	S
11.2	3.20E-03	S	7.17E+00	W	7.46E-04	S	2.06E-03	S
11.4	3.20E-03	S	7.18E+00	W	7.46E-04	S	2.06E-03	S
11.6	3.20E-03	S	7.19E+00	W	7.46E-04	S	2.06E-03	S
11.8	3.20E-03	S	7.20E+00	W	7.46E-04	S	2.06E-03	S
12	3.20E-03	S	7.21E+00	S	7.46E-04	S	2.06E-03	S
12.2	3.20E-03	S	7.38E+00	S	7.46E-04	S	2.06E-03	S
12.4	3.20E-03	S	7.87E+00	S	7.46E-04	S	2.06E-03	S
12.6	3.20E-03	S	8.38E+00	S	7.46E-04	S	2.06E-03	S
12.8	3.20E-03	S	8.91E+00	S	7.46E-04	S	2.06E-03	S
13	3.20E-03	S	9.47E+00	S	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	1.70E-01		1.00E+02		3.86E-02		4.28E-01	

Table C-5-37. Leachate Concentrations for Gypsum Export, Waste ID CaAW Med

Sample ID
Date Exported
Database Name :ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	1.27E-01	S	1.38E-04	S	3.41E-02	S	1.27E-02	S
3	1.15E-01	S	1.05E-04	S	3.12E-02	S	1.21E-02	S
3.2	1.04E-01	S	8.15E-05	S	2.88E-02	S	1.16E-02	S
3.4	9.50E-02	S	6.43E-05	S	2.66E-02	S	1.12E-02	S
3.6	8.71E-02	S	5.13E-05	S	2.47E-02	S	1.08E-02	S
3.8	8.03E-02	S	4.15E-05	S	2.31E-02	S	1.04E-02	S
4	7.43E-02	S	3.39E-05	S	2.16E-02	S	1.01E-02	S
4.2	6.90E-02	S	2.80E-05	S	2.03E-02	S	9.79E-03	S
4.4	5.34E-02	S	2.25E-05	S	2.36E-02	S	9.28E-03	S
4.6	4.18E-02	S	1.82E-05	S	2.73E-02	S	8.83E-03	S
4.8	3.31E-02	S	1.49E-05	S	3.14E-02	S	8.41E-03	S
5	2.64E-02	S	1.22E-05	S	3.59E-02	S	8.04E-03	S
5.2	2.13E-02	S	1.02E-05	S	4.08E-02	S	7.69E-03	S
5.4	1.73E-02	S	8.49E-06	S	4.62E-02	S	7.37E-03	S
5.6	1.42E-02	S	7.15E-06	S	5.21E-02	S	7.07E-03	S
5.8	1.17E-02	S	6.05E-06	S	5.84E-02	S	6.79E-03	S
6	1.17E-02	S	6.35E-06	S	6.18E-02	S	5.99E-03	S
6.2	1.18E-02	S	6.72E-06	S	6.51E-02	S	5.28E-03	S
6.4	1.19E-02	S	7.11E-06	S	6.84E-02	S	4.67E-03	S
6.6	1.20E-02	S	7.50E-06	S	7.18E-02	S	4.15E-03	S
6.8	1.21E-02	S	7.91E-06	S	7.53E-02	S	3.70E-03	S
7	1.22E-02	S	8.32E-06	S	7.88E-02	S	3.31E-03	S
7.2	1.24E-02	S	8.74E-06	S	8.24E-02	W	2.97E-03	S
7.4	1.26E-02	S	1.09E-05	S	8.59E-02	W	2.78E-03	S
7.6	1.31E-02	S	1.76E-05	S	8.91E-02	W	2.78E-03	S
7.8	1.36E-02	S	2.47E-05	S	9.21E-02	W	2.78E-03	S
8	1.39E-02	S	2.34E-05	S	9.43E-02	W	2.78E-03	S

Table C-5-37. Leachate Concentrations for Gypsum Export, Waste ID CaAW Med

Sample ID
Date Exported
Database Name ɨling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	1.43E-02	S	2.22E-05	S	9.64E-02	W	2.78E-03	S
8.4	1.46E-02	S	2.11E-05	S	9.86E-02	W	2.78E-03	S
8.6	1.50E-02	S	2.01E-05	S	1.01E-01	W	2.78E-03	S
8.8	1.53E-02	S	1.91E-05	S	1.03E-01	W	2.78E-03	S
9	1.57E-02	S	1.82E-05	S	1.05E-01	W	2.78E-03	S
9.2	1.59E-02	S	1.69E-05	S	1.07E-01	W	2.92E-03	S
9.4	1.62E-02	S	1.56E-05	S	1.09E-01	W	3.11E-03	S
9.6	1.64E-02	S	1.44E-05	S	1.10E-01	W	3.30E-03	S
9.8	1.66E-02	S	1.34E-05	S	1.12E-01	W	3.51E-03	S
10	1.69E-02	S	1.24E-05	S	1.14E-01	W	3.72E-03	S
10.2	1.71E-02	S	1.15E-05	S	1.15E-01	W	3.94E-03	S
10.4	1.73E-02	S	1.07E-05	S	1.17E-01	W	4.17E-03	S
10.6	1.75E-02	S	9.95E-06	S	1.19E-01	W	4.41E-03	S
10.8	1.78E-02	S	9.28E-06	S	1.20E-01	W	4.65E-03	S
11	1.80E-02	S	8.66E-06	S	1.22E-01	W	4.91E-03	S
11.2	1.82E-02	S	8.09E-06	S	1.24E-01	W	5.17E-03	S
11.4	1.84E-02	S	7.57E-06	S	1.25E-01	W	5.45E-03	S
11.6	1.86E-02	S	7.09E-06	S	1.27E-01	W	5.73E-03	S
11.8	1.89E-02	S	6.65E-06	S	1.29E-01	W	6.02E-03	S
12	1.91E-02	S	6.25E-06	S	1.30E-01	W	6.32E-03	S
12.2	1.97E-02	S	6.85E-06	S	1.32E-01	W	6.16E-03	S
12.4	2.10E-02	S	9.98E-06	S	1.35E-01	W	5.24E-03	S
12.6	2.24E-02	S	1.44E-05	S	1.38E-01	W	4.46E-03	S
12.8	2.39E-02	S	2.08E-05	S	1.40E-01	W	3.81E-03	S
13	2.54E-02	S	2.97E-05	S	1.43E-01	W	3.27E-03	S
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	7.09E-01		6.50E-04		1.58E+00		7.51E-02	

Table C-5-37. Leachate Concentrations for Gypsum Export, Waste ID CaAW Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	2.06E+00	S	1.59E-02	S	2.71E-01	S
3	1.97E+00	S	1.58E-02	S	2.24E-01	S
3.2	1.90E+00	S	1.57E-02	S	1.88E-01	S
3.4	1.83E+00	S	1.56E-02	S	1.60E-01	S
3.6	1.77E+00	S	1.55E-02	S	1.37E-01	S
3.8	1.71E+00	S	1.54E-02	S	1.18E-01	S
4	1.66E+00	S	1.53E-02	S	1.03E-01	S
4.2	1.61E+00	W	1.52E-02	S	8.99E-02	S
4.4	1.65E+00	W	1.48E-02	S	8.65E-02	S
4.6	1.69E+00	W	1.45E-02	S	8.33E-02	S
4.8	1.73E+00	W	1.42E-02	S	8.04E-02	S
5	1.77E+00	W	1.39E-02	S	7.77E-02	S
5.2	1.80E+00	W	1.36E-02	S	7.52E-02	S
5.4	1.84E+00	W	1.33E-02	S	7.29E-02	S
5.6	1.88E+00	W	1.31E-02	S	7.07E-02	S
5.8	1.91E+00	W	1.28E-02	S	6.86E-02	S
6	1.88E+00	W	1.26E-02	S	6.59E-02	S
6.2	1.84E+00	W	1.24E-02	S	6.33E-02	S
6.4	1.81E+00	W	1.23E-02	S	6.09E-02	S
6.6	1.77E+00	W	1.21E-02	S	5.86E-02	S
6.8	1.74E+00	W	1.19E-02	S	5.65E-02	S
7	1.71E+00	W	1.17E-02	S	5.45E-02	S
7.2	1.69E+00	W	1.16E-02	S	5.27E-02	S
7.4	1.74E+00	W	1.12E-02	S	5.21E-02	S
7.6	1.92E+00	W	1.07E-02	S	5.33E-02	S
7.8	2.09E+00	W	1.03E-02	S	5.55E-02	S
8	2.18E+00	W	1.06E-02	S	6.08E-02	S

Table C-5-37. Leachate Concentrations for Gypsum Export, Waste ID CaAW Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	2.27E+00	W	1.08E-02	S	6.64E-02	S
8.4	2.36E+00	W	1.11E-02	S	7.25E-02	S
8.6	2.45E+00	W	1.13E-02	S	7.89E-02	S
8.8	2.55E+00	W	1.16E-02	S	8.58E-02	S
9	2.65E+00	W	1.18E-02	S	9.30E-02	S
9.2	2.68E+00	W	1.19E-02	S	9.51E-02	S
9.4	2.70E+00	W	1.19E-02	S	9.53E-02	S
9.6	2.72E+00	W	1.20E-02	S	9.55E-02	S
9.8	2.74E+00	W	1.20E-02	S	9.58E-02	S
10	2.75E+00	W	1.20E-02	S	9.60E-02	S
10.2	2.77E+00	W	1.21E-02	S	9.62E-02	S
10.4	2.79E+00	W	1.21E-02	S	9.64E-02	S
10.6	2.80E+00	W	1.21E-02	S	9.66E-02	S
10.8	2.82E+00	W	1.21E-02	S	9.68E-02	S
11	2.83E+00	W	1.22E-02	S	9.70E-02	S
11.2	2.85E+00	W	1.22E-02	S	9.72E-02	S
11.4	2.86E+00	W	1.22E-02	S	9.74E-02	S
11.6	2.88E+00	W	1.22E-02	S	9.76E-02	S
11.8	2.89E+00	W	1.23E-02	S	9.78E-02	S
12	2.91E+00	S	1.23E-02	S	9.80E-02	S
12.2	2.95E+00	S	1.21E-02	S	8.60E-02	S
12.4	3.04E+00	S	1.17E-02	S	5.92E-02	S
12.6	3.13E+00	S	1.12E-02	S	4.10E-02	S
12.8	3.22E+00	S	1.08E-02	S	2.86E-02	S
13	3.32E+00	S	1.05E-02	S	2.00E-02	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	3.63E+01		1.22E-01		1.39E+00	

Table C-5-38. Leachate Concentrations for Gypsum Export, Waste ID DaAW Med

Sample ID	DaAW-[Med] (P,1,1)
Date Exported	9/20/2011, 7:36 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	9.58E-02	S	2.23E-01	W	7.46E-04	S	1.19E-02	S
3	7.55E-02	S	2.19E-01	W	7.46E-04	S	1.03E-02	S
3.2	6.04E-02	S	2.15E-01	W	7.46E-04	S	8.97E-03	S
3.4	4.90E-02	S	2.12E-01	W	7.46E-04	S	7.90E-03	S
3.6	4.02E-02	S	2.09E-01	W	7.46E-04	S	7.01E-03	S
3.8	3.19E-02	S	2.05E-01	W	7.46E-04	S	6.19E-03	S
4	2.37E-02	S	2.02E-01	W	7.46E-04	S	5.37E-03	S
4.2	1.79E-02	S	1.98E-01	W	7.46E-04	S	4.69E-03	S
4.4	1.36E-02	S	1.95E-01	W	7.46E-04	S	4.12E-03	S
4.6	1.05E-02	S	1.92E-01	W	7.46E-04	S	3.64E-03	S
4.8	8.24E-03	S	1.90E-01	W	7.46E-04	S	3.24E-03	S
5	6.50E-03	S	1.87E-01	W	7.46E-04	S	2.89E-03	S
5.2	5.18E-03	S	1.84E-01	W	7.46E-04	S	2.59E-03	S
5.4	4.16E-03	S	1.82E-01	W	7.46E-04	S	2.34E-03	S
5.6	3.37E-03	S	1.80E-01	W	7.46E-04	S	2.11E-03	S
5.8	3.20E-03	S	1.78E-01	W	7.46E-04	S	2.06E-03	S
6	3.20E-03	S	1.76E-01	W	7.46E-04	S	2.06E-03	S
6.2	3.20E-03	S	1.75E-01	W	7.46E-04	S	2.06E-03	S
6.4	3.20E-03	S	1.73E-01	W	7.46E-04	S	2.06E-03	S
6.6	3.20E-03	S	1.72E-01	W	7.46E-04	S	2.06E-03	S
6.8	3.20E-03	S	1.69E-01	W	7.46E-04	S	2.06E-03	S
7	3.20E-03	S	1.67E-01	W	7.46E-04	S	2.06E-03	S
7.2	3.20E-03	S	1.64E-01	W	7.46E-04	S	2.06E-03	S
7.4	3.20E-03	S	1.62E-01	W	7.46E-04	S	2.06E-03	S
7.6	3.20E-03	S	1.60E-01	W	7.46E-04	S	2.06E-03	S
7.8	3.20E-03	S	1.58E-01	W	7.46E-04	S	2.06E-03	S
8	3.20E-03	S	1.59E-01	W	7.46E-04	S	2.06E-03	S

Table C-5-38. Leachate Concentrations for Gypsum Export, Waste ID DaAW Med

Sample ID	DaAW-[Med] (P,1,1)
Date Exported	9/20/2011, 7:36 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	3.20E-03	S	1.60E-01	W	7.46E-04	S	2.06E-03	S
8.4	3.20E-03	S	1.61E-01	W	7.46E-04	S	2.06E-03	S
8.6	3.20E-03	S	1.62E-01	W	7.46E-04	S	2.06E-03	S
8.8	3.20E-03	S	1.63E-01	W	7.46E-04	S	2.06E-03	S
9	3.20E-03	S	1.64E-01	W	7.46E-04	S	2.06E-03	S
9.2	3.20E-03	S	1.66E-01	W	7.46E-04	S	2.06E-03	S
9.4	3.20E-03	S	1.69E-01	W	7.46E-04	S	2.06E-03	S
9.6	3.20E-03	S	1.71E-01	W	7.46E-04	S	2.06E-03	S
9.8	3.20E-03	S	1.73E-01	W	7.46E-04	S	2.06E-03	S
10	3.20E-03	S	1.75E-01	W	7.46E-04	S	2.06E-03	S
10.2	3.20E-03	S	1.77E-01	W	7.46E-04	S	2.06E-03	S
10.4	3.20E-03	S	1.79E-01	W	7.46E-04	S	2.06E-03	S
10.6	3.20E-03	S	1.81E-01	W	7.46E-04	S	2.06E-03	S
10.8	3.20E-03	S	1.83E-01	W	7.46E-04	S	2.06E-03	S
11	3.20E-03	S	1.85E-01	W	7.46E-04	S	2.06E-03	S
11.2	3.20E-03	S	1.87E-01	W	7.46E-04	S	2.06E-03	S
11.4	3.20E-03	S	1.89E-01	W	7.46E-04	S	2.06E-03	S
11.6	3.20E-03	S	1.91E-01	W	7.46E-04	S	2.06E-03	S
11.8	3.20E-03	S	1.93E-01	W	7.46E-04	S	2.06E-03	S
12	3.20E-03	S	1.95E-01	S	7.46E-04	S	2.06E-03	S
12.2	3.20E-03	S	2.52E-01	S	7.46E-04	S	2.06E-03	S
12.4	3.20E-03	S	3.40E-01	S	7.46E-04	S	2.06E-03	S
12.6	3.20E-03	S	4.55E-01	S	7.46E-04	S	2.06E-03	S
12.8	3.20E-03	S	6.06E-01	S	7.46E-04	S	2.06E-03	S
13	3.20E-03	S	8.05E-01	S	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	5.76E-01		7.36E+00		9.06E-03		7.83E-02	

Table C-5-38. Leachate Concentrations for Gypsum Export, Waste ID DaAW Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	9.59E-02	S	1.24E-05	S	9.57E-03	S	8.27E-03	S
3	8.81E-02	S	7.80E-06	S	7.66E-03	S	7.66E-03	S
3.2	8.15E-02	S	5.05E-06	S	6.22E-03	S	7.14E-03	S
3.4	7.56E-02	S	3.36E-06	S	5.12E-03	S	6.67E-03	S
3.6	7.06E-02	S	3.00E-06	S	4.25E-03	S	6.27E-03	S
3.8	6.38E-02	S	3.00E-06	S	3.80E-03	S	5.82E-03	S
4	5.44E-02	S	3.00E-06	S	3.80E-03	S	5.29E-03	S
4.2	4.68E-02	S	3.00E-06	S	3.80E-03	S	4.83E-03	S
4.4	4.05E-02	S	3.00E-06	S	3.80E-03	S	4.43E-03	S
4.6	3.53E-02	S	3.00E-06	S	3.80E-03	S	4.08E-03	S
4.8	3.09E-02	S	3.00E-06	S	3.80E-03	S	3.77E-03	S
5	2.72E-02	S	3.00E-06	S	3.80E-03	S	3.49E-03	S
5.2	2.41E-02	S	3.00E-06	S	3.80E-03	S	3.25E-03	S
5.4	2.14E-02	S	3.00E-06	S	3.80E-03	S	3.03E-03	S
5.6	1.92E-02	S	3.00E-06	S	3.80E-03	S	2.83E-03	S
5.8	1.93E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
6	2.02E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
6.2	2.11E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
6.4	2.21E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
6.6	2.29E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
6.8	2.32E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
7	2.34E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
7.2	2.36E-02	S	3.51E-06	S	3.80E-03	S	2.78E-03	S
7.4	2.38E-02	S	4.30E-06	S	3.80E-03	S	2.78E-03	S
7.6	2.41E-02	S	5.24E-06	S	3.80E-03	S	2.78E-03	S
7.8	2.47E-02	S	5.65E-06	S	4.03E-03	S	2.78E-03	S
8	2.63E-02	S	4.64E-06	S	4.92E-03	S	2.78E-03	S

Table C-5-38. Leachate Concentrations for Gypsum Export, Waste ID DaAW Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	2.79E-02	S	3.82E-06	S	5.98E-03	S	2.78E-03	S
8.4	2.96E-02	S	3.17E-06	S	7.24E-03	S	2.78E-03	S
8.6	3.13E-02	S	3.00E-06	S	8.71E-03	S	2.78E-03	S
8.8	3.31E-02	S	3.00E-06	S	1.04E-02	S	2.78E-03	S
9	3.50E-02	S	3.00E-06	S	1.25E-02	S	2.78E-03	S
9.2	3.50E-02	S	3.00E-06	S	1.28E-02	S	2.78E-03	S
9.4	3.46E-02	S	3.00E-06	S	1.28E-02	S	2.78E-03	S
9.6	3.42E-02	S	3.00E-06	S	1.28E-02	S	2.78E-03	S
9.8	3.38E-02	S	3.00E-06	S	1.27E-02	S	2.78E-03	S
10	3.35E-02	S	3.00E-06	S	1.27E-02	S	2.78E-03	S
10.2	3.31E-02	S	3.00E-06	S	1.27E-02	S	2.78E-03	S
10.4	3.28E-02	S	3.26E-06	S	1.27E-02	S	2.78E-03	S
10.6	3.24E-02	S	3.53E-06	S	1.27E-02	S	2.78E-03	S
10.8	3.21E-02	S	3.82E-06	S	1.27E-02	S	2.78E-03	S
11	3.18E-02	S	4.12E-06	S	1.27E-02	S	2.78E-03	S
11.2	3.15E-02	S	4.44E-06	S	1.27E-02	S	2.78E-03	S
11.4	3.12E-02	S	4.79E-06	S	1.27E-02	S	2.78E-03	S
11.6	3.09E-02	S	5.15E-06	S	1.26E-02	S	2.78E-03	S
11.8	3.07E-02	S	5.53E-06	S	1.26E-02	S	2.78E-03	S
12	3.04E-02	S	5.94E-06	S	1.26E-02	S	2.78E-03	S
12.2	3.03E-02	S	6.31E-06	S	1.45E-02	S	2.78E-03	S
12.4	3.02E-02	S	6.68E-06	S	1.70E-02	S	2.78E-03	S
12.6	3.01E-02	S	7.08E-06	S	1.98E-02	S	2.78E-03	S
12.8	3.00E-02	S	7.48E-06	S	2.31E-02	S	2.78E-03	S
13	2.99E-02	S	7.91E-06	S	2.69E-02	S	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	6.73E-01		9.08E-05		2.80E-01		5.85E-02	

Table C-5-38. Leachate Concentrations for Gypsum Export, Waste ID DaAW Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	2.69E+00	S	2.53E-03	S	3.21E-02	S
3	2.41E+00	S	2.53E-03	S	2.35E-02	S
3.2	2.18E+00	S	2.53E-03	S	1.76E-02	S
3.4	1.98E+00	S	2.53E-03	S	1.34E-02	S
3.6	1.81E+00	S	2.53E-03	S	1.03E-02	S
3.8	1.64E+00	S	2.53E-03	S	8.12E-03	S
4	1.46E+00	S	2.53E-03	S	6.48E-03	S
4.2	1.30E+00	S	2.53E-03	S	5.24E-03	S
4.4	1.17E+00	S	2.53E-03	S	4.27E-03	S
4.6	1.05E+00	S	2.53E-03	S	3.52E-03	S
4.8	9.51E-01	S	2.53E-03	S	2.92E-03	S
5	8.64E-01	S	2.53E-03	S	2.44E-03	S
5.2	7.89E-01	S	2.53E-03	S	2.06E-03	S
5.4	7.22E-01	S	2.53E-03	S	1.74E-03	S
5.6	6.63E-01	S	2.53E-03	S	1.49E-03	S
5.8	5.49E-01	S	2.53E-03	S	1.43E-03	S
6	4.41E-01	S	2.53E-03	S	1.43E-03	S
6.2	3.57E-01	S	2.53E-03	S	1.43E-03	S
6.4	2.91E-01	S	2.53E-03	S	1.43E-03	S
6.6	2.35E-01	S	2.53E-03	S	1.43E-03	S
6.8	1.68E-01	S	2.53E-03	S	1.43E-03	S
7	1.20E-01	S	2.53E-03	S	1.43E-03	S
7.2	8.75E-02	S	2.53E-03	S	1.43E-03	S
7.4	6.41E-02	S	2.53E-03	S	1.43E-03	S
7.6	4.73E-02	S	2.53E-03	S	1.43E-03	S
7.8	3.84E-02	S	2.53E-03	S	1.43E-03	S
8	3.83E-02	S	2.53E-03	S	1.43E-03	S

Table C-5-38. Leachate Concentrations for Gypsum Export, Waste ID DaAW Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	3.83E-02	S	2.53E-03	S	1.43E-03	S
8.4	3.82E-02	S	2.53E-03	S	1.43E-03	S
8.6	3.81E-02	S	2.53E-03	S	1.43E-03	S
8.8	3.81E-02	S	2.53E-03	S	1.43E-03	S
9	3.80E-02	S	2.53E-03	S	1.43E-03	S
9.2	4.35E-02	S	2.53E-03	S	1.43E-03	S
9.4	5.09E-02	S	2.53E-03	S	1.43E-03	S
9.6	5.94E-02	S	2.53E-03	S	1.43E-03	S
9.8	6.91E-02	S	2.53E-03	S	1.43E-03	S
10	8.01E-02	S	2.53E-03	S	1.43E-03	S
10.2	9.26E-02	S	2.53E-03	S	1.43E-03	S
10.4	1.07E-01	S	2.53E-03	S	1.43E-03	S
10.6	1.23E-01	S	2.53E-03	S	1.43E-03	S
10.8	1.41E-01	S	2.53E-03	S	1.43E-03	S
11	1.61E-01	S	2.53E-03	S	1.43E-03	S
11.2	1.84E-01	S	2.53E-03	S	1.43E-03	S
11.4	2.09E-01	S	2.53E-03	S	1.43E-03	S
11.6	2.37E-01	S	2.53E-03	S	1.43E-03	S
11.8	2.69E-01	S	2.53E-03	S	1.43E-03	S
12	3.04E-01	S	2.53E-03	S	1.43E-03	S
12.2	3.78E-01	S	2.53E-03	S	1.43E-03	S
12.4	4.75E-01	S	2.53E-03	S	1.43E-03	S
12.6	5.95E-01	S	2.53E-03	S	1.43E-03	S
12.8	7.43E-01	S	2.53E-03	S	1.43E-03	S
13	9.25E-01	S	2.53E-03	S	1.43E-03	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	1.84E+01		3.07E-02		1.80E-01	

Table C-5-38. Leachate Concentrations for Gypsum Export, Waste ID DaAW Med

Sample ID	NAU-[Med] (P,1,1)
Date Exported	9/20/2011, 7:36 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	2.17E-02	S	2.03E+00	W	1.22E-02	S	4.14E-03	S
3	2.01E-02	S	2.00E+00	W	1.19E-02	S	4.58E-03	S
3.2	1.89E-02	S	1.98E+00	W	1.16E-02	S	4.82E-03	S
3.4	1.80E-02	S	1.97E+00	W	1.13E-02	S	4.84E-03	S
3.6	1.72E-02	S	1.95E+00	W	1.11E-02	S	4.87E-03	S
3.8	1.65E-02	S	1.94E+00	W	1.08E-02	S	4.89E-03	S
4	1.59E-02	S	1.93E+00	W	1.06E-02	S	4.91E-03	S
4.2	1.55E-02	S	1.92E+00	W	1.04E-02	S	4.95E-03	S
4.4	1.54E-02	S	1.91E+00	W	1.04E-02	S	4.99E-03	S
4.6	1.53E-02	S	1.90E+00	W	1.03E-02	S	5.03E-03	S
4.8	1.35E-02	S	1.87E+00	W	9.96E-03	S	4.74E-03	S
5	1.19E-02	S	1.84E+00	W	9.62E-03	S	4.44E-03	S
5.2	9.34E-03	S	1.78E+00	W	9.02E-03	S	4.09E-03	S
5.4	7.37E-03	S	1.73E+00	W	8.47E-03	S	3.78E-03	S
5.6	5.86E-03	S	1.68E+00	W	7.97E-03	S	3.50E-03	S
5.8	4.70E-03	S	1.63E+00	W	7.52E-03	S	3.25E-03	S
6	3.80E-03	S	1.58E+00	W	7.10E-03	S	3.03E-03	S
6.2	3.31E-03	S	1.56E+00	W	6.72E-03	S	2.94E-03	S
6.4	3.20E-03	S	1.56E+00	W	6.32E-03	S	2.70E-03	S
6.6	3.20E-03	S	1.58E+00	W	5.95E-03	S	2.43E-03	S
6.8	3.20E-03	S	1.60E+00	W	5.61E-03	S	2.18E-03	S
7	3.20E-03	S	1.70E+00	W	3.64E-03	S	2.06E-03	S
7.2	3.20E-03	S	1.85E+00	W	1.61E-03	S	2.06E-03	S
7.4	3.20E-03	S	1.69E+00	W	1.36E-03	S	2.06E-03	S
7.6	3.20E-03	S	1.55E+00	W	1.16E-03	S	2.06E-03	S
7.8	3.20E-03	S	1.52E+00	W	9.98E-04	S	2.06E-03	S
8	3.20E-03	S	1.52E+00	W	8.58E-04	S	2.06E-03	S

Table C-5-38. Leachate Concentrations for Gypsum Export, Waste ID DaAW Med

Sample ID	NAU-[Med] (P,1,1)
Date Exported	9/20/2011, 7:36 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	3.20E-03	S	1.52E+00	W	7.46E-04	S	2.06E-03	S
8.4	3.20E-03	S	1.52E+00	W	7.46E-04	S	2.06E-03	S
8.6	3.20E-03	S	1.54E+00	W	7.46E-04	S	2.06E-03	S
8.8	3.20E-03	S	1.55E+00	W	7.46E-04	S	2.06E-03	S
9	3.20E-03	S	1.56E+00	W	7.46E-04	S	2.06E-03	S
9.2	3.20E-03	S	1.58E+00	W	7.46E-04	S	2.06E-03	S
9.4	3.20E-03	S	1.59E+00	W	7.46E-04	S	2.06E-03	S
9.6	3.20E-03	S	1.60E+00	W	7.46E-04	S	2.06E-03	S
9.8	3.20E-03	S	1.62E+00	W	7.46E-04	S	2.06E-03	S
10	3.20E-03	S	1.63E+00	W	7.46E-04	S	2.06E-03	S
10.2	3.20E-03	S	1.64E+00	W	7.46E-04	S	2.06E-03	S
10.4	3.20E-03	S	1.63E+00	W	7.46E-04	S	2.06E-03	S
10.6	3.20E-03	S	1.60E+00	W	7.46E-04	S	2.06E-03	S
10.8	3.20E-03	S	1.57E+00	W	7.46E-04	S	2.06E-03	S
11	3.20E-03	S	1.58E+00	W	7.46E-04	S	2.06E-03	S
11.2	3.20E-03	S	1.65E+00	W	7.46E-04	S	2.06E-03	S
11.4	3.20E-03	S	1.72E+00	W	7.46E-04	S	2.06E-03	S
11.6	3.20E-03	S	1.79E+00	W	7.46E-04	S	2.06E-03	S
11.8	3.20E-03	S	1.87E+00	W	7.46E-04	S	2.06E-03	S
12	3.20E-03	S	1.94E+00	S	7.46E-04	S	2.06E-03	S
12.2	3.20E-03	S	2.02E+00	S	7.46E-04	S	2.06E-03	S
12.4	3.20E-03	S	2.09E+00	S	7.46E-04	S	2.06E-03	S
12.6	3.20E-03	S	2.15E+00	S	7.46E-04	S	2.06E-03	S
12.8	3.20E-03	S	2.18E+00	S	7.46E-04	S	2.06E-03	S
13	3.20E-03	S	2.21E+00	S	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	2.01E-01		2.29E+01		1.19E-01		5.03E-02	

Table C-5-38. Leachate Concentrations for Gypsum Export, Waste ID DaAW Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	5.51E-01	S	3.09E-05	S	9.26E-03	S	3.52E-03	S
3	4.77E-01	S	2.12E-05	S	8.67E-03	S	3.01E-03	S
3.2	4.02E-01	S	1.50E-05	S	8.55E-03	S	2.78E-03	S
3.4	3.29E-01	S	1.36E-05	S	8.90E-03	S	2.78E-03	S
3.6	2.73E-01	S	1.24E-05	S	9.24E-03	S	2.78E-03	S
3.8	2.29E-01	S	1.14E-05	S	9.58E-03	S	2.78E-03	S
4	1.93E-01	S	1.05E-05	S	9.91E-03	S	2.78E-03	S
4.2	1.68E-01	S	1.13E-05	S	1.02E-02	S	2.78E-03	S
4.4	1.52E-01	S	1.50E-05	S	1.06E-02	S	2.78E-03	S
4.6	1.38E-01	S	1.97E-05	S	1.09E-02	S	2.78E-03	S
4.8	1.11E-01	S	2.57E-05	S	1.13E-02	S	2.78E-03	S
5	8.99E-02	S	3.30E-05	S	1.16E-02	S	2.78E-03	S
5.2	6.02E-02	S	2.05E-05	S	1.20E-02	S	2.78E-03	S
5.4	4.06E-02	S	1.25E-05	S	1.25E-02	S	2.78E-03	S
5.6	2.77E-02	S	7.76E-06	S	1.29E-02	S	2.78E-03	S
5.8	1.92E-02	S	4.90E-06	S	1.33E-02	S	2.78E-03	S
6	1.35E-02	S	3.14E-06	S	1.36E-02	S	2.78E-03	S
6.2	1.10E-02	S	2.32E-06	S	1.40E-02	S	2.78E-03	S
6.4	1.04E-02	S	2.40E-06	S	1.42E-02	S	2.78E-03	S
6.6	1.02E-02	S	2.82E-06	S	1.44E-02	S	2.78E-03	S
6.8	1.00E-02	S	3.29E-06	S	1.45E-02	S	2.78E-03	S
7	8.12E-03	S	3.43E-06	S	1.48E-02	S	2.78E-03	S
7.2	5.51E-03	S	3.06E-06	S	1.55E-02	W	2.78E-03	S
7.4	6.48E-03	S	2.73E-06	S	1.64E-02	W	2.78E-03	S
7.6	7.60E-03	S	2.45E-06	S	1.73E-02	W	2.78E-03	S
7.8	8.00E-03	S	2.20E-06	S	1.79E-02	W	2.78E-03	S
8	8.13E-03	S	1.98E-06	S	1.84E-02	W	2.78E-03	S

Table C-5-38. Leachate Concentrations for Gypsum Export, Waste ID DaAW Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	9.21E-03	S	1.80E-06	S	1.95E-02	W	2.78E-03	S
8.4	1.11E-02	S	1.80E-06	S	2.05E-02	W	2.78E-03	S
8.6	1.21E-02	S	1.80E-06	S	2.09E-02	W	2.78E-03	S
8.8	1.30E-02	S	1.80E-06	S	2.12E-02	W	2.78E-03	S
9	1.38E-02	S	1.80E-06	S	2.15E-02	W	2.78E-03	S
9.2	1.46E-02	S	1.80E-06	S	2.17E-02	W	2.78E-03	S
9.4	1.55E-02	S	1.80E-06	S	2.20E-02	W	2.78E-03	S
9.6	1.63E-02	S	1.80E-06	S	2.23E-02	W	2.78E-03	S
9.8	1.72E-02	S	1.80E-06	S	2.25E-02	W	2.78E-03	S
10	1.82E-02	S	1.80E-06	S	2.28E-02	W	2.78E-03	S
10.2	1.91E-02	S	1.80E-06	S	2.31E-02	W	2.78E-03	S
10.4	2.24E-02	S	1.80E-06	S	2.32E-02	W	2.78E-03	S
10.6	2.78E-02	S	1.80E-06	S	2.33E-02	W	2.78E-03	S
10.8	3.42E-02	S	1.80E-06	S	2.34E-02	W	2.78E-03	S
11	3.37E-02	S	1.86E-06	S	2.38E-02	W	2.78E-03	S
11.2	3.01E-02	S	2.52E-06	S	2.45E-02	W	2.78E-03	S
11.4	2.70E-02	S	3.39E-06	S	2.51E-02	W	2.78E-03	S
11.6	2.42E-02	S	4.55E-06	S	2.57E-02	W	2.78E-03	S
11.8	2.18E-02	S	6.08E-06	S	2.63E-02	W	2.78E-03	S
12	1.96E-02	S	8.07E-06	S	2.67E-02	W	2.78E-03	S
12.2	1.77E-02	S	1.07E-05	S	2.67E-02	W	2.78E-03	S
12.4	1.60E-02	S	1.40E-05	S	2.67E-02	W	2.78E-03	S
12.6	1.45E-02	S	1.84E-05	S	2.67E-02	W	2.78E-03	S
12.8	1.31E-02	S	2.40E-05	S	2.67E-02	W	2.78E-03	S
13	1.19E-02	S	3.12E-05	S	2.67E-02	W	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	4.77E+00		3.30E-04		2.81E-01		3.01E-02	

Table C-5-38. Leachate Concentrations for Gypsum Export, Waste ID DaAW Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	1.68E-01	S	2.53E-03	S	3.02E-01	S
3	1.64E-01	S	2.53E-03	S	2.70E-01	S
3.2	1.63E-01	S	2.53E-03	S	2.38E-01	S
3.4	1.65E-01	S	2.53E-03	S	2.07E-01	S
3.6	1.67E-01	S	2.53E-03	S	1.82E-01	S
3.8	1.69E-01	S	2.53E-03	S	1.60E-01	S
4	1.71E-01	S	2.53E-03	S	1.42E-01	S
4.2	1.73E-01	S	2.53E-03	S	1.27E-01	S
4.4	1.75E-01	S	2.53E-03	S	1.14E-01	S
4.6	1.76E-01	S	2.53E-03	S	1.03E-01	S
4.8	1.75E-01	S	2.53E-03	S	9.50E-02	S
5	1.73E-01	S	2.53E-03	S	8.81E-02	S
5.2	1.67E-01	S	2.53E-03	S	8.06E-02	S
5.4	1.62E-01	S	2.53E-03	S	7.39E-02	S
5.6	1.56E-01	S	2.53E-03	S	6.80E-02	S
5.8	1.52E-01	S	2.53E-03	S	6.28E-02	S
6	1.47E-01	S	2.53E-03	S	5.81E-02	S
6.2	1.41E-01	S	2.53E-03	S	5.35E-02	S
6.4	1.33E-01	S	2.53E-03	S	4.94E-02	S
6.6	1.25E-01	S	2.53E-03	S	4.57E-02	S
6.8	1.18E-01	S	2.53E-03	S	4.23E-02	S
7	7.75E-02	S	2.53E-03	S	3.06E-02	S
7.2	3.51E-02	S	2.53E-03	S	1.75E-02	S
7.4	2.78E-02	S	2.53E-03	S	1.72E-02	S
7.6	2.23E-02	S	2.53E-03	S	1.69E-02	S
7.8	1.89E-02	S	2.53E-03	S	1.68E-02	S
8	1.63E-02	S	2.53E-03	S	1.67E-02	S

Table C-5-38. Leachate Concentrations for Gypsum Export, Waste ID DaAW Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	1.42E-02	S	2.53E-03	S	1.99E-02	S
8.4	1.35E-02	S	2.53E-03	S	2.60E-02	S
8.6	1.30E-02	S	2.53E-03	S	2.86E-02	S
8.8	1.25E-02	S	2.53E-03	S	3.13E-02	S
9	1.24E-02	S	2.53E-03	S	3.34E-02	S
9.2	1.24E-02	S	2.53E-03	S	3.56E-02	S
9.4	1.23E-02	S	2.53E-03	S	3.79E-02	S
9.6	1.22E-02	S	2.53E-03	S	4.03E-02	S
9.8	1.22E-02	S	2.53E-03	S	4.28E-02	S
10	1.21E-02	S	2.53E-03	S	4.54E-02	S
10.2	1.21E-02	S	2.53E-03	S	4.81E-02	S
10.4	1.57E-02	S	2.53E-03	S	4.87E-02	S
10.6	2.32E-02	S	2.53E-03	S	4.86E-02	S
10.8	3.39E-02	S	2.53E-03	S	4.86E-02	S
11	4.27E-02	S	2.53E-03	S	4.89E-02	S
11.2	5.27E-02	S	2.53E-03	S	4.95E-02	S
11.4	6.47E-02	S	2.53E-03	S	5.01E-02	S
11.6	7.92E-02	S	2.53E-03	S	5.07E-02	S
11.8	9.66E-02	S	2.53E-03	S	5.13E-02	S
12	1.17E-01	S	2.53E-03	S	5.19E-02	S
12.2	1.42E-01	S	2.53E-03	S	5.24E-02	S
12.4	1.72E-01	S	2.53E-03	S	5.30E-02	S
12.6	1.95E-01	S	2.53E-03	S	5.36E-02	S
12.8	2.03E-01	S	2.53E-03	S	5.42E-02	S
13	2.03E-01	S	2.53E-03	S	5.47E-02	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	2.13E+00		2.66E-02		2.70E+00	

Table C-5-40. Leachate Concentrations for Gypsum Export, Waste ID NAW Med

Sample ID	NAW-[Med] (P,1,1)
Date Exported	9/20/2011, 7:37 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	1.81E-02	S	8.14E-02	W	1.05E-02	S	4.42E-03	S
3	1.71E-02	S	7.89E-02	W	1.03E-02	S	4.51E-03	S
3.2	1.63E-02	S	7.68E-02	W	1.00E-02	S	4.49E-03	S
3.4	1.56E-02	S	7.48E-02	W	9.81E-03	S	4.48E-03	S
3.6	1.49E-02	S	7.34E-02	W	9.61E-03	S	4.38E-03	S
3.8	1.41E-02	S	7.24E-02	W	9.42E-03	S	4.21E-03	S
4	1.34E-02	S	7.14E-02	W	9.24E-03	S	4.05E-03	S
4.2	1.28E-02	S	7.05E-02	W	9.08E-03	S	3.90E-03	S
4.4	1.22E-02	S	6.97E-02	W	8.92E-03	S	3.77E-03	S
4.6	1.17E-02	S	6.89E-02	W	8.78E-03	S	3.64E-03	S
4.8	1.12E-02	S	6.82E-02	W	8.64E-03	S	3.52E-03	S
5	1.08E-02	S	6.75E-02	W	8.51E-03	S	3.42E-03	S
5.2	1.04E-02	S	6.68E-02	W	8.39E-03	S	3.32E-03	S
5.4	9.95E-03	S	6.61E-02	W	8.26E-03	S	3.18E-03	S
5.6	8.70E-03	S	6.40E-02	W	7.80E-03	S	2.37E-03	S
5.8	7.37E-03	S	6.17E-02	W	7.37E-03	S	2.06E-03	S
6	6.46E-03	S	5.96E-02	W	7.07E-03	S	2.06E-03	S
6.2	5.69E-03	S	5.77E-02	W	6.78E-03	S	2.06E-03	S
6.4	5.54E-03	S	5.57E-02	W	6.03E-03	S	2.06E-03	S
6.6	4.78E-03	S	5.31E-02	W	3.76E-03	S	2.06E-03	S
6.8	3.92E-03	S	5.05E-02	W	2.14E-03	S	2.06E-03	S
7	3.95E-03	S	4.87E-02	W	1.11E-03	S	2.06E-03	S
7.2	5.29E-03	S	4.79E-02	W	1.18E-03	S	2.06E-03	S
7.4	5.15E-03	S	4.89E-02	W	1.30E-03	S	2.06E-03	S
7.6	4.52E-03	S	5.13E-02	W	1.18E-03	S	2.06E-03	S
7.8	3.97E-03	S	5.37E-02	W	1.07E-03	S	2.06E-03	S
8	3.51E-03	S	5.62E-02	W	9.77E-04	S	2.06E-03	S

Table C-5-40. Leachate Concentrations for Gypsum Export, Waste ID NAW Med

Sample ID	NAW-[Med] (P,1,1)
Date Exported	9/20/2011, 7:37 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	3.20E-03	S	5.90E-02	W	8.92E-04	S	2.06E-03	S
8.4	3.20E-03	S	6.27E-02	W	8.17E-04	S	2.06E-03	S
8.6	3.20E-03	S	6.66E-02	W	7.50E-04	S	2.06E-03	S
8.8	3.20E-03	S	6.97E-02	W	7.46E-04	S	2.06E-03	S
9	3.20E-03	S	7.29E-02	W	7.46E-04	S	2.06E-03	S
9.2	3.20E-03	S	7.58E-02	W	7.57E-04	S	2.06E-03	S
9.4	3.20E-03	S	7.82E-02	W	7.92E-04	S	2.06E-03	S
9.6	3.20E-03	S	8.06E-02	W	8.29E-04	S	2.06E-03	S
9.8	3.20E-03	S	8.30E-02	W	8.66E-04	S	2.06E-03	S
10	3.20E-03	S	8.54E-02	W	9.04E-04	S	2.06E-03	S
10.2	3.20E-03	S	9.05E-02	W	9.43E-04	S	2.06E-03	S
10.4	3.20E-03	S	9.76E-02	W	9.83E-04	S	2.06E-03	S
10.6	3.20E-03	S	1.05E-01	W	1.02E-03	S	2.06E-03	S
10.8	3.20E-03	S	1.14E-01	W	1.07E-03	S	2.06E-03	S
11	3.20E-03	S	1.26E-01	W	1.05E-03	S	2.06E-03	S
11.2	3.20E-03	S	1.38E-01	W	8.99E-04	S	2.06E-03	S
11.4	3.20E-03	S	1.46E-01	W	7.74E-04	S	2.06E-03	S
11.6	3.20E-03	S	1.47E-01	W	6.69E-04	S	2.06E-03	S
11.8	3.20E-03	S	1.47E-01	W	5.79E-04	S	2.06E-03	S
12	3.20E-03	S	1.47E-01	S	5.03E-04	S	2.06E-03	S
12.2	3.20E-03	S	1.47E-01	S	4.38E-04	S	2.06E-03	S
12.4	3.20E-03	S	1.47E-01	S	3.82E-04	S	2.06E-03	S
12.6	3.20E-03	S	1.47E-01	S	3.33E-04	S	2.06E-03	S
12.8	3.20E-03	S	1.47E-01	S	2.92E-04	S	2.06E-03	S
13	3.20E-03	S	1.47E-01	S	2.56E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	1.71E-01		1.49E+00		1.03E-01		4.51E-02	

Table C-5-40. Leachate Concentrations for Gypsum Export, Waste ID NAW Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	2.88E-01	S	1.80E-06	S	3.92E-03	S	2.78E-03	S
3	2.11E-01	S	1.80E-06	S	3.80E-03	S	2.78E-03	S
3.2	1.57E-01	S	1.80E-06	S	3.80E-03	S	2.78E-03	S
3.4	1.19E-01	S	1.80E-06	S	3.80E-03	S	2.78E-03	S
3.6	9.65E-02	S	1.80E-06	S	3.87E-03	S	2.78E-03	S
3.8	8.36E-02	S	1.80E-06	S	4.02E-03	S	2.78E-03	S
4	7.30E-02	S	1.80E-06	S	4.18E-03	S	2.78E-03	S
4.2	6.41E-02	S	1.80E-06	S	4.33E-03	S	2.78E-03	S
4.4	5.67E-02	S	1.80E-06	S	4.49E-03	S	2.78E-03	S
4.6	5.04E-02	S	1.80E-06	S	4.64E-03	S	2.78E-03	S
4.8	4.50E-02	S	1.80E-06	S	4.78E-03	S	2.78E-03	S
5	4.04E-02	S	1.80E-06	S	4.93E-03	S	2.78E-03	S
5.2	3.64E-02	S	1.80E-06	S	5.08E-03	S	2.78E-03	S
5.4	3.23E-02	S	1.80E-06	S	5.29E-03	S	2.78E-03	S
5.6	1.99E-02	S	1.80E-06	S	7.02E-03	S	2.78E-03	S
5.8	1.20E-02	S	1.80E-06	S	8.14E-03	S	2.78E-03	S
6	7.58E-03	S	1.80E-06	S	8.38E-03	S	2.78E-03	S
6.2	4.85E-03	S	1.80E-06	S	8.61E-03	S	2.78E-03	S
6.4	3.09E-03	S	1.80E-06	S	8.75E-03	S	2.78E-03	S
6.6	2.41E-03	S	1.80E-06	S	8.74E-03	S	2.78E-03	S
6.8	2.02E-03	S	1.80E-06	S	8.69E-03	S	2.78E-03	S
7	1.90E-03	S	1.80E-06	S	8.98E-03	S	2.78E-03	S
7.2	1.90E-03	S	1.80E-06	S	9.32E-03	W	2.78E-03	S
7.4	2.04E-03	S	1.80E-06	S	9.81E-03	W	2.78E-03	S
7.6	2.23E-03	S	1.80E-06	S	1.06E-02	W	2.78E-03	S
7.8	2.44E-03	S	1.80E-06	S	1.14E-02	W	2.78E-03	S
8	2.67E-03	S	1.80E-06	S	1.22E-02	W	2.78E-03	S

Table C-5-40. Leachate Concentrations for Gypsum Export, Waste ID NAW Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	2.93E-03	S	1.80E-06	S	1.30E-02	W	2.78E-03	S
8.4	3.31E-03	S	1.80E-06	S	1.36E-02	W	2.78E-03	S
8.6	3.73E-03	S	1.80E-06	S	1.41E-02	W	2.78E-03	S
8.8	4.70E-03	S	1.80E-06	S	1.42E-02	W	2.78E-03	S
9	5.93E-03	S	1.80E-06	S	1.43E-02	W	2.78E-03	S
9.2	7.22E-03	S	1.80E-06	S	1.44E-02	W	2.78E-03	S
9.4	8.16E-03	S	1.80E-06	S	1.44E-02	W	2.78E-03	S
9.6	9.19E-03	S	1.80E-06	S	1.44E-02	W	2.78E-03	S
9.8	1.03E-02	S	1.80E-06	S	1.44E-02	W	2.78E-03	S
10	1.16E-02	S	1.80E-06	S	1.44E-02	W	2.78E-03	S
10.2	1.23E-02	S	1.80E-06	S	1.46E-02	W	2.78E-03	S
10.4	1.25E-02	S	1.80E-06	S	1.48E-02	W	2.78E-03	S
10.6	1.27E-02	S	1.80E-06	S	1.51E-02	W	2.78E-03	S
10.8	1.29E-02	S	1.80E-06	S	1.53E-02	W	2.78E-03	S
11	1.33E-02	S	1.80E-06	S	1.55E-02	W	2.78E-03	S
11.2	1.40E-02	S	1.80E-06	S	1.56E-02	W	2.78E-03	S
11.4	1.48E-02	S	1.80E-06	S	1.57E-02	W	2.78E-03	S
11.6	1.56E-02	S	1.80E-06	S	1.57E-02	W	2.78E-03	S
11.8	1.64E-02	S	1.80E-06	S	1.57E-02	W	2.78E-03	S
12	1.73E-02	S	1.80E-06	S	1.57E-02	W	2.78E-03	S
12.2	1.81E-02	S	1.80E-06	S	1.57E-02	W	2.78E-03	S
12.4	1.90E-02	S	1.80E-06	S	1.57E-02	W	2.78E-03	S
12.6	2.00E-02	S	1.80E-06	S	1.57E-02	W	2.78E-03	S
12.8	2.09E-02	S	1.80E-06	S	1.57E-02	W	2.78E-03	S
13	2.19E-02	S	1.80E-06	S	1.57E-02	W	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	2.11E+00		1.83E-05		1.60E-01		2.82E-02	

Table C-5-40. Leachate Concentrations for Gypsum Export, Waste ID NAW Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	1.47E-01	W	2.53E-03	S	2.61E-01	S
3	1.46E-01	W	2.53E-03	S	2.27E-01	S
3.2	1.45E-01	W	2.53E-03	S	1.98E-01	S
3.4	1.45E-01	W	2.53E-03	S	1.74E-01	S
3.6	1.46E-01	W	2.53E-03	S	1.56E-01	S
3.8	1.47E-01	W	2.53E-03	S	1.41E-01	S
4	1.49E-01	W	2.53E-03	S	1.28E-01	S
4.2	1.51E-01	W	2.53E-03	S	1.17E-01	S
4.4	1.52E-01	W	2.53E-03	S	1.07E-01	S
4.6	1.54E-01	W	2.53E-03	S	9.90E-02	S
4.8	1.55E-01	W	2.53E-03	S	9.15E-02	S
5	1.56E-01	W	2.53E-03	S	8.49E-02	S
5.2	1.58E-01	W	2.53E-03	S	7.90E-02	S
5.4	1.59E-01	W	2.53E-03	S	7.37E-02	S
5.6	1.60E-01	W	2.53E-03	S	6.92E-02	S
5.8	1.56E-01	W	2.53E-03	S	6.49E-02	S
6	1.51E-01	S	2.53E-03	S	6.12E-02	S
6.2	1.45E-01	S	2.53E-03	S	5.77E-02	S
6.4	1.31E-01	S	2.53E-03	S	5.02E-02	S
6.6	8.42E-02	S	2.53E-03	S	3.30E-02	S
6.8	4.94E-02	S	2.53E-03	S	2.03E-02	S
7	2.37E-02	S	2.53E-03	S	1.18E-02	S
7.2	2.54E-02	S	2.53E-03	S	1.29E-02	S
7.4	2.87E-02	S	2.53E-03	S	1.64E-02	S
7.6	2.49E-02	S	2.53E-03	S	1.86E-02	S
7.8	2.17E-02	S	2.53E-03	S	2.11E-02	S
8	1.90E-02	S	2.53E-03	S	2.39E-02	S

Table C-5-40. Leachate Concentrations for Gypsum Export, Waste ID NAW Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	1.70E-02	S	2.53E-03	S	2.65E-02	S
8.4	1.61E-02	S	2.53E-03	S	2.82E-02	S
8.6	1.52E-02	S	2.53E-03	S	2.99E-02	S
8.8	1.65E-02	S	2.53E-03	S	3.21E-02	S
9	1.79E-02	S	2.53E-03	S	3.45E-02	S
9.2	1.90E-02	S	2.53E-03	S	3.65E-02	S
9.4	1.91E-02	S	2.53E-03	S	3.74E-02	S
9.6	1.93E-02	S	2.53E-03	S	3.83E-02	S
9.8	1.95E-02	S	2.53E-03	S	3.92E-02	S
10	1.96E-02	S	2.53E-03	S	4.01E-02	S
10.2	2.02E-02	S	2.53E-03	S	4.10E-02	S
10.4	2.10E-02	S	2.53E-03	S	4.19E-02	S
10.6	2.19E-02	S	2.53E-03	S	4.27E-02	S
10.8	2.40E-02	S	2.53E-03	S	4.43E-02	S
11	2.98E-02	S	2.53E-03	S	4.76E-02	S
11.2	4.12E-02	S	2.53E-03	S	5.29E-02	S
11.4	5.67E-02	S	2.53E-03	S	5.87E-02	S
11.6	7.76E-02	S	2.53E-03	S	6.49E-02	S
11.8	1.06E-01	S	2.53E-03	S	7.18E-02	S
12	1.43E-01	S	2.53E-03	S	7.92E-02	S
12.2	1.67E-01	S	2.53E-03	S	8.72E-02	S
12.4	1.78E-01	S	2.53E-03	S	9.59E-02	S
12.6	1.78E-01	S	2.53E-03	S	1.05E-01	S
12.8	1.78E-01	S	2.53E-03	S	1.15E-01	S
13	1.78E-01	S	2.53E-03	S	1.26E-01	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	1.80E+00		2.57E-02		2.27E+00	

Table C-5-41. Leachate Concentrations for Gypsum Export, Waste ID OAU Med

Sample ID	OAU-[Med] (P,1,1)
Date Exported	9/20/2011, 7:37 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	7.96E-03	S	5.94E+00	W	1.33E-02	W	1.83E-02	W
3	5.50E-03	S	5.89E+00	W	1.31E-02	W	1.80E-02	W
3.2	4.58E-03	S	5.85E+00	W	1.30E-02	W	1.78E-02	W
3.4	4.34E-03	S	5.83E+00	W	1.30E-02	W	1.78E-02	W
3.6	4.13E-03	S	5.81E+00	W	1.30E-02	W	1.78E-02	W
3.8	3.94E-03	S	5.79E+00	W	1.30E-02	W	1.78E-02	W
4	3.76E-03	S	5.77E+00	W	1.29E-02	W	1.78E-02	W
4.2	3.60E-03	S	5.75E+00	W	1.29E-02	W	1.78E-02	W
4.4	3.46E-03	S	5.73E+00	W	1.29E-02	W	1.78E-02	W
4.6	3.32E-03	S	5.69E+00	W	1.28E-02	W	1.77E-02	W
4.8	3.20E-03	S	5.65E+00	W	1.27E-02	W	1.76E-02	W
5	3.20E-03	S	5.64E+00	W	1.26E-02	S	1.75E-02	S
5.2	3.20E-03	S	5.63E+00	W	1.24E-02	S	1.74E-02	S
5.4	3.20E-03	S	5.65E+00	W	1.23E-02	S	1.69E-02	S
5.6	3.20E-03	S	5.70E+00	W	1.14E-02	S	1.45E-02	S
5.8	3.20E-03	S	5.69E+00	W	1.09E-02	S	1.27E-02	S
6	3.20E-03	S	5.65E+00	W	1.00E-02	S	1.03E-02	S
6.2	3.20E-03	S	5.62E+00	W	9.17E-03	S	8.32E-03	S
6.4	3.20E-03	S	5.58E+00	W	8.43E-03	S	6.75E-03	S
6.6	3.20E-03	S	5.54E+00	W	7.77E-03	S	5.51E-03	S
6.8	3.20E-03	S	5.50E+00	W	6.78E-03	S	4.52E-03	S
7	3.20E-03	S	5.42E+00	W	3.69E-03	S	3.62E-03	S
7.2	3.20E-03	S	5.35E+00	W	1.99E-03	S	2.91E-03	S
7.4	3.20E-03	S	5.27E+00	W	1.09E-03	S	2.35E-03	S
7.6	3.20E-03	S	5.24E+00	W	7.46E-04	S	2.06E-03	S
7.8	3.20E-03	S	5.28E+00	W	7.46E-04	S	2.06E-03	S
8	3.20E-03	S	5.31E+00	W	7.46E-04	S	2.06E-03	S

Table C-5-41. Leachate Concentrations for Gypsum Export, Waste ID OAU Med

Sample ID	OAU-[Med] (P,1,1)
Date Exported	9/20/2011, 7:37 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	3.20E-03	S	5.34E+00	W	7.46E-04	S	2.06E-03	S
8.4	3.20E-03	S	5.38E+00	W	7.46E-04	S	2.06E-03	S
8.6	3.20E-03	S	5.41E+00	W	7.46E-04	S	2.06E-03	S
8.8	3.20E-03	S	5.45E+00	W	7.46E-04	S	2.06E-03	S
9	3.20E-03	S	5.45E+00	W	7.46E-04	S	2.06E-03	S
9.2	3.20E-03	S	5.43E+00	W	7.46E-04	S	2.06E-03	S
9.4	3.20E-03	S	5.40E+00	W	7.46E-04	S	2.06E-03	S
9.6	3.20E-03	S	5.40E+00	W	7.46E-04	S	2.06E-03	S
9.8	3.20E-03	S	5.44E+00	W	7.46E-04	S	2.06E-03	S
10	3.20E-03	S	5.48E+00	W	7.46E-04	S	2.06E-03	S
10.2	3.20E-03	S	5.52E+00	W	7.46E-04	S	2.06E-03	S
10.4	3.20E-03	S	5.61E+00	W	7.46E-04	S	2.06E-03	S
10.6	3.20E-03	S	5.70E+00	W	7.46E-04	S	2.06E-03	S
10.8	3.20E-03	S	5.79E+00	W	7.46E-04	S	2.06E-03	S
11	3.20E-03	S	5.87E+00	W	7.46E-04	S	2.06E-03	S
11.2	3.20E-03	S	5.96E+00	W	7.46E-04	S	2.06E-03	S
11.4	3.20E-03	S	6.05E+00	W	7.46E-04	S	2.06E-03	S
11.6	3.20E-03	S	6.14E+00	W	7.46E-04	S	2.06E-03	S
11.8	3.20E-03	S	6.23E+00	W	7.46E-04	S	2.06E-03	S
12	3.20E-03	S	6.30E+00	W	7.46E-04	S	2.06E-03	S
12.2	3.20E-03	S	6.33E+00	W	7.46E-04	S	2.06E-03	S
12.4	3.20E-03	S	6.33E+00	W	7.46E-04	S	2.06E-03	S
12.6	3.20E-03	S	6.33E+00	W	7.46E-04	S	2.06E-03	S
12.8	3.20E-03	S	6.33E+00	W	7.46E-04	S	2.06E-03	S
13	3.20E-03	S	6.33E+00	W	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	5.50E-02		6.65E+01		1.31E-01		1.80E-01	

Table C-5-41. Leachate Concentrations for Gypsum Export, Waste ID OAU Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	1.01E-01	S	1.80E-06	S	6.32E-03	S	3.06E-03	S
3	8.96E-02	S	1.80E-06	S	4.42E-03	S	2.87E-03	S
3.2	6.93E-02	S	1.80E-06	S	3.80E-03	S	2.78E-03	S
3.4	4.76E-02	S	1.80E-06	S	3.80E-03	S	2.78E-03	S
3.6	3.34E-02	S	1.80E-06	S	3.80E-03	S	2.78E-03	S
3.8	2.39E-02	S	1.80E-06	S	3.80E-03	S	2.78E-03	S
4	1.74E-02	S	1.80E-06	S	3.80E-03	S	2.78E-03	S
4.2	1.29E-02	S	1.80E-06	S	3.80E-03	S	2.78E-03	S
4.4	9.42E-03	S	1.80E-06	S	3.80E-03	S	2.78E-03	S
4.6	5.70E-03	S	1.80E-06	S	3.80E-03	S	2.78E-03	S
4.8	3.53E-03	S	1.80E-06	S	3.80E-03	S	2.78E-03	S
5	2.66E-03	S	1.80E-06	S	3.80E-03	S	2.78E-03	S
5.2	2.03E-03	S	1.80E-06	S	3.80E-03	S	2.78E-03	S
5.4	1.90E-03	S	1.80E-06	S	3.80E-03	S	2.78E-03	S
5.6	1.90E-03	S	1.80E-06	S	3.90E-03	S	2.78E-03	S
5.8	1.90E-03	S	1.80E-06	S	4.48E-03	S	2.78E-03	S
6	1.90E-03	S	1.80E-06	S	5.93E-03	S	2.78E-03	S
6.2	1.90E-03	S	1.80E-06	S	8.08E-03	S	2.78E-03	S
6.4	1.90E-03	S	1.80E-06	S	1.09E-02	S	2.78E-03	S
6.6	1.90E-03	S	1.80E-06	S	1.45E-02	S	2.78E-03	S
6.8	1.90E-03	S	1.80E-06	S	1.86E-02	S	2.78E-03	S
7	1.90E-03	S	2.14E-06	S	1.88E-02	S	2.78E-03	S
7.2	1.90E-03	S	2.59E-06	S	1.88E-02	W	2.78E-03	S
7.4	1.90E-03	S	3.11E-06	S	1.87E-02	W	2.78E-03	S
7.6	1.90E-03	S	3.51E-06	S	1.88E-02	W	2.78E-03	S
7.8	1.90E-03	S	3.14E-06	S	1.90E-02	W	2.78E-03	S
8	1.90E-03	S	2.81E-06	S	1.92E-02	W	2.78E-03	S

Table C-5-41. Leachate Concentrations for Gypsum Export, Waste ID OAU Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	1.90E-03	S	2.53E-06	S	1.94E-02	W	2.78E-03	S
8.4	1.90E-03	S	2.28E-06	S	1.95E-02	W	2.78E-03	S
8.6	1.90E-03	S	2.06E-06	S	1.99E-02	W	2.78E-03	S
8.8	1.90E-03	S	1.86E-06	S	2.04E-02	W	2.78E-03	S
9	2.06E-03	S	1.80E-06	S	2.14E-02	W	2.78E-03	S
9.2	2.33E-03	S	1.80E-06	S	2.25E-02	W	2.78E-03	S
9.4	2.63E-03	S	1.80E-06	S	2.37E-02	W	2.78E-03	S
9.6	3.06E-03	S	1.94E-06	S	2.45E-02	W	2.78E-03	S
9.8	3.61E-03	S	2.37E-06	S	2.46E-02	W	2.78E-03	S
10	4.25E-03	S	2.90E-06	S	2.48E-02	W	2.78E-03	S
10.2	4.78E-03	S	3.53E-06	S	2.50E-02	W	2.78E-03	S
10.4	4.92E-03	S	3.34E-06	S	2.57E-02	W	2.78E-03	S
10.6	5.06E-03	S	3.07E-06	S	2.65E-02	W	2.78E-03	S
10.8	5.20E-03	S	2.84E-06	S	2.72E-02	W	2.78E-03	S
11	5.35E-03	S	2.62E-06	S	2.80E-02	W	2.78E-03	S
11.2	5.49E-03	S	2.43E-06	S	2.88E-02	W	2.78E-03	S
11.4	5.64E-03	S	2.25E-06	S	2.96E-02	W	2.78E-03	S
11.6	5.79E-03	S	2.09E-06	S	3.04E-02	W	2.78E-03	S
11.8	5.94E-03	S	1.94E-06	S	3.12E-02	W	2.78E-03	S
12	6.09E-03	S	1.81E-06	S	3.17E-02	W	2.78E-03	S
12.2	6.24E-03	S	1.80E-06	S	3.17E-02	W	2.78E-03	S
12.4	6.39E-03	S	1.80E-06	S	3.17E-02	W	2.78E-03	S
12.6	6.55E-03	S	1.80E-06	S	3.17E-02	W	2.78E-03	S
12.8	6.70E-03	S	1.80E-06	S	3.17E-02	W	2.78E-03	S
13	6.86E-03	S	1.80E-06	S	3.17E-02	W	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	8.96E-01		3.56E-05		3.33E-01		2.92E-02	

Table C-5-41. Leachate Concentrations for Gypsum Export, Waste ID OAU Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	1.05E-01	W	2.53E-03	S	7.19E-02	S
3	1.02E-01	W	2.53E-03	S	5.80E-02	S
3.2	1.01E-01	W	2.53E-03	S	3.81E-02	S
3.4	1.01E-01	W	2.53E-03	S	2.17E-02	S
3.6	1.01E-01	W	2.53E-03	S	1.28E-02	S
3.8	1.01E-01	W	2.53E-03	S	7.72E-03	S
4	1.01E-01	W	2.53E-03	S	4.80E-03	S
4.2	1.01E-01	W	2.53E-03	S	3.05E-03	S
4.4	1.01E-01	W	2.53E-03	S	2.03E-03	S
4.6	1.01E-01	W	2.53E-03	S	1.70E-03	S
4.8	1.01E-01	W	2.53E-03	S	1.43E-03	S
5	1.01E-01	W	2.53E-03	S	1.43E-03	S
5.2	1.02E-01	W	2.53E-03	S	1.43E-03	S
5.4	1.02E-01	W	2.53E-03	S	1.43E-03	S
5.6	1.05E-01	W	2.53E-03	S	1.45E-03	S
5.8	1.03E-01	W	2.53E-03	S	1.55E-03	S
6	1.01E-01	W	2.53E-03	S	1.66E-03	S
6.2	9.92E-02	W	2.53E-03	S	1.76E-03	S
6.4	9.75E-02	W	2.53E-03	S	1.87E-03	S
6.6	9.59E-02	W	2.53E-03	S	1.99E-03	S
6.8	9.43E-02	W	2.53E-03	S	2.11E-03	S
7	9.27E-02	W	2.53E-03	S	1.92E-03	S
7.2	9.11E-02	W	2.53E-03	S	1.72E-03	S
7.4	8.97E-02	W	2.53E-03	S	1.55E-03	S
7.6	8.86E-02	W	2.53E-03	S	1.43E-03	S
7.8	8.83E-02	W	2.53E-03	S	1.43E-03	S
8	8.80E-02	W	2.53E-03	S	1.43E-03	S

Table C-5-41. Leachate Concentrations for Gypsum Export, Waste ID OAU Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	8.77E-02	W	2.53E-03	S	1.43E-03	S
8.4	8.75E-02	W	2.53E-03	S	1.43E-03	S
8.6	8.78E-02	W	2.53E-03	S	1.58E-03	S
8.8	8.86E-02	W	2.53E-03	S	1.90E-03	S
9	9.03E-02	W	2.53E-03	S	2.76E-03	S
9.2	9.25E-02	W	2.53E-03	S	4.40E-03	S
9.4	9.47E-02	W	2.53E-03	S	6.94E-03	S
9.6	9.53E-02	W	2.53E-03	S	9.16E-03	S
9.8	9.34E-02	W	2.53E-03	S	9.18E-03	S
10	9.15E-02	W	2.53E-03	S	9.19E-03	S
10.2	8.98E-02	W	2.53E-03	S	9.20E-03	S
10.4	9.02E-02	W	2.53E-03	S	9.19E-03	S
10.6	9.08E-02	W	2.53E-03	S	9.20E-03	S
10.8	9.13E-02	W	2.53E-03	S	9.20E-03	S
11	9.19E-02	W	2.53E-03	S	9.21E-03	S
11.2	9.25E-02	W	2.53E-03	S	9.21E-03	S
11.4	9.30E-02	W	2.53E-03	S	9.21E-03	S
11.6	9.36E-02	W	2.53E-03	S	9.22E-03	S
11.8	9.41E-02	W	2.53E-03	S	9.22E-03	S
12	9.46E-02	W	2.53E-03	S	9.22E-03	S
12.2	9.52E-02	W	2.53E-03	S	9.22E-03	S
12.4	9.57E-02	W	2.53E-03	S	9.23E-03	S
12.6	9.62E-02	W	2.53E-03	S	9.23E-03	S
12.8	9.67E-02	W	2.53E-03	S	9.23E-03	S
13	9.72E-02	W	2.53E-03	S	9.24E-03	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	1.05E+00		2.66E-02		5.80E-01	

Table C-5-42. Leachate Concentrations for Gypsum Export, Waste ID OAW Med

Sample ID	OAW-[Med] (P,1,1)
Date Exported	9/20/2011, 7:37 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	1.10E-02	S	7.88E-01	S	8.81E-03	W	1.82E-02	W
3	8.69E-03	S	7.54E-01	S	8.61E-03	W	1.78E-02	W
3.2	6.90E-03	S	7.12E-01	S	8.47E-03	W	1.76E-02	W
3.4	5.54E-03	S	6.73E-01	S	8.36E-03	W	1.75E-02	W
3.6	4.51E-03	S	6.38E-01	S	8.25E-03	W	1.73E-02	W
3.8	4.06E-03	S	6.03E-01	S	8.13E-03	W	1.71E-02	W
4	3.83E-03	S	5.70E-01	S	8.01E-03	W	1.69E-02	W
4.2	3.62E-03	S	5.41E-01	S	7.90E-03	W	1.67E-02	W
4.4	3.43E-03	S	5.14E-01	S	7.79E-03	W	1.65E-02	W
4.6	3.26E-03	S	4.90E-01	S	7.70E-03	W	1.63E-02	W
4.8	3.20E-03	S	4.67E-01	S	7.46E-03	W	1.54E-02	W
5	3.20E-03	S	4.47E-01	S	7.16E-03	S	1.43E-02	S
5.2	3.20E-03	S	4.28E-01	S	6.89E-03	S	1.34E-02	S
5.4	3.20E-03	S	4.10E-01	S	6.64E-03	S	1.25E-02	S
5.6	3.20E-03	S	3.94E-01	S	6.41E-03	S	1.17E-02	S
5.8	3.20E-03	S	3.79E-01	S	6.19E-03	S	1.10E-02	S
6	3.20E-03	S	3.74E-01	S	5.67E-03	S	8.96E-03	S
6.2	3.20E-03	S	3.71E-01	W	5.16E-03	S	7.16E-03	S
6.4	3.54E-03	S	3.66E-01	W	3.46E-03	S	5.26E-03	S
6.6	4.04E-03	S	3.60E-01	W	1.99E-03	S	3.75E-03	S
6.8	4.60E-03	S	3.54E-01	W	1.17E-03	S	2.71E-03	S
7	5.21E-03	S	3.49E-01	W	7.90E-04	S	2.13E-03	S
7.2	4.78E-03	S	3.20E-01	W	7.46E-04	S	2.06E-03	S
7.4	4.10E-03	S	2.88E-01	W	7.46E-04	S	2.06E-03	S
7.6	3.54E-03	S	2.59E-01	W	7.46E-04	S	2.06E-03	S
7.8	3.20E-03	S	2.42E-01	W	7.46E-04	S	2.06E-03	S
8	3.20E-03	S	2.42E-01	W	7.46E-04	S	2.06E-03	S

Table C-5-42. Leachate Concentrations for Gypsum Export, Waste ID OAW Med

Sample ID	OAW-[Med] (P,1,1)
Date Exported	9/20/2011, 7:37 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	3.20E-03	S	2.42E-01	W	7.46E-04	S	2.06E-03	S
8.4	3.20E-03	S	2.42E-01	W	7.46E-04	S	2.06E-03	S
8.6	3.20E-03	S	2.61E-01	W	7.46E-04	S	2.06E-03	S
8.8	3.20E-03	S	2.90E-01	W	7.46E-04	S	2.06E-03	S
9	3.20E-03	S	3.22E-01	W	7.46E-04	S	2.06E-03	S
9.2	3.20E-03	S	3.52E-01	W	7.46E-04	S	2.06E-03	S
9.4	3.20E-03	S	3.53E-01	W	7.46E-04	S	2.06E-03	S
9.6	3.20E-03	S	3.54E-01	W	7.46E-04	S	2.06E-03	S
9.8	3.20E-03	S	3.54E-01	W	7.46E-04	S	2.06E-03	S
10	3.20E-03	S	3.55E-01	W	7.46E-04	S	2.06E-03	S
10.2	3.20E-03	S	3.56E-01	W	7.46E-04	S	2.06E-03	S
10.4	3.20E-03	S	3.57E-01	W	7.46E-04	S	2.06E-03	S
10.6	3.20E-03	S	3.58E-01	W	7.46E-04	S	2.06E-03	S
10.8	3.20E-03	S	3.71E-01	W	7.46E-04	S	2.06E-03	S
11	3.20E-03	S	3.91E-01	W	7.46E-04	S	2.06E-03	S
11.2	3.20E-03	S	4.11E-01	W	7.46E-04	S	2.06E-03	S
11.4	3.20E-03	S	4.32E-01	W	7.46E-04	S	2.06E-03	S
11.6	3.20E-03	S	4.54E-01	W	7.46E-04	S	2.06E-03	S
11.8	3.20E-03	S	4.76E-01	W	7.46E-04	S	2.06E-03	S
12	3.20E-03	S	4.99E-01	W	7.46E-04	S	2.06E-03	S
12.2	3.20E-03	S	5.23E-01	W	7.46E-04	S	2.06E-03	S
12.4	3.20E-03	S	5.47E-01	W	7.46E-04	S	2.06E-03	S
12.6	3.20E-03	S	5.73E-01	W	7.46E-04	S	2.06E-03	S
12.8	3.20E-03	S	5.98E-01	W	7.46E-04	S	2.06E-03	S
13	3.20E-03	S	6.25E-01	W	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	8.69E-02		7.54E+00		8.61E-02		1.78E-01	

Table C-5-42. Leachate Concentrations for Gypsum Export, Waste ID OAW Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	1.01E-01	S	1.80E-06	S	4.80E-03	S	3.04E-03	S
3	7.27E-02	S	1.80E-06	S	3.91E-03	S	2.81E-03	S
3.2	5.49E-02	S	1.80E-06	S	3.80E-03	S	2.78E-03	S
3.4	4.23E-02	S	1.80E-06	S	3.80E-03	S	2.78E-03	S
3.6	3.31E-02	S	1.80E-06	S	3.80E-03	S	2.78E-03	S
3.8	2.30E-02	S	1.93E-06	S	3.80E-03	S	2.78E-03	S
4	1.54E-02	S	2.14E-06	S	3.80E-03	S	2.78E-03	S
4.2	1.05E-02	S	2.34E-06	S	3.80E-03	S	2.78E-03	S
4.4	7.32E-03	S	2.56E-06	S	3.80E-03	S	2.78E-03	S
4.6	5.17E-03	S	2.79E-06	S	3.80E-03	S	2.78E-03	S
4.8	4.12E-03	S	3.03E-06	S	3.97E-03	S	2.78E-03	S
5	3.50E-03	S	3.28E-06	S	4.24E-03	S	2.78E-03	S
5.2	2.99E-03	S	3.54E-06	S	4.52E-03	S	2.78E-03	S
5.4	2.58E-03	S	3.80E-06	S	4.80E-03	S	2.78E-03	S
5.6	2.23E-03	S	4.08E-06	S	5.09E-03	S	2.78E-03	S
5.8	1.94E-03	S	4.36E-06	S	5.39E-03	S	2.78E-03	S
6	1.90E-03	S	3.14E-06	S	6.85E-03	S	2.78E-03	S
6.2	1.90E-03	S	2.13E-06	S	8.92E-03	S	2.78E-03	S
6.4	1.90E-03	S	1.80E-06	S	1.02E-02	S	2.78E-03	S
6.6	1.90E-03	S	1.80E-06	S	1.07E-02	S	2.78E-03	S
6.8	1.90E-03	S	1.80E-06	S	1.13E-02	S	2.78E-03	S
7	1.90E-03	S	1.80E-06	S	1.15E-02	S	2.78E-03	S
7.2	1.90E-03	S	1.84E-06	S	1.16E-02	W	2.78E-03	S
7.4	1.90E-03	S	2.07E-06	S	1.20E-02	W	2.78E-03	S
7.6	1.90E-03	S	2.32E-06	S	1.24E-02	W	2.78E-03	S
7.8	1.90E-03	S	2.59E-06	S	1.28E-02	W	2.78E-03	S
8	1.90E-03	S	2.89E-06	S	1.33E-02	W	2.78E-03	S

Table C-5-42. Leachate Concentrations for Gypsum Export, Waste ID OAW Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	1.90E-03	S	3.21E-06	S	1.38E-02	W	2.78E-03	S
8.4	1.90E-03	S	3.56E-06	S	1.44E-02	W	2.78E-03	S
8.6	2.16E-03	S	2.80E-06	S	1.48E-02	W	2.78E-03	S
8.8	2.58E-03	S	2.14E-06	S	1.51E-02	W	2.78E-03	S
9	3.22E-03	S	1.80E-06	S	1.54E-02	W	2.78E-03	S
9.2	4.26E-03	S	1.80E-06	S	1.56E-02	W	2.78E-03	S
9.4	5.04E-03	S	1.80E-06	S	1.58E-02	W	2.78E-03	S
9.6	5.95E-03	S	1.80E-06	S	1.61E-02	W	2.78E-03	S
9.8	6.99E-03	S	1.80E-06	S	1.64E-02	W	2.78E-03	S
10	8.20E-03	S	1.80E-06	S	1.66E-02	W	2.78E-03	S
10.2	9.58E-03	S	1.80E-06	S	1.69E-02	W	2.78E-03	S
10.4	1.12E-02	S	1.80E-06	S	1.71E-02	W	2.78E-03	S
10.6	1.15E-02	S	1.80E-06	S	1.73E-02	W	2.78E-03	S
10.8	1.15E-02	S	1.80E-06	S	1.74E-02	W	2.78E-03	S
11	1.13E-02	S	1.80E-06	S	1.73E-02	W	2.78E-03	S
11.2	1.11E-02	S	1.80E-06	S	1.73E-02	W	2.78E-03	S
11.4	1.09E-02	S	1.80E-06	S	1.73E-02	W	2.78E-03	S
11.6	1.08E-02	S	1.80E-06	S	1.73E-02	W	2.78E-03	S
11.8	1.06E-02	S	1.80E-06	S	1.73E-02	W	2.78E-03	S
12	1.04E-02	S	1.80E-06	S	1.73E-02	W	2.78E-03	S
12.2	1.03E-02	S	1.80E-06	S	1.72E-02	W	2.78E-03	S
12.4	1.01E-02	S	1.80E-06	S	1.72E-02	W	2.78E-03	S
12.6	9.99E-03	S	1.80E-06	S	1.72E-02	W	2.78E-03	S
12.8	9.85E-03	S	1.80E-06	S	1.72E-02	W	2.78E-03	S
13	9.71E-03	S	1.80E-06	S	1.72E-02	W	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	7.27E-01		4.36E-05		1.80E-01		2.88E-02	

Table C-5-42. Leachate Concentrations for Gypsum Export, Waste ID OAW Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	4.97E-02	W	2.53E-03	S	9.19E-02	S
3	4.84E-02	W	2.53E-03	S	6.61E-02	S
3.2	4.81E-02	W	2.53E-03	S	3.70E-02	S
3.4	4.81E-02	W	2.53E-03	S	2.05E-02	S
3.6	4.80E-02	W	2.53E-03	S	1.17E-02	S
3.8	4.75E-02	W	2.53E-03	S	8.31E-03	S
4	4.69E-02	W	2.53E-03	S	6.49E-03	S
4.2	4.63E-02	W	2.53E-03	S	5.13E-03	S
4.4	4.57E-02	W	2.53E-03	S	4.10E-03	S
4.6	4.52E-02	W	2.53E-03	S	3.30E-03	S
4.8	4.42E-02	W	2.53E-03	S	2.97E-03	S
5	4.31E-02	W	2.53E-03	S	2.82E-03	S
5.2	4.21E-02	W	2.53E-03	S	2.68E-03	S
5.4	4.11E-02	W	2.53E-03	S	2.56E-03	S
5.6	4.02E-02	W	2.53E-03	S	2.44E-03	S
5.8	3.93E-02	W	2.53E-03	S	2.34E-03	S
6	3.75E-02	W	2.53E-03	S	2.33E-03	S
6.2	3.57E-02	W	2.53E-03	S	2.35E-03	S
6.4	3.42E-02	W	2.53E-03	S	2.41E-03	S
6.6	3.26E-02	W	2.53E-03	S	2.50E-03	S
6.8	3.11E-02	W	2.53E-03	S	2.58E-03	S
7	3.14E-02	W	2.53E-03	S	2.66E-03	S
7.2	3.21E-02	W	2.53E-03	S	2.58E-03	S
7.4	3.06E-02	W	2.53E-03	S	2.57E-03	S
7.6	2.93E-02	W	2.53E-03	S	2.56E-03	S
7.8	2.85E-02	W	2.53E-03	S	2.62E-03	S
8	2.88E-02	W	2.53E-03	S	2.88E-03	S

Table C-5-42. Leachate Concentrations for Gypsum Export, Waste ID OAW Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	2.91E-02	W	2.53E-03	S	3.15E-03	S
8.4	2.94E-02	W	2.53E-03	S	3.44E-03	S
8.6	2.85E-02	W	2.53E-03	S	3.70E-03	S
8.8	2.75E-02	W	2.53E-03	S	3.99E-03	S
9	2.70E-02	W	2.53E-03	S	4.37E-03	S
9.2	2.75E-02	W	2.53E-03	S	4.94E-03	S
9.4	2.76E-02	W	2.53E-03	S	5.50E-03	S
9.6	2.77E-02	W	2.53E-03	S	6.12E-03	S
9.8	2.78E-02	W	2.53E-03	S	6.79E-03	S
10	2.79E-02	W	2.53E-03	S	7.52E-03	S
10.2	2.80E-02	W	2.53E-03	S	8.31E-03	S
10.4	2.81E-02	W	2.53E-03	S	9.17E-03	S
10.6	2.78E-02	W	2.53E-03	S	9.56E-03	S
10.8	2.79E-02	W	2.53E-03	S	9.71E-03	S
11	2.80E-02	W	2.53E-03	S	9.74E-03	S
11.2	2.81E-02	W	2.53E-03	S	9.77E-03	S
11.4	2.83E-02	W	2.53E-03	S	9.81E-03	S
11.6	2.84E-02	W	2.53E-03	S	9.84E-03	S
11.8	2.85E-02	W	2.53E-03	S	9.87E-03	S
12	2.87E-02	W	2.53E-03	S	9.90E-03	S
12.2	2.88E-02	W	2.53E-03	S	9.93E-03	S
12.4	2.89E-02	W	2.53E-03	S	9.96E-03	S
12.6	2.90E-02	W	2.53E-03	S	9.99E-03	S
12.8	2.92E-02	W	2.53E-03	S	1.00E-02	S
13	2.93E-02	W	2.53E-03	S	1.00E-02	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	4.84E-01		2.62E-02		6.61E-01	

Table C-5-43. Leachate Concentrations for Gypsum Export, Waste ID PAD Med

Sample ID	PAD-[Med] (P,1,1)
Date Exported	9/20/2011, 7:37 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	2.01E-02	S	3.14E-01	W	7.46E-04	W	2.13E-02	S
3	1.35E-02	S	3.14E-01	W	7.46E-04	W	1.66E-02	S
3.2	9.36E-03	S	3.15E-01	W	7.46E-04	W	1.31E-02	S
3.4	7.48E-03	S	3.19E-01	W	7.46E-04	W	1.13E-02	S
3.6	6.06E-03	S	3.24E-01	W	7.46E-04	W	9.86E-03	S
3.8	4.96E-03	S	3.28E-01	W	7.46E-04	W	8.64E-03	S
4	4.10E-03	S	3.32E-01	W	7.46E-04	W	7.63E-03	S
4.2	3.61E-03	S	3.33E-01	W	7.46E-04	W	6.77E-03	S
4.4	3.45E-03	S	3.31E-01	W	7.46E-04	W	6.04E-03	S
4.6	3.30E-03	S	3.29E-01	W	7.46E-04	W	5.41E-03	S
4.8	3.20E-03	S	3.26E-01	W	7.46E-04	W	4.75E-03	S
5	3.20E-03	S	3.20E-01	W	7.46E-04	S	3.92E-03	S
5.2	3.20E-03	S	3.14E-01	W	7.46E-04	S	3.26E-03	S
5.4	3.20E-03	S	3.09E-01	W	7.46E-04	S	2.73E-03	S
5.6	3.20E-03	S	3.04E-01	W	7.46E-04	S	2.30E-03	S
5.8	3.20E-03	S	3.01E-01	W	7.46E-04	S	2.07E-03	S
6	3.20E-03	S	3.06E-01	W	7.46E-04	S	2.06E-03	S
6.2	3.20E-03	S	3.14E-01	W	7.46E-04	S	2.06E-03	S
6.4	3.20E-03	S	3.20E-01	W	7.46E-04	S	2.06E-03	S
6.6	3.20E-03	S	3.16E-01	W	7.46E-04	S	2.06E-03	S
6.8	3.20E-03	S	2.97E-01	W	7.46E-04	S	2.06E-03	S
7	3.20E-03	S	3.01E-01	W	7.46E-04	S	2.06E-03	S
7.2	3.20E-03	S	3.05E-01	W	7.46E-04	S	2.06E-03	S
7.4	3.20E-03	S	3.09E-01	W	7.46E-04	S	2.06E-03	S
7.6	3.20E-03	S	3.17E-01	W	7.46E-04	S	2.06E-03	S
7.8	3.20E-03	S	3.25E-01	W	7.46E-04	S	2.06E-03	S
8	3.20E-03	S	3.33E-01	W	7.46E-04	S	2.06E-03	S

Table C-5-43. Leachate Concentrations for Gypsum Export, Waste ID PAD Med

Sample ID	PAD-[Med] (P,1,1)
Date Exported	9/20/2011, 7:37 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	3.20E-03	S	3.38E-01	W	7.46E-04	S	2.06E-03	S
8.4	3.20E-03	S	3.41E-01	W	7.46E-04	S	2.06E-03	S
8.6	3.20E-03	S	3.44E-01	W	7.46E-04	S	2.06E-03	S
8.8	3.20E-03	S	3.47E-01	W	7.46E-04	S	2.06E-03	S
9	3.20E-03	S	3.50E-01	W	7.46E-04	S	2.06E-03	S
9.2	3.20E-03	S	3.53E-01	W	7.46E-04	S	2.06E-03	S
9.4	3.20E-03	S	3.55E-01	W	7.46E-04	S	2.06E-03	S
9.6	3.20E-03	S	3.58E-01	W	7.46E-04	S	2.06E-03	S
9.8	3.20E-03	S	3.63E-01	W	7.46E-04	S	2.06E-03	S
10	3.20E-03	S	3.81E-01	S	7.46E-04	S	2.06E-03	S
10.2	3.20E-03	S	4.02E-01	S	7.46E-04	S	2.06E-03	S
10.4	3.20E-03	S	4.28E-01	S	7.46E-04	S	2.06E-03	S
10.6	3.20E-03	S	4.80E-01	S	7.46E-04	S	2.06E-03	S
10.8	3.20E-03	S	5.85E-01	S	7.46E-04	S	2.06E-03	S
11	3.20E-03	S	7.15E-01	S	7.46E-04	S	2.06E-03	S
11.2	3.20E-03	S	8.69E-01	S	7.46E-04	S	2.06E-03	S
11.4	3.20E-03	S	1.05E+00	S	7.46E-04	S	2.06E-03	S
11.6	3.20E-03	S	1.27E+00	S	7.46E-04	S	2.06E-03	S
11.8	3.20E-03	S	1.46E+00	S	7.46E-04	S	2.06E-03	S
12	3.20E-03	S	1.46E+00	S	7.46E-04	S	2.06E-03	S
12.2	3.20E-03	S	1.46E+00	S	7.46E-04	S	2.06E-03	S
12.4	3.20E-03	S	1.46E+00	S	7.46E-04	S	2.06E-03	S
12.6	3.20E-03	S	1.46E+00	S	7.46E-04	S	2.06E-03	S
12.8	3.20E-03	S	1.46E+00	S	7.46E-04	S	2.06E-03	S
13	3.20E-03	S	1.46E+00	S	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	1.35E-01		1.54E+01		7.84E-03		1.66E-01	

Table C-5-43. Leachate Concentrations for Gypsum Export, Waste ID PAD Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	4.19E-02	S	6.92E-06	S	3.80E-03	W	4.08E-03	S
3	3.13E-02	S	8.18E-06	S	3.80E-03	W	3.65E-03	S
3.2	2.39E-02	S	9.57E-06	S	3.80E-03	W	3.28E-03	S
3.4	2.01E-02	S	1.03E-05	S	3.80E-03	W	3.15E-03	S
3.6	1.71E-02	S	1.10E-05	S	3.80E-03	W	3.04E-03	S
3.8	1.46E-02	S	1.17E-05	S	3.80E-03	W	2.93E-03	S
4	1.26E-02	S	1.24E-05	S	3.80E-03	W	2.84E-03	S
4.2	1.09E-02	S	1.25E-05	S	3.80E-03	W	2.78E-03	S
4.4	9.24E-03	S	1.16E-05	S	3.80E-03	W	2.78E-03	S
4.6	7.93E-03	S	1.08E-05	S	3.80E-03	W	2.78E-03	S
4.8	6.78E-03	S	1.04E-05	S	3.80E-03	W	2.78E-03	S
5	5.67E-03	S	1.12E-05	S	3.80E-03	W	2.78E-03	S
5.2	4.77E-03	S	1.21E-05	S	3.80E-03	W	2.78E-03	S
5.4	4.05E-03	S	1.29E-05	S	3.80E-03	W	2.78E-03	S
5.6	3.45E-03	S	1.38E-05	S	3.80E-03	W	2.78E-03	S
5.8	2.63E-03	S	1.28E-05	S	3.80E-03	W	2.78E-03	S
6	2.02E-03	S	1.11E-05	S	3.80E-03	W	2.78E-03	S
6.2	2.24E-03	S	8.38E-06	S	3.80E-03	W	2.78E-03	S
6.4	2.97E-03	S	6.62E-06	S	3.80E-03	W	2.78E-03	S
6.6	5.69E-03	S	8.81E-06	S	3.80E-03	W	2.78E-03	S
6.8	3.55E-03	S	1.68E-05	S	3.80E-03	W	2.78E-03	S
7	3.14E-03	S	2.31E-05	S	3.80E-03	W	2.78E-03	S
7.2	2.79E-03	S	3.15E-05	S	3.80E-03	W	2.78E-03	S
7.4	2.62E-03	S	3.98E-05	S	3.80E-03	W	2.78E-03	S
7.6	2.86E-03	S	4.12E-05	S	3.80E-03	W	2.78E-03	S
7.8	3.12E-03	S	4.27E-05	S	3.80E-03	W	2.78E-03	S
8	3.39E-03	S	4.41E-05	S	3.80E-03	W	2.78E-03	S

Table C-5-43. Leachate Concentrations for Gypsum Export, Waste ID PAD Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	3.39E-03	S	4.35E-05	S	3.80E-03	W	2.78E-03	S
8.4	3.13E-03	S	4.10E-05	S	3.80E-03	W	2.78E-03	S
8.6	2.89E-03	S	3.87E-05	S	3.80E-03	W	2.78E-03	S
8.8	2.68E-03	S	3.66E-05	S	3.80E-03	W	2.78E-03	S
9	2.48E-03	S	3.46E-05	S	3.80E-03	W	2.78E-03	S
9.2	2.31E-03	S	3.28E-05	S	3.80E-03	W	2.78E-03	S
9.4	2.14E-03	S	3.11E-05	S	3.80E-03	W	2.78E-03	S
9.6	2.00E-03	S	2.96E-05	S	3.80E-03	W	2.78E-03	S
9.8	1.97E-03	S	2.89E-05	S	3.80E-03	W	2.78E-03	S
10	2.27E-03	S	2.94E-05	S	3.80E-03	W	2.78E-03	S
10.2	2.61E-03	S	2.97E-05	S	3.80E-03	W	2.78E-03	S
10.4	3.00E-03	S	3.02E-05	S	3.85E-03	W	2.78E-03	S
10.6	3.43E-03	S	3.19E-05	S	4.22E-03	W	2.78E-03	S
10.8	3.11E-03	S	3.27E-05	S	4.98E-03	W	2.78E-03	S
11	2.79E-03	S	3.36E-05	S	5.89E-03	S	2.78E-03	S
11.2	2.51E-03	S	3.45E-05	S	6.94E-03	S	2.78E-03	S
11.4	2.26E-03	S	3.53E-05	S	8.16E-03	S	2.78E-03	S
11.6	2.04E-03	S	3.62E-05	S	9.57E-03	S	2.78E-03	S
11.8	1.84E-03	S	3.68E-05	S	1.08E-02	S	2.78E-03	S
12	1.67E-03	S	3.66E-05	S	1.08E-02	S	2.78E-03	S
12.2	1.51E-03	S	3.65E-05	S	1.08E-02	S	2.78E-03	S
12.4	1.37E-03	S	3.63E-05	S	1.08E-02	S	2.78E-03	S
12.6	1.25E-03	S	3.62E-05	S	1.08E-02	S	2.78E-03	S
12.8	1.14E-03	S	3.60E-05	S	1.08E-02	S	2.78E-03	S
13	1.04E-03	S	3.59E-05	S	1.08E-02	S	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	3.13E-01		4.42E-04		1.13E-01		3.65E-02	

Table C-5-43. Leachate Concentrations for Gypsum Export, Waste ID PAD Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	2.43E-01	W	2.53E-03	S	8.97E-03	S
3	2.35E-01	W	2.53E-03	S	5.24E-03	S
3.2	2.28E-01	W	2.53E-03	S	3.16E-03	S
3.4	2.25E-01	W	2.53E-03	S	2.61E-03	S
3.6	2.22E-01	W	2.53E-03	S	2.18E-03	S
3.8	2.19E-01	W	2.53E-03	S	1.84E-03	S
4	2.17E-01	W	2.53E-03	S	1.57E-03	S
4.2	2.16E-01	W	2.53E-03	S	1.43E-03	S
4.4	2.16E-01	W	2.53E-03	S	1.43E-03	S
4.6	2.17E-01	W	2.53E-03	S	1.43E-03	S
4.8	2.18E-01	W	2.53E-03	S	1.43E-03	S
5	2.20E-01	W	2.53E-03	S	1.43E-03	S
5.2	2.22E-01	W	2.53E-03	S	1.43E-03	S
5.4	2.24E-01	W	2.53E-03	S	1.43E-03	S
5.6	2.26E-01	W	2.53E-03	S	1.43E-03	S
5.8	2.23E-01	W	2.53E-03	S	1.43E-03	S
6	2.13E-01	W	2.53E-03	S	1.43E-03	S
6.2	2.08E-01	W	2.53E-03	S	1.43E-03	S
6.4	2.05E-01	W	2.53E-03	S	1.43E-03	S
6.6	1.99E-01	W	2.53E-03	S	1.43E-03	S
6.8	1.95E-01	W	2.53E-03	S	1.53E-03	S
7	1.95E-01	W	2.53E-03	S	2.13E-03	S
7.2	1.95E-01	W	2.53E-03	S	2.94E-03	S
7.4	1.95E-01	W	2.53E-03	S	3.78E-03	S
7.6	1.94E-01	W	2.53E-03	S	3.99E-03	S
7.8	1.94E-01	W	2.53E-03	S	4.21E-03	S
8	1.94E-01	W	2.53E-03	S	4.43E-03	S

Table C-5-43. Leachate Concentrations for Gypsum Export, Waste ID PAD Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	1.94E-01	W	2.53E-03	S	4.43E-03	S
8.4	1.94E-01	W	2.53E-03	S	4.19E-03	S
8.6	1.95E-01	W	2.53E-03	S	3.98E-03	S
8.8	1.96E-01	W	2.53E-03	S	3.78E-03	S
9	1.96E-01	W	2.53E-03	S	3.59E-03	S
9.2	1.97E-01	W	2.53E-03	S	3.42E-03	S
9.4	1.97E-01	W	2.53E-03	S	3.26E-03	S
9.6	1.98E-01	W	2.53E-03	S	3.11E-03	S
9.8	1.98E-01	W	2.53E-03	S	3.01E-03	S
10	1.99E-01	W	2.53E-03	S	3.21E-03	S
10.2	2.00E-01	W	2.53E-03	S	3.46E-03	S
10.4	2.01E-01	W	2.53E-03	S	3.71E-03	S
10.6	2.03E-01	W	2.53E-03	S	3.86E-03	S
10.8	2.07E-01	W	2.53E-03	S	3.98E-03	S
11	2.11E-01	W	2.53E-03	S	4.10E-03	S
11.2	2.15E-01	W	2.53E-03	S	4.23E-03	S
11.4	2.18E-01	W	2.53E-03	S	4.35E-03	S
11.6	2.22E-01	W	2.53E-03	S	4.48E-03	S
11.8	2.26E-01	W	2.53E-03	S	4.61E-03	S
12	2.30E-01	W	2.53E-03	S	4.73E-03	S
12.2	2.34E-01	W	2.53E-03	S	4.87E-03	S
12.4	2.37E-01	W	2.53E-03	S	5.00E-03	S
12.6	2.41E-01	W	2.53E-03	S	5.13E-03	S
12.8	2.45E-01	W	2.53E-03	S	5.26E-03	S
13	2.49E-01	W	2.53E-03	S	5.40E-03	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	2.57E+00		2.66E-02		5.53E-02	

Table C-5-44. Leachate Concentrations for Gypsum Export, Waste ID QAU Med

Sample ID	QAU-[Med] (P,1,1)
Date Exported	9/20/2011, 7:37 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	1.02E-01	S	4.10E+00	W	5.69E-02	W	5.92E-02	S
3	9.62E-02	S	4.02E+00	W	5.71E-02	W	5.70E-02	S
3.2	8.86E-02	S	4.04E+00	W	5.66E-02	W	5.49E-02	S
3.4	8.21E-02	S	3.94E+00	W	5.63E-02	W	5.33E-02	S
3.6	7.65E-02	S	3.96E+00	W	5.62E-02	W	5.24E-02	S
3.8	7.15E-02	S	3.97E+00	W	5.61E-02	W	5.16E-02	S
4	6.76E-02	S	3.94E+00	W	5.60E-02	W	5.09E-02	S
4.2	6.45E-02	S	3.89E+00	W	5.59E-02	W	5.01E-02	S
4.4	6.16E-02	S	3.84E+00	W	5.57E-02	W	4.94E-02	S
4.6	5.72E-02	S	3.80E+00	W	5.55E-02	W	4.86E-02	S
4.8	5.06E-02	S	3.79E+00	W	5.52E-02	W	4.75E-02	S
5	4.49E-02	S	3.78E+00	W	5.49E-02	S	4.65E-02	S
5.2	4.01E-02	S	3.77E+00	W	5.47E-02	S	4.56E-02	S
5.4	2.94E-02	S	3.77E+00	W	5.39E-02	S	4.47E-02	S
5.6	1.69E-02	S	3.78E+00	W	5.25E-02	S	4.39E-02	S
5.8	9.94E-03	S	3.79E+00	W	5.12E-02	S	4.31E-02	S
6	7.76E-03	S	3.75E+00	W	3.51E-02	S	3.24E-02	S
6.2	6.29E-03	S	3.71E+00	W	2.30E-02	S	2.36E-02	S
6.4	5.13E-03	S	3.67E+00	W	1.53E-02	S	1.74E-02	S
6.6	4.22E-03	S	3.63E+00	W	1.03E-02	S	1.29E-02	S
6.8	3.48E-03	S	3.60E+00	W	6.99E-03	S	9.69E-03	S
7	3.20E-03	S	3.58E+00	W	5.21E-03	S	7.59E-03	S
7.2	3.20E-03	S	3.56E+00	W	3.87E-03	S	5.96E-03	S
7.4	3.20E-03	S	3.54E+00	W	2.90E-03	S	4.71E-03	S
7.6	3.20E-03	S	3.53E+00	W	2.19E-03	S	3.74E-03	S
7.8	3.20E-03	S	3.51E+00	W	1.66E-03	S	2.99E-03	S
8	3.20E-03	S	3.49E+00	W	1.27E-03	S	2.41E-03	S

Table C-5-44. Leachate Concentrations for Gypsum Export, Waste ID QAU Med

Sample ID	QAU-[Med] (P,1,1)
Date Exported	9/20/2011, 7:37 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	3.20E-03	S	3.44E+00	W	1.05E-03	S	2.06E-03	S
8.4	3.20E-03	S	3.33E+00	W	9.89E-04	S	2.06E-03	S
8.6	3.20E-03	S	3.22E+00	W	9.29E-04	S	2.06E-03	S
8.8	3.20E-03	S	3.11E+00	W	8.75E-04	S	2.06E-03	S
9	3.20E-03	S	3.02E+00	W	8.25E-04	S	2.06E-03	S
9.2	3.20E-03	S	2.92E+00	W	7.79E-04	S	2.06E-03	S
9.4	3.20E-03	S	2.88E+00	W	7.46E-04	S	2.06E-03	S
9.6	3.20E-03	S	2.92E+00	W	7.46E-04	S	2.06E-03	S
9.8	3.20E-03	S	2.96E+00	W	7.46E-04	S	2.06E-03	S
10	3.20E-03	S	3.00E+00	W	7.46E-04	S	2.06E-03	S
10.2	3.20E-03	S	3.04E+00	W	7.46E-04	S	2.06E-03	S
10.4	3.20E-03	S	3.07E+00	W	7.46E-04	S	2.06E-03	S
10.6	3.30E-03	S	3.16E+00	W	7.46E-04	S	2.06E-03	S
10.8	3.72E-03	S	3.32E+00	W	7.46E-04	S	2.06E-03	S
11	4.22E-03	S	3.50E+00	W	7.46E-04	S	2.06E-03	S
11.2	4.78E-03	S	3.68E+00	W	7.46E-04	S	2.06E-03	S
11.4	5.39E-03	S	3.86E+00	W	7.46E-04	S	2.06E-03	S
11.6	6.07E-03	S	4.06E+00	W	7.46E-04	S	2.06E-03	S
11.8	6.83E-03	S	4.25E+00	W	7.46E-04	S	2.06E-03	S
12	7.66E-03	S	4.42E+00	W	7.46E-04	S	2.06E-03	S
12.2	8.58E-03	S	4.53E+00	W	7.46E-04	S	2.06E-03	S
12.4	9.59E-03	S	4.63E+00	W	7.46E-04	S	2.06E-03	S
12.6	1.07E-02	S	4.74E+00	W	7.46E-04	S	2.06E-03	S
12.8	1.19E-02	S	4.77E+00	W	7.46E-04	S	2.06E-03	S
13	1.33E-02	S	4.77E+00	W	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	9.62E-01		5.13E+01		5.71E-01		5.70E-01	

Table C-5-44. Leachate Concentrations for Gypsum Export, Waste ID QAU Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	6.47E-01	S	6.99E-05	S	1.95E-02	W	1.17E-02	S
3	6.14E-01	S	6.66E-05	S	1.79E-02	W	1.13E-02	S
3.2	5.70E-01	S	4.69E-05	S	1.62E-02	W	1.11E-02	S
3.4	5.10E-01	S	3.66E-05	S	1.57E-02	W	1.12E-02	S
3.6	4.61E-01	S	2.81E-05	S	1.49E-02	W	1.09E-02	S
3.8	4.18E-01	S	2.19E-05	S	1.43E-02	W	1.07E-02	S
4	3.70E-01	S	3.36E-05	S	1.42E-02	W	1.05E-02	S
4.2	3.25E-01	S	6.66E-05	S	1.43E-02	W	1.03E-02	S
4.4	2.87E-01	S	1.28E-04	S	1.43E-02	W	1.02E-02	S
4.6	2.26E-01	S	2.26E-04	S	1.45E-02	W	9.78E-03	S
4.8	1.45E-01	S	3.55E-04	S	1.47E-02	W	8.97E-03	S
5	9.51E-02	S	5.47E-04	S	1.49E-02	W	8.26E-03	S
5.2	6.33E-02	S	8.27E-04	S	1.51E-02	W	7.62E-03	S
5.4	3.77E-02	S	9.23E-04	S	1.53E-02	W	7.07E-03	S
5.6	2.01E-02	S	6.88E-04	S	1.55E-02	W	6.62E-03	S
5.8	1.10E-02	S	5.18E-04	S	1.58E-02	W	6.20E-03	S
6	8.90E-03	S	2.04E-04	S	1.55E-02	W	5.35E-03	S
6.2	7.44E-03	S	7.67E-05	S	1.52E-02	W	4.58E-03	S
6.4	6.25E-03	S	2.97E-05	S	1.49E-02	W	3.93E-03	S
6.6	5.28E-03	S	1.19E-05	S	1.47E-02	W	3.40E-03	S
6.8	4.48E-03	S	4.87E-06	S	1.44E-02	W	2.94E-03	S
7	4.24E-03	S	3.65E-06	S	1.41E-02	W	2.78E-03	S
7.2	4.28E-03	S	3.89E-06	S	1.39E-02	W	2.78E-03	S
7.4	4.31E-03	S	4.14E-06	S	1.37E-02	W	2.78E-03	S
7.6	4.34E-03	S	4.39E-06	S	1.35E-02	W	2.78E-03	S
7.8	4.37E-03	S	4.65E-06	S	1.34E-02	W	2.78E-03	S
8	4.40E-03	S	4.92E-06	S	1.32E-02	W	2.78E-03	S

Table C-5-44. Leachate Concentrations for Gypsum Export, Waste ID QAU Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	4.69E-03	S	4.72E-06	S	1.32E-02	W	2.83E-03	S
8.4	5.65E-03	S	3.93E-06	S	1.39E-02	W	2.95E-03	S
8.6	6.78E-03	S	3.29E-06	S	1.46E-02	W	3.07E-03	S
8.8	8.09E-03	S	2.76E-06	S	1.53E-02	W	3.20E-03	S
9	9.62E-03	S	2.33E-06	S	1.60E-02	W	3.32E-03	S
9.2	1.14E-02	S	1.97E-06	S	1.67E-02	W	3.45E-03	S
9.4	1.27E-02	S	1.94E-06	S	1.73E-02	W	3.66E-03	S
9.6	1.27E-02	S	2.29E-06	S	1.77E-02	W	4.12E-03	S
9.8	1.27E-02	S	2.70E-06	S	1.80E-02	W	4.63E-03	S
10	1.26E-02	S	3.16E-06	S	1.84E-02	W	5.18E-03	S
10.2	1.26E-02	S	3.70E-06	S	1.87E-02	W	5.80E-03	S
10.4	1.26E-02	S	4.31E-06	S	1.91E-02	W	6.47E-03	S
10.6	1.27E-02	S	5.01E-06	S	1.96E-02	W	6.65E-03	S
10.8	1.20E-02	S	5.24E-06	S	2.02E-02	W	5.82E-03	S
11	1.13E-02	S	5.41E-06	S	2.08E-02	W	5.06E-03	S
11.2	1.06E-02	S	5.58E-06	S	2.14E-02	W	4.40E-03	S
11.4	9.97E-03	S	5.76E-06	S	2.21E-02	W	3.84E-03	S
11.6	9.39E-03	S	5.94E-06	S	2.27E-02	W	3.36E-03	S
11.8	8.85E-03	S	6.12E-06	S	2.33E-02	W	2.94E-03	S
12	8.36E-03	S	6.30E-06	S	2.40E-02	W	2.59E-03	S
12.2	7.90E-03	S	6.49E-06	S	2.47E-02	W	2.28E-03	S
12.4	7.47E-03	S	6.68E-06	S	2.53E-02	W	2.01E-03	S
12.6	7.07E-03	S	6.87E-06	S	2.60E-02	W	1.78E-03	S
12.8	6.70E-03	S	7.06E-06	S	2.67E-02	W	1.57E-03	S
13	6.35E-03	S	7.25E-06	S	2.74E-02	W	1.40E-03	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	6.14E+00		9.23E-03		2.87E-01		1.13E-01	

Table C-5-44. Leachate Concentrations for Gypsum Export, Waste ID QAU Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	4.06E+00	S	2.53E-03	S	2.10E+00	S
3	3.99E+00	S	2.53E-03	S	2.06E+00	S
3.2	3.85E+00	S	2.53E-03	S	1.98E+00	S
3.4	3.71E+00	S	2.53E-03	S	1.81E+00	S
3.6	3.59E+00	S	2.53E-03	S	1.66E+00	S
3.8	3.49E+00	S	2.53E-03	S	1.53E+00	S
4	3.38E+00	S	2.53E-03	S	1.39E+00	S
4.2	3.26E+00	S	2.53E-03	S	1.25E+00	S
4.4	3.16E+00	S	2.53E-03	S	1.13E+00	S
4.6	3.04E+00	S	2.53E-03	S	1.02E+00	S
4.8	2.89E+00	S	2.53E-03	S	9.11E-01	S
5	2.75E+00	S	2.53E-03	S	8.19E-01	S
5.2	2.62E+00	S	2.53E-03	S	7.40E-01	S
5.4	2.35E+00	S	2.53E-03	S	6.76E-01	S
5.6	1.96E+00	S	2.53E-03	S	6.26E-01	S
5.8	1.64E+00	S	2.53E-03	S	5.82E-01	S
6	1.21E+00	S	2.53E-03	S	4.13E-01	S
6.2	8.83E-01	S	2.53E-03	S	2.83E-01	S
6.4	6.50E-01	S	2.53E-03	S	1.96E-01	S
6.6	4.84E-01	S	2.53E-03	S	1.37E-01	S
6.8	3.63E-01	S	2.53E-03	S	9.71E-02	S
7	3.23E-01	S	2.53E-03	S	8.45E-02	S
7.2	3.18E-01	S	2.53E-03	S	8.43E-02	S
7.4	3.13E-01	S	2.53E-03	S	8.41E-02	S
7.6	3.08E-01	S	2.53E-03	S	8.39E-02	S
7.8	3.04E-01	S	2.53E-03	S	8.37E-02	S
8	3.00E-01	S	2.53E-03	S	8.35E-02	S

Table C-5-44. Leachate Concentrations for Gypsum Export, Waste ID QAU Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	3.00E-01	S	2.53E-03	S	8.54E-02	S
8.4	3.14E-01	S	2.53E-03	S	9.28E-02	S
8.6	3.28E-01	S	2.53E-03	S	1.01E-01	S
8.8	3.42E-01	S	2.53E-03	S	1.09E-01	S
9	3.56E-01	S	2.53E-03	S	1.18E-01	S
9.2	3.70E-01	S	2.53E-03	S	1.27E-01	S
9.4	3.98E-01	S	2.53E-03	S	1.38E-01	S
9.6	4.52E-01	S	2.53E-03	S	1.54E-01	S
9.8	5.12E-01	S	2.53E-03	S	1.72E-01	S
10	5.79E-01	S	2.53E-03	S	1.91E-01	S
10.2	6.53E-01	S	2.53E-03	S	2.12E-01	S
10.4	7.34E-01	S	2.53E-03	S	2.35E-01	S
10.6	8.08E-01	S	2.53E-03	S	2.37E-01	S
10.8	8.59E-01	S	2.53E-03	S	1.98E-01	S
11	9.12E-01	S	2.53E-03	S	1.64E-01	S
11.2	9.67E-01	S	2.53E-03	S	1.36E-01	S
11.4	1.02E+00	S	2.53E-03	S	1.13E-01	S
11.6	1.08E+00	S	2.53E-03	S	9.48E-02	S
11.8	1.14E+00	S	2.53E-03	S	7.95E-02	S
12	1.21E+00	S	2.53E-03	S	6.69E-02	S
12.2	1.27E+00	S	2.53E-03	S	5.64E-02	S
12.4	1.34E+00	S	2.53E-03	S	4.77E-02	S
12.6	1.41E+00	S	2.53E-03	S	4.05E-02	S
12.8	1.49E+00	S	2.53E-03	S	3.44E-02	S
13	1.56E+00	S	2.53E-03	S	2.94E-02	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	3.99E+01		2.72E-02		2.06E+01	

Table C-5-45. Leachate Concentrations for Gypsum Export, Waste ID RAU Med

Sample ID	RAU-[Med] (P,1,1)
Date Exported	9/20/2011, 7:37 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	3.20E-03	S	9.03E-02	S	2.73E-03	W	6.18E-02	S
3	3.20E-03	S	8.84E-02	S	2.70E-03	W	6.02E-02	S
3.2	3.20E-03	S	8.67E-02	S	2.68E-03	W	5.87E-02	S
3.4	3.20E-03	S	8.51E-02	S	2.66E-03	W	5.74E-02	S
3.6	3.20E-03	S	8.36E-02	S	2.64E-03	W	5.61E-02	S
3.8	3.20E-03	S	8.22E-02	S	2.62E-03	W	5.50E-02	S
4	3.20E-03	S	8.11E-02	S	2.60E-03	W	5.04E-02	S
4.2	3.20E-03	S	8.00E-02	S	2.57E-03	W	4.54E-02	S
4.4	3.20E-03	S	7.91E-02	S	2.54E-03	W	4.10E-02	S
4.6	3.20E-03	S	7.81E-02	S	2.52E-03	W	3.73E-02	S
4.8	3.20E-03	S	7.73E-02	S	2.50E-03	W	3.40E-02	S
5	3.20E-03	S	7.65E-02	S	2.48E-03	S	3.11E-02	S
5.2	3.20E-03	S	7.57E-02	S	2.45E-03	S	2.86E-02	S
5.4	3.20E-03	S	7.49E-02	S	2.43E-03	S	2.63E-02	S
5.6	3.20E-03	S	7.37E-02	S	2.34E-03	S	2.22E-02	S
5.8	3.20E-03	S	7.22E-02	S	2.22E-03	S	1.74E-02	S
6	3.20E-03	S	7.07E-02	S	2.11E-03	S	1.38E-02	S
6.2	3.20E-03	S	6.92E-02	S	1.94E-03	S	1.07E-02	S
6.4	3.20E-03	S	6.75E-02	S	1.68E-03	S	8.08E-03	S
6.6	3.20E-03	S	6.57E-02	S	1.42E-03	S	5.84E-03	S
6.8	3.20E-03	S	6.14E-02	S	9.09E-04	S	2.82E-03	S
7	3.20E-03	S	7.00E-02	S	7.46E-04	S	2.06E-03	S
7.2	3.20E-03	S	9.68E-02	W	7.46E-04	S	2.06E-03	S
7.4	3.20E-03	S	1.33E-01	W	7.46E-04	S	2.06E-03	S
7.6	3.20E-03	S	1.80E-01	W	7.46E-04	S	2.06E-03	S
7.8	3.20E-03	S	2.03E-01	W	7.46E-04	S	2.06E-03	S
8	3.20E-03	S	2.28E-01	W	7.46E-04	S	2.06E-03	S

Table C-5-45. Leachate Concentrations for Gypsum Export, Waste ID RAU Med

Sample ID	RAU-[Med] (P,1,1)
Date Exported	9/20/2011, 7:37 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	3.20E-03	S	2.56E-01	W	7.46E-04	S	2.06E-03	S
8.4	3.20E-03	S	2.75E-01	W	7.46E-04	S	2.06E-03	S
8.6	3.20E-03	S	2.79E-01	W	7.46E-04	S	2.06E-03	S
8.8	3.20E-03	S	2.84E-01	W	7.46E-04	S	2.06E-03	S
9	3.20E-03	S	2.88E-01	W	7.46E-04	S	2.06E-03	S
9.2	3.20E-03	S	2.92E-01	W	7.46E-04	S	2.06E-03	S
9.4	3.20E-03	S	2.97E-01	W	7.46E-04	S	2.06E-03	S
9.6	3.20E-03	S	3.11E-01	W	7.46E-04	S	2.06E-03	S
9.8	3.20E-03	S	3.26E-01	W	7.46E-04	S	2.06E-03	S
10	3.20E-03	S	3.42E-01	S	7.46E-04	S	2.06E-03	S
10.2	3.20E-03	S	3.59E-01	S	7.46E-04	S	2.06E-03	S
10.4	3.20E-03	S	3.81E-01	S	7.46E-04	S	2.06E-03	S
10.6	3.20E-03	S	4.27E-01	S	7.46E-04	S	2.06E-03	S
10.8	3.20E-03	S	4.80E-01	S	7.46E-04	S	2.06E-03	S
11	3.20E-03	S	5.73E-01	S	7.46E-04	S	2.06E-03	S
11.2	3.20E-03	S	7.38E-01	S	7.46E-04	S	2.06E-03	S
11.4	3.20E-03	S	9.52E-01	S	7.46E-04	S	2.06E-03	S
11.6	3.20E-03	S	1.22E+00	S	7.46E-04	S	2.06E-03	S
11.8	3.20E-03	S	1.56E+00	S	7.46E-04	S	2.06E-03	S
12	3.20E-03	S	1.92E+00	S	7.46E-04	S	2.06E-03	S
12.2	3.20E-03	S	1.96E+00	S	7.46E-04	S	2.06E-03	S
12.4	3.20E-03	S	1.96E+00	S	7.46E-04	S	2.06E-03	S
12.6	3.20E-03	S	1.96E+00	S	7.46E-04	S	2.06E-03	S
12.8	3.20E-03	S	1.96E+00	S	7.46E-04	S	2.06E-03	S
13	3.20E-03	S	1.96E+00	S	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	2.50E-02		1.53E+01		1.94E-02		4.32E-01	

Table C-5-45. Leachate Concentrations for Gypsum Export, Waste ID RAU Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	4.33E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
3	3.83E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
3.2	3.41E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
3.4	3.06E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
3.6	2.76E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
3.8	2.51E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
4	2.34E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
4.2	2.20E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
4.4	2.07E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
4.6	1.96E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
4.8	1.85E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
5	1.76E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
5.2	1.67E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
5.4	1.59E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
5.6	1.46E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
5.8	1.36E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
6	1.26E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
6.2	1.21E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
6.4	1.21E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
6.6	1.23E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
6.8	1.32E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
7	1.44E-02	S	3.00E-06	S	4.10E-03	S	2.78E-03	S
7.2	1.51E-02	S	3.00E-06	S	4.82E-03	W	2.78E-03	S
7.4	1.59E-02	S	3.00E-06	S	5.65E-03	W	2.78E-03	S
7.6	1.66E-02	S	2.32E-06	S	6.59E-03	W	2.78E-03	S
7.8	1.60E-02	S	3.00E-06	S	7.03E-03	W	2.78E-03	S
8	1.55E-02	S	3.00E-06	S	7.49E-03	W	2.78E-03	S

Table C-5-45. Leachate Concentrations for Gypsum Export, Waste ID RAU Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	1.50E-02	S	3.00E-06	S	7.96E-03	W	2.78E-03	S
8.4	1.45E-02	S	3.00E-06	S	8.32E-03	W	2.78E-03	S
8.6	1.41E-02	S	3.00E-06	S	8.48E-03	W	2.78E-03	S
8.8	1.37E-02	S	3.00E-06	S	8.64E-03	W	2.78E-03	S
9	1.33E-02	S	3.00E-06	S	8.79E-03	W	2.78E-03	S
9.2	1.30E-02	S	3.00E-06	S	8.95E-03	W	2.78E-03	S
9.4	1.26E-02	S	3.00E-06	S	9.12E-03	W	2.78E-03	S
9.6	1.18E-02	S	3.00E-06	S	9.05E-03	W	2.78E-03	S
9.8	1.10E-02	S	3.00E-06	S	8.91E-03	W	2.78E-03	S
10	1.02E-02	S	3.00E-06	S	8.77E-03	W	2.78E-03	S
10.2	9.55E-03	S	3.00E-06	S	8.63E-03	W	2.78E-03	S
10.4	9.25E-03	S	3.00E-06	S	8.77E-03	W	2.78E-03	S
10.6	9.44E-03	S	3.00E-06	S	9.36E-03	W	2.78E-03	S
10.8	9.68E-03	S	3.00E-06	S	1.00E-02	W	2.78E-03	S
11	1.01E-02	S	3.00E-06	S	1.12E-02	S	2.78E-03	S
11.2	1.07E-02	S	3.00E-06	S	1.30E-02	S	2.78E-03	S
11.4	1.14E-02	S	3.00E-06	S	1.52E-02	S	2.78E-03	S
11.6	1.20E-02	S	3.00E-06	S	1.77E-02	S	2.78E-03	S
11.8	1.27E-02	S	3.00E-06	S	2.06E-02	S	2.78E-03	S
12	1.34E-02	S	3.00E-06	S	2.33E-02	S	2.78E-03	S
12.2	1.42E-02	S	3.00E-06	S	2.37E-02	S	2.78E-03	S
12.4	1.49E-02	S	3.00E-06	S	2.37E-02	S	2.78E-03	S
12.6	1.58E-02	S	3.00E-06	S	2.37E-02	S	2.78E-03	S
12.8	1.66E-02	S	3.00E-06	S	2.37E-02	S	2.78E-03	S
13	1.74E-02	S	3.00E-06	S	2.37E-02	S	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	2.75E-01		2.35E-05		1.85E-01		2.18E-02	

Table C-5-45. Leachate Concentrations for Gypsum Export, Waste ID RAU Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	9.69E-02	W	2.53E-03	S	1.80E-02	S
3	9.55E-02	W	2.53E-03	S	1.36E-02	S
3.2	9.42E-02	W	2.53E-03	S	1.04E-02	S
3.4	9.30E-02	W	2.53E-03	S	8.11E-03	S
3.6	9.19E-02	W	2.53E-03	S	6.41E-03	S
3.8	9.09E-02	W	2.53E-03	S	5.13E-03	S
4	8.99E-02	W	2.53E-03	S	4.93E-03	S
4.2	8.90E-02	W	2.53E-03	S	5.07E-03	S
4.4	8.80E-02	W	2.53E-03	S	5.21E-03	S
4.6	8.72E-02	W	2.53E-03	S	5.35E-03	S
4.8	8.64E-02	W	2.53E-03	S	5.48E-03	S
5	8.56E-02	W	2.53E-03	S	5.61E-03	S
5.2	8.48E-02	W	2.53E-03	S	5.74E-03	S
5.4	8.41E-02	W	2.53E-03	S	5.84E-03	S
5.6	8.29E-02	W	2.53E-03	S	5.54E-03	S
5.8	8.21E-02	W	2.53E-03	S	5.22E-03	S
6	8.13E-02	W	2.53E-03	S	4.93E-03	S
6.2	8.03E-02	W	2.53E-03	S	4.78E-03	S
6.4	7.90E-02	W	2.53E-03	S	4.80E-03	S
6.6	7.75E-02	W	2.53E-03	S	4.81E-03	S
6.8	7.35E-02	W	2.53E-03	S	4.74E-03	S
7	7.53E-02	W	2.53E-03	S	5.16E-03	S
7.2	8.33E-02	W	2.53E-03	S	6.06E-03	S
7.4	9.19E-02	W	2.53E-03	S	7.08E-03	S
7.6	1.01E-01	W	2.53E-03	S	8.24E-03	S
7.8	1.05E-01	W	2.53E-03	S	8.70E-03	S
8	1.08E-01	W	2.53E-03	S	9.17E-03	S

Table C-5-45. Leachate Concentrations for Gypsum Export, Waste ID RAU Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	1.12E-01	W	2.53E-03	S	9.65E-03	S
8.4	1.14E-01	W	2.53E-03	S	1.01E-02	S
8.6	1.14E-01	W	2.53E-03	S	1.04E-02	S
8.8	1.15E-01	W	2.53E-03	S	1.07E-02	S
9	1.15E-01	W	2.53E-03	S	1.11E-02	S
9.2	1.16E-01	W	2.53E-03	S	1.14E-02	S
9.4	1.17E-01	W	2.53E-03	S	1.18E-02	S
9.6	1.17E-01	W	2.53E-03	S	1.18E-02	S
9.8	1.18E-01	W	2.53E-03	S	1.17E-02	S
10	1.18E-01	W	2.53E-03	S	1.16E-02	S
10.2	1.19E-01	W	2.53E-03	S	1.15E-02	S
10.4	1.21E-01	W	2.53E-03	S	1.16E-02	S
10.6	1.25E-01	W	2.53E-03	S	1.21E-02	S
10.8	1.29E-01	W	2.53E-03	S	1.26E-02	S
11	1.32E-01	W	2.53E-03	S	1.27E-02	S
11.2	1.27E-01	W	2.53E-03	S	1.15E-02	S
11.4	1.20E-01	W	2.53E-03	S	1.02E-02	S
11.6	1.15E-01	W	2.53E-03	S	9.12E-03	S
11.8	1.09E-01	W	2.53E-03	S	8.15E-03	S
12	1.04E-01	W	2.53E-03	S	7.30E-03	S
12.2	9.91E-02	W	2.53E-03	S	6.55E-03	S
12.4	9.46E-02	W	2.53E-03	S	5.89E-03	S
12.6	9.03E-02	W	2.53E-03	S	5.30E-03	S
12.8	8.63E-02	W	2.53E-03	S	4.78E-03	S
13	8.26E-02	W	2.53E-03	S	4.32E-03	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	9.62E-01		1.98E-02		9.74E-02	

Table C-5-46. Leachate Concentrations for Gypsum Export, Waste ID SAU Med

Sample ID	SAU-[Med] (P,1,1)
Date Exported	9/20/2011, 7:37 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	1.85E-01	S	2.12E+01	W	2.52E-02	S	4.82E-02	S
3	1.50E-01	S	2.12E+01	W	2.48E-02	S	4.61E-02	S
3.2	1.23E-01	S	2.12E+01	W	2.46E-02	S	4.44E-02	S
3.4	1.02E-01	S	2.11E+01	W	2.44E-02	S	4.29E-02	S
3.6	8.57E-02	S	2.10E+01	W	2.42E-02	S	4.16E-02	S
3.8	7.26E-02	S	2.10E+01	W	2.40E-02	S	4.03E-02	S
4	6.21E-02	S	2.09E+01	W	2.39E-02	S	3.92E-02	S
4.2	5.57E-02	S	2.09E+01	W	2.37E-02	S	3.83E-02	S
4.4	5.08E-02	S	2.10E+01	W	2.35E-02	S	3.77E-02	S
4.6	4.67E-02	S	2.10E+01	W	2.32E-02	S	3.71E-02	S
4.8	4.31E-02	S	2.11E+01	W	2.29E-02	S	3.66E-02	S
5	3.99E-02	S	2.12E+01	W	2.26E-02	S	3.61E-02	S
5.2	3.71E-02	S	2.13E+01	W	2.23E-02	S	3.56E-02	S
5.4	3.45E-02	S	2.13E+01	W	2.21E-02	S	3.51E-02	S
5.6	2.74E-02	S	2.15E+01	W	2.13E-02	S	3.41E-02	S
5.8	2.16E-02	S	2.16E+01	W	2.04E-02	S	3.30E-02	S
6	1.84E-02	S	2.17E+01	W	1.87E-02	S	3.11E-02	S
6.2	1.67E-02	S	2.17E+01	W	1.64E-02	S	2.68E-02	S
6.4	1.53E-02	S	2.17E+01	W	1.29E-02	S	2.22E-02	S
6.6	1.43E-02	S	2.17E+01	W	9.85E-03	S	1.86E-02	S
6.8	1.34E-02	S	2.18E+01	W	7.56E-03	S	1.56E-02	S
7	1.25E-02	S	2.18E+01	W	5.84E-03	S	1.32E-02	S
7.2	1.24E-02	S	2.17E+01	W	4.83E-03	S	1.14E-02	S
7.4	1.31E-02	S	2.16E+01	W	4.20E-03	S	1.02E-02	S
7.6	1.40E-02	S	2.15E+01	W	3.70E-03	S	9.16E-03	S
7.8	1.49E-02	S	2.14E+01	W	3.27E-03	S	8.25E-03	S
8	1.57E-02	S	2.13E+01	W	2.85E-03	S	7.30E-03	S

Table C-5-46. Leachate Concentrations for Gypsum Export, Waste ID SAU Med

Sample ID	SAU-[Med] (P,1,1)
Date Exported	9/20/2011, 7:37 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	1.56E-02	S	2.10E+01	W	2.15E-03	S	5.59E-03	S
8.4	1.54E-02	S	2.08E+01	W	1.63E-03	S	4.30E-03	S
8.6	1.53E-02	S	2.06E+01	W	1.24E-03	S	3.33E-03	S
8.8	1.51E-02	S	2.05E+01	W	9.54E-04	S	2.60E-03	S
9	1.46E-02	S	2.02E+01	W	7.56E-04	S	2.09E-03	S
9.2	1.20E-02	S	1.99E+01	W	7.46E-04	S	2.06E-03	S
9.4	9.72E-03	S	1.96E+01	W	7.46E-04	S	2.06E-03	S
9.6	9.29E-03	S	1.97E+01	W	7.46E-04	S	2.06E-03	S
9.8	8.88E-03	S	1.97E+01	W	7.46E-04	S	2.06E-03	S
10	8.50E-03	S	1.97E+01	W	7.46E-04	S	2.06E-03	S
10.2	8.67E-03	S	1.97E+01	W	7.46E-04	S	2.06E-03	S
10.4	9.57E-03	S	1.97E+01	W	7.46E-04	S	2.06E-03	S
10.6	1.00E-02	S	1.97E+01	W	7.46E-04	S	2.06E-03	S
10.8	9.66E-03	S	1.99E+01	W	7.46E-04	S	2.06E-03	S
11	9.31E-03	S	2.01E+01	W	7.46E-04	S	2.06E-03	S
11.2	8.99E-03	S	2.03E+01	W	7.46E-04	S	2.06E-03	S
11.4	8.68E-03	S	2.05E+01	W	7.46E-04	S	2.06E-03	S
11.6	8.39E-03	S	2.06E+01	W	7.46E-04	S	2.06E-03	S
11.8	8.11E-03	S	2.08E+01	W	7.46E-04	S	2.06E-03	S
12	7.85E-03	S	2.10E+01	W	7.46E-04	S	2.06E-03	S
12.2	7.59E-03	S	2.12E+01	W	7.46E-04	S	2.06E-03	S
12.4	7.35E-03	S	2.13E+01	W	7.46E-04	S	2.06E-03	S
12.6	7.13E-03	S	2.15E+01	W	7.46E-04	S	2.06E-03	S
12.8	6.91E-03	S	2.17E+01	W	7.46E-04	S	2.06E-03	S
13	6.70E-03	S	2.18E+01	W	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	1.50E+00		2.44E+02		2.48E-01		4.61E-01	

Table C-5-46. Leachate Concentrations for Gypsum Export, Waste ID SAU Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	2.42E-01	S	3.52E-06	S	8.75E-02	S	3.04E-02	S
3	2.11E-01	S	3.00E-06	S	7.25E-02	S	2.71E-02	S
3.2	1.86E-01	S	3.00E-06	S	6.64E-02	S	2.52E-02	S
3.4	1.65E-01	S	3.49E-06	S	6.44E-02	S	2.40E-02	S
3.6	1.47E-01	S	5.10E-06	S	6.27E-02	S	2.29E-02	S
3.8	1.32E-01	S	7.32E-06	S	6.10E-02	S	2.19E-02	S
4	1.19E-01	S	1.02E-05	S	5.98E-02	S	2.11E-02	S
4.2	9.89E-02	S	1.15E-05	S	6.27E-02	S	2.04E-02	S
4.4	7.74E-02	S	1.25E-05	S	6.84E-02	S	1.99E-02	S
4.6	5.93E-02	S	1.34E-05	S	7.54E-02	S	1.95E-02	S
4.8	4.60E-02	S	1.43E-05	S	8.28E-02	S	1.91E-02	S
5	3.61E-02	S	1.52E-05	S	9.06E-02	S	1.87E-02	S
5.2	2.85E-02	S	1.61E-05	S	9.88E-02	S	1.83E-02	S
5.4	2.28E-02	S	1.70E-05	S	1.07E-01	S	1.80E-02	S
5.6	1.75E-02	S	2.23E-05	S	1.17E-01	S	1.63E-02	S
5.8	1.36E-02	S	2.96E-05	S	1.26E-01	S	1.46E-02	S
6	1.15E-02	S	3.22E-05	S	1.34E-01	S	1.34E-02	S
6.2	1.09E-02	S	1.35E-05	S	1.46E-01	S	1.10E-02	S
6.4	1.10E-02	S	6.75E-06	S	1.56E-01	S	8.66E-03	S
6.6	1.12E-02	S	4.64E-06	S	1.64E-01	S	7.03E-03	S
6.8	1.15E-02	S	3.48E-06	S	1.72E-01	S	5.75E-03	S
7	1.17E-02	S	3.00E-06	S	1.79E-01	S	4.73E-03	S
7.2	1.11E-02	S	3.00E-06	S	1.85E-01	W	3.82E-03	S
7.4	1.04E-02	S	3.00E-06	S	1.83E-01	W	3.45E-03	S
7.6	9.74E-03	S	3.00E-06	S	1.78E-01	W	3.20E-03	S
7.8	9.16E-03	S	3.00E-06	S	1.74E-01	W	2.98E-03	S
8	8.72E-03	S	2.32E-06	S	1.71E-01	W	2.85E-03	S

Table C-5-46. Leachate Concentrations for Gypsum Export, Waste ID SAU Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	9.21E-03	S	3.00E-06	S	1.71E-01	W	3.50E-03	S
8.4	9.72E-03	S	3.00E-06	S	1.70E-01	W	4.27E-03	S
8.6	1.02E-02	S	3.00E-06	S	1.70E-01	W	5.18E-03	S
8.8	1.08E-02	S	3.00E-06	S	1.70E-01	W	6.27E-03	S
9	1.14E-02	S	3.00E-06	S	1.70E-01	W	7.62E-03	S
9.2	1.25E-02	S	3.00E-06	S	1.73E-01	W	9.08E-03	S
9.4	1.38E-02	S	2.32E-06	S	1.76E-01	W	1.07E-02	S
9.6	1.47E-02	S	3.00E-06	S	1.78E-01	W	1.12E-02	S
9.8	1.57E-02	S	3.00E-06	S	1.80E-01	W	1.17E-02	S
10	1.67E-02	S	3.00E-06	S	1.81E-01	W	1.22E-02	S
10.2	1.75E-02	S	3.00E-06	S	1.83E-01	W	1.28E-02	S
10.4	1.68E-02	S	3.00E-06	S	1.86E-01	W	1.32E-02	S
10.6	1.42E-02	S	3.00E-06	S	1.90E-01	W	1.29E-02	S
10.8	1.08E-02	S	3.00E-06	S	1.93E-01	W	1.17E-02	S
11	8.19E-03	S	3.00E-06	S	1.97E-01	W	1.07E-02	S
11.2	6.26E-03	S	3.00E-06	S	2.01E-01	W	9.75E-03	S
11.4	4.81E-03	S	3.00E-06	S	2.05E-01	W	8.91E-03	S
11.6	3.71E-03	S	3.00E-06	S	2.09E-01	W	8.16E-03	S
11.8	2.88E-03	S	3.00E-06	S	2.13E-01	W	7.48E-03	S
12	2.24E-03	S	3.00E-06	S	2.17E-01	W	6.86E-03	S
12.2	1.75E-03	S	3.00E-06	S	2.21E-01	W	6.31E-03	S
12.4	1.37E-03	S	3.00E-06	S	2.22E-01	W	5.81E-03	S
12.6	1.08E-03	S	3.00E-06	S	2.23E-01	W	5.36E-03	S
12.8	8.55E-04	S	3.00E-06	S	2.24E-01	W	4.94E-03	S
13	6.78E-04	S	3.00E-06	S	2.25E-01	W	4.57E-03	S
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	2.11E+00		3.22E-04		2.52E+00		2.71E-01	

Table C-5-46. Leachate Concentrations for Gypsum Export, Waste ID SAU Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	2.58E-01	S	1.88E-02	S	2.85E-01	S
3	2.28E-01	S	1.85E-02	S	2.53E-01	S
3.2	2.13E-01	S	1.82E-02	S	1.99E-01	S
3.4	2.07E-01	S	1.78E-02	S	1.44E-01	S
3.6	2.00E-01	S	1.75E-02	S	1.07E-01	S
3.8	1.95E-01	S	1.73E-02	S	8.02E-02	S
4	1.90E-01	S	1.70E-02	S	6.16E-02	S
4.2	1.87E-01	S	1.68E-02	S	5.38E-02	S
4.4	1.85E-01	S	1.66E-02	S	4.97E-02	S
4.6	1.83E-01	S	1.65E-02	S	4.70E-02	S
4.8	1.81E-01	S	1.64E-02	S	4.46E-02	S
5	1.78E-01	S	1.63E-02	S	4.25E-02	S
5.2	1.77E-01	S	1.62E-02	S	4.05E-02	S
5.4	1.75E-01	S	1.61E-02	S	3.86E-02	S
5.6	1.71E-01	S	1.52E-02	S	3.53E-02	S
5.8	1.68E-01	S	1.43E-02	S	3.22E-02	S
6	1.68E-01	S	1.38E-02	S	3.00E-02	S
6.2	1.89E-01	S	1.27E-02	S	3.11E-02	S
6.4	2.09E-01	S	1.20E-02	S	3.10E-02	S
6.6	2.21E-01	S	1.16E-02	S	2.97E-02	S
6.8	2.33E-01	S	1.13E-02	S	2.84E-02	S
7	2.45E-01	S	1.10E-02	S	2.73E-02	S
7.2	2.54E-01	S	1.10E-02	S	2.69E-02	S
7.4	2.58E-01	S	1.12E-02	S	2.72E-02	S
7.6	2.60E-01	S	1.14E-02	S	2.77E-02	S
7.8	2.63E-01	S	1.16E-02	S	2.81E-02	S
8	2.64E-01	S	1.18E-02	S	2.89E-02	S

Table C-5-46. Leachate Concentrations for Gypsum Export, Waste ID SAU Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	2.60E-01	S	1.22E-02	S	3.19E-02	S
8.4	2.55E-01	S	1.26E-02	S	3.51E-02	S
8.6	2.51E-01	S	1.30E-02	S	3.86E-02	S
8.8	2.47E-01	S	1.34E-02	S	4.23E-02	S
9	2.46E-01	S	1.36E-02	S	4.64E-02	S
9.2	2.62E-01	S	1.24E-02	S	4.94E-02	S
9.4	2.78E-01	S	1.13E-02	S	5.24E-02	S
9.6	2.82E-01	S	1.08E-02	S	5.34E-02	S
9.8	2.87E-01	S	1.04E-02	S	5.43E-02	S
10	2.91E-01	S	9.97E-03	S	5.53E-02	S
10.2	2.96E-01	S	9.76E-03	S	5.67E-02	S
10.4	3.00E-01	S	9.58E-03	S	5.69E-02	S
10.6	3.03E-01	S	8.74E-03	S	5.27E-02	S
10.8	3.03E-01	S	7.36E-03	S	4.52E-02	S
11	3.03E-01	S	6.22E-03	S	3.88E-02	S
11.2	3.03E-01	S	5.27E-03	S	3.34E-02	S
11.4	3.03E-01	S	4.48E-03	S	2.88E-02	S
11.6	3.02E-01	S	3.82E-03	S	2.50E-02	S
11.8	3.02E-01	S	3.26E-03	S	2.17E-02	S
12	3.02E-01	S	2.80E-03	S	1.88E-02	S
12.2	3.02E-01	S	2.40E-03	S	1.64E-02	S
12.4	3.02E-01	S	2.07E-03	S	1.44E-02	S
12.6	3.01E-01	S	1.79E-03	S	1.26E-02	S
12.8	3.01E-01	S	1.55E-03	S	1.10E-02	S
13	3.01E-01	S	1.34E-03	S	9.70E-03	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	3.40E+00		1.85E-01		2.53E+00	

Table C-5-47. Leachate Concentrations for Gypsum Export, Waste ID SAW Med

Sample ID	SAW-[Med] (P,1,1)
Date Exported	9/20/2011, 7:37 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	1.13E-01	S	5.19E-01	W	5.88E-03	S	2.05E-02	S
3	8.75E-02	S	5.06E-01	W	5.63E-03	S	1.89E-02	S
3.2	7.40E-02	S	4.96E-01	W	5.61E-03	S	1.79E-02	S
3.4	6.33E-02	S	4.88E-01	W	5.59E-03	S	1.71E-02	S
3.6	5.48E-02	S	4.81E-01	W	5.57E-03	S	1.64E-02	S
3.8	4.96E-02	S	4.77E-01	W	5.58E-03	S	1.59E-02	S
4	4.48E-02	S	4.76E-01	W	5.52E-03	S	1.55E-02	S
4.2	4.05E-02	S	4.75E-01	W	5.46E-03	S	1.52E-02	S
4.4	3.69E-02	S	4.74E-01	W	5.40E-03	S	1.48E-02	S
4.6	3.37E-02	S	4.73E-01	W	5.35E-03	S	1.46E-02	S
4.8	3.09E-02	S	4.72E-01	W	5.30E-03	S	1.43E-02	S
5	2.68E-02	S	4.62E-01	W	4.59E-03	S	1.23E-02	S
5.2	2.14E-02	S	4.41E-01	W	3.31E-03	S	8.94E-03	S
5.4	1.73E-02	S	4.23E-01	W	2.42E-03	S	6.55E-03	S
5.6	1.41E-02	S	4.05E-01	W	1.79E-03	S	4.86E-03	S
5.8	1.15E-02	S	3.89E-01	W	1.33E-03	S	3.64E-03	S
6	9.49E-03	S	3.74E-01	W	1.00E-03	S	2.75E-03	S
6.2	9.89E-03	S	3.70E-01	W	8.79E-04	S	2.42E-03	S
6.4	1.06E-02	S	3.68E-01	W	7.85E-04	S	2.16E-03	S
6.6	1.26E-02	S	3.69E-01	W	7.46E-04	S	2.06E-03	S
6.8	1.63E-02	S	3.73E-01	W	7.46E-04	S	2.06E-03	S
7	2.10E-02	S	3.77E-01	W	7.46E-04	S	2.06E-03	S
7.2	2.68E-02	S	3.82E-01	W	7.46E-04	S	2.06E-03	S
7.4	3.13E-02	S	3.84E-01	W	7.46E-04	S	2.06E-03	S
7.6	3.48E-02	S	3.85E-01	W	7.46E-04	S	2.06E-03	S
7.8	3.87E-02	S	3.87E-01	W	7.46E-04	S	2.06E-03	S
8	4.17E-02	S	3.88E-01	W	7.46E-04	S	2.06E-03	S

Table C-5-47. Leachate Concentrations for Gypsum Export, Waste ID SAW Med

Sample ID	SAW-[Med] (P,1,1)
Date Exported	9/20/2011, 7:37 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	4.14E-02	S	3.89E-01	W	7.46E-04	S	2.06E-03	S
8.4	4.11E-02	S	3.90E-01	W	7.46E-04	S	2.06E-03	S
8.6	4.08E-02	S	3.91E-01	W	7.46E-04	S	2.06E-03	S
8.8	4.06E-02	S	3.92E-01	W	7.46E-04	S	2.06E-03	S
9	4.03E-02	S	3.93E-01	W	7.46E-04	S	2.06E-03	S
9.2	3.97E-02	S	3.93E-01	W	7.46E-04	S	2.06E-03	S
9.4	3.92E-02	S	3.92E-01	W	7.46E-04	S	2.06E-03	S
9.6	3.92E-02	S	3.93E-01	W	7.46E-04	S	2.06E-03	S
9.8	3.94E-02	S	3.94E-01	W	7.46E-04	S	2.06E-03	S
10	3.96E-02	S	3.97E-01	S	7.46E-04	S	2.06E-03	S
10.2	3.97E-02	S	4.01E-01	S	7.46E-04	S	2.06E-03	S
10.4	3.97E-02	S	4.06E-01	S	7.46E-04	S	2.06E-03	S
10.6	3.99E-02	S	4.10E-01	S	7.46E-04	S	2.06E-03	S
10.8	4.01E-02	S	4.14E-01	S	7.46E-04	S	2.06E-03	S
11	3.62E-02	S	4.38E-01	S	7.46E-04	S	2.06E-03	S
11.2	2.93E-02	S	4.87E-01	S	7.46E-04	S	2.06E-03	S
11.4	2.38E-02	S	5.40E-01	S	7.46E-04	S	2.06E-03	S
11.6	1.94E-02	S	5.99E-01	S	7.46E-04	S	2.06E-03	S
11.8	1.58E-02	S	6.62E-01	S	7.46E-04	S	2.06E-03	S
12	1.30E-02	S	7.32E-01	S	7.46E-04	S	2.06E-03	S
12.2	1.07E-02	S	7.63E-01	S	7.46E-04	S	2.06E-03	S
12.4	8.84E-03	S	7.63E-01	S	7.46E-04	S	2.06E-03	S
12.6	7.32E-03	S	7.63E-01	S	7.46E-04	S	2.06E-03	S
12.8	6.08E-03	S	7.63E-01	S	7.46E-04	S	2.06E-03	S
13	5.06E-03	S	7.63E-01	S	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	6.70E-01		6.50E+00		4.30E-02		1.44E-01	

Table C-5-47. Leachate Concentrations for Gypsum Export, Waste ID SAW Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	2.06E-01	S	5.30E-06	S	3.10E-02	S	2.39E-02	S
3	1.75E-01	S	5.35E-06	S	2.39E-02	S	2.10E-02	S
3.2	1.64E-01	S	5.86E-06	S	2.21E-02	S	2.02E-02	S
3.4	1.54E-01	S	6.84E-06	S	2.05E-02	S	1.95E-02	S
3.6	1.44E-01	S	8.34E-06	S	1.93E-02	S	1.88E-02	S
3.8	1.21E-01	S	7.97E-06	S	2.02E-02	S	1.84E-02	S
4	8.90E-02	S	6.06E-06	S	2.27E-02	S	1.81E-02	S
4.2	6.52E-02	S	4.55E-06	S	2.56E-02	S	1.77E-02	S
4.4	4.84E-02	S	3.47E-06	S	2.87E-02	S	1.75E-02	S
4.6	3.65E-02	S	3.00E-06	S	3.20E-02	S	1.72E-02	S
4.8	2.78E-02	S	3.00E-06	S	3.56E-02	S	1.69E-02	S
5	2.27E-02	S	3.00E-06	S	3.92E-02	S	1.48E-02	S
5.2	2.02E-02	S	3.00E-06	S	4.30E-02	S	1.09E-02	S
5.4	1.81E-02	S	3.00E-06	S	4.70E-02	S	8.19E-03	S
5.6	1.63E-02	S	3.00E-06	S	5.11E-02	S	6.19E-03	S
5.8	1.47E-02	S	3.00E-06	S	5.55E-02	S	4.73E-03	S
6	1.33E-02	S	3.00E-06	S	6.01E-02	S	3.65E-03	S
6.2	1.25E-02	S	3.00E-06	S	6.37E-02	S	3.23E-03	S
6.4	1.18E-02	S	3.00E-06	S	6.72E-02	S	2.91E-03	S
6.6	1.15E-02	S	3.00E-06	S	6.99E-02	S	2.78E-03	S
6.8	1.16E-02	S	3.00E-06	S	7.19E-02	S	2.78E-03	S
7	1.16E-02	S	3.00E-06	S	7.39E-02	S	2.78E-03	S
7.2	1.17E-02	S	3.00E-06	S	7.59E-02	W	2.78E-03	S
7.4	1.18E-02	S	3.00E-06	S	7.72E-02	W	2.78E-03	S
7.6	1.19E-02	S	3.00E-06	S	7.80E-02	W	2.78E-03	S
7.8	1.21E-02	S	3.00E-06	S	7.89E-02	W	2.78E-03	S
8	1.22E-02	S	3.00E-06	S	7.96E-02	W	2.78E-03	S

Table C-5-47. Leachate Concentrations for Gypsum Export, Waste ID SAW Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	1.21E-02	S	3.00E-06	S	7.98E-02	W	2.78E-03	S
8.4	1.20E-02	S	3.00E-06	S	8.00E-02	W	2.78E-03	S
8.6	1.20E-02	S	3.00E-06	S	8.02E-02	W	2.78E-03	S
8.8	1.19E-02	S	3.00E-06	S	8.04E-02	W	2.78E-03	S
9	1.18E-02	S	3.00E-06	S	8.06E-02	W	2.78E-03	S
9.2	1.18E-02	S	3.00E-06	S	8.13E-02	W	2.78E-03	S
9.4	1.18E-02	S	3.00E-06	S	8.21E-02	W	2.78E-03	S
9.6	1.18E-02	S	3.00E-06	S	8.20E-02	W	2.78E-03	S
9.8	1.19E-02	S	3.22E-06	S	8.17E-02	W	2.78E-03	S
10	1.10E-02	S	3.88E-06	S	8.15E-02	W	2.78E-03	S
10.2	9.95E-03	S	4.33E-06	S	8.18E-02	W	2.78E-03	S
10.4	9.28E-03	S	4.33E-06	S	8.26E-02	W	2.78E-03	S
10.6	9.09E-03	S	4.33E-06	S	8.35E-02	W	2.78E-03	S
10.8	8.90E-03	S	4.33E-06	S	8.44E-02	W	2.78E-03	S
11	8.91E-03	S	4.44E-06	S	8.54E-02	W	2.78E-03	S
11.2	9.12E-03	S	4.72E-06	S	8.62E-02	W	2.78E-03	S
11.4	9.33E-03	S	5.02E-06	S	8.70E-02	W	2.78E-03	S
11.6	9.55E-03	S	5.33E-06	S	8.79E-02	W	2.78E-03	S
11.8	9.76E-03	S	5.65E-06	S	8.87E-02	W	2.78E-03	S
12	9.98E-03	S	5.99E-06	S	8.95E-02	W	2.78E-03	S
12.2	1.02E-02	S	6.12E-06	S	9.03E-02	W	2.78E-03	S
12.4	1.04E-02	S	6.12E-06	S	9.11E-02	W	2.78E-03	S
12.6	1.06E-02	S	6.12E-06	S	9.19E-02	W	2.78E-03	S
12.8	1.09E-02	S	6.12E-06	S	9.27E-02	W	2.78E-03	S
13	1.11E-02	S	6.12E-06	S	9.35E-02	W	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	1.34E+00		6.38E-05		7.90E-01		1.61E-01	

Table C-5-47. Leachate Concentrations for Gypsum Export, Waste ID SAW Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	1.28E-01	S	2.53E-03	S	1.72E-01	S
3	1.13E-01	S	2.53E-03	S	1.40E-01	S
3.2	1.10E-01	S	2.53E-03	S	9.66E-02	S
3.4	1.08E-01	S	2.53E-03	S	6.81E-02	S
3.6	1.06E-01	S	2.53E-03	S	4.95E-02	S
3.8	1.03E-01	S	2.53E-03	S	3.99E-02	S
4	1.02E-01	S	2.53E-03	S	3.52E-02	S
4.2	1.01E-01	S	2.53E-03	S	3.15E-02	S
4.4	1.00E-01	S	2.53E-03	S	2.83E-02	S
4.6	9.91E-02	S	2.53E-03	S	2.56E-02	S
4.8	9.82E-02	S	2.53E-03	S	2.32E-02	S
5	9.18E-02	S	2.53E-03	S	2.07E-02	S
5.2	7.94E-02	S	2.53E-03	S	1.80E-02	S
5.4	6.91E-02	S	2.53E-03	S	1.58E-02	S
5.6	6.05E-02	S	2.53E-03	S	1.39E-02	S
5.8	5.31E-02	S	2.53E-03	S	1.23E-02	S
6	4.69E-02	S	2.53E-03	S	1.09E-02	S
6.2	4.20E-02	S	2.53E-03	S	1.20E-02	S
6.4	3.79E-02	S	2.53E-03	S	1.34E-02	S
6.6	3.40E-02	S	2.53E-03	S	1.64E-02	S
6.8	3.03E-02	S	2.53E-03	S	2.15E-02	S
7	2.72E-02	S	2.53E-03	S	2.81E-02	S
7.2	2.44E-02	S	2.53E-03	S	3.64E-02	S
7.4	2.26E-02	S	2.53E-03	S	4.32E-02	S
7.6	2.13E-02	S	2.53E-03	S	4.90E-02	S
7.8	2.01E-02	S	2.53E-03	S	5.52E-02	S
8	1.92E-02	S	2.53E-03	S	6.06E-02	S

Table C-5-47. Leachate Concentrations for Gypsum Export, Waste ID SAW Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	1.92E-02	S	2.53E-03	S	6.15E-02	S
8.4	1.92E-02	S	2.53E-03	S	6.24E-02	S
8.6	1.92E-02	S	2.53E-03	S	6.32E-02	S
8.8	1.92E-02	S	2.53E-03	S	6.41E-02	S
9	1.92E-02	S	2.53E-03	S	6.50E-02	S
9.2	2.10E-02	S	2.53E-03	S	6.73E-02	S
9.4	2.32E-02	S	2.53E-03	S	6.99E-02	S
9.6	2.56E-02	S	2.53E-03	S	7.15E-02	S
9.8	2.81E-02	S	2.53E-03	S	7.26E-02	S
10	3.31E-02	S	2.53E-03	S	7.37E-02	S
10.2	3.99E-02	S	2.53E-03	S	7.48E-02	S
10.4	5.03E-02	S	2.53E-03	S	7.52E-02	S
10.6	6.49E-02	S	2.53E-03	S	7.54E-02	S
10.8	8.34E-02	S	2.53E-03	S	7.56E-02	S
11	9.29E-02	S	2.53E-03	S	6.63E-02	S
11.2	8.98E-02	S	2.53E-03	S	5.04E-02	S
11.4	8.68E-02	S	2.53E-03	S	3.85E-02	S
11.6	8.40E-02	S	2.53E-03	S	2.95E-02	S
11.8	8.14E-02	S	2.53E-03	S	2.28E-02	S
12	7.88E-02	S	2.53E-03	S	1.76E-02	S
12.2	7.64E-02	S	2.53E-03	S	1.37E-02	S
12.4	7.41E-02	S	2.53E-03	S	1.07E-02	S
12.6	7.19E-02	S	2.53E-03	S	8.38E-03	S
12.8	6.98E-02	S	2.53E-03	S	6.59E-03	S
13	6.78E-02	S	2.53E-03	S	5.20E-03	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	8.63E-01		2.16E-02		1.07E+00	

Table C-5-48. Leachate Concentrations for Gypsum Export, Waste ID TAU Med

Sample ID	TAU-[Med] (P,1,1)
Date Exported	9/20/2011, 7:38 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	1.77E-02	S	1.20E+01	W	1.09E-02	S	5.61E-02	S
3	1.25E-02	S	1.19E+01	W	9.53E-03	S	5.22E-02	S
3.2	9.02E-03	S	1.19E+01	W	8.38E-03	S	4.87E-02	S
3.4	6.92E-03	S	1.19E+01	W	8.07E-03	S	4.73E-02	S
3.6	5.58E-03	S	1.19E+01	W	8.31E-03	S	4.72E-02	S
3.8	4.55E-03	S	1.20E+01	W	8.55E-03	S	4.71E-02	S
4	3.75E-03	S	1.20E+01	W	8.78E-03	S	4.71E-02	S
4.2	3.46E-03	S	1.21E+01	W	8.55E-03	S	4.89E-02	S
4.4	3.26E-03	S	1.21E+01	W	8.90E-03	S	4.99E-02	S
4.6	3.20E-03	S	1.19E+01	W	9.31E-03	S	4.98E-02	S
4.8	3.20E-03	S	1.17E+01	W	9.59E-03	S	4.94E-02	S
5	3.20E-03	S	1.15E+01	W	9.87E-03	S	4.90E-02	S
5.2	3.20E-03	S	1.13E+01	W	1.01E-02	S	4.86E-02	S
5.4	3.20E-03	S	1.11E+01	W	1.04E-02	S	4.83E-02	S
5.6	3.20E-03	S	1.11E+01	W	1.08E-02	S	4.84E-02	S
5.8	3.20E-03	S	1.12E+01	W	1.17E-02	S	4.98E-02	S
6	3.20E-03	S	1.16E+01	W	1.33E-02	S	5.30E-02	S
6.2	3.20E-03	S	1.15E+01	W	1.02E-02	S	4.77E-02	S
6.4	3.20E-03	S	1.14E+01	W	5.90E-03	S	3.85E-02	S
6.6	3.20E-03	S	1.12E+01	W	3.21E-03	S	3.03E-02	S
6.8	3.20E-03	S	1.11E+01	W	1.78E-03	S	2.41E-02	S
7	3.20E-03	S	1.09E+01	W	1.03E-03	S	1.90E-02	S
7.2	3.20E-03	S	1.09E+01	W	7.87E-04	S	1.37E-02	S
7.4	3.20E-03	S	1.09E+01	W	7.46E-04	S	8.55E-03	S
7.6	3.20E-03	S	1.08E+01	W	7.46E-04	S	5.20E-03	S
7.8	3.20E-03	S	1.07E+01	W	7.46E-04	S	3.21E-03	S
8	3.20E-03	S	1.07E+01	W	7.46E-04	S	2.14E-03	S

Table C-5-48. Leachate Concentrations for Gypsum Export, Waste ID TAU Med

Sample ID	TAU-[Med] (P,1,1)
Date Exported	9/20/2011, 7:38 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	3.20E-03	S	1.07E+01	W	7.46E-04	S	2.06E-03	S
8.4	3.20E-03	S	1.06E+01	W	7.46E-04	S	2.06E-03	S
8.6	3.20E-03	S	1.06E+01	W	7.46E-04	S	2.06E-03	S
8.8	3.20E-03	S	1.06E+01	W	7.46E-04	S	2.06E-03	S
9	3.20E-03	S	1.05E+01	W	7.46E-04	S	2.06E-03	S
9.2	3.20E-03	S	1.03E+01	W	7.46E-04	S	2.06E-03	S
9.4	3.20E-03	S	1.00E+01	W	7.46E-04	S	2.06E-03	S
9.6	3.20E-03	S	1.00E+01	W	7.46E-04	S	2.06E-03	S
9.8	3.20E-03	S	1.00E+01	W	7.46E-04	S	2.06E-03	S
10	3.20E-03	S	1.00E+01	W	7.46E-04	S	2.06E-03	S
10.2	3.20E-03	S	1.00E+01	W	7.46E-04	S	2.06E-03	S
10.4	3.20E-03	S	1.00E+01	W	7.46E-04	S	2.06E-03	S
10.6	3.20E-03	S	1.00E+01	W	7.46E-04	S	2.06E-03	S
10.8	3.20E-03	S	9.97E+00	W	7.46E-04	S	2.06E-03	S
11	3.20E-03	S	9.99E+00	W	7.46E-04	S	2.06E-03	S
11.2	3.20E-03	S	1.04E+01	W	7.46E-04	S	2.06E-03	S
11.4	3.20E-03	S	1.07E+01	W	7.46E-04	S	2.06E-03	S
11.6	3.20E-03	S	1.08E+01	W	7.46E-04	S	2.06E-03	S
11.8	3.20E-03	S	1.09E+01	W	7.46E-04	S	2.06E-03	S
12	3.20E-03	S	1.10E+01	W	7.46E-04	S	2.06E-03	S
12.2	3.20E-03	S	1.11E+01	W	7.46E-04	S	2.06E-03	S
12.4	3.20E-03	S	1.12E+01	W	7.46E-04	S	2.06E-03	S
12.6	3.20E-03	S	1.13E+01	W	7.46E-04	S	2.06E-03	S
12.8	3.20E-03	S	1.14E+01	W	7.46E-04	S	2.06E-03	S
13	3.20E-03	S	1.15E+01	W	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	7.66E-02		8.03E+01		8.14E-02		3.25E-01	

Table C-5-48. Leachate Concentrations for Gypsum Export, Waste ID TAU Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	6.89E-02	S	1.44E-04	S	7.45E-03	S	2.78E-03	S
3	5.34E-02	S	9.77E-05	S	6.17E-03	S	2.78E-03	S
3.2	4.21E-02	S	6.80E-05	S	5.18E-03	S	2.78E-03	S
3.4	3.50E-02	S	5.51E-05	S	4.62E-03	S	2.78E-03	S
3.6	3.05E-02	S	5.02E-05	S	4.32E-03	S	2.78E-03	S
3.8	2.67E-02	S	4.59E-05	S	4.06E-03	S	2.78E-03	S
4	2.36E-02	S	4.21E-05	S	3.83E-03	S	2.78E-03	S
4.2	2.49E-02	S	4.26E-05	S	3.80E-03	S	2.78E-03	S
4.4	2.46E-02	S	3.62E-05	S	3.80E-03	S	2.78E-03	S
4.6	2.37E-02	S	2.28E-05	S	3.80E-03	S	2.78E-03	S
4.8	2.29E-02	S	1.30E-05	S	3.80E-03	S	2.78E-03	S
5	2.23E-02	S	7.60E-06	S	3.80E-03	S	2.78E-03	S
5.2	2.16E-02	S	4.58E-06	S	3.80E-03	S	2.78E-03	S
5.4	2.10E-02	S	3.48E-06	S	3.80E-03	S	2.78E-03	S
5.6	2.03E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
5.8	1.90E-02	S	3.88E-06	S	3.80E-03	S	2.78E-03	S
6	1.70E-02	S	5.02E-06	S	3.80E-03	S	2.78E-03	S
6.2	1.55E-02	S	6.44E-06	S	4.24E-03	S	2.78E-03	S
6.4	1.36E-02	S	5.75E-06	S	5.20E-03	S	2.78E-03	S
6.6	1.18E-02	S	4.59E-06	S	6.53E-03	S	2.78E-03	S
6.8	1.03E-02	S	3.68E-06	S	8.15E-03	S	2.78E-03	S
7	9.12E-03	S	3.00E-06	S	9.96E-03	S	2.78E-03	S
7.2	8.98E-03	S	3.00E-06	S	1.07E-02	W	2.78E-03	S
7.4	1.02E-02	S	3.00E-06	S	1.05E-02	W	2.78E-03	S
7.6	1.19E-02	S	3.00E-06	S	9.93E-03	W	2.78E-03	S
7.8	1.39E-02	S	3.00E-06	S	9.44E-03	W	2.78E-03	S
8	1.55E-02	S	3.00E-06	S	9.08E-03	W	2.78E-03	S

Table C-5-48. Leachate Concentrations for Gypsum Export, Waste ID TAU Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	1.52E-02	S	3.00E-06	S	9.35E-03	W	2.78E-03	S
8.4	1.48E-02	S	3.00E-06	S	9.71E-03	W	2.78E-03	S
8.6	1.44E-02	S	3.00E-06	S	1.01E-02	W	2.78E-03	S
8.8	1.40E-02	S	3.00E-06	S	1.04E-02	W	2.78E-03	S
9	1.46E-02	S	3.00E-06	S	1.09E-02	W	2.78E-03	S
9.2	1.92E-02	S	3.00E-06	S	1.16E-02	W	2.78E-03	S
9.4	2.51E-02	S	2.32E-06	S	1.23E-02	W	2.78E-03	S
9.6	2.36E-02	S	3.45E-06	S	1.31E-02	W	2.78E-03	S
9.8	2.23E-02	S	4.04E-06	S	1.39E-02	W	2.78E-03	S
10	2.10E-02	S	4.72E-06	S	1.47E-02	W	2.78E-03	S
10.2	1.98E-02	S	5.49E-06	S	1.56E-02	W	2.78E-03	S
10.4	1.90E-02	S	6.38E-06	S	1.63E-02	W	2.78E-03	S
10.6	1.87E-02	S	7.39E-06	S	1.66E-02	W	2.78E-03	S
10.8	1.84E-02	S	8.53E-06	S	1.69E-02	W	2.78E-03	S
11	1.81E-02	S	8.91E-06	S	1.73E-02	W	2.78E-03	S
11.2	1.83E-02	S	3.93E-06	S	1.76E-02	W	2.78E-03	S
11.4	1.82E-02	S	3.00E-06	S	1.82E-02	W	2.78E-03	S
11.6	1.74E-02	S	3.00E-06	S	1.95E-02	W	2.78E-03	S
11.8	1.67E-02	S	3.00E-06	S	2.09E-02	W	2.78E-03	S
12	1.61E-02	S	3.00E-06	S	2.23E-02	W	2.78E-03	S
12.2	1.54E-02	S	3.00E-06	S	2.38E-02	W	2.78E-03	S
12.4	1.49E-02	S	3.00E-06	S	2.42E-02	W	2.78E-03	S
12.6	1.43E-02	S	3.00E-06	S	2.42E-02	W	2.78E-03	S
12.8	1.38E-02	S	3.00E-06	S	2.42E-02	W	2.78E-03	S
13	1.33E-02	S	3.00E-06	S	2.42E-02	W	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	3.28E-01		6.00E-04		1.70E-01		1.96E-02	

Table C-5-48. Leachate Concentrations for Gypsum Export, Waste ID TAU Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	1.42E-01	S	1.05E-02	S	4.28E-02	S
3	1.17E-01	S	1.04E-02	S	3.48E-02	S
3.2	9.83E-02	S	1.03E-02	S	2.87E-02	S
3.4	8.72E-02	S	1.02E-02	S	2.52E-02	S
3.6	8.09E-02	S	1.02E-02	S	2.33E-02	S
3.8	7.53E-02	S	1.02E-02	S	2.16E-02	S
4	7.04E-02	S	1.01E-02	S	2.01E-02	S
4.2	7.08E-02	S	1.03E-02	S	1.98E-02	S
4.4	7.00E-02	S	1.03E-02	S	1.97E-02	S
4.6	6.87E-02	S	1.03E-02	S	1.99E-02	S
4.8	6.76E-02	S	1.04E-02	S	2.02E-02	S
5	6.66E-02	S	1.05E-02	S	2.04E-02	S
5.2	6.56E-02	S	1.05E-02	S	2.07E-02	S
5.4	6.47E-02	S	1.06E-02	S	2.10E-02	S
5.6	6.51E-02	S	1.06E-02	S	2.22E-02	S
5.8	6.60E-02	S	1.01E-02	S	2.37E-02	S
6	6.76E-02	S	9.18E-03	S	2.53E-02	S
6.2	6.60E-02	S	8.54E-03	S	2.67E-02	S
6.4	6.19E-02	S	7.25E-03	S	2.71E-02	S
6.6	5.76E-02	S	6.01E-03	S	2.72E-02	S
6.8	5.36E-02	S	5.00E-03	S	2.73E-02	S
7	5.01E-02	S	4.23E-03	S	2.73E-02	S
7.2	4.73E-02	S	3.96E-03	S	2.69E-02	S
7.4	4.43E-02	S	4.67E-03	S	2.66E-02	S
7.6	4.16E-02	S	5.82E-03	S	2.64E-02	S
7.8	3.90E-02	S	7.20E-03	S	2.62E-02	S
8	3.72E-02	S	8.52E-03	S	2.59E-02	S

Table C-5-48. Leachate Concentrations for Gypsum Export, Waste ID TAU Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	3.79E-02	S	8.69E-03	S	2.56E-02	S
8.4	3.89E-02	S	8.81E-03	S	2.53E-02	S
8.6	3.98E-02	S	8.93E-03	S	2.50E-02	S
8.8	4.07E-02	S	9.04E-03	S	2.47E-02	S
9	4.20E-02	S	9.10E-03	S	2.42E-02	S
9.2	4.59E-02	S	8.87E-03	S	2.31E-02	S
9.4	5.13E-02	S	8.49E-03	S	2.21E-02	S
9.6	5.96E-02	S	8.31E-03	S	2.20E-02	S
9.8	6.90E-02	S	8.13E-03	S	2.19E-02	S
10	7.96E-02	S	7.96E-03	S	2.19E-02	S
10.2	9.17E-02	S	7.80E-03	S	2.18E-02	S
10.4	1.03E-01	S	7.65E-03	S	2.16E-02	S
10.6	1.11E-01	S	7.51E-03	S	2.14E-02	S
10.8	1.20E-01	S	7.37E-03	S	2.12E-02	S
11	1.30E-01	S	7.25E-03	S	2.11E-02	S
11.2	1.48E-01	S	7.26E-03	S	2.18E-02	S
11.4	1.65E-01	S	7.28E-03	S	2.19E-02	S
11.6	1.74E-01	S	7.32E-03	S	2.12E-02	S
11.8	1.83E-01	S	7.36E-03	S	2.04E-02	S
12	1.93E-01	S	7.39E-03	S	1.97E-02	S
12.2	2.03E-01	S	7.43E-03	S	1.90E-02	S
12.4	2.14E-01	S	7.47E-03	S	1.84E-02	S
12.6	2.25E-01	S	7.50E-03	S	1.78E-02	S
12.8	2.36E-01	S	7.54E-03	S	1.72E-02	S
13	2.48E-01	S	7.57E-03	S	1.67E-02	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	1.67E+00		6.50E-02		2.14E-01	

Table C-5-49. Leachate Concentrations for Gypsum Export, Waste ID TAW Med

Sample ID	TAW-[Med] (P,1,1)
Date Exported	9/20/2011, 7:38 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	1.24E-02	S	7.92E-01	W	1.56E-03	S	2.19E-02	S
3	8.31E-03	S	7.82E-01	W	1.40E-03	S	2.13E-02	S
3.2	5.71E-03	S	7.73E-01	W	1.27E-03	S	2.08E-02	S
3.4	4.08E-03	S	7.72E-01	W	1.02E-03	S	1.76E-02	S
3.6	3.42E-03	S	7.73E-01	W	8.14E-04	S	1.38E-02	S
3.8	3.20E-03	S	7.68E-01	W	7.46E-04	S	1.23E-02	S
4	3.20E-03	S	7.62E-01	W	7.46E-04	S	1.21E-02	S
4.2	3.20E-03	S	7.56E-01	W	7.46E-04	S	1.19E-02	S
4.4	3.20E-03	S	7.51E-01	W	7.46E-04	S	1.17E-02	S
4.6	3.20E-03	S	7.46E-01	W	7.46E-04	S	1.15E-02	S
4.8	3.20E-03	S	7.41E-01	W	7.46E-04	S	1.13E-02	S
5	3.20E-03	S	7.36E-01	W	7.46E-04	S	1.12E-02	S
5.2	3.20E-03	S	7.26E-01	W	7.46E-04	S	8.00E-03	S
5.4	3.20E-03	S	7.14E-01	W	7.46E-04	S	5.23E-03	S
5.6	3.20E-03	S	7.03E-01	W	7.46E-04	S	3.47E-03	S
5.8	3.20E-03	S	7.07E-01	W	7.46E-04	S	2.90E-03	S
6	3.20E-03	S	7.14E-01	W	7.46E-04	S	2.58E-03	S
6.2	3.20E-03	S	7.21E-01	W	7.46E-04	S	2.29E-03	S
6.4	3.20E-03	S	7.18E-01	W	7.46E-04	S	2.06E-03	S
6.6	3.20E-03	S	7.12E-01	W	7.46E-04	S	2.06E-03	S
6.8	3.20E-03	S	7.06E-01	W	7.46E-04	S	2.06E-03	S
7	3.20E-03	S	7.00E-01	W	7.46E-04	S	2.06E-03	S
7.2	3.20E-03	S	6.97E-01	W	7.46E-04	S	2.06E-03	S
7.4	3.20E-03	S	7.24E-01	W	7.46E-04	S	2.06E-03	S
7.6	3.20E-03	S	7.40E-01	W	7.46E-04	S	2.06E-03	S
7.8	3.20E-03	S	7.38E-01	W	7.46E-04	S	2.06E-03	S
8	3.20E-03	S	7.36E-01	W	7.46E-04	S	2.06E-03	S

Table C-5-49. Leachate Concentrations for Gypsum Export, Waste ID TAW Med

Sample ID	TAW-[Med] (P,1,1)
Date Exported	9/20/2011, 7:38 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	3.20E-03	S	7.34E-01	W	7.46E-04	S	2.06E-03	S
8.4	3.20E-03	S	7.32E-01	W	7.46E-04	S	2.06E-03	S
8.6	3.20E-03	S	7.30E-01	W	7.46E-04	S	2.06E-03	S
8.8	3.20E-03	S	7.28E-01	W	7.46E-04	S	2.06E-03	S
9	3.20E-03	S	7.22E-01	W	7.46E-04	S	2.06E-03	S
9.2	3.20E-03	S	7.13E-01	W	7.46E-04	S	2.06E-03	S
9.4	3.20E-03	S	7.04E-01	W	7.46E-04	S	2.06E-03	S
9.6	3.20E-03	S	6.96E-01	W	7.46E-04	S	2.06E-03	S
9.8	3.20E-03	S	6.87E-01	W	7.46E-04	S	2.06E-03	S
10	3.20E-03	S	6.86E-01	S	7.46E-04	S	2.06E-03	S
10.2	3.20E-03	S	7.03E-01	S	7.46E-04	S	2.06E-03	S
10.4	3.20E-03	S	7.26E-01	S	7.46E-04	S	2.06E-03	S
10.6	3.20E-03	S	7.50E-01	S	7.46E-04	S	2.06E-03	S
10.8	3.20E-03	S	7.74E-01	S	7.46E-04	S	2.06E-03	S
11	3.20E-03	S	8.02E-01	S	7.46E-04	S	2.06E-03	S
11.2	3.20E-03	S	8.89E-01	S	7.46E-04	S	2.06E-03	S
11.4	3.20E-03	S	1.00E+00	S	7.46E-04	S	2.06E-03	S
11.6	3.20E-03	S	1.12E+00	S	7.46E-04	S	2.06E-03	S
11.8	3.20E-03	S	1.26E+00	S	7.46E-04	S	2.06E-03	S
12	3.20E-03	S	1.41E+00	S	7.46E-04	S	2.06E-03	S
12.2	3.20E-03	S	1.54E+00	S	7.46E-04	S	2.06E-03	S
12.4	3.20E-03	S	1.54E+00	S	7.46E-04	S	2.06E-03	S
12.6	3.20E-03	S	1.54E+00	S	7.46E-04	S	2.06E-03	S
12.8	3.20E-03	S	1.54E+00	S	7.46E-04	S	2.06E-03	S
13	3.20E-03	S	1.54E+00	S	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	6.16E-02		1.28E+01		1.04E-02		1.58E-01	

Table C-5-49. Leachate Concentrations for Gypsum Export, Waste ID TAW Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	5.82E-02	S	8.29E-06	S	6.77E-03	S	2.78E-03	S
3	4.51E-02	S	7.99E-06	S	5.35E-03	S	2.78E-03	S
3.2	3.55E-02	S	7.71E-06	S	4.28E-03	S	2.78E-03	S
3.4	2.86E-02	S	7.58E-06	S	3.80E-03	S	2.78E-03	S
3.6	2.41E-02	S	8.13E-06	S	3.80E-03	S	2.78E-03	S
3.8	2.15E-02	S	8.71E-06	S	3.80E-03	S	2.78E-03	S
4	2.04E-02	S	1.27E-05	S	3.80E-03	S	2.78E-03	S
4.2	1.93E-02	S	1.93E-05	S	3.80E-03	S	2.78E-03	S
4.4	1.83E-02	S	2.86E-05	S	3.80E-03	S	2.78E-03	S
4.6	1.74E-02	S	4.17E-05	S	3.80E-03	S	2.78E-03	S
4.8	1.66E-02	S	5.99E-05	S	3.80E-03	S	2.78E-03	S
5	1.59E-02	S	8.47E-05	S	3.80E-03	S	2.78E-03	S
5.2	1.57E-02	S	4.91E-05	S	4.50E-03	S	2.78E-03	S
5.4	1.56E-02	S	2.18E-05	S	5.62E-03	S	2.78E-03	S
5.6	1.55E-02	S	1.13E-05	S	6.95E-03	S	2.78E-03	S
5.8	1.56E-02	S	9.90E-06	S	6.68E-03	S	2.78E-03	S
6	1.56E-02	S	8.70E-06	S	6.06E-03	S	2.78E-03	S
6.2	1.57E-02	S	5.95E-06	S	5.52E-03	S	2.78E-03	S
6.4	1.59E-02	S	6.75E-06	S	6.60E-03	S	2.78E-03	S
6.6	1.64E-02	S	5.09E-06	S	6.69E-03	S	2.78E-03	S
6.8	1.69E-02	S	3.87E-06	S	6.78E-03	S	2.78E-03	S
7	1.74E-02	S	3.00E-06	S	6.87E-03	S	2.78E-03	S
7.2	1.78E-02	S	2.32E-06	S	7.14E-03	W	2.78E-03	S
7.4	1.78E-02	S	4.93E-06	S	1.08E-02	W	2.78E-03	S
7.6	1.79E-02	S	7.50E-06	S	1.39E-02	W	2.78E-03	S
7.8	1.83E-02	S	7.50E-06	S	1.41E-02	W	2.78E-03	S
8	1.87E-02	S	7.50E-06	S	1.43E-02	W	2.78E-03	S

Table C-5-49. Leachate Concentrations for Gypsum Export, Waste ID TAW Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	1.91E-02	S	7.50E-06	S	1.45E-02	W	2.78E-03	S
8.4	1.95E-02	S	7.50E-06	S	1.46E-02	W	2.78E-03	S
8.6	1.99E-02	S	7.50E-06	S	1.48E-02	W	2.78E-03	S
8.8	2.01E-02	S	7.31E-06	S	1.48E-02	W	2.78E-03	S
9	2.00E-02	S	7.10E-06	S	1.48E-02	W	2.78E-03	S
9.2	1.99E-02	S	6.90E-06	S	1.47E-02	W	2.78E-03	S
9.4	1.98E-02	S	6.71E-06	S	1.46E-02	W	2.78E-03	S
9.6	1.96E-02	S	6.53E-06	S	1.45E-02	W	2.78E-03	S
9.8	1.95E-02	S	6.36E-06	S	1.44E-02	W	2.78E-03	S
10	1.96E-02	S	6.20E-06	S	1.44E-02	W	2.78E-03	S
10.2	1.95E-02	S	6.12E-06	S	1.45E-02	W	2.78E-03	S
10.4	1.89E-02	S	6.12E-06	S	1.47E-02	W	2.78E-03	S
10.6	1.85E-02	S	6.12E-06	S	1.49E-02	W	2.78E-03	S
10.8	1.80E-02	S	6.12E-06	S	1.51E-02	W	2.78E-03	S
11	1.75E-02	S	6.10E-06	S	1.54E-02	W	2.78E-03	S
11.2	1.55E-02	S	5.95E-06	S	1.67E-02	W	2.78E-03	S
11.4	1.34E-02	S	5.80E-06	S	1.82E-02	W	2.78E-03	S
11.6	1.16E-02	S	5.66E-06	S	1.99E-02	W	2.78E-03	S
11.8	1.01E-02	S	5.53E-06	S	2.17E-02	W	2.78E-03	S
12	8.76E-03	S	5.40E-06	S	2.37E-02	W	2.78E-03	S
12.2	7.64E-03	S	5.28E-06	S	2.58E-02	W	2.78E-03	S
12.4	6.68E-03	S	5.16E-06	S	2.76E-02	W	2.78E-03	S
12.6	5.85E-03	S	5.05E-06	S	2.83E-02	W	2.78E-03	S
12.8	5.13E-03	S	4.94E-06	S	2.83E-02	W	2.78E-03	S
13	4.51E-03	S	4.83E-06	S	2.83E-02	W	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	3.35E-01		6.29E-04		2.35E-01		2.31E-02	

Table C-5-49. Leachate Concentrations for Gypsum Export, Waste ID TAW Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	6.21E-02	S	2.53E-03	S	2.09E-02	S
3	4.70E-02	S	2.53E-03	S	1.55E-02	S
3.2	3.63E-02	S	2.53E-03	S	1.17E-02	S
3.4	3.14E-02	S	2.53E-03	S	9.43E-03	S
3.6	3.04E-02	S	2.53E-03	S	8.84E-03	S
3.8	2.93E-02	S	2.53E-03	S	8.80E-03	S
4	2.96E-02	S	2.53E-03	S	8.98E-03	S
4.2	2.99E-02	S	2.53E-03	S	9.15E-03	S
4.4	3.02E-02	S	2.53E-03	S	9.31E-03	S
4.6	3.04E-02	S	2.53E-03	S	9.47E-03	S
4.8	3.07E-02	S	2.53E-03	S	9.63E-03	S
5	3.09E-02	S	2.53E-03	S	9.79E-03	S
5.2	2.81E-02	S	2.53E-03	S	9.31E-03	S
5.4	2.48E-02	S	2.53E-03	S	8.69E-03	S
5.6	2.19E-02	S	2.53E-03	S	8.13E-03	S
5.8	2.20E-02	S	2.53E-03	S	7.81E-03	S
6	2.28E-02	S	2.53E-03	S	7.55E-03	S
6.2	2.35E-02	S	2.53E-03	S	7.31E-03	S
6.4	2.21E-02	S	2.53E-03	S	7.13E-03	S
6.6	2.18E-02	S	2.53E-03	S	7.25E-03	S
6.8	2.15E-02	S	2.53E-03	S	7.37E-03	S
7	2.12E-02	S	2.53E-03	S	7.49E-03	S
7.2	2.11E-02	S	2.53E-03	S	7.63E-03	S
7.4	2.39E-02	S	2.53E-03	S	8.25E-03	S
7.6	2.60E-02	S	2.53E-03	S	8.76E-03	S
7.8	2.67E-02	S	2.53E-03	S	9.06E-03	S
8	2.75E-02	S	2.53E-03	S	9.35E-03	S

Table C-5-49. Leachate Concentrations for Gypsum Export, Waste ID TAW Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	2.82E-02	S	2.53E-03	S	9.65E-03	S
8.4	2.90E-02	S	2.53E-03	S	9.95E-03	S
8.6	2.97E-02	S	2.53E-03	S	1.03E-02	S
8.8	3.03E-02	S	2.53E-03	S	1.01E-02	S
9	3.19E-02	S	2.53E-03	S	9.70E-03	S
9.2	3.42E-02	S	2.53E-03	S	9.32E-03	S
9.4	3.67E-02	S	2.53E-03	S	8.96E-03	S
9.6	3.92E-02	S	2.53E-03	S	8.62E-03	S
9.8	4.19E-02	S	2.53E-03	S	8.31E-03	S
10	4.50E-02	S	2.53E-03	S	8.05E-03	S
10.2	5.11E-02	S	2.53E-03	S	8.14E-03	S
10.4	6.01E-02	S	2.53E-03	S	8.42E-03	S
10.6	7.05E-02	S	2.53E-03	S	8.71E-03	S
10.8	8.24E-02	S	2.53E-03	S	9.01E-03	S
11	9.55E-02	S	2.53E-03	S	9.32E-03	S
11.2	1.06E-01	S	2.53E-03	S	9.99E-03	S
11.4	1.18E-01	S	2.53E-03	S	1.09E-02	S
11.6	1.30E-01	S	2.53E-03	S	1.18E-02	S
11.8	1.44E-01	S	2.53E-03	S	1.28E-02	S
12	1.59E-01	S	2.53E-03	S	1.38E-02	S
12.2	1.75E-01	S	2.53E-03	S	1.50E-02	S
12.4	1.93E-01	S	2.53E-03	S	1.61E-02	S
12.6	2.12E-01	S	2.53E-03	S	1.74E-02	S
12.8	2.32E-01	S	2.53E-03	S	1.87E-02	S
13	2.55E-01	S	2.53E-03	S	2.02E-02	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	1.93E+00		2.10E-02		1.56E-01	

Table C-5-50. Leachate Concentrations for Gypsum Export, Waste ID UAU Med

Sample ID	UAU-[Med] (P,1,1)
Date Exported	9/20/2011, 7:38 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	6.67E-02	S	6.56E-01	W	5.30E-02	S	4.08E-02	S
3	6.86E-02	S	6.59E-01	W	5.26E-02	S	4.05E-02	S
3.2	7.04E-02	S	6.62E-01	W	5.23E-02	S	4.03E-02	S
3.4	7.22E-02	S	6.65E-01	W	5.19E-02	S	4.00E-02	S
3.6	7.39E-02	S	6.67E-01	W	5.16E-02	S	3.98E-02	S
3.8	7.56E-02	S	6.70E-01	W	5.13E-02	S	3.96E-02	S
4	7.72E-02	S	6.72E-01	W	5.11E-02	S	3.94E-02	S
4.2	7.87E-02	S	6.75E-01	W	5.08E-02	S	3.92E-02	S
4.4	8.03E-02	S	6.77E-01	W	5.05E-02	S	3.90E-02	S
4.6	5.51E-02	S	6.89E-01	W	4.28E-02	S	3.32E-02	S
4.8	3.49E-02	S	7.03E-01	W	3.50E-02	S	2.75E-02	S
5	2.25E-02	S	7.17E-01	W	2.89E-02	S	2.29E-02	S
5.2	1.39E-02	S	6.82E-01	W	1.23E-02	S	1.30E-02	S
5.4	8.69E-03	S	6.45E-01	W	5.01E-03	S	7.20E-03	S
5.6	5.52E-03	S	6.12E-01	W	2.11E-03	S	4.08E-03	S
5.8	3.56E-03	S	5.81E-01	W	9.15E-04	S	2.36E-03	S
6	3.20E-03	S	5.70E-01	W	7.46E-04	S	2.06E-03	S
6.2	3.20E-03	S	5.65E-01	W	7.46E-04	S	2.06E-03	S
6.4	3.20E-03	S	5.60E-01	W	7.46E-04	S	2.06E-03	S
6.6	3.20E-03	S	5.56E-01	W	7.46E-04	S	2.06E-03	S
6.8	3.20E-03	S	5.51E-01	W	7.46E-04	S	2.06E-03	S
7	3.20E-03	S	5.47E-01	W	7.46E-04	S	2.06E-03	S
7.2	3.20E-03	S	5.46E-01	W	7.46E-04	S	2.06E-03	S
7.4	3.20E-03	S	5.45E-01	W	7.46E-04	S	2.06E-03	S
7.6	3.20E-03	S	5.44E-01	W	7.46E-04	S	2.06E-03	S
7.8	3.20E-03	S	5.43E-01	W	7.46E-04	S	2.06E-03	S
8	3.20E-03	S	5.43E-01	W	7.46E-04	S	2.06E-03	S

Table C-5-50. Leachate Concentrations for Gypsum Export, Waste ID UAU Med

Sample ID	UAU-[Med] (P,1,1)
Date Exported	9/20/2011, 7:38 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	3.20E-03	S	5.42E-01	W	7.46E-04	S	2.06E-03	S
8.4	3.20E-03	S	5.57E-01	W	7.46E-04	S	2.06E-03	S
8.6	3.20E-03	S	5.74E-01	W	7.46E-04	S	2.06E-03	S
8.8	3.20E-03	S	5.90E-01	W	7.46E-04	S	2.06E-03	S
9	3.20E-03	S	6.07E-01	W	7.46E-04	S	2.06E-03	S
9.2	3.20E-03	S	6.23E-01	W	7.46E-04	S	2.06E-03	S
9.4	3.20E-03	S	6.19E-01	W	7.46E-04	S	2.06E-03	S
9.6	3.20E-03	S	6.16E-01	W	7.46E-04	S	2.06E-03	S
9.8	3.20E-03	S	6.12E-01	W	7.46E-04	S	2.06E-03	S
10	3.20E-03	S	6.09E-01	W	7.46E-04	S	2.06E-03	S
10.2	3.20E-03	S	5.97E-01	W	7.46E-04	S	2.06E-03	S
10.4	3.20E-03	S	5.75E-01	W	7.46E-04	S	2.06E-03	S
10.6	3.20E-03	S	5.54E-01	W	7.46E-04	S	2.06E-03	S
10.8	3.20E-03	S	5.53E-01	W	7.46E-04	S	2.06E-03	S
11	3.20E-03	S	5.59E-01	W	7.46E-04	S	2.06E-03	S
11.2	3.20E-03	S	5.64E-01	W	7.46E-04	S	2.06E-03	S
11.4	3.20E-03	S	5.70E-01	W	7.46E-04	S	2.06E-03	S
11.6	3.20E-03	S	5.76E-01	W	7.46E-04	S	2.06E-03	S
11.8	3.20E-03	S	5.81E-01	W	7.46E-04	S	2.06E-03	S
12	3.20E-03	S	5.87E-01	W	7.46E-04	S	2.06E-03	S
12.2	3.20E-03	S	5.92E-01	W	7.46E-04	S	2.06E-03	S
12.4	3.20E-03	S	5.98E-01	W	7.46E-04	S	2.06E-03	S
12.6	3.20E-03	S	6.03E-01	W	7.46E-04	S	2.06E-03	S
12.8	3.20E-03	S	6.09E-01	W	7.46E-04	S	2.06E-03	S
13	3.20E-03	S	6.14E-01	W	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	5.90E-01		5.27E+00		3.87E-01		2.98E-01	

Table C-5-50. Leachate Concentrations for Gypsum Export, Waste ID UAU Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	5.18E-02	S	3.23E-04	S	6.72E-02	W	1.26E-02	S
3	5.33E-02	S	3.22E-04	S	6.77E-02	W	1.26E-02	S
3.2	5.48E-02	S	3.20E-04	S	6.81E-02	W	1.25E-02	S
3.4	5.62E-02	S	3.19E-04	S	6.85E-02	W	1.24E-02	S
3.6	5.75E-02	S	3.17E-04	S	6.89E-02	W	1.23E-02	S
3.8	5.88E-02	S	3.16E-04	S	6.92E-02	W	1.23E-02	S
4	6.01E-02	S	3.15E-04	S	6.96E-02	W	1.22E-02	S
4.2	6.13E-02	S	3.14E-04	S	6.99E-02	W	1.22E-02	S
4.4	6.25E-02	S	3.13E-04	S	7.02E-02	W	1.21E-02	S
4.6	4.05E-02	S	2.36E-04	S	6.78E-02	W	9.84E-03	S
4.8	2.40E-02	S	1.69E-04	S	6.49E-02	W	7.68E-03	S
5	1.45E-02	S	1.23E-04	S	6.22E-02	W	6.06E-03	S
5.2	1.33E-02	S	4.53E-05	S	6.18E-02	W	4.97E-03	S
5.4	1.28E-02	S	1.61E-05	S	6.17E-02	W	4.13E-03	S
5.6	1.24E-02	S	5.95E-06	S	6.16E-02	W	3.45E-03	S
5.8	1.20E-02	S	3.00E-06	S	6.15E-02	W	2.90E-03	S
6	1.22E-02	S	3.00E-06	S	6.06E-02	W	2.78E-03	S
6.2	1.26E-02	S	3.05E-06	S	5.96E-02	W	2.78E-03	S
6.4	1.30E-02	S	4.06E-06	S	5.86E-02	W	2.78E-03	S
6.6	1.34E-02	S	5.36E-06	S	5.76E-02	W	2.78E-03	S
6.8	1.38E-02	S	7.03E-06	S	5.67E-02	W	2.78E-03	S
7	1.42E-02	S	9.14E-06	S	5.59E-02	W	2.78E-03	S
7.2	1.45E-02	S	7.18E-06	S	5.58E-02	W	2.78E-03	S
7.4	1.48E-02	S	5.38E-06	S	5.57E-02	W	2.78E-03	S
7.6	1.51E-02	S	4.06E-06	S	5.57E-02	W	2.78E-03	S
7.8	1.54E-02	S	3.09E-06	S	5.57E-02	W	2.78E-03	S
8	1.57E-02	S	3.00E-06	S	5.56E-02	W	2.78E-03	S

Table C-5-50. Leachate Concentrations for Gypsum Export, Waste ID UAU Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	1.60E-02	S	3.00E-06	S	5.56E-02	W	2.78E-03	S
8.4	1.65E-02	S	3.00E-06	S	5.73E-02	W	2.78E-03	S
8.6	1.70E-02	S	3.00E-06	S	5.91E-02	W	2.78E-03	S
8.8	1.74E-02	S	3.00E-06	S	6.09E-02	W	2.78E-03	S
9	1.79E-02	S	3.00E-06	S	6.27E-02	W	2.78E-03	S
9.2	1.83E-02	S	3.00E-06	S	6.44E-02	W	2.78E-03	S
9.4	1.73E-02	S	3.00E-06	S	6.44E-02	W	2.78E-03	S
9.6	1.64E-02	S	4.37E-06	S	6.43E-02	W	2.78E-03	S
9.8	1.56E-02	S	6.64E-06	S	6.43E-02	W	2.78E-03	S
10	1.48E-02	S	1.00E-05	S	6.42E-02	W	2.78E-03	S
10.2	1.46E-02	S	8.99E-06	S	6.21E-02	W	2.78E-03	S
10.4	1.50E-02	S	4.36E-06	S	5.77E-02	W	2.78E-03	S
10.6	1.55E-02	S	3.00E-06	S	5.37E-02	W	2.78E-03	S
10.8	1.58E-02	S	3.00E-06	S	5.36E-02	W	2.78E-03	S
11	1.61E-02	S	3.00E-06	S	5.46E-02	W	2.78E-03	S
11.2	1.65E-02	S	3.81E-06	S	5.57E-02	W	2.78E-03	S
11.4	1.68E-02	S	4.96E-06	S	5.67E-02	W	2.78E-03	S
11.6	1.71E-02	S	6.43E-06	S	5.78E-02	W	2.78E-03	S
11.8	1.74E-02	S	8.29E-06	S	5.88E-02	W	2.78E-03	S
12	1.77E-02	S	1.06E-05	S	5.99E-02	W	2.78E-03	S
12.2	1.80E-02	S	1.36E-05	S	6.10E-02	W	2.78E-03	S
12.4	1.84E-02	S	1.74E-05	S	6.20E-02	W	2.78E-03	S
12.6	1.87E-02	S	2.20E-05	S	6.31E-02	W	2.78E-03	S
12.8	1.90E-02	S	2.78E-05	S	6.41E-02	W	2.78E-03	S
13	1.93E-02	S	3.51E-05	S	6.52E-02	W	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	4.60E-01		2.37E-03		5.16E-01		9.23E-02	

Table C-5-50. Leachate Concentrations for Gypsum Export, Waste ID UAU Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	4.04E-01	S	1.34E-02	S	1.90E-01	S
3	4.00E-01	S	1.33E-02	S	1.88E-01	S
3.2	3.97E-01	S	1.32E-02	S	1.86E-01	S
3.4	3.94E-01	S	1.31E-02	S	1.85E-01	S
3.6	3.91E-01	S	1.31E-02	S	1.83E-01	S
3.8	3.88E-01	S	1.30E-02	S	1.82E-01	S
4	3.85E-01	S	1.29E-02	S	1.81E-01	S
4.2	3.83E-01	S	1.28E-02	S	1.79E-01	S
4.4	3.80E-01	S	1.28E-02	S	1.78E-01	S
4.6	3.21E-01	S	1.07E-02	S	1.27E-01	S
4.8	2.62E-01	S	8.74E-03	S	8.46E-02	S
5	2.16E-01	S	7.17E-03	S	5.73E-02	S
5.2	1.57E-01	S	5.56E-03	S	4.49E-02	S
5.4	1.13E-01	S	4.32E-03	S	3.60E-02	S
5.6	8.31E-02	S	3.39E-03	S	2.91E-02	S
5.8	6.15E-02	S	2.68E-03	S	2.37E-02	S
6	5.81E-02	S	3.03E-03	S	2.71E-02	S
6.2	5.93E-02	S	3.83E-03	S	3.46E-02	S
6.4	6.04E-02	S	4.80E-03	S	4.37E-02	S
6.6	6.16E-02	S	5.98E-03	S	5.48E-02	S
6.8	6.28E-02	S	7.40E-03	S	6.83E-02	S
7	6.39E-02	S	9.10E-03	S	8.46E-02	S
7.2	6.30E-02	S	9.19E-03	S	8.47E-02	S
7.4	6.18E-02	S	9.10E-03	S	8.28E-02	S
7.6	6.08E-02	S	9.01E-03	S	8.11E-02	S
7.8	5.97E-02	S	8.92E-03	S	7.94E-02	S
8	5.88E-02	S	8.83E-03	S	7.78E-02	S

Table C-5-50. Leachate Concentrations for Gypsum Export, Waste ID UAU Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	5.78E-02	S	8.75E-03	S	7.63E-02	S
8.4	5.68E-02	S	8.90E-03	S	7.95E-02	S
8.6	5.57E-02	S	9.06E-03	S	8.30E-02	S
8.8	5.47E-02	S	9.22E-03	S	8.65E-02	S
9	5.38E-02	S	9.39E-03	S	9.02E-02	S
9.2	5.30E-02	S	9.55E-03	S	9.37E-02	S
9.4	5.41E-02	S	9.74E-03	S	9.44E-02	S
9.6	5.53E-02	S	9.92E-03	S	9.50E-02	S
9.8	5.65E-02	S	1.01E-02	S	9.57E-02	S
10	5.77E-02	S	1.03E-02	S	9.63E-02	S
10.2	5.91E-02	S	1.05E-02	S	9.52E-02	S
10.4	6.08E-02	S	1.06E-02	S	9.23E-02	S
10.6	6.25E-02	S	1.07E-02	S	8.94E-02	S
10.8	6.56E-02	S	1.08E-02	S	8.40E-02	S
11	6.93E-02	S	1.09E-02	S	7.82E-02	S
11.2	7.30E-02	S	1.09E-02	S	7.29E-02	S
11.4	7.70E-02	S	1.10E-02	S	6.81E-02	S
11.6	8.10E-02	S	1.10E-02	S	6.36E-02	S
11.8	8.52E-02	S	1.11E-02	S	5.95E-02	S
12	8.96E-02	S	1.11E-02	S	5.58E-02	S
12.2	9.41E-02	S	1.11E-02	S	5.23E-02	S
12.4	9.87E-02	S	1.12E-02	S	4.91E-02	S
12.6	1.04E-01	S	1.12E-02	S	4.61E-02	S
12.8	1.08E-01	S	1.13E-02	S	4.34E-02	S
13	1.14E-01	S	1.13E-02	S	4.08E-02	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	2.94E+00		9.81E-02		1.38E+00	

Table C-5-51. Leachate Concentrations for Gypsum Export, Waste ID WAU Med

Sample ID	WAU-[Med] (P,1,1)
Date Exported	9/20/2011, 7:38 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	1.43E-01	S	8.39E+00	W	1.20E-03	S	1.48E-02	S
3	1.44E-01	S	8.38E+00	W	8.16E-04	S	1.47E-02	S
3.2	1.51E-01	S	8.33E+00	W	7.46E-04	S	1.42E-02	S
3.4	1.57E-01	S	8.27E+00	W	7.46E-04	S	1.37E-02	S
3.6	1.63E-01	S	8.23E+00	W	7.46E-04	S	1.31E-02	S
3.8	1.70E-01	S	8.18E+00	W	7.46E-04	S	1.27E-02	S
4	1.76E-01	S	8.14E+00	W	7.46E-04	S	1.22E-02	S
4.2	1.82E-01	S	8.10E+00	W	7.46E-04	S	1.18E-02	S
4.4	1.86E-01	S	8.06E+00	W	7.46E-04	S	1.15E-02	S
4.6	1.65E-01	S	8.07E+00	W	7.46E-04	S	1.15E-02	S
4.8	1.45E-01	S	8.08E+00	W	7.46E-04	S	1.15E-02	S
5	1.18E-01	S	8.10E+00	W	7.46E-04	S	1.13E-02	S
5.2	1.13E-01	S	8.21E+00	W	7.46E-04	S	1.09E-02	S
5.4	1.08E-01	S	8.32E+00	W	7.46E-04	S	1.04E-02	S
5.6	9.56E-02	S	8.43E+00	W	7.46E-04	S	9.59E-03	S
5.8	7.29E-02	S	8.55E+00	W	7.46E-04	S	8.19E-03	S
6	5.05E-02	S	8.66E+00	W	7.46E-04	S	6.78E-03	S
6.2	2.59E-02	S	8.75E+00	W	7.46E-04	S	5.06E-03	S
6.4	1.36E-02	S	8.84E+00	W	7.46E-04	S	3.81E-03	S
6.6	7.66E-03	S	8.92E+00	W	7.46E-04	S	2.95E-03	S
6.8	5.85E-03	S	8.94E+00	W	7.46E-04	S	2.55E-03	S
7	4.50E-03	S	8.97E+00	W	7.46E-04	S	2.22E-03	S
7.2	4.51E-03	S	8.95E+00	W	7.46E-04	S	2.06E-03	S
7.4	6.16E-03	S	8.86E+00	W	7.46E-04	S	2.06E-03	S
7.6	8.33E-03	S	8.78E+00	W	7.46E-04	S	2.06E-03	S
7.8	1.12E-02	S	8.70E+00	W	7.46E-04	S	2.06E-03	S
8	1.49E-02	S	8.62E+00	W	7.46E-04	S	2.06E-03	S

Table C-5-51. Leachate Concentrations for Gypsum Export, Waste ID WAU Med

Sample ID	WAU-[Med] (P,1,1)
Date Exported	9/20/2011, 7:38 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	2.18E-02	S	8.54E+00	W	7.46E-04	S	2.06E-03	S
8.4	3.52E-02	S	8.46E+00	W	7.46E-04	S	2.06E-03	S
8.6	4.37E-02	S	8.39E+00	W	7.46E-04	S	2.06E-03	S
8.8	5.41E-02	S	8.33E+00	W	7.46E-04	S	2.06E-03	S
9	5.60E-02	S	8.27E+00	W	7.46E-04	S	2.06E-03	S
9.2	4.54E-02	S	8.19E+00	W	7.46E-04	S	2.06E-03	S
9.4	3.86E-02	S	8.02E+00	W	7.46E-04	S	2.06E-03	S
9.6	3.29E-02	S	7.87E+00	W	7.46E-04	S	2.06E-03	S
9.8	2.81E-02	S	7.72E+00	W	7.46E-04	S	2.06E-03	S
10	2.45E-02	S	7.68E+00	W	7.46E-04	S	2.06E-03	S
10.2	2.06E-02	S	7.75E+00	W	7.46E-04	S	2.06E-03	S
10.4	1.73E-02	S	7.82E+00	W	7.46E-04	S	2.06E-03	S
10.6	1.46E-02	S	7.89E+00	W	7.46E-04	S	2.06E-03	S
10.8	1.24E-02	S	7.96E+00	W	7.46E-04	S	2.06E-03	S
11	1.22E-02	S	8.02E+00	W	7.46E-04	S	2.06E-03	S
11.2	1.62E-02	S	8.03E+00	W	7.46E-04	S	2.06E-03	S
11.4	2.14E-02	S	8.03E+00	W	7.46E-04	S	2.06E-03	S
11.6	2.82E-02	S	8.04E+00	W	7.46E-04	S	2.06E-03	S
11.8	3.69E-02	S	8.04E+00	W	7.46E-04	S	2.06E-03	S
12	4.81E-02	S	8.05E+00	W	7.46E-04	S	2.06E-03	S
12.2	6.25E-02	S	8.05E+00	W	7.46E-04	S	2.06E-03	S
12.4	8.07E-02	S	8.06E+00	W	7.46E-04	S	2.06E-03	S
12.6	1.04E-01	S	8.07E+00	W	7.46E-04	S	2.06E-03	S
12.8	1.26E-01	S	8.07E+00	W	7.46E-04	S	2.06E-03	S
13	1.37E-01	S	8.08E+00	W	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	1.20E+00		5.77E+01		5.34E-03		9.42E-02	

Table C-5-51. Leachate Concentrations for Gypsum Export, Waste ID WAU Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	4.84E-02	S	8.35E-06	S	4.24E-03	S	4.53E-03	S
3	4.67E-02	S	7.28E-06	S	3.80E-03	S	4.50E-03	S
3.2	4.30E-02	S	6.00E-06	S	3.80E-03	S	4.15E-03	S
3.4	3.87E-02	S	5.00E-06	S	3.80E-03	S	3.84E-03	S
3.6	3.51E-02	S	4.21E-06	S	3.80E-03	S	3.57E-03	S
3.8	3.20E-02	S	3.58E-06	S	3.80E-03	S	3.34E-03	S
4	2.92E-02	S	3.07E-06	S	3.80E-03	S	3.13E-03	S
4.2	2.69E-02	S	3.00E-06	S	3.80E-03	S	2.94E-03	S
4.4	2.47E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
4.6	2.10E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
4.8	1.79E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
5	1.40E-02	S	2.32E-06	S	3.80E-03	S	2.78E-03	S
5.2	1.18E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
5.4	9.92E-03	S	3.71E-06	S	3.80E-03	S	2.78E-03	S
5.6	8.90E-03	S	4.64E-06	S	3.90E-03	S	2.78E-03	S
5.8	8.82E-03	S	5.74E-06	S	4.19E-03	S	2.78E-03	S
6	8.82E-03	S	6.38E-06	S	4.58E-03	S	2.78E-03	S
6.2	9.03E-03	S	5.25E-06	S	5.23E-03	W	2.78E-03	S
6.4	9.23E-03	S	4.35E-06	S	5.96E-03	W	2.78E-03	S
6.6	9.40E-03	S	3.62E-06	S	6.71E-03	W	2.78E-03	S
6.8	9.35E-03	S	3.03E-06	S	7.24E-03	W	2.78E-03	S
7	9.30E-03	S	3.00E-06	S	7.80E-03	W	2.78E-03	S
7.2	9.21E-03	S	3.00E-06	S	8.35E-03	W	2.78E-03	S
7.4	9.06E-03	S	3.00E-06	S	8.87E-03	W	2.78E-03	S
7.6	8.92E-03	S	3.00E-06	S	9.40E-03	W	2.78E-03	S
7.8	8.79E-03	S	3.00E-06	S	9.96E-03	W	2.78E-03	S
8	8.66E-03	S	3.00E-06	S	1.05E-02	W	2.78E-03	S

Table C-5-51. Leachate Concentrations for Gypsum Export, Waste ID WAU Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	8.40E-03	S	3.00E-06	S	1.11E-02	W	2.78E-03	S
8.4	7.99E-03	S	3.00E-06	S	1.15E-02	W	2.78E-03	S
8.6	7.52E-03	S	3.00E-06	S	1.13E-02	W	2.78E-03	S
8.8	7.10E-03	S	3.00E-06	S	1.11E-02	W	2.78E-03	S
9	6.67E-03	S	3.00E-06	S	1.11E-02	W	2.78E-03	S
9.2	6.27E-03	S	3.00E-06	S	1.14E-02	W	2.78E-03	S
9.4	6.08E-03	S	3.00E-06	S	1.18E-02	W	2.78E-03	S
9.6	5.90E-03	S	3.00E-06	S	1.22E-02	W	2.78E-03	S
9.8	5.73E-03	S	3.00E-06	S	1.27E-02	W	2.78E-03	S
10	5.81E-03	S	3.00E-06	S	1.28E-02	W	2.78E-03	S
10.2	5.90E-03	S	3.00E-06	S	1.28E-02	W	2.78E-03	S
10.4	6.00E-03	S	3.00E-06	S	1.28E-02	W	2.78E-03	S
10.6	6.09E-03	S	3.00E-06	S	1.28E-02	W	2.78E-03	S
10.8	6.19E-03	S	3.00E-06	S	1.28E-02	W	2.78E-03	S
11	6.33E-03	S	3.00E-06	S	1.35E-02	S	2.78E-03	S
11.2	6.68E-03	S	3.05E-06	S	1.56E-02	S	2.78E-03	S
11.4	7.05E-03	S	3.80E-06	S	1.80E-02	S	2.78E-03	S
11.6	7.43E-03	S	4.73E-06	S	2.07E-02	S	2.78E-03	S
11.8	7.83E-03	S	5.86E-06	S	2.37E-02	S	2.78E-03	S
12	8.24E-03	S	7.23E-06	S	2.71E-02	S	2.78E-03	S
12.2	8.66E-03	S	8.89E-06	S	2.86E-02	S	2.78E-03	S
12.4	9.10E-03	S	1.09E-05	S	2.86E-02	S	2.78E-03	S
12.6	9.55E-03	S	1.33E-05	S	2.86E-02	S	2.78E-03	S
12.8	1.00E-02	S	1.62E-05	S	2.86E-02	S	2.78E-03	S
13	1.05E-02	S	1.83E-05	S	2.86E-02	S	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	3.00E-01		1.16E-04		2.05E-01		2.89E-02	

Table C-5-51. Leachate Concentrations for Gypsum Export, Waste ID WAU Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	7.40E-01	S	3.23E-02	S	1.78E-01	S
3	7.05E-01	S	3.26E-02	S	1.61E-01	S
3.2	7.02E-01	S	3.28E-02	S	1.33E-01	S
3.4	7.15E-01	S	3.29E-02	S	1.07E-01	S
3.6	7.28E-01	S	3.30E-02	S	8.78E-02	S
3.8	7.40E-01	S	3.31E-02	S	7.26E-02	S
4	7.52E-01	S	3.32E-02	S	6.07E-02	S
4.2	7.63E-01	S	3.32E-02	S	5.11E-02	S
4.4	7.67E-01	S	3.33E-02	S	4.36E-02	S
4.6	6.54E-01	S	3.35E-02	S	3.98E-02	S
4.8	5.53E-01	S	3.36E-02	S	3.64E-02	S
5	4.09E-01	S	3.30E-02	S	3.36E-02	S
5.2	4.05E-01	S	3.19E-02	S	2.98E-02	S
5.4	4.00E-01	S	3.09E-02	S	2.66E-02	S
5.6	3.81E-01	S	2.95E-02	S	2.44E-02	S
5.8	3.38E-01	S	2.73E-02	S	2.37E-02	S
6	2.70E-01	S	2.50E-02	S	2.34E-02	S
6.2	1.58E-01	S	2.19E-02	S	2.38E-02	W
6.4	9.36E-02	S	1.93E-02	S	2.43E-02	W
6.6	5.84E-02	S	1.74E-02	S	2.46E-02	W
6.8	4.44E-02	S	1.70E-02	S	2.43E-02	W
7	3.41E-02	S	1.67E-02	S	2.40E-02	W
7.2	3.22E-02	S	1.71E-02	S	2.32E-02	W
7.4	3.87E-02	S	1.85E-02	S	2.20E-02	W
7.6	4.63E-02	S	1.99E-02	S	2.09E-02	W
7.8	5.52E-02	S	2.14E-02	S	1.98E-02	W
8	6.55E-02	S	2.29E-02	S	1.89E-02	W

Table C-5-51. Leachate Concentrations for Gypsum Export, Waste ID WAU Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	8.49E-02	S	2.42E-02	S	1.84E-02	W
8.4	1.21E-01	S	2.51E-02	S	1.85E-02	W
8.6	1.39E-01	S	2.58E-02	S	2.09E-02	W
8.8	1.60E-01	S	2.64E-02	S	2.36E-02	W
9	1.58E-01	S	2.68E-02	S	2.59E-02	W
9.2	1.28E-01	S	2.69E-02	S	2.68E-02	W
9.4	1.18E-01	S	2.62E-02	S	2.55E-02	W
9.6	1.09E-01	S	2.55E-02	S	2.44E-02	W
9.8	1.01E-01	S	2.49E-02	S	2.33E-02	W
10	1.07E-01	S	2.46E-02	S	2.27E-02	W
10.2	1.17E-01	S	2.47E-02	S	2.26E-02	W
10.4	1.28E-01	S	2.48E-02	S	2.25E-02	W
10.6	1.40E-01	S	2.49E-02	S	2.25E-02	W
10.8	1.52E-01	S	2.50E-02	S	2.24E-02	W
11	1.61E-01	S	2.50E-02	S	2.24E-02	W
11.2	1.74E-01	S	2.48E-02	S	2.22E-02	W
11.4	1.89E-01	S	2.45E-02	S	2.21E-02	W
11.6	2.05E-01	S	2.43E-02	S	2.19E-02	W
11.8	2.21E-01	S	2.40E-02	S	2.18E-02	W
12	2.39E-01	S	2.38E-02	S	2.16E-02	W
12.2	2.58E-01	S	2.36E-02	S	2.15E-02	W
12.4	2.78E-01	S	2.33E-02	S	2.14E-02	W
12.6	2.99E-01	S	2.31E-02	S	2.12E-02	W
12.8	3.21E-01	S	2.29E-02	S	2.11E-02	W
13	3.44E-01	S	2.27E-02	S	2.10E-02	W
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	4.93E+00		2.16E-01		1.03E+00	

Table C-5-52. Leachate Concentrations for Gypsum Export, Waste ID WAW Med

Sample ID	WAW-[Med] (P,1,1)
Date Exported	9/20/2011, 7:38 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	8.63E-03	S	2.88E-01	W	2.66E-03	S	1.80E-02	S
3	7.43E-03	S	2.82E-01	W	2.57E-03	S	1.75E-02	S
3.2	6.47E-03	S	2.76E-01	W	2.49E-03	S	1.70E-02	S
3.4	5.67E-03	S	2.71E-01	W	2.42E-03	S	1.66E-02	S
3.6	5.01E-03	S	2.66E-01	W	2.35E-03	S	1.63E-02	S
3.8	4.46E-03	S	2.61E-01	W	2.29E-03	S	1.59E-02	S
4	3.99E-03	S	2.57E-01	W	2.23E-03	S	1.56E-02	S
4.2	3.60E-03	S	2.53E-01	W	2.18E-03	S	1.53E-02	S
4.4	3.38E-03	S	2.54E-01	W	2.17E-03	S	1.46E-02	S
4.6	3.20E-03	S	2.53E-01	W	2.16E-03	S	1.41E-02	S
4.8	3.20E-03	S	2.42E-01	W	2.13E-03	S	1.34E-02	S
5	3.20E-03	S	2.32E-01	W	2.10E-03	S	1.29E-02	S
5.2	3.20E-03	S	2.23E-01	W	2.07E-03	S	1.23E-02	S
5.4	3.20E-03	S	2.28E-01	W	2.09E-03	S	1.15E-02	S
5.6	3.20E-03	S	2.41E-01	W	2.09E-03	S	1.03E-02	S
5.8	3.20E-03	S	2.40E-01	W	1.24E-03	S	4.22E-03	S
6	3.20E-03	S	2.43E-01	W	1.22E-03	S	3.96E-03	S
6.2	3.20E-03	S	2.44E-01	W	1.19E-03	S	3.67E-03	S
6.4	3.20E-03	S	2.33E-01	W	1.03E-03	S	3.07E-03	S
6.6	3.20E-03	S	2.24E-01	W	8.95E-04	S	2.58E-03	S
6.8	3.20E-03	S	2.15E-01	W	7.82E-04	S	2.18E-03	S
7	3.20E-03	S	2.12E-01	W	7.46E-04	S	2.06E-03	S
7.2	3.20E-03	S	2.12E-01	W	7.46E-04	S	2.06E-03	S
7.4	3.20E-03	S	2.12E-01	W	7.46E-04	S	2.06E-03	S
7.6	3.20E-03	S	2.12E-01	W	7.46E-04	S	2.06E-03	S
7.8	3.20E-03	S	2.12E-01	W	7.46E-04	S	2.06E-03	S
8	3.20E-03	S	2.12E-01	W	7.46E-04	S	2.06E-03	S

Table C-5-52. Leachate Concentrations for Gypsum Export, Waste ID WAW Med

Sample ID	WAW-[Med] (P,1,1)
Date Exported	9/20/2011, 7:38 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	3.20E-03	S	2.12E-01	W	7.46E-04	S	2.06E-03	S
8.4	3.20E-03	S	2.13E-01	W	7.46E-04	S	2.06E-03	S
8.6	3.20E-03	S	2.14E-01	W	7.46E-04	S	2.06E-03	S
8.8	3.20E-03	S	2.15E-01	W	7.46E-04	S	2.06E-03	S
9	3.20E-03	S	2.15E-01	W	7.46E-04	S	2.06E-03	S
9.2	3.20E-03	S	2.16E-01	W	7.46E-04	S	2.06E-03	S
9.4	3.20E-03	S	2.17E-01	W	7.46E-04	S	2.06E-03	S
9.6	3.20E-03	S	2.18E-01	W	7.46E-04	S	2.06E-03	S
9.8	3.20E-03	S	2.19E-01	W	7.46E-04	S	2.06E-03	S
10	3.20E-03	S	2.21E-01	W	7.46E-04	S	2.06E-03	S
10.2	3.20E-03	S	2.25E-01	W	7.46E-04	S	2.06E-03	S
10.4	3.20E-03	S	2.27E-01	W	7.46E-04	S	2.06E-03	S
10.6	3.20E-03	S	2.28E-01	W	7.46E-04	S	2.06E-03	S
10.8	3.20E-03	S	2.29E-01	W	7.46E-04	S	2.06E-03	S
11	3.20E-03	S	2.32E-01	W	7.46E-04	S	2.06E-03	S
11.2	3.20E-03	S	2.44E-01	W	7.46E-04	S	2.06E-03	S
11.4	3.20E-03	S	2.58E-01	W	7.46E-04	S	2.06E-03	S
11.6	3.20E-03	S	2.71E-01	W	7.46E-04	S	2.06E-03	S
11.8	3.20E-03	S	2.85E-01	W	7.46E-04	S	2.06E-03	S
12	3.20E-03	S	3.00E-01	W	7.46E-04	S	2.06E-03	S
12.2	3.20E-03	S	3.01E-01	W	7.46E-04	S	2.06E-03	S
12.4	3.20E-03	S	3.02E-01	W	7.46E-04	S	2.06E-03	S
12.6	3.20E-03	S	3.04E-01	W	7.46E-04	S	2.06E-03	S
12.8	3.20E-03	S	3.05E-01	W	7.46E-04	S	2.06E-03	S
13	3.20E-03	S	3.06E-01	W	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	5.63E-02		2.47E+00		1.95E-02		1.32E-01	

Table C-5-52. Leachate Concentrations for Gypsum Export, Waste ID WAW Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	7.67E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
3	6.97E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
3.2	6.38E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
3.4	5.87E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
3.6	5.42E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
3.8	5.03E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
4	4.69E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
4.2	4.38E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
4.4	4.12E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
4.6	3.88E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
4.8	3.64E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
5	3.42E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
5.2	3.22E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
5.4	3.02E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
5.6	2.75E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
5.8	1.97E-02	S	3.00E-06	S	3.80E-03	S	2.78E-03	S
6	1.88E-02	S	3.00E-06	S	3.89E-03	S	2.78E-03	S
6.2	1.81E-02	S	3.00E-06	S	3.98E-03	S	2.78E-03	S
6.4	1.78E-02	S	3.00E-06	S	4.06E-03	S	2.78E-03	S
6.6	1.75E-02	S	3.00E-06	S	4.15E-03	S	2.78E-03	S
6.8	1.73E-02	S	3.00E-06	S	4.23E-03	S	2.78E-03	S
7	1.75E-02	S	3.00E-06	S	4.49E-03	S	2.78E-03	S
7.2	1.80E-02	S	3.00E-06	S	4.85E-03	S	2.78E-03	S
7.4	1.84E-02	S	3.00E-06	S	5.24E-03	S	2.78E-03	S
7.6	1.89E-02	S	3.00E-06	S	5.64E-03	S	2.78E-03	S
7.8	1.93E-02	S	3.00E-06	S	6.06E-03	S	2.78E-03	S
8	1.98E-02	S	3.00E-06	S	6.51E-03	S	2.78E-03	S

Table C-5-52. Leachate Concentrations for Gypsum Export, Waste ID WAW Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	2.03E-02	S	3.00E-06	S	6.97E-03	S	2.78E-03	S
8.4	2.02E-02	S	3.00E-06	S	7.17E-03	S	2.78E-03	S
8.6	2.00E-02	S	3.00E-06	S	7.35E-03	S	2.78E-03	S
8.8	1.99E-02	S	3.00E-06	S	7.52E-03	S	2.78E-03	S
9	1.97E-02	S	3.00E-06	S	7.70E-03	S	2.78E-03	S
9.2	1.96E-02	S	3.00E-06	S	7.87E-03	S	2.78E-03	S
9.4	1.94E-02	S	3.00E-06	S	8.05E-03	S	2.78E-03	S
9.6	1.93E-02	S	3.00E-06	S	8.22E-03	S	2.78E-03	S
9.8	1.78E-02	S	3.00E-06	S	7.42E-03	S	2.78E-03	S
10	1.52E-02	S	3.00E-06	S	5.94E-03	S	2.78E-03	S
10.2	1.34E-02	S	3.00E-06	S	5.81E-03	S	2.78E-03	S
10.4	1.22E-02	S	3.00E-06	S	5.69E-03	S	2.78E-03	S
10.6	1.25E-02	S	3.00E-06	S	6.94E-03	S	2.78E-03	S
10.8	1.29E-02	S	3.00E-06	S	8.51E-03	S	2.78E-03	S
11	1.32E-02	S	2.32E-06	S	9.92E-03	S	2.78E-03	S
11.2	1.27E-02	S	3.00E-06	S	1.14E-02	S	2.78E-03	S
11.4	1.23E-02	S	3.00E-06	S	1.32E-02	S	2.78E-03	S
11.6	1.18E-02	S	3.00E-06	S	1.51E-02	S	2.78E-03	S
11.8	1.14E-02	S	3.00E-06	S	1.73E-02	S	2.78E-03	S
12	1.11E-02	S	1.80E-06	S	1.98E-02	S	2.78E-03	S
12.2	1.07E-02	S	3.00E-06	S	1.98E-02	S	2.78E-03	S
12.4	1.04E-02	S	3.00E-06	S	1.98E-02	S	2.78E-03	S
12.6	1.00E-02	S	3.00E-06	S	1.98E-02	S	2.78E-03	S
12.8	9.73E-03	S	3.00E-06	S	1.98E-02	S	2.78E-03	S
13	9.43E-03	S	3.00E-06	S	1.98E-02	S	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	5.28E-01		2.43E-05		1.60E-01		2.26E-02	

Table C-5-52. Leachate Concentrations for Gypsum Export, Waste ID WAW Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	4.30E-01	S	2.53E-03	S	1.59E-01	S
3	3.76E-01	S	2.53E-03	S	1.16E-01	S
3.2	3.32E-01	S	2.53E-03	S	8.68E-02	S
3.4	2.96E-01	S	2.53E-03	S	6.61E-02	S
3.6	2.65E-01	S	2.53E-03	S	5.11E-02	S
3.8	2.38E-01	S	2.53E-03	S	4.00E-02	S
4	2.16E-01	S	2.53E-03	S	3.17E-02	S
4.2	1.98E-01	S	2.53E-03	S	2.56E-02	S
4.4	1.97E-01	S	2.53E-03	S	2.37E-02	S
4.6	1.98E-01	S	2.53E-03	S	2.21E-02	S
4.8	2.04E-01	S	2.53E-03	S	2.23E-02	S
5	2.10E-01	S	2.53E-03	S	2.25E-02	S
5.2	2.16E-01	S	2.53E-03	S	2.27E-02	S
5.4	2.13E-01	S	2.53E-03	S	2.12E-02	S
5.6	1.95E-01	S	2.53E-03	S	1.76E-02	S
5.8	5.77E-02	S	2.53E-03	S	1.03E-02	S
6	5.51E-02	S	2.53E-03	S	9.23E-03	S
6.2	5.16E-02	S	2.53E-03	S	8.36E-03	S
6.4	4.09E-02	S	2.53E-03	S	8.31E-03	S
6.6	3.26E-02	S	2.53E-03	S	8.26E-03	S
6.8	2.61E-02	S	2.53E-03	S	8.21E-03	S
7	2.52E-02	S	2.53E-03	S	8.45E-03	S
7.2	2.66E-02	S	2.53E-03	S	8.84E-03	S
7.4	2.80E-02	S	2.53E-03	S	9.25E-03	S
7.6	2.95E-02	S	2.53E-03	S	9.66E-03	S
7.8	3.11E-02	S	2.53E-03	S	1.01E-02	S
8	3.26E-02	S	2.53E-03	S	1.05E-02	S

Table C-5-52. Leachate Concentrations for Gypsum Export, Waste ID WAW Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	3.43E-02	S	2.53E-03	S	1.09E-02	S
8.4	3.47E-02	S	2.53E-03	S	1.11E-02	S
8.6	3.50E-02	S	2.53E-03	S	1.12E-02	S
8.8	3.52E-02	S	2.53E-03	S	1.14E-02	S
9	3.55E-02	S	2.53E-03	S	1.15E-02	S
9.2	3.58E-02	S	2.53E-03	S	1.17E-02	S
9.4	3.60E-02	S	2.53E-03	S	1.18E-02	S
9.6	3.63E-02	S	2.53E-03	S	1.19E-02	S
9.8	3.63E-02	S	2.53E-03	S	1.21E-02	S
10	3.62E-02	S	2.53E-03	S	1.22E-02	S
10.2	3.64E-02	S	2.53E-03	S	1.03E-02	S
10.4	3.95E-02	S	2.53E-03	S	8.32E-03	S
10.6	4.94E-02	S	2.53E-03	S	8.41E-03	S
10.8	6.17E-02	S	2.53E-03	S	8.54E-03	S
11	7.68E-02	S	2.53E-03	S	8.72E-03	S
11.2	9.47E-02	S	2.53E-03	S	9.16E-03	S
11.4	1.16E-01	S	2.53E-03	S	9.61E-03	S
11.6	1.42E-01	S	2.53E-03	S	1.01E-02	S
11.8	1.74E-01	S	2.53E-03	S	1.05E-02	S
12	2.11E-01	S	2.53E-03	S	1.10E-02	S
12.2	2.55E-01	S	2.53E-03	S	1.15E-02	S
12.4	3.09E-01	S	2.53E-03	S	1.20E-02	S
12.6	3.71E-01	S	2.53E-03	S	1.26E-02	S
12.8	4.46E-01	S	2.53E-03	S	1.31E-02	S
13	5.34E-01	S	2.53E-03	S	1.37E-02	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	3.62E+00		2.05E-02		8.80E-01	

Table C-5-53. Leachate Concentrations for Gypsum Export, Waste ID XAU Med

Sample ID	XAU-[Med] (P,1,1)
Date Exported	9/20/2011, 7:38 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	8.22E-03	S	5.63E-01	W	3.38E-03	S	2.37E-02	S
3	6.71E-03	S	5.64E-01	W	3.32E-03	S	2.28E-02	S
3.2	5.55E-03	S	5.65E-01	W	3.26E-03	S	2.19E-02	S
3.4	4.65E-03	S	5.66E-01	W	3.21E-03	S	2.11E-02	S
3.6	3.93E-03	S	5.67E-01	W	3.16E-03	S	2.04E-02	S
3.8	3.35E-03	S	5.68E-01	W	3.11E-03	S	1.97E-02	S
4	3.20E-03	S	5.66E-01	W	2.98E-03	S	1.92E-02	S
4.2	3.20E-03	S	5.63E-01	W	2.83E-03	S	1.88E-02	S
4.4	3.20E-03	S	5.60E-01	W	2.69E-03	S	1.84E-02	S
4.6	3.20E-03	S	5.57E-01	W	2.56E-03	S	1.80E-02	S
4.8	3.20E-03	S	5.55E-01	W	2.44E-03	S	1.77E-02	S
5	3.20E-03	S	5.52E-01	W	2.34E-03	S	1.73E-02	S
5.2	3.20E-03	S	5.50E-01	W	2.24E-03	S	1.70E-02	S
5.4	3.20E-03	S	5.48E-01	W	2.15E-03	S	1.67E-02	S
5.6	3.20E-03	S	5.46E-01	W	2.07E-03	S	1.65E-02	S
5.8	3.20E-03	S	5.44E-01	W	1.83E-03	S	1.58E-02	S
6	3.20E-03	S	5.42E-01	W	1.56E-03	S	1.50E-02	S
6.2	3.20E-03	S	5.39E-01	W	1.33E-03	S	1.43E-02	S
6.4	3.20E-03	S	5.37E-01	W	1.15E-03	S	1.36E-02	S
6.6	3.20E-03	S	5.35E-01	W	9.93E-04	S	1.30E-02	S
6.8	3.20E-03	S	5.34E-01	W	8.62E-04	S	1.24E-02	S
7	3.20E-03	S	5.32E-01	W	7.51E-04	S	1.19E-02	S
7.2	3.20E-03	S	5.42E-01	W	7.46E-04	S	1.11E-02	S
7.4	3.20E-03	S	5.52E-01	W	7.46E-04	S	1.03E-02	S
7.6	3.20E-03	S	5.63E-01	W	7.46E-04	S	9.65E-03	S
7.8	3.20E-03	S	5.70E-01	W	7.46E-04	S	8.25E-03	S
8	3.20E-03	S	5.70E-01	W	7.46E-04	S	5.98E-03	S

Table C-5-53. Leachate Concentrations for Gypsum Export, Waste ID XAU Med

Sample ID	XAU-[Med] (P,1,1)
Date Exported	9/20/2011, 7:38 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mod
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	3.20E-03	S	5.71E-01	W	7.46E-04	S	4.37E-03	S
8.4	3.20E-03	S	5.72E-01	W	7.46E-04	S	3.22E-03	S
8.6	3.20E-03	S	5.72E-01	W	7.46E-04	S	2.39E-03	S
8.8	3.20E-03	S	5.72E-01	W	7.46E-04	S	2.06E-03	S
9	3.20E-03	S	5.71E-01	W	7.46E-04	S	2.06E-03	S
9.2	3.20E-03	S	5.71E-01	W	7.46E-04	S	2.06E-03	S
9.4	3.20E-03	S	5.70E-01	W	7.46E-04	S	2.06E-03	S
9.6	3.20E-03	S	5.69E-01	W	7.46E-04	S	2.06E-03	S
9.8	3.20E-03	S	5.68E-01	W	7.46E-04	S	2.06E-03	S
10	3.20E-03	S	5.67E-01	W	7.46E-04	S	2.06E-03	S
10.2	3.20E-03	S	5.67E-01	W	7.46E-04	S	2.06E-03	S
10.4	3.20E-03	S	5.66E-01	W	7.46E-04	S	2.06E-03	S
10.6	3.20E-03	S	5.65E-01	W	7.46E-04	S	2.06E-03	S
10.8	3.20E-03	S	5.64E-01	W	7.46E-04	S	2.06E-03	S
11	3.20E-03	S	5.64E-01	W	7.46E-04	S	2.06E-03	S
11.2	3.20E-03	S	5.63E-01	W	7.46E-04	S	2.06E-03	S
11.4	3.20E-03	S	5.62E-01	W	7.46E-04	S	2.06E-03	S
11.6	3.20E-03	S	5.62E-01	W	7.46E-04	S	2.06E-03	S
11.8	3.20E-03	S	5.61E-01	W	7.46E-04	S	2.06E-03	S
12	3.20E-03	S	5.61E-01	S	7.46E-04	S	2.06E-03	S
12.2	3.20E-03	S	5.60E-01	S	7.46E-04	S	2.06E-03	S
12.4	3.20E-03	S	6.10E-01	S	7.46E-04	S	2.06E-03	S
12.6	3.20E-03	S	6.83E-01	S	7.46E-04	S	2.06E-03	S
12.8	3.20E-03	S	7.63E-01	S	7.46E-04	S	2.06E-03	S
13	3.20E-03	S	8.51E-01	S	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	4.39E-02		5.38E+00		2.17E-02		1.49E-01	

Table C-5-53. Leachate Concentrations for Gypsum Export, Waste ID XAU Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	7.53E-02	S	4.21E-04	S	1.19E-02	S	7.55E-03	S
3	6.20E-02	S	3.36E-04	S	9.33E-03	S	6.09E-03	S
3.2	5.16E-02	S	2.72E-04	S	7.41E-03	S	4.98E-03	S
3.4	4.35E-02	S	2.23E-04	S	5.97E-03	S	4.13E-03	S
3.6	3.70E-02	S	1.85E-04	S	4.87E-03	S	3.46E-03	S
3.8	3.17E-02	S	1.55E-04	S	4.01E-03	S	2.92E-03	S
4	2.77E-02	S	1.36E-04	S	4.16E-03	S	2.78E-03	S
4.2	2.44E-02	S	1.22E-04	S	4.71E-03	S	2.78E-03	S
4.4	2.16E-02	S	1.10E-04	S	5.30E-03	S	2.78E-03	S
4.6	1.92E-02	S	9.99E-05	S	5.94E-03	S	2.78E-03	S
4.8	1.72E-02	S	9.09E-05	S	6.62E-03	S	2.78E-03	S
5	1.55E-02	S	8.31E-05	S	7.35E-03	S	2.78E-03	S
5.2	1.40E-02	S	7.62E-05	S	8.12E-03	S	2.78E-03	S
5.4	1.27E-02	S	7.02E-05	S	8.94E-03	S	2.78E-03	S
5.6	1.15E-02	S	6.47E-05	S	9.81E-03	S	2.78E-03	S
5.8	1.18E-02	S	4.90E-05	S	1.04E-02	S	2.78E-03	S
6	1.28E-02	S	3.37E-05	S	1.09E-02	S	2.78E-03	S
6.2	1.38E-02	S	2.34E-05	S	1.14E-02	W	2.78E-03	S
6.4	1.49E-02	S	1.65E-05	S	1.18E-02	W	2.78E-03	S
6.6	1.60E-02	S	1.17E-05	S	1.23E-02	W	2.78E-03	S
6.8	1.71E-02	S	8.41E-06	S	1.28E-02	W	2.78E-03	S
7	1.83E-02	S	6.10E-06	S	1.33E-02	W	2.78E-03	S
7.2	1.81E-02	S	4.32E-06	S	1.38E-02	W	2.78E-03	S
7.4	1.77E-02	S	3.08E-06	S	1.43E-02	W	2.78E-03	S
7.6	1.74E-02	S	3.00E-06	S	1.47E-02	W	2.78E-03	S
7.8	1.72E-02	S	3.00E-06	S	1.50E-02	W	2.78E-03	S
8	1.73E-02	S	3.00E-06	S	1.49E-02	W	2.78E-03	S

Table C-5-53. Leachate Concentrations for Gypsum Export, Waste ID XAU Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	1.73E-02	S	3.00E-06	S	1.49E-02	W	2.78E-03	S
8.4	1.74E-02	S	3.00E-06	S	1.48E-02	W	2.78E-03	S
8.6	1.74E-02	S	3.00E-06	S	1.47E-02	W	2.78E-03	S
8.8	1.78E-02	S	3.00E-06	S	1.49E-02	W	2.78E-03	S
9	1.84E-02	S	3.00E-06	S	1.55E-02	W	2.78E-03	S
9.2	1.91E-02	S	3.00E-06	S	1.61E-02	W	2.78E-03	S
9.4	1.98E-02	S	3.00E-06	S	1.67E-02	W	2.78E-03	S
9.6	2.05E-02	S	3.18E-06	S	1.73E-02	W	2.78E-03	S
9.8	2.11E-02	S	3.58E-06	S	1.79E-02	W	2.78E-03	S
10	2.18E-02	S	4.02E-06	S	1.85E-02	W	2.78E-03	S
10.2	2.26E-02	S	4.51E-06	S	1.91E-02	W	2.78E-03	S
10.4	2.33E-02	S	5.05E-06	S	1.97E-02	W	2.78E-03	S
10.6	2.40E-02	S	5.64E-06	S	2.03E-02	W	2.78E-03	S
10.8	2.47E-02	S	6.28E-06	S	2.10E-02	W	2.78E-03	S
11	2.55E-02	S	6.98E-06	S	2.16E-02	S	2.78E-03	S
11.2	2.62E-02	S	7.75E-06	S	2.23E-02	S	2.78E-03	S
11.4	2.70E-02	S	8.58E-06	S	2.29E-02	S	2.78E-03	S
11.6	2.78E-02	S	9.49E-06	S	2.36E-02	S	2.78E-03	S
11.8	2.85E-02	S	1.05E-05	S	2.43E-02	S	2.78E-03	S
12	2.93E-02	S	1.15E-05	S	2.50E-02	S	2.78E-03	S
12.2	3.01E-02	S	1.27E-05	S	2.57E-02	S	2.78E-03	S
12.4	3.08E-02	S	1.65E-05	S	2.65E-02	S	2.78E-03	S
12.6	3.15E-02	S	2.24E-05	S	2.74E-02	S	2.78E-03	S
12.8	3.21E-02	S	3.04E-05	S	2.83E-02	S	2.78E-03	S
13	3.28E-02	S	4.11E-05	S	2.93E-02	S	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	4.06E-01		2.20E-03		2.00E-01		3.99E-02	

Table C-5-53. Leachate Concentrations for Gypsum Export, Waste ID XAU Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	8.56E-01	S	1.38E-02	S	4.39E-02	S
3	7.29E-01	S	1.38E-02	S	3.27E-02	S
3.2	6.27E-01	S	1.38E-02	S	2.49E-02	S
3.4	5.44E-01	S	1.38E-02	S	1.92E-02	S
3.6	4.76E-01	S	1.37E-02	S	1.51E-02	S
3.8	4.19E-01	S	1.37E-02	S	1.20E-02	S
4	4.18E-01	S	1.36E-02	S	1.11E-02	S
4.2	4.37E-01	S	1.33E-02	S	1.09E-02	S
4.4	4.56E-01	S	1.31E-02	S	1.07E-02	S
4.6	4.76E-01	S	1.29E-02	S	1.06E-02	S
4.8	4.95E-01	S	1.28E-02	S	1.04E-02	S
5	5.14E-01	S	1.26E-02	S	1.03E-02	S
5.2	5.33E-01	S	1.24E-02	S	1.01E-02	S
5.4	5.52E-01	S	1.23E-02	S	1.00E-02	S
5.6	5.70E-01	S	1.21E-02	S	9.87E-03	S
5.8	5.81E-01	S	1.20E-02	S	9.87E-03	S
6	5.86E-01	S	1.19E-02	S	9.92E-03	S
6.2	5.92E-01	S	1.17E-02	S	9.96E-03	S
6.4	5.97E-01	S	1.16E-02	S	1.00E-02	S
6.6	6.03E-01	S	1.15E-02	S	1.01E-02	S
6.8	6.08E-01	S	1.14E-02	S	1.01E-02	S
7	6.13E-01	S	1.13E-02	S	1.01E-02	S
7.2	6.39E-01	S	1.12E-02	S	1.04E-02	S
7.4	6.66E-01	S	1.12E-02	S	1.07E-02	S
7.6	6.94E-01	S	1.11E-02	S	1.10E-02	S
7.8	7.25E-01	S	1.10E-02	S	1.12E-02	S
8	7.61E-01	S	1.09E-02	S	1.13E-02	S

Table C-5-53. Leachate Concentrations for Gypsum Export, Waste ID XAU Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	7.97E-01	S	1.09E-02	S	1.14E-02	S
8.4	8.35E-01	S	1.09E-02	S	1.15E-02	S
8.6	8.74E-01	S	1.08E-02	S	1.16E-02	S
8.8	8.69E-01	S	1.07E-02	S	1.17E-02	S
9	8.24E-01	S	1.06E-02	S	1.18E-02	S
9.2	7.83E-01	S	1.05E-02	S	1.20E-02	S
9.4	7.44E-01	S	1.04E-02	S	1.21E-02	S
9.6	7.08E-01	S	1.03E-02	S	1.22E-02	S
9.8	6.74E-01	S	1.02E-02	S	1.24E-02	S
10	6.42E-01	S	1.01E-02	S	1.25E-02	S
10.2	6.13E-01	S	1.00E-02	S	1.26E-02	S
10.4	5.85E-01	S	9.91E-03	S	1.28E-02	S
10.6	5.60E-01	S	9.82E-03	S	1.29E-02	S
10.8	5.35E-01	S	9.73E-03	S	1.30E-02	S
11	5.13E-01	S	9.65E-03	S	1.32E-02	S
11.2	4.91E-01	S	9.57E-03	S	1.33E-02	S
11.4	4.71E-01	S	9.49E-03	S	1.34E-02	S
11.6	4.52E-01	S	9.41E-03	S	1.35E-02	S
11.8	4.34E-01	S	9.33E-03	S	1.37E-02	S
12	4.17E-01	S	9.26E-03	S	1.38E-02	S
12.2	4.01E-01	S	9.18E-03	S	1.39E-02	S
12.4	4.78E-01	S	9.11E-03	S	1.46E-02	S
12.6	6.08E-01	S	9.03E-03	S	1.54E-02	S
12.8	7.71E-01	S	8.95E-03	S	1.63E-02	S
13	9.74E-01	S	8.88E-03	S	1.73E-02	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	5.75E+00		9.03E-02		2.14E-01	

Table C-5-54. Leachate Concentrations for Gypsum Export, Waste ID XAW Med

Sample ID XAW-[Med] (P,1,1)
Date Exported 9/20/2011, 7:38 PM
Database Name C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term modeling\EPA Rpt 4 (5

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	0.003608426	S	0.024720832	S	0.002836	S	0.010197185	S
3	3.20E-03	S	2.35E-02	S	2.81E-03	S	9.86E-03	S
3.2	3.20E-03	S	2.34E-02	S	2.80E-03	S	9.72E-03	S
3.4	3.20E-03	S	2.33E-02	S	2.78E-03	S	9.59E-03	S
3.6	3.20E-03	S	2.32E-02	S	2.77E-03	S	9.47E-03	S
3.8	3.20E-03	S	2.32E-02	S	2.76E-03	S	9.35E-03	S
4	3.20E-03	S	2.31E-02	S	2.74E-03	S	9.25E-03	S
4.2	3.20E-03	S	2.30E-02	S	2.73E-03	S	9.14E-03	S
4.4	3.20E-03	S	2.24E-02	S	2.62E-03	S	8.88E-03	S
4.6	3.20E-03	S	2.18E-02	S	2.52E-03	S	8.63E-03	S
4.8	3.20E-03	S	2.13E-02	S	2.42E-03	S	8.40E-03	S
5	3.20E-03	S	2.08E-02	S	2.33E-03	S	8.18E-03	S
5.2	3.20E-03	S	1.85E-02	S	1.85E-03	S	6.20E-03	S
5.4	3.20E-03	S	1.65E-02	S	1.47E-03	S	4.68E-03	S
5.6	3.20E-03	S	1.48E-02	S	1.17E-03	S	3.57E-03	S
5.8	3.20E-03	S	1.33E-02	S	9.47E-04	S	2.75E-03	S
6	3.20E-03	S	1.20E-02	S	7.70E-04	S	2.14E-03	S
6.2	3.20E-03	S	1.34E-02	S	7.46E-04	S	2.06E-03	S
6.4	3.20E-03	S	1.55E-02	S	7.46E-04	S	2.06E-03	S
6.6	3.20E-03	S	1.79E-02	S	7.46E-04	S	2.06E-03	S
6.8	3.20E-03	S	2.05E-02	S	7.46E-04	S	2.06E-03	S
7	3.20E-03	S	2.35E-02	S	7.46E-04	S	2.06E-03	S
7.2	3.20E-03	S	2.70E-02	S	7.46E-04	S	2.06E-03	S
7.4	3.20E-03	S	3.08E-02	S	7.46E-04	S	2.06E-03	S
7.6	3.20E-03	S	3.50E-02	S	7.46E-04	S	2.06E-03	S
7.8	3.20E-03	S	3.97E-02	S	7.46E-04	S	2.06E-03	S
8	3.20E-03	S	4.43E-02	S	7.46E-04	S	2.06E-03	S

Table C-5-54. Leachate Concentrations for Gypsum Export, Waste ID XAW Med

Sample ID XAW-[Med] (P,1,1)
Date Exported 9/20/2011, 7:38 PM
Database Name C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term modeling\EPA Rpt 4 (5

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	3.20E-03	S	4.41E-02	S	7.46E-04	S	2.06E-03	S
8.4	3.20E-03	S	4.39E-02	S	7.46E-04	S	2.06E-03	S
8.6	3.20E-03	S	4.38E-02	S	7.46E-04	S	2.06E-03	S
8.8	3.20E-03	S	4.36E-02	S	7.46E-04	S	2.06E-03	S
9	3.20E-03	S	4.35E-02	S	7.46E-04	S	2.06E-03	S
9.2	3.20E-03	S	4.33E-02	S	7.46E-04	S	2.06E-03	S
9.4	3.20E-03	S	4.46E-02	S	7.46E-04	S	2.06E-03	S
9.6	3.20E-03	S	4.68E-02	S	7.46E-04	S	2.06E-03	S
9.8	3.20E-03	S	4.90E-02	S	7.46E-04	S	2.06E-03	S
10	3.20E-03	S	5.12E-02	S	7.46E-04	S	2.06E-03	S
10.2	3.20E-03	S	5.39E-02	S	7.46E-04	S	2.06E-03	S
10.4	3.20E-03	S	5.77E-02	S	7.46E-04	S	2.06E-03	S
10.6	3.20E-03	S	6.17E-02	S	7.46E-04	S	2.06E-03	S
10.8	3.20E-03	S	6.59E-02	S	7.46E-04	S	2.06E-03	S
11	3.20E-03	S	7.04E-02	S	7.46E-04	S	2.06E-03	S
11.2	3.20E-03	S	7.50E-02	S	7.46E-04	S	2.06E-03	S
11.4	3.20E-03	S	9.37E-02	S	7.46E-04	S	2.06E-03	S
11.6	3.20E-03	S	1.33E-01	S	7.46E-04	S	2.06E-03	S
11.8	3.20E-03	S	1.87E-01	S	7.46E-04	S	2.06E-03	S
12	3.20E-03	S	2.62E-01	S	7.46E-04	S	2.06E-03	S
12.2	3.20E-03	S	3.65E-01	S	7.46E-04	S	2.06E-03	S
12.4	3.20E-03	S	3.96E-01	S	7.46E-04	S	2.06E-03	S
12.6	3.20E-03	S	3.96E-01	S	7.46E-04	S	2.06E-03	S
12.8	3.20E-03	S	3.96E-01	S	7.46E-04	S	2.06E-03	S
13	3.20E-03	S	3.96E-01	S	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		1.00E-03		1.70E-04		4.10E-04	
Availability (mg/kg)	2.56E-02		3.17E+00		2.13E-02		7.47E-02	

Table C-5-54. Leachate Concentrations for Gypsum Export, Waste ID XAW Med

Sample ID
Date Exported
Database Name 5-25-11 working db 3 reference-source term rev2).mdb

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	0.07718966	S	1.64626E-05	S	0.004344573	S	0.007361	S
3	6.91E-02	S	1.56E-05	S	3.80E-03	S	6.27E-03	S
3.2	6.44E-02	S	1.56E-05	S	3.80E-03	S	5.37E-03	S
3.4	6.04E-02	S	1.56E-05	S	3.80E-03	S	4.64E-03	S
3.6	5.68E-02	S	1.56E-05	S	3.80E-03	S	4.05E-03	S
3.8	5.36E-02	S	1.56E-05	S	3.80E-03	S	3.56E-03	S
4	5.07E-02	S	1.56E-05	S	3.80E-03	S	3.15E-03	S
4.2	4.81E-02	S	1.56E-05	S	3.80E-03	S	2.80E-03	S
4.4	4.19E-02	S	3.45E-05	S	3.80E-03	S	2.78E-03	S
4.6	3.65E-02	S	7.65E-05	S	3.80E-03	S	2.78E-03	S
4.8	3.21E-02	S	1.64E-04	S	3.80E-03	S	2.78E-03	S
5	2.83E-02	S	3.41E-04	S	3.80E-03	S	2.78E-03	S
5.2	2.93E-02	S	1.96E-04	S	3.80E-03	S	2.78E-03	S
5.4	3.05E-02	S	1.08E-04	S	3.80E-03	S	2.78E-03	S
5.6	3.17E-02	S	6.05E-05	S	3.80E-03	S	2.78E-03	S
5.8	3.30E-02	S	3.47E-05	S	3.80E-03	S	2.78E-03	S
6	3.42E-02	S	2.03E-05	S	3.80E-03	S	2.78E-03	S
6.2	3.43E-02	S	1.80E-05	S	4.50E-03	W	2.78E-03	S
6.4	3.43E-02	S	1.72E-05	S	5.48E-03	W	2.78E-03	S
6.6	3.42E-02	S	1.65E-05	S	6.62E-03	W	2.78E-03	S
6.8	3.41E-02	S	1.58E-05	S	7.95E-03	W	2.78E-03	S
7	3.32E-02	S	1.79E-05	S	8.65E-03	W	2.78E-03	S
7.2	3.21E-02	S	2.13E-05	S	9.10E-03	W	2.78E-03	S
7.4	3.11E-02	S	2.53E-05	S	9.57E-03	W	2.78E-03	S
7.6	3.01E-02	S	2.99E-05	S	1.00E-02	W	2.78E-03	S
7.8	2.91E-02	S	3.52E-05	S	1.05E-02	W	2.78E-03	S
8	2.84E-02	S	4.01E-05	S	1.10E-02	W	2.78E-03	S

Table C-5-54. Leachate Concentrations for Gypsum Export, Waste ID XAW Med

Sample ID
Date Exported
Database Name 5-25-11 working db 3 reference-source term rev2).mdb

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	2.86E-02	S	3.53E-05	S	1.09E-02	W	2.78E-03	S
8.4	2.88E-02	S	3.12E-05	S	1.09E-02	W	2.78E-03	S
8.6	2.90E-02	S	2.76E-05	S	1.08E-02	W	2.78E-03	S
8.8	2.92E-02	S	2.45E-05	S	1.08E-02	W	2.78E-03	S
9	2.94E-02	S	2.18E-05	S	1.07E-02	W	2.78E-03	S
9.2	2.96E-02	S	1.95E-05	S	1.07E-02	W	2.78E-03	S
9.4	2.97E-02	S	1.82E-05	S	1.09E-02	W	2.78E-03	S
9.6	2.98E-02	S	1.75E-05	S	1.13E-02	W	2.78E-03	S
9.8	2.98E-02	S	1.67E-05	S	1.17E-02	W	2.78E-03	S
10	2.98E-02	S	1.61E-05	S	1.21E-02	W	2.78E-03	S
10.2	3.01E-02	S	1.52E-05	S	1.23E-02	W	2.78E-03	S
10.4	3.10E-02	S	1.39E-05	S	1.22E-02	W	2.78E-03	S
10.6	3.18E-02	S	1.27E-05	S	1.21E-02	W	2.78E-03	S
10.8	3.27E-02	S	1.16E-05	S	1.19E-02	W	2.78E-03	S
11	3.36E-02	S	1.06E-05	S	1.18E-02	S	2.78E-03	S
11.2	3.45E-02	S	9.74E-06	S	1.17E-02	S	2.78E-03	S
11.4	3.43E-02	S	9.96E-06	S	1.16E-02	S	2.78E-03	S
11.6	3.32E-02	S	1.11E-05	S	1.14E-02	S	2.78E-03	S
11.8	3.22E-02	S	1.24E-05	S	1.13E-02	S	2.78E-03	S
12	3.12E-02	S	1.37E-05	S	1.12E-02	S	2.78E-03	S
12.2	3.03E-02	S	1.52E-05	S	1.10E-02	S	2.78E-03	S
12.4	2.94E-02	S	1.69E-05	S	1.09E-02	S	2.78E-03	S
12.6	2.86E-02	S	1.86E-05	S	1.08E-02	S	2.78E-03	S
12.8	2.78E-02	S	2.06E-05	S	1.07E-02	S	2.78E-03	S
13	2.70E-02	S	2.27E-05	S	1.05E-02	S	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		6.00E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	5.23E-01		2.58E-03		9.38E-02		4.75E-02	

Table C-5-54. Leachate Concentrations for Gypsum Export, Waste ID XAW Med

Sample ID
Date Exported
Database Name

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	0.3427866	S	0.00253	S	0.0547779	S
3	2.72E-01	S	2.53E-03	S	3.97E-02	S
3.2	2.22E-01	S	2.53E-03	S	2.79E-02	S
3.4	1.83E-01	S	2.53E-03	S	2.01E-02	S
3.6	1.52E-01	S	2.53E-03	S	1.47E-02	S
3.8	1.28E-01	S	2.53E-03	S	1.09E-02	S
4	1.09E-01	S	2.53E-03	S	8.27E-03	S
4.2	9.29E-02	S	2.53E-03	S	6.34E-03	S
4.4	8.86E-02	S	2.53E-03	S	6.13E-03	S
4.6	8.52E-02	S	2.53E-03	S	6.00E-03	S
4.8	8.20E-02	S	2.53E-03	S	5.88E-03	S
5	7.91E-02	S	2.53E-03	S	5.76E-03	S
5.2	7.74E-02	S	2.53E-03	S	5.86E-03	S
5.4	7.59E-02	S	2.53E-03	S	5.97E-03	S
5.6	7.45E-02	S	2.53E-03	S	6.07E-03	S
5.8	7.31E-02	S	2.53E-03	S	6.18E-03	S
6	7.18E-02	S	2.53E-03	S	6.28E-03	S
6.2	6.78E-02	W	2.53E-03	S	6.63E-03	S
6.4	6.36E-02	W	2.53E-03	S	7.04E-03	S
6.6	5.98E-02	W	2.53E-03	S	7.46E-03	S
6.8	5.63E-02	W	2.53E-03	S	7.90E-03	S
7	6.83E-02	W	2.53E-03	S	9.21E-03	S
7.2	8.97E-02	W	2.53E-03	S	1.10E-02	S
7.4	1.17E-01	W	2.53E-03	S	1.32E-02	S
7.6	1.51E-01	W	2.53E-03	S	1.56E-02	S
7.8	1.94E-01	W	2.53E-03	S	1.85E-02	S
8	2.42E-01	W	2.53E-03	S	2.14E-02	S

Table C-5-54. Leachate Concentrations for Gypsum Export, Waste ID XAW Med

Sample ID
Date Exported
Database Name

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	2.42E-01	W	2.53E-03	S	2.09E-02	S
8.4	2.42E-01	W	2.53E-03	S	2.05E-02	S
8.6	2.42E-01	W	2.53E-03	S	2.01E-02	S
8.8	2.41E-01	W	2.53E-03	S	1.97E-02	S
9	2.41E-01	W	2.53E-03	S	1.94E-02	S
9.2	2.41E-01	W	2.53E-03	S	1.90E-02	S
9.4	2.45E-01	W	2.53E-03	S	1.95E-02	S
9.6	2.51E-01	W	2.53E-03	S	2.06E-02	S
9.8	2.57E-01	W	2.53E-03	S	2.16E-02	S
10	2.63E-01	W	2.53E-03	S	2.27E-02	S
10.2	2.68E-01	W	2.53E-03	S	2.36E-02	S
10.4	2.73E-01	W	2.53E-03	S	2.41E-02	S
10.6	2.77E-01	W	2.53E-03	S	2.45E-02	S
10.8	2.82E-01	W	2.53E-03	S	2.50E-02	S
11	2.87E-01	S	2.53E-03	S	2.54E-02	S
11.2	2.91E-01	S	2.53E-03	S	2.58E-02	S
11.4	2.90E-01	S	2.53E-03	S	2.43E-02	S
11.6	2.84E-01	S	2.53E-03	S	2.16E-02	S
11.8	2.78E-01	S	2.53E-03	S	1.92E-02	S
12	2.73E-01	S	2.53E-03	S	1.70E-02	S
12.2	2.68E-01	S	2.53E-03	S	1.52E-02	S
12.4	2.63E-01	S	2.53E-03	S	1.36E-02	S
12.6	2.58E-01	S	2.53E-03	S	1.21E-02	S
12.8	2.53E-01	S	2.53E-03	S	1.09E-02	S
13	2.49E-01	S	2.53E-03	S	9.76E-03	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	2.23E+00		2.02E-02		3.00E-01	

Table C-5-55. Leachate Concentrations for Sludge Scrubber, Waste ID AGD Med

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	0.066084	S	7.307756	W	0.001781	S	0.0887829	W
3	0.045071	S	7.196089	W	0.001769	S	0.0883382	W
3.2	0.031509	S	7.093176	W	0.001757	S	0.0879243	W
3.4	0.022026	S	6.997846	W	0.001742	S	0.0875372	W
3.6	0.015458	S	6.90914	W	0.001712	S	0.0871738	W
3.8	0.010582	S	6.837153	W	0.001719	S	0.0868501	W
4	0.009131	S	6.810452	W	0.001716	S	0.0866143	W
4.2	0.008896	S	6.78515	W	0.001696	S	0.0863906	W
4.4	0.008678	S	6.772903	W	0.001677	S	0.0856465	W
4.6	0.008475	S	6.769568	W	0.001659	S	0.0845701	W
4.8	0.008284	S	6.766377	W	0.001642	S	0.0835523	W
5	0.008106	S	6.763318	W	0.001626	S	0.0825875	W
5.2	0.007869	S	6.76038	W	0.00161	S	0.081671	W
5.4	0.006988	S	6.751062	W	0.001528	S	0.0808791	W
5.6	0.004691	S	6.721415	W	0.001519	S	0.0803781	W
5.8	0.0032	S	6.692595	W	0.001508	S	0.0798667	W
6	0.0032	S	6.599711	W	0.001219	S	0.0735792	S
6.2	0.0032	S	6.511099	W	0.000992	S	0.0679691	S
6.4	0.0032	S	6.426435	W	0.000813	S	0.0629451	S
6.6	0.00352	S	6.328562	W	0.000746	S	0.0508885	S
6.8	0.004156	S	6.376549	W	0.000746	S	0.0555803	S
7	0.004884	S	6.423493	W	0.000746	S	0.0585954	S
7.2	0.005705	S	6.397274	W	0.000746	W	0.0090067	S
7.4	0.006599	S	6.395388	W	0.000746	W	0.002062	S
7.6	0.00661	S	6.247808	W	0.000746	W	0.002062	S
7.8	0.00661	S	6.037282	W	0.000746	W	0.002062	S
8	0.006631	S	5.838914	W	0.000746	W	0.002062	S

Table C-5-55. Leachate Concentrations for Sludge Scrubber, Waste ID AGD Med

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	0.006687	S	5.651726	W	0.000746	W	0.002062	S
8.4	0.006741	S	5.474835	W	0.000746	W	0.002062	S
8.6	0.006795	S	5.307451	W	0.000746	W	0.002062	S
8.8	0.006848	S	5.148859	W	0.000746	W	0.002062	S
9	0.00689	S	5.017067	W	0.000746	W	0.002062	S
9.2	0.006888	S	5.027445	W	0.000746	W	0.002062	S
9.4	0.006885	S	5.096129	W	0.000746	W	0.002062	S
9.6	0.006598	S	5.164276	W	0.000746	W	0.002062	S
9.8	0.006602	S	5.231901	W	0.000746	W	0.002062	S
10	0.006605	S	5.299019	W	0.000746	W	0.002062	S
10.2	0.006608	S	5.365643	W	0.000746	W	0.002062	S
10.4	0.006611	S	5.427014	W	0.000746	W	0.002062	S
10.6	0.006614	S	5.483464	W	0.000746	W	0.002062	S
10.8	0.006617	S	5.539429	W	0.000746	W	0.002062	S
11	0.00662	S	5.598123	W	0.000746	W	0.002062	S
11.2	0.006623	S	5.691801	W	0.000746	W	0.002062	S
11.4	0.006626	S	5.755721	W	0.000746	W	0.002062	S
11.6	0.006629	S	5.819228	W	0.000746	W	0.002062	S
11.8	0.006631	S	5.882333	W	0.000746	W	0.002062	S
12	0.006634	S	5.945044	W	0.000746	W	0.002062	S
12.2	0.006637	S	6.00737	W	0.000746	W	0.002062	S
12.4	0.006639	S	6.069321	W	0.000746	W	0.002062	S
12.6	0.006642	S	6.130904	W	0.000746	W	0.002062	S
12.8	0.006645	S	6.192127	W	0.000746	W	0.002062	S
13	0.006647	S	6.252998	W	0.000746	W	0.002062	S
Detection Limit (min, mg/L)	0.00064		0.00065		0.00017		0.00041	
Detection Limit (max, mg/L)	0.00064		0.00065		0.00017		0.00041	
Availability (mg/kg)	0.450711		71.96089		0.017686		0.8833822	

Table C-5-55. Leachate Concentrations for Sludge Scrubber, Waste ID AGD Med

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	0.7568581	S	1.28437E-05	S	0.02815497	S	0.018813	S
3	0.750013	S	1.46388E-05	S	0.01760686	S	0.017904	S
3.2	0.7436659	S	1.65444E-05	S	0.01101181	S	0.017093	S
3.4	0.7365715	S	1.85599E-05	S	0.00751322	S	0.016365	S
3.6	0.7265664	S	2.06113E-05	S	0.00509241	S	0.015707	S
3.8	0.6892985	S	1.9154E-05	S	0.003795	S	0.011293	S
4	0.6692473	S	1.63999E-05	S	0.003795	S	0.008317	S
4.2	0.6519085	S	1.563E-05	S	0.003795	S	0.007018	S
4.4	0.6376217	S	1.76681E-05	S	0.003795	S	0.005968	S
4.6	0.6267923	S	1.66885E-05	S	0.003795	S	0.005113	S
4.8	0.6171115	S	1.58015E-05	S	0.003795	S	0.004409	S
5	0.6079664	S	1.49951E-05	S	0.003795	S	0.003824	S
5.2	0.5993076	S	1.42591E-05	S	0.003795	S	0.003262	S
5.4	0.5910922	S	1.3585E-05	S	0.003795	S	0.002783	S
5.6	0.590496	S	1.29656E-05	S	0.003795	S	0.002783	S
5.8	0.5940076	S	1.23947E-05	S	0.00380491	S	0.002783	S
6	0.5970769	S	1.30672E-05	S	0.00635446	S	0.002783	S
6.2	0.600381	S	1.61636E-05	S	0.0104354	S	0.002783	S
6.4	0.6014909	S	1.79486E-05	S	0.01686937	S	0.002783	S
6.6	0.601169	S	1.50877E-05	S	0.03253571	S	0.002783	S
6.8	0.601493	S	2.36318E-05	S	0.02695917	S	0.002783	S
7	0.6018077	S	2.30296E-05	S	0.02877251	S	0.002783	S
7.2	0.6008583	S	2.22821E-05	S	0.03248639	W	0.002783	S
7.4	0.6007295	S	2.11775E-05	S	0.0384734	W	0.002783	S
7.6	0.601728	S	1.7043E-05	S	0.03933924	W	0.002783	S
7.8	0.6027021	S	1.49128E-05	S	0.04020132	W	0.002783	S
8	0.6036531	S	1.30931E-05	S	0.04105974	W	0.002783	S

Table C-5-55. Leachate Concentrations for Sludge Scrubber, Waste ID AGD Med

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	0.604582	S	1.15324E-05	S	0.04191462	W	0.002783	S
8.4	0.6054899	S	1.01888E-05	S	0.04276606	W	0.002783	S
8.6	0.6063778	S	9.02811E-06	S	0.04361415	W	0.002783	S
8.8	0.6072465	S	8.02188E-06	S	0.04445898	W	0.002783	S
9	0.607882	S	7.31891E-06	S	0.04525756	W	0.002783	S
9.2	0.606869	S	8.01996E-06	S	0.04626985	W	0.002783	S
9.4	0.6058794	S	8.7709E-06	S	0.04758863	W	0.002783	S
9.6	0.6049122	S	9.57408E-06	S	0.04891605	W	0.002783	S
9.8	0.6039665	S	1.0432E-05	S	0.05025198	W	0.002783	S
10	0.6030413	S	1.1347E-05	S	0.0515963	W	0.002783	S
10.2	0.6021358	S	1.23218E-05	S	0.0529489	W	0.002783	S
10.4	0.6012492	S	1.33589E-05	S	0.05430965	W	0.002783	S
10.6	0.6003808	S	1.44611E-05	S	0.05567846	W	0.002783	S
10.8	0.5995298	S	1.5631E-05	S	0.05705521	W	0.002783	S
11	0.5986956	S	1.68714E-05	S	0.05843981	W	0.002783	S
11.2	0.5978776	S	1.81852E-05	S	0.05983215	W	0.002783	S
11.4	0.5970751	S	1.95754E-05	S	0.06123213	W	0.002783	S
11.6	0.5962877	S	2.10448E-05	S	0.06268585	W	0.002783	S
11.8	0.5955147	S	2.16092E-05	S	0.06420281	W	0.002783	S
12	0.5947557	S	2.16092E-05	S	0.06573006	W	0.002783	S
12.2	0.5940101	S	2.16092E-05	S	0.06726749	W	0.002783	S
12.4	0.5932776	S	2.16092E-05	S	0.068815	W	0.002783	S
12.6	0.5925578	S	2.16092E-05	S	0.0703725	W	0.002783	S
12.8	0.5918501	S	2.16092E-05	S	0.07193989	W	0.002783	S
13	0.5911542	S	2.16092E-05	S	0.07351708	W	0.002783	S
Detection Limit (min, mg/L)	0.0005		0.0000036		0.00076		0.00008	
Detection Limit (max, mg/L)	0.0005		0.0000036		0.00076		0.00008	
Availability (mg/kg)	7.5001304		0.000236318		0.75536885		0.179039	

Table C-5-55. Leachate Concentrations for Sludge Scrubber, Waste ID AGD Med

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	0.050728	S	0.007681	S	0.038851	S
3	0.045029	S	0.007598	S	0.026784	S
3.2	0.040279	S	0.00752	S	0.018913	S
3.4	0.036274	S	0.007449	S	0.013641	S
3.6	0.032864	S	0.007381	S	0.010023	S
3.8	0.027792	S	0.007399	S	0.006509	S
4	0.025527	S	0.007277	S	0.003515	S
4.2	0.024711	S	0.007162	S	0.003272	S
4.4	0.023859	S	0.007163	S	0.003354	S
4.6	0.023959	S	0.007242	S	0.003435	S
4.8	0.024054	S	0.007318	S	0.003513	S
5	0.024146	S	0.007392	S	0.003591	S
5.2	0.024234	S	0.007464	S	0.004137	S
5.4	0.023801	S	0.007507	S	0.004244	S
5.6	0.021835	S	0.007463	S	0.003857	S
5.8	0.020098	S	0.007421	S	0.004001	S
6	0.019728	S	0.007422	S	0.004144	S
6.2	0.019376	S	0.007415	S	0.004288	W
6.4	0.018832	S	0.007099	S	0.004788	W
6.6	0.017749	S	0.006887	S	0.00512	W
6.8	0.018038	S	0.006989	S	0.004898	W
7	0.018324	S	0.00709	S	0.004692	W
7.2	0.014994	S	0.007039	S	0.005194	W
7.4	0.013708	S	0.006805	S	0.005754	W
7.6	0.01314	S	0.006606	S	0.0058	W
7.8	0.012609	S	0.006418	S	0.005846	W
8	0.012113	S	0.006239	S	0.005891	W

Table C-5-55. Leachate Concentrations for Sludge Scrubber, Waste ID AGD Med

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	0.011647	S	0.00607	S	0.005935	W
8.4	0.01121	S	0.00591	S	0.005979	W
8.6	0.010799	S	0.005757	S	0.006021	W
8.8	0.010419	S	0.005611	S	0.006063	W
9	0.010188	S	0.005547	S	0.006111	W
9.2	0.009702	S	0.005487	S	0.00621	W
9.4	0.009691	S	0.005362	S	0.006307	W
9.6	0.009685	S	0.005021	S	0.006404	W
9.8	0.009679	S	0.004674	S	0.006501	W
10	0.009674	S	0.004357	S	0.006597	W
10.2	0.009613	S	0.004067	S	0.006692	W
10.4	0.009527	S	0.003801	S	0.006787	W
10.6	0.009494	S	0.003558	S	0.006881	W
10.8	0.009501	S	0.003334	S	0.006975	W
11	0.009508	S	0.003128	S	0.007069	W
11.2	0.009514	S	0.002938	S	0.007161	W
11.4	0.00952	S	0.002763	S	0.007254	W
11.6	0.009527	S	0.0026	S	0.007346	W
11.8	0.009533	S	0.002451	S	0.007438	W
12	0.009539	S	0.002333	S	0.007529	W
12.2	0.009545	S	0.002222	S	0.00762	W
12.4	0.009551	S	0.002118	S	0.00771	W
12.6	0.009556	S	0.00202	S	0.0078	W
12.8	0.009562	S	0.001929	S	0.00789	W
13	0.009568	S	0.001842	S	0.007979	W
Detection Limit (min, mg/L)	0.00052		0.00051		0.00031	
Detection Limit (max, mg/L)	0.00052		0.00051		0.00031	
Availability (mg/kg)	0.450291		0.075977		0.267838	

Table C-5-56. Leachate Concentrations for Sludge Scrubber, Waste ID BGD Med

Table C-5-56. Leachate Concentrations for Sludge Scrubber, Waste ID BGD Med

Sample ID	BGD-[Med] (P,1,1)
Date Exported	9/20/2011, 8:44 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

2.8	1.03E-01	S	1.54E+01	W	7.46E-04	S	6.06E-02	S
3	9.73E-02	S	1.53E+01	W	7.46E-04	S	5.59E-02	S
3.2	9.28E-02	S	1.51E+01	W	7.46E-04	S	5.18E-02	S
3.4	8.88E-02	S	1.50E+01	W	7.46E-04	S	4.82E-02	S
3.6	8.51E-02	S	1.48E+01	W	7.46E-04	S	4.51E-02	S
3.8	8.18E-02	S	1.47E+01	W	7.46E-04	S	4.37E-02	S
4	7.88E-02	S	1.46E+01	W	7.46E-04	S	4.25E-02	S
4.2	7.60E-02	S	1.45E+01	W	7.46E-04	S	4.13E-02	S
4.4	7.35E-02	S	1.44E+01	W	7.46E-04	S	4.02E-02	S
4.6	7.11E-02	S	1.43E+01	W	7.46E-04	S	3.92E-02	S
4.8	6.89E-02	S	1.42E+01	W	7.46E-04	S	3.83E-02	S
5	6.69E-02	S	1.41E+01	W	7.46E-04	S	3.74E-02	S
5.2	6.50E-02	S	1.40E+01	W	7.46E-04	S	3.66E-02	S
5.4	6.32E-02	S	1.39E+01	W	7.46E-04	S	3.58E-02	S
5.6	6.16E-02	S	1.38E+01	W	7.46E-04	S	3.51E-02	S
5.8	6.00E-02	S	1.37E+01	W	7.46E-04	S	3.44E-02	S
6	5.85E-02	S	1.36E+01	W	7.46E-04	S	3.37E-02	S
6.2	5.71E-02	S	1.36E+01	W	7.46E-04	S	3.31E-02	S
6.4	5.56E-02	S	1.35E+01	W	7.46E-04	S	3.25E-02	S
6.6	5.05E-02	S	1.34E+01	W	7.46E-04	S	2.37E-02	S
6.8	4.60E-02	S	1.33E+01	W	7.46E-04	S	2.12E-02	S
7	4.39E-02	S	1.32E+01	S	7.46E-04	S	1.18E-02	S
7.2	2.54E-02	S	1.10E+01	S	7.46E-04	S	2.43E-03	S
7.4	1.97E-02	S	1.05E+01	S	7.46E-04	S	2.06E-03	S
7.6	1.96E-02	S	7.22E+00	S	7.46E-04	S	2.06E-03	S
7.8	1.95E-02	S	5.00E+00	S	7.46E-04	S	2.06E-03	S
8	1.94E-02	S	3.49E+00	S	7.46E-04	S	2.06E-03	S

Table C-5-56. Leachate Concentrations for Sludge Scrubber, Waste ID BGD Med

Table C-5-56. Leachate Concentrations for Sludge Scrubber, Waste ID BGD Med

Sample ID	BGD-[Med] (P,1,1)
Date Exported	9/20/2011, 8:44 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

8.2	1.93E-02	S	2.79E+00	S	7.46E-04	S	2.06E-03	S
8.4	1.61E-02	S	2.40E+00	S	7.46E-04	S	2.06E-03	S
8.6	1.30E-02	S	2.06E+00	S	7.46E-04	S	2.06E-03	S
8.8	1.70E-02	S	2.03E+00	S	7.46E-04	S	2.06E-03	S
9	2.11E-02	S	2.41E+00	S	7.46E-04	S	2.06E-03	S
9.2	1.91E-02	S	2.38E+00	S	7.46E-04	S	2.06E-03	S
9.4	1.72E-02	S	2.35E+00	S	7.46E-04	S	2.06E-03	S
9.6	1.56E-02	S	2.02E+00	S	7.46E-04	S	2.06E-03	S
9.8	1.42E-02	S	1.35E+00	S	7.46E-04	S	2.06E-03	S
10	1.06E-02	S	1.48E+00	S	7.46E-04	S	2.06E-03	S
10.2	7.46E-03	S	1.67E+00	S	7.46E-04	S	2.06E-03	S
10.4	5.29E-03	S	1.88E+00	S	7.46E-04	S	2.06E-03	S
10.6	3.77E-03	S	2.11E+00	S	7.46E-04	S	2.06E-03	S
10.8	3.20E-03	S	2.19E+00	S	7.46E-04	S	2.06E-03	S
11	3.20E-03	S	2.16E+00	S	7.46E-04	S	2.06E-03	S
11.2	3.20E-03	S	2.14E+00	S	7.46E-04	S	2.06E-03	S
11.4	3.20E-03	S	2.12E+00	S	7.46E-04	S	2.06E-03	S
11.6	3.73E-03	S	2.15E+00	S	7.46E-04	S	2.06E-03	S
11.8	5.66E-03	S	2.28E+00	S	7.46E-04	S	2.06E-03	S
12	8.53E-03	S	2.42E+00	S	7.46E-04	S	2.06E-03	S
12.2	1.28E-02	S	2.57E+00	S	7.46E-04	S	2.06E-03	S
12.4	1.84E-02	S	2.72E+00	S	7.46E-04	S	2.06E-03	S
12.6	2.81E-02	S	2.87E+00	S	7.46E-04	S	2.06E-03	S
12.8	4.13E-02	S	3.04E+00	S	7.46E-04	S	2.06E-03	S
13	6.03E-02	S	3.21E+00	S	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	9.73E-01		1.53E+02		8.21E-03		5.59E-01	

Table C-5-56. Leachate Concentrations for Sludge Scrubber, Waste ID BGD Med

Table C-5-56. Leachate Concer
Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

2.8	1.90E-01	S	2.14E-03	S	2.11E-01	S	9.13E-03	S
3	1.90E-01	S	2.18E-03	S	2.12E-01	S	9.20E-03	S
3.2	1.90E-01	S	2.21E-03	S	2.16E-01	S	9.22E-03	S
3.4	1.90E-01	S	2.25E-03	S	2.21E-01	S	9.25E-03	S
3.6	1.90E-01	S	2.28E-03	S	2.25E-01	S	9.27E-03	S
3.8	1.90E-01	S	2.31E-03	S	2.28E-01	S	9.29E-03	S
4	1.90E-01	S	2.34E-03	S	2.32E-01	S	9.31E-03	S
4.2	1.90E-01	S	2.36E-03	S	2.36E-01	S	9.33E-03	S
4.4	1.90E-01	S	2.39E-03	S	2.39E-01	S	9.35E-03	S
4.6	1.90E-01	S	2.42E-03	S	2.43E-01	S	9.37E-03	S
4.8	1.90E-01	S	2.44E-03	S	2.46E-01	S	9.38E-03	S
5	1.90E-01	S	2.46E-03	S	2.49E-01	S	9.40E-03	S
5.2	1.90E-01	S	2.49E-03	S	2.52E-01	S	9.42E-03	S
5.4	1.90E-01	S	2.51E-03	S	2.55E-01	S	9.43E-03	S
5.6	1.90E-01	S	2.53E-03	S	2.58E-01	S	9.45E-03	S
5.8	1.90E-01	S	2.55E-03	S	2.61E-01	S	9.46E-03	S
6	1.90E-01	S	2.57E-03	S	2.64E-01	S	9.47E-03	S
6.2	1.90E-01	S	2.60E-03	S	2.67E-01	S	9.49E-03	S
6.4	1.90E-01	S	2.62E-03	S	2.71E-01	S	9.52E-03	S
6.6	1.90E-01	S	2.63E-03	S	2.94E-01	S	9.79E-03	S
6.8	1.90E-01	S	3.16E-03	S	3.19E-01	S	1.01E-02	S
7	1.90E-01	S	2.76E-03	S	3.30E-01	S	9.73E-03	S
7.2	1.90E-01	S	1.94E-03	S	3.58E-01	S	1.15E-02	S
7.4	1.90E-01	S	1.34E-03	S	3.32E-01	S	1.06E-02	S
7.6	1.90E-01	S	3.57E-04	S	2.51E-01	S	7.05E-03	S
7.8	1.90E-01	S	9.82E-05	S	1.91E-01	S	4.72E-03	S
8	1.90E-01	S	2.80E-05	S	1.46E-01	S	3.20E-03	S

Table C-5-56. Leachate Concentrations for Sludge Scrubber, Waste ID BGD Med

Table C-5-56. Leachate Concer
Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

8.2	1.90E-01	S	2.81E-05	S	1.24E-01	S	2.78E-03	S
8.4	1.90E-01	S	2.92E-05	S	1.10E-01	S	2.78E-03	S
8.6	1.90E-01	S	3.03E-05	S	1.09E-01	S	2.78E-03	S
8.8	1.90E-01	S	3.13E-05	S	1.21E-01	S	2.78E-03	S
9	1.90E-01	S	3.25E-05	S	1.32E-01	S	2.78E-03	S
9.2	1.90E-01	S	3.44E-05	S	1.23E-01	S	2.78E-03	S
9.4	1.90E-01	S	3.63E-05	S	1.14E-01	S	2.78E-03	S
9.6	1.90E-01	S	3.83E-05	S	1.07E-01	S	2.78E-03	S
9.8	1.90E-01	S	3.69E-05	S	9.94E-02	S	2.78E-03	S
10	1.90E-01	S	3.51E-05	S	9.29E-02	S	2.78E-03	S
10.2	1.90E-01	S	3.35E-05	S	8.69E-02	S	2.78E-03	S
10.4	1.90E-01	S	3.20E-05	S	7.63E-02	S	2.78E-03	S
10.6	1.90E-01	S	3.06E-05	S	6.67E-02	S	2.78E-03	S
10.8	1.90E-01	S	2.93E-05	S	6.21E-02	S	2.78E-03	S
11	1.90E-01	S	2.81E-05	S	6.15E-02	S	2.78E-03	S
11.2	1.90E-01	S	2.69E-05	S	6.11E-02	S	2.78E-03	S
11.4	1.90E-01	S	2.58E-05	S	6.04E-02	S	2.78E-03	S
11.6	1.90E-01	S	2.80E-05	S	5.98E-02	S	2.78E-03	S
11.8	1.90E-01	S	3.78E-05	S	6.19E-02	S	2.78E-03	S
12	1.90E-01	S	3.05E-05	S	6.53E-02	S	2.78E-03	S
12.2	1.90E-01	S	2.28E-05	S	6.90E-02	S	2.78E-03	S
12.4	1.90E-01	S	1.71E-05	S	7.27E-02	S	2.78E-03	S
12.6	1.90E-01	S	1.29E-05	S	7.59E-02	S	2.78E-03	S
12.8	1.90E-01	S	9.79E-06	S	7.89E-02	S	2.78E-03	S
13	1.90E-01	S	7.68E-06	S	8.20E-02	S	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	2.09E+00		3.16E-02		3.58E+00		1.15E-01	

Table C-5-56. Leachate Concentrations for Sludge Scrubber, Waste ID BGD Med

Table C-5-56. Leachate Concer
Sample ID
Date Exported
Database Name
LeachXS Version

2.8	9.29E-02	S	2.66E-02	S	1.86E-02	S
3	8.87E-02	S	2.60E-02	S	1.72E-02	S
3.2	8.50E-02	S	2.55E-02	S	1.53E-02	S
3.4	8.17E-02	S	2.50E-02	S	1.40E-02	S
3.6	7.86E-02	S	2.45E-02	S	1.28E-02	S
3.8	7.59E-02	S	2.41E-02	S	1.19E-02	S
4	7.33E-02	S	2.37E-02	S	1.10E-02	S
4.2	7.10E-02	S	2.33E-02	S	1.03E-02	S
4.4	6.89E-02	S	2.29E-02	S	9.73E-03	S
4.6	6.69E-02	S	2.26E-02	S	9.23E-03	S
4.8	6.50E-02	S	2.23E-02	S	8.78E-03	S
5	6.33E-02	S	2.20E-02	S	8.36E-03	S
5.2	6.17E-02	S	2.17E-02	S	7.98E-03	S
5.4	6.01E-02	S	2.14E-02	S	7.64E-03	S
5.6	5.85E-02	S	2.11E-02	S	7.31E-03	S
5.8	5.67E-02	S	2.09E-02	S	7.02E-03	S
6	5.50E-02	S	2.06E-02	S	6.74E-03	S
6.2	5.34E-02	S	2.04E-02	S	6.48E-03	S
6.4	5.20E-02	S	2.02E-02	S	6.24E-03	S
6.6	5.11E-02	S	1.91E-02	S	8.11E-03	S
6.8	5.01E-02	S	1.80E-02	S	1.15E-02	S
7	4.97E-02	S	1.70E-02	S	1.21E-02	S
7.2	4.06E-02	S	1.11E-02	S	1.45E-02	S
7.4	3.47E-02	S	1.10E-02	S	1.99E-02	S
7.6	2.56E-02	S	8.70E-03	S	2.99E-02	S
7.8	1.90E-02	S	6.94E-03	S	4.45E-02	S
8	1.42E-02	S	5.57E-03	S	5.38E-02	S

Table C-5-56. Leachate Concentrations for Sludge Scrubber, Waste ID BGD Med

Table C-5-56. Leachate Concer
Sample ID
Date Exported
Database Name
LeachXS Version

8.2	1.10E-02	S	4.81E-03	S	5.74E-02	S
8.4	8.70E-03	S	4.34E-03	S	6.12E-02	S
8.6	8.45E-03	S	4.24E-03	S	6.21E-02	S
8.8	1.06E-02	S	4.68E-03	S	5.79E-02	S
9	1.26E-02	S	5.06E-03	S	5.40E-02	S
9.2	1.10E-02	S	4.76E-03	S	5.14E-02	S
9.4	9.55E-03	S	4.48E-03	S	5.91E-02	S
9.6	8.36E-03	S	4.22E-03	S	6.58E-02	S
9.8	7.33E-03	S	3.99E-03	S	6.06E-02	S
10	6.45E-03	S	3.77E-03	S	5.60E-02	S
10.2	5.17E-03	S	3.43E-03	S	5.18E-02	S
10.4	3.91E-03	S	3.03E-03	S	5.18E-02	S
10.6	2.97E-03	S	2.68E-03	S	5.32E-02	S
10.8	2.60E-03	S	2.53E-03	S	5.47E-02	S
11	2.60E-03	S	2.53E-03	S	5.61E-02	S
11.2	2.60E-03	S	2.53E-03	S	5.76E-02	S
11.4	2.60E-03	S	2.53E-03	S	5.91E-02	S
11.6	2.60E-03	S	2.72E-03	S	6.15E-02	S
11.8	2.60E-03	S	3.42E-03	S	6.58E-02	S
12	2.60E-03	S	4.27E-03	S	7.04E-02	S
12.2	2.60E-03	S	5.32E-03	S	7.52E-02	S
12.4	2.60E-03	S	6.77E-03	S	8.02E-02	S
12.6	2.60E-03	S	8.62E-03	S	8.74E-02	S
12.8	2.60E-03	S	1.09E-02	S	9.38E-02	S
13	2.60E-03	S	1.38E-02	S	9.94E-02	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	8.87E-01		2.60E-01		1.03E+00	

Table C-5-57. Leachate Concentrations for Sludge Scrubber, Waste ID CGD Med

Sample ID	CGD-[Med] (P,1,1)
Date Exported	9/20/2011, 8:45 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	2.17E-02	S	6.74E+00	S	7.46E-04	S	3.02E-02	S
3	1.57E-02	S	6.76E+00	S	7.46E-04	S	2.83E-02	S
3.2	1.27E-02	S	6.77E+00	S	7.46E-04	S	2.66E-02	S
3.4	1.05E-02	S	6.78E+00	S	7.46E-04	S	2.52E-02	S
3.6	8.67E-03	S	6.79E+00	S	7.46E-04	S	2.39E-02	S
3.8	7.26E-03	S	6.80E+00	S	7.46E-04	S	2.27E-02	S
4	6.14E-03	S	6.81E+00	S	7.46E-04	S	2.17E-02	S
4.2	5.23E-03	S	6.82E+00	S	7.46E-04	S	2.08E-02	S
4.4	4.49E-03	S	6.83E+00	S	7.46E-04	S	2.00E-02	S
4.6	3.72E-03	S	6.84E+00	S	7.46E-04	S	1.92E-02	S
4.8	3.20E-03	S	6.82E+00	S	7.46E-04	S	1.80E-02	S
5	3.20E-03	S	6.71E+00	S	7.46E-04	S	1.57E-02	S
5.2	3.20E-03	S	6.63E+00	S	7.46E-04	S	1.22E-02	S
5.4	3.20E-03	S	6.54E+00	S	7.46E-04	S	9.57E-03	S
5.6	3.20E-03	S	6.46E+00	S	7.46E-04	S	7.58E-03	S
5.8	3.20E-03	S	6.38E+00	S	7.46E-04	S	6.55E-03	S
6	3.20E-03	S	6.33E+00	S	7.46E-04	S	5.75E-03	S
6.2	3.20E-03	S	6.28E+00	S	7.46E-04	S	4.89E-03	S
6.4	3.20E-03	S	6.27E+00	S	7.46E-04	S	3.62E-03	S
6.6	3.20E-03	S	6.29E+00	S	7.46E-04	S	2.48E-03	S
6.8	3.20E-03	S	5.93E+00	S	7.46E-04	S	2.06E-03	S
7	3.20E-03	S	5.66E+00	S	7.46E-04	S	2.06E-03	S
7.2	3.20E-03	S	5.52E+00	S	7.46E-04	S	2.06E-03	S
7.4	3.20E-03	S	5.38E+00	S	7.46E-04	S	2.06E-03	S
7.6	3.20E-03	S	5.38E+00	S	7.46E-04	S	2.06E-03	S
7.8	3.20E-03	S	5.45E+00	S	7.46E-04	S	2.06E-03	S
8	3.20E-03	S	5.51E+00	S	7.46E-04	S	2.06E-03	S

Table C-5-57. Leachate Concentrations for Sludge Scrubber, Waste ID CGD Med

Sample ID	CGD-[Med] (P,1,1)
Date Exported	9/20/2011, 8:45 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	3.20E-03	S	5.57E+00	S	7.46E-04	S	2.06E-03	S
8.4	3.20E-03	S	5.63E+00	S	7.46E-04	S	2.06E-03	S
8.6	3.20E-03	S	5.69E+00	S	7.46E-04	S	2.06E-03	S
8.8	3.20E-03	S	5.67E+00	S	7.46E-04	S	2.06E-03	S
9	3.20E-03	S	5.47E+00	S	7.46E-04	S	2.06E-03	S
9.2	3.20E-03	S	5.52E+00	S	7.46E-04	S	2.06E-03	S
9.4	3.20E-03	S	5.46E+00	S	7.46E-04	S	2.06E-03	S
9.6	3.20E-03	S	5.37E+00	S	7.46E-04	S	2.06E-03	S
9.8	3.20E-03	S	5.31E+00	S	7.46E-04	S	2.06E-03	S
10	3.20E-03	S	5.32E+00	S	7.46E-04	S	2.06E-03	S
10.2	3.20E-03	S	5.33E+00	S	7.46E-04	S	2.06E-03	S
10.4	3.20E-03	S	5.35E+00	S	7.46E-04	S	2.06E-03	S
10.6	3.20E-03	S	5.28E+00	S	7.46E-04	S	2.06E-03	S
10.8	3.20E-03	S	5.18E+00	S	7.46E-04	S	2.06E-03	S
11	3.20E-03	S	5.08E+00	S	7.46E-04	S	2.06E-03	S
11.2	3.20E-03	S	4.91E+00	S	7.46E-04	S	2.06E-03	S
11.4	3.20E-03	S	4.71E+00	S	7.46E-04	S	2.06E-03	S
11.6	3.20E-03	S	4.52E+00	S	7.46E-04	S	2.06E-03	S
11.8	3.20E-03	S	4.34E+00	S	7.46E-04	S	2.06E-03	S
12	3.20E-03	S	4.19E+00	S	7.46E-04	S	2.06E-03	S
12.2	3.20E-03	S	4.09E+00	S	7.46E-04	S	2.06E-03	S
12.4	3.20E-03	S	4.00E+00	S	7.46E-04	S	2.06E-03	S
12.6	3.20E-03	S	3.91E+00	S	7.46E-04	S	2.06E-03	S
12.8	3.20E-03	S	3.82E+00	S	7.46E-04	S	2.06E-03	S
13	3.20E-03	S	3.74E+00	S	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	1.57E-01		6.84E+01		8.02E-03		2.83E-01	

Table C-5-57. Leachate Concentrations for Sludge Scrubber, Waste ID CGD Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	1.03E-01	S	4.09E-05	S	1.97E-02	S	1.18E-02	S
3	7.64E-02	S	3.98E-05	S	1.22E-02	S	9.86E-03	S
3.2	5.63E-02	S	3.98E-05	S	9.47E-03	S	8.33E-03	S
3.4	4.23E-02	S	3.98E-05	S	8.20E-03	S	7.12E-03	S
3.6	3.27E-02	S	3.97E-05	S	7.16E-03	S	6.14E-03	S
3.8	2.62E-02	S	3.97E-05	S	6.30E-03	S	5.33E-03	S
4	2.06E-02	S	3.96E-05	S	5.58E-03	S	4.67E-03	S
4.2	1.60E-02	S	3.96E-05	S	4.99E-03	S	4.09E-03	S
4.4	1.26E-02	S	3.96E-05	S	4.58E-03	S	3.50E-03	S
4.6	1.01E-02	S	3.96E-05	S	4.23E-03	S	3.04E-03	S
4.8	8.40E-03	S	3.95E-05	S	3.80E-03	S	2.78E-03	S
5	7.55E-03	S	3.84E-05	S	3.80E-03	S	2.78E-03	S
5.2	6.40E-03	S	3.65E-05	S	3.80E-03	S	2.78E-03	S
5.4	5.59E-03	S	3.49E-05	S	3.80E-03	S	2.78E-03	S
5.6	4.99E-03	S	3.33E-05	S	3.80E-03	S	2.78E-03	S
5.8	4.61E-03	S	3.18E-05	S	3.80E-03	S	2.78E-03	S
6	3.81E-03	S	3.03E-05	S	3.80E-03	S	2.78E-03	S
6.2	4.08E-03	S	2.88E-05	S	3.80E-03	S	2.78E-03	S
6.4	4.66E-03	S	2.99E-05	S	4.70E-03	S	2.78E-03	S
6.6	5.09E-03	S	3.12E-05	S	6.55E-03	S	2.78E-03	S
6.8	4.78E-03	S	3.25E-05	S	8.41E-03	S	2.78E-03	S
7	4.85E-03	S	3.35E-05	S	9.96E-03	S	2.78E-03	S
7.2	3.16E-03	S	3.46E-05	S	1.07E-02	S	2.78E-03	S
7.4	2.08E-03	S	3.57E-05	S	1.07E-02	S	2.78E-03	S
7.6	2.18E-03	S	3.40E-05	S	1.15E-02	S	2.78E-03	S
7.8	2.59E-03	S	3.17E-05	S	1.24E-02	S	2.78E-03	S
8	2.94E-03	S	2.96E-05	S	1.33E-02	S	2.78E-03	S

Table C-5-57. Leachate Concentrations for Sludge Scrubber, Waste ID CGD Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	3.10E-03	S	2.76E-05	S	1.42E-02	S	2.78E-03	S
8.4	3.49E-03	S	2.59E-05	S	1.52E-02	S	2.78E-03	S
8.6	3.92E-03	S	2.43E-05	S	1.62E-02	S	2.78E-03	S
8.8	4.38E-03	S	2.28E-05	S	1.73E-02	S	2.78E-03	S
9	4.82E-03	S	2.19E-05	S	1.85E-02	S	2.78E-03	S
9.2	4.43E-03	S	2.72E-05	S	1.95E-02	S	2.78E-03	S
9.4	4.09E-03	S	3.04E-05	S	2.01E-02	S	3.40E-03	S
9.6	3.66E-03	S	3.27E-05	S	2.08E-02	S	4.40E-03	S
9.8	3.28E-03	S	3.52E-05	S	2.14E-02	S	5.67E-03	S
10	2.95E-03	S	3.77E-05	S	2.20E-02	S	7.27E-03	S
10.2	2.66E-03	S	4.04E-05	S	2.26E-02	S	9.27E-03	S
10.4	2.40E-03	S	4.32E-05	S	2.33E-02	S	1.18E-02	S
10.6	2.17E-03	S	4.62E-05	S	2.39E-02	S	1.49E-02	S
10.8	1.96E-03	S	4.93E-05	S	2.46E-02	S	1.87E-02	S
11	2.14E-03	S	5.19E-05	S	2.71E-02	S	1.55E-02	S
11.2	2.40E-03	S	5.44E-05	S	2.98E-02	S	1.09E-02	S
11.4	2.69E-03	S	5.69E-05	S	3.30E-02	S	7.87E-03	S
11.6	3.01E-03	S	6.44E-05	S	3.67E-02	S	5.88E-03	S
11.8	3.36E-03	S	7.51E-05	S	4.06E-02	S	4.41E-03	S
12	3.74E-03	S	8.74E-05	S	4.49E-02	S	3.33E-03	S
12.2	4.16E-03	S	9.70E-05	S	4.92E-02	S	2.52E-03	S
12.4	4.61E-03	S	9.70E-05	S	5.39E-02	S	1.91E-03	S
12.6	5.11E-03	S	9.70E-05	S	5.89E-02	S	1.44E-03	S
12.8	5.65E-03	S	9.70E-05	S	6.43E-02	S	1.09E-03	S
13	6.24E-03	S	9.70E-05	S	7.02E-02	S	8.25E-04	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	7.64E-01		1.04E-03		6.92E-01		1.91E-01	

Table C-5-57. Leachate Concentrations for Sludge Scrubber, Waste ID CGD Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	2.36E-01	S	2.53E-03	S	3.28E-02	S
3	1.88E-01	S	2.53E-03	S	2.47E-02	S
3.2	1.65E-01	S	2.53E-03	S	1.89E-02	S
3.4	1.46E-01	S	2.53E-03	S	1.47E-02	S
3.6	1.31E-01	S	2.53E-03	S	1.16E-02	S
3.8	1.17E-01	S	2.53E-03	S	9.28E-03	S
4	1.06E-01	S	2.53E-03	S	7.51E-03	S
4.2	9.51E-02	S	2.53E-03	S	6.14E-03	S
4.4	8.08E-02	S	2.53E-03	S	5.06E-03	S
4.6	6.92E-02	S	2.53E-03	S	4.21E-03	S
4.8	6.92E-02	S	2.53E-03	S	3.78E-03	S
5	7.97E-02	S	2.53E-03	S	3.99E-03	S
5.2	9.53E-02	S	2.53E-03	S	4.22E-03	S
5.4	1.10E-01	S	2.53E-03	S	4.44E-03	S
5.6	1.25E-01	S	2.53E-03	S	4.67E-03	S
5.8	1.42E-01	S	2.53E-03	S	4.90E-03	S
6	1.45E-01	S	2.53E-03	S	5.05E-03	S
6.2	1.45E-01	S	2.53E-03	S	5.06E-03	S
6.4	1.17E-01	S	2.53E-03	S	5.02E-03	S
6.6	9.40E-02	S	2.53E-03	S	5.01E-03	S
6.8	5.10E-02	S	2.53E-03	S	4.87E-03	S
7	2.73E-02	S	2.53E-03	S	4.72E-03	S
7.2	1.49E-02	S	2.53E-03	S	4.58E-03	S
7.4	8.30E-03	S	2.53E-03	S	4.45E-03	S
7.6	7.74E-03	S	2.53E-03	S	4.75E-03	S
7.8	7.80E-03	S	2.53E-03	S	5.09E-03	S
8	7.85E-03	S	2.53E-03	S	5.45E-03	S

Table C-5-57. Leachate Concentrations for Sludge Scrubber, Waste ID CGD Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	7.91E-03	S	2.53E-03	S	5.67E-03	S
8.4	7.96E-03	S	2.53E-03	S	5.82E-03	S
8.6	8.01E-03	S	2.53E-03	S	5.98E-03	S
8.8	8.32E-03	S	2.53E-03	S	6.13E-03	S
9	9.13E-03	S	2.53E-03	S	6.27E-03	S
9.2	1.00E-02	S	2.53E-03	S	5.76E-03	S
9.4	1.24E-02	S	2.53E-03	S	5.48E-03	S
9.6	1.54E-02	S	2.53E-03	S	5.71E-03	S
9.8	1.90E-02	S	2.53E-03	S	5.94E-03	S
10	2.34E-02	S	2.53E-03	S	6.17E-03	S
10.2	2.90E-02	S	2.53E-03	S	6.41E-03	S
10.4	3.61E-02	S	2.53E-03	S	6.65E-03	S
10.6	4.47E-02	S	2.53E-03	S	6.90E-03	S
10.8	5.51E-02	S	2.53E-03	S	7.15E-03	S
11	5.96E-02	S	2.53E-03	S	6.88E-03	S
11.2	5.83E-02	S	2.53E-03	S	6.37E-03	S
11.4	5.43E-02	S	2.53E-03	S	5.90E-03	S
11.6	5.06E-02	S	2.53E-03	S	5.47E-03	S
11.8	4.94E-02	S	2.53E-03	S	5.08E-03	S
12	4.91E-02	S	2.53E-03	S	4.73E-03	S
12.2	4.88E-02	S	2.53E-03	S	4.40E-03	S
12.4	4.85E-02	S	2.53E-03	S	4.10E-03	S
12.6	4.82E-02	S	2.53E-03	S	3.83E-03	S
12.8	4.79E-02	S	2.53E-03	S	3.58E-03	S
13	4.76E-02	S	2.53E-03	S	3.35E-03	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	1.88E+00		2.72E-02		2.47E-01	

Table C-5-58. Leachate Concentrations for Sludge Scrubber, Waste ID DGD Med

Sample ID	DGD-[Med] (P,1,1)
Date Exported	9/20/2011, 8:45 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	3.27E-01	S	1.38E+01	S	4.18E-03	S	5.99E-02	S
3	2.44E-01	S	1.20E+01	S	1.73E-03	S	2.69E-02	S
3.2	1.31E-01	S	1.05E+01	S	7.46E-04	S	1.18E-02	S
3.4	9.28E-02	S	1.04E+01	S	7.46E-04	S	1.07E-02	S
3.6	6.72E-02	S	1.03E+01	S	7.46E-04	S	9.77E-03	S
3.8	5.00E-02	S	1.03E+01	S	7.46E-04	S	9.00E-03	S
4	4.38E-02	S	1.02E+01	S	7.46E-04	S	8.32E-03	S
4.2	3.87E-02	S	1.01E+01	S	7.46E-04	S	7.73E-03	S
4.4	3.43E-02	S	1.01E+01	S	7.46E-04	S	7.20E-03	S
4.6	3.06E-02	S	1.00E+01	S	7.46E-04	S	6.73E-03	S
4.8	2.75E-02	S	9.98E+00	S	7.46E-04	S	6.31E-03	S
5	2.67E-02	S	9.98E+00	S	7.46E-04	S	5.93E-03	S
5.2	2.60E-02	S	1.00E+01	S	7.46E-04	S	5.30E-03	S
5.4	2.54E-02	S	1.00E+01	S	7.46E-04	S	4.41E-03	S
5.6	2.48E-02	S	1.01E+01	S	7.46E-04	S	3.69E-03	S
5.8	2.34E-02	S	1.02E+01	S	7.46E-04	S	3.11E-03	S
6	2.12E-02	S	1.03E+01	S	7.46E-04	S	2.63E-03	S
6.2	1.92E-02	S	1.03E+01	S	7.46E-04	S	2.32E-03	S
6.4	1.75E-02	S	1.02E+01	S	7.46E-04	S	2.15E-03	S
6.6	1.60E-02	S	1.00E+01	S	7.46E-04	S	2.06E-03	S
6.8	1.45E-02	S	9.76E+00	S	7.46E-04	S	2.06E-03	S
7	1.32E-02	S	9.51E+00	S	7.46E-04	S	2.06E-03	S
7.2	1.19E-02	S	9.22E+00	S	7.46E-04	S	2.06E-03	S
7.4	1.09E-02	S	8.56E+00	S	7.46E-04	S	2.06E-03	S
7.6	9.93E-03	S	7.97E+00	S	7.46E-04	S	2.06E-03	S
7.8	9.04E-03	S	7.28E+00	S	7.46E-04	S	2.06E-03	S
8	8.25E-03	S	6.26E+00	S	7.46E-04	S	2.06E-03	S

Table C-5-58. Leachate Concentrations for Sludge Scrubber, Waste ID DGD Med

Sample ID	DGD-[Med] (P,1,1)
Date Exported	9/20/2011, 8:45 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	5.91E-03	S	5.41E+00	W	7.46E-04	S	2.06E-03	S
8.4	3.94E-03	S	4.79E+00	W	7.46E-04	S	2.06E-03	S
8.6	3.20E-03	S	4.34E+00	W	7.46E-04	S	2.06E-03	S
8.8	3.20E-03	S	3.92E+00	W	7.46E-04	S	2.06E-03	S
9	3.20E-03	S	3.55E+00	W	7.46E-04	S	2.06E-03	S
9.2	3.20E-03	S	3.53E+00	W	7.46E-04	S	2.06E-03	S
9.4	3.20E-03	S	3.42E+00	W	7.46E-04	S	2.06E-03	S
9.6	3.20E-03	S	3.51E+00	W	7.46E-04	S	2.06E-03	S
9.8	3.20E-03	S	3.62E+00	W	7.46E-04	S	2.06E-03	S
10	3.20E-03	S	3.76E+00	W	7.46E-04	S	2.06E-03	S
10.2	3.20E-03	S	3.90E+00	W	7.46E-04	S	2.06E-03	S
10.4	3.20E-03	S	4.06E+00	W	7.46E-04	S	2.06E-03	S
10.6	3.20E-03	S	4.20E+00	W	7.46E-04	S	2.06E-03	S
10.8	3.20E-03	S	4.30E+00	W	7.46E-04	S	2.06E-03	S
11	3.20E-03	S	4.39E+00	W	7.46E-04	S	2.06E-03	S
11.2	3.20E-03	S	4.49E+00	W	7.46E-04	S	2.06E-03	S
11.4	3.20E-03	S	4.62E+00	W	7.46E-04	S	2.06E-03	S
11.6	3.20E-03	S	5.00E+00	W	7.46E-04	S	2.06E-03	S
11.8	3.20E-03	S	5.48E+00	W	7.46E-04	S	2.06E-03	S
12	3.20E-03	S	6.00E+00	W	7.46E-04	S	2.06E-03	S
12.2	3.20E-03	S	6.47E+00	W	7.46E-04	S	2.06E-03	S
12.4	3.20E-03	S	7.15E+00	W	7.46E-04	S	2.06E-03	S
12.6	3.20E-03	S	7.82E+00	W	7.46E-04	S	2.06E-03	S
12.8	3.20E-03	S	8.52E+00	W	7.46E-04	S	2.06E-03	S
13	3.20E-03	S	9.26E+00	W	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Availability (mg/kg)	2.44E+00		1.20E+02		1.73E-02		2.69E-01	

Table C-5-58. Leachate Concentrations for Sludge Scrubber, Waste ID DGD Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	1.85E-02	S	1.14E-02	S	2.27E-01	S	6.32E-03	S
3	1.63E-02	S	1.10E-02	S	2.12E-01	S	7.69E-03	S
3.2	1.26E-02	S	1.02E-02	S	2.11E-01	S	8.57E-03	S
3.4	9.85E-03	S	9.31E-03	S	2.21E-01	S	8.62E-03	S
3.6	7.82E-03	S	8.54E-03	S	2.23E-01	S	8.66E-03	S
3.8	6.29E-03	S	7.86E-03	S	2.28E-01	S	8.72E-03	S
4	5.12E-03	S	7.27E-03	S	2.33E-01	S	8.77E-03	S
4.2	4.21E-03	S	6.70E-03	S	2.39E-01	S	8.82E-03	S
4.4	3.49E-03	S	6.06E-03	S	2.44E-01	S	8.91E-03	S
4.6	2.92E-03	S	5.51E-03	S	2.49E-01	S	8.98E-03	S
4.8	2.46E-03	S	5.03E-03	S	2.54E-01	S	9.06E-03	S
5	2.09E-03	S	4.60E-03	S	2.58E-01	S	9.13E-03	S
5.2	1.90E-03	S	4.23E-03	S	2.66E-01	S	9.20E-03	S
5.4	1.90E-03	S	3.90E-03	S	2.78E-01	S	9.27E-03	S
5.6	1.90E-03	S	3.61E-03	S	2.90E-01	S	9.34E-03	S
5.8	1.90E-03	S	3.35E-03	S	3.01E-01	S	9.41E-03	S
6	1.90E-03	S	3.11E-03	S	3.05E-01	S	9.58E-03	S
6.2	1.90E-03	S	2.90E-03	S	3.09E-01	S	9.78E-03	S
6.4	1.90E-03	S	2.71E-03	S	3.13E-01	S	9.85E-03	S
6.6	1.90E-03	S	2.28E-03	S	3.29E-01	S	1.03E-02	S
6.8	1.90E-03	S	1.67E-03	S	3.45E-01	S	1.07E-02	S
7	1.90E-03	S	7.67E-04	S	3.60E-01	S	1.15E-02	S
7.2	1.90E-03	S	3.60E-04	S	3.65E-01	S	1.22E-02	S
7.4	1.90E-03	S	1.73E-04	S	3.58E-01	S	1.24E-02	S
7.6	1.90E-03	S	1.25E-04	S	3.64E-01	S	1.23E-02	S
7.8	1.90E-03	S	9.44E-05	S	3.57E-01	S	1.24E-02	S
8	1.90E-03	S	7.14E-05	S	3.46E-01	S	1.18E-02	S

Table C-5-58. Leachate Concentrations for Sludge Scrubber, Waste ID DGD Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	1.90E-03	S	5.79E-05	S	3.36E-01	S	1.14E-02	S
8.4	1.90E-03	S	4.47E-05	S	3.32E-01	S	1.11E-02	S
8.6	2.15E-03	S	3.75E-05	S	2.84E-01	S	9.83E-03	S
8.8	2.78E-03	S	4.16E-05	S	2.00E-01	S	7.57E-03	S
9	3.57E-03	S	4.49E-05	S	1.46E-01	S	5.60E-03	S
9.2	3.99E-03	S	4.12E-05	S	1.24E-01	S	3.47E-03	S
9.4	4.25E-03	S	3.93E-05	S	1.14E-01	S	2.78E-03	S
9.6	4.51E-03	S	3.88E-05	S	1.06E-01	S	2.78E-03	S
9.8	4.78E-03	S	3.84E-05	S	9.76E-02	S	2.78E-03	S
10	5.07E-03	S	3.79E-05	S	9.04E-02	S	2.78E-03	S
10.2	5.34E-03	S	3.75E-05	S	8.38E-02	S	2.78E-03	S
10.4	4.20E-03	S	3.71E-05	S	7.78E-02	S	2.78E-03	S
10.6	3.31E-03	S	3.89E-05	S	7.24E-02	S	2.78E-03	S
10.8	2.62E-03	S	4.04E-05	S	6.74E-02	S	2.78E-03	S
11	2.09E-03	S	3.98E-05	S	6.25E-02	S	2.78E-03	S
11.2	1.90E-03	S	3.84E-05	S	6.05E-02	S	2.78E-03	S
11.4	1.90E-03	S	4.16E-05	S	6.01E-02	S	2.78E-03	S
11.6	1.90E-03	S	4.24E-05	S	6.09E-02	S	2.78E-03	S
11.8	1.90E-03	S	4.12E-05	S	6.30E-02	S	2.78E-03	S
12	1.90E-03	S	4.77E-05	S	6.49E-02	S	2.78E-03	S
12.2	1.90E-03	S	4.55E-05	S	6.63E-02	S	2.78E-03	S
12.4	1.90E-03	S	4.35E-05	S	6.86E-02	S	2.78E-03	S
12.6	1.90E-03	S	4.16E-05	S	7.12E-02	S	2.78E-03	S
12.8	1.90E-03	S	3.99E-05	S	7.38E-02	S	2.78E-03	S
13	1.90E-03	S	3.82E-05	S	7.64E-02	S	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Availability (mg/kg)	1.63E-01		1.10E-01		3.65E+00		1.24E-01	

Table C-5-58. Leachate Concentrations for Sludge Scrubber, Waste ID DGD Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	1.62E-01	S	5.06E-02	S	2.32E-01	S
3	1.58E-01	S	3.52E-02	S	1.42E-01	S
3.2	1.45E-01	S	2.45E-02	S	7.87E-02	S
3.4	1.35E-01	S	2.36E-02	S	5.98E-02	S
3.6	1.27E-01	S	2.30E-02	S	5.08E-02	S
3.8	1.19E-01	S	2.24E-02	S	4.56E-02	S
4	1.13E-01	S	2.19E-02	S	4.11E-02	S
4.2	1.06E-01	S	2.15E-02	S	3.72E-02	S
4.4	9.63E-02	S	2.10E-02	S	3.39E-02	S
4.6	8.81E-02	S	2.06E-02	S	3.10E-02	S
4.8	8.29E-02	S	2.02E-02	S	2.84E-02	S
5	8.03E-02	S	1.99E-02	S	2.62E-02	S
5.2	7.54E-02	S	1.93E-02	S	2.58E-02	S
5.4	6.77E-02	S	1.85E-02	S	2.61E-02	S
5.6	6.11E-02	S	1.78E-02	S	2.63E-02	S
5.8	5.53E-02	S	1.71E-02	S	2.63E-02	S
6	5.17E-02	S	1.65E-02	S	2.43E-02	S
6.2	4.84E-02	S	1.60E-02	S	2.31E-02	S
6.4	4.54E-02	S	1.57E-02	S	2.21E-02	S
6.6	4.05E-02	S	1.50E-02	S	2.05E-02	S
6.8	3.37E-02	S	1.38E-02	S	2.08E-02	S
7	2.81E-02	S	1.26E-02	S	2.05E-02	S
7.2	2.54E-02	S	1.17E-02	S	1.79E-02	S
7.4	2.31E-02	S	1.12E-02	S	1.58E-02	S
7.6	2.23E-02	S	1.08E-02	S	1.40E-02	S
7.8	2.17E-02	S	1.02E-02	S	1.25E-02	S
8	2.18E-02	S	9.45E-03	S	1.12E-02	S

Table C-5-58. Leachate Concentrations for Sludge Scrubber, Waste ID DGD Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	2.19E-02	S	8.91E-03	S	1.00E-02	S
8.4	2.20E-02	S	8.43E-03	S	8.99E-03	S
8.6	2.24E-02	S	6.72E-03	S	8.54E-03	S
8.8	2.28E-02	S	4.25E-03	S	8.77E-03	S
9	2.24E-02	S	2.81E-03	S	8.62E-03	S
9.2	2.23E-02	S	2.53E-03	S	8.84E-03	S
9.4	2.24E-02	S	2.53E-03	S	9.31E-03	S
9.6	2.24E-02	S	2.53E-03	S	9.78E-03	S
9.8	2.24E-02	S	2.53E-03	S	1.02E-02	S
10	2.24E-02	S	2.53E-03	S	1.05E-02	S
10.2	2.24E-02	S	2.53E-03	S	1.08E-02	S
10.4	2.24E-02	S	2.53E-03	S	1.12E-02	S
10.6	2.24E-02	S	2.53E-03	S	1.15E-02	S
10.8	2.24E-02	S	2.53E-03	S	1.18E-02	S
11	2.24E-02	S	2.53E-03	S	1.22E-02	S
11.2	2.23E-02	S	2.53E-03	S	1.26E-02	S
11.4	2.21E-02	S	2.53E-03	S	1.32E-02	S
11.6	2.20E-02	S	2.90E-03	S	1.37E-02	S
11.8	2.39E-02	S	3.70E-03	S	1.34E-02	S
12	2.38E-02	S	4.81E-03	S	1.30E-02	S
12.2	2.38E-02	S	5.94E-03	S	1.27E-02	S
12.4	2.50E-02	S	7.45E-03	S	1.24E-02	S
12.6	2.61E-02	S	9.34E-03	S	1.21E-02	S
12.8	2.73E-02	S	1.17E-02	S	1.18E-02	S
13	2.86E-02	S	1.45E-02	S	1.16E-02	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Availability (mg/kg)	1.58E+00		3.52E-01		1.42E+00	

Table C-5-59. Leachate Concentrations for Sludge Scrubber, Waste ID KGD Med

Sample ID	KGD-[Med] (P,1,1)
Date Exported	9/20/2011, 8:45 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	9.12E-03	S	1.19E+01	W	4.42E-03	S	2.11E-01	S
3	3.19E-02	S	1.59E+01	W	4.68E-03	S	2.95E-01	S
3.2	1.21E-01	S	2.08E+01	W	4.93E-03	S	4.03E-01	S
3.4	1.86E-01	S	2.31E+01	W	4.93E-03	S	4.42E-01	S
3.6	1.46E-01	S	2.26E+01	W	4.75E-03	S	4.10E-01	S
3.8	1.16E-01	S	2.21E+01	W	4.58E-03	S	3.83E-01	S
4	9.52E-02	S	2.18E+01	W	4.43E-03	S	3.62E-01	S
4.2	7.92E-02	S	2.15E+01	W	4.30E-03	S	3.44E-01	S
4.4	7.28E-02	S	2.13E+01	W	4.23E-03	S	3.32E-01	S
4.6	6.82E-02	S	2.11E+01	W	4.16E-03	S	3.22E-01	S
4.8	6.40E-02	S	2.10E+01	W	4.10E-03	S	3.13E-01	S
5	6.03E-02	S	2.09E+01	W	4.05E-03	S	3.04E-01	S
5.2	5.69E-02	S	2.07E+01	W	4.00E-03	S	2.96E-01	S
5.4	5.31E-02	S	2.05E+01	W	3.87E-03	S	2.78E-01	S
5.6	4.95E-02	S	2.02E+01	W	3.74E-03	S	2.60E-01	S
5.8	4.39E-02	S	1.99E+01	W	3.58E-03	S	2.34E-01	S
6	3.76E-02	S	1.95E+01	S	3.40E-03	S	2.05E-01	S
6.2	2.99E-02	S	1.88E+01	S	3.24E-03	S	1.61E-01	S
6.4	2.37E-02	S	1.80E+01	S	3.09E-03	S	1.26E-01	S
6.6	1.89E-02	S	1.73E+01	S	2.95E-03	S	9.86E-02	S
6.8	1.66E-02	S	1.67E+01	S	2.80E-03	S	7.72E-02	S
7	1.51E-02	S	1.60E+01	S	2.66E-03	S	6.07E-02	S
7.2	1.54E-02	S	1.53E+01	S	2.57E-03	S	4.44E-02	S
7.4	1.66E-02	S	1.45E+01	S	2.50E-03	S	3.14E-02	S
7.6	1.84E-02	S	1.36E+01	S	2.45E-03	S	2.22E-02	S
7.8	2.08E-02	S	1.27E+01	S	2.41E-03	S	1.59E-02	S
8	2.28E-02	S	1.12E+01	S	2.25E-03	S	1.10E-02	S

Table C-5-59. Leachate Concentrations for Sludge Scrubber, Waste ID KGD Med

Sample ID	KGD-[Med] (P,1,1)
Date Exported	9/20/2011, 8:45 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	2.51E-02	S	9.53E+00	S	1.89E-03	S	7.60E-03	S
8.4	2.90E-02	S	7.85E+00	S	1.45E-03	S	5.26E-03	S
8.6	3.35E-02	S	6.49E+00	S	1.13E-03	S	3.67E-03	S
8.8	3.86E-02	S	5.40E+00	S	8.78E-04	S	2.59E-03	S
9	4.01E-02	S	4.61E+00	S	7.57E-04	S	2.10E-03	S
9.2	3.61E-02	S	4.02E+00	S	7.46E-04	S	2.06E-03	S
9.4	3.20E-02	S	3.52E+00	S	7.46E-04	S	2.06E-03	S
9.6	2.85E-02	S	3.09E+00	S	7.46E-04	S	2.06E-03	S
9.8	2.59E-02	S	2.76E+00	S	7.46E-04	S	2.06E-03	S
10	2.42E-02	S	2.54E+00	S	7.46E-04	S	2.06E-03	S
10.2	2.29E-02	S	2.37E+00	S	7.46E-04	S	2.06E-03	S
10.4	2.17E-02	S	2.21E+00	S	7.46E-04	S	2.06E-03	S
10.6	2.06E-02	S	2.07E+00	S	7.46E-04	S	2.06E-03	S
10.8	1.95E-02	S	1.94E+00	S	7.46E-04	S	2.06E-03	S
11	1.91E-02	S	1.83E+00	S	7.46E-04	S	2.06E-03	S
11.2	2.71E-02	S	1.87E+00	S	7.46E-04	S	2.06E-03	S
11.4	3.82E-02	S	1.91E+00	S	7.46E-04	S	2.06E-03	S
11.6	5.35E-02	S	1.95E+00	S	7.46E-04	S	2.06E-03	S
11.8	7.45E-02	S	1.99E+00	S	7.46E-04	S	2.06E-03	S
12	1.03E-01	S	2.03E+00	S	7.46E-04	S	2.06E-03	S
12.2	1.42E-01	S	2.08E+00	S	7.46E-04	S	2.06E-03	S
12.4	1.95E-01	S	2.12E+00	S	7.46E-04	S	2.06E-03	S
12.6	2.66E-01	S	2.16E+00	S	7.46E-04	S	2.06E-03	S
12.8	2.81E-01	S	2.20E+00	S	7.46E-04	S	2.06E-03	S
13	2.81E-01	S	2.24E+00	S	7.46E-04	S	2.06E-03	S
Detection Limit (min, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	
Detection Limit (max, mg/L)	6.40E-04		6.50E-04		1.70E-04		4.10E-04	

Table C-5-59. Leachate Concentrations for Sludge Scrubber, Waste ID KGD Med

Sample ID	KGD-[Med] (P,1,1)
Date Exported	9/20/2011, 8:45 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
Availability (mg/kg)	3.09E+00		2.31E+02		4.93E-02		4.42E+00	

Table C-5-59. Leachate Concentrations for Sludge Scrubber, Waste ID KGD Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	2.56E-03	S	1.08E-04	S	6.15E-01	S	9.70E-03	W
3	2.42E-03	S	4.54E-04	S	6.44E-01	S	9.73E-03	W
3.2	1.04E-02	S	2.44E-03	S	5.03E-01	S	9.51E-03	W
3.4	2.02E-02	S	4.04E-03	S	4.00E-01	S	9.08E-03	W
3.6	1.77E-02	S	2.78E-03	S	4.46E-01	S	9.12E-03	W
3.8	1.56E-02	S	1.95E-03	S	4.95E-01	S	9.15E-03	W
4	1.44E-02	S	1.44E-03	S	5.34E-01	S	9.12E-03	W
4.2	1.34E-02	S	1.08E-03	S	5.73E-01	S	9.08E-03	W
4.4	1.36E-02	S	9.44E-04	S	5.91E-01	S	9.05E-03	W
4.6	1.41E-02	S	8.54E-04	S	6.06E-01	S	9.02E-03	W
4.8	1.46E-02	S	7.77E-04	S	6.20E-01	S	9.00E-03	W
5	1.51E-02	S	7.09E-04	S	6.34E-01	S	8.98E-03	W
5.2	1.55E-02	S	6.50E-04	S	6.48E-01	S	8.96E-03	W
5.4	1.53E-02	S	5.73E-04	S	6.72E-01	S	9.05E-03	W
5.6	1.50E-02	S	5.02E-04	S	6.99E-01	S	9.17E-03	W
5.8	1.42E-02	S	4.29E-04	S	7.32E-01	S	9.26E-03	W
6	1.31E-02	S	3.62E-04	S	7.69E-01	S	9.33E-03	W
6.2	1.34E-02	S	2.85E-04	S	8.25E-01	S	9.32E-03	W
6.4	1.38E-02	S	2.24E-04	S	8.87E-01	S	9.30E-03	W
6.6	1.43E-02	S	1.77E-04	S	9.51E-01	S	9.28E-03	W
6.8	1.32E-02	S	1.75E-04	S	9.89E-01	S	9.35E-03	W
7	1.19E-02	S	1.86E-04	S	1.02E+00	S	9.43E-03	W
7.2	1.06E-02	S	2.23E-04	S	1.03E+00	S	9.65E-03	W
7.4	9.52E-03	S	2.82E-04	S	1.05E+00	S	9.95E-03	W
7.6	8.45E-03	S	3.92E-04	S	1.05E+00	S	1.02E-02	W
7.8	7.46E-03	S	5.77E-04	S	1.04E+00	S	1.04E-02	W
8	6.68E-03	S	1.00E-03	S	1.01E+00	S	1.04E-02	S

Table C-5-59. Leachate Concentrations for Sludge Scrubber, Waste ID KGD Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	6.62E-03	S	9.80E-04	S	9.26E-01	S	9.57E-03	S
8.4	6.52E-03	S	4.75E-04	S	8.09E-01	S	7.46E-03	S
8.6	6.42E-03	S	2.34E-04	S	7.08E-01	S	5.86E-03	S
8.8	6.32E-03	S	1.17E-04	S	6.22E-01	S	4.62E-03	S
9	5.68E-03	S	7.55E-05	S	5.40E-01	S	4.11E-03	S
9.2	4.68E-03	S	6.94E-05	S	4.52E-01	S	3.78E-03	S
9.4	3.85E-03	S	6.64E-05	S	3.78E-01	S	3.46E-03	S
9.6	3.18E-03	S	6.36E-05	S	3.17E-01	S	3.18E-03	S
9.8	3.04E-03	S	6.17E-05	S	2.73E-01	S	2.92E-03	S
10	3.55E-03	S	6.11E-05	S	2.44E-01	S	2.78E-03	S
10.2	4.46E-03	S	6.11E-05	S	2.23E-01	S	2.78E-03	S
10.4	5.58E-03	S	6.11E-05	S	2.04E-01	S	2.78E-03	S
10.6	6.96E-03	S	6.11E-05	S	1.87E-01	S	2.78E-03	S
10.8	8.64E-03	S	6.11E-05	S	1.72E-01	S	2.78E-03	S
11	1.06E-02	S	6.05E-05	S	1.60E-01	S	2.78E-03	S
11.2	1.09E-02	S	5.69E-05	S	1.67E-01	S	2.78E-03	S
11.4	1.12E-02	S	5.37E-05	S	1.75E-01	S	2.78E-03	S
11.6	1.16E-02	S	5.07E-05	S	1.82E-01	S	2.78E-03	S
11.8	1.19E-02	S	4.79E-05	S	1.90E-01	S	2.78E-03	S
12	1.22E-02	S	4.53E-05	S	1.98E-01	S	2.78E-03	S
12.2	1.26E-02	S	4.29E-05	S	2.06E-01	S	2.78E-03	S
12.4	1.29E-02	S	4.06E-05	S	2.15E-01	S	2.78E-03	S
12.6	1.32E-02	S	3.85E-05	S	2.24E-01	S	2.78E-03	S
12.8	1.36E-02	S	3.65E-05	S	2.32E-01	S	2.78E-03	S
13	1.39E-02	S	3.47E-05	S	2.42E-01	S	2.78E-03	S
Detection Limit (min, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	
Detection Limit (max, mg/L)	5.00E-04		3.60E-06		7.60E-04		8.00E-05	

Table C-5-59. Leachate Concentrations for Sludge Scrubber, Waste ID KGD Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
Availability (mg/kg)	2.02E-01		4.04E-02		1.05E+01		1.04E-01	

Table C-5-59. Leachate Concentrations for Sludge Scrubber, Waste ID KGD Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	1.86E-01	S	5.13E-02	S	3.15E-03	S
3	2.64E-01	S	8.90E-02	S	2.74E-03	S
3.2	3.66E-01	S	1.49E-01	S	1.52E-02	S
3.4	4.05E-01	S	1.76E-01	S	4.08E-02	S
3.6	3.80E-01	S	1.60E-01	S	2.90E-02	S
3.8	3.57E-01	S	1.47E-01	S	2.10E-02	S
4	3.42E-01	S	1.37E-01	S	1.65E-02	S
4.2	3.29E-01	S	1.29E-01	S	1.31E-02	S
4.4	3.23E-01	S	1.25E-01	S	1.23E-02	S
4.6	3.18E-01	S	1.22E-01	S	1.20E-02	S
4.8	3.14E-01	S	1.20E-01	S	1.16E-02	S
5	3.10E-01	S	1.17E-01	S	1.13E-02	S
5.2	3.06E-01	S	1.15E-01	S	1.09E-02	S
5.4	2.95E-01	S	1.13E-01	S	1.10E-02	S
5.6	2.83E-01	S	1.10E-01	S	1.11E-02	S
5.8	2.67E-01	S	1.07E-01	S	1.11E-02	S
6	2.49E-01	S	1.03E-01	S	1.10E-02	S
6.2	2.26E-01	S	9.55E-02	S	9.98E-03	S
6.4	2.04E-01	S	8.82E-02	S	8.91E-03	S
6.6	1.85E-01	S	8.17E-02	S	7.99E-03	S
6.8	1.74E-01	S	7.69E-02	S	8.27E-03	S
7	1.66E-01	S	7.29E-02	S	8.94E-03	S
7.2	1.63E-01	S	6.91E-02	S	1.05E-02	S
7.4	1.62E-01	S	6.57E-02	S	1.28E-02	S
7.6	1.67E-01	S	6.29E-02	S	1.59E-02	S
7.8	1.78E-01	S	6.06E-02	S	2.01E-02	S
8	1.93E-01	S	5.71E-02	S	2.55E-02	S

Table C-5-59. Leachate Concentrations for Sludge Scrubber, Waste ID KGD Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	1.82E-01	S	5.26E-02	S	3.31E-02	S
8.4	1.47E-01	S	4.88E-02	S	4.67E-02	S
8.6	1.20E-01	S	4.53E-02	S	6.55E-02	S
8.8	9.85E-02	S	4.22E-02	S	9.12E-02	S
9	7.89E-02	S	3.92E-02	S	1.10E-01	S
9.2	5.92E-02	S	3.58E-02	S	1.11E-01	S
9.4	4.44E-02	S	3.27E-02	S	1.09E-01	S
9.6	3.34E-02	S	2.99E-02	S	1.07E-01	S
9.8	2.61E-02	S	2.73E-02	S	1.06E-01	S
10	2.09E-02	S	2.46E-02	S	1.06E-01	S
10.2	1.66E-02	S	2.20E-02	S	1.07E-01	S
10.4	1.32E-02	S	1.97E-02	S	1.08E-01	S
10.6	1.06E-02	S	1.77E-02	S	1.09E-01	S
10.8	8.51E-03	S	1.59E-02	S	1.10E-01	S
11	7.19E-03	S	1.46E-02	S	1.13E-01	S
11.2	9.15E-03	S	1.66E-02	S	1.39E-01	S
11.4	1.16E-02	S	1.88E-02	S	1.71E-01	S
11.6	1.46E-02	S	2.13E-02	S	2.09E-01	S
11.8	1.84E-02	S	2.40E-02	S	2.55E-01	S
12	2.30E-02	S	2.70E-02	S	3.06E-01	S
12.2	2.87E-02	S	3.04E-02	S	3.09E-01	S
12.4	3.56E-02	S	3.41E-02	S	3.09E-01	S
12.6	4.41E-02	S	3.81E-02	S	3.09E-01	S
12.8	5.44E-02	S	4.26E-02	S	3.09E-01	S
13	6.69E-02	S	4.76E-02	S	3.09E-01	S
Detection Limit (min, mg/L)	5.20E-04		5.10E-04		3.10E-04	
Detection Limit (max, mg/L)	5.20E-04		5.10E-04		3.10E-04	

Table C-5-59. Leachate Concentrations for Sludge Scrubber, Waste ID KGD Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
Availability (mg/kg)	4.05E+00		1.76E+00		3.39E+00	

Table C-5-60. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID ACC Med

Sample ID	ACC-[Med] (P,1,1)
Date Exported	9/20/2011, 8:58 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	0.236743	S	11.02168	W	0.0206406	S	0.154882	S
3	0.175572	S	10.86108	W	0.0194627	S	0.150439	S
3.2	0.13906	S	11.05345	W	0.0188857	S	0.147964	S
3.4	0.133345	S	11.80503	W	0.0186784	S	0.154114	S
3.6	0.1254	S	12.64599	W	0.0188261	S	0.160145	S
3.8	0.119509	S	13.08998	W	0.0187179	S	0.166068	S
4	0.105265	S	12.66932	W	0.0170272	S	0.15849	S
4.2	0.093295	S	12.28284	W	0.0155609	S	0.150311	S
4.4	0.083151	S	11.92532	W	0.0146307	S	0.142906	S
4.6	0.074491	S	11.59343	W	0.0138604	S	0.136172	S
4.8	0.066587	S	11.28433	W	0.0127975	S	0.12988	S
5	0.061732	S	10.95828	W	0.0117489	S	0.123276	S
5.2	0.061144	S	10.55365	W	0.0106683	S	0.116565	S
5.4	0.060483	S	10.17839	W	0.0098592	S	0.110453	S
5.6	0.059818	S	9.841586	W	0.0092419	S	0.104642	S
5.8	0.059183	S	9.989616	W	0.0082156	S	0.09583	S
6	0.058883	S	10.02367	W	0.0069289	S	0.084809	S
6.2	0.058464	S	10.04047	W	0.0058764	S	0.074506	S
6.4	0.057819	S	10.05677	W	0.0050099	S	0.065724	S
6.6	0.057201	S	10.0726	W	0.0042922	S	0.058201	S
6.8	0.056607	S	10.00001	W	0.0036944	S	0.049927	S
7	0.057121	S	9.490108	S	0.0030085	S	0.04454	S
7.2	0.060352	S	9.019494	S	0.0021755	S	0.030743	S
7.4	0.063671	S	8.584173	S	0.0015943	S	0.020168	S
7.6	0.067475	S	8.180647	S	0.0011781	S	0.01338	S
7.8	0.070567	S	7.805848	S	0.0008774	S	0.008972	S
8	0.071574	S	6.974352	S	0.0007464	S	0.006962	S

Table C-5-60. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID ACC Med

Sample ID	ACC-[Med] (P,1,1)
Date Exported	9/20/2011, 8:58 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	0.050594	S	4.245174	S	0.0007464	S	0.004284	S
8.4	0.041896	S	3.126153	S	0.0007464	S	0.004413	S
8.6	0.038118	S	3.035993	S	0.0007464	S	0.002828	S
8.8	0.035765	S	2.970285	S	0.0007464	S	0.002062	S
9	0.034568	S	2.907428	S	0.0007464	S	0.002062	S
9.2	0.033464	S	2.847239	S	0.0007464	S	0.002062	S
9.4	0.032419	S	2.745238	S	0.0007464	S	0.002062	S
9.6	0.031427	S	2.296872	S	0.0007464	S	0.002062	S
9.8	0.030485	S	1.928814	S	0.0007464	S	0.002062	S
10	0.02959	S	1.625461	S	0.0007464	S	0.002062	S
10.2	0.028567	S	1.374467	S	0.0007464	S	0.002062	S
10.4	0.027242	S	1.166021	S	0.0007464	S	0.002062	S
10.6	0.026384	S	0.992291	S	0.0007464	S	0.002062	S
10.8	0.025568	S	0.846997	S	0.0007464	S	0.002062	S
11	0.024792	S	0.72508	S	0.0007464	S	0.002062	S
11.2	0.024053	S	0.622453	S	0.0007464	S	0.002062	S
11.4	0.022805	S	0.521667	S	0.0007464	S	0.002062	S
11.6	0.020061	S	0.407918	S	0.0007464	S	0.002062	S
11.8	0.017686	S	0.320316	S	0.0007464	S	0.002062	S
12	0.015626	S	0.252551	S	0.0007464	S	0.002062	S
12.2	0.013891	S	0.199906	S	0.0007464	S	0.002062	S
12.4	0.012381	S	0.158838	S	0.0007464	S	0.002062	S
12.6	0.010989	S	0.126672	S	0.0007464	S	0.002062	S
12.8	0.009772	S	0.10138	S	0.0007464	S	0.002062	S
13	0.008706	S	0.081419	S	0.0007464	S	0.002062	S
Detection Limit (min, mg/L)	0.00064		0.00065		0.00017		0.00041	
Detection Limit (max, mg/L)	0.00064		0.00065		0.00017		0.00041	
Availability (mg/kg)	1.755723		130.8998		0.1946267		1.660681	

Table C-5-60. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID ACC Med

Sample ID
Date Exported
Database Name ing\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	2.06570089	S	2.47582E-05	S	0.027406405	S	0.17092095	S
3	1.9420914	S	2.29505E-05	S	0.015714832	S	0.1657731	S
3.2	1.74978844	S	2.20387E-05	S	0.012543319	S	0.12607312	S
3.4	1.37479786	S	2.49123E-05	S	0.014500633	S	0.0703833	S
3.6	1.09516874	S	2.79639E-05	S	0.016624972	S	0.04062476	S
3.8	0.89644455	S	3.11938E-05	S	0.018907075	S	0.02477752	S
4	0.85113208	S	3.17714E-05	S	0.021015396	S	0.02622007	S
4.2	0.81015812	S	2.66474E-05	S	0.022920126	S	0.02767009	S
4.4	0.77292899	S	2.23766E-05	S	0.024896783	S	0.02904708	S
4.6	0.73895453	S	1.89367E-05	S	0.026944629	S	0.03035326	S
4.8	0.7078265	S	1.61399E-05	S	0.029572548	S	0.03165886	S
5	0.68545255	S	1.51861E-05	S	0.037550723	S	0.0356094	S
5.2	0.69165489	S	1.89343E-05	S	0.059125928	S	0.04255597	S
5.4	0.69991529	S	2.34119E-05	S	0.085214571	S	0.04908228	S
5.6	0.70796857	S	2.87257E-05	S	0.118402391	S	0.05631645	S
5.8	0.7221928	S	2.87356E-05	S	0.153869277	S	0.06365289	S
6	0.7429065	S	2.87356E-05	S	0.187276178	S	0.07090263	S
6.2	0.76350597	S	2.87356E-05	S	0.225923973	S	0.07869921	S
6.4	0.78706195	S	2.87356E-05	S	0.272224238	S	0.08706425	S
6.6	0.82693508	S	2.87356E-05	S	0.325371444	S	0.09601946	S
6.8	0.86437692	S	2.87356E-05	S	0.386829611	S	0.10558671	S
7	0.88542201	S	2.87356E-05	S	0.439772674	S	0.11469807	S
7.2	0.90636502	S	4.16704E-05	S	0.452603004	S	0.12149973	S
7.4	0.93369198	S	6.084E-05	S	0.463052311	S	0.1283234	S
7.6	0.94813811	S	8.00805E-05	S	0.472515211	S	0.13319258	S
7.8	0.96861379	S	9.81463E-05	S	0.48367802	S	0.13908059	S
8	0.98917976	S	0.000111345	S	0.45318012	S	0.12887793	S

Table C-5-60. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID ACC Med

Sample ID
Date Exported
Database Name ing\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	0.96941568	W	8.55865E-05	S	0.31573509	W	0.08046617	S
8.4	0.96312136	W	7.72899E-05	S	0.247049302	W	0.05831164	S
8.6	0.96238377	W	6.56608E-05	S	0.2530681	W	0.03466073	S
8.8	0.96175457	W	5.75158E-05	S	0.251715172	W	0.02802244	S
9	0.9612412	W	4.94135E-05	S	0.25519357	W	0.02276403	S
9.2	0.96073937	W	4.25945E-05	S	0.258642003	W	0.01857703	S
9.4	0.9602486	W	3.6834E-05	S	0.261756276	W	0.01523866	S
9.6	0.95943599	W	3.7761E-05	S	0.262108014	W	0.01264156	S
9.8	0.95829189	W	3.74511E-05	S	0.262452957	W	0.01052756	S
10	0.95717222	W	3.614E-05	S	0.262791372	W	0.00879955	S
10.2	0.956076	W	3.48994E-05	S	0.263123508	W	0.00738134	S
10.4	0.95500228	W	3.37243E-05	S	0.263449602	W	0.00621287	S
10.6	0.95395018	W	3.261E-05	S	0.263769877	W	0.00524656	S
10.8	0.95291888	W	3.15524E-05	S	0.265176174	W	0.00444457	S
11	0.95190759	W	3.05475E-05	S	0.266057404	W	0.00377665	S
11.2	0.95091556	W	2.95919E-05	S	0.266462947	W	0.00321853	S
11.4	0.95045844	W	2.87692E-05	S	0.264781079	W	0.002783	S
11.6	0.95806098	W	2.93294E-05	S	0.262238295	W	0.002783	S
11.8	0.96559281	W	2.98907E-05	S	0.259762778	W	0.002783	S
12	0.97305578	W	3.0453E-05	S	0.257351653	W	0.002783	S
12.2	0.98045164	W	3.10164E-05	S	0.255002211	W	0.002783	S
12.4	0.98678761	W	3.15807E-05	S	0.252711904	W	0.002783	S
12.6	0.98433165	W	3.01991E-05	S	0.250478323	W	0.002783	S
12.8	0.98192034	W	2.76E-05	S	0.248256521	W	0.002783	S
13	0.97955218	W	2.52598E-05	S	0.245405281	W	0.002783	S
Detection Limit (min, mg/L)	0.0005		0.0000036		0.00076		0.00008	
Detection Limit (max, mg/L)	0.0005		0.0000036		0.00076		0.00008	
Availability (mg/kg)	19.4209139		0.001113448		4.836780171		1.65773096	

Table C-5-60. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID ACC Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	0.1755029	S	0.106778	S	0.1899509	S
3	0.1492192	S	0.100546	S	0.0817083	S
3.2	0.1315965	S	0.097681	S	0.04772	S
3.4	0.1276216	S	0.097985	S	0.0390276	S
3.6	0.1243241	S	0.098274	S	0.0322876	S
3.8	0.1241419	S	0.098547	S	0.0272242	S
4	0.1156928	S	0.086197	S	0.0277534	S
4.2	0.1081903	S	0.075501	S	0.0282662	S
4.4	0.1014904	S	0.067067	S	0.0287641	S
4.6	0.0951675	S	0.059889	S	0.0292479	S
4.8	0.089197	S	0.053738	S	0.0297189	S
5	0.0879027	S	0.048626	S	0.0350973	S
5.2	0.0935249	S	0.043736	S	0.0424938	S
5.4	0.0992741	S	0.039639	S	0.051079	S
5.6	0.1052196	S	0.03654	S	0.060989	S
5.8	0.1142198	S	0.033825	S	0.0697202	S
6	0.1236452	S	0.031436	S	0.0763689	S
6.2	0.1335009	S	0.029287	S	0.0834021	S
6.4	0.1449391	S	0.02697	S	0.0940797	S
6.6	0.1559934	S	0.024751	S	0.1011677	S
6.8	0.1675227	S	0.022931	S	0.1085539	S
7	0.1817246	S	0.02151	S	0.1162417	S
7.2	0.2025258	S	0.017582	S	0.1186189	S
7.4	0.2250387	S	0.014996	S	0.116845	S
7.6	0.2437273	S	0.01259	S	0.114889	S
7.8	0.2697741	S	0.0104	S	0.1130154	S
8	0.2490561	S	0.009027	S	0.1027868	S

Table C-5-60. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID ACC Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	0.1280791	S	0.007799	S	0.0718773	S
8.4	0.0831313	S	0.007459	S	0.0575941	S
8.6	0.0689597	S	0.007098	S	0.065595	S
8.8	0.0635986	S	0.006665	S	0.0708521	S
9	0.0587611	S	0.006361	S	0.0824518	S
9.2	0.054386	S	0.006077	S	0.0952328	S
9.4	0.0502051	S	0.005812	S	0.1064286	S
9.6	0.0442727	S	0.005429	S	0.1107594	S
9.8	0.0392126	S	0.004951	S	0.1151717	S
10	0.0348161	S	0.004524	S	0.1196652	S
10.2	0.0309854	S	0.00414	S	0.1242399	S
10.4	0.0276387	S	0.003796	S	0.1288955	S
10.6	0.0247072	S	0.003486	S	0.1336319	S
10.8	0.0221329	S	0.003207	S	0.1384489	S
11	0.020293	S	0.002954	S	0.1488826	S
11.2	0.0189497	S	0.002725	S	0.1530481	S
11.4	0.0174161	S	0.00253	S	0.1495243	S
11.6	0.0176303	S	0.00253	S	0.1103803	S
11.8	0.0178435	S	0.00253	S	0.0819076	S
12	0.0180555	S	0.00253	S	0.0610851	S
12.2	0.0182665	S	0.00253	S	0.0457775	S
12.4	0.0184765	S	0.00253	S	0.0350846	S
12.6	0.0186855	S	0.00253	S	0.0270659	S
12.8	0.0188709	S	0.00253	S	0.0209654	S
13	0.0189166	S	0.00253	S	0.0163044	S
Detection Limit (min, mg/L)	0.00052		0.00051		0.00031	
Detection Limit (max, mg/L)	0.00052		0.00051		0.00031	
Availability (mg/kg)	2.6977413		1.005461		1.5917006	

Table C-5-61. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID BCC Med

Sample ID	BCC-[Med] (P,1,1)
Date Exported	9/20/2011, 8:58 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	0.199934	S	8.542333	W	0.0042447	S	0.203831	S
3	0.125674	S	8.30627	W	0.0051298	S	0.189868	S
3.2	0.0814	S	8.009297	W	0.0054867	S	0.173704	S
3.4	0.068816	S	7.952334	W	0.0034694	S	0.166934	S
3.6	0.064519	S	7.843859	W	0.0034296	S	0.157403	S
3.8	0.0607	S	7.593205	W	0.0033924	S	0.148889	S
4	0.057287	S	7.469571	W	0.0033575	S	0.141237	S
4.2	0.054219	S	7.353838	W	0.0033879	S	0.133014	S
4.4	0.048171	S	7.245161	W	0.0034629	S	0.127734	S
4.6	0.042571	S	7.142816	W	0.003536	S	0.122326	S
4.8	0.037821	S	7.084383	W	0.0036075	S	0.117087	S
5	0.033764	S	7.078404	W	0.0036775	S	0.112273	S
5.2	0.032752	S	7.072663	W	0.0037459	S	0.107834	S
5.4	0.033292	S	7.067144	W	0.0039037	S	0.103728	S
5.6	0.033821	S	7.053773	W	0.0041586	S	0.09992	S
5.8	0.03434	S	6.994545	W	0.0044204	S	0.096378	S
6	0.034848	S	6.937798	W	0.004689	S	0.093075	S
6.2	0.034939	S	6.883349	W	0.0049642	S	0.089989	S
6.4	0.034686	S	6.854603	W	0.0052461	S	0.087097	S
6.6	0.036317	S	6.87511	W	0.0055346	S	0.084384	S
6.8	0.03679	S	6.895064	W	0.0058297	S	0.081832	S
7	0.037255	S	6.914496	W	0.0048916	S	0.079429	S
7.2	0.035032	S	6.779724	W	0.0039838	S	0.077513	S
7.4	0.031608	S	6.614025	W	0.0032628	S	0.072568	S
7.6	0.021083	S	6.547541	W	0.0026866	S	0.016587	S
7.8	0.017265	S	6.576364	W	0.0019579	S	0.006156	S
8	0.016822	S	6.184895	W	0.002025	S	0.005621	S

Table C-5-61. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID BCC Med

Sample ID	BCC-[Med] (P,1,1)
Date Exported	9/20/2011, 8:58 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	0.01729	S	5.470447	W	0.0020046	S	0.005144	S
8.4	0.018248	S	5.151538	W	0.0018822	S	0.004925	S
8.6	0.019395	S	5.022557	W	0.0018169	S	0.004721	S
8.8	0.017737	S	4.899659	W	0.0017554	S	0.004349	S
9	0.016019	S	4.596382	S	0.0017564	S	0.004015	S
9.2	0.0145	S	4.191971	S	0.001803	S	0.003701	S
9.4	0.013153	S	3.830722	S	0.0018497	S	0.003405	S
9.6	0.011955	S	3.507253	S	0.0018966	S	0.003138	S
9.8	0.010888	S	3.216944	S	0.0019437	S	0.002897	S
10	0.009935	S	2.955821	S	0.001991	S	0.002678	S
10.2	0.009163	S	2.72045	S	0.0020384	S	0.00248	S
10.4	0.008553	S	2.507859	S	0.002086	S	0.0023	S
10.6	0.007994	S	2.315467	S	0.0021338	S	0.002136	S
10.8	0.007482	S	2.141027	S	0.0021818	S	0.002062	S
11	0.007359	S	2.383962	S	0.002374	S	0.002062	S
11.2	0.007357	S	2.750351	S	0.0026015	S	0.002062	S
11.4	0.007356	S	3.165031	S	0.0028463	S	0.002062	S
11.6	0.007354	S	3.633349	S	0.0031091	S	0.002062	S
11.8	0.007353	S	4.161135	S	0.0033912	S	0.002062	S
12	0.007351	S	4.754736	S	0.0036934	S	0.002062	S
12.2	0.00735	S	5.421053	S	0.0040169	S	0.002062	S
12.4	0.007348	S	6.16758	S	0.0043217	S	0.002062	S
12.6	0.007276	S	7.00244	S	0.0045025	S	0.002062	S
12.8	0.007229	S	7.855425	S	0.0046878	S	0.002062	S
13	0.007221	S	8.542333	S	0.0048777	S	0.002062	S
Detection Limit (min, mg/L)	0.00064		0.00065		0.00017		0.00041	
Detection Limit (max, mg/L)	0.00064		0.00065		0.00017		0.00041	
Availability (mg/kg)	1.256738		96.95547		0.0582967		1.898685	

Table C-5-61. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID BCC Med

Sample ID
Date Exported
Database Name :ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	0.712	W	0.002626778	S	0.089725733	S	0.00593048	S
3	0.712	W	0.002382419	S	0.092768083	S	0.00495359	S
3.2	0.71983225	W	0.002174457	S	0.073556432	S	0.002783	S
3.4	0.712	W	0.008468502	S	0.084042383	S	0.00357361	S
3.6	0.71019022	W	0.004838015	S	0.078922408	S	0.00307855	S
3.8	0.70866417	W	0.00315747	S	0.080384084	S	0.002783	S
4	0.71100581	W	0.002743335	S	0.08272901	S	0.002783	S
4.2	0.71254435	W	0.002399928	S	0.085022953	S	0.002783	S
4.4	0.71276378	W	0.002335476	S	0.088722419	S	0.002783	S
4.6	0.71297352	W	0.002530932	S	0.092737056	S	0.002783	S
4.8	0.71317439	W	0.002733378	S	0.096750923	S	0.002783	S
5	0.71336711	W	0.002942758	S	0.100764051	S	0.002783	S
5.2	0.71355233	W	0.003159017	S	0.10477647	S	0.002783	S
5.4	0.71373059	W	0.003061236	S	0.107157865	S	0.002783	S
5.6	0.71390242	W	0.002794252	S	0.107859803	S	0.002783	S
5.8	0.71406825	W	0.002558734	S	0.108541466	S	0.002783	S
6	0.7142285	W	0.002448601	S	0.109204108	S	0.002783	S
6.2	0.71438353	W	0.002914692	S	0.109848868	W	0.002783	S
6.4	0.71453366	W	0.003450361	S	0.110476784	W	0.002783	S
6.6	0.71467921	W	0.004063324	S	0.111088801	W	0.002783	S
6.8	0.71482044	W	0.004761877	S	0.111685786	W	0.002783	S
7	0.7149576	W	0.001810003	S	0.113262292	W	0.002783	S
7.2	0.72170592	W	0.000594937	S	0.114616094	W	0.002783	S
7.4	0.72310361	W	0.000315726	S	0.116112695	W	0.002783	S
7.6	0.72446661	W	0.000147546	S	0.118355196	W	0.002783	S
7.8	0.70083886	W	3.56275E-05	S	0.126013062	W	0.002783	S
8	0.73354618	W	4.23017E-05	S	0.11990532	W	0.002783	S

Table C-5-61. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID BCC Med

Sample ID
Date Exported
Database Name :ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	0.73148956	W	2.39815E-05	S	0.115377678	W	0.002783	S
8.4	0.72752245	W	2.05615E-05	S	0.114344788	W	0.002783	S
8.6	0.72551659	W	2.15517E-05	S	0.114072533	W	0.002783	S
8.8	0.72356218	W	2.0723E-05	S	0.111147234	W	0.00303892	S
9	0.72165679	W	1.98674E-05	S	0.106769333	S	0.00334044	S
9.2	0.71979813	W	1.90648E-05	S	0.102654499	S	0.00366424	S
9.4	0.71798408	W	1.83109E-05	S	0.098781711	S	0.00401144	S
9.6	0.71621265	W	1.67366E-05	S	0.095132024	S	0.00437158	S
9.8	0.71448198	W	1.4489E-05	S	0.09168833	S	0.00464998	S
10	0.71279034	W	1.25798E-05	S	0.088299052	S	0.00493995	S
10.2	0.71113608	W	1.21011E-05	S	0.084634765	S	0.00524171	S
10.4	0.70951768	W	1.16698E-05	S	0.081189337	S	0.00555551	S
10.6	0.70793368	W	1.12617E-05	S	0.077945854	S	0.00588157	S
10.8	0.6975808	W	1.08751E-05	S	0.075606815	S	0.00623977	S
11	0.7026498	W	1.1478E-05	S	0.077205616	S	0.00561832	S
11.2	0.69853116	W	1.24606E-05	S	0.080088698	S	0.00488564	S
11.4	0.69440172	W	1.35076E-05	S	0.083025548	S	0.00425903	S
11.6	0.69106005	W	1.46222E-05	S	0.086016199	S	0.00372167	S
11.8	0.69149537	W	1.73039E-05	S	0.089060683	S	0.0032596	S
12	0.69192364	W	1.78638E-05	S	0.092159031	S	0.00286128	S
12.2	0.69234509	W	1.84322E-05	S	0.095311276	S	0.00251704	S
12.4	0.69275994	W	1.98173E-05	S	0.098517449	S	0.00221884	S
12.6	0.69316839	W	2.13168E-05	S	0.101044349	S	0.00195992	S
12.8	0.69357065	W	2.29034E-05	S	0.103541049	S	0.0017346	S
13	0.69396689	W	2.45807E-05	S	0.106059294	S	0.0015381	S
Detection Limit (min, mg/L)	0.0005		0.0000036		0.00076		0.00008	
Detection Limit (max, mg/L)	0.0005		0.0000036		0.00076		0.00008	
Availability (mg/kg)	7.8765242		0.084685021		1.260130609		0.06582954	

Table C-5-61. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID BCC Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	0.1018986	S	0.012693	S	0.121773	S
3	0.0849358	S	0.011046	S	0.106159	S
3.2	0.0716339	S	0.009697	S	0.0770586	S
3.4	0.0644091	S	0.009553	S	0.0827645	S
3.6	0.0633205	S	0.009295	S	0.0738707	S
3.8	0.0623078	S	0.009058	S	0.0684827	S
4	0.0613621	S	0.008838	S	0.0687592	S
4.2	0.0604758	S	0.008446	S	0.0676754	S
4.4	0.0596426	S	0.008083	S	0.0662203	S
4.6	0.0588572	S	0.007751	S	0.0648591	S
4.8	0.056716	S	0.007446	S	0.0635821	S
5	0.0537186	S	0.007165	S	0.0623808	S
5.2	0.0509881	S	0.006904	S	0.061248	S
5.4	0.0482442	S	0.006712	S	0.0612456	S
5.6	0.045506	S	0.00658	S	0.0623323	S
5.8	0.0430114	S	0.006455	S	0.0633992	S
6	0.0407313	S	0.006337	S	0.0644472	S
6.2	0.038641	S	0.006224	S	0.0654773	S
6.4	0.0367194	S	0.006117	S	0.0664904	S
6.6	0.0354124	S	0.006015	S	0.0674873	S
6.8	0.0348734	S	0.005918	S	0.0684687	S
7	0.032934	S	0.005603	S	0.0648724	S
7.2	0.0328193	S	0.004251	S	0.0609181	S
7.4	0.0325683	S	0.003589	S	0.0573034	S
7.6	0.0323943	S	0.003044	S	0.0537255	S
7.8	0.0322257	S	0.002593	S	0.0509492	S
8	0.0345078	S	0.00253	S	0.0482061	S

Table C-5-61. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID BCC Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	0.0284635	S	0.00253	S	0.0497661	S
8.4	0.0255823	S	0.00253	S	0.0513372	S
8.6	0.0222813	S	0.00253	S	0.0529192	S
8.8	0.0226155	S	0.00253	S	0.0545119	S
9	0.0232334	S	0.00253	S	0.0553451	S
9.2	0.0239398	S	0.00253	S	0.0555962	S
9.4	0.0246519	S	0.00253	S	0.055843	S
9.6	0.0252187	S	0.00253	S	0.0560857	S
9.8	0.0248625	S	0.00253	S	0.0563243	S
10	0.0245673	S	0.00253	S	0.0565592	S
10.2	0.0248843	S	0.00253	S	0.0567903	S
10.4	0.0251992	S	0.00253	S	0.0570179	S
10.6	0.025512	S	0.00253	S	0.057242	S
10.8	0.0258226	S	0.00253	S	0.0574628	S
11	0.0263923	S	0.00253	S	0.05822	S
11.2	0.0270525	S	0.00253	S	0.0590848	S
11.4	0.0277171	S	0.00253	S	0.0601884	S
11.6	0.0283861	S	0.00253	S	0.0615067	S
11.8	0.0290594	S	0.00253	S	0.0628307	S
12	0.0297369	S	0.00253	S	0.0641601	S
12.2	0.0304186	S	0.00253	S	0.065495	S
12.4	0.0309789	S	0.00253	S	0.0668353	S
12.6	0.0317945	S	0.00253	S	0.068181	S
12.8	0.0324886	S	0.00253	S	0.0695319	S
13	0.0331867	S	0.00253	S	0.070888	S
Detection Limit (min, mg/L)	0.00052		0.00051		0.00031	
Detection Limit (max, mg/L)	0.00052		0.00051		0.00031	
Availability (mg/kg)	0.8493577		0.110462		1.0615901	

Table C-5-62. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID CCC Med

Sample ID	CCC-[Med] (P,1,1)
Date Exported	9/20/2011, 8:58 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	0.205935	S	8.72552	W	0.0155481	S	0.149959	W
3	0.151408	S	8.835719	W	0.0149606	S	0.153841	W
3.2	0.113551	S	8.684359	W	0.0144312	S	0.157237	W
3.4	0.087457	S	8.571123	W	0.014158	S	0.159286	W
3.6	0.069798	S	8.247022	W	0.0139155	S	0.161242	W
3.8	0.057054	S	8.467667	W	0.0134947	S	0.15544	W
4	0.048037	S	8.40002	W	0.0131452	S	0.149639	W
4.2	0.044498	S	8.296738	W	0.0127248	S	0.144323	W
4.4	0.041831	S	8.20085	W	0.0123394	S	0.139962	W
4.6	0.041038	S	8.12835	W	0.0118596	S	0.13778	W
4.8	0.040292	S	8.059537	W	0.0113726	S	0.135723	W
5	0.03959	S	7.994081	W	0.0109455	S	0.133778	W
5.2	0.038927	S	7.931693	W	0.0105503	S	0.131936	W
5.4	0.0383	S	7.8869	W	0.0101835	S	0.130188	W
5.6	0.037704	S	7.871295	W	0.009842	S	0.128525	W
5.8	0.037139	S	7.856267	W	0.0095235	S	0.12694	W
6	0.036601	S	7.718203	S	0.0092255	S	0.125006	S
6.2	0.039238	S	7.65784	S	0.007542	S	0.097722	S
6.4	0.042879	S	7.568779	S	0.0055979	S	0.066477	S
6.6	0.04673	S	7.351488	S	0.0041933	S	0.045761	S
6.8	0.050797	S	7.146648	S	0.0031683	S	0.031854	S
7	0.053449	S	6.953209	S	0.0024134	S	0.022408	S
7.2	0.056359	S	6.770238	S	0.0018525	S	0.01592	S
7.4	0.060479	S	6.5969	S	0.0014323	S	0.011417	S
7.6	0.064778	S	6.444356	S	0.001115	S	0.00826	S
7.8	0.06926	S	6.317882	S	0.0008737	S	0.006027	S
8	0.072352	S	5.638437	S	0.0007464	S	0.004665	S

Table C-5-62. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID CCC Med

Sample ID	CCC-[Med] (P,1,1)
Date Exported	9/20/2011, 8:58 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	0.072448	S	4.33007	S	0.0007464	S	0.004008	S
8.4	0.071061	S	3.346527	S	0.0007464	S	0.003297	S
8.6	0.072636	S	2.602118	S	0.0007464	S	0.002647	S
8.8	0.072726	S	2.035035	S	0.0007464	S	0.002135	S
9	0.072814	S	1.600353	S	0.0007464	S	0.002062	S
9.2	0.066076	S	1.133544	S	0.0007464	S	0.002062	S
9.4	0.048868	S	0.642057	S	0.0007464	S	0.002062	S
9.6	0.036372	S	0.368049	S	0.0007464	S	0.002062	S
9.8	0.026386	S	0.213413	S	0.0007464	S	0.002062	S
10	0.019003	S	0.125118	S	0.0007464	S	0.002062	S
10.2	0.017109	S	0.081878	S	0.0007464	S	0.002062	S
10.4	0.01458	S	0.055064	S	0.0007464	S	0.002062	S
10.6	0.012463	S	0.037312	S	0.0007464	S	0.002062	S
10.8	0.010685	S	0.027404	S	0.0007464	S	0.002062	S
11	0.007647	S	0.019525	S	0.0007464	S	0.002062	S
11.2	0.005437	S	0.013504	S	0.0007464	S	0.002062	S
11.4	0.003889	S	0.009674	S	0.0007464	S	0.002062	S
11.6	0.00272	S	0.007062	S	0.0007464	S	0.002062	S
11.8	0.001822	S	0.005182	S	0.0007464	S	0.002062	S
12	0.001291	S	0.003823	S	0.0007464	S	0.002062	S
12.2	0.000946	S	0.002834	S	0.0007464	S	0.002062	S
12.4	0.000697	S	0.002112	S	0.0007464	S	0.002062	S
12.6	0.000516	S	0.001574	S	0.0007464	S	0.002062	S
12.8	0.000384	S	0.001175	S	0.0007464	S	0.002062	S
13	0.00032	S	0.000882	S	0.0007464	S	0.002062	S
Detection Limit (min, mg/L)	0.00064		0.00065		0.00017		0.00041	
Detection Limit (max, mg/L)	0.00064		0.00065		0.00017		0.00041	
Availability (mg/kg)	1.514078		88.35719		0.1496063		1.612415	

Table C-5-62. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID CCC Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	0.71002193	S	2.87356E-05	S	0.151692518	S	0.3147164	S
3	0.69878631	S	2.87356E-05	S	0.099935515	S	0.28435651	S
3.2	0.68491351	S	2.87356E-05	S	0.067635878	S	0.25861359	S
3.4	0.55024877	S	2.87356E-05	S	0.061622082	S	0.17598522	S
3.6	0.34831533	S	2.87356E-05	S	0.08029248	S	0.08363163	S
3.8	0.21046067	S	2.87356E-05	S	0.096311463	S	0.0487192	S
4	0.10708468	S	2.81874E-05	S	0.095764382	S	0.0459106	S
4.2	0.05631238	S	2.76971E-05	S	0.093796844	S	0.04338945	S
4.4	0.03347102	S	2.86311E-05	S	0.093327919	S	0.04156904	S
4.6	0.03651076	S	2.72124E-05	S	0.117899722	S	0.04602586	S
4.8	0.04261747	S	2.59226E-05	S	0.148711086	S	0.05130698	S
5	0.04943246	S	2.64714E-05	S	0.208548376	S	0.05948979	S
5.2	0.05700457	S	2.70097E-05	S	0.2886087	S	0.06857842	S
5.4	0.06538389	S	2.7538E-05	S	0.377923094	S	0.07712667	S
5.6	0.07462177	S	2.80568E-05	S	0.478732448	S	0.08618479	S
5.8	0.08477075	S	2.85667E-05	S	0.60142075	S	0.09593215	S
6	0.09655141	S	2.72955E-05	S	0.749729266	S	0.10639471	S
6.2	0.10987771	S	2.53179E-05	S	0.86503023	S	0.11525466	S
6.4	0.12453106	S	2.35397E-05	S	0.952379788	S	0.12303242	S
6.6	0.1405959	S	2.19355E-05	S	1.045450188	S	0.13107138	S
6.8	0.15815918	S	2.04837E-05	S	1.144425658	S	0.13937199	S
7	0.17731038	S	1.91661E-05	S	1.249490596	S	0.14793469	S
7.2	0.19814148	S	1.79668E-05	S	1.360829561	S	0.15675993	S
7.4	0.22074701	S	1.79598E-05	S	1.478627272	S	0.16584811	S
7.6	0.24522396	S	1.79598E-05	S	1.603068601	S	0.17519966	S
7.8	0.27167186	S	1.79598E-05	S	1.734338571	S	0.18481497	S
8	0.30780473	S	1.79598E-05	S	1.79583582	S	0.18757983	S

Table C-5-62. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID CCC Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	0.29085901	W	1.90644E-05	S	1.580563263	W	0.16009956	S
8.4	0.27297018	W	2.20838E-05	S	1.424150259	W	0.1407035	S
8.6	0.25656451	W	2.63968E-05	S	1.286366409	W	0.12403362	S
8.8	0.24148871	W	3.14231E-05	S	1.164634221	W	0.10965616	S
9	0.22729191	W	3.4732E-05	S	1.056780313	W	0.09721407	S
9.2	0.21794049	W	3.33975E-05	S	0.95782662	W	0.07576129	S
9.4	0.2153394	W	4.10267E-05	S	0.864014159	W	0.04501917	S
9.6	0.21282314	W	4.44721E-05	S	0.781083259	W	0.02704624	S
9.8	0.21038727	W	4.81269E-05	S	0.707583086	W	0.01642024	S
10	0.20802765	W	4.80861E-05	S	0.642280421	W	0.01007002	S
10.2	0.19755669	W	4.34476E-05	S	0.610163108	W	0.00713118	S
10.4	0.18636857	W	3.93339E-05	S	0.583239349	W	0.00521429	S
10.6	0.17640834	W	3.56773E-05	S	0.548100328	W	0.00373156	S
10.8	0.17330597	W	3.24197E-05	S	0.52951876	W	0.00280665	S
11	0.18217124	W	3.12858E-05	S	0.559252764	W	0.002783	S
11.2	0.18984874	W	3.02651E-05	S	0.584450389	W	0.002783	S
11.4	0.1952531	W	2.92949E-05	S	0.6137081	W	0.002783	S
11.6	0.20071331	W	2.83719E-05	S	0.647467558	W	0.002783	S
11.8	0.20622895	W	2.7493E-05	S	0.682459069	W	0.002783	S
12	0.21179963	W	2.66554E-05	S	0.718705568	W	0.002783	S
12.2	0.21742497	W	2.58565E-05	S	0.756230022	W	0.002783	S
12.4	0.22310461	W	2.5094E-05	S	0.795055429	W	0.002783	S
12.6	0.22883817	W	2.43657E-05	S	0.835204815	W	0.002783	S
12.8	0.23462529	W	2.36695E-05	S	0.876701236	W	0.002783	S
13	0.24046564	W	2.30035E-05	S	0.919567777	W	0.002783	S
Detection Limit (min, mg/L)	0.0005		0.0000036		0.00076		0.00008	
Detection Limit (max, mg/L)	0.0005		0.0000036		0.00076		0.00008	
Availability (mg/kg)	6.98786308		0.000481269		17.95835818		2.84356508	

Table C-5-62. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID CCC Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	0.1777939	S	0.108389	S	0.43297	S
3	0.1281955	S	0.104238	S	0.1973116	S
3.2	0.0987352	S	0.1005	S	0.0945982	S
3.4	0.0909932	S	0.09627	S	0.0536283	S
3.6	0.0842508	S	0.092422	S	0.0367971	S
3.8	0.0874722	S	0.085899	S	0.0295074	S
4	0.0913224	S	0.078458	S	0.0299833	S
4.2	0.0951419	S	0.072571	S	0.0313798	S
4.4	0.1003116	S	0.067075	S	0.0330425	S
4.6	0.1108609	S	0.061433	S	0.0371544	S
4.8	0.1219992	S	0.056134	S	0.0449408	S
5	0.1337328	S	0.051635	S	0.0524692	S
5.2	0.1460679	S	0.047653	S	0.0593857	S
5.4	0.1590103	S	0.044111	S	0.0669005	S
5.6	0.1725657	S	0.040947	S	0.0750404	S
5.8	0.1867398	S	0.03811	S	0.0838321	S
6	0.2015381	S	0.035556	S	0.0933027	S
6.2	0.217722	S	0.031438	S	0.097656	S
6.4	0.2351224	S	0.026979	S	0.0985599	S
6.6	0.2533134	S	0.023262	S	0.099444	S
6.8	0.2723053	S	0.020146	S	0.1003092	S
7	0.2921082	S	0.01752	S	0.1011566	S
7.2	0.3127321	S	0.015297	S	0.1019869	S
7.4	0.3341869	S	0.013405	S	0.1028011	S
7.6	0.3564821	S	0.011938	S	0.1035997	S
7.8	0.3796274	S	0.010698	S	0.1043836	S
8	0.3697696	S	0.009606	S	0.1055212	S

Table C-5-62. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID CCC Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	0.314441	S	0.008634	S	0.1139144	S
8.4	0.2663207	S	0.007886	S	0.1243307	S
8.6	0.2264479	S	0.007276	S	0.1333163	S
8.8	0.193264	S	0.006726	S	0.1427222	S
9	0.1655313	S	0.006228	S	0.1525578	S
9.2	0.1254723	S	0.005934	S	0.1595619	S
9.4	0.0734761	S	0.005768	S	0.1597644	S
9.6	0.0435149	S	0.005611	S	0.1599628	S
9.8	0.0261742	S	0.005461	S	0.1601574	S
10	0.0157581	S	0.004983	S	0.1614812	S
10.2	0.0136643	S	0.004191	S	0.1617901	S
10.4	0.0126928	S	0.003536	S	0.1634563	S
10.6	0.011807	S	0.002975	S	0.1651074	S
10.8	0.0105291	S	0.00253	S	0.1667439	S
11	0.0108182	S	0.00253	S	0.1420802	S
11.2	0.0113302	S	0.00253	S	0.1234525	S
11.4	0.0119468	S	0.00253	S	0.1060501	S
11.6	0.0125854	S	0.00253	S	0.0904853	S
11.8	0.0132464	S	0.00253	S	0.0774148	S
12	0.01393	S	0.00253	S	0.0664062	S
12.2	0.0146368	S	0.00253	S	0.0571076	S
12.4	0.015367	S	0.00253	S	0.0492317	S
12.6	0.0161211	S	0.00253	S	0.0425429	S
12.8	0.0168995	S	0.00253	S	0.0368475	S
13	0.0177024	S	0.00253	S	0.0319858	S
Detection Limit (min, mg/L)	0.00052		0.00051		0.00031	
Detection Limit (max, mg/L)	0.00052		0.00051		0.00031	
Availability (mg/kg)	3.7962739		1.042385		1.9731164	

Table C-5-63. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID DCC Med

Sample ID	DCC-[Med] (P,1,1)
Date Exported	9/20/2011, 8:58 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	0.312848	S	13.87143	W	0.0007464	S	0.048173	W
3	0.299716	S	13.92666	W	0.0007464	S	0.047046	W
3.2	0.287931	S	13.91004	W	0.0007464	S	0.04895	W
3.4	0.279222	S	13.83793	W	0.0007464	S	0.046714	W
3.6	0.273802	S	13.84397	W	0.0007464	S	0.04604	W
3.8	0.268771	S	13.8497	W	0.0007464	S	0.045412	W
4	0.264084	S	13.85274	W	0.0007464	S	0.044823	W
4.2	0.258111	S	13.84284	W	0.0007464	S	0.044271	W
4.4	0.248389	S	13.86522	W	0.0007464	S	0.04375	W
4.6	0.239441	S	13.86993	W	0.0007464	S	0.043259	W
4.8	0.231177	S	13.87444	W	0.0007464	S	0.042793	W
5	0.223518	S	13.87877	W	0.0007464	S	0.042351	W
5.2	0.215873	S	13.88293	W	0.0007464	S	0.041931	W
5.4	0.199272	S	13.88693	W	0.0007464	S	0.041531	W
5.6	0.186341	S	13.89079	W	0.0007464	S	0.041148	W
5.8	0.174659	S	13.89452	W	0.0007464	S	0.040783	W
6	0.16407	S	13.89812	W	0.0007464	S	0.040433	S
6.2	0.154439	S	13.75752	W	0.0007464	S	0.040097	S
6.4	0.139519	S	13.6932	W	0.0007464	S	0.03933	S
6.6	0.124615	S	13.52253	W	0.0007464	S	0.038754	S
6.8	0.11168	S	12.9735	W	0.0007464	S	0.029999	S
7	0.100405	S	12.50582	W	0.0007464	S	0.023047	S
7.2	0.09054	S	12.06748	W	0.0007464	S	0.017839	S
7.4	0.085576	S	11.65589	W	0.0007464	S	0.013904	S
7.6	0.082846	S	11.26877	W	0.0007464	S	0.01091	S
7.8	0.08027	S	10.90406	W	0.0007464	S	0.008615	S
8	0.074931	S	10.55996	W	0.0007464	S	0.006843	S

Table C-5-63. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID DCC Med

Sample ID	DCC-[Med] (P,1,1)
Date Exported	9/20/2011, 8:58 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	0.068236	S	10.23481	W	0.0007464	S	0.005467	S
8.4	0.06228	S	9.92715	W	0.0007464	S	0.004391	S
8.6	0.056223	S	9.635659	W	0.0007464	S	0.003545	S
8.8	0.048049	S	9.789927	W	0.0007464	S	0.002876	S
9	0.041208	S	9.438718	S	0.0007464	S	0.002345	S
9.2	0.035461	S	9.509843	S	0.0007464	S	0.002062	S
9.4	0.030614	S	11.27878	S	0.0007464	S	0.002062	S
9.6	0.026204	S	7.680139	S	0.0007464	S	0.002062	S
9.8	0.02236	S	3.521824	S	0.0007464	S	0.002062	S
10	0.01914	S	1.640617	S	0.0007464	S	0.002062	S
10.2	0.016435	S	0.77592	S	0.0007464	S	0.002062	S
10.4	0.014154	S	0.372341	S	0.0007464	S	0.002062	S
10.6	0.012224	S	0.181192	S	0.0007464	S	0.002062	S
10.8	0.010586	S	0.089369	S	0.0007464	S	0.002062	S
11	0.008773	S	0.044654	S	0.0007464	S	0.002062	S
11.2	0.006942	S	0.025315	S	0.0007464	S	0.002062	S
11.4	0.005476	S	0.017493	S	0.0007464	S	0.002062	S
11.6	0.004469	S	0.012166	S	0.0007464	S	0.002062	S
11.8	0.003731	S	0.008514	S	0.0007464	S	0.002062	S
12	0.0032	S	0.015918	S	0.0007464	S	0.002062	S
12.2	0.0032	S	0.838595	S	0.0007464	S	0.002062	S
12.4	0.0032	S	7.22491	S	0.0007464	S	0.002062	S
12.6	0.0032	S	14.42702	S	0.0007464	S	0.002062	S
12.8	0.0032	S	14.42702	S	0.0007464	S	0.002062	S
13	0.0032	S	14.42702	S	0.0007464	S	0.002062	S
Detection Limit (min, mg/L)	0.00064		0.00065		0.00017		0.00041	
Detection Limit (max, mg/L)	0.00064		0.00065		0.00017		0.00041	
Availability (mg/kg)	2.997157		144.2702		0.0074635		0.489504	

Table C-5-63. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID DCC Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	0.01851753	S	0.002095386	S	0.350155376	S	0.01829238	S
3	0.02710016	S	0.002133795	S	0.268551421	S	0.0140037	S
3.2	0.01686711	S	0.002170361	S	0.272549856	S	0.01374165	S
3.4	0.00797204	S	0.001798469	S	0.322469032	S	0.01546756	S
3.6	0.00794736	S	0.001512458	S	0.327071236	S	0.01535029	S
3.8	0.00792409	S	0.001283902	S	0.331484981	S	0.01524018	S
4	0.00790208	S	0.001099083	S	0.335727323	S	0.01513645	S
4.2	0.0078812	S	0.000948033	S	0.33981301	S	0.01503843	S
4.4	0.00786134	S	0.000823387	S	0.343754892	S	0.01494557	S
4.6	0.00784241	S	0.000719625	S	0.326751062	S	0.01485738	S
4.8	0.00782433	S	0.000632555	S	0.299068296	S	0.01460815	S
5	0.00780702	S	0.000558955	S	0.301877132	S	0.01425159	S
5.2	0.00779043	S	0.000496322	S	0.304600635	S	0.01437463	S
5.4	0.00777451	S	0.000442688	S	0.307244533	S	0.01449403	S
5.6	0.00775919	S	0.000396496	S	0.309813978	S	0.01447329	S
5.8	0.00774443	S	0.000356499	S	0.312313617	S	0.01440582	S
6	0.00691829	S	0.000321695	S	0.314747657	S	0.01434094	S
6.2	0.00617998	S	0.000291269	S	0.317119923	S	0.01485513	S
6.4	0.00501786	S	0.000262578	S	0.320414304	S	0.0146343	S
6.6	0.00287608	S	0.000340102	S	0.350495673	S	0.01412093	S
6.8	0.00278165	S	0.000389643	S	0.364311614	S	0.0136401	S
7	0.00252897	S	0.000444643	S	0.36504576	S	0.01354171	S
7.2	0.0026561	S	0.000505524	S	0.36576064	S	0.01346085	S
7.4	0.00296064	S	0.00037281	S	0.366457275	S	0.01338266	S
7.6	0.00329056	S	0.000269183	S	0.367136606	S	0.013307	S
7.8	0.00364723	S	0.000196011	S	0.3677995	S	0.01323372	S
8	0.00403203	S	0.000143881	S	0.368446762	S	0.01316268	S

Table C-5-63. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID DCC Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	0.0044464	S	0.000106425	S	0.369079137	S	0.01309376	S
8.4	0.00489181	S	7.92932E-05	S	0.36969732	S	0.01302685	S
8.6	0.00536977	S	8.46647E-05	S	0.370301955	S	0.01270115	S
8.8	0.0058818	S	0.000112163	S	0.363205366	S	0.01190897	S
9	0.00642948	S	0.000147655	S	0.348195653	S	0.01182742	S
9.2	0.00828741	S	0.000103424	S	0.348175691	S	0.00936395	S
9.4	0.01424529	S	5.07313E-05	S	0.346300677	S	0.00398105	S
9.6	0.01710306	S	3.98738E-05	S	0.335299532	S	0.002783	S
9.8	0.01708549	S	4.03875E-05	S	0.329346245	S	0.002783	S
10	0.01706829	S	4.08973E-05	S	0.323615766	S	0.002783	S
10.2	0.01705145	S	2.71565E-05	S	0.318095546	S	0.002783	S
10.4	0.01718399	S	2.02412E-05	S	0.317591394	S	0.002783	S
10.6	0.01769595	S	1.83723E-05	S	0.317836997	S	0.002783	S
10.8	0.01766673	S	1.67062E-05	S	0.318078193	S	0.002783	S
11	0.01763809	S	1.52177E-05	S	0.307301314	S	0.002783	S
11.2	0.01760632	S	1.53082E-05	S	0.289809855	S	0.002783	S
11.4	0.0175691	S	1.80907E-05	S	0.273597655	S	0.002783	S
11.6	0.0175326	S	2.1317E-05	S	0.258551113	S	0.002783	S
11.8	0.01749679	S	2.50482E-05	S	0.244568434	S	0.002783	S
12	0.01646755	S	2.62858E-05	S	0.21718265	S	0.002783	S
12.2	0.01318099	S	1.3669E-05	S	0.138445453	S	0.002783	S
12.4	0.01332255	S	4.66502E-05	S	0.105640837	S	0.002783	S
12.6	0.01201362	S	4.66278E-05	S	0.074319287	S	0.002783	S
12.8	0.01085096	S	4.66057E-05	S	0.052574667	S	0.002783	S
13	0.00981629	S	4.65839E-05	S	0.037392306	S	0.002783	S
Detection Limit (min, mg/L)	0.0005		0.0000036		0.00076		0.00008	
Detection Limit (max, mg/L)	0.0005		0.0000036		0.00076		0.00008	
Availability (mg/kg)	0.27100163		0.021703613		3.703019558		0.15467556	

Table C-5-63. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID DCC Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	0.1886928	S	0.041709	S	0.0565085	S
3	0.1827534	S	0.042222	S	0.049907	S
3.2	0.178042	S	0.03112	S	0.0444317	S
3.4	0.1716967	S	0.021918	S	0.0222266	S
3.6	0.1675786	S	0.021666	S	0.0209475	S
3.8	0.1653317	S	0.02143	S	0.0198053	S
4	0.1632281	S	0.021208	S	0.0187794	S
4.2	0.1612519	S	0.020999	S	0.0178528	S
4.4	0.1593899	S	0.020802	S	0.017012	S
4.6	0.1576309	S	0.020616	S	0.0162456	S
4.8	0.1559648	S	0.020439	S	0.0155442	S
5	0.1543834	S	0.02027	S	0.0148999	S
5.2	0.1528791	S	0.02011	S	0.0143061	S
5.4	0.15028	S	0.019957	S	0.013757	S
5.6	0.1492386	S	0.01981	S	0.0132478	S
5.8	0.1482405	S	0.01967	S	0.0127744	S
6	0.1472826	S	0.019535	S	0.0125557	S
6.2	0.1463111	S	0.019406	S	0.0123595	S
6.4	0.1353486	S	0.017659	S	0.0128033	S
6.6	0.1279588	S	0.011419	S	0.0140289	S
6.8	0.1267694	S	0.008208	S	0.01533	S
7	0.1201568	S	0.007704	S	0.0163166	S
7.2	0.1140612	S	0.007293	S	0.0154262	S
7.4	0.1084293	S	0.006914	S	0.0179591	S
7.6	0.1032148	S	0.006564	S	0.0208234	S
7.8	0.1000855	S	0.00624	S	0.0232391	S
8	0.1041874	S	0.005598	S	0.0274713	S

Table C-5-63. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID DCC Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	0.10835	S	0.004948	S	0.031744	S
8.4	0.1125726	S	0.004387	S	0.0362854	S
8.6	0.1135814	S	0.0039	S	0.0413463	S
8.8	0.1119869	S	0.003477	S	0.0469717	S
9	0.1104499	S	0.003107	S	0.0532098	S
9.2	0.1028605	S	0.002784	S	0.0556206	S
9.4	0.0866855	S	0.00253	S	0.0553532	S
9.6	0.0758863	S	0.00253	S	0.0547927	S
9.8	0.0683144	S	0.00253	S	0.0501178	S
10	0.0616288	S	0.00253	S	0.0459244	S
10.2	0.055711	S	0.00253	S	0.0421547	S
10.4	0.0504602	S	0.00253	S	0.0387589	S
10.6	0.0457906	S	0.00253	S	0.0356937	S
10.8	0.0416286	S	0.00253	S	0.0329216	S
11	0.0379112	S	0.00253	S	0.0253827	S
11.2	0.0333731	S	0.00253	S	0.0173164	S
11.4	0.03086	S	0.00253	S	0.0118937	S
11.6	0.0286934	S	0.00253	S	0.0082227	S
11.8	0.0267122	S	0.00253	S	0.0057208	S
12	0.0213503	S	0.002816	S	0.0043148	S
12.2	0.0163424	S	0.004727	S	0.0052392	S
12.4	0.0160652	S	0.00253	S	0.0050858	S
12.6	0.015797	S	0.00253	S	0.004441	S
12.8	0.0155374	S	0.00253	S	0.0044825	S
13	0.015286	S	0.00253	S	0.0045238	S
Detection Limit (min, mg/L)	0.00052		0.00051		0.00031	
Detection Limit (max, mg/L)	0.00052		0.00051		0.00031	
Availability (mg/kg)	1.8275344		0.422215		0.5562061	

Table C-5-64. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID KCC Med

Sample ID	KCC-[Med] (P,1,1)
Date Exported	9/20/2011, 8:58 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	0.041684	S	33.12917	W	0.0007464	S	0.018493	S
3	0.023245	S	30.46188	W	0.0007464	S	0.013877	S
3.2	0.012599	S	27.53974	W	0.0007464	S	0.010557	S
3.4	0.011188	S	27.81901	W	0.0007464	S	0.009667	S
3.6	0.010355	S	27.72851	W	0.0007464	S	0.008866	S
3.8	0.009805	S	27.64547	W	0.0007464	S	0.008373	S
4	0.009311	S	27.56693	W	0.0007464	S	0.00793	S
4.2	0.008685	S	27.39934	W	0.0007464	S	0.007547	S
4.4	0.008086	S	27.21795	W	0.0007464	S	0.007204	S
4.6	0.007553	S	27.04574	W	0.0007464	S	0.00689	S
4.8	0.007076	S	26.88188	W	0.0007464	S	0.006603	S
5	0.006646	S	26.72565	W	0.0007464	S	0.006339	S
5.2	0.006343	S	26.70675	W	0.0007464	S	0.00599	S
5.4	0.00608	S	26.7112	W	0.0007464	S	0.005654	S
5.6	0.005836	S	26.71548	W	0.0007464	S	0.005349	S
5.8	0.00561	S	26.71962	W	0.0007464	S	0.005071	S
6	0.0054	S	26.72362	W	0.0007464	S	0.004815	S
6.2	0.005204	S	26.72749	W	0.0007464	S	0.00458	S
6.4	0.004848	S	26.4361	W	0.0007464	S	0.004097	S
6.6	0.004442	S	26.00318	W	0.0007464	S	0.003556	S
6.8	0.004081	S	25.58996	W	0.0007464	S	0.003099	S
7	0.003758	S	25.19501	S	0.0007464	S	0.002712	S
7.2	0.003535	S	22.38716	S	0.0007464	S	0.002445	S
7.4	0.003338	S	19.73261	S	0.0007464	S	0.002216	S
7.6	0.0032	S	17.14999	S	0.0007464	S	0.002062	S
7.8	0.0032	S	14.92008	S	0.0007464	S	0.002062	S
8	0.0032	S	13.50637	S	0.0007464	S	0.002062	S

Table C-5-64. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID KCC Med

Sample ID	KCC-[Med] (P,1,1)
Date Exported	9/20/2011, 8:58 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	0.0032	S	11.89956	S	0.0007464	S	0.002062	S
8.4	0.0032	S	10.6694	S	0.0007464	S	0.002062	S
8.6	0.0032	S	9.729319	S	0.0007464	S	0.002062	S
8.8	0.0032	S	9.760976	S	0.0007464	S	0.002062	S
9	0.0032	S	9.176669	S	0.0007464	S	0.002062	S
9.2	0.0032	S	8.651123	S	0.0007464	S	0.002062	S
9.4	0.0032	S	8.66565	S	0.0007464	S	0.002062	S
9.6	0.0032	S	8.751344	S	0.0007464	S	0.002062	S
9.8	0.0032	S	8.836091	S	0.0007464	S	0.002062	S
10	0.0032	S	8.919923	S	0.0007464	S	0.002062	S
10.2	0.0032	S	9.002866	S	0.0007464	S	0.002062	S
10.4	0.0032	S	9.36261	S	0.0007464	S	0.002062	S
10.6	0.0032	S	9.780801	S	0.0007464	S	0.002062	S
10.8	0.0032	S	10.20933	S	0.0007464	S	0.002062	S
11	0.0032	S	10.64825	S	0.0007464	S	0.002062	S
11.2	0.0032	S	11.09762	S	0.0007464	S	0.002062	S
11.4	0.0032	S	11.55749	S	0.0007464	S	0.002062	S
11.6	0.0032	S	12.02793	S	0.0007464	S	0.002062	S
11.8	0.0032	S	12.50898	S	0.0007464	S	0.002062	S
12	0.0032	S	13.00069	S	0.0007464	S	0.002062	S
12.2	0.0032	S	13.50313	S	0.0007464	S	0.002062	S
12.4	0.0032	S	14.01634	S	0.0007464	S	0.002062	S
12.6	0.0032	S	14.54037	S	0.0007464	S	0.002062	S
12.8	0.0032	S	15.07528	S	0.0007464	S	0.002062	S
13	0.0032	S	15.62112	S	0.0007464	S	0.002062	S
Detection Limit (min, mg/L)	0.00064		0.00065		0.00017		0.00041	
Detection Limit (max, mg/L)	0.00064		0.00065		0.00017		0.00041	
Availability (mg/kg)	0.23245		304.6188		0.0079486		0.138774	

Table C-5-64. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID KCC Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	0.00403346	S	0.046083498	S	0.03795	S	0.002783	S
3	0.00328107	S	0.037427564	S	0.03795	S	0.002783	S
3.2	0.00362233	S	0.030859778	S	0.03795	S	0.002783	S
3.4	0.00365407	S	0.025636631	S	0.03795	S	0.002783	S
3.6	0.00278571	S	0.021118003	S	0.037396064	S	0.002783	S
3.8	0.00322931	S	0.017180369	S	0.035912239	S	0.002783	S
4	0.00371528	S	0.014125704	S	0.034559002	S	0.002783	S
4.2	0.00388636	S	0.012874068	S	0.033319154	S	0.002783	S
4.4	0.00397021	S	0.012056146	S	0.032178442	S	0.002783	S
4.6	0.00405202	S	0.011323185	S	0.031124951	S	0.002783	S
4.8	0.00413193	S	0.010663216	S	0.030148639	S	0.002783	S
5	0.00421006	S	0.010066364	S	0.029240974	S	0.002783	S
5.2	0.00432942	S	0.009595235	S	0.028394663	S	0.002783	S
5.4	0.00445514	S	0.00917448	S	0.027603429	S	0.002783	S
5.6	0.00457975	S	0.008786494	S	0.026861841	S	0.002783	S
5.8	0.00470328	S	0.008427687	S	0.026165172	S	0.002783	S
6	0.00482579	S	0.008094967	S	0.025509288	S	0.002783	S
6.2	0.00494732	S	0.007785659	S	0.024890558	S	0.002783	S
6.4	0.00480423	S	0.005796946	S	0.023317965	S	0.002783	S
6.6	0.00453905	S	0.003800223	S	0.021412355	S	0.002783	S
6.8	0.00429579	S	0.002522866	S	0.019712588	S	0.002783	S
7	0.00407206	S	0.001694872	S	0.018191319	S	0.002783	S
7.2	0.00392698	S	0.001125876	S	0.016975996	S	0.002783	S
7.4	0.00379736	S	0.000754471	S	0.01588741	S	0.002783	S
7.6	0.00381591	S	0.000484153	S	0.014936734	S	0.002783	S
7.8	0.00423175	S	0.000183162	S	0.014445221	S	0.002783	S
8	0.00464044	S	5.54584E-05	S	0.014135867	S	0.002783	S

Table C-5-64. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID KCC Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	0.0051432	S	2.94108E-05	S	0.013374431	S	0.002783	S
8.4	0.00558026	S	1.97653E-05	S	0.012705734	S	0.002783	S
8.6	0.00593146	S	1.66899E-05	S	0.012117876	S	0.002783	S
8.8	0.00609547	S	5.98157E-05	S	0.012536637	S	0.002783	S
9	0.00633114	S	0.000101244	S	0.012316732	S	0.002783	S
9.2	0.00655901	S	0.000164635	S	0.012107627	S	0.002783	S
9.4	0.00656732	S	0.000108996	S	0.012138128	S	0.002783	S
9.6	0.00657453	S	6.67102E-05	S	0.012215721	S	0.002783	S
9.8	0.00658161	S	4.1245E-05	S	0.012292196	S	0.002783	S
10	0.00658855	S	2.57495E-05	S	0.012367589	S	0.002783	S
10.2	0.00659537	S	1.62263E-05	S	0.012441938	S	0.002783	S
10.4	0.00650405	S	1.40335E-05	S	0.01268857	S	0.002783	S
10.6	0.00639895	S	1.2843E-05	S	0.012966384	S	0.002783	S
10.8	0.00629746	S	1.17731E-05	S	0.013244918	S	0.002783	S
11	0.0061994	S	1.08095E-05	S	0.013524159	S	0.002783	S
11.2	0.0061046	S	9.94004E-06	S	0.013804098	S	0.002783	S
11.4	0.00601288	S	9.15411E-06	S	0.014084722	S	0.002783	S
11.6	0.0059241	S	8.4424E-06	S	0.014366021	S	0.002783	S
11.8	0.00583812	S	7.79681E-06	S	0.014647986	S	0.002783	S
12	0.0057548	S	7.21022E-06	S	0.014930607	S	0.002783	S
12.2	0.00567401	S	6.67639E-06	S	0.015213874	S	0.002783	S
12.4	0.00559565	S	6.18982E-06	S	0.015497778	S	0.002783	S
12.6	0.0055196	S	5.74566E-06	S	0.015782311	S	0.002783	S
12.8	0.00544575	S	5.33963E-06	S	0.016067463	S	0.002783	S
13	0.00537402	S	4.96794E-06	S	0.016353226	S	0.002783	S
Detection Limit (min, mg/L)	0.0005		0.0000036		0.00076		0.00008	
Detection Limit (max, mg/L)	0.0005		0.0000036		0.00076		0.00008	
Availability (mg/kg)	0.06859181		0.37427564		0.379500001		0.02963895	

Table C-5-64. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID KCC Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	0.1786144	S	0.005065	S	0.0362558	S
3	0.1531948	S	0.003624	S	0.0160094	S
3.2	0.1335871	S	0.002572	S	0.0071239	S
3.4	0.1275204	S	0.00253	S	0.0065055	S
3.6	0.1173723	S	0.00253	S	0.0063966	S
3.8	0.1108855	S	0.00253	S	0.0063741	S
4	0.1050632	S	0.00253	S	0.0063528	S
4.2	0.1015488	S	0.00253	S	0.0063312	S
4.4	0.0987234	S	0.00253	S	0.0063103	S
4.6	0.0960971	S	0.00253	S	0.0062905	S
4.8	0.0936481	S	0.00253	S	0.0062715	S
5	0.0913577	S	0.00253	S	0.0062533	S
5.2	0.0859693	S	0.00253	S	0.0061688	S
5.4	0.0805667	S	0.00253	S	0.0060772	S
5.6	0.075682	S	0.00253	S	0.0059902	S
5.8	0.0712497	S	0.00253	S	0.0059074	S
6	0.0672144	S	0.00253	S	0.0058286	S
6.2	0.063529	S	0.00253	S	0.0057533	S
6.4	0.0597725	S	0.00253	S	0.0057195	S
6.6	0.0561544	S	0.00253	S	0.0057072	S
6.8	0.0528537	S	0.00253	S	0.0056953	S
7	0.0498344	S	0.00253	S	0.0056837	S
7.2	0.0445312	S	0.00253	S	0.0051901	S
7.4	0.0396738	S	0.00253	S	0.0047052	S
7.6	0.0348582	S	0.00253	S	0.0041348	S
7.8	0.0310541	S	0.00253	S	0.0035984	S
8	0.0284622	S	0.00253	S	0.0032569	S

Table C-5-64. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID KCC Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	0.0211926	S	0.00253	S	0.002176	S
8.4	0.0176403	S	0.00253	S	0.0017855	S
8.6	0.0163492	S	0.00253	S	0.0017862	S
8.8	0.0211346	S	0.00253	S	0.0028434	S
9	0.0153555	S	0.00253	S	0.0031886	S
9.2	0.0114384	S	0.00253	S	0.0035741	S
9.4	0.0117858	S	0.00253	S	0.0040126	S
9.6	0.0120802	S	0.00253	S	0.0044551	S
9.8	0.0123756	S	0.00253	S	0.0049358	S
10	0.0126721	S	0.00253	S	0.0054569	S
10.2	0.0129695	S	0.00253	S	0.0060212	S
10.4	0.0130462	S	0.00253	S	0.0068062	S
10.6	0.0130832	S	0.00253	S	0.0077106	S
10.8	0.0131196	S	0.00253	S	0.0087148	S
11	0.0131555	S	0.00253	S	0.0098278	S
11.2	0.0131908	S	0.00253	S	0.0110589	S
11.4	0.0132256	S	0.00253	S	0.0124183	S
11.6	0.0132599	S	0.00253	S	0.0139167	S
11.8	0.0132937	S	0.00253	S	0.0155655	S
12	0.0133269	S	0.00253	S	0.0173769	S
12.2	0.0133598	S	0.00253	S	0.0193639	S
12.4	0.0133921	S	0.00253	S	0.0215401	S
12.6	0.013424	S	0.00253	S	0.0239201	S
12.8	0.0134555	S	0.00253	S	0.0265193	S
13	0.0134866	S	0.00253	S	0.0293539	S
Detection Limit (min, mg/L)	0.00052		0.00051		0.00031	
Detection Limit (max, mg/L)	0.00052		0.00051		0.00031	
Availability (mg/kg)	1.5319476		0.036243		0.3126189	

Table C-5-65. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID MAD Med

Sample ID	MAD-[Med] (P,1,1)
Date Exported	9/20/2011, 8:58 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	1.91406	S	28.39436	W	0.0023115	S	0.055746	S
3	1.388512	S	28.61074	W	0.0023805	S	0.053435	S
3.2	1.29089	S	28.38692	W	0.0024469	S	0.053768	S
3.4	1.265567	S	27.9448	W	0.0027359	S	0.057435	S
3.6	1.313541	S	27.53427	W	0.0031168	S	0.062684	S
3.8	1.360592	S	27.15149	W	0.0035257	S	0.06809	S
4	1.406786	S	27.26573	W	0.0039631	S	0.07365	S
4.2	1.452181	S	27.76486	W	0.0044295	S	0.079358	S
4.4	1.496827	S	27.85418	W	0.0049251	S	0.085213	S
4.6	1.594153	S	27.30305	W	0.0054505	S	0.09121	S
4.8	1.716078	S	26.78561	W	0.0060059	S	0.097347	S
5	1.626706	S	26.2985	W	0.0065918	S	0.103621	S
5.2	1.66877	S	25.83885	W	0.0072084	S	0.11003	S
5.4	1.710272	S	25.40414	W	0.0076188	S	0.11657	S
5.6	1.499162	S	25.39124	W	0.0079241	S	0.113226	S
5.8	1.297987	S	26.07993	W	0.0082769	S	0.118548	S
6	1.129311	S	26.763	W	0.0086086	S	0.121538	S
6.2	0.987051	S	28.21581	W	0.0088802	S	0.124502	S
6.4	0.866407	S	28.4274	W	0.0089039	S	0.122955	S
6.6	0.710066	S	28.55158	W	0.0089271	S	0.113768	S
6.8	0.726675	S	28.12914	W	0.0091866	S	0.111224	S
7	1.012026	S	26.26874	S	0.0097268	S	0.103334	S
7.2	0.934538	S	25.62783	S	0.0088799	S	0.100556	S
7.4	0.864868	S	30.30964	S	0.0081269	S	0.097925	S
7.6	0.738541	S	28.24611	S	0.0072923	S	0.060064	S
7.8	0.496012	S	25.72867	S	0.0061457	S	0.031765	S
8	0.336502	S	21.464	S	0.0052019	S	0.020382	S

Table C-5-65. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID MAD Med

Sample ID	MAD-[Med] (P,1,1)
Date Exported	9/20/2011, 8:58 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	0.230485	S	21.04512	S	0.0044212	S	0.013222	S
8.4	0.167992	S	20.64423	S	0.0037724	S	0.008226	S
8.6	0.157415	S	20.26013	S	0.0032309	S	0.005584	S
8.8	0.135968	S	17.45974	S	0.0028641	S	0.004297	S
9	0.11376	S	14.51837	S	0.0028966	S	0.003493	S
9.2	0.095553	S	12.33208	S	0.0029287	S	0.002853	S
9.4	0.080562	S	10.35706	S	0.0026859	S	0.00234	S
9.6	0.076044	S	8.730364	S	0.0024406	S	0.002062	S
9.8	0.064787	S	7.385135	S	0.0023601	S	0.002062	S
10	0.05355	S	6.572996	S	0.0022837	S	0.002062	S
10.2	0.04443	S	5.253345	S	0.002175	S	0.002062	S
10.4	0.033448	S	4.431795	S	0.0020674	S	0.002062	S
10.6	0.024389	S	3.750855	S	0.0019671	S	0.002062	S
10.8	0.017889	S	3.184456	S	0.0018733	S	0.002062	S
11	0.013196	S	2.711719	S	0.0017974	S	0.002062	S
11.2	0.010375	S	2.022688	S	0.0017036	S	0.002062	S
11.4	0.008275	S	0.999802	S	0.0016266	S	0.002062	S
11.6	0.006637	S	0.471967	S	0.0015543	S	0.002062	S
11.8	0.005584	S	0.261975	S	0.0014865	S	0.002062	S
12	0.004712	S	0.187464	S	0.0014226	S	0.002062	S
12.2	0.003987	S	0.134889	S	0.0013625	S	0.002062	S
12.4	0.003383	S	0.09758	S	0.0013058	S	0.002062	S
12.6	0.002878	S	0.070957	S	0.0012524	S	0.002062	S
12.8	0.002454	S	0.051857	S	0.0012019	S	0.002062	S
13	0.002098	S	0.038083	S	0.0011542	S	0.002062	S
Detection Limit (min, mg/L)	0.00064		0.00065		0.00017		0.00041	
Detection Limit (max, mg/L)	0.00064		0.00065		0.00017		0.00041	
Availability (mg/kg)	17.16078		303.0964		0.0972683		1.245023	

Table C-5-65. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID MAD Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	0.00298296	S	0.008229165	S	0.568054593	S	0.04363135	S
3	0.00154628	S	0.008229165	S	0.553270615	S	0.04122161	S
3.2	0.00106593	S	0.008229165	S	0.556884691	S	0.04114483	S
3.4	0.0009112	S	0.008229165	S	0.574341046	S	0.04514608	S
3.6	0.00078594	S	0.008229165	S	0.591300197	S	0.04927429	S
3.8	0.00068335	S	0.007956873	S	0.607802814	S	0.0535261	S
4	0.00059843	S	0.007662405	S	0.623884294	S	0.05789842	S
4.2	0.00052746	S	0.007392426	S	0.639575674	S	0.06238836	S
4.4	0.00046765	S	0.007143872	S	0.654904349	S	0.06699328	S
4.6	0.00041685	S	0.006914182	S	0.669894642	S	0.07171069	S
4.8	0.00037339	S	0.006701191	S	0.678457653	S	0.07214974	S
5	0.00033597	S	0.006503064	S	0.679241627	S	0.07166413	S
5.2	0.00030355	S	0.006534311	S	0.679995703	S	0.07505117	S
5.4	0.00027531	S	0.006779088	S	0.681810282	S	0.08205055	S
5.6	0.00029588	S	0.007023634	S	0.693848594	S	0.08941225	S
5.8	0.00032299	S	0.006800015	S	0.705665874	S	0.09032922	S
6	0.00042363	S	0.005687284	S	0.717273599	S	0.08922841	S
6.2	0.00066041	S	0.005682453	S	0.728682291	S	0.08532738	S
6.4	0.00041303	S	0.006222183	S	0.741474356	S	0.08412491	S
6.6	0.00026213	S	0.006794179	S	0.775060732	S	0.08217196	S
6.8	0.00025	S	0.004873063	S	0.809097631	S	0.07025278	S
7	0.00025	S	0.006085987	S	0.853842309	S	0.07564665	S
7.2	0.00061101	S	0.006417922	S	0.884585932	S	0.08094904	S
7.4	0.00067676	S	0.006758121	S	0.878566169	S	0.08646245	S
7.6	0.00073793	S	0.006075776	S	0.912088317	S	0.08142676	S
7.8	0.00077268	S	0.004902027	S	0.926501966	S	0.06776978	S
8	0.00080811	S	0.003976583	S	0.940769844	S	0.05854378	S

Table C-5-65. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID MAD Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	0.00090965	S	0.003242562	S	0.954897016	S	0.04499244	S
8.4	0.001223	S	0.002657064	S	0.968888251	S	0.03479795	S
8.6	0.00163288	S	0.002187515	S	0.982748049	S	0.02707658	S
8.8	0.00196729	S	0.000639078	S	0.987136677	S	0.02004006	S
9	0.0022661	S	0.000122009	S	0.987495072	S	0.01458374	S
9.2	0.00318064	S	9.59691E-05	S	1.001884044	S	0.0190165	S
9.4	0.00297927	S	3.22287E-05	S	0.988188938	S	0.01178494	S
9.6	0.00340127	S	1.10747E-05	S	0.98852505	S	0.00706933	S
9.8	0.00387246	S	3.89034E-06	S	0.964371145	S	0.004663	S
10	0.00427396	S	0.0000018	S	0.935886438	S	0.0029748	S
10.2	0.00432612	S	0.0000018	S	0.908782511	S	0.002783	S
10.4	0.00437788	S	0.0000018	S	0.882967283	S	0.002783	S
10.6	0.00442926	S	0.0000018	S	0.858356431	S	0.002783	S
10.8	0.00448026	S	0.0000018	S	0.834872599	S	0.002783	S
11	0.00449758	S	0.0000018	S	0.812444713	S	0.002783	S
11.2	0.00391144	S	0.0000018	S	0.746642264	S	0.002783	S
11.4	0.00361218	S	0.0000018	S	0.677436756	S	0.002783	S
11.6	0.00406486	S	0.0000018	S	0.615686536	S	0.002783	S
11.8	0.00391568	S	0.0000018	S	0.584034513	S	0.002783	S
12	0.00377434	S	0.0000018	S	0.561838194	S	0.002783	S
12.2	0.00364032	S	0.0000018	S	0.54083172	S	0.002783	S
12.4	0.00351312	S	0.0000018	S	0.520933342	S	0.002783	S
12.6	0.0033923	S	0.0000018	S	0.50206812	S	0.002783	S
12.8	0.00327744	S	0.0000018	S	0.484167264	S	0.002783	S
13	0.00316816	S	0.0000018	S	0.467167543	S	0.002783	S
Detection Limit (min, mg/L)	0.0005		0.0000036		0.00076		0.00008	
Detection Limit (max, mg/L)	0.0005		0.0000036		0.00076		0.00008	
Availability (mg/kg)	0.0449758		0.082291646		10.01884039		0.90329221	

Table C-5-65. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID MAD Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	0.3971332	S	0.053155	S	0.0298035	S
3	0.3706197	S	0.045422	S	0.0205709	S
3.2	0.3593231	S	0.04458	S	0.0163936	S
3.4	0.3793715	S	0.048501	S	0.0155638	S
3.6	0.4007104	S	0.052513	S	0.0166702	S
3.8	0.4219988	S	0.056613	S	0.017789	S
4	0.4432395	S	0.060798	S	0.0189197	S
4.2	0.4644349	S	0.065066	S	0.0200619	S
4.4	0.4855874	S	0.069414	S	0.021215	S
4.6	0.5219694	S	0.07384	S	0.0223788	S
4.8	0.5277715	S	0.078342	S	0.0235529	S
5	0.5488065	S	0.082917	S	0.0247368	S
5.2	0.5698058	S	0.087565	S	0.0259303	S
5.4	0.5907706	S	0.092283	S	0.023131	S
5.6	0.4885374	S	0.096635	S	0.0247533	S
5.8	0.3968366	S	0.098435	S	0.0256808	S
6	0.3246287	S	0.094173	S	0.022712	S
6.2	0.2921577	S	0.089982	S	0.0201674	S
6.4	0.2750503	S	0.085187	S	0.0198161	S
6.6	0.259426	S	0.080783	S	0.0224988	S
6.8	0.258985	S	0.076865	S	0.0152879	S
7	0.3144151	S	0.073399	S	0.0251514	S
7.2	0.2630267	S	0.068846	S	0.034302	S
7.4	0.2359023	S	0.069523	S	0.0292119	S
7.6	0.1817955	S	0.05789	S	0.0375282	S
7.8	0.1387417	S	0.046166	S	0.052072	S
8	0.102757	S	0.0388	S	0.0716555	S

Table C-5-65. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID MAD Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	0.0753816	S	0.034298	S	0.0978298	S
8.4	0.0641702	S	0.030409	S	0.132069	S
8.6	0.0502349	S	0.027037	S	0.1438477	S
8.8	0.0395478	S	0.024044	S	0.1600152	S
9	0.0383201	S	0.020995	S	0.1827922	S
9.2	0.0414587	S	0.019333	S	0.2207143	S
9.4	0.0315514	S	0.017373	S	0.2608776	S
9.6	0.0243615	S	0.017697	S	0.2486941	S
9.8	0.0222872	S	0.016951	S	0.2707381	S
10	0.0202104	S	0.016092	S	0.2393998	S
10.2	0.0177928	S	0.015891	S	0.1919029	S
10.4	0.0157031	S	0.015697	S	0.1359288	S
10.6	0.0138919	S	0.015508	S	0.0969157	S
10.8	0.0123178	S	0.015163	S	0.0695382	S
11	0.011184	S	0.013279	S	0.0501993	S
11.2	0.0107277	S	0.011657	S	0.039563	S
11.4	0.0102976	S	0.010257	S	0.0317637	S
11.6	0.0098917	S	0.009134	S	0.0255995	S
11.8	0.0095084	S	0.008814	S	0.0207078	S
12	0.0092088	S	0.008511	S	0.0150085	S
12.2	0.0089325	S	0.008222	S	0.0097672	S
12.4	0.0086689	S	0.007948	S	0.0064008	S
12.6	0.008417	S	0.007688	S	0.0042231	S
12.8	0.0081763	S	0.007439	S	0.0028047	S
13	0.007946	S	0.007203	S	0.0018745	S
Detection Limit (min, mg/L)	0.00052		0.00051		0.00031	
Detection Limit (max, mg/L)	0.00052		0.00051		0.00031	
Availability (mg/kg)	5.9077064		0.984352		2.7073805	

Table C-5-65. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID MAD Med

Sample ID	MAS-[Med] (P,1,1)
Date Exported	9/20/2011, 8:58 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	0.651717	S	28.29772	W	0.0103772	S	0.189133	S
3	0.628388	S	27.92793	W	0.0104137	S	0.177573	S
3.2	0.593591	S	27.76181	W	0.0103258	S	0.168925	S
3.4	0.558516	S	27.66331	W	0.010205	S	0.161657	S
3.6	0.527347	S	27.57077	W	0.0100924	S	0.155092	S
3.8	0.499467	S	27.48351	W	0.009987	S	0.149128	S
4	0.47438	S	27.40099	W	0.009888	S	0.143682	S
4.2	0.451688	S	27.32273	W	0.0097948	S	0.138686	S
4.4	0.431063	S	27.24831	W	0.0097067	S	0.134085	S
4.6	0.412236	S	27.1774	W	0.0096233	S	0.12983	S
4.8	0.394981	S	27.10967	W	0.0095441	S	0.125884	S
5	0.38158	S	27.07321	W	0.009459	S	0.122658	S
5.2	0.371491	S	27.06602	W	0.0093684	S	0.120066	S
5.4	0.362035	S	27.0591	W	0.0092821	S	0.117624	S
5.6	0.35315	S	27.05243	W	0.0091996	S	0.115317	S
5.8	0.344784	S	27.046	W	0.0091208	S	0.113134	S
6	0.33689	S	27.03979	W	0.0090452	S	0.111065	S
6.2	0.329426	S	27.03378	W	0.0089728	S	0.109099	S
6.4	0.322358	S	27.02797	W	0.0089031	S	0.107229	S
6.6	0.315651	S	27.02234	W	0.0088362	S	0.105447	S
6.8	0.298456	S	26.94733	W	0.0084452	S	0.097359	S
7	0.264814	S	26.74821	S	0.00754	S	0.080205	S
7.2	0.219682	S	26.3556	S	0.006456	S	0.055421	S
7.4	0.162898	S	25.34095	S	0.0053631	S	0.02451	S
7.6	0.127124	S	24.12308	S	0.0047314	S	0.010971	S
7.8	0.108985	S	22.65715	S	0.0045387	S	0.005535	S
8	0.093799	S	21.31411	S	0.0043584	S	0.002841	S

Table C-5-65. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID MAD Med

Sample ID	MAS-[Med] (P,1,1)
Date Exported	9/20/2011, 8:58 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	0.088573	S	20.49924	S	0.0042315	W	0.002062	S
8.4	0.099777	S	18.77486	S	0.0043164	W	0.002062	S
8.6	0.105459	S	17.89222	S	0.0043524	W	0.002062	S
8.8	0.09292	S	19.08632	S	0.0042458	W	0.002062	S
9	0.082105	S	20.33057	S	0.0041442	W	0.002062	S
9.2	0.087249	S	17.70487	S	0.0041357	W	0.002062	S
9.4	0.093475	S	15.30395	S	0.004132	W	0.002062	S
9.6	0.099999	S	13.26926	S	0.0041284	W	0.002062	S
9.8	0.106831	S	11.53898	S	0.0041249	W	0.002062	S
10	0.113976	S	10.06269	S	0.0041215	W	0.002062	S
10.2	0.121444	S	8.799103	S	0.0041181	W	0.002062	S
10.4	0.127463	S	6.666161	S	0.0041209	W	0.002062	S
10.6	0.132872	S	4.771862	S	0.0041263	W	0.002062	S
10.8	0.138403	S	3.437272	S	0.0041316	W	0.002062	S
11	0.144057	S	2.490888	S	0.0041368	W	0.002062	S
11.2	0.150819	S	1.647357	S	0.0039872	W	0.002062	S
11.4	0.159644	S	0.953913	S	0.0035516	W	0.002062	S
11.6	0.1734	S	0.543603	S	0.0034845	W	0.002062	S
11.8	0.27502	S	0.42246	S	0.0037769	W	0.002062	S
12	0.486465	S	0.36721	S	0.0040957	W	0.002062	S
12.2	0.852401	S	0.319926	S	0.0044355	W	0.002062	S
12.4	0.955732	S	0.279356	S	0.0047972	W	0.002062	S
12.6	1.058103	S	0.244461	S	0.0051819	W	0.002062	S
12.8	1.058103	S	0.214374	S	0.0055778	W	0.002062	S
13	1.058103	S	0.188374	S	0.0054845	W	0.002062	S
Detection Limit (min, mg/L)	0.00064		0.00065		0.00017		0.00041	
Detection Limit (max, mg/L)	0.00064		0.00065		0.00017		0.00041	
Availability (mg/kg)	11.11008		279.2793		0.1041374		1.775733	

Table C-5-65. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID MAD Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	0.00501971	S	0.002968096	S	0.575310267	S	0.07267789	S
3	0.00445237	S	0.004121037	S	0.573777622	S	0.07635295	S
3.2	0.00397984	S	0.004262	S	0.585583871	S	0.07646238	S
3.4	0.00358175	S	0.004026604	S	0.601325241	S	0.0754661	S
3.6	0.00324296	S	0.003816587	S	0.616553955	S	0.07453867	S
3.8	0.00295204	S	0.003628019	S	0.63131387	S	0.07367189	S
4	0.00270021	S	0.003457745	S	0.645643009	S	0.0728589	S
4.2	0.00248063	S	0.003303202	S	0.659574583	S	0.07209391	S
4.4	0.00228792	S	0.003162287	S	0.673137801	S	0.07137199	S
4.6	0.00211778	S	0.003033257	S	0.686358512	S	0.07068893	S
4.8	0.00196675	S	0.002914656	S	0.699259715	S	0.07004107	S
5	0.0018975	S	0.002933962	S	0.717571493	S	0.07008738	S
5.2	0.0018975	S	0.003085411	S	0.741401551	S	0.07078776	S
5.4	0.0018975	S	0.003238519	S	0.765078972	S	0.0714683	S
5.6	0.0018975	S	0.003393242	S	0.788610336	S	0.07213028	S
5.8	0.0018975	S	0.003549539	S	0.812001716	S	0.07277483	S
6	0.0018975	S	0.00370737	S	0.83525873	S	0.07340301	S
6.2	0.0018975	S	0.003866699	S	0.858386593	S	0.07401574	S
6.4	0.0018975	S	0.00402749	S	0.881390156	S	0.07461389	S
6.6	0.0018975	S	0.004189712	S	0.904273941	S	0.07519825	S
6.8	0.0018975	S	0.00412917	S	0.92395426	S	0.07598802	S
7	0.0018975	S	0.00369573	S	0.937729482	S	0.07716849	S
7.2	0.0018975	S	0.00332014	S	0.957496721	W	0.07997228	S
7.4	0.0018975	S	0.003072436	S	0.996420153	W	0.08457755	S
7.6	0.0018975	S	0.002363883	S	1.031442722	W	0.08528562	S
7.8	0.0018975	S	0.001161859	S	1.048491647	W	0.0785737	S
8	0.0018975	S	0.000581422	S	1.065380061	W	0.0725404	S

Table C-5-65. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID MAD Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	0.00202841	S	0.000487447	S	1.083876407	W	0.0653608	S
8.4	0.00271683	S	0.000442568	S	1.106700383	W	0.05082645	S
8.6	0.0034959	S	0.00033709	S	1.123272236	W	0.03843427	S
8.8	0.00405285	S	0.000152427	S	1.121311431	W	0.02645462	S
9	0.00468295	S	7.01653E-05	S	1.119398001	W	0.01836242	S
9.2	0.00458238	S	5.30146E-05	S	1.130459367	W	0.01659988	S
9.4	0.00444815	S	4.13149E-05	S	1.1420725	W	0.01524108	S
9.6	0.00432055	S	3.23666E-05	S	1.153556679	W	0.01401869	S
9.8	0.00419913	S	2.54844E-05	S	1.164915978	W	0.01291659	S
10	0.00408347	S	2.01627E-05	S	1.176154264	W	0.01192084	S
10.2	0.00397319	S	1.60265E-05	S	1.187275208	W	0.01101934	S
10.4	0.00378353	S	1.31212E-05	S	1.196085049	W	0.00939966	S
10.6	0.00357266	S	1.08992E-05	S	1.203852265	W	0.00776767	S
10.8	0.00337716	S	9.08498E-06	S	1.211523322	W	0.00644195	S
11	0.00319566	S	7.59806E-06	S	1.21910116	W	0.00536087	S
11.2	0.00285464	S	6.85887E-06	S	1.2135952	W	0.00482936	S
11.4	0.00237606	S	7.19445E-06	S	1.18621477	W	0.00491853	S
11.6	0.00198403	S	1.06627E-05	S	1.144530319	W	0.00530963	S
11.8	0.0018975	S	2.34537E-05	S	1.103445373	W	0.00749782	S
12	0.0018975	S	5.18947E-05	S	1.068663684	W	0.01129014	S
12.2	0.0018975	S	0.000113327	S	1.035526432	W	0.01688593	S
12.4	0.0018975	S	0.00024436	S	1.003930788	W	0.02509041	S
12.6	0.0018975	S	0.000520458	S	0.973781872	W	0.03704578	S
12.8	0.0018975	S	0.001095394	S	0.944992024	W	0.05436314	S
13	0.0018975	S	0.001423162	S	0.917480155	W	0.07930268	S
Detection Limit (min, mg/L)	0.0005		0.0000036		0.00076		0.00008	
Detection Limit (max, mg/L)	0.0005		0.0000036		0.00076		0.00008	
Availability (mg/kg)	0.0468295		0.042620001		12.19101165		0.85285619	

Table C-5-65. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID MAD Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	0.4248412	S	0.066133	S	0.0755979	S
3	0.4358752	S	0.060304	S	0.0737456	S
3.2	0.4243739	S	0.057141	S	0.0657652	S
3.4	0.4071126	S	0.054895	S	0.0573384	S
3.6	0.3914818	S	0.052857	S	0.0503849	S
3.8	0.3772491	S	0.051	S	0.0445852	S
4	0.3642251	S	0.049298	S	0.0397014	S
4.2	0.3522543	S	0.047732	S	0.0355534	S
4.4	0.341207	S	0.046286	S	0.0320026	S
4.6	0.3309747	S	0.044944	S	0.0289415	S
4.8	0.3214656	S	0.043696	S	0.0262854	S
5	0.3120439	S	0.042667	S	0.0248689	S
5.2	0.3027215	S	0.041831	S	0.0244495	S
5.4	0.2940139	S	0.041042	S	0.0240527	S
5.6	0.2858602	S	0.040296	S	0.0236764	S
5.8	0.278207	S	0.039589	S	0.0233189	S
6	0.2710079	S	0.038918	S	0.0229786	S
6.2	0.2642222	S	0.03828	S	0.0226542	S
6.4	0.2578139	S	0.037671	S	0.0223445	S
6.6	0.2517512	S	0.037091	S	0.0220483	S
6.8	0.2428704	S	0.035898	S	0.0227551	S
7	0.2291045	S	0.033672	S	0.0254542	S
7.2	0.2127745	S	0.030462	S	0.0299363	S
7.4	0.1954612	S	0.02579	S	0.0381287	S
7.6	0.1835515	S	0.022352	S	0.0484813	S
7.8	0.1774314	S	0.020301	S	0.0627524	S
8	0.1716626	S	0.018483	S	0.0806954	S

Table C-5-65. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID MAD Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	0.1653415	S	0.017106	S	0.098127	S
8.4	0.1583139	S	0.015433	S	0.1483761	S
8.6	0.1441137	S	0.014012	S	0.2115185	S
8.8	0.1128275	S	0.012902	S	0.258482	S
9	0.0888206	S	0.011902	S	0.3144526	S
9.2	0.0836645	S	0.01141	S	0.3514403	W
9.4	0.079628	S	0.010969	S	0.3902015	W
9.6	0.0758653	S	0.010554	S	0.4322845	W
9.8	0.0723525	S	0.010162	S	0.4778958	W
10	0.0690685	S	0.009793	S	0.52725	W
10.2	0.0659942	S	0.009444	S	0.5805702	W
10.4	0.0616786	S	0.009136	S	0.6106144	W
10.6	0.0571591	S	0.008853	S	0.6297209	W
10.8	0.0530462	S	0.008584	S	0.6490514	W
11	0.0492967	S	0.008328	S	0.6686042	W
11.2	0.046187	S	0.007986	S	0.5949069	W
11.4	0.0458791	S	0.00748	S	0.3712251	W
11.6	0.0404773	S	0.007809	S	0.4852507	W
11.8	0.0413217	S	0.009843	S	1.1373979	W
12	0.0459755	S	0.012702	S	1.2449889	W
12.2	0.0510634	S	0.016321	S	1.2449889	W
12.4	0.0566175	S	0.020887	S	1.2449889	W
12.6	0.0626722	S	0.026625	S	1.2449889	W
12.8	0.0692634	S	0.033809	S	1.2449889	W
13	0.0764292	S	0.042773	S	1.2449889	W
Detection Limit (min, mg/L)	0.00052		0.00051		0.00031	
Detection Limit (max, mg/L)	0.00052		0.00051		0.00031	
Availability (mg/kg)	4.3587517		0.603037		13.072383	

Table C-5-67. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID UGF Med

Sample ID	UGF-[Med] (P,1,1)
Date Exported	9/20/2011, 8:58 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	0.170429	S	3.33414	W	0.0519957	S	0.064309	S
3	0.14451	S	3.332239	W	0.0499608	S	0.061509	S
3.2	0.117952	S	3.323924	W	0.0473012	S	0.05875	S
3.4	0.097468	S	3.316132	W	0.0449319	S	0.056271	S
3.6	0.081425	S	3.308803	W	0.0428069	S	0.054029	S
3.8	0.068687	S	3.301885	W	0.0408894	S	0.051991	S
4	0.058449	S	3.295335	W	0.0391497	S	0.050129	S
4.2	0.053248	S	3.324343	W	0.0375171	S	0.048872	S
4.4	0.050673	S	3.37558	W	0.0359949	S	0.047995	S
4.6	0.048328	S	3.425277	W	0.034598	S	0.047171	S
4.8	0.046185	S	3.473544	W	0.0333114	S	0.046395	S
5	0.044219	S	3.52048	S	0.0321224	S	0.045663	S
5.2	0.043574	S	3.505845	S	0.031697	S	0.046014	S
5.4	0.043908	S	3.444314	S	0.0318403	S	0.047216	S
5.6	0.044232	S	3.386043	S	0.0319789	S	0.048405	S
5.8	0.037278	S	2.393761	S	0.0189193	S	0.031176	S
6	0.03131	S	1.683262	S	0.0110862	S	0.019898	S
6.2	0.026448	S	1.197395	S	0.0066111	S	0.012888	S
6.4	0.022461	S	0.861033	S	0.0040077	S	0.008463	S
6.6	0.019171	S	0.625474	S	0.0024672	S	0.00563	S
6.8	0.016441	S	0.458715	S	0.001541	S	0.003791	S
7	0.014162	S	0.339454	S	0.0009757	S	0.002583	S
7.2	0.012563	S	0.275716	S	0.0007464	S	0.002062	S
7.4	0.011606	S	0.255272	S	0.0007464	S	0.002062	S
7.6	0.010744	S	0.236831	S	0.0007464	S	0.002062	S
7.8	0.009967	S	0.22015	S	0.0007464	S	0.002062	S
8	0.009263	S	0.205023	S	0.0007464	S	0.002062	S

Table C-5-67. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID UGF Med

Sample ID	UGF-[Med] (P,1,1)
Date Exported	9/20/2011, 8:58 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	0.008624	S	0.191272	S	0.0007464	S	0.002062	S
8.4	0.008003	S	0.193375	S	0.0007464	S	0.002062	S
8.6	0.007415	S	0.205852	S	0.0007464	S	0.002062	S
8.8	0.007236	S	0.206066	S	0.0007464	S	0.002062	S
9	0.007256	S	0.199782	S	0.0007464	S	0.002062	S
9.2	0.007275	S	0.193823	S	0.0007464	S	0.002062	S
9.4	0.007294	S	0.188163	S	0.0007464	S	0.002062	S
9.6	0.007313	S	0.182783	S	0.0007464	S	0.002062	S
9.8	0.007331	S	0.177663	S	0.0007464	S	0.002062	S
10	0.007349	S	0.172786	S	0.0007464	S	0.002062	S
10.2	0.007367	S	0.168135	S	0.0007464	S	0.002062	S
10.4	0.006933	S	0.140755	S	0.0007464	S	0.002062	S
10.6	0.006447	S	0.124089	S	0.0007464	S	0.002062	S
10.8	0.005828	S	0.129592	S	0.0007464	S	0.002062	S
11	0.005279	S	0.13523	S	0.0007464	S	0.002062	S
11.2	0.00479	S	0.141006	S	0.0007464	S	0.002062	S
11.4	0.004354	S	0.146919	S	0.0007464	S	0.002062	S
11.6	0.003964	S	0.152971	S	0.0007464	S	0.002062	S
11.8	0.003615	S	0.159163	S	0.0007464	S	0.002062	S
12	0.003302	S	0.165495	S	0.0007464	S	0.002062	S
12.2	0.00302	S	0.171967	S	0.0007464	S	0.002062	S
12.4	0.002767	S	0.178582	S	0.0007464	S	0.002062	S
12.6	0.002538	S	0.185339	S	0.0007464	S	0.002062	S
12.8	0.002331	S	0.192239	S	0.0007464	S	0.002062	S
13	0.002144	S	0.199283	S	0.0007464	S	0.002062	S
Detection Limit (min, mg/L)	0.00064		0.001		0.00017		0.00041	
Detection Limit (max, mg/L)	0.00064		0.001		0.00017		0.00041	
Availability (mg/kg)	1.222073		29.7715		0.4225018		0.520161	

Table C-5-67. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID UGF Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	0.33609738	S	0.000365435	S	0.299761642	S	0.01749736	S
3	0.29168755	S	0.000368326	S	0.288405559	S	0.01648806	S
3.2	0.24974311	S	0.000418263	S	0.288229902	S	0.0152672	S
3.4	0.21585299	S	0.000471321	S	0.288064995	S	0.01420284	S
3.6	0.18812383	S	0.000527496	S	0.287909603	S	0.01326739	S
3.8	0.16518057	S	0.000586782	S	0.287762691	S	0.0124393	S
4	0.14600646	S	0.000649175	S	0.287623387	S	0.01170153	S
4.2	0.11591717	S	0.000702204	S	0.296014277	S	0.01154855	S
4.4	0.08639843	S	0.000748171	S	0.310087874	S	0.01174376	S
4.6	0.06524373	S	0.000794903	S	0.324160481	S	0.01193337	S
4.8	0.04986128	S	0.000842379	S	0.338232141	S	0.01211778	S
5	0.03852617	S	0.000890579	S	0.352302894	S	0.01229734	S
5.2	0.0308847	S	0.000843331	S	0.350952214	S	0.01201672	S
5.4	0.02550761	S	0.000733785	S	0.337791319	S	0.01140675	S
5.6	0.02121376	S	0.000641707	S	0.325576264	S	0.01084828	S
5.8	0.02246646	S	0.000280713	S	0.281630261	S	0.00895113	S
6	0.02403774	S	0.000121812	S	0.243433803	S	0.00737893	S
6.2	0.02566197	S	5.43255E-05	S	0.2114259	S	0.00612153	S
6.4	0.02733912	S	2.48573E-05	S	0.184450315	S	0.00510861	S
6.6	0.02906919	S	1.16508E-05	S	0.161593866	S	0.00428709	S
6.8	0.03085218	S	5.58572E-06	S	0.142129968	S	0.00361657	S
7	0.03268807	S	0.000003	S	0.125476474	S	0.00306599	S
7.2	0.03217423	S	0.000003	S	0.116568592	W	0.002783	S
7.4	0.02847989	S	0.000003	S	0.116408003	W	0.002783	S
7.6	0.02529188	S	0.000003	S	0.116251909	W	0.002783	S
7.8	0.02253011	S	0.000003	S	0.116100072	W	0.002783	S
8	0.02012876	S	0.000003	S	0.115952269	W	0.002783	S

Table C-5-67. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID UGF Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	0.01803347	S	0.000003	S	0.115808298	W	0.002783	S
8.4	0.0193626	S	0.000003	S	0.118231796	W	0.002783	S
8.6	0.02334347	S	0.000003	S	0.122402557	W	0.002783	S
8.8	0.02549786	S	0.000003	S	0.122776468	W	0.002783	S
9	0.02643334	S	0.000003	S	0.121138715	W	0.002783	S
9.2	0.02738144	S	0.000003	S	0.119558093	W	0.002783	S
9.4	0.02834206	S	0.000003	S	0.118031431	W	0.002783	S
9.6	0.02931509	S	0.000003	S	0.116555796	W	0.002783	S
9.8	0.03030044	S	0.000003	S	0.115128472	W	0.002783	S
10	0.03129799	S	0.000003	S	0.113746939	W	0.002783	S
10.2	0.03230765	S	0.000003	S	0.112408855	W	0.002783	S
10.4	0.02259128	S	0.000003	S	0.116508921	W	0.002783	S
10.6	0.01726121	S	0.000003	S	0.120095338	W	0.002783	S
10.8	0.01795424	S	0.000003	S	0.121067625	W	0.002783	S
11	0.01866162	S	0.000003	S	0.122029728	W	0.002783	S
11.2	0.01938336	S	0.000003	S	0.122981934	W	0.002783	S
11.4	0.0201195	S	0.000003	S	0.123924519	W	0.002783	S
11.6	0.02087006	S	0.000003	S	0.124857748	W	0.002783	S
11.8	0.02163507	S	0.000003	S	0.125781872	W	0.002783	S
12	0.02241456	S	0.000003	S	0.126697131	W	0.002783	S
12.2	0.02320855	S	0.000003	S	0.127603757	W	0.002783	S
12.4	0.02401706	S	0.000003	S	0.128501971	W	0.002783	S
12.6	0.02484013	S	0.000003	S	0.129391984	W	0.002783	S
12.8	0.02567777	S	0.000003	S	0.130273999	W	0.002783	S
13	0.02653002	S	0.000003	S	0.131148213	W	0.002783	S
Detection Limit (min, mg/L)	0.0005		0.000006		0.00076		0.00008	
Detection Limit (max, mg/L)	0.0005		0.000006		0.00076		0.00008	
Availability (mg/kg)	2.4667023		0.007531323		2.979305654		0.13943391	

Table C-5-67. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID UGF Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	0.384471	S	0.042387	S	0.7175652	S
3	0.3563424	S	0.040229	S	0.593018	S
3.2	0.3161224	S	0.037533	S	0.4609003	S
3.4	0.2824862	S	0.035164	S	0.3637343	S
3.6	0.2540579	S	0.033068	S	0.2909648	S
3.8	0.229805	S	0.031201	S	0.2355805	S
4	0.20894	S	0.029527	S	0.192816	S
4.2	0.1904101	S	0.028267	S	0.1588509	S
4.4	0.1740108	S	0.027271	S	0.1317767	S
4.6	0.1596619	S	0.026353	S	0.1102288	S
4.8	0.1470339	S	0.025503	S	0.0929079	S
5	0.135861	S	0.024714	S	0.0788571	S
5.2	0.1271408	S	0.024253	S	0.0654164	S
5.4	0.120201	S	0.024036	S	0.0533789	S
5.6	0.1138723	S	0.023828	S	0.0438799	S
5.8	0.0875445	S	0.017411	S	0.0493057	S
6	0.06717	S	0.012657	S	0.0560637	S
6.2	0.051987	S	0.009298	S	0.0634801	S
6.4	0.0405646	S	0.006897	S	0.0715945	S
6.6	0.0318944	S	0.005164	S	0.0804478	S
6.8	0.0252581	S	0.003899	S	0.0900818	S
7	0.0201384	S	0.002969	S	0.1005394	S
7.2	0.0172086	S	0.00253	S	0.1095691	S
7.4	0.0162095	S	0.00253	S	0.1155303	S
7.6	0.0152927	S	0.00253	S	0.1216438	S
7.8	0.0144497	S	0.00253	S	0.1279094	S
8	0.0136727	S	0.00253	S	0.1343268	S

Table C-5-67. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID UGF Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	0.0129552	S	0.00253	S	0.1408957	S
8.4	0.0132229	S	0.00253	S	0.1462939	S
8.6	0.014155	S	0.00253	S	0.1508676	S
8.8	0.0146814	S	0.002744	S	0.1521562	S
9	0.0149734	S	0.003102	S	0.1516743	S
9.2	0.0152647	S	0.003498	S	0.1512044	S
9.4	0.0155552	S	0.003934	S	0.1507461	S
9.6	0.015845	S	0.004413	S	0.1502987	S
9.8	0.016134	S	0.004939	S	0.1498619	S
10	0.0164222	S	0.005515	S	0.1494351	S
10.2	0.0167098	S	0.006145	S	0.149018	S
10.4	0.0124952	S	0.006647	S	0.1308095	S
10.6	0.0099833	S	0.007055	S	0.1154959	S
10.8	0.0100613	S	0.007129	S	0.1052915	S
11	0.0101384	S	0.007202	S	0.0961518	S
11.2	0.0102147	S	0.007275	S	0.0879492	S
11.4	0.0102902	S	0.007348	S	0.0805735	S
11.6	0.010365	S	0.00742	S	0.0739288	S
11.8	0.010439	S	0.007491	S	0.067932	S
12	0.0105123	S	0.007562	S	0.0625104	S
12.2	0.0105848	S	0.007632	S	0.0576007	S
12.4	0.0106567	S	0.007702	S	0.0531472	S
12.6	0.0107279	S	0.007771	S	0.0491013	S
12.8	0.0107984	S	0.00784	S	0.0454199	S
13	0.0108683	S	0.007908	S	0.0420654	S
Detection Limit (min, mg/L)	0.00052		0.00051		0.00031	
Detection Limit (max, mg/L)	0.00052		0.00051		0.00031	
Availability (mg/kg)	3.0134665		0.340207		5.0149516	

Table C-5-68. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID VSD Med

Sample ID	VSD-[Med] (P,1,1)
Date Exported	9/20/2011, 8:58 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	0.021922	S	25.82672	S	0.0455954	S	2.107023	S
3	0.851966	S	36.65751	S	0.1573169	S	3.112229	S
3.2	0.239429	S	33.50198	S	0.1387351	S	3.162106	S
3.4	0.096927	S	31.78382	S	0.1035519	S	3.093469	S
3.6	0.05201	S	30.45572	S	0.078247	S	2.960458	S
3.8	0.03795	S	29.49354	S	0.0597129	S	2.762408	S
4	0.028143	S	28.60883	S	0.0462054	S	2.586779	S
4.2	0.021177	S	27.79194	S	0.0362036	S	2.430095	S
4.4	0.016147	S	27.03479	S	0.0286906	S	2.289548	S
4.6	0.012461	S	26.33058	S	0.0229731	S	2.16285	S
4.8	0.009723	S	25.67354	S	0.0185698	S	2.048121	S
5	0.007977	S	25.1077	S	0.0151063	S	1.94767	S
5.2	0.008232	S	24.84377	S	0.0122298	S	1.876438	S
5.4	0.008486	S	24.59243	S	0.0099802	S	1.810355	S
5.6	0.009438	S	24.1536	S	0.008415	S	1.649638	S
5.8	0.009427	S	23.47815	S	0.0067511	S	1.430101	S
6	0.007422	S	22.27484	S	0.004802	S	1.102904	S
6.2	0.005889	S	20.89532	S	0.0030924	S	0.803378	S
6.4	0.004708	S	19.64107	S	0.0020195	S	0.591114	S
6.6	0.003789	S	18.49731	S	0.0013362	S	0.43906	S
6.8	0.0032	S	17.43887	S	0.000938	S	0.326384	S
7	0.0032	S	16.42258	S	0.0008004	S	0.237061	S
7.2	0.0032	S	15.36151	S	0.0007464	W	0.162146	S
7.4	0.0032	S	14.29759	S	0.0007464	W	0.105989	S
7.6	0.0032	S	13.33286	S	0.0007464	W	0.070071	S
7.8	0.0032	S	12.4558	S	0.0007464	W	0.046826	S
8	0.0032	S	11.65651	S	0.0007464	W	0.031613	S

Table C-5-68. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID VSD Med

Sample ID	VSD-[Med] (P,1,1)
Date Exported	9/20/2011, 8:58 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term model
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	0.0032	S	10.98276	S	0.0007464	W	0.022736	S
8.4	0.0032	S	10.30835	S	0.0007464	W	0.020073	S
8.6	0.0032	S	8.876371	S	0.0007464	W	0.017683	S
8.8	0.0032	S	5.422514	S	0.0007464	W	0.01531	S
9	0.0032	S	3.349469	S	0.0007464	W	0.013299	S
9.2	0.0032	S	2.0413	S	0.0007464	W	0.011921	S
9.4	0.0032	S	1.470385	S	0.0007464	W	0.011205	S
9.6	0.0032	S	1.066485	S	0.0007464	W	0.010546	S
9.8	0.0032	S	0.778672	S	0.0007464	W	0.009938	S
10	0.0032	S	0.572156	S	0.0007464	W	0.009377	S
10.2	0.0032	S	0.422985	S	0.0007464	W	0.008857	S
10.4	0.0032	S	0.314545	S	0.0007464	W	0.008375	S
10.6	0.0032	S	0.264926	S	0.0007464	W	0.008019	S
10.8	0.0032	S	0.223851	S	0.0007464	W	0.007685	S
11	0.0032	S	0.189731	S	0.0007464	W	0.00737	S
11.2	0.0032	S	0.161291	S	0.0007464	W	0.007073	S
11.4	0.0032	S	0.138952	S	0.0007464	W	0.006517	S
11.6	0.0032	S	0.12002	S	0.0007464	W	0.005765	S
11.8	0.0032	S	0.103927	S	0.0007464	W	0.005111	S
12	0.0032	S	0.090209	S	0.0007464	W	0.00454	S
12.2	0.0032	S	0.078486	S	0.0007464	W	0.004041	S
12.4	0.0032	S	0.068441	S	0.0007464	W	0.003604	S
12.6	0.0032	S	0.059813	S	0.0007464	W	0.003219	S
12.8	0.0032	S	0.052383	S	0.0007464	W	0.002881	S
13	0.0032	S	0.045971	S	0.0007464	W	0.002583	S
Detection Limit (min, mg/L)	0.00064		0.001		0.00017		0.00041	
Detection Limit (max, mg/L)	0.00064		0.001		0.00017		0.00041	
Availability (mg/kg)	8.39375		361.1577		1.5499198		31.15375	

Table C-5-68. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID VSD Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	0.04250708	S	0.009098806	S	0.068849437	S	0.00493199	S
3	6.06254728	S	0.013395627	S	0.551618162	S	0.00986152	S
3.2	2.51320264	S	0.012060639	S	0.275456235	S	0.0115007	S
3.4	1.12051008	S	0.00669879	S	0.233095889	S	0.01121921	S
3.6	0.6381568	S	0.004121433	S	0.219903653	S	0.01142478	S
3.8	0.47455319	S	0.002824807	S	0.234172134	S	0.01221124	S
4	0.35829638	S	0.001973996	S	0.248563416	S	0.01300733	S
4.2	0.2742557	S	0.001403781	S	0.263072335	S	0.01381268	S
4.4	0.21255448	S	0.00101424	S	0.277694178	S	0.01462695	S
4.6	0.16661185	S	0.00074346	S	0.292424629	S	0.01544983	S
4.8	0.13196037	S	0.000552226	S	0.307259717	S	0.01628103	S
5	0.10568938	S	0.000429166	S	0.322741181	S	0.0169329	S
5.2	0.08617447	S	0.000404867	S	0.34154435	S	0.01654077	S
5.4	0.07080633	S	0.000382785	S	0.360671291	S	0.01617201	S
5.6	0.05331939	S	0.000265673	S	0.387334633	S	0.01534605	S
5.8	0.04011867	S	0.000197625	S	0.418557868	S	0.01452174	S
6	0.02973525	S	0.000169034	S	0.460212221	S	0.0136221	S
6.2	0.02778184	S	0.000252316	S	0.503496899	S	0.01281731	S
6.4	0.02601282	S	0.000371871	S	0.549282697	S	0.0120834	S
6.6	0.02440581	S	0.000541572	S	0.597629189	S	0.01141221	S
6.8	0.02368432	S	0.000719995	S	0.643822729	S	0.01084194	S
7	0.02608248	S	0.000692722	S	0.672230016	S	0.01048689	S
7.2	0.02737354	S	0.000469278	S	0.688183475	S	0.01018451	S
7.4	0.02765787	S	0.000241877	S	0.693625741	S	0.00992357	S
7.6	0.02793744	S	0.000126892	S	0.698964191	S	0.00967601	S
7.8	0.02821247	S	6.76942E-05	S	0.704203462	S	0.00944082	S
8	0.02848314	S	3.66926E-05	S	0.709347869	S	0.00921709	S

Table C-5-68. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID VSD Med

Sample ID
Date Exported
Database Name ling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	0.03154131	S	2.27226E-05	S	0.716376565	S	0.00843234	S
8.4	0.04085896	S	2.02165E-05	S	0.714776369	S	0.00562268	S
8.6	0.05771947	S	1.80662E-05	S	0.706714258	S	0.00397304	S
8.8	0.11672267	S	1.62923E-05	S	0.674063531	S	0.00342751	S
9	0.23233513	S	1.47267E-05	S	0.643605118	S	0.00296672	S
9.2	0.35694789	S	1.40481E-05	S	0.60790774	S	0.002783	S
9.4	0.36245562	S	1.42898E-05	S	0.58009603	S	0.002783	S
9.6	0.3679297	S	1.45304E-05	S	0.554102755	S	0.002783	S
9.8	0.37337103	S	1.47699E-05	S	0.529774759	S	0.002783	S
10	0.37878047	S	1.50085E-05	S	0.506974554	S	0.002783	S
10.2	0.38415883	S	1.5246E-05	S	0.485578451	S	0.002783	S
10.4	0.38950691	S	1.54826E-05	S	0.465474934	S	0.002783	S
10.6	0.37698017	S	1.51912E-05	S	0.44190069	S	0.002783	S
10.8	0.36507932	S	1.49106E-05	S	0.419928146	S	0.002783	S
11	0.35376233	S	1.46402E-05	S	0.399421768	S	0.002783	S
11.2	0.34299071	S	1.43795E-05	S	0.380259669	S	0.002783	S
11.4	0.32226617	S	1.50321E-05	S	0.33116712	S	0.002783	S
11.6	0.29555977	S	1.62952E-05	S	0.270782496	S	0.002783	S
11.8	0.2714677	S	1.76401E-05	S	0.222171583	S	0.002783	S
12	0.24969604	S	1.90706E-05	S	0.182894539	S	0.002783	S
12.2	0.22998806	S	2.05905E-05	S	0.151046102	S	0.002783	S
12.4	0.21211899	S	2.22038E-05	S	0.125132304	S	0.002783	S
12.6	0.19589161	S	2.39146E-05	S	0.103976994	S	0.002783	S
12.8	0.18113253	S	2.57272E-05	S	0.086650641	S	0.002783	S
13	0.16768898	S	2.76458E-05	S	0.072415864	S	0.002783	S
Detection Limit (min, mg/L)	0.0005		0.000006		0.00076		0.00008	
Detection Limit (max, mg/L)	0.0005		0.000006		0.00076		0.00008	
Availability (mg/kg)	59.7295299		0.131976623		7.057897191		0.16682661	

Table C-5-68. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID VSD Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	1.1576225	S	0.004852	S	0.0605665	S
3	5.1057843	S	0.029302	S	23.638584	S
3.2	4.1720416	S	0.021619	S	9.5885098	S
3.4	3.381112	S	0.017995	S	2.9879587	S
3.6	2.8526916	S	0.016249	S	1.4251639	S
3.8	2.5120723	S	0.016053	S	1.0844818	S
4	2.2266023	S	0.015869	S	0.8368868	S
4.2	1.9852253	S	0.015696	S	0.6540394	S
4.4	1.7794902	S	0.015532	S	0.5170381	S
4.6	1.6028536	S	0.015378	S	0.4130282	S
4.8	1.4501894	S	0.015232	S	0.333111	S
5	1.3290773	S	0.014947	S	0.2712573	S
5.2	1.2834718	S	0.01391	S	0.2237333	S
5.4	1.2410657	S	0.012979	S	0.185882	S
5.6	1.1979054	S	0.011838	S	0.1464559	S
5.8	1.1536757	S	0.01049	S	0.1136495	S
6	1.1036825	S	0.008672	S	0.0842686	S
6.2	1.039981	S	0.006511	S	0.0702142	S
6.4	0.9818077	S	0.004933	S	0.0588437	S
6.6	0.9285318	S	0.00377	S	0.0495834	S
6.8	0.8684001	S	0.002987	S	0.0438246	S
7	0.7736142	S	0.002662	S	0.0459925	S
7.2	0.6876528	S	0.00253	S	0.048754	S
7.4	0.6105198	S	0.00253	S	0.0520753	S
7.6	0.5437614	S	0.00253	S	0.0555252	S
7.8	0.4857619	S	0.00253	S	0.0591051	S
8	0.4351898	S	0.00253	S	0.0628163	S

Table C-5-68. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID VSD Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	0.3941387	S	0.00253	S	0.067339	S
8.4	0.3484185	S	0.00253	S	0.0764078	S
8.6	0.3132505	S	0.00253	S	0.0871577	S
8.8	0.2983866	S	0.00253	S	0.1024114	S
9	0.2845388	S	0.00253	S	0.1198994	S
9.2	0.2612165	S	0.00253	S	0.1304109	S
9.4	0.2340072	S	0.00253	S	0.1258714	S
9.6	0.2101182	S	0.00253	S	0.1215806	S
9.8	0.1890873	S	0.00253	S	0.1175201	S
10	0.1705244	S	0.00253	S	0.1136732	S
10.2	0.1540988	S	0.00253	S	0.1100247	S
10.4	0.1395295	S	0.00253	S	0.1065607	S
10.6	0.1330512	S	0.00253	S	0.1029373	S
10.8	0.1269864	S	0.00253	S	0.0995013	S
11	0.1213018	S	0.00253	S	0.09624	S
11.2	0.1159674	S	0.00253	S	0.0931415	S
11.4	0.1077267	S	0.00253	S	0.0795324	S
11.6	0.0981852	S	0.00253	S	0.0616008	S
11.8	0.0896308	S	0.00253	S	0.047921	S
12	0.0819472	S	0.00253	S	0.0374367	S
12.2	0.0750333	S	0.00253	S	0.0293658	S
12.4	0.0688012	S	0.00253	S	0.0231261	S
12.6	0.0631744	S	0.00253	S	0.0182819	S
12.8	0.0580858	S	0.00253	S	0.014506	S
13	0.0534766	S	0.00253	S	0.0115513	S
Detection Limit (min, mg/L)	0.00052		0.00051		0.00031	
Detection Limit (max, mg/L)	0.00052		0.00051		0.00031	
Availability (mg/kg)	50.303294		0.288691		232.89245	

Table C-5-69. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID YSD Med

Sample ID	YSD-[Med] (P,1,1)
Date Exported	9/20/2011, 8:59 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
2.8	0.036033	S	13.63553	S	0.0877817	S	4.269105	S
3	0.036033	S	13.63553	S	0.0877817	S	4.269105	S
3.2	0.036033	S	13.63553	S	0.0877817	S	4.269105	S
3.4	0.036033	S	13.52439	S	0.0877817	S	4.269105	S
3.6	0.035758	S	13.40264	S	0.0869955	S	4.238166	S
3.8	0.030812	S	13.28849	S	0.0730375	S	3.679403	S
4	0.028135	S	13.24082	S	0.0656282	S	3.339878	S
4.2	0.028272	S	13.3042	S	0.0659622	S	3.259137	S
4.4	0.027683	S	13.27542	S	0.0635075	S	3.150721	S
4.6	0.027095	S	13.2434	S	0.0611126	S	3.048848	S
4.8	0.026544	S	13.21282	S	0.0589044	S	2.954399	S
5	0.026026	S	13.18355	S	0.0568614	S	2.866557	S
5.2	0.025538	S	13.15549	S	0.0549652	S	2.784622	S
5.4	0.025077	S	13.12854	S	0.0532004	S	2.707991	S
5.6	0.016965	S	12.65716	S	0.0399736	S	2.388483	S
5.8	0.011549	S	12.23764	S	0.0303797	S	2.112437	S
6	0.007123	S	12.16975	S	0.0221827	S	1.729012	S
6.2	0.0032	S	11.47057	S	0.0103728	S	1.103218	S
6.4	0.0032	S	10.98014	S	0.0054029	S	0.77459	S
6.6	0.0032	S	10.35436	S	0.0032449	S	0.53159	S
6.8	0.0032	S	9.64889	S	0.0030658	S	0.373823	S
7	0.0032	S	9.009895	S	0.0029014	S	0.265575	S
7.2	0.0032	S	8.429474	S	0.0027501	S	0.190499	S
7.4	0.0032	S	7.900847	S	0.0026105	S	0.137896	S
7.6	0.0032	S	7.418173	S	0.0024814	S	0.100682	S
7.8	0.0032	S	6.943882	S	0.0023675	S	0.076732	S
8	0.0032	S	6.391754	S	0.0022834	S	0.067535	S

Table C-5-69. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID YSD Med

Sample ID	YSD-[Med] (P,1,1)
Date Exported	9/20/2011, 8:59 PM
Database Name	C:\Users\kossonds\Documents\LeachXS Databases\EPA Report 4 Database\Source term mode
LeachXS Version	1.2.12.11227

pH	Arsenic	Solubility/ Washout	Boron	Solubility/ Washout	Cadmium	Solubility/ Washout	Cobalt	Solubility/ Washout
8.2	0.0032	S	5.895578	S	0.0022042	W	0.059628	S
8.4	0.0032	S	5.448518	S	0.0021296	W	0.052805	S
8.6	0.0032	S	4.649074	S	0.0021454	W	0.050071	S
8.8	0.0032	S	3.867746	S	0.0021914	W	0.048374	S
9	0.0032	S	3.218893	S	0.0022392	W	0.046416	S
9.2	0.0032	S	2.803114	S	0.0022356	W	0.044437	S
9.4	0.0032	S	2.041365	S	0.0022009	W	0.043543	S
9.6	0.0032	S	1.469018	S	0.0021665	W	0.042783	S
9.8	0.0032	S	1.13143	S	0.0021338	W	0.041712	S
10	0.0032	S	0.905732	S	0.0021032	W	0.040517	S
10.2	0.0032	S	0.728258	S	0.0020737	W	0.039379	S
10.4	0.0032	S	0.520211	S	0.0021015	W	0.036291	S
10.6	0.0032	S	0.373121	S	0.00216	W	0.030166	S
10.8	0.0032	S	0.289772	S	0.002176	W	0.023902	S
11	0.0032	S	0.25874	S	0.0021146	W	0.017305	S
11.2	0.0032	S	0.231503	S	0.0020559	W	0.012602	S
11.4	0.0032	S	0.207542	S	0.0019999	W	0.009229	S
11.6	0.0032	S	0.186414	S	0.0019463	W	0.006796	S
11.8	0.0032	S	0.167745	S	0.001895	W	0.00503	S
12	0.0032	S	0.151214	S	0.0018459	W	0.003742	S
12.2	0.0032	S	0.136545	S	0.0017989	W	0.002797	S
12.4	0.0032	S	0.123505	S	0.0017538	W	0.002101	S
12.6	0.0032	S	0.111889	S	0.0017105	W	0.001586	S
12.8	0.0032	S	0.101524	S	0.001669	W	0.001202	S
13	0.0032	S	0.092257	S	0.001629	W	0.000915	S
Detection Limit (min, mg/L)	0.00064		0.001		0.00017		0.00041	
Detection Limit (max, mg/L)	0.00064		0.001		0.00017		0.00041	
Availability (mg/kg)	0.355883		134.6719		0.86698		42.164	

Table C-5-69. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID YSD Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
2.8	0.38983051	S	0.000766976	S	0.225364982	S	0.01416645	S
3	0.24814397	S	0.000766976	S	0.220323107	S	0.01421202	S
3.2	0.16262863	S	0.000766976	S	0.215708907	S	0.01425478	S
3.4	0.10935003	S	0.000766976	S	0.211462591	S	0.01429507	S
3.6	0.07521363	S	0.000750638	S	0.207535644	S	0.0142382	S
3.8	0.05279144	S	0.000493932	S	0.20388821	S	0.0125442	S
4	0.04106211	S	0.000383435	S	0.206537868	S	0.0116513	S
4.2	0.03768771	S	0.000391101	S	0.22066657	S	0.0118124	S
4.4	0.0347289	S	0.000345502	S	0.235037039	S	0.01196808	S
4.6	0.03211892	S	0.000304657	S	0.249642138	S	0.01211876	S
4.8	0.02980404	S	0.000270084	S	0.264475243	S	0.0122648	S
5	0.02774059	S	0.000240614	S	0.279530189	S	0.01240653	S
5.2	0.02589277	S	0.000215334	S	0.294801219	S	0.01254424	S
5.4	0.024231	S	0.000193519	S	0.310282943	S	0.0126782	S
5.6	0.02560142	S	0.000180861	S	0.3670906	S	0.01228779	S
5.8	0.02705581	S	0.000172279	S	0.435190341	S	0.01188926	S
6	0.02975938	S	0.00022836	S	0.594027106	S	0.01126777	S
6.2	0.0350396	S	0.000379866	S	0.81509121	S	0.01101169	S
6.4	0.03820385	S	0.00035165	S	0.925461708	S	0.01018735	S
6.6	0.04049972	S	0.000311981	S	1.023771732	S	0.00911138	S
6.8	0.04120462	S	0.000213862	S	1.068140965	S	0.00875569	S
7	0.04190082	S	0.000148216	S	1.113063296	S	0.0084236	S
7.2	0.04258867	S	0.000103787	S	1.158529522	S	0.00811294	S
7.4	0.04326851	S	7.33888E-05	S	1.204530843	S	0.00782179	S
7.6	0.04394064	S	5.23759E-05	S	1.251058838	S	0.00754843	S
7.8	0.04438244	S	4.08286E-05	S	1.292834064	S	0.00722812	S
8	0.04393926	S	4.3843E-05	S	1.313611531	S	0.0066946	S

Table C-5-69. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID YSD Med

Sample ID
Date Exported
Database Name eling\EPA Rpt 4 (5-25-11 working db 3 reference-source term rev2).mdb
LeachXS Version

pH	Chromium	Solubility/ Washout	Mercury	Solubility/ Washout	Molybdenum	Solubility/ Washout	Antimony	Solubility/ Washout
8.2	0.04351128	S	4.69972E-05	S	1.334197532	W	0.00621222	S
8.4	0.04309764	S	5.02941E-05	S	1.354598439	W	0.00577499	S
8.6	0.04228543	S	6.5437E-05	S	1.36504665	W	0.00454777	S
8.8	0.04994915	S	5.48837E-05	S	1.369060515	W	0.0035068	S
9	0.08307162	S	1.85208E-05	S	1.367410169	W	0.00286723	S
9.2	0.13724358	S	8.01966E-06	S	1.362205933	W	0.002783	S
9.4	0.099277	S	9.59506E-06	S	1.329145472	W	0.002783	S
9.6	0.06962589	S	1.41555E-05	S	1.294103151	W	0.002783	S
9.8	0.07594641	S	1.53243E-05	S	1.275161665	W	0.002783	S
10	0.0955502	S	1.52173E-05	S	1.263727195	W	0.002783	S
10.2	0.11966883	S	1.51132E-05	S	1.252618679	W	0.002783	S
10.4	0.18628329	S	1.63641E-05	S	1.224011808	W	0.002783	S
10.6	0.26566066	S	1.75464E-05	S	1.195868504	W	0.002783	S
10.8	0.36464963	S	1.83536E-05	S	1.180969879	W	0.002783	S
11	0.46951245	S	1.83707E-05	S	1.188823488	W	0.002783	S
11.2	0.60178377	S	1.83876E-05	S	1.196586405	W	0.002783	S
11.4	0.76793751	S	1.84042E-05	S	1.20426127	W	0.002783	S
11.6	0.97582	S	1.84205E-05	S	1.2118506	W	0.002783	S
11.8	1.23490894	S	1.84365E-05	S	1.219356798	W	0.002783	S
12	1.55661543	S	1.84523E-05	S	1.226782162	W	0.002783	S
12.2	1.74153615	S	1.84679E-05	S	1.234128888	W	0.002783	S
12.4	1.74153615	S	1.84832E-05	S	1.241399078	W	0.002783	S
12.6	1.74153615	S	1.84982E-05	S	1.248594745	W	0.002783	S
12.8	1.74153615	S	1.85131E-05	S	1.255717816	W	0.002783	S
13	1.74153615	S	1.85277E-05	S	1.262770143	W	0.002783	S
Detection Limit (min, mg/L)	0.0005		0.000006		0.00076		0.00008	
Detection Limit (max, mg/L)	0.0005		0.000006		0.00076		0.00008	
Availability (mg/kg)	17.200357		0.00757507		13.52158534		0.14118584	

Table C-5-69. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID YSD Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
2.8	1.2374912	S	0.011501	S	0.304672	S
3	1.2374912	S	0.011501	S	0.3009614	S
3.2	1.2374912	S	0.011501	S	0.2975313	S
3.4	1.2374912	S	0.011501	S	0.2575821	S
3.6	1.232045	S	0.011456	S	0.1991502	S
3.8	1.1308197	S	0.010606	S	0.1561307	S
4	1.0713262	S	0.010096	S	0.1343484	S
4.2	1.0692375	S	0.010056	S	0.1347777	S
4.4	1.0525282	S	0.009912	S	0.1351883	S
4.6	1.0360648	S	0.00977	S	0.1355819	S
4.8	1.0205435	S	0.009636	S	0.1359597	S
5	1.0058744	S	0.00951	S	0.1363231	S
5.2	0.9919794	S	0.00939	S	0.1366732	S
5.4	0.9787901	S	0.009276	S	0.1370109	S
5.6	0.8711547	S	0.008808	S	0.1403208	S
5.8	0.7780516	S	0.008371	S	0.1435163	S
6	0.7012639	S	0.007717	S	0.145705	S
6.2	0.5719786	S	0.006532	S	0.1510276	S
6.4	0.547017	S	0.006008	S	0.1582867	S
6.6	0.5024441	S	0.00545	S	0.1642999	S
6.8	0.4612671	S	0.004846	S	0.1680471	S
7	0.4245156	S	0.004324	S	0.1717675	S
7.2	0.3916073	S	0.00387	S	0.175462	S
7.4	0.3620496	S	0.003474	S	0.1791314	S
7.6	0.3354242	S	0.003128	S	0.1827767	S
7.8	0.3139835	S	0.00286	S	0.1880764	S
8	0.3042713	S	0.002751	S	0.2003568	S

Table C-5-69. Leachate Concentrations for Mixed CCR's (gypsum, fly ash, sludge scrubber), Waste ID YSD Med

Sample ID
Date Exported
Database Name
LeachXS Version

pH	Selenium	Solubility/ Washout	Thallium	Solubility/ Washout	Vanadium	Solubility/ Washout
8.2	0.2950885	S	0.002649	S	0.2131059	S
8.4	0.2863941	S	0.002553	S	0.2263296	S
8.6	0.2550443	S	0.00253	S	0.2469418	S
8.8	0.2305839	S	0.00253	S	0.2754853	S
9	0.2252909	S	0.00253	S	0.3150631	S
9.2	0.2549067	S	0.00253	S	0.3654792	S
9.4	0.2440135	S	0.00253	S	0.3780552	S
9.6	0.2275782	S	0.00253	S	0.3839065	S
9.8	0.2114307	S	0.00253	S	0.3673189	S
10	0.2017247	S	0.00253	S	0.3527294	S
10.2	0.1926435	S	0.00253	S	0.3389913	S
10.4	0.179057	S	0.00253	S	0.3091858	S
10.6	0.163868	S	0.00253	S	0.2806543	S
10.8	0.1524182	S	0.00253	S	0.2592038	S
11	0.1458099	S	0.00253	S	0.2466787	S
11.2	0.1395995	S	0.00253	S	0.2349684	S
11.4	0.1337566	S	0.00253	S	0.2240068	S
11.6	0.1282537	S	0.00253	S	0.213734	S
11.8	0.1230655	S	0.00253	S	0.2040961	S
12	0.1181691	S	0.00253	S	0.195044	S
12.2	0.1135438	S	0.00253	S	0.1865332	S
12.4	0.1091703	S	0.00253	S	0.1785232	S
12.6	0.1050313	S	0.00253	S	0.1709772	S
12.8	0.1011107	S	0.00253	S	0.1638616	S
13	0.0973939	S	0.00253	S	0.1571457	S
Detection Limit (min, mg/L)	0.00052		0.00051		0.00031	
Detection Limit (max, mg/L)	0.00052		0.00051		0.00031	
Availability (mg/kg)	12.222136		0.113593		3.7916691	

Appendix D.

Human Exposure Factors

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D.1 Introduction

Exposure factors are data that quantify human behavior patterns (e.g., ingestion rates of drinking water and fish) and physiological characteristics (e.g., body weight) that affect an individual's exposure to environmental contaminants. These data can be used to construct realistic assumptions concerning the magnitude of exposure to and subsequent intake of a contaminant in the environment. The exposure factors data also enable the U.S. Environmental Protection Agency (EPA or the Agency) to differentiate the exposures of individuals of different ages. The derivation of human exposure factors used in both the screening and probabilistic analyses are described below.

D.1.1 Data Sources

The Agency relied primarily on the *Exposure Factors Handbook* (*EFH*) (U.S. EPA, 1997a,b,c) for data on adult receptors and the *Child-Specific Exposure Factors Handbook* (*CSEFH*) (U.S. EPA, 2008) for data on child receptors. Where sufficient data were available, the percentiles and corresponding data points obtained from these two sources were used to develop a cumulative distribution in order to capture variability within the U.S. population. Otherwise, EPA relied on point values selected based on the recommendations of the EFH, CSEFH or established Agency guidance (U.S. EPA, 1991).

EPA acknowledges that the 2011 *Exposure Factors Handbook* (U.S. EPA, 2011) has been completed and updates some of the data from the 1997 EFH and 2008 CSEFH. During the finalization of this risk assessment, EPA released *Office of Solid Waste and Emergency Response Directive 9200.1-120* (U.S. EPA, 2014). Although this document provides protective, default exposure factors to use as point estimates, EPA is still in the process of updating the full distributions necessary for a probabilistic analysis. Therefore, this risk assessment does not incorporate the data from the 2011 EFH and instead relies on the 1997 EFH and 2008 CSEFH, referred to simply as the "EPA exposure factor data" throughout the remainder of this appendix.

D.1.2 Age Cohorts

There has been considerable effort across the Agency to improve the accuracy and consistency of childhood exposure assessments. In the *Guidance on Selecting Age Groups for Monitoring and Assessing Childhood Exposures to Environmental Contaminants* (U.S. EPA, 2005), EPA recommended specific age cohorts (i.e., groups) intended to better capture the large variability in physiological and behavioral characteristics of child receptors during different stages of development. Narrower age cohorts were identified where rapid developmental changes occur, while broader age groups were identified where the rate of development decreases. These age groupings and the supporting rationale for their selection have been subjected to internal and external scientific peer review. In total, receptors were divided into the eight distinct age cohort groupings recommended by U.S. EPA (2005). **Table D-1** below presents a comparison between the age groups used in the 2010 Risk Assessment and those used in the revised risk assessment. As seen in this table, this risk assessment adopts the notation proposed in U.S. EPA (2005), where

age groupings are described in terms of "X to < Y." For example, the age cohort of "3 to < 6 years" represents a 3-yr time interval from a child's third birthday up until the day before the child's sixth birthday.

Table D-1. Age Cohorts Used in the 2010 and Revised Risk Assessments

2010 Age Cohorts	Revised Age Cohorts
Not Evaluated	Infant (< 1 year)
1 to 5 years	1 to < 2 years
	2 to < 3 years
	3 to < 6 years
6 to 11 years	6 to < 11 years
11 to 20 years	11 to < 16 years
	16 to < 21 years
Adult (> 20 years)	Adult (> 21 years)

D.2 Exposure Factors for Screening Analysis

EPA conducted a deterministic screening analysis by using point estimates for all exposure factors. The majority of the exposure factors were set to median values in this analysis because the purpose was to streamline the evaluation and identify the constituents of potential concern most likely to pose risk to receptors. Where available distributions were not comprehensive enough to allow identification of a median value, high-end values were used instead. In addition, averaging time (i.e., anticipated lifetime over which cancer may occur) was set to a high-end because of the dependency between this exposure factor and many toxicity values used to calculate cancer risks. In instances where data were not available for a specific age cohort, the data fit to the closest age cohort available was used instead. Consistent with the regional screening tables used in the Superfund program, EPA screened risks using children and adult age cohorts, but not infants. The specific values used in the screening analysis are presented in **Table D-2**. These values are point estimates selected from the distributions developed for the probabilistic analysis, as described in **Section D.3**.

Table D-2. Exposure Data Used in the Screening Analysis

Parameter		Age Cohort	Value	Units	Basis
Averaging Time		All Cohorts	70	yr	Agency Policy U.S. EPA, 1989
Body Weight		1 to < 2 yrs	11.3	kg	50th Percentile from CSEFH, Table 8-3
		2 to < 3 yrs	13.6		
		3 to < 6 yrs	17.8		
		6 to < 11 yrs	29.3		
		11 to < 16 yrs	54.2		
		16 to < 21 yrs	67.6		
		Adult	69.3		50th Percentile from EFH, Table 7-4 & 7-5
Total Exposure Duration **Note:** Total exposure durations longer than the duration of the cohort indicate that the cohort will age into each subsequent cohort until the specified total duration has elapsed.		1 to < 2 yrs	5	yr	50th Percentile from EFH, Table 15-168
		2 to < 3 yrs	5		
		3 to < 6 yrs	5		
		6 to < 11 yrs	7.7		
		11 to < 16 yrs	8.5		
		16 to < 21 yrs	7		
		Adult	10*		50th Percentile from EFH, Table 15-164
Exposure Frequency		All Cohorts	350	days/yr	Agency Policy U.S. EPA (1991)
Fraction Contaminated	All media and foods	All Cohorts	1	fraction	Agency Policy U.S. EPA (1991)
Fraction Of Fish Consumed	Trophic Level 3 (TL3)	All cohorts	0.36	fraction	Calculated from EFH Table 10-66
	Trophic Level 4 (TL4)	All cohorts	0.64	fraction	

(continued)

Table D-2. Exposure Data Used in the Screening Analysis

Parameter		Age Cohort	Value	Units	Basis
Ingestion Rate	Beef	1 to < 2 yrs	2.11	g WW/kg/day	50th Percentile from EFH, Table 13-36
		2 to < 3 yrs	2.11		
		3 to < 6 yrs	2.11		
		6 to < 11 yrs	2.11		
		11 to < 16 yrs	1.51		
		16 to < 21 yrs	1.51		
		Adult	1.64*		
	Fish	All Cohorts	2.0	g/day	50th Percentile from EFH, Table 10-64
	Drinking Water	1 to < 2 yrs	20	mL/kg-day	50th Percentile from CSEFH, Table 3-19
		2 to < 3 yrs	21		
		3 to < 6 yrs	19		
		6 to < 11 yrs	13		
		11 to < 16 yrs	10		
		16 to < 21 yrs	10		
		Adult	1,275	mL/day	50th Percentile from EFH, Table 3-6
	Exposed Fruit	1 to < 2 yrs	1.82	g WW/kg/day	50th Percentile from EFH, Table 13-61
		2 to < 3 yrs	1.82		
		3 to < 6 yrs	1.82		
		6 to < 11 yrs	1.11		
		11 to < 16 yrs	0.609		
		16 to < 21 yrs	0.609		
		Adult	1.30*		
	Exposed Vegetables	1 to < 2 yrs	1.89	g WW/kg/day	50th Percentile from EFH, Table 13-63
		2 to < 3 yrs	1.89		
		3 to < 6 yrs	1.16		
		6 to < 11 yrs	0.643		
		11 to < 16 yrs	0.656		
		16 to < 21 yrs	0.656		
		Adult	1.38*		

(continued)

Table D-2. Exposure Data Used in the Screening Analysis

Parameter		Age Cohort	Value	Units	Basis
Ingestion Rate	Milk	1 to < 2 yrs	31.3	g/kg-day (as consumed)	50th Percentile of total dairy from CSEFH Table 11-4
		2 to < 3 yrs	31.3		
		3 to < 6 yrs	20.8		
		6 to < 11 yrs	11.7		
		11 to < 16 yrs	4.2		
		16 to < 21 yrs	4.2		
		Adult	12.1*	g WW/kg/day	50th Percentile from households that farm EFH, Table 13-28
	Protected Fruit	1 to < 2 yrs	2.34	g WW/kg/day	50th Percentile from EFH, Table 13-62
		2 to < 3 yrs	2.34		
		3 to < 6 yrs	2.34		
		6 to < 11 yrs	2.34		
		11 to < 16 yrs	1.23		
		16 to < 21 yrs	1.23		
		Adult	2.13*+		
	Protected Vegetables	1 to < 2 yrs	1.94	g WW/kg/day	50th Percentile from EFH, Table 13-64
		2 to < 3 yrs	1.94		
		3 to < 6 yrs	1.04		
		6 to < 11 yrs	0.791		
		11 to < 16 yrs	0.583		
		16 to < 21 yrs	0.583		
		Adult	0.599*		
	Root Vegetables	1 to < 2 yrs	0.920	g WW/kg/day	50th Percentile from EFH, Table 13-65
		2 to < 3 yrs	0.920		
		3 to < 6 yrs	0.462		
		6 to < 11 yrs	0.523		
		11 to < 16 yrs	0.565		
		16 to < 21 yrs	0.565		
		Adult	0.883*		
	Soil + Dust	All Child Cohorts	100	mg/day	Central tendency (no percentiles) from CSEFH Table 5-1
		Adult	50		Mean from EFH Table 4-23

(continued)

Table D-2. Exposure Data Used in the Screening Analysis

Parameter		Age Cohort	Value	Units	Basis
Skin Surface Area		Adult	18,000	cm^2/kg	RAGS, Part E (U.S. EPA, 2004), Exhibit 3-2.
Event Frequency	Bath/ Shower	All Cohorts	1	event/day	
Event Duration		Adult	0.58	hr	

* Used data for households that farm (not broken out by age) to capture highly exposed individuals.
\+ Weighted (by number of observations) average of 20-39 and 40-69.

D.3 Exposure Factors for Probabilistic Analysis

The general methodology for collecting human exposure data for the probabilistic analysis relied on the EPA data from the 1997 EFH or 2008 CSEFH in one of three ways:

1. When the available data were adequate (as for most input variables), nonparametric approaches were used to fit distributions to the cumulative distribution (percentiles) of the data using @Risk software (available at www.palisade.com/risk/). Fitting nonparametric distributions removed parameter uncertainty associated with the fitting of specific parametric distributions (U.S. EPA, 2000).
2. When the available data were not adequate to support the statistical fitting for a specific age cohort, the data fit to the closest age cohort available was used instead.
3. When available data were not adequate for either of the above methods, variables were fixed at values recommended in the EFH or CSEFH or according to established EPA policy.

D.3.1 Variable Parameters

This section describes how the various distributions of exposure factor data were collected and processed for use in the probabilistic analysis. Probabilistic exposure analyses involve sampling values from a distribution with the same characteristics as the data using the values to estimate risk. For most variables for which distributions were developed, EPA exposure factor data were analyzed to fit nonparametric models. Steps in the development of distributions included preparing data, fitting models, assessing fit, and preparing parameters to characterize distributional uncertainty in the model inputs.

For many exposure factors, the data from the EFH and CSEFH include sample sizes and estimates of the following parameters for specific receptor types and age groups: mean, standard deviation, standard error, and percentiles corresponding to some subset of the following probabilities: 0.01, 0.02, 0.05, 0.10, 0.15, 0.25, 0.50, 0.75, 0.85, 0.90, 0.95, 0.98, and 0.99. These percentile data, where available, were used as a basis for fitting distributions. Although in no case are all of these

percentiles provided for a single factor, seven or more are typically available. Therefore, using the percentiles provided a better representation of the available information than fitting distributions simply based on the method of moments (i.e., selecting models that agree with the data mean and standard deviation).

Neither the EFH nor the CSEFH makes use of the standardized age cohorts recommended in U.S. EPA (2005). Different exposure factors are reported for different age categories based on the information available in the scientific literature. Therefore, to obtain the percentiles for fitting the eight standardized age cohorts used for the revised risk assessment, each cohort-specific value for a given exposure factor was assigned to one of the cohorts. When multiple cohorts fitted into a single CCR cohort, the percentiles from the EFH or CSEFH were averaged within each CCR cohort (e.g., data on 6 year olds and 9 year olds were averaged for the 6 to <11 age cohort). If sample sizes were available, weighted averages were used, with weights proportional to sample sizes. If sample sizes were not available, equal weights were assumed (i.e., the percentiles were simply averaged).

Nonparametric distributions were used to characterize the data. The nonparametric approach fits an optimal smooth curve to the cumulative distribution (percentiles) of the data. The best nonparametric fit is selected as the one that minimized the distance between the smooth curve and the empirical curve generated by the percentiles of the data. The maximum, minimum are used to specify the range of the simulated values. Depending on the data set, there could be more than one distribution (parametric or nonparametric) that could be considered a good fit for the data. Selecting an incorrect exposure distribution model may bias the risk assessment results, producing incorrect conclusions. Therefore, the application of goodness-of-fit statistics was required to select between competing distributions and to reduce model uncertainty. One goodness-of-fit statistic available was the root mean squared error, defined as the root of the average of the squared differences between the predicted percentile and the observed percentile. The other goodness-of-fit statistic available was the Chi-square based comparison of the empirical cumulative distribution (derived from the cumulative data) or the nonparametric cumulative distribution. Graphical displays were also used to evaluate the appropriateness of the selected distribution. A plot of the observed percentiles (from the cumulative data) vs. the nonparametric cumulative distribution was created. In some cases, exposure distributions are highly skewed, and there is a probability, although small, that a combination of extreme values might be selected from the tails of the distributions.

Drinking Water Intake

Drinking water intake data were obtained from Table 3-19 of the *CSEFH* and Table 3-6 of the *EFH* (U.S. EPA, 1997a), for children and adults, respectively. Weighted averages of percentiles and means were calculated for the 0 to < 1 yr infant (based on birth to < 1 month, 1 to < 3 months, 3 to < 6 months and 6 to < 12 months), the 16 to < 21 years age group (based on 16 to < 18 years and 18 to < 21 years) and adults (based on 20 to 44, 45 to 64, and 64 to 74 years), using the number of observations in each subcohort as weights. **Table D-3** presents drinking water intake data used

to prepare Monte Carlo simulations (note that the infant and child values are normalized by body weight and reported in mL/kg-day, while the adult ones are not and are reported in mL/day).

Table D-3. Drinking Water Consumption Rate Data (mL/kg-day)(1)

Age Group (Years)	N	Mean	Percentile						
			P10	P25	P50	P75	P90	P95	P99
Infant(2)	948	71	7	25	66	104	140	164	217
1 to < 2	880	27	4	9	20	36	56	75	109
2 to < 3	879	26	4	9	21	36	52	62	121
3 to < 6	3,703	24	3	8	19	33	49	65	97
6 to < 11	1,439	17	3	6	13	23	35	45	72
11 to < 16	911	13	2	5	10	17	26	34	54
16 to < 21	700	13	2	5	10	17	27	34	61
Adult	13,394	1,384	607	900	1,275	1,741	2,260	2,682	3,737

Source: Table 3-19, CSEFH for child cohorts and Table 3-6, EFH (U.S. EPA, 1997b) for adults.

1) Adult values are mL/day.

2) Weighted average based on subcohorts presented in the CSEFH or EFH.

Drinking water consumption rate data for infants (birth to < 1 month, 1 to < 3 months, 3 to < 6 months and 6 to < 12 months) are available from the CSEFH (U.S. EPA, 2008). **Table D-4** presents the water ingestion data used for infants. As drinking water concentrations are provided by the model as annual averages, the infant consumption rates were averaged to estimate a 0 to < 1 year infant. The data were weighted by sample size because the small sample sizes did not meet minimum requirements as described in the *Third Report on Nutrition Monitoring in the United States* (FASEB, 1995) for numerous percentiles in numerous subcohorts.

Table D-4. Drinking Water Consumption Rates for Infant Subcohorts (mL/kg-day)

Age Group (Months)	N	Mean	Percentile						
			P10	P25	P50	P75	P90	P95	P99
Birth to < 1	37	137	11	65	138	197	235	238	263
1 to < 3	108	119	12	71	107	151	228	285	345
3 to < 6	269	80	7	27	77	118	148	173	222
6 to < 12	534	53	5	12	47	81	112	129	186
Infant	948	71	7	25	66	104	140	164	217

Source: Table 3-19, *CSEFH*.

Body Weight

Weighted averages of percentiles and means were calculated for the infant age group (based on birth to < 1 month, 1 to < 3 months, 3 to < 6 months and 6 to < 12 months) and adults (based on male and female data). **Table D-5** presents body weight data. Body weight data were obtained from Table 8-8 of the CSEFH and Tables 7-4 and 7-5 of the EFH (U.S. EPA, 1997a). Data in the EFH tables were presented by race, age, gender. The female and male distributions for "all races" were weighted based on sample size to develop the percentile data presented in Table D-5 for all adults.

Table D-5. Body Weight Data (kg)

Age Group (Years)	N	Mean	Percentile								
			P05	P10	P15	P25	P50	P75	P85	P90	P95
Infant	1,858	7.8	6	6.4	6.7	7.1	7.8	8.6	9.0	9.3	9.7
1 to < 2	1,176	11.4	8.9	9.3	9.7	10.3	11.3	12.4	13	13.4	14
2 to < 3	1,144	13.8	10.9	11.5	11.9	12.4	13.6	14.9	15.8	16.3	17.1
3 to < 6	2,318	18.6	13.5	14.4	14.9	15.8	17.8	20.3	22	23.6	26.2
6 to < 11	3,593	31.8	19.7	21.3	22.3	24.4	29.3	36.8	42.1	45.6	52.5
11 to < 16	5,297	56.8	34	37.2	40.6	45	54.2	65	73	79.3	88.8
16 to < 21	4,851	71.6	48.2	52	54.5	58.4	67.6	80.6	90.8	97.7	108
Adult	12,504	71.4	52.9	56.0	58.2	61.7	69.3	78.5	84.9	89.8	97.6

Sources: Table 8-3 *CSEFH* (U.S. EPA, 2008) for children and Table 7-4 and 7-5 *EFH* (U.S. EPA, 1997a) for adults.

Fish Consumption

Fish consumption data were obtained from Table 10-64 of the EFH (U.S. EPA, 1997b). These data originate from a fish consumption study of recreational anglers conducted in Maine, one of four freshwater angler studies recommended in the 1997 EFH. Fish consumption rates for subsistence anglers were not considered, in part because fish ingestion rates for Native American subsistence anglers are currently limited and can vary widely among individual tribes. EPA selected the Maine data because it was the most complete of the data sets available and because it agrees most closely with the mean intake rates reported in a separate U.S. Department of Agriculture study of national fish consumption (USDA, 1992). The Maine study provides percentile data necessary to develop a distribution that were not available in the USDA study. **Table D-6** presents fish consumption rate data used to prepare Monte Carlo simulations. Age-specific data for children were not available; children were assumed to consume the same amount of fish as adults.

Table D-6. Fish Consumption Rates for All Ages (g/day)

Age Group	N	Mean	Percentile				
			P50	P66	P75	P90	P95
All	1,053	6.4	2	4	5.8	13	26

Source: Table 10-64, *EFH* (U.S. EPA, 1997b)

Exposure Duration

Exposure durations for adult and child residents were determined using data on residential occupancy from Tables 15-164 and 15-168 of the EFH (U.S. EPA, 1997c). The data represent the total time a person (both male and female) is expected to live at a single location, based on age. For adult residents, data reported for farm residents were used to capture highly exposed receptors within the population. For child residents, data reported for the 3-yr age group were used to represent infants to < 6 yrs. Data reported for ages 6 and 9 were averaged to represent 6 to < 11 yrs. Data on ages 12 and 15 were averaged to represent 11 to < 16 yrs. Data reported for age 18 were used to represent 16 to < 21 yrs. **Table D-7** presents exposure duration data. The underlying source for the recommended EFH distribution was a Monte Carlo simulation that estimated a probability distribution function for residential occupancy period based on the probability of moving and dying. There are no sample sizes, as these data do not derive from a survey.

Table D-7. Human Exposure Durations for All Ages (yr)

Age Group (Years)	Mean	Percentile					
		P25	P50	P75	P90	P95	P99
Infant	6.5	3	5	8	13	17	22
1 to < 2	6.5	3	5	8	13	17	22
2 to < 3	6.5	3	5	8	13	17	22
3 to < 6	6.5	3	5	8	13	17	22
6 to < 11	8.45	4.5	7.7	11	15.5	18	22
11 to < 16	9.2	5	8.5	12.5	16	18	23
16 to < 21	8.2	4	7	11	16	19	23
Adult	N/A	2.4	10.0	26.7	48.3	58.4	N/A

Sources: Children: Table 15-168, EFH (U.S. EPA, 1997c)
Adult farmer: Table 15-164, EFH (U.S. EPA, 1997c)
N/A – Not Available

D.3.2 Fixed Parameters

Certain parameters were fixed because the available data were not adequate to generate distributions. These parameters are shown in **Table D-8** along with the value selected for the risk analysis and the data source. For fraction of fish consumed that is trophic level 3 (TL 3) vs. trophic level 4 (TL 4), EFH Table 10-66 presents grams of fish consumed per year by species and type of fishing (ice fishing, lakes and ponds, and rivers and streams). The fraction of TL3 and TL4 fish consumed were calculated from these data using all fishing types and categorizing the fish species as either TL3 (i.e., carp, smelt, perch, catfish, sucker, bullhead, perch, and white fish) or TL4 (i.e., salmon, trout, bass, chub, and other).

Table D-8. Summary of Human Exposure Factor Data Used in Modeling: Constants

Description		Value	Units	Source
Averaging Time for Carcinogens		70	yr	EPA Policy (U.S. EPA, 1989)
Exposure Frequency		350	d/yr	EPA Policy (U.S. EPA, 1991)
Fraction Contaminated: All media and food items		1	Fraction	EPA Policy (U.S. EPA, 1991)
Fraction of Fish Consumed that is:	Trophic Level 3	0.36	Fraction	Calculated from EFH, Table 10-66
	Trophic Level 4	0.64		

D.4 References

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Appendix E.

Human Health and Ecological Benchmarks

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E.1 Introduction

This appendix provides the benchmarks for human and ecological receptors used in the coal combustion residuals (CCR) risk assessment, and describes the data sources.

E.2 Human Health Benchmarks

Human health benchmarks are based on the specific adverse effects that may occur. Adverse effect is a broad term for any abnormal, harmful, or undesirable change that results from exposure to a stressor. Adverse health effects are divided into two main categories: carcinogenic and noncarcinogenic. Carcinogenic effects are those that result in the development of cancer somewhere in the organism. Noncarcinogenic effects are those that result in any adverse health effect other than cancer. Some stressors may result in both carcinogenic and noncarcinogenic effects, depending on the route through which the receptor is exposed and the magnitude of the exposure. Benchmarks were collected for ingestion and inhalation because these are the primary routes through which residential receptors who live close to CCR surface impoundments and landfills may be exposed.

E.2.1 Chronic Human Health Benchmarks

Reference doses (RfDs) and reference concentrations (RfCs) are used to evaluate noncancer effects from oral and inhalation exposures, respectively. RfDs and RfCs are estimates of a daily exposure to the human population (including sensitive subgroups) that is likely to be without appreciable risk of deleterious noncancer effects. However, an average lifetime exposure above the RfD (or RfC) does not imply that an adverse health effect will necessarily occur.

Oral cancer slope factors (CSFo's) and inhalation unit risk factors (URFs) are used to evaluate carcinogenic effects. The CSFo is an upperbound estimate (approximating a 95% confidence limit) of the increased human cancer risk from a lifetime of exposure. The URF is a cancer benchmark for inhalation exposures, where the air concentrations are used as a threshold.

The Office of Solid Waste and Emergency Response 2003 Directive 9285.7-53 encourages prioritization of sources that are most current, those for which the basis is transparent and publicly available and those that have been peer reviewed (U.S. EPA, 2003). Accordingly, a three-tiered approach was followed to use higher priority data sources based on availability.

Tier I

Integrated Risk Information System (IRIS): IRIS (U.S. EPA, 2012a) provides the highest quality science-based chronic human health assessments to support EPA regulatory activities. IRIS assessments have been peer-reviewed and represent Agency-wide consensus. Thus, EPA used values from IRIS whenever available. IRIS contains RfDs and RfCs for chronic noncarcinogenic health effects, and oral CSFs and inhalation URFs for carcinogenic effects.

Tier II

Provisional Peer-Reviewed Toxicity Values (PPRTVs): When a value is not available in IRIS, the Superfund Program may derive a PPRTV after a review of the relevant scientific literature using the methods, sources of data and guidance for value derivation used by the EPA IRIS Program. All provisional peer-reviewed toxicity values receive internal review by EPA scientists and external peer review by independent scientific experts. However, PPRTVs do not reflect Agency-wide consensus, because PPRTVs are developed specifically for the Superfund Program. PPTRVs included cancer and noncancer benchmarks for both oral and inhalation exposure.

Tier III

Agency for Toxic Substances and Disease Registry (ATSDR) Chronic Minimal Risk Levels (MRLs): The ATSDR MRLs (ATSDR, 2013) are substance-specific health guidance levels for noncarcinogenic effects. An MRL is intended to be an estimate of the daily human exposure to a hazardous substance that is likely to be without appreciable risk of adverse noncancer health effects over a specified duration of exposure. MRLs are derived for oral and inhalation routes of exposure in a manner similar to RfDs and RfCs, respectively. MRLs have undergone both internal and external peer review.

California EPA (CalEPA) Cancer Potency Factors and Reference Exposure Levels: CalEPA has developed cancer potency factors (CalEPA, 2011) for chemicals regulated under California's Hot Spots Air Toxics Program. The cancer potency factors are analogous to the EPA's oral and inhalation CSFs. CalEPA has also developed chronic inhalation RELs, analogous to the EPA's RfC (CalEPA, 2014). The cancer potency factors and inhalation RELs have undergone peer review by various California agencies and have been made available for public comment.

Other Health Benchmarks: Some other organizations have also developed human health benchmarks. In limited cases where no other benchmarks from the above sources were available, such benchmarks were used:

- An oral cancer benchmark for chromium (VI), developed by the New Jersey Department of Environmental Protection for their soil cleanup program (NJDEP, 2009) based on information from a study by the National Toxicity Program (NTP, 2008).
- An RfD for lanthanum carbonate, compiled for the International Toxicity Estimates for Risk database, that was developed by National Sanitation Foundation (NSF) International (NSF, 2010).
- For lead, EPA currently has no consensus on the development of an RfD or CSFo because of the difficulty associated with identifying an effect threshold needed to develop these benchmarks. Therefore, the maximum contaminant level (MCL) for drinking water was used as an alternative method of approximating human health risk.

Health Effects Assessment Summary Tables: HEAST (U.S. EPA, 1997a) is a listing of provisional noncarcinogenic and carcinogenic health toxicity values (RfDs, RfCs, URFs and CSFos) derived by the EPA. Although the health toxicity values in HEAST have undergone review and have the concurrence of individual EPA program offices, the values have not been externally reviewed as extensively as those in IRIS. Values for chemical exposures are not updated at this time.

The chronic human health benchmarks used in the CCR risk assessment are summarized in **Table E-1** (cancer benchmarks) and **Table E-2** (noncancer benchmarks). These tables provide the constituent name, Chemical Abstract Service Registry Number (CASRN), CSFo and inhalation URF (**Table E-1**) or RfD and RfC (**Table E-2**), and the reference for each benchmark. A key to the references cited is provided at the end of the tables. All values are current as of May 2014.

Table E-1. Chronic Human Health Benchmarks: Cancer

Constituent	CASRN	CSFo $(mg/kg\text{-}d)^{-1}$	Ref	Last Updated	URF $(\mu g/m^3)^{-1}$	Ref	Last Updated
Arsenic	7440-38-2	1.50E+00	IRIS	04/1998	4.30E-03	IRIS	04/1998
Beryllium	7440-41-7	—	—	—	2.40E-03	IRIS	04/1998
Cadmium	7440-43-9	—	—	—	1.80E-03	IRIS	06/1992
Chromium (VI)	18540-29-9	5.00E-01	NJDEP	06/2009	1.20E-02	IRIS	09/1998
Cobalt	7440-48-4	—	—	—	9.00E-03	PPRTV	08/2008

Table E-2. Chronic Human Health Benchmarks: Noncancer

Constituent	CASRN	RfD (mg/kg-d)	Target Organ	Ref	Last Updated	RfC (mg/m^3)	Target Organ	Ref	Last Updated	Additional Notes
Aluminum	7429-90-5	1E+00	Neurological	PPRTV	10/2006	5E-03	Neurological	PPRTV	10/2006	—
Ammonia	7664-41-7	9.7E-01*	Sensory	HEAST	07/1997	1E-01	Respiratory	IRIS	05/1991	—
Antimony	7440-36-0	4E-04	Hematological	IRIS	02/1991	2E-04	Respiratory	IRIS	09/1995	RfC for Antimony Trioxide
Arsenic	7440-38-2	3E-04	Dermal	IRIS	02/1993	1.5E-05	Neurological	CalEPA	10/2013	—
Barium	7440-39-3	2E-01	Kidney	IRIS	07/2005	—	—	—	—	—
Beryllium	7440-41-7	2E-03	Gastrointestinal	IRIS	04/1998	2E-05	Respiratory	IRIS	04/1998	—
Boron	7440-42-8	2E-01	Developmental	IRIS	08/2004	—	—	—	—	—
Cadmium	7440-43-9	5E-04 (Water) 1E-03 (Food)	Kidney	IRIS	02/1994	1E-05	Kidney	ATSDR	09/2012	
Calcium	7440-70-2	No Benchmarks								
Chloride	16887-00-6	No Benchmarks								
Chromium III	16065-83-1	1.5E+00	NOAEL	IRIS	09/1998	—	—	—	—	—
Chromium VI	18540-29-9	3E-03	NOAEL	IRIS	09/1998	1E-04	Respiratory	IRIS	09/1998	—
Cobalt	7440-48-4	3E-04	Thyroid	PPRTV	08/2008	6E-06	Respiratory	PPRTV	08/2008	—
Copper	7440-50-8	1E-02	Gastrointestinal	ATSDR	09/2004	—	—	—	—	Intermediate Oral MRL

(continued)

Table E-2. Chronic Human Health Benchmarks: Noncancer

Constituent	CASRN	RfD (mg/kg-d)	Target Organ	Ref	Last Updated	RfC (mg/m^3)	Target Organ	Ref	Last Updated	Additional Notes
Fluoride	16984-48-8	6E-02	Bone/Teeth	IRIS	06/1989	—	—	—	—	RfD for Fluorine
Iron	7439-89-6	7E-01	Gastrointestinal	PPRTV	09/2006	—	—	—	—	—
Lanthanum	7439-91-0	5E-01	Hematological	ITER	11/2010	—	—	—	—	RfD for Lanthanum Carbonate
Lead	7439-92-1	MCL of 0.015 mg/L used for water								
Lithium	7439-93-2	2E-03	Several Organs and Systems	PPRTV	06/2008	—	—	—	—	—
Magnesium	7439-95-4	No Benchmarks								
Manganese	7439-96-5	1.4E-01 (Food/Soil) 4.7E-02 (Water)	Neurological	IRIS	05/1996	5E-05	Neurological	IRIS	12/1993	—
Mercury (Chloride)	7487-94-7	3E-04	Immunological	IRIS	05/1995	—	—	—	—	RfD used for produce, livestock, water, soil
Mercury (Elemental)	7439-97-6	—	—	—	—	3E-04	Neurological	IRIS	06/1995	RfC used for ambient air
Mercury (Methyl)	22967-92-6	1E-04	Developmental	IRIS	07/2001	—	—	—	—	RfD used for fish
Molybdenum	7439-98-7	5E-03	Metabolic	IRIS	08/1993	—	—	—	—	—
Nickel	7440-02-0	2E-02	Body Weight, Cardiovascular, Liver	IRIS	12/1996	9E-05	Respiratory	ATSDR	08/2005	—
Nitrate/ Nitrite	14797-55-8	1.6E+00	Hematological	IRIS	10/1991	—	—	—	—	—

(continued)

Table E-2. Chronic Human Health Benchmarks: Noncancer

Constituent	CASRN	RfD (mg/kg-d)	Target Organ	Ref	Last Updated	RfC (mg/m^3)	Target Organ	Ref	Last Updated	Additional Notes
Potassium	7440-09-7	No Benchmarks								
Selenium	7782-49-2	5E-03	Dermal, Hematological, Neurological	IRIS	09/1991	2E-02	Cardiovascular, Hematological, Liver, Neurological	CalEPA	10/2013	—
Silicon	7631-86-9	No Benchmarks								
Silver	7440-22-4	5E-03	Dermal	IRIS	12/1996	—	—	—	—	—
Sodium	7440-23-5	No Benchmarks								
Strontium	7440-24-6	6E-01	Bone/Teeth	IRIS	12/1996	—	—	—	—	—
Sulfate	14808-79-8	No Benchmarks								
Sulfide	18496-25-8	No Benchmarks								
Sulfur	7704-34-9	No Benchmarks								
Thallium	7440-28-0	1E-05	Hair Loss	PPRTV	10/2012	—	—	—	—	RfD for soluble thallium
Uranium	7440-61-1	3E-03	Body Weight, Kidney	IRIS	10/1989	3E-04	Kidney	ATSDR	02/2013	—
Vanadium	7440-62-2	9E-03	Hair	IRIS	12/1996	1E-04	Respiratory	ATSDR	09/2012	—
Zinc	7440-66-6	3E-01	Hematological	IRIS	08/2005	—	—	—	—	—

* RfD for ammonia was provided as a concentration in drinking water of 34 mg/L, which was converted to mg/kg-day assuming a drinking water consumption rate of 2 L/day (approximately 90th percentile for adults) and a body weight of 70 kg (approximately 50th percentile for adults). Thus, 34 mg/L × 2 L/day ÷ 70 kg = 9.7E-1 mg/kg-day.

E.2.2 Acute Inhalation Human Health Benchmarks

In addition to chronic exposures, another exposure scenario of potential concern for the screening analysis is acute inhalation. The *Human Health Risk Assessment Protocol for Hazardous Waste Combustion Facilities* (HHRAP, U.S. EPA, 2005i) recommends evaluating an acute exposure scenario to ensure that an assessment evaluates all receptors that may be significantly exposed to emissions from facility sources. However, short-term emissions are unlikely to cause an adverse impact through the indirect exposure pathways (as compared to impacts from long-term emissions through those pathways). Therefore, HHRAP recommends evaluating acute effects only through the short-term (maximum 1-hour) inhalation of vapors and particulates.

Acute inhalation exposure guidelines and criteria are designed to protect a variety of exposure groups, including occupational workers, military personnel, and the general public. Acute guidelines are based on varying exposure durations up to 24 hours (e.g., 10, 30 and 60 minutes; 4 and 8 hours; and 1 day). Acute exposure guidelines are based on adverse health effects reflecting a wide range of severity, from mild, transient effects (e.g., respiratory irritation) to irreversible or serious effects, to potentially life threatening effects. Reflecting the conservative nature of a screening assessment, EPA used guidelines based on the mild, transient effects, as those would also be protective of more severe effects.

To identify acute inhalation guidelines, EPA used the hierarchy established by HHRAP (U.S. EPA, 2005i). Preference is given to sources and values that 1) have undergone rigorous scientific review, 2) address intermittent exposures (as opposed to one-time exposures), 3) are based on one-hour exposures, and 4) apply to the general population, including susceptible individuals. The hierarchy is as follows:

1. **CalEPA Acute Reference Exposure Levels (RELs):** concentration in air at or below which no adverse health effects are anticipated in the general population, including sensitive individuals, for a specified exposure period (1 and 8 hours). CalEPA Acute RELs are meant to address routine short-term emissions rather than industrial accidents, another reason they are the most preferred source. They are peer-reviewed by the State's Scientific Review Panel on Toxic Air Contaminants and have been made available for public comment.
2. **U.S. EPA Acute Exposure Guideline Levels (AEGL-1):** the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain asymptomatic non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure (10 and 30 minutes and 1, 4 and 8 hours). AEGLs are intended to protect against rare, typically accidental or once-in-a-lifetime exposures. AEGL values and methods undergo peer review by the National Advisory Committee for AEGLs and the National Research Council of the National Academy of Sciences, and also receive public comment.

3. **American Industrial Hygiene Association Level 1 Emergency Response Planning Guidelines (ERPG-1):** the maximum concentration in air below which it is believed nearly all individuals could be exposed for up to one hour without experiencing other than mild transient adverse health effects or perceiving a clearly defined objectionable odor (1 hour). ERPGs are meant to anticipate adverse health effects from chemical release emergencies. ERPG-1 values are peer reviewed.
4. **U.S. Department of Energy Temporary Emergency Exposure Limits (TEEL-1):** the maximum concentration in air below which it is believed nearly all individuals could be exposed without experiencing other than mild transient adverse health effects or perceiving a clearly defined odor. TEELs are meant to fill in where ERPGs are not available, until ERPGs are developed. The TEEL-1s are based on 15 minute exposures. Although individual TEELs are not peer reviewed, they are developed based on a peer-reviewed process.

Two constituents, chromium III and chromium VI, did not have values in any of the above sources on HHRAP's hierarchy. For these, EPA used the National Institute for Occupational Safety and Health Immediately Dangerous to Life or Health Values (IDLH) and, following the same process as EPA's Air Toxics Program, divided by 10 to more closely match the milder effect levels developed by the other sources; this approach is consistent with the methodology used to develop levels of concern under Title III of the Superfund Amendments and Reauthorization Act, and their use in the accidental release prevention requirements under section 112(r) of the Clean Air Act (see www.epa.gov/ttn/atw/toxsource/acutesources.html).

The acute inhalation health benchmarks used in the CCR risk assessment are summarized in Table E-3. All values were current as of May 2014, except the TEELs, which were current as of January 2012, when the acute benchmark data were collected. The TEELs were updated in February 2012, but those have not been incorporated here, as they occurred after the CCR modeling was completed.

Table E-3. Acute Inhalation Benchmarks

Constituent	CASRN	1-Hour Value (mg/m^3)	Source	Last Updated
Aluminum	7429-90-5	3	TEEL-1	02/2012
Ammonia	7664-41-7	3.2	CalEPA REL	01/2014
Antimony	7440-36-0	1.5	TEEL-1	02/2012
Arsenic	7440-38-2	0.0002	CalEPA REL	01/2014
Barium	7440-39-3	1.5	TEEL-1	02/2012
Beryllium	7440-41-7	0.0035	TEEL-1	02/2012
Boron	7440-42-8	4	TEEL-1	02/2012
Cadmium	7440-43-9	0.1	AEGL1	01/2012
Calcium	7440-70-2	30	TEEL-1	02/2012

(continued)

Table E-3. Acute Inhalation Benchmarks

Constituent	CASRN	1-Hour Value (mg/m^3)	Source	Last Updated
Chloride	16887-00-6	1.45	TEEL-1	02/2012
Chromium (III)	16065-83-1	2.5	IDLH/10	03/1995
Chromium (VI)	18540-29-9	1.5	IDLH/10	03/1995
Chromium (total)	7440-47-3	1	TEEL-1	02/2012
Cobalt	7440-48-4	0.3	TEEL-1	02/2012
Copper	7440-50-8	0.1	CalEPA REL	01/2014
Fluoride	16984-48-8	7.5	TEEL-1	02/2012
Iron	7439-89-6	6	TEEL-1	02/2012
Lanthanum	7439-91-0	30	TEEL-1	02/2012
Lead	7439-92-1	0.15	TEEL-1	02/2012
Magnesium	7439-95-4	4	TEEL-1	02/2012
Manganese	7439-96-5	3	TEEL-1	02/2012
Mercury (divalent)	7439-97-6	0.0006	CalEPA REL	01/2014
Molybdenum	7439-98-7	15	TEEL-1	02/2012
Nickel	7440-02-0	0.006	CalEPA REL	01/2014
Nitrate/Nitrite	14797-55-8	30	TEEL-1	02/2012
Potassium	7440-09-7	No Benchmarks		
Selenium	7782-49-2	0.6	TEEL-1	02/2012
Silicon	7631-86-9	45	TEEL-1	02/2012
Silver	7440-22-4	0.3	TEEL-1	02/2012
Sodium	7440-23-5	2	TEEL-1	02/2012
Strontium	7440-24-6	125	TEEL-1	02/2012
Sulfate	14808-79-8	0.12	CalEPA REL	01/2014
Sulfide	18496-25-8	No Benchmarks		
Sulfur	7704-34-9	No Benchmarks		
Thallium	7440-28-0	0.06	TEEL-1	02/2012
Uranium	7440-61-1	0.6	TEEL-1	02/2012
Vanadium	7440-62-2	1.5	TEEL-1	02/2012
Zinc	7440-66-6	3	TEEL-1	02/2012

E.3 Ecological Benchmarks

Ecological benchmarks used in this assessment are medium-specific constituent concentrations that are intended to protect ecological receptors from adverse effects. Depending on the medium (surface water, sediment, or soil), the benchmarks may represent a class-specific value (e.g., an EPA Ecological Soil Screening Level for mammals) or it may represent a higher level of biological organization (e.g., National Water Quality Criteria are developed to protect a generalized aquatic community). In either case, the ecological benchmarks are considered to be environmental quality criteria and do not provide information on the likelihood or severity of the effects on the ecosystem. Ecological receptors may be exposed through the ingestion and/or direct contact with a contaminated medium, or they may be exposed through the food chain (i.e., consuming plants and prey that have, themselves, become contaminated). The ecological benchmarks presented in this section assume that the receptors are exposed to the constituent concentration over a significant portion of their life cycle (i.e., the exposure is assumed to be chronic in nature) or, for aquatic receptors, the exposure can be assumed to be indefinite. This appendix describes the ecological benchmarks used in the revised risk assessment.

E.3.1 Data Sources and Methodology

For this assessment, concentration-based ecological benchmarks for surface water, sediment and soil receptors were used to characterize the potential for adverse ecological effects. For each medium, EPA established a hierarchy for the selection of ecological benchmarks. In instances where multiple benchmarks were available at the same level of the hierarchy, EPA selected the lowest benchmark to ensure that the most sensitive ecological receptors were protected. The following sections summarize the benchmark derivation methods for each medium included in the modeling scenarios.

E.3.2 Surface Water Benchmarks

Surface water benchmarks were selected to protect animals in water bodies that may be exposed through direct contact with surface water or through ingestion of other biota that live in the water body. EPA chose aquatic criteria appropriate for species living in the freshwater bodies because brackish and coastal waters were not modeled in this risk assessment. The hierarchy for these benchmarks was originally defined during the development of the Multimedia, Multipathway, and Multireceptor Risk Assessment Modeling System (3MRA; U.S. EPA, 2003c). The hierarchy is as follows, with the selected values presented in **Table E-4**:

- Criterion Continuous Concentration (CCC) developed by the EPA Office of Water as part of the National Ambient Water Quality Program.
- Final Chronic Value (FCV) developed using the methods Stephan et al. (1985), and implemented under the Great Lakes Water Quality Initiative (U.S. EPA, 1993; 1995a,b),
- Secondary Chronic Value (SCV) as presented in Suter and Tsao (1996).

Table E-4. Ecological Benchmarks for Surface Water (Freshwater Community)

Constituent	CASRN	Aquatic Criterion (mg/L)	Type	Sources[+]
Aluminum	7429-90-5	0.087	CCC	U.S. EPA (1988)
Ammonia	7664-41-7	—	—	—
Antimony	7440-36-0	0.03	FCV	U.S. EPA (1988)
Arsenic (total)	7440-38-2	0.15	CCC	U.S. EPA (1995)
Arsenic III	22569-72-8	0.15	FCV	U.S. EPA (1995)
Arsenic V	15584-04-0	0.0081	SCV	Suter and Tsao (1996)
Barium	7440-39-3	0.004	SCV	Suter and Tsao (1996)
Beryllium	7440-41-7	0.00066	SCV	Suter and Tsao (1996)
Boron	7440-42-8	1.1	SCV	Suter and Tsao (1996)*
Cadmium	7440-43-9	0.00025	CCC	U.S. EPA (2001)
Calcium	7440-70-2	—	—	—
Carbon	7440-44-0	—	—	—
Chloride	16887-00-6	230	CCC	U.S. EPA (1986)
Chromium III	16065-83-1	0.074	CCC	U.S. EPA (1995)
Chromium VI	18540-29-9	0.011	CCC	U.S. EPA (1995)
Cobalt	7440-48-4	0.02	SCV	Suter and Tsao (1996)
Copper	7440-50-8	0.0093	FCV	U.S. EPA (1995)
Fluoride	16984-48-8	—	—	—
Iron	7439-89-6	1	CCC	U.S. EPA (1986)
Lanthanum	7439-91-0	—		
Lead	7439-92-1	0.0025	CCC	U.S. EPA (1980)
Magnesium	7439-95-4	—	—	—
Manganese	7439-96-5	—	—	—
Mercury	7487-94-7	0.00077	CCC	U.S. EPA (1995)
Molybdenum	7439-98-7	0.37	SCV	Suter and Tsao (1996)
Nickel	7440-02-0	0.052	CCC	U.S. EPA (1995)
Nitrate/Nitrite	14797-55-8	—	—	—
Phosphate	98059-61-1	—	—	—
Potassium	7440-09-7	—	—	—

(continued)

Table E-4. Ecological Benchmarks for Surface Water (Freshwater Community)

Constituent	CASRN	Aquatic Criterion (mg/L)	Type	Sources+
Selenium (total)	7782-49-2	0.005	CCC	U.S. EPA (1999)
Selenium IV	7446-08-4	0.03	FCV	U.S. EPA (1995)
Selenium VI	7782-49-2	0.0095	FCV	U.S. EPA (1995)
Silicon	7631-86-9	—	—	—
Silver	7440-22-4	0.00036	SCV	Suter and Tsao (1996)
Sodium	7440-23-5	—	—	—
Strontium	7440-24-6	—	—	—
Sulfate	14808-79-8	—	—	—
Sulfide	18496-25-8	0.002	CCC	U.S. EPA (1986)
Sulfur	7704-34-9	—	—	—
Thallium	7440-28-0	0.01	SCV	Suter and Tsao (1996)
Uranium	7440-61-1	—	—	—
Vanadium	7440-62-2	0.02	SCV	Suter and Tsao (1996)
Zinc	7440-66-6	0.12	CCC	U.S. EPA (1995)

+ Data sources for CCC are discussed online at: water.epa.gov/scitech/swguidance/standards/criteria/current/index.cfm#A.

* Public commenters (EPA-HQ-RCRA-2009-0640-06526) noted that the units in the fish study from which the SCV was derived (Hamilton, 1995) had been erroneously transcribed in Suter and Tsao as µg/L instead of mg/L. The SCV was recalculated using the corrected units, resulting in a boron SCV of 1.1 mg/L. The revised value has been corroborated by EPA.

E.3.3 Sediment Benchmarks

Sediment benchmarks were selected to protect animals in sediment that may be exposed through direct contact with sediment or through ingestion of other biota that live in the sediment. The hierarchy for these benchmarks was originally defined during the development of 3MRA (U.S. EPA, 2003c). Since the completion of the 3MRA database, NOAA has updated their methodology, making this information available for national analyses. The hierarchy is as follows, with the selected values presented in **Table E-5**:

- Threshold Effect Level (TEL) from Buchman (2008), geometric mean of the 15th percentile in the effects data set and the 50th percentile in the no effects data set.
- Effects Range Low (ERL), the lower 10th percentile concentration estimated to correspond with adverse effects as identified in alternate literature sources including, for example, Long et al. (1995); Long and Morgan (1991); Jones, Suter and Hull (1997); MacDonald (1994); and U.S. EPA (1995c, 1997b).

Table E-5. Ecological Benchmarks for Sediment (Sediment Community)

Constituent	CASRN	Sediment Criterion (mg/kg DWsed)	Sediment Receptor	Type	Sources
Aluminum	7429-90-5	—	—	—	—
Ammonia	7664-41-7	—	—	—	—
Antimony	7440-36-0	2	Sediment Biota	ERL	Long et al. (1991)
Arsenic (total)	7440-38-2	5.9	Sediment Biota	TEL	Buchman (2008)
Barium	7440-39-3	190	Spotted Sandpiper	ERL	Long et al. (1995)
Beryllium	7440-41-7	—	—	—	—
Boron	7440-42-8	—	—	—	—
Cadmium	7440-43-9	0.596	Sediment Biota	TEL	Buchman (2008)
Calcium	7440-70-2	—	—	—	—
Carbon	7440-44-0	—	—	—	—
Chloride	16887-00-6	—	—	—	—
Chromium (total)	7440-47-3	37.3	Sediment Biota	TEL	Buchman (2008)
Cobalt	7440-48-4	—	—	—	—
Copper	7440-50-8	35.7	Sediment Biota	TEL	Buchman (2008)
Fluoride	16984-48-8	—	—	—	—
Iron	7439-89-6	—	—	—	—
Lanthanum	7439-91-0	—	—	—	—
Lead	7439-92-1	35	Sediment Biota	TEL	Buchman (2008)
Magnesium	7439-95-4	—	—	—	—
Manganese	7439-96-5	—	—	—	—
Mercury	7487-94-7	0.174	Sediment Biota	TEL	Buchman (2008)
Molybdenum	7439-98-7	34	Spotted Sandpiper	ERL	Long et al. (1995)
Nickel	7440-02-0	18	Sediment Biota	TEL	Buchman (2008)
Nitrate/Nitrite	14797-55-8	—	—	—	—
Phosphate	98059-61-1	—	—	—	—
Potassium	7440-09-7	—	—	—	—
Selenium	7782-49-2	—	—	—	—
Silicon	7631-86-9	—	—	—	—

(continued)

Table E-5. Ecological Benchmarks for Sediment (Sediment Community)

Constituent	CASRN	Sediment Criterion (mg/kg DWsed)	Sediment Receptor	Type	Sources
Silver	7440-22-4	0.73	Sediment Biota	TEL	MacDonald et al. (1994)
Sodium	7440-23-5	—	—	—	—
Strontium	7440-24-6	—	—	—	—
Sulfate	14808-79-8	—	—	—	—
Sulfide	18496-25-8	—	—	—	—
Sulfur	7704-34-9	—	—	—	—
Thallium	7440-28-0	—	—	—	—
Vanadium	7440-62-2	18	Spotted Sandpiper	ERL	Long et al. (1995)
Zinc	7440-66-6	123	Sediment Biota	TEL	Buchman (2008)

E.3.4 Soil Benchmarks

The soil benchmarks are developed to be protective of plants, animals and soil invertebrates that may be chronically exposed to constituents in soil through direct contact, as well as the ingestion of biota that live in or on the soil. The hierarchy is as follows, with the selected values presented in **Table E-6**:

- Ecological Soil Screening Levels (Eco-SSLs) (U.S. EPA, 2005a–h; 2006c; 2007a–e; 2008b) derived through a collaborative effort of a multi-stakeholder workgroup consisting of federal, state, consulting, industry and academic participants led by the EPA Office of Emergency and Remedial Response, as documented in *Guidance for Developing Soil Screening Levels* (U.S. EPA, 2005).
- Oak Ridge National Lab (ORNL) screening benchmarks developed for the U.S. Department of energy (Efroymson et al., 1997; Efroymson, Will, and Suter, 1997; Sample, Opresko, and Suter 1996),

Table E-6. Ecological Benchmarks for Soil (Terrestrial Receptors)

Constituent	CASRN	Soil Criterion (mg/kg DW soil)	Terrestrial Receptor	Sources
Aluminum	7429-90-5	—	—	—
Ammonia	7664-41-7	—	—	—
Antimony	7440-36-0	0.27	Mammals	U.S. EPA (2005a)
Arsenic (total)	7440-38-2	18	Plants	U.S. EPA (2005b)

(continued)

Table E-6. Ecological Benchmarks for Soil (Terrestrial Receptors)

Constituent	CASRN	Soil Criterion (mg/kg DW soil)	Terrestrial Receptor	Sources
Barium	7440-39-3	330	Soil Invertebrates	U.S. EPA (2005c)
Beryllium	7440-41-7	21	Mammalian	U.S. EPA (2005d)
Boron	7440-42-8	0.5	Plants	Efroymson et al. (1997)
Cadmium	7440-43-9	0.36	Mammalian	U.S. EPA (2005e)
Calcium	7440-70-2	—	—	—
Carbon	7440-44-0	—	—	—
Chloride	16887-00-6	—	—	—
Chromium III	16065-83-1	26	Avian	U.S. EPA (revised 2008b)
Cobalt	7440-48-4	13	Plants	U.S. EPA (2005f)
Copper	7440-50-8	28	Avian	U.S. EPA (revised 2007a)
Fluoride	16984-48-8	—	—	—
Iron	7439-89-6	—	—	—
Lanthanum	7439-91-0	—	—	—
Lead	7439-92-1	11	Avian	U.S. EPA (2005g)
Magnesium	7439-95-4	—	—	—
Manganese	7439-96-5	220	Plants	U.S. EPA (2007b)
Mercury	7487-94-7	0.1	Soil Invertebrates	Efroymson, Will, and Suter (1997)
Molybdenum	7439-98-7	42.08	American Woodcock	Sample, Opresko, and Suter (1996)
Nickel	7440-02-0	38	Plants	U.S. EPA (2007c)
Nitrate	14797-55-8	—	—	—
Nitrite	98059-61-1	—	—	—
Phosphate	7440-09-7	—	—	—
Potassium	7782-49-2	—	—	—
Selenium (total)	7446-08-4	0.52	Plants	U.S. EPA (2007d)
Silicon	7440-22-4	—	—	—
Silver	7440-23-5	4.2	Avian	U.S. EPA (2006c)
Sodium	7440-24-6	—	—	—

(continued)

Table E-6. Ecological Benchmarks for Soil (Terrestrial Receptors)

Constituent	CASRN	Soil Criterion (mg/kg DW soil)	Terrestrial Receptor	Sources
Strontium	14808-79-8	—	—	—
Sulfate	18496-25-8	—	—	—
Sulfide	7704-34-9	—	—	—
Sulfur	7440-28-0	—	—	—
Thallium	7440-61-1	—	—	—
Vanadium	7440-62-2	7.8	Avian	U.S. EPA (2005h)
Zinc	7440-66-6	46	Avian	U.S. EPA (2007e)

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Appendix F.

Air Modeling for Screening Analysis

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F.1 Introduction

Modeling was performed to estimate ambient air concentrations (for inhalation pathways) and deposition rates (for food chain pathways) for particulates released from landfills and landfill operations. Particulate emissions were estimated, and then air dispersion modeling was used to estimate air concentrations and deposition rates at off-site receptor locations.

F.2 Particulate Emissions

Particulate emission estimates were developed and evaluated for windblown emissions, as well as for vehicular activity, unloading operations and compacting operations, using established methods published by the U.S. Environmental Protection Agency (EPA or the Agency), specifically *AP-42: Compilation of Air Pollutant Emission Factors* and windblown emission equations (U.S. EPA, 1985a). The applied approach is consistent with the landfill model methodology reviewed by EPA's Science Advisory Board in 2003 (U.S. EPA, 2003). Modifications to this methodology were made to reflect coal combustion residual (CCR)–specific releases focusing on particulate matter (PM) 10 micrometers or less in diameter or smaller (PM_{10}) and fine particles or particles 2.5 micrometers or less in diameter or smaller ($PM_{2.5}$). The emissions modeling approach is described in more detail in **Attachment F-1**. The following inputs were used for the emissions modeling:

- **Meteorological Parameters:** Meteorological parameters associated with each of the 57 meteorological stations in the EPA's Industrial Waste AIR model (IWAIR; U.S EPA, 2002) were used. The IWAIR meteorological stations are described in **Section F.3**. Particulate emissions were calculated for each station to capture national variability in meteorological conditions.
- **Landfill Operations:** CCR-specific data were used to characterize landfill dimensions. **Table F-1** shows five landfill surface areas ranging from 35 to 126 acres that were modeled. These represent the 50th to the 90th percentile of the distribution of landfill areas. For other data elements, default parameter values were applied as shown in **Attachment F-1**.

Table F-1. Distribution of Landfill Sizes (acres)

Percentile	50th	60th	70th	80th	90th
Surface Area	35.3	48.3	59	85	126

- **Particle Size Distribution:** Data on particle size range mass fractions for coal ash are limited for different CCR types. EPA made the assumption that all particulate releases would have the characteristics of fly ash. Based on a literature review and data presented in Moreno et al. (2005), a profile consisting of 15 percent fine particles or $PM_{2.5}$ (< 2.5 microns) was applied.

- **Dust Controls:** EPA considered various control options such as covering or otherwise managing CCR waste to control wind dispersal of dust. Control efficiencies applied under the "controlled scenario" were based on the above particle size profile and the collection efficiencies from AP-42 (Appendix B.2; U.S. EPA, 2006) for dust suppression by wet spray or by chemical stabilization or wetting agents and are shown in **Table F-2**. Based on these data, a uniform control efficiency of 40 percent was assumed for the $PM_{2.5}$ releases. In the absence of an overall reported control efficiency for $PM_{10,}$ a CCR-specific value was calculated. The $PM_{2.5}$ control efficiency shown in the table was weighted as 15% and the efficiencies for the two size bins greater than 2.5 were averaged and weighted as 85%, reflecting the percentage of coarse particles. This results in in a control efficiency of approximately 70 percent for particulates less than 10 micrometers in diameter.

Table F-2. EPA's AP-42 Collection Efficiencies*

Type of Control	Particle Size		
	0–2.5 µm	2.5–6 µm	6–10 µm
Dust suppression by wet spray	40%	65%	90%
Dust suppression by chemical stabilizer or wetting agents	40%	65%	90%

* These efficiencies reflect ideal operating conditions with appropriate application rates and frequencies.

- **Percent Silt:** EPA assumed that fugitive dust emissions were 80 percent silt, consistent with the previous fugitive dust CCR analysis and based on the value for fly ash presented in AP-42 Chapter 13, Table 13.24-1. Although this value is potentially conservative, EPA deemed it appropriate for screening purposes in the absence of sufficient data to support a lower percent silt value.
- Other source parameters were characterized as shown in **Attachment F-1**, **Table F-1-2**.

F.3 Air Dispersion Modeling

EPA conducted dispersion modeling to estimate ambient air concentrations. Modeling was performed with the American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) and its screening model AERSCREEN (U.S. EPA, 2011). Modeling was performed using a phased approach starting with AERSCREEN to estimate conservative maximum air concentrations for each landfill size/location combination discussed above. AERSCREEN also calculates maximum air concentrations for other averaging times (e.g., 3-hour, annual) by scaling the estimated 1-hour maximum air concentrations. In the case of an area source, such as a landfill, a scaling factor of 1 is applied producing very conservative short-term and long-term concentrations that are identical to the 1-hour maximum values. Thus, the 1-hour AERSCREEN results were used as an initial screen of the inhalation pathway.

Subsequent modelling was performed with AERMOD to produce results for the refined inhalation screen and to develop deposition rates to evaluate ingestion exposures (AERSCREEN does not

produce deposition estimates). Modeling was performed using 5 years of meteorological from the weather station associated with the 90th percentile landfill PM_{10} emissions. Weather stations whose natural characteristics lead to high fugitive dust concentrations in AERSCREEN (e.g., dry, high wind speeds) are likely to also lead to high short term and long term concentrations in AERMOD especially in close proximity to the area source as was considered in this analysis. These more refined air modeling results were considered if an AERSCREEN modeled COPC concentration was above the inhalation health benchmark.

Both AERSCREEN and AERMOD modeling was conducting based on a unitized emission rate (e.g., 1 g/m^2-s). The resulting air concentrations and deposition rates are called unitized air concentrations (e.g., $\mu g\ m^{-3}$ per unit emission rate of 1 g/m^2-s) and unitized deposition rates (e.g., g/m^2-yr per unitized emission rate of 1 g/m^2-s), and these are multiplied by the constituent-specific emission rates and appropriate conversion factors to calculate chemical-specific particle-phase air concentrations and deposition rates.

Chronic exposures to specific constituents were evaluated using outputs averaged over 1 year. Acute exposures to specific constituents were evaluated using outputs averaged over 1 hour. Exposures to $PM_{2.5}$ and PM_{10} were evaluated by comparing EPA's National Ambient Air Quality Standards (NAAQS) to ambient air concentration estimates reflecting appropriate averaging times (i.e., 24-hour and annual for $PM_{2.5}$ and 24-hour for PM_{10}). Because the NAAQS for lead reflects a rolling 3-month average, which is not an available output from AERSCREEN or AERMOD, EPA evaluated those exposures using monthly concentrations.

For this screening, total particulate concentrations output by the model were adjusted with constituent-specific 90th percentile whole waste concentrations to predict corresponding constituent-specific ambient air concentrations. The total particulate concentrations were also apportioned to $PM_{2.5}$ using the particle size distribution discussed in **Section F.1**. **Attachment F-2** summarizes the inputs needed for AERSCREEN; two critical inputs are receptor distance and meteorological data. These are discussed below:

- **Receptor Distances:** Air concentrations were evaluated at a range of distances included in previous EPA analyses and models, such as the Multimedia, Multiple Exposure Pathway, Multiple Receptor Risk Assessment (3MRA) modeling system (U.S. EPA, 2003) and the solvent wipes risk assessment (U.S. EPA, 2009). The specific distances (25 m, 50 m, 75 m, 150 m, 300 m, 500 m, 1,000 m, and 2,000 m) were selected to ensure complete coverage in the air estimates, particularly near the source of the emissions.
- **Meteorological Data:** To capture national variability in the estimates, the air dispersion modeling used representative meteorological and land use data associated with the 57 IWAIR meteorological regions where coal combustion facilities are located. The IWAIR model and meteorological regions have been subjected to extensive peer review. **Figure F-1** shows the coal combustion facilities cross-referenced to the IWAIR meteorological regions (U.S. EPA, 2002). As part of the initial screening, EPA performed AERSCREEN modeling using meteorological and land use data for all of the IWAIR meteorological regions where coal

combustion facilities are located. Because it was not feasible to run AERMOD (to obtain results for longer averaging times) for all of the 57 meteorological stations, EPA selected the location with the 90th percentile particulate air concentration (which accounts for meteorological and land use effects on both emissions and dispersion) and performed AERMOD modeling for that location. AERMOD outputs were generated for the range of receptor distances (i.e., 25 m, 50 m, 75 m, 150 m, 300 m, 500 m, 1,000 m, and 2,000 m) and included unitized 1-, 3-, 8, and 24-hour, monthly, and annual average air concentrations for $PM_{2.5}$ and PM_{10} and yearly average wet and dry deposition rates from particle phase. EPA then used those meteorological conditions to calculate emissions and used the associated dispersion factors and deposition rates as representative of the 90th percentile meteorological conditions for the chronic screening.

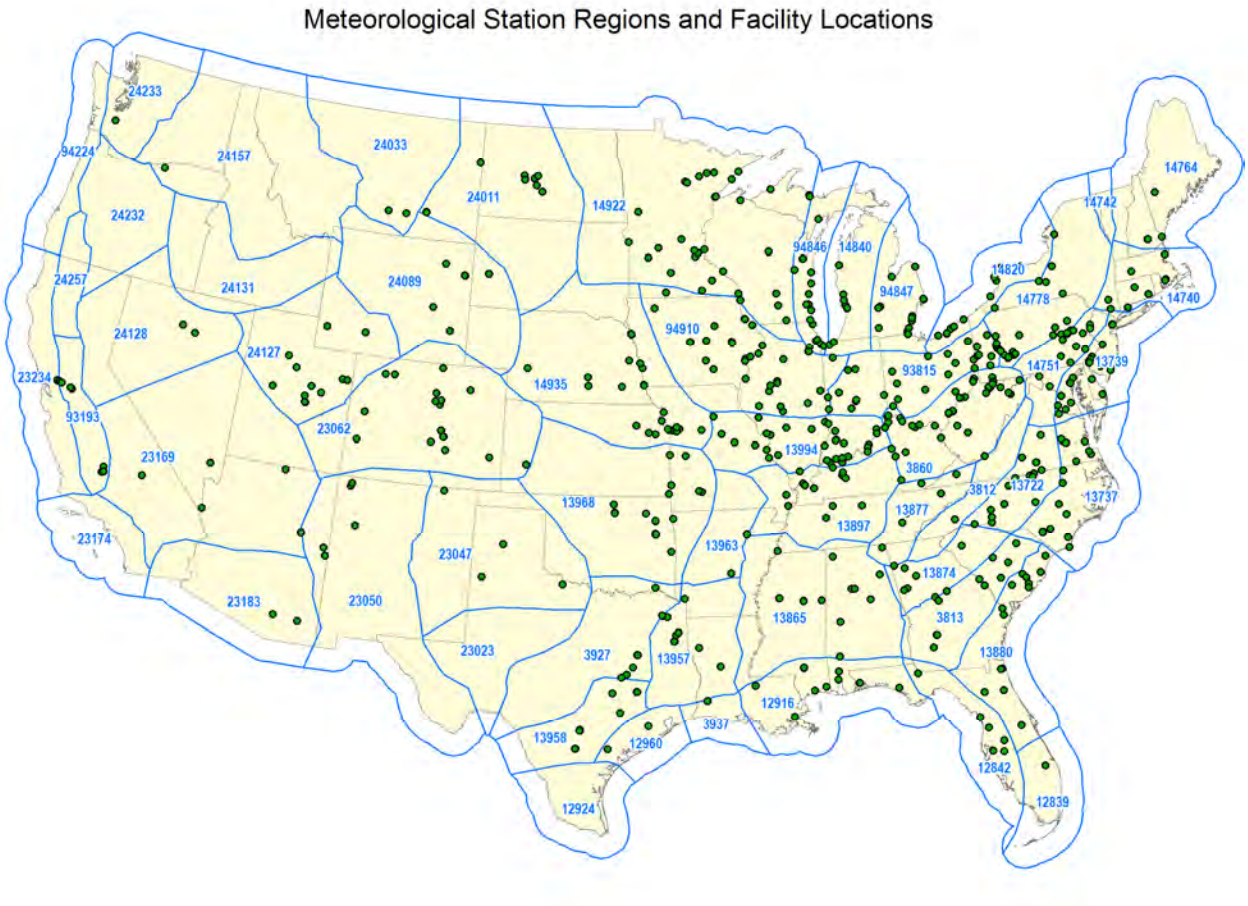

Figure F-1. IWAIR meteorological regions and coal combustion sites.

F.4 References

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Attachment F-1.
Particulate Emissions Equations

F-1.1 Introduction

The following release mechanisms are considered: wind erosion, vehicular activity, unloading operations and spreading/ compacting operations. The sources for each of these mechanisms are summarized in **Table F-1-1**.

Table F-1-1. Mechanisms of Release of Particulate Emissions for Active Landfills

Mechanism of Release	Ei Subscript	Algorithm Reference
Wind Erosion from Open Area	wd	U.S. EPA, 1985a
Vehicular Activity	ve	AP-42 (U.S. EPA, 2006, Chapter 13.2.2: Unpaved Roads)
Unloading	un	AP-42 (U.S. EPA, 2006, Chapter 13.2.4: Aggregate Handling and Storage Piles)
Spreading/Compacting	sc	AP-42 (U.S. EPA, 1985b)*

* This equation was removed from the most recent (5th) edition of AP-42 but is still widely used, including, for example, in the 3MRA landfill model (U.S. EPA, 1999) and in Western Regional Air Partnership (see MRI, 2006). It can be found in the cited 4th edition.

This attachment describes the algorithms and assumptions used to estimate emissions for each landfill:

- Ei (g of PM/m^2-d), the annual average PM emission rate due to each release mechanism i (wind erosion, vehicular activity, unloading, and spreading and compacting)
- $\sum$Ei (g/m^2-d), the total annual average PM emission rate due to all release mechanisms, and
- CE (g/m^2-d), the annual average emission rate of contaminant as PM.

The equations all estimate emissions of PM_{10}, which are adjusted to $PM_{2.5}$ using the particle size distribution described in **Section F-1.3**. **Table F-1-2** presents the landfill-specific values used as inputs to these algorithms.

Table F-1-2. Emissions Equation Inputs

Variable	Units	Variable Name	Value	Comments
Waste-Specific Parameters				
Fly ash bulk density	g/cm^3	BD	1.19	U.S. EPA (1998)
Fraction $PM_{2.5}$	unitless	$PM_{2.5}$frac	0.15	See Section F-1.3
Fraction PM_{10}	unitless	PM_{10}frac	1	Reflects respirable releases*
Wind Erosion				
Mode of aggregate size distribution	mm	asdm	0.5	Based on the Soil Screening Guidance (U.S. EPA, 1996)
Silhouette area ratio	unitless	Lc	0.0003	Mean value (U.S. EPA, 1999b)
Fraction vegetative cover	frac	Veg	0	Assumed worst case
Surface roughness height	cm	z_0	1	Value of zruf for active landfill (U.S. EPA, 1999b)
Silt content (wind erosion)	%	S	80	AP-42, Chap. 13, Table 13.2.4-1 (fly ash) (U.S.EPA, 2006)
Frequency of disturbances (active)	1/mo	fd'	30	Consistent with worst case U.S. EPA, 1985a
Surface area	m^2	A	510,000	126 acres based on 90th percentile size; see Table F-2
Vehicular Emissions				
Silt content of roads	%	S_{roads}	24	Based on value from AP-42 for western surface coal mining–haul road (freshly graded) (U.S. EPA, 2006, Table 13.2.2-1). Maximum value in range of source conditions tested to develop Eqn 1a (U.S. EPA, 2006, p. 13.2.2.2-1) was 25.2%.
Mean vehicle weight	Short tons	V_w	40	Assumes trucks weigh 30 tons empty. Mean weight during travel equals half payload (i.e., approximately 10 tonsbased on truck volume and waste bulk density). Applied value is a combined weight of 40 tons.
Mean no. vehicles per day	1/day	N_v	88	Estimated based on 90th percentile loading rate, truck volume of 21 cubic yards, and waste bulk density
Meters traveled per vehicle	m	M_t	714	Length of landfill (truck travels to center of unit and back)
Dust suppression control efficiency (roads)	unitless	$EFF_{DustRoads}$	0	Assumed worst case of no controls

(continued)

Table F-1-2. Emissions Equation Inputs

Variable	Units	Variable Name	Value	Comments
Unloading Operations				
Waste moisture content	%	mcW	27	AP-42, Chap. 13, Table 13.2.4-1 (fly ash) (U.S. EPA, 2006)
Annual average waste loading rate	Mg/y	L	612,000	90th percentile value from DOE EIA-923 form data on landfill disposal in 2009 (161 plants; 675,000 sh. ton/yr; converted to Mg/yr using 0.907 Mg/sh. ton)
Surface area	m^2	A	510,000	90th percentile unit size (126 acres)
Spreading/Compacting/Tilling				
Silt content (spreading)	%	$S_{spreading}$	80	AP-42, Chap. 13, Table 13.2.4-1 (fly ash) (U.S. EPA, 2006)
No. of tilling/ spreading operations/day	1/day	NopC	3	Assumes spreading occurs once per 8-hour shift
Surface area/day	m^2	A	1,400	Estimated from daily loading rate & waste bulk density.

* EPA's Office of Air and Radiation considers PM_{10} and smaller to be respirable; available online at: www.epa.gov/airquality/particulatematter

F-1.2 Particulate Emission Rate (E_i) Algorithms

F-1.2.1 Wind Erosion from Open Fields (E10wd)

The algorithm for the estimation of PM_{10} emissions due to wind erosion from an open field is based on the procedure developed by U.S. EPA. (1985a). The input parameters are summarized in **Table F-1-3**.

Table F-1-3. Input Parameter Units and Definitions for $E10_{wd}$

Symbol	Units	Definition
asdm	mm	Mode of the aggregate particle size distribution
Lc	—	Ratio of the silhouette area of roughness elements too large to be included in sieving to total base area
veg´	—	Fraction of surface covered with vegetation (see Table F-2-2)
z´0	cm	Surface roughness height (see Table F-2-2)
S	w/w, %	Silt content of surface material
U+	m/s	Observed or probable fastest mile of wind between disturbances
PE	—	Thornthwaite Precipitation Evaporation Index
u	m/s	Mean annual wind speed
p	d/yr	Mean number of days per year with ≥0.01 in precipitation
fd´	1/mo	Frequency of disturbance per month where a disturbance is defined as an action that exposes fresh surface material

*Step 1: Calculate U*t*

Calculate the threshold friction velocity, U_{*t} (m/s), the threshold wind speed for the onset of wind erosion:

(F-2-1a) $$U_{*t} = 0.65(cf)(asdm)^{0.425}$$

Where:

(F-2-1b) $$cf = \begin{cases} 1.0 & \textbf{for } Lc < 2 \times 10^{-4} \\ 1.05 + 50.18(Lc) - 647.89(Lc)^2 + 6{,}863.5(Lc)^3 & \textbf{for } 2 \times 10^{-4} \le Lc \le 1 \times 10^{-1} \end{cases}$$

Table F-1-2 provides definitions of asdm and Lc. Lc is measured by inspection of a representative 1-m^2 transect of the site surface. Lc can range from zero to 0.1. High Lc ($\geq 2 \times 10^{-4}$) increases the threshold friction velocity, which results in a relatively low or zero particulate emission rate due to wind erosion. Low Lc ($<2 \times 10^{-4}$) is indicative of a bare surface with homogeneous finely divided material (e.g., an agricultural field). Such surfaces have a relatively low threshold friction velocity and increased particulate emissions. Equations (F-2-1a) and (F-2-1b) were derived from U.S. EPA. (1985a, Figures 3-4 and 3-5).

Step 2: Calculate U_t

U_t (m/s) is the threshold wind velocity at a height of 7.0 m (7.0 m is the typical weather station anemometer height). It is calculated using U.S. EPA. (1985a; Equation, 4-3, with z = 700 cm):

(F-2-2) $$U_t = \frac{U_{*t}}{0.4} \ln\left(\frac{700}{z'_0}\right) \qquad \textbf{for } z'_0 < 700$$

Where z'_0 is the roughness height in cm. Values for z'_0 for various surface conditions are provided in U.S. EPA. (1985a, Figure 3-6).

Step 3: Calculate $E10_{wd}$

$E10_{wd}$ is the annual average emission rate of particulate matter less than 10 μm in diameter per unit area of the contaminated surface.

For Sites with Limited Erosion Potential ($U_{*t} > 0.75$ m/s), the following equation was derived by using U.S. EPA. (1985a, Equations 4-1 to 4-3), converting units to g/m^2-d:

(F-2-3) $$E10_{wd} = \begin{cases} \dfrac{5.56(U^+ - U_t)(1 - veg')(24 \cdot fd')}{10^3 \cdot \left(\frac{PE}{50}\right)^2} & \textbf{for } U^+ \ge U_t \\ 0 & \textbf{for } U^+ < U_t \end{cases}$$

Data for peak gust wind velocities, which can be converted to U^+, and PE for locations throughout the United States can be found in the *Climatic Wind Data for the United States* (U.S. Department

of Commerce, 1998) and U.S. EPA (1985a, Figure 4-2), respectively. U.S. EPA (1985a) advises that, in the worst case, f_d should be assumed to be 30 per month. When $U_{*t} \leq 0.75$ m/s, the site is considered to have unlimited erosion potential and $E10_{wd}$ is calculated using U.S. EPA (1985a, Equation 4-4):

(F-2-4a) $$E10_{wd} = 0.036(1 - veg')\left(\frac{u}{U_t}\right)^3 g(x) \cdot 24\frac{h}{d}$$

Where:

(F-2-4b) $$x = 0.886\left(\frac{U_t}{u}\right)$$

(F-2-4c) $$g(x) = \begin{cases} 1.91 & \textbf{for } 0 \leq x < 0.5 \\ 2.2 - 0.6x & \textbf{for } 0.5 \leq x \leq 1.0 \\ 2.9 - 1.3x & \textbf{for } 1.0 < x \leq 2.0 \\ 0.18(8x^3 + 12x)e^{(-x^2)} & \textbf{for } x > 2.0 \end{cases}$$

Where g(x) was derived from U.S. EPA (1985a, Figure 4-3). Data for u for locations throughout the United States can be found in the *Climatic Wind Data for the United States* (U.S. Department of Commerce, 1998).

F-1.2.2 Vehicular Activity (E_{ve})

To estimate E_{ve} (g/m^2/d), the quantity of particulate emissions from vehicular travel on the surface of the landfill, the following equation for vehicles traveling on unpaved surfaces at industrial sites from AP-42 (updated November 2006) was used, adapted to convert from lb/VMT (vehicle mile traveled) to g/m^2/d:

(F-2-5) $$E_{ve} = 281.9k\left(\frac{S}{12}\right)^a \left(\frac{W}{3}\right)^b nv \left(\frac{mt}{A}\right)\left(\frac{km}{10^3 m}\right)$$

Where k, a and b are empirical constants that depend on particle size desired (see **Table F-1-4**) and the other parameter definitions are provided in **Table F-1-5**.

Table F-1-4. Coefficient Values for E_{ve} Equation

Symbol	Units	PM_{10}
k	lb/VMT	1.5
a	unitless	0.9
b	unitless	0.45

Table F-1-5. Parameter Units and Definitions for E_{ve}

Symbol	Units	Definition
S	w/w, %	Surface silt material content
W	tons	Mean vehicle weight
nv	1/d	Mean annual number of vehicles per day
A	m^2	Contaminated surface area
mt	m	Meters traveled per vehicle (nv) on contaminated surface

F-1.2.3 Unloading Operations (E_{un})

The equation for estimating E_{un} ($g/m^2/d$), the PM emission rate due to unloading operations at landfills, was adapted from U.S. EPA. (2006, Equation 1, p. 13.2.4-4). The EPA equation was adapted by multiplying it by the average annual loading rate (L, Mg/yr) and normalizing the emissions for the contaminated surface area:

(F-2-6) $$E_{un} = 0.0016k\frac{\left(\frac{u}{2.2}\right)^{1.3}}{\left(\frac{mcW}{2}\right)^{1.4}}\left(\frac{L}{A}\right)\left(\frac{10^3 g}{kg}\right)\left(\frac{yr}{365d}\right)$$

Where k is an empirical constant that depends on particle size desired (see **Table F-1-6**), and the other parameter definitions are provided in **Table F-1-7**.

Table F-1-6. Coefficient Values for E_{un} Equation

Symbol	Units	PM_{10}
k	Unitless	0.35

Table F-1-7. Parameter Units and Definitions for $E10_{un}$

Symbol	Units	Definition
U	m/s	Mean annual wind speed
mcW	Volume %	Waste moisture content
L	Mg/yr	Annual average waste loading rate
A	m2	Contaminated surface area

F-1.2.4 Spreading/Compacting or Tilling Operations (E_{sc})

As in the 3MRA landfill model (U.S. EPA, 1999), the equation for estimating E_{sc} ($g/m^2/d$), the rate of PM emissions due to spreading and compacting or tilling operations, was adapted from an equation in U.S. EPA (1985b, Equation 1, p. 11.2.2-1) that was developed for estimating emissions due to agricultural tilling in units of kilogram of particulate emissions per hectare per tilling (or spreading/compacting) event.

(F-2-7) $$E_{sc} = 5.38k(S^{0.6})(N_{op})\left(\frac{ha}{10^4 m^2}\right)$$

Where k is an empirical constant that depends on particle size desired (see **Table F-1-8**), and the other parameter definitions are provided in **Table F-1-9**.

Table F-1-8. Coefficient Values for E_{sc} Equation

Symbol	Units	PM_{10}
k	Unitless	0.21

Table F-1-9. Parameter Units and Definitions for E_{sc}

Symbol	Units	Definition
S	w/w, %	Silt content of surface material
Nop	1/d	Number of spreading and compacting operations per day

F-1.3 Particle Size Distribution for $PM_{2.5}$

To calculate $PM_{2.5}$ emissions of fly ash for the $PM_{2.5}$ NAAQS, EPA conducted a literature search for particle size distributions for fly ash. EPA did not find any data for U.S. coal-fired power plant sites. However, Moreno et al. (2005) provide distributions for 23 pulverized coal-fired power plant sites in Europe. These sites were selected to cover most of the fly ash types produced in the European Union. The range of coal types in this study is similar to the range used in the United States, and electrostatic precipitators are used in over 90 percent of facilities in the United States (Bein et al., 2007). Therefore, EPA used these data to estimate a particle size distribution.

Moreno et al. (2005) list the particle sizes for the 10th, 50th and 90th percentiles for selected fly ash samples from each of the listed power plants (see **Table F-1-10**. EPA omitted one plant (the power station As Pontes) because its sample was a mixture of fly ash and molten slag. All other samples were collected at the ESP. EPA plotted the 10th and 50th percentiles on log-probability paper and determined the probabilities for particle sizes 2.5 and 10 µm, and then calculated the ratio of the PM_{10} to $PM_{2.5}$ percentiles for each power plant. The overall mass ratio of PM_{10} to $PM_{2.5}$

has a mean of 6.8 and a median of 6.2. Using the mean, this suggests a particle size distribution in which $PM_{2.5}$ account for about 15 percent of the total PM_{10}.

Table F-1-10. Particle Size Distributions for Selected Power Stations in the European Union

Power Station	Location	Size Percentile			Percentile		Ratio
		10th	50th	90th	PM_{10}	$PM_{2.5}$	$PM_{10}/PM_{2.5}$
Narcea	N Spain	3.0	11.8	50.3	44	7.3	6.0
Barrios	S Spain	4.6	24.6	84.6	24	3.9	6.2
Escucha	EN Spain	8.3	53.4	183.8	13	1.8	6.9
Meirama	N Spain	8.9	40.5	248.0	12	1.0	12.6
Teruel	EN Spain	4.6	21.8	75.7	26	3.8	6.8
Espiel	S Spain	3.8	21.0	99.5	29	5.7	5.1
Compostilla	N Spain	4.2	17.3	77.4	31	4.0	7.8
La Robla	N Spain	2.3	12.3	76.2	43	11	3.9
Soto Ribera	N Spain	7.5	43.8	221.0	14	1.8	7.8
Puertollano	Central Spain	4.7	26.2	123.8	23	3.8	6.1
Alkaline	Netherlands	4.5	26.1	114.1	24	4.2	5.7
Nijmegen	Netherlands	4.7	21.4	74.2	26	3.5	7.4
Neutral	Netherlands	3.9	18.8	85.8	30	5.0	6.0
CCB	Netherlands	7.6	53.2	173.5	14	2.2	6.1
Acid	Netherlands	2.6	13.7	43.8	40	9.5	4.2
Amer-8	Netherlands	4.6	25.9	151.8	24	4.2	5.7
Amer-9	Netherlands	3.1	18.6	63.9	32	7.5	4.3
Hemweg-8	Netherlands	4.7	21.9	69.9	26	3.8	6.8
Lignite	N Greece	7.3	32.8	156.8	15	1.4	10.7
Fusina	Italy	6.5	29.3	171.2	18	1.8	10.0
Monfalcone	Italy	7.9	42.2	295.3	14	1.6	8.4
Sardegna	Italy	4.5	28.6	114.0	24	4.5	5.2
Minimum							3.9
Mean							6.8
Median							6.2
Maximum							12.6

F-1.4 References

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Attachment F-2.
AERSCREEN Inputs

In general, AERSCREEN provides added capabilities that allow refinement of the screen estimates based on environmental setting and location. **Table F-2-1** shows the inputs needed. Not all input options presented in this table apply to this assessment, given that the sources that were modeled are ground-level area sources (so inputs specific to elevated point sources, such as building parameters and terrain, will not apply). However, these inputs were included in the table to allow for a comprehensive listing of the parameters. The following key components of the AERSCREEN model allow for the refinement of the CCR high-end dispersion estimates, as follows:

- AERSCREEN executes MAKEMET to generate a site-specific matrix of meteorological conditions, interfaces with AERMAP to process terrain, interfaces with BPIPPRM (Building Profile Input Program for PRIME) to process building information and executes AERMOD with special screening options. One of its postprocessing functions is to search for and isolate the receptor distance with the highest impact.
- MAKEMET takes into account many factors when creating the matrix of meteorological conditions. These include wind speeds, cloud covers, ambient temperatures, solar elevation angles and convective velocity scales for user-specific surface characteristics (albedo, Bowen ratio and surface roughness length). MAKEMET calculates mechanical mixing height and convective mixing height for convective conditions and includes AERMET subroutines for boundary layer calculations.
- As part of its screening function, MAKEMET eliminates sets of conditions that are not necessary for identifying worst-case impacts.
- The surface characteristics can be specified using three methods: constants input by the user (i.e., no spatial or temporal variation), seasonally varying for generic land use classifications or output from AERSURFACE.

Table F-2-1. Inputs Needed for AERSCREEN

Parameter	Units*	Values or Options Available
Model basis	—	AERMOD
Averaging time options	—	1-hour, 3-hour, 8-hour, 24-hour, annual
Emission rate	Model specific	g/s
Emission type	—	Vapor and particles
Source types	—	Point, flare, capped stack, horizontal stack, volume, rectangular area, circular area
Source release height above ground	m	Set to zero
Length of larger side of the rectangular area	m	Based on modeled unit size
Length of smaller side of the rectangular area	m	Based on modeled unit size
Radius of circular source	m	Based on modeled unit size
Receptor height above ground (flagpole receptor)	m	Set to zero
Initial vertical dimension of plume	m	Not applicable
Urban/rural option	U or R	Location specific
Urban population (if urban)	Count	Location specific
Wind direction search option (yes/no)	—	Set to yes
Wind direction angle (if wind direction search option set to no)	Degrees	(0° from N; long side is x-axis)
Meteorology option	—	Site-specific matrix of screening meteorological conditions (MAKEMET)
Minimum ambient air temperature	°K	Default available
Maximum ambient air temperature	°K	Default available
Minimum wind speed	m/s	Default available

(continued)

Table F-2-1. Inputs Needed for AERSCREEN

Parameter	Units*	Values or Options Available
Anemometer height	m	Default available
Land use type for surface characteristics	—	0=user-entered, 1=water, 2=deciduous forest, 3=coniferous forest, 4=swamp, 5=cultivated land, 6=grassland, 7=urban, 8=desert shrub land, 9=external file
Seasonally varying surface characteristics (option)	—	Not applied
Detailed temporally and spatially explicit surface characteristics (option)	—	AERSURFACE results
Climatology type	—	1=average, 2=wet, 3=dry
Albedo	—	Location-specific
Bowen ratio	—	Location-specific
Surface roughness	—	Location-specific
Distance to receptor	m	Minimum
Building parameters for wake effects	—	Executes BPIPPRM; not for area or volume sources
Terrain impacts	—	Automates AERMAP; not for rectangular area source
Geographic coordinates	—	Latitude/longitude, or UTM (UTM required for automated mode), NAD 1927 or NAD 1983

* AERSCREEN can accommodate either metric or English units; metric are shown here.

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Appendix G.

Food Chain Equations and Data

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G.1 Introduction

The equations used to calculate concentrations in food chain items and total intake for human receptors are shown in this section.

- **Attachment G-1** provides each of the chemical-specific bioconcentration and biotransfer factors needed.

G.2 Food Chain Equations

G.2.1 Concentrations in Fish

This section contains the equations for contaminant concentrations in fish:

- **Table G-1.** Concentration in Fish at Different Trophic Levels
- **Table G-2.** Average Fish Fillet Concentration Ingested by Humans.

Table G-1. Concentration in Fish at Different Trophic Levels (mg/kg)

C_{fish}	
For Nonvolatile Metals:	**For Mercury:**
$C_{fish} = C_{wTot} \times BCF_i$	$C_{fish} = 0.15 \times C_{dw} \times BCF_i$

Name	Description	Value
BCF_i	Bioconcentration factor for specified trophic level (L/kg)	See **Table G-1-1**
C_{dw}	Dissolved waterbody concentration (mg/L)	Calculated
C_{wTot}	Total waterbody concentration from loading (g/m^3 or mg/L)	Calculated
0.15	Fraction of dissolved mercury assumed to be methyl mercury (unitless)	Source: HHRAP (U.S. EPA, 2005)

Table G-2. Average Fish Fillet Concentration Ingested by Humans (mg/kg)

C_{fish_fillet}

$$C_{fish_fillet} = F_{T3} \times C_{fishT3F} + F_{T4} \times C_{fishT4F}$$

Name	Description	Value
$C_{fishT3F}$	Concentration of contaminant in fish at different trophic levels (mg/kg)	Calculated
$C_{fishT4F}$	Concentration of contaminant in fish at different trophic levels (mg/kg)	Calculated
F_{T3}	Fraction of trophic level 3 intake (unitless)	See **Appendix D**
F_{T4}	Fraction of trophic level 4 intake (unitless)	See **Appendix D**

G.2.2. Concentrations in Produce

This section contains the equations for contaminant concentration in produce, forage, silage, grain, and animal products:

- **Table G-3.** Concentration in Aboveground Produce Due to Soil Uptake
- **Table G-4.** Concentration in Root Vegetables Due to Soil Uptake
- **Table G-5.** Concentration in Aboveground Produce due to Deposition
- **Table G-6.** Concentration in Exposed Fruits and Vegetables Due to Deposition
- **Table G-7.** Concentration in Protected Fruits and Vegetables Due to Deposition
- **Table G-8.** Concentration in Forage and Silage
- **Table G-9.** Concentration in Grain.

Table G-3. Concentration in Aboveground Produce Due to Soil Uptake (mg/kg DW)

Pr_i

$$Pr_i = C_{soil} \times Br_i$$

Name	Description	Value
C_{soil}	Soil concentration (mg/kg)	Calculated
Br_i	Plant-soil bioconcentration factor for aboveground produce type i ([mg/kg DW plant]/[mg/kg soil]) (chemical specific)	See **Table G-1-1**

Table G-4. Concentration in Root Vegetables Due to Soil Uptake (mg/kg WW)

Pr_{bg}

$$Pr_{bg} = C_{soil} \times Br_{root} \times \frac{(100 - MAF_{root})}{100}$$

Name	Description	Value
C_{soil}	Soil concentration (mg/kg)	Calculated
Br_{root}	Plant-soil bioconcentration factor for root vegetables ([mg/kg DW plant]/[mg/kg soil]) = RCF (root concentration factor) divided by K_d of soil (chemical specific)	See **Table G-1-1**
MAF_{root}	Moisture adjustment factor for root vegetables (% water)	See Table G-15

Table G-5. Concentration in Aboveground Produce due to Deposition (mg/kg DW)

Pd_i

$$Pd_i = \frac{Dp \times Rp_i \times (1 - e^{-KpPart \times Tp_i})}{Yp_i \times KpPar}$$

Name	Description	Value
Dp	Deposition term for plants (mg/m^2-yr)	Calculated
Rp_i	Interception fraction for aboveground produce type i (unitless)	See **Table G-15**
KpPar	Plant surface loss coefficient for particulates (1/yr)	Mercury: 40.41* Other constituents: 18.07*
Tp_i	Length of plant exposure to deposition per harvest of edible portion of plant for aboveground produce type i (yr)	See **Table G-15**
Yp_i	Yield or standing crop biomass of the edible portion of the plant (productivity) for aboveground produce type i (kg DW/m^2)	See **Table G-15**

* Source: U.S. EPA (1997b)

Table G-6. Concentration in Exposed Produce Due to Deposition (mg/kg DW)

P_{exp}

$$P_{exp} = (Pd_i + Pr_i) \times \frac{(100 - MAF_i)}{100}$$

Name	Description	Value
Pdi	Concentration in aboveground produce type i due to deposition (mg/kg DW)	Calculated
Pri	Concentration in aboveground produce type i due to soil uptake (mg/kg DW)	Calculated
MAFi	Moisture adjustment factor for aboveground produce type i (unitless)	See **Table G-15**

Table G-7. Concentration in Protected Produce Due to Deposition (mg/kg DW)

P_{pro}

$$P_{pro} = Pr_i \times \frac{(100 - MAF_i)}{100}$$

Name	Description	Value
Pr_i	Concentration in aboveground produce type i due to soil uptake (mg/kg DW)	Calculated
MAF_i	Moisture adjustment factor for aboveground produce type i (unitless)	See **Table G-15**

Table G-8. Concentration in Forage and Silage (mg/kg DW)

P_{forage}, P_{silage}

$$P_{forage} = (Pd_{forage} + Pr_{forage})$$

$$P_{silage} = (Pd_{silage} + Pr_{silage})$$

Name	Description	Value
Pd_i	Concentration in aboveground produce type i due to deposition (mg/kg DW)	Calculated
Pr_i	Concentration in aboveground produce type i due to soil uptake (mg/kg DW)	Calculated

Table G-9. Concentration in Grain (mg/kg DW)

P_{grain}

$$P_{grain} = Pr_i$$

Name	Description	Value
Pr_i	Concentration in aboveground produce type i due to soil uptake (mg/kg DW)	Calculated

G.2.3. Concentrations in Animal Products

This section contains the equations for contaminant concentration animal products:

- **Table G-10.** Concentration in Beef
- **Table G-11.** Concentration in Dairy.

Table G-10. Concentration in Beef (mg/kg)

A_{beef}

$$A_{beef} = Ba_{beef} \times [(F_{grain} \times Q_{gbs} \times P_{grain}) + (F_{forage} \times Q_{fbs} \times P_{forage}) + (F_{silage} \times Q_{sbs} \times P_{silage}) + (Q_{soilbs} \times C_{soil})]$$

Name	Description	Value
Ba_{beef}	Biotransfer factor from soil or feed to beef ([mg/kg-WW]/[mg/day])	See **Table G-1-1**
P_{forage}	Concentration in forage (mg/kg DW)	Calculated
P_{silage}	Concentration in silage (mg/kg DW)	Calculated
P_{grain}	Concentration in grain (mg/kg DW)	Calculated
F_{forage}	Fraction of forage that is contaminated (unitless)	See **Table G-15**
F_{silage}	Fraction of silage that is contaminated (unitless)	See **Table G-15**
F_{grain}	Fraction of grain that is contaminated (unitless)	See **Table G-15**
Q_{fbs}	Quantity of forage consumed by beef cattle (kg-DW/day)	See **Table G-15**
Q_{gbs}	Quantity of grain consumed by beef cattle (kg-DW/day)	See **Table G-15**
Q_{sbs}	Quantity of silage consumed by beef cattle (kg-DW/day)	See **Table G-15**
Q_{soilbs}	Quantity of soil consumed by beef cattle (kg/day)	See **Table G-15**
C_{soil}	Concentration in soil (mg/kg)	Calculated

Table G-11. Concentration in Dairy (mg/kg)

Amilk

$$A_{milk} = Ba_{milk} \times [(F_{grain} \times Q_{gds} \times P_{grain}) + (F_{forage} \times Q_{fds} \times P_{forage}) + (F_{silage} \times Q_{sds} \times P_{silage}) + (Q_{soilds} \times C_{soil})]$$

Name	Description	Value
Ba_{milk}	Biotransfer factor from soil or feed to dairy ([mg/kg-WW]/[mg/day])	See **Table G-1-1**
P_{forage}	Concentration in forage (mg/kg DW)	Calculated
P_{silage}	Concentration in silage (mg/kg DW)	Calculated
P_{grain}	Concentration in grain (mg/kg DW)	Calculated
F_{forage}	Fraction of forage that is contaminated (unitless)	See **Table G-15**
F_{grain}	Fraction of grain that is contaminated (unitless)	See **Table G-15**
F_{silage}	Fraction of silage that is contaminated (unitless)	See **Table G-15**
Q_{fds}	Quantity of forage consumed by dairy cattle (kg-DW/day)	See **Table G-15**
Q_{gds}	Quantity of grain consumed by dairy cattle (kg-DW/day)	See **Table G-15**
Q_{sds}	Quantity of silage consumed by dairy cattle (kg-DW/day)	See **Table G-15**
Q_{soilds}	Quantity of soil consumed by dairy cattle (kg/day)	See **Table G-15**
C_{soil}	Concentration in soil (mg/kg).	Calculated

G.2.4. Intake Rates

This section contains the equations for intake of drinking water, soil, produce, animal products, and fish:

- **Table G-12.** Contaminant Intake from Drinking Water
- **Table G-13.** Daily Intake of Contaminant from Fish Ingestion
- **Table G-14.** Daily Intake of Contaminant from Produce or Animal Product Ingestion.

Table G-12. Daily Intake from Drinking Water (mg/kg-day)

I_{dw}

$$I_{dw} = \frac{C_{dw} \times CR_{dw} \times F_{dw}}{1{,}000}$$

Name	Description	Value
C_{dw}	Dissolved waterbody concentration (mg/L)	Calculated
CR_{dw}	Consumption rate of water (mL/kg-day)	See **Appendix D**
F_{dw}	Fraction of drinking water ingested that is contaminated (unitless)	See **Appendix D**

Table G-13. Daily Intake from Fish Ingestion (mg/kg-day)

I_{fish}

$$I_{fish} = \frac{C_{fish_fillet} \times CR_{fish} \times F_{fish}}{1000 \times BW}$$

Name	Description	Value
BW	Body weight (kg)	See **Appendix D**
C_{fish_fillet}	Average fish fillet concentration ingested by humans (mg/kg)	Calculated
CR_{fish}	Consumption rate of fish (g WW/day)	See **Appendix D**
F_{fish}	Fraction of fish intake from contaminated source (unitless)	See **Appendix D**

Table G-14. Daily Intake from Produce or Animal Product Ingestion (mg/kg-day)

$I_{produce}$, I_{beef}, I_{milk}

$$I_i = \frac{C_i \times CR_i \times F_i}{1{,}000}$$

Name	Description	Value
C_i	Average concentration in plant or animal product *i* ingested by humans (mg/kg)*	Calculated
CR_i	Consumption rate of plant or animal product *i* (g/day) [a]	See **Appendix D**
F_i	Fraction of plant or animal product *i* intake from contaminated source (unitless)	See **Appendix D**

* Concentrations and consumption rates must be in dry weight for aboveground plants (so mg/kg DW or g DW/day) and whole weight for root vegetables and animal products (so mg/kg WW or g WW/day).

G.3 Biota Data

The biota data needed for the above equations are presented in **Table G-15**. These values are all constants and were all drawn from the U.S. Environmental Protection Agency's (EPA's or the Agency's) *Parameter Guidance Document* (U.S. EPA, 1997b).

Table G-15. Biota Data

Model Code	Description	Value
F_forage	Fraction of pasture grasses grown on contaminated soil and eaten. (unitless)	1
F_grain	Fraction of grain grown on contaminated soil and eaten (unitless)	1
F_silage	Fraction of silage grown on contaminated soil and eaten (unitless)	1
MAF_exfruit	Moisture adjustment factor for exposed fruits (% water)	85
MAF_exveg	Moisture adjustment factor for exposed vegetables (% water)	92
MAF_profruit	Moisture adjustment factor for protected fruits (% water)	90
MAF_proveg	Moisture adjustment factor for protected vegetables (% water)	80
MAF_root	Moisture adjustment factor for root vegetables (% water)	87
Rp_exfruit	Interception fraction for exposed fruit (unitless)	0.052
Rp_exveg	Interception fraction for exposed vegetation (unitless)	0.052
Rp_forage	Interception fraction for forage (unitless)	0.47
Rp_silage	Interception fraction for silage (unitless)	0.44
Tp_exfruit	Length of plant exposure to deposition for exposed fruit (yr)	0.123
Tp_exveg	Length of plant exposure to deposition for exposed vegetables (yr)	0.123
Tp_forage	Length of plant exposure to deposition for forage (yr)	0.123
Tp_silage	Length of plant exposure to deposition for silage (yr)	0.164
Yp_exfruit	Crop yield for exposed fruit (kg DW/m^2)	0.09
Yp_exveg	Crop yield for exposed veg (kg DW/m^2)	0.18
Yp_forage	Crop yield for forage (kg DW/m^2)	0.31
Yp_silage	Crop yield for silage (kg DW/m^2)	0.31
Q_{fbs}	Quantity of forage consumed by beef cattle (kg-DW/day)	8.8
Q_{gbs}	Quantity of grain consumed by beef cattle (kg-DW/day)	0.47
Q_{sbs}	Quantity of silage consumed by beef cattle (kg-DW/day)	2.5
Q_{soilbs}	Quantity of soil consumed by beef cattle (kg/day)	0.39
Q_{fds}	Quantity of forage consumed by dairy cattle (kg-DW/day)	11
Q_{gds}	Quantity of grain consumed by dairy cattle (kg-DW/day)	2.6
Q_{sds}	Quantity of silage consumed by dairy cattle (kg-DW/day)	3.3
Q_{soilds}	Quantity of soil consumed by dairy cattle (kg/day)	0.41

G.4 Bioconcentration and Biotransfer Data

Data on certain chemical-specific factors were used to estimate the degree to which constituents of potential concern (COPCs) may accumulate in exposed plants and animals. In turn, this information is used to calculate residential exposures from consumption of produce, livestock, and fish. Available data was gathered for each of the following 25 COPCs identified during hazard identification (**Section 2**):

- Aluminum
- Antimony
- Arsenic
- Barium
- Beryllium
- Boron
- Cadmium
- Chromium
- Cobalt
- Copper
- Fluoride
- Iron
- Lanthanum
- Lead
- Lithium
- Manganese
- Mercury
- Molybdenum
- Nickel
- Nitrate
- Selenium
- Silver
- Strontium
- Thallium
- Uranium
- Vanadium
- Zinc

Bioconcentration factors (BCFs) and biotransfer factors (BTFs) are based on the compilation of field and laboratory study results to develop a single factor or ratio for estimating the amount of constituent transferred into specific plant or animal tissue. EPA estimated fish tissue concentrations for trophic level 3 (TL3) and trophic level 4 (TL4) fish filets to account for the variability in fish likely consumed by human receptors. The following source hierarchy was used for fish BCFs:

- **Primary literature:** These are generally papers that may focus on a single chemical (Eisler, 1989; Kumada et al., 1973; Lemly, 1985; Murphy et al., 1978) or may contain data on multiple chemicals (Barrows et al., 1980; Stephan, 1993).
- **U.S. EPA databases/publications:** These included ECOTOX (U.S. EPA, 2009) and the Mercury Report to Congress (U.S. EPA, 1997a).
- **Other government agency resources:** These included Agency for Toxic Substances and Disease Registry (ATSDR) Toxicological Profiles (ATSDR, 2008) and the Hazardous Substances Data Bank (HSDB; U.S. NLM, 2011).

Where data for only one trophic level of fish were available, those data were used as a surrogate for the other trophic level. Where data were only available for whole fish, those were used as a surrogate for filet. Whole fish values from the correct trophic level were preferred as surrogates to filet values from the other trophic level. So, given a TL3 whole fish value and a TL4 filet value, the TL3 whole value would be preferred to the TL4 filet as a surrogate for TL3 filet. Similarly, EPA evaluated different categories of produce and animal products to capture the variability in farm-raised foods consumed by human receptors. The key source for biotransfer factors for animal products and plants was Baes et al. (1984).

G.5 References

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Attachment G-1. Bioconcentration and Biotransfer Factors

Table B-1-1 lists all of the chemical-specific parameters collected for this analysis, presented in alphabetical order based on the name of the constituent. In some instances, adequate data was not available on one or more of the parameters for a given constituent. In these cases, the analysis could not quantitatively consider exposures through the associated pathway. The factor abbreviations are defined below as follows:

- **Ba_{Beef} & Ba_{Milk}:** Biotransfer factor for beef or milk (day/kg-wet weight); primary data source is Baes et al. (1984).
- **BCF_{T3F} & BCF_{T4F}:** Bioconcentration factor for trophic level 3 (TL3) and trophic level 4 (TL4) fish filet (L/kg); data mostly drawn from primary literature or ECOTOX (U.S. EPA, 2009)
- **Br_i:** Soil-to-plant bioconcentration factor for plant type *i* (µg/g-plant dry weight)/(µg/g soil); primary data source is Baes et al. (1984), but some factors are calculated based on U.S. EPA (2009) if not available in Baes et al. Plant types are:
  - **ExFruit:** Exposed fruits eaten by human receptors;
  - **ExVeg:** Exposed vegetables eaten by human receptors;
  - **Forage:** Forage eaten by cattle;
  - **Grain:** Grains eaten by cattle;
  - **ProFruit:** Protected fruits eaten by human receptors;
  - **ProVeg:** Protected vegetables eaten by human receptors;
  - **Root:** Root vegetables eaten by human receptors; and
  - **Silage:** Silage eaten by cattle.

When the reference is a compilation, the original paper from which the value was drawn is also shown, if available. For example, "ECOTOX Wright, 1977" means the value was obtained from ECOTOX, which cites Wright (1977). Similarly, "ATSDR Hope 1996" means we obtained it from the ATSDR toxicological profile, which cites Hope (1996).

Table G-1-1. Bioconcentration and Biotransfer Factors for CCR Constituents Evaluate

Parameter	Value	Reference	Comment
Aluminum (7429-90-5)			
Ba_{beef}	1.5E-03	Baes et al., 1984	—
Ba_{milk}	2.0E-04	Baes et al., 1984	—
BCF_{T3F}	3.6E+01	ECOTOX Cleveland, 1991	BCFfor TL4 whole fish was used as a surrogate for TL3 filet
BCF_{T4F}	3.6E+01	ECOTOX Cleveland, 1991	BCF for TL4 whole fish was used as a surrogate for TL4 filet
$Br_{Exfruit}$	6.5E-04	Baes et al., 1984	—
Br_{Exveg}	4.0E-03	Baes et al., 1984	—
Br_{Forage}	4.0E-03	Baes et al., 1984	—
Br_{Grain}	6.5E-04	Baes et al., 1984	—
$Br_{Profruit}$	6.5E-04	Baes et al., 1984	—
Br_{Proveg}	6.5E-04	Baes et al., 1984	—
Br_{Root}	4.0E-03	Baes et al., 1984	—
Br_{Silage}	4.0E-03	Baes et al., 1984	—
Antimony (7440-36-0)			
Ba_{beef}	1.0E-03	Baes et al., 1984	—
Ba_{milk}	1.0E-04	Baes et al., 1984	—
BCF_{T3F}	0	Barrows et al., 1980	BCF for TL3 whole fish (sunfish) was used as a surrogate for TL3 filet.
BCF_{T4F}	0	Barrows et al., 1980	BCF for TL3 whole fish (sunfish) was used as a surrogate for TL4 filet.
$Br_{Exfruit}$	3.0E-02	Baes et al., 1984	—
Br_{Exveg}	2.0E-01	Baes et al., 1984	—
Br_{Forage}	2.0E-01	Baes et al., 1984	—
Br_{Grain}	3.0E-02	Baes et al., 1984	—
$Br_{Profruit}$	3.0E-02	Baes et al., 1984	—
Br_{Proveg}	3.0E-02	Baes et al., 1984	—
Br_{Root}	2.0E-01	Baes et al., 1984	—
Br_{Silage}	2.0E-01	Baes et al., 1984	—

Table G-1-1. Bioconcentration and Biotransfer Factors for CCR Constituents Evaluate

Parameter	Value	Reference	Comment
Arsenic (7440-38-2)			
Ba_{beef}	2.0E-03	Baes et al., 1984	—
Ba_{milk}	6.0E-05	Baes et al., 1984	—
BCF_{T3F}	4.0E+00	Barrows et al., 1980	BCF for TL3 whole fish (sunfish) was used as a surrogate for TL3 filet.
BCF_{T4F}	4.0E+00	Barrows et al., 1980	BCF for TL3 whole fish (sunfish) was used as a surrogate for TL4 filet.
$Br_{Exfruit}$	2.0E-03	Calculated based on U.S. EPA, 1999	—
Br_{Exveg}	1.0E-02	Calculated based on U.S. EPA, 1999	—
Br_{Forage}	5.3E-02	Calculated based on U.S. EPA, 1999	—
Br_{Grain}	4.3E-03	Calculated based on U.S. EPA, 1999	—
$Br_{Profruit}$	2.0E-03	Calculated based on U.S. EPA, 1999	—
Br_{Proveg}	2.0E-03	Calculated based on U.S. EPA, 1999	—
Br_{Root}	4.6E-03	Calculated based on U.S. EPA, 1999	—
Br_{Silage}	5.3E-02	Calculated based on U.S. EPA, 1999	—
Barium (7440-39-3)			
Ba_{beef}	1.5E-04	Baes et al., 1984	—
Ba_{milk}	3.5E-04	Baes et al., 1984	—
BCF_{T3F}	1.3E+02	ATSDR Hope, 1996	BCF for TL3 whole fish (sunfish) was used as a surrogate for TL3 filet.
BCF_{T4F}	1.3E+02	ATSDR Hope, 1996	BCF for TL3 whole fish (sunfish) was used as a surrogate for TL4 filet.
$Br_{Exfruit}$	1.5E-02	Baes et al., 1984	—
Br_{Exveg}	1.5E-01	Baes et al., 1984	—
Br_{Forage}	1.5E-01	Baes et al., 1984	—
Br_{Grain}	1.5E-02	Baes et al., 1984	—
$Br_{Profruit}$	1.5E-02	Baes et al., 1984	—
Br_{Proveg}	1.5E-02	Baes et al., 1984	—
Br_{Root}	1.5E-01	Baes et al., 1984	—
Br_{Silage}	1.5E-01	Baes et al., 1984	—

Table G-1-1. Bioconcentration and Biotransfer Factors for CCR Constituents Evaluate

Parameter	Value	Reference	Comment
Beryllium (7440-41-7)			
Ba_{beef}	1.0E-03	Baes et al., 1984	—
Ba_{milk}	9.0E-07	Baes et al., 1984	—
BCF_{T3F}	1.9E+01	Barrows et al., 1980	BCF for TL3 whole fish (sunfish) was used as a surrogate for TL3 filet.
BCF_{T4F}	1.9E+01	Barrows et al., 1980	BCF for TL3 whole fish (sunfish) was used as a surrogate for TL4 filet.
$Br_{Exfruit}$	1.5E-03	Baes et al., 1984	—
Br_{Exveg}	1.0E-02	Baes et al., 1984	—
Br_{Forage}	1.0E-02	Baes et al., 1984	—
Br_{Grain}	1.5E-03	Baes et al., 1984	—
$Br_{Profruit}$	1.5E-03	Baes et al., 1984	—
Br_{Proveg}	1.5E-03	Baes et al., 1984	—
Br_{Root}	1.0E-02	Baes et al., 1984	—
Br_{Silage}	1.0E-02	Baes et al., 1984	—
Boron (7440-42-8)			
Ba_{beef}	8.0E-04	Baes et al., 1984	—
Ba_{milk}	1.5E-03	Baes et al., 1984	—
BCF_{T3F}	—	—	—
BCF_{T4F}	—	—	—
$Br_{Exfruit}$	2.0E+00	Baes et al., 1984	—
Br_{Exveg}	4.0E+00	Baes et al., 1984	—
Br_{Forage}	4.0E+00	Baes et al., 1984	—
Br_{Grain}	2.0E+00	Baes et al., 1984	—
$Br_{Profruit}$	2.0E+00	Baes et al., 1984	—
Br_{Proveg}	2.0E+00	Baes et al., 1984	—
Br_{Root}	4.0E+00	Baes et al., 1984	—
Br_{Silage}	4.0E+00	Baes et al., 1984	—

Table G-1-1. Bioconcentration and Biotransfer Factors for CCR Constituents Evaluate

Parameter	Value	Reference	Comment
Cadmium (7440-43-9)			
Ba_{beef}	5.5E-04	Baes et al., 1984	—
Ba_{milk}	1.0E-03	Baes et al., 1984	—
BCF_{T3F}	2.7E+02	Kumada et al., 1972	BCF for TL3 whole fish (rainbow trout) was used as a surrogate for TL3 filet. Geomean of mulitple values.
BCF_{T4F}	2.7E+02	Kumada et al., 1972	BCF for TL3 whole fish (rainbow trout) was used as a surrogate for TL4 filet. Geomean of mulitple values.
$Br_{Exfruit}$	2.5E-03	Calculated based on U.S. EPA, 1999	—
Br_{Exveg}	6.7E-01	Calculated based on U.S. EPA, 1999	—
Br_{Forage}	4.0E-01	Calculated based on U.S. EPA, 1999	—
Br_{Grain}	1.1E-01	Calculated based on U.S. EPA, 1999	—
$Br_{Profruit}$	2.5E-03	Calculated based on U.S. EPA, 1999	—
Br_{Proveg}	2.5E-03	Calculated based on U.S. EPA, 1999	—
Br_{Root}	2.5E-01	Calculated based on U.S. EPA, 1999	—
Br_{Silage}	4.0E-01	Calculated based on U.S. EPA, 1999	—
Chromium (7440-47-3)			
Ba_{beef}	5.5E-03	Baes et al., 1984	—
Ba_{milk}	1.5E-03	Baes et al., 1984	—
BCF_{T3F}	6.0E-01	Stephan, 1993	BCF for TL4 filet was used as a surrogate for TL3 filet.
BCF_{T4F}	6.0E-01	Stephan, 1993 derived from Buhler et al., 1977 and Calamari et al., 1982	—
$Br_{Exfruit}$	1.4E-04	Calculated based on U.S. EPA, 1999	—
Br_{Exveg}	5.8E-04	Calculated based on U.S. EPA, 1999	—
Br_{Forage}	1.9E-03	Calculated based on U.S. EPA, 1999	—
Br_{Grain}	9.0E-05	Calculated based on U.S. EPA, 1999	—
$Br_{Profruit}$	1.4E-04	Calculated based on U.S. EPA, 1999	—
Br_{Proveg}	1.4E-04	Calculated based on U.S. EPA, 1999	—
Br_{Root}	9.5E-04	Calculated based on U.S. EPA, 1999	—
Br_{Silage}	1.9E-03	Calculated based on U.S. EPA, 1999	—

Table G-1-1. Bioconcentration and Biotransfer Factors for CCR Constituents Evaluate

Parameter	Value	Reference	Comment
Cobalt (7440-48-4)			
Ba_{beef}	2.0E-02	Baes et al., 1984	—
Ba_{milk}	2.0E-03	Baes et al., 1984	—
BCF_{T3F}	—	—	—
BCF_{T4F}	—	—	—
$Br_{Exfruit}$	7.0E-03	Baes et al., 1984	—
Br_{Exveg}	2.0E-02	Baes et al., 1984	—
Br_{Forage}	2.0E-02	Baes et al., 1984	—
Br_{Grain}	7.0E-03	Baes et al., 1984	—
$Br_{Profruit}$	7.0E-03	Baes et al., 1984	—
Br_{Proveg}	7.0E-03	Baes et al., 1984	—
Br_{Root}	2.0E-02	Baes et al., 1984	—
Br_{Silage}	2.0E-02	Baes et al., 1984	—
Copper (7440-50-8)			
Ba_{beef}	1.0E-02	Baes et al., 1984	—
Ba_{milk}	1.5E-03	Baes et al., 1984	—
BCF_{T3F}	0	Stephan (1993)	—
BCF_{T4F}	0	Stephan (1993)	—
$Br_{Exfruit}$	2.5E-01	Baes et al., 1984	—
Br_{Exveg}	4.0E-01	Baes et al., 1984	—
Br_{Forage}	4.0E-01	Baes et al., 1984	—
Br_{Grain}	2.5E-01	Baes et al., 1984	—
$Br_{Profruit}$	2.5E-01	Baes et al., 1984	—
Br_{Proveg}	2.5E-01	Baes et al., 1984	—
Br_{Root}	4.0E-01	Baes et al., 1984	—
Br_{Silage}	4.0E-01	Baes et al., 1984	—

Table G-1-1. Bioconcentration and Biotransfer Factors for CCR Constituents Evaluate

Parameter	Value	Reference	Comment
Fluoride (16984-48-8)			
BCF_{T3F}	2.3E+00	ECOTOX Wright, 1977	BCF for TL4 whole fish was used as a surrogate for TL3 filet
BCF_{T4F}	2.3E+00	ECOTOX Wright, 1977	BCF for TL4 whole fish (brown trout) was used as a surrogate for TL4 filet
Iron (7439-89-6)			
Ba_{beef}	2.0E-02	Baes et al., 1984	—
Ba_{milk}	2.5E-04	Baes et al., 1984	—
BCF_{T3F}	1.9E+01	ECOTOX Preez et al., 1993	Species is banded bream
BCF_{T4F}	1.9E+01	HSDB Nakamoto and Hassler, 1992	BCF for TL3 filet (banded bream) was used as a surrogate for TL4 filet
$Br_{Exfruit}$	1.0E-03	Baes et al., 1984	—
Br_{Exveg}	4.0E-03	Baes et al., 1984	—
Br_{Forage}	4.0E-03	Baes et al., 1984	—
Br_{Grain}	1.0E-03	Baes et al., 1984	—
$Br_{Profruit}$	1.0E-03	Baes et al., 1984	—
Br_{Proveg}	1.0E-03	Baes et al., 1984	—
Br_{Root}	4.0E-03	Baes et al., 1984	—
Br_{Silage}	4.0E-03	Baes et al., 1984	—
Lanthanum (7439-91-0)			
Ba_{beef}	3.0E-04	Baes et al., 1984	—
Ba_{milk}	2.0E-05	Baes et al., 1984	—
BCF_{T3F}	1.2E+00	ECOTOX Hao, et. al., 1996	Species was common carp
BCF_{T4F}	1.2E+00	ECOTOX Hao, et. al., 1996	BCF for TL3 filet (common carp) was used as a surrogate for TL4 filet
$Br_{Exfruit}$	4.0E-03	Baes et al., 1984	—
Br_{Exveg}	1.0E-02	Baes et al., 1984	—
Br_{Forage}	1.0E-02	Baes et al., 1984	—
Br_{Grain}	4.0E-03	Baes et al., 1984	—
$Br_{Profruit}$	4.0E-03	Baes et al., 1984	—
Br_{Proveg}	4.0E-03	Baes et al., 1984	—
Br_{Root}	1.0E-02	Baes et al., 1984	—
Br_{Silage}	1.0E-02	Baes et al., 1984	—

Table G-1-1. Bioconcentration and Biotransfer Factors for CCR Constituents Evaluate

Parameter	Value	Reference	Comment
Lead (7439-92-1)			
BCF_{T3F}	4.6E+01	Stephan (1993)	BCF for TL3 whole fish (bluegill) was used as a surrogate for TL3 filet
BCF_{T4F}	4.6E+01	Stephan (1993)	BCF for TL3 whole fish (bluegill) was used as a surrogate for TL4 filet
Lithium (7439-93-2)			
BCF_{T3F}	—	—	—
BCF_{T4F}	—	—	—
Manganese (7439-96-5)			
Ba_{beef}	4.0E-04	Baes et al., 1984	—
Ba_{milk}	3.5E-04	Baes et al., 1984	—
BCF_{T3F}	4.0E-01	ECOTOX Litzke and Hubel, 1993	Species was common carp
BCF_{T4F}	2.0E-01	ECOTOX Litzke and Hubel, 1993	Species was rainbow trout
$Br_{Exfruit}$	5.0E-02	Baes et al., 1984	—
Br_{Exveg}	2.5E-01	Baes et al., 1984	—
Br_{Forage}	2.5E-01	Baes et al., 1984	—
Br_{Grain}	5.0E-02	Baes et al., 1984	—
$Br_{Profruit}$	5.0E-02	Baes et al., 1984	—
Br_{Proveg}	5.0E-02	Baes et al., 1984	—
Br_{Root}	2.5E-01	Baes et al., 1984	—
Br_{Silage}	2.5E-01	Baes et al., 1984	—
Mercury (99-99-1)			
Ba_{beef}	7.7E-03	U.S. EPA, 1997a	For divalent mercury
Ba_{milk}	2.6E-03	U.S. EPA, 1997a	For divalent mercury
BCF_{T3F}	1.6E+06	U.S. EPA, 1997a	For methyl mercury
BCF_{T4F}	6.8E+06	U.S. EPA, 1997a	For methyl mercury
$Br_{Exfruit}$	1.4E-02	Calculated based on U.S. EPA, 1999	For divalent mercury
Br_{Exveg}	1.7E-01	Calculated based on U.S. EPA, 1999	For divalent mercury
Br_{Forage}	6.7E-01	Calculated based on U.S. EPA, 1999	For divalent mercury
Br_{Grain}	8.6E-02	Calculated based on U.S. EPA, 1999	For divalent mercury
$Br_{Profruit}$	1.4E-02	Calculated based on U.S. EPA, 1999	For divalent mercury
Br_{Proveg}	1.4E-02	Calculated based on U.S. EPA, 1999	For divalent mercury
Br_{Root}	3.6E-02	Calculated based on U.S. EPA, 1999	For divalent mercury
Br_{Silage}	6.7E-01	Calculated based on U.S. EPA, 1999	For divalent mercury

Table G-1-1. Bioconcentration and Biotransfer Factors for CCR Constituents Evaluate

Parameter	Value	Reference	Comment
Molybdenum (7439-98-7)			
Ba_{beef}	6.0E-03	Baes et al., 1984	—
Ba_{milk}	1.53E-03	Baes et al., 1984	—
BCF_{T3F}	4.0E+00	Eisler, 1989	BCF for TL4 filet (rainbow trout and steelhead trout) was used as a surrogate for TL3 filet
BCF_{T4F}	4.0E+00	Eisler, 1989	Geomean of multiple values. Species were rainbow trout and steelhead trout.
$Br_{Exfruit}$	6.0E-02	Baes et al., 1984	—
Br_{Exveg}	2.5E-01	Baes et al., 1984	—
Br_{Forage}	2.5E-01	Baes et al., 1984	—
Br_{Grain}	6.0E-02	Baes et al., 1984	—
$Br_{Profruit}$	6.0E-02	Baes et al., 1984	—
Br_{Proveg}	6.0E-02	Baes et al., 1984	—
Br_{Root}	2.5E-01	Baes et al., 1984	—
Br_{Silage}	2.5E-01	Baes et al., 1984	—
Nickel (7440-02-0)			
Ba_{beef}	6.0E-03	Baes et al., 1984	—
Ba_{milk}	1.0E-03	Baes et al., 1984	—
BCF_{T3F}	8.0E-01	Stephan, 1993 dervied from Calamari et al., 1982	BCF for TL4 filet was used as a surrogate for TL3 filet
BCF_{T4F}	8.0E-01	Stephan, 1993 dervied from Calamari et al., 1982	—
$Br_{Exfruit}$	6.0E-02	Baes et al., 1984	—
Br_{Exveg}	1.0E-02	Calculated based on U.S. EPA, 1999	—
Br_{Forage}	2.0E-02	Calculated based on U.S. EPA, 1999	—
Br_{Grain}	6.0E-02	Baes et al., 1984	—
$Br_{Profruit}$	6.0E-02	Baes et al., 1984	—
Br_{Proveg}	6.0E-02	Baes et al., 1984	—
Br_{Root}	6.0E-02	Baes et al., 1984	—
Br_{Silage}	2.0E-02	Calculated based on U.S. EPA, 1999	—

Table G-1-1. Bioconcentration and Biotransfer Factors for CCR Constituents Evaluate

Parameter	Value	Reference	Comment
Nitrate (14797-55-8)			
No Data		—	—
Selenium (7782-49-2)			
Ba_{beef}	1.5E-02	Baes et al., 1984	—
Ba_{milk}	4.0E-03	Baes et al., 1984	—
BCF_{T3F}	4.9E+02	Lemly, 1985	Species were threadfin shad and blueback herring.*
BCF_{T4F}	1.7E+03	Lemly, 1985	Species were threadfin shad and blueback herring.*
$Br_{Exfruit}$	2.5E-02	Baes et al., 1984	—
Br_{Exveg}	2.5E-02	Baes et al., 1984	—
Br_{Forage}	2.5E-02	Baes et al., 1984	—
Br_{Grain}	2.5E-02	Baes et al., 1984	—
$Br_{Profruit}$	2.5E-02	Baes et al., 1984	—
Br_{Proveg}	2.5E-02	Baes et al., 1984	—
Br_{Root}	2.5E-02	Baes et al., 1984	—
Br_{Silage}	2.5E-02	Baes et al., 1984	—
Silver (7440-22-4)			
Ba_{beef}	3.0E-03	Baes et al., 1984	—
Ba_{milk}	2.0E-02	Baes et al., 1984	—
BCF_{T3F}	—	—	—
BCF_{T4F}	—	—	—
$Br_{Exfruit}$	1.0E-01	Baes et al., 1984	—
Br_{Exveg}	4.0E-01	Baes et al., 1984	—
Br_{Forage}	4.0E-01	Baes et al., 1984	—
Br_{Grain}	1.0E-01	Baes et al., 1984	—
$Br_{Profruit}$	1.0E-01	Baes et al., 1984	—
Br_{Proveg}	1.0E-01	Baes et al., 1984	—
Br_{Root}	4.0E-01	Baes et al., 1984	—
Br_{Silage}	4.0E-01	Baes et al., 1984	—

Table G-1-1. Bioconcentration and Biotransfer Factors for CCR Constituents Evaluate

Parameter	Value	Reference	Comment
Strontium (7440-24-6)			
Ba_{beef}	3.0E-04	Baes et al., 1984	—
Ba_{milk}	1.5E-03	Baes et al., 1984	—
BCF_{T3F}	9.5E+00	ECOTOX Aleksanyan et al., 1978	Species was common carp
BCF_{T4F}	9.5E+00	ECOTOX Aleksanyan et al., 1978	BCF for TL3 filet (common carp) was used as a surrogate for TL4 filet
$Br_{Exfruit}$	2.5E-01	Baes et al., 1984	—
Br_{Exveg}	2.5E+00	Baes et al., 1984	—
Br_{Forage}	2.5E+00	Baes et al., 1984	—
Br_{Grain}	2.5E-01	Baes et al., 1984	—
$Br_{Profruit}$	2.5E-01	Baes et al., 1984	—
Br_{Proveg}	2.5E-01	Baes et al., 1984	—
Br_{Root}	2.5E+00	Baes et al., 1984	—
Br_{Silage}	2.5E+00	Baes et al., 1984	—
Thallium (7440-28-0)			
Ba_{beef}	4.0E-02	Baes et al., 1984	—
Ba_{milk}	2.0E-03	Baes et al., 1984	—
BCF_{T3F}	3.4E+01	Barrows et al., 1980	BCF for TL3 whole fish (sunfish) was used as a surrogate for TL3 filet
BCF_{T4F}	1.3E+02	Stephan, 1993 derived from Zitko et al., 1975	—
$Br_{Exfruit}$	4.0E-04	Baes et al., 1984	—
Br_{Exveg}	4.0E-03	Baes et al., 1984	—
Br_{Forage}	4.0E-03	Baes et al., 1984	—
Br_{Grain}	4.0E-04	Baes et al., 1984	—
$Br_{Profruit}$	4.0E-04	Baes et al., 1984	—
Br_{Proveg}	4.0E-04	Baes et al., 1984	—
Br_{Root}	4.0E-03	Baes et al., 1984	—
Br_{Silage}	4.0E-03	Baes et al., 1984	—

Table G-1-1. Bioconcentration and Biotransfer Factors for CCR Constituents Evaluate

Parameter	Value	Reference	Comment
Uranium (7440-61-1)			
Ba_{beef}	2.0E-04	Baes et al., 1984	—
Ba_{milk}	6.0E-04	Baes et al., 1984	—
BCF_{T3F}	3.7E+01	Poston, 1982	BCF for TL4 whole fish was used as a surrogate for TL3 filet
BCF_{T4F}	3.7E+01	Poston, 1982	BCF for TL4 whole fish was used as a surrogate for TL4 filet
$Br_{Exfruit}$	4.0E-03	Baes et al., 1984	—
Br_{Exveg}	8.5E-03	Baes et al., 1984	—
Br_{Forage}	8.5E-03	Baes et al., 1984	—
Br_{Grain}	4.0E-03	Baes et al., 1984	—
$Br_{Profruit}$	4.0E-03	Baes et al., 1984	—
Br_{Proveg}	4.0E-03	Baes et al., 1984	—
Br_{Root}	8.5E-03	Baes et al., 1984	—
Br_{Silage}	8.5E-03	Baes et al., 1984	—
Vanadium (7440-62-2)			
Ba_{beef}	2.5E-03	Baes et al., 1984	—
Ba_{milk}	2.0E-05	Baes et al., 1984	—
BCF_{T3F}	3.2E+01	ECOTOX Bell et al., 1980	BCF for TL4 whole fish was used as a surrogate for TL3 filet
BCF_{T4F}	3.2E+01	ECOTOX Bell et al., 1980	BCF for TL4 whole fish was used as a surrogate for TL4 filet
$Br_{Exfruit}$	3.0E-03	Baes et al., 1984	—
Br_{Exveg}	5.5E-03	Baes et al., 1984	—
Br_{Forage}	4.9E-03	Calculated based on U.S. EPA, 1999	—
Br_{Grain}	3.0E-03	Baes et al., 1984	—
$Br_{Profruit}$	3.0E-03	Baes et al., 1984	—
Br_{Proveg}	3.0E-03	Baes et al., 1984	—
Br_{Root}	5.5E-03	Baes et al., 1984	—
Br_{Silage}	4.9E-03	Calculated based on U.S. EPA, 1999	—

Table G-1-1. Bioconcentration and Biotransfer Factors for CCR Constituents Evaluate

Parameter	Value	Reference	Comment
Zinc (7440-66-6)			
Ba_{beef}	1.0E-01	Baes et al., 1984	—
Ba_{milk}	1.0E-02	Baes et al., 1984	—
BCF_{T3F}	3.5E+02	Murphy et al., 1978	BCF for TL3 whole fish (bluegill) was used as a surrogate for TL34 filet. Geomean of multiple values.
BCF_{T4F}	3.5E+02	Murphy et al., 1978	BCF for TL3 whole fish (bluegill) was used as a surrogate for TL4 filetGeomean of multiple values
$Br_{Exfruit}$	9.0E-01	Baes et al., 1984	—
Br_{Exveg}	3.3E-01	Calculated based on U.S. EPA, 1999	—
Br_{Forage}	3.2E-01	Calculated based on U.S. EPA, 1999	—
Br_{Grain}	3.3E-01	Calculated based on U.S. EPA, 1999	—
$Br_{Profruit}$	9.0E-01	Baes et al., 1984	—
Br_{Proveg}	9.0E-01	Baes et al., 1984	—
Br_{Root}	1.3E-01	Calculated based on U.S. EPA, 1999	—
Br_{Silage}	3.2E-01	Calculated based on U.S. EPA, 1999	—

* In Lemly's paper on selenium, the BCFs are reported in L/g, but based on other data in the paper, the units are clearly actually L/kg. Used the values as L/kg.

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Appendix H.

Estimation of Contaminant Partition Coefficients for the CCR Risk Assessment

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H.1 Introduction

The following appendix details the development of soil-water partitioning coefficients used to model COPC concentrations in ground water.

- **Attachment H-1** provides a report developed for EPA by Allison Geoscience Consultants. This report summarized the statistical analysis of the concentrations of major ions in the pore water that was conducted to identify distinct waste types. This report has been reformatted by EPA for consistency; however, no substantive changes have been made to the content.
- **Attachment H-2** provides plots of the nonlinear sorption isotherms used in the CCR risk assessment, organized by waste management unit type (landfill or surface impoundment), constituent, soil/aquifer environment (carbonate or noncarbonate), and saturated (aquifer) or unsaturated (soil) zone.
- **Attachment H-3** tabulates, by constituent, K_d percentiles for the saturated and unsaturated zones from the inputs of the probabilistic modeling described in **Section 4** of this document.

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Attachment H-1.
Estimation of Contaminant Partition Coefficients for the Coal Combustion Residues Risk Assessment

Prepared for:

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December 2011

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Executive Summary

This report describes the development of concentration-dependent partition coefficients for use in modeling subsurface leaching of Coal Combustion Residues (CCR) using the fate and transport model EPACMTP (EPA Composite Model with Transformation Products). EPACMTP incorporates the option of using nonlinear contaminant-specific tables of partitioning values in which the contaminant partitioning is presented over a range of contaminant concentration levels (isotherms) for particular settings of environmental variables that control partitioning. These tables of sorption isotherms reflect the tendency of Kd to decrease as the total contaminant concentration in the system increases. The isotherms were estimated using the geochemical speciation model MINTEQA2. For a particular contaminant, Kd values in a soil or aquifer are dependent upon the contaminant concentration and various geochemical characteristics of the soil or aquifer and the associated porewater.

Geochemical parameters that have the greatest influence on the magnitude of Kd include the pH of the system and the nature and concentration of sorbents associated with the soil or aquifer matrix. In the subsurface beneath a disposal facility, the concentration of leachate constituents may also influence Kd. This is especially true of some CCR leachates that may have high concentrations of calcium, sulfate, and other inorganic constituents. The use of a speciation model allows Kd values to be estimated for a range of total contaminant concentrations in various model systems designed to depict natural variability in those geochemical characteristics that most influence contaminant partitioning.

The CCR constituents whose partition coefficients have been estimated using MINTEQA2 correspond to those that failed the screen of CCR wastes (discussed in Appendix K of the risk assessment document) through the groundwater exposure pathways: aluminum, antimony (V), arsenic (III and V), barium, beryllium, boron, cadmium (II), chromium (III and VI), cobalt (II), copper (II), fluoride ion, iron (II), lead (II), manganese (II), mercury (II), molybdenum (VI), nickel (II), selenium (IV and VI), silver (I), thallium(I), vanadium (V), and zinc (II). Expected natural variability in Kd for a particular contaminant was included in the MINTEQA2 modeling by including variability in important input parameters upon which Kd depends.

The input parameters for which variability was incorporated include groundwater chemical composition, pH, concentration of aquifer sorbents, composition and concentration level of CCR leachate, and concentration of the contaminant. Two groundwater compositions were used: carbonate and noncarbonate. The natural pH range for each of these groundwater types is restricted (about 7 to 9 for carbonate terrain waters and 4 to 10 for noncarbonate. However, CCR leachate ranges from very acidic (pH < 2) to highly alkaline (pH > 12) and intrusion of leachate into the soil/aquifer system can impact the groundwater pH. For many contaminants modeled here, the magnitude of the partition coefficient is very much dependent on pH. This dependence was

included in the estimated partition coefficients by equilibrating the leachate/groundwater system at a series of pH values that span the range of expected variability in mixed leachate-groundwater systems. The influence of variability in the sorption capacity of soil and aquifer materials on Kd estimates was included by equilibrating the groundwater systems with various concentrations of two commonly occurring natural sorbents: ferric oxyhydroxide and particulate organic matter (POM). CCR leachate can include elevated concentrations of inorganic constituents such as calcium, sulfate, sodium, potassium, and chloride. Elevated concentrations of leachate constituents may reduce sorption of metals due to competition for sorption sites or complexation with metals in solution. The influence of elevated concentrations of leachate constituents on Kd estimates was included in the modeling by adding leachate components at concentrations representative of CCR leachate. Examination of the major ion concentrations in a database of CCR porewater and leachate samples led to the choice of four representative leachate chemistries: ash codisposed with coal refuse, fluidized bed combustion (FBC) waste leachate, flue gas desulfurization (FGD) waste leachate, and combined ash (primarily non-FBC fly ash) leachate.

Each MINTEQA2 model execution produced an isotherm for a particular contaminant and was defined by the following selections of system variables:

- groundwater type (carbonate or noncarbonate)
- hydrologic zone (unsaturated or saturated)
- ferric oxide (FeOx) sorbent concentration level (low, medium, high)
- POM/dissolved organic matter (DOM) concentration level (low, medium, high)
- equilibrium pH (range depends on groundwater type and leachate type)
- leachate type (ash and coal refuse, FBC waste, FGD waste, or combined ash)
- leachate "richness" or ionic strength

For each constituent modeled, the results of each MINTEQA2 model run were compiled as the equilibrium distribution of the contaminant among dissolved, sorbed, and precipitated fractions. These results were saved in a separate file indexed with the settings of all variables defining the system. Such files were produced for all possible values for the variables defining the system and were compiled into a database of indexed K_d values for use in the EPACMTP fate and transport model. A typical plot of K_d versus total contaminant concentration from a MINTEQA2 output file for arsenic is shown in **Figure 1**.

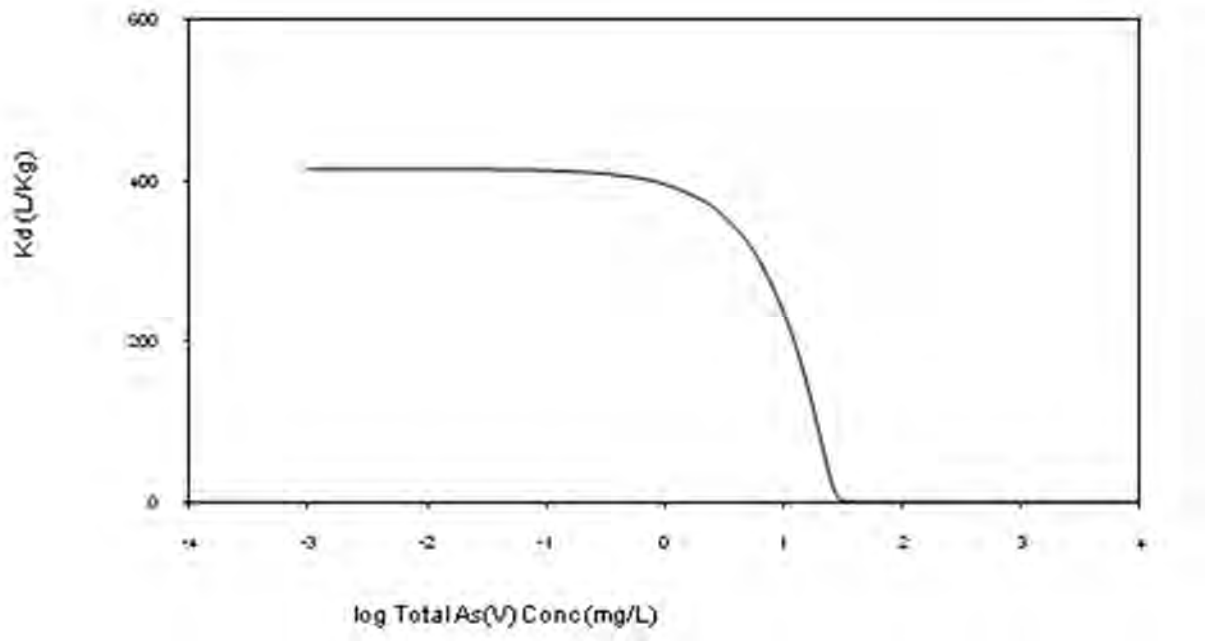

Figure 1. Typical K_d versus total contaminant concentration response curve from MINTEQA2.

1 Introduction

This report describes the development of concentration-dependent partition coefficients for use in modeling subsurface leaching of coal combustion residues (CCR) using the groundwater fate and transport model EPACMTP. In the subsurface, metal and nonmetal contaminants undergo reactions with ligands in the porewater and with surface sites on the solid aquifer or soil matrix material. Reactions in which the contaminant is bound to the solid matrix are referred to as sorption reactions, and a contaminant that is bound to the solid is said to be sorbed. The ratio of the concentration of contaminant sorbed to the concentration in the mobile aqueous phase at equilibrium is referred to as the partition coefficient (K_d). During contaminant transport, sorption to the solid matrix results in retardation of the contaminant front. Transport models such as EPACMTP incorporate the contaminant partition coefficient into the overall retardation factor (the ratio of the average linear particle velocity to the velocity of that portion of the plume where the contaminant is at 50 percent dilution. The use of K_d in EPACMTP transport modeling implies the assumption that local equilibrium between the solutes and the sorbents is attained. This implies that the rate of sorption reactions is fast relative to advective-dispersive transport of the contaminant.

EPACMTP incorporates the option of using contaminant-specific tables of partitioning values in which the contaminant partitioning is presented over a range of contaminant concentration levels for particular settings of environmental variables that control partitioning. These tables of sorption isotherms reflect the tendency of K_d to decrease as the total contaminant concentration in the system increases. Isotherms for use in EPACMTP are specified in terms of the dissolved contaminant concentration and the corresponding sorbed concentration at a series of total contaminant concentrations. The isotherms were estimated using the geochemical speciation model MINTEQA2.

For a particular contaminant, K_d values in a soil or aquifer are dependent upon the contaminant concentration and various geochemical characteristics of the soil or aquifer and the associated porewater. Geochemical parameters that have the greatest influence on the magnitude of K_d include the pH of the system and the nature and concentration of sorbents associated with the soil or aquifer matrix. In the subsurface beneath a disposal facility, the concentration of leachate constituents may also influence K_d. This is especially true of some CCR leachates that may have high concentrations of calcium, sulfate, and other inorganic constituents. Although the dependence of partitioning on the total contaminant concentration and on pH and other geochemical characteristics is apparent from partitioning studies reported in the scientific literature, K_d values for individual contaminants are not available for the range of concentrations or geochemical conditions relevant in the CCR land disposal scenarios. It is for this reason that the U.S. Environmental Protection Agency (EPA) has chosen to use an equilibrium speciation model to estimate partition coefficients for the CCR study. The use of a speciation model allows K_d values

to be estimated for a range of total contaminant concentrations in various model systems designed to depict natural variability in those geochemical characteristics that most influence partitioning.

1.1 Description of MINTEQA2

The nonlinear sorption isotherms for contaminants were produced by using MINTEQA2,[1] a geochemical speciation model maintained and distributed by the U.S. EPA. From input data consisting of total concentrations of chemical constituents, MINTEQA2 calculates the fraction of a contaminant that is dissolved, adsorbed, and precipitated at equilibrium (see **Figure 2**). The total concentrations of major and minor ions, trace metals, and other chemicals are specified in terms of key species known as components. MINTEQA2 automatically includes an extensive database of solution species and solid phase species representing reaction products of two or more of the components. The model does not automatically include sorption reactions, but these can be included in the calculations if supplied by the user. When sorption reactions are included, the dimensionless partition coefficient can be calculated from the ratio of the sorbed contaminant concentration to the dissolved concentration at equilibrium. The dimensionless partition coefficient is converted to K_d with units of liters per kilogram (L/kg) by normalizing by the mass of soil (in kilograms) with which 1 liter of porewater is equilibrated (the phase ratio). An isotherm is generated when the equilibrium distribution between sorbed and dissolved fractions is estimated for a series of total contaminant concentrations.

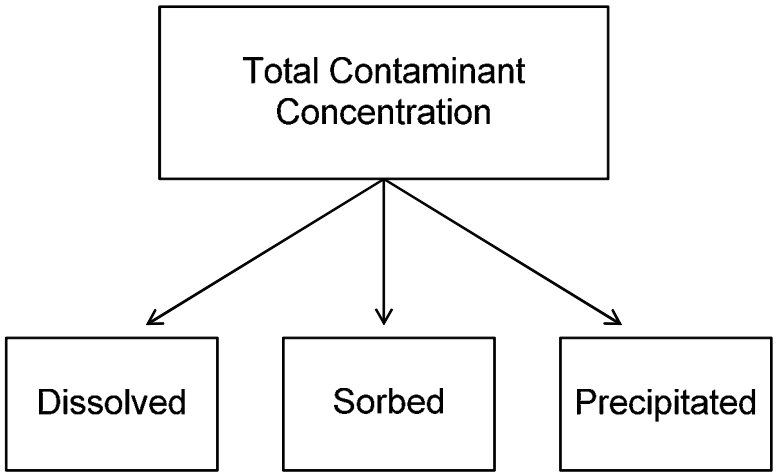

Figure 2. MINTEQA2 computes the equilibrium distribution of contaminant.

Progress in accounting for sorption in equilibrium calculations over the past decade has resulted in the development of coherent databases of sorption reactions for particular sorbents. These databases include acid-base sorption reactions and reactions for major ions in aquatic systems (calcium, magnesium, sulfate [SO_4], etc. Including such reactions along with those representing sorption of the contaminant makes it possible to estimate sorption in systems of varying pH and

[1] The version of MINTEQA2 used in this modeling was modified from version 4.02.

composition. Examples of coherent databases of sorption reactions include that for the hydrous ferric oxide (HFO) surface presented by Dzombak and Morel (1990) and a similar database for goethite presented by Mathur (1995).

1.2 Contaminants of Interest

The contaminants whose partition coefficients have been estimated using MINTEQA2 correspond to those that failed the groundwater pathway screening described in **Section 3**. These contaminants are listed in **Table 1**.

Table 1. Contaminants for which Partition Coefficients Were Computed

Contaminant	Oxidation State(s) Modeled	MINTEQA2 Component
Aluminum (Al)	+3	Al^{3+}
Antimony (Sb)	+5	$Sb(OH)_6^-$
Arsenic (As)	+3, +5	H_3AsO_3, H_3AsO_4
Barium (Ba)	+2	Ba^{2+}
Beryllium	+2	Be+2
Boron (B)	+3	H_3BO_3
Cadmium (Cd)	+2	Cd^{2+}
Chromium (Cr)	+3, +6	$Cr(OH)_2^+$, CrO_4^{2-}
Cobalt (Co)	+2	Co^{2+}
Copper (Cu)	+2	Cu^{2+}
Fluoride (F)	-1	F^-
Iron (Fe)	+2	Fe^{2+}
Lead (Pb)	+2	Pb^{2+}
Manganese	+2	Mn^{2+}
Mercury (Hg)	+2	$Hg(OH)_2$
Molybdenum (Mo)	+6	MoO_4^{2-}
Nickel (Ni)	+2	Ni^{2+}
Selenium (Se)	+4, +6	$HSeO3^-$, SeO_4^{2-}
Silver (Ag)	+1	Ag^+
Thallium (Tl)	+1	Tl^+
Vanadium (V)	+5	VO_2^+
Zinc (Zn)	+2	Zn^{2+}

Several of these contaminants occur naturally in more than one oxidation state. The modeling described here is restricted to the oxidation states that are most likely to occur in waste systems or

most likely to be mobile in groundwater-waste systems. Partition coefficients were modeled for two oxidation states each for arsenic, selenium, and chromium. These were arsenic (III) and (V), selenium (IV) and (VI), and chromium (III) and (VI). For antimony, molybdenum, thallium, copper, iron, and vanadium only one oxidation state was modeled although multiple oxidation states occur. For these metals, the choice of which state to model was dictated by practical aspects such as availability of sorption reactions and by subjective assessment of the appropriate (or predominant) oxidation state. The oxidation states modeled were antimony (V) (there were no sorption reactions available for antimony [III]), molybdenum (VI) (molybdate seems the most relevant form from literature reports), thallium (I) (this form is more frequently cited in the literature as having environmental implications), copper (II) (this oxidation state seemed to be more likely in coal ash leachate), iron (II) (ferric iron is more likely to be precipitated), and vanadium (V) (this seems the most relevant form, and sorption reactions were available for this form only. Table 1 lists the oxidation states modeled for all contaminants.

2 Modeling Approach

Expected natural variability in K_d for a particular contaminant was included in the MINTEQA2 modeling by including variability in important input parameters upon which K_d depends. The input parameters for which variability was incorporated include groundwater composition, pH, concentration of aquifer sorbents, composition and concentration level of CCR leachate, and concentration of the contaminant.

The groundwater chemistry exerts an important influence on partition coefficients. The major ions present in groundwater may compete with trace metals for sorption sites. Also, inorganic ligands may complex with some metals, reducing their tendency to sorb. For the purposes of this modeling, it is assumed that the influence of groundwater composition on sorption of the contaminant can be adequately represented by dividing the universe of groundwater compositional types into two categories: carbonate and noncarbonate. The natural pH range for each of these groundwater types is restricted (about 7 to 9 for carbonate terrain waters and 4 to 10 for noncarbonate. However, CCR leachate ranges from acidic ($pH < 2$) to highly alkaline ($pH > 12$) and intrusion of leachate into the soil/aquifer system can impact the groundwater pH. For many metals, the magnitude of the partition coefficient is very much dependent on pH. This dependence was included in the estimated partition coefficients by equilibrating the leachate/groundwater system at a series of pH values that span the range of expected variability.

The influence of variability in sorption capacity of soil and aquifer materials on K_d estimates was included by equilibrating the groundwater systems with various concentrations of two commonly occurring natural sorbents: ferric oxyhydroxide and particulate organic matter (POM). Although other sorbents such as clay minerals, carbonate minerals, hydrous aluminum and manganese oxides, and silica may sorb metals in the subsurface, representation of ferric oxyhydroxide and

particulate organic matter in the model is sufficient to provide a conservative assessment of the sorption capacity of most natural groundwater systems.

CCR leachate can include elevated concentrations of inorganic constituents such as calcium, sulfate, sodium, potassium, and chloride. Elevated concentrations of iron and manganese also occur in certain types of leachate. Upon mixing with groundwater, elevated concentrations of leachate constituents may reduce sorption of metals due to competition for sorption sites or complexation with metals in solution. The influence of elevated concentrations of leachate constituents on K_d estimates was included in the modeling by adding leachate components at concentrations representative of CCR leachate. In this way, the MINTEQA2 model systems included competitive sorption reactions, metal complexation, and elevated ionic strength effects from CCR leachate in computing the K_d values.

2.1 Characterization of Model Groundwater Systems

The extent of contaminant sorption in a groundwater system is dependent upon the chemical characteristics of the porewater solution and the interactions between all solutes and the sorbing sites present on the exposed surfaces of the soil and aquifer matrix material. Here, partition coefficients were estimated separately for two groundwater compositional types, one with composition representative of a carbonate-terrain system and one representative of a noncarbonate system. The two groundwater compositional types are correlated with the hydrogeologic environment parameter in EPACMTP. In EPACMTP, this parameter may take on 1 of 13 values, each indicative of a particular groundwater type (see **Table 2**). Issues of practicality limit the number of groundwater types for which separate partition coefficients can be estimated to just two. The broadest division that may be made of the 13 groundwater types in EPACMTP is carbonate and noncarbonate. Thus, coefficients were estimated for these two broad types. The carbonate type corresponds to the "solution limestone" hydrogeologic environment setting in EPACMTP (hydrogeologic environment parameter = 12). The other 12 possible hydrogeologic settings in EPACMTP are represented by the noncarbonate groundwater type.

Table 2. Settings for the Hydrogeologic Environment Parameter in EPACMTP

Hydrogeologic Environment Parameter	Environment (Groundwater Type) Represented
1	Metamorphic and Igneous (noncarbonate)
2	Bedded Sedimentary Rock (noncarbonate)
3	Till Over Sedimentary Rock (noncarbonate)
4	Sand and Gravel (noncarbonate)
5	Alluvial Basins Valleys and Fans (noncarbonate)
6	River Valleys and Floodplains with Overbank Deposits (noncarbonate)

(continued)

Table 2. Settings for the Hydrogeologic Environment Parameter in EPACMTP

Hydrogeologic Environment Parameter	Environment (Groundwater Type) Represented
7	River Valleys and Floodplains without Overbank Deposits (noncarbonate)
8	Outwash (noncarbonate)
9	Till and Till Over Outwash (noncarbonate)
10	Unconsolidated and Semi-consolidated Shallow Aquifers (noncarbonate)
11	Coastal Beaches (noncarbonate)
12	Solution Limestone (carbonate)
13	Others (unclassified hydrogeologic environments) (noncarbonate)

2.1.1 Model Groundwater Composition

For both groundwater types, representative charge-balanced groundwater chemistry specified in terms of major ion concentrations and natural pH was selected from the literature. The carbonate system was represented by a well sample reported for a limestone aquifer (Freeze and Cherry, 1979). This groundwater had a natural pH of 7.5 and was saturated with respect to calcite. The noncarbonate system was represented by a sample reported from an unconsolidated sand and gravel aquifer with a natural pH of 7.4 (White et al., 1963). An unconsolidated sand and gravel aquifer was selected to represent the noncarbonate compositional type because it is the most frequently occurring of the 12 (noncarbonate) hydrogeologic environments in EPACMTP. The compositions of both the carbonate and noncarbonate representative groundwater samples are shown in **Table 3**. These compositions were used in MINTEQA2 to estimate partition coefficients for carbonate and noncarbonate groundwater types. When EPACMTP is used in site-specific or Monte Carlo mode, the choice of the hydrogeologic environment by the user (or the Monte Carlo routine) dictates the set of partition coefficients (carbonate or noncarbonate) that should be accessed.

Table 3. Composition of Representative Ground Waters

Constituent Chemical	Concentrations (mg/L)	
	Carbonate Groundwater	Noncarbonate Groundwater
Ca	55	49
Mg	28	13
SO_4	20	27
HCO_3	265	384
Na	3.1	105
Cl	10	34

(continued)

Table 3. Composition of Representative Ground Waters

Constituent Chemical	Concentrations (mg/L)	
	Carbonate Groundwater	Noncarbonate Groundwater
K	1.5	3.0
NO_3	---	7.8
F	---	0.3
SiO_2	---	21
pH	7.5	7.4
Temp	18 C	14 C
Other	Equilibrium with calcite	Equilibrium with quartz

2.1.2 Model Adsorbents

Two types of adsorbents were represented in the MINTEQA2 equilibrium modeling: ferric oxide and POM. FeOx (and hydroxides) and POM are among the most important sorbents in natural systems. The former may be present as amorphous substances or crystalline minerals such as hematite, goethite, or ferrihydrite dispersed in soil as discrete particles or as coatings on particles of other materials. In recent years, databases of equilibrium sorption reactions for HFO and goethite have been compiled from studies described in the literature (Dzombak and Morel, 1990; Mathur, 1995). Both of the databases cited were designed for use with the MIT Two-Layer sorption model, also called the diffuse-layer model (DLM; Dzombak and Morel, 1990).

Owing to the complexity and variability of natural organic substances, the science of modeling surface reactions on POM is less advanced than for sorption onto hydrous metal oxides. The modeling described here assumes that reactions on POM are analogous to those on dissolved organic matter (DOM); a DOM model was adapted for the POM calculation. This model, the Gaussian distribution model (Dobbs et al., 1989), assumes that organic matter is a complex mixture of substances exhibiting highly variable binding affinities for metals. Reactions are represented like conventional pure substance reactions except that the usual single equilibrium constant is replaced by a distribution of constants (log K values). The distribution of log K is assumed to be Gaussian in shape. This model is also supplied with a database of reactions, including acid-base and major ion reactions, each with its mean log K for depicting the Gaussian distribution.

When included in equilibrium models, these databases of sorption reactions provide a means of including competition for sorption sites among major groundwater ions such as calcium, magnesium, and SO_4 and contaminants. More importantly, by including in equilibrium calculations the acid-base reactions for these surfaces, the dependence of trace metal sorption on pH can be reflected in the model.

Goethite Sorbent

Mineralogically, the FeOx sorbent was assumed to be goethite (α-FeOOH). Goethite is a common form of FeOx in soils. The database of sorption reactions for goethite reported by Mathur (1995) was used with the diffuse-layer sorption model in MINTEQA2 to represent the interactions of protons, major ions, and contaminant with the FeOx surface.

The concentration of sorption sites used in the MINTEQA2 model runs was based on a measurement of ferric iron extractable from soil samples using hydroxylamine hydrochloride as reported in EPRI (1986). This method of iron extraction is intended to provide a measure of the exposed FeOx present as mineral coatings and discrete particles and available for surface reactions with solutes in the associated pore water. The variability in FeOx sorbent concentration represented by the variability in extractable iron from these samples was included in the modeling by selecting low, medium, and high extractable iron concentrations corresponding to the 17th, 50th, and 83rd percentiles of the sample measurements. The extractable iron weight percentages used in the modeling are shown in **Table 4**.

Table 4. Concentration Levels for Goethite Sorbent

Concentration Level	Weight Percent Iron (extractable)	Geothite Sorbent Concentration (g/L)
Unsaturated zone		
Low	0.0182	1.325
Medium	0.0729	5.309
High	0.1190	8.667
Saturated zone		
Low	0.0182	1.032
Medium	0.0729	4.136
High	0.1190	6.751

Although the same distribution of extractable iron sorbent was used in modeling the saturated and unsaturated zones, the actual concentration of sorbing sites corresponding to the low, medium, and high FeOx settings in MINTEQA2 was different in the two zones because the assumed ratio of soil mass to solution volume (the phase ratio) was different. For both zones, the phase ratio was calculated as the mean soil bulk density divided by the mean water content (product of mean porosity and mean water saturation). In EPACMTP, the mean soil bulk density and mean porosity are 1.6 kg/L and 45 percent, respectively. The mean water saturation in the unsaturated zone is 77.7 percent. The water saturation in the saturated zone is, of course, 100 percent. Thus, the phase ratio for the unsaturated zone is 4.57 kg/L and that for the saturated zone is 3.56 kg/L. These values and the molar mass ratio of goethite to Fe were used to convert the weight percent extractable iron to the mass of goethite appropriate for 1 liter of porewater solution (see Table 4).

The specific surface area and site density used in the diffuse-layer adsorption model were as prescribed by Mathur (1995) for goethite. These values along with the molar concentration of FeOx sorbing sites are shown in **Table 5**. The complete database of goethite sorption reactions used in MINTEQA2, including acid-base surface reactions and reactions for major ions, is shown in **Table 6**. The reactions shown in Table 6 have been reformulated for use in MINTEQA2. The

reformulation step is necessary in order to present the reaction to MINTEQA2 in a manner consistent with its database conventions and its predetermined set of reactants (components. The MINTEQA2 conventions include the requirement that all reactions be written as formation reactions. In some cases, the reformulation may have involved adding ancillary reactions to those presented by Mathur (1995). The addition of ancillary reactions is necessary if the original reaction is not written in terms of MINTEQA2 components. All ancillary reactions used to reformulate the Mathur (1995) goethite reactions were obtained directly from the MINTEQA2 (v4.02) thermodynamic database.

Table 5. Model Parameters for the Goethite Sorbent

Parameter	Model Value
Specific surface area (m^2/g)	60
Site density (moles of sites per mole Fe)	0.018
Unsaturated zone: Site concentration (mol/L)	
Low	2.680×10^{-4}
Medium	1.074×10^{-3}
High	1.753×10^{-3}
Saturated zone: Site concentration (mol/L)	
Low	2.087×10^{-4}
Medium	8.365×10^{-4}
High	1.365×10^{-3}

Table 6. Goethite Sorption Reactions Used in MINTEQA2

Goethite Sorption Reaction	Intrinsic Equilibrium Constant
$\equiv FeOH_2^+ = \equiv FeOH^o + H^+$	$\log K_{a1} = 6.93$
$\equiv FeOH^o = \equiv FeO^- + H^+$	$\log K_{a2} = -9.65$
$\equiv FeOH^o + Ca^{2+} = \equiv FeOCa^+ + H^+$	$\log K_1 = -6.48$
$\equiv FeOH^o + Ca^{2+} = \equiv FeOHCa^{2+}$	$\log K_2 = 3.98$
$\equiv FeOH^o + Ca^{2+} + H^+ = \equiv FeOCa^+ + H_2O$	$\log K_3 = 12.26$
$\equiv FeOH^o + Mg^{2+} = \equiv FeOMg^+ + H^+$	$\log K_1 = -3.02$
$\equiv FeOH^o + Mg^{2+} = \equiv FeOHMg^{2+}$	$\log K_2 = 5.24$
$\equiv FeOH^o + Ba^{2+} = \equiv FeOBa^+ + H^+$	$\log K_1 = -5.62$
$\equiv FeOH^o + Ba^{2+} = \equiv FeOHBa^{2+}$	$\log K_2 = 3.43$
$\equiv FeOH^o + Cd^{2+} = \equiv FeOCd^+ + H^+$	$\log K_1 = -1.96$
$\equiv FeOH^o + Cd^{2+} = \equiv FeOHCd^{2+}$	$\log K_2 = 6.28$

(continued)

Table 6. Goethite Sorption Reactions Used in MINTEQA2

Goethite Sorption Reaction	Intrinsic Equilibrium Constant
$\equiv FeOH^o + Pb^{2+} = \equiv FeOPb^+ + H^+$	$\log K_1 = 0.44$
$\equiv FeOH^o + Pb^{2+} = \equiv FeOHPb^{2+}$	$\log K_2 = 8.25$
$\equiv FeOH^o + Co^{2+} = \equiv FeOCo^+ + H^+$	$\log K_1 = -0.79$
$\equiv FeOH^o + Co^{2+} = \equiv FeOHCo^{2+}$	$\log K_2 = 7.28$
$\equiv FeOH^o + Hg(OH)_2^o = \equiv FeOHgOH^o + H_2O$	$\log K_0 = 2.86$
$\equiv FeOH^o + Hg(OH)_2^o + H^+ = \equiv FeOHg^+ + 2\ H_2O$	$\log K_1 = 10.03$
$\equiv FeOH^o + Hg(OH)_2^o + 2H^+ = \equiv FeOHHg^{2+} + 2\ H_2O$	$\log K_2 = 18.58$
$\equiv FeOH^o + Hg(OH)_2^o + H^+ + Cl^- = \equiv FeOHgCl^o + 2\ H_2O$	$\log K_4 = 13.51$
$\equiv FeOH^o + Tl^+ = \equiv FeOTl^o + H^+$	$\log K_1 = -5.37$
$\equiv FeOH^o + Tl^+ = \equiv FeOHTl^+$	$\log K_2 = 3.66$
$\equiv FeOH^o + Cu^{2+} = \equiv FeOCu^+ + H^+$	$\log K_1 = 1.39$
$\equiv FeOH^o + Cu^{2+} = \equiv FeOHCu^{2+}$	$\log K_2 = 8.92$
$\equiv FeOH^o + Mn^{2+} = \equiv FeOMn^+ + H^+$	$\log K_1 = -2.66$
$\equiv FeOH^o + Mn^{2+} = \equiv FeOHMn^{2+}$	$\log K_2 = 5.99$
$\equiv FeOH^o + Fe^{2+} = \equiv FeOFe^+ + H^+$	$\log K_1 = -1.43$
$\equiv FeOH^o + Fe^{2+} = \equiv FeOHFe^{2+}$	$\log K_2 = 7.05$
$\equiv FeOH^o + Zn^{2+} = \equiv FeOZn^+ + H^+$	$\log K_1 = -0.96$
$\equiv FeOH^o + Zn^{2+} = \equiv FeOHZn^{2+}$	$\log K_2 = 7.50$
$\equiv FeOH^o + Ni^{2+} = \equiv FeONi^+ + H^+$	$\log K_1 = -1.96$
$\equiv FeOH^o + Ni^{2+} = \equiv FeOHNi^{2+}$	$\log K_2 = 6.38$
$\equiv FeOH^o + Be^{2+} = \equiv FeOBe^+ + H^+$	$\log K_1 = 2.69$
$\equiv FeOH^o + Be^{2+} = \equiv FeOHBe^{2+}$	$\log K_2 = 10.61$
$\equiv FeOH^o + Ag^+ = \equiv FeOAg + H^+$	$\log K_1 = -4.11$
$\equiv FeOH^o + Ag^+ = \equiv FeOHAg^+$	$\log K_2 = 4.74$
$\equiv FeOH^o + VO_2^+ + H_2O = \equiv FeH_2VO_4^o + H^+$	$\log K_1 = 2.35$
$\equiv FeOH^o + VO_2^+ + H_2O = \equiv FeHVO_4^- + 2H^+$	$\log K_2 = -5.91$
$\equiv FeOH^o + VO_2^+ + 2H_2O = \equiv FeOHVO_4^{3-} + 4H^+$	$\log K_3 = -17.53$
$\equiv FeOH^o + H_3AsO_3^o = \equiv FeH_2AsO_3^o + H_2O$	$\log K_1 = 4.33$
$\equiv FeOH^o + H_3AsO_4^o = \equiv FeH_2AsO_4^o + H_2O$	$\log K_1 = 6.87$
$\equiv FeOH^o + H_3AsO_4^o = \equiv FeHAsO_4^- + H^+ + H_2O$	$\log K_2 = -0.89$
$\equiv FeOH^o + H_3AsO_4^o = \equiv FeOHAsO_4^{3-} + 3H^+$	$\log K_4 = -11.09$
$\equiv FeOH^o + Sb(OH)_6^- + H^+ = \equiv FeOH_2Sb(OH)_6^o$	$\log K_1 = 11.94$
$\equiv FeOH^o + Sb(OH)_6^- = \equiv FeOHSb(OH)_6^-$	$\log K_2 = 5.76$
$\equiv FeOH^o + SO_4^{2-} + 2H^+ = \equiv FeHSO_4^o + H_2O$	$\log K_1 = 12.89$
$\equiv FeOH^o + SO_4^{2-} + H^+ = \equiv FeSO_4^- + H_2O$	$\log K_2 = 6.74$

(continued)

Table 6. Goethite Sorption Reactions Used in MINTEQA2

Goethite Sorption Reaction	Intrinsic Equilibrium Constant
$\equiv FeOH^o + SO_4^{2-} = \equiv FeOSO_4^{3-} + H^+$	$\log K_4 = -6.26$
$\equiv FeOH^o + HSeO_3^- + H^+ = \equiv FeHSeO_3^o + H_2O$	$\log K_1 = 3.25$
$\equiv FeOH^o + HSeO_3^- = \equiv FeSeO_3^- + H_2O$	$\log K_2 = 2.09$
$\equiv FeOH^o + HSeO_3^- = \equiv FeOSeO_3^{3-} + 2H^+$	$\log K_4 = -14.25$
$\equiv FeOH^o + SeO_4^{2-} + 2H^+ = \equiv FeHSeO_4^o + H_2O$	$\log K_1 = 11.65$
$\equiv FeOH^o + SeO_4^{2-} + H^+ = \equiv FeSeO_4^- + H_2O$	$\log K_2 = 6.54$
$\equiv FeOH^o + MoO_4^{2-} + 2H^+ = \equiv FeHMoO_4^o + H_2O$	$\log K_1 = 14.65$
$\equiv FeOH^o + MoO_4^{2-} + H^+ = \equiv FeMoO_4^- + H_2O$	$\log K_2 = 8.18$
$\equiv FeOH^o + CrO_4^{2-} + 2H^+ = \equiv FeHCrO_4^o + H_2O$	$\log K_1 = 17.11$
$\equiv FeOH^o + CrO_4^{2-} + H^+ = \equiv FeCrO_4^- + H_2O$	$\log K_2 = 11.17$
$\equiv FeOH^o + CrO_4^{2-} = \equiv FeOHCrO_4^{2-}$	$\log K_3 = 4.05$
$\equiv FeOH^o + Cr(OH)_2^+ = \equiv FeOCrOH^+ + H_2O$	$\log K_1 = 8.072$
$\equiv FeOH^o + Cr(OH)_2^+ + H^+ = \equiv FeOHCrOH^{2+} + H_2O$	$\log K_2 = 16.07$
$\equiv FeOH^o + F^- + H^+ = \equiv FeOH_2F$	$\log K_1 = 9.20$
$\equiv FeOH^o + F^- = \equiv FeOHF^-$	$\log K_2 = 1.59$

Particulate Organic Matter Sorbent

The concentration of the second adsorbent, POM, was obtained from organic matter distributions already present in EPACMTP. EPACMTP includes frequency distributions for organic matter for three soil types in the unsaturated zone: silty clay loam, sandy loam, and silty loam. The silty loam soil type is intermediate in weight percent organic matter in comparison with the other two and is the most frequently occurring soil type. Therefore, low, medium, and high POM content levels for the MINTEQA2 modeling in the unsaturated zone were established as the 7.5th, 50th, and 92.5th percentiles of the silty loam organic matter distribution. In the saturated zone, the EPACMTP distribution of organic matter is identical to that for the sandy loam soil type of the unsaturated zone. Low, medium, and high POM content levels in MINTEQA2 modeling of the saturated zone were established as the 7.5th, 50th, and 92.5th percentile levels, respectively, of this distribution.

As was the case for the goethite sorbent, the concentration of POM included in the MINTEQA2 modeling was determined from the low, medium, and high content levels (expressed in weight percent POM) and the mass of soil appropriate for 1 liter of porewater solution (see **Section 2.1.2**). Thus, phase ratios of 4.57 kg/L in the unsaturated zone and 3.56 kg/L in the saturated zone were used to compute the POM concentration for MINTEQA2 model runs.

A dissolved organic carbon (DOC) distribution for the saturated zone was obtained from the U.S. EPA STORET database. This distribution is based on 1,343 groundwater samples and is approximated by a log normal distribution with a median $\log_e$ DOC of 1.974 (corresponding to 7.2 mg C per liter) and $\log_e$ standard deviation of 1.092. Assuming DOM is approximately 50 percent

organic carbon, the DOC values are multiplied by two to approximate DOM concentrations. The MINTEQA2 modeling employed low, medium, and high concentrations for DOM corresponding to the 7.5th, 50th, and 92.5th percentiles, respectively, of this approximated DOM distribution. An important point to note is that POM and DOM were not treated as independent variables in the MINTEQA2 modeling: the high DOM value was associated with the high POM value, the medium DOM with the medium POM, etc.

Because no directly measured data were available for describing the variation in DOM concentration in the unsaturated zone, high, medium, and low DOM concentrations were assumed to reflect a constant ratio of POM content (in weight percent) to DOM concentration. The constant ratio was arbitrarily chosen as the ratio of the median DOM (mg/L) from the saturated zone distribution to the median value of POM (weight percent) from the saturated zone distribution. This ratio, 194.6, was applied to the low, medium, and high weight percent POM values of the unsaturated zone to obtain DOM concentrations at the low, medium, and high levels. The weight percent POM and concentration (mg/L) of both POM and DOM are shown in **Table 7** for all three concentration levels in both zones.

Table 7. POM and DOM Concentration Levels

POM Category	POM wt%	POM Concentration (mg/L)	DOM Concentration (mg/L)
Unsaturated zone			
Low	0.034	1,553.8	6.6
Medium	0.105	4,798.5	20.4
High	0.325	14,852.5	63.2
Saturated zone			
Low	0.02	712	3
Medium	0.074	2,634.4	14.4
High	0.275	9,790	69.38

For both POM and DOM, a site density of 1.2 x 10^{-6} moles of sites per mg organic matter was assumed. The site concentrations for organic matter in both zones are listed in **Table 8**.

Table 8. Site Concentrations for POM and DOM Components in MINTEQA2

POM Category	POM Site Concentration (mol/L)	DOM Site Concentration (mol/L)
Unsaturated zone		
Low	1.865 x10-3	7.896 x10-6
Medium	5.758 x10-3	2.439 x10-5
High	1.782 x10-2	7.548 x10-5
Saturated zone		
Low	8.544×10^{-4}	3.600×10^{-6}
Medium	3.161×10^{-3}	1.728×10^{-5}
High	1.175×10^{-2}	8.326×10^{-5}

A specialized submodel within MINTEQA2 was used for calculations involving the POM and DOM. This submodel, called the Gaussian distribution model, assumes that natural organic matter is a mixture of various functional groups having a mean log K for binding protons and metals and a standard deviation in log K (Dobbs et al., 1989). This is in contrast to all other reactants in MINTEQA2, which are implicitly treated as pure substances with a single equilibrium constant for a particular metal. A database of DOM reactions proposed by Susetyo et al. (1991) for the metals barium, cadmium, chromium (III), copper, lead, nickel, and zinc and for protons and various other MINTEQA2 components is included with v4.02 of the model. Adsorption of metals onto POM was included in the model calculations by assuming that the reactions were identical to those for metal complexation with DOM. **Table 9** shows Gaussian organic matter reactions used in MINTEQA2 for this work. Although the Gaussian model was proposed for metal–DOM reactions, it has been used here to account for metal–POM reactions as well. The only difference between the method of calculation for metal–DOM and metal–POM species in MINTEQA2 was that POM species were excluded from contributing to the ionic strength.

For the metals cobalt, mercury, and thallium, it was necessary to estimate the mean log K for DOM and POM binding for use in MINTEQA2. The mean log K values for cobalt and thallium were derived from a linear free-energy relationship based upon the known mean log K values for several metals, their first hydrolysis constants, and their log K values for complexation with acetate. For mercury, the mean log K was estimated from a linear regression based on binding constants for humic and fulvic acid as given by Tipping (1994).

Table 9. POM and DOM Reactions Included in MINTEQA2 Modeling

Organic Matter (OM) Reaction	Mean log K	Standard Deviation	Species Charge
OM+ H^+ = OM-H	3.87	1.7	-1.8
OM+ Ca^{2+} = OM-Ca	2.9	1.7	-0.8
OM+ Mg^{2+} = OM-Mg	1.9	1.7	-0.8
OM+ Ba^{2+} = OM-Ba	3.1	1.7	-0.8
OM+ Be^{2+} = OM-Be	3.5	1.7	-0.8
OM+ Cd^{2+} = OM-Cd	3.3	1.7	-0.8
OM+ Al^{3+} = OM-Al	5.2	1.7	0.2
OM+ $Cr(OH)2^+ + 2H^+$ = OM-Cr + $2H_2O$	15.22	1.7	0.2
OM+ Cu^{2+} = OM-Cr	4.9	1.7	-0.8
OM+ Pb^{2+} = OM-Pb	5.2	1.7	-0.8
OM+ Ni^{2+} = OM-Ni	3.3	1.7	-0.8
OM+ $Hg(OH)_2^o$ + $2H^+$ = OM-Hg+$2H_2O$	15.2	1.7	-0.8
OM+ Zn^{2+} = OM-Zn	3.5	1.7	-0.8
OM+ Co^{2+} = OM-Co	3.3	1.7	-0.8
OM+ Fe^{2+} = OM-Fe	3.4	1.7	-0.8
OM+ Mn^{2+} = OM-Mn	3.0	1.7	-0.8
OM+ Ag^+ = OM-Ag	2.0	1.7	-1.8
OM+ Tl^+ = OM-Tl	1.0	1.7	-1.8

2.2 Characterization of Model CCR Leachate

Leachate from CCR landfills and impoundments is known to span a broad pH range and to exhibit highly variable concentrations of inorganic ions. Preliminary to the CCR risk assessment modeling, EPA assembled a constituent database with CCR leachate characteristics encompassing many types of CCR wastes. The database includes analyte concentration data for three types of analyses: (1) analysis of landfill leachate from toxicity characteristic leaching procedure (TCLP), synthetic precipitation leaching procedure (SPLP), or other leaching/extraction methods; (2) analysis of surface impoundment and landfill porewater; and (3) analysis of whole waste samples from landfills and other sources. Each of these three analysis types includes waste samples from various locations representing different coal source types (bituminous, subbituminous, lignite, anthracite), different combustion processes (fluidized bed combustion [FBC], flue gas desulfurization [FGD], Na FGD, non-FBC) or combustion product types (fly ash, bottom ash, combined fly ash and bottom ash, slag, mixed ash and coal waste, and ash not otherwise specified). (Please refer to **Appendix C** for a more detailed discussion of the CCR database.)

The analysis type assumed to best represent long-term waste monofill porewater composition is the landfill and surface impoundment porewater data. Accordingly, the porewater analyte concentration data were examined to identify which constituents exhibit significantly elevated concentrations and to identify trends in concentration levels among samples from different coal source types, combustion process types, and combustion product types. MINTEQA2 sensitivity runs using extremes of analyte concentrations from the porewater data were used to determine which analytes were most likely to influence estimated K_d values. Results indicated that calcium, SO_4, sodium, and chlorine were the analytes most likely to affect partitioning. Consequently, multivariate statistical analyses were performed to identify trends in concentrations of these analytes and pH across all coal source types (bituminous, subbituminous, etc.), combustion process types (FBC, non-FBC, FGD, etc.), and combustion product types (fly ash, bottom ash, etc.). Single-variable analyses for each of the dependent variables (pH, calcium, SO_4, sodium, chlorine concentrations) were also performed because few samples presented measurements for all five dependent variables. The goal of these analyses was to evaluate similarities among these diverse samples with regard to the dependent variables for the purpose of choosing leachate chemistries for use in MINTEQA2 modeling.

Results of the statistical analyses and geochemical judgment were used to select four representative leachate chemistries. The most statistically significant differences in the porewater data for the five dependent variables occurred across combustion process type, especially FBC versus non-FBC. Statistically significant differences across coal source type occurred, but these were not consistent across combustion process or product types. Examination of the five dependent variables and the concentrations of other analytes in the porewater data and consideration of the result from the statistical analysis led to the following four choices to represent leachate chemistries:

- Leachate 1 (L1): Ash and Coal Refuse
  Characterized by low to mid pH (1.7–8.2), high SO4, elevated iron and manganese.
- Leachate 2 (L2): FBC Waste
  Characterized by very high pH (12–13), high calcium, high SO4, some CO3, may have high sodium, potassium, and chlorine
- Leachate 3 (L3): FGD Waste
  Characterized by mid to high pH (8.7–11.3), high calcium, high SO_4, high sodium, high chlorine
- Leachate 4 (L4): Combined Ash
  As a reflection of various CCR codisposal practices, this group has more variability in pH (3.9–12.3), calcium, and SO_4

The landfill and surface impoundment porewater data were grouped according to these categories. Within each category, plots of sum of anions versus sum of cations (in equivalents per liter) were prepared to assess the degree of charge balance (see example in **Figure 3**).

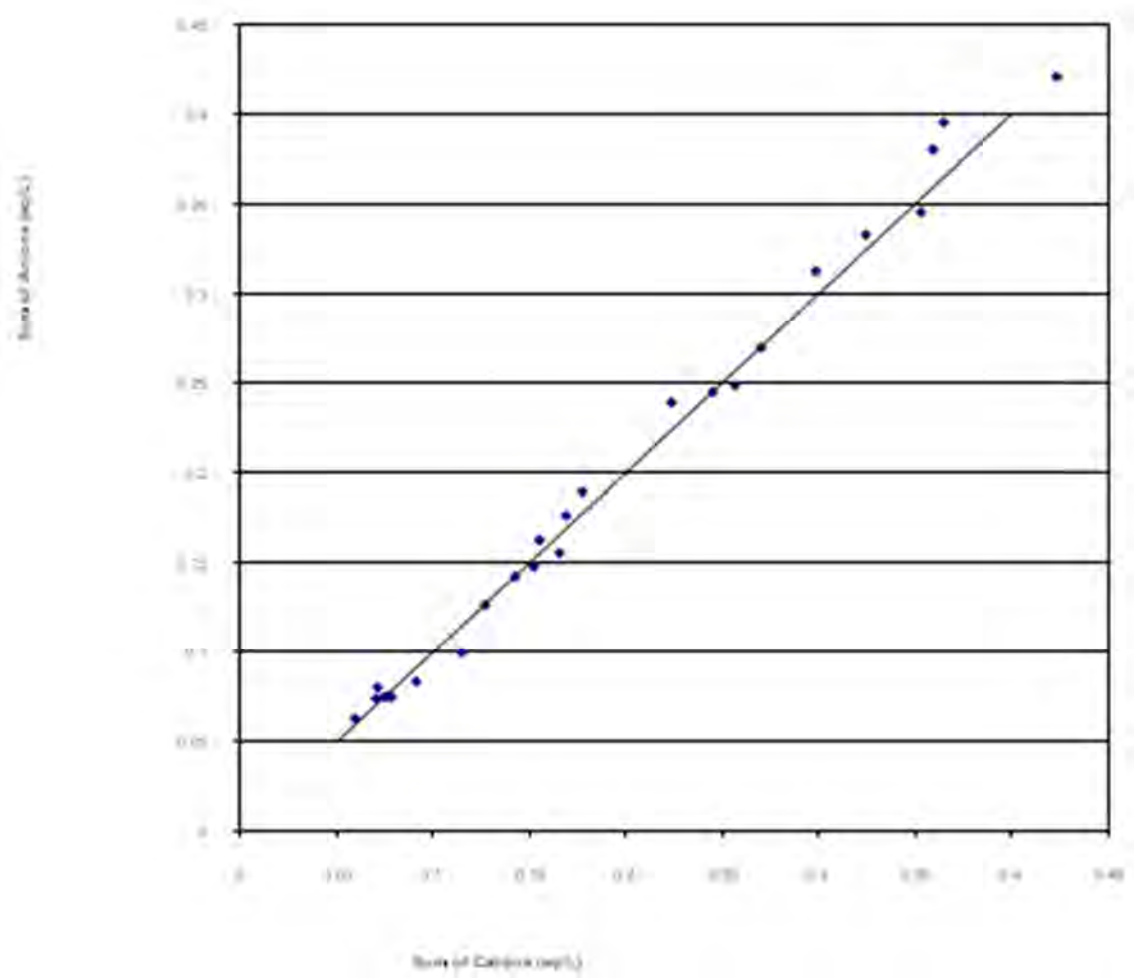

Figure 3. Sum of anions versus sum of cations plotted to assess charge balance of sample.

Although these four leachate categories served to segregate the data in accord with measurements likely to impact K_d values, considerable variability in important analyte concentrations occurred within each leachate type. Therefore, within each of the leachate categories, three representative samples were selected based on sum of anions. (Because the samples were reasonably well charge balanced, selection based on sum of cations would have resulted in the same selected samples.) Selection based on sum of anions (or cations) is analogous to selection based on ionic strength or overall leachate "richness." The samples within each of the four leachate categories were ranked according to sum of anions and the sample closest to the 17th, 50th, and 83rd percentiles were selected and labeled low, medium, and high. The composition (all major ions) of each of the low, medium, and high samples was made available to the MINTEQA2 model in the runs used to estimate K_d (see modeling procedure section below). **Table 10** gives the composition of each of the low, medium, and high porewater samples for each of the four leachate types.

Table 10. Composition of Four Leachates at Three Concentrations Levels

Analyte	Low (mg/L)	Medium (mg/L)	High (mg/L)
L1: Codisposed Ash and Coal Refuse Leachate			
Ca	12.3	572.1	602.9
Mg	7.0	179.4	333.1
Na	3.1	12.4	71.7
K	4.2	41.8	447.7
SO4	387.0	6,231.7	53,918.0
Cl	1.7	19.4	11.1
Al	53.7	58.0	58.0
Fe (II)	0.2	2,050.0	22,394.0
Mn	0.9	52.7	30.4
L2: FBC Waste Leachate			
Ca	1,346.6	809.6	697.4
Mg	0.2	0.0	0.2
Na	87.8	1,425.4	4,023.2
K	208.4	2,040.9	4,457.2
SO4	1,498.6	3,640.8	9,606.4
Cl	52.1	535.3	1,138.0
CO3	678.1	960.1	1,524.2
Al	2.2	2.2	1.1
L3: FGD Waste Leachate			
Ca	952.0	93.7	604.5
Mg	161.0	0.6	812.5
Na	913.0	2,087.0	6,115.0
K	57.0	52.8	240.0
SO4	2,040.0	4,611.0	9,630.0
Cl	898.0	29.9	4,880.0
Al	0.3	3.1	0.1
L4: Combined Ash Leachate			
Ca	159.9	250.0	500.0
Mg	21.7	0.5	0.5
Na	48.0	200.0	840.0
K	60.9	1,200.0	3,000.0
SO4	223.5	1,800.0	4,100.0
Cl	109.0	610.0	2,000.0
Al	0.3	0.1	0.1

3 MINTEQA2 Modeling Procedure

The MINTEQA2 modeling was conducted separately for each of the 22 contaminants selected for the full-scale groundwater risk assessment (see Table 1 in **Section 1.2**). For each contaminant, the modeling was performed separately for the unsaturated and saturated zones for each of the two groundwater chemistries (carbonate and noncarbonate). Thus, results were produced in four main categories: the carbonate unsaturated zone, the carbonate saturated zone, the noncarbonate unsaturated zone, and the noncarbonate saturated zone. Within each of these four categories, separate results were produced for each of the four leachate types discussed in **Section 2.2**. A similar modeling procedure was followed for all contaminants, groundwater chemistries, hydrologic zones, and leachate types. The modeling procedure consisted of two steps, each involving execution of the MINTEQA2 model. First, the sorbents were pre-equilibrated with the groundwater at the natural groundwater pH. This step was performed with original "pristine" groundwater at the ambient pH of the original groundwater for both carbonate and noncarbonate systems and before introduction of the contaminant and leachate. In the second step, leachate and the contaminant were added to the pre-equilibrated systems and the new equilibrium distribution of contaminant among dissolved, sorbed, and precipitated phases was computed.

3.1 Pre-equilibration with Sorbents

The goethite and POM sorbents were pre-equilibrated with the groundwater at all nine combinations of their concentration levels. Because the sorbents adsorb some of the noncontaminant ions present as groundwater constituents (calcium, magnesium, sulfate), it is to be supposed that the representative compositions used for both the carbonate and noncarbonate groundwaters reflect dissolved concentrations at equilibrium with an unknown sorbed concentration. The purpose of the pre-equilibration step is to estimate this unknown sorbed concentration so that it may be included with the total concentrations for these constituents in subsequent model runs. The method of discovering the sorbed concentrations for each of the groundwater constituents that undergoes sorption was trial and error. Specifically, MINTEQA2 was executed repeatedly with adjusted total concentrations of these sorbing constituents until the equilibrium dissolved concentration for each was equal to the measured dissolved concentrations reported for the groundwater. This trial and error pre-equilibration method was performed separately for each of nine possible combinations of the FeOx and POM sorbent concentrations (low FeOx, low POM; low FeOx, medium POM; etc.).

The pre-equilibration step was conducted at the natural pH of each groundwater with calcite imposed as an equilibrium mineral for the carbonate groundwater type and quartz imposed as an equilibrium mineral for the noncarbonate groundwater type. Small additions of inert ions (Na^+, K^+, NO_3^-, etc.) were added to maintain charge balance.

3.2 Equilibration with Leachate and Contaminants

The model representations of leachate and the contaminant were introduced to the pre-equilibrated groundwater model systems. In this step, the equilibrium pH was specified at a series of discrete values selected to span the range of expected pH values given the groundwater type and leachate type modeled. For each selected pH, a preliminary run was performed to estimate the ionic strength of the system being modeled, and subsequent model runs at ever increasing contaminant concentrations were constrained to this same ionic strength. Thus, each MINTEQA2 model execution to produce an isotherm for a particular contaminant was defined by the following selections of system variables:

- groundwater type (carbonate or noncarbonate)
- hydrologic zone (unsaturated or saturated)
- FeOx sorbent concentration level (low, medium, high)
- POM/DOM concentration level (low, medium, high)
- equilibrium pH (range depends on groundwater type and leachate type; see **Table 11**)
- leachate type (ash and coal refuse, FBC waste, FGD waste, or combined ash)
- leachate "richness" or ionic strength (low, medium, or high).

Table 11. Range of Equilibrium pH Values Used in Modeling

Waste Leachate Type	pH Range	
	Carbonate GW	Non-Carbonate GW
Ash and Coal Refuse	5.1–8.2	1.8–8.2
FBC Waste	5.1–12.6	4.5–12.6
FGD Waste	5.1–12.6	4.5–12.6
Combined Ash	5.1–12.6	4.5–12.6

For the purpose of establishing the concentration of calcium, magnesium, SO_4, sodium, and other leachate ions in the saturated zone, a constant dilution ratio of one part leachate to six parts groundwater was used for all modeling. For each system modeled (defined by the selections of system variables), the system was equilibrated at a series of 44 total concentrations of the contaminant spanning the range from 0.001 to 10,000 mg/L. The results were compiled as the equilibrium distribution of the contaminant among dissolved, sorbed, and precipitated fractions for each contaminant concentration. The compilation of the equilibrium contaminant distribution at a series of total contaminant concentrations was saved in a separate file indexed with the settings of all variables defining the system.

4 Results

The files containing the equilibrium dissolved, sorbed, and precipitated fractions, each indexed with the settings of all system variables, were compiled into a database for use in transport modeling using EPACMTP. The contaminant concentration in the dissolved and sorbed fractions, along with the corresponding total contaminant concentration, defines each nonlinear isotherm. All three concentrations (dissolved, sorbed, and precipitated) are made available for use in EPACMTP. The ratio of the equilibrium sorbed and dissolved concentrations recorded in the isotherm is the dimensionless K_d. For the sorbed fraction, the concentration recorded in the isotherm is the amount of contaminant sorbed *from* 1 liter of solution. Of course, this amount is also sorbed *onto* the mass of soil with which 1 liter was equilibrated. This mass is the phase ratio: 4.57 kg/L for the unsaturated zone and 3.56 kg/L for the saturated zone. The K_d in units of L/kg is thus computed by normalizing the dimensionless K_d by the appropriate phase ratio.

For each contaminant, the modeling resulted in 432 isotherms for the carbonate groundwater for the ash and coal refuse leachate type and 702 isotherms for all other leachate types. For the noncarbonate groundwater, 702 isotherms were produced for the ash and coal refuse leachate type and 756 for each of the other leachate types. Given the groundwater and leachate types, each isotherm corresponds to particular concentration levels of FeOx and POM sorbents, pH, and leachate richness. In Monte Carlo or site-specific mode, EPACMTP selects the appropriate isotherm based on the conditions being modeled. Isotherms were produced for all 22 contaminants listed in **Section 1.2**, Table 1.

Isotherms were computed for two environmentally relevant oxidation states of arsenic, selenium, and chromium. The different oxidation states of these contaminants exhibit differences in sorption behavior, but both arsenic and selenium tend always to behave as anions in groundwater. Separate human toxicity values have not been established for the two forms of these metals, and most of the available leachate data are based on total metal concentrations rather than concentrations of the individual species. Isotherms were generated for each to be used for separate model runs in EPACMTP to reflect the differences in fate and transport that could result depending on which form is predominant in a particular subsurface environment.

4.1 Example Isotherms

Example isotherms illustrating the influence of key variables on the estimated K_d values are shown in **Figures 4** through **8**. **Figure 4** shows K_d versus total As (V) concentration for the carbonate groundwater saturated zone for the combined ash leachate type at three levels of FeOx sorbent concentration. The isotherms plotted are for the medium level for leachate richness and the medium POM concentration level for pH 6.6. As expected, sorption is enhanced at the higher FeOx concentrations resulting in larger K_d values.

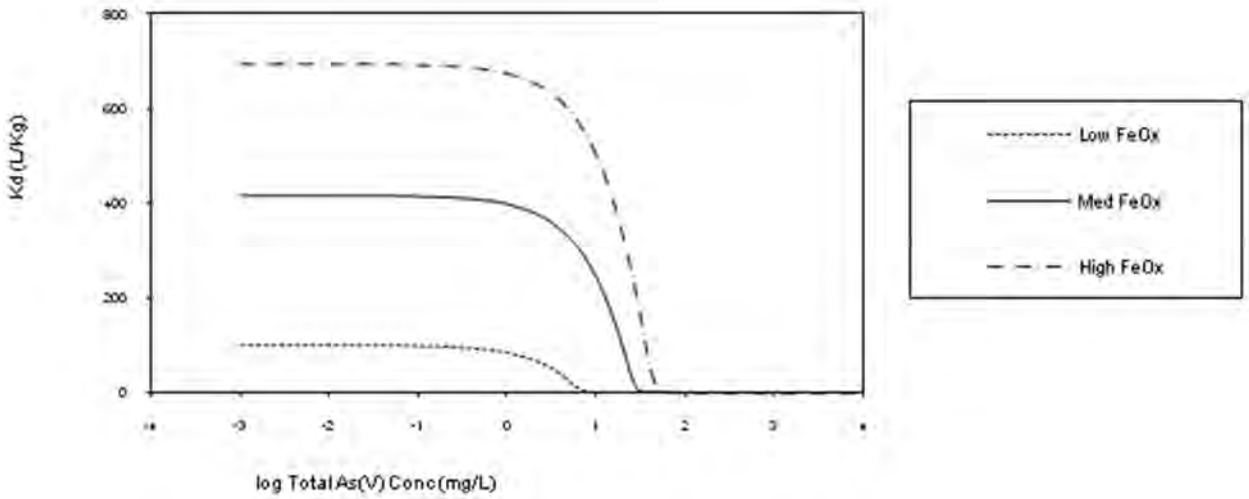

Figure 4. Estimated K_d versus total arsenic concentration for three FeOx sorbent concentration levels (combined ash).

The impact of varying the POM concentration level differs among the various metals. The effect of POM concentration level also depends on the pH. The variable impact of POM is due to two factors: the absence of organic matter reactions for anionic metals and the concurrent influence of DOM for those metals for which organic matter reactions are included. In the MINTEQA2 modeling procedure used here, increasing the POM sorbent concentration is always accompanied by a proportional increase in the DOM concentration. The overall impact on the amount of metal sorbed depends on the relative competition among all constituents in the systems for these two substances. The "winner" of this relative competition (POM or DOM) shifts with pH because both substances undergo acid-base reactions.

Figure 5 shows the impact of varying the POM/DOM concentration level on lead sorption for the noncarbonate groundwater unsaturated zone with medium FeOx concentration level and leachate richness level at pH 8.2. In this example, the highest POM level results in the highest K_d values. However, this is not true for all cases; the outcome due to increasing the POM is dependent on the aforementioned competition between the trace metal and major ions on all three sorbing surfaces (FeOx, POM, and DOM).

The influence of the leachate "richness" level is illustrated in **Figure 6** for cobalt sorption. Leachate richness refers to a general concentration level analogous to ionic strength. The low, medium, and high settings represent concentration levels for sum of anions. Figure 6 shows the K_d response for each of the three levels for the noncarbonate groundwater, unsaturated zone with ash and coal refuse leachate, and medium concentration levels of FeOx and POM sorbents. The pH for this example was 9.8.

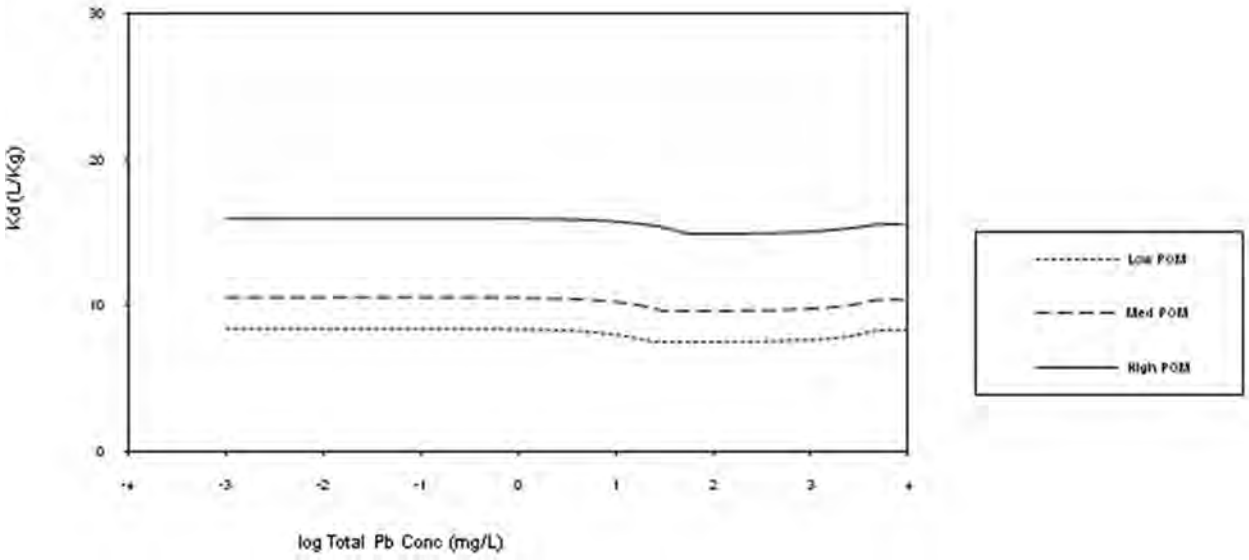

Figure 5. Estimated K_d versus total lead concentration for three POM/DOM concentration levels.

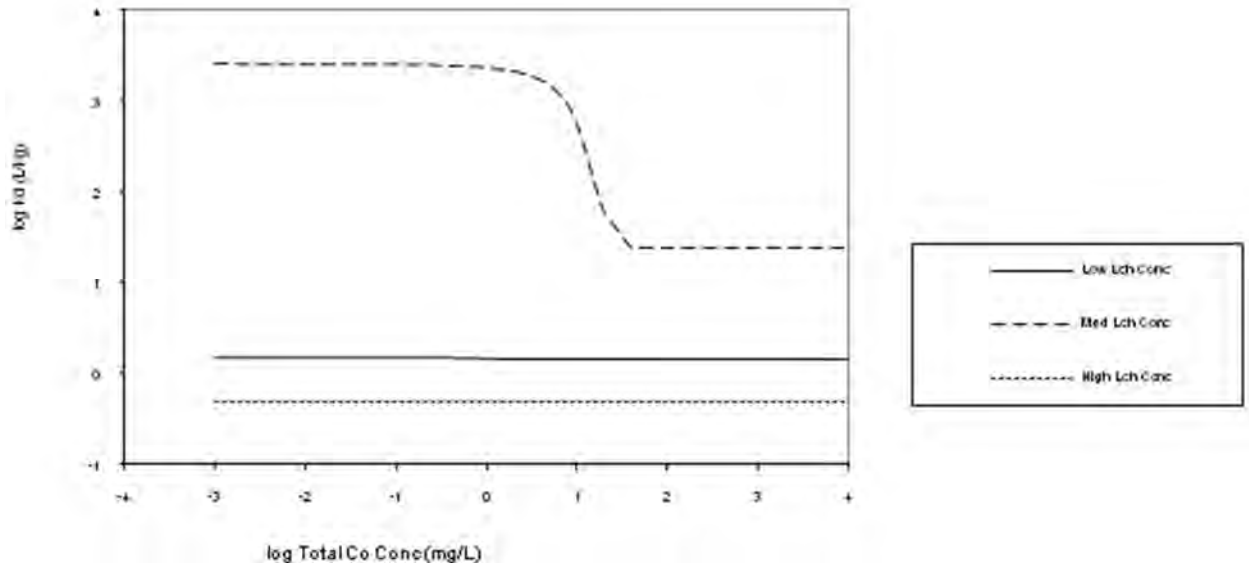

Figure 6. Estimated K_d versus total cobalt concentration for three different leachate richness levels (ash and coal refuse).

Figure 7 depicts the K_d versus pH for lead in a single system (noncarbonate groundwater, unsaturated zone, high FeOx and POM sorbent levels, medium leachate richness level for combined ash leachate type) at a single total lead concentration (0.001 mg). K_d values in this system increase steadily from pH 4 to 7, then increase more rapidly up to pH 9.8. After pH 9.8, K_d begins to decrease abruptly due to formation of lead-hydroxy solution species.

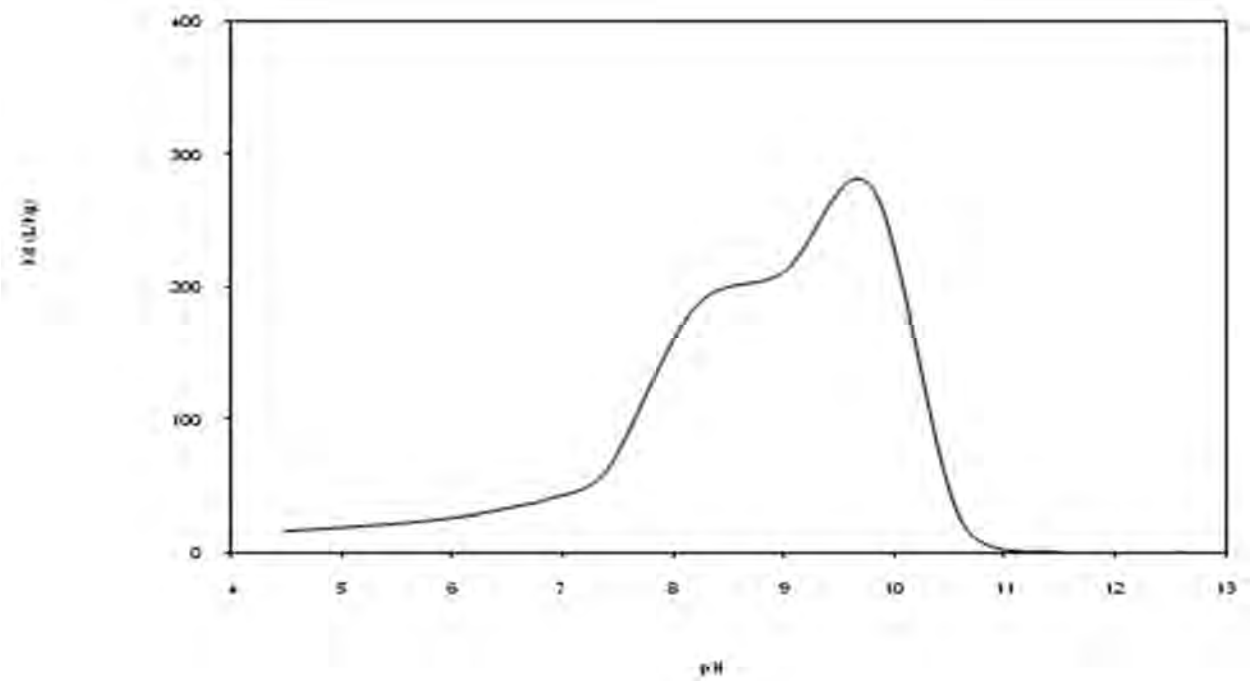

Figure 7. Estimated K_d versus pH for lead in a single system at a single total lead concentration (0.001 mg/L) (combined ash).

Figure 8 shows the K_d response for lead in a single system (noncarbonate groundwater, unsaturated zone, high FeOx and POM sorbent levels, and pH 8.2) for each of the four different waste leachate types at the high leachate richness level.

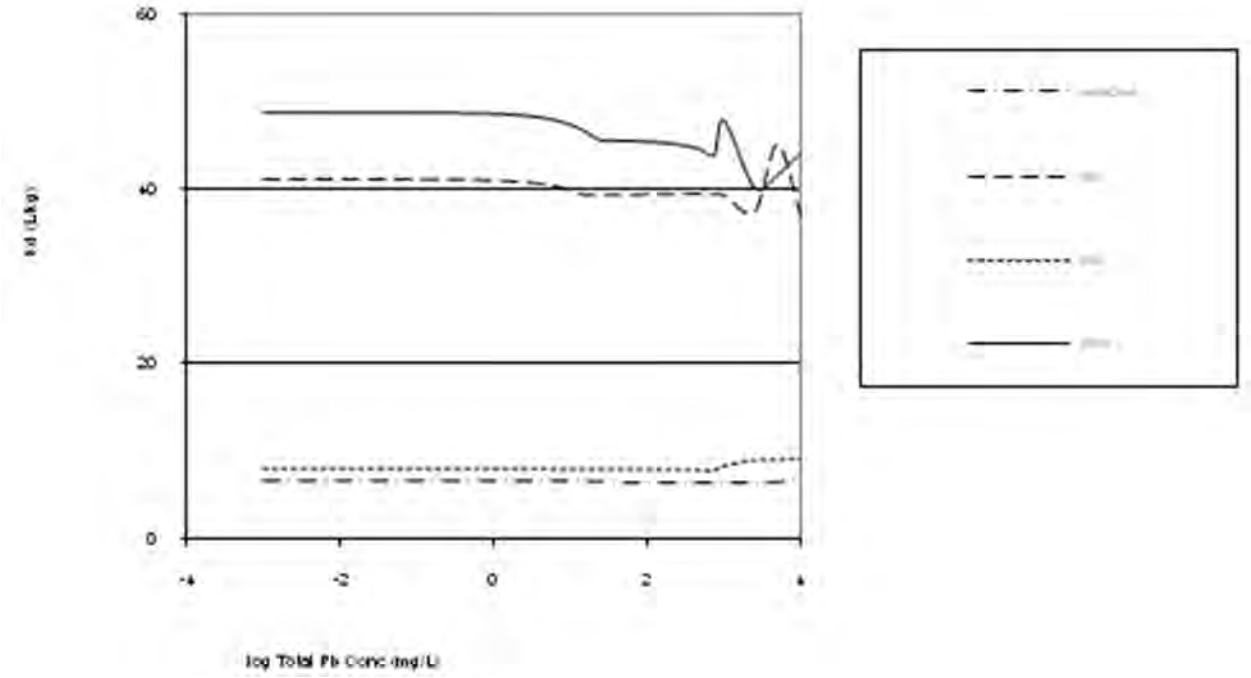

Figure 8. Estimated K_d versus pH for a single setting of system variables shown for each of four waste leachate types.

5 Assumptions and Limitations

Many assumptions are inherent in using a speciation model to estimate partition coefficients. Some of these must be acknowledged to result in limitations on the utility of the model results. Undoubtedly, the results are better for some contaminants than for others. Various modeling assumptions and limitations are presented below. These are organized as those resulting from the manner in which the groundwater composition, the sorbents, and the leachate were characterized and certain broader, more general issues. The discussion is limited to pointing out each assumption or limitation. Although the direction of possible error in the estimated K_d values is apparent from some of these limitations, it would be difficult to quantify the uncertainty in the estimated K_d values.

5.1 Groundwater Characterization Issues

- The categorization of all groundwater chemistries into two types, carbonate and noncarbonate, is quite broad. The noncarbonate category is especially broad, and sorption behavior among different groundwater compositions that might fall into this category could be quite variable. This variability is not accounted for in the current approach.
- Although the pre-equilibration step is helpful in more realistically establishing appropriate major ion concentrations, it is somewhat artificial in the sense that the concentrations of the sorbents are not correlated with groundwater major ion concentrations. Both the FeOx and POM sorbents were represented as general concentration distributions obtained from sources separate from the groundwater data. Therefore, the sorbent concentration levels used do not correlate specifically to the groundwater compositions used.
- Both groundwater chemistries were artificially adjusted to different pHs by simply specifying a desired equilibrium pH. Potassium, sodium, and nitrate were used to balance charge in this procedure, so the result should be analogous to titrating with strong acid or base. The degree to which this procedure can result in model groundwater chemistries that adequately represent true variability in factors that impact Kd is unknown.

5.2 Sorbent Characterization Issues

- Only two sorbents are represented in the model systems. Other sorbents are important in some circumstances, including clays, hydrous aluminum and manganese oxides, calcite, and silica. Failure to include all potential sorbents could result in underestimation of sorption.
- The FeOx was accounted in the modeling as goethite. Other FeOx may be important in groundwater, including HFO. HFO has a higher specific surface area and greater reactivity for some metals than does goethite. The degree of sorption may be underestimated for some contaminants in systems where HFO is the dominant form of FeOx. Also, equilibrium constants for adsorption onto goethite were unavailable for some contaminants; estimates were used.

- The data used to quantify the FeOx and POM sorbents (and the DOM) are sparse. The degree to which the true variability in concentration levels of these sorbents has been captured in the modeling is unknown.
- There is no provision in the modeling to account for occlusion of sorbents. Both FeOx and organic matter may form coatings over other surfaces. Failure to account for occlusion could result in overestimating the available sorption sites.
- The FeOx (goethite) sorbent is included in all model runs. This implies that it is ubiquitous. However, there are natural groundwater conditions that preclude the formation of FeOx precipitates. As illustrated in **Figure 9**, FeOx is not the stable iron solid phase at conditions of low pH and low Eh (oxidation/reduction potential), so these conditions are inconsistent with the use of FeOx as a sorbing phase. Including the goethite sorbent where it cannot exist could obviously lead to overestimating sorption, unless other sorbents that are not modeled (e.g., clays) are important. The omission of the stable iron phases siderite and pyrite as model sorbents serves to compensate for this flaw, although the extent of this compensation is unknown.

- The Gaussian model for estimating metal interactions with organic matter was developed for DOM. It has not been tested for estimating the degree of metal sorption onto POM. Also, mean log K values for some metals have not been measured, so estimates were used.

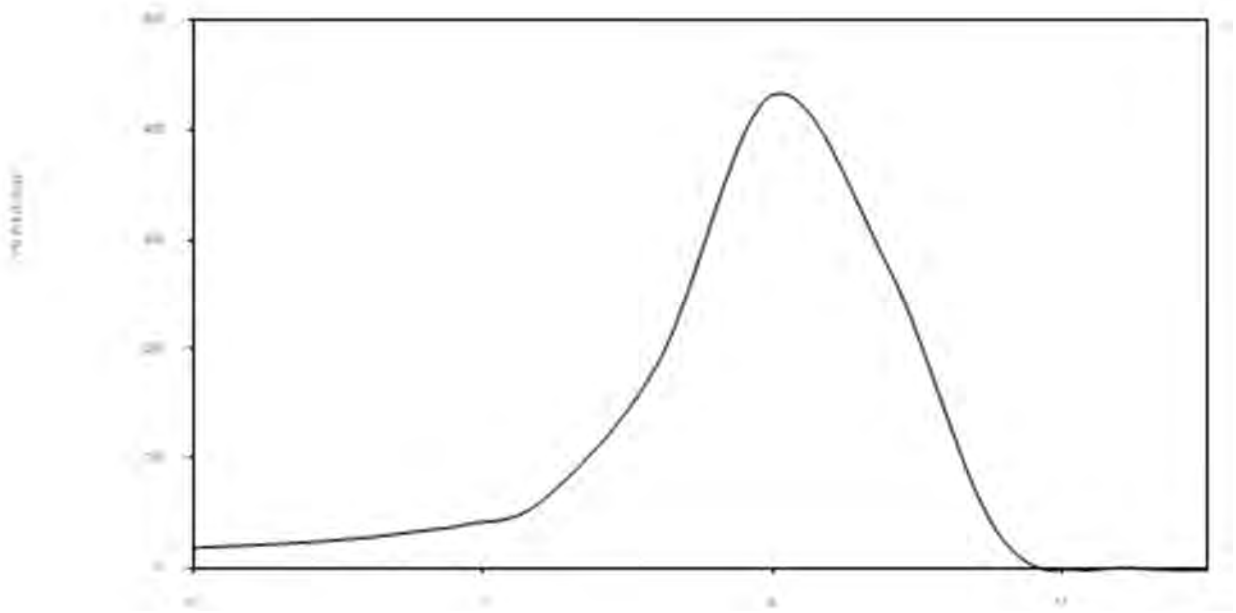

Figure 9. Stability fields for iron minerals (after Hem, 1977).

5.3 Leachate Characterization Issues

The concentration levels for important leachate constituents (e.g., calcium, magnesium, SO_4, chlorine) is based on a limited CCR constituent data set. This is especially true for the FBC wastes; leachate and porewater data were available for only one site. (Note: Other FBC waste characterization data are available but were measured on extraction procedures such as TCLP or SPLP.)

- The presence of CCR leachate constituents at elevated concentrations is accounted for in the MINTEQA2 modeling, but the dilution of the leachate in the mixing zone is oversimplified. A single dilution ratio of one part leachate to six parts groundwater was assumed for all saturated zone modeling. Some of these constituents are themselves adsorbed onto aquifer and soil matrix materials; it is their propensity to sorb that requires they be included in the modeling. Sorbing constituents (including H^+) will be transported away from the facility at different rates in accordance with their implied retardation factors. Use of a single recipe for leachate composition for all points in the unsaturated or saturated zones cannot represent this effect. The degree to which this oversimplification will result in errors in K_d estimates of contaminants is unknown.
- Methylated forms were not accounted for in this modeling. Mercury and arsenic are known to undergo methylation in the environment.

5.4 Other Issues

- The system redox potential was not explicitly defined in the modeling. All species that might undergo oxidation–reduction reactions were constrained to remain in the form in which they were entered in the model. This restriction applied to major ions such as sulfate and to all trace metals. The impact on K_d is unknown but is expected to be contaminant specific.
- All contaminants were introduced separately and individually in the modeling. The possible simultaneous presence of multiple contaminants is unaccounted for. The impact on K_d is not expected to be great except at high contaminant concentrations where competition for sorption sites may result in less sorption for some contaminants than suggested by this modeling.

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Attachment H-2.
Nonlinear Sorption Isotherm Plots

This attachment presents graphs plotting the nonlinear sorption isotherms discussed in **Appendix H**. For each model iteration of the probabilistic analysis presented in **Section 4**, EPACMTP selected values from these isotherms based on constituent concentration (x-axis), whether the groundwater composition type is carbonate or noncarbonate, the groundwater or soil pH, the natural organic matter level (NOM), the iron oxide content (FeOx), and the leachate ionic strength (Xtra 1). Each constituent's isotherms are presented separately for carbonate and noncarbonate environments as the upper and lower panels within each figure. Furthermore, separate figures are presented for the saturated zone (red plots) and the unsaturated zone (blue plots). The groundwater or soil pH, NOM, FeOx, and Xtra 1 (ionic strength) levels used to select the isotherms presented in each plot are listed in the boxes to the left in each panel; the values in these boxes are explained in **Section 2** of **Attachment H-1**. Sorption isotherms for landfills (LFs) with combined ash are presented in **Figures H-2-1** through **H-2-20**. Sorption isotherms for surface impoundments (SIs) with combined ash, ash and coal refuse, and FGD wastes are presented in **Figures H-2-21** through **H-2-50**. **Table H-2-1** summarizes which isotherms are in which figures. Isotherms are shown only for contaminant-WMU combinations that were modeled in the probabilistic analysis.

Table H-2-1. Guide to Figures Showing Isotherms

Contaminant	Landfills		Surface Impoundments	
	Saturated Zone	Unsaturated Zone	Saturated Zone	Unsaturated Zone
Antimony	Figure H-2-1	Figure H-2-2	Figure H-2-21	Figure H-2-22
Arsenic III	Figure H-2-3	Figure H-2-4	Figure H-2-23	Figure H-2-24
Arsenic V	Figure H-2-5	Figure H-2-6	Figure H-2-25	Figure H-2-26
Boron	Figure H-2-7	Figure H-2-8	Figure H-2-27	Figure H-2-28
Cadmium	Figure H-2-9	Figure H-2-10	Figure H-2-29	Figure H-2-30
Chromium III	–	–	Figure H-2-31	Figure H-2-32
Chromium VI	Figure H-2-11	Figure H-2-12	Figure H-2-33	Figure H-2-34
Cobalt	Figure H-2-13	Figure H-2-14	Figure H-2-35	Figure H-2-36
Fluoride	–	–	Figure H-2-37	Figure H-2-38
Lead	–	–	Figure H-2-39	Figure H-2-40
Mercury	Figure H-2-15	Figure H-2-16	Figure H-2-41	Figure H-2-42
Molybdenum	Figure H-2-17	Figure H-2-18	Figure H-2-43	Figure H-2-44
Selenium	–	–	Figure H-2-45	Figure H-2-46
Thallium	Figure H-2-19	Figure H-2-20	Figure H-2-47	Figure H-2-48
Vanadium	–	–	Figure H-2-49	Figure H-2-50

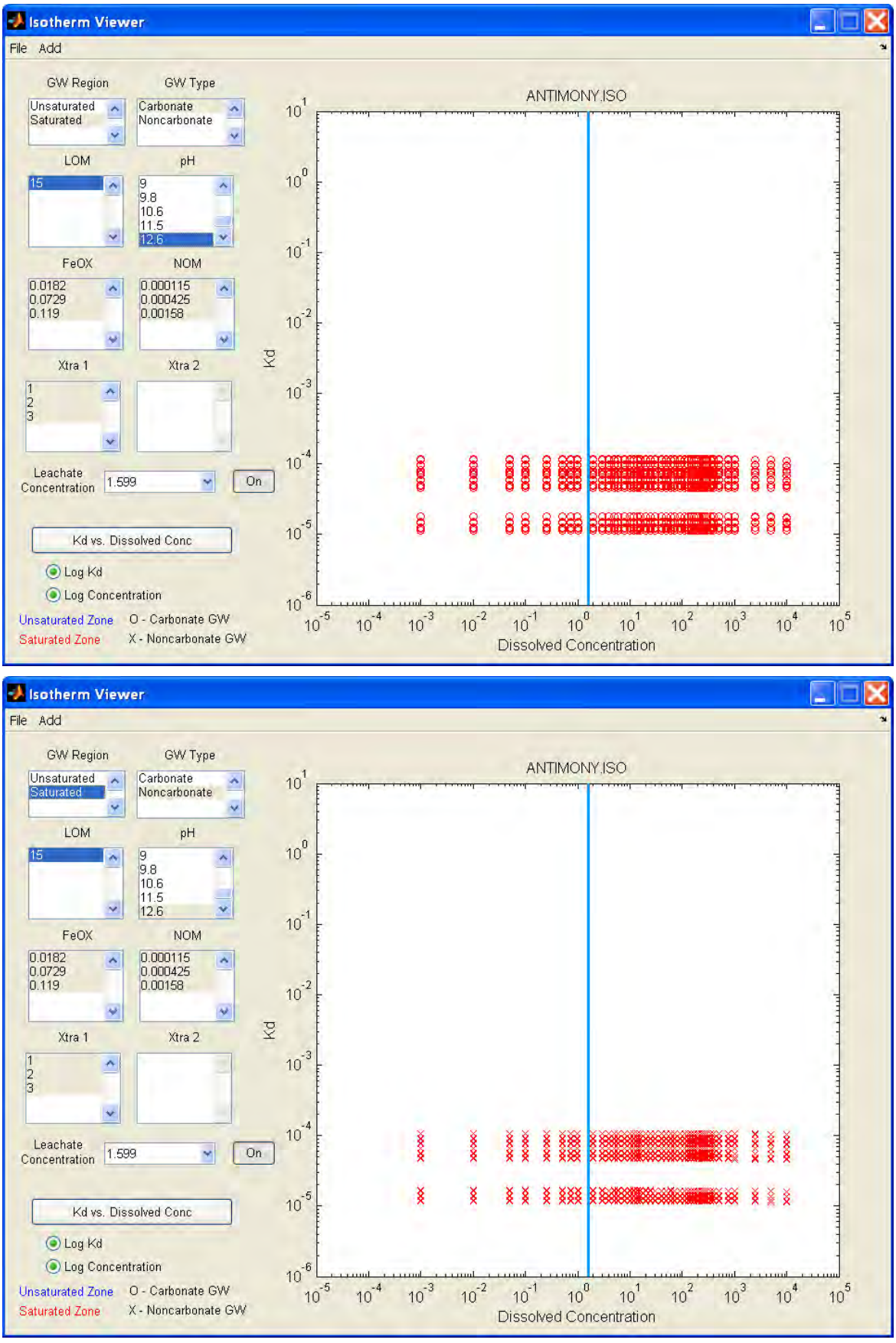

Figure H-2-1. Antimony saturated zone nonlinear sorption isotherms for LFs.

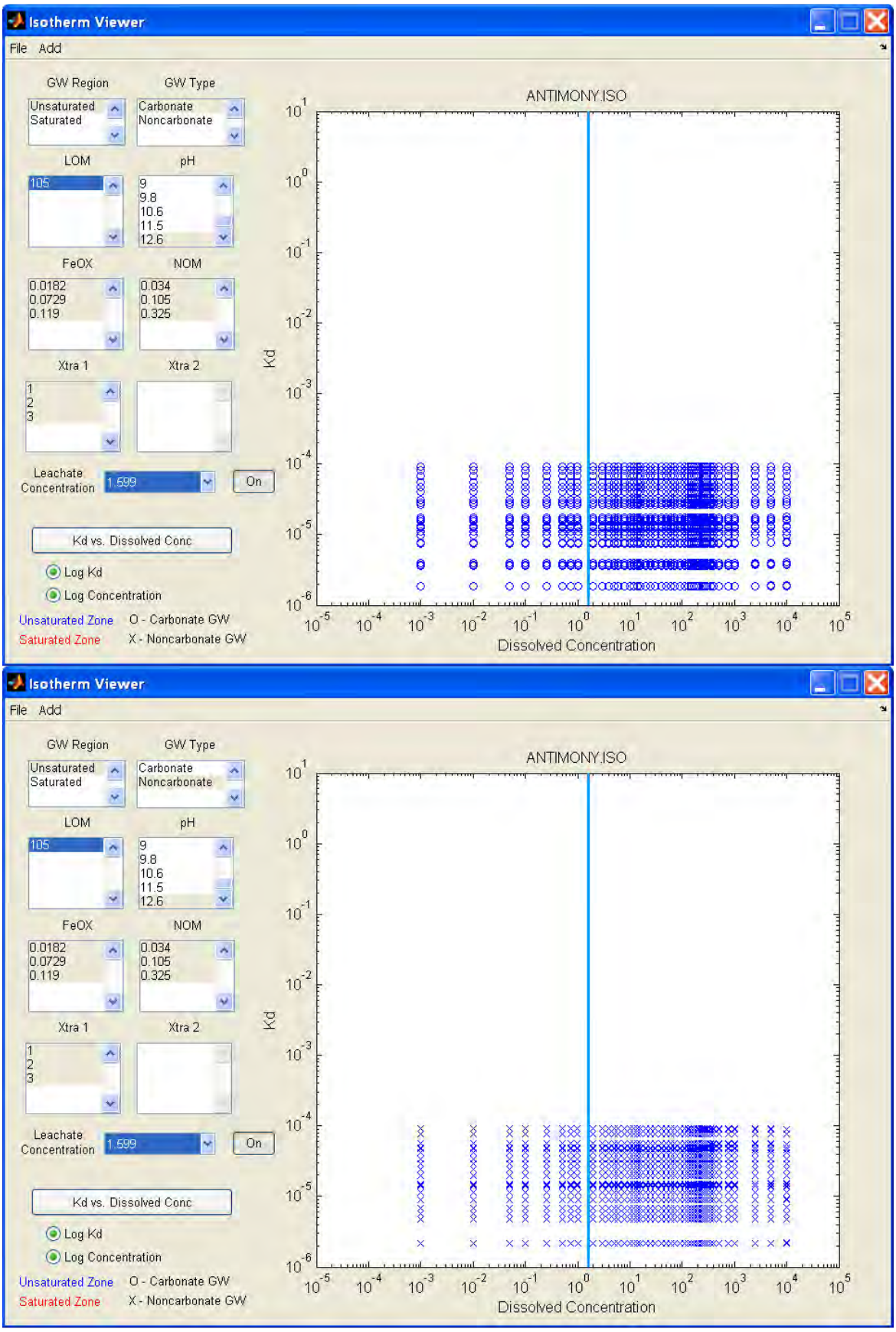

Figure H-2-2. Antimony unsaturated zone nonlinear sorption isotherms for LFs.

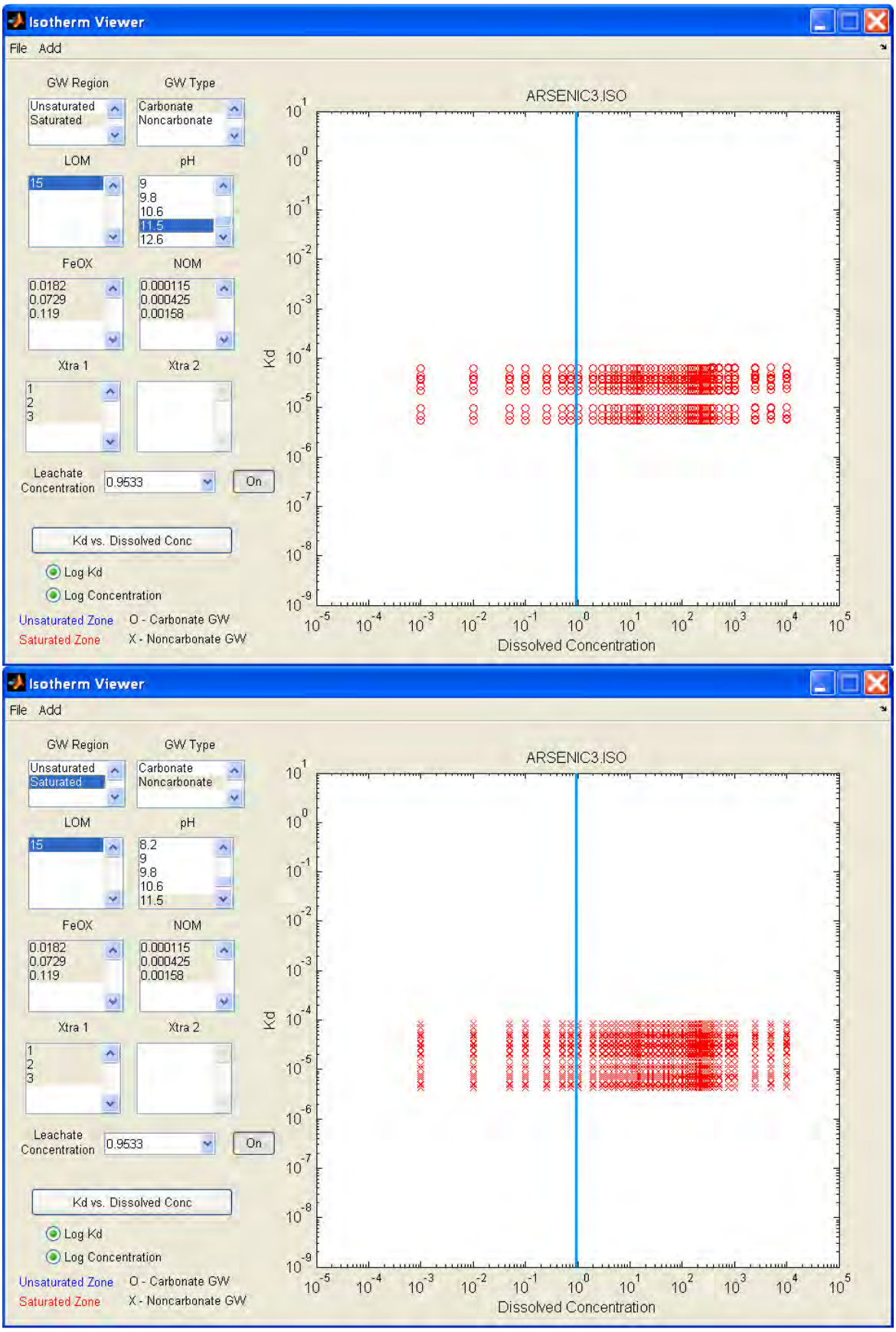

Figure H-2-3. Arsenic III saturated zone nonlinear sorption isotherms for LFs.

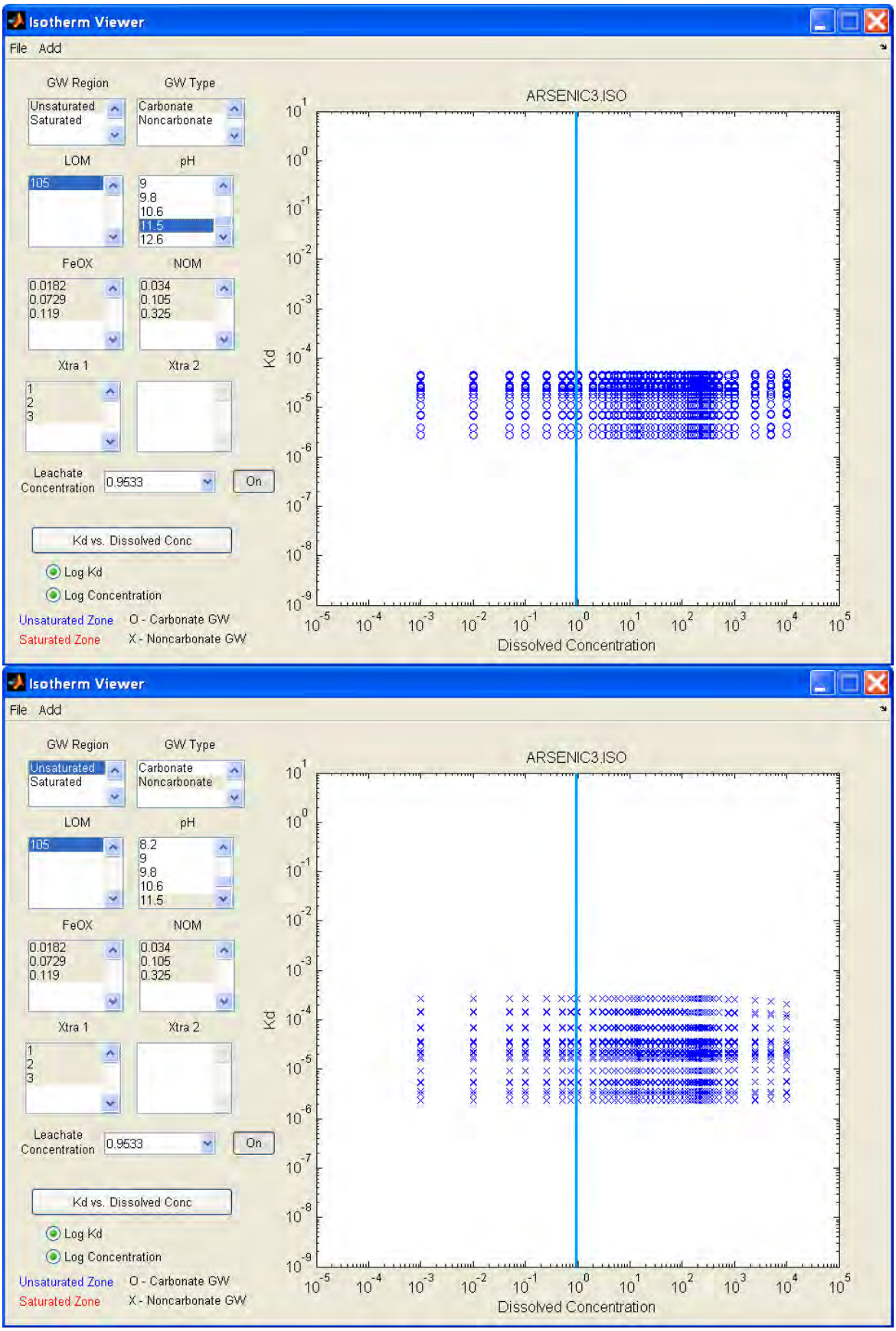

Figure H-2-4. Arsenic III unsaturated zone nonlinear sorption isotherms for LFs.

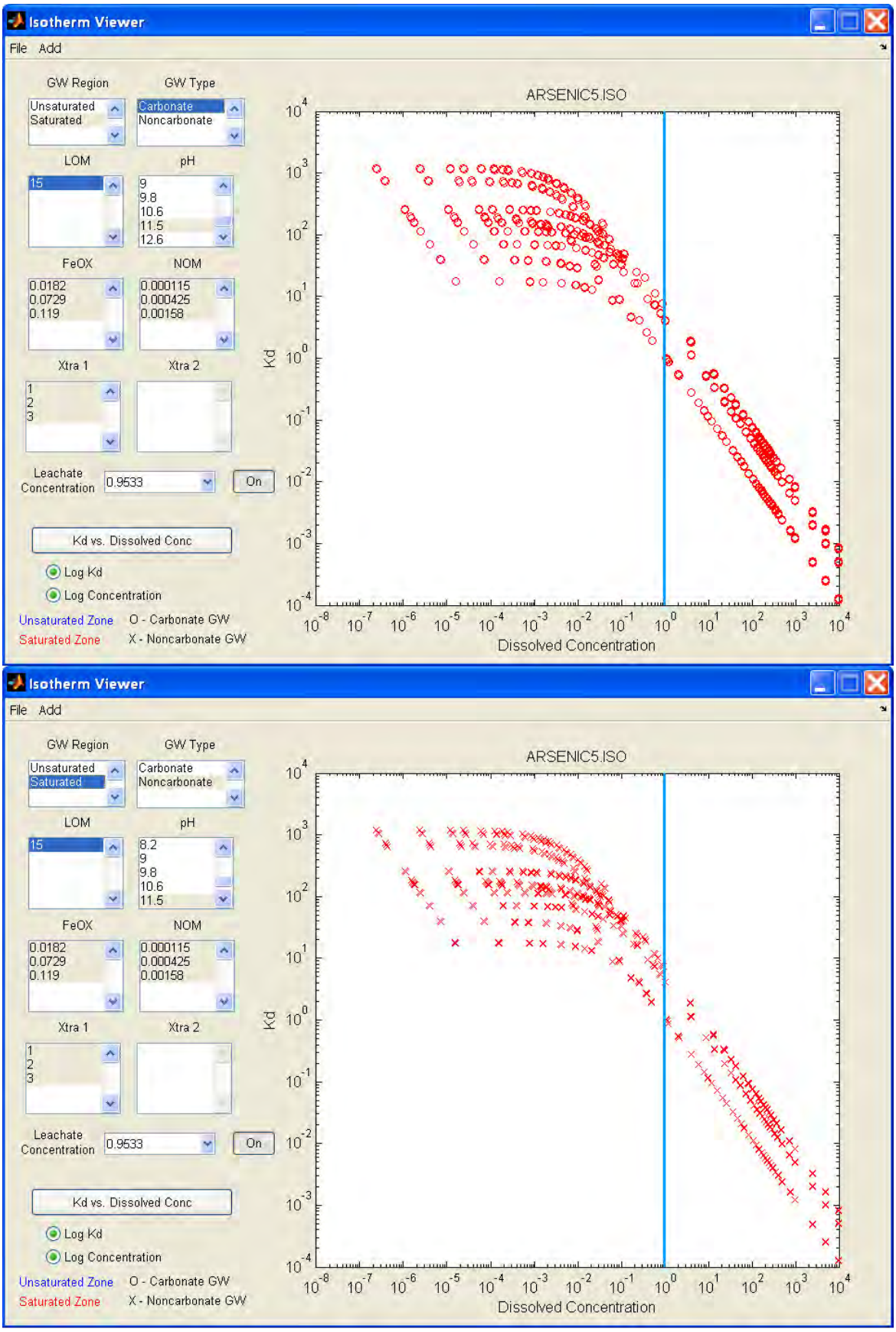

Figure H-2-5. Arsenic V saturated zone nonlinear sorption isotherms for LFs.

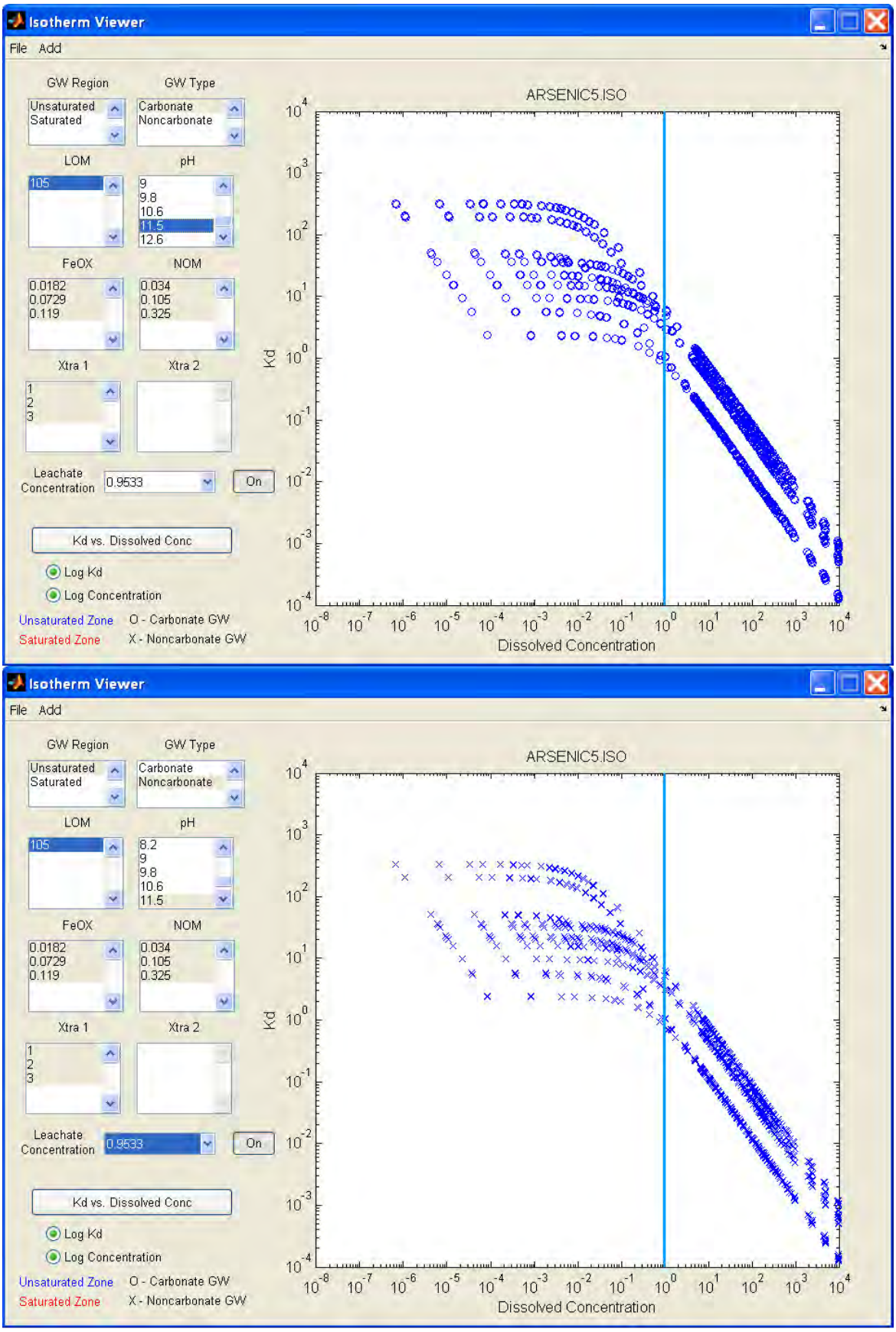

Figure H-2-6. Arsenic V unsaturated zone nonlinear sorption isotherms for LFs.

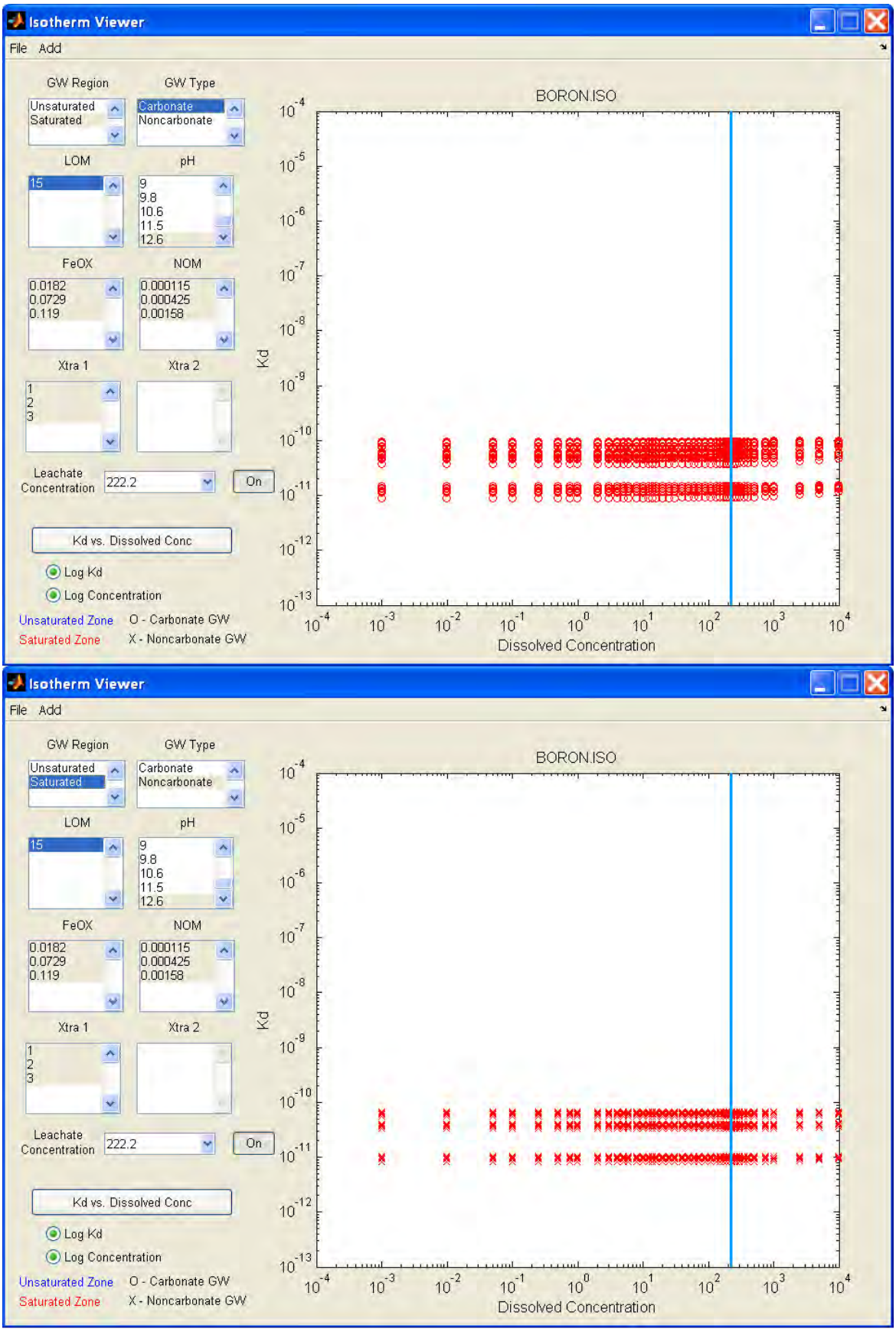

Figure H-2-7. Boron saturated zone nonlinear sorption isotherms for LFs.

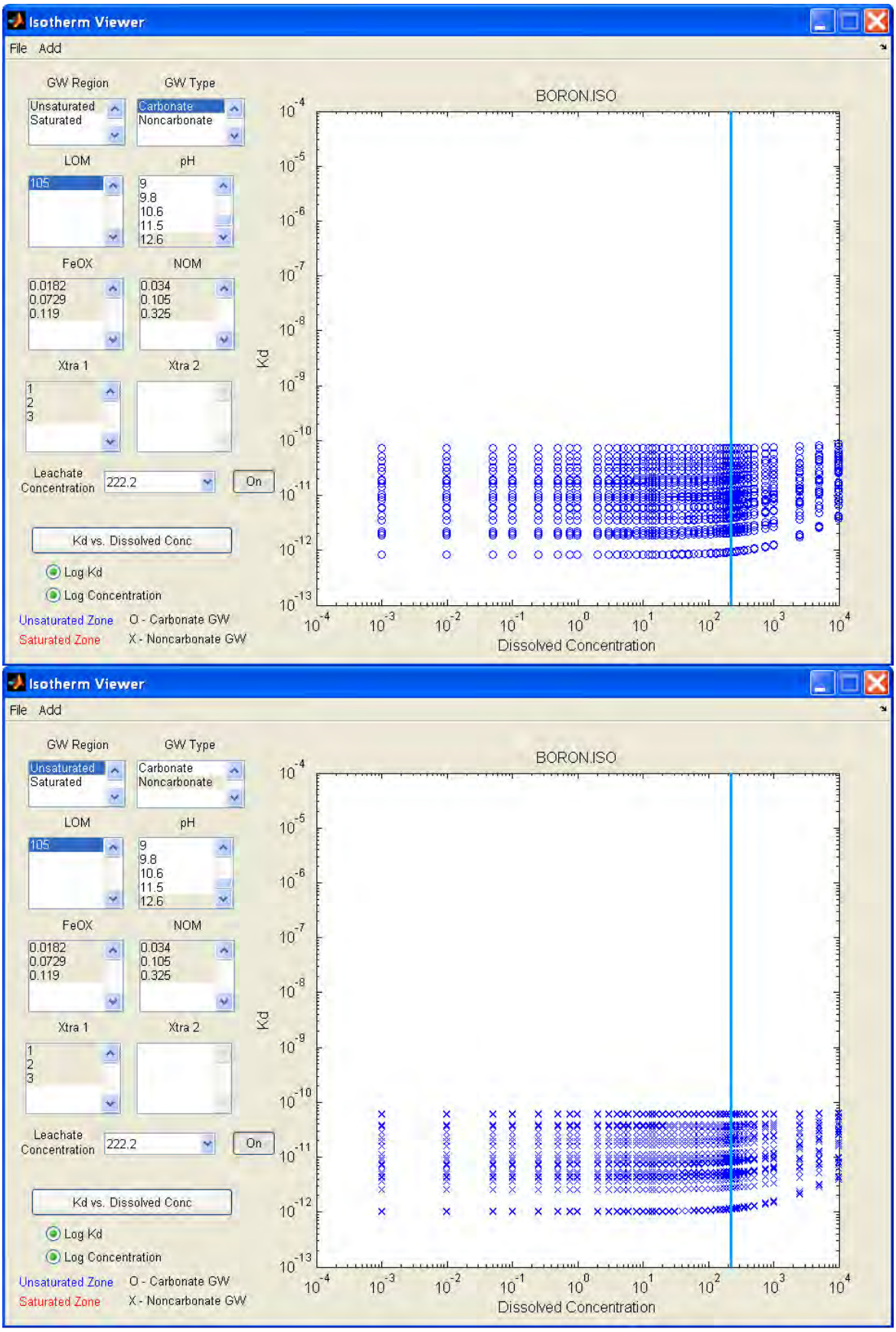

Figure H-2-8. Boron unsaturated zone nonlinear sorption isotherms for LFs.

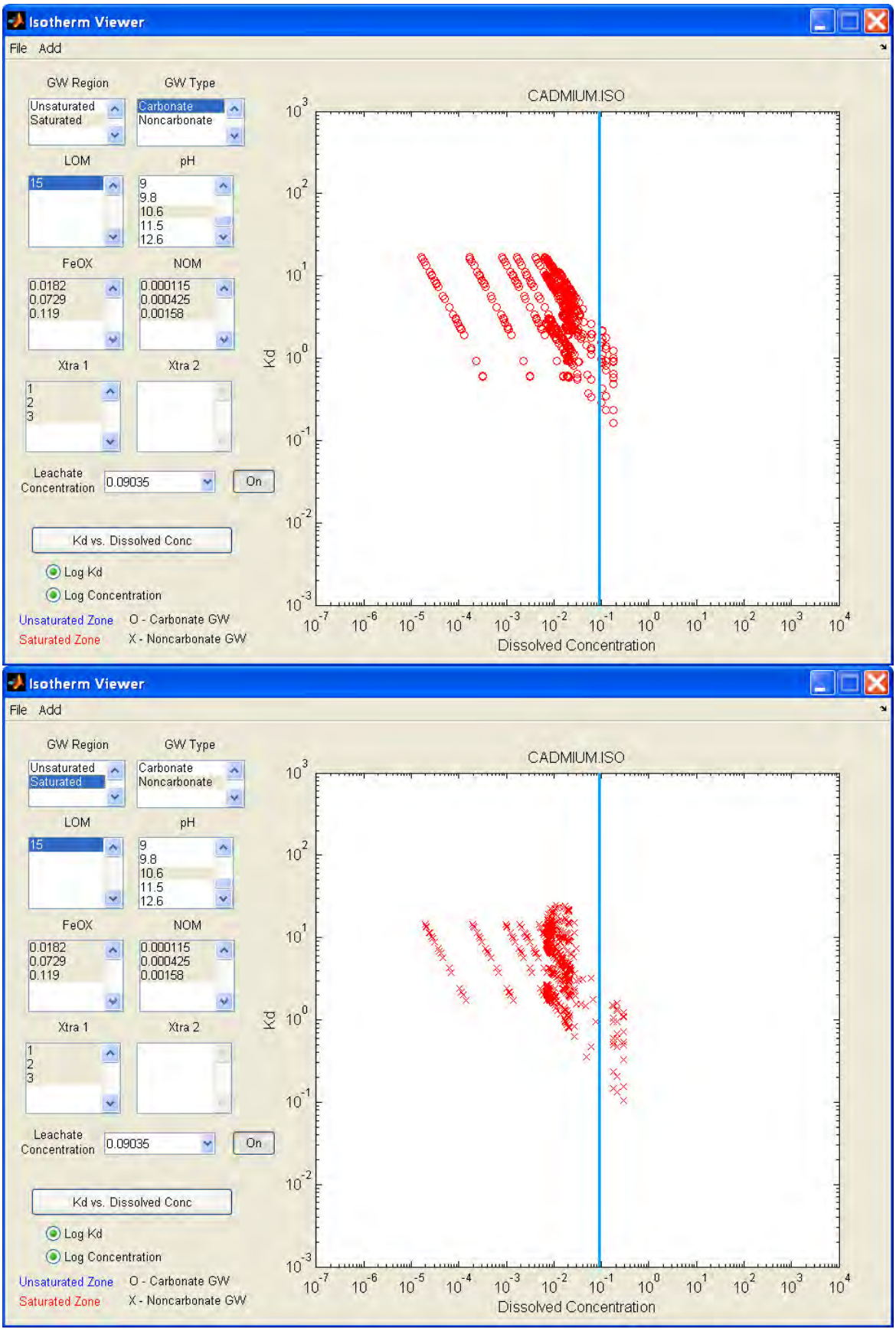

Figure H-2-9. Cadmium saturated zone nonlinear sorption isotherms for LFs.

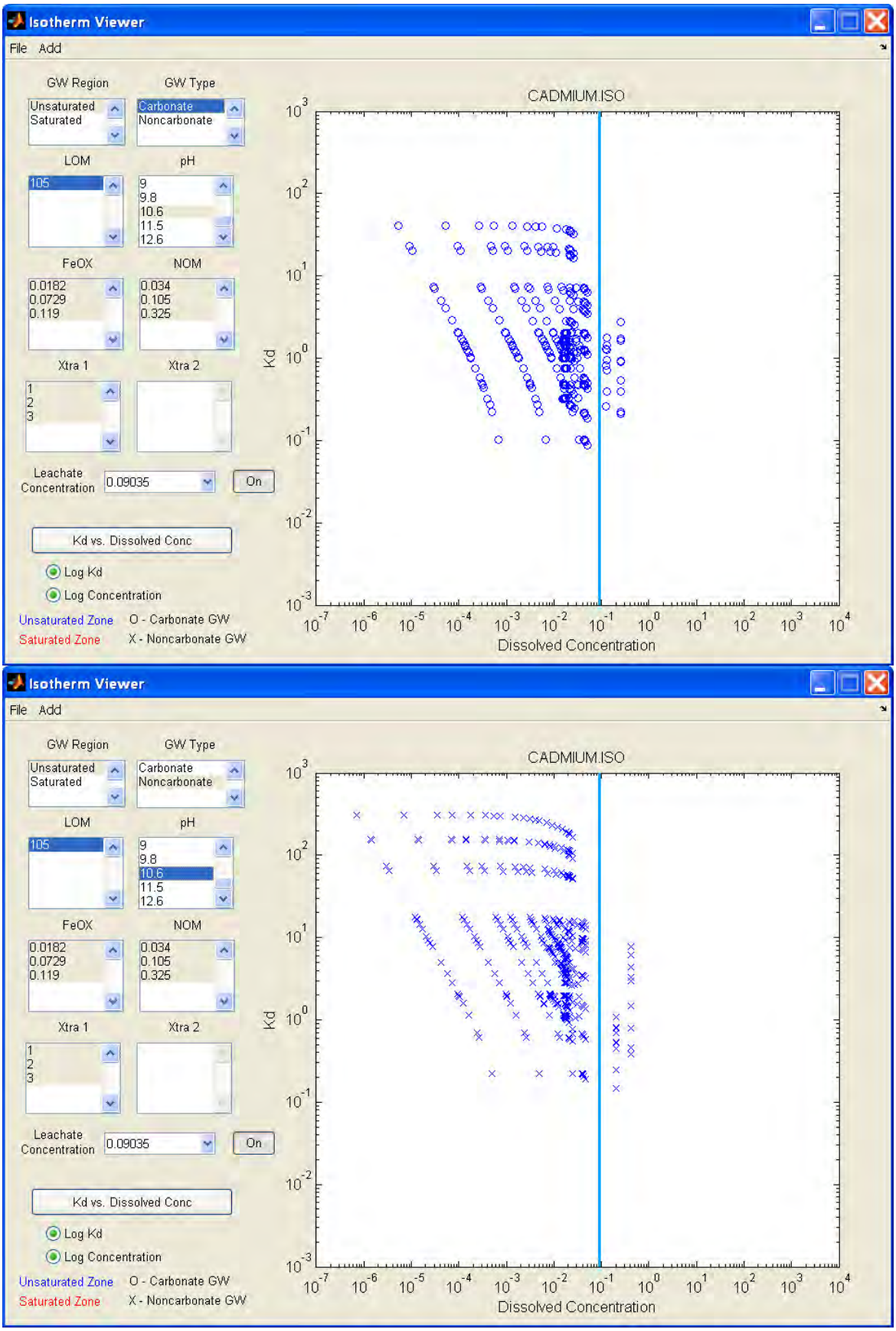

Figure H-2-10. Cadmium unsaturated zone nonlinear sorption isotherms for LFs.

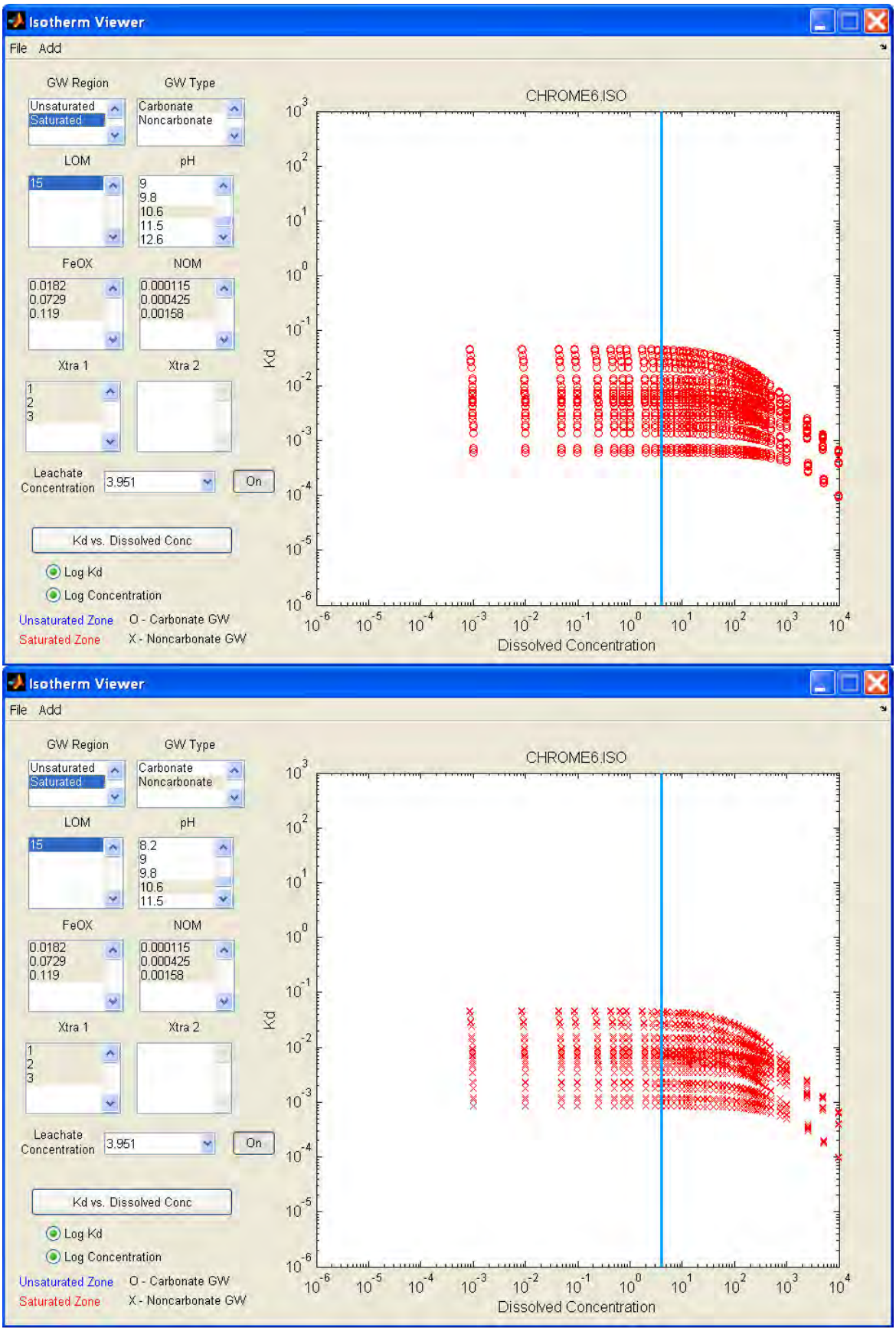

Figure H-2-11. Chromium VI saturated zone nonlinear sorption isotherms for LFs.

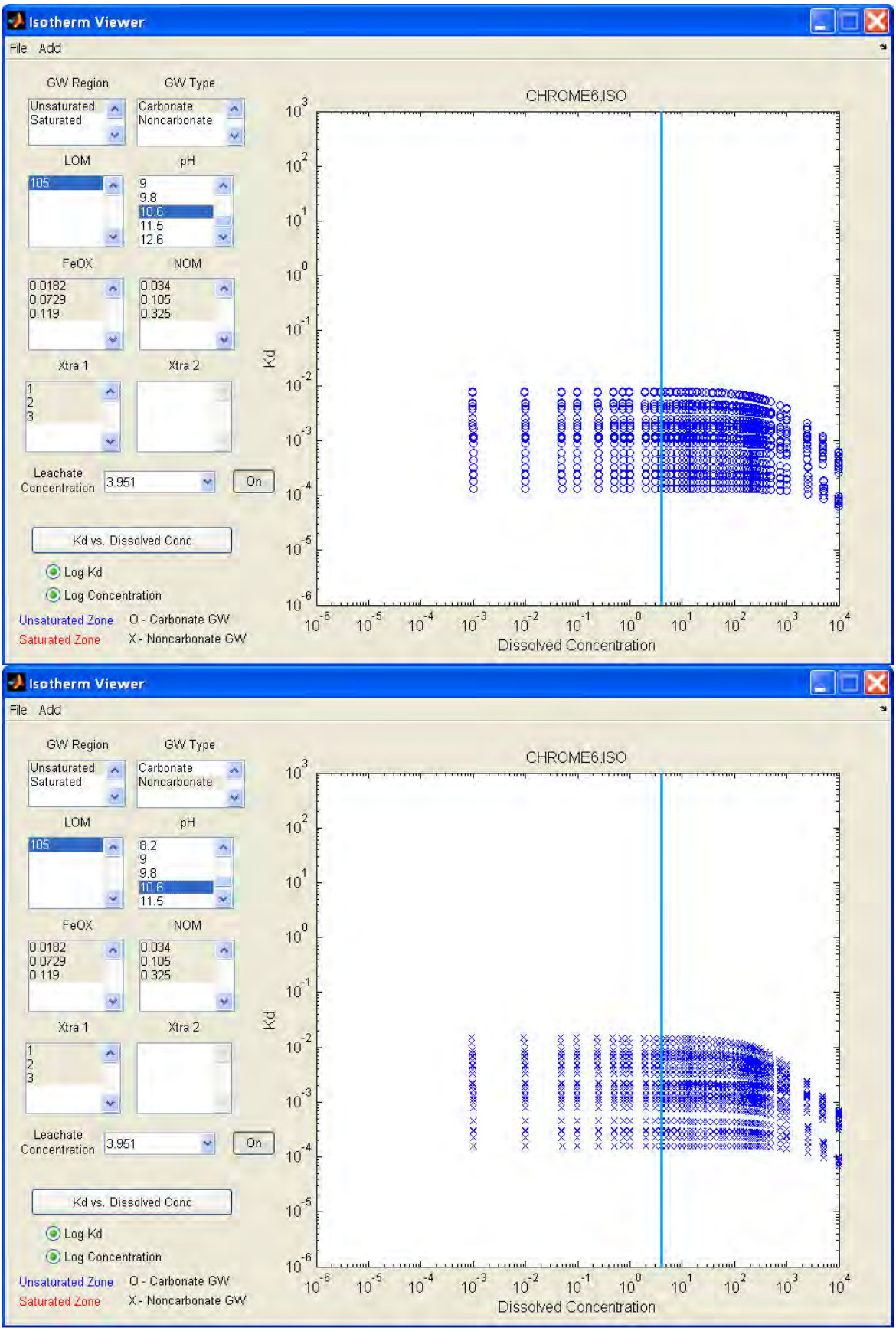

Figure H-2-12. Chromium VI unsaturated zone nonlinear sorption isotherms for LFs.

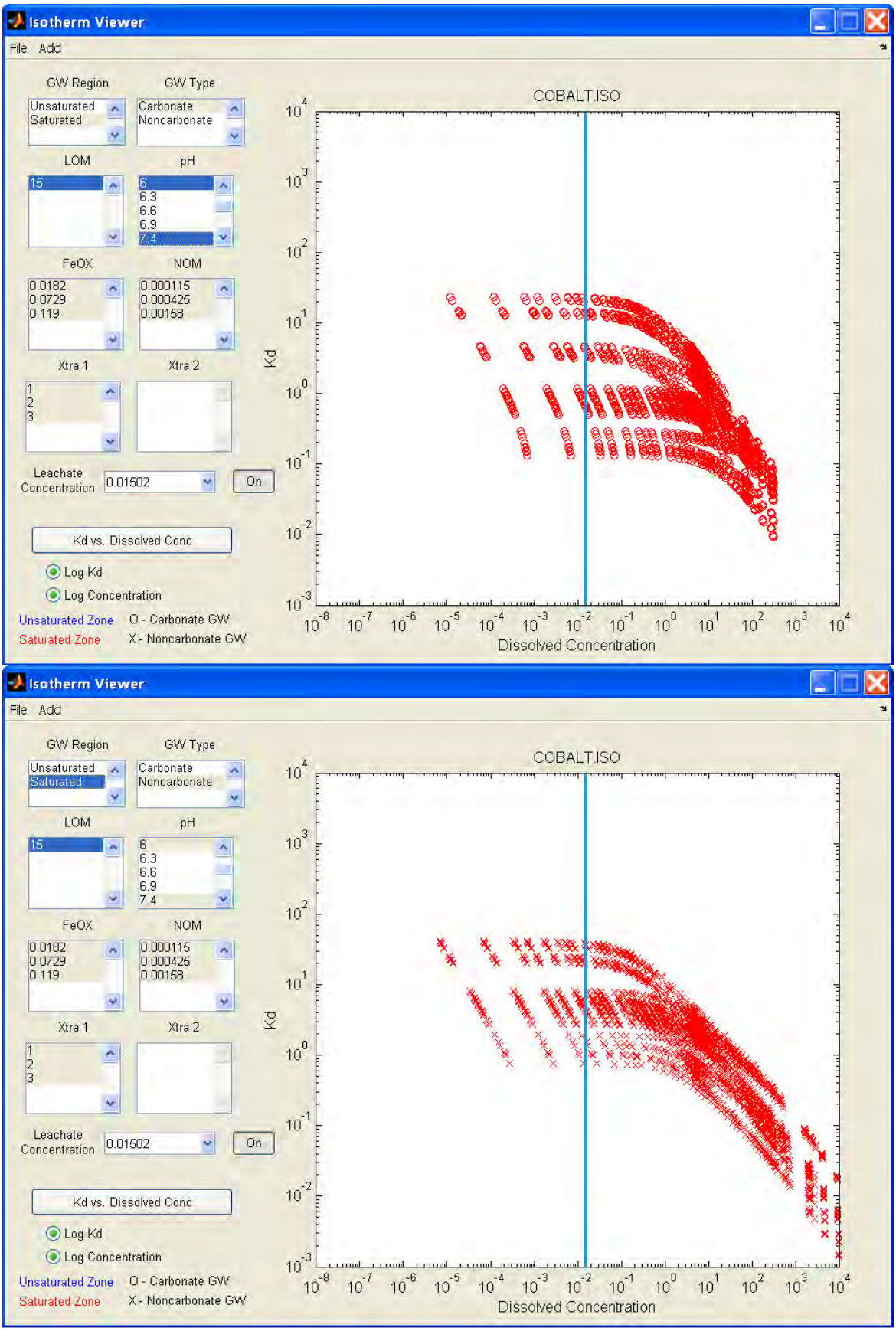

Figure H-2-13. Cobalt saturated zone nonlinear sorption isotherms for LFs.

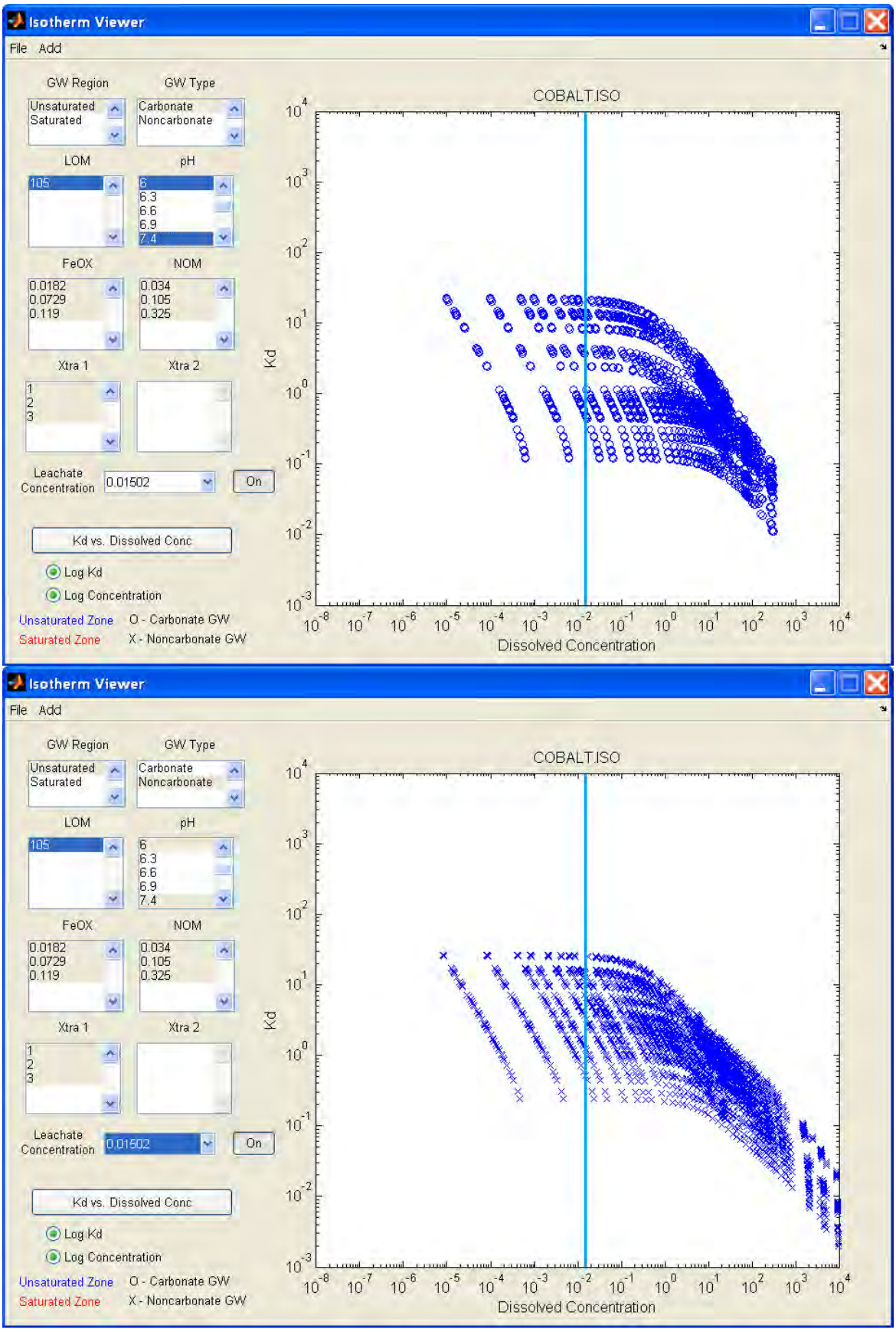

Figure H-2-14. Cobalt unsaturated zone nonlinear sorption isotherms for LFs.

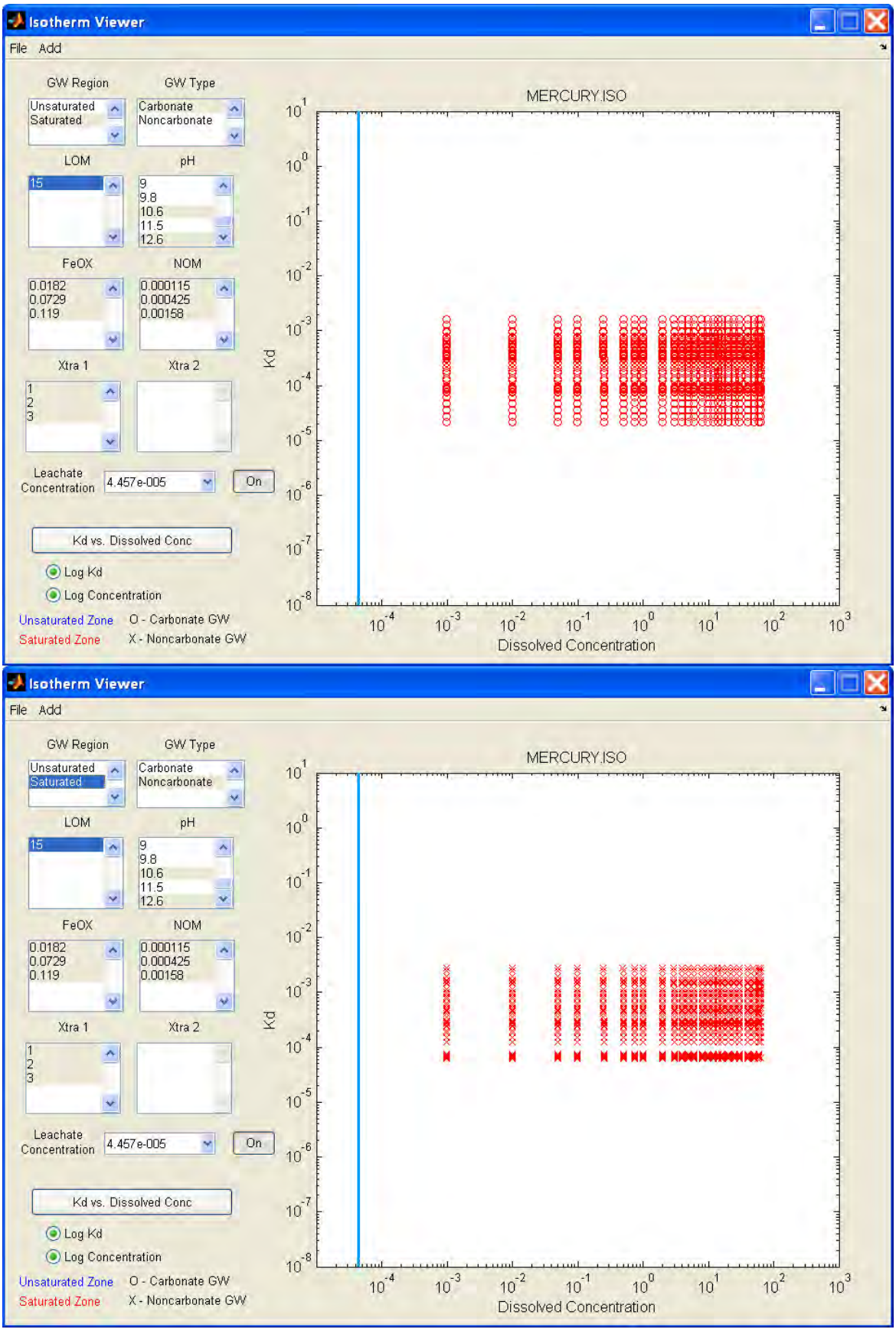

Figure H-2-15. Mercury saturated zone nonlinear sorption isotherms for LFs.

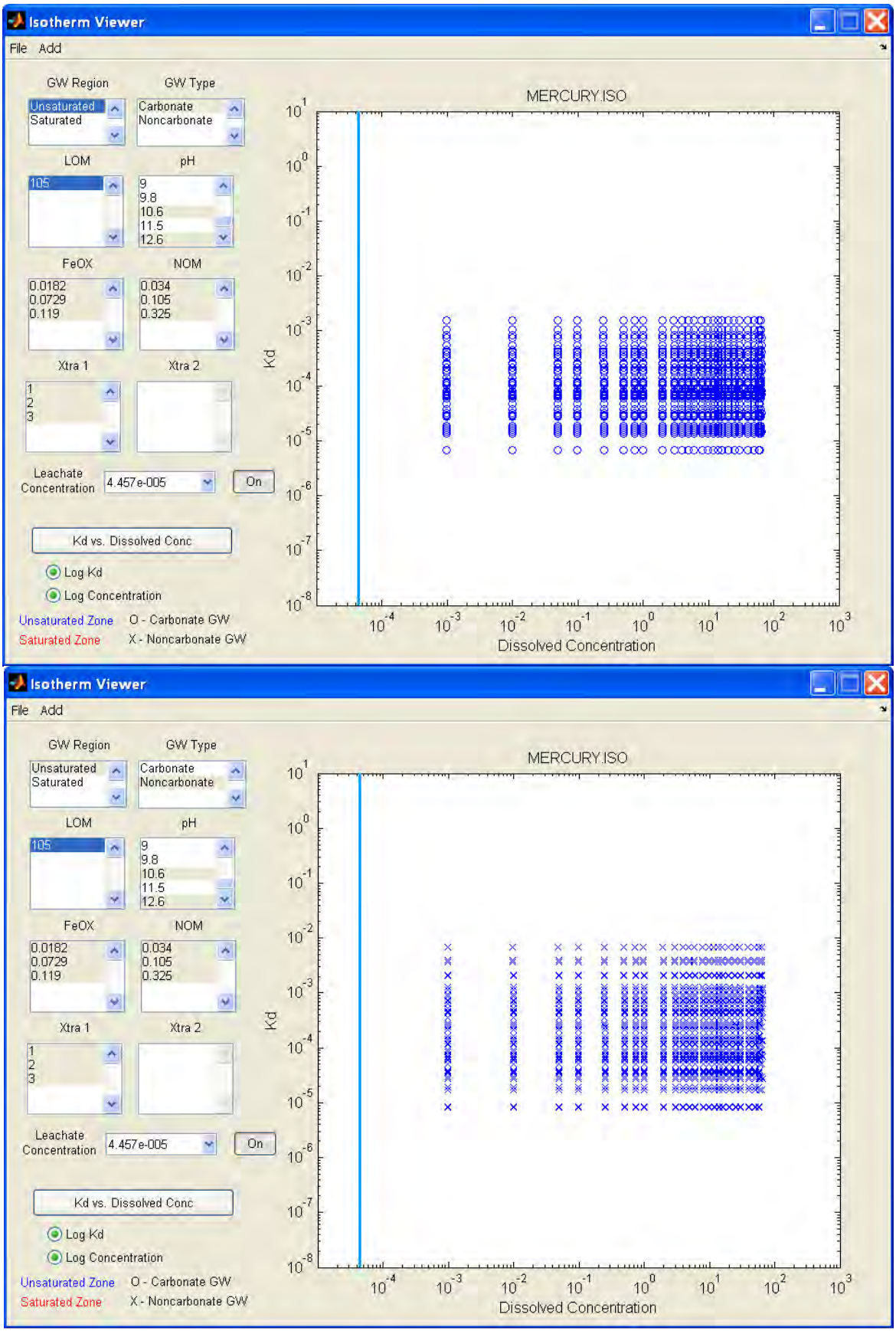

Figure H-2-16. Mercury unsaturated zone nonlinear sorption isotherms for LFs.

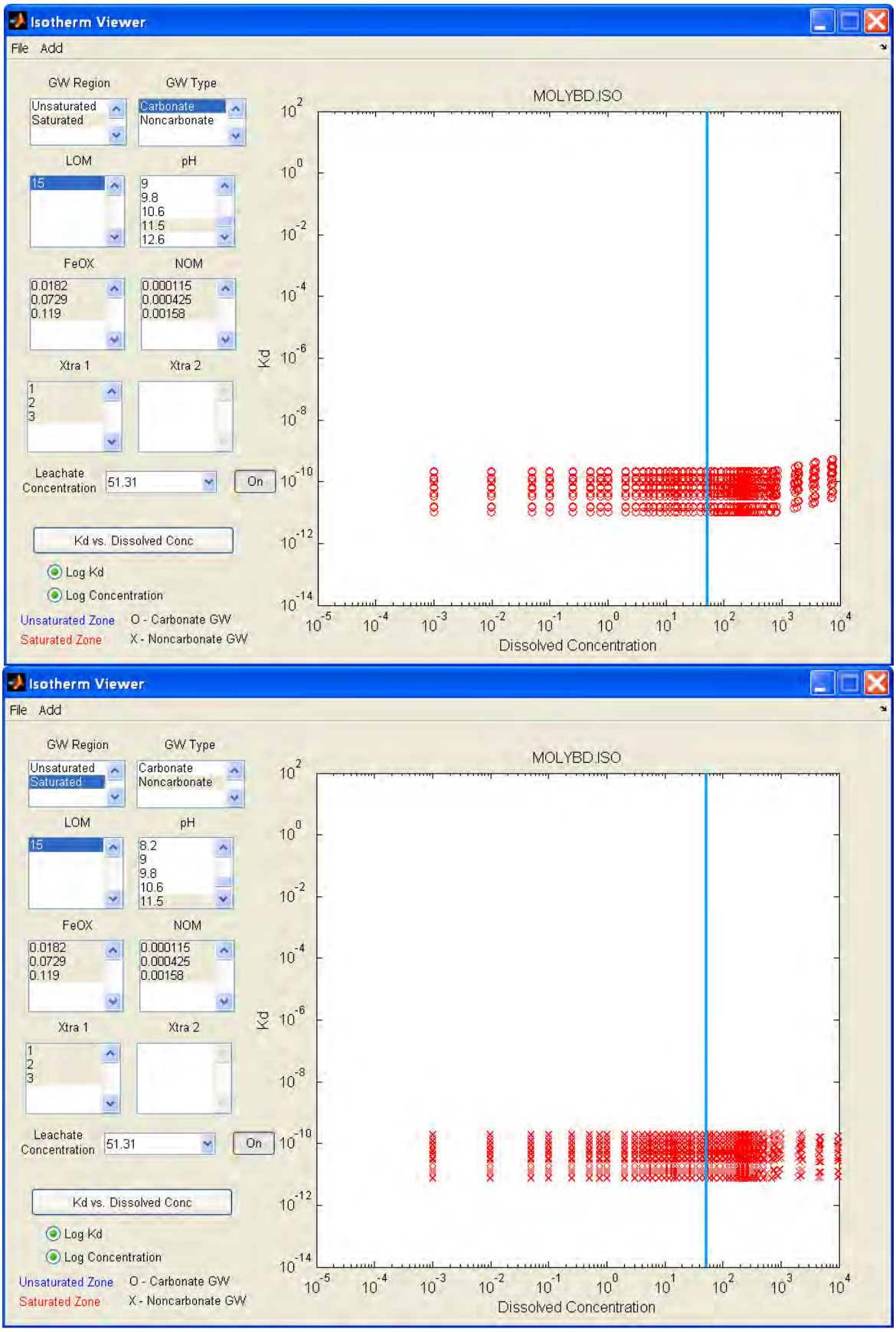

Figure H-2-17. Molybdenum saturated zone nonlinear sorption isotherms for LFs.

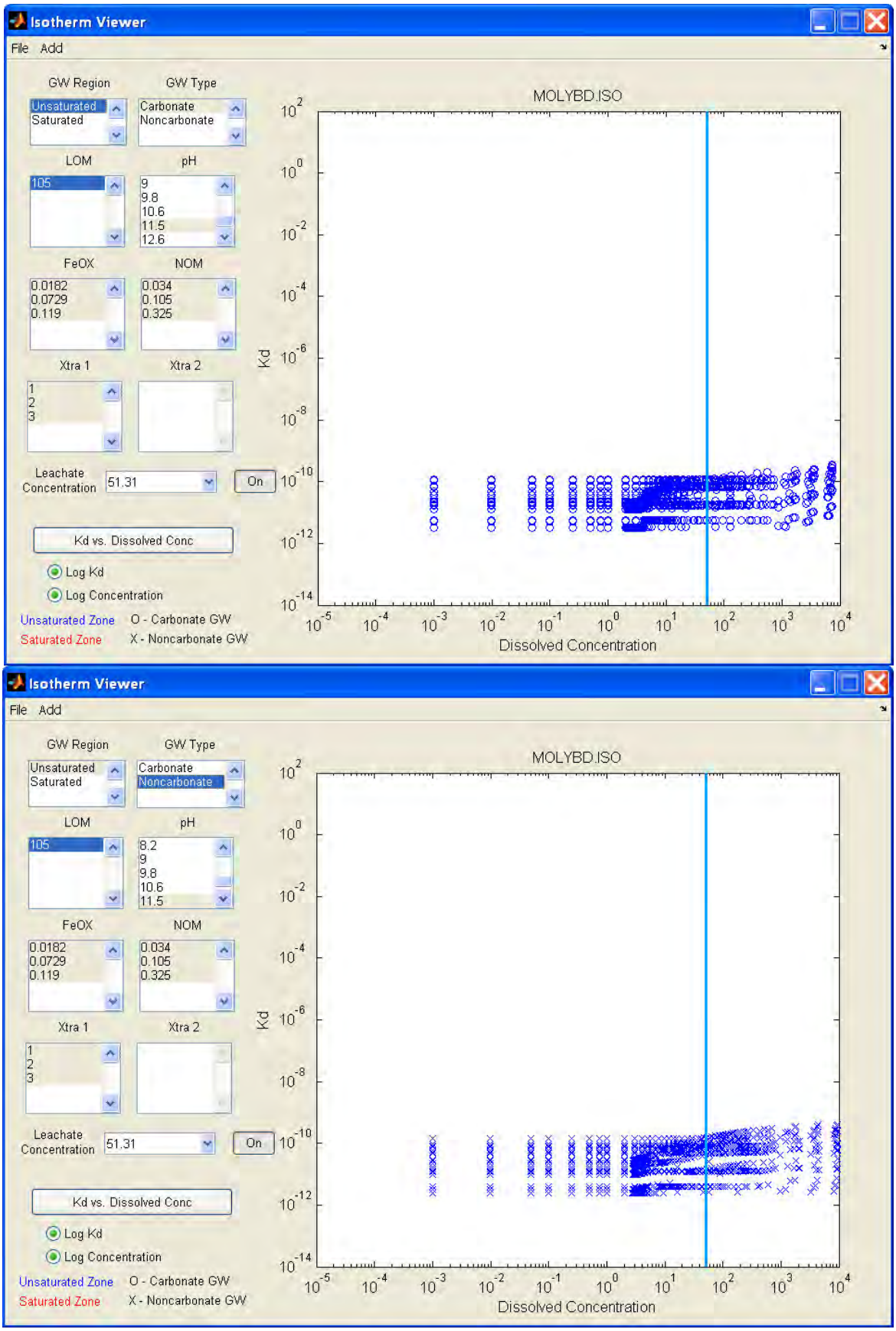

Figure H-2-18. Molybdenum unsaturated zone nonlinear sorption isotherms for LFs.

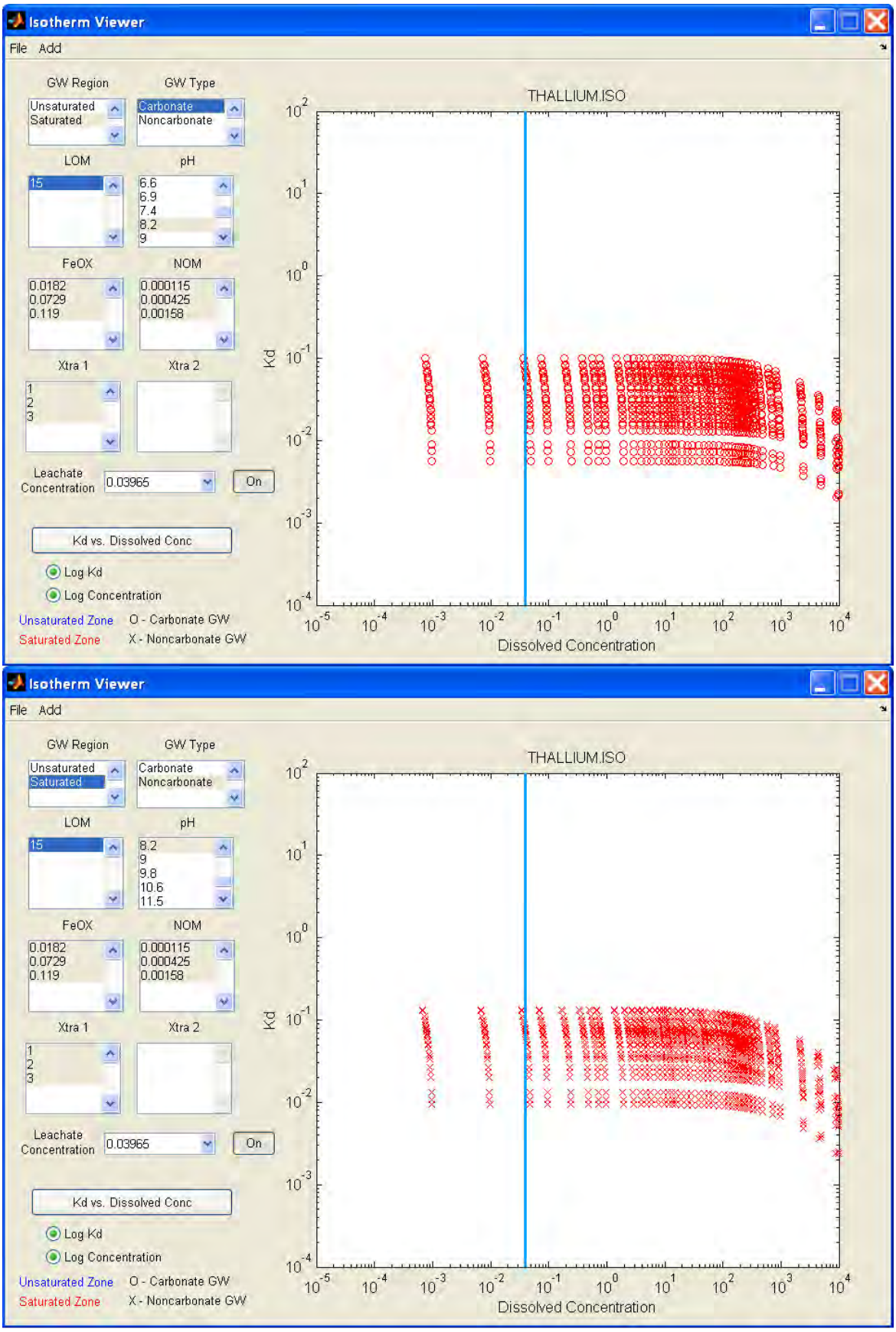

Figure H-2-19. Thallium saturated zone nonlinear sorption isotherms for LFs.

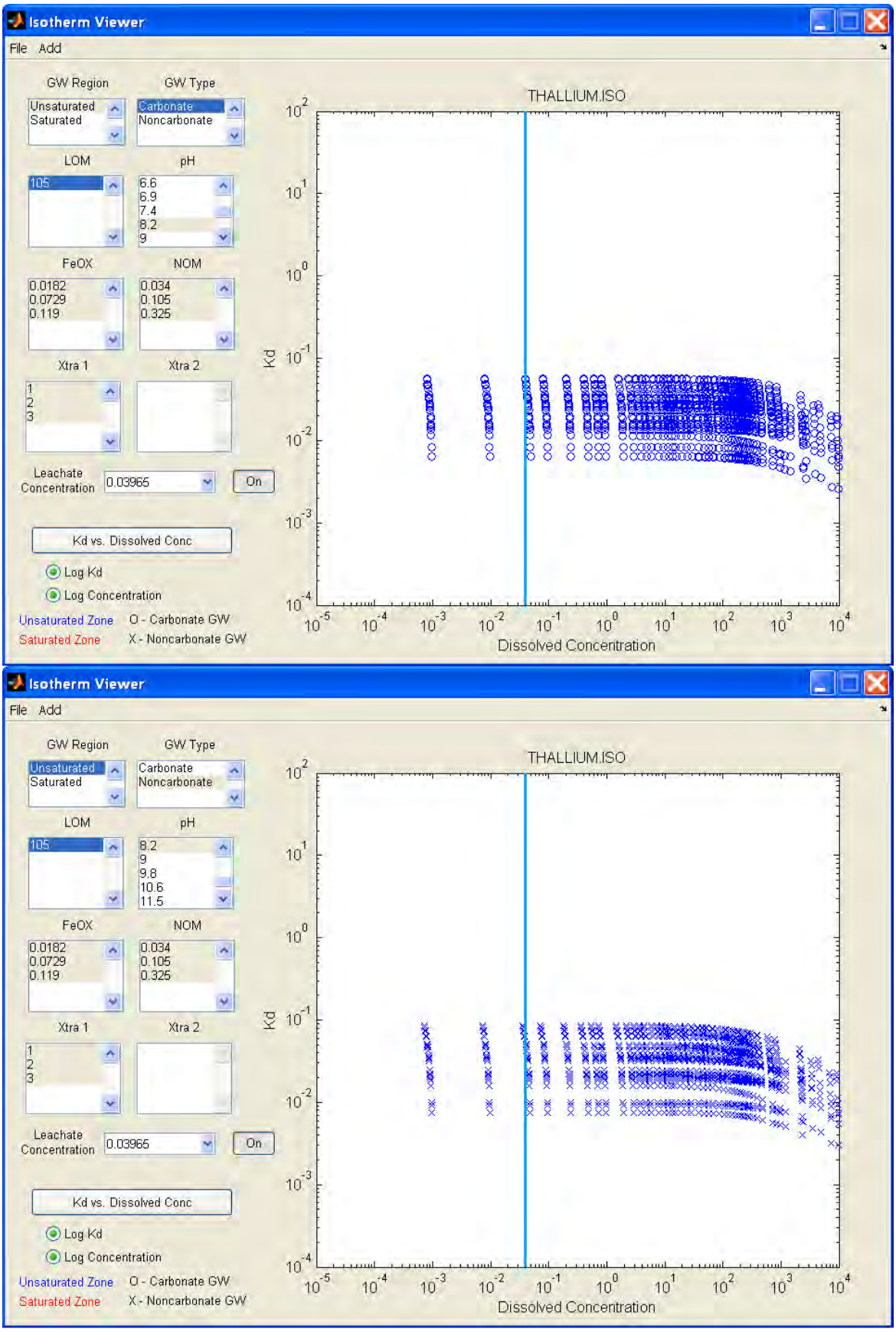

Figure H-2-20. Thallium unsaturated zone nonlinear sorption isotherms for LFs.

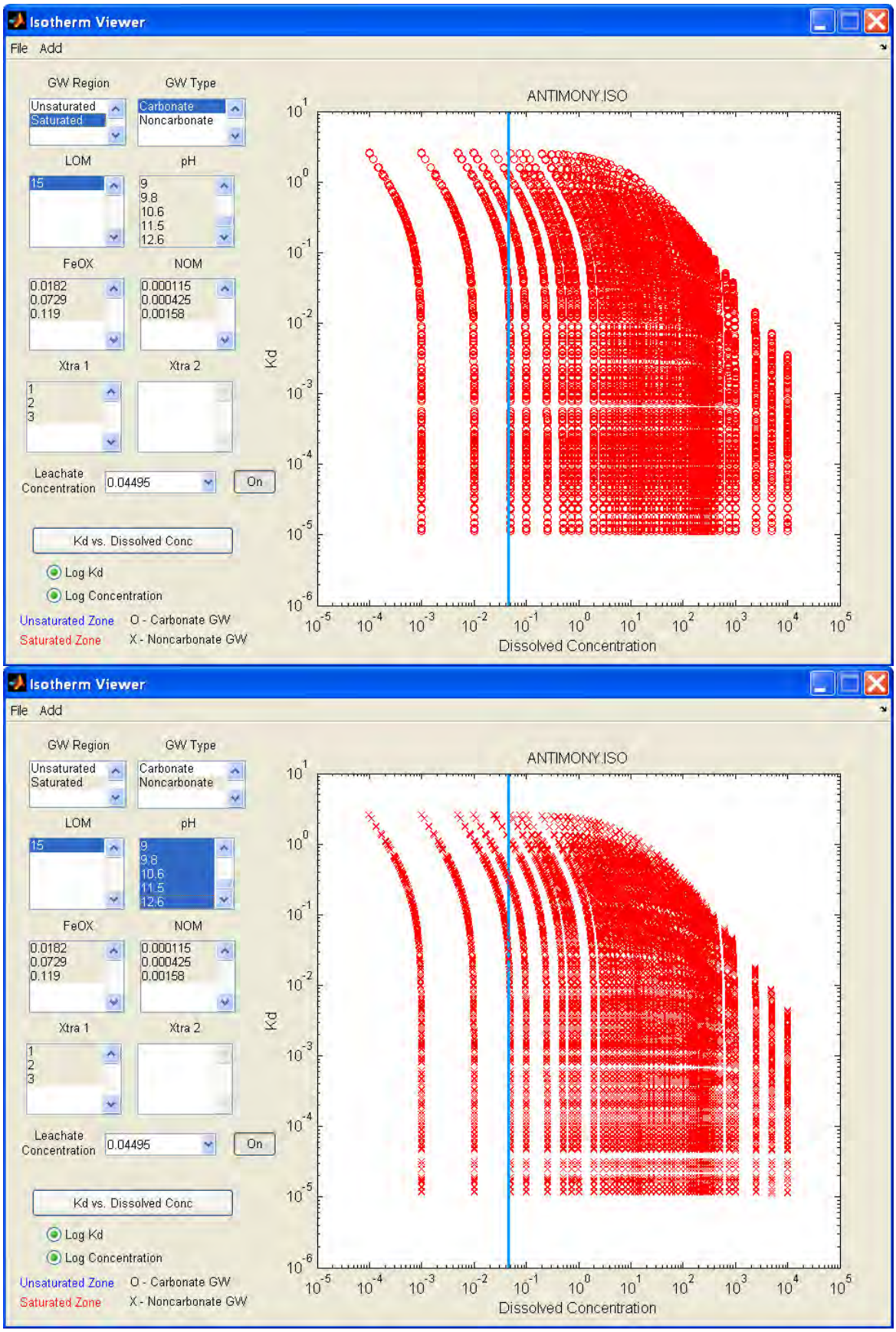

Figure H-2-21. Antimony saturated zone nonlinear sorption isotherms for SIs.

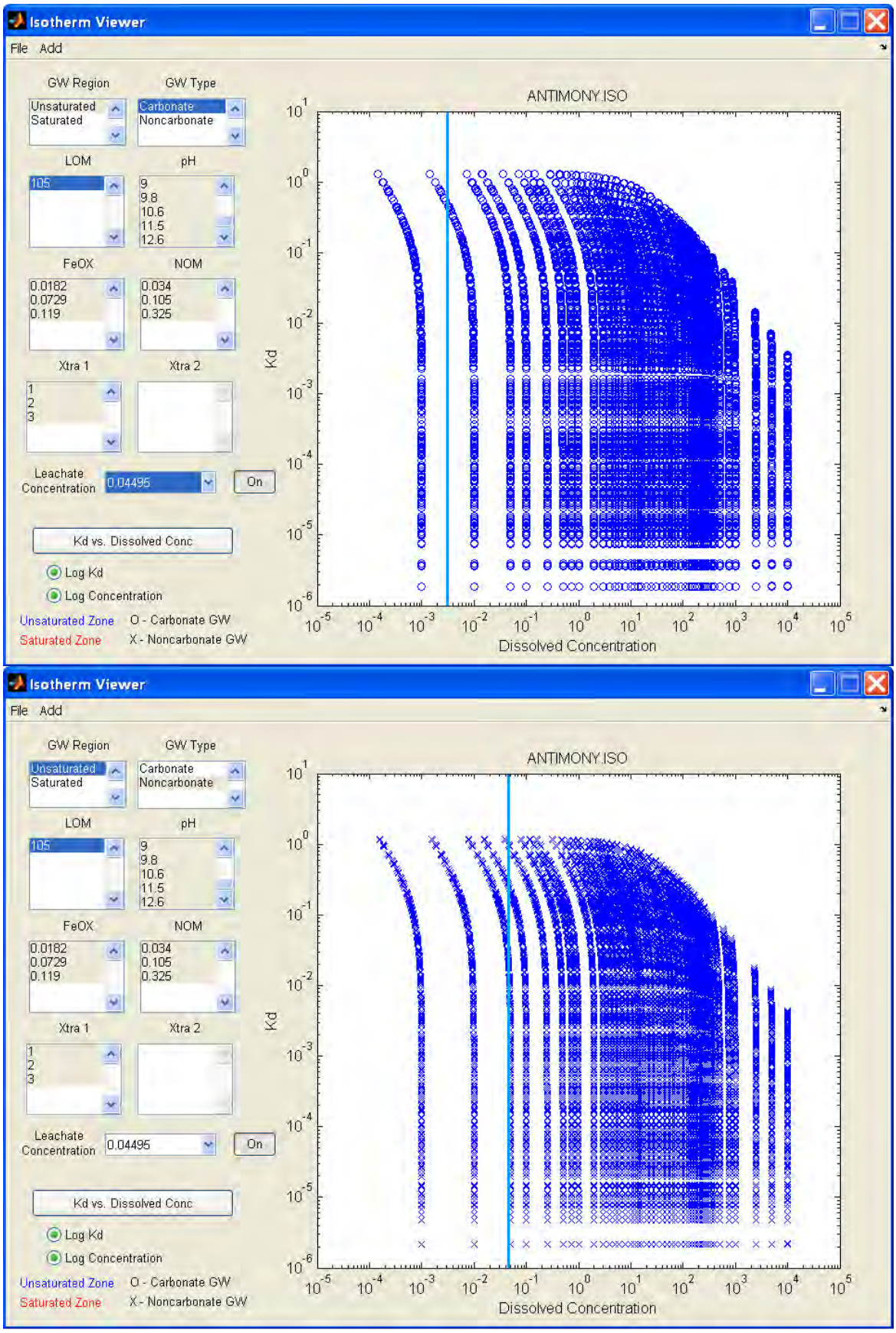

Figure H-2-22. Antimony unsaturated zone nonlinear sorption isotherms for SIs.

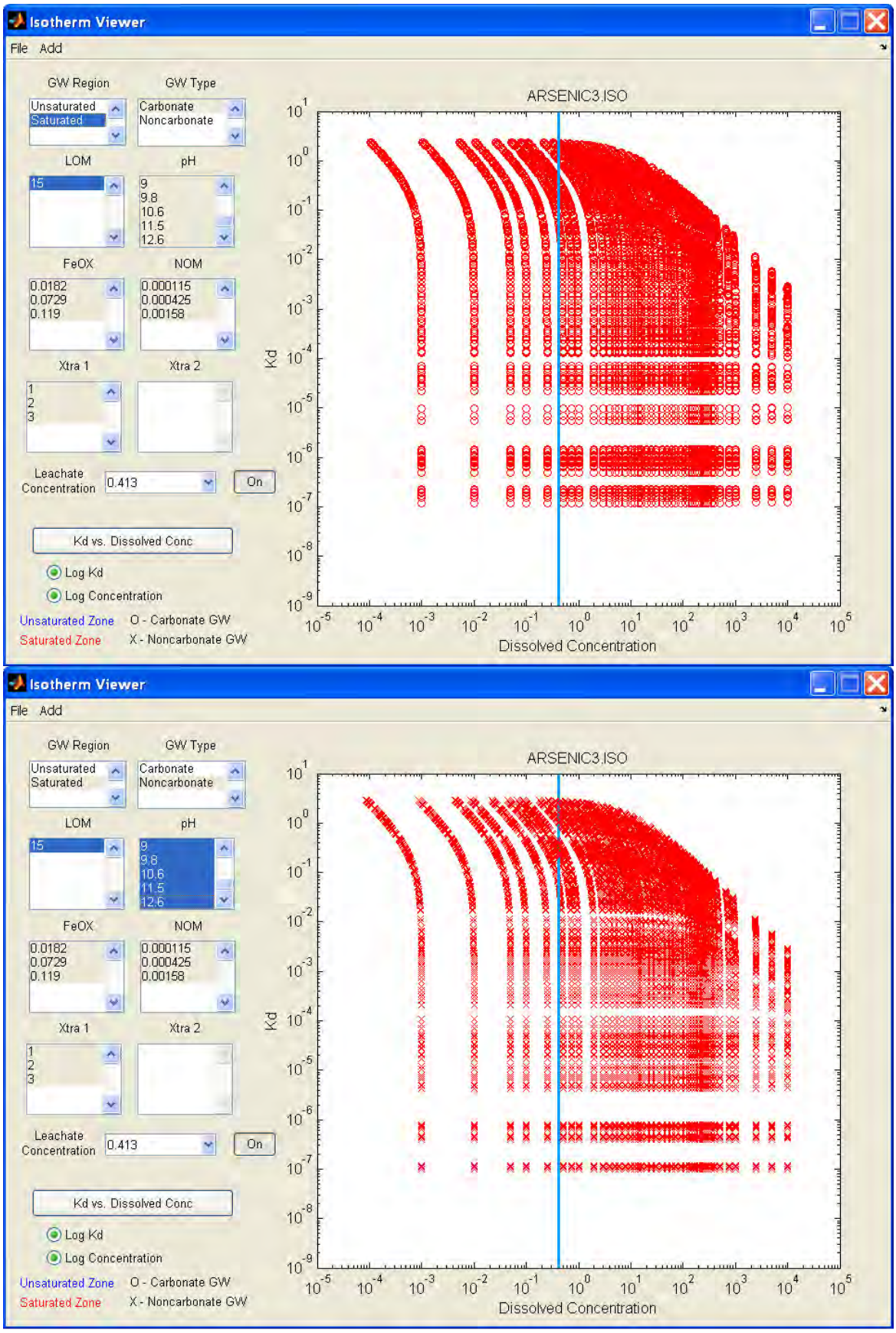

Figure H-2-23. Arsenic III saturated zone nonlinear sorption isotherms for SIs.

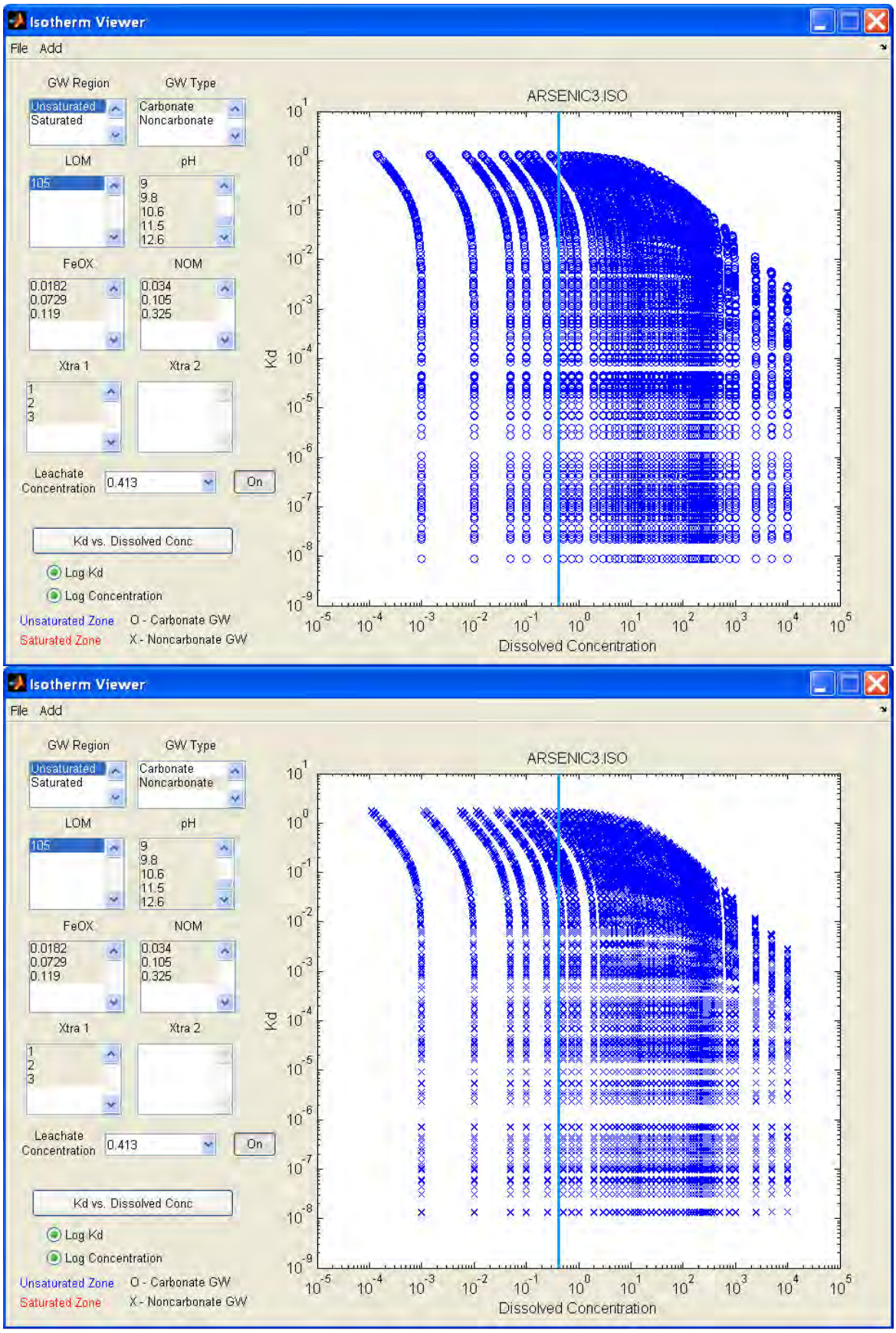

Figure H-2-24. Arsenic unsaturated zone nonlinear sorption isotherms for SIs.

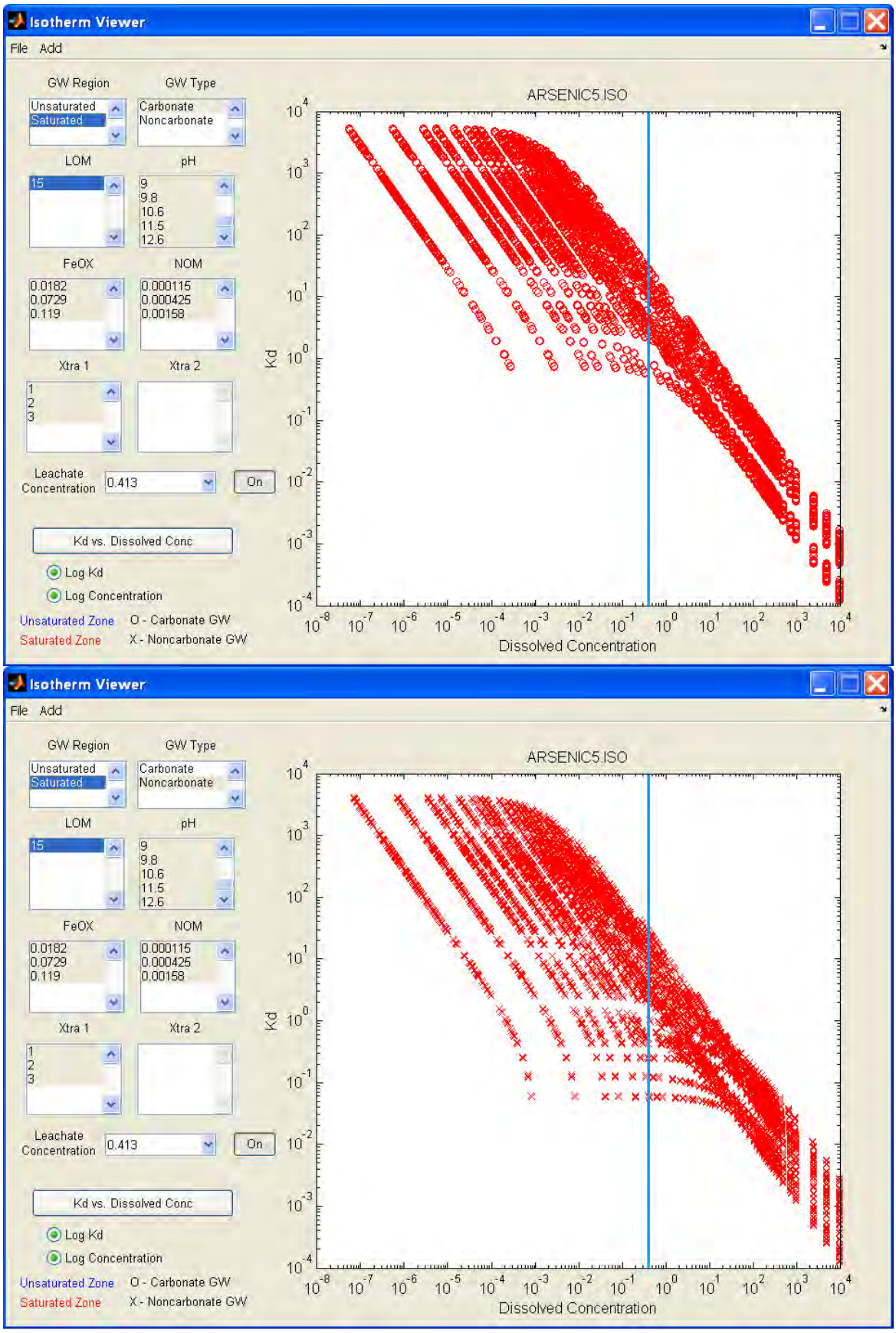

Figure H-2-25. Arsenic V saturated zone nonlinear sorption isotherms for SIs.

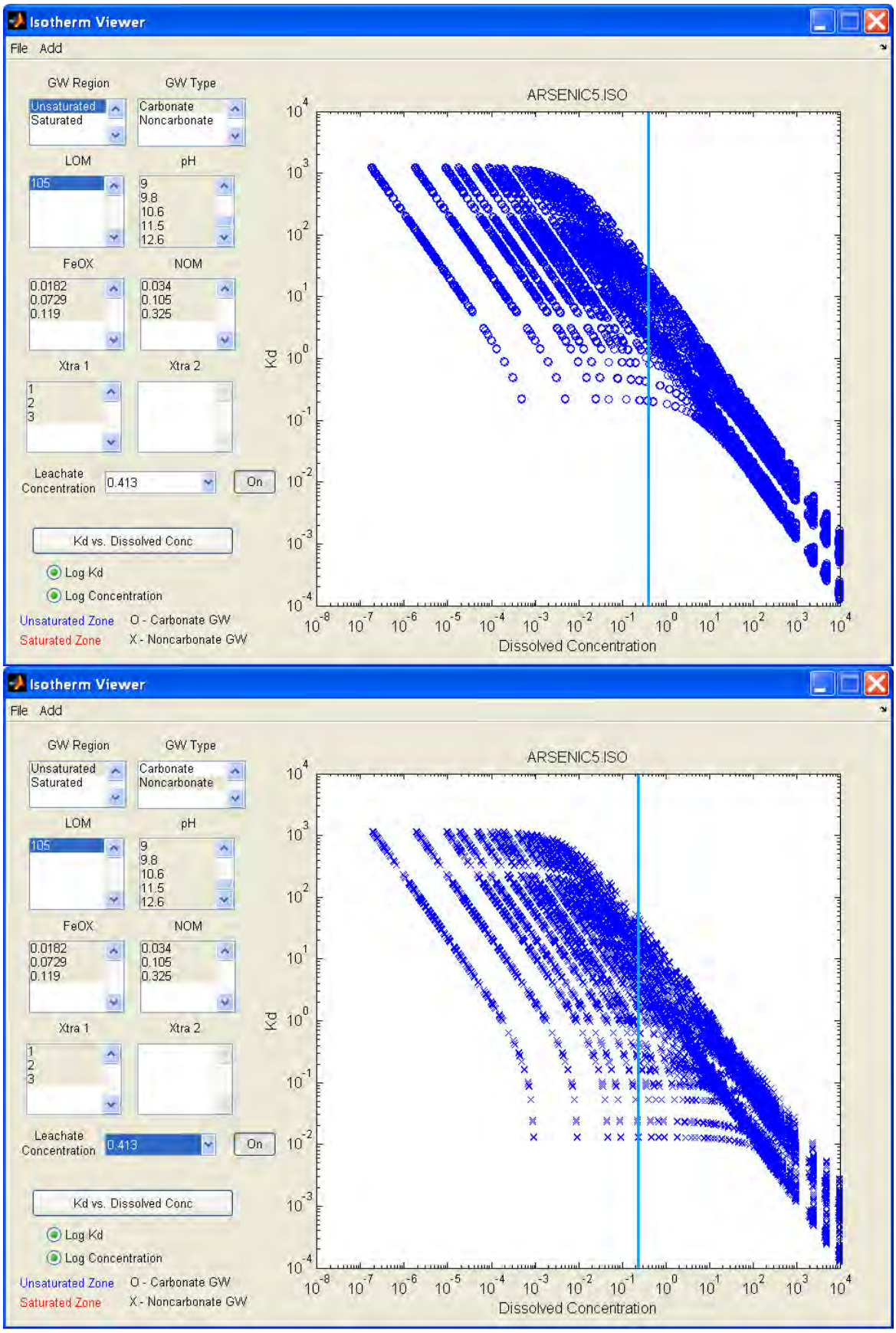

Figure H-2-26 Arsenic V unsaturated zone nonlinear sorption isotherms for SIs.

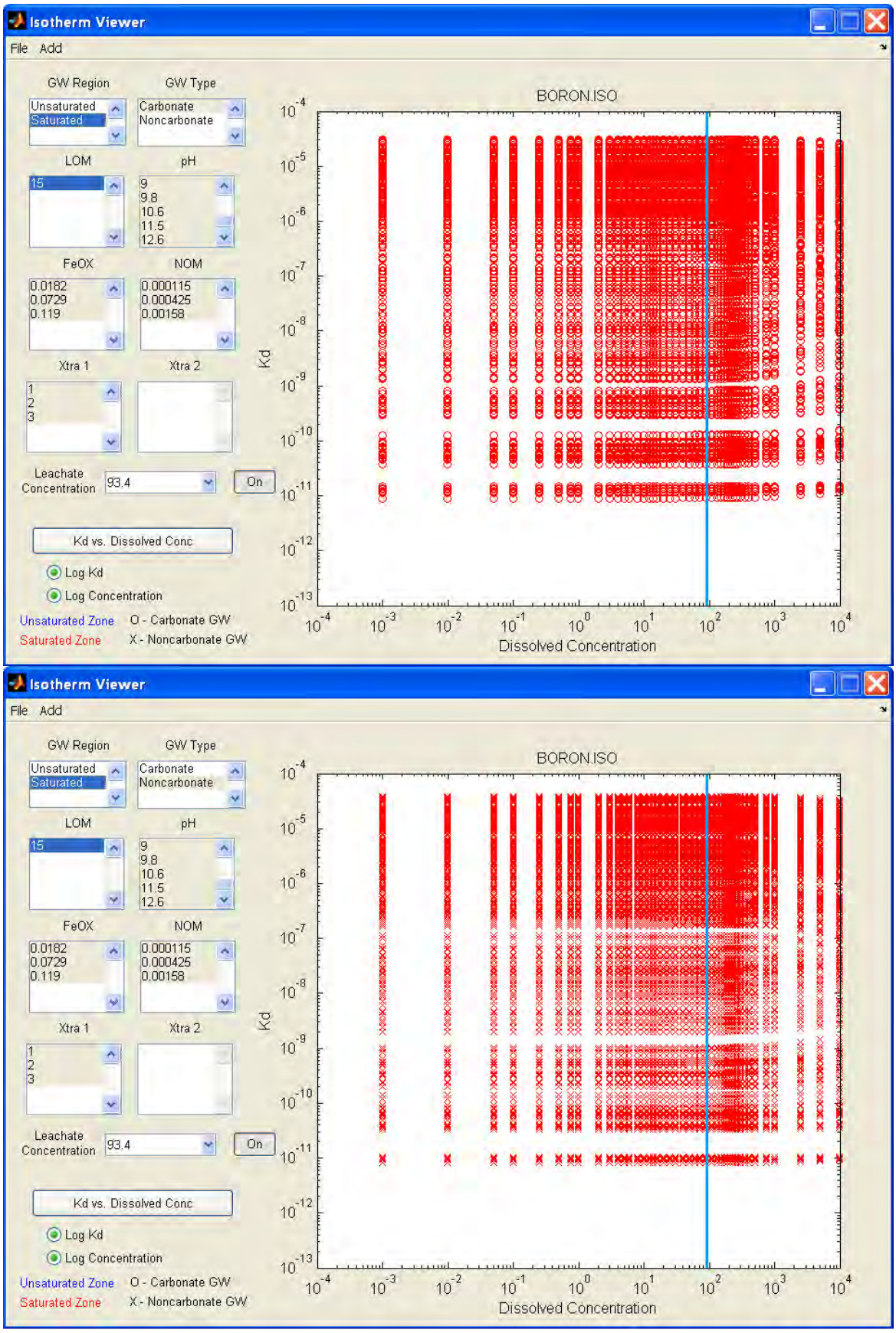

Figure H-2-27. Boron saturated zone nonlinear sorption isotherms for SIs.

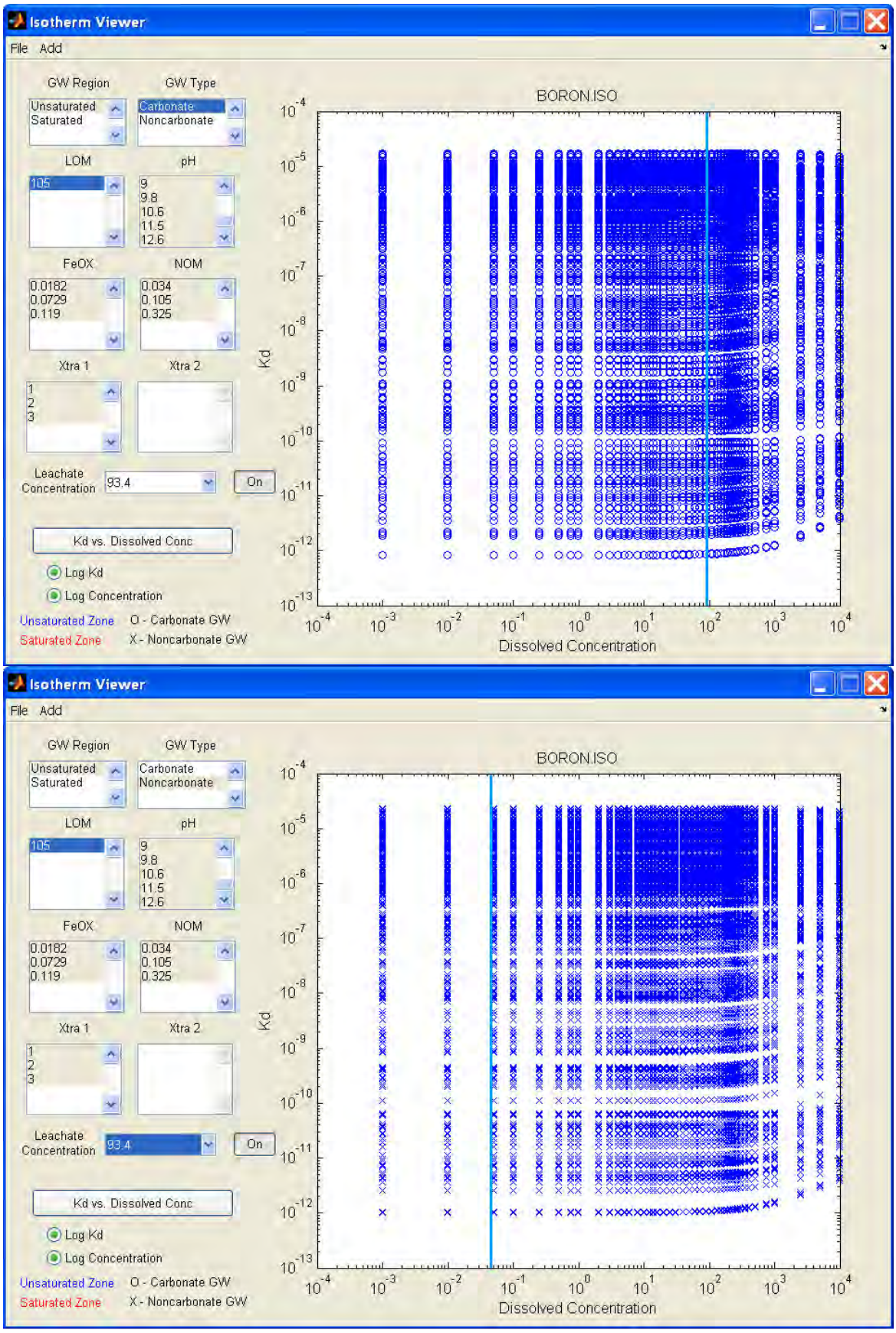

Figure H-2-28. Boron unsaturated zone nonlinear sorption isotherms for SIs.

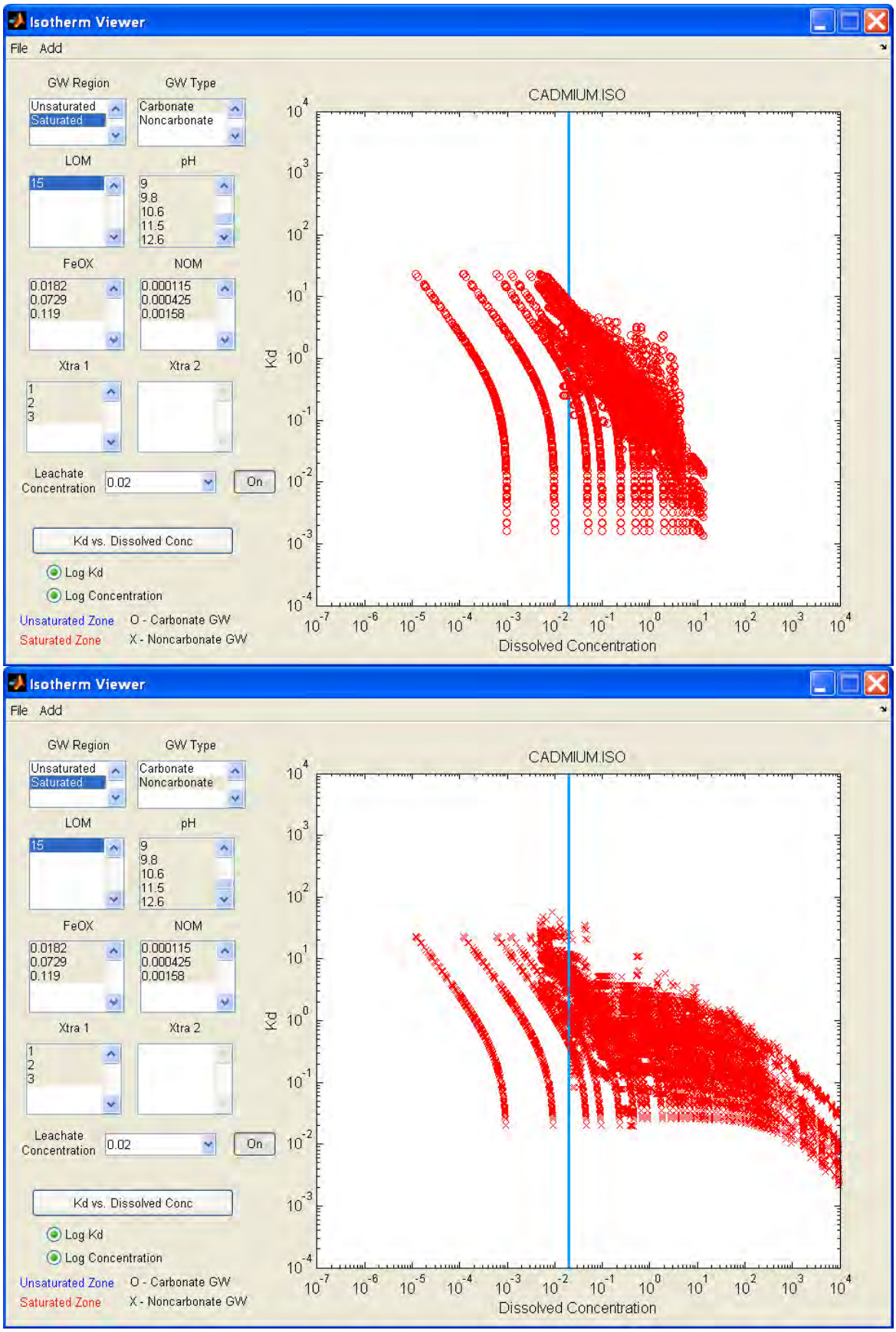

Figure H-2-29. Cadmium saturated zone nonlinear sorption isotherms for SIs.

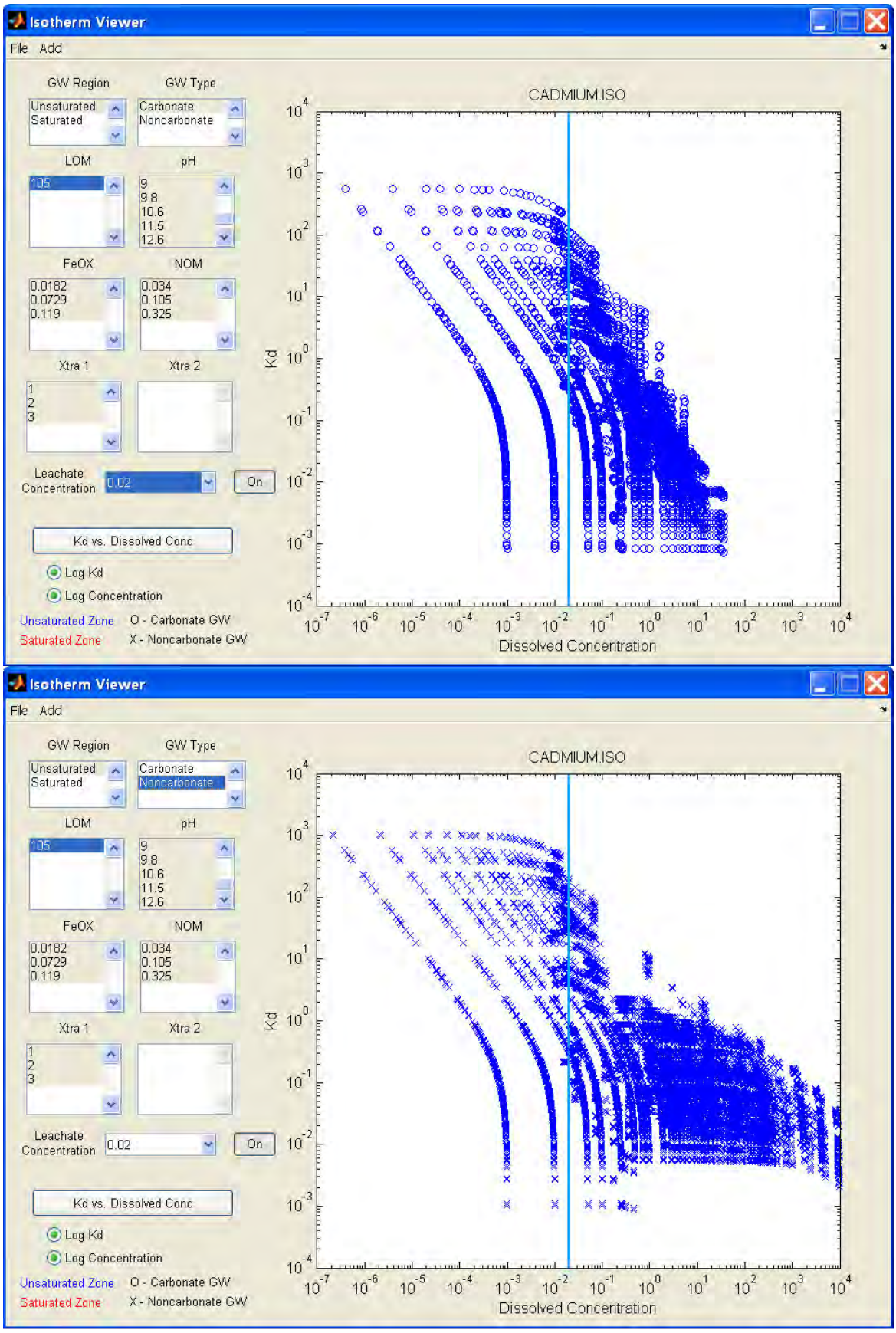

Figure H-2-30. Cadmium unsaturated zone nonlinear sorption isotherms for SIs.

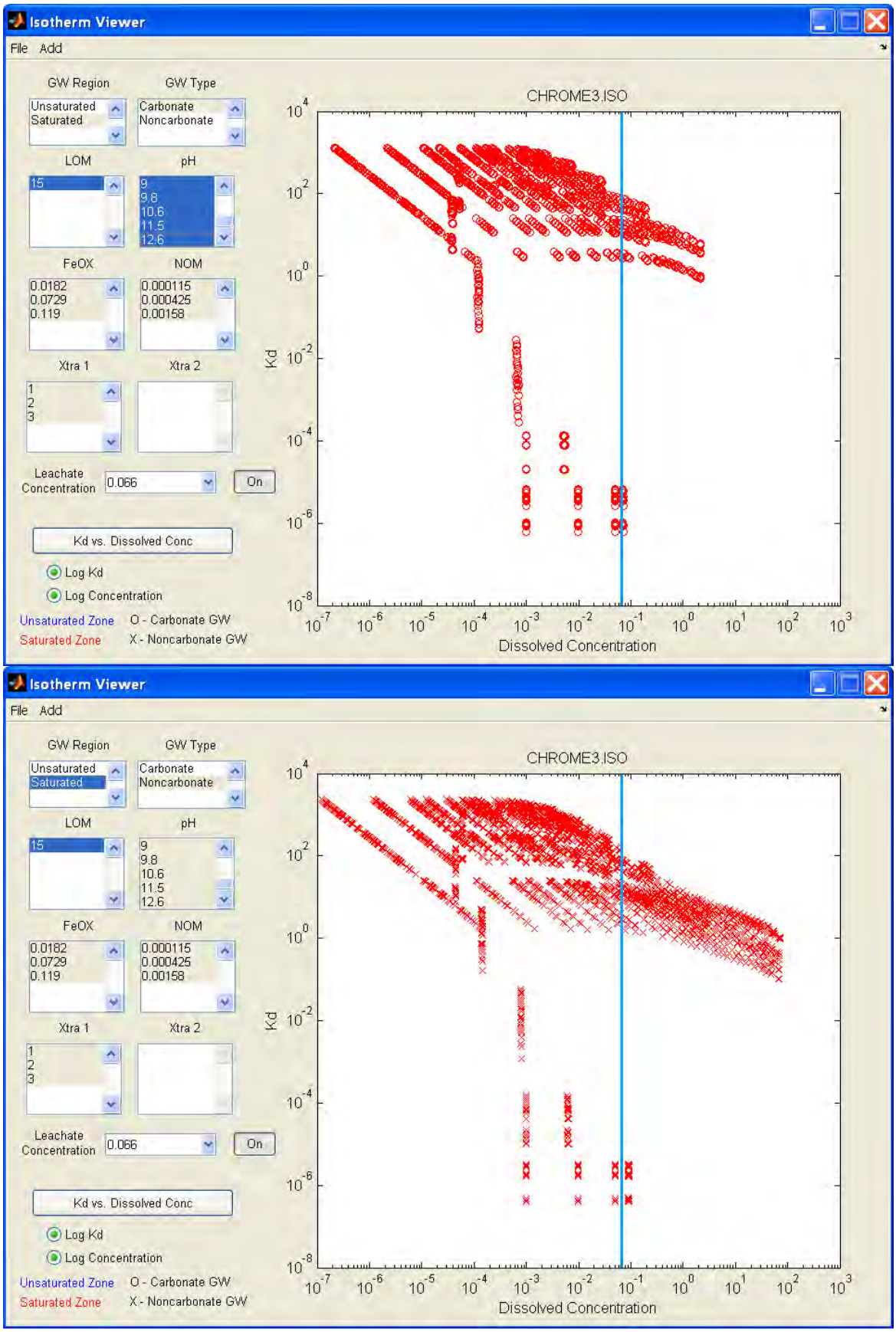

Figure H-2-31. Chromium III saturated zone nonlinear sorption isotherms for SIs.

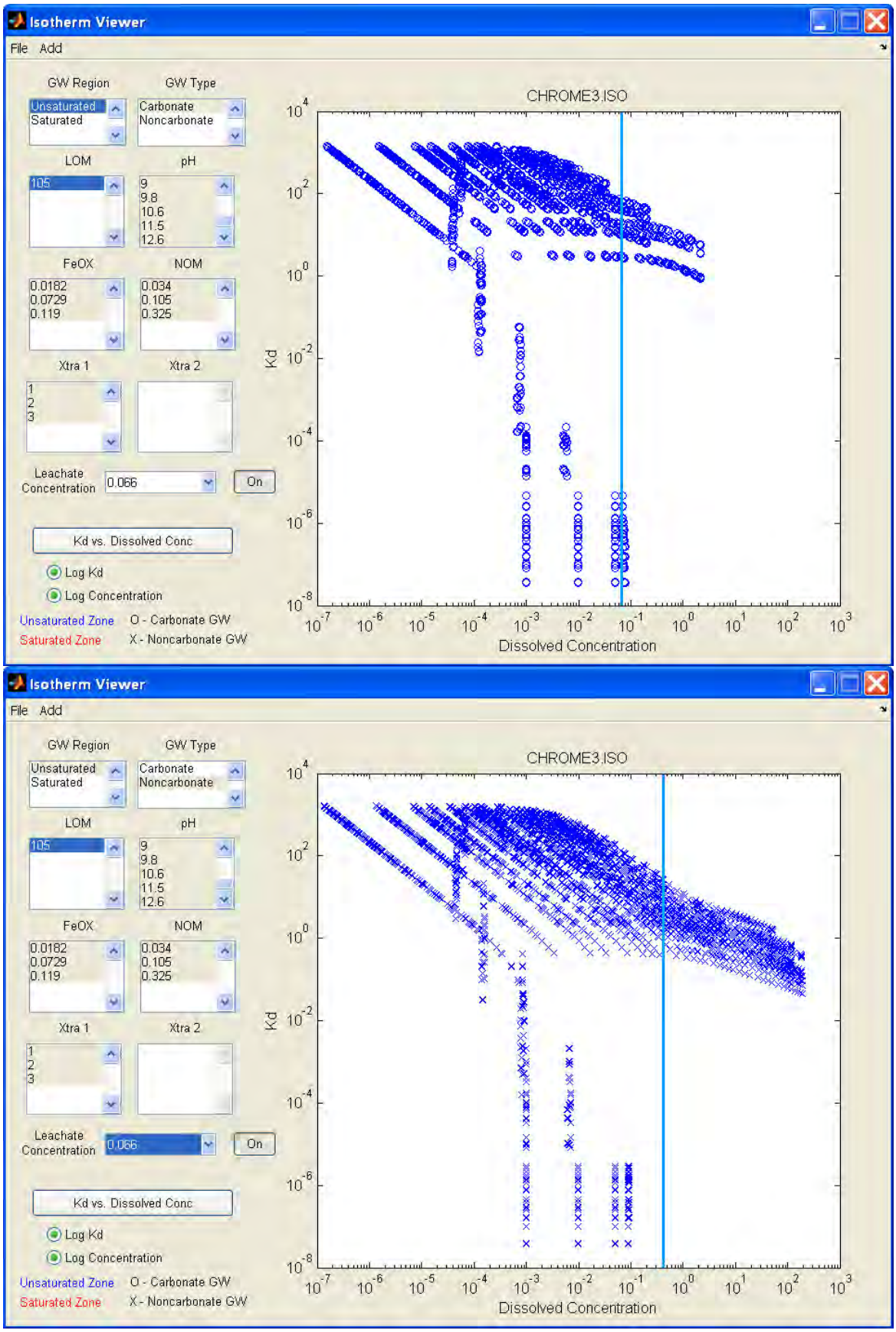

Figure H-2-32. Chromium III unsaturated zone nonlinear sorption isotherms for SIs.

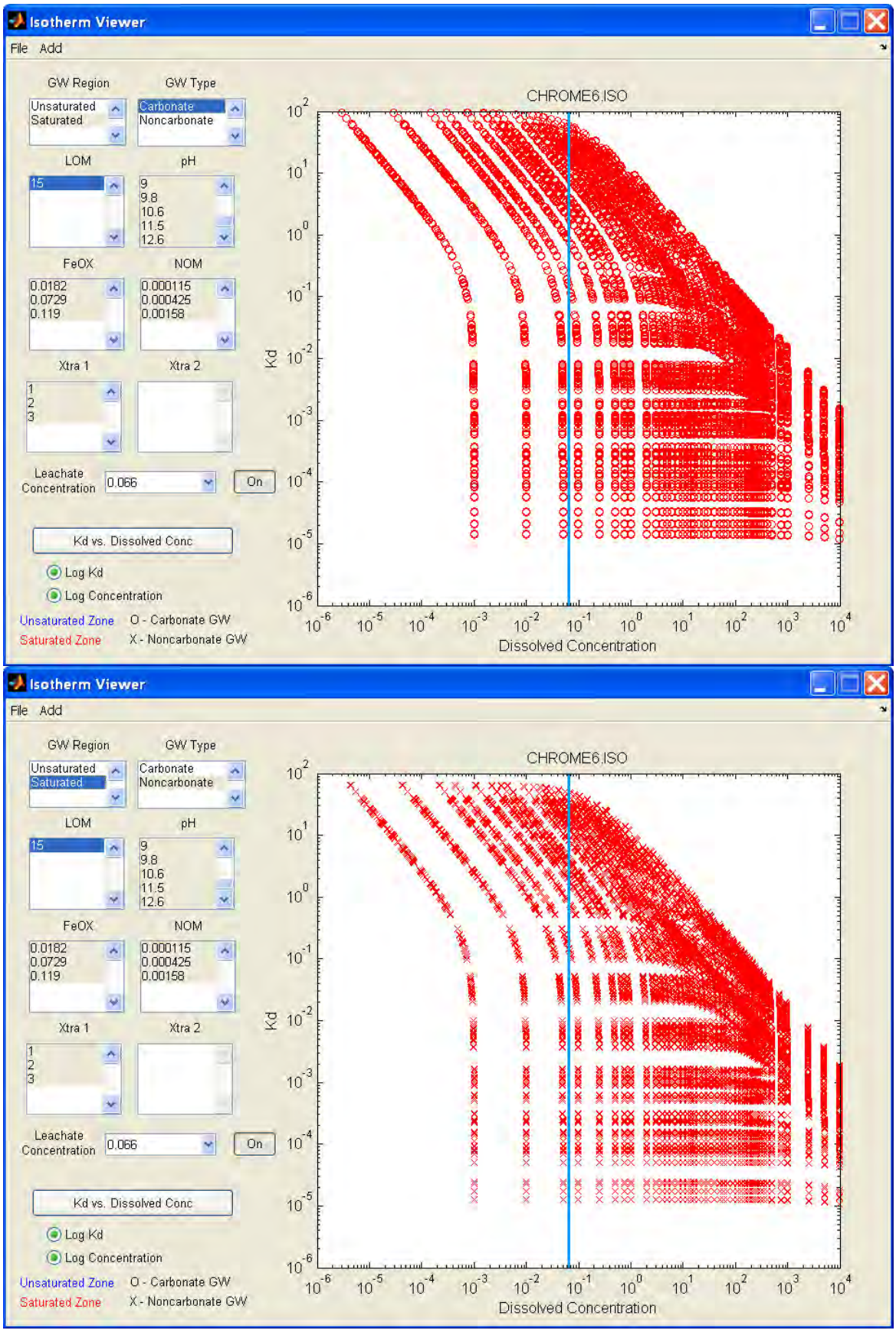

Figure H-2-33. Chromium VI saturated zone nonlinear sorption isotherms for SIs.

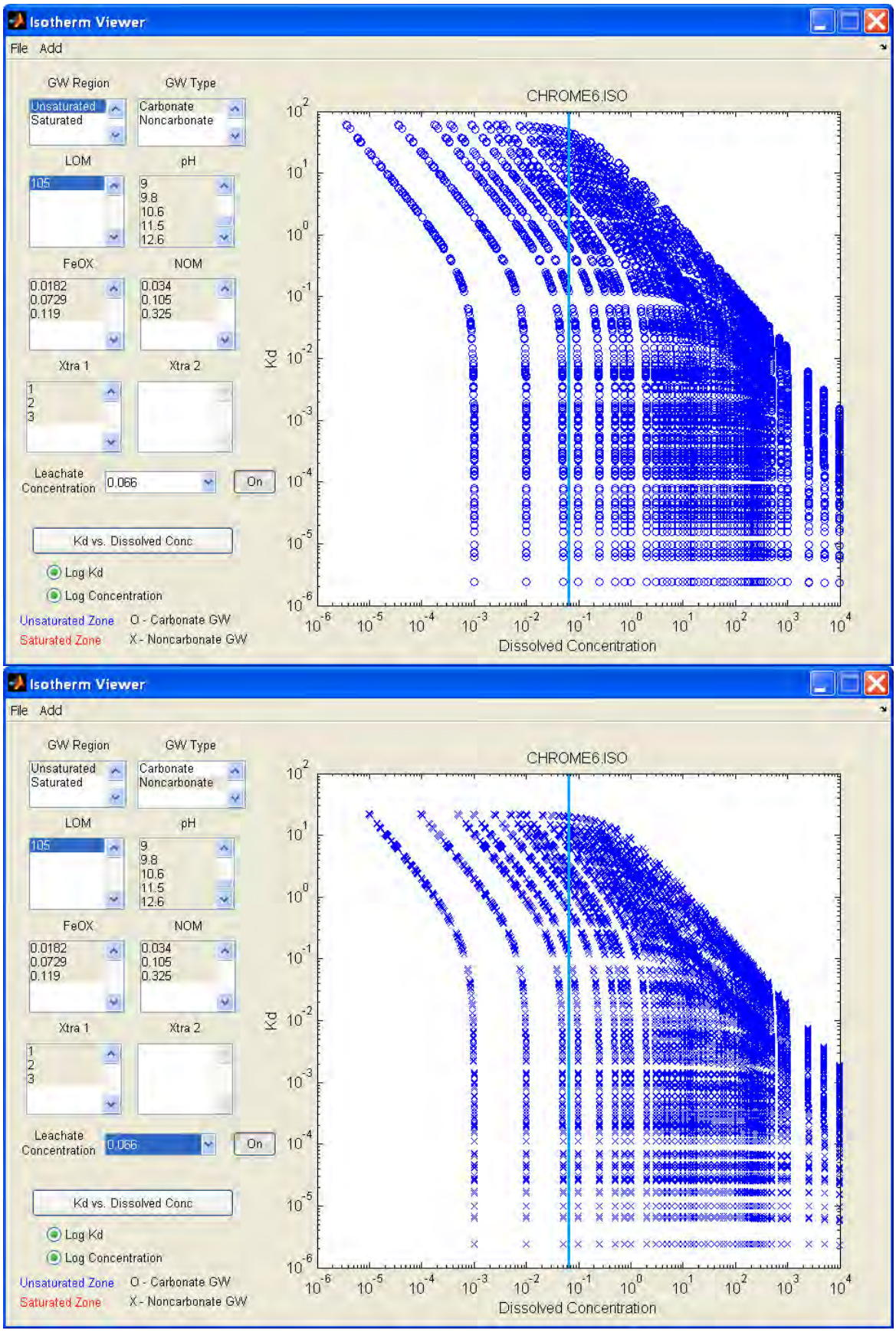

Figure H-2-34. Chromium VI unsaturated zone nonlinear sorption isotherms for SIs.

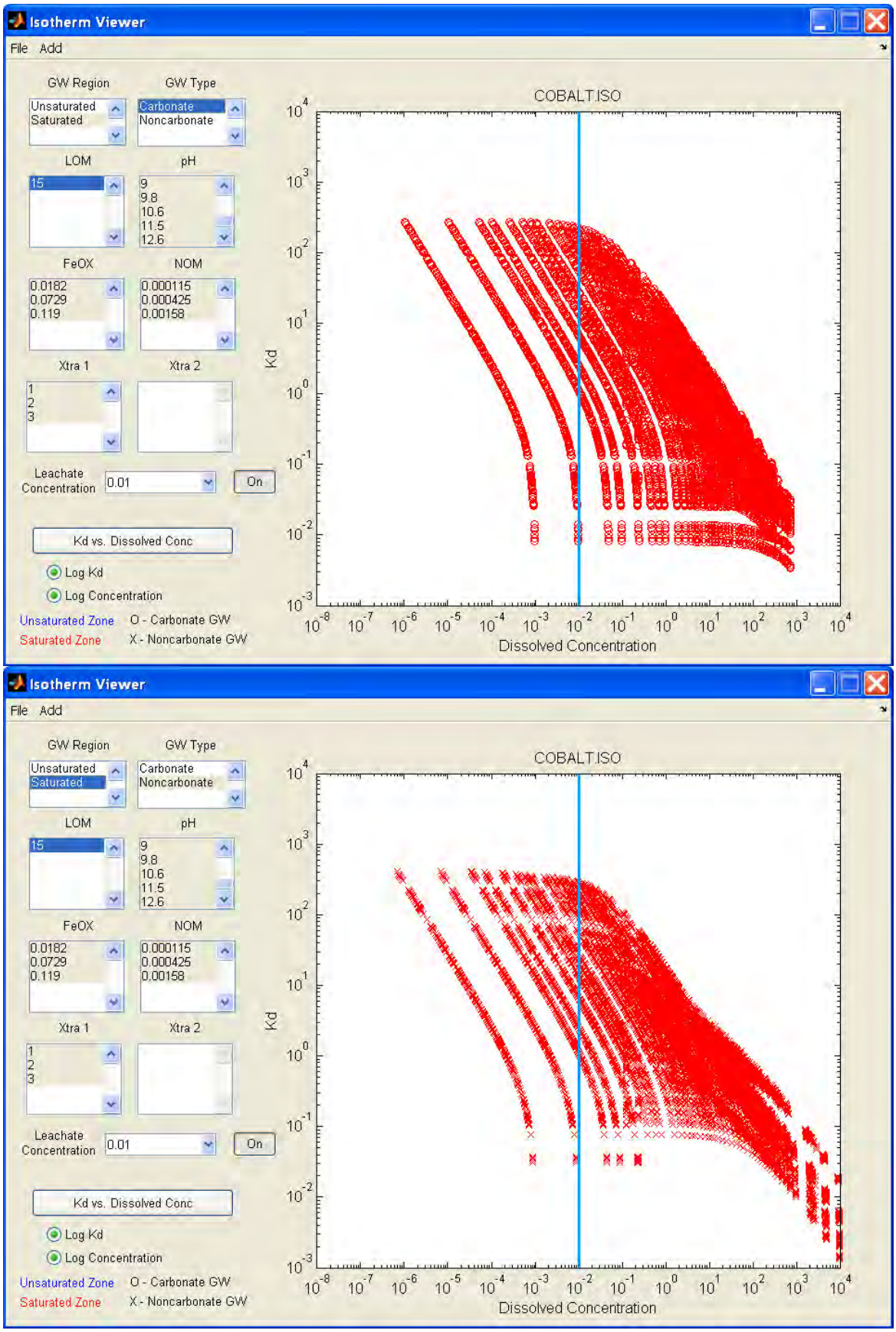

Figure H-2-35. Cobalt saturated zone nonlinear sorption isotherms for SIs.

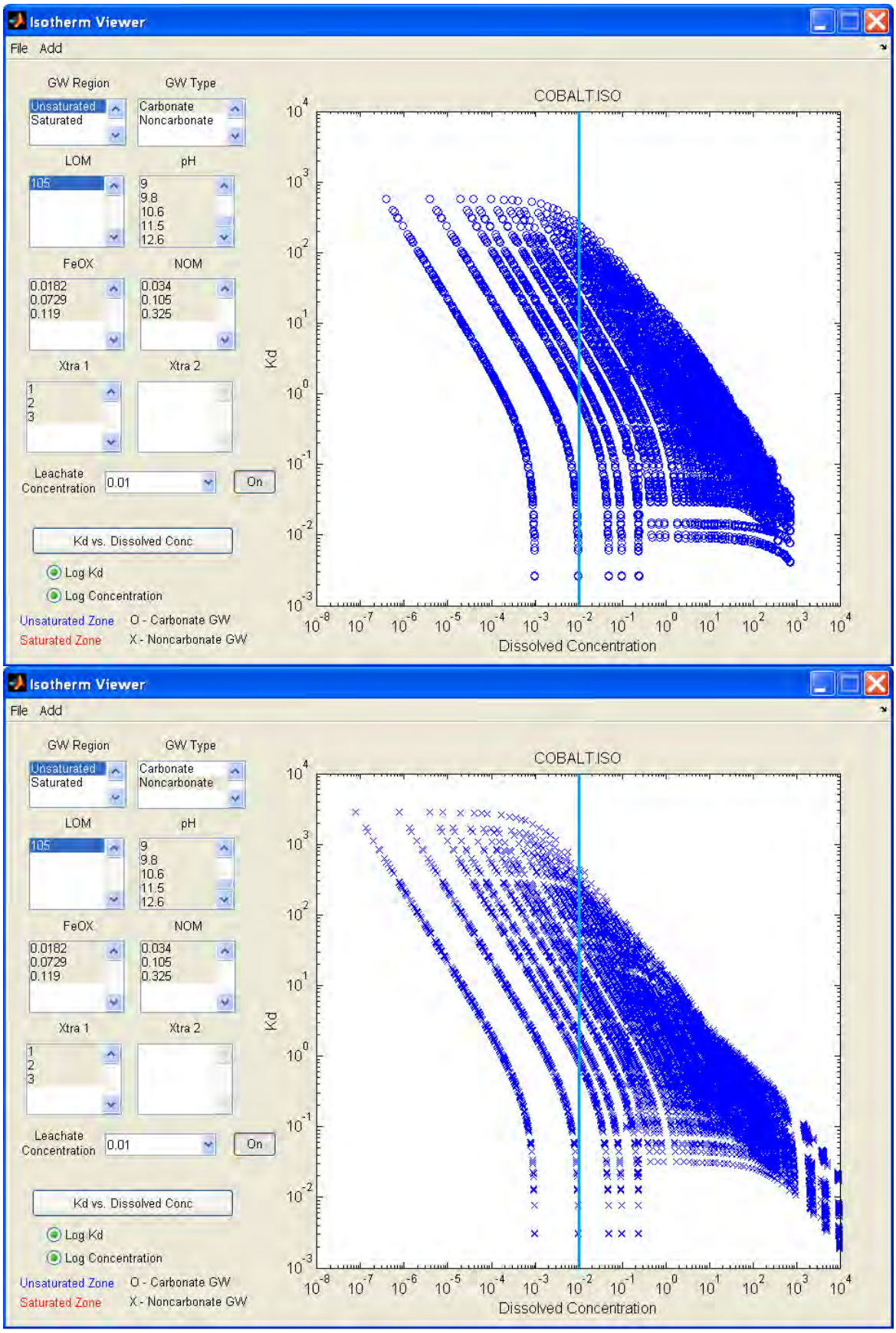

Figure H-2-36. Cobalt unsaturated zone nonlinear sorption isotherms for SIs.

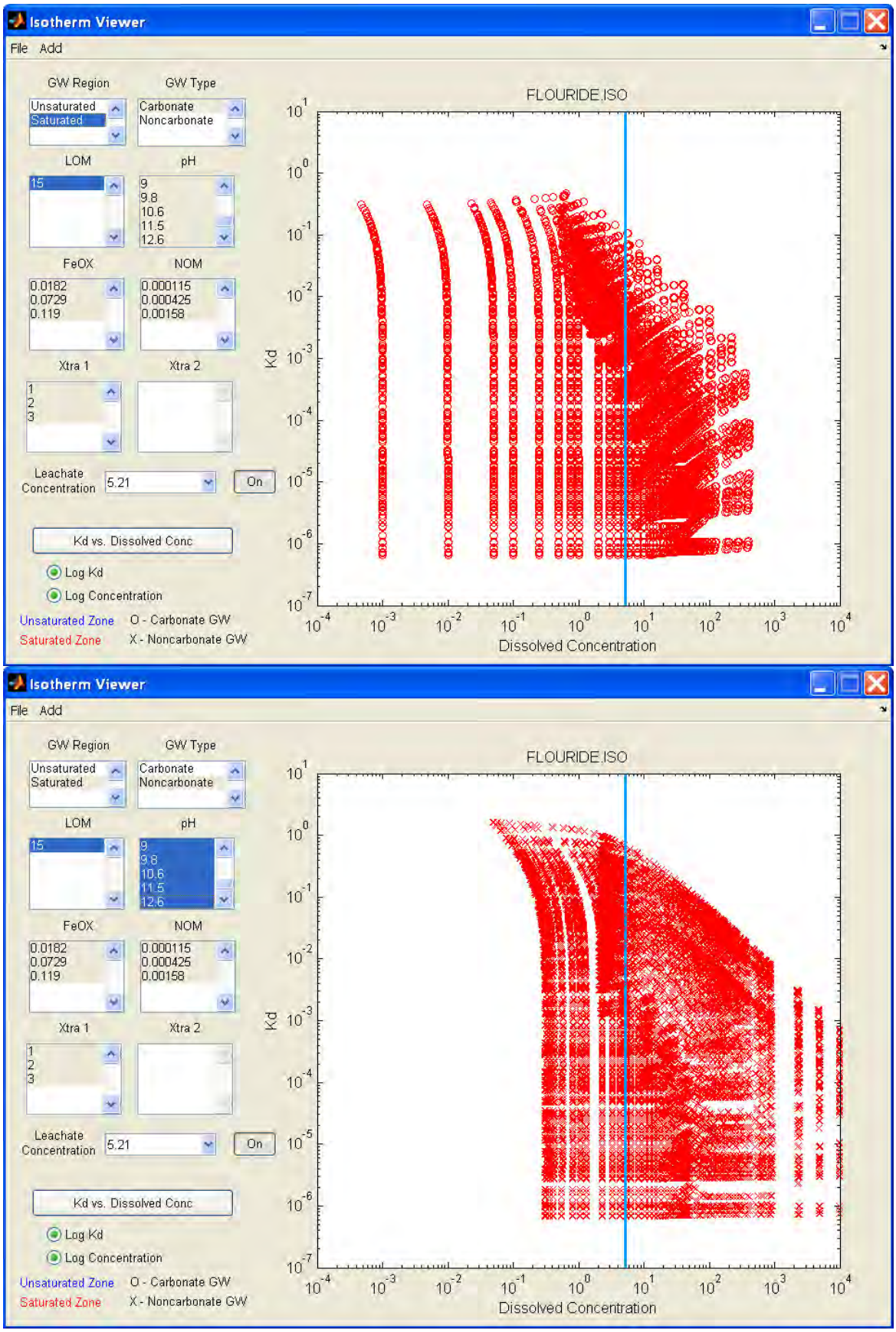

Figure H-2-37. Fluoride saturated zone nonlinear sorption isotherms for SIs.

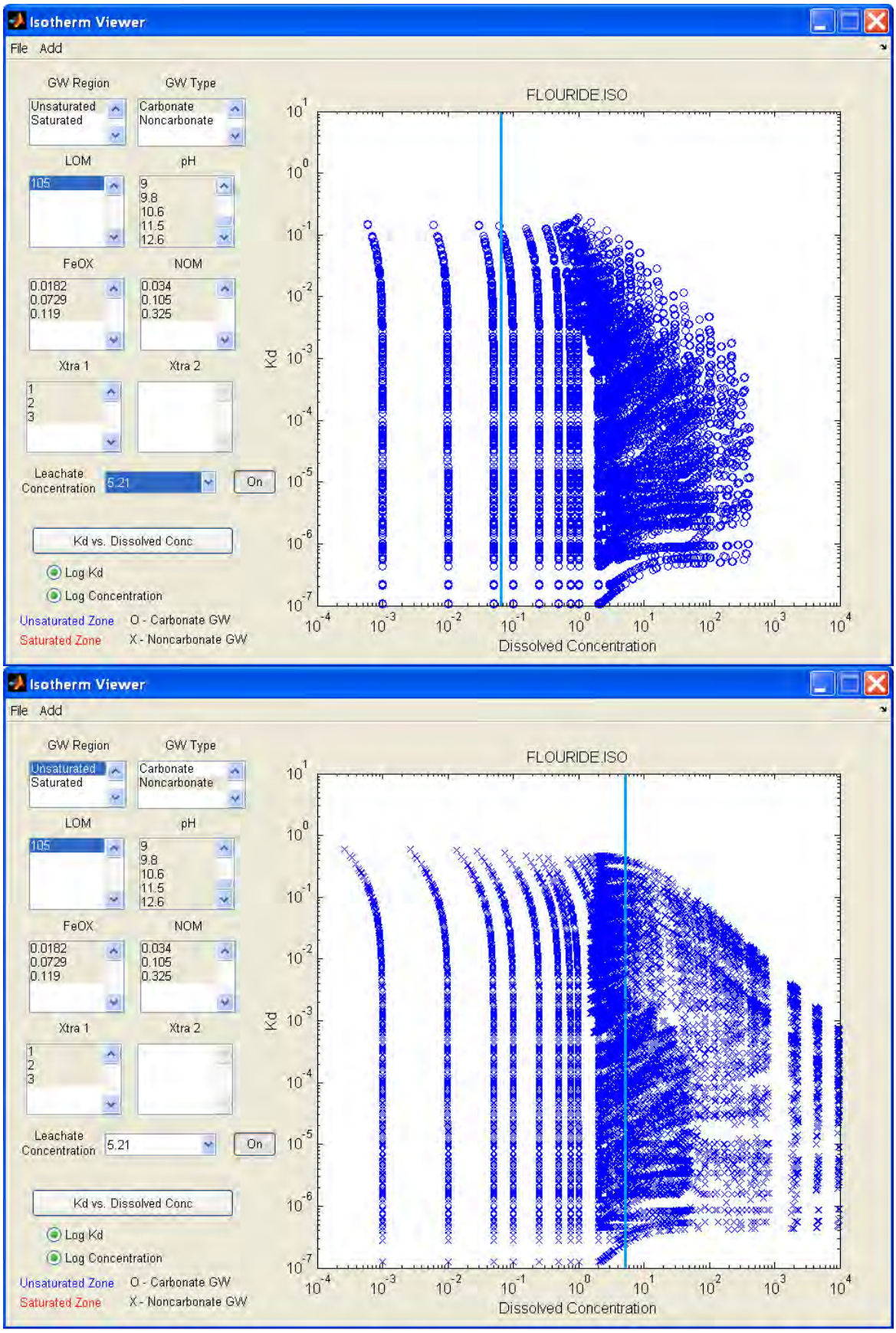

Figure H-2-38. Fluoride unsaturated zone nonlinear sorption isotherms for SIs.

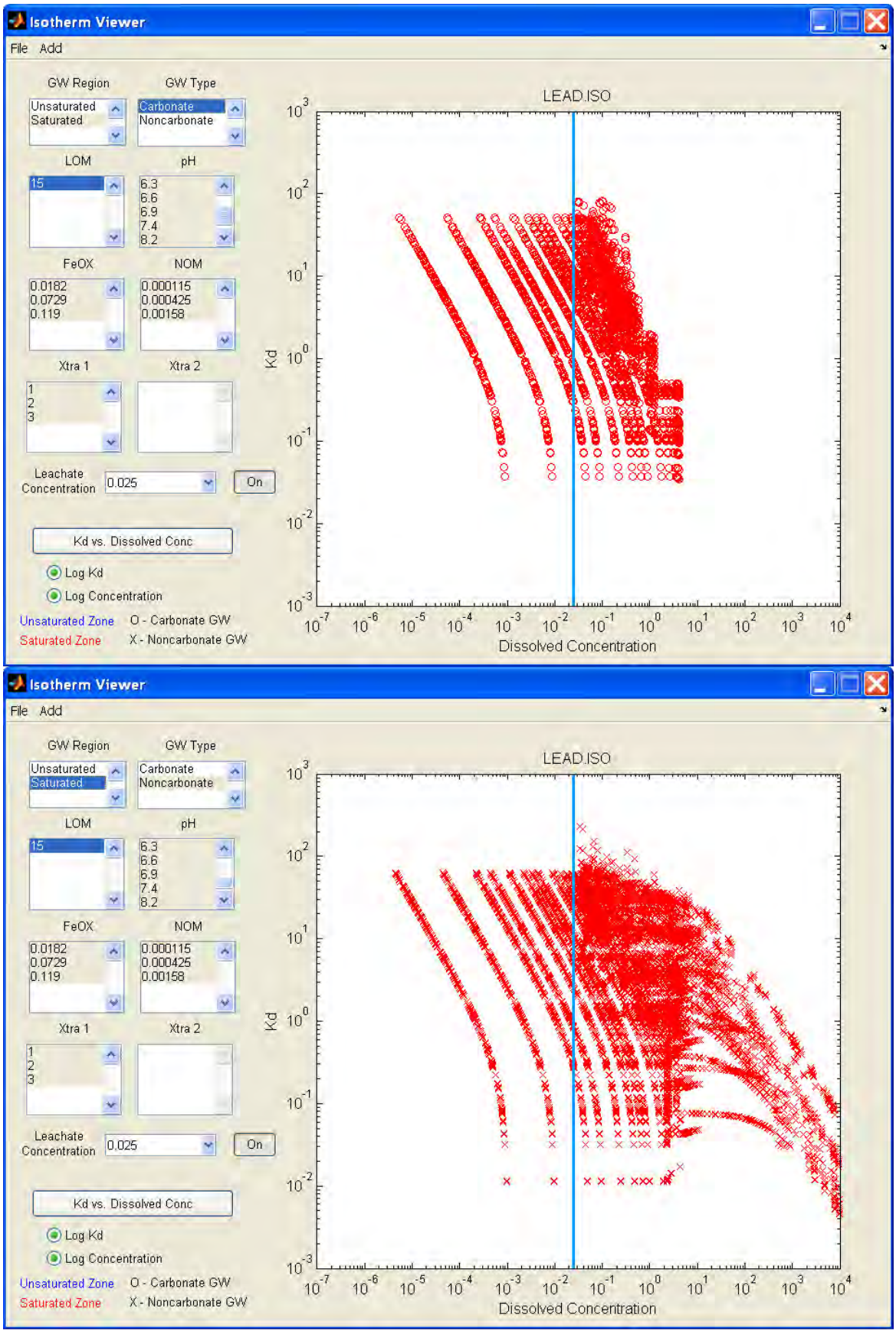

Figure H-2-39. Lead saturated zone nonlinear sorption isotherms for SIs.

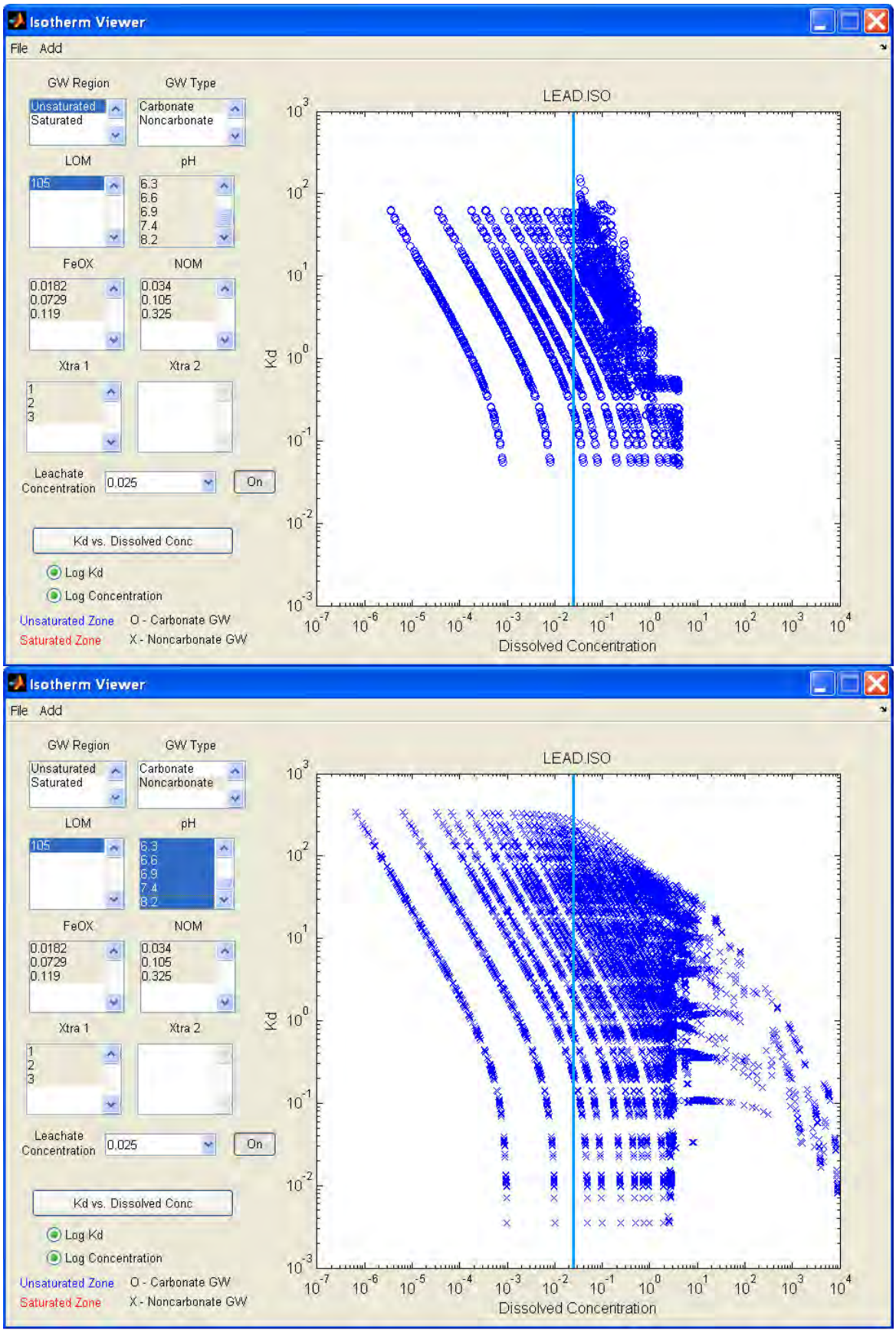

Figure H-2-40. Lead unsaturated zone nonlinear sorption isotherms for SIs.

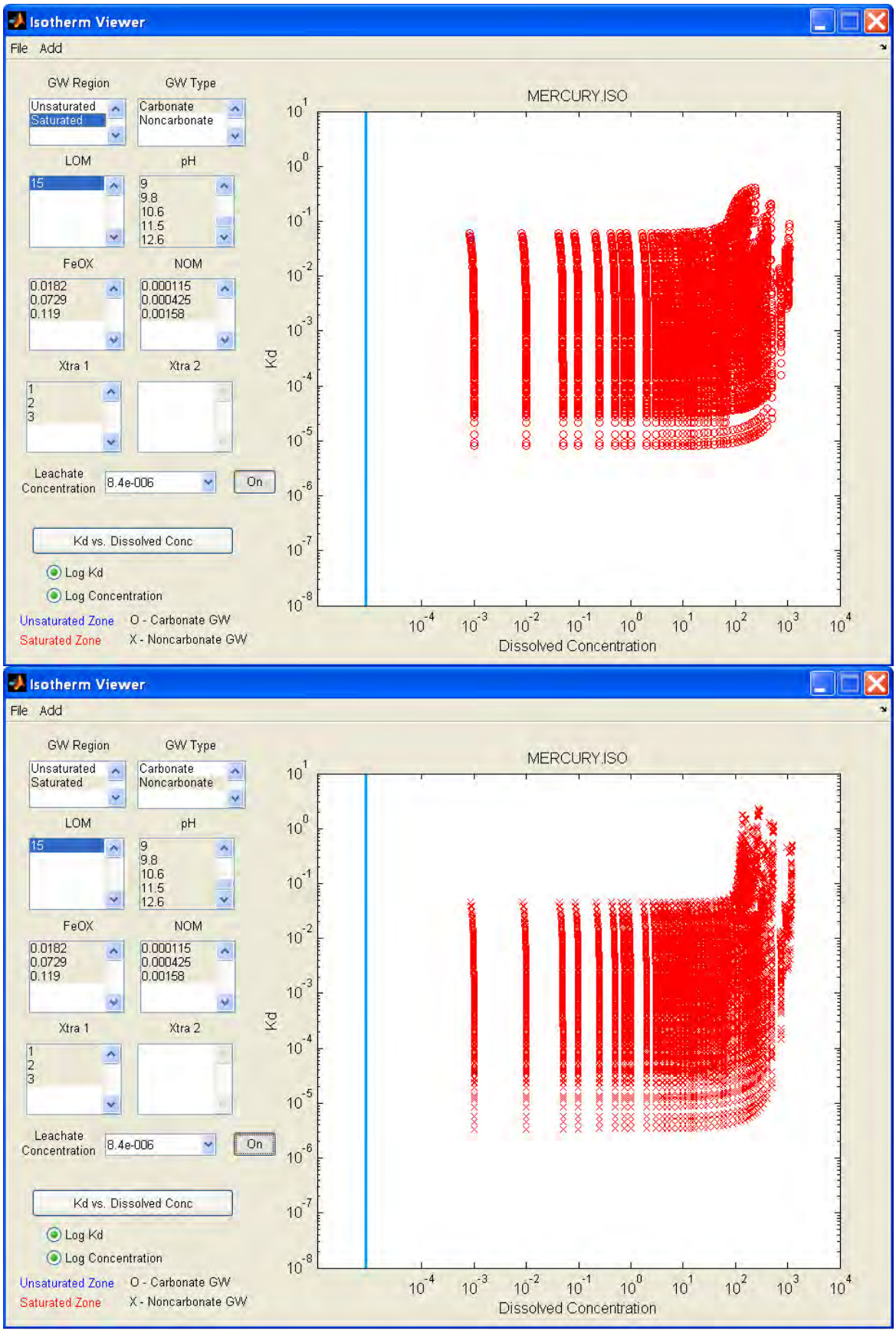

Figure H-2-40. Mercury saturated zone nonlinear sorption isotherms for SIs.

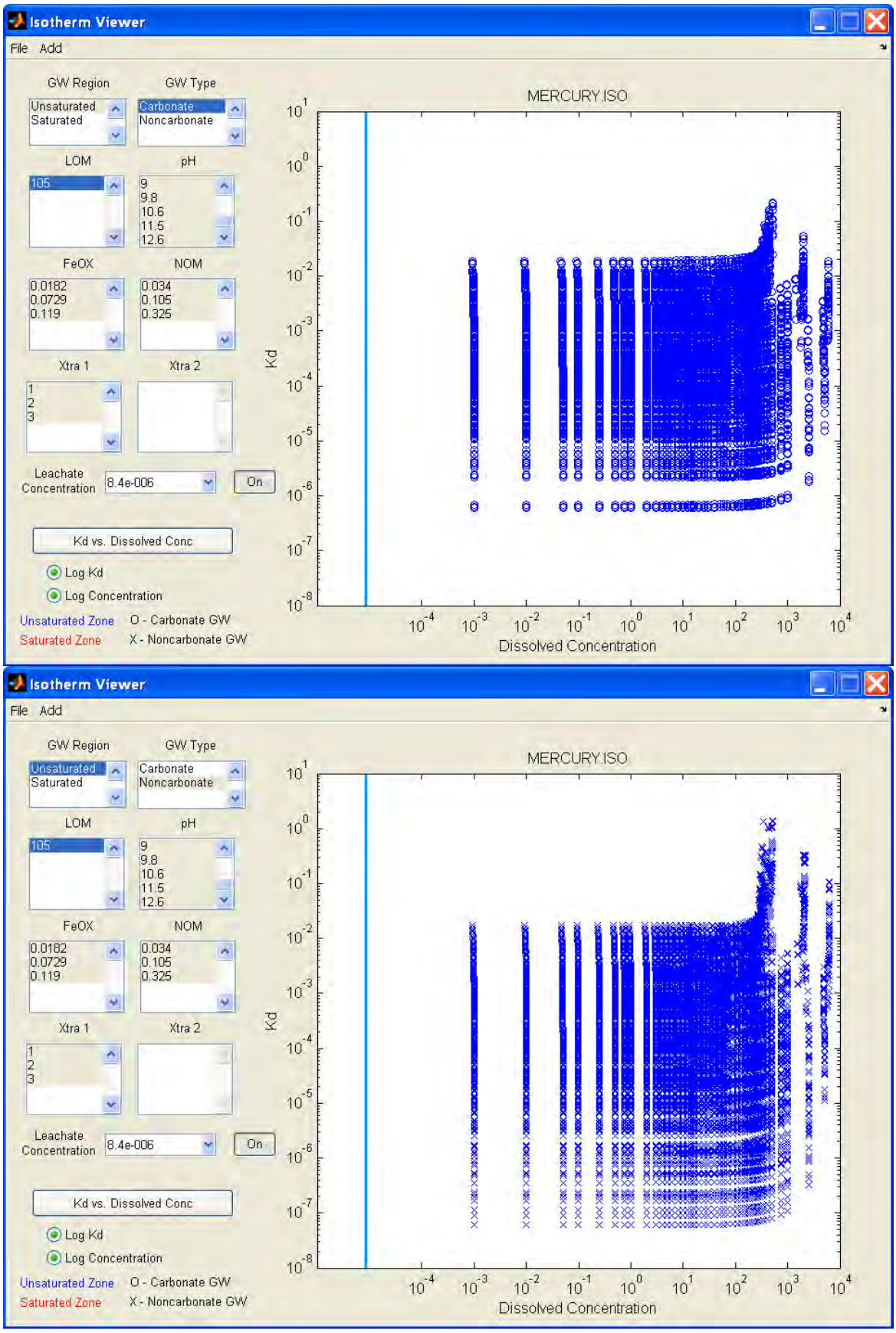

Figure H-2-40. Mercury unsaturated zone nonlinear sorption isotherms for SIs.

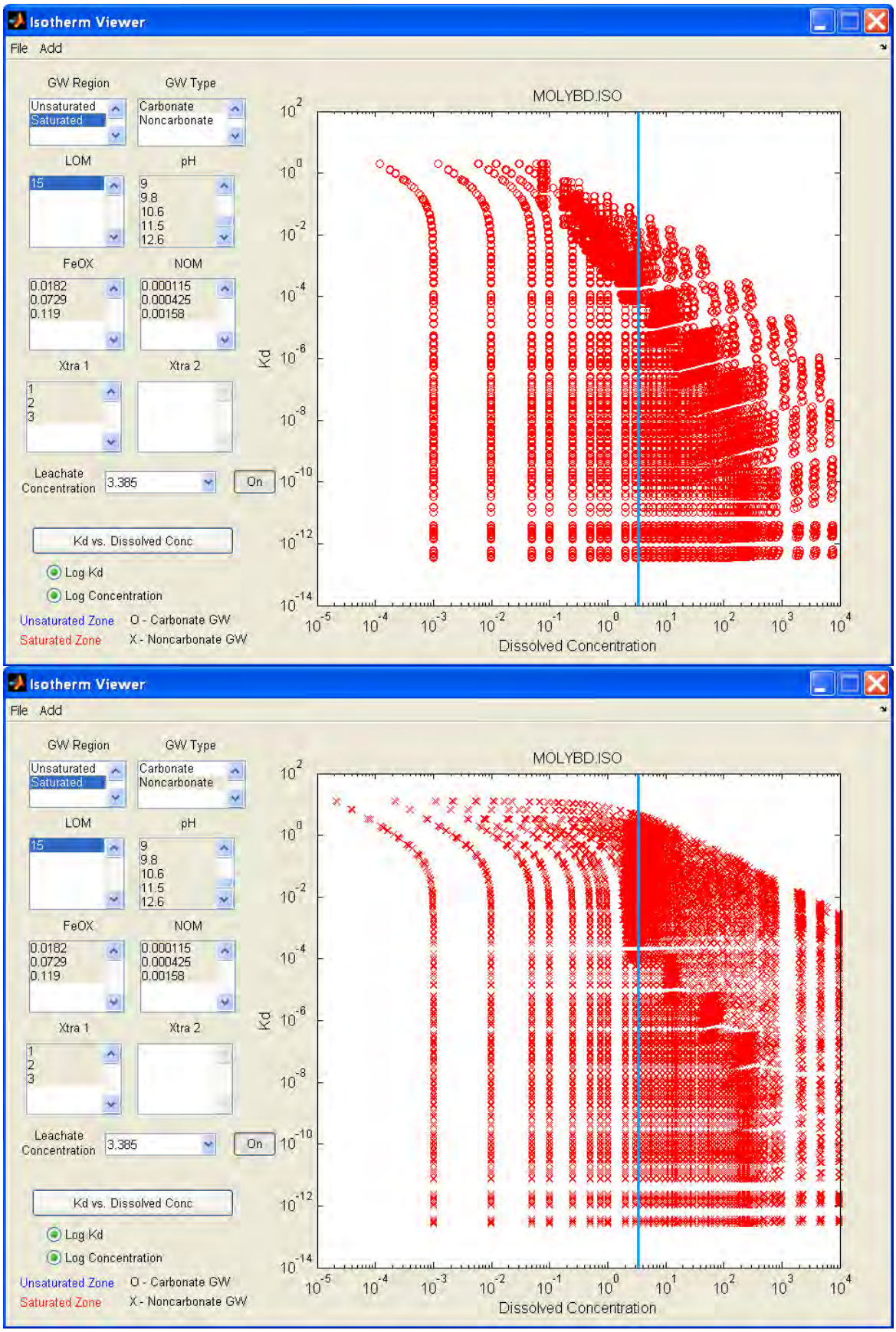

Figure H-2-41. Molybdenum saturated zone nonlinear sorption isotherms for SIs.

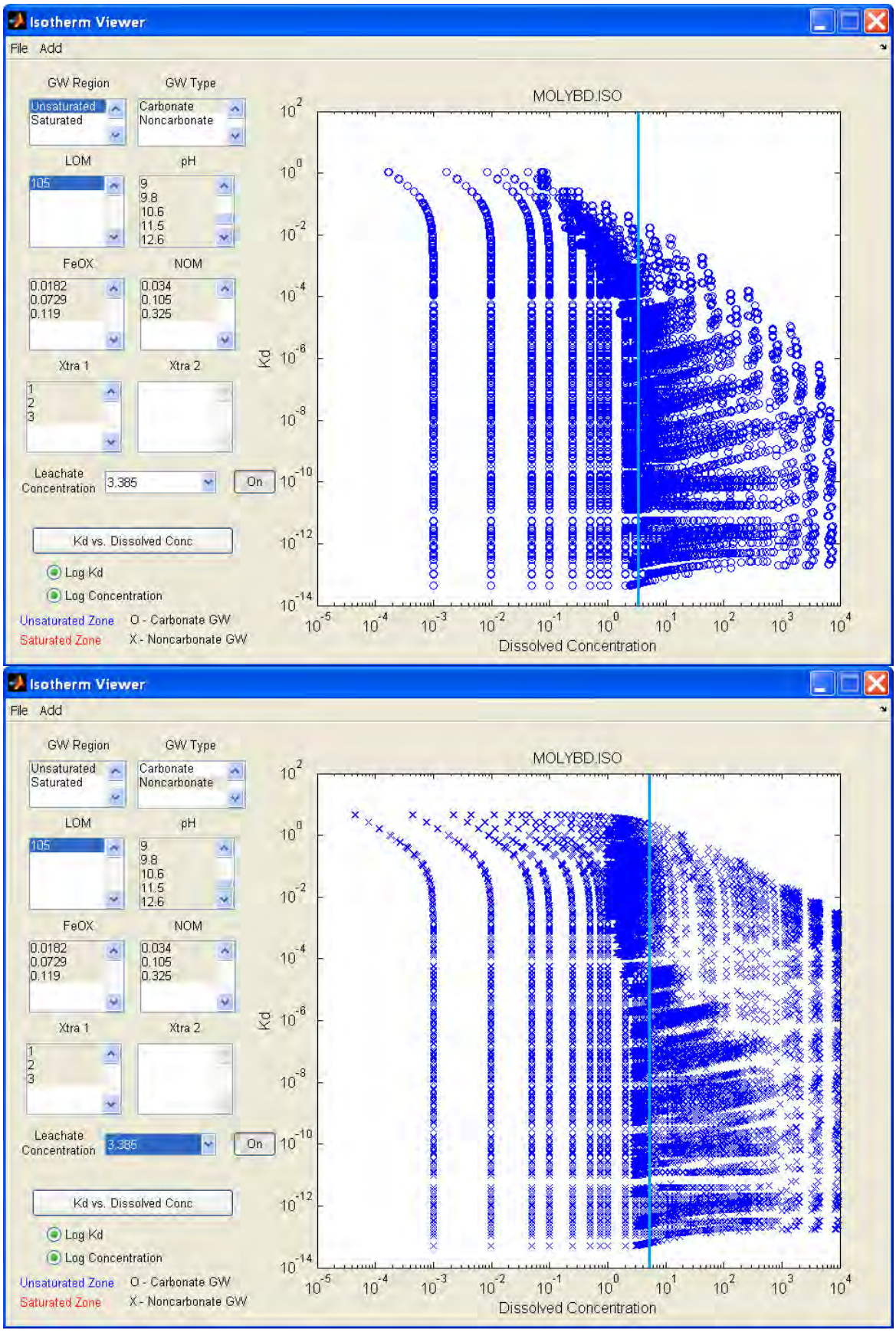

Figure H-2-42. Molybdenum unsaturated zone nonlinear sorption isotherms for SIs.

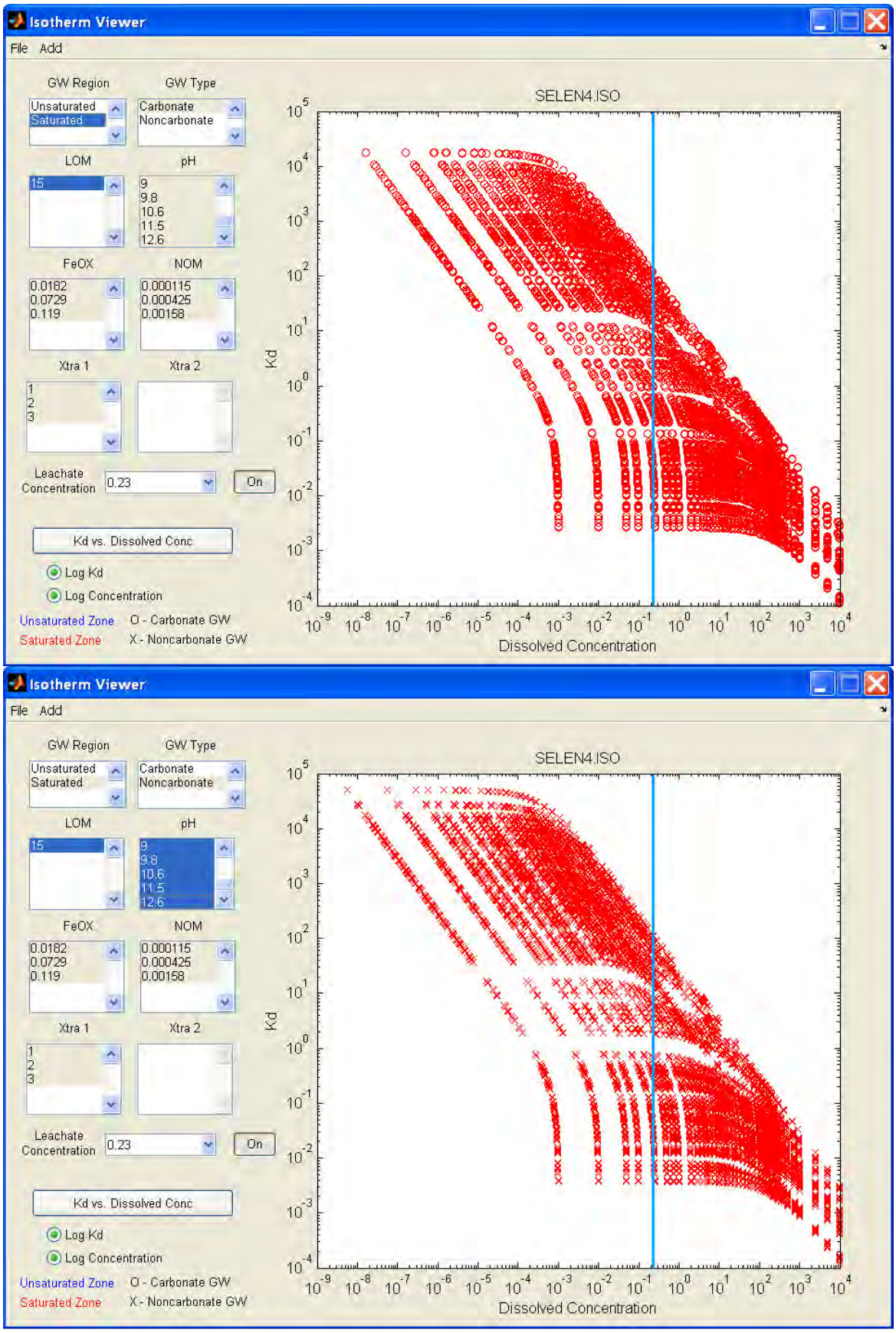

Figure H-2-43. Selenium IV saturated zone nonlinear sorption isotherms for SIs.

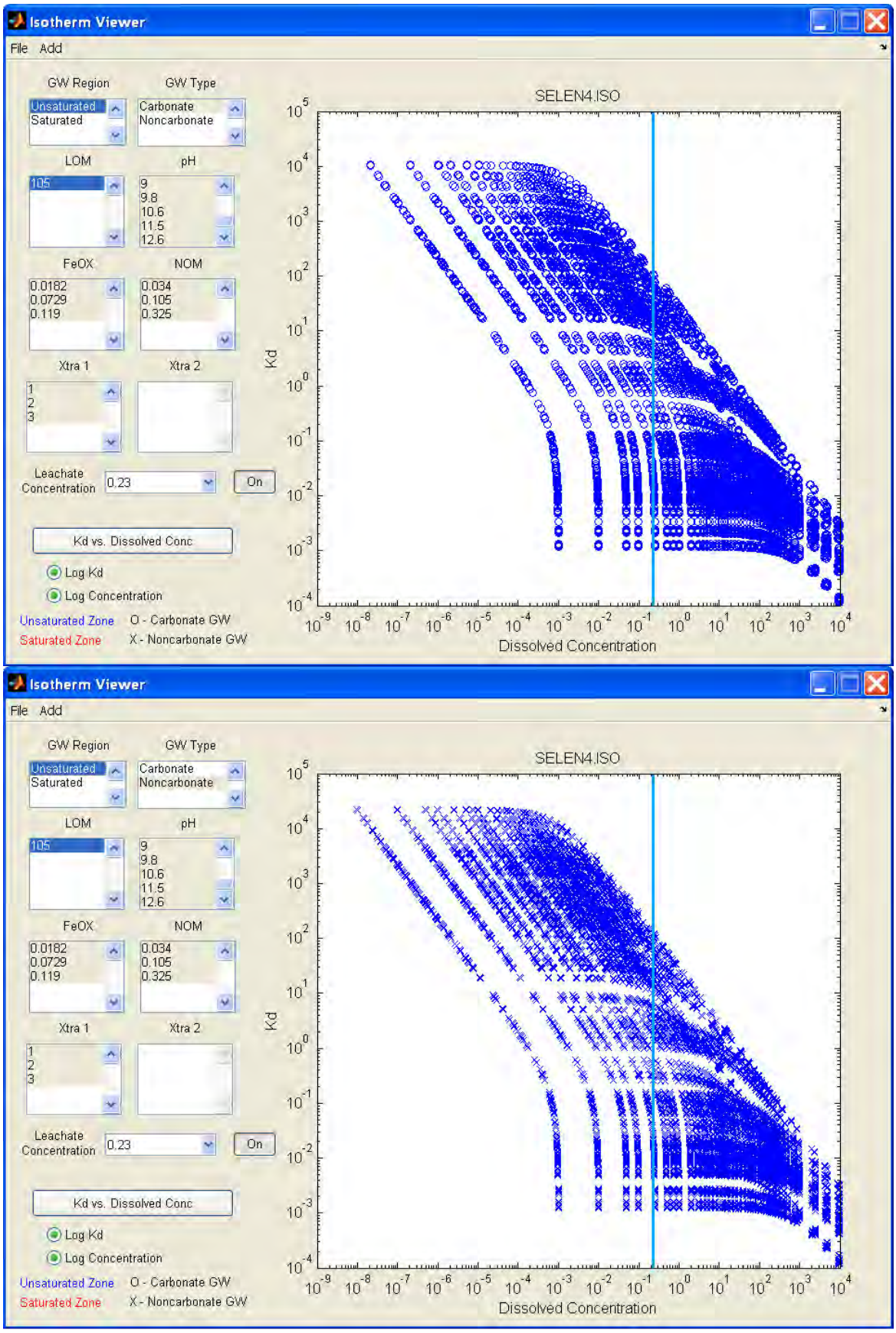

Figure H-2-44. Selenium IV saturated zone nonlinear sorption isotherms for SIs.

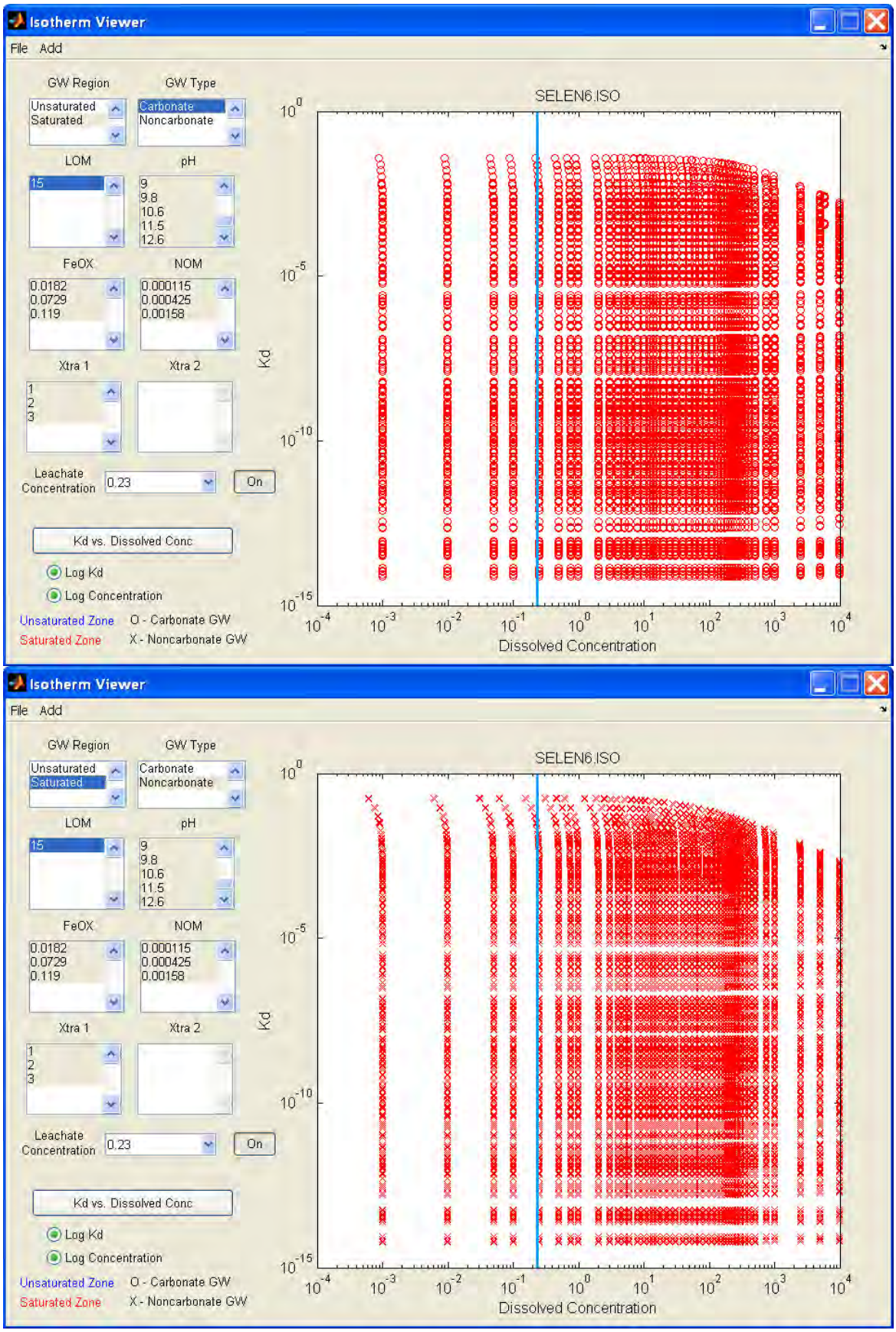

Figure H-2-45. Selenium VI saturated zone nonlinear sorption isotherms for SIs.

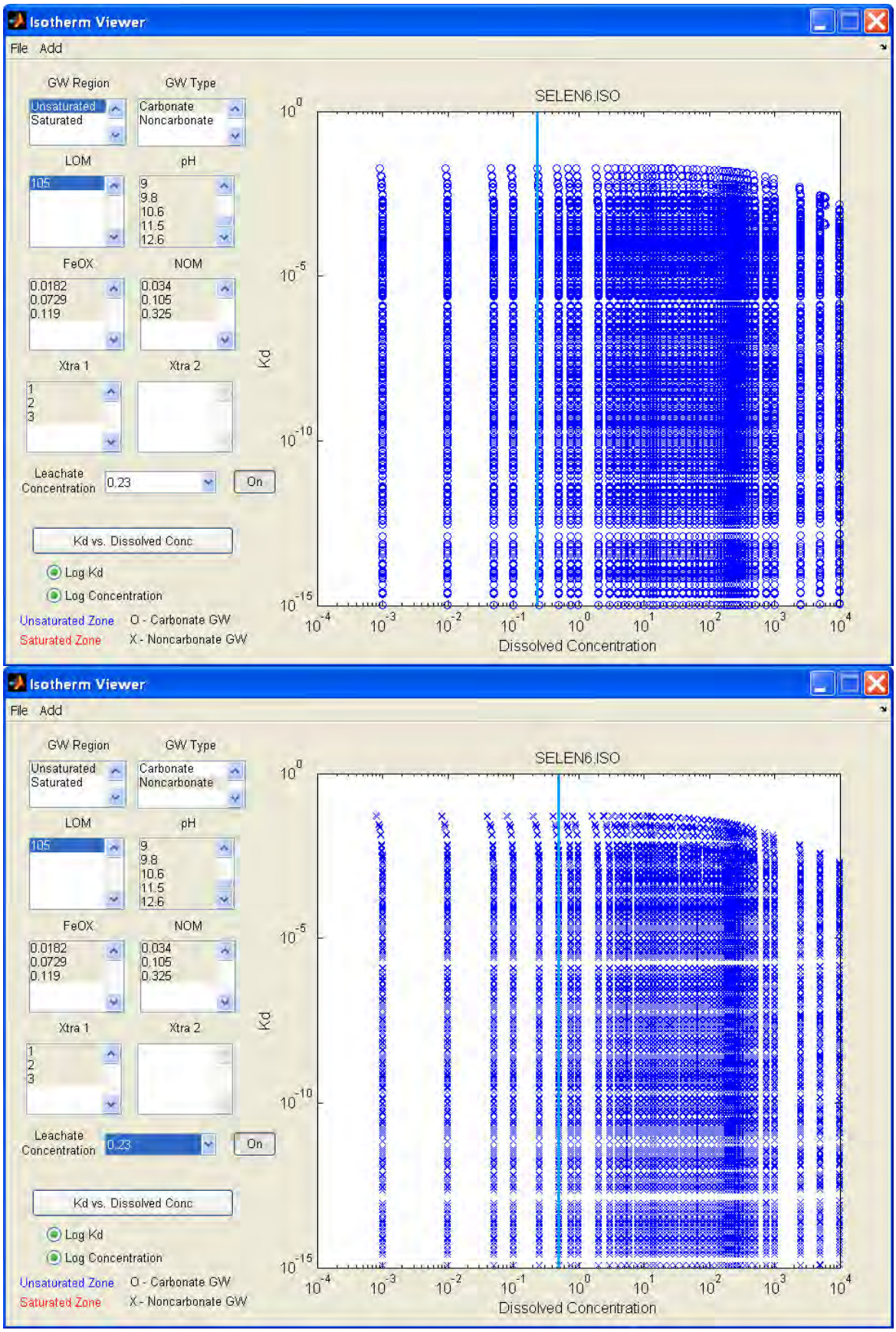

Figure H-2-46. Selenium VI unsaturated zone nonlinear sorption isotherms for SIs.

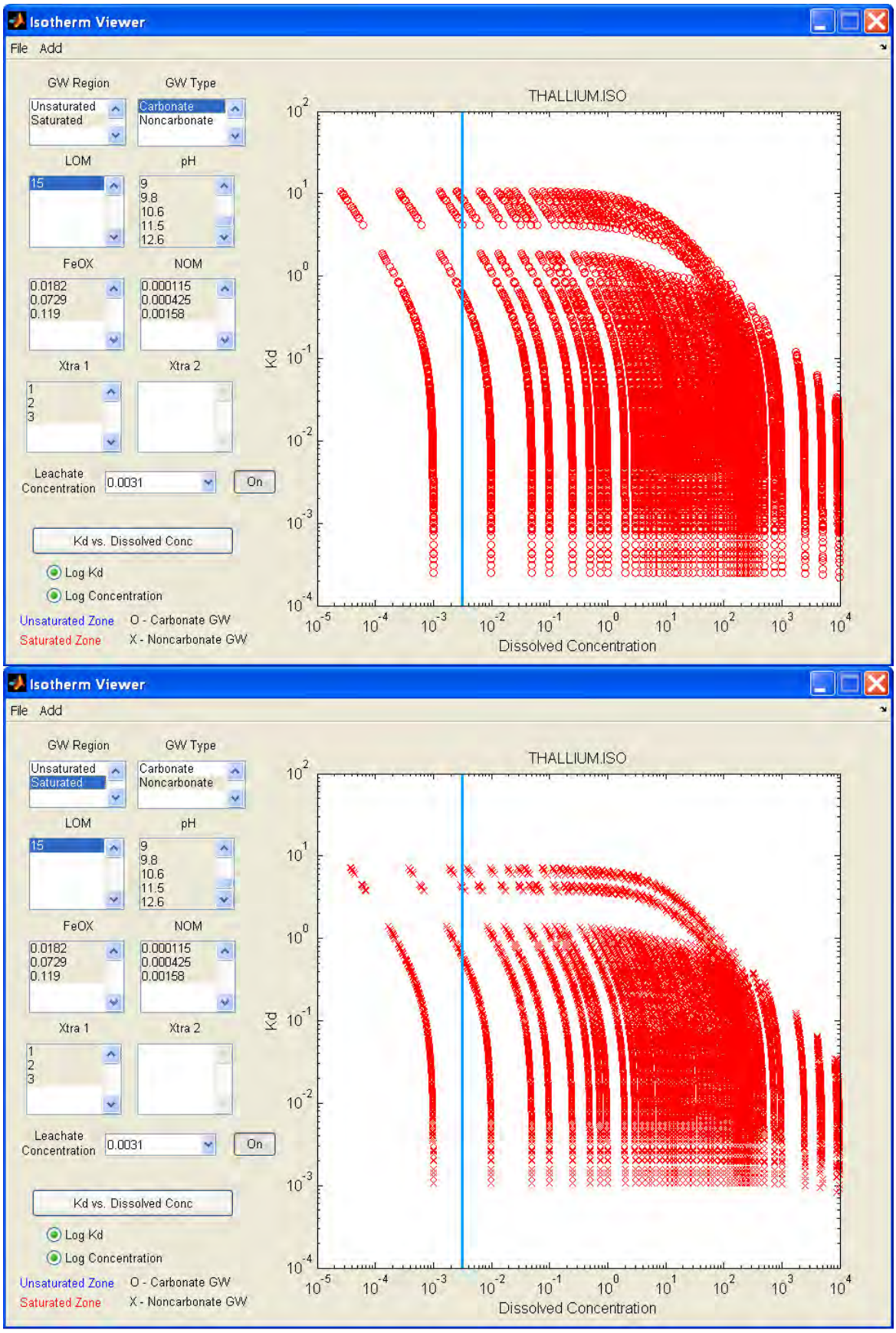

Figure H-2-47. Thallium saturated zone nonlinear sorption isotherms for SIs.

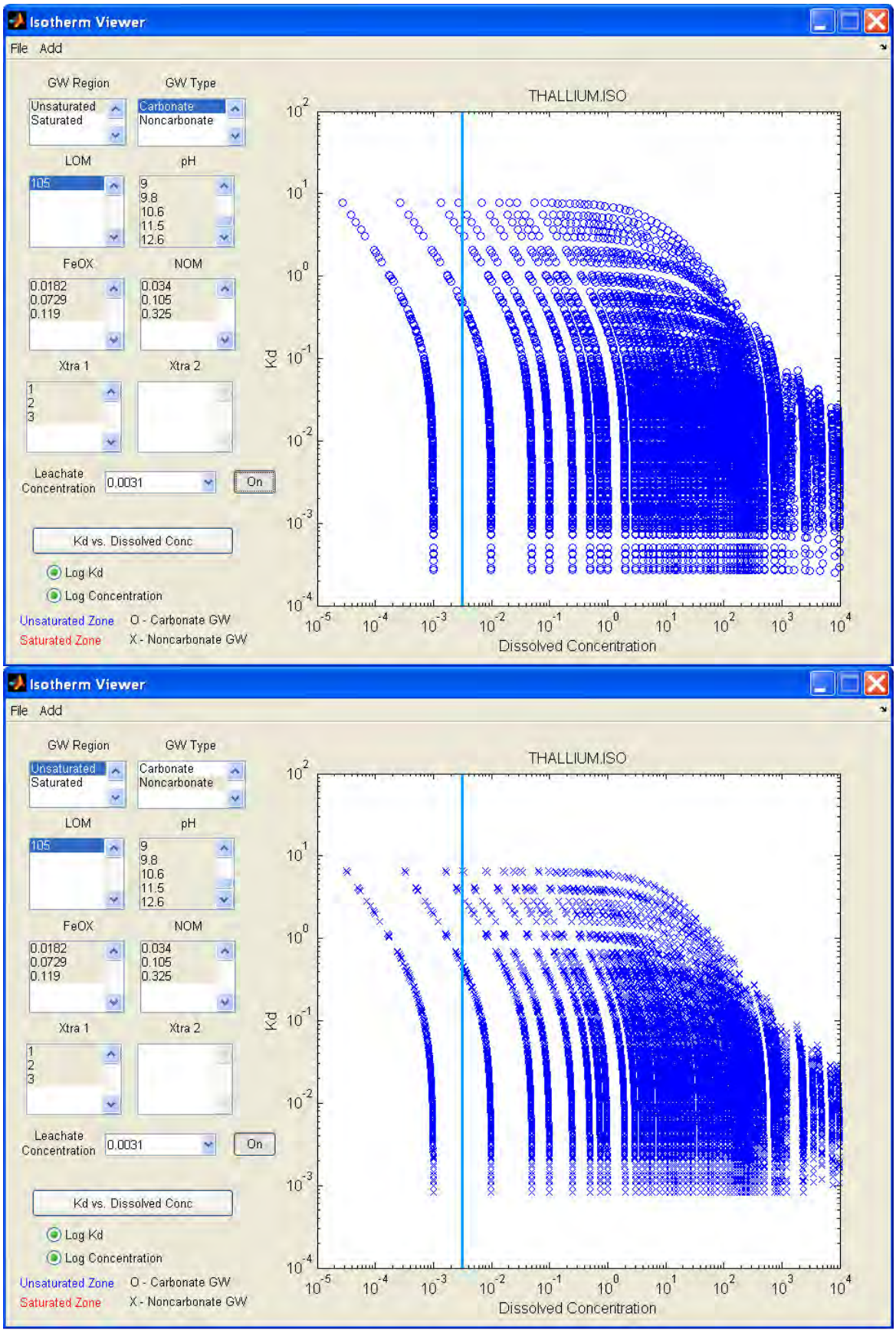

Figure H-2-48. Thallium unsaturated zone nonlinear sorption isotherms for SIs.

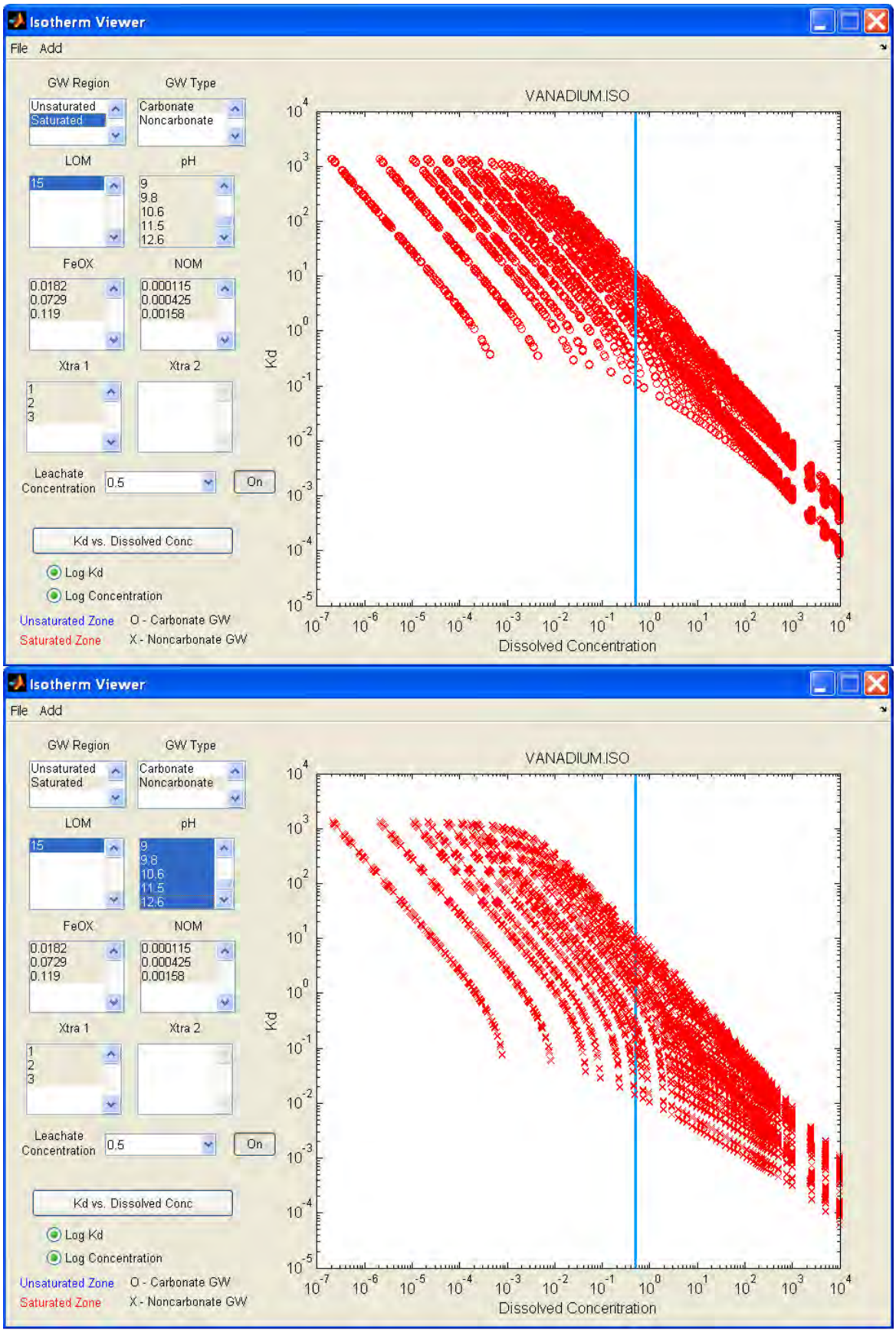

Figure H-2-49. Vanadium saturated zone nonlinear sorption isotherms for SIs.

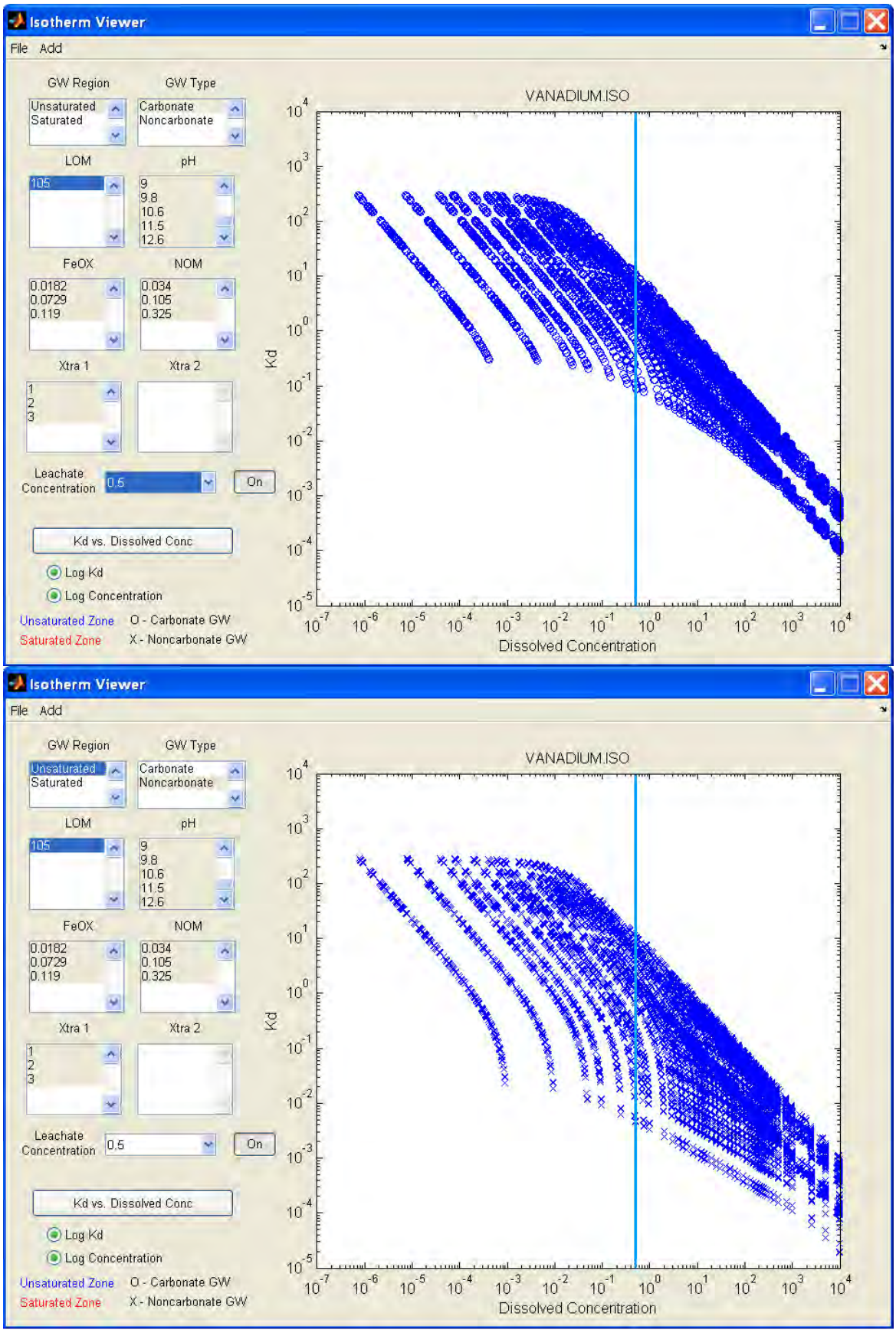

Figure H-2-50. Vanadium unsaturated zone nonlinear sorption isotherms for SIs.

Attachment H-3. Percentiles of K_d as Modeled

This attachment presents K_d percentiles selected from the inputs of the probabilistic modeling conducted in **Section 4**. For each constituent that was modeled, K_d values are presented for both the saturated and unsaturated zones[2] in the following tables:

- **Table H-3-1.** Select Percentiles of K_d (cm^3/g) for Landfills Containing Combined Ash Sampled from MINTEQA2 Isotherms by Updated EPACMTP via Constituent Species and Subsurface Domain
- **Table H-3-2.** Select Percentiles of K_d (cm^3/g) for Surface Impoundments Containing Combined Ash Sampled from MINTEQA2 Isotherms by Updated EPACMTP via Constituent Species and Subsurface Domain
- **Table H-3-3.** Select Percentiles of K_d (cm^3/g) for Surface Impoundments Containing Ash and Coal Refuse Sampled from MINTEQA2 Isotherms by Updated EPACMTP via Constituent Species and Subsurface Domain
- **Table H-3-4.** Select Percentiles of K_d (cm^3/g) for Surface Impoundments Containing FGD Wastes Sampled from MINTEQA2 Isotherms by Updated EPACMTP via Constituent Species and Subsurface Domain.

[2] As discussed in **Section 4**, chloride and iron are ions for which EPACMTP assigns concentrations. Thus, these ions were not modeled using isotherms. Instead, the chloride and lithium K_d values were fixed at 0 and the iron K_d value was fixed at 25.

Table H-3-1. Select Percentiles of K_d (cm^3/g) for Landfills Containing Combined Ash Sampled from MINTEQA2 Isotherms by Updated EPACMTP via Constituent Species and Subsurface Domain

Constituent	CASID	Zone	Percentiles of K_d (cm^3/g)						
			5%	10%	25%	50%	75%	90%	95%
Arsenic III	22569728	Saturated	4.5E-07	7.4E-07	2.9E-05	2.9E-03	1.4E-01	7.2E-01	1.1E+00
		Unsaturated	9.4E-08	2.3E-07	2.1E-05	1.3E-03	9.0E-02	4.4E-01	6.4E-01
Arsenic V	15584040	Saturated	1.8E+00	4.1E+00	3.5E+01	1.3E+02	3.2E+02	6.3E+02	1.1E+03
		Unsaturated	1.0E+00	1.9E+00	9.4E+00	3.5E+01	8.8E+01	2.2E+02	4.5E+02
Boron	7440428	Saturated	1.4E-06	2.2E-06	3.9E-06	1.1E-05	1.7E-05	2.3E-05	2.9E-05
		Unsaturated	0.0E+00	0.0E+00	0.0E+00	1.2E-01	2.0E-01	3.2E-01	8.0E-01
Cadmium	7440439	Saturated	1.7E-01	2.7E-01	5.5E-01	1.2E+00	2.3E+00	4.0E+00	7.3E+00
		Unsaturated	0.0E+00	0.0E+00	0.0E+00	9.1E-01	3.4E+00	1.4E+01	2.3E+01
Cobalt	7440484	Saturated	4.5E-01	9.2E-01	2.9E+00	8.8E+00	2.1E+01	4.1E+01	1.1E+02
		Unsaturated	0.0E+00	0.0E+00	0.0E+00	4.5E+00	3.1E+01	9.0E+01	2.1E+02
Mercury	7439976	Saturated	9.6E-05	2.1E-04	9.7E-04	3.8E-03	1.1E-02	2.2E-02	2.6E-02
		Unsaturated	0.0E+00	0.0E+00	0.0E+00	1.8E-01	3.8E-01	3.5E+00	1.5E+01
Molybdenum	7439987	Saturated	2.9E-05	9.1E-05	8.5E-04	9.5E-03	1.1E-01	8.1E-01	1.8E+00
		Unsaturated	0.0E+00	0.0E+00	0.0E+00	1.4E-01	2.2E-01	4.4E-01	8.3E-01

Table H-3-2. Select Percentiles of K_d (cm^3/g) for Surface Impoundments Containing Combined Ash Sampled from MINTEQA2 Isotherms by Updated EPACMTP via Constituent Species and Subsurface Domain

Constituent	CASID	Zone	Percentiles of K_d (cm^3/g)						
			5%	10%	25%	50%	75%	90%	95%
Aluminum	7429905	Saturated	1.6E-07	7.4E-07	7.6E-05	1.4E-02	8.1E-02	2.4E-01	4.5E-01
		Unsaturated	0.0E+00	1.3E-07	4.8E-02	1.5E-01	4.3E-01	2.8E+00	4.4E+00
Antimony	7440360	Saturated	1.9E-02	3.1E-02	8.0E-02	2.0E-01	4.1E-01	8.3E-01	1.1E+00
		Unsaturated	0.0E+00	2.9E-02	9.9E-02	2.0E-01	3.5E-01	5.0E-01	7.7E-01
Arsenic III	22569728	Saturated	1.1E-01	1.8E-01	3.1E-01	8.7E-01	1.4E+00	1.8E+00	2.2E+00
		Unsaturated	0.0E+00	4.0E-02	1.7E-01	4.2E-01	1.0E+00	1.5E+00	1.9E+00
Arsenic V	15584040	Saturated	1.1E+00	5.4E+00	2.7E+01	1.1E+02	3.4E+02	8.2E+02	1.6E+03
		Unsaturated	0.0E+00	7.2E-01	6.9E+00	3.3E+01	8.8E+01	2.0E+02	5.1E+02
Barium	7440393	Saturated	6.5E-02	8.0E-02	1.0E-01	3.2E-01	4.0E-01	1.3E+00	1.5E+00
		Unsaturated	0.0E+00	4.2E-01	1.0E+00	2.8E+00	1.0E+01	3.5E+01	5.4E+01
Beryllium	7440417	Saturated	1.0E+02	1.8E+02	4.2E+02	1.1E+03	1.9E+03	2.7E+03	2.9E+03
		Unsaturated	0.0E+00	4.2E-01	1.7E+02	5.7E+02	1.3E+03	1.8E+03	2.4E+03
Boron	7440428	Saturated	1.4E-06	2.3E-06	3.9E-06	1.1E-05	1.7E-05	2.2E-05	2.6E-05
		Unsaturated	0.0E+00	1.0E-05	3.6E-02	1.1E-01	1.9E-01	3.4E-01	4.2E-01
Cadmium	7440439	Saturated	1.6E-01	2.5E-01	5.4E-01	1.1E+00	2.2E+00	3.6E+00	5.1E+00
		Unsaturated	0.0E+00	2.3E-01	5.0E-01	1.2E+00	3.2E+00	8.5E+00	1.4E+01
Chromium III	16065831	Saturated	1.6E+01	7.1E+01	2.1E+02	5.9E+02	1.2E+03	1.7E+03	1.9E+03
		Unsaturated	0.0E+00	4.0E-01	3.9E+01	2.1E+02	7.2E+02	1.1E+03	1.4E+03

(continued)

Table H-3-2. Select Percentiles of K_d (cm^3/g) for Surface Impoundments Containing Combined Ash Sampled from MINTEQA2 Isotherms by Updated EPACMTP via Constituent Species and Subsurface Domain

Constituent	CASID	Zone	Percentiles of K_d (cm^3/g)						
			5%	10%	25%	50%	75%	90%	95%
Chromium VI	18540299	Saturated	9.9E-01	1.8E+00	5.5E+00	1.9E+01	4.0E+01	7.0E+01	1.1E+02
		Unsaturated	0.0E+00	9.4E-02	3.9E-01	3.0E+00	1.3E+01	3.1E+01	5.3E+01
Cobalt	7440484	Saturated	4.5E-01	8.1E-01	2.2E+00	5.9E+00	1.5E+01	3.3E+01	4.2E+01
		Unsaturated	0.0E+00	4.0E-01	1.0E+00	3.7E+00	1.6E+01	6.1E+01	1.1E+02
Copper	7440508	Saturated	1.5E+01	2.3E+01	4.2E+01	1.1E+02	2.2E+02	3.1E+02	3.4E+02
		Unsaturated	0.0E+00	4.1E-01	2.3E+01	6.3E+01	1.6E+02	3.3E+02	7.9E+02
Fluoride	16984488	Saturated	1.3E-03	1.9E-03	7.1E-03	2.2E-02	8.3E-02	2.7E-01	4.0E-01
		Unsaturated	0.0E+00	5.4E-04	4.4E-02	1.2E-01	2.0E-01	3.3E-01	4.2E-01
Lead	7439921	Saturated	7.6E+00	1.0E+01	1.7E+01	2.9E+01	3.9E+01	5.4E+01	5.9E+01
		Unsaturated	0.0E+00	4.1E-01	1.3E+01	2.4E+01	4.0E+01	7.2E+01	1.6E+02
Mercury	7439976	Saturated	9.6E-05	2.1E-04	9.7E-04	3.8E-03	1.0E-02	2.2E-02	2.7E-02
		Unsaturated	0.0E+00	1.1E-02	5.4E-02	1.4E-01	2.3E-01	4.1E-01	4.4E-01
Molybdenum	7439987	Saturated	2.2E-05	6.1E-05	5.8E-04	5.6E-03	6.8E-02	8.0E-01	1.8E+00
		Unsaturated	0.0E+00	3.0E-04	4.9E-02	1.3E-01	2.3E-01	4.2E-01	6.4E-01
Nickel	7440020	Saturated	2.0E-01	3.3E-01	5.8E-01	1.3E+00	2.2E+00	3.6E+00	4.9E+00
		Unsaturated	0.0E+00	1.2E-01	4.8E-01	1.4E+00	3.6E+00	9.1E+00	1.5E+01
Selenium IV	10026036	Saturated	5.6E+00	3.2E+01	1.1E+02	6.5E+02	3.1E+03	7.5E+03	1.1E+04
		Unsaturated	0.0E+00	1.2E-01	4.1E+00	1.7E+02	1.3E+03	3.6E+03	5.8E+03

(continued)

Table H-3-2. Select Percentiles of K_d (cm^3/g) for Surface Impoundments Containing Combined Ash Sampled from MINTEQA2 Isotherms by Updated EPACMTP via Constituent Species and Subsurface Domain

Constituent	CASID	Zone	Percentiles of K_d (cm^3/g)						
			5%	10%	25%	50%	75%	90%	95%
Selenium VI	7782492	Saturated	5.1E-07	1.4E-06	1.3E-05	1.2E-04	1.2E-03	8.6E-03	1.9E-02
		Unsaturated	0.0E+00	2.9E-05	3.8E-02	1.1E-01	1.9E-01	3.7E-01	4.2E-01
Silver	7440224	Saturated	3.6E-03	6.5E-03	1.4E-02	3.7E-02	7.9E-02	1.5E-01	2.0E-01
		Unsaturated	0.0E+00	2.1E-02	7.8E-02	1.7E-01	3.0E-01	4.3E-01	6.4E-01
Thallium	7440280	Saturated	4.8E-03	7.8E-03	1.3E-02	3.1E-02	4.7E-02	6.1E-02	8.0E-02
		Unsaturated	0.0E+00	3.9E-02	9.9E-02	2.0E-01	3.5E-01	4.8E-01	6.9E-01
Vanadium	7440622	Saturated	4.4E-01	7.9E-01	2.1E+00	9.9E+00	4.6E+01	1.6E+02	3.2E+02
		Unsaturated	0.0E+00	3.0E-01	1.2E+00	6.2E+00	3.3E+01	1.2E+02	2.1E+02
Zinc	7440666	Saturated	7.1E-01	1.4E+00	3.4E+00	8.9E+00	2.1E+01	3.5E+01	4.4E+01
		Unsaturated	0.0E+00	1.2E-01	1.2E+00	5.2E+00	1.6E+01	3.7E+01	6.0E+01

Table H-3-3. Select Percentiles of K_d (cm^3/g) for Surface Impoundments Containing Ash & Coal Refuse Sampled from MINTEQA2 Isotherms by Updated EPACMTP via Constituent Species and Subsurface Domain

Constituent	CASID	Zone	Percentiles of K_d (cm^3/g)						
			5%	10%	25%	50%	75%	90%	95%
Aluminum	7429905	Saturated	9.1E-08	2.9E-06	6.4E-05	1.2E-02	1.1E-01	4.9E-01	1.4E+00
		Unsaturated	0.0E+00	4.0E-07	8.6E-02	2.6E-01	4.9E-01	2.3E+00	1.0E+01
Antimony	7440360	Saturated	–	–	–	–	–	–	–
		Unsaturated	–	–	–	–	–	–	–
Arsenic III	22569728	Saturated	8.4E-04	3.4E-03	2.3E-02	1.1E-01	2.5E-01	9.9E-01	1.6E+00
		Unsaturated	0.0E+00	1.3E-03	8.4E-02	2.1E-01	4.2E-01	8.2E-01	1.3E+00
Arsenic V	15584040	Saturated	1.3E-02	2.2E-02	8.6E-01	1.6E+01	9.5E+01	3.3E+02	1.0E+03
		Unsaturated	0.0E+00	2.0E-03	2.9E-01	4.0E+00	2.2E+01	5.7E+01	1.6E+02
Barium	7440393	Saturated	4.3E-03	6.5E-03	2.3E-02	7.9E-02	2.5E-01	5.4E-01	9.1E-01
		Unsaturated	0.0E+00	1.2E-02	1.3E-01	1.4E+00	9.8E+00	5.2E+01	5.5E+01
Beryllium	7440417	Saturated	–	–	–	–	–	–	–
		Unsaturated	–	–	–	–	–	–	–
Boron	7440428	Saturated	1.1E-08	4.4E-08	2.9E-07	1.5E-06	3.2E-06	1.2E-05	2.1E-05
		Unsaturated	0.0E+00	7.0E-10	1.1E-02	1.0E-01	2.0E-01	3.7E-01	4.5E-01
Cadmium	7440439	Saturated	5.2E-03	7.7E-03	4.4E-02	1.8E-01	7.0E-01	2.0E+00	3.2E+00
		Unsaturated	0.0E+00	2.6E-02	1.3E-01	3.6E-01	9.6E-01	3.9E+00	8.4E+00
Chromium III	16065831	Saturated	6.7E-02	3.0E-01	2.9E+00	3.3E+01	2.1E+02	5.9E+02	1.2E+03
		Unsaturated	0.0E+00	7.6E-02	4.8E-01	9.4E+00	9.0E+01	3.2E+02	8.7E+02

(continued)

Table H-3-3. Select Percentiles of K_d (cm^3/g) for Surface Impoundments Containing Ash & Coal Refuse Sampled from MINTEQA2 Isotherms by Updated EPACMTP via Constituent Species and Subsurface Domain

Constituent	CASID	Zone	Percentiles of K_d (cm^3/g)						
			5%	10%	25%	50%	75%	90%	95%
Chromium VI	18540299	Saturated	1.0E-01	2.9E-01	6.9E-01	2.6E+00	1.3E+01	5.3E+01	8.1E+01
		Unsaturated	0.0E+00	2.9E-02	2.4E-01	8.0E-01	6.7E+00	3.1E+01	4.6E+01
Cobalt	7440484	Saturated	8.7E-03	1.4E-02	6.2E-02	4.1E-01	2.9E+00	1.0E+01	1.9E+01
		Unsaturated	0.0E+00	4.3E-02	2.7E-01	1.4E+00	5.9E+00	2.2E+01	4.2E+01
Copper	7440508	Saturated	3.3E-01	5.9E-01	3.0E+00	1.3E+01	5.1E+01	1.2E+02	1.9E+02
		Unsaturated	0.0E+00	2.7E-01	1.5E+00	4.5E+00	4.8E+01	1.4E+02	3.4E+02
Fluoride	16984488	Saturated	1.3E-04	2.5E-04	7.4E-04	2.4E-03	1.0E-02	3.2E-02	7.9E-02
		Unsaturated	0.0E+00	6.5E-06	1.6E-02	9.6E-02	2.1E-01	3.9E-01	4.8E-01
Lead	7439921	Saturated	2.8E-01	3.5E-01	1.6E+00	5.6E+00	1.6E+01	3.6E+01	4.2E+01
		Unsaturated	0.0E+00	1.4E-01	6.1E-01	4.8E+00	2.2E+01	4.7E+01	7.6E+01
Mercury	7439976	Saturated	1.6E-04	3.2E-04	9.6E-04	5.7E-03	1.6E-02	3.5E-02	4.6E-02
		Unsaturated	0.0E+00	1.5E-02	1.3E-01	2.9E-01	5.7E-01	2.6E+00	4.3E+00
Molybdenum	7439987	Saturated	1.1E-05	3.0E-05	2.1E-04	8.2E-03	1.1E-01	7.5E-01	2.9E+00
		Unsaturated	0.0E+00	1.8E-06	3.8E-02	1.5E-01	3.8E-01	1.5E+00	2.6E+00
Nickel	7440020	Saturated	7.6E-03	9.1E-03	4.7E-02	2.0E-01	7.3E-01	1.9E+00	2.9E+00
		Unsaturated	0.0E+00	2.4E-02	1.2E-01	4.2E-01	1.3E+00	4.2E+00	7.1E+00
Selenium IV	10026036	Saturated	1.5E+00	5.5E+00	2.4E+01	1.5E+02	8.1E+02	3.6E+03	8.1E+03
		Unsaturated	0.0E+00	1.3E-01	4.7E+00	1.1E+02	8.0E+02	4.0E+03	7.0E+03

(continued)

Table H-3-3. Select Percentiles of K_d (cm^3/g) for Surface Impoundments Containing Ash & Coal Refuse Sampled from MINTEQA2 Isotherms by Updated EPACMTP via Constituent Species and Subsurface Domain

Constituent	CASID	Zone	Percentiles of K_d (cm^3/g)						
			5%	10%	25%	50%	75%	90%	95%
Selenium VI	7782492	Saturated	2.4E-07	6.8E-07	4.5E-06	1.4E-04	1.9E-03	1.1E-02	7.3E-02
		Unsaturated	0.0E+00	6.4E-08	2.9E-02	1.2E-01	2.2E-01	4.1E-01	5.6E-01
Silver	7440224	Saturated	1.3E-03	2.1E-03	5.0E-03	2.7E-02	8.3E-02	1.9E-01	2.8E-01
		Unsaturated	0.0E+00	2.1E-02	1.3E-01	3.0E-01	4.8E-01	1.2E+00	1.5E+00
Thallium	7440280	Saturated	–	–	–	–	–	–	–
		Unsaturated	–	–	–	–	–	–	–
Vanadium	7440622	Saturated	5.2E-03	2.2E-02	1.8E-01	2.0E+00	1.5E+01	7.0E+01	1.7E+02
		Unsaturated	0.0E+00	4.8E-05	1.8E-01	1.7E+00	1.1E+01	4.2E+01	6.5E+01
Zinc	7440666	Saturated	1.1E-02	2.1E-02	9.5E-02	6.1E-01	3.6E+00	1.2E+01	2.5E+01
		Unsaturated	0.0E+00	1.7E-02	1.7E-01	4.9E-01	3.0E+00	1.0E+01	2.5E+01

Table H-3-4. Select Percentiles of K_d (cm^3/g) for Surface Impoundments Containing FGD Wastes Sampled from MINTEQA2 Isotherms by Updated EPACMTP via Constituent Species and Subsurface Domain

Constituent	CASID	Zone	Percentiles of K_d (cm^3/g)						
			5%	10%	25%	50%	75%	90%	95%
Aluminum	7429905	Saturated	8.5E-08	2.8E-07	1.0E-04	9.4E-03	6.7E-02	2.3E-01	4.0E-01
		Unsaturated	0.0E+00	0.0E+00	1.8E-02	1.5E-01	4.0E-01	1.2E+00	1.9E+00
Antimony	7440360	Saturated	6.6E-03	1.6E-02	4.2E-02	1.2E-01	2.7E-01	4.0E-01	5.7E-01
		Unsaturated	0.0E+00	0.0E+00	5.8E-02	1.6E-01	2.5E-01	4.0E-01	4.2E-01
Arsenic III	22569728	Saturated	6.0E-02	1.0E-01	1.9E-01	5.4E-01	9.2E-01	1.3E+00	1.5E+00
		Unsaturated	0.0E+00	0.0E+00	7.9E-02	2.4E-01	5.7E-01	9.7E-01	1.3E+00
Arsenic V	15584040	Saturated	3.3E-01	1.6E+00	1.2E+01	5.4E+01	1.6E+02	3.0E+02	4.3E+02
		Unsaturated	0.0E+00	0.0E+00	8.7E-01	9.7E+00	3.2E+01	6.0E+01	8.7E+01
Barium	7440393	Saturated	4.4E-02	4.9E-02	1.2E-01	2.0E-01	4.5E-01	1.0E+00	1.5E+00
		Unsaturated	0.0E+00	0.0E+00	2.4E-01	8.8E-01	5.2E+00	2.0E+01	5.1E+01
Beryllium	7440417	Saturated	7.3E+01	1.2E+02	3.2E+02	8.3E+02	1.7E+03	2.7E+03	3.7E+03
		Unsaturated	0.0E+00	0.0E+00	1.7E+01	3.0E+02	7.0E+02	2.1E+03	3.1E+03
Boron	7440428	Saturated	7.4E-07	1.3E-06	2.4E-06	7.0E-06	1.2E-05	1.7E-05	1.9E-05
		Unsaturated	0.0E+00	0.0E+00	1.6E-02	1.0E-01	1.8E-01	2.5E-01	4.0E-01
Cadmium	7440439	Saturated	9.1E-02	1.4E-01	2.9E-01	6.6E-01	1.6E+00	3.0E+00	4.0E+00
		Unsaturated	0.0E+00	0.0E+00	1.8E-01	4.3E-01	1.1E+00	6.9E+00	1.3E+01
Chromium III	16065831	Saturated	9.8E+00	2.7E+01	1.2E+02	3.7E+02	9.0E+02	1.6E+03	2.1E+03
		Unsaturated	0.0E+00	0.0E+00	6.1E+00	5.5E+01	2.8E+02	1.1E+03	1.5E+03

(continued)

Table H-3-4. Select Percentiles of K_d (cm^3/g) for Surface Impoundments Containing FGD Wastes Sampled from MINTEQA2 Isotherms by Updated EPACMTP via Constituent Species and Subsurface Domain

Constituent	CASID	Zone	Percentiles of K_d (cm^3/g)						
			5%	10%	25%	50%	75%	90%	95%
Chromium VI	18540299	Saturated	2.5E-01	6.5E-01	2.6E+00	7.8E+00	1.9E+01	3.2E+01	3.9E+01
		Unsaturated	0.0E+00	0.0E+00	1.2E-01	4.2E-01	5.7E+00	1.1E+01	1.7E+01
Cobalt	7440484	Saturated	2.9E-01	5.4E-01	1.5E+00	3.9E+00	1.1E+01	2.4E+01	4.1E+01
		Unsaturated	0.0E+00	0.0E+00	4.6E-01	1.9E+00	7.1E+00	5.3E+01	1.2E+02
Copper	7440508	Saturated	1.0E+01	1.6E+01	3.1E+01	7.7E+01	1.7E+02	2.6E+02	3.5E+02
		Unsaturated	0.0E+00	0.0E+00	1.0E+01	2.9E+01	9.4E+01	3.0E+02	5.8E+02
Fluoride	16984488	Saturated	3.9E-04	1.2E-03	4.3E-03	1.3E-02	4.2E-02	1.1E-01	1.7E-01
		Unsaturated	0.0E+00	0.0E+00	3.5E-02	1.2E-01	2.0E-01	3.1E-01	4.1E-01
Lead	7439921	Saturated	3.8E+00	6.4E+00	1.2E+01	1.9E+01	3.5E+01	4.7E+01	6.5E+01
		Unsaturated	0.0E+00	0.0E+00	3.8E+00	1.1E+01	2.6E+01	7.0E+01	1.4E+02
Mercury	7439976	Saturated	2.7E-05	7.1E-05	4.8E-04	3.4E-03	1.3E-02	2.5E-02	3.3E-02
		Unsaturated	0.0E+00	0.0E+00	3.9E-02	1.3E-01	2.1E-01	3.7E-01	4.1E-01
Molybdenum	7439987	Saturated	8.2E-06	2.8E-05	3.8E-04	3.6E-03	4.4E-02	3.2E-01	9.2E-01
		Unsaturated	0.0E+00	0.0E+00	1.8E-02	1.1E-01	1.9E-01	3.0E-01	4.1E-01
Nickel	7440020	Saturated	1.2E-01	2.0E-01	3.9E-01	8.1E-01	1.7E+00	3.0E+00	4.1E+00
		Unsaturated	0.0E+00	0.0E+00	2.6E-01	6.4E-01	1.5E+00	6.7E+00	1.1E+01
Selenium IV	10026036	Saturated	1.8E+00	9.6E+00	6.2E+01	3.6E+02	1.5E+03	4.3E+03	6.0E+03
		Unsaturated	0.0E+00	0.0E+00	1.8E-01	3.6E+01	6.0E+02	1.8E+03	2.4E+03

(continued)

Table H-3-4. Select Percentiles of K_d (cm^3/g) for Surface Impoundments Containing FGD Wastes Sampled from MINTEQA2 Isotherms by Updated EPACMTP via Constituent Species and Subsurface Domain

Constituent	CASID	Zone	Percentiles of K_d (cm^3/g)						
			5%	10%	25%	50%	75%	90%	95%
Selenium VI	7782492	Saturated	1.9E-07	6.4E-07	8.4E-06	7.7E-05	7.9E-04	4.4E-03	9.5E-03
		Unsaturated	0.0E+00	0.0E+00	1.6E-02	1.0E-01	1.8E-01	2.5E-01	3.9E-01
Silver	7440224	Saturated	8.0E-04	1.5E-03	3.3E-03	3.0E-02	1.5E-01	2.4E-01	2.7E-01
		Unsaturated	0.0E+00	0.0E+00	6.9E-02	2.0E-01	4.2E-01	8.9E-01	1.4E+00
Thallium	7440280	Saturated	3.5E-03	5.5E-03	1.0E-02	1.8E-02	3.5E-02	5.5E-02	6.3E-02
		Unsaturated	0.0E+00	0.0E+00	6.3E-02	1.6E-01	2.6E-01	4.1E-01	4.8E-01
Vanadium	7440622	Saturated	2.6E-01	5.0E-01	1.3E+00	5.8E+00	2.7E+01	7.9E+01	1.7E+02
		Unsaturated	0.0E+00	0.0E+00	3.7E-01	2.2E+00	2.0E+01	5.9E+01	8.5E+01
Zinc	7440666	Saturated	4.6E-01	8.6E-01	2.2E+00	5.6E+00	1.4E+01	2.9E+01	4.4E+01
		Unsaturated	0.0E+00	0.0E+00	4.6E-01	1.5E+00	5.3E+00	3.1E+01	7.9E+01

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Appendix I.

Landfill Source Term Development

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I.1 Introduction

The U.S. Environmental Protection Agency (EPA or the Agency) used SW-846 Leaching Evaluation Assessment Framework (LEAF) Methods 1313, 1314 and 1316 to characterize the leaching behavior of coal combustion residual (CCR) waste over a range of environmental conditions. These methods were developed through a collaborative research effort between EPA, Vanderbilt University, ARCADIS, Inc., the Energy Centre of the Netherlands, and Dutch and Danish partners (Kosson et al, 2002; Sanchez et al, 2002; Thorneloe et al, 2010; U.S. EPA, 2010b). EPA originally proposed the use of LEAF data in a 2011 Notice of Data Availability (NODA)[1] and further described how it might use the data in the subsequent 2013 NODA.[2] Further discussion of these LEAF methods is provided in **Appendix C**. The remainder of this appendix summarizes how data from these methods were used in the revised risk assessment to model leaching from landfills.

I.2 Source Term Development

The information provided by the three LEAF methods were used together to identify trends in leaching behavior and to characterize both the total mass available to be leached (i.e., leachable mass) and the leachate concentrations of individual COPCs in each sample. Method 1313 provided data on the equilibrium leachate concentration as a function of waste pH. Method 1314 provided data on the leachate concentration as a function of cumulative liquid to solid (L/S) ratio. Method 1316 provided data on the equilibrium leachate concentration as a function of L/S ratio.

Leachable mass was characterized using Method 1313 data. For all samples, the leachable mass was taken as the maximum concentration measured over the pH range of 2.8 to 12.8 multiplied by the L/S ratio used in Method 1313 (10 L/kg), as described in U.S. EPA (2009a). The calculated value was used by EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP) to determine the duration of leaching. Once all leachable mass was depleted, leaching of that particular constituent ceased.

Leachate concentrations were characterized using Method 1313 data. The representativeness of these equilibrium concentrations was confirmed with data obtained from Methods 1314 and 1316. The application of Method 1313 data depended on the leaching behavior exhibited by a constituent at a given pH. Leaching behavior fell into one of two categories: washout-controlled and solubility-controlled. A single constituent may alternate between these two behaviors over the relevant pH range (e.g. washout-controlled at a low pH and solubility-controlled at a high pH). In addition, this behavior profile as a function of pH is not constant across all wastes. Ashes generated by different coal and pollution controls may exhibit a completely different leaching profile for the same constituent. These handling of data for these two leaching behaviors is discussed in greater detail in the following subsections.

[1] Available online at: www.regulations.gov/#!documentDetail;D=EPA-HQ-RCRA-2011-0392

[2] Available online at: www.regulations.gov/#!documentDetail;D=EPA-HQ-RCRA-2012-0028

I.2.1 Solubility-Controlled Leaching Behavior

Solubility-controlled leaching is characterized by the releases where the leachate concentration is limited by solubility of the species. This behavior occurs when the total constituent mass available to be released from the waste is greater than the maximum amount that can be dissolved in the mass of water present. In Method 1313 data, this is characterized by highly variable leachate concentrations over the pH range because the maximum amount that can be dissolved varies with pH (U.S. EPA, 2014). **Figure I-1** shows an example of an ash (Sample ID: AaFA) for which chromium falls within the solubility-controlled zone over the entire pH range.

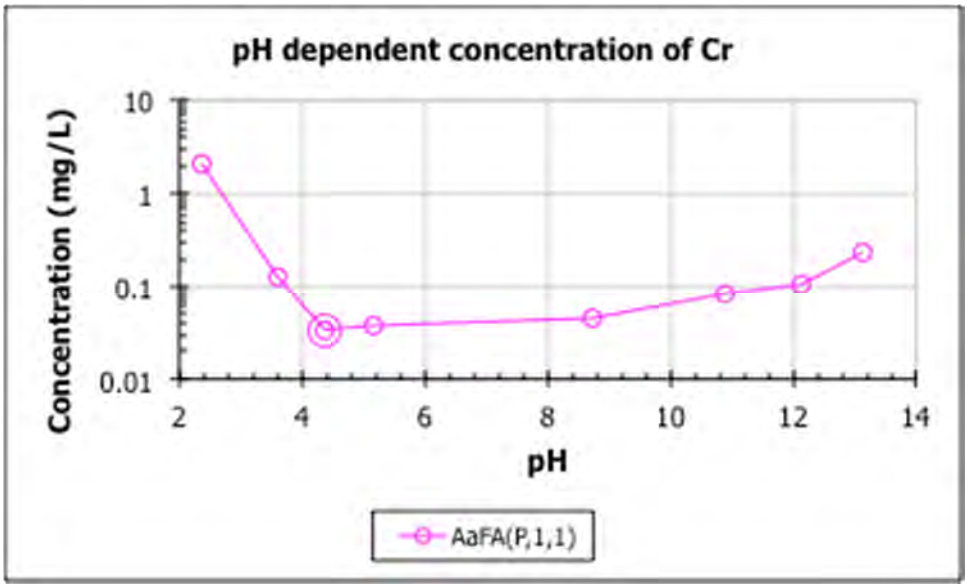


Figure I-1. Example of a solubility-controlled species over the full experimental pH domain (Adapted from data in U.S. EPA, 2009a).

If a constituent was determined to fall within the solubility-controlled zone at a particular pH, then the initial leachate concentration for that sample, C_0 (mg/L), was modeled as the concentration obtained from Method 1313. This leachate concentration was held constant over time until the leachable mass, M_0 (mg/kg), was depleted. This occurs when the cumulative L/S ratio is equal to M_0/C_0, also referred to as LS_{max}. The empirical relationship identified with Methods 1314 and 1316 agree well with this approach. **Figure I-2** illustrates this empirical relationship for solubility-controlled leaching as a function of cumulative L/S ratio.

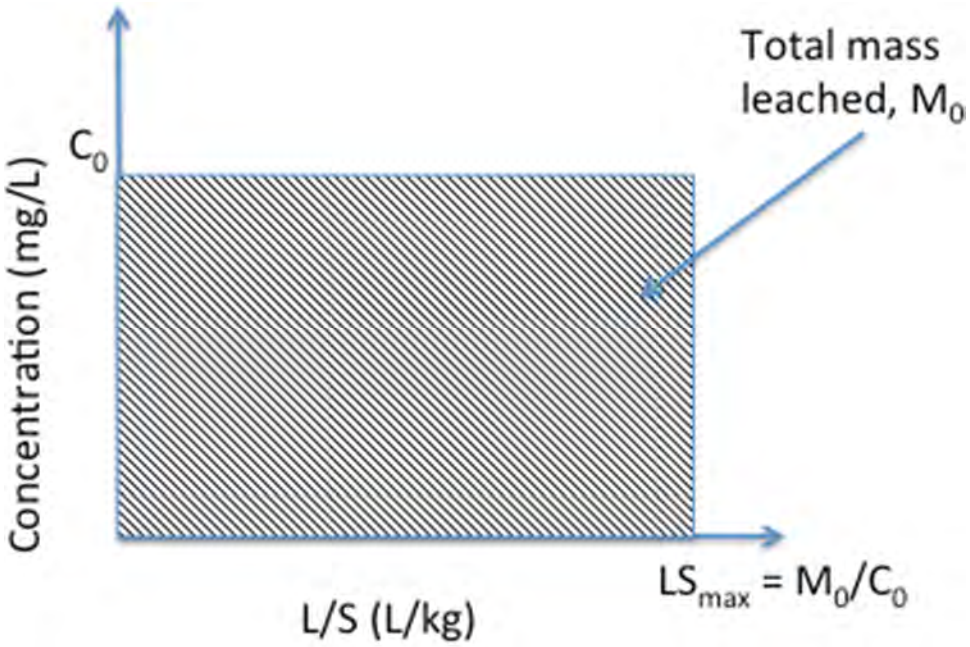


Figure I-2. L/S partitioning curve for solubility-controlled constituents at simulation pH.

I.2.2 Washout-Controlled Leaching Behavior

Washout-controlled leaching is characterized by the quick dissolution and release of the more soluble species from the CCR waste into the pore water. In Method 1313 data, this behavior is characterized by a generally constant leachate concentration over a pH range (U.S. EPA, 2014). **Figure I-3** shows an example of an ash (Sample ID: AaFA) for which boron falls in the washout-controlled zone over the entire pH range evaluated and leachate concentrations are almost constant.

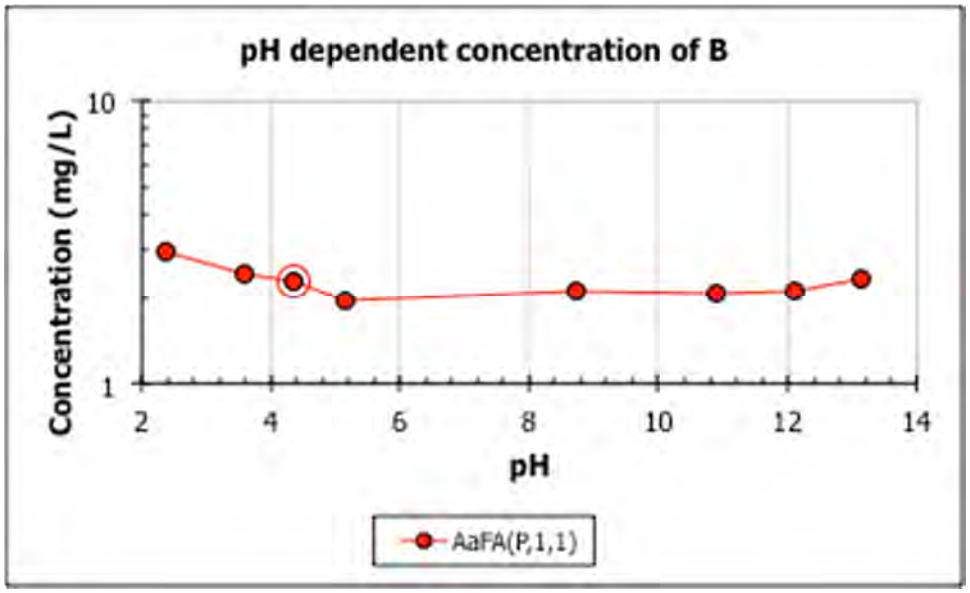


Figure I-3. Example of a washout-controlled constituent over the full experimental pH domain (Adapted from data in U.S. EPA, 2009a).

Method 1313 is carried out at a single L/S ratio of 10 mL/g (U.S. EPA, 2012). However, the L/S ratio present in the field is closer to 0.5 mL/g, based on a typical porosity of around 0.2 to 0.5 (unitless). Thus, if a constituent was determined to fall within the washout-controlled zone at a particular pH value, then C_0 was modeled as the concentration obtained from Method 1313 at that pH multiplied by a factor of 20. This factor adjusts for the difference between the L/S ratio specified in the Method 1313 test and those that occur in the field (U.S. EPA, 2014). The results of Methods 1314 and 1316 agree well with an initial leachate concentration defined by 20 times the Method 1313 leachate concentration, but show a variable leaching profile as the cumulative L/S ratio increases. The following empirical relationship was developed based on the observed changes in leachate concentration:

(I-1) $$M_0 = C_0 \cdot LS_{0.2} + \int_{0.2}^{1} 1.78C_0\left(e^{-2.9LS}\right)dLS + 0.1C_0\left(LS_{max} - LS_1\right)$$

Where:

M_0 = Total available mass (mg/kg);
C_0 = Initial leaching concentration (mg/L);
LS_X = Liquid-to-solid ratio of X (L/kg); and
LS_{max} = Liquid-to-solid ratio at which total available mass is depleted (L/kg).

At a cumulative L/S ratio of 0.2, the measured leachate concentration began to decrease exponentially until a cumulative L/S ratio of 1. At this point, the concentration stabilized at a tenth of the original value and remained at this concentration until all of the remaining leachable mass was depleted. **Figure I-4** illustrates this empirical relationship for washout-controlled leaching as a function of cumulative L/S ratio.

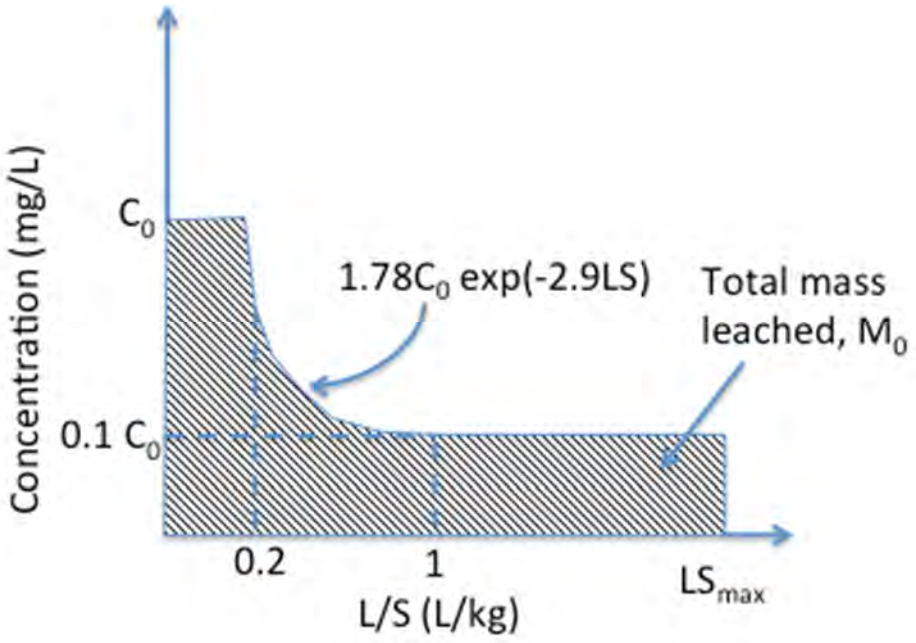


Figure I-4. L/S partitioning curve for washout-controlled species at simulated pH.

As seen in the figure above, leaching is not constant for constituents in the washout-controlled zone. As shown in the 2009 Sensitivity Analysis, higher leachate concentrations consistently led to higher well concentrations in the 2010 Risk Assessment (U.S. EPA, 2009b). Thus, the initial pulses of higher concentration in the washout-controlled releases are anticipated to capture peak ground water concentrations in down-gradient wells. Furthermore, the use of the EPACMTP non-linear sorption isotherms requires the use of a square pulse source as described in U.S. EPA (2003a,b). As a result, EPA chose not to represent the entire washout leaching profile laid forth in the figure above. Instead, all washout-controlled releases were modeled as square pulses selected to represent leachate concentrations that would not underestimate risks. These pulses are similar to the solubility-controlled pulse portrayed in **Figure I-2**, except that C_0 was set to 20 times the Method 1313 leachate concentration.

I.3 Arsenic Source Term Development

Arsenic exhibits washout- and solubility-controlled leaching behaviors like other constituents. However, the data collected with LEAF methods have demonstrated that the leaching behavior of arsenic is also strongly influenced by the presence of calcium, which inhibits arsenic release through oxidation and complexation (Wang et al, 2007). To more accurately characterize the leaching behavior of arsenic, EPA used Method 1314 data to link arsenic leachate concentrations with the mass of calcium present as a function of the cumulative L/S ratios. **Sections I.3.1** and **I.3.2** discuss the leaching behaviors of calcium and arsenic, respectively. **Section I.3.3** discusses the integration of these data to calculate arsenic-specific leachate profiles for EPACMTP.

I.3.1 Summary of Calcium Leaching Behavior

Through a comparison of Method 1313 and 1314 data, EPA observed that the initial calcium leachate concentration is strongly dependent on the mass available to be leached. If the availability of calcium is high (> 5,000 mg/kg), then the initial leachate concentration is around 1,000 mg/L. If the calcium availability is low (≤ 5,000 mg/kg) then the initial leachate concentration of calcium is around 700 mg/L. Regardless of the initial amount of calcium available, once 90 percent of leachable mass has been depleted, the leachate concentration decreased to approximately 10 mg/L.

I.3.2 Summary of Arsenic Leaching Behavior

Arsenic leaching from landfills was modeled as having one of two relationships with dissolved calcium concentrations based on empirical data. This behavior as a function of the cumulative L/S ratio is described, as well as illustrated in **Figure I-5**, below:

- **Case (a) High Calcium Arsenic Leaching:** In high-calcium waste, arsenic complexation with the calcium restricts the amount of arsenic initially available for leaching. Empirical data shows that little to no arsenic will leach from the material after an L/S ratio of 1 is reached, as long as significant levels of calcium remain. Initially, arsenic leaches at C_0 calculated from Method 1313 data from a cumulative L/S ratio of 0 to 1. After this point, arsenic concentrations become non-detect and are assumed to be negligible. Once 90 percent of the calcium has been depleted ($LS_{90,Ca}$), the complexation that had bound the

arsenic originally can no longer be sustained at levels high enough to keep the arsenic in the material. A second pulse of arsenic leaching begins at $LS_{90,Ca}$ at the same concentration and continues until the leachable mass of arsenic has been depleted ($LS_{max,As}$).

- **Case (b) Low-Calcium Arsenic Leaching:** In low-calcium waste, little complexation occurs between arsenic and calcium. Empirical data shows that, in these cases, arsenic leaching is not inhibited. Arsenic leaching begins at C_0 calculated from Method 1313 data and is held constant until the leachable mass is depleted.

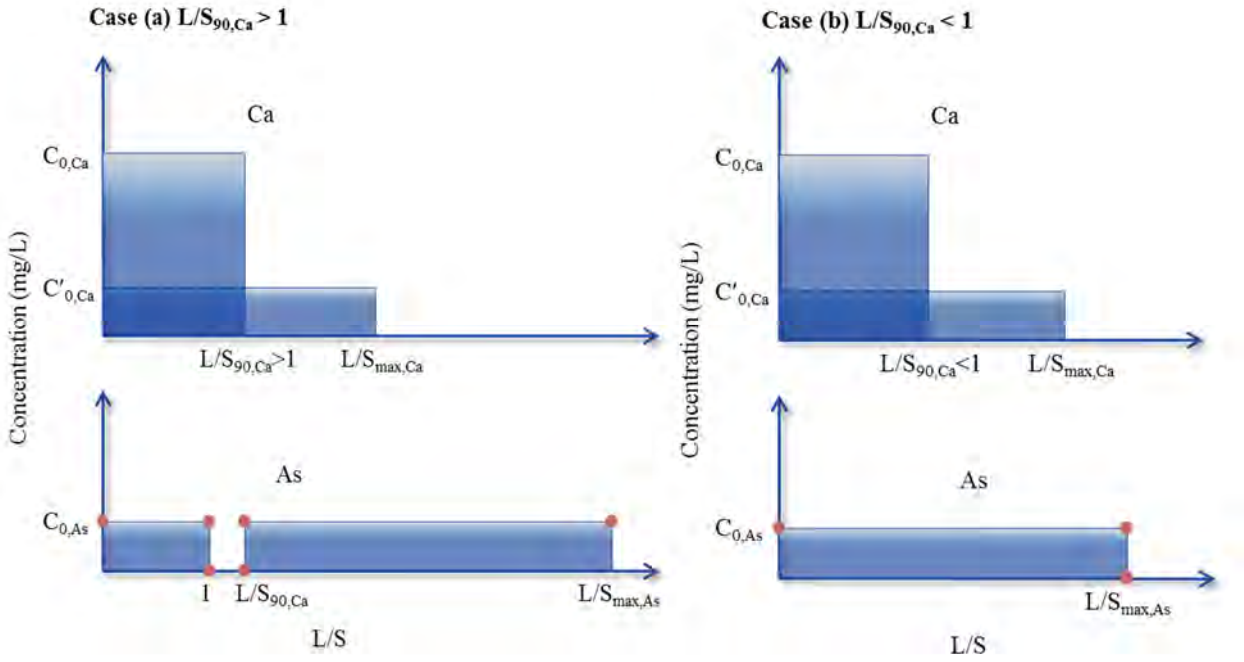
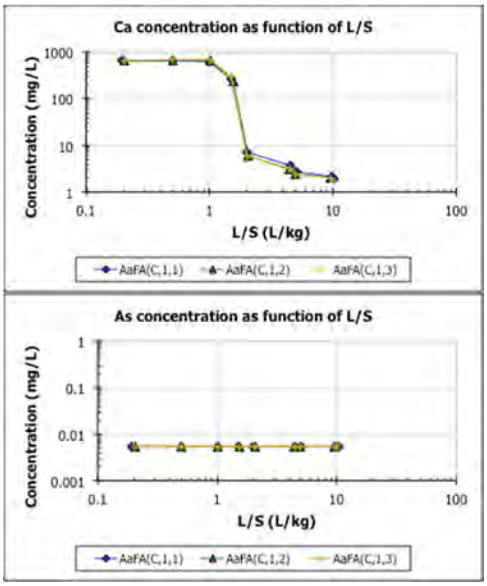


Figure I-5. Generic high- and low calcium leaching and generic calcium-dependent arsenic leaching as a function of cumulative L/S ratio.

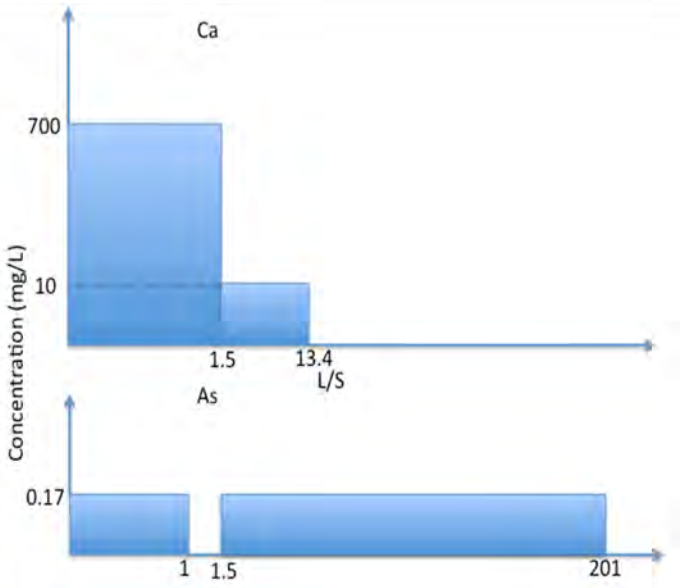
I.3.3 Calculation of Specific High-Calcium Arsenic Leachate Curves

A total of five samples analyzed with the LEAF methods contained high-calcium levels (Sample ID: AaFA, CaFA, DaFA, EaFA, and UFA). For each of these samples, EPA evaluated $LS_{90,Ca}$ and $LS_{max,As}$ to determine the duration of the first and second leachate pulses for purposes of modeling in EPACMTP. **Figures I-6** through **I-10** show the interaction between arsenic and calcium leachate over the range of cumulative L/S ratios for these five samples. These idealizations mirror the empirical Method 1314 test results.

Fly Ash Sample	Own pH	Calcium		Arsenic		
		$M_{0,Ca}$ (mg/kg)	$LS_{90,Ca}$ (L/kg)	$M_{0,As}$ (mg/kg)	$C_{0,As}$ (mg/L)	$LS_{Max,As}$ (L/kg)
AaFA	4.4	1,189	2	34	0.17	201



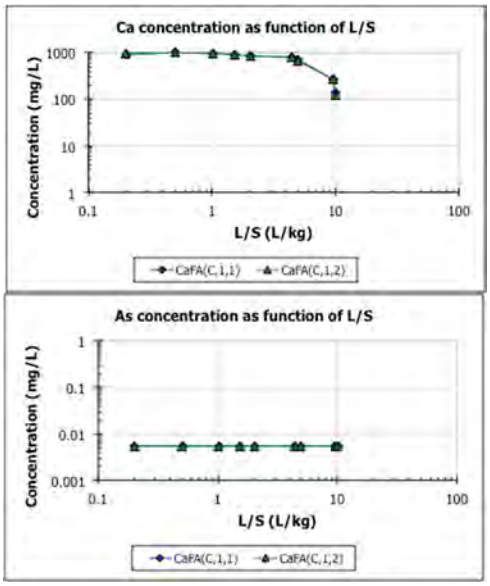
AaFA Method 1314 Results



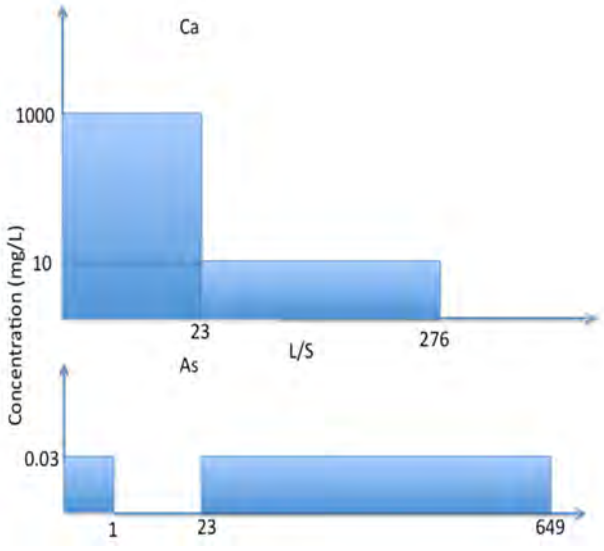
AaFA Idealized Curves

Figure I-6. Method 1314 results and idealized leaching curves for sample AaFA.

Fly Ash Sample	Own pH	Calcium		Arsenic		
		$M_{0,Ca}$ (mg/kg)	$LS_{90,Ca}$ (L/kg)	$M_{0,As}$ (mg/kg)	$C_{0,As}$ (mg/L)	$LS_{Max,As}$ (L/kg)
CaFA	12.0	25,311	23	21	0.03	649



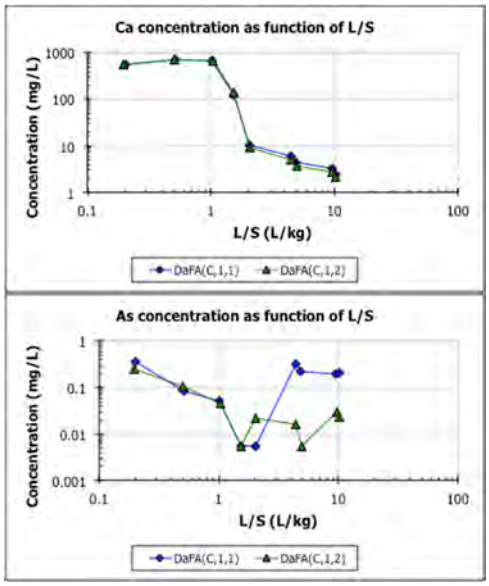
CaFA Method 1314 Results



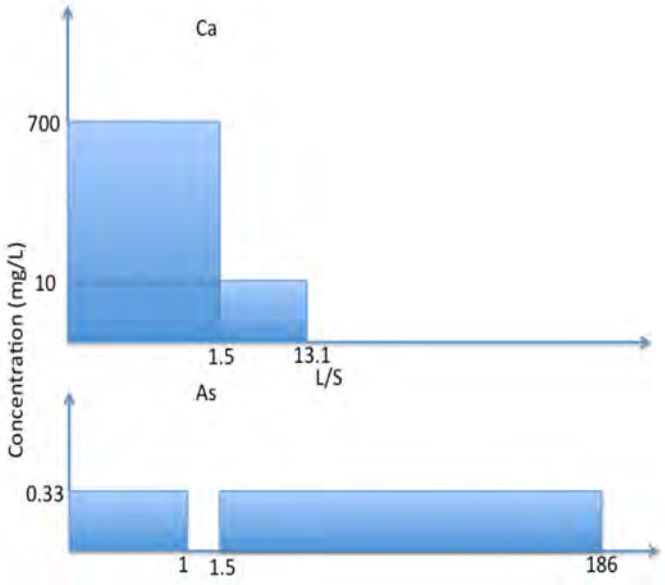
CaFA Idealized Curves

Figure I-7. Method 1314 results and idealized leaching curves for sample CaFA.

Fly Ash Sample	Own pH	Calcium		Arsenic		
		$M_{0,Ca}$ (mg/kg)	$LS_{90,Ca}$ (L/kg)	$M_{0,As}$ (mg/kg)	$C_{0,As}$ (mg/L)	$LS_{Max,As}$ (L/kg)
DaFA	4.3	1,160	1	61	0.33	186



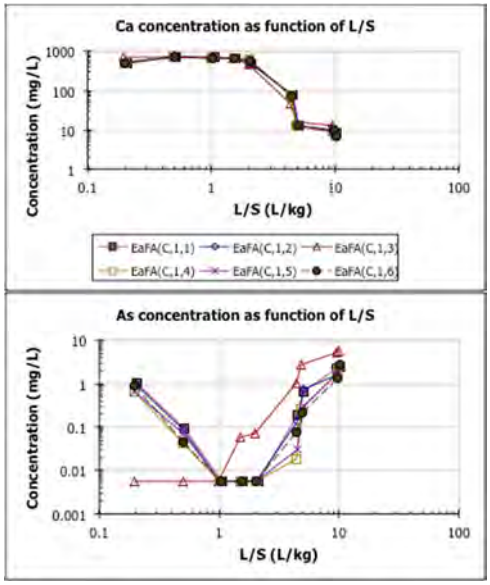
DaFA Method 1314 Results



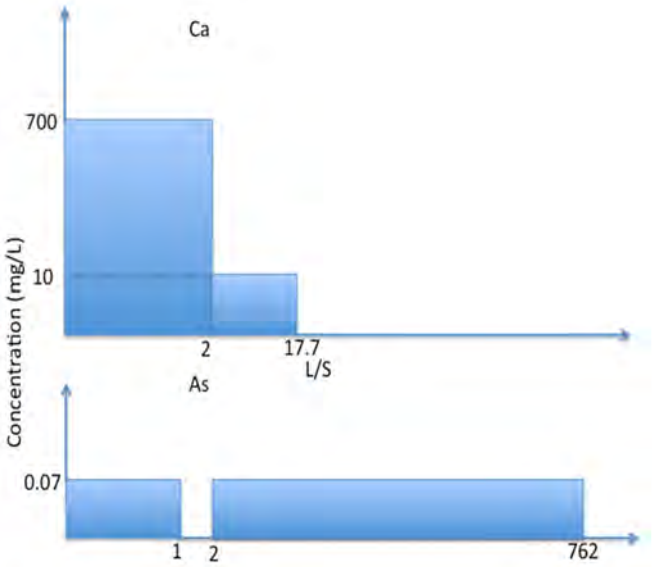
DaFA Idealized Curves

Figure I-8. Method 1314 results and idealized leaching curves for sample DaFA.

Fly Ash Sample	Own pH	Calcium		Arsenic		
		$M_{0,Ca}$ (mg/kg)	$LS_{90,Ca}$ (L/kg)	$M_{0,As}$ (mg/kg)	$C_{0,As}$ (mg/L)	$LS_{Max,As}$ (L/kg)
EaFA	7.2	1,572	2	54	0.07	762



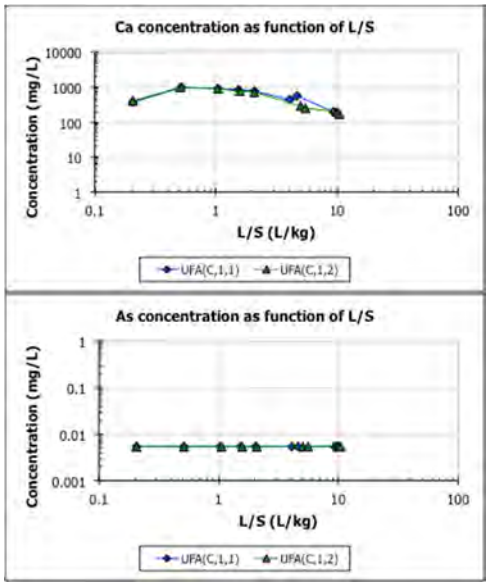
EaFA Method 1314 Results



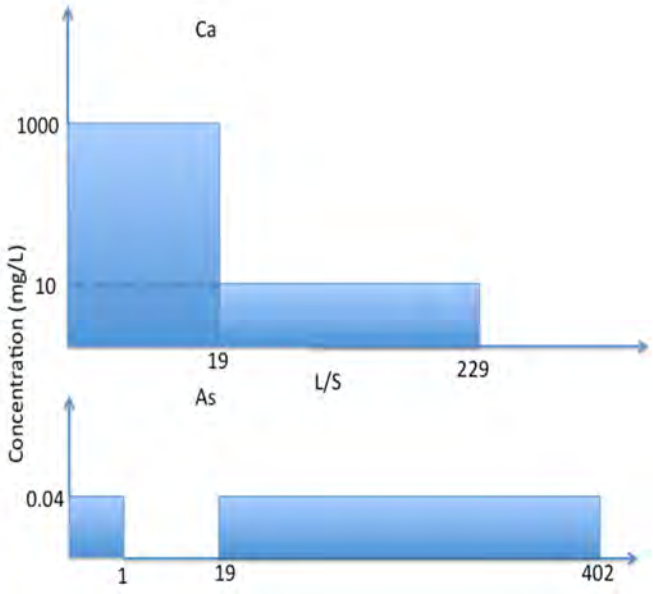
EaFA Idealized Curves

Figure I-9. Method 1314 results and idealized leaching curves for sample EaFA.

Fly Ash Sample	Own pH	Calcium		Arsenic		
		$M_{0,Ca}$ (mg/kg)	$LS_{90,Ca}$ (L/kg)	$M_{0,As}$ (mg/kg)	$C_{0,As}$ (mg/L)	$LS_{Max,As}$ (L/kg)
UFA	11.8	20,990	19	15	0.04	402



UFA Method 1314 Results



UFA Idealized Curves

Figure I-10. Method 1314 results and idealized leaching curves for sample UFA.

I.4 Estimating Flux and Leaching Duration

The leaching profiles discussed above are presented in terms of C_0 and cumulative L/S ratio. Additional steps are required to translate these data into inputs for EPACMTP. While C_0 represents a concentration released into infiltrating water (mg/L), EPACMTP requires leachate to be expressed as a mass flux per unit area of the WMU (g/m^2-yr). Similarly, while the cumulative L/S ratio is measured in units of L/kg, EPACMTP requires that leaching duration be expressed as time (yr). This subsection presents a general description of the methods used to convert C_0 into mass flux and the cumulative L/S ratio into time.

I.4.1 Converting Concentration into Flux

Mass flux, the total amount of constituent mass that is released from a landfill over specific period of time, was calculated with **Equation I-2**. EPA used C_0 calculated from Method 1313 data, together with infiltration rates calculated with precipitation data from the most representative climate center, to calculate site-based values for each landfill:

(I-2) $$\dot{m} = C_0 \cdot I \left(\frac{g}{1{,}000\ mg}\right)\left(\frac{1{,}000\ L}{m^3}\right)$$

Where:

$\dot{m}$ = Annual constituent mass flux (g/m2-yr);
C_0 = Initial Leachate Concentration (mg/L);
I = Infiltration rate (m/yr).

I.4.2 Converting Cumulative Liquid-to-Solid Ratio into Time

The amount of time required to reach a specific cumulative L/S ratio was calculated with **Equation I-3**, adapted from U.S. EPA (2006). EPA used landfill depths drawn from survey data and infiltration rates calculated with precipitation data from the most representative climate center, together with a fixed landfill density, to calculate site-based values for each landfill.

(I-3) $$t = LS_{cum}\left(\frac{\rho_{LF} \cdot d_{LF}}{I}\right)\left(\frac{m^3}{1{,}000\ L}\right)$$

Where:

t = Time (yr);
LS = Liquid-to-solid ratio (L/kg);
ρ_{LF} = Landfill density of 1,600 kg/m3 based on Kosson et al (2006);
d_{LF} = Landfill depth (m);
I = Infiltration rate (m/yr).

Using this equation, the times to reach different cumulative L/S ratios were calculated for landfills using the regional recharge rates assigned based on the most representative climate station. For reference, percentiles of the calculated times necessary to reach cumulative L/S ratios of 1 and 10 are presented in **Table I-1**.

Table I-1. Time to Reach Cumulative L/S Ratio of 1 and 10

Percentiles	L/S Ratio of 1 (years)	L/S Ratio of 10 (years)
5th	24.4	244
10th	41.6	416
25th	85.4	854
50th	143	1,425
75th	291	2,910
90th	1,171	11,710
95th	5,087	50,870

I.5 References

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Appendix J.

Surface Water Modeling

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J.1 Introduction

The probabilistic analysis considered risks resulting from Constituents of Potential Concern (COPCs) in surface water that result from ground water discharges. Modeling this pathway required estimating the mass flux of ground water (and COPC mass in that ground water) into surface water, as well as modeling the fate of COPCs once in the surface water. EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP), which was used to model ground water transport, does not include transfer from ground water to surface water bodies. This appendix presents the equations used to model surface water concentrations due to ground water intercepting surface water. It also describes the surface water models used to determine constituent partitioning between water and sediments.

- **Attachment J-1** provides the equations comprising the surface water equilibrium partitioning model, including equations that estimate steady-state concentrations in the water column (dissolved and total) and sediments.

J.2 Ground Water to Surface Water Modeling

At some sites, waste management units (WMUs) are located upgradient from one or more surface water bodies (e.g., stream, lake). At these sites, it is possible that the water body intercepts the flow of ground water before it reaches a receptor well. To determine the mass flux of constituents into these surface water bodies, as well as the effect of surface water interception on receptor well concentrations further downgradient, two separate procedures were developed. These two procedures were developed only for the case of gaining streams, which are streams that receive baseflow from ground water. Losing streams, which discharge to ground water, receive no water or constituent loading from ground water. Instead, the stream may discharge to the surficial aquifer, potentially diluting the constituent concentrations that are present.

Although it is known that some water bodies alternate between gaining and losing on a seasonal basis, this analysis assumed that each modeled water body was gaining year-round. While this approach may underestimate some fraction of potential exposures from ingestion of ground water by always intercepting and capturing some ground water flow, it does not include the dilution effect from losing streams that could balance this effect. Also, this assumption will not significantly affect the high-end ground water receptor risks that are dominated by sites where no intercepting water bodies are present.

The mathematical descriptions of ground water flow into a gaining stream and chemical transport downgradient from the stream must be modified to account for the mass of both water and constituents lost to the stream. To handle these special cases, two independent procedures were developed. The first procedure was developed to estimate the mass flux of constituents into the intercepting stream. The second procedure was developed to estimate the constituent concentrations at a receptor well located downgradient from an intercepting stream.

J.2.1 Mass Flux from Aquifer into a Stream

To predict the mass flux of a constituent from an aquifer into a stream, the distribution of constituent concentrations and volumetric ground water fluxes along the upgradient edge of the stream must be known. The volumetric ground water flux depends on the difference between the stream stage and the hydraulic head in the aquifer. If the hydraulic head in the aquifer is higher than the stream stage, the ground water from the aquifer will enter the stream as baseflow. When this occurs, the stream is said to be a gaining stream. The procedure below was developed for gaining streams only. **Figure J-1** provides a graphical conceptualization of the modeled scenario.

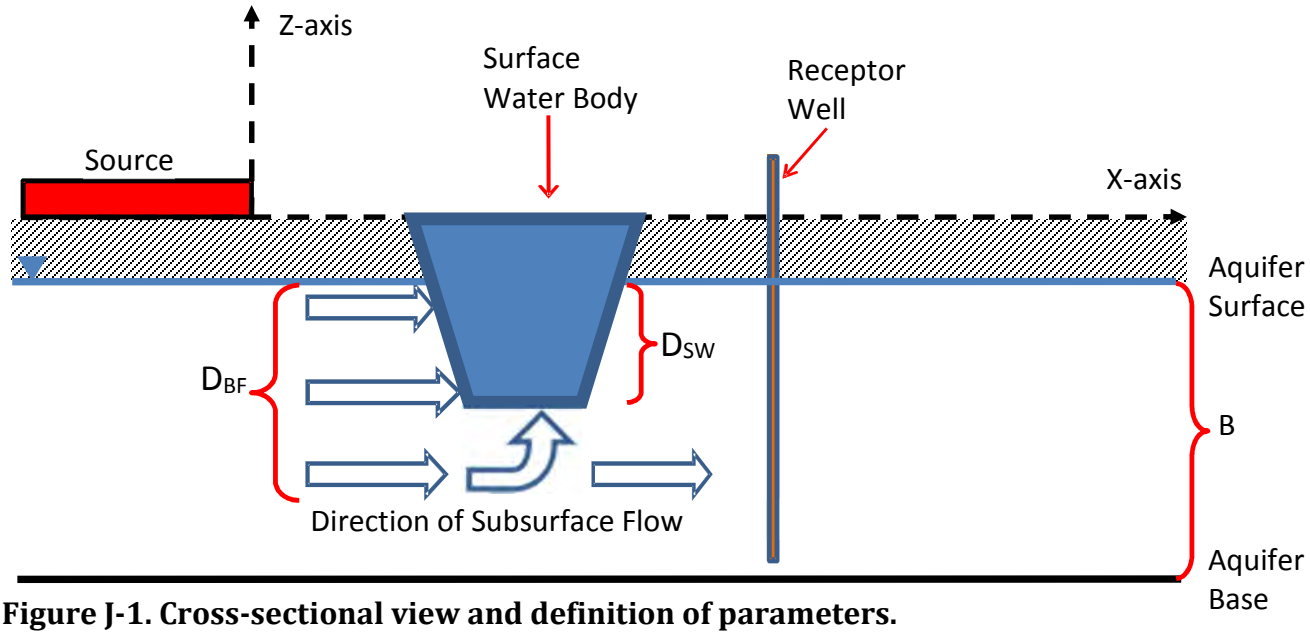


Figure J-1. Cross-sectional view and definition of parameters.

The ground water volumetric flux per unit area of stream bed is governed by the difference in ground water hydraulic head, hydraulic conductivity of streambed, and streambed thickness. In many watersheds, baseflow in terms of volumetric inflow rate per unit length of stream is available. Assuming that the base flow information is available, mass flux may be estimated by integrating the product of baseflow flux per unit area and constituent concentration over the total baseflow area. The total baseflow area is determined by the baseflow depth, D_{BF}, and the domain half width, Y_B. The total mass flux is determined using the baseflow rate and the output constituent concentration from EPACMTP according to the equation below.

(J-1)
$$M = 2\,\frac{q_{Baseflow}}{D_{BF}} \int_{y=0}^{y=Y_B} \int_{z=0}^{z=D_{BF}} C(X = X_{SW}, y, z, t)\,dy\,dz$$

Where:

D_{BF} = Baseflow depth (L);
C = Chemical concentration at $X = X_{SW}$ (M/L^3);
x = Horizontal distance of stream from the downgradient edge of the WMU (L);
X_{SW} = Distance of stream from the downgradient edge of the WMU (L);

y = Horizontal distance (L) from the plume center line along a vertical plane at the upgradient side of the surface water body; and

z = Vertical distance (L) from the top of a vertical plane at the upgradient side of the surface water body, positive downward.

The concentration term, C, is obtained from Equation (4.92) in the EPACMTP Technical Background Document (U.S. EPA, 2003a) and baseflow depth which is defined by:

(J-2) $$D_{BF} = \left(\frac{q_{Baseflow}}{q_{Aquifer}}\right) B$$

Where:

B = saturated thickness of the aquifer.

The baseflow depth, D_{BF}, which is based on the Dupuit approximation (Bear, 1972), is considered more accurate than the surface water depth, D_{SW} for the following reasons: 1) baseflow is a measured quantity in gauged streams; 2) reference elevations for stream depth are not always known; 3) a reported stream depth for a given stream may not reflect its average depth; and 4) stream depth may not account for the contraction of ground water flow tube due to localized steepening of hydraulic gradient before entering the stream. **Figure J-2** provides a graphical conceptualization of the modeled scenario.

J.2.2 Concentration at Wells Located Downgradient from a Stream

In this scenario, a stream flows perpendicular to the direction of regional ground water flow. The distance between the downgradient edge of the WMU and the upgradient edge of the surface water body is X_{SW}. A receptor well is located at a distance of X_{RW} from the downgradient edge of the WMU. If $X_{RW} > X_{SW}$, the well is located downgradient from the surface water body, a situation the original EPACMTP transport module does not allow. This procedure was developed to overcome the deficiency.

The procedure described here estimates the surface water baseflow (the water transferred from the aquifer to the surface water body) and the ground water flow rate between the surface water body and the receptor well location. It corrects the EPACMTP transport module to reflect the presence of the surface water body, by relocating the well to a distance X'_{RW} from the downgradient edge of the WMU where the concentration is equivalent to the concentration from the actual receptor well. **Figure J-2** provides a graphical conceptualization of the modeled scenario. By relocating the receptor well location to X'_{RW} from the downgradient edge of the WMU, the concentration equivalent to the concentration from the actual receptor well (located at the distance of X_{RW}) is calculated using the solution of the ground water flow and constituent transport equations at the new well location, X'_{RW}.

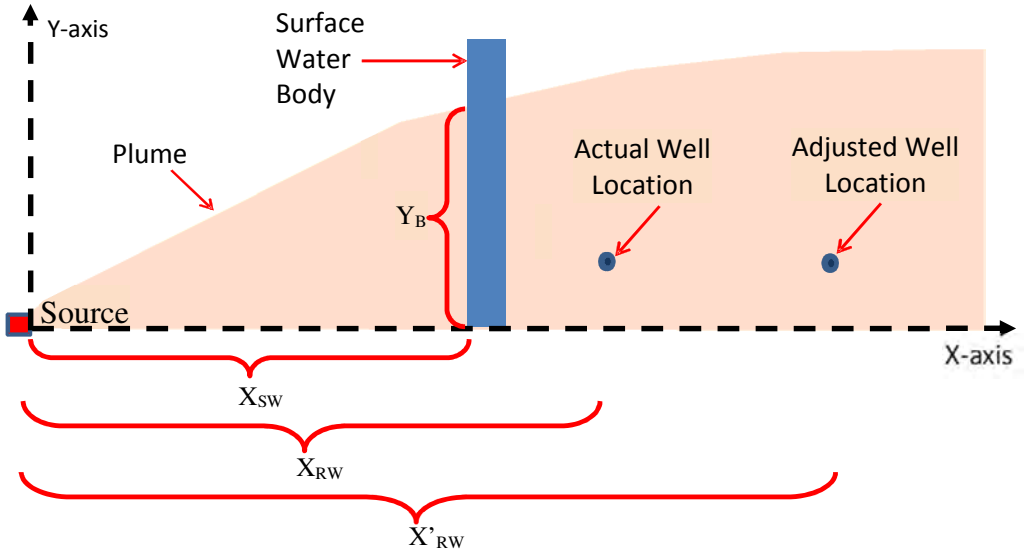


Figure J-2. Aerial view and definition of parameters.

The aquifer modeled by EPACMTP is assumed to receive clean and uniform recharge from the infiltration of precipitation across the entire area around the WMU, which includes the entire footprint of the constituent plume (U.S. EPA, 2003a). As a result, the aquifer flow rate per unit width, $q_{Aquifer}$, along the x-axis may gradually increase due to the cumulative effects of recharge along the flow direction. In the EPACMTP transport module, the aquifer flow rate is assumed to be uniform. To account for variations in the flow rate, spatial averaging of $q_{Aquifer}$ between two points of interest is performed. Between the surface water body and the receptor well, spatially averaged flow rate per unit width is given by:

(J-3) $$q_{Averageflow} = \frac{1}{X_{RW} - X_{SW}} \int_{x=X_{SW}}^{x=X_{RW}} q_{Aquifer}\, dx$$

Where:

$q_{Averageflow}$ = Averaged aquifer flow rate per unit width of the flow domain with baseflow included (L2/T);
$q_{Aquifer}$ = Aquifer flow rate per unit width of the flow domain with baseflow included (L2/T);
X_{SW} = Distance to the stream from the downgradient edge of the WMU (L); and
X_{RW} = Distance to the receptor well from the downgradient edge of the WMU (L).

However, EPACMTP is not designed to account for loss to water bodies. Therefore, $q_{Averageflow}$ is calculated as though the water body does not exist and includes the baseflow that would be intercepted. Baseflow, or the total volumetric flux of water intercepted by a gaining stream, is:

(J-4) $$Q_{Baseflow} = 2\, Y_B\, q_{Baseflow}$$

Where:

$Q_{Baseflow}$ = Total baseflow water flux intercepted by the stream (L3/T);
$q_{Baseflow}$ = Baseflow water flux intercepted per unit length of the stream (L2/T); and
Y_B = Half-width of the intercepted constituent plume (L).

Note that because of the assumed symmetry of the plume, only half the plume is explicitly modeled; the other half is assumed to be a mirror image of that modeled. After excluding baseflow to the stream, the resulting net aquifer flow rate per unit width between the stream and the well is given by:

(J-5) $$q_{Netflow} = q_{Averageflow} - q_{Baseflow}$$

Where:

$q_{Netflow}$ = Net aquifer flow rate per unit width of with the constituent plume with baseflow removed (L^2/T).

As shown above, the interception of baseflow changes the ground water flow rate per unit width downgradient from the surface water body from $q_{Averageflow}$ to $q_{Netflow}$. Knowing $q_{Netflow}$, it is possible to use the original solution to the ground water fate and transport equations by relocating the receptor well from X_{RW} to X_{RW}', where X_{RW}' represents a new distance that will result in the same concentration based on $q_{Netflow}$ as a receptor well at X_{RW} based on $q_{Averageflow}$. This relocation procedure is based on an assumption that the dispersion is much smaller than the advection. This assumption is valid when the Peclet number is greater than 10 (Garges and Baehr, 1998).[1] An estimate of the Peclet numbers for the sites modeled in this analysis was conducted based on the dispersivity of the aquifers and the receptor well distribution data in the EPACMTP Background document (US EPA, 2003b) as the characteristic length. This estimate showed that the majority of sites modeled have Peclet numbers varying from 10 to 5,000. Therefore, a transformation procedure was developed to modify the receptor well locations using the equations below:

(J-6) $$(X'_{RW} - X_{SW}) = \frac{q_{Averageflow}}{q_{Netflow}}(X_{RW} - X_{SW})$$

Since $q_{Netflow}$ is not known *a priori*, it is necessary to locate X'_{RW} iteratively, as follows:

Step 1: As an initial estimate, assume that the new location of the receptor well is at the original position, so that the current approximate receptor well location $\bar{X}_{RW}$ is equal to X_{RW}.

Step 2: Estimate $q_{Netflow}$ using the current value of $\bar{X}_{RW}$, as follows:

(J-7) $$q_{Netflow} = \left(\frac{1}{\bar{X}_{RW} - X_{SW}} \int_{X=X_{SW}}^{X=\bar{X}_{RW}} q_{Aquifer}\, dx\right) - q_{Baseflow}$$

Step 3: Use $q_{Netflow}$ obtained in Step 2 to estimate a new value of X'_{RW}:

[1] The Peclet number (Pe) is a dimensionless number used to describe the flow of fluids. It is defined as the ratio of the rate of advection and the rate of diffusion of a fluid through a given medium. In general, where Pe >> 1, advection dominates transport and, where Pe << 1, diffusion dominates transport.

(J-8) $$X'^{i}_{RW} = \frac{q_{Averageflow}}{q_{Netflow}}(X^{o}_{RW} - X_{SW}) + X_{SW}$$

Where:

X'^{i}_{RW} = ith iteratation of X'RW.

Step 4: Update the approximate location of the receptor well (Note that $X'^{0}_{RW} = X_{RW}$).

(J-9) $$\overline{X}_{RW} = \frac{1}{2}\left(X'^{i}_{RW} + X'^{i-1}_{RW}\right)$$

Step 5: Check convergence until the difference between the most current X'_{RW} is sufficiently close to the value calculated in the previous iteration. In other words,

(J-10) $$\left|X'^{i}_{RW} - X'^{i-1}_{RW}\right| < \epsilon$$

Where:

ϵ = acceptable tolerance (a typical value is 0.1 m or 0.3 ft).

J.2.3 Post-Processor Verification

The stream interception routine was verified by comparing results obtained from a number of scenarios using EPACMTP (U.S. EPA, 2003a) and MODFLOW-based Hydrologic Modeling System (MODHMS) (HydroGeoLogic, 2011). MODHMS is an enhanced version of the U.S. Geological Survey MODFLOW modular three-dimensional ground water flow code (McDonald and Harbaugh, 1988). The MODHMS code has been selected for this verification because it can handle variable saturation, has been extensively verified and documented, and has been implemented by a number of government agencies in different settings. MODHMS can solve the equations without any approximate transformation for the case of baseflow intercepted by a surface water body. The transport equation solutions provided by the MODHMS code were considered accurate and treated as a standard against which the EPACMTP solutions were compared. The mass flux into the intercepting water body (**Section J.2.1**) and the concentration in a receptor well downgradient from an intercepting water body (**Section J.2.2**) were verified separately.

Verification Scenario Description

The verification scenario is shown in **Figure J-3**. The size of the model domain is (1,000 ft × 1,000 ft). The regional ground water gradient in the MODHMS-based model was imposed by constant heads along the upgradient (western) and downgradient (eastern) boundaries. Regional gradient across the flow domain from is 0.005 ft/ft. The model domain is homogeneous with an effective porosity of 0.3 and a hydraulic conductivity of 10 ft/day. A 60 ft × 60 ft square source is located 40 ft from the upstream boundary and 470 ft from the lateral boundary. An infiltration rate of 4.49 × 10^{-4} ft/day is imposed at the source only. A 10-ft wide stream, perpendicular to the regional flow direction, traverses the x-axis 400 ft downgradient from the source. The longitudinal, transverse and vertical dispersivities are 100 ft, 10 ft and 1 ft, respectively. The saturated thickness is 100 ft and uniform. The domain is mainly discretized into horizontally uniform grid cells with the 10 ft × 10 ft dimensions with a 1 ft thickness for the top 10 layers, a 5-ft thickness for the bottom 16 layers and increasing thickness for the middle 4 layers from 1 ft to 4 ft. To allow comparison of

receptor well concentrations at various locations downgradient from the water body, two discrete receptor well locations were chosen. Both wells are located at 250 ft from the water body. One well is located 0 ft from the centerline of the plume and the other is offset by 30 ft. Each well is screened at depths of 0.5 ft, 1.5 ft, and 2.5 ft below the ground water table. Leachate concentration from the surface impoundment is 1 mg/L.

Constituent transport was simulated using the EPACMTP postprocessing module and MODHMS under a baseflow flux of approximately 10% and 1% of the regional aquifer flux. This range was chosen to test the accuracy of the procedures when the baseflow depth is relatively small (thus making the mass flux estimation relatively difficult) and when a large fraction of mass is allowed to travel to the receptor well (thus making the constituent concentration relatively significant). In both cases, it was assumed that the vadose zone did not exist so that the infiltration with constituent entered the water table immediately after leaving the bottom of the WMU. This configuration makes the leachate influx at the top of the water table (a model input) the same for both models, thereby allowing the mass fluxes and concentrations at the receptor well location predicted by the MODHMS and the EPACMTP models to be compared directly. It was assumed that neither adsorption nor degradation occurred in the ground water.

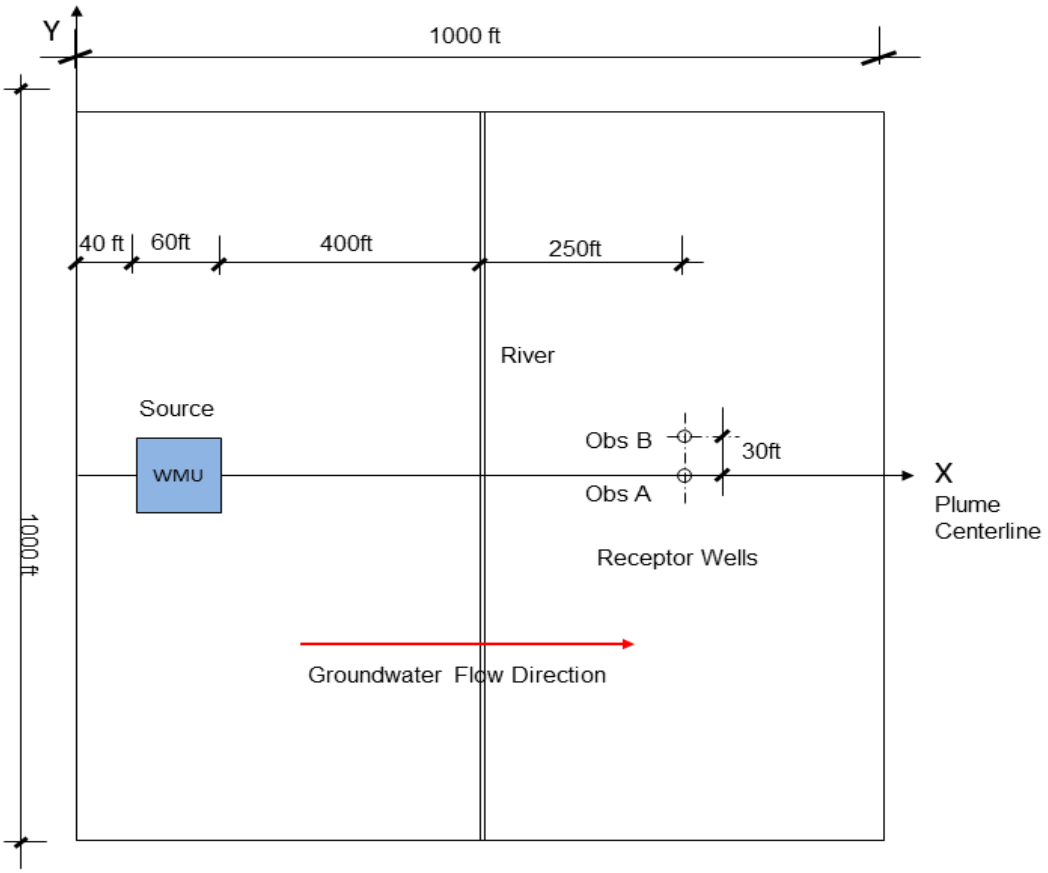
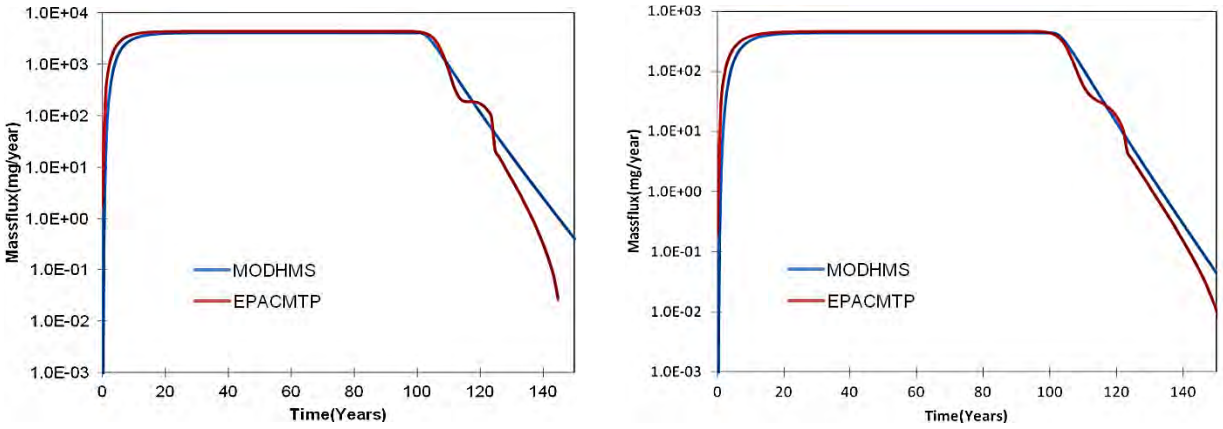


Figure J-3. Simulation domain for verifying surface water interception routine.

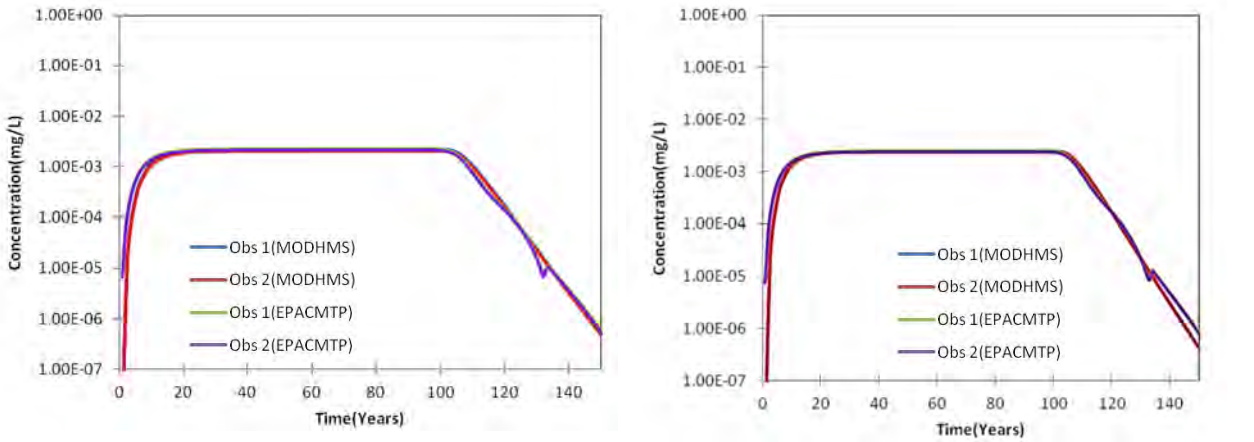
Verification Results

Figure J-4 compares the EPACMTP-generated and MODHMS-generated mass fluxes to the stream from Scenarios 1 and 2. As shown in these figures, the EPACMTP-based mass fluxes agree reasonably well with those based on the more accurate numerical MODHMS-based model. However, the EPACMTP model tends to be more conservative than the MODHMS-based model. **Figure J-5** compares the EPACMTP-generated breakthrough curves at adjusted well locations and the corresponding MODHMS-generated breakthrough curves at actual observation locations from Scenario 1, Layers 1, 2 and 3. In all of these figures, breakthrough curves are almost identical. EPACMTP tends to return slightly more conservative results than MODHMS. Minor oscillations in the EPACMTP curve as it decreases are artifacts of the limitation of computer precision in the numerical computations and should be ignored.



Scenario 1: 10% baseflow Scenario 2: 1% baseflow

Figure J-4. Mass flux entering the stream downgradient from the WMU.



Scenario 1: Obs. Locations 1 and 2 in Layer 1 Scenario 2: Obs. Locations 1 and 2 in Layer 1

Figure J-5. Breakthrough curves at various observation locations for two scenarios.

J.3 Surface Water Model Overview

The surface water model used in this analysis is a simple steady-state model used previously in the EPA *Methodology for Assessing Health Risks Associated with Multiple Pathways of Exposure to Combustor Emissions* (U.S. EPA, 1998). The specific equations used are presented in **Attachment J-1**. The following are the key assumptions of this model and the specifics on how it was applied for the revised risk assessment:

- The model assumes steady-state flow and transport conditions. Long-term average annual stream flow and climatic data and assumptions were used.
- The model is able to account for constituent loadings into the water body through ground water discharge, waste outfalls, and direct air deposition. The only source relevant to the revised risk assessment is discharges from ground water.
- The model estimates the rate of incorporation, or burial, of constituents into bed sediments as a function of the rate at which sediments deposit from the water column onto the surficial sediment layer. For the coal combustion residual (CCR) risk assessment, the burial rate was set to zero (a protective assumption) because of the lack of national data available to estimate this process.
- The model can incorporate separate decay rate constants for the water column and the benthic sediments to allow for consideration of decay mechanisms that remove constituents from the water body. However, because all of the inorganics considered are persistent in the environment, degradation was not relevant to this risk assessment.

The model describes the partitioning of constituents between aquatic sediments, suspended solids, and surface water using linear equilibrium partition coefficients (i.e., equilibrium is maintained between dissolved constituents within the water column and constituents in suspended solids and bed sediments). **Table J-1** provides distributions for the partitioning coefficients used by the surface water model. These distributions were derived primarily from published empirical data presented in U.S. EPA (2005) and were sampled during the preparation of the input files in the Monte Carlo process.

Table J-1. Sediment/Water and Suspended Solids/Water Partition Coefficients: Empirical Distributions*

Constituent	Sediment/Water				Suspended Solids/Water			
	Min	Mean	Max	SD	Min	Mean	Max	SD
Aluminum	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Antimony	0.6	3.6	4.8	1.8	3.9	4.8	4.9	0.5
Arsenic	1.6	2.4	4.3	0.7	2	3.9	6	0.5
Barium	0.9	2.5	3.2	0.8	2.9	4	4.5	0.4

(continued)

Table J-1. Sediment/Water and Suspended Solids/Water Partition Coefficients: Empirical Distributions*

Constituent	Sediment/Water				Suspended Solids/Water			
	Min	Mean	Max	SD	Min	Mean	Max	SD
Beryllium	0.8	2.8	6.5	1.9	2.8	4.2	6.8	0.7
Boron	-0.5	0.8	1.4	0.5	3.4	3.9	4.1	0.2
Cadmium	0.5	3.3	7.3	1.8	2.8	4.9	6.3	0.6
Chloride	0	0	0	0	0	0	0	0
Chromium III	1.9	4.9	5.9	1.5	3.9	5.1	6	0.4
Chromium VI	0	1.7	4.4	1.4	3.6	4.2	5.1	0.5
Cobalt	2.9	3.1	3.6	1	3.2	4.8	6.3	0.8
Copper	0.7	3.5	6.2	1.7	3.1	4.7	6.1	0.4
Fluoride	N/A	2.2	N/A	N/A	N/A	2.2	N/A	N/A
Iron	N/A	1.4	N/A	N/A	N/A	1.4	N/A	N/A
Lead	2	4.6	7	1.9	3.4	5.7	6.5	0.4
Mercury	3.8	4.9	6	0.6	4.2	5.3	6.9	0.4
Methyl mercury	2.8	3.9	5	0.5	4.2	4.9	6.2	0.7
Molybdenum	0.4	2.5	3.7	0.8	3.5	4.4	5.7	0.4
Nickel	0.3	3.9	4	1.8	3.7	4.4	4.9	1
Selenium IV	1	3.6	4	1.2	3.8	4.4	4.8	0.4
Selenium VI	-1.4	0.6	3	1.2	3.1	3.8	4.6	1
Silver	2.1	3.6	5.8	1.1	4.4	5.2	6.3	0.6
Thallium	-0.5	1.3	3.5	1.1	3	4.1	4.5	1
Vanadium	0.4	2.1	3.2	0.9	2.5	3.7	4.5	0.6
Zinc	1.5	4.1	6.2	1.6	3.5	5	6.9	0.5

Source: U.S. EPA (2005) except for boron, iron, chloride and fluoride. The K_d distribution for boron was created by Dr. Jerry Allison for the previous CCR risk assessment in the same manner as described for the other metals in U.S. EPA (2005). The K_d values for fluoride and iron are from Baes (1984), which does not provide a full distribution. A protective K_d of 0 was assumed for chloride in the absence of other data.

*All values are log values and distribution type is log-normal.

SD = standard deviation.

N/A = data not available.

J.4 Aluminum Surface Water Precipitation

This section describes solubility-based surface water algorithms used to model aluminum in the CCR risk assessment. Because the fate and transport of aluminum is controlled more by solubility than by sorption in surface water, the surface water model includes algorithms to estimate aluminum concentrations in the water column and sediments by accounting for precipitation and fallout of aluminum in the water column. Gibbsite, a simple mineral form of aluminum hydroxide, was used as the basis for these calculations based on the prevalence of this mineral in the environment. The calculations proceed in a stepwise fashion, as follows:

Step 1: Initially, all aluminum entering the water body is assumed to be dissolved.

$$f_{water} = f_d = 1$$
$$f_{benth} = 0$$
$$C_{wctot} = C_{wd}$$

Where:

f_{water} = Fraction in water column (unitless)
f_d = Fraction dissolved (unitless)
f_{benth} = Fraction in sediment layer (unitless)
C_{wctot} = Total water column concentration (mg/L)
C_{wd} = Dissolved water column concentration (mg/L)

Step 2: Compare the dissolved water column concentration (C_{wd}) with the maximum soluble concentration (C_{sol}) calculated in Metal Speciation Equilibrium Model for Surface and Ground Water (MINTEQA2) for the water body pH, presented in **Table J-2**.

Table J-2. Aluminum Solubility Calculated by MINTEQA2 as a Function of Water Body pH

Minimum pH	Maximum pH	Solubility (mg/L)
3.5	4.5	26.2
4.5	5	1.84
5	5.5	0.196
5.5	6	0.0112
6	6.5	0.00143
6.5	7	0.000662
7	7.5	0.000915
7.5	8	0.00229
8	8.5	0.00682
8.5	9	0.0212
9	9.5	0.0666
9.5	10	0.211
10	10.5	0.668

Step 3: If the dissolved water concentration (C_{wd}) is greater than the solubility limit (C_{sol}), reset the dissolved water concentration to the solubility limit, and precipitate and settle out the excess aluminum to the benthic sediment layer:

$$f_{water} = \frac{C_{sol}}{C_{wctot}}$$

$$f_{benth} = \frac{(C_{wctot} - C_{sol})}{C_{wctot}}$$

$$C_{wbs} = (C_{wctot} - C_{sol})\frac{d_{wc}}{d_b}$$

$$C_{wtot} = C_{wctot}\frac{d_{wc}}{d_z}$$

$$C_{wd} = C_{sol}$$

$$C_{wctot} = C_{sol}$$

Where (in addition to the variables previously defined):

C_{sol} = Solubility limit (mg/L)
C_{wbs} = Total concentration in bed sediment
C_{wtot} = Total water body concentration from loading
d_b = Depth of the upper benthic layer (m)
d_{wc} = Depth of the water column (m)
d_z = Depth of the water body (m)

Otherwise, set the dissolved concentration to the total water column concentration, and do not precipitate and settle out any aluminum to the sediment:

$$C_{dw} = C_{wctot}$$

$$C_{wbs} = 0$$

$$C_{wtot} = C_{wctot}\frac{d_{wc}}{d_z}$$

J.5 References

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Attachment J-1.
Surface Water Concentrations

This attachment contains the equations for surface water concentrations.

- **Table J-1-1.** Fraction of Contaminant in Water Column
- **Table J-1-2.** Fraction of Contaminant in Benthic Sediments
- **Table J-1-3.** Dissolved Fraction
- **Table J-1-4.** Liquid-Phase Transfer Coefficient – Lakes (Mercury Only)
- **Table J-1-5.** Liquid-Phase Transfer Coefficient – Streams (Mercury Only)
- **Table J-1-6.** Gas-Phase Transfer Coefficient – Lakes (Mercury Only)
- **Table J-1-7.** Diffusion Transfer Rate (Mercury Only)
- **Table J-1-8.** Water Concentration Dissipation Rate Constant
- **Table J-1-9.** Total Water Body Concentration from Loading
- **Table J-1-10.** Total Water Column Concentration
- **Table J-1-11.** Dissolved Water Body Concentration
- **Table J-1-12.** Total Concentration in Bed Sediment.

Table J-1-1. Fraction of Contaminant in Water Column (Unitless)

f_{Water}

$$d_w = d_z - d_b$$

$$f_{Water} = \frac{\left[1+\left(K_{dsw}\times TSS\times 0.000001\right)\right]\times\frac{d_w}{d_z}}{\left[\left[1+\left(K_{dsw}\times TSS\times 0.000001\right)\right]\times\frac{d_w}{d_z}\right]+\left[\left(bsp+K_{dbs}\times bsc\right)\times\frac{d_b}{d_z}\right]}$$

Name	Description	Value
bsc	Bed sediment particle concentration (g/cm^3) or (kg/L)	1
bsp	Bed sediment porosity (cm^3/cm^3)	0.6
db	Depth of upper benthic layer (m)	0.03
dw	Depth of water column (m)	Calculated
dz	Depth of the water body (m)	See **Appendix B**
K_{dbs}	Sediment-water partition coefficient (mL/g)	See Table J-1
K_{dsw}	Suspended sediment-water partition coefficient (mL/g)	See **Table J-1**
TSS	Total suspended solids (mg/L)	See **Appendix B**
--	Conversion factor (L/mL)(g/mg)	0.000001

Table J-1-2. Fraction of Contaminant in Benthic Sediments (Unitless)

f_{Benth}

$$f_{Benth} = \frac{(bsp + K_{dbs} \times bsc) \times \frac{d_b}{d_z}}{\left[(1 + K_{dsw} \times TSS \times 0.000001) \times \frac{d_W}{d_z}\right] + \left[(bsp + K_{dbs} \times bsc) \times \frac{d_b}{d_z}\right]}$$

Name	Description	Value
bsc	Bed sediment particle concentration (g/cm^3) or (kg/L)	1
bsp	Bed sediment porosity (cm^3/cm^3)	0.6
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Calculated (**Table J-1-1**)
d_z	Depth of the water body (m)	See **Appendix B**
K_{dbs}	Sediment-water partition coefficient (mL/g)	See **Table J-1**
K_{dsw}	Suspended sediment-water partition coefficient (mL/g)	See **Table J-1**
TSS	Total suspended solids (mg/L)	See **Appendix B**
--	Conversion factor (L/mL)(g/mg)	0.000001

Table J-1-3. Dissolved Fraction (Unitless)

f_d

$$f_d = \frac{1}{1 + K_{dsw} \times TSS \times 0.000001}$$

Name	Description	Value
K_{dsw}	Suspended sediment-water partition coefficient (mL/g)	See **Table J-1**
TSS	Total suspended solids (mg/L)	See **Appendix B**
--	Conversion factor (L/mL)(g/mg)	0.000001

Table J-1-4. Liquid-Phase Transfer Coefficient – Lakes (m/day) (Mercury Only)

KL_{lakes}

$$KL_{Lakes} = \sqrt{C_d} \times u_w \times \sqrt{\frac{R_a}{R_w}} \times \frac{k^{0.33}}{L_2} \times \left(\frac{\mu_w}{R_w \times D_w} \right)^{-0.67} \times 86400$$

Name	Description	Value
C_d	Drag coefficient (unitless)	0.0011
D_w	Diffusivity in water (cm^2/s)	1.8×10^{-5}
k	von Karman's constant (unitless)	0.4
L_2	Viscous sublayer thickness (unitless)	4
μ_w	Viscosity of water (g/cm-s)	0.0169
R_a	Density of air (g/cm^3)	0.0012
R_w	Density of water (g/cm^3)	1
u_w	Mean annual wind speed (m/sec)	See **Appendix B**
--	Conversion factor (sec/day)	86,400

Table J-1-5. Liquid-Phase Transfer Coefficient – Streams (m/day) (Mercury Only)

$KL_{streams}$

$$KL_{streams} = \sqrt{\frac{D_w \times U \times 0.0001}{d_z}} \times 86400$$

Name	Description	Value
D_w	Diffusivity in water (cm^2/s)	2×10^{-5}
d_z	Depth of the water body (m)	See **Appendix B**
U	Current velocity of the water body (m/s)	See **Appendix B**
--	Conversion factor (sec/day)	86,400

Table J-1-6. Gas-Phase Transfer Coefficient – Lakes (m/day) (Mercury Only)

K_{gas}

$$K_{gas} = \sqrt{C_d} \times u_w \times \frac{k^{0.33}}{L_2} \times \left(\frac{\mu_a}{R_a \times D_a} \right)^{-0.67} \times 86400$$

Name	Description	Value
C_d	Drag coefficient (unitless)	0.0011
D_a	Diffusivity of chemical in air (cm^2/s)	0.05
k	von Karman's constant (unitless)	0.4
L_2	Viscous sublayer thickness (unitless)	4
μ_A	Viscosity of air (g/cm-s)	0.000181
R_a	Density of air (g/cm^3)	0.0012
u_w	Mean annual wind speed (m/sec)	See **Appendix B**
--	Conversion factor (sec/day)	86,400

Table J-1-7. Diffusion Transfer Rate (m/day) (Mercury Only)

K_v

$$Tempadjust = \theta_{water}^{(T_w - T_{hlc})}$$

$$K_v = \frac{1}{\frac{1}{K_L} + \frac{1}{K_g \times H'}} \times TempAdjust$$

$$H' = \frac{HLC}{R \times T_w}$$

Name	Description	Value
HLC	Henry's law constant (atm-m^3/mole)	7 x 10^{-10}
H’	Dimensionless Henry's law constant (unitless)	Calculated
K_g	Gas-phase transfer coefficient (m/d)	Calculated (**Table J-1-6**)
KL	Liquid-phase transfer coefficient (m/d)	Calculated (**Table J-1-4** [lakes], **Table J-1-5** [streams])
R	Ideal gas constant (atm-m^3/K-mole)	0.00008205
θ_{water}	Temperature correction (unitless)	1.026
T_{hlc}	Temperature of HLC (K)	298
T_w	Temperature of the water body (K)	See Appendix B

Note: Drawn from U.S. EPA, 1998 (EPA-530-D-98-001A and EPA-600/R-98/137).

Table J-1-8. Water Concentration Dissipation Rate Constant (1/day)

K_{wt}

$$K_{wt} = \left(f_{Water} \times f_d \times k_{vol}\right) + \left(f_{benth} \times K_b\right) + \left(f_{Water} \times k_{sw}\right) + \left(f_{benth} \times k_{sed}\right) + k_h$$

$$K_b = \frac{WB}{d_b}$$

$$k_{vol} = \frac{K_v}{d_w}$$

Name	Description	Value
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Calculated (**Table J-1-1**)
f_{benth}	Fraction of contaminant in benthic sediments (unitless)	Calculated (**Table J-1-2**)
f_d	Dissolved fraction (unitless)	Calculated (**Table J-1-3**)
f_{Water}	Fraction of contaminant in water column (unitless)	Calculated (**Table J-1-1**)
K_b	Benthic burial rate constant (1/day)	Calculated (see above)
k_h	Hydrolysis rate (1/day)	0
k_{sed}	Degradation rate for sediment (1/day)	0
k_{sw}	Degradation rate for water column (1/day)	0
K_v	Diffusion transfer rate (m/day)	Calculated (mercury only)
k_{vol}	Water column volatilization rate constant (1/day)	Calculated (mercury only)
WB	Rate of burial (m/day)	0

Table J-1-9. Total Water Body Concentration from Loading (g/m³ or mg/L)

C_{wtot}

$$C_{wtot} = \frac{L_{total}}{\left(\left(V_{fx} \times f_{Water} \times \frac{d_z}{d_w}\right) + \left(K_{wt} \times V\right)\right)}$$

$$V = Area \times d_z$$

Name	Description	Value
V_{fx}	Water body annual flow mixing volume (m^3/day)	See **Appendix B**
f_{Water}	Fraction of contaminant in water column (unitless)	Calculated (**Table J-1-1**)
d_z	Water body depth (m)	See Appendix B
d_w	Depth of water column (m)	Calculated (**Table J-1-1**)
K_{wt}	Water concentration dissipation rate constant (1/day)	Calculated (**Table J-1-8**)
V	Flow independent mixing volume (m^3)	Calculated (see above)
Area	Area of the water body (m^2)	See **Appendix B**

Table J-1-10. Total Water Column Concentration (g/m³ or mg/L)

C_{wcTot}

$$d_w = d_z - d_b$$

$$C_{wcTot} = C_{wTot} \times f_{water} \times \frac{d_z}{d_w}$$

Name	Description	Value
C_{wTot}	Total water body concentration from loading (g/m³ or mg/L)	Calculated (**Table J-1-9**)
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Calculated (**Table J-1-1**)
d_z	Depth of the water body (m)	See **Appendix B**
f_{Water}	Fraction of contaminant in water column (unitless)	Calculated (**Table J-1-1**)

Table J-1-11. Dissolved Water Body Concentration (mg/L)

C_{dw}

$$d_w = d_z - d_b$$

$$C_{dw} = Cw_{Tot} \times f_{Water} \times f_d \times \frac{d_Z}{d_w}$$

Name	Description	Value
C_{wTot}	Total water body concentration from loading (g/m³ or mg/L)	Calculated (**Table J-1-9**)
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Calculated
d_z	Depth of the water body (m)	See **Appendix B**
f_d	Dissolved fraction (unitless)	Calculated (**Table J-1-3**)
f_{Water}	Fraction of contaminant in water column (unitless)	Calculated (**Table J-1-1**)

Table J-1-12. Total Concentration in Bed Sediment (g/m^3 or mg/L)

C_{wbs}

$$C_{bs} = C_{wTot} \times f_{benth} \times \frac{d_z}{d_b}$$

Name	Description	Value
C_{wTot}	Total water body concentration from loading (g/m^3 or mg/L)	Calculated (**Table J-1-9**)_
f_{benth}	Fraction of contaminant in benthic sediments (unitless)	Calculated (**Table J-1-2**)_
d_b	Depth of upper benthic layer (m)	0.03
d_z	Depth of the water body (m)	See **Appendix B**

Appendix K.

Uncertainty Analyses

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K.1 Introduction

To confirm the results of the probabilistic analysis and to better understand whether any particular subset of disposal practices drives the risks identified, the U.S. Environmental Protection Agency (EPA or the Agency) retained each of the exposure pathways from the probabilistic analyses for additional uncertainty analyses. This appendix details the methodology used for some of the uncertainty analyses summarized in **Section 5** the document.

- **Attachment K-1** provides graphs of the times to peak concentration for select constituents.

K.2 Surface Impoundment Preclosure and Postclosure Releases

This section presents the approach used to evaluate uncertainties associated with the modeling of preclosure and postclosure releases for surface impoundments. EPA used the results of this analysis to draw conclusions, summarized in **Section 5**, about the potential for this uncertainty to affect the risk results of the probabilistic analysis.

K.2.1 Technical Approach

The lifetime of a surface impoundment is conceptualized in two phases: a 75-year operational period, during which a constant amount of wastewater is maintained, and a postclosure period, when all free liquid remaining in the impoundment is removed, leaving behind coal combustion residual (CCR) sludges and sediments that are capped with an appropriate final cover. The forces driving leaching from surface impoundments during operation and postclosure are different. During operation, free liquids that are ponded in the impoundment create a strong hydraulic head that acts to increase infiltration through the base of the impoundment. The removal of free liquids and capping during closure reduces the hydraulic head and the rate of contaminant migration. After closure is complete, infiltration through the impoundments is driven only by percolation of incident precipitation through the cap.

In the 2010 Risk Assessment, the postclosure period was not modeled because the hydraulic head reduction between the operational and postclosure periods is so great that the peak ground water exposures used in the HEI risk assessment are unlikely to be affected. However, based on a number of public and peer-review comments received, the revised risk assessment estimated the risks associated with postclosure to determine if any significant risks to ground water had been overlooked. The operational phase of an impoundment is modeled using the standard impoundment source term in EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP). Liquid wastes in the impoundment are assumed to be replenished over the operational life to maintain a constant level of liquid in the unit with constant constituent concentrations. At the end of the 75-year operational life, no additional contaminant mass is introduced into the system. Modeling the postclosure portion of the surface impoundment required a second run of EPACMTP where the surface impoundment was re-conceptualized as a closed landfill. This run was conducted using the database of impoundment and site characteristics supplemented with the additional inputs necessary to define the landfill source term as follows:

- **Infiltration Rate**: The infiltration rate through the closed impoundment was determined using the following criteria:
  - If the impoundment is unlined, the postclosure infiltration rate is set equal to the regional recharge rate that corresponds to the regional soil type, which is assumed to also be the source for the native soil cap.
  - If the impoundment is lined with clay, the postclosure infiltration rate is set equal to the Hydrologic Evaluation Of Landfill Performance-modeled infiltration rate calculated based on the assigned climate center (see **Appendix C**) and the modeled clay liner hydraulic conductivity of 1×10^{-7} cm/sec.
  - If the impoundment has a geomembrane/composite liner, the infiltration rate from the preclosure period is used as the governing rate.

- **Depth:** The depth of waste in a landfill is one of the parameters used to determine how long constituents leach from the waste. The depth of waste in the landfill (i.e., the closed impoundment) is assumed to be the thickness of the sludge in the impoundment.

- **Total Leachable Concentration:** Following closure, the mass of constituents present in the impoundment are no longer replenished and become finite. This parameter was estimated by assuming that the concentrations in the interstitial pore water and in the sludge sediments are at equilibrium defined by the sorption coefficient (K_d) for the unsaturated zone from the preclosure period simulations. EPA developed K_d values for the unsaturated native soils immediately beneath the waste management units (WMUs), rather than the sludges within the WMUs. These sludges are expected to have a higher sorptive capacity than underlying soils because of the generally higher organic carbon contents of these sludges. A higher sorptive capacity would result in a slower release into the vadose zone. Therefore, the assumption that the K_d in the sludge is identical to that in the vadose zone is conservative for the purposes of these analyses.

For each constituent, peak concentrations are derived from the composite time series results using the following approach. Ground water concentrations resulting from preclosure and postclosure are estimated through the superposition (addition) of the modeled results for both phases. The time series of receptor well concentrations are modeled and saved for each simulation. We conducted preclosure and postclosure simulations separately. Results are interpolated from the model-specified time steps (chosen by EPACMTP in each simulation to maximize computing power) to whole years (e.g., 0, 1, 2, and 3). EPACMTP assumes that time zero corresponds to the time of first release of leachate from a waste management unit; however, postclosure releases are assumed to begin 75 years after the preclosure period begins. To properly combine the two results, the post closure releases must be translated forward in time by 75 years to account for relative perspective of time in EPACMTP simulation results. The two interpolated time series are superimposed by simply adding the simulation results together for each equivalent time step.

The approach was implemented using EPACMTP with non-linear sorption isotherms to investigate whether postclosure releases influence peak ground water concentrations. Trivalent arsenic (arsenic III) and hexavalent chromium (chromium VI) were selected for this uncertainty

analysis because they are the only carcinogens modeled. Twelve Monte Carlo simulations were performed: both a preclosure and a postclosure simulation of the two metal species for the three waste types modeled in the full-scale analysis [combined ash, ash and coal refuse, and flue-gas desulfurization waste (FGD)]. Peak receptor well concentrations were calculated for the preclosure simulations alone, and in combination with the postclosure simulations. For each waste type / metal species combination, the peak concentrations from the two scenarios were compared to determine the likelihood that the combined peak concentration would exceeded the preclosure peak.

K.2.2 Results of Pre- and Postclosure Modeling

As shown in the following table, consideration of postclosure leaching resulted in higher peak concentrations for only about five percent of all modeled surface impoundments. However, the magnitude of these higher concentrations was typically small. The vast majority (99.3 percent) of the exceedances resulted in a difference of less than 0.000001 mg/L, or four orders of magnitude below the arsenic maximum concentration limit. Only 0.02 percent resulted in a difference greater than 0.01 mg/L, with a maximum difference of 0.017 mg/L. Because the frequency of higher concentrations is very small and the magnitude of the higher concentrations that do occur is typically small, the decision to neglect these postclosure releases is not a major source of uncertainty. **Table K-1** summarizes the frequency at which consideration of postclosure leaching resulted in higher peak concentrations. Percentages are calculated based on the total number of results for all model runs and for each liner type. Any increase in risks attributable to postclosure releases would not be sufficient to change the results presented in **Section 4**.

Table K-1. Summary of Frequencies and Percentages of Combined Peak Concentrations Exceeding Preclosure Peak Concentrations

Liner	Total Model Iterations	Number of Exceedances	All Liners		By Liner Type	
			Percent Exceed	Percent > 1×10^{-6} mg/L	Percent Exceed	Percent > 1×10^{-6} mg/L
All	17,424	866	5.0%	0.7%	—	—
Unlined	12,111	422	2.4%	0.6%	3.5%	0.9%
Clay	2,596	149	0.9%	0.1%	5.7%	1.0%
Composite	2,717	295	1.7%	< 0.1%	10.9%	0.2%

K.2.3 Verification of Pre- and Postclosure Results

EPACMTP is a composite of two modules: a one-dimensional variably saturated module for the vadose zone and a three-dimensional saturated module for the aquifer. A more robust ground water fate and transport model was necessary to verify the EPACMTP results that peak exposures associated with the ground water pathway are dominated by preclosure releases. The MODFLOW-based Hydrologic Modeling System (MODHMS) (HydroGeoLogic, Inc., 2011) was selected. MODHMS is an enhanced version of the U.S. Geological Survey Modular Three-Dimensional Finite-Difference Ground-Water Flow (MODFLOW) model (McDonald and Harbaugh, 1988) that

can simulate the same subsurface conditions as EPACMTP, but can account for a single, variably saturated domain.

MODHMS Model Design

To validate the combined pre- and postclosure EPACMTP results, a MODHMS conceptual model was developed to be as similar as possible to the conceptual model used by EPACMTP. **Figure K-1** depicts the settings of the verification scenario. A single, fixed set of inputs to characterize a surface impoundment was chosen at random from the set of As III releases from the combined ash waste type. Next, it was assumed that neither adsorption nor degradation occurred in the ground water. Finally, the regional ground water gradient in the MODHMS-based model was imposed by constant heads along the boundaries. A separate set of boundary conditions were applied to represent pre- and postclosure phases of the surface impoundment:

- **Complete clean closure:** constant leaching for a 75-year operational life, after which the infiltration rate is reduced to the regional recharge rate and leaching is discontinued.
- **Partial clean closure:** constant leaching for 75-year operational life, after which the infiltration rate is reduced to the regional recharge rate while the leachate concentration held at the same value.

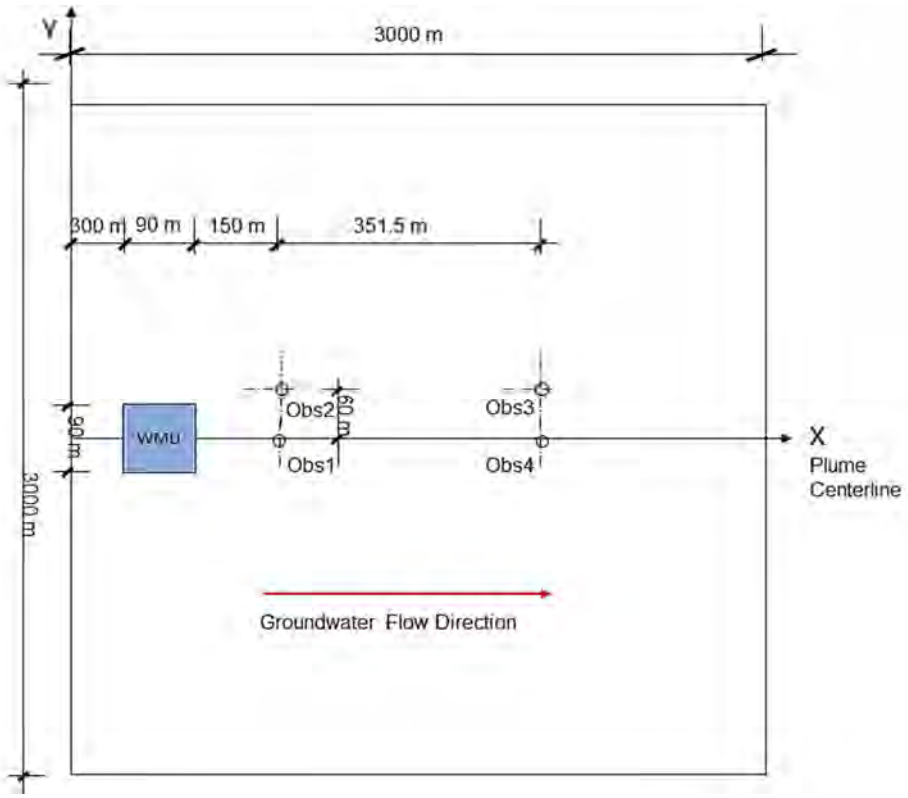

Figure K-1. Diagram of verification cases (not to scale).

The total size of the modeled domain is 3,000 m × 3,000 m. The depth from ground surface to water table is 6.1 m and the thickness of the saturated zone is a uniform 15.2 m. The domain is discretized into uniform grid cells with the horizontal dimensions of 30 m × 30 m. A 90 m × 90 m square impoundment is located 300 m from the upstream boundary and 500 m from the upper

boundary. To allow comparison of receptor well concentrations at various locations in the flow path from the source, four receptor well cluster locations were chosen. A pair of well clusters is located at 150 m and another pair at 501.5 m downgradient from the impoundment. One well in each pair is located 0 m from the centerline of the plume and the other is offset by 60 m. Each well is screened at depths of 1.1 m, 5.4 m, and 9.8 m below the water table.

The vadose zone is discretized into six equally spaced layers, while the saturated zone is discretized into seven equally spaced layers. The model domain is homogeneous with a hydraulic conductivity of 21,800 m/year for the saturated layers and a saturated hydraulic conductivity of 78.7 m/year for the unsaturated layers with an effective porosity of 0.45. A hydraulic gradient of 0.004 is assigned across the model domain. The regional recharge rate is 0.0912 m/year and an infiltration rate of 3.547 m/year is imposed at the source. The longitudinal, transverse and vertical dispersivities are set at 10 m, 1 m and 0.1 m, respectively. The leachate concentration during operational life is 0.05212 mg/L. The postclosure leachate concentration is held at the same value.

MODHMS Results

As shown in **Figure K-2**, the arsenic concentrations at even the closest sample location quickly fell far below the peak levels following both complete and partial closure. This indicates that the contribution from postclosure impoundment releases to peak risks is minimal. These additional MODHMS model runs are consistent with and provide a high degree of confidence in the EPACMTP results discussed earlier. Based on these results, EPA elected to not include postclosure releases in the full-scale modeling. This decision is based on consideration of the time and resources saved by avoiding additional analyses that would have no appreciable effect on the full-scale characterization of peak risks.

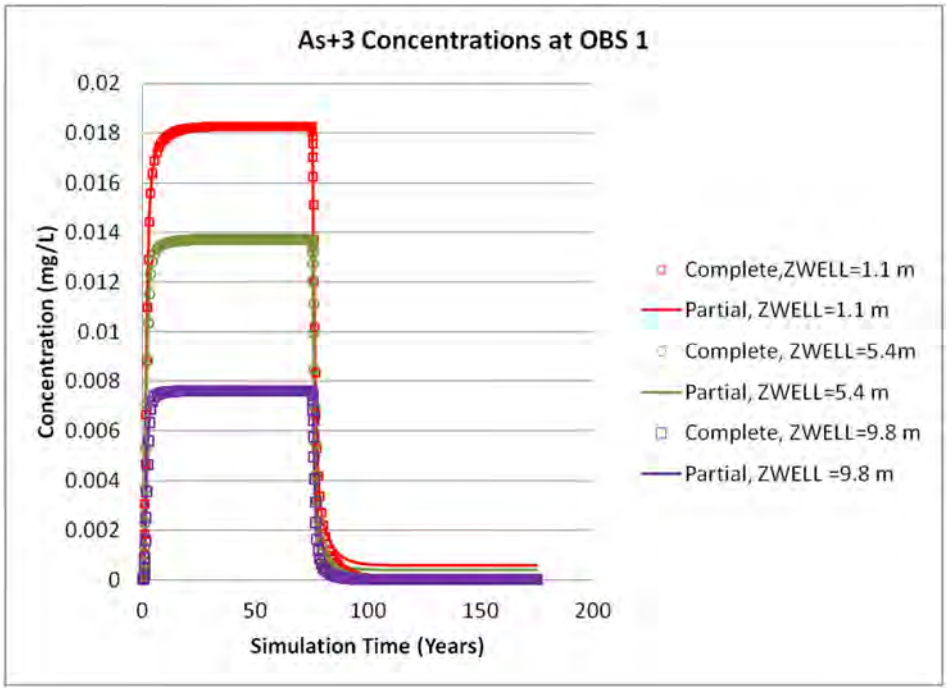

Figure K-2. Breakthrough curves with complete clean closure and partial clean closure at Observation Well 1 (OBS 1).

K.3 Evaluating Two-Pulse Source Term Modeling for Constituents in the Washout Phase

This section presents the approach used to evaluate uncertainties associated with the modeling of washout-controlled constituents in EPACMTP. EPA used the results of this analysis to draw conclusions, summarized in **Section 5**, about the potential for this uncertainty to affect the risk results of the probabilistic analysis.

K.3.1 Technical Approach

The empirical relationship between leachate concentration and cumulative liquid-to-solid (L/S) ratio for washout-controlled constituents is discussed in **Appendix I**. Due to the constraints of EPACMTP, EPA simplified this relationship into a single, constant concentration pulse for the probabilistic analysis. To understand the uncertainty introduced through this simplification, EPA considered the effects of modeling a two-step function. The original exponential liquid-solid partitioning curve (hatched) and the simplified two-step liquid-solid partitioning curve (red) are shown in **Figure K-3**.

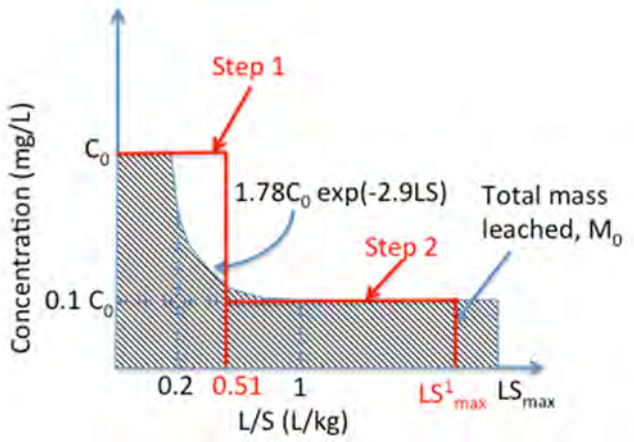

Figure K-3. Two-step idealization of L/S partitioning curve for washout-controlled species at simulation pH.

The first step is represented by a leachate concentration of C_0 that continues until a cumulative L/S ratio of 0.51 L/kg. The profile then immediately decreases to a second step represented by a leachate concentration of $0.1C_0$. Leaching continues at this level until the remaining leachable mass is depleted. **Equations K-1** and **K-2** provide the resulting, two-step equation for total mass and the adjusted L/S ratio where all available mass is leached, respectively.

(K-1) $$M_0 = C_0 \cdot LS_{0.51} + 0.1C_0(LS_{max} - LS_1)$$

(K-2) $$LS^1_{max} = LS_{max} - LS_{0.49}$$

Where:

M_0 = Total available mass (mg/kg);
C_0 = Initial leaching concentration (mg/L);
LS_X = Liquid-to-solid ratio of X (L/kg);
LS_{max} = Liquid-to-solid ratio at which total available mass is depleted (L/kg); and
LS^1_{max} = Adjusted liquid to solid ratio at which total available mass is depleted (L/kg).

To determine whether modeling only the first step of washout-controlled leaching sufficiently captures peak ground water concentrations, an uncertainty analysis was conducted. This analysis used boron and vanadium leachate data from fly ash sample AaFA. These two constituents provide a good bounding on potential washout-controlled leaching behavior. Vanadium is strongly sorbing, with concentrations that sometimes fall in the nonlinear range of the sorption isotherms. By contrast, boron is weakly sorbing, with concentrations that often fall in the linear range of the sorption isotherms.

A CCR landfill was selected from the New Johnsonville power plant in Tennessee to represent a landfill in the eastern half of the United States with fairly consistent monthly precipitation rates. All available and applicable site-specific data were used for the sensitivity simulations, supplemented by median default values for other required EPACMTP input parameters (e.g., depth to water table, soil material properties). To allow comparison of receptor well concentrations at various locations downgradient from the landfill, the three discrete receptor well locations presented below in **Figure K-4** were chosen with the following coordinates:

- **X-Distance:** 150 m from the landfill boundary. This was selected to represent the closest quartile of distances in the probabilistic assessment where risks are likely highest.
- **Y-Distance:** 0 m, 143 m, and 286 m from the centerline of the plume. The 0 m distance was selected to represent the centerline where dilution is minimized. The two non-zero distances correspond to locations that line up with the edge of the landfill (143 m) and the same distance beyond the edge of the landfill (286 m).
- **Z-Distance:** 5.2 m below the water table. The 5.2 m depth below the water table was selected to represent a central tendency depth.

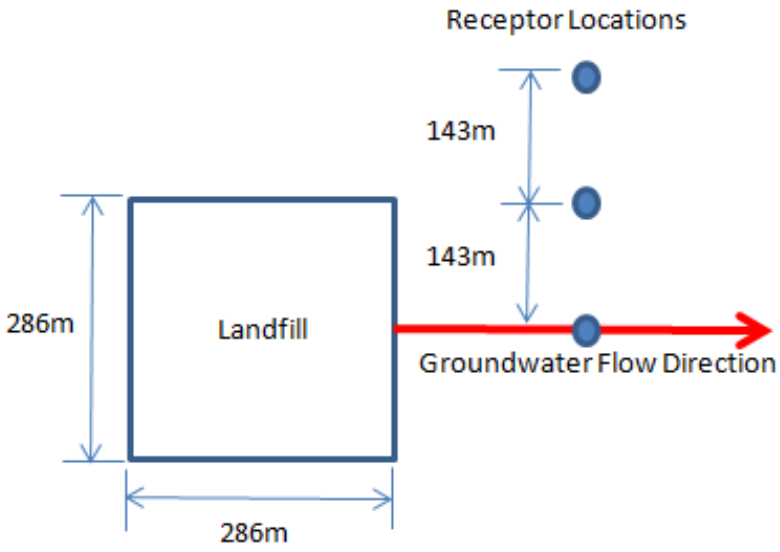

Figure K-4. Landfill and receptor locations for sensitivity analyses for washout-controlled leaching analyses.

The sensitivity analysis was conducted for each pH-specific, washout-controlled leachate concentration identified from available Method 1313 data. Vanadium in AaFA is washout-controlled over a pH range of 11.2 to 13 and represented by 10 leachate concentrations. Boron in

AaFA is washout-controlled over the entire pH range of 2.8 to 13 and is represented by 52 leachate concentrations. For each of the locations in **Figure K-4** and washout leachate concentrations the sensitivity analysis involved two separate simulations:

- **Square Pulse Simulation:** Model the leachate concentration as C_0 until all available mass was depleted. This is the same approach used in the probabilistic analysis of **Section 4**. Due to the use of the higher leachate concentration for the entire leaching duration, this alternative likely overestimates risks.
- **Two-Step Simulation**: Simulate the first leaching step at C_0 until reaching an L/S of 0.51 L/kg. Separately simulate the second leaching step at $0.1C_0$ until the remaining available mass is depleted. These two simulations were superposed with the year one of the second step lining up with the time equivalent of an L/S of 0.51 L/kg. Superposition is an accurate assumption where a constituent concentration falls in the linear portion of the nonlinear isotherms. However, where a concentration falls in the nonlinear portion, superposition may underestimate the effect that the second pulse has on risk.

K. 3.2 Results of Two-Pulse Modeling

The results of the sensitivity analyses were compared by examining the difference in peak concentration at the three receptor wells between the square pulse simulation and the two-step simulation. As explained above, the time series of simulated ground water concentrations resulting from the combined steps more accurately approximates the ground water concentrations of the true release profile in the linear range of the isotherms, but it may underestimate true concentrations to some degree in the nonlinear range. Maximum average concentrations were calculated for a series of increasing exposure durations, in increments of 5 years, over the interval of 5 to 45 years. These averaging periods were chosen to cover the majority of averaging times considered in the probabilistic analysis. Plotting the change in average well concentration ($\Delta_{\mathrm{AveConc}}$) as a function of averaging period is defined by:

(K-3) $$\Delta_{\mathrm{AveConc}} = \frac{\left|\mathrm{Max}\left(\mathrm{C}_{\mathrm{Composite}}\right) - \mathrm{Max}\left(\mathrm{C}_{\mathrm{Single}}\right)\right|}{\mathrm{Max}\left(\mathrm{C}_{\mathrm{Composite}}\right)}$$

Where:

$\Delta_{\mathrm{AveConc}}$ = Change in average well concentration (%);
$C_{composite}$ = Average concentration for two-step results over an averaging period (mg/L);
C_{single} = Average concentration for single-step results over an averaging period (mg/L).

The peak concentration associated with the initial pulse is always an order of magnitude higher than the secondary pulse, which is proportional to the ratio of the leaching concentrations for the two pulses. **Figures K-5** and **K-6** compare the difference in maximum average concentrations of vanadium and boron, respectively, between the two simulations. Separate graphs are presented for each of the three well locations identified in Figure K-4.

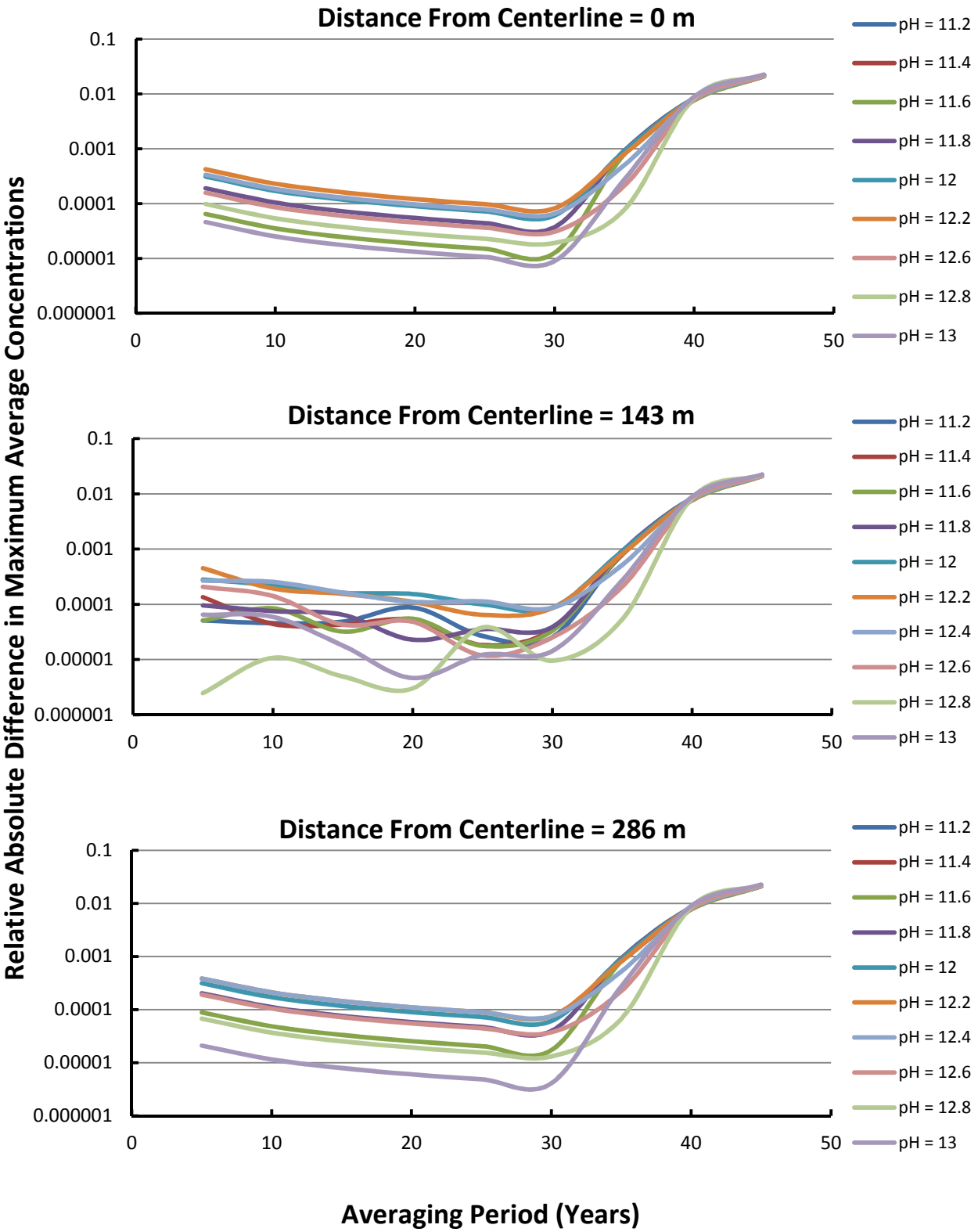

Figure K-5. Relative difference in average concentrations of vanadium based on composite releases and initial releases from the plume centerline.

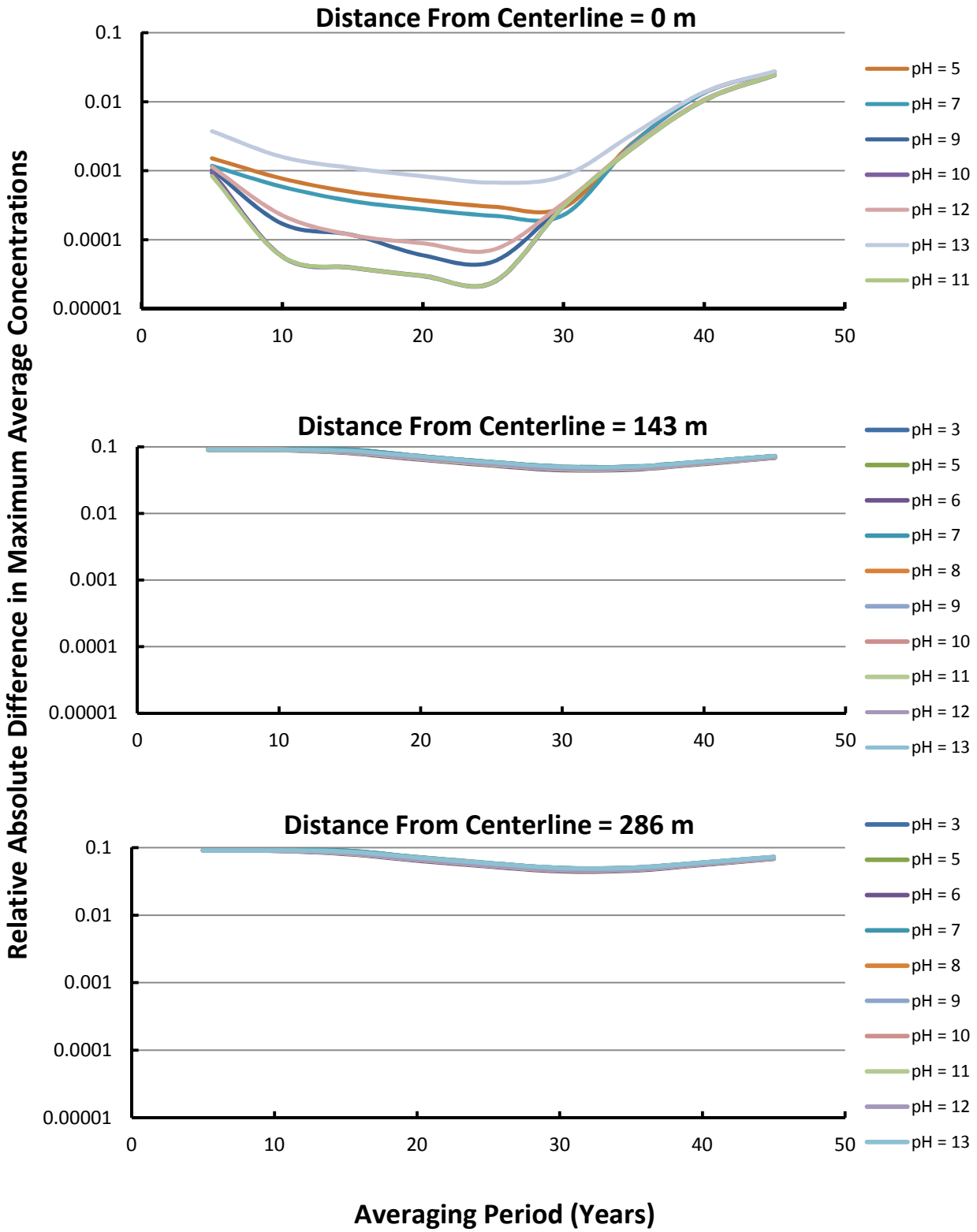

Figure K-6. Relative difference in average concentrations of boron based on composite releases and initial releases from the plume centerline.

These figures show that average vanadium concentrations in the two simulations differ by less than 0.01 (1 percent) for all pH values at all but the longest averaging times. Boron behaves similar to vanadium along the centerline of the plume. However, as the distance from the centerline of the plume increases, the concentrations from the two simulations differ between 0.04 and 0.09 (4 and 9 percent, respectively) for the modeled range of pH values and averaging times. Thus, EPA concludes that the modeling of constituents in the washout-controlled phase by a single pulse is unlikely to have a significant effect on the results.

K.4 Time to Peak Concentration at Receptor Well for Selected CCR Constituents

This section presents the approach used to evaluate uncertainties associated with the timeframe over which fate and transport was modeled. EPA used the results of this analysis to draw conclusions, summarized in **Section 5**, about the potential for this uncertainty to affect the risk results of the probabilistic analysis.

To better understand the time frames over which risks associated with exposures to contaminated ground water may occur, the EPA performed an analysis to graphically represent distributions of arrival time of the peak ground water concentrations at the nearby drinking water well. The analysis was performed by WMU type and liner, across all waste types. A description is provided below of how the peak concentrations and their arrival times were treated to create the plots presented in this appendix, including the treatment of zero-value observations. These plots reflect the time to peak concentration used to calculate risks for the ground water to drinking water [Ground Water (GW)→Drinking Water (DW)] exposure pathway. Plots are presented for the following selected constituents from the 2010 risk assessment: arsenic III and V, boron, cobalt, selenium IV and VI, and thallium. While only the 2010 arrival times were presented in the document for comparison, the 2014 data were used here to confirm the continued appropriateness of relying on these 2010 data. From the revised risk assessment, the following constituents were selected: arsenic III, boron, and vanadium. These select constituents represent those with the highest modeled risks and span the range of mobility in the subsurface.

The outputs generated by the GW→DW pathway include the peak concentration observed at a receptor well and the number of years required to reach that concentration. For each scenario modeled (i.e., combination of waste management unit type and liner type), approximately 10,000 sets of inputs were probabilistically selected and modeled, resulting in the same number of well concentrations. For this analysis, the model results were segregated based on the different constituents of potential concern (COPCs) and WMU type. Some of the modeled well concentrations are zero because of negligible infiltration rates (which occur only for WMUs with composite liners) or subsurface conditions that inhibit the movement of a constituent to such an extent that it cannot reach the receptor well within the 10,000 year modeled time frame. Model runs that resulted in zero-value concentrations were treated in the following manner:

- Zero-value concentrations corresponding to negligible infiltration rates were assigned an arbitrary value of −1, effectively excluding those data from the graphs. Only composite liner scenarios produced zero-value infiltration rates.
- Zero-value concentrations corresponding to nonzero infiltration rates were assigned an arbitrarily high arrival time, greater than 10,000 years, the maximum simulation time frame (i.e., constituent did not reach the well during the simulation period).

Table K-2 shows the distribution of zero-value concentrations by WMU for all liners and for composite liners. The presented ranges for the zero well concentrations reflect the COPC-specific fate and transport variability. Note that for surface impoundments, there are fewer model runs (observations) for thallium because thallium data were not available for the ash and coal waste type due to limited data in the 2011 CCR constituent database. All of the percentage values are based on the total number of observations for each COPC.

Table K-2. Percentage of Zero Concentration Results by WMU Type

WMU Type	COPC	Number of Runs Per COPC	Range of Zero Observations (%)		
			Zero Well Concentration All Liners	Zero Well Concentration Composite Liners	Zero Infiltration All Liners
2010 Data					
Impoundments	As, B, Co, Se	19,825	3.1 – 8.8	2.9 – 6.5	2.5
	Tl	9,905	5.8	5.5	3.9
Landfills	As, B, Co, Se, Tl	29,717	28.6 – 46.3	15.3 – 16.1	11.9
2014 Data					
Impoundments	As, B, V	99,691	16.3 – 23.7	10.1 – 16.1	7.3
Landfills	As, B, V	45,699	56.3 – 63.5	25.6 – 27.2	20.4

After zero concentrations were addressed, the remaining time to peak concentrations were plotted as a series of cumulative distributions. These distributions are shown in **Attachments K-1** through **K-8**. Even with lined units, peak arrival times typically occur sooner for surface impoundments than landfills. This may be a result of the combination of the shorter, 75 year modeled operating life for surface impoundments. Landfills are modeled postclosure as a depleting source, requiring hundreds to tens of thousands of years to cease leaching. Thus, ground water plumes from landfills will take longer to plateau at a peak value, compared to surface impoundments. To provide a better resolution for this data, some surface impoundment plots are provided both the full 10,000 years and a second 1,000 year time frame to highlight the rapid changes that occur in the first several hundred years.

Differences between liner types for different WMU types and constituents reflect the degree to which infiltration rates impact regional ground water flow. High infiltration rates associated with unlined units are more likely to increase local ground water flow velocities and reduce travel times to receptors. Low infiltration rates associated with lined units are less likely to change regional flow fields and ambient flow velocities. The shorter arrival times shown for some constituents for clay-lined landfills compared with unlined landfills are a result of the relatively small number of units modeled in 2010 and the site-based subsurface geology assigned to these units. The shorter arrival times mainly reflect more transmissive soils and aquifer materials at the clay-lined facility locations.

In general, differences in times to peak between the 2010 and 2014 results can be attributed to interception by surface water bodies. The 2010 Risk Assessment did not account for interception, resulting in an overestimation of ground water transport. The updated methodology used in the revised risk assessment requires that downstream receptor wells be moved farther downgradient by a distance that makes the travel time between the intercepting stream and the original receptor location (based on the reduced ground water velocity after baseflow removal) the same as the travel time between the stream and the relocated receptor well (based on the original ground water velocity before baseflow removal). Applying this requirement, the relocated receptor well is farther from the associated waste management unit than the original location. As a consequence, greater travel distances artificially increase the time for peak concentrations to arrive at downstream receptor locations.

K.5 References

HydroGeoLogic, Inc. 2011. MODHMS, A Comprehensive MODFLOW-Based Hydrologic Modeling System. HydroGeoLogic, Inc., Reston, VA.

McDonald, M.G., and A.W. Harbaugh. 1988. A modular three-dimensional finite-difference ground-water flow model. *Techniques of Water-Resources Investigations of the United States Geological Survey, Book 6*. U.S. Geological Survey. Available online at: pubs.usgs.gov/twri/twri6a1/pdf/TWRI_6-A1.pdf.

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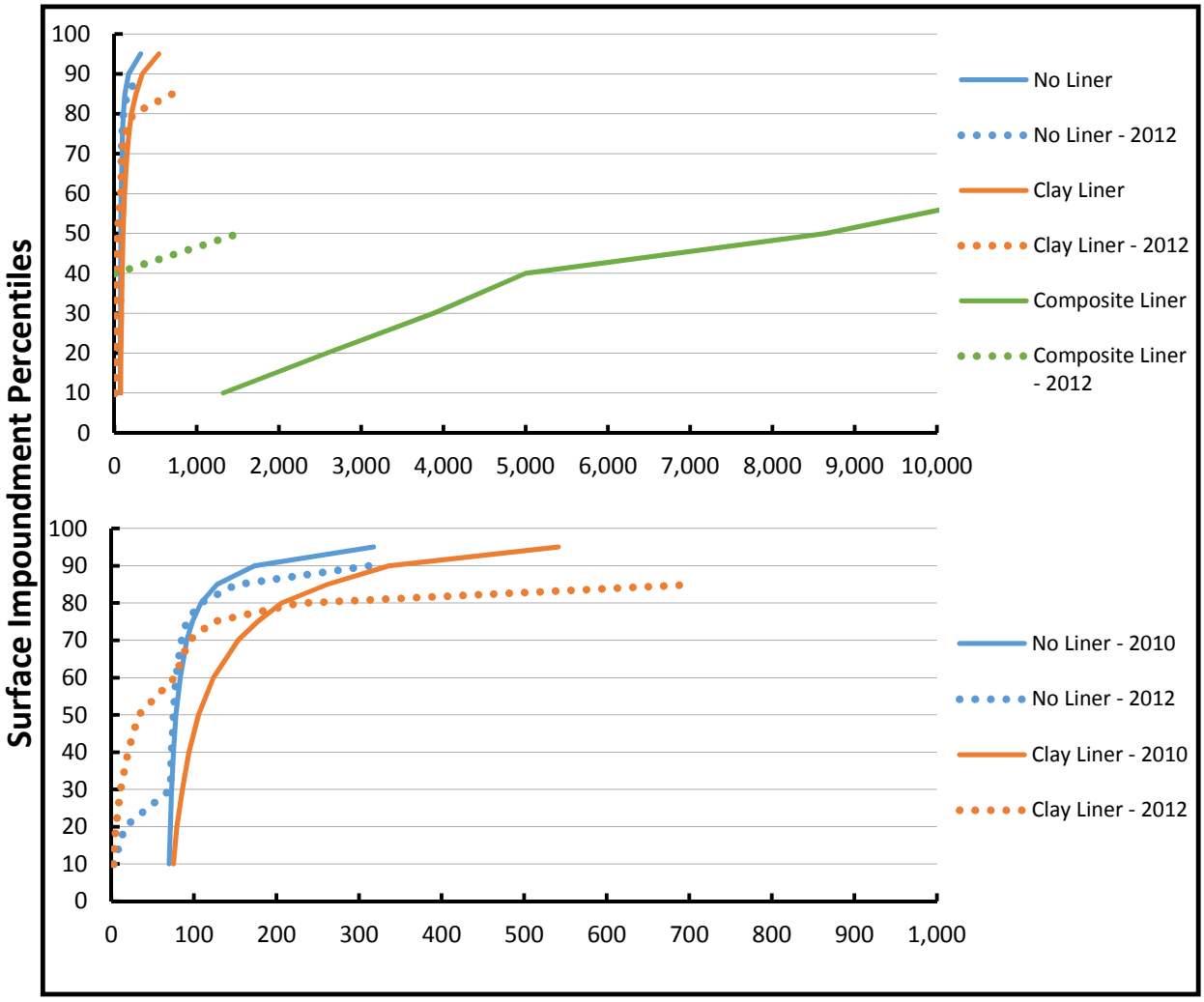
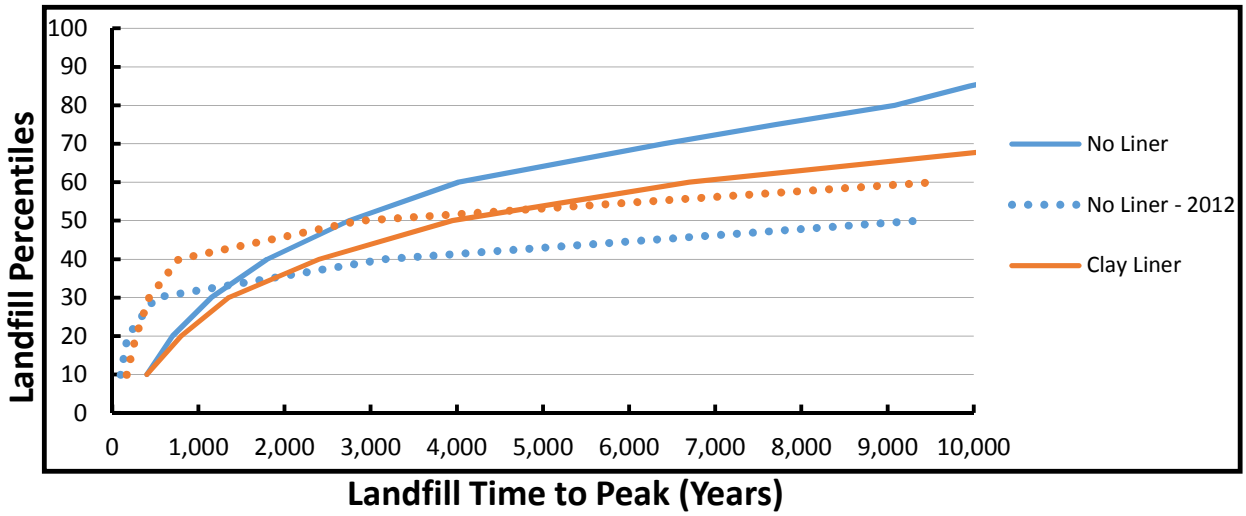
Attachment K-1.

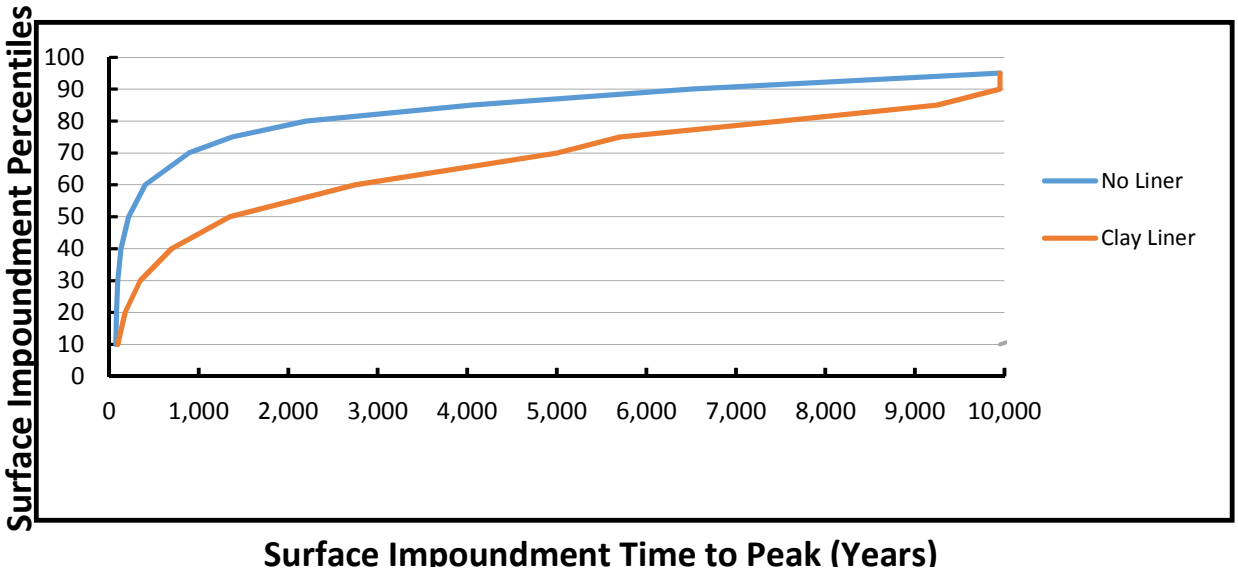
Surface Impoundment and Landfill Time to Peak Charts for Selected Constituents

2010/2014 Arsenic III Times to Peak for All Waste

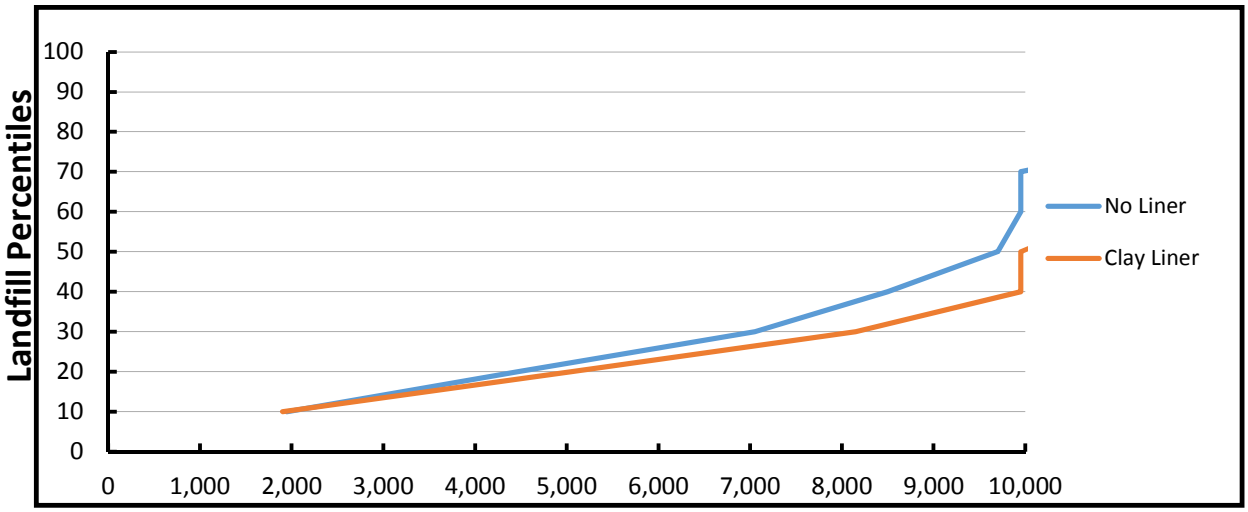




2010 Arsenic V Times to Peak for All Waste

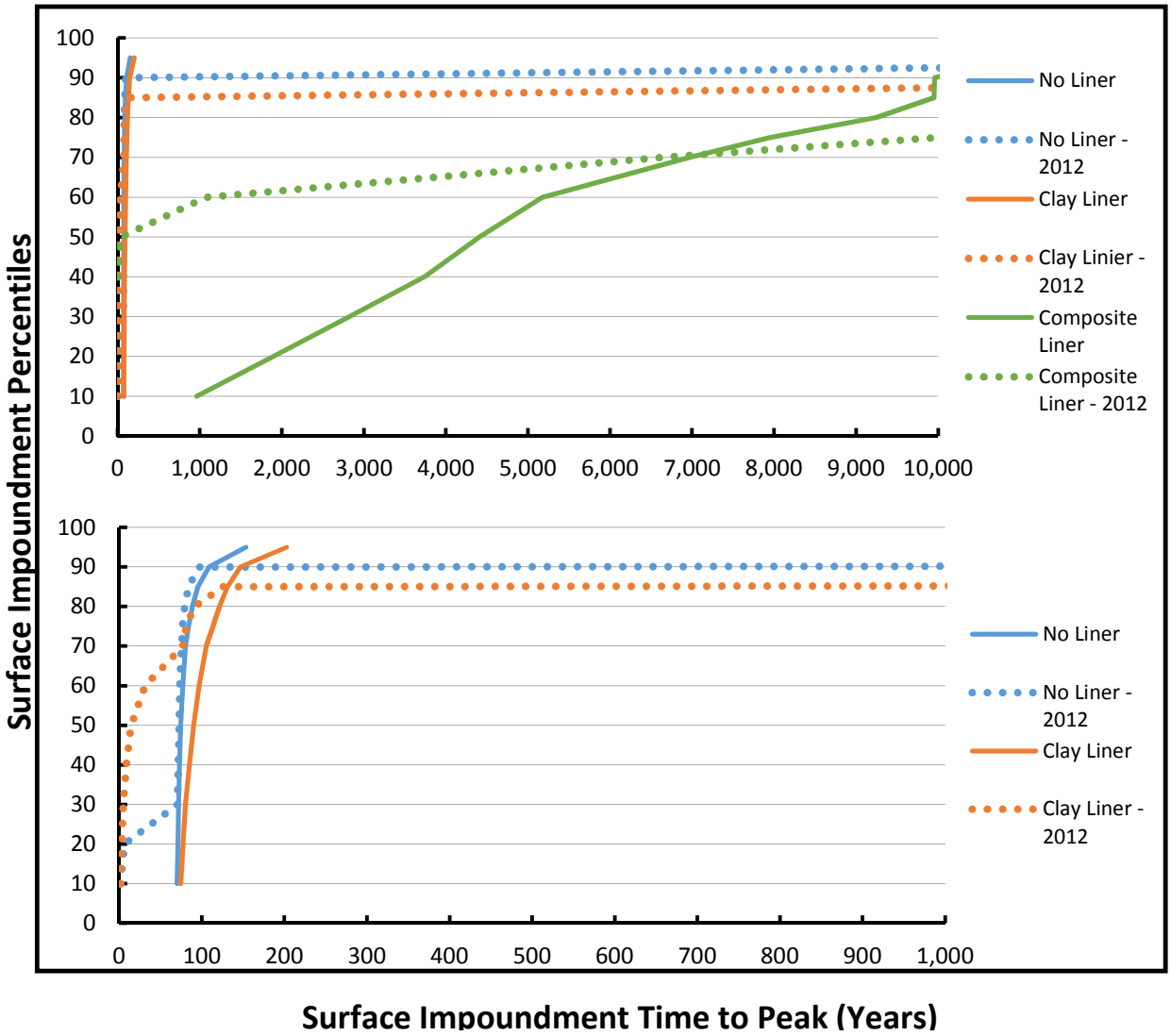


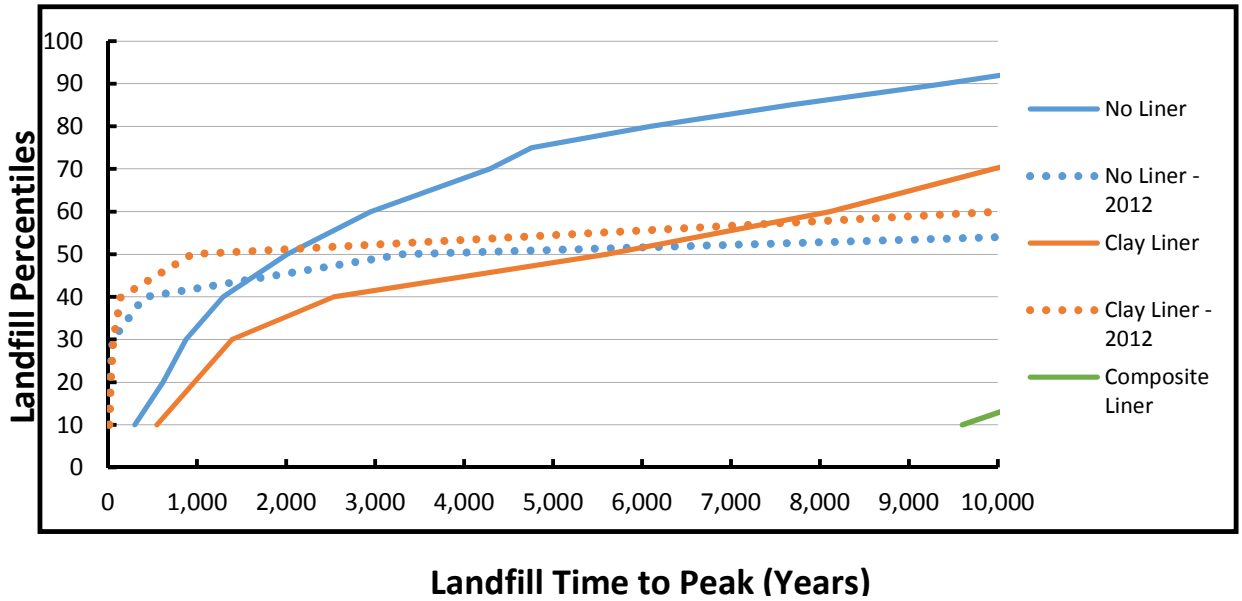
Surface Impoundment Time to Peak (Years)

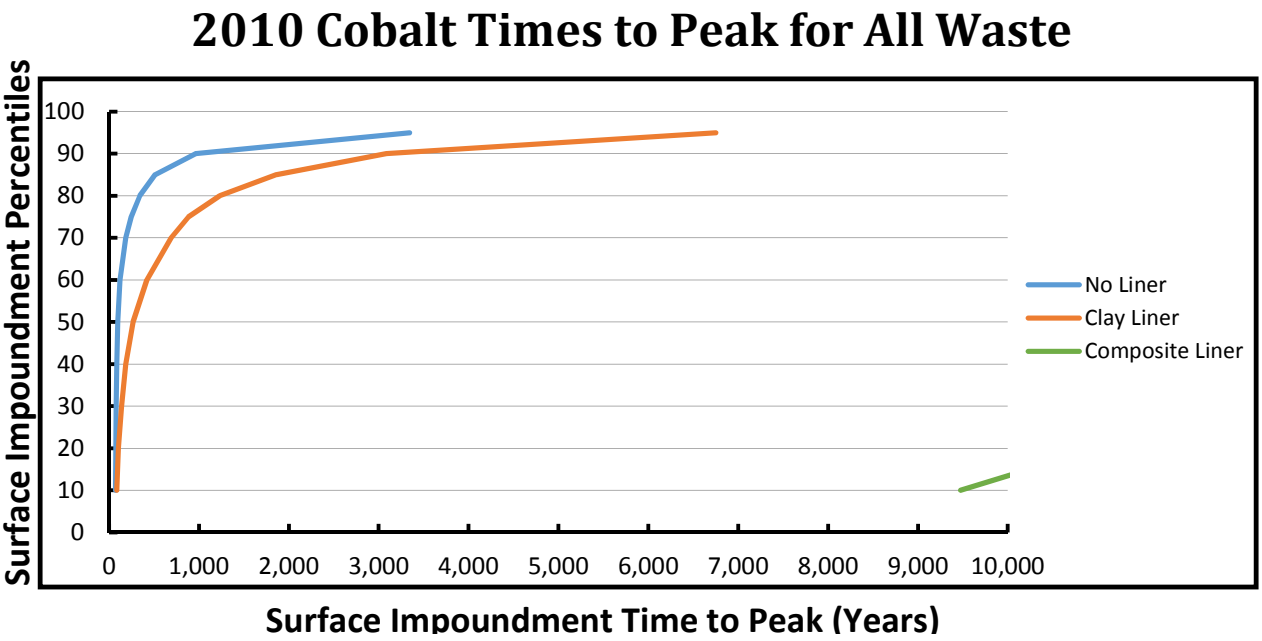


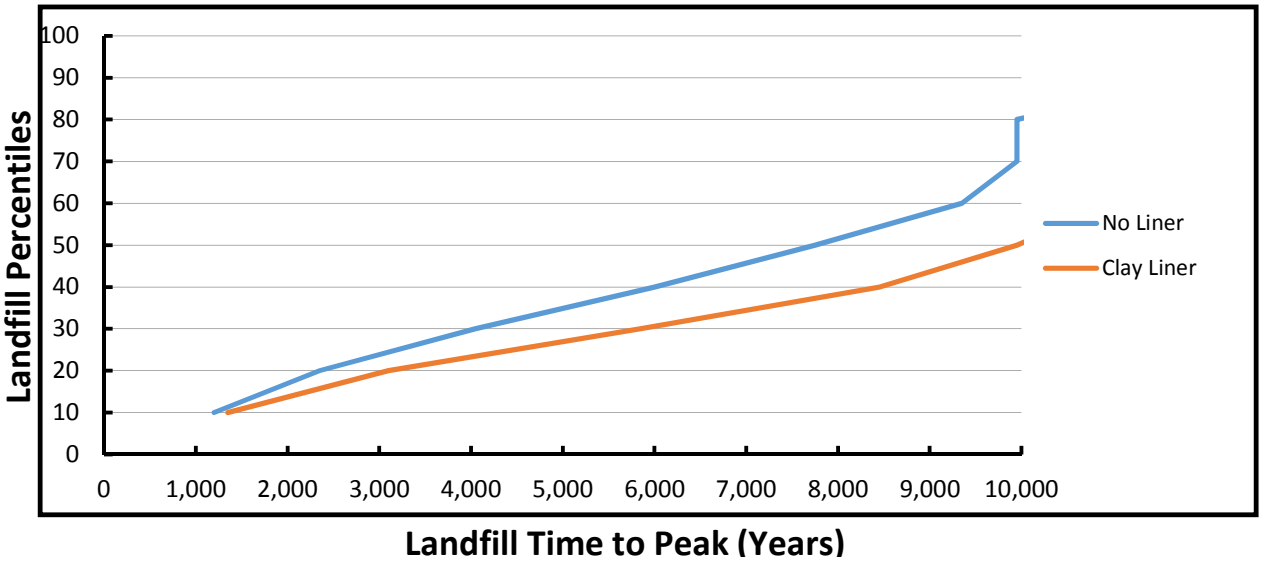
Landfill Time to Peak (Years)

2010/2014 Boron Times to Peak for All Waste

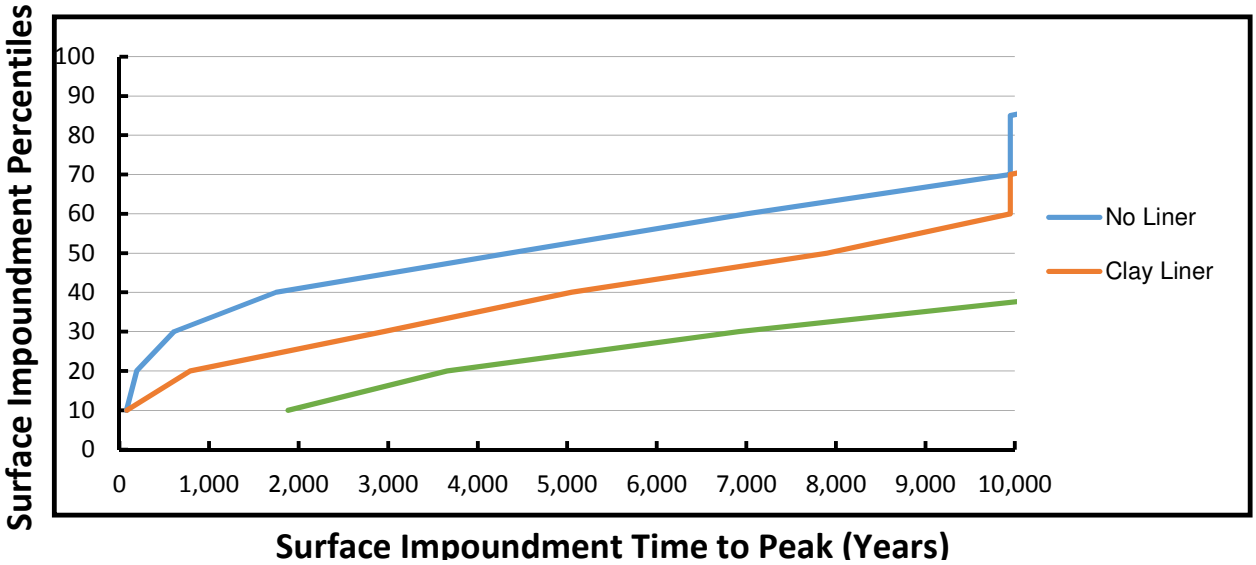


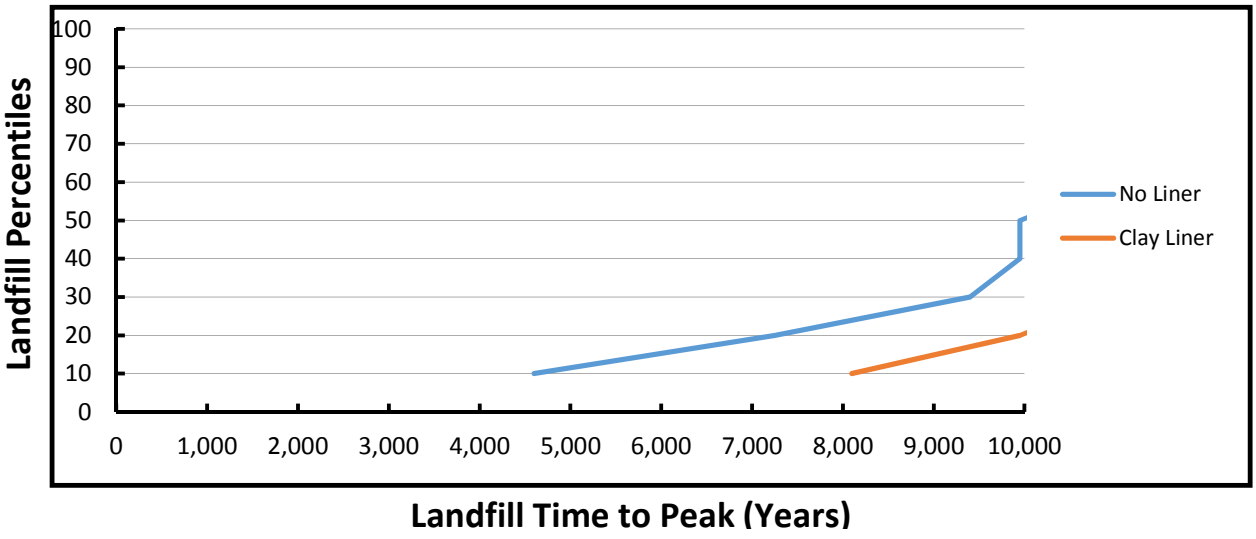



2010 Cobalt Times to Peak for All Waste
Surface Impoundment Percentiles
100
90
80
70
60
50
40
30
20
10
0
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
No Liner
Clay Liner
Composite Liner
Surface Impoundment Time to Peak (Years)

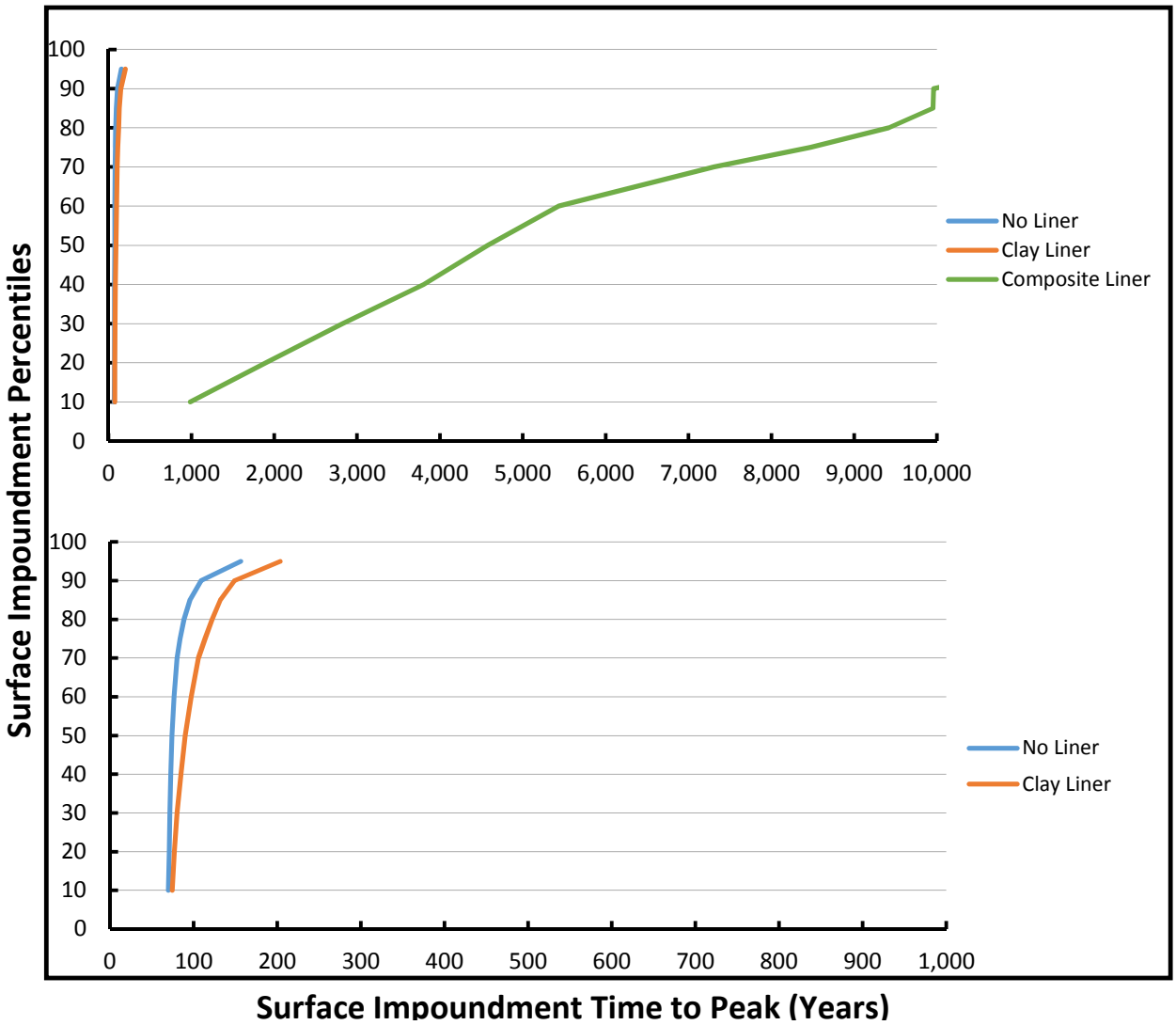

Landfill Percentiles
100
90
80
70
60
50
40
30
20
10
0
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
No Liner
Clay Liner
Landfill Time to Peak (Years)

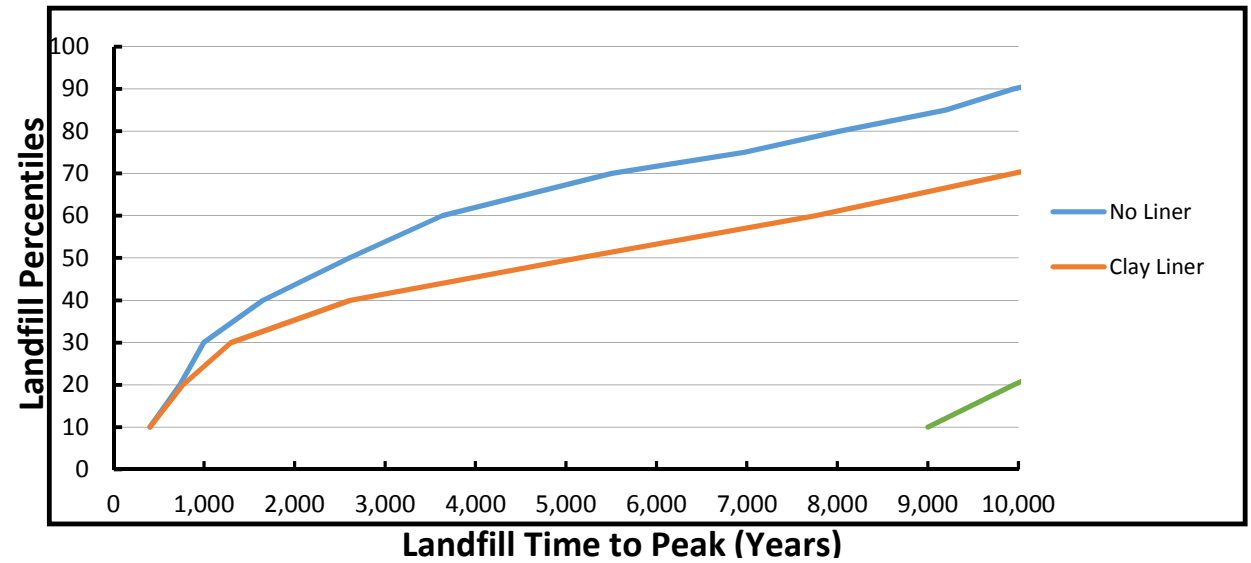
2010 Selenium IV Times to Peak for All Waste



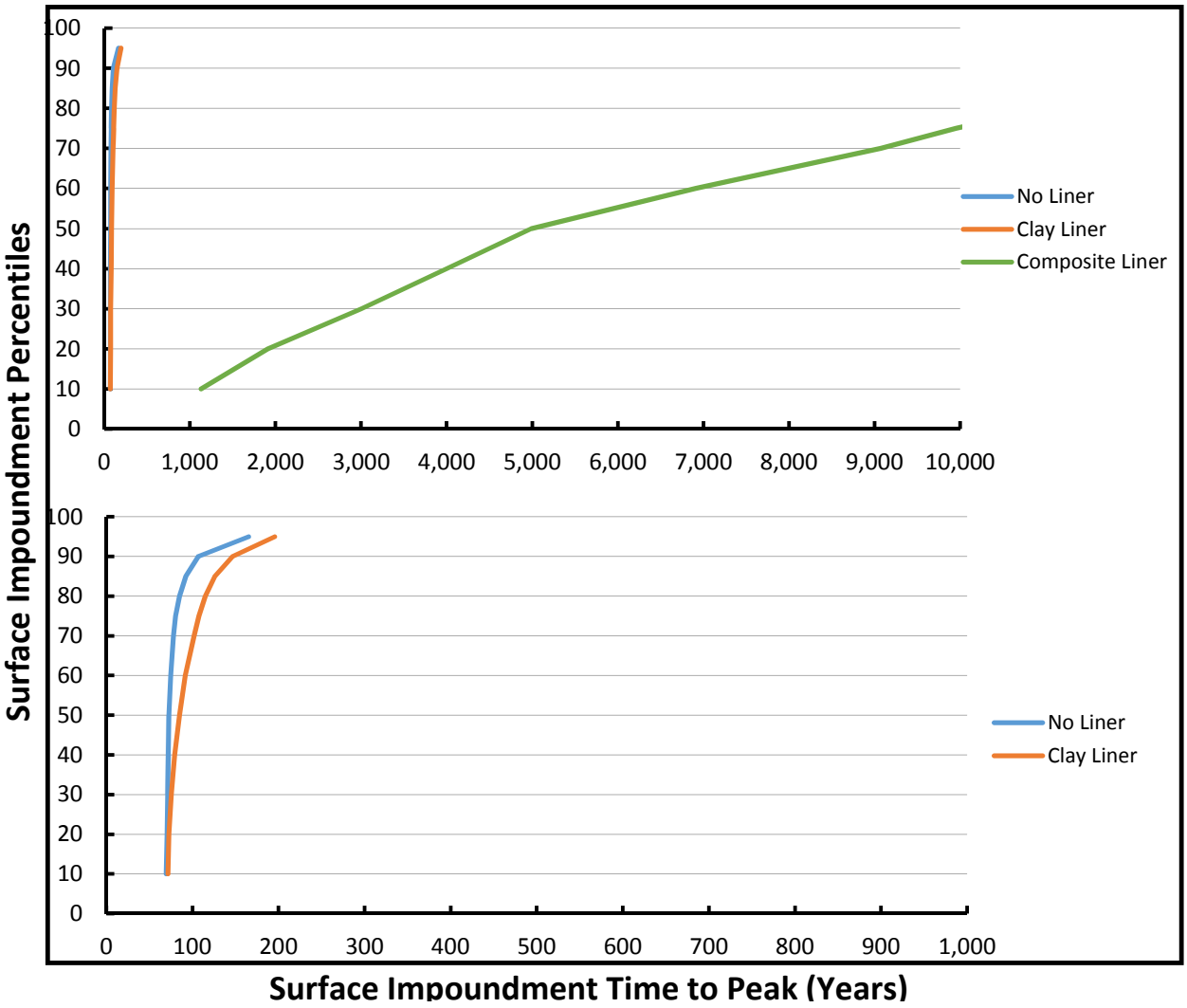


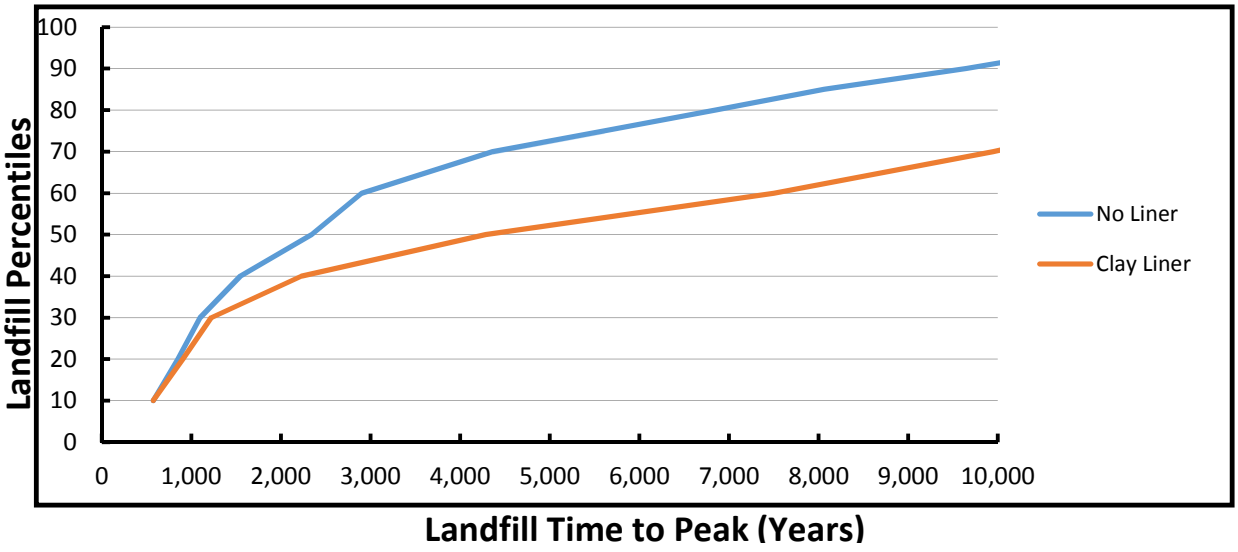
2010 Selenium VI Times to Peak for All Waste



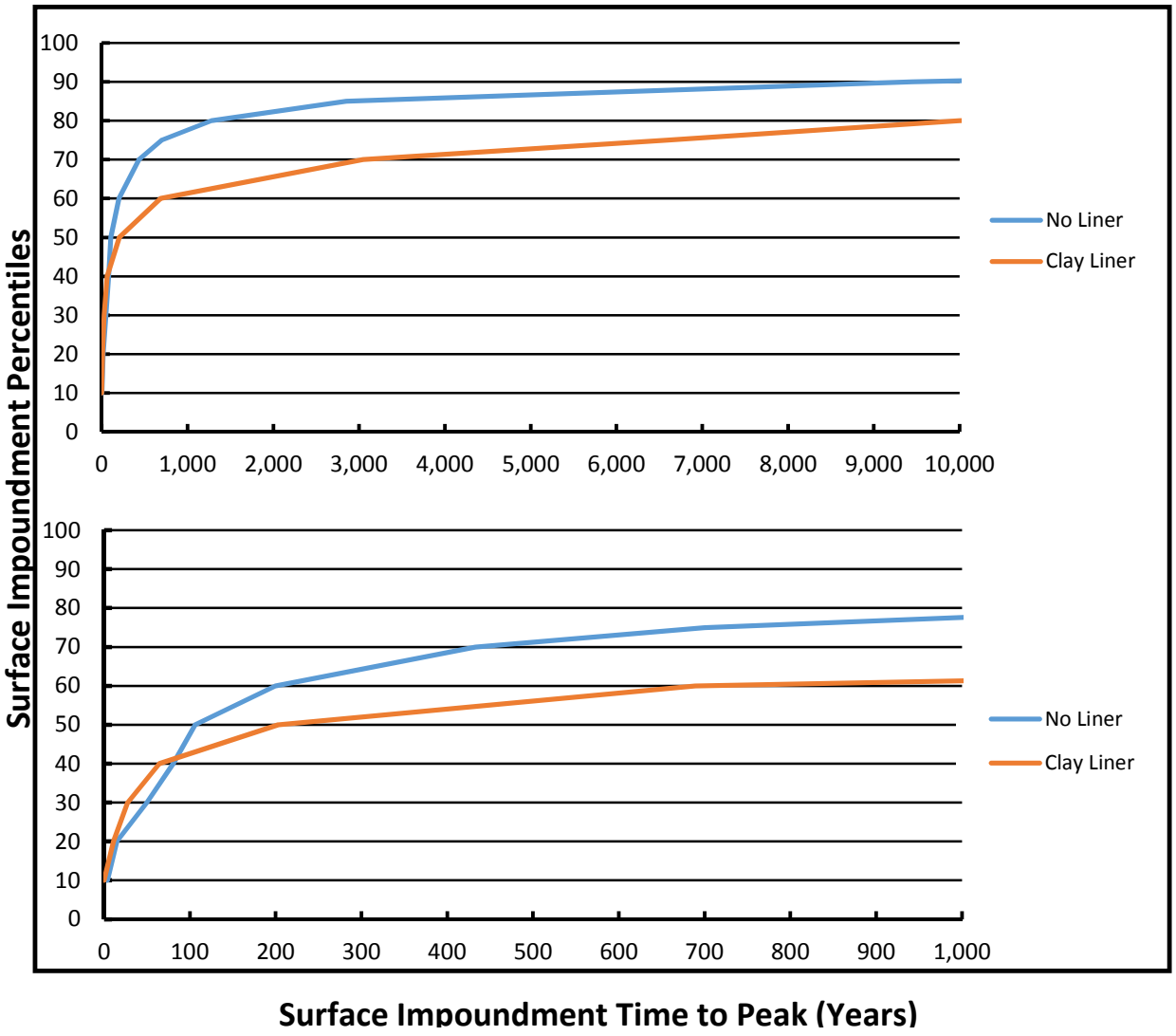


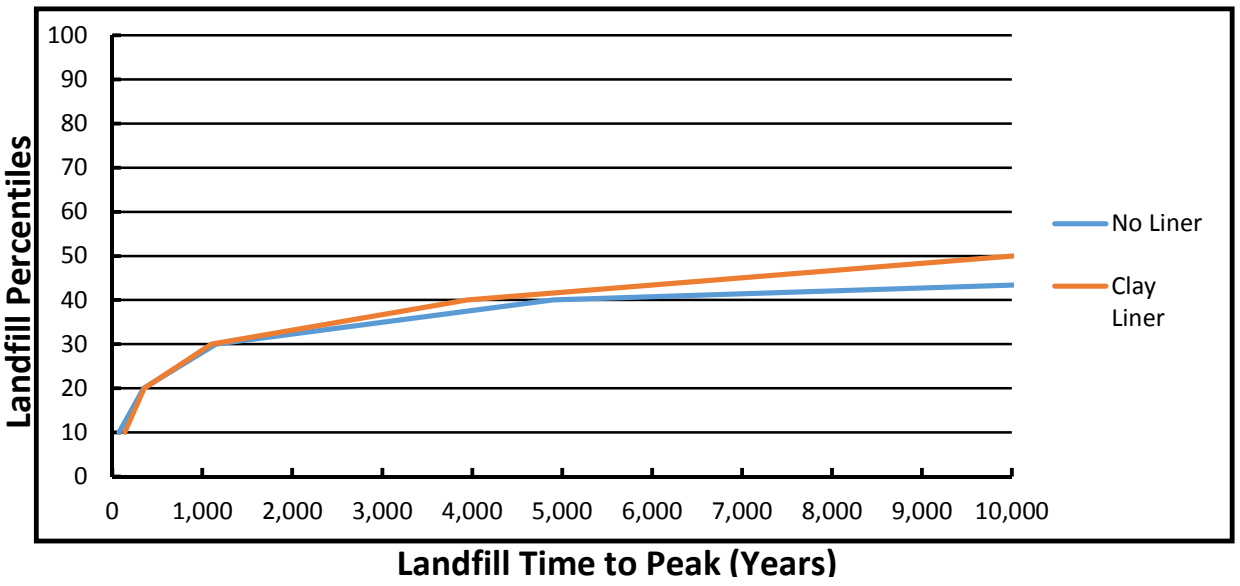
2010 Thallium Times to Peak for Combined Ash





2012 Vanadium Times to Peak for All Waste





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Document 24

U.S. EPA, 80 FR 21302 40 CFR Parts 257 and 261 Hazardous and Solid Waste Management System: Disposal of Coal Combustion Residuals from Electric Utilities, Final Rule April 17, 2015.

ENVIRONMENTAL PROTECTION AGENCY

40 CFR Parts 257 and 261

[EPA–HQ–RCRA–2009–0640; FRL–9919–44–OSWER]

RIN–2050–AE81

Hazardous and Solid Waste Management System; Disposal of Coal Combustion Residuals From Electric Utilities

AGENCY: Environmental Protection Agency (EPA).

ACTION: Final rule.

SUMMARY: The Environmental Protection Agency (EPA or the Agency) is publishing a final rule to regulate the disposal of coal combustion residuals (CCR) as solid waste under subtitle D of the Resource Conservation and Recovery Act (RCRA). The available information demonstrates that the risks posed to human health and the environment by certain CCR management units warrant regulatory controls. EPA is finalizing national minimum criteria for existing and new CCR landfills and existing and new CCR surface impoundments and all lateral expansions consisting of location restrictions, design and operating criteria, groundwater monitoring and corrective action, closure requirements and post closure care, and recordkeeping, notification, and internet posting requirements. The rule requires any existing unlined CCR surface impoundment that is contaminating groundwater above a regulated constituent's groundwater protection standard to stop receiving CCR and either retrofit or close, except in limited circumstances. It also requires the closure of any CCR landfill or CCR surface impoundment that cannot meet the applicable performance criteria for location restrictions or structural integrity. Finally, those CCR surface impoundments that do not receive CCR after the effective date of the rule, but still contain water and CCR will be subject to all applicable regulatory requirements, unless the owner or operator of the facility dewaters and installs a final cover system on these inactive units no later than three years from publication of the rule. EPA is deferring its final decision on the Bevill Regulatory Determination because of regulatory and technical uncertainties that cannot be resolved at this time.

DATES: This final rule is effective on October 14, 2015.

ADDRESSES: EPA has established three dockets for this regulatory action under Docket ID No. EPA–HQ–RCRA–2009–0640, Docket ID No. EPA–HQ–RCRA–2011–0392, and Docket ID No. EPA–HQ–RCRA–2012–0028. All documents in these dockets are available at *http://www.regulations.gov*. Although listed in the index, some information is not publicly available, *e.g.*, Confidential Business Information (CBI) or other information whose disclosure is restricted by statute. Certain other material, such as copyrighted material, is not placed on the Internet and will be publicly available only in hard copy form. Publicly available docket materials are available either electronically in *http://www.regulations.gov* or in hard copy at the OSWER Docket, EPA/DC, WJC West Building, Room 3334, 1301 Constitution Ave. NW., Washington, DC 20460. The Public Reading Room is open from 8:30 a.m. to 4:30 p.m., Monday through Friday, excluding legal holidays. The telephone number for the Public Reading Room is (202) 566–1744, and the telephone number for the OSWER Docket is 202–566–0276.

FOR FURTHER INFORMATION CONTACT: For questions on technical issues: Alexander Livnat, Office of Resource Conservation and Recovery, Environmental Protection Agency, 5304P; telephone number: (703) 308–7251; fax number: (703) 605–0595; email address: *livnat.alexander@epa.gov*, or Steve Souders, Office of Resource Conservation and Recovery, Environmental Protection Agency, 5304P; telephone number: (703) 308–8431; fax number: (703) 605–0595; email address: *souders.steve@epa.gov*. For questions on the regulatory impact analysis: Richard Benware, Office of Resource Conservation and Recovery, Environmental Protection Agency, 5305P; telephone number: (703) 308–0436; fax number: (703) 308–7904; email address: *benware.richard@epa.gov*. For questions on the risk assessment: Jason Mills, Office of Resource Conservation and Recovery, Environmental Protection Agency, 5305P; telephone number: (703) 305–9091; fax number: (703) 308–7904; email address: *mills.jason@epa.gov*.

For more information on this rulemaking please visit *http://www.epa.gov/epawaste/nonhaz/industrial/special/fossil/index.htm*.

SUPPLEMENTARY INFORMATION:

A. Does this action apply to me?

This rule applies to all coal combustion residuals (CCR) generated by electric utilities and independent power producers that fall within the North American Industry Classification System (NAICS) code 221112 and may affect the following entities: Electric utility facilities and independent power producers that fall under the NAICS code 221112. The industry sector(s) identified above may not be exhaustive; other types of entities not listed could also be affected. The Agency's aim is to provide a guide for readers regarding those entities that potentially could be affected by this action. To determine whether your facility, company, business, organization, etc., is affected by this action, you should refer to the applicability criteria discussed in Unit VI.A. of this document If you have any questions regarding the applicability of this action to a particular entity, consult the person listed in the preceding **FOR FURTHER INFORMATION CONTACT** section.

B. What actions are not addressed in this rule?

This rule does not address the placement of CCR in coal mines. The U.S. Department of Interior (DOI) and, as necessary, EPA will address the management of CCR in minefills in separate regulatory action(s), consistent with the approach recommended by the National Academy of Sciences, recognizing the expertise of DOI's Office of Surface Mining Reclamation and Enforcement in this area. See Unit VI of this document for further details. This rule does not regulate practices that meet the definition of a beneficial use of CCR. Beneficial uses that occur after the effective date of the rule need to determine if they comply with the criteria contained in the definition of ''beneficial use of CCRs.'' This rule does not affect past beneficial uses (*i.e.*, uses completed before the effective date of the rule.) See Unit VI of this document for further details on proposed clarifications of beneficial use. Furthermore, CCR from non-utility boilers burning coal are also not addressed in this final rule. EPA will decide on an appropriate action for these wastes through a separate rulemaking effort. See Unit IV of this document for further details. Finally, this rule does not apply to municipal solid waste landfills (MSWLFs) that receive CCR for disposal or use as daily cover.

C. The Contents of This Preamble Are Listed in the Following Outline

I. Executive Summary
II. Statutory Authority
III. Background
IV. Bevill Regulatory Determination Relating to CCR From Electric Utilities and Independent Power Producers
V. Development of the Final Rule—RCRA Subtitle D Regulatory Approach

VI. Development of the Final Rule—Technical Requirements
VII. Summary of Major Differences Between the Proposed and Final Rules
VIII. Implementation Timeframes for Minimum National Criteria and Coordination With Steam Electric ELG Rule
IX. Implementation of the Minimum Federal Criteria and State Solid Waste Management Plans
X. Risk Assessment
XI. Summary of Damage Cases
XII. Summary of Regulatory Impact Analysis
XIII. Uniquely Associated Wastes
XIV. Statutory and Executive Order Reviews

I. Executive Summary

This rule establishes nationally applicable minimum criteria for the safe disposal of coal combustion residuals in landfills and surface impoundments. This section summarizes these criteria. Detailed discussions of the criteria and the Agency's rationale for finalizing these requirements are provided in Unit VI of this document.

A. What are coal combustion residuals?

Coal combustion residuals (CCR) are generated from the combustion of coal, including solid fuels classified as anthracite, bituminous, subbituminous, and lignite, for the purpose of generating steam for the purpose of powering a generator to produce electricity or electricity and other thermal energy by electric utilities and independent power producers. CCR includes fly ash, bottom ash, boiler slag, and flue gas desulfurization materials. A description of the types of CCR can be found in the proposed rule (see 75 FR 35137).

CCR is one of the largest industrial waste streams generated in the U.S. In 2012, over 470 coal-fired electric utilities burned over 800 million tons of coal, generating approximately 110 million tons of CCR in 47 states and Puerto Rico. CCR may be generated wet or dry; however, this composition may change after generation. Some CCR is dewatered while other CCR is mixed with water to facilitate transport (*i.e.*, sluiced). CCR can be sent off-site for disposal or beneficial use or disposed in on-site landfills or surface impoundments. In 2012, approximately 40 percent of the CCR generated was beneficially used, with the remaining 60 percent disposed in surface impoundments and landfills. Of that 60 percent, approximately 80 percent was disposed in on-site disposal units. CCR disposal currently occurs at over 310 active on-site landfills, averaging over 120 acres in size with an average depth of over 40 feet, and at over 735 active on-site surface impoundments, averaging over 50 acres in size with an average depth of 20 feet.

B. Background

The Agency first solicited comments on the regulation of CCR in a proposed rule published in the **Federal Register** on June 21, 2010. This proposal, under the Resource Conservation and Recovery Act (RCRA), addressed the risks from disposal of CCR generated from the combustion of coal at electric utilities and from independent power producers. Two regulatory options were proposed. Under the first option, EPA proposed to list CCR as special waste subject to regulation under subtitle C of RCRA, when destined for disposal in landfills or surface impoundments. Under this option, CCR would require ''cradle-to-grave'' management and would be subject to requirements for, among other things, composite liners, groundwater monitoring, structural stability requirements, corrective action, closure/post closure care and financial assurance. States would be required to adopt the rule before it went into effect and a permitting program would be established with direct federal oversight. The subtitle C option, as proposed, would also effectively result in the closure of all CCR surface impoundments.

Under the second option, EPA proposed to regulate the disposal of CCR under subtitle D of RCRA by issuing minimum national criteria. Similar to the subtitle C option, this option would require composite liners, groundwater monitoring, structural stability requirements, corrective action, and closure/post closure care. However, consistent with the available statutory authority under subtitle D, EPA proposed this option to be a self-implementing rule with no direct federal oversight, with an effective date six months after publication in the **Federal Register**. This option required all unlined surface impoundments to either retrofit to a composite liner or close within five years.

After reviewing all the comments and additional data received, EPA is promulgating this final rule to regulate the disposal of CCR as solid waste under subtitle D of RCRA. This rule addresses the risks from structural failures of CCR surface impoundments, groundwater contamination from the improper management of CCR in landfills and surface impoundments and fugitive dust emissions. The rule has also been designed to provide electric utilities and independent power producers generating CCR with a practical approach for implementation of the requirements and has established implementation timelines that take into account, among other things, other upcoming regulatory actions affecting electric utilities and site specific practical realities. In order to ease implementation of the regulatory requirements for CCR units with state programs, EPA is also providing the opportunity for states to secure approval of its CCR program through the State Solid Waste Management Plan (''SWMP''). EPA strongly recommends that states take advantage of this process by revising their SWMPs to address the issuance of the revised federal requirements in this final rule, and to submit revisions of these plans to EPA for review. EPA would then review and approve the revised SWMPs provided they demonstrate that the minimum federal requirements in this final rule will be met. In this way, EPA's approval of a revised SWMP signals EPA's opinion that the state SWMP meets the minimum federal criteria.

C. What types of CCR units are covered by this rule?

The final rule applies to owners and operators of new and existing landfills and new and existing surface impoundments, including all lateral expansions of landfills and surface impoundments that dispose or otherwise engage in solid waste management of CCR generated from the combustion of coal at electric utilities and independent power producers. The requirements of the rule also apply to CCR units located off-site of the electric utilities' or independent power producers' facilities that receive CCR for disposal. In addition, the rule applies to certain inactive CCR surface impoundments (*i.e.*, units not receiving CCR after the effective date of the rule) at active electric utilities' or independent power producers' facilities, regardless of the fuel currently used at the facility to produce electricity (*e.g.* coal, natural gas, oil), if the CCR unit still contains CCR and liquids.

The requirements do not apply to: (1) CCR landfills that ceased receiving CCR prior to the effective date of the rule; (2) CCR units at facilities that have ceased producing electricity (or electricity and other thermal energy) prior to the effective date of the rule; (3) CCR generated at facilities that are not part of an electric utility or independent power producer, such as manufacturing facilities, universities, and hospitals; (4) fly ash, bottom ash, boiler slag, and flue gas desulfurization materials, generated primarily from the combustion of fuels (including other fossil fuels) other than coal, for the purpose of generating electricity unless the fuel burned

consists of more than fifty percent coal on a total heat input or mass input basis, whichever results in the greater mass feed rate of coal; (5) CCR that is beneficially used; (6) CCR placement at active or abandoned underground or surface coal mines; or (7) municipal solid waste landfills (MSWLF) that receive CCR.

D. What minimum national criteria are being established for CCR landfills and CCR surface impoundments?

This final rule establishes minimum national criteria for CCR landfills, CCR surface impoundments, and all lateral expansions of CCR units including location restrictions, liner design criteria, structural integrity requirements, operating criteria, groundwater monitoring and corrective action requirements, closure and post-closure care requirements, and recordkeeping, notification, and internet posting requirements.

1. Location Restrictions. To ensure there will be no reasonable probability of adverse effects on health or the environment from the disposal of CCR in CCR landfills, CCR surface impoundments, and all lateral expansions of CCR landfills and CCR surface impoundments (together ''CCR units''), this final rule establishes five location restrictions. The location criteria include restrictions relating to placement of CCR above the uppermost aquifer, in wetlands, within fault areas, in seismic impact zones, and in unstable areas. All of these location restrictions require the owner or operator of a CCR unit to demonstrate that they meet the specific criteria. As discussed elsewhere in this preamble, the five location restrictions apply to all new CCR landfills, all new and existing CCR surface impoundments, and all lateral expansions of CCR units; however, existing CCR landfills are only subject to the location restriction for unstable areas. Units that do not meet these restrictions can retrofit or make appropriate engineering demonstrations to meet this criteria. This final rule requires owner or operators of existing CCR units that cannot make the required demonstrations to close, while owners or operators of new CCR units and all lateral expansions who fail to make the required demonstrations are prohibited from placing CCR in the CCR unit.

2. Liner Design Criteria. The final rule also establishes liner design criteria to help prevent contaminants in CCR from leaching from the CCR unit and contaminating groundwater. All new CCR landfills, new CCR surface impoundments, and lateral expansions of CCR units must be lined with composite liner, which is a liner system consisting of two components—a geomembrane and a two-foot layer of compacted soil—installed in direct and uniform contact with one another. The final rule allows an owner or operator to construct a new CCR unit with an alternative composite liner, provided the alternative composite liner performs no less effectively than the composite liner. In addition, new landfills are required to operate with a leachate collection and removal system which is designed to remove excess leachate that may accumulate on top of the composite (or alternative composite) liner. Existing CCR landfills are not required to close or retrofit with a composite (or alternative composite) liner and a leachate collection and removal system. These existing CCR units can continue to receive CCR after this rule is in effect; however, the CCR units must meet all applicable groundwater monitoring and corrective action criteria to address any groundwater releases promptly. Existing CCR surface impoundments can also continue to operate as designed. However, if the existing CCR surface impoundment was not constructed with a composite (or alternative composite) liner or with at least two feet of compacted soil with a specified hydraulic conductivity, the rule would require the unit to retrofit or close if the CCR surface impoundment detects concentrations of one or more constituents listed in appendix IV at statistically significant levels above the groundwater protection standard established by the rule.

3. Structural Integrity Requirements. To help prevent the damages associated with structural failures of CCR surface impoundments, the final rule establishes structural integrity criteria for new and existing surface impoundments (and all lateral expansions) as part of the design criteria. While the applicability of the structural integrity requirements to individual CCR surface impoundments vary depending on factors such as dike heights and the potential for loss of life, environmental damage and economic loss if there is a dike failure, the final rule establishes requirements for owner or operators to conduct a number of structural integrity-related assessments regularly. These include: (1) Conducting periodic hazard potential classification assessments to assess the potential adverse incremental consequences that would occur if there was a failure of the CCR surface impoundment; (2) conducting periodic structural stability assessments by a qualified professional engineer to document whether the design, construction, operation and maintenance is consistent with recognized and generally accepted good engineering practices; and (3) conducting periodic safety factor assessments to document whether the CCR unit achieves minimum factors of safety for slope stability. If a CCR unit required to conduct a safety factor assessment fails to demonstrate that the unit achieves the specified factors of safety, the owner or operator must close the unit. In addition, certain CCR surface impoundments are required to develop an emergency action plan which defines the events and circumstances involving the CCR unit that represent an emergency and identifies the actions that will be taken in the event of a safety emergency.

4. Operating Criteria. The operating criteria include air criteria for all CCR units, run-on and run-off controls for CCR landfills, hydrologic and hydraulic capacity requirements for CCR surface impoundments, and periodic inspection requirements for all CCR units. These criteria address the day-to-day operations of CCR units and are established to prevent health and environmental impacts from CCR units. The air criteria address the pollution caused by windblown dust from CCR units, and require owners and operators to minimize CCR from becoming airborne at the facility. The run-on controls for CCR landfills minimize the amount of surface water entering the unit that will help prevent erosion, surface discharges of CCR in solution or suspension, and will mitigate the generation of landfill leachate, while run-off controls help prevent erosion, protect downstream surface water from releases from the unit, and minimize storm water run-off volume and velocity. CCR surface impoundments are subject to hydrologic and hydraulic capacity requirements to ensure the unit can safely handle flood flows, which will help prevent uncontrolled overtopping of the unit or erosion of the materials used to construct the surface impoundment. The final rule also requires periodic inspections of CCR units to identify any appearance of structural weakness or other conditions that are not consistent with recognized and generally accepted good engineering standards.

5. Groundwater Monitoring and Corrective Action. The groundwater monitoring and corrective action criteria require an owner or operator of a CCR unit to install a system of monitoring wells and specify procedures for sampling these wells, in addition to methods for analyzing the groundwater data collected, to detect the presence of

hazardous constituents (*e.g.,* toxic metals) and other monitoring parameters (*e.g.,* pH, total dissolved solids) released from the units. The final rule establishes a groundwater monitoring program consisting of detection monitoring, assessment monitoring and corrective action. Once a groundwater monitoring system and groundwater monitoring program has been established for a CCR unit, the owner or operator must conduct groundwater monitoring and, if the monitoring demonstrates an exceedance of a groundwater protection standard for any of the identified constituents in CCR, must initiate corrective action.

6. Closure and Post-Closure Requirements. The closure and post-closure care criteria require all CCR units to close in accordance with specified standards and to monitor and maintain the units for a period of time after closure, including the groundwater monitoring and corrective action programs. These criteria are essential to ensuring the long-term safety of closed CCR units. Closure of a CCR unit must be completed either by leaving the CCR in place and installing a final cover system or through removal of the CCR and decontamination of the CCR unit. The final rule establishes timeframes to initiate and complete closure activities, and authorize owners or operators to obtain time extensions due to circumstances beyond the facility's control. As discussed elsewhere in this preamble, the rule also establishes alternative closure procedures in situations where an owner or operator is closing a CCR unit, but has no alternative CCR disposal capacity or is permanently closing the coal-fired boiler unit in the foreseeable future. Finally, owners and operators are required to prepare closure and post-closure care plans describing these activities.

7. Record Keeping, Notification, and Internet Posting Requirements. The final rule requires owners or operators of CCR units to record certain information in the facility's operating record. In addition, owners and operators are required to provide notification to States and/or appropriate Tribal authorities when the owner or operator places information in the operating record, as well as to maintain a publicly accessible internet site for this information.

8. Severability. EPA intends that the provisions of this rule be severable. In the event that any individual provision or part of this rule is invalidated, EPA intends that this would not render the entire rule invalid, and that any individual provisions that can continue to operate will be left in place. The following tables provide a summary of the specific technical requirements applicable to existing and new CCR landfills, existing and new CCR surface impoundments, and all lateral expansions of CCR units.

CCR Landfill Requirements				
Requirement	**Existing CCR Landfills**		**New CCR Landfills and Lateral Expansions**	
	Required? [1]	Rule Section	Required? [1]	Rule Section
Location Restrictions:	√	§257.64	√	§257.60 - §257.64
Placement Above the Uppermost Aquifer			√	§257.60
Wetlands			√	§257.61
Fault Areas			√	§257.62
Seismic Impact Zones			√	§257.63
Unstable Areas	√	§257.64	√	§257.64
Floodplains[2]	√	§257.3-1	√	§257.3-1
Endangered Species[2]	√	§257.3-2	√	§257.3-2
Design Requirements:			√	§257.70
Composite Liner			√	§257.70 (b & c)
Leachate Collection and Removal System			√	§257.70 (d)
Groundwater Monitoring and Corrective Action	√	§257.90 - §257.98	√	§257.90 - §257.98
Weekly Inspections	√	§257.84 (a)	√	§257.84 (a)
Annual Inspections	√	§257.84 (b)	√	§257.84 (b)
Fugitive Dust Controls	√	§257.80	√	§257.80
Run-on, Run-off Controls	√	§257.81	√	§257.81
Surface Water Protection[2]	√	§257.3-3	√	§257.3-3
Closure Requirements	√	§257.100 - §257.103	√	§257.100 - §257.103
Post-Closure Care	√	§257.104	√	§257.104
Recordkeeping Requirements	√	§257.105	√	§257.105
Notification Requirements	√	§257.106	√	§257.106
Publicly Accessible Internet Site Requirements	√	§257.107	√	§257.107

[1] √ = required, = not required.
[2] In existing regulations at 40 CFR part 257, subpart A.

CCR Surface Impoundment Requirements								
Requirement	Existing Surface Impoundments				New Surface Impoundments and Lateral Expansions			
	Five feet high AND 20 acre-feet, or 20 feet high				Five feet high AND 20 acre-feet, or 20 feet high			
	Yes		No		Yes		No	
	Required? [1]	Rule Section	Required? [1]	Rule Section	Required? [1]	Rule Section	Required? [1]	Rule Section
Location Restrictions:	√	§257.60 - §257.64	√	§257.60 - §257.64	√	§257.60 - §257.64	√	§257.60 - §257.64
Placement Above the Uppermost Aquifer	√	§257.60	√	§257.60	√	§257.60	√	§257.60
Wetlands	√	§257.61	√	§257.61	√	§257.61	√	§257.61
Fault Areas	√	§257.62	√	§257.62	√	§257.62	√	§257.62
Seismic Impact Zones	√	§257.63	√	§257.63	√	§257.63	√	§257.63
Unstable Areas	√	§257.64	√	§257.64	√	§257.64	√	§257.64
Floodplains[4]	√	§257.3-1	√	§257.3-1	√	§257.3-1	√	§257.3-1
Endangered Species[4]	√	§257.3-2	√	§257.3-2	√	§257.3-2	√	§257.3-2
Design Requirements:	√	§257.71	√	§257.71	√	§257.72	√	§257.72
Composite Liner	[2]	§257.71	[2]	§257.71	√	§257.72	√	§257.72
Leachate Collection and Removal System								
Groundwater Monitoring and Corrective Action	√	§257.90 - §257.98	√	§257.90 - §257.98	√	§257.90 - §257.98	√	§257.90 - §257.98
Structural Integrity Criteria:	√	§257.73 & §257.83	√	§257.73 & §257.83	√	§257.74 & §257.83	√	§257.74 & §257.83
History of Construction	√	§257.73 (c)						
Construction Plan					√	§257.74 (c)		
Marker [3]	√	§257.73 (a)(1)	√	§257.73 (a)(1)	√	§257.74 (a)(1)	√	§257.74 (a)(1)
Hazard Potential Classification Assessments [3]	√	§257.73 (a)(2)	√	§257.73 (a)(2)	√	§257.74 (a)(2)	√	§257.74 (a)(2)
Structural Stability Assessments	√	§257.73 (d)			√	§257.74 (d)		
Safety Factor Assessments	√	§257.73 (e)			√	§257.74 (e)		
Emergency Action Plan [3]	√	§257.73 (a)(3)	√	§257.73 (a)(3)	√	§257.74 (a)(3)	√	§257.74 (a)(3)
Weekly Inspections	√	§257.83 (a)	√	§257.83 (a)	√	§257.83 (a)	√	§257.83 (a)
Annual Inspections	√	§257.83 (b)			√	§257.83 (b)		
Fugitive Dust Controls	√	§257.80	√	§257.80	√	§257.80	√	§257.80

CCR Surface Impoundment Requirements								
Requirement	Existing Surface Impoundments				New Surface Impoundments and Lateral Expansions			
	Five feet high AND 20 acre-feet, or 20 feet high				Five feet high AND 20 acre-feet, or 20 feet high			
	Yes		No		Yes		No	
	Required? [1]	Rule Section	Required? [1]	Rule Section	Required? [1]	Rule Section	Required? [1]	Rule Section
Hydrologic & Hydraulic Capacity Requirements	√	§257.82	√	§257.82	√	§257.82	√	§257.82
Surface Water Protection[4]	√	§257.3-3	√	§257.3-3	√	§257.3-3	√	§257.3-3
Closure Requirements	√	§257.100 - §257.103	√	§257.100 - §257.103	√	§257.100 - §257.103	√	§257.100 - §257.103
Post-Closure Care	√	§257.104	√	§257.104	√	§257.104	√	§257.104
Recordkeeping Requirements	√	§257.105	√	§257.105	√	§257.105	√	§257.105
Notification Requirements	√	§257.106	√	§257.106	√	§257.106	√	§257.106
Publicly Accessible Internet Site Requirements	√	§257.107	√	§257.107	√	§257.107	√	§257.107

[1] √ = required, ▒▒ = not required.
[2] Existing CCR surface impoundments are required to be constructed with two feet of compacted soil with a hydraulic conductivity of no more than $1x10^{-7}$ cm/sec, a composite liner that meets the requirements of §257.70(b), or an alternative liner that meets the requirements of §257.70(c).
[3] This requirement does not apply to an incised CCR surface impoundment.
[4] In existing regulations at 40 CFR part 257, subpart A.

E. When must owners or operators of CCR landfills and CCR surface impoundments meet the minimum national criteria?

The rule becomes effective six months after the publication date of this rule. The final rule establishes timeframes for certain technical criteria based on the amount of time determined to be necessary to implement the requirements (*e.g.*, installing the groundwater monitoring wells and establishing the groundwater monitoring program). In establishing these timeframes, EPA accounted for other Agency rulemakings that are anticipated to also affect the owners or operators of CCR units, namely the Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category (78 FR 34432; proposed rule issued June 7, 2013) and the Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units (79 FR 34830; proposed rule issued June 18, 2014). Specifically, EPA developed implementation timeframes that would ensure that owner or operators of CCR units would not be required to make decisions about those CCR units without first understanding the implications that such decisions would have for meeting the requirements of all applicable EPA rules.

F. Deferral of Final Bevill Determination

This rule defers a final Bevill Regulatory Determination with respect to CCR that is disposed in CCR landfills and CCR surface impoundments until additional information is available on a number of key technical and policy questions. This includes information needed to quantify the risks of CCR disposal, and the potential impacts of recent Agency regulations on the chemical composition of CCR. The Agency also needs further information on adequacy of the state programs.

G. Beneficial Use

The final rule retains the Bevill exclusion for CCR that is beneficially used, and provides a definition of beneficial use to distinguish between beneficial use and disposal.

H. Implementation

Because the regulations have been promulgated under sections 1008(a), 4004(a), and 4005(a) of RCRA, the rule does not require permits, does not require states to adopt or implement these requirements, and EPA cannot enforce these requirements. Instead, states or citizens can enforce the requirements of this rule under RCRA's citizen suit authority; the states can also continue to enforce any state regulation under their independent state enforcement authority. (For a more detailed discussion of EPA authorities under RCRA and its relationship to this rule, see 75 FR 35128, June 21, 2010). EPA recognizes the significant role states play in implementing these requirements and EPA strongly encourages states to revise their SWMPs to show how these new criteria will be implemented. EPA would then review and approve the revised plan provided it demonstrates that the minimum federal requirements in this final rule will be met. In this way, EPA's approval of a revised plan signals EPA's opinion that the State's SWMP meets the minimum federal criteria. For a more detailed discussion on the role of the states in implementing this rule, please refer to Unit IX of this document.

I. Characterization of Baseline Affected Entities and CCR Management Practices

This action will affect CCR generated by coal-fired electric utility plants in the NAICS industry code 221112 (*i.e.*, the ''Fossil Fuel Electric Power Generation'' industry within the NAICS 22 ''Utilities'' sector code). Based on 2012 electricity generation data published by the Energy Information Administration (EIA), the Regulatory Impact Analysis (RIA) for this action estimated that a total of 478 operational coal-fired electric utility plants in this NAICS code could be affected by this action. These plants are owned by 242 entities consisting of 166 companies, 17 cooperative organizations, 58 state or local governments, and one federal agency. A sub-total of 81 of the 242 owner entities (*i.e.*, 33 percent may be classified as small businesses, small organizations, or small governments). The 478 coal-fired electric utility plants operate a total of 1,045 CCR management units (735 surface impoundments and 310 landfills). These 478 plants generate 110 million tons of CCR, consisting of 201 plants (42 percent) disposing in on-site landfills, 169 (35 percent) disposing in on-site ponds, and 197 (41 percent) disposing in off-site landfills. Because some plants use more than one CCR management method, these plant counts exceed 478 total plants. In addition, 293 of the 478 plants supply CCR for beneficial uses in at least 14 industries. Nineteen of the 293 plants solely supply CCR for beneficial uses. As of 2012, CCR beneficial uses (*i.e.*, industrial applications) involved about 52 million tons annually.

J. Summary of Estimated Regulatory Costs and Benefits

The EPA estimated future regulatory compliance costs and expected future human health and environmental protection benefits can be found in the RIA document which is available from the docket for this action. The estimated costs and benefits for the CCR rule are incremental to the baseline (current) practices by the electric utility industry to manage CCR in accordance with (a) existing state government environmental regulations and (b) utility company CCR management methods.

The RIA estimates the cost of the rule over a 100 year period because of: (1) CCR unit lifespans (40 years to 80 years of age); (2) groundwater migration (estimated time to peak potential exposures of CCR through groundwater migration to drinking water wells is 75 years); and (3) latency periods for onset of illness after exposure to CCR, which can average 20 years.

The table below summarizes the estimated incremental costs and benefits of the rule. The RIA estimates costs to comply with the 12 pollution control requirements associated with the rule, as well as estimated monetized values for 11 expected benefits, and discusses 11 other non-monetized benefits.

EPA Estimated Incremental Costs & Benefits of the CCR Rule

[millions 2013$ over 100-year period of analysis 2015–2114]

	3% Discount rate	7% Discount rate
A. Annualized Values		
A1. Total Costs	$735	$509
A2. Total monetized benefits	$294	$236
A3. Net Benefits (A2–A1)	($441)	($441)
A4. Benefit to Cost Ratio (A3/A1)	0.40	0.46

EPA ESTIMATED INCREMENTAL COSTS & BENEFITS OF THE CCR RULE—Continued

[millions 2013$ over 100-year period of analysis 2015–2114]

	3% Discount rate	7% Discount rate
B. Present Value		
B1. Total Costs	$23,200	$7,260
B2. Total monetized benefits	$8,710	$3,360
B3. Net Benefits (B2–B1)	($14,490)	($3,900)
B4. Benefit to Cost Ratio (B2/B1)	0.38	0.46

II. Statutory Authority

These regulations are established under the authority of sections 1006(b), 1008(a), 2002(a), 3001, 4004, and 4005(a) of the Solid Waste Disposal Act of 1970, as amended by the Resource Conservation and Recovery Act of 1976 (RCRA), as amended by the Hazardous and Solid Waste Amendments of 1984 (HSWA), 42 U.S.C. 6906(b), 6907(a), 6912(a), 6944 and 6945(a).

RCRA section 1006(b) directs EPA to integrate the provisions of RCRA for purposes of administration and enforcement and to avoid duplication, to the maximum extent practicable, with the appropriate provisions of other EPA statutes. Section 1006(b) conditions EPA's authority to reduce or eliminate RCRA requirements on the Agency's ability to demonstrate that the integration meets RCRA's protectiveness mandate (42 U.S.C. 6005(b)(1)). *See Chemical Waste Management* v. *EPA*, 976 F.2d 2, 23, 25 (D.C. Cir. 1992).

RCRA section 1008(a) authorizes EPA to publish ''suggested guidelines for solid waste management.'' 42 U.S.C. 6907(a). RCRA defines solid waste management as ''the systematic administration of activities which provide for the collection, source separation, storage, transportation, transfer, processing, treatment, and disposal of solid waste.'' 42 U.S.C. 6903(28).

Pursuant to section 1008(a)(3), the guidelines are to include the minimum criteria to be used by the states to define the solid waste management practices that constitute the open dumping of solid waste or hazardous waste and are prohibited as ''open dumping''under section 4005. Only those requirements promulgated under the authority of section 1008(a)(3) are enforceable under section 7002 of RCRA.

RCRA section 4004 generally requires EPA to promulgate regulations containing criteria for determining which facilities shall be classified as sanitary landfills (and therefore not ''open dumps''). The statute directs that, ''at a minimum, the criteria are to ensure that units are classified as sanitary landfills only if there is no reasonable probability of adverse effects on health or the environment from disposal of solid wastes at such facility.'' 42 U.S.C. 6944(a).

RCRA section 4005(a), entitled ''Closing or upgrading of existing open dumps'' generally establishes the key implementation and enforcement provisions applicable to EPA regulations issued under sections 1008(a) and 4004(a). Specifically, this section prohibits any solid waste management practices or disposal of solid waste that does not comply with EPA regulations issued under RCRA section 1008(a) and 4004(a). 42 U.S.C. 6944(a). See also 42 U.S.C. 6903(14) (definition of ''open dump''). This prohibition takes effect ''upon promulgation'' of any rules issued under section 1008(a)(3) and is enforceable through a citizen suit brought pursuant to section 7002. As a general matter, this means that facilities must be in compliance with any EPA rules issued under this section no later than the effective date of such rules, or be subject to a citizen suit for ''open dumping'' 42 U.S.C. 6945. RCRA section 4005 also directs that open dumps, *i.e.*, facilities out of compliance with EPA's criteria, must be ''closed or upgraded.''

Section 7004 lays out specific requirements relating to public participation in regulatory actions under RCRA. Subsection (b) provides that ''[p]ublic participation in the . . . implementation, and enforcement of any regulation under this chapter shall be provided for, encouraged, and assisted by the Administrator.'' 42 U.S.C. 6974(b).

A. Regulation of Solid Wastes Under RCRA Subtitle D

Solid wastes that are neither a listed nor characteristic hazardous waste are subject to the requirements of RCRA subtitle D. Subtitle D of RCRA establishes a framework for federal, state, and local government cooperation in controlling the management of non-hazardous solid waste. The federal role is to establish the overall regulatory direction, by providing minimum nationwide standards that will protect human health and the environment, and to provide technical assistance to states for planning and developing their own environmentally sound waste management practices. The actual planning and any direct implementation of solid waste programs under RCRA subtitle D, however, remains a state and local function, and the Act envisions that states will devise programs to deal with state-specific conditions and needs. EPA has no role in the planning and direct implementation of the minimum national criteria or solid waste programs under RCRA subtitle D, and has no authority to enforce the criteria. However, states are not required to adopt solid waste management programs, and thus, Congress developed a statutory structure that creates incentives for states to implement and enforce the federal criteria, but that does not necessarily rely on or require a regulatory entity to oversee or implement them. While Congress developed the statutory structure to create incentives for states to implement and enforce the federal criteria, it does not require them to do so. As a result, subtitle D is also structured to be self-implementing.

RCRA sections 1008(a)(3) and 4004(a) delegate broad authority to EPA to establish regulations governing the management of solid waste. Under section 4004(a) EPA is charged with establishing requirements to ensure that facilities will be classified as sanitary landfills ''only if there is no reasonable probability of adverse effects on health or the environment from the disposal of solid waste'' at the facility. Or in other words, under section 4004(a) EPA is charged with issuing regulations to address all ''reasonable probabilities of adverse effects'' (*i.e.*, all reasonably anticipated risks) to health and the environment from the disposal of solid waste. Section 1008(a)(3) expands EPA's authority to address the risks from any of the listed activities. Specifically, EPA is authorized to establish requirements applicable to ''storage, transportation, transfer, processing, treatment, and disposal of solid waste.'' (42 U.S.C. 6907(a), 6903(28)).

EPA interprets the standard in section 4004(a) to apply equally to criteria issued under sections 1008(a)(3) and 4004(a); namely that the criteria must ensure that a facility is to be classified as a sanitary landfill, and thus allowed to continue to operate, ''only if there is no reasonable probability of adverse effects on health or the environment'' from either the disposal or other solid waste management practices at the facility. Thus, under the combined authority conferred by sections 1008(a)(3) and 4004(a), a facility is an ''open dump'' if it engages in any activity involving the management of solid waste that does not meet the standard in section 4004(a); or in other words, any activity involved with the management of solid waste that presents a reasonable probability of causing adverse effects on health or the environment. EPA also interprets these provisions to authorize the establishment of criteria that define the manner in which facilities upgrade or close, consistent with the standard in section 4004(a), to ensure there will be no reasonable probability of adverse effects on health or the environment.

As discussed previously, Congress created a regulatory structure that limited EPA's role to the creation of national criteria that would operate even in the absence of a regulatory entity to oversee or implement the criteria. Under RCRA section 4005(a), upon promulgation of criteria under section 1008(a)(3), any solid waste management practice or disposal of solid waste that constitutes the ''open dumping'' of solid waste is prohibited. The federal standards apply directly to the facility (are self-implementing) and facilities are directly responsible for ensuring that their operations comply with these requirements. States are not required to incorporate or implement these requirements under any state permitting program or other state law requirement, and EPA is not authorized to impose such requirements, directly or indirectly on the states. States and citizens may enforce this prohibition (and therefore, the federal criteria) using the authority under RCRA section 7002.[1]

The statute also creates incentives to states to implement the criteria. Chief among the incentives is a greater role in implementation and enforcement of the solid waste program, including to a limited extent the ability to give facilities that are operating within their state additional time to come into compliance with newly promulgated EPA criteria. Specifically, if the facility is located in a state with a plan that was approved under section 4003(b), the state may grant the facility an extension of up to five years from the date the final rule was published in the **Federal Register** to come into compliance with EPA regulations, provided: (a) The facility is listed in a state inventory of open dumps; and (b) the facility has demonstrated that it has considered other public or private alternatives for solid waste management to comply with the prohibition on open dumping and is unable to utilize such alternative. For facilities that meet these requirements, the state may establish a ''schedule for compliance'' which specifies a schedule of remedial measures, including an enforceable sequence of actions or operations, leading to compliance with the requirements ''within a reasonable time (not to exceed five years from the date of publication of criteria under section [1008] (a)(3) of this title).'' 42 U.S.C. 6945(a).

As a consequence of this statutory structure—the requirement to establish national criteria and the absence of any requirement for direct regulatory oversight—to establish the criteria EPA must demonstrate, through factual evidence available in the rulemaking record, that the final rule will achieve the statutory standard (''no reasonable probability of adverse effects on health or the environment'') at all sites subject to the standards based exclusively on the final rule provisions. This means that the standards must account for and be protective of all sites, including those that are highly vulnerable.

III. Background

A. EPA's Proposed Rule

On June 21, 2010 (75 FR 35128), EPA proposed to regulate CCR under RCRA to address the risks from the disposal of CCR generated from the combustion of coal at electric utilities and independent power producers. As described in the proposal, CCR are residuals generated from the combustion of coal and include fly ash, bottom ash, boiler slag (all composed predominantly of silica and aluminosilicates), and flue gas desulfurization (FGD) materials (predominantly Ca-SO_X compounds) and can be managed in either wet (surface impoundments) or dry (landfills) disposal systems. EPA noted in the proposed rule that the constituents of most environmental concern in CCR are metals, such as antimony, arsenic, barium, beryllium, cadmium, chromium, lead, mercury, nickel, selenium, silver and thallium. EPA also presented data showing numerous instances where these constituents (especially arsenic) have leached at levels of concern from unlined and inadequately clay-lined landfills and surface impoundments.

In the proposal, EPA revisited its August 1993 and May 2000 Bevill Regulatory Determinations regarding CCR generated at electric utilities and independent power producers. The results from this effort led the Agency to consider two primary options for the management of CCR and thus, propose two alternative regulatory strategies. Under the first option, EPA proposed to reverse its August 1993 and May 2000 Bevill Regulatory Determinations (58 FR 42466 and 65 FR 32214 respectively) regarding CCR and to list these residuals as special wastes subject to regulation under subtitle C of RCRA when they are destined for disposal in landfills or surface impoundments. Under this proposed option, CCR would be regulated from the point of generation to the point of final disposition and would generally be subject to the existing subtitle C regulations at 40 CFR parts 260 through 268, as well as the permitting requirements in 40 CFR part 270, and the state authorization process in 40 CFR parts 271–272. Among other things, the regulatory requirements included waste characterization, location restrictions, liner and, if applicable, leachate collection requirements for land disposal units, fugitive dust controls, groundwater monitoring and corrective action requirements, closure and post-closure care requirements, financial assurance, permitting requirements, and recordkeeping and reporting requirements. This option also imposed requirements on generators and transporters of CCR destined for disposal, including manifesting (if the CCR destined for disposal is sent off-site). However, in light of practical difficulties in implementing certain subtitle C regulatory requirements, EPA also proposed to revise selected requirements under the subtitle C option. Consequently, EPA proposed, pursuant to its authority under section 3004(x) of RCRA, modifications to the CCR landfill and surface impoundment liner and leak detection system requirements, the effective dates for the land disposal restrictions, and the surface impoundment retrofit requirements. EPA also proposed to establish new land disposal prohibitions and treatment standards for both wastewater and non-wastewater forms of CCR. In part, the proposed

[1] EPA also may act if the handling, storage, treatment, transportation, or disposal of such wastes may present an imminent and substantial endangerment to health or the environment, pursuant to RCRA section 7003.

modifications to the treatment standards would result in the closure of existing surface impoundments and the prohibition of all new surface impoundments. (See 75 FR 35128 for a complete discussion of this proposed option).

Under the second option, EPA proposed to retain the August 1993 and May 2000 Bevill Regulatory Determinations and to regulate CCR disposal under subtitle D of RCRA by issuing national minimum criteria to ensure the safe disposal of CCR in surface impoundments and landfills. Under this option, CCR would remain classified as a non-hazardous RCRA solid waste. EPA proposed to establish technical requirements, many of which were nearly identical to the technical standards proposed under the subtitle C option. The technical standards included, among other things, locations standards, liner and leachate collection requirements, groundwater monitoring and corrective action standards for releases from the units, operating criteria, such as fugitive dust control, closure and post-closure care requirements, and recordkeeping and reporting requirements. Under this option, EPA did not propose to establish regulatory requirements that would restrict the generation, transportation, storage, or treatment of CCR prior to disposal, nor did EPA propose to establish financial assurance requirements under RCRA.[2] Also, because of subtitle D's limitations, the proposed rule did not require permits; nor could EPA enforce the national minimum criteria. Rather, states or citizens could enforce the national minimum criteria under RCRA's citizen suit authority, and states could continue to enforce any state regulation that applies to CCR under their independent state enforcement authority.

The subtitle D proposed option was designed to be self-implementing, meaning that the requirements were such that facilities could comply with the regulatory requirements without the need to interact with a regulatory authority. EPA sought to enhance the protectiveness of the proposed option by requiring certified demonstrations by an independent registered professional engineer to provide verification that the regulatory requirements were being adhered to. In addition, the option provided for state and public notification of the certifications, as well as required posting of certain information on a Web site maintained by the facility and in the operating record. (See 75 FR 35128 for a complete discussion of this proposed option).[3]

The Agency also described other alternatives considered. For example, one subtitle D option, called ''D-prime'' was structured so that all existing CCR surface impoundments could continue to receive CCR after the effective date of the rule for the remainder of the unit's useful life, irrespective of their liner type, provided the other provisions of the subtitle D option were met (*e.g.,* groundwater monitoring). (See 75 FR 35128 for a complete discussion of this and other possible regulatory alternatives on which the Agency solicited comment.)

Under both the subtitle C and subtitle D alternatives, EPA proposed establishing dam safety requirements to address the structural integrity of surface impoundments. EPA also proposed not to change the May 2000 Regulatory Determination for beneficially used CCR, which are currently exempt from the hazardous waste regulations under section 3001(b)(3)(A) of RCRA. EPA also did not propose to address the placement of CCR in mines, or non-minefill uses of CCR at coal mine sites.

In addition to proposing these two regulatory options for the management of CCR, EPA identified many issues on which it solicited comment, information, and data. Certain solicitations were very general, such as comments on alternative options for regulating CCR, while other requests for comment were very specific in nature, for example, whether clay liners designed to meet a specified hydraulic conductivity might perform differently in practices than modeled in the risk assessment. (The Agency requested comment on issues throughout the preamble; however specific issues for which EPA solicited comment can be found at 75 FR 35221–34224.)

B. Comments Received on the Proposed Rule

The Agency received over 450,000 comments on the proposed rule. The majority of the commenters focused on which regulatory path the Agency should pursue for regulating CCR, *i.e.,* RCRA's subtitle C or subtitle D. A number of commenters, however, argued that no additional regulation was necessary and that the states were adequately regulating the management of CCR. Generally, environmental groups and individual citizens favored a subtitle C rule arguing that state programs have failed and damage cases are growing in number. State organizations, individual states, and industry groups (electric utilities, recycling firms, trade associations), largely favored a subtitle D rule with a permitting program.

One area that received extensive comment was the re-evaluation of the eight Bevill study factors.[4] Numerous commenters provided detailed analysis related to the study factors and provided their own interpretations of the data (*e.g.,* state programs and damage cases). Other areas that received significant comment included beneficial use and the risk assessment.

Discussion of the specific comments germane to this rulemaking are provided in the relevant sections of this document.

C. Other Actions During Which Comment Was Taken

1. Public Hearings

EPA conducted eight public hearings during the months of August, September, and October in 2010. There were over 1300 individual speakers at the eight public hearings that commented on the proposed rule. Testimony at the public hearings focused generally on whether EPA

[2] In the proposal, the Agency stated that the RCRA subtitle D alternative did not include proposed financial responsibility requirements and that any such requirements would be proposed separately. The Agency solicited comment on whether financial responsibility requirements under CERCLA section 108(b) should be a key Agency focus under a RCRA subtitle D approach. While the Agency received numerous comments urging the Agency to establish financial responsibility as part of the subtitle D option, the CERCLA 108(b) option did not receive significant support. As discussed in the proposal and reiterated here, EPA will not be requiring financial assurance requirements as part of this rule. The Agency however will continue to investigate the use of other statutory authorities (*e.g.,* CERCLA) to establish financial responsibility requirements for owners or operators of CCR landfills, CCR surface impoundments and any lateral expansion.

[3] While EPA cannot enforce the subtitle D proposed rules, EPA can take action under section 7003 of RCRA to abate conditions that ''may present an imminent and substantial endangerment to health or the environment.'' EPA can also use the imminent and substantial endangerment authorities under the CERCLA, or under other federal authorities to address those circumstances where a unit(s) may pose a threat.

[4] In considering whether to retain or to reverse the August 1993 and May 2000 Regulatory Determinations regarding the Bevill exemption of CCR destined for disposal, the Agency re-examined the RCRA section 8002(n) study factors. These eight study factors are: (1) Source and volumes of CCR generated per year; (2) present disposal and utilization practices (which includes evaluation of existing state regulatory oversight and beneficial use); (3) potential danger, if any, to human health and the environment from the disposal and reuse of CCR; (4) documented cases in which danger to human health or the environment from surface runoff or leachate has been proved; (5) alternatives to current disposal methods; (6) the cost of such alternative disposal methods; (7) the impact of the alternative disposal methods on the use of coal and other natural resources; and (8) the current and potential utilization of CCR (see 75 FR 35128).

should adopt a subtitle C or subtitle D approach for regulating CCR. Many commenters were also concerned with fugitive dust emissions and the affect these emissions had on their health and overall well-being. Other commenters were concerned that adopting a subtitle C rule for CCR would negatively affect the beneficial use of the material. In addition to their testimonies that were entered into the rulemaking record, over 1200 additional documents were submitted in hard copy and entered into the docket (see EPA–HQ–RCRA–2009–0640).

2. Notices of Data Availability

Subsequent to the proposed rule, the Agency published several Notices of Data Availability (NODAs), the first on October 21, 2010, (75 FR 64974); the second on October 12, 2011 (76 FR 63252) and the third on August 2, 2013 (78 FR 46940). Specifically:

- The first NODA invited comment on the responses EPA received on Information Collection Requests that were sent to electric utilities on their CCR surface impoundments, as well as reports and materials related to the site assessments EPA had conducted on a subset of these impoundments.
- The second NODA invited comment on a number of topics, including (1) chemical constituent data from coal combustion residuals; (2) facility and waste management unit data; (3) information on additional alleged damage cases; (4) the adequacy of state programs; and (5) beneficial use.
- The third NODA invited comment on (1) supplemental data for the risk assessment; (2) supplemental data for the RIA; (3) information regarding large-scale fill; and (4) data on the CCR Assessment Program. EPA also sought comment on two technical issues associated with the requirements for CCR management units: closure requirements and regulation of overfills (*i.e.,* CCR management units built directly over pre-existing CCR landfills or CCR surface impoundments).

Specific comments received on each of the three NODAs are discussed in the relevant sections of this rule.

3. Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category Proposed Rule

On June 7, 2013 (78 FR 34432), EPA proposed a regulation that would strengthen the controls on discharges from certain steam electric power plants by revising the technology-based effluent limitation guidelines (ELG) and standards for the steam electric power generating point source category. As part of this proposal, EPA discussed its current thinking on how a final RCRA CCR rule might be aligned and structured to account for any final requirements adopted under the ELG for the Steam Electric Power Generating point source category. Two primary means of integrating the two rules were discussed: (1) Coordinating the design of any final substantive CCR regulatory requirements and (2) coordinating the timing and implementation of the rules to allow facilities to coordinate their compliance planning and implementation and to protect electricity reliability for consumers. EPA stated that consistent with RCRA section 1006(b), effective coordination of any final RCRA requirements with the ELG requirements would be sought in order to minimize the overall complexity of the two regulatory structures, and facilitate implementation of engineering, financial, and permitting activities. EPA solicited comments on how any final CCR final rule might be aligned and structured to account for any final requirements adopted under the ELG for the Steam Electric Power Generation point source category.

D. EPA's CCR Assessment Program

In March 2009, the Agency's CCR Assessment Program (herein referred to as the Assessment Program) was initiated. This effort was in response to the December 22, 2008 dike failure of a coal ash impoundment at the Tennessee Valley Authority (TVA) Kingston Fossil Plant in Harriman, Tennessee where over one billion gallons of coal ash slurry were released, affecting more than 300 acres, including residences and infrastructure. The TVA Kingston impoundment failure ignited a nation-wide concern over the safety of coal ash impoundments; and EPA was tasked with determining whether the potential existed for similar impoundment failures at other coal-fired power plants. In response, EPA developed the Assessment Program to evaluate the structural stability and safety of all coal ash impoundments throughout the country.[5] As of September 2014, 559 impoundments had been assessed at over 230 coal-fired power plants.

The Assessment Program began as a separate effort from the development of this final rule.[6] However, the information and experience developed in carrying out the site assessments during the Assessment Program is directly relevant to many of the issues addressed in this rulemaking, and provide further technical support for many of the technical criteria. Consequently, many of the final technical criteria were developed in direct response to findings from the site assessments. For example, several of the technical criteria contained in the proposed rule were modified to account for the widely accepted engineering methodologies and practices used in conducting the site assessments, as well as current facility practices documented during the assessments. In a few instances, the criteria were supplemented to better align the technical requirements with the Assessment Program. Included among the final criteria that directly rely on the Assessment Program are the provisions relating to structural integrity assessments to address factors of safety, periodic reassessments, hazard potential classifications, and the hydrologic and hydraulic capacity of CCR surface impoundments. These requirements are further discussed in Unit VI of this preamble.

The Assessment Program focused on impoundments meeting four general criteria that were designed to identify the units most likely to present the same risks as the collapsed TVA impoundment: (1) Above ground or diked; (2) of sufficient height to be susceptible to structural failure (*i.e.,* six feet); (3) receiving CCR; and (4) located at operating coal-fired power plants selling power to the electric grid. Also included in the assessments were a number of inactive impoundments, *i.e.,* impoundments not receiving CCR but still containing CCR and/or liquid. The Agency included these inactive units in the assessment reasoning that these units would be as susceptible to structural failure as units currently receiving CCR, given that they still contained CCR and maintained an ability to impound liquid (*i.e.,* the unit had not been breached). The Assessment Program did not evaluate, however, incised (not having above ground berms or dikes) impoundments or landfills (not containing liquid slurried CCR wastes). EPA chose not to assess these units because they did not share the characteristics of

[5] The focus of the Assessment Program was to assess the structural integrity of CCR impoundments meeting specified criteria. The Agency did not include, as part of its evaluation, the assessment of other conditions/characteristics of the impoundment that may present potential risks to human health or the environment, *i.e.,* groundwater contamination due to an insufficient liner design.

[6] EPA issued two Notices of Data Availability (75 FR 35128 (October 21, 2010) and 78 FR 46940 (August 2, 2013)) specifically soliciting comment on the information generated by the Assessment Program and the materials posted on our Web site.

impoundments likely to raise concern for catastrophic releases, and because no known catastrophic structural failures were associated with these types of units.

Prior to initiating the assessments, EPA consulted with two key dam safety organizations, the Association of State Dam Safety Officials (ASDSO) and the Mine Safety and Health Administration (MSHA) to better understand how these federal and state dam inspection programs operated, including how earthen dams and impoundments were assessed.[7] These groups provided the Agency with critical insight and information for inspecting and evaluating CCR impoundments. The Agency also reviewed various technical documents relating to dam safety and conducting impoundment inspections, many of which were recommended by these organizations. They were: (1) U.S. Army Corp of Engineers (USACE) 2008 National Inventory of Dams (NIDS); (2) Federal Emergency Management Agency's (FEMA) Federal Guidelines for Dam Safety—Hazard Potential Classification System for Dams (April 2004); (3) FEMA's Risk Prioritization Tool for Dams User Manual (March 2008); (4) MSHA's Handbook (PH07–01); (5) MSHA's Coal Mine Impoundment Inspection and Plan Review Handbook (October 2007); and (6) MSHA's Engineering and Design Manual: Coal Refuse Disposal Facility (May 2009); (7) ASDSO's ''Summary of State Dam Safety Laws and Regulations,'' (2000); (8) ASDSO's ''Owner Responsible Periodic Inspection Guidance,'' (2005); (9) ''Guidelines for Inspections of Existing Dams.'' New Jersey Department of Environmental Protection—Dam Safety (January 2008).

In developing the criteria that were used to conduct the assessments, a standard rating system was developed to classify the units' suitability for continued safe and reliable operation. EPA modeled its impoundment condition rating criteria on those developed by the State of New Jersey (see reference above).

1. Conducting the Site Assessments

In order to prioritize the assessments, a preliminary hazard potential classification ranking was identified for each impoundment, based on criteria developed by the FEMA and found generally in USACE's NID. EPA elected to evaluate first those impoundments with a high hazard potential classification, which signifies that a failure or mis-operation of the unit would probably result in the loss of human life.

Upon initiation of the Assessment Program, every owner or operator of a CCR impoundment was contacted by the Agency and supplied with information on the objectives of the assessment and how the assessments were to be conducted. Assessments were conducted in rounds, consisting of groups of 12–26 facilities per round.[8] Prior to each site assessment, to ensure uniformity throughout the study, a statement of work and an impoundment field checklist was developed and adhered to during the assessment.

To ensure objectivity, EPA contracted with professional engineers (PEs) in the state where the impoundment was located who were experts in the area of dam safety to perform the site assessments. Each individual assessment was performed by PEs qualified in the areas of geotechnical engineering, hydrology and hydraulics, and overall dam safety. Upon evaluation of a robust set of technical documents addressing dam safety and inspections as well as comprehensive discussions with key dam safety organizations, the Assessment Program developed a comprehensive set of factors that were to be used to evaluate the overall safety of CCR surface impoundments, which concluded that, among other important factors, the static and seismic factors of safety, hydrologic and hydraulic capacity, liquefaction potential analysis and a post-liquefaction stability analysis if the soils of the embankment were identified to be susceptible to liquefaction, and operation and maintenance protocols, *e.g.* instrumentation monitoring, inspection program, emergency response protocols were critical parameters for assessing the overall safety of CCR surface impoundments.

The individual evaluations or assessments were conducted at each impoundment at each facility using standard, accepted engineering practices, including a visual assessment of the CCR surface impoundment, interviews with site personnel, a review of the history of the CCR surface impoundment, and a review of engineering documentation related to the design, construction, operation, and maintenance of the impoundments, including available technical analyses. At each site visit, additional documentation was collected and reviewed as available, including descriptions, along with supporting information, of: (1) The impoundment, including location, size, age, design and/or alterations to the design, and the amount of residuals currently in the unit; (2) known, measured settlement of the impoundment embankment; (3) known, measured movement of the impoundment embankment; (4) observed erosion of the impoundment embankment; (5) seepage; (6) leakage; (7); observed cracking of the impoundment embankment; (8) deterioration, such as scarps, boils, or sloughs, of the — embankment; (9); seismicity; (10) internal stresses; (11) functioning of foundation drains and relief wells; (12) stability of critical slopes adjacent to the units; and (13) regional and site geological conditions. If available, state and federal inspections reports were also reviewed.[9]

In addition, for each assessment, the following factors were identified, to the extent feasible, for evaluation: (1) The presence and adequacy of spillways; (2) hydrologic and hydraulic capacity of the unit; (3) overall structural adequacy and stability of structures under all credible loading conditions through a review of static, seismic, and liquefaction analyses with determined factors of safety; (4) soil, groundwater, surface water, geology, and geohydrology characteristics associated with the unit, including hydrological data accumulated since the impoundment was constructed or last inspected; (5) a history of the performance of the management unit through analysis of data from monitoring instruments, interviews with facility personnel, and review of available operating records; (6) quality and adequacy of maintenance, surveillance, and methods of unit operations for the protection of public safety; (7) location of schools, hospitals, or other critical infrastructures within five miles down gradient of the impoundment; and (8) whether the impoundment is located within federally designated flood plains. Finally, each impoundment and any associated spillways were evaluated to determine whether the impoundment and the spillways could withstand the loading or overtopping from appropriate inflow design flood events.

Each CCR surface impoundment was classified with a hazard potential classification following the New Jersey Department of Environmental Protection

[7] ASDSO identified for EPA key documents to review including Federal Energy Regulatory Commission (FERC) and MSHA guidance.

[8] The results of this effort are either presented on a facility by facility basis or are summarized by round. All of these data have been posted on the Agency Web site.

[9] It is important to note that during the assessment, no physical drilling, coring or sampling was conducted, while on site; however, studies were reviewed that often included such information.

Bureau of Dam Safety and Flood Control's hazard potential ranking. Each impoundment was classified with a hazard potential classification of either; ''high,'' ''significant,'' ''low,'' or ''less-than-low.'' The hazard potential classification was a qualitative assessment of the potential adverse incremental consequences of a dam failure.

At the conclusion of each assessment, a report was generated and the impoundment was given a condition rating of either; satisfactory, fair, poor, or unsatisfactory. The condition ratings were based on the availability of information on the unit and evaluation of the previously mentioned factors, including the static, seismic, and liquefaction factors of safety. No impoundments received an ''unsatisfactory'' rating. Numerous impoundments were, however, rated as ''poor,'' often for lack of appropriate technical documentation in the aforementioned areas. ''Poor'' or ''fair'' ratings were also an indication that additional measures were needed to improve the stability of the unit. Of 559 impoundments assessed, 241 received a condition rating of ''satisfactory,'' 166 received a condition rating of ''fair,'' and 152 received a ''poor'' condition rating.

It is important to note that the condition rating did not necessarily imply that the unit had inadequate structural integrity. On the contrary, in many instances a structurally sound impoundment may have been given a condition rating or ''fair'' or ''poor'' based on other factors such as a lack of documented information on the unit or insufficient operations and maintenance protocols. For example, an impoundment could be rated as ''poor'' if it lacked the appropriate technical documentation and analyses regarding structural or hydrologic and hydraulic analyses. EPA rated numerous units as ''poor'' based primarily on unavailable technical analyses.

Once the assessment was performed, a draft report was prepared. Draft reports were reviewed by the appropriate state agency, the utility, and by EPA.[10] Once comments were received and incorporated, a final report was issued along with recommendations for additional actions to be taken by the facility (if needed). Facilities then developed action plans and schedules to implement the recommendations. EPA also informed facility owners and operators that in addition to implementing their action plans, they need to adopt an ongoing, routine program to assess each surface impoundment and to take necessary corrective measures to ensure the units' continued structural integrity.

2. Assessment Program Findings

Upon completion of the Assessment Program, a review was undertaken to ascertain the key findings or lessons learned from the effort. These key findings included: (1) The majority of CCR surface impoundments are currently inspected on a periodic basis; (2) most utilities were readily able to supplement outdated or missing information with new or updated evaluations of their impoundments after the on-site portion of EPA's assessment was conducted; (3) in response to the assessment report recommendations, facilities typically willingly conducted remedial actions; (4) interaction with the states and the utilities assured accuracy in the final assessment reports; (5) placing site assessment materials on an internet site assured that the public, states, and utilities had full access to information about the design and operation of CCR impoundments and did not present either homeland security or other confidentiality concerns; (6) static, seismic, and liquefaction analyses did not pose a significant technical or cost burden on facilities since many already routinely conducted these types of evaluations; (7) state regulatory bodies viewed the assessments as a means to further support existing assessment programs; and (8) the use of PEs to certify all final reports ensured that the assessments reflected the PE's best judgments.

3. Assessment Program's Support for the Structural Integrity Requirements of the Rule

As noted, the findings from EPA's Assessment Program provide technical and factual support for many of the final requirements for structural stability in this rule. A more detailed discussion of several of the most significant of these is presented below. Additional discussion of the relevance of these findings is included throughout Unit VI of this document.

a. Periodic Inspections/Assessments

Consistent with the findings from the assessments and with EPA's recommendations to facilities as part of the Assessment Program, this rule requires that all CCR surface impoundments be inspected at intervals not exceeding seven days for any appearances of actual or potential structural weakness and other conditions that are disrupting or have the potential to disrupt the operation or safety of the CCR surface impoundment. Monitoring of instrumentation is also required to be conducted at intervals not exceeding 30 days. The Assessment Program found that virtually all utility companies conduct some sort of periodic inspection or monitoring at CCR surface impoundments, although practices varied among facilities and between states. The Assessment Program also found that while many facilities were conducting regularly scheduled inspections, some did not adequately document the results of these inspections.

In the final rule, CCR surface impoundments exceeding a specified size threshold, *i.e.,* height of five feet or more and capacity of 20 acre-feet or more or a height of 20 feet or more, are required to perform annual inspections as well as two assessments of structural stability quinquennially, (*i.e.,* every five years) that include a structural stability assessment of specified parameters and a factor of safety assessment. Annual inspections are broader in scope than weekly inspections and are conducted to ensure that the design, construction, operation and maintenance of the CCR unit is consistent with recognized and generally accepted good engineering standards. Annual inspections must include a review of available information regarding the status and condition of the unit and a visual inspection to identify signs of distress or malfunction of the unit and appurtenant structures. The annual inspections must be conducted by a qualified professional engineer.

The Assessment Program also reviewed how detailed structural stability reviews and inspections were recommended to be conducted by FEMA, MSHA, and the USACE guidelines and found that such inspections were recommended to take place every three to five years. Review of state dam safety programs demonstrated that similar detailed inspections were also conducted on a three-to-five year cycle. Therefore, in the final rule, EPA is requiring that structural integrity assessments, including the calculation of factors of safety under various loading conditions, be conducted within 18 months of publication of the rule, and be repeated every five years. The five year review timeframe is based on documentation showing that the factual bases for such reviews are only sound for that time

[10] As noted many times in this document, states play a critical role in implementing and overseeing these units. To assist states in this effort, EPA has, in the majority of cases directly provided the states with all of the information from our assessments. The Assessment Program reports may be accessed at: *http://www.epa.gov/wastes/nonhaz/industrial/special/fossil/surveys2/index.htm.*

period, and is consistent with federal dam safety guidance, specifically FEMA. FEMA recommends in *Federal Guidelines for Dam Safety* that dams be formally assessed at a frequency not to exceed five years by a qualified professional engineer. EPA has adopted this timeframe to maintain consistency with FEMA guidance. The inspection and assessment requirements in this rule will ensure that there are consistent and uniform inspection and assessment practices across states and facilities and will ensure that problems related to their stability will be promptly identified and remediated as necessary.

b. Static, Seismic, and Liquefaction Factors of Safety

(1) Static Factors of Safety.

Factor of safety (FOS) means the ratio of the forces tending to resist the failure of a structure, as compared to the forces tending to cause such failure as determined by accepted engineering practice. This analysis is used to determine whether a CCR surface impoundment's dikes are engineered to withstand the specific loading conditions that can be reasonably anticipated to occur during the lifetime of the unit without failure of the dike, if accepted good engineering practices are employed. Static factors of safety refer to the factors of safety (FOS) under static loading conditions that can reasonably be anticipated to occur during the lifetime of the unit. Static loading conditions are unique from other loading conditions (*e.g.,* seismic, liquefaction) in that static loading conditions are those which are in equilibrium, meaning the load is at rest or is applied with constant velocity.

EPA reviewed a series of USACE guidance documents addressing how to determine static FOS. These documents included, but were not limited to, Engineer Manual EM 1110–2–1902 ''Slope Stability'' (October 2003), and EM 1110–2–1902 ''Stability of Earth and Rock-Fill Dams.'' The Agency also assessed the recommendations on how to conduct static analysis contained in the Engineering and Design Manual for Coal Refuse Disposal Facilities, originally published by the Mining Enforcement and Safety Administration (MESA) in 1975 and updated for MSHA in May 2009, and in particular Chapter 6, ''Geotechnical Exploration, Material Testing, Engineering Analysis and Design.'' Based on recommendations from ASDSO, among others, the Agency adopted the USACE guidance to determine static FOS, both in the Assessment Program and in this rulemaking, as these manuals are recognized throughout industry as the standard routinely used in field assessment of structural integrity.

In EPA's Assessment Program all CCR units were assessed to determine their static FOS. Each assessment classified a CCR unit as having sufficient structural stability under static loading conditions if analysis of critical sections of embankments demonstrated FOS that met or exceeded the values defined by USACE for static specific loading conditions. EPA found that most CCR surface impoundments exhibited sufficient calculated factors of safety under static loading conditions. EPA also found that in those CCR units which insufficient factors of safety against failure due to static loading were calculated, the owner or operator was able to implement actions which increased the factors of safety under static loading conditions to acceptable levels. Oftentimes, these implemented actions were of a simple nature, such as installing riprap (rock armoring the slopes) or buttressing the slopes.

Similarly, this rule adopts the static FOS from USACE Engineer Manual EM 1110–2–1902 ''Slope Stability,'' with the exception of the rapid drawdown loading condition,[11] which was determined not to be relevant to CCR surface impoundments. EPA found the factors of safety identified by EM 1110–2–1902, specifically the Maximum Storage pool, Maximum Surcharge pool, and End-Of-Construction loading conditions, provided consistent, achievable levels of safety in CCR surface impoundment dikes, comprehensively assessed static stability, and provided sufficient consideration of compounding stresses on dikes (*e.g.,* factors of safety values greater than 1.00 to account for unanticipated loadings acting in conjunction or misidentified strength of materials).

(2) Seismic Factor of Safety.

Seismic FOS means the FOS determined using analysis under earthquake conditions for a seismic loading event, based on the U.S. Geological Survey (USGS) seismic hazard maps for seismic events with a specified return period for the location where the CCR surface impoundment is located. The seismic FOS analysis is used to determine whether a dam would remain stable during an earthquake or other seismic event. The Agency relied on guidance from USACE and MSHA to evaluate the appropriate methods to determine if a dam would remain stable during a seismic event. This includes the USACE guidance Engineer Circular 1110–2–6061: Safety of Dams—Policy and Procedures 2204, Engineer Circular 1110–2–6000: Selection of Design Earthquakes and Associated Ground Motions 2008, and Engineer Circular 1110–2–6001: Dynamic Stability of Embankment Dams 2004). EPA also reviewed MSHA's 2009 Engineering and Design Manual for Coal Refuse Disposal Facilities, in particular Chapter 7, ''Seismic Design: Stability and Deformation Analyses.'' These documents are viewed by ASDSO, FEMA and MSHA as generally accepted guidance on how to conduct seismic stability analyses.

As noted earlier, in performing the assessments, EPA directed its engineering contractors to assess seismic stability of CCR impoundments during and following a seismic event with a 2% probability of exceedance in 50 years (*i.e.* probable earthquake within approximately 2,500 years) and a horizontal spectral response acceleration for 1.0-second period (5% of Critical Damping). EPA selected this return period for determining the maximum design earthquake (MDE) by first considering the operating life anticipated for CCR surface impoundments. EPA has identified the operating life of CCR surface impoundments to range between 40–80 years. EPA then consulted the United States Geological Survey (USGS) and ASDSO to determine a conservative probability that should be used in the assessments.[12] To reduce the likelihood of a CCR unit failing during a seismic

[11] Rapid (or sudden) drawdown is a condition in earthen dikes that may develop when the embankment becomes saturated through seepage during a high pool elevation in the reservoir. Rapid drawdown becomes a threat to the dike when the reservoir pool is drawn down or lowered at a rate significantly higher than the excess poor water pressure within the dike can dissipate. Typically, rapid drawdown scenarios are considered for dikes with reservoirs used for water supply and management or agricultural supply. In these scenarios, a high pool elevation is maintained in the reservoir in storage months. Subsequently, the water supply is drawn on in months where there is a demand for the reservoirs contents. This drawing down of the pool can present issues for the structural integrity of the unit. However, the management of CCR surface impoundments differs from that of conventional water supply reservoirs. CCR surface impoundments are never used for water supply, and the only instance in which EPA determined through its Assessment Program that rapid drawdown loading conditions would be relevant to CCR surface impoundments was in the event that the CCR surface impoundment had already released the contents of the impoundment through a breach of the dike or emergency discharge. Since the threat of release of CCR and the reservoir has already been realized, any failure due to rapid drawdown of the embankment is no longer critical to the overall containment of the now-released contents of the CCR unit.

[12] Wieland, M., ''Seismic Design and Performance Criteria for Large Storage Dams'', Proc. 15th World Conf. on Earthquake Engineering, Lisbon, Portugal, Sep. 24–28, 2012.

event, the Agency assessed various return periods and chose a conservative 2500 year return period. The use of this ''return'' period was chosen because it is conservative, reflects the fact that many CCR impoundments are located in active seismic zones, and the use of a conservative ''return'' period ensures that if a unit meets the seismic FOS it is unlikely to fail under most seismic events. By evaluating seismic stability under a conservative return period and requiring the unit to maintain structural stability under that design seismic event, the likelihood of a seismic event occurring at the location of the CCR surface impoundment in which the strength of the unit is exceeded and the unit fails is considerably reduced. Additionally, the unit can reasonably be anticipated to withstand seismic events of a more frequent return period (*i.e.,* smaller magnitude).

The Agency assessed CCR impoundments and classified them as having seismic stability if modeling results of critical failure surfaces were calculated to have a FOS greater than 1.0 under the specified seismic loading condition. The Assessment Program found that most CCR impoundments did meet the required seismic FOS. This rule also adopts this seismic stability FOS under the 2% probability of exceedance in 50 years event.

The Assessment Program found that many CCR impoundments had not undergone static or seismic analyses in sufficient detail that an independent professional engineer could assert that they were stable. The assessments gave impoundments a condition rating of ''poor'' if the utility was unable to provide static and seismic studies of their units conducted in a fashion which represented acceptable professional engineering practice. As the Assessment Program advanced, many utilities independently conducted new or updated static and seismic analyses of CCR surface impoundments in anticipation of their facilities being assessed. By the end of the program, virtually all facilities had conducted or were in the process of conducting static and seismic analyses. While some utilities noted concern over the costs of conducting additional static or seismic stability studies, none found that completing these studies presented any significant engineering challenges.

(3) Liquefaction Factors of Safety

Liquefaction FOS means the factor of safety determined using analysis under liquefaction conditions. Liquefaction is a phenomenon which typically occurs in loose, saturated or partially-saturated soils in which the effective stress of the soils reduces to zero, corresponding to a total loss of shear strength of the soil. The most common occurrence of liquefaction is in loose soils, typically sands. The liquefaction FOS determination in the final rule is used to determine if a CCR unit would remain stable if the soils of the embankment of the CCR unit were to experience liquefaction. EPA relied primarily on one source to evaluate the appropriate methods to determine if a dam would remain stable under liquefaction conditions. This source was ''Soil Liquefaction during Earthquakes,'' Idriss and Boulanger, Earthquake Engineering Research Institute, 2008.[13] EPA also reviewed several technical resources regarding soil liquefaction, including ''Ground Motions and Soil Liquefaction During Earthquakes,'' Seed and Idriss, 1982,[14] ''Liquefaction Resistance of Soils: Summary report from the 1996 and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils,'' Youd and Idriss, 2001,[15] and *Seismic Design Guidance for Municipal Solid Waste Landfill Facilities,* US EPA, Office of Research and Development, 1995.[16] These documents are viewed as generally accepted guidance on how to conduct liquefaction potential analyses and residual strength analyses under post-liquefaction conditions.

As noted earlier, in performing the assessments, EPA assessed the liquefaction potential of soils that compose the embankments of the CCR unit to determine if the soils present in the embankment were of the soil classification and configuration that was susceptible to liquefaction. This determination was based on evidence available through interviews with facility personnel, construction documentation, or representative soil sampling, such as information provided by corings and borings. Identical to the requirements for seismic factor of safety calculation, EPA selected a return period for a seismic event for analysis of liquefaction potential, under a seismic loading which may induce liquefaction in embankments, of a 2% probability of exceedance in 50 years. The discussion of the selection of this return period can be found in the ''Seismic Factor of Safety'' section above.

The Agency assessed CCR impoundments and classified them as having stability under liquefaction conditions if representative soil sampling, anecdotal evidence from interviews with facility personnel, or construction documentation indicated that there was no susceptibility to liquefaction of the embankment soils or if modeling or analysis in critical failure planes in the embankment expected to be susceptible to liquefaction were calculated to have a FOS greater than 1.00 under post-liquefaction conditions. The Assessment Program found that most CCR surface impoundments did not contain soils in detrimental volumes or configurations in the embankment that would indicate susceptibility to liquefaction. However, the assessment effort found that in embankments with a presence of soils susceptible to liquefaction, most CCR surface impoundments did not meet the required liquefaction FOS.

The Assessment Program found that many CCR surface impoundments had not undergone liquefaction potential analyses or post-liquefaction residual strength analyses in those instances in which liquefaction potential was identified (*i.e.,* soils subject to liquefaction were present). The assessments gave impoundments a condition rating of ''poor'' if there was no information available to characterize the soils of the embankment, and a condition rating of ''poor'' or ''fair'' if post-liquefaction residual strength analysis of soils previously identified as being susceptible to liquefaction had not been available, with the rating dependent on the determined severity of the liquefaction potential in the embankment. Impoundments with calculated liquefaction factors of safety which did not meet or exceed 1.00 were given a condition rating of ''poor.''

As the Assessment Program advanced, many utilities independently conducted new or updated liquefaction potential analyses or residual strength analyses of CCR surface impoundments in anticipation of their facilities being assessed. By the end of the program, virtually all facilities had conducted or were in the process of conducting liquefaction potential analyses or residual strength analyses. While some utilities noted concern over the costs of

[13] *https://www.eeri.org/products-page/monographs/soil-liquefaction-during-earthquakes-3/.*

[14] Seed, H. B., and Idriss, I. M., 1982, ''Ground Motions and Soil Liquefaction During Earthquakes,'' Monograph No. 5, Earthquake Engineering Research Institute, Berkeley, California, pp. 134.

[15] Youd, T. L., Idriss, I. M., 2001, ''Liquefaction Resistance of Soils: Summary report from the 1996 and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils.'' Journal of Geotechnical and Geoenvironmental Engineering, ASCE.

[16] United States EPA, Office of Research and Development, 1995, EPA/600/R–95/051, RCRA Subtitle D (258) Seismic Design Guidance for Municipal Solid Waste Landfill Facilities. Available as of the Writing of this policy at *www.epa.gov/clhtml/pubtitle.html* on the U.S. EPA Web site.

conducting additional liquefaction potential or residual strength studies, none found that completing these studies presented any significant engineering challenges.

Based on its experience in the Assessment Program and subsequent review of numerous technical resources, EPA determined that a post-liquefaction residual strength factor of safety in the embankment of 1.00 is not sufficient. Liquefaction potential analysis and post-liquefaction residual strength analysis involves a larger degree of uncertainties, *e.g.,* liquefiable stratum configuration, in assumptions and analysis which must be accounted for with a factor of safety above 1.00. The final rule therefore requires CCR surface impoundments which are constructed of soils determined to be susceptible to liquefaction to meet or exceed a liquefaction factor of safety of 1.20. EPA has determined that 1.20 is an appropriate liquefaction factor of safety based on several technical guidances and memos, including *Federal Guidelines for Dam Safety: Earthquake Analyses and Design of Dams,* Document 65, FEMA May 2005, which states that ''post-liquefaction factors of safety are generally required to be a minimum of 1.2 to 1.3.'' [17] [18] [19] [20] [21]

c. Impoundment Height and Relationship to Regulatory Requirements

During the Assessment Program, the Agency reviewed the stability issues related to various heights of impoundments. The Assessment Program concluded that impoundments with heights less than five feet or those retaining less than 20 acre feet were unlikely to cause significant environmental or economic loss should they undergo a catastrophic failure. The Agency's review of MSHA and FEMA guidance also noted that ''small'' units were unlikely to cause significant losses should they fail. Based on the Agency's experience and FEMA and MSHA's guidance, the Agency has concluded that there is a substantial benefit in having impoundments which exceed a specified size threshold, *i.e.,* height of five feet or more and capacity of 20 acre-feet or more or a height of 20 feet or more determine their static, seismic, and liquefaction FOS on a regular basis. The analyses and experience gained in conducting the Assessment Program indicates that a catastrophic failure of a CCR surface impoundment is unlikely to occur so long as the factors of safety are maintained or exceeded throughout the unit's operating life. This conclusion is also consistent with relevant guidance and regulations which do not require such evaluations for units below a certain size threshold.

d. Hazard Potential Ratings

Each impoundment assessed in the Assessment Program was given a Hazard Potential Classification rating of either *Less-than-Low, Low, Significant, and High.* Previous classifications were reviewed and amended as necessary to reflect guidance developed for the Assessment Program. The hazard potential ratings refer to the potential for loss of life or damage if there is a dam failure. The ratings do not refer to the condition or structural stability of the dam. Four hazard potential classifications were used in assessing the impoundments in the Assessment Program:

High Hazard Potential—Dams assigned the high hazard potential classification are those where failure or mis-operation will probably cause loss of human life.

Significant Hazard Potential—Dams assigned the significant hazard potential classification are those dams where failure or mis-operation results in no probable loss of human life, but can cause economic loss, environment damage, disruption of lifeline facilities, or impact other concerns. Significant hazard potential classification dams are often located in predominantly rural or agricultural areas, but could be located in areas with population and significant infrastructure.

Low Hazard Potential—Dams assigned the low hazard potential classification are those where failure or mis-operation results in no probable loss of human life and low economic and/or environmental losses. Losses are principally limited to the owner's property.

Less Than Low Hazard Potential—Dams which do not pose high, significant, or low hazard potential.

There is a substantial benefit in having owners or operators of all CCR impoundments determine the hazard potential classification of their units. The Assessment Program found that many CCR surface impoundments had not been given a hazard potential classification and consequently, their potential threat to human health and the environment if a failure were to occur was not clearly identified, nor had response plans been developed to respond to any catastrophic failure. Moreover, these classifications should be updated over time, particularly to account for changes such as population growth, construction of key infrastructure, or changes to the impoundment's size or operation. The Assessment Program also found that some states do not classify CCR impoundments as ''dams'' and therefore those units may not be required to determine their hazard potential classification or otherwise evaluate the potential effects of a catastrophic failure. Consistent with the guidance from ASDSO, FEMA, and the state of New Jersey, this rule requires that all diked CCR impoundments determine their hazard potential classification according to the definitions set out in this regulation. For those units with a hazard potential classification of significant or high, the owner or operator of such impoundments is also required to develop an Emergency Action Plan to address the higher potential impacts of a potential failure.

e. Condition Ratings

While the rule does require facilities to evaluate the same engineering factors that went into developing these ratings, the rule does not require that each impoundment be given a condition rating. After evaluation of the use of these ratings, the Agency determined that the rating may have relied too heavily on subjective factors. For that reason, this rule requires that the qualified professional engineer certify, based on quantitative determinations, that an impoundment meets the requirements for FOS and hydraulic and hydrologic capacity. This approach is less subjective and allows the professional engineer to make quantifiable certifications.

IV. Bevill Regulatory Determination Relating to CCR From Electric Utilities and Independent Power Producers

As discussed in the preceding sections, in the proposed rule EPA reopened its August 1993 and May 2000 Regulatory Determinations regarding CCR generated at electric utilities and independent power producers, to re-evaluate whether regulation of CCR under RCRA subtitle C is necessary in light of subsequent information. EPA explained that this was based on several

[17] US Bureau of Reclamation (USBR), ''Water Operation and Maintenance Bulletin No. 222,'' Denver, Colorado, December 2007.

[18] *http://www.oregon.gov/odot/hwy/bridge/docs/bddm/pdfs/psha.pdf.*

[19] Canadian Dam Association. Canadian Dam Safety Guidelines, 2007, 88 pp.

[20] Sonmez, H., 2003. Modification of the liquefaction potential index and liquefaction susceptibility mapping for a liquefaction-prone area (Inegol, Turkey), Env. Geology, (44): 862–871.

[21] Seed, R.B., Cetin, O.K., Moss, R.E.S., Kammerer, A.M., Wu, J., Pestana, J.M., Riemer, M.F., Sancio, R.B., Bray, J.D., Kayen, R.E., Faris, A., 2003. Recent advances in soil liquefaction engineering: a unified and consistent framework, 26th annual ASCE L.A. Geot. Spring Sem., Long Beach, California, April 30, 71 pp.

relatively recent developments, such as a newly completed quantitative risk assessment that concluded that the disposal of CCR in unlined waste management units posed substantial risks, with upper end risk estimates ranging from 10^{-2}–10^{-4}. Citing to the recent structural failures of surface impoundments, the proposed rule also noted that these wastes have caused greater damage to human health and the environment than EPA originally estimated. Finally, EPA explained that recently collected information regarding the existing state regulatory programs had called into question whether those programs, in the absence of national minimum standards specific to these wastes, had sufficiently improved to address the gaps originally identified in the May 2000 Regulatory Determination. EPA ultimately concluded that federal regulation of this material was necessary, but did not reach any conclusion as to whether regulation under subtitle D would be sufficient or whether regulation under subtitle C would be necessary to adequately address the risks.

Of the over 450,000 comments received on the proposed rule, the vast majority focused on whether the Bevill exemption should be retained, and the corresponding question of whether CCR regulations should be established under RCRA subtitle C or subtitle D. In terms of the sheer numbers, the majority of commenters supported a decision to revoke the Bevill exemption and to regulate CCR under a subtitle C rule. These commenters, largely individual members of the public and environmental groups, generally argued that the Bevill exemption should be revoked because state programs have failed to adequately regulate the disposal of CCR and because the risks associated with the management of these wastes are significant. In support of both points, these commenters pointed to the fact that the number of damage cases that have been discovered has increased substantially since the original 2000 Regulatory Determination, and have continued to grow since publication of the proposed rule in 2010.

By contrast, state organizations, individual states, and industry groups (electric utilities, recycling firms, trade associations), largely favored a subtitle D rule. Overall, these commenters raised concern about the costs of the subtitle C regime, arguing that the subtitle C requirements were more stringent than necessary to address the risks from CCR disposal. Commenters also raised concern that regulation of these wastes under subtitle C would negatively affect the beneficial use of these materials, arguing that the stigma associated with regulating the disposal of CCR as a hazardous waste would ''cripple'' the current beneficial reuse market. Many of these commenters also argued that EPA lacks the legal authority to regulate these wastes under subtitle C on a variety of grounds, including claims that EPA entirely lacks the authority to revisit its Bevill Regulatory Determination, and that EPA had failed to comply with statutory procedures in doing so.

A. Deferral of a Final Decision on the Bevill Regulatory Determination for CCR Destined for Disposal

In determining whether the Bevill exemption should be retained for CCR, EPA must evaluate and weigh eight factors that were enumerated in section 8002(n) of RCRA. 42 U.S.C. 6921(b)(3)(C). The eight factors are: (1) The source and volumes of CCR generated per year; (2) present disposal and utilization practices; (3) potential danger, if any, to human health or the environment from the disposal and reuse of CCR; (4) documented cases in which danger to human health or the environment from surface run-off or leachate has been proved; (5) alternatives to current disposal methods; (6) the cost of such alternative disposal methods; (7) the impact of those alternatives on the use of coal and other natural resources; and (8) the current and potential utilization of CCR. 42 U.S.C. 6982(n).

EPA addressed each of these study factors in the 1988 and 1999 Reports to Congress, and in reaching our decisions in the August 1993 and the May 2000 Regulatory Determinations to maintain the Bevill exemption for CCR. 58 FR 42466 (August 9, 1993); 65 FR 32214 (May 22, 2000). Consequently, in considering whether to reverse these Regulatory Determinations for CCR destined for disposal, EPA reexamined the RCRA section 8002(n) study factors against all of the available data, which included both the data that formed the basis for the May 2000 Regulatory Determination and the most recent data available. (See 75 FR 35150–35156.)

As discussed at length in the proposed rule, three of these factors weighed the most heavily in the Agency's decision to reconsider its previous Regulatory Determinations. (See 75 FR 35133 and 35156–35158.) The first of these related to the extent of the risks posed by the current management of these wastes. Since the 2000 Regulatory Determination, EPA had completed a quantitative risk assessment that estimated significant risks to human health and the environment. EPA's 2010 CCR risk assessment estimated the cancer risk from arsenic that leaches into groundwater from CCR managed in units without composite liners to exceed EPA's typical risk thresholds of 10^{-4} to 10^{-6}. For example, depending on various assumptions about disposal practices (*e.g.,* whether CCR is co-disposed with coal refuse), groundwater interception and arsenic speciation, the 90th percentile risks from unlined surface impoundments ranged from 2×10^{-3} to 1×10^{-4}. The risks from clay lined surface impoundments ranged from 7×10^{-2} to 4×10^{-5}. Similarly, estimated risks from unlined landfills ranged from 5×10^{-4} to 3×10^{-6}, and from 2×10^{-4} to 5×10^{-9} for clay-lined landfills. EPA's risk assessment also estimated Hazard Quotients (HQs)[22] above 1 for other metals, including selenium and lead in unlined and clay-lined units. However, a number of technical questions were raised regarding this quantitative risk assessment that called into question the accuracy of these risk estimates.

A second and equally significant consideration related to how effectively state regulatory programs address the risks associated with the improper management of these wastes. The existing reports on state regulatory programs had called into question whether the trend in improving state regulatory regimes that EPA identified in May 2000 had materialized to the degree anticipated in the Regulatory Determination. EPA noted concern about the lack of substantial details regarding the full extent of state regulatory authority over the disposal of these materials, and the manner in which states have, in practice, implemented this oversight.

The final consideration, which is tightly related to the first two, was the recent information documenting continued instances involving the contamination of ground or surface water from the management of these wastes. Since the 2000 Regulatory Determination EPA had gathered or received information on 67 ''proven or potential'' cases involving damage to (*i.e.,* contamination of) ground and surface water, and to human health and the environment from improper management of CCR in landfills and surface impoundments. These also included cases involving the structural failure of surface impoundments and the catastrophic release of CCR.

[22] For more information on HQs please see Unit X. Risk Assessment of this preamble.

For each of these key areas, EPA identified a number of issues on which the absence of critical information prevented the Agency from reaching an initial decision on whether to revise the Bevill Determination. Some of these issues or uncertainties have been resolved during the development of the final rule, either as a result of information received from commenters or through additional information and analyses EPA obtained or developed, which were held out for comment in subsequent NODAs. See 75 FR 35128 (October 21, 2010) and 78 FR 46940 (August 2, 2013). However, as discussed in more detail below, critical information necessary to make a final Regulatory Determination is still lacking in two of these three areas. This information bears directly on the extent and magnitude of the risks over the course of the next several years, and the degree to which those risks can be managed sufficiently under each of the two regulatory structures available to the Agency. In the absence of this information, EPA is unable to reach a conclusion on the issue that is central to a Bevill Determination: Whether the risks presented by management of CCR waste streams can only be adequately mitigated through regulation under RCRA subtitle C. As a consequence, EPA is deferring a final Regulatory Determination for these wastes.[23]

Nevertheless, the record is clear that current management of these wastes can present, and in many cases has presented, significant risks to human health and the environment. Although EPA cannot reach conclusions as to the full extent or magnitude of those risks over the long term, the current level of risk clearly warrants the issuance of federal standards to ensure consistent management practices and a national minimum level of safety.

In the following sections, EPA describes the information that was obtained over the course of the rulemaking relating to each area of concern, and the extent to which the new information addressed the issue.

[23] Because EPA is deferring its final Bevill Determination, EPA has not responded to comments that pertain exclusively to that issue. However EPA has responded to significant comments that relate to topics that are otherwise relevant to the final subtitle D regulation. For example, because EPA is relying on the damage cases to support certain aspects of the technical requirements, EPA has responded to comments relating to the accuracy of the facts involved in the damage cases. EPA has not, however, responded to many comments on state programs because the Agency has made no final conclusions on the adequacy of those programs and is not relying on state programs to support any of the final rule's provisions.

1. Risks Posed by Current Management of CCR and Potential Danger to Human Health From the Disposal of CCR

In the proposed rule, EPA specifically noted that several uncertainties remained in the Agency's quantitative risk analysis of the current management of CCR. Chief among these uncertainties was the evolving character and composition of CCR due to electric utility upgrades and retrofits of multi-pollutant controls needed to comply with the emerging Clean Air Act (CAA) requirements, which could present new or otherwise unforeseen contaminant issues (*e.g.,* addition of calcium bromide to coal prior to combustion increasing mercury capture; use of selective catalytic reduction for post-NO_X controls forming hexavalent chromium). As EPA explained, changes to fly ash and other types of CCR is expected to occur as a result of increased use and application of advanced air pollution control technologies in coal-fired power plants. These technologies include flue gas desulfurization (FGD) systems for SO_2 control, selective catalytic reduction (SCR) systems for NO_X control, and activated carbon injection (ACI) systems for mercury control. These technologies are being installed or are expected to be installed in response to federal regulations, state regulations, legal consent decrees, and voluntary actions taken by industry to adopt more stringent air pollution controls. Use of these more advanced air pollution control technologies reduces air emissions of metals and other pollutants in the flue gas of a coal-fired power plant by capturing and transferring the pollutants to the fly ash and other air pollution control residues. Previous EPA studies of whether increased pollutant content would increase the risks correspondingly were inconclusive. For example, EPA evaluated the environmental fate of metals that are captured in CCR through use of enhanced air pollution controls, by characterizing the leaching behavior of 73 air pollution control residues, using the Leaching Environmental Assessment Framework (LEAF) methodology. Materials were tested over the pH conditions and liquid/solid ratios expected during management via land disposal or beneficial use. Leachate concentrations for most metals were highly variable over a range of coal type, facility configurations, and air pollution control residues. In addition, the data showed significantly different leaching behavior for similar residue types and facility configurations. Overall, the variability in leaching of the metals in the CCR was greater than the variability in totals concentrations by several orders of magnitude, suggesting that total pollutant content may not be predictive of leaching behavior, and consequently the risks.[24]

The Agency received no data from commenters that would aid in resolving this uncertainty. To try to establish some parameters around the uncertainty, EPA attempted to develop estimates of the extent to which this issue could meaningfully affect the risks.

As an initial step, EPA focused on mercury pollution controls, as mercury levels in these wastes was an issue of particular concern in the public comments. It has been established that mercury pollution controls can affect both the mercury content and the general leaching behavior of ash (US EPA 2006, 2008, 2009). Using the limited data available, EPA attempted to evaluate the extent to which mercury controlled wastes could ultimately affect the overall risk associated with disposal of CCR.

EPA conducted a sensitivity analysis that filtered the full 2014 risk assessment results for the subset of fly ash samples generated by facilities that have currently installed ACI systems. The samples were collected from five different facilities that were either installing or evaluating an ACI system for increasing mercury capture. At each facility, samples were collected both before and after the installation of an ACI system. Ultimately the results were inconclusive, likely because of the small sample size, and EPA can draw no conclusions about the exact effects of ACI systems on the risks from CCR disposal. Nevertheless, the analysis provided some useful information. Capturing and transferring pollutants from air emission to the fly ash and other air pollution control residues would normally be expected to increase the risks associated with disposal of these wastes. EPA's analyses, however, showed only a marginal difference in risks for ash generated with or without the use of an ACI system, and in some instances the risks decreased slightly with the addition of activated carbon. The significance of these results should not be overstated—the observed decreases were not consistent and were thought to be an artifact of the relatively small number of model iterations. It is also important to remember that these results provide no information about the potential effects from the installation of

[24] Thorneloe, S, Kosson, D., Sanchez, F., Garrabrants, A.C., and Helms, G., Evaluating the Fate of Metals in Air Pollution Control Residues from Coal-Fired Power Plants, Environ. Sci. Technol. 2010, 44, 7351–7356.

FGD systems for SO_2 control, or SCR systems for NO_X control, any of which could also significantly affect the characteristics of the wastes. But these results also suggest that EPA should be cautious about assuming that the risks will necessarily increase as a result of the imposition of additional air pollution controls.

Other uncertainties in the risk assessment developed for the proposal related to the extent to which some sampled data with high concentrations of constituents used in the risk assessment accurately reflect coal ash leaching from landfills or surface impoundments. For example, as explained in the proposed rule, some data reflected pore water taken in the upper section of a surface impoundment where coal refuse was placed. There were acid generating conditions and high concentrations of arsenic, but the data demonstrated that the underlying coal ash neutralized the acid conditions and greatly reduced the arsenic which leached from the bottom of the impoundment. EPA also noted that much of the pore water samples and leachate data were several years old, and questions had been raised whether these data accurately reflected current management practices. Finally, EPA noted that recent research indicated that traditional leach procedures (*e.g.,* Toxicity Characteristic Leaching Procedure (TCLP) and Synthetic Precipitation Leaching Procedure (SPLP)) may underestimate the actual leach rates of toxic constituents from CCR under different field conditions.

First, regarding the question of appropriate pH conditions in CCR units, and the resulting leachate concentrations in impoundments where coal refuse was placed, EPA obtained data during the development of this rule directly relevant to this issue. A survey conducted by the Electric Power Research Institute (EPRI) in 1995 had shown that 34 percent of unlined landfills and 68 percent of unlined surface impoundments actively managed CCR with coal refuse. However, more recent data collected by EPA as part of the Clean Water Act ELG rulemaking in 2009–2010 indicates that this management practice has declined significantly to approximately five percent of current units.

EPA also obtained sufficient data to resolve concerns about the accuracy of the concentrations in pore water and leachate used in the risk assessment. EPA received a substantial amount of data on CCR chemical constituents from commenters, which included total concentrations, pore water, and leaching test results for various types of CCR, *i.e.,* bottom ash, FGD gypsum, FGD sludge, fly ash cenospheres, boiler slag, and combined waste streams. This included data from several EPRI reports, which provided field leachate results for bottom ash, fly ash, and FGD solids from a number of landfills and surface impoundments. EPA also received leachate data from the Alaska Department of Environmental Conservation, the Michigan Department of Natural Resources and Environment (MI DNRE), and from the Maryland Department of the Environment on total metals, TCLP, and SPLP results for bottom ash and fly ash. Included among these data were TCLP results for 102 CCR samples and 12 FGD gypsum samples, and two landfill leachate samples, as well as several laboratory reports on CCR leachate from 2008 through 2010. EPA also received several reports from the University of North Dakota Energy & Environmental Research Center, with leaching test results for 58 fly ash, five FGD, and four FGD gypsum samples using various leaching methods other than TCLP, and TCLP mercury results for 15 fly ash samples, as well as leaching test results for five fly ash and two bottom ash samples using 18-hr, 30-day, and 60-day leach methods, plus bulk and trace element data for five fly ash samples, two bottom ash samples, and one slag sample. (See 76 FR 63252, October 12, 2011.)

In addition to the data submitted by commenters, EPA's Office of Research and Development (ORD), in collaboration with Vanderbilt University (VU), developed additional CCR leaching data using a revised methodology, the Leaching Environmental Assessment Framework, or LEAF, consisting of four methods that evaluate leaching potential for various waste forms at different plausible pH values and liquid-solid ratios, in order to more accurately simulate leaching potential over a variety of field conditions. The LEAF methods went through validation working with 20 different laboratories, different waste matrices, and documented in two EPA reports finding good agreement between the labs for the four methods.[25] In addition, EPA compiled decades of data for ten different case studies to compare field and laboratory leach data.[26] These data also showed LEAF methods to be a good predictor of field leachate behavior using geochemical speciation modeling for factors such as oxidation that are difficult to account for in the lab. When considered along with the methods validation, the field-to-lab leachate data comparison provides additional confidence that LEAF methods can more accurately predict environmental release over a range of materials, waste form, pH, liquid-solid ratio, and other parameters influencing leaching behavior such as calcium depletion for a material.

In updating the risk assessment for the final rule, EPA relied on surface impoundment pore water data and impoundment wastewater data, including the data submitted by commenters. For landfills, EPA only used LEAF data to characterize the leachate for the range of materials resulting from various air pollution control technologies. The CCR data documented in three EPA reports[27] and summarized in Thorneloe et al, 2010[28]

[25] Garrabrants A.C., D.S. Kosson, H.A. van der Sloot, F. Sanchez and O. Hjelmar (2010) Background information for the Leaching Environmental Assessment Framework (LEAF) Test Methods, EPA–600/R–10/170, U.S. Environmental Protection Agency, Air Pollution Prevention and Control Division, December 2010.

Garrabrants A.C., D.S. Kosson, L. Stefanski, R. DeLapp, P.F.A.B. Seignette, H.A. van der Sloot, P. Kariher and M. Baldwin (2012a) Interlaboratory Validation of the Leaching Environmental Assessment Framework (LEAF) Method 1313 and Method 1316, EPA/600/R–12/623, U.S. Environmental Protection Agency, Air Pollution Prevention and Control Division, September 2012.

Garrabrants A.C., D.S. Kosson, R. DeLapp, P. Kariher, P.F.A.B. Seignette, H.A. van der Sloot, L. Stefanski and M. Baldwin (2012b) Interlaboratory Validation of the Leaching Environmental Assessment Framework (LEAF) Method 1314 and Method 1315, EPA–600/R–12/624, U.S. Environmental Protection Agency, Air Pollution Prevention and Control Division, September 2012.

[26] Kosson D.S., van der Sloot, H.A., Seignette, P.F.A.B. 2014. Leaching Test Relationships, Laboratory-to-Field Comparisons and Recommendations for Leaching Evaluation using the Leaching Environmental Assessment Framework (LEAF), EPA–600/R–14/061. EPA Office of Research and Development, National Risk Management Research Laboratory, Research Triangle Park, NC, 27711. December.

[27] Sanchez F., R. Keeney, D.S. Kosson and R. DeLapp (2006) Characterization of Mercury-Enriched Coal Combustion Residues from Electric Utilities using Enhanced Sorbents for Mercury Control, EPA–600/R–06/008, U.S. Environmental Protection Agency, Air Pollution Prevention and Control Division, February 2006.

Sanchez F., D.S. Kosson, R. Keeney, R. DeLapp, L. Turner and P. Kariher (2008) Characterization of Coal Combustion Residues from Electric Utilities using Wet Scrubbers for Multi-pollutant Control, EPA–600/R–08/077, U.S. Environmental Protection Agency, Air Pollution Prevention and Control Division, July 2008.

Kosson D.S., F. Sanchez, P. Kariher, L.H. Turner, R. DeLapp, and P. Seignette (2009) Characterization of Coal Combustion Residues from Electric Utilities—Leaching and Characterization Data, EPA–600/R–09/151, U.S. Environmental Protection Agency, Air Pollution Prevention and Control Division, December 2009.

[28] Thorneloe S.A., D.S. Kosson, F. Sanchez, A.C. Garrabrants and G. Helms (2010) ''Evaluating the fate of metals in air pollution control residues from coal-fired power plants,'' *Environmental Science and Technology,* 44, 7351–7356.

provides a robust characterization of air pollution control residues from coal-fired power plants and indicates that leaching rates can vary by several orders of magnitude, depending on pH levels and the amount of liquid that comes into contact with the CCR solids (*i.e.,* the liquid to solid ratio).

The 2014 risk assessment incorporates these new data, and accounts for both the pH of the waste in field conditions, as well as the liquid-to-solid ratio of the leachate and CCR, which effectively addresses the concerns raised in the proposed rule that TCLP and SPLP methods could underestimate leachate concentrations.

A further area of uncertainty related to one of the primary inputs into the risk assessment. As noted in the proposed rule, the Agency's risk estimates were based on the existing cancer slope factor of 1.5 $mg/kg/d^{-1}$ for arsenic in EPA's Integrated Risk Information System (IRIS). However, EPA noted that was in the process of revaluating the arsenic cancer slope factor in light of recent recommendations from the National Research Council (NRC) of the National Academy of Sciences (NAS) in ''Critical Aspects Arsenic in Drinking Water, 2001 Update.'' In the proposal, EPA estimated that using this NRC data analysis would increase the individual risk estimates by approximately 17 times.

EPA is currently evaluating the arsenic cancer slope factor in light of more recent NRC recommendations, regarding the approach and the science for estimating cancer and non-cancer risk in ''Critical Aspects of EPA's IRIS Assessment of Inorganic Arsenic, (NRC 2013).'' EPA is in the process of implementing these recommendations, but to date has been unable to finalize its IRIS reassessment. Nor did EPA receive any other information during the development of this final rule that would help to resolve this uncertainty.

A final source of uncertainty in the risk assessment developed for the proposed rule related to the potential impact from the interception of contaminated groundwater plumes by surface water bodies that exist between a waste management unit and a down-gradient drinking water well. It is common for coal-fired utilities to be located near water bodies, which are used as a source of cooling water and waste conveyancing. Releases from surface impoundments located in close proximity to water bodies can be intercepted, which can significantly affect the contaminants that reach drinking water wells. For example, surface impoundments are commonly placed next to rivers, which can intercept the leachate plume and prevent contamination of drinking water wells on the other side of the river. Also, in such circumstances the direction of groundwater flow on both sides of the river may be towards the river; thus, the drinking water well on the opposite side of a river may not be impacted.

Over the course of the rulemaking, EPA was able to obtain sufficient data to model the impact from interception of contamination by surface water bodies. The risk assessment developed for the final rule accounts for the interception of the groundwater contamination plume by surface water bodies, and the resulting decrease in constituent mass to downstream drinking water sources. As a consequence of this modeling, the median risks for surface impoundments and landfills were substantially lower than both the high-end and median risks modeled in the 2010 risk assessment, *i.e.,* by approximately an order of magnitude.

2. Adequacy of Existing State Regulatory Oversight

The assessment of state regulatory programs in the proposed rule was based largely on two reports: A joint U.S. Department of Energy (DOE) and EPA study completed in 2006, ''Coal Combustion Waste Management at Landfills and Surface Impoundments, 1994–2004,'' and a 2009 survey conducted by the Association of State and Territorial Solid Waste Management Officials (ASTSWMO). EPA's preliminary conclusion was that while states seem to be regulating landfills to a greater extent than in 2000, significant gaps in state programs appeared to remain, particularly with respect to the oversight of surface impoundments.

In reaching this conclusion EPA noted the following findings from the DOE/EPA study: only 19 percent (three out of 19) of the surveyed surface impoundment permits included requirements addressing groundwater protection standards (*i.e.,* contaminant concentrations that cannot be exceeded) or closure/post-closure care, and only 12 percent (two out of 12) of surveyed units were required to obtain bonding or financial assurance. The EPA/DOE report also concluded that approximately 30 percent of the net disposable CCR generated was potentially exempt from all state solid waste permitting requirements (EPA/DOE Report at pp 45–46). For example, at the time of the report, Alabama did not regulate CCR disposal under any state waste authority and nor had a dam safety program. Texas (the largest coal ash producer) did not require permits for waste managed on-site, which is defined as waste managed at any site owned by the generator, up to 50 miles away from the generating facility. Finally, the report found that a number of states only regulated surface impoundments under CWA authorities, and consequently primarily addressed the risks from effluent discharges to navigable waters, but did not require liners or groundwater monitoring.

The more recent 2009 ASTSWMO survey reached similar conclusions. With respect to liner requirements, 36 percent of surveyed states did not have minimum liner requirements for CCR landfills, while 67 percent did not have CCR liner requirements for surface impoundments. Similarly, 19 percent of states surveyed did not have minimum groundwater monitoring requirements for landfills and 61percent did not have groundwater monitoring requirements for surface impoundments. The 2009 ASTSWMO survey also indicated that only 36 percent of states regulated the structural stability of surface impoundments.

In the proposal, EPA identified several issues that complicated its preliminary assessment and prevented the Agency from reaching overall conclusions as to the adequacy of state regulatory programs. First, EPA raised concern about the absence of any real details in the two reports regarding how states, in practice, oversee the disposal or other solid waste management of CCR. For example, even though the disposal units might not be regulated under the state solid waste provisions, some states may use performance based standards or implement requirements to control CCR landfills and surface impoundments under other state programs. Second, EPA noted that most of the more recent data primarily focused on the requirements applicable to new management units, which only represented approximately 10 percent of currently operating units. EPA had little, if any, information that described the extent to which states and utilities had implemented requirements, such as groundwater monitoring, on the many existing landfills and surface impoundments that receive CCR. Moreover, the information in the record for the proposal with respect to these older units was fifteen years old. EPA assumed it to be unlikely that states would have required existing units to install liners, but suggested states may have been more likely to have imposed groundwater monitoring for such units over the last 15 years.

EPA also identified several issues that would be relevant to the Agency's evaluation of the overall adequacy of state regulatory programs. Specifically, EPA explained that it would consider how state regulatory programs have, in practice, evaluated and imposed requirements to address: (1) Leachate collection; (2) groundwater monitoring; (3) whether a unit must be lined and the type of liner needed; (4) the effectiveness of existing management units as opposed to new management units; (5) whether the state requires routine analysis of CCR; (6) whether financial responsibility requirements are in place for the management of CCR; (7) the extent of permit requirements, including under what authorities these disposal units are permitted, the types of controls that are included in permits, and the extent of oversight provided by the states, (8) whether state programs include criteria for siting new units; (9) the extent of requirements for corrective action, post-closure monitoring and maintenance; (10) the state's pattern of active enforcement and public involvement; and (11) whether or not these facilities have insurance against catastrophic failures.

EPA received a substantial amount of information on state programs from commenters. Extensive comments were submitted by a coalition of environmental groups, outlining the alleged gaps in state regulatory programs applicable to the management of CCR. These comments contained a comprehensive analysis of 37 state programs based on the findings of the DOE/EPA 2006 report as well as on an independent compilation of state program requirements. According to these commenters' analysis, only four states (representing approximately four percent of the CCR generated in the U.S. in 2005) required groundwater monitoring in all new and existing landfills, and only six states (representing approximately 19 percent of the CCR generated in 2005) required groundwater monitoring in all new and existing surface impoundments; only five states (representing approximately seven percent of the CCR generated in 2005) required composite liners for all new landfills; and only four states (representing approximately 19 percent of the CCR generated) required composite liners for all new surface impoundments. The commenters' analysis discounted any state law that included any provision that granted permit writers discretion to modify the requirement on a case-by-case basis, and/or to grant waivers and exemptions based on the waste's toxicity, onsite location, and management practice.

EPA also received comments from ASTSWMO, the Environmental Council of the States (ECOS), and 36 individual states. In its comments, ASTSWMO submitted a report with revisions of the aggregated statistics in its 2009 report, which they claim demonstrated that state CCR programs were more robust than described in the proposed rule. These commenters generally agreed with EPA's conclusion that state requirements for key CCR requirements are typically more robust for landfills than for surface impoundments. ASTSWMO's comments included the following examples: 71 percent of the surveyed states required a liner for landfills, compared to 65 percent that required that surface impoundments be lined; 87 percent of surveyed states required groundwater monitoring at landfills, compared to 67 percent of states that required groundwater monitoring at surface impoundments; and while 83 percent of surveyed states required structural stability monitoring at landfills, only 64 percent of surveyed states required it at surface impoundments. The sole exception related to permit requirements, where the report claimed that 91 percent of the surveyed states required a permit of some type for surface impoundments, as compared to 86 percent of states that required a permit for landfills. In addition, ASTSWMO claimed that all 42 surveyed states had the authority to require remediation. The report also alleged that in 43 of 44 states, states had the authority to require surface impoundments to implement repair and maintenance efforts during operation. ASTSWMO also claimed that 43 out of 44 states required that steps be taken to protect human health and the environment, and that 41 of 43 states also had authority to require closure.

According to this revised survey, state requirements also vary with respect to whether they applied to all waste units, or only to new units or lateral expansions. ASTSWMO stated that in 34 percent of the surveyed states, liner requirements applied equally to new and existing landfills, and to both existing and new surface impoundments in 46 percent of the surveyed states. Similarly, ASTSWMO stated that groundwater monitoring was required for both existing and new landfills in 82 percent of the surveyed states, and to both existing and new surface impoundments in 74 percent of the surveyed states.

Nineteen states and state organizations also directly responded to the environmental groups' report by submitting comments on their programs, although only four of these states were among the leading CCR generators: Kentucky, North Dakota, Ohio, and Michigan. These states identified specific instances where the assertions made by the environmental groups were factually incorrect or omitted relevant information. In response to both the proposed rule and the NODA (76 FR 63252, October 12, 2011) most states provided only summaries of their regulatory programs rather than detailed descriptions.

As EPA explained in the proposed rule, there are significant limitations to the kind of aggregated survey statistics presented in ASTSWMO's comments. Such statistics fail to provide the information necessary to meaningfully address the question of how, in practice, state programs regulate the relevant risks presented by the management or disposal of CCR, which was the issue that EPA explained was necessary to resolve. For example, even assuming that 91 percent of the surveyed states actually do require a permit of some type for surface impoundments, this provides no information on the nature or extent of the specific requirements in the permit. As noted in the proposal, most CCR surface impoundments are regulated under a NPDES permit, and while the risks from effluent discharges to navigable waters are addressed, these units are not subject to the provisions designed to protect groundwater, such as liners or groundwater monitoring. Nor does it address the extent of the requirement; for example, although Texas generally requires landfills to be permitted and to monitor groundwater, the majority of CCR units are exempt from these requirements because all industrial wastes managed on-site (*i.e.,* any site owned by the generator, up to 50-miles away from the generator's facility) are exempt. Finally, since the ASTSWMO survey does not identify the individual surveyed states but merely presents aggregated statistics, this information cannot be correlated with the amount of CCR generated, which significantly limits its value; for example, information demonstrating the strength of the regulatory program in a state responsible for two percent of the net CCR generated nationally is less significant than similar information on a state responsible for 25 percent of the net CCR generated.

In addition to the information provided by commenters, EPA independently reviewed state statutes and regulations, with a more detailed focus on the 16 states responsible for approximately 74 percent of the CCR generated in 2009. It is clear from this

review, as well as from information submitted by the commenters, that the degree of state regulatory oversight of these wastes and the overall protectiveness of the particular state programs varies widely.

Overall, the information from commenters and from EPA's own review of state programs generally confirms EPA's original conclusion that significant gaps remain in many state programs. Some programs provide minimal or no regulatory oversight of CCR units. For example, Arizona, New Mexico, and Utah have no regulations applicable to CCR units or entirely exempt CCR from state regulations governing solid waste. Similarly, Mississippi, Montana, and Texas (the largest coal-ash producer) exempt the on-site disposal of CCR (as ''non-hazardous industrial solid waste'') from some or all key requirements, such as permits or groundwater monitoring.[29] Such exemptions would cover most of the disposal of CCR within the state, as the majority of utilities dispose of their CCR on-site. Other states, such as Florida, Indiana, Ohio and Pennsylvania, exempt CCR landfills or ''monofills'' from many requirements. For example, Indiana regulations consider surface impoundments that are dredged at least annually to be ''storage units'' that are exempt from solid waste regulations, including from corrective action requirements. Many of these states are among the leading generators of CCR wastes. In total, EPA estimates that approximately 20 percent of the net disposable CCR is entirely exempt from state regulatory oversight.

State programs that entirely exempt CCR management from regulatory oversight, however, are the exception. Most states do regulate the management of CCR to varying degrees, although the particular requirements can vary significantly. Still, some general conclusions can be drawn.

Most CCR surface impoundments are permitted exclusively under NPDES or other surface water pollution prevention programs. In these states, requirements to protect groundwater, such as liners or groundwater monitoring systems, are frequently less robust than the corresponding requirements applicable to CCR landfills.

Many state programs require that new disposal units be lined and groundwater monitoring systems installed, although many exempt existing waste units from the liner and groundwater monitoring requirements. Consequently, for newer units, the facts are less alarming: 89 percent of the 114 CCR surface impoundments constructed between 1994 and 2010 have liners, and 70 percent have composite liners. Similarly, 37 of 45 CCR surface impoundments EPA surveyed had installed groundwater monitoring systems. By contrast, 79 percent of the landfills constructed during this timeframe had installed liners, but only 58 percent were composite-lined. However the majority of the older (pre-1994) waste units still lack liners; 63 percent of older landfills have no liners and 63 percent and 24 percent of older surface impoundments have either no liners or clay liners, respectively.

Information on the extent of groundwater monitoring at older units was either unavailable, or was too unreliable to support any conclusions as to the overall number or percentage of older units with groundwater monitoring systems in most states. ASTSWMO's comments in response to the October 2011 NODA identified eight states [30] that required groundwater monitoring at existing facilities, but only a few of these states addressed this issue in their comments. EPA has some anecdotal evidence on the status of groundwater monitoring in six states, including four states that are among the leading CCR generators. In the wake of the Kingston TVA spill, groundwater monitoring wells were installed at 12 of Illinois's existing surface impoundments, almost doubling the number of monitored surface impoundments in the state. However, 55 additional surface impoundments, both active and inactive, still lack groundwater monitoring systems. In Ohio, 44 CCR units, out of a total of 57 CCR units in the state (42 surface impoundments and 15 landfills) still lack groundwater monitoring, even though all of the surface impoundments were permitted decades ago under Ohio's NPDES program. Ohio acknowledged in their comments that the extent of groundwater risks in the state is poorly documented, as 40 out of 44 unlined CCR units do not have a groundwater monitoring system. In sum, the available information is limited, but at least some of that information indicates that significant gaps remain with respect to the implementation of groundwater monitoring requirements under some state regulatory programs.

Of the states that require groundwater monitoring, most appear to require monitoring wells to be placed around the waste unit boundary, although the distance from the unit boundary varies from 50 feet to 150 meters. However, some state programs also authorize a buffer zone or a ''zone of discharge,'' which allows the facility to defer remediation of groundwater contamination for some period of time, usually until the contaminant plume has migrated to the facility site boundary. Florida, Illinois, North Dakota, and Tennessee are among that states with such a regulatory provision. For example, under Florida regulations, primary and secondary maximum contaminant levels (MCLs) do not apply even beyond the ''zone of discharge,'' absent a specific order by state regulatory authorities.

Most state programs allow the state regulatory authority to grant variances or exemptions for some or all of the requirements based on site-specific factors. For example, all of the following states require groundwater monitoring at CCR surface impoundments, but also authorize the regulatory authority to exempt or waive those requirements: Alabama, Florida, Georgia, Illinois, Indiana, Kentucky, North Carolina, North Dakota, Pennsylvania, and West Virginia. Contrary to the analysis presented by the environmental groups' comments, the mere fact that state law grants a permit authority the discretion to tailor requirements to account for a facility's site specific conditions does not support a conclusion that the regulatory program is necessarily inadequate. In fact, EPA noted in the proposal that one of the strengths of the subtitle C program was that, as a result of the permit process, requirements could be tailored to account for site specific conditions. Nor does the existence of a waiver process provide any evidence of actual practices; in their comments, a few states acknowledged that state law allowed for variances, but asserted that none had been requested.

To complicate matters further, several states explained that while state law does not mandate certain requirements, state regulatory authorities have, in practice, begun to require them in more recent permits. For example, several states, including Ohio, Texas, Michigan, Florida, and Kentucky, noted that recent practice was to require older disposal units to retrofit or close where they failed to meet relevant standards. Similarly, it appears that in the 16 leading CCR-generating states, 94 percent of new landfills have installed liners (either composite or clay), although only 19 percent of these state programs actually mandate CCR landfills to install a liner. And although only six percent of these state programs require installation of a liner in a new surface impoundment, 75 percent of

[29] See 30 TX ADC 335.2(d);

[30] Georgia, Illinois, Indiana, Iowa, Montana, Ohio, Pennsylvania, and South Carolina.

new CCR surface impoundments in these states are lined.

All of this information suggests that, at least in some cases, the concerns raised in the proposal regarding the protectiveness of state programs remain warranted. But it also is clear it would be impossible to accurately evaluate whether, in practice, state programs are protective without reviewing individual permit decisions and permit requirements. Such an evaluation would necessarily involve not only a review of the specific permit requirements, but also the site conditions and other factual bases supporting the decision to impose the particular requirements. Unfortunately, this information was not provided by commenters or found in any source currently available to the Agency.

3. Documented Cases in Which Danger to Human Health or the Environment From Surface Run-off or Leachate Has Been Proved

In the proposed rule, EPA described the information it had compiled on specific cases where CCR mismanagement had caused harm to human health or the environment since the 2000 Regulatory Determination. Specifically, EPA explained that it had identified 27 proven damage cases: 17 cases of damage to groundwater, and ten cases of damage to surface water, seven of which are ecological damage cases. Sixteen of the 17 proven damage cases to groundwater involved disposal in unlined units; for the one additional unit, it is unknown whether the unit was lined. EPA also identified 40 potential damage cases to groundwater and surface water. The Agency noted that these numbers likely underestimated the number of damage cases and its expectation that additional cases of damage would be found if a more comprehensive evaluation was conducted, particularly since much of this waste has been (and continues to be) managed in unlined disposal units. EPA also noted its concern that several of the new damage cases involved activities that differ from prior damage cases, including the catastrophic release of waste due to the structural failure of CCR surface impoundments, such as the dam failures that occurred in Martins Creek, Pennsylvania and Kingston, Tennessee, as well as the large-scale placement, akin to disposal, of CCR, under the guise of ''beneficial use.''

EPA noted as well that it had received new reports from industry and environmental and citizen groups regarding damage cases. Industry provided information to demonstrate that many of EPA's listed proven damage cases did not meet EPA's criteria for a damage case to be considered ''a proven damage case,'' that had been developed for purposes of the Bevill Regulatory Determinations. Environmental and citizen groups, on the other hand, had submitted reports alleging the existence of more recent damage cases beyond those EPA had previously documented.

EPA raised questions concerning the following areas associated with the damage cases; first, whether the damage cases discovered to date accurately reflected the true number of damage cases associated with the mismanagement of CCR. Second, EPA highlighted concern regarding the accuracy of the available information on damage cases, as in certain instances, much of the information was largely anecdotal. EPA therefore specifically solicited comments from state regulatory authorities and the facilities involved with the incidents, in the hope of obtaining direct evidence of the facts in each case and to obtain a better understanding of the nature of the damage caused by past and current management practices. For the same reason, on October 12, 2011, EPA published a NODA, soliciting comment on the extensive reports received during the original comment period on the proposed rule. (See 76 FR 63252.)

As discussed in more detail in Unit XI of this document, EPA received a significant number of comments on this topic, both during the original comment period on the proposal, and in response to the NODA. EPA received information on additional damage cases from a number of citizen groups, including the report from Environmental Integrity Project and Earthjustice titled, ''Out of Control: Mounting Damages From Coal Ash Waste Sites,'' which presented information on 31 alleged CCR damage cases that were not included or were not recognized as damage cases in EPA's July 2007 report. EPA also received an August 26, 2010 report by the Environmental Integrity Project, Earthjustice, and the Sierra Club titled ''In Harm's Way: Lack of Federal Coal Ash Regulations Endangers Americans and Their Environment,'' which presented an additional 39 alleged CCR damage cases.[31] EPA also received information on ten additional damage cases from state officials in Michigan and Wisconsin.

EPRI submitted two draft reports titled ''Evaluation of Coal Combustion Product Damage Cases: Volume 1: Data Summary and Conclusions'' (finalized in July 2010), and ''Evaluation of Coal Combustion Product Damage Cases: Volume 2: Case Summaries'' (finalized in September 2010). In these reports, EPRI provided information that, they claimed, showed that many of EPA's previously identified ''proven'' damage cases did not meet EPA's criteria for a damage case to be considered ''proven.'' In response to the 2010 NODA, USWAG submitted a report that reviewed the 70 additional damage cases submitted by citizen groups as part of their comments on the proposed rule. These reports focused primarily on the degree to which the contamination had been contained ''on-site'' or had migrated off-site of the facility.

In Unit XI of this document, EPA discusses at length all of the comments received and its subsequent analysis of the information obtained throughout the rulemaking. In sum, after analyzing all of the information submitted in response to this rulemaking, EPA has confirmed a total of 157 cases, both proven and potential, in which CCR mismanagement has caused damage to human health and the environment. Although EPA expects that additional damage cases will be discovered in response to the installation of the groundwater monitoring systems required by the final rule, overall EPA has a significantly better understanding of the extent and nature of the damage caused by CCR mismanagement than when the proposed rule was issued. EPA has sufficient confidence in the veracity of the information collected to rely on it in making decisions in this rule.

4. Conclusions

EPA explained in the proposed rule that the decision on whether to retain the Bevill exemption is inherently discretionary, in that it ultimately requires the Agency to make a policy judgment as to the appropriate balance among the eight statutory factors. Chief among the several principles that EPA stated would guide its decision was that any action must protect human health and the environment. To this end, EPA singled out three key areas of analyses that bear directly on that guiding principle: the extent of the risks posed by mismanagement of CCR; the adequacy of state programs to ensure proper management of CCR; and the extent and nature of damage cases.

The first of these largely related to the 2010 quantitative risk assessment of the potential for contamination to

[31] EPA also received several additional reports that contained allegations of further damage cases. However, because these were submitted after the close of the comment period, EPA did not evaluate these damage cases for this rulemaking or otherwise consider the information in those reports.

groundwater. During the rulemaking, EPA received information that allowed the Agency to resolve two of the four primary uncertainties identified in the proposal. The risk assessment has been revised with updated pore water concentration data and with LEAF leachate data, and accounts for the potential reduction of contaminants reaching drinking water sources due to interception of contamination by surface water bodies. However, two sources of uncertainty remain: the potential effect of pollution control technologies on the CCR characteristics, and the appropriate IRIS value for arsenic.

EPA's risk assessment evaluated current management practices, and generally did not attempt to account for or evaluate the potential for future changes in the wastes. While EPA has great confidence in the assessment, its ability to definitively resolve this question is therefore limited, given the very real potential for significant changes in CCR characteristics and constituents in the near future, due to the required installation of pollution control technologies. Changes in the CCR characteristics are particularly significant, as the risk assessment concluded that one of the parameters most likely to affect the agency's risk estimates was the characteristic of the wastes.

With respect to the second area, EPA is unable to reach any definitive conclusions as to whether state regulatory programs are so deficient that the level of federal oversight under subtitle C is necessary. Specifically, EPA cannot determine from the available information how states, in practice, have implemented regulatory requirements. At this point, only limited conclusions are possible.

Clear deficiencies exist in some state regulatory programs, and questions remain with respect to others. And many of these concerns exist with respect to programs in states responsible for the majority of CCR generation and disposal. However, most state programs, although they vary considerably, are not clearly deficient on their face. But it is equally clear that exclusive reliance on the regulatory programs as written, without any examination of how states have implemented those requirements in practice, would not support sweeping conclusions about the overall adequacy of state programs. It is critical to ensure that any decision accurately accounts for how the states have exercised their judgment in implementing those requirements, before concluding that state programs cannot adequately oversee the management of CCR without the degree of federal involvement mandated by subtitle C. Notwithstanding EPA's inability to draw conclusions on the overall adequacy of state programs, the high degree of variation across state programs strongly supports the need for federal requirements to establish a consistent national standard of groundwater and human health protection.

In contrast to the other two areas identified in the proposed rule, while some uncertainty remains with respect to the damage cases—namely, whether the 157 identified to date represent the total number of damage cases caused by CCR mismanagement, and whether some of the ''potential'' damage cases should be classified as ''proven'' damage cases—at this point, EPA has concluded that the available information provides a sufficient evidentiary base on which decisions can be made. In the absence of the necessary information on two of the three critical areas, however, EPA cannot reach any final conclusions regarding the appropriate balance among the eight statutory factors. Consequently, EPA is also not reaching any final conclusions as to whether a damage case is best categorized as ''proven'' or ''potential.'' Such a finding is relevant only to the Bevill Regulatory Determination.

However, as discussed in more detail in Unit XI of this document, the damage cases provide extremely valuable evidence that is directly relevant to the question of whether and how to regulate CCR waste. For example, the damage cases provide ''real world'' evidence against which to compare EPA's risk modeling estimates, such as evidence regarding the frequency with which particular constituents leach into groundwater. They also provide direct evidence regarding specific waste management practices at electric utilities, along with the potential consequences of those practices. Finally, both the specifics of the damage cases and the fact that they continue to occur provide strong evidence of the need for this rule under subtitle D while EPA obtains the information that will allow the Agency to make a final Regulatory Determination for these wastes.

Thus, even though EPA is not able to reach a final conclusion on the Regulatory Determination for these wastes, the totality of the information in the rulemaking record clearly demonstrates that the risks associated with the current management and disposal of CCR remain substantial. EPA's risk assessment concluded that the cancer risks from unlined surface impoundments ranged from 3×10^{-4} for trivalent arsenic to 4×10^{-5} for pentavalent arsenic. Non-cancer risks from these same units also significantly exceeded EPA's level of concern, with estimates ranging from an HQ of 2 for thallium, to HQs[32] of 4 for molybdenum and 8 for trivalent arsenic. The risks associated with unlined landfills were also estimated to be significant, with cancer risks of 2×10^{-5} for trivalent arsenic. It is important to note that these risk numbers are based on national disposal practices. Risks at an individual site may be even higher based on individual site conditions, waste characteristics, and management practices. EPA's risk assessment identified the potential for higher risks based on different waste pH values and management practices. Multiple constituents presented higher risks when considered in waste management units that co-dispose both ash and coal refuse at more acidic pHs or FGD wastes at more basic pHs. For example, the modeled cancer risks for the co-disposal of ash and coal refuse (pH 1.7–8.2) ranged between 10^{-3} for trivalent arsenic to 4×10^{-4} for pentavalent arsenic. Non-cancer risks were similarly high, ranging between and an HQ of 13 for cobalt, and HQs of 14 for pentavalent arsenic to 26 for trivalent arsenic, based on the ingestion of contaminated drinking water. Although this management practice is declining, recent information indicates that approximately five percent of facilities continue to co-dispose of ash and coal refuse in surface impoundments.

Moreover, EPA's risk estimates are consistent with the continued damage cases compiled through this rulemaking. As further discussed in Unit XI of this document, EPA has confirmed that 157 cases of proven or potential contamination of groundwater have occurred in states across the nation since the initial Regulatory Determination. These damage cases were primarily associated with unlined units and were most frequently associated with releases of arsenic. While new units are typically constructed with composite liners, which under EPA's current risk assessment adequately mitigate the risks, older units still comprise the overwhelming majority of currently operating units. EPA's data show that approximately 63 percent of currently operating surface impoundments and landfills are unlined, and thus more prone to leach contaminants into groundwater. Analysis of the information from the damage cases also demonstrates that unlined surface

[32] For more information on HQs please see Unit X. Risk Assessment of this preamble.

impoundments typically operate for 20 years before they begin to leak. Most of the currently operating surface impoundments are between 20 and 40 years old.

The age of the units also has implications for their structural stability and the potential for catastrophic releases. Of the approximately 735 CCR surface impoundments currently operating in the United States, a certain percentage have a great potential for loss of human life and environmental damage in the event of catastrophic failure. Based on the information collected from EPA's Assessment Program, 318 surface impoundments have either a high or significant hazard potential rating, at least 13 of which were not designed by a professional engineer. Of the total universe of surface impoundments, approximately 186 of these units were not designed by a professional engineer. Surface impoundments are generally designed to last the typical operating life of coal-fired boilers, on the order of 40 years. However, many impoundments are aging; based on the subset of units for which age data were available, approximately 195 active surface impoundments exceed 40 years of age; 56 units are older than 50 years, and 340 are between 26 and 40 years old. In recent years, problems have continued to arise from these units, which appear to be related to the aging infrastructure, and the fact that many units may be nearing the end of their useful lives. For example, as a result of the administrative consent order issued after the December 2008 spill, TVA conducted testing which showed that another dike at TVA's Kingston, Tennessee plant had significant safety deficiencies. Collectively, these facts indicate a high likelihood that in the absence of any regulatory action, such units will leak in the near future, or are currently leaking, undetected, since groundwater monitoring is not installed at many of these older units. Moreover, damage cases continue to occur; in response to EPA's CERCLA 104(e) information request letter, a total of 35 units at 25 facilities reported historical releases. These range from minor spills to a spill of 0.5 million cubic yards of water and fly ash. And as recently as February 2014, CCR slurry was released into the Dan River from an inactive surface impoundment in North Carolina.

All of which demonstrates a compelling need for a uniform system of requirements to address these risks without waiting for the information and analyses necessary to complete a final Regulatory Determination. EPA will continue to monitor these critical areas, and will provide the public with an additional opportunity to comment on any proposed Regulatory Determination, prior to issuing a final Regulatory Determination.

B. Final Regulatory Determination Regarding Beneficial Use

EPA generally proposed to retain the May 2000 Regulatory Determination that beneficially used CCR did not warrant federal regulation under subtitle C of RCRA. As EPA stated in the May 2000 Regulatory Determination, ''In the [Report to Congress], we were not able to identify damage cases associated with these types of beneficial uses, nor do we now believe that these uses of coal combustion wastes present a significant risk to human health and the environment. While some commenters disagreed with our findings, no data or other support for the commenters' position was provided, nor was any information provided to show risk or damage associated with agricultural use. Therefore, we conclude that none of the beneficial uses of coal combustion wastes listed above pose risks of concern.'' (See 65 FR 32230.) EPA noted that since the original Regulatory Determination, the Agency had found no data or other information to indicate that existing efforts of states, EPA, and other federal agencies had been inadequate to address the environmental issues associated with the beneficial use of CCR that were originally identified in the Regulatory Determination. EPA explained that it had proposed this approach in recognition that some uses of CCR, such as encapsulated uses in concrete, and use as an ingredient in the manufacture of wallboard, provide benefits and raise minimal health or environmental concerns. Consequently, EPA preliminarily concluded that encapsulated uses of CCR, which are common in many consumer products, did not merit regulation based on the available information.

However, EPA noted that the issues were more difficult with respect to unencapsulated uses of CCR and specifically solicited comment on whether such uses should continue to be included as ''beneficial use'' under the Bevill exemption. EPA explained that unencapsulated uses have raised concerns and therefore merited closer attention. For example, the placement of unencapsulated CCR on the land, such as in road embankments or in agricultural uses, presented a set of issues similar to those that caused the Agency to propose to regulate CCR destined for disposal. But the Agency also acknowledged that the amounts and, in some cases, the manner in which CCR is used—*i.e.,* subject to engineering specifications and material requirements rather than landfilling techniques—are potentially very different from land disposal.

EPA is retaining the original 2000 Regulatory Determination for CCR that is beneficially used. EPA has made this determination based on consideration of the available information and the RCRA section 8002(n) study factors.

1. Source and Volume of CCR Generated Each Year

The American Coal Ash Association (ACAA) conducts a voluntary, annual survey of the coal-fired electric utility industry to track the quantities of CCR generated and beneficially used. According to the latest survey, the electric utility industry generated nearly 110 million tons of CCR in 2012. Approximately 39 million tons of these CCR was identified by ACAA as beneficially used in either encapsulated or unencapsulated products. An additional 12.8 million tons were placed in mine-fill operations, while the remaining 57.8 million tons were disposed of in landfills and surface impoundments (ACAA, 2013).[33]

2. Present Utilization Practices

Based on the beneficial use rates reported by ACAA, approximately 50 percent of the CCR beneficially used on an annual basis falls into two categories: (1) Fly ash used as a direct substitute for Portland cement during the production of concrete (referred to as ''fly ash concrete''); and (2) FGD gypsum used as a replacement for mined gypsum in wallboard (referred to as ''FGD gypsum wallboard''). Specifically, the 2012 ACAA survey indicates that the largest encapsulated beneficial uses of CCR, by more than a factor of two, are fly ash used in ''concrete/concrete products/grout'' (12.6 million tons) and FGD gypsum used in ''gypsum panel products'' (7.6 million tons).

3. Potential Danger, if Any, to Human Health or the Environment From the Reuse of CCR

The risks associated with the disposal of CCR stems from the specific nature of that activity; that is, the disposal of CCR in (often unlined) landfills or surface impoundments, with thousands, if not millions, of tons placed in a single

[33] ACAA (American Coal Ash Association). 2013. 2012 Coal Combustion Product (CCP) Production & Use Survey Report. Farmington Hills, MI 48331. Available online at: *http://www.acaa-usa.org/Portals/9/Files/PDFs/revisedFINAL2012CCPSurveyReport.pdf*

concentrated location. And in the case of surface impoundments, the CCR is managed with water, under a hydraulic head, which promotes rapid leaching of contaminants into neighboring groundwater. The beneficial uses identified as excluded under the Bevill exemption for the most part present a significantly different risk profile.

a. Encapsulated Beneficial Uses

An encapsulated beneficial use is one that binds the CCR into a solid matrix that minimizes mobilization into the surrounding environment. Examples of encapsulated uses include, but are not limited to: (1) Filler or lightweight aggregate in concrete; (2) a replacement for, or raw material used in production of, cementitious components in concrete or bricks; (3) filler in plastics, rubber, and similar products; and (4) raw material in wallboard production.

Since publication of the proposal, EPA has developed a methodology for evaluating encapsulated beneficial uses. A copy of the methodology can be found at *http://www2.epa.gov/coalash/methodology-evaluating-encapsulated-beneficial-uses-coal-combustion-residuals*. EPA applied this methodology to the two largest CCR uses—the use of fly ash as a replacement for Portland cement in concrete, and the use of FGD gypsum as a replacement for mined gypsum in wallboard. A complete copy of the evaluation can be found at *http://www.epa.gov/wastes/conserve/imr/ccps/pdfs/ccr_bu_eval.pdf*.

The evaluation considered products that meet relevant physical and performance standards, that conform to standard design specifications, and that incorporate fly ash and FGD gypsum from pollution control devices currently used in the United States. Based on the findings of the evaluation, the Agency concluded that environmental releases of constituents of potential concern from CCR fly ash concrete and FGD gypsum wallboard during use by the consumer are comparable to or lower than those from analogous non-CCR products, or are at or below relevant regulatory and health-based benchmarks for human and ecological receptors.

b. Unencapsulated Uses

EPA acknowledged in the proposal that unencapsulated uses generally presented more difficult issues than encapsulated uses. CCR can leach toxic metals at levels of concern, so depending on the characteristics of the CCR, the amount of material placed, how it is placed, and the site conditions, there is a potential for environmental concern. However, EPA cannot extrapolate from the risk assessments conducted to evaluate the management practices associated with CCR landfills and CCR surface impoundments, because the exposure patterns are too dissimilar: The amounts and manner involved with beneficial use are very different than the thousands, if not millions of tons of CCR that are mounded in a single concentrated location in a landfill. And the potential exposures are entirely unlike surface impoundments, where CCR is managed with water under a hydraulic head, which promotes more rapid leaching of contaminants. By contrast ''beneficial uses,'' even unencapsulated uses, are typically subject to engineering specifications, and for certain uses, federal oversight, and material requirements. For example, fly ash used as a stabilized base course in highway construction is subject to both regulatory standards under the U.S. Department of Transportation (DOT) and the Federal Highway Administration (FHWA), and engineering specifications, such as the ASTM C 593 test for compaction, the ASTM D 560 freezing and thawing test, and a seven day compressive strength above 2760 kPa (400 psi). (See 75 FR 35163–35165 for additional examples.)

In 1999, EPA conducted a risk assessment of certain agricultural uses of CCR, since this practice was considered the most likely to raise human health or environmental concerns.[34] EPA estimated the risks associated with such uses to be within the range of 1×10^{-6}. These results as well as EPA's conclusion that the use of CCR in agricultural settings was the most likely use to raise concerns, caused EPA to conclude that none of the beneficial uses identified in the 2000 Regulatory Determination warranted federal regulation, because ''we were not able to identify damage cases associated with these types of beneficial uses, nor do we now believe that these uses of coal combustion wastes present a significant risk to human health or the environment.'' (65 FR 32230, May 22, 2000.)

EPA also noted that beneficially using secondary materials conserves natural resources, and can serve as an important alternative to disposal.

[34] For more information on this risk assessment see EPA's Notice of Regulatory Determination on Wastes from the Combustion of Fossil Fuels (65 FR 32214, May 22, 2000).

4. Documented Cases in Which Damage to Human Health or the Environment From Surface Run-off or Leachate Has Been Proved

To date, EPA has seen no evidence of damages from the encapsulated beneficial uses of CCR that EPA identified in the proposal. For example, there is wide acceptance of the use of CCR in encapsulated uses, such as wallboard, concrete, and bricks because the CCR is bound into products. However, as of the date of the proposed rule, seven proven damage cases associated with unencapsulated uses have occurred, in which large quantities of unencapsulated CCR were used indiscriminately to re-grade the landscape or to fill old quarries or gravel pits. The proposed rule discussed two of these cases. (See 75 FR 35147.) The first case was in Gambrills, Maryland and involved the disposal of fly ash and bottom ash (beginning in 1995) in two sand and gravel quarries. EPA considers this site a proven damage case, because groundwater samples from residential drinking wells near the site include heavy metals and sulfates at or above groundwater quality standards, and the state of Maryland is overseeing remediation. The second case is the Battlefield Golf Course in Chesapeake, Virginia where 1.5 million yards of fly ash were used as fill and to contour a golf course. Groundwater contamination above MCLs has been found at the edges and corners of the golf course, but not in residential wells. An EPA study in April 2010, established that residential wells near the site were not impacted by the fly ash and, therefore, EPA does not consider this site to be a proven damage case. However, due to the onsite groundwater contamination, EPA considers this site to be a potential damage case.

During the development of this final rule, EPA obtained information on a comparable situation in which large quantities of unencapsulated CCR were placed on the land in a manner that presented significant concerns. The AES coal-fired power plant in Puerto Rico lacked capacity to dispose of their CCR on-site, and off-site landfills in Puerto Rico were prohibited from accepting CCR. In lieu of transporting their CCR off of the island for disposal, AES created an aggregate (''AGREMAX'') with the CCR generated at their facility, and used the aggregate as fill in housing developments and in road projects. Over two million tons of this material was used between 2004 and 2012.

Currently, there is insufficient information to determine whether groundwater has been contaminated as

a result of this practice, and thus, EPA cannot classify this as either a proven or potential ''damage case.'' Nevertheless, the available facts illustrate several of the significant concerns associated with unencapsulated uses. Specifically, the AGREMAX was applied without appropriate engineering controls and in volumes that far exceeded the amounts necessary for the engineering use of the materials. Inspections of some of the sites where the material had been placed showed use in residential areas, and to environmentally vulnerable areas, including areas close to wetlands and surface waters and over shallow, sole-source drinking water aquifers. In addition, some sites appeared to have been abandoned.

Consistent with the proposed rule, EPA does not consider the practices described in this section to be beneficial use, but rather waste management that would be subject to the requirements of the final rule.

5. Alternatives to Current Disposal Methods, the Costs of Such Alternatives, and the Impact of Such Alternatives on the Use of Coal and Other Natural Resources

The beneficial use of CCR is a primary alternative to current disposal methods. And as EPA has repeatedly concluded, it is a method that, when performed correctly, can offer significant environmental benefits, including greenhouse gas (GHG) reduction, energy conservation, reduction in land disposal (along with the corresponding avoidance of potential CCR disposal impacts), and reduction in the need to mine and process virgin materials and the associated environmental impacts.

a. Greenhouse Gas and Energy Benefits

The beneficial use of CCR reduces energy consumption and GHG emissions in a number of ways. Three of the most widely recognized beneficial applications of CCR are the use of coal fly ash as a substitute for Portland cement in the manufacture of concrete, the use of FGD gypsum as a substitute for mined gypsum in the manufacture of wallboard, and the use of CCR as a substitute for sand, gravel, and other materials in structural fill. Reducing the amount of cement, mined gypsum, and virgin fill produced by substituting CCR leads to large supply chain-wide reductions in energy use and GHG emissions. Specifically, the RIA estimates three-year rolling average of 53,054,246 million British thermal units (MMBtu) per year in energy savings and 11,571,116 tons per year in GHG (*i.e.,* carbon dioxide and methane) emissions reductions in 2015. This estimate is likely to underestimate the total benefits that can be achieved from all beneficial uses. Furthermore, the use of fly ash generally makes concrete stronger and more durable. This results in a longer lasting material, thereby marginally reducing the need for future cement manufacturing and corresponding avoided emissions and energy use.

b. Benefits From Reducing the Need To Mine and Process Virgin Materials

CCR can be substituted for many virgin materials that would otherwise have to be mined and processed for use. These virgin materials include limestone to make cement, and Portland cement to make concrete; mined gypsum to make wallboard, and aggregate, such as stone and gravel for uses in concrete and road bed. Using virgin materials for these applications requires mining and processing, which can impair wildlife habitats and disturb otherwise undeveloped land. It is beneficial to use secondary materials—provided it is done in an environmentally sound manner—that would otherwise be disposed of, rather than to mine and process virgin materials, while simultaneously reducing waste and environmental footprints. Reducing mining, processing and transport of virgin materials also conserves energy, avoids GHG emissions, and reduces impacts on communities.

c. Benefits From Reducing the Disposal of CCR

Beneficially using CCR instead of disposing of it in landfills and surface impoundments also reduces the need for additional landfill space and any risks associated with their disposal. In particular, the United States disposed of over 57.8 million tons of CCR in landfills and surface impoundments in 2012, which is equivalent to the space required of 20,222 quarter-acre home sites under eight feet of CCR.

As discussed in the final rule RIA, the current beneficial use of CCR as a replacement for industrial raw materials (*e.g.,* Portland cement, virgin stone aggregate, lime, gypsum) provides substantial annual life cycle environmental benefits for these industrial applications. Specifically, the three-year rolling average of environmental benefits estimated for 2015 includes: (1) 53,054,246 MMBtu per year in energy savings; (2) 1,661,900 million gallons per year in water savings; (3) 11,571,116 tons per year in GHG (*i.e.,* carbon dioxide and methane) emissions reductions; (4) 45,770 tons of criteria air pollutant (*i.e.,* NO_X, SO_X, particulate matter, and CO) emissions reductions; and (5) 3,207 pounds of toxic air pollutant (*i.e.,* mercury and lead) emissions reductions. All together, the beneficial use of CCR in 2015 is estimated to provide over $2.3 billion in annual national environmental benefits. In addition, since EPA estimates annual baseline disposal costs of approximately $2.4 billion for the just over 50 percent of tons disposed each year, current beneficial use and minefilling also result in annual material and disposal cost savings of approximately $2 billion annually.

6. Current and Potential Utilization of CCR

In 2012, nearly 36 percent (39 million tons) of CCR were beneficially used (excluding minefill operations) and nearly 12 percent (12.8 million tons) were placed in minefills. (This compares to 23 percent of CCR that were beneficially used, excluding minefilling, at the time of the May 2000 Regulatory Determination, and represents a significant increase.)

7. Conclusions

On balance, after considering all of the available information, EPA has concluded that the most appropriate approach toward beneficial use is to retain the May 2000 Regulatory Determination that regulation under subtitle C of the beneficial use of CCR is not warranted. EPA has also determined that regulation under subtitle D is generally not necessary for these beneficial uses.

As discussed in the preceding section, the most important of the section 8002(n) factors are those relating to the potential risks to human health and the environment. See *e.g., Horsehead Resource Development Co.* v. *EPA*, 16 F.3d 1246, 1258 (D.C. Cir, 1994) (Upholding EPA's interpretation that wastes resulting from the combustion of mixtures of Bevill-exempt and non-exempt wastes could only retain Bevill-exempt status so long as the combustion waste remained of low toxicity); *EDF* v. *EPA*, 852 F.2d 1316, 1328–1329 (D.C. Cir. 1988) (Overturning EPA rule that included as Bevill exempt, wastes that were not of low toxicity). EPA is adopting this Regulatory Determination in recognition that many uses of CCR, such as encapsulated uses in concrete, and use as an ingredient in the manufacture of wallboard, provide environmental benefits and raise minimal health or environmental concerns. To date, the information available does not demonstrate the existence of any risks associated with encapsulated uses of CCR that merit

regulation under either subtitle C or subtitle D of RCRA.

While there can be some risks associated with unencapsulated uses—for example, the placement of unencapsulated CCR on the land, such as in large scale fill operations or in agricultural uses, depending on the specific site conditions—in general the amounts and, in some cases, the manner in which they are used are very different than land disposal. For example, agricultural uses involve the placement of inches rather than tons of CCR, and placement of CCR in a thin layer rather than mounded in a single concentrated location. In addition, these uses are subject to engineering specifications and materials requirements, which will limit the ultimate amount of material placed on the land.

EPA recognizes that several proven damage cases involving the large-scale placement, akin to disposal, of CCR have occurred under the guise of ''beneficial use''— the ''beneficial'' use being the filling up of old quarries or gravel pits, or the re-grading of landscape with large quantities of CCR. EPA did not consider this type of use as a ''beneficial'' use in its May 2000 Regulatory Determination, and still does not consider this type of use to be covered by the exclusion. Therefore, the final rule explicitly removes these types of uses from the category of beneficial use, and from this Regulatory Determination. As discussed in the next section of this preamble, EPA has adopted criteria in the final rule to ensure that inappropriate uses that effectively are disposal will be regulated as disposal. The final rule expressly defines the placement of CCR in sand and gravel pits or quarries as disposal in a landfill. In addition, the final rule provides that the use of large volumes of CCR in restructuring landscape that does not meet specific criteria will constitute disposal.

While EPA has not definitively concluded that all unencapsulated beneficial uses are ''safe,'' based on the current record for this rulemaking, EPA is unable to point to evidence demonstrating that the unencapsulated uses subject to this Determination warrant federal regulation. While the absence of demonstrated harm in this instance is not proof of safety, neither is the lack of information proof of risk.[35]

In this regard, EPA notes that many states have developed beneficial use programs that allow the use of CCR, provided they are demonstrated to be non-hazardous materials; and many require a site specific assessment before authorizing placement on the land of large amounts of unencapsulated CCR. For example, Wisconsin's Department of Natural Resources has developed a regulation (NR 538 Wis. Adm. Code), which includes a five-category system to allow for the beneficial use of industrial by-products, including coal ash, provided they meet the specified criteria. In addition, the ASTSWMO 2006 Beneficial Use Survey Report states that a total of 34 of the 40 reporting states, or 85 percent, indicated they had either formal or informal decision-making processes or beneficial use programs relating to the use of solid wastes. (*http://www.astswmo.org/Files/Policies_and_Publications/Solid_Waste/2007BUSurveyReport11-30-07.pdf*) [36] Because EPA has not identified significant risks associated with the beneficial uses covered by this Regulatory Determination, the adequacy of these state programs does not factor into EPA's Determination. Nevertheless, to the extent that that these materials do have the potential to pose risk at an individual site, the fact that many states exercise regulatory oversight of these materials provides an additional level of assurance.

Finally, EPA does not wish to inhibit or eliminate the measurable environmental and economic benefits derived from the use of this valuable material given the current lack of evidence affirmatively demonstrating an environmental or health risk. Consequently, EPA is confident that the combination of the final rule, EPA guidance, current industrial standards and practices, and in many cases, state regulatory oversight is sufficient to address concerns associated with the beneficial uses to which this Determination applies.

V. Development of the Final Rule—RCRA Subtitle D Regulatory Approach

As previously discussed in Unit II of this document, the authority to develop and promulgate the national minimum criteria governing the disposal of CCR in landfills and surface impoundments is found under the provisions of sections 1008(a), 4004, and 4005(a) of RCRA (*i.e.*, subtitle D of RCRA). These authorities, however, do not provide EPA with the ability to issue permits, require states to issue permits, approve state programs to operate in lieu of the federal program, or to enforce any of the requirements addressing the disposal of CCR. Consequently, EPA designed the proposed RCRA subtitle D option to ensure that the requirements will effectively protect human health and the environment within those limitations. The final rule establishes self-implementing requirements—primarily performance standards—that owners or operators of regulated units can implement without any interaction with regulatory officials.

In developing the subtitle D option for the proposal, EPA considered a number of existing programs as relevant models. EPA drew most heavily on the existing 40 CFR part 258 program applicable to MSWLFs. While this program does not address CCR disposal in surface impoundments, it provided EPA with a general regulatory framework that addressed all aspects of disposal in certain land-based units. Given the Agency's expansive history and experience with these requirements, EPA concluded that the part 258 criteria with certain modifications for other land-based disposal units (*i.e.*, surface impoundments) represented a reasonable balance between ensuring the protection of human health and the environment from the risk of CCR disposal and the absence of any regulatory oversight. (See 75 FR 35192–35195.)

EPA also considered that many of the technical requirements developed to specifically address the risks from the disposal of CCR as part of the subtitle C alternative would be equally justified under a RCRA subtitle D regulatory regime. The factual record—*i.e.*, the risk analysis and the damage cases—supporting such requirements was the same, irrespective of the statutory authority under which the Agency was operating. Thus, several of the provisions under RCRA subtitle D either corresponded to the proposal under RCRA subtitle C, or were modeled after the existing subtitle C requirements; for example, EPA proposed the same MSHA-based structural stability standards for surface impoundments under the subtitle C and subtitle D options. However, because there is no corresponding guaranteed permit mechanism under the RCRA subtitle D requirements, EPA also considered the 40 CFR part 265 interim status requirements for hazardous waste facilities, which were designed to operate in the absence of a permit. These requirements were particularly

[35] The Agency is currently developing a Framework to address the risks associated with the beneficial use of unencapsulated materials. This Framework is expected to be finalized in 2015. See Unit VI of this document for more information.

[36] EPA has worked with the states to support the development of a national database on state beneficial use determinations. Information on the beneficial use determination database can be found on the Northeast Waste Management Officials' Association (NEWMOA) Web site at *http://www.newmoa.org/solidwaste/bud.cfm*. This database helps states share information on beneficial use decisions providing for more consistent and informed decisions.

relevant in developing the requirements for surface impoundments since such units are not regulated under 40 CFR part 258. Beyond their self-implementing design, these requirements provided a useful model because, based on decades of experience in implementing these requirements, EPA had assurance that these requirements were protective for a variety of waste, under a wide variety of site conditions.

In an effort to ensure that the proposed RCRA subtitle D requirements would achieve the statutory standard of ''*no reasonable probability of adverse effects on health and the environment*'' in the absence of guaranteed regulatory oversight, EPA also proposed to require facilities to obtain third party certifications and to provide enhanced state and public notifications of actions taken to comply with the regulatory requirements. Specifically, EPA proposed that certain technical demonstrations made by the owner or operator be certified by an independent registered professional engineer or hydrologist, in order to provide verification and otherwise ensure that the provisions of the rule were properly applied. EPA also provided a regulatory definition of the term, ''independent registered professional engineer or hydrologist,'' to identify the minimum qualifications necessary to make these certifications. While EPA acknowledged that relying upon a third party certification was not the same as relying upon a state or federal regulatory authority and was not expected to provide the same level of independence as a state permit program, the availability of meaningful third party (*i.e.*, independent) verification provided critical support that the rule would achieve the statutory standard, as it would provide at least some degree of control over a facility's discretion in implementing the rule.

As part of the notification requirements, EPA further proposed that all owners and operators create and maintain an operating record and publically accessible Web site, containing comprehensive documentation of compliance with the rule. EPA also proposed that owners or operators provide notification to the state and the public of third party certifications as well as other information documenting actions taken to comply with the technical criteria of the rule.

A. The Self-Implementing Approach

While the vast majority of state and industry commenters supported regulating the management of CCR under subtitle D of RCRA, a very limited number of commenters favored the proposed self-implementing option. Most commenters argued that if the Agency were to adopt the proposed subtitle D approach it would most certainly result in parallel and redundant regulatory programs for CCR in many states, creating an unworkable situation for industry, as well as the state. Some commenters argued that under this dual regulatory approach, an owner or operator of a CCR unit could conceivably be in non-compliance with both a federal requirement and an independently administered state regulatory requirement, subjecting the owner or operator to both a citizen suit enforcement action in federal court for the alleged violation and to a wholly separate enforcement action in state court for violation of the parallel state requirement. Commenters argued that this regulatory construct made no sense and would waste federal and state judicial resources and company resources, as well as possibly resulting in inconsistent federal and state court determinations with respect to an identical regulatory requirement. It also could result in duplicative federal and state penalties for essentially the same regulatory infraction.

Commenters further argued that the prescriptive one-size-fits-all approach was overly stringent and inflexible and had the potential to greatly disrupt implementation of a state's regulatory programs, which have been tailored to provide for site specific conditions and situations. Moreover, commenters argued that because of the many state regulatory programs addressing CCR disposal, there would be many instances where state requirements could be in conflict with, in addition to, or separate from the federal requirements and it was unclear how these differences would be resolved.

Many commenters simply argued that a permitting program similar to that for MSWLFs was the only viable approach for the regulation of CCR. A significant number of commenters, however, proposed various alternative approaches for regulating CCR disposal under subtitle D of RCRA. One option would have EPA allow qualified state programs to directly administer the subtitle D requirements for CCR when the state regulatory program meets or exceeds the federal requirements, thereby minimizing duplicative regulations and avoiding the self-implementing ''one size fits all'' approach contained in EPA's proposal. This option, commenters reasoned, could be implemented utilizing a process developed by the Agency for evaluating whether the state's CCR regulations were equivalent to the federal minimum criteria (much like EPA does now in the case of MSWLFs under 40 CFR part 258). Another suggested approach involved EPA clarifying that a state can be more restrictive than the federal rule, and that where a state has a subtitle D regulatory program that is more restrictive, the state program and permitting process would take precedence over any self-implementation aspects of a final rule. (The proposed rule had simply stated that an owner or operator must comply with any other applicable federal, state, tribal or local laws or other requirements.) Commenters also proposed a third option, similar to the 40 CFR part 258 program, recognizing that EPA cannot approve state programs in this rule. Specifically, 40 CFR part 258 provides a definition for ''Director of an approved state'' that means they are the chief administrative officer of a state agency responsible for implementing the state permit program that is deemed to be adequate by EPA under regulations published pursuant to sections 2002 and 4005 of RCRA. The commenters suggested that the final rule adopt a similar approach by defining a ''state permit program'' and allowing a state permit program that met the definition to approve compliance with a specified regulatory requirement, *e.g.*, landfill design. The commenter suggested the following definition: ''state permit program means a permit program implemented by a state agency that adopts and implements the minimum requirements for the disposal of coal combustion residuals outlined in this final rule.'' The commenter claimed that such an approach should not affect enforcement through citizen suits under RCRA section 7002 or by EPA under RCRA section 7003. Taking such an approach, commenters reasoned, would allow states to utilize their own enforcement authority and not rely upon the citizen suit authority under RCRA section 7002. Furthermore, allowing states to consider alternative approaches to the technical standards may give states an incentive to adopt the minimum requirements of the final federal rule into their state permit programs.

As noted, many commenters suggested that EPA rely on the same combination of RCRA statutory authorities, *i.e.*, RCRA sections 4010(c) and 4005(c), to establish controls for CCR units that it employed in promulgating federally enforceable subtitle D rules for MSWLFs and for non-MSWLFs that receive household

hazardous waste and small quantity generator waste under 40 CFR parts 257 and 258. RCRA sections 4010(c) and 4005(c), the commenters reasoned, provides EPA that authority because non-hazardous waste CCR disposal facilities have the potential to receive household wastes or conditionally exempt small quantity generator waste, whether or not such waste is actually received at the CCR disposal facility. Commenters contended that the combination of these two provisions could enable EPA to promulgate non-hazardous waste rules for CCR that could be directly administered through state permitting programs and backed up by direct EPA enforcement powers in those states that fail to adequately implement the federal rules. Such an approach, commenters concluded provides the Agency with the enforcement authority it desires under a subtitle D regulatory program, while enabling states to have a prominent role in the administration of any subtitle D rules, and preventing the duplication of potentially conflicting federal and state controls.

Finally, some commenters encouraged EPA to request from Congress the statutory authority necessary to propose non-hazardous regulations under subtitle D that could be implemented by the states and provide federal enforceability (similar to RCRA's part 258 requirements for MSWLFs). Commenters argued that states should be allowed to enforce compliance through a traditional permitting system, and that solid waste operating permits are critical to ensuring coal ash disposal facilities design, construct, operate and close their waste facilities safely. Commenters argued that permits are important because they can dictate the use of specific operating practices and control technologies that may be essential for minimizing releases. Permits also provide an important enforcement vehicle, as well as a process by which the public can be informed and participate in the siting, operation and closure of the waste disposal unit.

While the Agency appreciates commenters' attempts to craft alternative approaches to address the limitations in the proposed self-implementing subtitle D option, EPA has not ''chosen'' to design standards under subtitle D that are self-implementing. The sections of RCRA that are currently applicable to CCR—sections 1008(a), 4004(a), and 4005(a)—only authorize the Agency to establish minimum national criteria that apply to ''facilities.''

As previously discussed, these provisions do not authorize EPA to require that facilities obtain a permit from EPA or a state. The fact that section 4004(a) does not contain any provision that either expressly requires a permit to manage waste, such as in section 3005, or that requires states to adopt a permit program, such as in section 4004(c)(1), provides strong evidence that Congress did not authorize EPA to impose such a requirement on facilities managing solid waste. Compare 42 U.S.C. 6925(a), 6944(a), and 6945(c)(1). This is further confirmed by the fact that Congress thought it necessary to expressly add provisions to require state permit programs in 4010(c) and 4005(c). And the fact that the HSWA provisions are limited to two specifically enumerated types of units provides further evidence that Congress intended to authorize EPA to require permits only for these units.

The restriction that the criteria apply only to ''facilities'' also means that EPA cannot establish any requirements on states or state programs, either directly or indirectly. This means, for example, that EPA cannot adopt a regulation that restricts certain provisions to those ''state permit programs'' that meet EPA requirements, as one commenter suggested, since this would indirectly regulate state programs—leaving aside that EPA never proposed anything of the sort. This also means that EPA cannot require a facility to obtain state approval, as this not only presupposes the existence of a state permit program, but also that the state will approve the facility action on the basis of EPA's criteria. EPA cannot condition a facility's compliance on actions beyond its control.

However, these provisions restrict EPA's authority only. The legislation is clear that these are minimum requirements only, and without preemptive effect; states may therefore impose more stringent requirements, including the requirement that CCR facilities obtain a permit. This is also wholly consistent with longstanding EPA interpretations. See 44 FR 53438, 53439 (September 13, 1979) (''the standards established in the criteria constitute minimum requirements. These criteria do not preempt other state and federal requirements. Nothing in the Act precludes the imposition of additional obligations under authority of other laws on parties engaged in solid waste disposal.''); see also 44 FR 45066 (July 31, 1979) (''EPA establishes only 'minimum' requirements under this portion of the Act which should not prevent States from developing broader programs or stricter standards under authority of State law.''). States may also incorporate the federal requirements into state law—whether through revisions to existing legislation or regulation, or through incorporating them into any permits issued to CCR facilities. Such an approach would also resolve commenters' concerns about the potential for ''parallel and redundant regulatory programs.''

While subtitle C and 4005(c) provide for state oversight on rule implementation and allow approved state requirements to operate in lieu of federal criteria, the Agency lacks the authority to do so under the subsections of RCRA currently applicable to CCR. The provisions applicable to solid waste—sections 1008(a)(3), 4003, 4004(a) and 4005(a)—establish a regulatory structure that differs in key respects from those established under subtitle C and for MSWLFs under section 4005(c). Under subtitle C and section 4005(c), Congress required EPA to establish federal criteria that will serve as national minimum standards, which is comparable to the authority under section 4004(a). But subtitle C and section 4005(c) also include detailed provisions governing both the state implementation of those requirements and the relationship between the federal requirements and the state programs that implement them. No comparable provisions appear in either section 4004(a) or section 4003, which governs the approval of state SWMPs. And the consequences of these omissions are significant.

Subtitle C of RCRA contains several provisions that establish the relationship between the federal program and state requirements; these include provisions authorizing EPA to approve state programs and to retain a direct role in the implementation of the federal minimum requirements, whether through continued oversight of state implementation or direct implementation of the regulations. See, 42 U.S.C. 6926, 6928(a)(2), and 6929. For purposes of this issue, the most critical of these is the explicit direction in section 3006 that authorized state programs ''operate in lieu of the Federal program.'' 42 U.S.C. 6926(b), (c)(1). See also 42 U.S.C. 6929 (prohibiting the adoption of less stringent state requirements than those in EPA regulations, and authorizing states to establish more stringent requirements).

The provisions for MSWLFs under section 4005(c) are less detailed, but establish a similar regulatory structure. Section 4005(c)(1) expressly directs the states to ''adopt and implement a permit program or other system of prior approval and conditions,'' for covered

facilities in order to implement federal requirements established for such facilities. 42 U.S.C. 6945(c)(1). The statute directs EPA to determine the adequacy of such programs, and directs EPA to enforce the federal requirements in states that have not adopted an adequate program. 42 U.S.C. 6945(c)(1)(C), (2). While less detailed than the provisions under subtitle C, section 4005(c) establishes a system that is equally predicated on mandated implementation by a state regulatory authority of the federal requirements, rather than the potential coexistence of two separate regulatory systems.

The absence of any similar provisions in the ''solid waste'' provisions of subtitle D demonstrates that Congress intended to create a different regulatory structure. EPA's role under sections 1008(a)(3) and 4004(a) is to establish minimum criteria to determine which facilities ''shall be classified as sanitary landfills and which shall be classified as open dumps,'' and to encourage states to use the criteria as a part of their solid waste management planning. Under this regulatory structure, Congress intended that the federal requirements apply directly to facilities and operate independent of state involvement, unless *the state* chooses to do otherwise. The ability to approve state SWMPs under section 4003 does not alter this relationship. Indeed, the fact that Congress thought it necessary to revise section 4005 to include the specific provisions in subsection (c) confirms that Congress did not believe such authority already existed under sections 4003 and 4004.

Approval of a state's SWMP pursuant to section 4003 qualifies the state to receive federal funds (no longer available) and authorizes the state to issue compliance schedules; but unlike under section 3006 or 4005(c), an authorized plan does not affect the federal minimum standards themselves, or authorize states to do so. Section 4003 contains nothing that explicitly or implicitly authorizes state requirements to operate ''in lieu of'' the federal requirement as a consequence of EPA approval of the state plan. The closest analogue is that states with an approved plan may establish a ''timetable or schedule'' to bring existing open dumps into compliance with the federal requirements; but notably, Congress only authorized the state to modify the timeframes by which such facilities must be in compliance, not the substantive requirements themselves. 42 U.S.C. 6945(a).

The combination of this regulatory structure and the need to demonstrate that the final rule achieves section 4004(a)'s protectiveness standard based on the record at the time the rule is promulgated also effectively limits EPA's ability to establish the kind of regulatory provisions commenters have requested (*i.e.,* establish an alternative that allows a state permit program to approve a less stringent technical requirement based on site specific conditions). Because as discussed in Unit IV of this document, EPA is currently unable to reach a conclusion regarding the adequacy of state programs, EPA cannot demonstrate that such an alternative would meet the section 4004(a) standard. And in the absence of a mandatory mechanism for subsequent public involvement and review, which would create decisions with their own record, subject to judicial review in their own right, the lack of such information is dispositive.

With respect to the proposal to rely on RCRA sections 4010(c) and 4005(c) authorities, EPA also disagrees that this is a viable option. As the comment appears to acknowledge, construing sections 4010(c) and 4005(c) to apply to CCR units on the basis that they could *potentially* receive conditionally-exempt small quantity generator waste is inconsistent with EPA's longstanding interpretation of those sections. EPA directly addressed this issue nearly 20 years ago in the preamble for EPA's final rules at 40 CFR part 257, subpart B. In that discussion which we summarize in the next several paragraphs, EPA explained that the proposed rule was written to provide that only those non-municipal non-hazardous waste disposal units which meet the requirements in §§ 257.5 through 257.30 ''may receive'' CESQG waste, as required by RCRA section 4010(c). Any non-municipal non-hazardous waste disposal unit that did not meet the proposed requirements may not receive CESQG hazardous wastes. The proposal was written to apply to non-municipal non-hazardous waste disposal units that receive CESQG waste for storage, treatment, or disposal, including such units as surface impoundments, landfills, land application units and waste piles. The regulatory definition of the term ''disposal'' cover all placement of wastes on the land. See 40 CFR 257.2.

EPA further noted that several commenters addressed the Agency's interpretation of the statutory language ''may receive.'' One commenter supported the Agency's decision to limit the proposed regulatory requirements to only those non-municipal non-hazardous waste disposal units that receive CESQG wastes. Another commenter, however, stated that a closer reading of section 4010(c) reveals that Congress was not only concerned about modifying the criteria for ''facilities that may receive hazardous household wastes or hazardous wastes from small quantity generators . . .'' but also for ''facilities potentially receiving such wastes.'' According to the commenter, the ''may receive'' clause of the first sentence in section 4010(c) merely refers to whether a facility may legally receive CESQG waste for disposal. The ''potentially receiving such wastes'' clause of the third sentence of Section 4010(c) refers to the actual potential for such facilities to receive CESQG wastes. The potential for CESQG waste to be disposed of at many types of industrial D landfills is high even with the proposed prohibition under § 261.5. It is the ''potentially receiving'' clause that specifically commands the Agency to promulgate provisions for all industrial facilities that could potentially receive CESQG wastes.

EPA disagreed with the commenter's interpretation of the statutory language in RCRA section 4010(c). More specifically, for a number of reasons, the Agency did not believe that the statutory language cited by the commenter evidenced congressional intent that the revised criteria promulgated in the rule should address disposal of solid waste in all industrial disposal facilities. First, EPA believed that the commenter erred by focusing only on the ''facilities potentially receiving'' language in the last sentence of section 4010(c). If one reviews this language together with the statutory language in RCRA section 4010(a), it is clear that Congress did not intend for the revised criteria being promulgated in this rule to apply to all industrial landfills.

RCRA section 4010(a) required EPA to conduct a study of the then existing guidelines and criteria issued under RCRA sections 1008 and 4004 which were applicable to ''solid waste management and disposal facilities, including, but not limited to landfills and surface impoundments.'' 42 U.S.C. 6949a(a). This statutory language does indeed suggest that EPA was to study a wide range of solid waste disposal facilities, including industrial landfills. (As the commenter stated, because the information on industrial disposal facilities was quite limited, EPA's report to Congress did focus on municipal landfills.)

However, the statutory language in section 4010(c) directing EPA to promulgate a rule revising the criteria in 40 CFR part 257 limits the rule's applicability only to those facilities which may receive hazardous

household waste or small quantity generator waste. 42 U.S.C. 6949a(c). If Congress had intended the revised criteria under section 4010(c) to apply to all solid waste disposal facilities, including industrial landfills and surface impoundments, it clearly could have done so by enacting language similar to that already used in section 4010(a).

Secondly, the legislative history of RCRA section 4010 suggests that Congress expressly rejected a provision that would have required rules to be promulgated under section 4010(c) to apply to the entire universe of RCRA subtitle D solid waste disposal facilities. Indeed, the House version of section 4010 would have required EPA to promulgate revised guidelines and criteria such that they would be applicable to all ''solid waste management and disposal facilities, including, but not limited to landfills and surface impoundments. . . .'' H.R. 2867, section 30, 98th Cong., 1st Sess. (as introduced in the Senate on November 9, 1983). However, the Conference Committee instead adopted a Senate amendment which limited the scope of the revised criteria to those facilities that may receive hazardous household waste or small quantity generator waste. H. Rept. No. 98–1133, 98th Cong., 2d Sess., at 116–117.

Another indication that RCRA section 4010(c) was not intended to cover the entire universe of solid waste disposal facilities is the fact that subsequent to the enactment of section 4010(c) (as part of the Hazardous and Solid Waste Amendments in 1984), a number of bills were introduced in Congress which would have either authorized or required EPA to issue additional regulations that would address all disposal facilities receiving industrial waste as opposed to addressing those which may receive CESQG waste as stated in section 4010(c). See, *e.g.,* H.R. 3735, ''Waste Materials Management Act of 1989,'' section 324 (would have required EPA to promulgate standards for the management of industrial solid waste) (Luken Bill); S. 1113, ''Waste Minimization and Control Act of 1989,'' section 204 (would have required EPA to promulgate requirements for facilities that manage different types of industrial waste) (Baucus Bill). Neither of these provisions (although neither was enacted) would have been necessary if RCRA section 4010(c) required EPA to promulgate revised criteria for all types of industrial disposal facilities. (See 61 FR 34252, 34254–55 (July 1, 1996).)

The commenter on the proposed CCR rule makes essentially the same argument based on the same language in 4010(c) that EPA rejected in the 1996 rule. The commenter provided no legal analysis that contravenes the basis for EPA's interpretation of subtitle D. EPA thus declines to reopen or reconsider this interpretative question. EPA also notes that in any case, information in its record for this rulemaking indicates that CCR landfills or surface impoundments do not actually or potentially receive CESQG wastes.

Nevertheless, EPA recognizes that this regulatory structure gives rise to legitimate concerns about the potential for duplicative or conflicting state and federal regulatory systems. EPA has adopted measures to address these concerns within the confines of the regulatory structure that Congress established in subtitle D. First, EPA has made every effort to ensure that the final rule does not establish any requirements that truly conflict with existing state programs. To clarify, this does not mean that the requirements are necessarily the same, but rather that it is possible to comply with both federal and state requirements simultaneously. Or in other words, compliance with the more stringent standard—whether federal or state—will ensure compliance with the less stringent. Based on the comments received, EPA is aware of no example of a situation in which truly conflicting requirements will exist. Second, as discussed, these regulations do not constrain or direct state action. States can impose more stringent or different requirements, such as requiring a permit. Nor does the regulation require the state to enforce the federal requirements; even with promulgation of the final rule, the decision to bring an action under section 7002 remains entirely within the state's discretion. Third, as discussed in greater detail in Unit IX of this document, EPA has developed a number of measures to clarify the relationship between an individual state program, or particular requirements, and the federal criteria. Specifically, for those states that choose to submit a revised SWMP that incorporates the federal criteria, EPA intends to rely on the existing processes in 40 CFR part 256 relating to approval of SWMPs. EPA expects that approval of a state SWMP, while it cannot prevent a citizen group from filing a lawsuit, will carry substantial weight in any court proceeding charged with determining whether compliance with state requirements constitutes compliance with the federal criteria.

B. Enforceability of the Subtitle D Approach

Numerous commenters raised concern that reliance on a RCRA citizen suit as the basic enforcement mechanism to address non-compliance with the CCR requirements presents environmental justice concerns. Commenters argued that as a practical matter, this self-implementing approach would result in unenforced regulations affecting neighborhoods where environmental, legal, and technical services are unavailable or difficult to obtain. Commenters stated that it would be highly unreasonable for EPA to place the burden of enforcement of the CCR regulations on citizens, arguing that it is EPA's duty to make sure federal regulations protecting human health and the environment are enforced fairly and effectively, and that enforcement by citizen suits puts an unacceptable burden on low income populations located near these facilities. Commenters contended that environmental justice communities were the least likely to mount a serious challenge to the industry because low income people are often less well-educated, have less access to computers and internet technology, are less knowledgeable of how to access and interpret environmental data, and are the least likely to have the resources for a time consuming legal battle. Commenters argued that given the high number of damage cases in this industry, it was clear that the industry cannot police itself and neither can state governments. For these reasons, commenters asserted that the regulations and the enforcement must come from the federal level.

Conversely, other commenters were encouraged by the opportunity to enforce the rule through citizen suits, stating that it would result in very effective regulation since citizens have shown no reluctance to challenge companies that they believe are not responsibly following environmental regulations. Similarly, other commenters noted that other incentives existed to comply with the regulations, including the possibility of state and third party litigation (for both regulatory compliance and actual damages), and the requirements of investors, lenders, and insurers to demonstrate compliance with environmental requirements, *i.e.,* investors and lenders typically condition capital investments and loans on environmental compliance. Commenters also noted that incentives to comply were created by environmental insurance policies, which ''invariably exclude damage claims arising from non-compliance from covered events'' as well as typical corporate policies that call for

environmental compliance as a standard operating procedure.

Other commenters focused on the role of the professional engineer in the self-implementing framework, arguing that EPA is requiring the certifying professional to inappropriately take on a quasi-regulatory and enforcement role which places the certifying professional at great risk of being subject to nuisance lawsuits from project opponents, creating a scenario where some professionals may decline to be involved in such reviews. Still other commenters argued with EPA's basic premise that the RCRA subtitle D program lacks federal enforceability. Commenters contended that EPA's concerns about the lack of direct federal enforcement authority failed to recognize the significant enforcement opportunities available under existing law, namely the ''imminent and substantial endangerment authority'' under RCRA section 7003 to take action against any CCR unit that posed a risk to human health and the environment, as well as, the imminent and substantial endangerment authorities under CERCLA, as well as other federal authorities, including the federal Clean Water Act, to address circumstances where a CCR unit posed a threat.

EPA acknowledges that the lack of federal enforcement under Subtitle D presents challenges. However, as discussed above, issuing minimum national standards under the authority that is currently applicable to CCR (*i.e.,* subtitle D) is significantly more protective than the current federal standards in part 257 that apply to these wastes. It is more consistent with EPA's obligations under RCRA to put in place the additional protections that, based on the information currently available, are needed to protect health and the environment. As part of those requirements, EPA has developed a number of provisions designed to facilitate citizens to enforce the rule pursuant to RCRA section 7002. Chief among these is the requirement to publicly post monitoring data, along with critical documentation of facility operations, so that the public will have access to the information to monitor activities at CCR disposal facilities. Moreover, as noted elsewhere, a state seeking EPA's approval for a State SWMP would be required to conduct a public comment process to avail itself of the benefits of an EPA's approval.

EPA also agrees that the Agency retains the authority to bring an action under RCRA section 7003, as well as other statutes, when the facts support the necessary findings. However, an action under section 7003 does not enforce the requirements of this rule. Certainly, EPA believes that the failure to comply with the requirements of the rule increases the probability that an imminent and substantial endangerment may arise, but the fact that a facility has not complied with one or more of the requirements of this rule does not *per se* establish that a section 7003 order is warranted.

The Agency also acknowledges that the self-implementing frameworks could potentially place certifying professionals at risk for lawsuits; several of the performance standards in the proposed rule were adopted from part 258, which were designed to operate in the context of an approved state program, under the oversight of a state regulatory authority, rather than a purely private entity. In part due to this concern, the Agency has re-evaluated the performance standards throughout the final rule, and has revised them where necessary to ensure that the requirements are sufficiently objective and technically precise that a qualified professional engineer will be able to certify that they have been met.

C. Reliance on Certification by Independent Qualified Professional Engineers

As previously discussed, the majority of commenters were highly skeptical of a regulatory approach that substituted state oversight with an owner or operator hiring a consultant or professional, *i.e.,* an independent registered professional engineer or hydrologist, to certify compliance with a federal regulatory requirement and posting that information on an internet site. More specifically, commenters were concerned that relying almost entirely on professional certifications for ensuring regulatory compliance did not seem like a reliable way to provide for protection of human health and or the environment.

As explained in Unit IV.A of this document, EPA is issuing national minimum criteria under subtitle D to put in place the technical requirements the Agency has determined are necessary to protect human health and the environment from the disposal of CCR in surface impoundments and landfills, while the Agency completes its Bevill Determination. EPA is relying on the certification in this context to partially compensate for one of the more significant limitations under the authorities currently applicable to CCR: The lack of any guaranteed regulatory oversight mechanism. However, EPA disagrees that the rules rely ''almost entirely'' on professional engineers to protect human health and the environment. The final rule relies on multiple mechanisms to ensure that the regulated community properly implements requirements in this rule. As one part of this multi-mechanism approach, owners or operators must obtain certifications by qualified individuals verifying that the technical provisions of the rule have been properly applied and met. However, a more significant component supporting EPA's determination that the technical requirements will achieve the level of protection required under section 4004(a) is the performance standards that the rules lay out. These standards impose specific technical requirements, and, even where they provide flexibility, will operate to significantly constrain the facility's activities and discretion. The certifications required by the rule supplement these technical requirements, and while they are important, they are not the sole mechanism ensuring regulatory compliance.

The rule also contains a number of provisions requiring the owner or operator to document their compliance with the rule's technical requirements, and to post those documents on a publically available Web site in a timely and transparent manner. The rule also requires owners or operators to notify State Directors of numerous actions, including that certified demonstrations have been completed. This transparency will facilitate citizen and state oversight and overall enforcement of the requirements. Finally, the rule establishes specific timeframes by which these actions must occur, including timeframes by which facilities must document compliance with the various technical requirements in the rule. Timeframes have been established for: (1) Technical compliance demonstrations made by the owner or operator; (2) certifications made by a qualified professional engineer verifying the technical accuracy and veracity of the compliance demonstration; (3) notifications made to the State Director; (4) submittals (*e.g.,* data, reports and other documentation) to the operating record; and (5) postings to the owner or operator's publicly accessible internet site. Further details pertaining to all of these requirements can be found in the Recordkeeping, Notification, and Posting of Information to the Internet section of the regulations published in this rule.

1. Changes to the Definition of Independent Registered Professional Engineer or Hydrologist

EPA proposed to define ''*independent registered professional engineer or*

hydrologist'' to mean a scientist or engineer who is not an employee of the owner or operator of a CCR landfill or CCR surface impoundment, who has received a baccalaureate or post-graduate degree in the natural sciences or engineering, and who has sufficient training and experience in groundwater hydrology and related fields as may be demonstrated by state registration, professional certifications, or completion of accredited university programs that enable that individual to make sound professional judgment regarding the technical information for which a certification under this subpart is necessary.

Many comments were received on the definition. Some commenters agreed with the proposed definition, but most commenters argued that significant changes were needed. These changes included removing the requirement that the engineer be ''independent,'' adding the word ''qualified,'' and limiting the ability to make certifications to ''licensed'' professional engineers. Still other commenters felt that EPA should broaden the qualifications beyond a professional engineer or hydrologist, to include geologists, hydrogeologists, groundwater scientists or ''other qualified environmental professionals'' among the individuals able to certify regulatory demonstrations.

By far the issue receiving the most comment was whether the Agency should require a professional engineer to be ''independent.'' Commenters disagreed with EPA that the certification must be made by an independent registered professional engineer (*i.e.,* not an employee of the owner or operator of the CCR unit). Commenters argued that most utilities employ a number of professional engineers that typically possess the most relevant experience and knowledge about the unit, and that company-employed engineers and hydrologists were in a much better technical position to certify technical provisions of the rule were being met. Furthermore, commenters asserted that these professionals would be subject to the same state registration and licensing requirements as those not employed by the facility and would have an equally strong incentive to maintain their licenses in good standing as those that are independent of the utility. These commenters also pointed to several EPA rulemakings in which EPA allowed ''qualified'' professional engineers to make the kind of certifications contemplated by this rulemaking, without requiring that they be ''independent.'' Commenters also contended that state licensing and registration programs help to ensure that all professionals exercise proper judgment or ''independence'' regarding the operation of CCR landfills and CCR surface impoundments. Similarly, commenters claimed that a professional engineer without the required expertise would refuse to make any certifications for which they were not qualified. Some commenters suggested that EPA provide some criteria requiring demonstrated experience and training. Commenters also took issue with the fact that the definition focused entirely on groundwater hydrology and failed to include training or experience in other areas that would also be necessary to effectively certify specific technical criteria of the rule (*e.g.,* structural integrity, composite liner design).

The definition EPA proposed for ''independent registered professional engineer or hydrologist,'' focused on three components that were intended to define the minimum qualifications necessary to independently verify that a specific technical standard was met and to provide sufficient objectivity to reduce the opportunity for abuse. These components were: (1) The individual was a scientist or engineer by academic training or education; (2) the individual was not an employee of the owner or operator of the CCR unit; and (3) the individual had sufficient training in groundwater hydrology or related fields. The proposed definition did not require the individual to be a licensed professional engineer or hydrologist; instead the Agency prohibited the individual providing the certification from being an employee of the owner or operator of the CCR unit, reasoning that this requirement would provide some degree of independent verification of facility practices.[37] The Agency stated that the availability of meaningful independent verification was critical to EPA's ability to conclude that the performance standards laid out in the proposed rule would meet the RCRA section 4004 protectiveness standard.

In the course of developing this final rule, the Agency concluded that it needed to better define the connection between the technical requirements of the rule and the technical qualifications an individual must possess to certify the demonstrations being made by the owner or operator of the CCR unit. In doing so, the Agency looked for direction in the following rules, the ''Resource Conservation and Recovery Act (RCRA) Burden Reduction Initiative'' (71 FR 16826, April 4, 2006) and the ''Oil Pollution Prevention and Response; Non-Transportation-Related Onshore and Offshore Facilities rule (67 FR 47042, July 17, 2002). In both of these actions, the Agency had come to similar conclusions. First, that professional engineers, whether independent or employees of a facility, being professionals, will uphold the integrity of their profession and only certify documents that meet the prescribed regulatory requirements; and that the integrity of both the professional engineer and the professional oversight of boards licensing professional engineers are sufficient to prevent any abuses. (For an example see: 67 FR 47084, July 17, 2002.) And second, that in-house professional engineers may be the persons most familiar with the design and operation of the facility and that a restriction on in-house professional certifications might place an undue and unnecessary financial burden on owners or operators of facilities by forcing them to hire an outside engineer.

Reviewing these other regulatory actions and the Agency's rationale for making its decisions, has led the Agency to a similar conclusion with regard to this rule—that it is unnecessary to require the individual making certifications under this rule to be ''independent.'' Thus the final rule does not prohibit an employee of the facility from making the certification, provided they are a professional engineer that is licensed by a state licensing board. The personal liability of the professional engineer provides strong support for both the requirement that certifications must be performed by licensed professional engineers, and for removing the requirement that the engineer be ''independent.''

While other commenters argued that the word ''independent'' should be retained because an independent review and certification avoids any potential of conflict of interest, the Agency is convinced that an employee of a facility, who is a qualified professional engineer and who has been licensed by a state licensing board would be no more likely to be biased than a qualified professional engineer who is not an employee of the owner or operator. Moreover, it is not clear that an in-house engineer faces a greater economic temptation than an independent

[37] While the definition did not require the independent registered professional engineer or hydrologist to be licensed, the preamble did state that EPA expects that professionals in the field will have adequate incentive to provide an honest certification, given that the regulations require that the engineer not be an employee of the owner or operator of the CCR landfill or CCR surface impoundment, and that they operate under penalty of losing their license, implying that the professional was, in fact, licensed. This narrative and the title of independent registered professional engineer caused many commenters to assume that the certifiers indeed had to be licensed professional engineers. (See 75 FR 35194, June 21, 2010.)

engineer seeking to cultivate an ongoing relationship with a client. EPA has concluded that the programs established by state licensing boards provide sufficient guarantees that a professional engineer, regardless of whether he/she is ''independent'' of the facility, will give a fair technical review.

As an additional protection, the Agency has re-evaluated the performance standards throughout the final rule to ensure that the requirements are sufficiently objective and technically precise that a qualified professional engineer will be able to certify that they have been met.

The Agency agrees with concerns that a professional engineer may not be qualified to address all the varied aspects of CCR landfill and CCR surface impoundment design, and has amended the definition to clarify and strengthen the qualifications of the individual authorized to certify the technical demonstrations under the rule. In the proposed rule, the Agency did not require an independent registered professional engineer to be licensed, only that they be an engineer or hydrologist who had received a baccalaureate or post graduate degree in the natural sciences with training and experience in groundwater hydrology or a related field. While the term ''independent registered professional engineer or hydrologist'' conveyed to some commenters that the individual was in fact ''licensed,'' the definition in the proposal did not require it. Furthermore, as noted by commenters, the proposed definition focused primarily on hydrogeology expertise and did not include training and experience qualifications necessary to accurately certify some of the requirements being promulgated in the rule, *e.g.,* landfill and surface impoundment design and construction, structural stability assessments, analysis of unstable areas. In reviewing this proposed requirement, the Agency has determined that specifying exact qualifications and or experience for the professional engineer is neither necessary nor practical, given the range of technical specifications that will require certification. EPA has therefore adopted a more succinct requirement focused on the professional engineer's qualifications to perform the task or certification.

In making this change, the Agency was again strongly influenced by the ''Resource Conservation and Recovery Act (RCRA) Burden Reduction Initiative'' rule. (See 71 FR 16826, April 4, 2006.) In that rule, EPA amended the majority of RCRA provisions requiring the certification of an ''independent, qualified, registered, professional engineer'' to substitute the phrase, a ''qualified professional engineer,'' reasoning that a requirement for a qualified professional engineer maintains the most important components of any certification requirement: (1) That the engineer be qualified to perform the task based on training and experience; and (2) that she or he be a professional engineer licensed to practice engineering under the title Professional Engineer which requires following a code of ethics with the potential of losing his/her license for negligence (see 71 FR 16868.)

In the ''Burden Reduction Rule'' the Agency concluded that a professional engineer is able to give fair and technical review because of the oversight programs established by the state licensing boards that will subject the professional engineer to penalties, including the loss of license and potential fines if certifications are provided when the facts do not warrant it. In fact, this personal liability of the professional engineer is one of the primary reasons that commenters to the ''Burden Reduction Rule'' supported the idea that RCRA certifications should only be done by licensed professional engineers (See 71 FR 16868.) Upon further analysis and reflection, the Agency sees no reason to deviate from the position EPA held in that rule. Despite some concerns raised by commenters that problems could occur if an owner or operator hires an engineering firm that is small, inexperienced, or operating outside of their past professional practice, the Agency continues to believe that with the protections afforded by the specific performance standards in this rule and the standards and ethics to which a qualified professional engineer is subject, situations in which an unqualified or un-licensed engineer certifies a technical demonstration will be avoided. Furthermore, it is important to reiterate that state licensing boards can investigate complaints of negligence or incompetence on the part of professional engineers, and may impose fines and other disciplinary actions, such as cease-and-desist orders or license revocation. (See 71 FR 16868.) In light of the third party oversight provided by the state licensing boards in combination with the numerous recordkeeping and recording requirements established in this rule, the Agency is confident that abuses of the certification requirements will be minimal and that human health and the environment will be protected.

The Agency wants to make it clear that qualified professional engineers can utilize a qualified team of professionals in performing the analyses that underlie these certifications. In most instances, EPA expects that the basis for certification by a qualified professional engineer will be the result of a team of professionals (*e.g.,* geologists, hydrologists, scientists and engineers) who have collectively worked together in order to provide the data and analyses necessary for the professional engineer to certify the specific demonstration.

The Agency is convinced that the change to the certification requirements to allow the use of in-house expertise will not compromise environmental safety. Professional engineers employed by a facility are more familiar with the facility's particular situation and are in a position to provide more on-site review and oversight of the activity being certified. To this end, the Agency is also requiring that the qualified professional engineer be licensed in the state in which the CCR unit is located. The Agency has made this decision for a number of reasons, but primarily because state licensing boards can provide the necessary oversight on the actions of the professional engineer and investigate complaints of negligence or incompetence as well as impose fines and other disciplinary actions such as cease-and-desist orders or license revocation. Oversight may not be as rigorous if the professional engineer is operating under a license issued from another state.

Finally, the Agency disagrees with comments that professional geologists or geoscientists should be added to the list of those professionals that have expertise and authority to certify compliance with certain RCRA subtitle D regulatory requirements. In developing this final rule, the Agency has re-considered the qualifications necessary to certify compliance with the technical requirements of the rule and is limiting compliance certifications to qualified professional engineers only. While some environmental professionals, *e.g.,* hydrologists, geologists may be qualified to make certain certifications, EPA is not convinced that hydrologists or geologists licensed by a state are held to the same standards as a professional engineer licensed by a state licensing board. For example, it is unclear that hydrologists or geologists are subject to the rigorous testing required by professional engineers or that state licensing boards can investigate complaints of negligence or incompetence. Further, professional engineers have licensing boards in all 50 states, a standard not achieved by other

professional disciplines. Consequently, hydrologists, geologists, or other professionals may only perform analyses that underlie the certification, but it is the responsibility of a qualified professional engineer to make the actual certification.

D. State and Public Notifications of Certifications

To address concerns about the absence of adequate regulatory oversight under subtitle D, EPA proposed to require state and public notifications of the third party certifications, as well as other information documenting the decisions made or actions taken by the owner or operator to comply with the technical criteria in the rule. As stated in the proposal and reiterated here, the Agency cannot conclude that the regulations promulgated in this rule will ensure there is no reasonable probability of adverse effects on health or the environment unless there is a mechanism for states and citizens, as the entities responsible for enforcing the rule, to effectively monitor or oversee its implementation. Mandated documentation and transparency of the owner or operator's actions to comply with the rule provides this mechanism, and will help to minimize the potential for abuse. The proposal specified that the documentation of how the various technical standards had been met were to be placed in the facility's operating record, along with notification to the appropriate state authority. Additionally, EPA proposed to require the owner or operator to maintain a Web site available to the public that would also provide access to this documentation. EPA proposed that owners or operators post notices and relevant information on the internet site with a link clearly identified as being a link to notifications, reports, and demonstrations required under the regulations. While EPA recognized that the internet is currently the most widely accessible means for gathering and disseminating information, the Agency also solicited comments regarding alternative methods to provide notifications to the public and the states. The Agency also solicited comment on whether to require the establishment of a publicly accessible internet site to provide regulatory information to the public and the states, including whether there could be homeland security implications associated with internet posting of information, and whether the posting would duplicate information that is already available to the public through the state.

In response to most of these proposals, the Agency received little comment. Significant comment, however, was received on the publicly accessible internet site. Commenters argued that absent specific statutory authorization, it was inappropriate for EPA to delegate a regulatory oversight function to the regulated community by requiring the creation of a Web site and posting of regulatory compliance information. Commenters identified at least three substantial problems associated with ''outsourcing information management responsibilities'' to CCR facilities. First, commenters argued that EPA lacked the authority to impose such a requirement. Specifically, the commenters alleged that no statute authorizes EPA to demand that private parties act as an information clearinghouse for information pertaining to EPA's regulatory functions, either generally or in the specific context of CCR. To the contrary, the commenters argued, public information access statutes, such as the Freedom of Information Act are predicated on an assumption that information held by the government is presumptively public, while information held by a private entity presumptively is not.

Second, some commenters were concerned that facilities would not post information the facility deems to be confidential (*e.g.,* the structural stability of ash pond impoundments) and by attempting to outsource the information management role to industry, EPA effectively allows industry to make the initial determination as to confidentiality and places the burden on citizens and EPA to take action to compel disclosure.

Third, commenters were concerned that citizen groups would not accept an electric utility's self-reported information, regardless of the amount of effort the facility exerts to ensure the accuracy of the information, without a regulatory agency acting as the intermediary or providing some degree of oversight (*e.g.,* EPA's Toxic Release Inventory, EPA's Biennial Report of hazardous waste facilities). By requiring citizen groups to obtain their information from industry instead of a regulator, the commenters argued that EPA is inviting conflict as to the adequacy of data and the sufficiency of the utilities' responses to citizen groups' requests for clarification or additional information. The fact that the industry has provided information to a federal agency, subject to criminal penalties for providing false information, provides a useful public assurance of the integrity of the information.

Other commenters stated that the proposed requirement to maintain a Web site was excessive, and generated a regulatory burden upon companies that serves no useful function. Commenters urged that the same purpose could be served simply through making the certification of the registered professional engineer available on the Web site. Other commenters argued that internet posting of information on a surface impoundment's construction raised homeland security issues. These commenters alleged that the information ''can be extremely sensitive and may contain information that could be used by certain individuals with an intent to destroy a dam (*e.g.,* engineering information on the structure's foundation, detailed information on physical and engineering properties, the basis for the structure hazard classification, slope stability information, etc.).''

Finally, some commenters offered an alternative to the requirement to establish and maintain a publicly accessible internet site. Under this alternative the information would be included in the owner or operator's operating record only, and persons with ''legitimate interests in reviewing these data'' could make a written request to the owner or operator or the permitting authority to obtain the information. The commenters alleged that this would also allow the owner, operator, and federal and state authorities to know the names and identities of all organizations requesting information on the facility, which would help protect against the misuse of these data.

EPA disagrees that RCRA section 4004(a) does not authorize EPA to require facilities to disclose all of the information required under these final rule provisions. Section 4004(a) delegates broad authority to EPA to establish criteria governing facilities' management of solid waste, requiring only that such criteria ensure that there will be no reasonable probability of adverse effects on health or the environment from the disposal of solid waste. The statute imposes no limits on the actions EPA may require facilities to perform to achieve that level of protection. Moreover, unlike other statutes, *e.g.,* the Toxic Substances Control Act, or the Federal Insecticide, Rodenticide and Fungicide Act, RCRA contains neither provisions that grant facilities the right to withhold regulatory compliance information from the public, nor provisions that establish any reasonable expectation that such information will be kept confidential. To the contrary, section 7004 explicitly provides that ''[p]ublic participation in

the . . . implementation, and enforcement of any regulation under this chapter shall be provided for, encouraged, and assisted by the Administrator.'' 42 U.S.C. 6974(b). And in fact, this kind of information would routinely be publically available under the permitting process for hazardous waste facilities. Accordingly, RCRA provides more than ample authority to support these requirements.

As repeatedly discussed throughout this preamble, under section 4004(a) EPA must be able to demonstrate, based on the record available at the time the rule is promulgated that the final rule provisions will achieve the statutory standard. EPA explained in the proposal that a key component of EPA's support for determining that the rule achieves the statutory standard is the existence of a mechanism for states and citizens to monitor the situation, such as when groundwater monitoring shows evidence of potential contamination, so that they can determine when intervention is appropriate. The existence of effective oversight measures provides critical support for the statutory finding, particularly with respect to some of the more flexible alternatives EPA has adopted in certain of the technical standards in response to commenters' requests for greater flexibility. These ''transparency'' requirements serve as a key component by ensuring that the entities primarily responsible for enforcing the requirements have access to the information necessary to determine whether enforcement is warranted. Unlike a federal or state regulatory authority, private citizens cannot access a private facility to conduct inspections. While EPA encourages states to adopt and implement a CCR regulatory program, and seek EPA's approval of it via a state SWMP, EPA cannot require it. The final rule therefore must establish oversight mechanisms that will function effectively even in the absence of a state regulatory authority.

Such notifications will also reduce the incentives for owners or operators to abuse the rule's self-implementing requirements, and can improve compliance. Indeed, the public disclosure of information is an increasingly common and important regulatory tool, as evidenced by the 2010 guidance issued by the Office of Management and Budget (OMB), with principles to assist agencies in using information disclosure to achieve regulatory objectives.

Thus, even if the commenters were correct that there exists a general ''presumption'' that information held by private entities need not be made publically available, that presumption can be, and has been, effectively rebutted by the facts at hand.

None of the alternatives offered by the commenters would fulfill these same objectives. For example, simply making the certification of the qualified professional engineer available on the Web site without the underlying support information fails to provide the same incentives because no one could evaluate the accuracy of that certification. This alternative could also present the same concerns raised in comments on other sections of the rule, *i.e.,* that such a requirement could place the engineer at great risk of being subject to lawsuits. Requiring persons with ''legitimate interests in reviewing these data'' to request the data from the owner or operator also fails to provide an effective guarantee, as facilities that have failed to comply will have a strong incentive to withhold information documenting their non-compliance, however ''legitimate'' the request. And as noted, the absence of a guaranteed state permitting program means that requiring citizens to request information from such entities is also not a viable alternative. Given the absence of a guaranteed regulatory authority, EPA also disagrees that posting such information on a company internet site is necessarily duplicative, particularly in those states that have no regulatory program for controlling CCR. In addition, state requirements, whether pursuant to permits or other regulatory mechanisms, may not necessarily correspond to the requirements of this rule.

EPA acknowledges that parties may be suspicious of information self-reported by regulated entities. However, it is important to remember that facilities that provide information in compliance with these regulation remain subject to the penalties for providing false information under 18 U.S.C. 1001, even though the information will not be submitted to EPA. For example, the Tenth Circuit has held that federal jurisdiction lies under 18 U.S.C. 1001 when a defendant has submitted false information to a state delegated to enforce a federal environmental statute. *United States* v. *Wright,* 988 F.2d 1036 (10th Cir. 1993) (defendant submitted false monitoring reports required by the Safe Drinking Water Act to Oklahoma officials). This is consistent with rulings in other areas that the false statement need not be made directly to the federal government. *United States* v. *Uni Oil Co.,* 646 F.2d 946, 954–55 (9th Cir. 1981); *see also United States* v. *Patullo,* 709 F.2d 1178, 1180 (7th Cir. 1983); *United States* v. *Ross,* 77 F.3d 1525, 1544 (7th Cir. 1996) (''This court has repeatedly found the submission of a fraudulent statement to a private (or non-federal government) entity to be within the jurisdiction of a federal agency where the agency has given funding to the entity and fraudulent statements cause the entity to utilize the funds improperly.''). As commenters recognized, the potential for criminal penalties under 18 U.S.C. 1001 provides a significant guarantee, as well as a strong incentive for compliance.

EPA also disagrees with the comments raising concern about the homeland security implications of posting information on a CCR surface impoundment's construction, as it relates to structural stability. Much of the information relevant to an impoundment's structural stability is currently available through Google Earth or through EPA's Web site. For example, EPA's Web site currently provides access to all of the information from the responses to EPA's original 104(e) information requires and the information obtained through the CCR Assessment Program. This information can be accessed at the following pages: *http://www.epa.gov/osw/nonhaz/industrial/special/fossil/surveys/index.htm*, *http://www.epa.gov/osw/nonhaz/industrial/special/fossil/surveys2/index.htm*, and *http://www.epa.gov/osw/nonhaz/industrial/special/fossil/ccrs-fs/index.htm.* Moreover, the Department of Homeland Security has cleared both the internet posting of all of the information currently on EPA's Web site, as well as, in general, information on the design, hydraulic parameters, volume of contained liquids and solids, and hazard rating of all major CCR surface impoundments across the U.S.

VI. Development of the Final Rule—Technical Requirements

A. Applicability

EPA proposed general provisions to identify those solid waste disposal units subject to the proposed RCRA subpart D requirements (*i.e.,* CCR landfills and CCR surface impoundments as defined under proposed § 257.40(b)). The applicability section also identified three of the existing subpart A criteria that would continue to apply to these facilities: § 257.3–1 *Floodplains,* § 257.3–2 *Endangered Species,* and § 257.3–3 *Surface Water.* Consistent with RCRA section 4004(c), EPA specified an effective date of 180 days after publication of the final rule.

The Agency received numerous comments on this part of the rule. In

general, commenters were concerned with three specific areas. First, commenters requested additional clarification as to the specific sources of CCR that would be subject to the requirements of the rule, *i.e.,* CCR generated by the electric utilities and independent power producers. Second, commenters requested clarification on the applicability of the proposed regulations to MSWLFs disposing of CCR and third, the definition and status of ''uniquely associated wastes.'' Uniquely associated wastes are addressed in Unit XIII of this preamble. EPA also received numerous comments regarding the proposal to apply the rule to ''inactive'' CCR surface impoundments that had not completed closure prior to the effective date of the rule.

EPA is finalizing minimum national criteria that apply to owners and operators of new and existing CCR landfills and CCR surface impoundments, including any lateral expansions of these units that dispose, or otherwise conduct solid waste management of CCR generated from the combustion of coal at electric utilities and independent power producers. The rule applies only to CCR units at ''active'' electric utilities and independent power producers, *i.e.,* those that generate electricity, regardless of the fuel currently used to produce electricity. However, disposal units at facilities that are ''closed''—*i.e.,* the entire facility has been permanently taken out of service and no longer produces electricity—are outside of the scope of this rule.

Unless otherwise provided, the rule applies to CCR units located both on-site and off-site of the electric utility or independent power producer.

1. CCR Generated by Non-Utility Boilers

The requirements of this rule do not apply to wastes, including fly ash, bottom ash, boiler slag, and FGD materials generated at facilities that are not part of the electric power sector or an independent power producer and that use coal as the fuel in non-utility boilers, such as manufacturing facilities, universities, and hospitals. Industries that primarily burn coal to generate power for their own purposes (*i.e.,* non-utilities), also known as combined heat and power (CHP) plants, are primarily engaged in business activities, such as agriculture, mining, manufacturing, transportation, and education. The electricity that they generate is mainly for their own use, but any excess may be sold in the wholesale market. According to the Energy Information Administration (EIA), CHPs produced less than one percent of the total electricity generated from coal combustion in 2013 and, similarly, burned less than one percent of the total coal consumed for electricity generation or less than 5 million tons (*http://www.eia.gov/electricity/data.cfm*).

EPA never proposed to include these wastes in the rule because EPA lacked critical data from these facilities that would allow us to address key Bevill criteria (see 75 FR 35165). These other industries, and the manufacturing industries in particular, generate other types of wastes which are likely to be mixed or co-managed with the CCR at least at some facilities. As a result, the chemical compositions of the co-managed wastes are likely to be fundamentally different from the chemical composition of CCR generated by electric utilities or independent power producers. In addition, EPA noted that insufficient information was available on non-utility boilers burning coal to determine whether a regulatory flexibility analysis would be required under the Regulatory Flexibility Act, and to conduct one if it is necessary. Without such data, we were unable to fully assess CCR wastes from non-utility operations and indicated that we would decide on an appropriate course of action for these wastes after completing this rulemaking (see 75 FR 35129).

Several commenters stated that EPA's decision to propose limiting the scope of the rule only to CCR generated by the electric power sector (electric utilities and independent power producers) was arbitrary. These commenters claimed that CCR generated by the electric power sector and CCR generated by non-utilities are generally comparable in physical and chemical composition and are typically managed similarly. As a result, these commenters suggested that EPA amend the applicability of the rule to subject all facilities that generate CCR to the same disposal requirements. EPA also received comments maintaining that important differences exist between CCR generated by electric power sector facilities and non-utility facilities, and that supported EPA's proposed decision to exclude CCR generated by non-utilities from the rule. Differences identified by the commenters included waste management issues (*e.g.,* mixing and subsequent co-management of non-utility CCR and other industrial wastes generated by non-utilities), CCR generation rates, CCR management unit design, and CCR management unit operation. In response to our request for additional information, a few commenters provided either waste characterization data for non-utility CCR or information on alleged damage cases involving non-utility CCR.

Based on the proposed rule, EPA cannot include these facilities in this final rule, even if the Agency had concluded that it had received the necessary information from commenters. EPA specifically stated its intention to exclude them, and clearly stated that it had not assessed the operations. (See 75 FR 35166.) The Agency provided no indication of any intention to include such facilities, and did not solicit comment on such an option. Moreover, under the Administrative Procedure Act, the public must be given the opportunity to comment on not only the information that would support such an action, but also EPA's evaluation of that information, and the reasoning behind the Agency's decision. And with respect to this subset of facilities, no such opportunity has been presented. EPA will consider the information provided by commenters at a future point, and will determine whether the information is sufficient to address key Bevill criteria and to decide on the appropriate regulatory scheme for disposal of CCR generated by non-utilities. Accordingly, this rule does not apply to owners and operators of landfills and surface impoundments in which CCR are disposed that were generated by non-utility boilers burning coal.

2. CCR Generated Primarily From the Combustion of Fuels Other Than Coal

These requirements also do not apply to fly ash, bottom ash, boiler slag, and flue gas desulfurization materials, generated primarily from the combustion of fuels (including other fossil fuels) other than coal, for the purpose of generating electricity unless the coal comprises more than fifty percent (50%) of the fuel burned on a total heat input or mass input basis, whichever results in the greater mass feed rate of coal (see § 266.112). Fuel mixtures that contain less than 50% coal are not considered to be CCR, but other fossil fuel wastes. Other fossil fuels that are typically co-combusted with coal are oil and natural gas. In the May 22, 2000 Regulatory Determination, EPA determined that it is not appropriate to establish national regulations applicable to oil combustion wastes (OCW) because: (1) We found in most cases that OCW, whether managed alone or co-managed, are rarely characteristically hazardous; (2) we have not identified any beneficial uses that are likely to present significant risks to human health or the environment; (3) we identified no significant ecological risks posed by

land disposal of OCW; (4) we identified only one documented damage case involving OCW in combination with coal combustion wastes, and it did not affect human receptors; and (5) except for two unlined surface impoundments, we have not identified any significant risks to human health and the environment associated with any waste management practices. Similarly, EPA determined that regulating natural gas combustion wastes is not warranted because the burning of natural gas produces virtually no solid waste. Therefore, the Agency has determined that regulations for wastes generated primarily from the combustion of fuels (including other fossil fuels) other than coal are not warranted unless the fuel mixture consists primarily of coal.

3. Placement of CCR in Minefilling Operations

Consistent with the approach in the proposed rule, this rule does not apply to CCR placed in active or abandoned underground or surface coal mines. The U. S. Department of Interior (DOI) and EPA will address the management of CCR in minefills in a separate regulatory action(s). EPA will work with the OSM to develop effective federal regulations to ensure that the placement of coal combustion residuals in minefill operations is adequately controlled. In doing so, EPA and OSM will consider the recommendations of the National Research Council (NRC), which, at the direction of Congress, studied the health, safety, and environmental risks associated with the placement of CCR in active and abandoned coal mines in all major U.S. coal basins. The NRC published its findings on March 1, 2006, in a report entitled ''Managing Coal Combustion Residues (CCR) in Mines,'' which is available at *http://books.nap.edu/openbook.php?isbn=0309100496*.

The report concluded that the ''placement of CCR in mines as part of coal mine reclamation may be an appropriate option for the disposal of this material. In such situations, however, an integrated process of CCR characterization, site characterization, management and engineering design of placement activities, and design and implementation of monitoring is required to reduce the risk of contamination moving from the mine site to the ambient environment.'' The NRC report recommended that enforceable federal standards be established for the disposal of CCR in minefills to ensure that states have specific authority and that states implement adequate safeguards. The NRC Committee on Mine Placement of Coal Combustion Wastes also stated that OSM and its SMCRA state partners should take the lead in developing new national standards for CCR use in mines because the framework is in place to deal with mine-related issues. Consistent with the recommendations of the National Academy of Sciences, EPA anticipates that the U.S. Department of the Interior (DOI) will take the lead in developing these regulations. EPA will work closely with DOI throughout that process.

4. Municipal Solid Waste Landfills

The issue receiving the majority of comment in this section focused on the applicability of the rule to MSWLFs accepting CCR. The vast majority of commenters on this issue requested that EPA clarify that permitted MSWLFs, receiving CCR as daily cover or for disposal were not covered by the rule.

While most CCR is currently disposed of at electric utility owned CCR landfills or surface impoundments, there is no prohibition against disposing of CCR in state-permitted MSWLFs. However, many commenters interpreted the proposed CCR subtitle D regulations to apply to a state permitted MSWLF disposing of CCR, which as a consequence would be subject to the additional burden of posting documentation to a Web site, having a professional engineer review certification, etc. (See 75 FR 35210, where the preamble states that under a subtitle D regulation, regulated CCR wastes shipped off-site for disposal would have to be sent to facilities that meet the standards above.) Commenters argued that since MSWLFs were never mentioned in the proposed rule, that it should be made clear that the rule did not apply to these facilities. Commenters further contended that since the requirements for CCR landfills were directly modeled from the MSWLF requirements found at 40 CFR part 258, disposal in MSWLFs would be protective of human health and the environment. Commenters also contended that a benefit of MSWLFs would be their ability to provide additional capacity for the disposal of CCR as utilities seek to close, upgrade, or develop their own compliant CCR disposal sites.

EPA recognizes that there are MSWLFs that either accept CCR for disposal, use CCR for as daily cover, or both. Since the proposed and final RCRA subtitle D standards for CCR landfills are modeled after the standards for MSWLFs found at 40 CFR part 258, EPA has concluded that disposal of CCR in MSWLFs is as protective as disposal in a CCR landfill and that permitted MSWLFs are not subject to the requirements of this rule. Like the MSWLF requirements, the CCR technical criteria require new units to have composite liners or their equivalent, and all units are subject to location restrictions, run-on and run-off controls, fugitive dust controls, groundwater monitoring and corrective action, closure and post-closure care requirements.[38]

While the MSWLF fugitive dust criteria (air criteria) are not as specific as those in this rule, § 258.4(a) states that owners or operators of all MSWLFs must ensure that the units not violate any applicable requirements developed under a State Implementation Plan (SIP) approved or promulgated by the Administrator pursuant to section 110 of the Clean Air Act, as amended. It is expected that states will impose additional requirements to address fugitive dusts, of the sort codified in Illinois' 415 ILCS 5/9(a)(2012)[39] and enforced by the state (see *People of the State of Illinois* v. *KCBX Terminals Company,* Injunction no. 2013CH24788 in the Circuit Court of Cook County, Illinois. Moreover, if used as a daily cover, § 258.21 requires that the alternative cover (*i.e.,* CCR) control disease, vectors, odors, blowing litter, and scavenging without presenting a threat to human health and the environment.

The Agency is not requiring MSWLFs that receive CCR for disposal or for use as daily cover to modify their groundwater monitoring programs to comply with the rule; however the Agency expects that State Directors will require MSWLFs to modify their MSWLF permits to address the addition of CCR to the unit as it relates to groundwater monitoring and corrective action. Section 258.54(a)(2) allows for the Director of an approved state to establish an alternative list of inorganic indicator parameters for a MSWLF unit if the alternative parameters provide a reliable indication of inorganic releases

[38] One significant difference however is that MSWLFs are required to have financial assurance, a requirement not applicable to CCR under the subtitle D requirements.

[39] ''No person shall (a) Cause or threaten or allow the discharge or emission of any contaminant into the environment in any state so as to cause or tend to cause air pollution in Illinois, either alone or in combination with contaminants from other sources, or so as to violate regulations or standards adopted by the Board under this Act; (b) Construct, install or operate any equipment, facility, vehicle, vessel, or aircraft capable of causing or contributing to air pollution or designed to prevent air pollution, of any typed designated by Board regulations, (1) without a permit granted by the Agency unless otherwise exempt by this Act or Board regulations; or (2) in violation of any conditions imposed by such permit.''

from the MSWLF unit to the groundwater (*i.e.,* as would be the case if CCR was disposed in the MSWLF unit). In determining alternative parameters, the Director shall consider, among other things: (1) The types, quantities, and concentrations in wastes managed at the MSWLF unit; (2) the mobility, stability, and persistence of waste constituents or their reaction products in the unsaturated zone beneath the MSWLF unit; and (3) the detectability of indicator parameters, waste constituents, and reaction products in the groundwater. In situations where the MSWLF unit is receiving CCR for disposal and/or daily cover, EPA expects the controlled management of CCR in these units. Specifically, EPA expects State Directors to utilize the provisions in § 258.54(a)(2) to revise the detection monitoring constituents to include those constituents being promulgated in this rule under § 257.90. These detection monitoring constituents or inorganic indicator parameters are: boron, calcium, chloride, fluoride, pH, sulfate and total dissolved solids (TDS). These inorganic indicator parameters are known to be leading indicators of releases of contaminants associated with CCR and the Agency strongly recommends that State Directors add these constituents to the list of indicator parameters to be monitored during detection monitoring of groundwater if and when a MSWLF decides to accept CCR.

The Agency has concluded that CCR can readily be handled in permitted MSWLFs provided that they are evaluated for waste compatibility and placement as required under the part 258 requirements. Furthermore, consistent with the recordkeeping requirements in § 258.29, the Agency further expects State Directors to encourage MSWLF units receiving CCR after the effective date of this rule to do so pursuant to a ''CCR acceptance plan'' that is maintained in the facility operating record. This plan would assure that the MSWLF facility is aware of the physical and chemical characteristics of the waste received (*i.e.,* CCR) and handles it with the additional precautions necessary to avoid dust, maintain structural integrity, and avoid compromising the gas and leachate collection systems of the landfill so that human health and the environment are protected. While the Agency sees no need to impose duplicative requirements for MSWLFs that receive CCR for disposal or daily cover; development of these acceptance plans as well as a revised list of groundwater detection monitoring constituents will help ensure that CCR is being managed in the most protective manner consistent with the Part 258 requirements.

5. Inactive CCR Surface Impoundments

The final rule also applies to ''inactive'' CCR surface impoundments at any active electric utilities or independent power producers, regardless of the fuel currently being used to produce electricity; *i.e.,* surface impoundments at any active electric utility or independent power producer that have ceased receiving CCR or otherwise actively managing CCR. While it is true that EPA exempted inactive units from the part 258 requirements in 1990, the original subtitle D regulations at 40 CFR part 257 (which are currently applicable to CCR wastes) applied to ''all solid waste disposal facilities and practices'' except for eleven specifically enumerated exemptions (none of which are relevant). 40 CFR 257.1(c). See also, 40 CFR 257.1(a)(1)–(2). And as discussed in greater detail below, subtitle D of RCRA does not limit EPA's authority to active units—that is, units that receive or otherwise manage wastes after the effective date of the regulations. EPA has documented several damage cases that have occurred due to inactive CCR surface impoundments, including the release of CCR and wastewater from an inactive CCR surface impoundment into the Dan River which occurred since publication of the CCR proposed rule. As discussed in the proposal, the risks associated with inactive CCR surface impoundments do not differ significantly from the risks associated with active CCR surface impoundments; much of the risk from these units is driven by the hydraulic head imposed by impounded units. These conditions remain present in both active and inactive units, which continue to impound liquid along with CCR. For all these reasons, the Agency has concluded that inactive CCR surface impoundments require regulatory oversight.

The sole exception is for ''inactive'' CCR surface impoundments that have completed dewatering and capping operations (in accordance with the capping requirements finalized in this rule) within three years of the publication of this rule. EPA considers these units to be analogous to inactive CCR landfills, which are not subject to the final rule. As noted, EPA's risk assessment shows that the highest risks are associated with CCR surface impoundments due to the hydraulic head imposed by impounded water. Dewatered CCR surface impoundments will no longer be subjected to hydraulic head so the risk of releases, including the risk that the unit will leach into the groundwater, would be no greater than those from CCR landfills. Similarly, the requirements of this rule do not apply to inactive CCR landfills—which are CCR landfills that do not accept waste after the effective date of the regulations. The Agency is not aware of any damage cases associated with inactive CCR landfills, and as noted, the risks of release from such units are significantly lower than CCR surface impoundments or active CCR landfills. In the absence of this type of evidence, and consistent with the proposal, the Agency has decided not to cover these units in this final rule.

Under both the subtitle C and subtitle D options, EPA proposed to regulate ''inactive'' CCR surface impoundments that had not completed closure prior to the effective date of the rule. EPA proposed that if any inactive CCR surface impoundment had not met the interim status closure requirements (*i.e.,* dewatered and capped) by the effective date of the rule, the unit would be subject to all of the requirements applicable to CCR surface impoundments. Under the subtitle C option, those requirements would have included compliance with the interim status and permitting regulations. Under subtitle D, such units would have been required to comply with all of the criteria applicable to CCR surface impoundments that continued to receive wastes, including groundwater monitoring, corrective action, and closure.

EPA acknowledged that this represented a departure from the Agency's long-standing implementation of the regulatory program under subtitle C. While the statutory definition of ''disposal'' has been broadly interpreted to include passive leaking, historically EPA has construed the definition of ''disposal'' more narrowly for the purposes of implementing the subtitle C regulatory requirements. For examples see 43 FR 58984 (Dec. 18, 1978); and 45 FR 33074 (May 1980). Although in some situations, post-placement management has been considered to be disposal triggering RCRA subtitle C regulatory requirements, *e.g.,* dredging of impoundments or management of leachate, EPA has generally interpreted the statute to require a permit only if a facility treats, stores, or actively disposes of the waste after the effective date of its designation as a hazardous waste. EPA explained that relying on a broader interpretation was appropriate in this instance given that the

substantial risks associated with currently operating CCR surface impoundments, *i.e.,* the potential for leachate and other releases to contaminate groundwater and the potential for catastrophic releases from structural failures, were not measurably different than the risks associated with ''inactive'' CCR surface impoundments that continued to impound liquid, even though the facility had ceased to place additional wastes in the unit. EPA noted as well that the risks are primarily driven by the older existing units, which are generally unlined.

In the section of the preamble discussing the subtitle D option, EPA did not expressly highlight the application of the rule to inactive CCR surface impoundments, but generally explained that EPA's approach to developing the proposed subtitle D requirements for surface impoundments (which are not addressed by the part 258 regulations that served as the model for the proposed landfill requirements) was to seek to be consistent with the technical requirements developed under the subtitle C option. (See 75 FR 35193.) (''In addition, EPA considered that many of the technical requirements that EPA developed to specifically address the risks from the disposal of CCR as part of the subtitle C alternative would be equally justified under a RCRA subtitle D regime . . . The factual record—*i.e.,* the risk analysis and the damage cases—supporting such requirements is the same, irrespective of the statutory authority under which the Agency is operating . . . Thus several of the provisions EPA is proposing under RCRA subtitle D either correspond to the provisions EPA is proposing to establish for RCRA subtitle C requirement. These provisions include the following regulatory provisions specific to CCR that EPA is proposing to establish: *Scope and applicability (i.e., who will be subject to the rule criteria/ requirements*) . . .'') (emphasis added).

EPA received numerous comments on this aspect of the proposal. On the whole, the comments were focused on EPA's legal authority under subtitle C to regulate inactive and closed units, as well as inactive and closed facilities. One group of commenters, however, specifically criticized the proposed subtitle D regulation on the grounds that it failed to address the risks from inactive CCR surface impoundments. The majority of commenters, however, argued that RCRA does not authorize EPA to regulate inactive or closed surface impoundments. These commenters focused on two primary arguments: first, that RCRA's definition of ''disposal'' cannot be interpreted to include ''passive migration'' based on the plain language of the statute, and second, that such an interpretation conflicted with court decisions in several circuits, holding that under CERCLA ''disposal'' does not include passive leaking or the migration of contaminants.

In support of their first argument, commenters argued that the plain language of RCRA demonstrates that the requirements are ''prospective in nature'' and thus cannot be interpreted to apply to past activities, *i.e.,* the past disposals in inactive CCR units. They also argued that the absence of the word ''leaching'' from the definition of ''disposal'' clearly indicates that Congress did not intend to cover passive leaking or migration from CCR units. The commenters also selectively quoted portions of past EPA statements, claiming that these demonstrated that EPA had conclusively interpreted RCRA to preclude jurisdiction over inactive units and facilities. In particular, they pointed to EPA's decision in 1980 not to require permits for closed or inactive facilities.

Commenters cited several cases to support their second claim. These include *Carson Harbor Vill.* v. *Unocal Corp.,* 270 F.3d 863 (9th Cir. 2001); *United States* v. *150 Acres of Land,* 204 F.3d 698, 706 (2000); *ABB Industrial Systems* v. *Prime Technology,* 120 F.3d 351, 358 (2d Cir. 1997); *United States* v. *CMDG Realty Co.,* 96 F.3d 706, 711 (3rd Cir. 1996); *Joslyn Mfg. Co.* v. *Koppers Co.,* 40 F.3d 750, 762 (5th Cir. 1994); *Delaney* v. *Town of Carmel,* 55 F. Supp. 2d 237, 256 (S.D.N.Y. 1999); *see also Interfaith Cmty. Org.* v. *Honey-Well Intl Inc.,* 263 F. Supp. 2d 796, 846 n.10 (D.N.J. 2003). The commenters acknowledged that these cases were all decided under CERCLA, but claim that the cases are all equally dispositive with respect to RCRA's definition of disposal because CERCLA specifically incorporates by reference RCRA's statutory definition of disposal.

As an initial matter, it is important to correct certain misunderstandings contained throughout a number of the comments. First, EPA did propose to include inactive units under the subtitle D alternative. EPA clearly signaled its intent to cover the same universe of units and facilities covered under the subtitle C proposal. EPA did not include a corresponding discussion in its explanation of the subtitle D alternative because application of the criteria to inactive units did not represent such a significant departure from EPA's past practice or interpretation. As discussed in more detail below, the original subtitle D regulations applied to all existing disposal units. See 40 CFR 257.1(a)(1)–(2), (c) and 43 FR 4942–4943, 4944.

Second, several commenters criticized EPA's purported proposal to cover both ''closed'' and ''inactive'' surface impoundments, using the terms interchangeably. These same commenters also refer to both ''inactive facilities'' and ''inactive units.'' These are all different concepts, and EPA clearly distinguished between them.

EPA proposed to regulate only ''inactive'' surface impoundments that had not completed closure of the surface impoundment before the effective date. ''Inactive'' surface impoundments are those that contain both CCR and water, but no longer receive additional wastes. By contrast, a ''closed'' surface impoundment would no longer contain water, although it may continue to contain CCR (or other wastes), and would be capped or otherwise maintained. There is little difference between the potential risks of an active and inactive surface impoundment; both can leak into groundwater, and both are subject to structural failures that release the wastes into the environment, including catastrophic failures leading to massive releases that threaten both human health and the environment. This is clearly demonstrated by the recent spill in the Dan River in North Carolina, which occurred as the result of a structural failure at an inactive surface impoundment. Similarly, as demonstrated by the discovery of additional damage cases upon the recent installation of groundwater monitoring systems at existing CCR surface impoundments in Michigan and Illinois, many existing CCR surface impoundments are currently leaking, albeit currently undetected. These are the risks the disposal rule specifically seeks to address, and there is no logical basis for distinguishing between units that present the same risks.

EPA did not propose to require ''closed'' surface impoundments to ''reclose.'' Nor did EPA intend, as the same commenters claim, that ''literally hundreds of previously closed . . . surface impoundments—many of which were properly closed decades ago under state solid waste programs, have changed owners, and now have structures built on top of them—would be considered active CCR units.'' Accordingly, the final rule does not impose any requirements on any CCR surface impoundments that have in fact ''closed'' before the rule's effective date—*i.e.,* those that no longer contain water and can no longer impound liquid.

Further, EPA never proposed that the rule would apply to inactive facilities. The proposal was clear that the regulations would apply to active facilities—*i.e.,* those that continue to generate electricity for distribution to the public, and those that continue to manage CCR. Consistent with that proposal, the final rule applies only to inactive surface impoundments at active electric utilities, *i.e.,* facilities that are actively generating electricity irrespective of the fuel used.

Finally, some comments focused on issues that were specific to the plain language of subtitle C provisions. While most of the issues the commenters raised relate equally to EPA's authority under both subtitles C and D, because the final rule establishes standards under subtitle D of RCRA, EPA has not addressed comments that are purely relevant or applicable to the extent of EPA's authority under subtitle C.

a. Plain Language of RCRA and EPA's Past Interpretations

Under both subtitle C and subtitle D, EPA's authority to regulate ''inactive'' units primarily stems from the agency's authority to regulate ''disposal.'' The term is defined once in RCRA and applies to both subtitles C and D. Moreover, the definition explicitly includes ''leaking'' and ''placing of any solid waste . . . into or on any land so that such [waste] or any constituent thereof may enter the environment . . . or be discharged into any waters, including groundwaters.'' 42 U.S.C. 6903(3).

Commenters focused on the past statements that EPA cited in the proposal in acknowledging that the Agency was proposing to revise its interpretation for this rulemaking. In general, the comments misconstrue the significance of these past statements. The cited passages merely explain that the *permitting requirements* in subtitle C were written to be ''prospective in nature'' and as a consequence, EPA has chosen to interpret ''disposal'' more narrowly *in that context.* Thus EPA's historic interpretation under subtitle C was not based on an interpretation that the plain language of RCRA's definition of ''disposal'' precluded reaching inactive units, but on a determination that a narrower interpretation would be reasonable in light of specific language in sections 3004 and 3005, and the practical consequences of applying *these* requirements to inactive facilities.[40]

None of EPA's past statements included any interpretation that ''leaking'' does not include leaking from an inactive disposal unit, or that the statutory definition of ''disposal'' cannot be interpreted to apply to the current consequences of past disposals. To the contrary, EPA was clear in the original 1978 proposed hazardous waste regulations that leaking from inactive disposal units constitutes ''disposal'' under RCRA.

Neither RCRA nor its legislative history discusses whether section 3004 standards for owners and operators of hazardous waste treatment, storage, or disposal facilities apply or were intended to apply to inactive facilities, *i.e.,* those facilities which have ceased receiving, treating, storing, and disposing of wastes prior to the effective date of the subtitle C regulations. ''*This is an important issue, however, because some, and perhaps most, inactive facilities may still be ''disposing of waste'' within the meaning of that term in Section 1004(3) of RCRA.* 'Disposal' includes: the discharge, dumping, spilling, leaking, . . . of any solid waste or hazardous waste into or on any land or water so that such solid waste or hazardous waste or any constituent thereof may enter the environment or be emitted into the air or discharged into any waters, including groundwaters. *Many inactive facilities may well be leaking solid or hazardous waste into groundwater and thus be ''disposing'' under RCRA.*'' 43 FR 58984 (emphasis added).

Note as well that EPA declined to impose requirements on ''inactive *facilities*'' not ''inactive *units* at active facilities,'' which are the entities covered in this final CCR rule. Further, the complications discussed in 1978 were specific to inactive or closed facilities: the concern that the present owner of the land on which an inactive site was located might have no connection (other than present ownership of the land) with the prior disposal activities. Id. These considerations are not relevant to inactive CCR surface impoundments at active electric utilities.

EPA further clarified this position in the 1980 final hazardous waste rule, explaining that, while the Agency did not generally intend to regulate those portions of facilities that had closed before the effective date, there were exceptions to this, and that in individual cases, inactive portions of a facility—or in other words, inactive units, might be regulated.

> [O]wners and operators which continue to operate after the effective date of the regulations must ensure that portions of facilities closed before the effective date of these rules do not interfere with the monitoring or control of active portions. This requirement regulates the facility which operates under the RCRA regulations, although it may require the owner or operator before he receives a permit, or, as a permit condition, to take certain measures on portions of his facility closed before the effective date of these regulations.

45 FR 33068. (See also 45 FR 33170.)

In other words, EPA was clear that its jurisdiction under RCRA extended to these portions of the facility but that the Agency had made a policy choice not to exert its regulatory jurisdiction as a general matter over inactive facilities, choosing instead to rely on section 7003 and CERCLA to address the risks and require clean-up of these sites. EPA has adopted a substantially similar approach here, requiring the current owner or operator of an active facility to address the risks associated with an inactive portion of the facility that could potentially interfere with the monitoring or control of the actively operating portion of the facility through leaking contaminants or other releases.

Similarly, in the 1980 final rules, EPA expressly declined to revise the regulatory definition of disposal to exclude accidental or unintentional releases. EPA noted that ''[r]egardless of whether a discharge of hazardous waste is intentional or not, the human health and environmental effects are the same. Thus intentional and unintentional discharges are included in the definition of 'disposal.' '' (See 45 FR 33068.) While EPA revised other provisions to clarify that a permit would not be required for accidental discharges, EPA was clear that such activities are properly considered to be ''disposal.''

By contrast, EPA's past implementation of subtitle D, following from the legislative history and the statutory language, consistently applied regulatory requirements equally to all facilities, without distinguishing between active and inactive or new and existing facilities.

Congress was clear that subtitle D was intended to specifically address the problem of abandoned leaking ''open dumps'' scattered across the country, ''where frequently the use of the site for waste disposal is neither authorized nor supervised.'' H. Rep. No. 94–1491, p 37, 94th Cong., 2d Sess (1976). For example, the report described the consequences when ''the City of Texarcana Arkansas/Texas, abandoned its six open dumps, in 1968'' to support the need to require open dumps to upgrade or close.

[40] It is also clear that certain subtitle C requirements in fact do apply to inactive units, for example, section 3004(u) requires facilities to clean up releases from inactive units located on the facility site.

Similarly, in describing the need for the legislation, the House report stated:

> Disposal of solid wastes, including hazardous wastes, can have adverse environmental impacts in several ways. The following paragraphs discuss five different types of such impacts.
>
> (i) Perhaps the most pernicious effect is the contamination of groundwater by leachate from land disposal of waste. About half of the U.S. domestic water supply is from underground water, and thus is potentially subject to contamination. Such contamination is particularly vexing because often it is discovered after the damage is done and because the contamination is very long lasting. Thus leachate from a landfill or dump may not show up for years, *maybe not even until after the landfill is closed*.

Id. at 89 (emphasis added).

Consequently, subtitle D of RCRA provides clear authority to address inactive or abandoned disposal sites. The relevant provisions of RCRA subtitle D do not distinguish between ''active'' and ''inactive'' disposal units. Nor do any of the relevant provisions tie jurisdiction to the receipt or disposal of waste after a specific date.

RCRA section 1004(14) defines an ''open dump'' as ''*any* facility or site where solid waste is disposed of which is not a sanitary landfill which meets the criteria promulgated under section [4004] of this chapter and which is not a facility for disposal of hazardous waste.'' 42 U.S.C. 6903(14) (emphasis added). Section 4004(a) delegates broad authority to EPA to determine the facilities that will be considered ''open dumps,'' without any requirement that the units or facilities be in operation. ''[T]he Administrator shall promulgate regulations containing criteria for determining which facilities shall be classified as sanitary landfills and which shall be classified open dumps within the meaning of this chapter.'' 42 U.S.C. 6944(a). Section 4005(a), which is titled, ''Closing or upgrading of existing open dumps,'' is also not limited in scope: ''Upon promulgation of criteria under [1008(a)(3)] of this title, *any* solid waste management practice of disposal of solid waste or hazardous waste which constitutes the open dumping of solid or hazardous waste is prohibited, . . .'' 42 U.S.C. 6945(a) (emphasis added). See also, section 4003(a)(3), requiring state plans to provide for the closing or upgrading of ''*all existing* open dumps''). 42 U.S.C. 6943(a)(3) (emphasis added).

Consistent with the statutory provisions, EPA's current subtitle D regulations at 40 CFR part 257 apply to ''all solid waste disposal facilities and practices'' whether active or inactive, and did not differentiate between new and existing facilities.[41] 40 CFR 257.1(c). See also, 40 CFR 257.1(a)(1)–(2). EPA was clear in both the proposed and final rules that the rules applied to all existing facilities: ''These criteria for the classification of disposal facilities apply to all ''solid waste'' and ''disposal'' facilities, which are defined in the Act [in] (section 1004).'' 43 FR 4942–4943, 4944. The final rule was equally clear: ''These criteria apply to the full range of facilities and practices for ''disposal'' of ''solid waste,'' as those terms are defined in the Act.'' 44 FR 53440. (See also 44 FR 53438.) The final rule describes eight categories of materials or activities that are excluded; inactive facilities or units are not among them. This stands in stark contrast to the hazardous waste regulations, which, as discussed, specifically exempted inactive facilities from the permitting and associated regulatory requirements.

b. Case Law on the Definition of Disposal

EPA also disagrees with the commenters' second claim that regulating inactive surface impoundments would be inconsistent with case law in six circuits. The commenters are correct that some courts have held that the subsequent passive migration of contamination left on-site is insufficient to support liability against a *third party* that merely owned the property *under CERCLA.* But the commenters misconstrue this case law and fundamentally overstate its significance to the issue at hand. Of greater significance, however, is that federal courts have almost universally reached different conclusions under RCRA, holding that the statutory definition of disposal does include the passive migration of contamination from previously disposed of wastes.

As an initial matter, the issue decided by the courts in the cited CERCLA cases was narrower than the commenters allege; these cases generally focused on whether current or past owners of land contaminated by the activities of *other owners* were liable for passive migration that occurred during their ownership of the land. This is very different than the situation at hand, in which regulatory requirements are being imposed to address the existing and future contamination caused by the past and current activities of the current owner.

In addition, these decisions were largely predicated on language that is unique to CERCLA, rather than on a definitive reading of RCRA's definition of disposal. *See, e.g., United States* v. *CMDG Realty Co.,* supra at 712–717. For example, in *CMDG Realty,* the court found that passive migration was not disposal because Congress had clearly distinguished between ''releases,'' and ''disposal,'' defining the two terms differently and imposing liability on different parties for the two activities. Id. *Accord, Carson Harbor Village, supra,* at 880–885; *ABB Industrial Systems* v. *Prime Technology,* supra at 358.

Moreover, even under CERCLA courts have not universally reached the same conclusions on whether ''passive migration'' can be considered ''disposal.'' *See, e.g., Nurad, Inc.* v. *William E. Hooper & Sons Co.,* 966 F.2d 837, 844–46 (4th Cir. 1992) (concluding that because the definition of disposal includes ''leaking,'' prior owners are liable if they acquired a site with leaking barrels or underground storage tanks even though the prior owner's actions are purely passive); *ABB Industrial Systems,* Id., n.3 (expressly declining to decide whether passive migration could ever be considered ''disposal'').

But in any event, courts have consistently interpreted RCRA to apply to passive migration. Two cases under RCRA are the most directly analogous to the current situation as they address the extent of EPA's authority to regulate based on the statutory definition of ''disposal'': *In re Consolidated Land Disposal Regulation Litigation,* 938 F.2d 1386 (D.C. Cir. 1991), and *United States* v. *Power Engineering Co.,* 10 F. Supp. 2d 1145 (D. Colo. 1998), *aff'd* 191 F.3d 1224 (10th Cir. 1999). In both cases, the court considered whether EPA could impose or enforce regulatory requirements to address passive migration under the interpretation that this constituted ''disposal'' under RCRA. And in both cases the court agreed that RCRA's definition encompassed such activities.

The issue in *Consolidated Land Disposal* was whether EPA could require closed hazardous waste facilities to obtain a ''post-closure'' permit. 938 F.2d at 1388–1389. EPA had relied on the definition of disposal to support the regulation, concluding that a facility ''at which hazardous wastes have been disposed by placement in or on the land'' remains subject to both permitting and regulation because ''such hazardous wastes or constituents may continue 'leaking' or 'may enter the environment or be emitted . . . or discharged . . .'" into the environment.'' Id. Similar to the commenters' current arguments, the petitioners argued that under § 3005, a permit can only be required for ''on-

[41] The regulations establish eleven specifically enumerated exemptions, none of which are relevant to the units at issue.

going activities''—the treatment, storage, or disposal of waste at such facilities—not for the facility itself post-closure. The petitioners argued that linguistically, ''disposal . . . is not a continuing activity but occurs anew each time waste is placed into or on land.'' The D.C. Circuit summarily rejected the petitioners' interpretation, holding that this ''may be one way in which the word is used in ordinary language, but is not necessarily how it is used in the statute; the equation of ''disposal'' with ''leaking,'' which is a continuous phenomenon rather than a discrete event, is enough to blunt the sting of the petitioners' point.'' Id. This case is essentially dispositive of the issue, given the similarities between the requirement for a post-closure permit and the final requirements applicable to inactive CCR surface impoundments. Electric utilities retain ownership and control over these existing CCR units, just as hazardous waste facilities retain ownership and control over the closed units subject to post-closure permitting. In both situations, EPA requirements are designed to address both the existing and future risks of further ''releases'' or ''leaking'' from these units—*i.e.,* further disposal, as that term is defined in section 1004.

Similarly, in *Power Engineering* the court considered whether under section 3008 of RCRA, EPA could bring an action to compel the operator of a metal refinishing plant to comply with the state's RCRA regulations relating to financial assurance.[42] 10 F. Supp.2d at 1159. The defendants argued that since they were not currently disposing of waste, they were operating in compliance with state regulations and were exempt from financial assurance requirements. The court disagreed. It held that the use of the word ''leaking'' in the definition of ''disposal'' indicated that the leaching of hazardous waste into the groundwater constitutes the continuing disposal of hazardous waste. Id. at 1159–60 (''Because the definition of ''disposal'' includes the word ''leaking,'' disposal occurs not only when a solid waste or a hazardous waste is first deposited onto ground or into water, but also when such wastes migrate from their initial disposal location.'').

Courts in several circuits have also considered whether the passive migration of previously dumped waste constitutes a current or ongoing violation of RCRA, *i.e.,* illegal ''disposal,'' under the citizen suit provisions of section 7002(a)(1)(A). Most have concluded that it does. *See, Scarlett & Associates* v. *Briarcliff Center Partners,* 2009 WL 3151089 (N.D. Ga 2009) (deciding to ''follow the majority rule'' and holding that ''the continued presence of migrating waste constitutes a continuing violation under the RCRA''); *Marrero Hernandez* v. *Esso Standard Oil Co.,* 597 F. Supp. 2d 272, 283 (D.P.R. 2009) (holding that unremedied, migrating contamination is not a wholly past violation); *Cameron* v. *Peach County, GA,* No. 5:02–CV–41–1 (CAR), 2004 WL 5520003 (M.D. Ga. 2004) (holding that the continued presence of illegal contamination that remains remedial constitutes a continuing violation, even though the acts of unlawful disposal occurred in the past); *California* v. *M&P Investments,* 308 F. Supp. 2d 1137, 1146–1147 (E.D. CA 2003) (Allowing RCRA 7002 claim of continuing violation to proceed on evidence that wastes ''continue to exist unremediated'' as a result of improper discharge that had ceased over 20 years prior to filing of suit); *Aurora National Bank* v. *TriStar Marketing,* 990 F. Supp. 1020, 1025 (N.D. Ill. 1998) (''Although subsection (a)(1)(A) does not permit a citizen suit for wholly past violations of the statute, the continued presence of illegally dumped materials generally constitutes a 'continuing violation' of the RCRA, which is cognizable under § 6972(a)(1)(A).'') (internal citation omitted); *City of Toledo* v. *Beazer Materials & Servs., Inc.,* 833 F. Supp. 646, 656 (N.D. Ohio 1993) (''[T]he disposal of wastes can constitute a continuing violation so long as no proper disposal procedures are put into effect or as long as the waste has not been cleaned up and the environmental effects remain remediable.''); *Gache* v. *Town of Harrison,* 813 F. Supp. 1037, 1041–42 (S.D.N.Y. 1993) (''The environmental harms do not stem from the act of dumping when waste materials slide off the dump truck but rather after they land and begin to seep into the ground, contaminating soil and water. So long as wastes remain in the landfill threatening to leach into the surrounding soil and water, a continuing violation sure may exist.''); *Acme Printing Ink Co.* v. *Menard, Inc.,* 812 F. Supp. 1498, 1512 (E.D. Wisc. 1992) (''RCRA includes in its broad definition of 'disposal' the continuous leaking of hazardous substances. . . . Accordingly, leaking of hazardous substances may constitute a continuous or intermittent violation of RCRA.''); *Fallowfield Dev. Corp.* v. *Strunk,* No. 89–8644, 1990 WL 52745 (E.D. Pa. 1990) (''If a person disposes of hazardous waste on a parcel of property, the hazardous waste remains in that property insidiously infecting the soil and groundwater aquifers. In other words, the violation continues until the proper disposal procedures are put into effect or the hazardous waste is cleaned up.''). It is particularly notable that these cases were all decided under subsection (A); in contrast to subsection (B), section 7002(a)(1)(A) does not include any reference to liability for past actions or for prior owners. *Compare,* 42 U.S.C. 6972(a)(1)(A) and (B). In reaching their holdings, therefore, the courts necessarily relied [solely] on the reach of the statutory definition of ''disposal,'' which is at the heart of EPA's authority to regulate inactive CCR surface impoundments.

Courts have also addressed the limits of RCRA's definition of ''disposal'' is in the context of an EPA action under RCRA section 7003. Section 7003 authorizes EPA to obtain injunctive relief for actions, including disposal that ''may present an imminent and substantial endangerment to health or the environment.'' 42 U.S.C. 6973(a). Several courts have evaluated whether an inactive disposal site, where no affirmative acts of disposal are occurring, constitute an ''imminent and substantial endangerment'' under this provision. Once again, most courts accept a definition of disposal that encompasses leaking or contaminant migration from previously discarded wastes. *See United States* v. *Price,* 523 F. Supp. 1055, 1071 (D.N.J. 1981), *aff'd United States* v. *Price,* 688 F.2d 204 (3rd Cir. 1982) (''There is no doubt, however, that [section 70003] authorizes the cleanup of a site, even a dormant one, if that action is necessary to abate a present threat to the public health or the environment.'') *citing* S. Rep. No. 96–848, 96th Cong., 2d Sess., at 11 (1980); H. R. Rep. 96–1016 (Part I), 96th Cong., 2nd Sess., at 21 reprinted in [1980] U.S. Code Cong. & Ad. News, 6119, 6124; *United States* v. *Waste Indus.,* 734 F.2d 159 (4th Cir. 1984) (Rejecting district court interpretation that disposal only includes ''active human conduct'' based on the inclusion of ''leaking'' in the definition of disposal, and interpreting the ''movement of the waste after it has been placed in a state of repose [to be] encompassed in the broad definition of disposal''); *United States* v. *Diamond Shamrock Corp.,* 12 Envtl. L. Rep. 20819, 20821 (N.D. Ohio May 29, 1981) (noting that ''a disposal clearly requires no active human conduct''); *United States* v. *Conservation Chemical Co.,*

[42] Under RCRA's financial assurance regulations, owners and operators of hazardous waste facilities must document that they have sufficient resources to close their facilities and pay third-party claims that may arise.

619 F. Supp. 162, 200 (D. Mo. 1985) (''disposal' occurs. . .when [wastes] migrate from their initial location''). See also S. Rep. 98–284, p 58 (98th Cong. 1st Sess.) (''The Environmental Protection Agency and the Department of Justice have used the equitable authority and [sic] granted in section 7003 to seek court orders directing those persons whose past or present acts have contributed to or are contributing to the existence of an imminent and substantial endangerment to abate such conditions. This has been an intended use of the section 7003 since 1976. . . . An [sic] evidenced by the definition of 'disposal' in section 1004(3), which includes the leaking of hazardous wastes, section 7003 has always provided the authority to require the abatement of present conditions of endangerment resulting from past disposal practices, whether intentional or unintentional.'').

While EPA continues to maintain that the statutory definition of disposal does in fact authorize regulation of inactive CCR surface impoundments, this is not the sole basis for that authority. Under section 1008(a)(3), EPA is authorized to establish criteria governing solid waste management, which includes the ''storage'' of solid waste. 42 U.S.C. 6904(28) and 6908(a)(3). RCRA's definition of ''storage'' is limited to hazardous waste; under subtitle D, therefore, the definition Congress intended was the dictionary definition, which incontrovertibly covers the activities associated with continuing to maintain CCR in inactive surface impoundments. For example, Merriam Webster defines ''storage'' as ''the state of being kept in a place when not being used'' and ''the act of putting something that is not being used in a place where it is available, where it can be kept safely, etc.''

Finally, consistent with the proposed rule and the final Regulatory Determination in Unit IV.B of this document, the final rule does not apply to CCR that is beneficially used.

6. Beneficial Use

The proposed rule generally distinguished between the disposal of CCR and the beneficial use of CCR. Disposal activities would be subject to regulation under one of two alternative regulatory schemes. But under either alternative, beneficial use would remain Bevill exempt and would not be subject to regulation. The proposal identified specific criteria that would be used to distinguish between legitimate beneficial uses of CCR and the disposal of CCR. These criteria were largely drawn from the approach contained in the May 2000 Bevill Regulatory Determination. The criteria were:

—The material used must provide a functional benefit. For example, CCR in concrete increases the durability of concrete—and is more effective in combating degradation from salt water; synthetic gypsum serves exactly the same function in wallboard as mined gypsum, and meets all commercial specifications; CCR as a soil amendment adjusts the pH of soil to promote plant growth.

—The material substitutes for the use of a virgin material, conserving natural resources that would otherwise need to be obtained through practices, such as extraction. For example, the use of FGD gypsum in the manufacture of wallboard (drywall) decreases the need to mine natural gypsum, thereby conserving the natural resource and conserving energy that otherwise would be needed to mine natural gypsum; the use of fly ash in lieu of Portland cement reduces the need for cement. CCR used in road bed replace quarried aggregate or other industrial materials.

—Where relevant product specifications or regulatory standards are available, the materials meet those specifications, and where such specifications or standards have not been established, they are not being used in excess quantities. For example, when CCR is used as a commercial product, the amount of CCR used is controlled by product specifications, or the demands of the user. Fly ash used as a stabilized base course in highway construction is part of many engineering considerations, such as the ASTM C 593 test for compaction, the ASTM D 560 freezing and thawing test, and a seven day compressive strength above 2760 kPa (400 psi). If excessive volumes of CCR are used—*i.e.,* greater than were necessary for a specific project,—that could be grounds for a determination that the use is not beneficial, but rather is being disposed of. 75 FR 35162–35163.

EPA explained that in the case of agricultural uses, CCR would be expected to meet appropriate standards, constituent levels, prescribed total loads, application rates, etc. EPA has developed specific standards governing agricultural application of biosolids. While the management scenarios differ between biosludge application and the use of CCR as soil amendments, EPA stated that the Agency would consider application of CCR for agriculture uses not to be a legitimate beneficial use if they occurred at constituent levels or loading rates greater than EPA's biosolids regulations allow. (75 FR 35162–35163, June 21, 2010)

EPA proposed to codify these criteria in the term, ''beneficial use of coal combustion products (CCPs).'' This definition stated that the beneficial use of CCPs was the use of CCPs that provides a functional benefit; replaces the use of an alternative material, conserving natural resources that would otherwise need to be obtained through practices such as extraction; and meets relevant product specifications and regulatory standards (where these are available). CCPs that are used in excess quantities (*e.g.,* the field-applications of FGD gypsum in amounts that exceed scientifically-supported quantities required for enhancing soil properties and/or crop yields), placed as fill in sand and gravel pits, or used in large scale fill projects, such as restructuring the landscape, are excluded from this definition. (75 FR 35129–35130, June 21, 2010).

Commenters generally supported the criteria in the proposal but raised concern that the criteria lacked specificity; some commenters stated that the criteria were those that states already considered in doing their beneficial use determination. Commenters also suggested the use of a ''no toxics'' provision and others suggested that the criteria include a requirement that ''environmental benefits'' be achieved. A more general comment raised by several commenters was that the proposed criteria failed to establish any standard that ensured protection of human health and the environment. Finally, one commenter raised concern that EPA's approach to beneficial use, and particularly to large scale fill operations, inappropriately assumed that these operations constituted the disposal of solid waste, which, the commenter claimed was inconsistent with a series of judicial decisions.

There are generally three critical issues in determining whether a material is regulated under RCRA subtitle D: whether the material is a ''solid waste,'' whether the activity constitutes ''disposal,'' and whether regulation of the disposal is warranted. Although there can be some overlap between these issues in that the same facts may be relevant to each of them, understanding the distinction between them is critical to understanding the final approach to the beneficial use of CCR adopted in this rulemaking.

In order to be subject to RCRA, the material must be a solid waste. The statute defines a solid waste as ''any garbage, refuse . . . and other discarded material. . . .'' 42 U.S.C. 6903(27). As EPA noted in the proposed rule, for some beneficial uses, CCR is a raw

material used as an ingredient in a manufacturing process that have never been ''discarded,'' and thus, would not be considered solid wastes under the existing RCRA regulations. For example, synthetic gypsum is a product of the FGD process at coal-fired power plants. In this case, the utility designs and operates its air pollution control devices to produce an optimal product, including the oxidation of the FGD to produce synthetic gypsum. In this example, after its production, the utility treats FGD as a valuable input into a production process, *i.e.,* as a product, rather than as something that is intended to be discarded. Wallboard plants are sited in close proximity to power plants for access to raw material, with a considerable investment involved. Thus, FGD gypsum used for wallboard manufacture is a product rather than a waste or discarded material. This use and similar uses of CCR that meet product specifications would not be regulated under the final rule.

However, this does not describe the majority of CCR, which are unambiguously wastes; after generation in the boiler, they are placed into landfills or surface impoundments. While they may subsequently be dredged from these units and reused, placement in a landfill or surface impoundment presents prima facie evidence of discard. At the time the material is placed into the unit, the utility is not treating the material as a valuable product or otherwise seeking to protect the material for use. Although the material may subsequently be reused if a buyer is found, the material is originally placed in the unit with the intent to let it remain in place if no buyer is found. The waste designation does not change merely because a material in a surface impoundment or landfill may in the future be beneficially reused.

For those materials that are ''wastes'' the second issue becomes relevant: whether the activities involved with the material constitutes ''disposal'' or ''solid waste management.'' The statute distinguishes between these activities and ''use;'' several activities are listed in the definitions of ''disposal'' and ''solid waste management'' and ''use'' is not among them. See 42 U.S.C. 6903(3) and (28). In general, commenters agreed that the three criteria in the proposal, and discussed above, would identify those activities that were properly considered to be legitimate beneficial uses rather than disposal. As several commenters noted, many state beneficial use programs rely on similar (or identical) criteria. And for encapsulated uses, EPA agrees that these three criteria are sufficient to distinguish between the activities that will be regulated as disposal under this final rule and those that will be considered beneficial use. Accordingly, EPA has adopted them in the final definition of ''beneficial use.''

But as EPA acknowledged in the proposal, the issues are more difficult with regard to unencapsulated uses. Because these uses involve the direct placement of CCR on the land, they are clearly more analogous to activities that have consistently been considered to be ''disposal.'' RCRA defines disposal to specifically include the ''placing of any solid waste or hazardous waste into or on any land or water so that such solid waste or hazardous waste or any constituent thereof may enter the environment . . .'' 42 U.S.C. 6903(3). The issue is further complicated by the fact that there can be risks associated with placement of unencapsulated CCR on the land. As described in the proposal, CCR can leach toxic metals at levels of concern. The major risks associated with the placement of unencapsulated CCR on the land for beneficial use involved using large volumes of CCR to restructure the landscape, such as occurred at the Battlefield golf course, and placement in quarries and sand and gravel pits, such as occurred at the Gambrills, Maryland site. EPA acknowledged in the proposal that these types of operations would be subject to regulation as disposal, and so were not directly on point. However, because these damage cases involved the placement of unencapsulated CCR on the land, they raised questions regarding the safety of other uses of unencapsulated CCR that involved direct placement on the land. In addition, previous risk analyses do not address many of the use applications currently being implemented, and have not addressed the improved leachate characterization methods. EPA also noted that some scientific literature indicates that the uncontrolled (*i.e.,* excessive) application of CCR can lead to the potentially toxic accumulation of metals.[43]

As noted, several commenters raised concern that EPA's beneficial use criteria did not include any standard that ensured protection of human health and the environment. EPA agrees that a criterion that accounted for the potential risks of the land placement of unencapsulated CCR would be an appropriate element to include in differentiating between disposal and beneficial use. RCRA's definition of disposal includes some elements related to risk: specifically, the definition includes as a relevant concept that the waste or any constituent of concern ''may enter the environment.'' In this regard it is also relevant that not all disposal activities are regulated by EPA under subtitle D; rather, EPA only regulates those that present risks that exceed the Agency's acceptable risk levels.

Building off of these concepts, the Agency has developed an additional criterion to address both the question of whether the activity is appropriately considered to be ''disposal,'' and the question of whether that ''disposal'' warrants regulation. Because uses that fail to meet the beneficial use criteria will be considered disposal and would therefore be considered disposal subject to the final regulation, this fourth criterion was designed to exclude uses likely to present the same risks as the management practices regulated under other sections of the final rule. Thus, the final criterion directly correlates to the practices and the risks that the disposal regulations are designed to address: the risks associated with the placement of large quantities of CCR in a single concentrated location, such as a CCR landfill, as documented in the 2014 risk assessment and the damage cases.

As discussed in more detail below, to be considered a ''beneficial use,'' prior to initiating an activity that involves placing unencapsulated CCR on the land in amounts greater than 12,400 tons, in non-roadway applications, the user must demonstrate that environmental releases to groundwater, surface water, soil and air are comparable to or lower than those from analogous products made without CCR, or that environmental releases to groundwater, surface water, soil and air will be at or below relevant regulatory and health-based benchmarks for human and ecological receptors during use.

EPA acknowledges that there may be risks associated with uses that are below this threshold, depending on the characteristics of the CCR, the amount of material and the manner in which it is placed, and (perhaps most important) the site conditions. Consequently, all unencapsulated uses, including use in road construction and agriculture, should be conducted with care, according to appropriate management

[43] See, for example, ''Effects of coal fly ash amended soils on trace element uptake in plant,'' S.S. Brake, R.R. Jensen, and J.M. Mattox, Environmental Geology, November 7, 2003 available at *http://www.springerlink.com/content/3c5gaq2qrkr5unvp/fulltext.pdf*; See information regarding the Town of Pines Groundwater Plume at *http://www.epa.gov/region5superfund/npl/sas_sites/INN000508071.htm.* Also see additional information for this site at *http://www.epa.gov/region5/sites/pines/#updates.*

practices, and with appropriate characterization of the material and the site where the material will be placed. However, as discussed in the previous section, because the amounts and, in some cases, the manner in which the CCR are used are very different from the land disposal modeled in the risk assessment, EPA cannot extrapolate from the risk assessment to reach conclusions regarding the risks these uses may pose. And in the absence of such information, EPA cannot establish criteria to regulate these uses.

a. Final Definition of the Term ''Beneficial Use of CCR''

The final beneficial use criteria are as follows: (1) The CCR must provide a functional benefit; (2) The CCR must substitute for the use of a virgin material, conserving natural resources that would otherwise need to be obtained through practices such as extraction; (3) the use of CCR must meet relevant product specifications, regulatory standards, or design standards when available, and when such standards are not available, CCR are not used in excess quantities; and (4) when unencapsulated use of CCR involves placement on the land of 12,400 tons or more in non-roadway applications, the user must demonstrate and keep records, and provide such documentation upon request, that environmental releases to groundwater, surface water, soil and air are comparable to or lower than those from analogous products made without CCR, or that environmental releases to groundwater, surface water, soil and air will be at or below relevant regulatory and health-based benchmarks for human and ecological receptors during use. Any use that fails to comply with all of the relevant criteria will be considered to be disposal of CCR, subject to all of the requirements in the disposal regulations, and the user will be considered to be the owner or operator of a CCR disposal unit. Encapsulated uses need only comply with the first three criteria. Unencapsulated uses involving placement on the land of 12,400 tons or more in non-roadway applications that fail to meet all of the beneficial use criteria are considered a CCR unit. As previously noted, the first three criteria were discussed in the proposal and commenters generally supported these criteria, which establish flexible performance standards. As discussed above, the Agency has developed an additional criterion in response to comments, which generally reflects the issues discussed in the proposal. This additional criterion is designed to address the environmental and human health concerns associated with large-scale, unencapsulated uses that have features similar to landfills. These four criteria are discussed in greater detail in the sections below. Any user of CCR that, at a later time, believes that there could be a health or environmental issue associated with their beneficial use should work with their state agency to address any potential issue.

As noted above, encapsulated uses of CCR must only comply with the first three criteria. Encapsulated beneficial uses are those that bind the CCR into a solid matrix that minimizes their mobilization into the surrounding environment. Examples of encapsulated uses include, but are not limited to: (1) Filler or lightweight aggregate in concrete; (2) a replacement for, or raw material used in production of, cementitious components in concrete or bricks; (3) filler in plastics, rubber, and similar products; and (4) raw material in wallboard production.

Compliance with the first three criteria suffices because, as discussed in Unit IV of this document, the available information demonstrates that encapsulated uses of CCR raise minimal health or environmental concerns. The Agency did not receive any data to contradict this assessment during any of the comment periods. In addition, since publication of the proposal, the Agency conducted a study of FGD gypsum in wallboard and fly ash concrete, which further supports this conclusion. This study ''*Coal Combustion Residual Beneficial Use Evaluation: Fly Ash Concrete and FGD Gypsum Wallboard*'' (February 2014) concluded that ''environmental releases of constituents of potential concern (COPCs) from CCR fly ash concrete and FGD gypsum wallboard during use by the consumer are comparable to or lower than those from analogous non-CCR products, or are at or below relevant regulatory and health-based benchmarks for human and ecological receptors.''

Criteria 1: CCR must provide a functional benefit. This criterion is designed to ensure that the material performs a genuine function in the product or use; while it need not improve product performance when compared to the material for which it is substituting, CCR must genuinely be a necessary component of the product. In other words, there must be a legitimate reason for using CCR in the product other than the fact that it is an alternative to disposal of the material, *e.g.,* the material fulfils material specifications. For example, CCR provides a functional benefit when used as a replacement for cement in concrete because the CCR increases the durability of the concrete and is also more effective against degradation from salt water. FGD gypsum serves the same function in the production of wallboard as mined gypsum, and meets all product specification. Additionally, CCR can be used to adjust the pH of soils thereby increasing and promoting plant growth.

One commenter noted that many states already consider whether the material provides a functional benefit when making beneficial use determinations under their regulatory programs. The Agency agrees that this is an important criterion in determining whether a use is a ''beneficial use.'' To the extent that a state regulatory program has determined that a particular use provides a functional benefit, this may serve as evidence that this criterion has been met.

Criteria 2: CCR must substitute for the use of a virgin material, conserving natural resources that would otherwise need to be obtained through practices, such as extraction. This criterion is intended to ensure that the use is truly ''beneficial'' from an environmental perspective. Examples of CCR used as a substitute for a virgin material include FGD gypsum for mined gypsum and the use of fly ash in lieu of Portland cement thereby reducing the need for cement. The use of FGD gypsum in the manufacture of wallboard reduces the need to use virgin gypsum, thereby conserving natural resources (virgin gypsum) while conserving valuable energy that would be needed to mine the virgin gypsum. Similarly, the use of CCR fly ash in lieu of Portland cement reduces the overall need for cement. CCR used in a road bed application substitutes for the use of quarried natural materials that provide structural support for the road surface.

One commenter again highlighted that many states consider this criterion in their current state beneficial use programs. The Agency agrees that this second criterion is appropriate, and that conserving natural resources is an important function that should be encouraged. Here as well, potential users of CCR materials may choose to rely on a state determination to provide evidence that this criterion has been met.

Criteria 3: The use of CCR must meet relevant product specifications, regulatory standards, or design standards, when available, and where such specifications or standards have not been established, CCR may not be used in excess quantities. This criterion was intended to address both the legitimacy of the use and the potential environmental and human health

consequences associated with the use of excess quantities of CCR, particularly unencapsulated CCR. If excessive volumes of CCR are used—*i.e.,* greater than necessary for a specific project—that calls into question whether the purpose of the application was in fact a sham to avoid compliance with the disposal regulations. In addition, the record demonstrates that the risks from use of CCR are more likely to be associated with large volumes, particularly for unencapsulated uses.

The Agency has modified this criterion slightly from the proposed rule. The proposed rule merely referenced ''relevant product specifications or regulatory standards'' and EPA was concerned that this was too narrow, and might not incorporate all of the relevant technical information currently available that provides guidance on what constitutes an excess amount. Consequently, in the final definition the Agency has added the phrase ''design standards.'' Design standards are different from product specifications, because they include things other than ''products.'' An example of a ''design standard'' would be technical guidance specifying that six inches of CCR is to be used in constructing a road.

EPA received several comments on this provision, several of which criticized the sole reliance on engineering performance standards. For example, one commenter questioned how the Agency would quantify acceptable amounts for each use if no specifications or standards were in place. One commenter stated that the Agency needs to rely on more than the existence of engineering performance standards or comparisons to typical application rates of mined materials as coal combustion wastes are unique materials and comparisons to typical rates of application of natural gypsum or other soil amendments are inappropriate. Another commenter suggested a provision that would require users to follow a plan to only use what is necessary to reach the desired effect, in lieu of product specifications.

EPA purposely did not attempt to establish product specifications for each potential beneficial use application. The potential products are too varied, and in many instances EPA lacks the necessary expertise (*e.g.,* to develop manufacturing specifications for individual products.). Nor is such an approach necessary. When CCR substitutes for other materials, the amount used is typically controlled by product specifications, particularly for encapsulated uses. Product specifications currently exist for many, if not most, of the significant uses of CCR and can be found in a variety of sources. For example, as previously described, fly ash used as a stabilized base course in highway construction is subject to both regulatory standards under DOT/FHWA, and engineering specifications, such as the ASTM C 593 test for compaction, the ASTM D 560 freezing and thawing test, and a seven-day compressive strength above 2760 kPa (400 psi).

Similarly, in an agricultural setting, EPA expects all appropriate standards, constituent levels, prescribed total loads, and application rates to be met. For example, EPA has developed specific standards governing the agricultural application of biosolids. While the management scenarios differ between biosludge application and the use of CCR as soil amendments, EPA would consider application of CCR for agriculture uses not to be a legitimate beneficial use if they occurred at constituent levels or loading rates greater than EPA's biosolids regulations. Several commenters also noted that agronomic rates currently exist for certain items such as peanuts, cotton, tomatoes, corn and soybeans.[44] EPA would generally consider application of CCR above these rates, or any other rate that has been scientifically justified, to constitute disposal rather than beneficial use.

Many other sources of technical reports and documents exist for other uses. ASTM Standard E2277–03 provides standard guidance and a methodology for using CCR in a structural fill and includes a consideration of engineering properties and behaviors, testing procedures, and design considerations relevant to constructing a structural fill project using CCR. Industry guidance, such as USWAG's ''*Engineering and Environmental Guidance on the Beneficial Use of Coal Combustion Products in Engineered Structural Fill Projects*'' may also provide information relevant to this issue. Further, some states, such as Wisconsin and Virginia, have developed environmental guidance for evaluating the suitability of a site prior to construction of a CCR structural fill.

While many of these documents do not establish binding requirements, nor is EPA seeking to make them binding on users, they provide evidence of the design and construction practices, including the amounts that are typically used throughout the industry, and provide a basis on which to evaluate whether excessive quantities have been used in a particular application. These types of documents are also relevant in making judgments on the larger question—whether the activity is legitimate reuse or merely sham disposal. In essence, product specifications serve the same function as the requirement suggested by a commenter for a plan to only use what is necessary to reach the desired effect.

Commenters were also concerned that the proposed standards, and particularly this criterion, did not include any provision that would ensure that CCR reuse was protective of human health and the environment. One commenter stated that product specifications and engineering standards do not speak to environmental risk or consumer exposure. This same commenter was concerned that the proposed criteria used circular logic by stating that excess materials were not to be used in cases where specifications or standards have not been established. Another commenter criticized this criterion because it did not include threshold levels that protect public health from the range of toxicants routinely found in coal ash.

EPA generally disagrees that the requirement to ensure that excessive volumes have not been used is unrelated to environmental and safety concerns. Minimizing the amount of material used in a product or released to the environment decreases potential exposures to the material. EPA agrees, however, that an additional criterion that more directly addresses the potential health and environmental risks is appropriate for unencapsulated uses, which present the greater potential for exposures of concern. As discussed in more detail below, the Agency has added a criterion to specifically require users of unencapsulated CCR to demonstrate that environmental and health related standards have been met. The criterion is a general performance standard that is equally applicable to all sites and uses and will account for a wide variety of potential exposures. By contrast, in order to establish toxicant ''threshold levels,'' EPA would need to develop risk assessments that account for the wide variety of potential uses and exposures. This is neither practical nor feasible, given the site specific nature of the potential risks and the myriad of potential uses. In addition, EPA disagrees that this is necessary, as the performance standard laid out in the fourth criterion will appropriately address the risks documented in the current record for these uses.

[44] Commenters argued that, at least in agronomic settings, there is no incentive to use excess amounts because it simply increases the grower's cost.

Furthermore, as the Agency has previously stated in the May 2000 Regulatory Determination and the 2010 proposal, leaving the Bevill determination in place for beneficial use does not conflict with EPA's view that certain beneficial uses, *e.g.,* use in road construction and agriculture, should be conducted with care, according to appropriate management practices, and with appropriate characterization of the material and the site where the materials will be placed. EPA has concluded that the potential risks of these uses do not warrant federal regulation, but can be addressed, if necessary, in other ways.

State programs exist and have the expertise to address beneficial use applications. In addition, the Agency is currently developing a framework to address the risks associated with the beneficial use of unencapsulated materials. This framework is expected to be finalized in 2015; the framework will be available to assist in the implementation of issues associated with the unencapsulated uses of CCR. The Agency has also been working with the U.S. Department of Agriculture to address the risks associated with the agricultural use of CCR. In conclusion, the Agency believes that sufficient tools are available (or will soon be available) to address the site-specific risks associated with the beneficial use of CCR.

Criteria 4: When unencapsulated use of CCR involving placement on the land of 12,400 tons or more in non-roadway applications, the user must demonstrate and keep records, and provide such documentation upon request, that environmental releases to groundwater, surface water, soil and air are comparable to or lower than those from analogous products made without CCR, or that environmental releases to groundwater, surface water, soil and air will be at or below relevant regulatory and health-based benchmarks for human and ecological receptors during use. The Agency has established an environmental criterion to protect human health and the environment in response to numerous comments received on the proposal raising concern that additional provisions were necessary to ensure that unencapsulated uses of CCR needed to be conducted in an environmentally protective manner. The Agency discussed in the proposed rule the ways in which the use of CCR in an unencapsulated manner could affect groundwater, surface water, air and be associated with dust emissions. This fourth ''environmental'' criterion requires potential users to addresses potential risks from all of these pathways in order to avoid compliance with the final disposal requirements. Existing sources of guidance and standards (*e.g.,* ASTM E2277–03 and USWAG's ''*Engineering and Environmental Guidance on the Beneficial Use of Coal Combustion Products in Engineered Structural Fill Projects,*'' to name just two that are currently available), are available and may provide useful assistance for determining if the use of CCR are comparable to or lower than those from analogous products made without CCR, or that environmental releases to groundwater, surface water, soil and air will be at or below relevant regulatory and health-based benchmarks for human and ecological receptors during use. Information (*e.g.,* modeling results, proposed designs, risk assessments, etc.) that have been proposed or developed to comply with state standards that explicitly address the environmental impacts of unencapsulated uses may also be relevant to this determination.

i. Source of the 12,400 Ton Threshold and Fill Operations.

As discussed earlier in this section, the fourth criterion was designed to address whether the activity is appropriately considered to be ''disposal'' and whether that ''disposal'' warrants regulation. Thus, the final criterion correlates to the practices and the risks at issue: The placement of large quantities of CCR in a single concentrated location, as documented by the 2014 risk assessment and the damage cases.

In the proposed rule, EPA explained that the risks of greatest concern from unencapsulated beneficial uses were associated with the placement of CCR in quarries and sand and gravel pits, and with large scale fill operations used to re-grade the landscape. EPA generally proposed to define these operations as ''disposal'' rather than ''beneficial use.'' As discussed below, EPA has retained that approach with respect to the placement in sand and gravel pits and quarries; consequently the fourth criterion need not account for these uses. By contrast, EPA has not definitively concluded that ''large scale fill operations,'' per se, constitute the disposal of CCR. This is because EPA agrees with commenters that, if constructed correctly, large scale fill operations can meet all of the criteria for a beneficial use. But EPA also agrees that these applications can present risks to human health and the environment, and therefore has drafted the fourth criterion to specifically address the risks presented by these operations. The fourth criterion is thus tied to the Agency's general approach to large scale fill.

The Agency acknowledged in the proposal that additional guidance was warranted on what would constitute a large scale fill operation, and received numerous comments on this issue in response to the proposal. EPA requested comments again on the topic of large scale fills in a Notice of Data Availability (NODA). 78 FR 46940 (August 2, 2013). The NODA discussed the fact that many commenters on the proposed CCR rule stated that EPA should have developed a size criterion to define large scale fill operations. One commenter suggested 5,000 cubic yards as a size criterion for a CCR landfill, but did not provide a basis for this. Other commenters suggested size criteria but for different reasons than defining disposal criteria; for example, Wisconsin has a standard where all CCR used for unconfined and confined ''fill projects exceeding 5,000 cubic yards require concurrence by the State prior to commencement of the project.'' Similarly, West Virginia stated that ''unencapsulated use of CCR as structural fills not exceeding 10,000 cubic yards are approvable on a case-by-case basis.''

In the NODA, EPA identified three different types of data sets that could provide information relevant to developing appropriate criteria or to otherwise defining what constitutes a ''large scale'' fill operation. EPA solicited comment on the adequacy of the data sets and whether EPA should consider them for the purpose of creating criteria or a definition. The three data sets were: (1) The size of the structural fills that have resulted in damage cases; (2) the distribution of landfill sizes, derived either from an EPA Office of Water's questionnaire or from the landfill size distribution used in the proposed rule; and (3) the size distribution for large scale fills that have been constructed in North Carolina. Many commenters argued that it was entirely inappropriate for EPA to specify in the rule when a project constitutes beneficial use simply by volume or amount of structural fill necessary to construct a stable base for a building. Commenters argued that a large scale fill operation, if designed appropriately, constituted a legitimate beneficial use. In fact, industry commenters universally claimed that they were not aware of any damage cases or adverse environmental impacts associated with structural fills that had adhered to industry guidance (*e.g.,* ASTM standard E2277–03 for structural fills and the USWAG *Engineering and Environmental Guidance on the Beneficial Use of CCPs*

in Engineered Structural Fill Projects), and argued that the history of well-designed and implemented engineered structural fills demonstrate that CCR can serve as a valuable resource in avoiding disturbing native ground to secure borrow soils where fill materials are needed to establish a final grade for a project site that meets the need of the proposed final use. To this end, the commenters also acknowledged that site characterization and characterization of the CCR are fundamental to the construction of fills across the U.S. Similarly, other commenters stated that size should not be the only criterion used to define large scale fill operations and highlighted that the site conditions, including such features as the hydraulic conductivity of the area, should also be an important criterion to consider. Still other commenters stated that CCR landfills cannot include large scale fill CCR beneficial use projects because such operations do not involve disposal of a solid waste. Rather, industry commenters argue that the determination as to what is disposal as opposed to beneficial use should be a determination that rests solely with state agencies. These commenters suggested that the determination as to whether a particular fill project constituted disposal, rather than beneficial use should be based on a series of factors, and not simply a size-cut-off. Finally, other commenters argued that the Agency incorrectly presumed that only large scale fill operations could cause environmental damage, and suggested that rather than regulating large scale fill operations solely on the basis of the volume or the amount of CCR involved, the information available to EPA from damage cases and monitoring data suggests that an additional, if not primary criteria for regulating fill operations, including those involved in highway construction, should include the prevention of CCR coming into contact with water. Focusing on the risks of concern—that large scale fills were effectively operating as landfills—the Agency reviewed the database of landfills used in the 2014 risk assessment and has established a threshold limit that corresponds to the smallest size landfill in the risk assessment database. EPA selected this threshold as the trigger for requiring an affirmative demonstration by the user that there will be no releases of concern as a consequence of the land application, because the available evidence in the record (*i.e.,* the 2014 risk assessment) demonstrates that at these volumes the potential risks are of such significance to warrant regulation. Based on this evidence, the burden then shifts to the potential user to demonstrate that these potential risks do not exist at the particular site or have been adequately mitigated. Under this approach, unencapsulated beneficial use applications greater than or equal to 12,400 tons can still be conducted without becoming subject to the disposal regulations by using engineering principles, such as a liner system, and demonstrating that environmental releases to groundwater, surface water, soil and air are comparable to or lower than those from analogous products made without CCR, or that environmental releases to groundwater, surface water, soil and air will be at or below relevant regulatory and health-based benchmarks for human and ecological receptors. EPA agrees that the volume of CCR involved should not be the sole basis for determining whether an operation constitutes disposal. As such, the Agency is requiring the use of the fourth criterion in order to address any potential risks associated with unencapsulated uses of CCR that are in excess of 12,400 tons. Users will be required to make an affirmative demonstration relating to the potential environmental releases and the potential risks of the application (in addition to requiring compliance with the other three criteria). Specifically, users will be required to demonstrate that environmental releases to groundwater, surface water, soil and air are comparable to or lower than those from analogous products made without CCR, or that environmental releases to groundwater, surface water, soil and air will be at or below relevant regulatory and health-based benchmarks for human and ecological receptors during use. EPA expects such determinations to take into account a wide variety of factors, including the hydraulic conductivity of the area, proximity of the material to water, and the likelihood of contact with water. EPA also expects that such determinations would take into account, as many commenters acknowledged to be appropriate and necessary, the need for site characterization and characterization of the CCR. The fourth criterion was adopted in part, to address commenters' concern that the EPA should include a criterion that prevents the placement of CCR in water sources. These are legitimate concerns; existing damage cases show that the placement of CCR in sand and gravel pits was almost always associated with CCR being placed in contact with water. The fourth criterion will require the user to demonstrate that environmental releases to groundwater, surface water, soil and air are comparable to or lower than those from analogous products made without CCR, or that environmental releases to groundwater, surface water, soil and air will be at or below relevant regulatory and health-based benchmarks for human and ecological receptors during use. As a consequence of this requirement, EPA expects that significant changes may need to be made in order to proceed with a proposed use; for example, conducting the required assessment, may demonstrate that the only way to achieve the performance standard is to install engineering features, such a liner, as part of the proposed project.

Application of unencapsulated CCR to the land in volumes less than the 12,400 tons will not require an affirmative demonstration to be considered a beneficial use. While the Agency has sufficient information to document that unencapsulated uses can present a hazard, based on the current rulemaking record, EPA lacks the information necessary to demonstrate that unencapsulated uses in smaller amounts are likely to present a risk.[45] In other words, the evidence relating to these uses is not sufficient to shift the burden to the potential user to affirmatively demonstrate the safety of the proposed use. Nevertheless, the Agency expects potential users of unencapsulated CCR below this threshold to work with the states to determine the potential risks of the proposed use at the site and to adopt the appropriate controls necessary to address the risks. In this regard, EPA notes that the composition and leaching behavior of CCR being beneficially used may change over time due to upgrades in air pollution controls devices at coal-fired power plants. Further, initial determinations for existing beneficial use (BU) applications may have relied on single-point pH test methods (*e.g.,* TCLP, SPLP) that, depending on actual field conditions in which the applications are occurring, can under- or over-estimate leachate concentrations. Scientific advancements

[45] In November 2014, EPA received reports alleging that extensive groundwater monitoring data collected by the Wisconsin Department of Natural Resources demonstrated a correlation between beneficial uses of unencapsulated CCR below these thresholds and contaminated drinking water wells in southeastern Wisconsin. Insufficient time was available to allow EPA to evaluate these reports as part of this rulemaking. However, EPA will continue to evaluate the issues associated with unencapsulated uses of CCR, and to the extent available data demonstrate the need for revisions to these criteria, EPA will initiate the necessary rulemaking procedures.

in leach test protocols have found that the degree of leaching can vary by several orders of magnitude. Accordingly, states overseeing CCR BU programs are encouraged to closely evaluate existing BU applications in light of ongoing scientific advances in tools and technologies to ensure these applications remain protective of human health and the environment. In addition, the Agency is working to provide assistance to states and potential users; this includes the release of the Agency's *Industrial Waste Evaluation Model* (IWEM), and the development of a framework for systematically assessing unencapsulated BU applications to aid in assessing whether there are environmental risks associated with site specific structural fills.

ii. Exclusion of Roadway Applications from the 4th Criterion. In the 2010 proposal, the Agency stated that the placement of unencapsulated CCR on the land, such as in road embankments, presented concerns, but that the amount and the manner in which they are used—subject to engineering specifications and material requirements rather than landfilling techniques—are very different from land disposal. The Agency highlighted the 2005 guidance that was developed by EPA, FHWA, DOE, ACAA, and USWAG, addressing the appropriate methodologies and engineering requirements for the use of coal ash in highway construction. Lastly, the Agency noted the difference in terms of volume; the difference between the amounts of CCR that could be disposed of in a landfill vs. the amount of CCR used in the construction of a roadbase (typically on the order of six to twelve inches thick).

EPA received a number of comments requesting that the definition of a CCR landfill exclude CCR used in highway and road construction projects and similar beneficial use projects authorized by an appropriate state agency. These commenters reasoned that the ''arbitrary cutoff' discussed in the NODA would inappropriately capture such uses.

The Agency has excluded roadways and associated embankments from the fourth criterion because the methods of application are sufficiently different from CCR landfills that EPA cannot extrapolate from the available risk information to determine whether these activities present similar risks. Roadways are subject to engineering specifications that generally specify CCR to be placed in a thin layer (*e.g.,* six to 12 inches) under a road. The placement under the surface of the road limits the degree to which rainwater can influence the leaching of the CCR.

There are also significant differences between the manner in which roadways and landfills can potentially impact groundwater. These include the nature of mixing in the media, the leaching patterns, and how input infiltration rates are generated. First, CCR landfills are typically a homogenously mixed system, and as a result, there are no spatial variations of the chemical and physical properties of the media (for example, bulk density, hydraulic conductivity and contaminant concentration). By contrast, roadways are generally constructed of several layers with different material properties (heterogeneity). This difference affects the hydraulic conductivity of a mass of CCR in a landfill, as compared to CCR placed in an embankment. Any potential leaching will tend to spread over the length of the embankment, as opposed to the leaching in a downward motion that would occur in a homogenously filled landfill.

Finally, (and perhaps most critically) the construction of roads and associated embankments are supervised and approved by State and/or Federal Department of Transportation (DOT) engineers who ensure compliance with engineering specifications

While EPA is exempting roadbed applications of 12,400 tons or larger from the fourth criterion, EPA is mindful of situations where large quantities of CCR have been used without appropriate engineering controls or where placement on the land has apparently far exceeded those necessary for the engineering use of the materials. One such situation occurred in Puerto Rico with CCR generated by the AES Coal Fired Power Plant in Guayama. As discussed in Unit IV.B of this document, CCR and an aggregate created from them (''AGREMAX'') were being used as fill in housing developments and in road projects. Over two million tons of this material was used between 2004 and 2012. When made aware of the situation, EPA raised concerns over the use of CCR and AGREMAX based on the fact that the Environmental Quality Board had not imposed engineering controls, specified appropriate uses, or otherwise limited the use of AGREMAX by the end users. Inspections of some of the sites where the material had been placed showed use in residential areas, areas close to wetlands and surface waters and/or over shallow sole source drinking water aquifers. In addition, in some cases the volumes appeared to be in excess of what was necessary for engineering uses and some sites appeared to be abandoned. This kind of situation will be directly addressed by the new beneficial use criteria promulgated in the final rule. To qualify as a beneficial use, the use of AGREMAX would need to meet all four of the criteria—that is, it must provide a functional benefit, substitute for a virgin material, meet product specifications, and in this case, the user would be required to make the environmental demonstration for the non-roadbed applications.

iii. Kinds of unencapsulated uses of CCR required to comply with the fourth criterion.

Unencapsulated uses of CCR are numerous and range, in total use, from hundreds of thousands of tons to millions of tons per year. These applications include, as examples, the following: (1) Flowable fill; (2) structural fills; (3) soil modification/ stabilization; (4) waste stabilization/ solidification; (5) use in agriculture as a soil amendment; and (6) aggregate.

Many of these unencapsulated uses, other than structural fills, are not generally expected to be used in amounts that would require an environmental demonstration under the fourth criterion. And for several of these applications, which can be structurally very different from landfills, EPA expects that even if these applications are used in amounts greater than 12,400 tons, potential users will be easily able to meet the performance standard. For example, the use of CCR for soil modification or stabilization, agriculture, waste stabilization/ solidification, aggregate or flowable fill applications, is generally not similar to the mounding that occurs in a landfill situation. These differences can have a tremendous bearing on the leaching potential of the CCR materials.

Structural fills, however, can be larger applications and so may be required to demonstrate compliance with the environmental standards in the fourth criterion more frequently. In addition, because structural fills can be similar to the landfills regulated in the final disposal rule, some proposed applications may need to install engineering features to meet the performance standard.

iv. Demonstration that ''environmental releases to groundwater, surface water, soil and air are comparable to or lower than those from analogous products made without CCR, or that environmental releases to groundwater, surface water, soil and air will be at or below relevant regulatory and health-based benchmarks for human and ecological receptors during use.''

The environmental fourth criterion requires a potential use of CCR to compare analogous products or to perform an environmental assessment evaluating whether releases to the environment are at or below relevant regulatory and health-based benchmarks for human and ecological receptors during use. A demonstration should consider the development of a conceptual model to assist in the determination of whether the environmental criteria contained in the definition of the term ''beneficial use of CCR'' can be demonstrated. Numerous potential pathways exist and these should be evaluated as necessary depending on the potential application of the CCR. Potential exposure pathways include exposure to groundwater, surface water, air, and soils. Generation of dust, leaching to groundwater and surface water, inhalation of mercury, and plant uptake are areas that need to be evaluated. A complete evaluation of the types of releases, the types of exposure and the receptors that may be potentially affected by a potential application will need to be conducted. A screening comparison will need to be performed comparing the concentrations of individual constituents of potential concern to the following benchmarks: human soil ingestion, ecological soil, tap water ingestion, fish ingestion, surface water, sediment, and inhalation. As an example, a user could compare a mercury concentration to a human health screening benchmark with an inhalation value of 300 ng/m^3. Existing documents that can be used to gain an understanding of conceptual models, pathways and regulatory limits include: *Risk Assessment Guidance for Superfund, Exposure Factors Handbook, Volumes I, II and III, Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual Part A, Industrial Waste Management Model (IWEM) Technical Backgrounds Document, Exposure Factors Handbook, Human and Ecological Risk Assessment of Coal Combustion Wastes*. In addition, although it is not directly applicable, a potential user of unencapsulated CCR may find it useful to consult the previously mentioned ''*Coal Combustion Residual Beneficial Use Evaluation: Fly Ash Concrete and FGD Gypsum Wallboard''* and the ''*Methodology for Evaluating Encapsulated Beneficial Uses of Coal Combustion Residuals*'' to assist in the determination of whether the unencapsulated CCR is comparable to or lower than those from analogous products made without CCR, or that environmental releases to groundwater, surface water, soil and air will be at or below relevant regulatory and health-based benchmarks for human and ecological receptors during use.

After the effective date of the final rule, any potential user of CCR that makes the demonstration in the fourth criterion must keep records and provide such documentation upon request.

b. Placement in Sand and Gravel Pits and Quarries

EPA proposed that, without exception, unencapsulated CCR placed in sand and gravel pits, and quarries should not constitute beneficial use, but disposal. The Agency highlighted a number of damage cases that involved the filling of old, unlined quarries or gravel pits with large quantities of unencapsulated CCR, under the guise of ''beneficial use.'' Because of the damage cases and the concern that in such instances, sand and gravel pits and quarries were essentially operating as landfills, EPA proposed to define the placement of CCR in sand and gravel pits or quarries as land disposal that would be subject to regulation under either of the proposed regulatory options. The proposal specifically defined a *CCR landfill* as a disposal facility or part of a facility where CCR are placed in or on land and which is not a land treatment facility, a surface impoundment, an underground injection well, a salt dome formation, a salt bed formation, an underground mine, a cave, or a corrective action management unit. For purposes of this part, landfills also include piles, sand and gravel pits, quarries, and/or large scale fill operations. Sites that are excavated so that more coal ash can be used as fill are also considered CCR landfills.

Commenters stated that there were numerous examples of harm caused by the unencapsulated ''reuse'' in sand and gravel pits and quarries, which demonstrate that these unencapsulated uses were merely disposal in disguise, and must be regulated stringently under Subtitle C of RCRA to prevent the risks they pose of contaminating groundwater, surface water, and ecological systems with heavy metals and other harmful pollutants. In particular, they argue that ''There have already been at least 13 damage cases caused by the disposal of coal ash in sand and gravel pits or former quarries that led to contamination of water sources and/or ecological damages.'' Some commenters also agreed that placement in sand and gravel pits and quarries should not be considered beneficial use. For example, one commenter agreed that CCR placement in sand and gravel pits and quarries is ''disposal'' and not beneficial use while another commenter wrote that it concurs that large-scale fills in quarries in poorly engineered applications can cause negative impacts. Other commenters highlighted that damage cases related to sand and gravel pits and quarries were old practices that no longer take place. These commenters argued that while sand and gravel quarries have been used to dispose of CCR, it is not correct to assume that with proper engineering and environmental standards that CCR cannot be used beneficially to reclaim quarries for uses such as recreational areas, commercial or industrial uses, or to aesthetically improve the characteristics of the land.

EPA is finalizing its proposal that placement of CCR in sand and gravel pits constitutes disposal, rather than beneficial use. The final definition of a CCR landfill explicitly includes placement of CCR in sand and gravel pits and quarries. EPA has adopted this approach because the practice has resulted in numerous damage cases as a result of the highly permeable strata typically present at such sites. Moreover, while the commenters may be correct that ''with proper engineering measures, placement in sand and gravel pits and quarries can be conducted safely'', they submitted no data to support this contention. The only engineering features the available information demonstrate would be protective are those that have been determined to be necessary for CCR landfills—*i.e.,* composite liners and groundwater monitoring. And in the absence of these features, any future placement in sand and gravel pits and quarries could not meet the performance standard in the fourth criterion: *i.e.,* that environmental releases to groundwater, surface water, soil and air will be at or below relevant regulatory and health-based benchmarks for human and ecological receptors during use.

B. Definitions

EPA proposed definitions for a number of key terms used in the proposed subtitle D rule that the Agency determined were necessary for the proper interpretation of the proposed requirements, *e.g., coal combustion residuals, existing CCR landfill.* (See 75 FR 35196–97, June 21, 2010.) In addition, EPA also proposed definitions for terms that were specific to certain regulatory requirements, *e.g., seismic impact zone*.

EPA is finalizing many of the regulatory definitions that were proposed, some with modifications. Several definitions that were proposed have been removed because they are no longer relevant to this rulemaking and a number of new definitions have been added. Specifically, definitions that have been removed from the final rule include: natural water table, probable maximum precipitation, surface water, systemic toxicants and upstream toe. New definitions are discussed in the technical section of the rule for which they apply. The majority of the regulatory definitions contained in the proposed rule have been retained in the final rule, as proposed or with minor clarifying changes. These definitions are codified in § 257.53 and include the following: *acre foot, active life, aquifer, area capacity curves, areas susceptible to mass movement, coal combustion residuals (CCR), displacement, facility, factor of safety, fault, freeboard, groundwater, hazard potential classification, high hazard potential surface impoundment, significant hazard potential surface impoundment, low hazard potential surface impoundment, holocene, hydraulic conductivity, karst terrain, lithified earth material, maximum horizontal acceleration in lithified earth material, new CCR landfill, new CCR surface impoundment, operator, owner, poor foundation conditions, recognized and generally accepted good engineering practices, representative sample, run-off, run-on, sand and gravel pit or quarry, seismic impact zone, state, structural components, unstable area, uppermost aquifer,* and *waste boundary*.

Several definitions received a significant number of comments and upon further evaluation by EPA have been modified to better explain their meaning or intent. This includes the definitions for the following terms: *CCR landfill or landfill, CCR surface impoundment or impoundment, existing CCR landfill* and *existing CCR surface impoundment*. These comments, along with the revisions made in response are discussed in more detail below. In addition, EPA has revised a number of definitions, or added new definitions, to be consistent with revisions made in the corresponding technical requirements. These are discussed in the various sections of the preamble that address the specific technical requirement. For example, as discussed in Unit V of this document, EPA has revised the definition of ''independent registered professional engineer or hydrologist'' to ''qualified professional engineer'' to address the concerns raised in comments.

1. Definition of *CCR Landfill*

EPA proposed to define a *CCR landfill* as a disposal facility or part of a facility where CCR is placed in or on land and which is not a land treatment facility, a surface impoundment, an underground injection well, a salt dome formation, a salt bed formation, an underground mine, a cave, or a corrective action management unit. For purposes of this subpart, landfills also include piles, sand and gravel pits, quarries, and/or large scale fill operations. Sites that are excavated so that more coal ash can be used as fill are also considered CCR landfills. (See 75 FR 35239.) The Agency received a significant number of comments on the proposed definition. These comments focused almost exclusively on the inclusion of ''large-scale fill operations'' and ''piles'' within the definition of CCR landfill. Regarding large-scale fills, commenters argued that one of the fundamental problems with the proposed definition was that it assumed all CCR placed in large scale fill operations constituted ''disposal'' of CCR (and that these operations therefore constitute CCR landfills) rather than beneficial use. Commenters further argued that CCR is often used in engineered fills, such as road base and road embankments and that these legitimate beneficial use operations should not be subject to the CCR landfill regulations.

Commenters also argued that ''piles'' should be omitted from the definition of a CCR landfill for a variety of reasons. Several commenters argued that including the word ''pile'' was overly broad and insufficiently prescriptive and would inappropriately capture on-going or short-term CCR management activities that did not constitute disposal, such as storage for beneficial use. These commenters also raised concern that including ''piles'' in the definition of CCR landfill without further clarification or specificity, *i.e.,* when used as part of a beneficial use operation, would negatively affect beneficial use activities. Other commenters raised concern that the term ''piles'' was too vague, and suggested that whether piles were treated as CCR landfills should be determined by the size of the piles, or the intent for which such piles exist. These commenters suggested the Agency should exclude small piles of CCR that are staged and/or consolidated prior to transport or placement for disposal. These commenters argued that subjecting all CCR piles to all of the landfill requirements was ''illogical and inappropriate.''

Certain commenters argued that piles should not be regulated under this rule because they do not present a significant risk to the environment, as evidenced by a lack of damage cases. Alternately, other commenters suggested that if EPA were to regulate piles, the Agency should consider a regulatory strategy other than regulation as a CCR landfill. One alternative regulatory strategy suggested was to include an option establishing a limit (*e.g.,* 180 days) on the amount of time that the CCR could be allowed to be maintained in a pile without regulation as a CCR landfill. Another option suggested was to develop a set of reasonable design and operating standards consistent with the uses and risks posed by piles. Such design standards could include the requirement for a low permeability underlayment or base such as asphalt, concrete or a high density polyethylene (HDPE) liner. Operating standards could include such provisions as labeling, and the requirement to remove at least 90 percent of the contents every 90 days, with a full cleanout annually.

EPA believes the suggested option to establish a time limit would be difficult to oversee and verify. States and citizens would have no way to determine when CCR is placed in a pile and when the CCR was subsequently removed. Therefore, EPA is rejecting this suggested option. The suggested option to develop appropriate design and operating standards is essentially the approach EPA has adopted, as discussed in more detail below. However, the final design and operating standards differ according to the management practices, and include measures to control fugitive dust, and for certain practices, require the installation of a composite liner and leachate collection system.

EPA discussed its final approach to large-scale fill operations in Unit V of this document; the definition of a CCR landfill has been revised to be consistent with the approach described in that section. As explained at length, EPA has adopted a final approach that distinguishes between beneficial use and the ''disposal'' of CCR. Activities that meet the definition of beneficial use are not subject to these regulations. Activities that do not meet all of the criteria in the definition of a beneficial use—and in particular, such activities that involve the placement of unencapsulated CCR on the land—are considered disposal and are subject to the requirements of this final rule. Consistent with this approach the final definition of a CCR landfill has been revised to clarify that it includes ''the

use of CCR that does not meet the definition of a beneficial use of CCR.'' Waste piles, including those used to temporarily store or manage CCR on-site prior to disposal in a CCR landfill or subsequent beneficial use, have been retained within the definition of a CCR landfill. In making this determination the Agency was strongly influenced by the similarities in the potential risks posed by both waste piles and CCR landfills to human health, groundwater resources, or the air if improperly managed. Both CCR piles and CCR landfills are subject to external factors such as rain and wind, which can adversely affect human health and the environment. For example, uncontrolled run-on and run-off can result in ponding of water in and around the unit resulting in increased leachate which has the potential to affect groundwater. Similarly, absent dust control measures, such as the conditioning of CCR, both CCR landfills and CCR piles have the potential to generate significant amount of fugitive dust. Indeed, CCR piles are generally more susceptible to the creation of fugitive dusts. And contrary to the commenters' contention about the absence of damage cases, the single most frequent issue presented during the public hearings was the allegation by individual citizens of damage caused by fugitive dusts from neighboring CCR facilities. Moreover, the same pollution control measures, such as liners, leachate collection systems, and groundwater monitoring, will address the potential adverse effects from both of these units. As such, the Agency sees no reason to treat piles and landfills differently.

EPA also disagrees that the inclusion of CCR piles would capture on-going or short-term CCR management activities that do not constitute disposal. Irrespective of whether the facility is using the pile as ''temporary storage'' or ultimately intends to direct the CCR to beneficial use, by placing the CCR on the land with no containment or other method of preventing environmental exposures, the facility is engaging in an activity that clearly falls within the statutory definition of disposal. See 42 U.S.C. 6903(3)(''placing of solid waste . . . on any land, so that such solid waste . . . or any constituent thereof may enter the environment.'') Moreover, even where the facility intends the pile to be ''temporary,'' some amount of CCR inevitably remains in place. And if this was not the case, under section 1008(a)(3), EPA is authorized to establish criteria governing all aspects of solid waste management—which explicitly is defined to include ''storage'' as well as all of the other activities identified by the commenters—to ensure the protection of human health and the environment. See 42 U.S.C. 6903(28).

Nevertheless, EPA agrees that not every activity that involves the management of CCR must occur in a unit that meets all of the technical requirements of a CCR landfill (*e.g.,* groundwater monitoring). The key concern EPA is seeking to address with the inclusion of piles is the uncontrolled exposure from the extended, repeated, or indefinite placement of large amounts of unconsolidated CCR directly on the land. To the extent those exposures are controlled, whether through the use of tanks or some other kind of containment measures, the practice is neither considered to be a ''pile'' nor disposal in a landfill.

To clarify this, and in response to the concern that the term ''piles'' was too vague, EPA has adopted a definition of the term ''CCR pile'' to identify those ''piles'' that are subject to the disposal requirements in this regulation. The final regulation specifies that a CCR pile means any non-containerized accumulation of solid, non-flowing CCR that is placed on the land. This definition mirrors the existing definition of ''waste pile or pile'' from the part 257 regulations, (*i.e.,* the regulations that currently apply to CCR facilities), as well as the definition in part 260. The use of the phrase ''non-containerized'' is not intended to require that all activities occur within tanks or containment structures, but merely that specific measures have been adopted to control exposures to human health and the environment. This could include placement of the CCR on an impervious base such as asphalt, concrete, or a geomembrane; leachate and run-off collection; and walls or wind barriers. CCR managed in such a fashion would not be CCR piles and, therefore, not CCR landfills subject to this regulation. To further clarify how this relates to EPA's overall approach to beneficial use it is important to distinguish between CCR that is actually being used beneficially and CCR that may someday be used beneficially. CCR that is currently being used beneficially—for example, fly ash that has been transferred to a cement manufacturer and that is stored off-site in a ''temporary pile,'' and that complies with all of the criteria in the definition to be considered a beneficial use including the fourth criterion relating to the placement of large quantities of unconsolidated CCR on the land—would not be subject to the regulations applicable to CCR disposal. Accordingly, the final regulation specifies that practices that meet the definition of beneficial use of CCR are not subject to the 'disposal'' requirements of the rule.

By contrast, CCR located on-site that may someday be used beneficially but is not yet beneficially used remains subject to the disposal rule. Given that landfills and surface impoundments can be periodically dredged to provide material for beneficial use, any other approach would be impracticable, and would exclude from regulation many of the greatest sources of risk. An example of a ''pile'' that is not yet beneficially used is unconsolidated CCR placed on the land, that have been designated by the CCR facility to be transferred to another location for subsequent beneficial use (*e.g.,* use as road bed) in the near future.

Several commenters also suggested that the definition of a CCR landfill should explicitly exclude the use of CCR at surface coal mining and reclamation operations, to reflect the Agency's intention not to cover such activities. The Agency agrees and has revised the definition to explicitly provide that the term CCR landfill does not include the use of CCR at coal mining and reclamation operations.

Consequently, the Agency is finalizing a definition of ''CCR landfill or landfill'' that can be found in § 257.73. On a related matter, the definition of CCR landfill or landfill contains the terms ''sand and gravel pits or quarries.'' EPA proposed a ''sand and gravel pit and/or quarry'' to mean an excavation for the commercial extraction of aggregate for use in construction projects. The Agency received comments on the definition of sand and gravel pit and/or quarry suggesting that the term ''commercial extraction'' was too narrow. Specifically commenters were concerned it would exclude non-commercial extraction, such as gravel pits operated by municipalities, and exclude metallic mineral mines, nonmetallic mining for other than sand and gravel, and coal mines. EPA agrees that the use of the term ''commercial extraction'' renders the proposed definition too narrow, as there is no basis for distinguishing between commercial and non-commercial extraction, either because of the risks these activities pose, or any other consideration relevant to this rulemaking. EPA is, therefore, revising ''sand and gravel pit and/or quarry'' to mean an excavation for the extraction of aggregate, minerals, or metals. The term sand and gravel pit and/or quarry does not include subsurface or surface coal mines.

2. Definition of CCR Surface Impoundment

EPA proposed to define a CCR surface impoundment to mean a facility or part of a facility which is a natural topographic depression, man-made excavation, or diked area formed primarily of earthen materials (although it may be lined with man-made materials) which is designed to hold an accumulation of CCR containing free liquids, and which is not an injection well. Examples of CCR surface impoundments are holding, storage, settling, and aeration pits, ponds and lagoons. CCR surface impoundments are used to receive CCR that have been sluiced (flushed or mixed with water to facilitate movement), or wastes from wet air pollution control devices, often in addition to other solid wastes.

The Agency received many comments on the proposed definition of CCR surface impoundment. The majority of commenters argued that the definition was overly broad and would inappropriately capture surface impoundments that are not designed to hold an accumulation of CCR. Commenters were concerned that the proposed definition could be interpreted to include downstream secondary and tertiary surface impoundments, such as polishing, cooling, wastewater and holding ponds that receive only de minimis amounts of CCR. Commenters reasoned that these types of units in no practical or technical sense could be described as units ''used to receive CCR that has been sluiced.''

Other commenters raised concern that the definition did not differentiate between temporary and permanent surface impoundments. Commenters stated that many facilities rely on short-term processing and storage before moving CCR off-site for beneficial use or permanent disposal and that these units should not be required to comply with all of the technical criteria required for more permanent disposal impoundments.

Upon further evaluation of the comments, the Agency has amended the definition of CCR surface impoundment to clarify the types of units that are covered by the rule. After reviewing the comments, EPA reviewed the risk assessment and the damage cases to determine the characteristics of the surface impoundments that are the source of the risks the rule seeks to address. Specifically, these are units that contain a large amount of CCR managed with water, under a hydraulic head that promotes the rapid leaching of contaminants. These risks do not differ materially according to the management activity (*i.e.,* whether it was ''treatment,'' ''storage'' or ''disposal'') that occurred in the unit, or whether the facility someday intended to divert the CCR to beneficial use. However, EPA agrees with commenters that units containing only truly ''de minimis'' levels of CCR are unlikely to present the significant risks this rule is intended to address.

EPA has therefore revised the definition to provide that a CCR surface impoundment as defined in this rule must meet three criteria: (1) The unit is a natural topographic depression, man-made excavation or diked area; (2) the unit is designed to hold an accumulation of CCR and liquid; and (3) the unit treats, stores or disposes of CCR. These criteria correspond to the units that are the source of the significant risks covered by this rule, and are consistent with the proposed rule. EPA agrees with commenters that relying solely on the criterion from the proposed rule that the unit be designed to accumulate CCR could inadvertently capture units that present significantly lower risks, such as process water or cooling water ponds, because, although they will accumulate any trace amounts of CCR that are present, they will not contain the significant quantities that give rise to the risks modeled in EPA's assessment. By contrast, units that are designed to hold an accumulation of CCR and in which treatment, storage, or disposal occurs will contain substantial amounts of CCR and consequently are a potentially significant source of contaminants. However, EPA disagrees that impoundments used for ''short-term processing and storage'' should not be required to comply with all of the technical criteria applicable to CCR surface impoundments. By ''short-term,'' the commenters mean that some portion of the CCR is removed from the unit; however, in EPA's experience these units are never completely dredged free of CCR. But however much is present at any given time, over the lifetime of these ''temporary'' units, large quantities of CCR impounded with water under a hydraulic head will be managed for extended periods of time. This gives rise to the conditions that both promote the leaching of contaminants from the CCR and are responsible for the static and dynamic loadings that create the potential for structural instability. These units therefore pose the same risks of releases due to structural instability and of leachate contaminating ground or surface water as the units in which CCR are ''permanently'' disposed.

The final definition makes extremely clear the impoundments that are covered by the rule, so an owner or operator will be able to easily discern whether a particular unit is a CCR surface impoundment. CCR surface impoundments do not include units generally referred to as cooling water ponds, process water ponds, wastewater treatment ponds, storm water holding ponds, or aeration ponds. These units are not designed to hold an accumulation of CCR, and in fact, do not generally contain significant amounts of CCR. Treatment, storage, or disposal of accumulated CCR also does not occur in these units. Conversely, a constructed primary settling pond that receives sluiced CCR directly from the electric utility would meet the definition of a CCR surface impoundment because it meets all three criteria of the definition: It is a man-made excavation and it is designed to hold an accumulation of CCR (*i.e.,* directly sluiced CCR). It also engages in the treatment of CCR through its settling operation. The CCR may be subsequently dredged for disposal or beneficial use elsewhere, or it may be permanently disposed within the unit. Similarly, secondary or tertiary impoundments that receive wet CCR or liquid with significant amounts of CCR from a preceding impoundment (*i.e.,* from a primary impoundment in the case of a secondary impoundment, or from a secondary impoundment in the case of a tertiary impoundment), even if they are ultimately dredged for land disposal elsewhere are also considered CCR surface impoundments and are covered by the rule. To illustrate further, consider a diked area in which wet CCR is accumulated for future transport to a CCR landfill or beneficial use. The unit is accumulating CCR, while allowing for the evaporation or removal of liquid (no free liquids) to facilitate transport to a CCR landfill or for beneficial use. In this instance, the unit again meets all three definition criteria, it is a diked area (*i.e.,* there is an embankment), it is accumulating CCR for ultimate disposal or beneficial use; and it is removing any free liquids, (*i.e.,* treatment). As such, this unit would meet the definition of CCR surface impoundment. In all of these examples significant quantities of CCR are impounded with water under a hydraulic head that will be managed for extended periods of time. This gives rise to the conditions that both promote the leaching of contaminants from the CCR and are responsible for the static and dynamic loadings that create the potential for structural instability. These units therefore all pose the same risks of

releases due to structural instability and of leachate contaminating ground or surface water.

3. Definition of Existing CCR Landfill

EPA proposed to define an existing CCR landfill to mean a CCR landfill which was in operation on, or for which construction commenced prior to the effective date of the final rule. The proposed definition specified that a CCR landfill has commenced construction if the owner or operator has obtained the federal, state, and local approvals or permits necessary to begin physical construction; and either: (1) A continuous on-site, physical construction program has begun; or (2) the owner or operator has entered into contractual obligations—which cannot be cancelled or modified without substantial loss—for physical construction of the CCR landfill to be completed within a reasonable time.

In response to the proposed definition, the Agency received several comments arguing that the use of the phrase ''was in operation on, or for which construction commenced prior to'' would lead to confusion. Commenters contended that most units defined as CCR landfills at some point in time ''were in operation'' and had ''commenced construction'' prior to the effective date of the regulation. Commenters claimed that this definition would unnecessarily capture thousands of closed structural fill projects, including residential properties, commercial properties used by small businesses, and many recreational facilities. Furthermore, commenters doubted that EPA intended for the rule to cover all of these units and urged the Agency to clarify that closed units are excluded from the definition of existing CCR landfill.

Other commenters argued that the proposed definition of *existing CCR landfill* should be modified to include lateral expansions of operation units where such an expansion is within the site footprint of an area already approved and permitted by the state for the landfill. Commenters contended that while the proposed definition included undeveloped areas within the footprint of an approved permitted site, it also required that the construction be initiated at the site or that some type of binding contractual obligation be present. Commenters contended that the existence of a contractual obligation unfairly subjects undeveloped, yet approved permitted areas to design and operating standards for new CCR landfills based merely on the existence of a contract to commence construction. Commenters argued that such a distinction was arbitrary and capricious and provided no practical benefit. Other commenters questioned the usefulness of requiring a contractual obligation at all. As written, the commenters argued, that the definition was vague, unenforceable, and thus, not protective of human health and the environment. Commenters reasoned that there was no definitive or generally accepted meaning for the term ''substantial loss'' or the term ''reasonable time'' and an owner or operator, sensing that these proposed rules may be passed, could sign a contract now with minimum predetermined cancellation or modification penalties and a contract term of say five years or even longer to avoid the new unit requirements, *i.e.,* a composite liner.

The commenters are correct that EPA did not intend to cover inactive landfills under this rule. The Agency agrees that, as drafted, the proposed definition could cause confusion. EPA therefore deleted the phrase ''was in operation on the effective date of the rule'' and has substituted the phrase ''that receives CCR both before and after [the effective date of the rule].'' EPA also agrees that the phrase ''commenced construction prior to the effective date of the rule'' could similarly cause confusion. Therefore, the Agency has made a similar revision, by adding the phrase ''and receives CCR on or after [the effective date of the rule]'' after the phrase ''for which construction commenced prior to [the effective date of the rule].'' These revisions will clarify which units are covered by the technical requirement of the rule and alleviate any confusion. EPA is also making conforming modifications to the definition of *existing CCR surface impoundment.*

EPA disagrees that lateral expansions should be considered to be ''existing'' based solely on the fact that such an expansion is within the site footprint of an area already approved and permitted by the state. EPA has frequently distinguished between the types of requirements applicable to new and existing units, reasoning that in many instances, risk mitigation measures would be adequate such that existing units need not wholly retrofit to meet the new ''state of the art.'' For new units, however, the balance is generally struck in favor of requiring a greater degree of risk prevention, rather than relying solely on risk mitigation measures. In determining whether a unit is ''new'' or ''existing,'' EPA has historically considered that the equities lie in favor of considering a unit to be ''existing'' when there has been an irretrievable commitment of resources on the part of the facility. That has not occurred merely because permits have been obtained. While admittedly resources have been committed, at this stage modifications to the design and construction of the unit are still feasible. Specifically, the critical differences between the requirements applicable to new and existing CCR landfills are the type of liner that must be installed and the location restrictions that apply. Compliance with these requirements can be addressed through modifications to the design and construction of the unit, and are therefore readily feasible until construction has begun.

EPA agrees with those commenters who were concerned that the phrase, ''the owner or operator has entered into contractual obligations—which cannot be cancelled or modified without substantial loss—for physical construction of the CCR landfill to be completed within a reasonable time,'' is vague and potentially subject to abuse. While this phrase has been included in other EPA regulations, those regulations operate within a regulatory program overseen by a regulatory authority. No similar guarantee exists under these regulations. EPA could not discover a definitive or generally accepted meaning for the terms ''substantial loss'' or ''reasonable time,'' or develop sufficiently objective and determinate criteria for these concepts. Consequently, the Agency has decided to remove this provision from the definition of *existing CCR landfill.* EPA is retaining the two most important elements of the definition that will effectively determine whether the facility has irretrievably committed resources such that it would not reasonable to require compliance with all of the requirements applicable to new units. Accordingly, a unit will be considered to be existing if, first, the owner or operator has obtained the federal, state, and local approvals or permits necessary to begin physical construction; and second, that a continuous on-site, physical construction program has begun (*i.e.,* groundbreaking has occurred). Therefore, EPA is finalizing the definition of *existing CCR landfill* that can be found in § 257.53.

4. Definition of *Existing CCR Surface Impoundment*

EPA proposed to define an *existing CCR surface impoundment* to mean a surface impoundment which was in operation on, or for which construction commenced prior to the effective date of the final rule. The proposal also specified that a CCR surface impoundment has commenced

construction if the owner or operator has obtained the federal, state, and local approvals or permits necessary to begin physical construction; and either: (1) A continuous on-site, physical construction program has begun; or (2) the owner or operator has entered into contractual obligations—which cannot be cancelled or modified without substantial loss—for physical construction of the CCR landfill to be completed within a reasonable time.

EPA received many of the same comments on the definition of an existing CCR surface impoundment that were received on an existing CCR landfill. This included comments requesting clarification that the term did not include impoundments that had ceased receiving CCR before the effective date of the rule. Commenters also suggested that EPA modify the definition to include the phrase that the surface impoundment ''was in operation and had not yet ceased receiving CCR prior to the effective date of the rule'' to make clear that the definition did not encompass units that are no longer receiving CCR on the effective date of the rule, even though the unit may not have completed final closure prior to the rule's effective date. Commenters reasoned that units no longer receiving CCR on the effective date of the rule are not ''in operation'' and therefore should not be subject to the standards applicable to active units. Commenters also requested that EPA clarify that the definition of ''existing CCR surface impoundment'' include units that were in operation on the effective date of the rule and that periodically dredged out during the operating life of the impoundment. Commenters contended that while this may seem self-evident, EPA needed to clarify that these impoundments would not be characterized as ''new CCR surface impoundments.''

The Agency is generally conforming the definition of an existing CCR surface impoundment to the revised definition of an existing CCR landfill. Although inactive CCR surface impoundments are covered by the final rule (unlike inactive CCR landfills), EPA decided it would provide greater clarity to establish a section specific to inactive CCR surface impoundments rather than merely including such units within the definition of an existing CCR surface impoundment. As discussed in greater detail in Unit VI.A of this document, under § 257.100, any CCR surface impoundment that continues to impound CCR and water after the effective date of the rule, must either (1) breach, dewater, and place a cover on the unit within three years or (2) must comply with all of the requirements applicable to existing CCR surface impoundments. Without the need to account for inactive CCR surface impoundments within the definition, the definitions of ''existing'' landfills and surface impoundments should be the same.

Thus, the Agency has removed the term ''in operation'' from the definition and has instead focused on when the surface impoundment received or will receive CCR. EPA has also deleted the provision that would have allowed a unit to be considered to be ''existing'' based on the existence of a contract. Accordingly, for purposes of this rule, a CCR surface impoundment will be considered to be ''existing'' if the unit received CCR both before and after the effective date of the rule. For example, if a CCR surface impoundment received CCR prior to the effective date and was in the process of dredging on the effective date with the intent of receiving additional CCR after the effective date, the unit would still be considered to be an ''existing'' rather than a new unit. Conversely, if a unit received CCR prior to the effective date and was no longer receiving CCR, this unit would be considered ''inactive,'' and would only be subject to the technical criteria applicable to ''existing'' CCR surface impoundments if they had not completed closure within three years. Similarly, if a CCR surface impoundment had commenced construction prior to the effective date with the intention of receiving CCR on or after the effective date of the rule, the unit would be considered an ''existing'' unit only if the physical construction program had begun (*e.g.,* groundbreaking had occurred) with the appropriate federal, state and local approvals or permits in place. But if prior to the effective date of the rule, the permits had been obtained but the physical construction of the unit had not begun (*e.g.,* groundbreaking had not occurred), the unit would be considered ''new'' and would be subject to all the applicable technical criteria for new CCR surface impoundments. Therefore, the Agency is finalizing the definition of *existing CCR surface impoundment* that can be found in § 257.53.

C. Location Restrictions and Individual Location Requirements

In the proposed rule, EPA stated that any RCRA subtitle D regulation would need to ensure that CCR landfills, CCR surface impoundments and all lateral expansions were appropriately sited to ensure that no reasonable probability of adverse effects on health or the environment from the disposal of CCR would occur. Under the subtitle D option, EPA proposed location restrictions for CCR units which included requirements relating to the placement of CCR in five general locations: (1) Above the natural water table; (2) wetlands; (3) fault areas; (4) seismic impact zones; and (5) unstable areas. The proposed requirements relied in large measure, on the record EPA developed to support the 40 CFR part 258 requirements for MSWLFs and on EPA's Guide for Industrial Waste Management (EPA530–R–03–001, February 2003). EPA also chose to add one additional location restriction that would ban the placement of CCR units within two feet of the upper limit of the natural water table. This proposed requirement was originally included in the proposed rule, *Standards for the Management of Cement Kiln Dust* (64 FR 45631, August 20, 1999) because of the potential damage to groundwater caused by the management of cement kiln dust at sites located below the natural water table. While the proposed cement kiln dust rule has not yet been finalized, EPA extended this reasoning to CCR by applying the same location restriction to CCR units. The proposed applicability of these location requirements varied depending on whether the unit was an existing or new CCR landfill, an existing or new CCR surface impoundment, or a lateral expansion of such units. For example, for existing CCR landfills, the Agency proposed that only the location requirement for unstable areas would apply. By contrast, the proposed rule applied all of the location restrictions to new CCR landfills and all CCR surface impoundments, both existing and new—an approach consistent with RCRA subtitle C and Congressional distinctions between the risks presented by landfills and surface impoundments. (See 75 FR 35198–35199.) This meant that owners or operators would need to close existing CCR surface impoundments located less than two feet above the natural water table, or for existing CCR units in sensitive but not prohibited locations, make a technical demonstration that the unit met the requirements of a performance standard that serves as the alternative to the location restriction, retrofit the unit so that it could meet the performance standard, or close. For those CCR units that need to close (*i.e.,* owners or operators that could not make the necessary technical demonstrations), EPA proposed that the unit must close within five years of the effective date of the rule. If closure could not occur within the five year timeframe, the

Agency proposed allowing for a case-by-case extension for up to two more years if the facility demonstrated that there was no alternative disposal capacity and no immediate threat to health or the environment.

EPA proposed not to impose all of the location requirements on existing CCR landfills based on the conclusion that CCR landfills pose less risk and are structurally less vulnerable than existing CCR surface impoundments. EPA also raised concern that a significant number of these CCR landfills could be located in areas subject to these requirements, (particularly wetlands), which could cause disposal capacity shortfalls in certain regions of the U.S., if existing CCR landfills in these locations were required to close. Disposal capacity shortfalls can pose significant environmental and public health concerns based on the potential for significant disruption of solid waste management state-wide from the closure of these units. EPA concluded that these risks would be greater than the potential risks from allowing existing CCR landfills to remain in these locations, given that these units would be subject to all of the design and operating requirements of the rule. To ensure the accuracy of its preliminary conclusions, the Agency requested commenters to provide any available information regarding the number of existing CCR landfills located in these sensitive areas. The Agency also sought information regarding the extent to which CCR landfill capacity would be affected by applying all of the location restrictions to existing CCR landfills, the extent to which facilities could comply with the proposed performance standards, and the costs that would be incurred to retrofit existing CCR landfills to meet these standards.

The Agency received numerous comments in response to the Agency's request for additional information regarding the extent to which landfill capacity would be affected by applying all the proposed subtitle D location restrictions to existing CCR landfills. Commenters generally agreed with the Agency that applying the other location restrictions to existing CCR landfills would cause a significant decrease in disposal capacity across the country, although they did not provide any data or information which would support this concern. Commenters noted, however, that if existing CCR landfills located in these areas were to close, it would greatly complicate operations at many utilities. Affected facilities would need to find additional disposal capacity, which would require utilities to procure new real estate on which to site a new CCR landfill (which may be a significant distance from a power plant), obtain a new disposal permit for the CCR landfill (which can take an extended period of time), and potentially transport significant volumes of CCR great distances to newly-permitted facilities. Commenters argued that there was simply no environmental basis for causing this level of disruption to utility CCR disposal practices.

EPA received no data or information in response to the Agency's request for the costs associated with retrofitting a CCR surface impoundment or CCR landfill to meet the demonstrations for existing units. Similarly, the Agency received little to no information in response to EPA's request for additional information on the location of these facilities. Some commenters acknowledged that specific states were located in some of these restricted areas but did not provide specific information on specific units.

Overwhelmingly, the issue receiving the most comment was EPA's intention to subject existing CCR surface impoundments to all of the new location criteria. Commenters contended that subjecting existing units to all of the location criteria was a radical departure from the location restriction provisions of the existing MSWLF rules on which the subtitle D option is based (*i.e.,* existing MSWLFs are only subject to the floodplains and unstable areas restrictions) without any justification for regulating CCR surface impoundments more stringently than existing CCR landfills. Commenters argued that EPA must demonstrate that there are increased risks posed by each CCR surface impoundments based on its location; otherwise, they claimed, there was no justification for EPA to subject CCR surface impoundments to more stringent location restrictions. Some commenters suggested that a more reasonable approach would be to limit the restrictions for existing CCR surface impoundments to unstable areas, consistent with the approach proposed for existing CCR landfills. Finally, commenters raised concern about the inconsistency between the preamble language and the corresponding regulatory text. Specifically, the preamble stated EPA's intention to apply all of the location criteria to all CCR surface impoundments (existing and new) while the proposed regulatory language applied all location criteria only to new CCR surface impoundments and lateral expansions.

1. Applicability of the Location Criteria to Existing CCR Surface Impoundments

EPA acknowledges the discrepancies between the preamble language and the regulatory text regarding the proposed regulatory language for the location restrictions as it applies to existing CCR surface impoundments. In the proposed rule, the regulatory language should have included, ''all surface impoundments'' as opposed to only ''new surface impoundments.''

EPA disagrees that in order to justify national minimum standards applicable to existing CCR surface impoundments, the Agency must demonstrate an adverse impact to human health and the environment from each individual unit, based on the specific risks posed at each location. As an initial matter, it is well established that an agency may regulate a class of similarly situated entities through rulemaking, rather than on the basis of an individualized assessment of every entity that will be subject to the rule. And indeed, Congress specifically directed EPA to proceed by rulemaking to establish minimum national standards under RCRA sections 1008(a) and 4004(a). Moreover, section 4004(a) does not require a demonstration of actual impacts, merely that these units present an unacceptable *risk* of harm. Thus, it is sufficient for EPA to establish a factual record demonstrating that the specific location restrictions in the final rule are necessary for CCR units (landfills and surface impoundments), as a class, to ensure that there will be no reasonable probability of adverse effects on health or the environment. As discussed in greater detail in the next section and in Unit X of the preamble, the factual record supports the need for all of the location standards for existing CCR surface impoundments imposed by this rule.

The Agency also rejects the suggestion that EPA establish the same location restrictions for both existing CCR landfills and CCR surface impoundments. As laid out in the proposal and elsewhere in this final rule in greater detail, the risks associated with CCR surface impoundments are substantially higher than the risks associated with CCR landfills, by approximately an order of magnitude. Surface impoundments are utilized by 45 percent of coal-fired power plants and in 2000 accounted for disposal of one-third of all CCR generated.[46] Unlike landfills, CCR surface impoundments

[46] Rowe, C.L., Hopkins, W.A., Congdon, J.D., 2002. Ecotoxicological Implications of Aquatic Disposal of Coal Combustion Residues in the United States: A Review. Environmental Monitoring and Assessment, Vol. 80, pp. 207–276.

contain slurried residuals that remain in contact with ponded waters until closure. In a statewide investigation of impacts to groundwater quality from CCR disposal sites, the Wisconsin Department of Natural Resources reported that closed sites which originally contained sluiced coal-combustion residuals displayed extremely elevated mean arsenic levels (as high as 364 µg/l).[47] The highest contaminant concentrations in the study were associated with sluiced CCR residuals. In addition, releases of toxic contaminants to surface water and groundwater from mostly unlined CCR surface impoundments and ponds are a relevant factor in 34 of 40 cases of proven damage to the environment (as well as in several cases of ''potential'' damage to the environment) from mismanagement of CCR.[48] In many of these cases, effluent discharges from the surface impoundments caused significant ecological damage to aquatic life in nearby streams and wetlands. In one case, in 2002, the structural stability of a CCR surface impoundment was directly compromised by sinkhole development, leading to the release of 2.25 million gallons of CCR slurry. In another, an unusually weak foundation of ash and silt beneath a CCR surface impoundment (*i.e.,* man-made unstable ground) was identified as one of several likely factors contributing to the dike failure that in 2008 resulted in the largest CCR spill in United States history.

Unlike RCRA subtitle C, subtitle D does not explicitly authorize EPA to establish different standards for existing and new units, and Congress specifically intended subtitle D to address the risks from existing, abandoned ''open dumps.'' In the proposed rule preamble, EPA explained the rationale for applying these provisions to existing CCR surface impoundments, and the commenters have submitted nothing to rebut that rationale. Thus, EPA maintains its determination that application of the location standards to existing CCR surface impoundments is necessary to achieve the standard in section 4004(a). Absent these location restrictions, the risk of impacts to human health and the environment from releases from CCR units, including from the rapid and catastrophic destruction of CCR surface impoundments, sited in these sensitive areas would exceed acceptable levels. Given that the risks associated with CCR surface impoundments are substantially higher than the risks posed by CCR landfills, this is the appropriate regulatory course for existing CCR surface impoundments.

In this rule, EPA is finalizing location restrictions that will ensure that CCR units are appropriately sited, that the structure of the CCR unit will not be adversely impacted by conditions at the site, and that overall there will be ''no reasonable probability of harm to human health or the environment'' due to the location of the CCR unit. EPA is finalizing different sets of location restrictions depending on whether the unit is a CCR landfill or CCR surface impoundment and whether it is an existing or new unit. Lateral expansions fall within the definitions of new units and are treated accordingly. These standards provide minimum national siting and performance criteria for all CCR units. The location restrictions under § 257.60 through § 257.64 include: (1) Placement above the uppermost aquifer; (2) wetlands; (3) fault areas; (4) seismic impact zones; and (5) unstable areas. Each of these locations is generally recognized as having the potential to impact the structure of any disposal unit negatively and as such, increase the risks to human health or the environment through structural failures or leaching of contaminants into the groundwater. Under the final rule and as proposed, new CCR landfills, existing and new CCR surface impoundments, and all lateral expansions will be required to comply with all of the location restrictions. Existing CCR landfills however, will be subject to only two of the location restrictions—floodplains, and unstable areas. As noted in the proposed rule, and restated here, existing landfills and surface impoundments are already subject to the location standards in subpart A of 40 CFR part 257 for floodplains, endangered species and surface waters. The final rule does not change this requirement, and so facilities should already be in compliance. The Agency is finalizing, as proposed, the unstable area location restriction for existing CCR landfills because the record clearly shows that failure of CCR units in these areas (*e.g.,* due to instabilities in Karst terrains) have and in all likelihood would continue, in the absence of the restrictions in the final rule, to result in damage caused by the release of CCR constituents, affecting both groundwater and surface waters. As the Agency stated in the proposed rule, the impacts resulting from the failure of CCR units from location instability are of far more concern than any disposal capacity concerns resulting from the closure of existing CCR units in unstable areas.

Conversely, and also consistent with the proposed rule, EPA is not applying the following location restrictions to existing CCR landfills: The requirement to construct a unit with a base located no less than 1.52 meters (five feet) above the upper limit of the uppermost aquifer, as well as the siting restrictions applicable to wetlands, fault areas, and seismic impact areas. Existing CCR landfills pose lower risks and are structurally less vulnerable than existing CCR surface impoundments. In addition, disposal capacity shortfalls, which could result if existing CCR landfills in these locations were required to close, raise greater environmental and public health concerns than the potential failure of the CCR landfills in these locales.

2. Placement Above the Uppermost Aquifer

Under § 257.60(a) EPA is requiring new CCR landfills, existing and new CCR surface impoundments and all lateral expansions to be constructed with a base that is located no less than 1.52 meters (five feet) above the uppermost aquifer, or to demonstrate that there will not be an intermittent, recurring, or sustained hydraulic connection between any portion of the base of the CCR unit and the uppermost aquifer due to normal fluctuations in groundwater elevations (including groundwater elevations during the wet season). Existing surface impoundments that fail to achieve this standard must close. New CCR landfills, new CCR surface impoundments and all lateral expansions of existing and new CCR landfills and CCR surface impoundments cannot be constructed unless they meet one of these two standards. In response to comment, the Agency has modified the criteria in two ways. First, EPA has replaced ''a base that is located a minimum of two feet above the upper limit of the natural water table'' with ''a base no less than 1.52 meters (five feet) above the uppermost aquifer.'' EPA received comment explaining that fluctuations in groundwater levels in many geological settings can exceed ten feet over the course of the year, and alleging that the proposed two foot minimum buffer between the base of the unit and the top of the water table would therefore be insufficiently protective. The

[47] Zillmer, M. and Fauble, P., 2004. Groundwater Impacts from Coal Combustion Ash Disposal Sites in Wisconsin. Waste & Materials Management, Wisconsin Department of Natural Resources, PUB–WA 1174 2004.

[48] Cases of damage attributable to disposal of coal combustion residuals are summarized in the appendix to the preamble of the proposed rule, 75 FR 35230–35239, June 21, 2010, and can be found in the RCRA Docket.

commenter recommended that the minimum vertical separation be at least three to five feet from the base of the liner components. After additional research, EPA is finalizing a minimum buffer of five feet instead of two feet. EPA's research confirmed the commenter's claims. In addition, EPA determined that several states consider five feet between the base of the surface impoundment and the top of the uppermost aquifer to be the minimum distance that is protective of human health and the environment. These are California, Michigan, Nebraska, New York, West Virginia, and Wisconsin. The Agency has concluded from geographic and climatic spacing of these states that the hydrogeologic conditions within them encompass the range of conditions found in the United States. Therefore, EPA is finalizing a minimum buffer of five feet instead of two feet.

EPA is also clarifying the definition of the natural water table. As some commenters noted, there are many factors (hydrologic and geologic settings, nearby pumping, etc.) that influence the location of the groundwater table making it difficult to determine the ''natural'' level. In addition, as noted, local site-specific hydrogeologic conditions within the aquifer may cause the natural groundwater table to exceed five feet and vary as much as ten feet. To account for the possibility of such large seasonal fluctuations, EPA is revising the definition of ''uppermost aquifer'' to specify that the measurement of the upper limit of the aquifer must be made at a point nearest to the natural ground surface to which the aquifer rises during the wet season. This definition of ''uppermost aquifer'' will encompass large seasonal variations, and is a more appropriate parameter than ''seasonal high groundwater table'' as suggested by several commenters and the proposed ''natural water table'' because it is more clearly defined.

In § 257.60(a) the term *uppermost aquifer* has the same definition as under the general provisions of § 257.40: The geologic formation nearest the natural ground surface that is an aquifer, as well as lower aquifers that are hydraulically interconnected with this aquifer within the facility's property boundary. This definition includes a shallow, deep, perched, confined or unconfined aquifer, provided it yields usable water. Although EPA originally proposed that all CCR surface impoundments be located ''. . . above the upper limit of the natural water table'', the Agency is amending this requirement and replacing ''water table'' with ''uppermost aquifer'' to make it consistent with the way natural underground water sources are described elsewhere in the rule. EPA made a second revision to the criteria that were originally proposed. As an alternative to requiring that the CCR units described in this section be constructed with a base that is located no less than five feet above the uppermost aquifer, owners and operators may instead demonstrate that there will not be an intermittent, recurring, or sustained hydraulic connection between any portion of the base of the CCR unit and the uppermost aquifer due to normal fluctuations in groundwater elevations (including groundwater elevations during the wet season).

This alternative standard was developed in response to concerns from commenters that a single depth to the aquifer failed to account for the wide variations in the level of water table fluctuations in different regions of the country. For example, arid regions of the country, such as Arizona, under normal conditions generally do not experience the same degree of fluctuations in groundwater elevations as more temperate regions, such as Minnesota. Accordingly, EPA developed an alternative performance standard focused on the conditions identified in the damage cases and the risk assessment that this location criterion was designed to prevent: Specifically, where the groundwater elevation is high enough to intersect the base of the waste management unit. In such situations, this hydraulic connection can enhance the transport of contaminants of concern from the CCR unit into groundwater. By requiring owners and operators to ensure that these conditions do not occur, the alternative standard to allow owners and operators to account for situations where there are relatively small variations in groundwater levels and a buffer of five feet is not necessary. This will also ensure that a CCR unit need not address situations where an infrequent, unexpected event (*e.g.,* hurricane) could cause a brief, temporary condition where the uppermost aquifer rises to less than the prescribed five feet but which would not in and of itself constitute a long-term threat to the aquifer. However, where normal fluctuations in groundwater elevation (including, but not limited to, seasonal or temporal variations, groundwater withdrawal, mounding effects,[49] etc.) will result in the failure of the unit to meet the performance standard (*i.e.,* no intermittent, recurring, or sustained hydraulic connection between the base of the CCR unit and the uppermost aquifer), the unit must close.

In some recent damage cases, placement of large volumes of CCR into highly permeable strata in the disposal area promoted CCR-water interactions. For example, from 1995 to 2006 in Anne Arundel County, Maryland 4.6 million tons of CCR were placed directly in two sand and gravel quarries without a geomembrane liner or leachate collection system. Rainwater infiltration into exposed CCR coupled with groundwater-CCR interactions and the transmissivity characteristics of local strata contributed to rapid migration of heavy metals, including antimony, arsenic, cadmium, nickel, and thallium to residential drinking water wells located near the mine pits and significant deterioration of water quality as a result of placement of CCR. Similarly, from 1980 to 1997 in Lansing, Michigan, around 0.5 million tons of coal ash was dumped for disposal into a gravel pit with an elevated water table. A remedial investigation has established that groundwater mounding has immersed the CCR into the upper aquifer resulting in on-site exceedances of groundwater quality protection standards for sulfate, manganese, lead, selenium, lithium, and boron. Placement of CCR into un-engineered, unlined units in permeable strata has plainly led to adverse impacts to groundwater. The phrase ''normal fluctuations'' has been used to clarify that EPA does not intend for the facility to account for extraordinary or highly aberrant conditions (*e.g.,* one-in-a million or ''freak'' events). Normal fluctuation can include those resulting from natural as well as anthropogenic sources. Natural sources that could affect groundwater levels include, but are not limited to precipitation, run-off, and high river levels. Anthropogenic sources that could affect groundwater levels include groundwater withdrawal, pumping, well(s) abandonment, and groundwater mounding. In satisfying this location restriction, it may be necessary for a professional engineer to model these effects before he can make the necessary certifications.[50] EPA also

[49] A phenomenon usually created by the recharge of groundwater from a manmade structure, such as a surface impoundment, into a permeable geologic material, resulting in outward and upward expansion of the free water table. Mounding can alter groundwater flow rates and direction; however, the effects are usually localized and may be temporary, depending upon the frequency and duration of the surface recharge events.

[50] For example, evaluations can be done to estimate groundwater mounding such as *pubs.usgs.gov/sir/2010/5102/*, *www.groundwatersoftware.com/calculator_9_*

notes that this modeling may include the same considerations already evaluated under some state programs.[51] EPA expects that owners and operators will have sufficient information to determine whether their CCR unit meets either performance standard. Most, if not all, of this information would be information a facility would typically have as part of normal operations (*e.g.,* the depth of the CCR unit itself), or that will be developed as part of implementing other rule requirements. For example, through the groundwater monitoring system required under §§ 257.90–257.98, the facility can obtain water level measurements in a sufficient number of locations (*e.g.,* monitoring wells, piezometers) to use in determining whether they satisfy either performance standard. Similarly, under § 257.91 a thorough characterization of the geology and hydrogeology of the site must be conducted. Finally, EPA notes that available technology and guidance are available for using existing groundwater monitoring wells, like those required under this final rule, to measure groundwater levels.[52]

3. Wetlands

In § 257.61 of this rule, EPA is finalizing the regulatory text essentially as proposed. Specifically, EPA is adopting a prohibition on locating all CCR surface impoundments and new CCR landfills, as well as lateral expansions of existing CCR units, in wetlands as defined in 40 CFR 232.2, absent specific demonstrations made by the owner or operator that ensure the CCR unit will not degrade sensitive wetland ecosystems. These provisions place the burden of proof for these demonstrations directly on the owner or operator (the discharger). The owner or operator must make the results of these demonstrations available in the facility record. Failure to make any of the demonstrations will bar siting of the CCR unit in a wetland.

In 2003, disposal of CCR in natural or man-made aquatic basins accounted for nearly one-third of all CCR land disposal. Historically, aquatic disposal of CCR has been attractive economically to facilities because of its lower overall cost relative to dry management and the ease of handling of residuals. During aquatic disposal, CCR is commonly piped as a slurried mixture to surface impoundments designed to retain the solids in contact with water for the life of the unit. Particulate solids from the waste stream gravitationally settle while clarified waters ultimately discharge into nearby streams and wetlands.

The term 'wetlands' refers to those areas inundated or saturated by surface or groundwater at a frequency and over a duration sufficient to support a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands include marshes, swamps, bogs and similar areas that are commonly located between open water and dry land. Under the CWA, wetlands are considered 'special aquatic sites' deserving of special protection because of their ecologic significance. Wetlands are very important, fragile ecosystems that must be protected, and EPA has long identified wetlands protection as a high priority.

Undisturbed, natural wetlands provide many benefits to society by improving water quality, providing essential breeding, rearing, and feeding grounds for fish and wildlife, reducing shoreline erosion, and absorbing flooding waters and pollution. Wetlands are also commercial source areas of products for human use such as timber, fish, and shellfish. Recreational hunters harvest wetland-dependent waterfowl. Wetland environments, however, may be adversely impacted by releases of wastes from co-located industrial facilities. Wetland ecosystems can be degraded by accidental discharges that can change the habitat value for fish and wildlife by obstructing surface water circulation patterns, altering substrate elevation, dewatering, or permanent flooding.

In support of the provisions finalized in this rule, EPA is citing several damage cases, including 30 cases of ''proven'' damage to the environment that involve aquatic disposal of CCR, 14 of which involve impacts to wetlands from release of CCR. For example, at the Hyco Reservoir in Roxboro, North Carolina from 1966 to 1990 the lake received contaminated effluent from coal ash disposal basins that were authorized by National Pollutant Discharge Elimination System (NPDES) permits under the CWA. High levels of the trace element selenium bioaccumulated in aquatic food chains (phytoplankton), poisoning invertebrates and fish in the lake, particularly species of sport fish (bluegill, largemouth bass), causing reproductive failure and severe declines in fish populations in the late 1970's and early 1980's. Consequently, from 1988–2001 the North Carolina Department of Health and Human Services (NCDHHS) issued a consumption restriction advisory for selenium contamination in fish from the reservoir. In 1990, a dry ash handling system was implemented resulting in lower selenium discharge and reduced mean selenium concentration in reservoir waters. As of 2005, concentrations of selenium in fish tissues remained above a toxic threshold even with reduced influx of selenium, due to migration of the element from contaminated sediments to benthic food chains. The total monetized value of damage can be divided among ecologic factors (*e.g.,* major impacts on fish), recreational factors (*e.g.,* fishing trips not taken), depreciated real estate values, aesthetic factors, and human health damages (*e.g.,* losses due to stress and anxiety from knowing ecosystem is poisoned) and is estimated at $877 million.[53]

Although this consideration is not relevant for purposes of establishing the minimum national criteria under RCRA sections 1008(a) and 4004(a), the rulemaking record demonstrates that the monetary cost of environmental damage from releases of CCR at surface impoundments could be considerable. A report on the environmental damage caused by releases of CCR at 22 sites estimates the total cost of poisoned fish and wildlife at the surface impoundment sites at $2.32 billion. At twelve of these sites the releases were legally permitted under the CWA. Five of the 22 cases were caused by structural failures, two resulted from an unpermitted discharge, and one was from a landfill.[54] Effluent contaminated with coal combustion residues is directly linked with high loadings of toxic metals in the discharge areas of aquatic basins, where some metals (primarily arsenic, cadmium, chromium, copper, lead, and selenium) have accumulated in aquatic food chains.[55] In a research overview (literature synthesis) on the environmental effects of disposal of CCR, Rowe et al. (2002) listed adverse biological responses, including histopathological, behavioral, and physiological (reproductive, energetic, and endocrinological) effects, that have been observed in some vertebrates and invertebrates following exposure to and bioaccumulation of CCR-related contaminants.

Under the criteria finalized in this rule, in order to locate a CCR unit or

hantush_mounding.htm, and *www.ndwrcdp.org/documents/wu-ht-02-45/wuht0245_electronic.pdf.*

[51] See, *e.g., dnr.wi.gov/topic/stormwater/standards/gw_mounding.html.*

[52] See, *e.g.,* U.S. EPA (Environmental Protection Agency). 2013. Groundwater Level and Well Depth Measurement. SESDPROC–105–R2. Region 4. Athens, GA. Available online at: *www.epa.gov/region4/sesd/fbqstp/Groundwater-Level-Measurement.pdf.*

[53] Lemly, A.D. 2010. Op.cit.

[54] Lemly, A.D.2010. Op. cit.

[55] Rowe, C.L. et. al. 2002. Op. cit.

lateral expansion in a wetland, the owner or operator must: (1) Successfully rebut the presumption that an alternative site (*i.e.,* one that does not involve a wetland) is reasonably available for the CCR unit or lateral expansion; (2) show that the construction or operation of the unit will not cause or contribute to violations of any applicable state water quality standard, violate any applicable toxic effluent standard or prohibition, jeopardize the continued existence of endangered or threatened species or critical habitats, or violate any requirement for protection of a marine sanctuary; (3) show that the CCR unit or lateral expansion will not cause or contribute to significant degradation of wetlands; and (4) demonstrate that steps have been taken to attempt to achieve no net loss of wetlands.

In addition to these requirements, other federal laws may be applicable in siting a CCR unit in a wetland. These include: Sections 401, 402, and 404 of the CWA; the Rivers and Harbors Act of 1989; the National Environmental Policy Act; the Migratory Bird Conservation Act; the Fish and Wildlife Coordination Act; the Coastal Zone Management Act; the Wild and Scenic Rivers Act; and the National Historic Preservation Act. In addition, the use of a wetlands location for a CCR unit may require a permit from the U.S. Army Corps of Engineers. To the extent these are applicable, compliance with these RCRA criteria does not alleviate the need to comply with these other federal requirements, and the owner or operator of the facility remains responsible for ensuring compliance with all applicable federal and state requirements.

The rule adopts a regulatory presumption that a less damaging alternative to locating a disposal unit in a wetland exists, unless the owner or operator can demonstrate otherwise. Thus, when proposing to locate a new facility or lateral expansion in a wetland, owners and operators must be able to demonstrate that alternative sites are not available and that the impact to wetlands is unavoidable. If this presumption is not clearly rebutted, then the CCR unit may not be sited in a wetland location. Such an analysis necessarily includes a review of reasonable alternatives to locating or laterally expanding CCR units in wetlands. As part of the evaluation of reasonable (that is, available and feasible) alternatives the owner or operator must show, and a qualified professional engineer must verify, that operation or construction of the CCR unit will not: (1) Violate any applicable state water quality standards; (2) cause or contribute to the violation of any applicable toxic effluent standard or prohibition; (3) cause or contribute to violation of any requirement for the protection of a marine sanctuary; and jeopardize the continued existence of endangered or threatened species or critical habitats.

When evaluating the impacts of a CCR unit on a wetland, the owner or operator must ensure that the unit cannot cause or contribute to significant wetland degradation. Therefore, the owner or operator and the qualified professional engineer must: (1) Verify the integrity of the CCR unit, and its ability to protect ecological resources by addressing the erosion, stability, and migration potential of native wetland soils, and dredged and fill materials used to support the unit; (2) verify that the design and operation of the CCR unit minimizes impacts on fish, wildlife, and other aquatic resources and their habitat(s) from any release of coal combustion residuals; (3) evaluate the effects of catastrophic release of CCR to the wetland and the resulting impacts on the environment; and (4) verify that ecological resources in the wetland are sufficiently protected, including consideration of the volume and chemistry of the CCR managed in the unit; and any additional factors, as necessary.

When a wetland functions properly, it provides water quality protection, fish and wildlife habitat, natural floodwater storage, and reduction in the erosive potential of surface water. A degraded wetland is less able to effectively perform these functions. For this reason, wetland degradation is as big a problem as outright wetland loss, though often more difficult to identify and quantify. Any change in hydrology can significantly alter the soil chemistry and plant and animal communities. The common hydrologic alterations that can lead to significant degradation in wetland areas include: (1) Deposition of fill material, including CCR; (2) drainage for development; (3) dredging and stream channelization for development; (4) diking and damming to form ponds or impoundments; (5) diversion of CCR-bearing waters or other flows to or from wetlands; (6) addition of impervious surfaces in the watershed, thereby increasing water and CCR-bearing run-off into wetlands. These activities can mobilize CCR-bearing sediment; and once the sediment is discharged into the environment, toxic metals in CCR can become available to organisms within the wetland. Consequently, while the mere presence of one or more of these activities does not necessarily demonstrate that the CCR unit causes or contributes to significant degradation, the fact that they may do so means these activities need to be carefully evaluated.

In determining what constitutes ''significant'' degradation, it is important to understand that although wetlands are capable of absorbing pollutants from the surface water, there is a limit to their capacity to do so. For the purposes of this rule, the primary pollutants of concern are CCR-bearing sediment and toxic metals. Although the risk assessment did not assess the exposure and hazard to wetlands, these can originate from uncontrolled run-off from the facility, fugitive dust from uncovered CCR landfills and piles, and uncontrolled discharge from CCR units (landfills, waste piles, surface impoundments). A clear example of biologically significant degradation in wetlands is when these toxic metals accumulate in benthic and aquatic food chains as a result of uncontrolled runoff. Another is obrution (smothering) of benthic organisms from discharge(s) of CCR to surface water, thereby jeopardizing the continued existence of organisms or critical habitats within the wetland. EPA notes that there are other requirements established under this rule that can also be relevant in this context, as they have the potential to reduce the likelihood that facility operations will cause or contribute to significant wetland degradation. EPA anticipates that as the facility begins to implement all of the requirements under this rule, the facility will consider how modifications to facility operations to address one requirement can affect compliance with other requirements.

After consideration of these factors, if an existing CCR unit cannot meet all of the requirements in paragraphs (1)–(3) (*i.e.,* if it causes or contributes to significant degradation, or if no reasonable alternative to locating a new CCR unit in wetlands is available), the facility can comply with the location criterion by compensatory steps that must be taken to achieve no net loss of wetlands (as defined by acreage and function). Owners or operators must first take measures to avoid impacts to wetlands. If potential impacts cannot be avoided, all reasonable steps are to be taken to minimize such impacts to the extent feasible. Appropriate measures (for example, engineered containment systems to control discharge of leachate or surface water run-off to wetlands) will likely be site-specific and should be incorporated into the design and operation of the CCR unit. Any remaining unavoidable impacts must be offset, or compensated for through all appropriate and feasible compensatory mitigation actions. This compensatory

mitigation may take the form of restoration (re-establishment or rehabilitation of a wetland), establishment (creation of a man-made wetland where one did not previously exist), enhancement (improving one or more wetland functions), and preservation (permanent protection of important wetlands through implementation of appropriate legal and physical mechanisms). The functions and values of a wetland will vary based on any number of site specific characteristics, including location, wetland type, hydrology, degradation, and whether it is natural or constructed to treat waste. Strictly limited to the application of the wetlands location requirements under this rule, any assessment of the nature and extent of mitigation required under the CCR rule shall consider these kinds of characteristics, including wetlands designed for the treatment of CCR. The Agency recognizes that the function and value of a particular man-made wetland constructed to perform a wastewater treatment function may present a unique situation that may affect both the determination of whether the wetland is significantly degraded, and the nature and extent of any required compensatory mitigation. This discussion refers only to the wetlands-related requirements of this rule and does not affect any requirements or obligations under the Federal Water Pollution Control Act (33 U.S.C. 1251, *et seq.*) and its implementing regulations.

Although EPA is not finalizing an outright ban on siting of existing or new CCR units in wetlands, the Agency continues to believe that discharges to wetlands of pollutants that can be reasonably avoided should be avoided. Therefore, the amount and quality of compensatory mitigation may not substitute for avoiding and minimizing impacts. For purposes of this rule, EPA assumes CCR units that are designed to avoid discharge of CCR into wetlands have less adverse impact to the aquatic environment than CCR units that ultimately discharge such residuals in wetlands.

4. Fault Areas

In § 257.62 of this rule, EPA is banning the location of new CCR landfills, existing and new CCR surface impoundments, and all new lateral expansions within 60 meters (200 feet) of a fault that has had displacement in Holocene time, unless the owner or operator demonstrates that an alternative setback distance of less than 60 meters (200 feet) will prevent damage to the structural integrity of the unit. For existing surface impoundments, the demonstration is required only if the unit is located closer than 60 meters (200 feet) to an active Holocene fault. If a demonstration cannot be made, the existing surface impoundment must close. These requirements have been adopted with only minor changes from the proposal, and will minimize the risks associated with CCR units located in fault areas.

Stresses produced during earthquake motion can cause serious damage to landfill integrity via seismically induced ground failure and associated rupture of liner systems and subsequent damage to leachate collection systems. Or if the unit is unlined, seismic motion could disrupt landfill caps and foundation soils that impede migration of percolating water. Potential damage to CCR units resulting from structures located across a fault include surface breakage, cracks and fissures between fill and confining slopes, slope failure via landslides, liquefaction-induced lateral spreading and settlement of the pile, disruption of surface water and drainage control systems, and rupture of leachate collection systems. In impoundments, for example, interior dike failure and leakage, and rupture of multilayer liner systems would also be of concern. Failure of the leachate collection system may prevent removal of generated leachate, allowing it to pond on the liner. If the liner system is ruptured, this may create a pathway for leachate to migrate into and contaminate the uppermost aquifer. In addition to the potential damage to leachate collection and liner systems, the integrity of the landfill slopes could also be impaired by fault rupture, potentially exposing coal combustion residuals to surface run-off.

The best protection is to avoid locating new CCR landfills and all CCR surface impoundments across faults and fault zones subject to displacement. For new units or lateral expansions there is no need to construct units in these areas. For existing surface impoundments, the Agency has been unable to find any way to retrofit or engineer the unit to be protective. A setback distance of 60 meters (200 feet) from the outermost damage zone of a Holocene fault will provide an adequate margin of safety to protect the facility from displacements due to surface faulting and any associated damage because 60 meters typically covers the zone of deformation where the ground may be bent or warped as a consequence of fault movement. By including this as a siting requirement for new units the risk of rupture of the unit, including any liner and leachate collection systems, due to surface faulting will be minimized.

Observations of engineered landfill response during earthquake motion come primarily from California where field data have been reported from MSWLFs (including some meeting the current part 258 standards) affected by strong shaking from six major nearby earthquakes. In these large magnitude events ($M \geq 6.7$), bedrock peak horizontal ground accelerations, an index of the intensity of earthquake motion, endured by the landfills were in excess of 0.3g. Engineered dry MSWLFs in California are reported to have performed well after strong earthquake motion (no documented incidence of an earthquake-induced release of contaminants harmful to human health or to the environment). Minor cracking of cover soils and breaking of vertical wells and headers were among the most common types of damage reported at MSWLFs subject to strong ground shaking. In the 1994 Northridge earthquake, only one landfill compliant with RCRA Part 258 standards experienced tears in a liner (a geomembrane liquid barrier): One tear 23 meters in length. However, there is little data on seismic stability and performance from industrial solid waste landfills with geosynthetic liners or units with water-saturated CCR waste. The Agency, therefore, remains concerned over the potential instability of engineered disposal units, and particularly CCR surface impoundments, under seismic loadings. Accordingly, EPA is prohibiting new CCR landfills, CCR surface impoundments, and any new extensions from sites located within an active fault zone, unless the owner or operator makes a demonstration, certified by a qualified professional engineer, that an alternative setback distance of less than 60 meters will prevent damage to the structural integrity of the unit.

EPA is clarifying its definition of fault to incorporate updated technical information.[56] Although a fault can be thought of as a simple planar surface across which there has been measurable displacement of one side relative to the other, field-based observations show fault architecture to often be complex. In the geologic literature faults developed in the upper crust are characterized as zones of brittle deformation composed of linked fault segments, with each segment composed of one or more subparallel, curved, or anastomosing fault cores nested within

[56] Sibson, R.H. 2003. Thickness of the Seismic Slip Zone. Bulletin of the Seismological Society of America, Vol. 93, No. 3, pp. 1169–1178.

a damage zone. Some fault zones may contain broad deformational features such as pressure ridges and sags rather than clearly defined fault scarps or shear zones.[57] Fault cores are regions of high strain slip that have accommodated most of the displacement and are marked by mylonites, cataclastites, and gouge, whereas the damage zone is characterized by low strain structures mechanically related to the growth of the fault zone such as small faults, fractures, veins and folds. To avoid displacement that would damage unit integrity, it is best to restrict new CCR landfills and surface impoundments, and all new extensions, to locations no less than 60 meters from the outermost damage zone created by an active fault. Fault zones can range from one meter to several kilometers in width.

For purposes of this section, a fault is considered active if it has moved during Holocene time. Holocene time is defined as the geological epoch which began at the end of the Pleistocene, at 11,700 years BP (before present), and continues to the present. In the field, evidence for Holocene activity may be hard to obtain. Therefore, the Agency cautions that faults which show no evidence for Holocene activity may not necessarily be inactive.

To investigate active faults, EPA expects owners and operators of CCR units to follow standard engineering and geologic practices. Technical considerations include: (1) A geologic reconnaissance of the site to determine the location of active faults. Such a reconnaissance would include utilizing the seismic analysis maps and tools (Quaternary fault maps, earthquake probability maps) of the United States Geological Survey (USGS) Earthquake Hazards Program (*http://earthquake.usgs.gov/hazards/apps/*); and (2) a site fault characterization within 1000 meters of a site to determine whether it is within 60 meters of an active fault. Such characterizations would include subsurface exploration, including drilling or trenching, to locate any fault zones and evidence of faulting, trenching perpendicular to any faults or lineaments found within 60 meters of the site, and determination of the age of any displacements. Based on this information, the qualified professional engineer would prepare a report that delineates the location of any active (Holocene) fault, including any damage zones, and the associated 60 meter setback. To take advantage of an alternative setback distance of less than 60 meters, the owner or operator must make a demonstration, certified by a qualified professional engineer, that the CCR landfill, surface impoundment, or lateral expansion has a foundation or base capable of providing support for the structure, and capable of withstanding hydraulic pressure gradients to prevent failure due to settlement, compression, or uplift, and all effects of ground motions resulting from at least the maximum surface acceleration expected from a probable earthquake.

5. Seismic Impact Zones

In § 257.63, EPA is adopting the provisions applicable to seismic impact zones, as proposed. The rule prohibits new CCR landfills, existing and new CCR surface impoundments and all lateral extensions from being located in seismic impact zones unless the owner or operator makes a demonstration, certified by a qualified professional engineer, that all containment structures, including liners, leachate collection systems, and surface water control systems, are designed to resist the maximum horizontal acceleration in lithified earth material from a probable earthquake. A *Seismic impact zone* means an area having a 2% or greater probability that the maximum expected horizontal acceleration, expressed as a percentage of the earth's gravitational pull (g), will exceed 0.10 g in 50 years. Seismic zones, which represent areas of the United States with the greatest seismic risk, are mapped by the U.S. Geological Survey and readily available for all the U.S. (*http://earthquake.usgs.gov/hazards/apps/*).

Maximum Horizontal Acceleration in lithified earth material means the maximum expected horizontal acceleration at the ground surface as depicted on a seismic hazard map, with a 98% or greater probability that the acceleration will not be exceeded in 50 years, or the maximum expected horizontal acceleration based on a site-specific seismic risk assessment. This requirement translates to a 10% probability of exceeding the maximum horizontal acceleration in 250 years.

For units located in seismic impact zones, as part of any demonstration, owners and operators should include: (1) A determination of the expected peak ground acceleration from a maximum strength earthquake that could occur in the area; (2) a determination of the site-specific seismic hazards such as soil settlement; and (3) a facility design that is capable of withstanding the peak ground acceleration. Seismic designs broadly should include a response analysis to quantify the demands of earthquake motion on facility structures (*i.e.,* landfills, surface impoundments, liners, covers, leachate collection systems, surface water handling systems), liquefaction analyses of both waste and foundation soils to evaluate stability under seismic loading, and a slope stability and deformation analyses. Design modifications to accommodate seismic risks should include use of conservative design factors, use of ductile materials, built-in redundancy for critical system components, and other measures capable of mitigating the potential for seismic upset.[58]

Following trends in earthquake engineering, seismic design criteria for new CCR landfills, new CCR surface impoundment and all lateral expansions should be based on a ''withstand without discharge'' standard.[59] EPA interprets the performance standard in this criterion (''designed to resist the maximum horizontal acceleration in lithified earth material from a probable earthquake'') to require any new CCR unit located in a seismic impact zone to be designed to withstand seismic motion from a credible earthquake without damage to the foundation or to the structures that control leachate, surface drainage, or erosion. In other words, the CCR unit must be able to withstand an expected earthquake without discharging waste or contaminants. The owner or operator must make a demonstration, certified by a qualified professional engineer, that the CCR unit has a foundation or base capable of providing support for the structure, and capable of withstanding hydraulic pressure gradients to prevent failure due to settlement, compression, or uplift and all effects of ground motions resulting from at least the maximum surface acceleration expected from a probable earthquake. In practice, the Agency recognizes that the CCR unit may sustain some limited damage during an earthquake, but ultimately, the CCR unit design must remain

[57] Bryant, W.A. and Hart, E.W., 2007. Fault-Rupture Zones in California. Special Publication 42 (Interim Revision), California Division of Mines and Geology, Sacramento, California.

[58] The *seismic location standard* requires a demonstration that a CCR disposal unit can withstand the stresses imposed by peak ground acceleration during earthquake motion. The *seismic factor of safety* is a unitless measure of strength calculated for fill material assuming earthquake conditions. It is the ratio of material shear strength relative to the magnitude of shear forces acting on the material. For a CCR disposal unit, the *seismic location demonstration* could be composed of numerous *factor of safety* calculations showing that the structural components of the unit have factors of safety greater than or equal to 1.00.

[59] Kavazanjian, E., 1999. Seismic Design of Solid Waste Containment Facilities. Proceedings of the Eight Canadian Conference on Earthquake Engineering Vancouver, BC, pp. 51–89.

capable of preventing harmful release of CCR, leachate, and contaminants both during and after the seismic event.

6. Unstable Areas

EPA laid out its rationale for these requirements in the proposal at 75 FR 35201. No significant comments were received on either this rationale or the specific regulatory provisions. Consequently, EPA is adopting the regulatory text as proposed. Specifically, under § 257.64(a) new and existing CCR landfills, new and existing CCR surface impoundments and all lateral expansions are prohibited from sites classified as unstable areas unless the owner or operator makes a demonstration, certified by a qualified professional engineer, that engineering measures have been incorporated into the CCR unit's design to ensure that the structural components will not be disrupted. EPA considers a structural component to include any component used in the construction and operation of CCR landfill or CCR surface impoundment that is necessary to ensure the integrity of the unit and to ensure that the contents will not be released to the environment, including liners, leachate collection system, embankments, spillways, outlets, final covers, inflow design flood controls systems. Liners and leachate collection systems require a firm, secure foundation to maintain their integrity, and may be disrupted as a result of uneven settlement induced by hydrocompaction. Similarly, sudden differential movement resulting from CCR placement and the consequent exceedance of the weight-bearing strength of subsurface materials in unstable areas can destroy liners and damage the unit's structural integrity, resulting in catastrophic release of CCR. It is essential for the owner or operator of any CCR unit to extensively evaluate the adequacy of the subsurface foundation support for the structural components of the unit. Therefore, the Agency is making this demonstration mandatory for all CCR units; existing CCR units for which a demonstration cannot be made must be closed.

EPA has adopted the following definitions without material change from the proposal: *Unstable area* means a location that is susceptible to natural or human-induced events or forces capable of impairing the integrity of some or all of the structural components responsible for preventing releases from a CCR unit. Natural unstable areas include those areas that have poor soils for foundations, areas susceptible to mass movements, and karst terrains. *Structural components* mean liners, leachate collection systems, final covers, run-on/run-off systems, and any other component used in the construction and operation of a CCR unit. *Poor foundation conditions* means those areas where features exist which may result in inadequate foundation support for the structural components of a CCR unit. *Areas susceptible to mass movement* means those areas of influence (*i.e.,* areas characterized as having an active or substantial possibility of mass movement) where the movement of earth material at, beneath, or adjacent to the CCR unit, because of natural or man-induced events, results in the downslope transport of soil and rock material by means of gravitational influence. Areas of mass movement include, but are not limited to, landslides, avalanches, debris slides and flows, solifluction, block sliding, and rock fall. *Karst terrain* means an area where karst topography, with its characteristic erosional surface and subterranean features, is developed as the result of dissolution of limestone, dolomite, or other soluble rock. Characteristic physiographic features present in karst terrains include, but are not limited to, dolines (sinkholes), vertical shafts, sinking streams, caves, seeps, large springs, and blind valleys.

The owner or operator must consider at a minimum, the following factors when determining whether an area is unstable: (1) On-site or local soil conditions that may result in significant differential settling; (2) on-site or local geologic or geomorphologic features; and (3) on-site or local human-made features or events (both surface and subsurface). To evaluate subsurface conditions for purposes of § 257.64(c)(3), EPA considers it essential that the owner or operator conduct a geotechnical site investigation, certified by a qualified professional engineer, to identify any potential thick layers of soil that are soft and compressible (*e.g.,* loess, unconsolidated clays, wetland soils), which could cause a significant amount of post-construction differential settlement of foundation soils, adjacent embankments, and slopes unless improved. In addition, it is essential that the investigation identify on-site or local soil conditions that are conducive to downslope movement of soil, rock, and/or debris (alone or mixed with water) under the influence of gravity. Local topography, surface and subsurface soils, surface slope angles, surface drainage and run-off patterns, seepage patterns, rock mass orientations, joint patterns, fissures, and any other landscape factors that could influence downslope movement should be identified. Anthropogenic activities that could induce instability include mining, cut and fill activities during construction, excessive drawdown of groundwater, which may cause excessive settlement or bearing capacity failure of foundation soils, and use of an old landfill as the foundation for a new landfill without verification of complete settlement of the underlying wastes.

In designing a new CCR unit located in an unstable area, recognized and generally accepted good engineering practices dictate that a stability assessment should be conducted to prevent a destabilizing event from damaging the structural integrity of the component systems. For CCR units this involves three components: (1) An evaluation of subsurface conditions, (2) an analysis of slope stability, and (3) an examination of related design needs. In addition to explaining site constraints, identifying any soft soils, and recommending any appropriate ground improvement techniques, the assessment report should include a description of: The site, site geology; and investigative methodology; the results from all site investigations including subsurface exploration, field and laboratory tests, and test results; the subsurface profile, recommended foundation types, depths, and bearing capacities; the water content, grain-size distribution, shear strength, plasticity, and liquefaction potential of foundation soils and subsoils; and other foundation consolidation and settlement issues relevant to site development.

In addition to assessing the ability of soils and rocks to serve as a foundation, it is essential that the report also include a stability assessment of excavated sideslopes, aboveground embankments or dikes, and retaining structures. The slope stability analyses are performed as part of an evaluation of the design configuration under all potential hydraulic and loading conditions, including conditions that may exist during construction of a lateral or vertical expansion. As part of any demonstration, owners and operators should make an assessment, certified by a qualified professional engineer, that finalized site embankments and slopes are able to maintain a stable condition. In addition to evaluating the potential for post-construction differential settlement, the stability assessment should also consider seepage-induced saturation and softening of soils, particularly at CCR surface impoundments and CCR landfill sites that manage effluent.

Engineering considerations for CCR landfills and lateral expansions located in unstable areas are expected to be

similar to those for MSWLFs, which can be found in EPA's 1993 Technical Manual on Solid Waste Disposal Facility Criteria (EPA530–R–93–017). For surface impoundments the relevant design criteria are found in the Agency's 1991 Technical Resource Document on Design, Construction and Operation of Hazardous and Non-Hazardous Waste Surface Impoundments (EPA/530/SW–91/054). Any stability assessment should consider the following: (1) The adequacy of the subsurface exploration program; (2) the liquefaction potential of the embankment, slopes and foundation soils; (3) the expected behavior of the embankment slopes, and foundation soils when they are subjected to seismic activity; (4) the potential for seepage-induced failure; and (5) the potential for differential settlement.

For facilities in areas of karst, to support the demonstration required under the regulations, the owner or operator would need to evaluate the subsurface conditions to ensure that the unit is located away from the influence of potential sinkholes. For areas where the solution-weathered limestone is close to the surface (*e.g.,* Florida) recognized and generally accepted good engineering practices dictate that there must be no conduits beneath the CCR unit that allow piping of groundwater into the karst aquifer, or shallow caves that could cause sudden collapse of the unit foundation. Where unconsolidated sediments cover underlying limestone, piping is commonly marked by paleosinks where sands and clays from the overburden have filled solution cavities in the underlying limestone.[60] Local hydraulic gradients in paleosinks typically point downward. EPA generally expects the potential for sinkhole development to be minimal at locations in karst areas where there are no paleosinks, or historical record of sinkhole development, and where there are no local hydraulic gradients that point downward.

In making a demonstration, it is important for owners and operators of CCR landfills and surface impoundments in karst areas to adequately characterize subsurface conditions. Karst hydrogeology is complex, since contaminant flows can occur along paths and networks that are discreet and tortuous, and groundwater monitoring wells must be capable of detecting any contaminants released from the CCR unit into the karst aquifer. Therefore, the owner or operator will need to ensure, with verification by a qualified professional engineer, that monitoring wells installed in accordance with § 257.91 will intercept these pathways. Verification will usually necessitate the use of tracers to track groundwater flow towards offsite seeps or springs from the uppermost aquifer beneath the facility.

Any engineered solution employed to mitigate weak ground strength in karst areas must be able to prevent the kind of foundation collapse and settlement that could lead to sudden release to the environment of CCR with its toxic constituents and associated leachate. Solution cavities present at the site should be filled with grout or other suitable stiff material to avoid further crumbling and erosion. Where necessary, CCR unit foundations could be reinforced with engineered ground supports such as concrete footings that bridge voids. Larger caverns could be filled with concrete to underpin the CCR unit foundation by transferring load to the cavern floor. However, such engineered solutions are complex and costly, and the best protection is not to site CCR landfills and surface impoundments in karst areas. Nevertheless, this rule does not ban the location of CCR landfills, surface impoundments, or lateral extensions in karst areas.

7. Closure of Existing CCR Landfills and Existing CCR Surface Impoundments

The final provisions of § 257.60 require owners or operators of an existing CCR surface impoundment to demonstrate that the unit meets the minimum requirements for placement above the uppermost aquifer (*i.e.,* constructed with a base located no less than 1.52 meters (five feet) above the upper limit of the uppermost aquifer) no later than 42 months after the date of publication of this rule in the **Federal Register**.

Owners and operators of existing CCR surface impoundments subject to §§ 257.61–257.64 of this rule and existing CCR landfills subject to § 257.64, must complete demonstrations by the date corresponding to 42 months from publication of this rule. The Agency is setting the compliance deadline at 42 months to allow owners and operators time to complete the requisite studies (*e.g.,* to adequately characterize seasonal variations in the elevation of the top of the uppermost aquifer) and to complete any engineering measures necessary to allow the CCR unit to meet the performance standards. If closure is warranted, it must be initiated no later than 48 months from publication of this rule. Closure and post-closure care must be done in accordance with §§ 257.100–103; which allow certain regulatory flexibilities provided specific conditions are met.

D. Design Criteria—Liner Design

EPA proposed that existing CCR landfills without a composite liner could continue to operate and receive CCR without violating the open dumping prohibition. Conversely, EPA proposed that existing CCR surface impoundments would be required to retrofit with a composite liner system, as defined in the proposed rule, within five years of the effective date of the rule or to close. EPA also proposed that all new CCR units must be constructed with a composite liner and leachate collection and removal system.

In the proposal, EPA defined a *composite liner* to mean a liner system consisting of two components; the upper component consisting of a minimum 30-mil flexible membrane liner (FML), and the lower component consisting of at least a two-foot layer of compacted soil with a hydraulic conductivity of no more than 1×10^{-7} cm/sec.[61] FML components consisting of high density polyethylene (HDPE) were required to be at least 60-mil thick; and the FML component was required to be installed in direct and uniform contact with the compacted soil component.

EPA solicited comment on a number of issues, including: (1) Whether EPA should allow facilities to use an alternative design for new CCR units; (2) whether clay liners designed to meet a 1×10^{-7} cm/sec hydraulic conductivity might perform differently in practice than modeled in the risk assessment, including a request for specific data on the hydraulic conductivity of clay liners associated with CCR units; and (3) whether the effectiveness of such additives as organosilanes, would allow the use of these additives in lieu of composite liners. (See 75 FR 35203 and 35222.)[62] With respect to the last two issues, the Agency received little comment. However, in response to the use of alternative liner designs in lieu of a composite liner (as defined in the rule), significant comment was received. Commenters advocated for a number of alternative composite liner designs, with a majority recommending that a

[60] For examples, see Garlanger, J.E., Foundation Design in Florida Karst. Online presentation by Ardaman & Associates. *http://www.ardaman.com/foundation_design.htm.*

[61] The definition of *hydraulic conductivity* is being promulgated as proposed, and will mean the rate at which water can move through a permeable medium (*i.e.,* the coefficient of permeability).

[62] The terms compacted soil and compacted clay are used interchangeably, *i.e.,* when referring to a compacted soil liner this is the same as referring to a compacted clay liner (CCL).

geosynthetic clay liner (GCL) be allowed as an alternative to the lower component of the composite liner. Other commenters stated that GCLs alone should be allowed as an alternative to the proposed composite liner. Still others argued that alternative liner designs, such as an FML/FML [63] provided a level of performance similar to the proposed composite liner system and should be allowed. Conversely, there were also comments opposing the use of any alternative liners, claiming that alternatives have not been proven to be effective.

EPA also received significant comment on the actual design of the composite liner system proposed by the Agency as it pertained to CCR surface impoundments (see 75 FR 35202–35203).[64] Commenters argued that the proposed requirement for a leachate collection and removal system in a CCR surface impoundment was illogical since it would have to be constructed between the lower component (two feet of compacted soil) and upper component (flexible membrane liner) and the proposed rule specifically states that the flexible membrane liner component must be installed in direct and uniform contact with the compacted soil component. Commenters reasoned that the inclusion of a leachate collection and removal system between the upper and lower components precluded direct and uniform contact between the two components and that placing a leachate collection and removal system between the lower and upper components of a composite liner would compromise the integrity of the composite liner. With regard to this last point, the Agency has reviewed the requirements for a proposed composite liner system as it would pertain to CCR surface impoundments and agrees that the leachate collection and removal system requirements proposed for CCR surface impoundments would be counterproductive; EPA proposed this requirement in error. The integrity of the composite liner system is indeed dependent upon the direct and uniform contact of the upper GM component with the lower soil component. The proposed requirement for CCR surface impoundments to construct a leachate collection system between the FML and soil components would prevent the direct and uniform contact of the upper and lower components and, therefore, compromise the integrity of the composite liner. For this reason, EPA is not requiring a leachate collection and removal system for new surface impoundments or any lateral expansion of a CCR surface impoundment.

While EPA agrees with those commenters arguing that new CCR units should only be installed with a composite liner system of some kind, the Agency has concluded that not all alternative designs for a composite liner system should necessarily be rejected as insufficiently protective. Many commenters provided strong and compelling evidence that the specific composite liner system described in the proposed rule was not always feasible or necessary to protect groundwater resources and that alternate composite liner designs could be equally protective, and may be a necessity in many areas of the country where soil with the appropriate hydraulic conductivity may not be available (*e.g.,* Alaska).[65]

In re-evaluating the proposed requirement for a composite liner system, EPA was influenced by a number of factors.[66] First, the data provided by commenters showing the performance of a GM/GCL design. Second, EPA's own studies showing that a GM/GCL liner can be constructed to achieve hydraulic efficiencies in the range of 99 to 99.9% which meets or exceeds the hydraulic performance of a GM/compacted clay liner (CCL) design.[67] In addition, these high efficiencies demonstrate that the GCL component of a GM/GCL composite liner is at least as effective in impeding leakage through holes in the GM component of the composite liner system as a CCL with a hydraulic conductivity no more than 1×10^{-7} cm/sec.[68] In fact, EPA has developed guidance for the selection and installation of various types of liners including a GM/GCL.[69] And third, EPA was influenced by the many comments arguing that a ''one-size-fits all'' approach to liner design stifles design innovation and regulatory flexibility in addressing site specific factors such as geologic or climatic conditions. These commenters reasoned that if EPA established some type of performance standard for composite liners, it would mitigate the negative impacts of a ''one-size fits all'' regulatory framework.

1. Development of Composite Liner Design Criteria

In this final rule EPA is requiring all new CCR units to be designed and constructed with a composite liner as specified in § 257.70. EPA is also providing the owner or operator with an option to install an alternative composite liner provided it meets the required performance standard and it is certified by a qualified professional engineer. EPA has concluded, consistent with many of the comments received and its own analysis, that an alternative composite liner for new CCR units is warranted if it can be shown to be equivalent to the performance of a composite liner and affords the same protections to groundwater resources as a composite liner. The Agency is promulgating this alternative option to provide flexibility in designing and constructing a protective composite liner system that addresses site specific conditions and situations. The Agency acknowledges that it was overly prescriptive by requiring one particular type of liner rather than relying on a performance standard to define the lower component of the composite liner. The overwhelming amount of data supporting the effectiveness of a GC/GCL liner has convinced the Agency that the final rule should allow for some flexibility in composite liner designs. As such, the Agency is allowing new CCR units to be designed and constructed

[63] Current terminology favors the use of geomembrane liner or GM when referring to flexible membrane liners or FMLs. Hereafter in the preamble, except when referring to specific comments or the proposed rule, and in the final rule, the Agency will use the term geomembrane liner or GM in place of flexible membrane liner or FML.

[64] See proposed § 257.71 which states that an existing CCR surface impoundment shall be constructed with a composite liner and a leachate collection system between the upper and lower components of the composite liner; where a composite liner means a system consisting of two components; the upper component consisting of a minimum 30-mil flexible membrane liner (FML) and a lower component consisting of at least a two-foot layer of compacted soil with a hydraulic conductivity of no more than 1×10^{-7} cm/sec. The FML component would be required to be installed in direct and uniform contact with the compacted soil component (see 75 FR 35243).

[65] See for example comments from the states of Alaska (EPA–HQ–RCRA–2009–0640–06409); Florida (EPA–HQ–RCRA–2009–0640–06846); and North Carolina (EPA–HQ–RCRA–2009–0640–09282) available at *www.regulations.gov.*

[66] Geomembranes (GMs), which are flexible membrane liners (FMLs), are thin materials manufactured from polymers and reinforced with woven fabric or fibers which are used as hydraulic barriers. Resins used to manufacture geomembrane liners typically include high density polyethylene (HDPE), linear low density polyethylene (LLDPE), low density linear polyethlene (LDLPE), very low density polyethylene (VLDPE) and polyvinyl chloride (PVC). Geomembranes manufactured using HDPE are the least flexible of the geomembranes.

[67] USEPA, ''Assessment and Recommendations for Improving the Performance of Waste Containment Systems,'' EPA 600/R–02/029, December 2002. *http://nepis.epa.gov/Adobe/PDF/P1001O83.pdf.*

[68] USEPA, ''Assessment and Recommendations for Improving the Performance of Waste Containment Systems,'' EPA 600/R–02/029, December 2002.

[69] USEPA, ''Guide for Industrial Waste Management,'' Chapter 7 (*http://www.epa.gov/osw/nonhaz/industrial/guide/pdf/chap7b.pdf*).

with an alternative composite liner, as described below, provided the lower component of the composite liner meets a specified performance standard that ensures it functions in a manner equivalent to the composite liner system defined in the rule.

Composite liner systems installed in either a CCR landfill or CCR surface impoundment provide an effective hydraulic barrier by combining the complementary properties of the two different liner components. The geomembrane provides a highly impermeable layer that can maximize leachate collection and removal in a CCR landfill or minimize infiltration of leachate in a CCR surface impoundment, while the soil component (*e.g.,* CCL) serves as a backup in the event of any leakage/infiltration from the geomembrane occurs. Data indicate that alternatives to the lower component of the composite liner system (*e.g.,* GCLs) are available and can perform at a level equivalent to a compacted soil liner, based on a comparison of their flow rates with two feet of compacted soil with a hydraulic conductivity of no more than 1×10^{-7} cm/sec.

2. Liner Designs That Would Not Meet the Requirements of a Composite Liner or Alternative Liner

Contrary to the arguments made by several commenters, EPA has concluded that a composite liner consisting of two 30-mil GMs (GM/GM) will not provide an equivalent degree of protection as a composite liner consisting of a GM and two feet of compacted soil, or an alternative composite liner such as a GM/GCL. While GMs have the advantages of extremely low rates of water permeation, the disadvantages of a composite liner consisting of two GMs include leakage through occasional GM imperfections and punctures, potential for slippage along the interface between the GMs, and GM embrittlement over time. Furthermore, a critical component of a composite liner is the compacted soil or GCL component beneath the GM layer that will impede the flow of liquid that may leak through a hole or defect in the GM. This added protection cannot be achieved using two GMs for the composite liner. Additionally, the potential exists for liquid transport through the GMs through holes caused by punctures, tears, flawed seams, etc. If a puncture occurs, the puncture could compromise both GMs and create a conduit for liquid flow to underlying permeable soil. Moreover, a liner system consisting of two GMs in contact with each other poses the risk of creating a slip plane that may compromise the stability of the disposal unit (although EPA acknowledges that using textured GMs would reduce or eliminate this particular risk). These data are documented in EPA research.[70]

Consistent with the previous determination, EPA has also determined that the double liner system set forth in Florida regulations (see Florida Rules 62–701.400(3)(c), F.A.C) also does not meet the level of performance achieved by EPA's composite liner system or the alternative liner system. While this double liner system provides the advantage of a leak detection system between the two GMLs, the lower composite liner, consisting of a 60-mil HDPE over six inches of soil with a saturated hydraulic conductivity of less than or equal to 1×10^{-5} cm/sec, is not equivalent to a GM over two feet of compacted soil with a hydraulic conductivity of less than or equal to 1×10^{-7} cm/sec. To be hydraulically equivalent, soil with a hydraulic conductivity of 1×10^{-5} cm/sec would need to be on the order of 100 times thicker than soil with a hydraulic conductivity of less than or equal to 1×10^{-7} cm/sec. Similarly, a lower composite liner consisting of a 60-mil HDPE over a GCL with a hydraulic conductivity not greater than 1×10^{-7} cm/sec would require a GCL thickness of 24 inches to be equivalent to a GM over two feet of compacted soil with a hydraulic conductivity of less than or equal to 1×10^{-7} cm/sec.

EPA has also examined the performance of GCLs approved for use as alternatives to composite liners in MSWLFs.[71] The EPA report titled ''Assessment and Recommendations for Improving the Performance of Waste Containment Systems,'' [72] concluded that if a CCL or GCL is used alone, liquid migration can occur over the entire area of the liner that is subject to a hydraulic head. The report also concluded that in a composite liner, leakage will only occur at the location of the geomembrane penetration (*e.g.,* hole, tear), and will be much slower than flow through an orifice due to the hydraulic impedance provided by the CCL or GCL alone. The report also evaluated, among other characteristics, the hydraulic efficiencies of a GM/GCL composite liner system for 28 cells at seven landfills. Liner hydraulic efficiencies were reported between 97% and 100%. However, potential stability problems were reported with GCLs constructed on slopes greater than 10 H:1 V (5.7°), and GCLs may not be appropriate for the disposal of liquid wastes or sludges. The Agency is also concerned that GCLs, being much thinner than the two feet of compacted soil required for composite liners, may allow for the flow of liquids through the GCL at a faster rate than through two feet of compacted soil. Taking all of this information into account, the Agency remains unconvinced that a GCL alone is a viable alternative to a composite liner.

3. Design Requirements

a. Existing CCR Landfills

As proposed, the final rule allows existing CCR landfills as defined in § 257.54, to continue to operate without retrofitting with a composite liner and leachate collection and removal system. As previously discussed, given the volume of the material currently managed in CCR landfills, the potential for disruption in CCR disposal capacity if existing CCR landfills were required to retrofit would be significant. Significant disruptions in the state-wide solid waste management (and possibly power generation) are associated with significant risks to public health and the environment in their own right. EPA has concluded that these risks are greater than the risks associated with allowing unlined CCR landfills to continue to operate. Further, existing CCR landfills will be required to comply with the extensive groundwater monitoring and corrective action requirements, among others, to ensure that any groundwater releases from the CCR unit are identified and promptly remediated, which will significantly mitigate the risks from these existing units. By themselves, the risk assessment results and the risk migration from the other regulatory requirements in this rule would not support a decision to allow these CCR units to continue to operate on a national basis. But when the risks associated with the level of disruption EPA estimates to be possible from requiring existing CCR landfills to retrofit are also included, the totality of the evidence supports a determination that allowing these units to continue operating meets the section 4004(a) standard.

[70] ''Assessment and Recommendations for Improving the Performance of Waste Containment Systems.''

[71] ''Geosynthetic Clay Liners Used in Municipal Solid Waste Landfills,'' *http://www.epa.gov/wastes/nonhaz/municipal/landfill/geosyn.pdf*; ''Geosynthetic Clay Liners in Waste Containment,'' *http://www.epa.gov/superfund/remedytech/tsp/download/2001_meet/prez/carson.pdf*; and ''Assessment and Recommendations for Improving the Performance of Waste Containment Systems,'' *http://nepis.epa.gov/Adobe/PDF/P1001O83.pdf.*

[72] ''Assessment and Recommendations for Improving the Performance of Waste Containment Systems.''

b. Existing CCR Surface Impoundments

In a departure from the proposed rule and after considerable evaluation and analysis, the Agency is finalizing a provision to allow all existing CCR surface impoundments to remain in operation provided certain conditions are met.[73] Owners or operators of existing CCR surface impoundments are required, within one year of the effective date of the rule, to document, certified by a qualified professional engineer, whether the unit is constructed with any one of the three liner types: (1) A liner consisting of a minimum of two feet of compacted soil with a hydraulic conductivity of no more than 1×10^{-7} cm/sec; (2) a composite liner that meets the requirements of § 257.70(b); or (3) an alternative liner that meets the requirements of § 257.70(c). In some instances, owners or operators may have information readily available to determine if an existing CCR surface impoundment is constructed with one of the three liner types listed above. On the other hand, this information may not be readily available and may require an owner or operator to conduct an engineering evaluation to determine if the unit was constructed with any of the three liner type. Factors such as the availability of engineering personnel and weather may impede the engineering evaluation. Therefore, EPA believes that 12 months from the effective date, or 18 months from publication of the rule, is a reasonable amount of time to make the determination of whether the existing CCR surface impoundment was constructed with one of the three liner types described above. Existing surface impoundments with liners that meet the criteria established for any of the three specified liner types are considered to be an ''existing lined CCR surface impoundments.'' These existing lined surface impoundments can continue to operate until the owner or operator decides to initiate closure, provided the unit does not meet other requirements of the rule that independently mandate closure of the unit (*e.g.,* location criteria (§§ 257.60–257.64) or structural integrity factors of safety (§ 257.73)). Existing unlined CCR surface impoundments must also cease receiving CCR and initiate closure if an owner or operator determines, at any point in time, as part of its groundwater monitoring program that the concentrations of one or more constituents listed in appendix IV to part 257 are detected at a statistically significant level above the groundwater protection standard established for that unit. EPA agrees with the many commenters who argued that existing unlined CCR surface impoundments should not be required to close prematurely if they are operating as designed and are complying with all of the requirements of the rule, including all groundwater protection standards. Taking into account the additional protections required under this rule (*e.g.,* location restrictions, groundwater monitoring, corrective action, structural integrity criteria, inspections and fugitive dust controls), the Agency has concluded that the risks posed by unlined CCR surface impoundments that are not ''leaking'' (*i.e.,* exceeding any groundwater protection standard) are not sufficient to warrant requiring these units to close. However, once a groundwater protection standard is exceeded (*i.e.,* the unit is leaking), without any type of liner system in place, leachate will flow through the unit and into the environment unrestrained and the only corrective action strategy that EPA can determine will be effective at all sites nation-wide requires as its foundation the closure of the unit.

EPA acknowledges that it may be possible at certain sites to engineer an alternative to closure of the unit that would adequately control the source of the contamination and would otherwise protect human health and the environment. However, the efficacy of those engineering solutions will necessarily be determined by individual site conditions. As previously discussed, the regulatory structure under which this rule is issued effectively limits the Agency's ability to develop the type of requirements that can be individually tailored to accommodate particular site conditions. Under sections 1008(a) and 4004(a), EPA must establish national criteria that will operate effectively in the absence of any guaranteed regulatory oversight (*i.e.,* a permitting program), to achieve the statutory standard of ''no reasonable probability of adverse effects on health or the environment'' at all sites subject to the standards. EPA was unable to develop a performance standard that would allow for alternatives to closure, but would also be sufficiently objective and precise to minimize the potential for abuse. There are too many factors that determine whether a particular engineering solution will meet the section 4004(a) standard at a particular site. And the risks of these units are simply too high.

Conversely, existing lined surface impoundments that exceed their groundwater protection standard are in a better position to manage the leak because it is usually caused by some localized or specific defect in the liner system that can more readily be identified and corrected. Consequently, this rule is not requiring existing lined CCR surface impoundment to close if an exceedance of a groundwater protection standard is detected; rather the Agency is affording the owner or operator with the opportunity to rely on corrective action measures to bring the risks back to acceptable levels (*i.e.,* control the source of the release and remediate the contamination), without mandating closure of the unit.

c. New CCR Landfills and New CCR Surface Impoundments and All Lateral Expansions

Both the CCR damage case history and the risk assessment clearly show the need for and the effectiveness of appropriate liners in reducing the potential for groundwater contamination at CCR landfills and CCR surface impoundments. Accordingly, EPA is finalizing liner and leachate collection and removal system requirements for new CCR landfills and all lateral expansions of these units. Similarly, EPA is finalizing liner requirements for new CCR surface impoundments and all lateral expansions of these units.

Specifically, EPA is requiring new CCR landfills, new CCR surface impoundments, and all lateral expansions be constructed with a composite liner (see § 257.70). The composite liner must consist of two components; an upper component consisting of a minimum 30-mil geomembrane liner (GM), and a lower component consisting of at least a two-foot layer of compacted soil with a hydraulic conductivity of no more than 1×10^{-7} centimeters per second (cm/sec). GM components consisting of high density polyethylene (HDPE) must be at least 60-mil thick and the GM or upper liner component must be installed in direct and uniform contact with the compacted soil or lower liner component

New CCR landfills or lateral expansions of these units are also required to be constructed with a leachate collection and removal system designed to maintain less than a 30-centimeter depth of leachate over the composite liner. A leachate collection and removal system is not required for new CCR surface impoundments

[73] Existing CCR surface impoundments will not be required, as was proposed, to retrofit to a composite liner or close within five years of the effective date of the rule (see 57 FR 35202).

because, as previously discussed, a leachate collection system installed between a single composite liner system is not practicable and would compromise the integrity of the composite liner system.

In addition, in response to comments on the proposed rule, EPA is allowing alternatives to the lower component of the composite liner system provided the flow rate through the lower component is no greater than the flow rate through two feet of compacted soil with a hydraulic conductivity of 1×10^{-7} cm/sec. The lower component must also be a recognized liner material; *e.g.,* soil, clay, or GCL. Alternative composite liners using compacted soil or clay as the lower component must be constructed with the upper component in intimate contact with the lower component; *i.e.,* the geomembrane must be installed to ensure good and uniform contact with the lower component. The hydraulic conductivity for the two feet of compacted soil used in the flow rate comparison must be no greater than 1×10^{-7} cm/sec. The hydraulic conductivity of the lower component must be determined using recognized and generally accepted engineering methods, for example, ASTM D5084–10, ''Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter,'' ASTM International, West Conshohocken, PA, 2012, DOI: 10.1520/D5084–10, *www.astm.org* for compacted soils or clays, or ASTM Standard D6766–12, ''Standard Test Method for Evaluation of Hydraulic Properties of Geosynthetic Clay Liners Permeated with Potentially Incompatible Aqueous Solutions,'' ASTM International, West Conshohocken, PA, 2012, DOI: 10.1520/D6766–12, *www.astm.org* for GCLs. The flow rate comparison for the lower component must be made using Darcy's Law for gravity flow through porous media, which is an empirical law which states that the velocity of flow through porous media is directly proportional to the hydraulic gradient. The use of Darcy's Law to calculate fluid flow through porous media is a well-established and generally accepted engineering methodology, and is the foundation for EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP) and is generally recognized to evaluate steady state flow of liquids through soils and GCLs.[74] EPACMTP is a subsurface fate and transport model EPA uses to simulate the impact of the release of constituents present in waste that is managed in land disposal units. Accordingly, the flow rate comparison for the lower component of alternative composite liner must be made using the following equation which is derived from Darcy's Law.

$$\frac{Q}{A} = q = k\left(\frac{h}{t} + 1\right)$$

where:

Q = flow rate,
A = surface area of the liner,
q = flow rate per unit area,
k = hydraulic conductivity of the liner,
h = hydraulic head above the liner, and
t = thickness of the liner.

A qualified professional engineer must certify that the design and construction of either the composite liner or the alternative composite liner meets the requirements of §§ 257.70(b) or (c).

EPA has also supplemented the composite liner criteria for landfills with performance standards that provide more precise direction to the professional engineer regarding the ''recognized and generally accepted good engineering practices'' that need to be used in the design and construction of composite liner systems to ensure that the liner system will continue to perform as designed. These criteria, which have been codified at §§ 257.70(b) and 257.70(c), have been adopted in response to comments requesting that EPA provide the professional engineers that will be required to certify that CCR units meet the requirements of the rule, with more precise and objective criteria. These criteria reflect the engineering specifications necessary to prevent liner failures resulting from improper design and construction and to ensure that the liner will continue to perform correctly. These provisions will ensure not only that the liner is properly designed and constructed, but also that the system will continue to safely perform throughout the landfill's active life and through post closure care. The criteria have been adopted from the technical provisions proposed under the subtitle C provisions for CCR landfills, and are consistent with design requirements set forth for hazardous waste landfills regulated under part 265 of RCRA, as well as existing guidance and recognized good engineering practices for the design and construction of MSWLFs.[75]

Specifically, the Agency is modifying the composite and alternative liner design requirements by requiring the composite or alternative liner to be chemically compatible with the CCR and of adequate strength and thickness to prevent failure. The liner system must also provide appropriate shear strength between the two components to prevent sliding of the upper component. In addition, the Agency is requiring that liners be placed on an adequate foundation and installed to cover all areas that might come into contact with the CCR.

For new CCR landfills, which are required to have a leachate collection and removal system designed and operated to maintain less than a 30 centimeter depth of leachate, the Agency is also requiring, that the leachate collection and removal system be constructed of sufficient strength and thickness to prevent collapse from the pressure of the CCR and to minimize clogging during the active life and post closure care period.[76]

4. Vertical Expansions of New and Existing CCR Landfills and All Lateral Expansions

In the proposed rule, EPA stated that CCR landfills could vertically expand without retrofitting, in order to alleviate concerns with regard to CCR disposal capacity in the short term. In the few comments to the proposed rule which mentioned vertical expansions of landfills, commenters requested that the Agency clarify the design standards that vertical expansions would have to meet. Information collected to date, which is included in the docket supporting the final rule, leads the Agency to conclude there are no issues unique to vertical expansions of CCR landfills that warrant modifications to the technical standards

[74] See for example EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP) at *http://www.epa.gov/epawaste/nonhaz/industrial/tools/cmtp/*, ''Assessment and Recommendations for Improving the Performance of Waste Containment Systems.'' Giroud, J.P., Badu-Tweneboah, K. and Soderman, K.L., 1997, ''Comparison of Leachate Flow Through Compacted Clay Liners and Geosynthetic Clay Liners in Landfill Liner Systems,'' Geosynthetics International, Vol. 4, Nos. 3–4, pp. 391–431 (*http://www.geosyntheticssociety.org/Resources/Archive/GI/src/V4I34/GI-V4-N3&4-Paper7.pdf*), and ''Design Considerations for Geosynthetic Clay Liners (GCLs) in Various Applications,'' Geosynthetic Research Institute, January 9, 2013 (*http://www.geosynthetic-institute.org/grispecs/gcl5.pdf*).

[75] ''Technical Guidance Document: Quality Assurance and Quality Control for Waste Containment Systems.'' U.S. Environmental Protection Agency. Risk Reduction Engineering Laboratory, Office of Research and Development, Cincinnati, OH 45268. EPA/600/R–93/182. September 1993.

[76] Hardin, PE, Christopher D, and Perotta, PE Nick L. ''Operations and Maintenance Guidelines for Coal Ash Landfills—Coal Ash Landfill are NOT the Same as Subtitle D Solid Waste Landfills''. Presented at the 2011 World of Coal Ash Conference; May 9–12, 2011 in Denver, Colorado. *http://www.flyash.info/2011/127-Hardin-2011.pdf.*

being promulgated in this rule. Therefore, vertical expansions of existing CCR landfills are not subject to the provisions governing new units, but are subject to all applicable requirements for existing CCR landfills. To be clear however, while the location requirements relating to the placement above the water table, wetlands, fault areas, and seismic impact zones do not apply to existing CCR landfills, all of these restrictions apply to lateral expansions of existing CCR units, as well as new CCR units. Consequently, under this rule, owners or operators of existing CCR landfills can continue to vertically expand their existing facilities in these locations, but must comply with the provisions governing new units if they wish to laterally expand.

5. Construction of New CCR Landfills or Any Lateral Expansion Over an Existing CCR Unit

On August 2, 2013, EPA published a NODA that among other things, solicited comment regarding a particular type of CCR management unit described by some commenters in the proposed rule as ''overfills'' (see 78 FR 46940). Overfills are CCR landfills constructed over a closed CCR surface impoundment. As discussed in the NODA, in developing the proposed rule, EPA was not aware that CCR was managed in this fashion and so did not either evaluate this specific management scenario or propose technical requirements specifically tailored to this type of unit. Under the proposed rule, these types of units would need to comply with both the requirements applicable to the closure of surface impoundments or landfills, and with all of the technical requirements applicable to new landfills. Information collected since the proposal confirmed that the practice of constructing overfills for the disposal of CCR is conducted with some regularity, and raised questions as to whether overfills would be effectively regulated under the proposed technical requirements of the rule. In the NODA, to aid in the development of final technical requirements, EPA solicited data and information that directly addressed existing engineering guidelines or practices applicable to this units, as well as any regulatory requirements governing the siting, design, construction, and long-term protectiveness of these units for the disposal of CCR.

The Agency received numerous comments on the NODA. The majority of commenters agreed that overfills are commonly employed to allow continuing use of CCR disposal sites and to avoid the need to develop CCR management units at other sites. Some commenters added that: (1) The engineering design of an overfill can increase the stability of the underlying surface impoundment or landfill; (2) the use of an overfill facility reduces the need for new infrastructure construction; and (3) an overfill avoids having to transport CCR significant distances for off-site disposal.

Other commenters mentioned that several states had experience with overfills and have applied requirements such as liner systems, monitoring wells, and stormwater modeling on a case-by-case basis using best engineering practices. They added that overfills pose unique construction and operational issues depending on the site and the characteristics of the underlying unit, and that the construction of these units will therefore vary to account for these conditions. Commenters identified several issues requiring additional attention during design and construction of overfills including seismic and static liquefaction, settlement, foundation improvement, partial overfills, groundwater upwelling, groundwater monitoring, and wastewater infrastructure.

Upon review of these comments and further evaluation, the Agency has concluded that while there may be technical issues relating to the design, construction, and maintenance of overfills, the technical standards for CCR landfills are sufficiently flexible that no modifications are necessary to accommodate such units. For example, while the design and construction of groundwater monitoring systems may be technically more challenging, the final standards already allow for the construction of a multi-unit system. The performance standards and technical specifications laid out in the technical criteria developed for this rule are equally as applicable to overfills (and as protective) as to other new units. In essence, EPA is retaining the approach from the proposal that overfills will need to comply with both the requirements applicable to the closure of surface impoundments or landfills, and with all of the technical requirements applicable to new landfills. Thus, overfills cannot be constructed unless the underlying foundation—*i.e.,* the existing CCR surface impoundment has first been dewatered, capped, and completely closed. And because overfills are considered to be ''new CCR landfills,'' the design and construction of such units must comply with the technical requirements that address foundation settlement, overall and side slope stability, side slope and subgrade reinforcement, and leachate collection and groundwater monitoring system requirements, which will all need to be evaluated independent of the underlying CCR unit to ensure that the overfill design is environmentally protective. This evaluation must also be certified by a qualified professional engineer.

Under the location standards applicable to new CCR units, subgrade soils must be capable of providing stable structural support to the new liner system. A foundation composed of unconsolidated materials, such as CCR that is susceptible to slip-plane failure, is an unstable area (man-made) and, under provisions of this rule, is therefore a prohibited location for new CCR units. The TVA Kingston ash fill failure was at least partly attributable to slip-plane failure of saturated CCR that made up the subgrade and foundation beneath the unit.

Similarly, prudent and standard engineering practice for new CCR landfills requires that the base and side slopes of the overlying CCR landfill be able to maintain the structural integrity of the unit. If necessary, the subgrade should be reinforced with a geotextile fabric, or otherwise improved, to stabilize existing CCR in the underlying unit and to minimize tensile strain in the liner system. Slopes should be reinforced to prevent downhill sliding and to protect the leachate drainage system.

EPA is aware from comments that at least one facility is consolidating wet CCR in an active CCR surface impoundment through placement of dry ash over the wet CCR, and thereby converting the impoundment to a dry landfill, without stabilizing the CCR in the unit or capping the unit. This practice will no longer be permitted under the final rule criteria. Although no modifications were determined to be necessary to the individual technical criteria, EPA has added specific provisions that clarify the status of overfills, and clearly prohibit construction of a CCR landfill over a CCR surface impoundment unless the CCR in the underlying unit has first been dewatered and the unit is capped and completely closed. Dewatering, capping and closure of the underlying CCR unit prior to construction of the overlying CCR landfill renders the CCR overfill less susceptible to slip-plane failure. Conversion of an impoundment to a landfill without these measures involves a complex construction process that is highly site specific; EPA was unable to develop sufficiently objective performance standards that could be

independently verified outside of a supervised permit program. Because this rule is self-implementing EPA is, therefore, prohibiting construction of new CCR landfills over operational CCR surface impoundments to prevent the creation of structurally unstable units that could lead to catastrophic failures.

E. Design Criteria—Structural Integrity

Under the design criteria requirements, EPA proposed to establish structural stability standards for existing and new CCR surface impoundments and lateral expansions of these units based on a combination of existing federal programs and requirements applicable to dam safety. The proposed rule was largely based on the requirements promulgated for coal slurry impoundments regulated by the MSHA at 30 CFR 77.216. (See 75 FR 35176.) EPA also developed aspects of the proposal based on the USACE and FEMA's dam safety programs. Consistent with the MSHA requirements, EPA proposed that existing and new CCR surface impoundments that could impound CCR to an elevation of five feet or more above the upstream toe of the structure and have a storage volume of 20 acre feet or more, or that impound CCR to an elevation of 20 feet or more above the upstream toe of the structure would be required to provide detailed information on the history of construction of the existing CCR surface impoundment and to meet certain performance standards. Specifically, facilities would need to (1) develop plans for the design, construction, and maintenance of existing impoundments, (2) conduct periodic inspections by trained personnel knowledgeable in impoundment design and safety, and (3) provide an annual certification by an independent registered professional engineer that all construction, operation, and maintenance of impoundments is in accordance with the approved plan.

EPA also proposed to require the facility to obtain certification from a professional engineer that the ''design of the CCR surface impoundment is in accordance with current, prudent engineering practices for the maximum volume of CCR slurry and CCR wastewater which can be impounded therein and for the passage of run-off from the design storm which exceeds the capacity of the CCR surface impoundment. To support this performance standard, EPA proposed to require the facility to conduct specific analyses, and to provide information on critical structures. This includes the proposed requirements to compute the minimum factor of safety for slope stability of the retaining structures of the unit, including the methods and calculations used to determine each factor of safety, and to provide information on the physical and engineering properties of the foundations of the CCR surface impoundment, any foundation improvements, drainage provisions, spillways, diversion ditches, outlet instrument locations and slope protections, and area capacity curves. EPA proposed to require more extensive information from new CCR surface impoundments addressing the design, construction, and maintenance of the new CCR unit, recognizing that such information may not be available for existing units.[77] In addition, EPA proposed to require existing and new CCR surface impoundments of a specified size to calculate and report the hazard potential classification of the unit. Finally, EPA proposed that any CCR surface impoundments classified as having a high or significant hazard potential, as certified by an independent registered professional engineer, be required to develop and maintain an Emergency Action Plan defining the responsible persons and actions to be taken in the event of a dam safety emergency.

The Agency solicited comment on a number of issues relating to the proposed structural stability requirements. In particular, the Agency solicited comment on the scope of these requirements and whether they should apply to all CCR surface impoundments regardless of height and/or storage volume or whether EPA should adopt, as proposed and consistent with the MSHA requirements, the size cut-off described in the proposed rule; *i.e.,* impounding CCR to an elevation of five feet or more above the upstream toe of the structure and have a storage volume of 20 acre feet or more, or impounding CCR to an elevation of 20 feet or more above the upstream toe of the structure.

EPA also solicited comment on several alternative strategies for regulating the structural stability of CCR surface impoundments in lieu of regulation under RCRA subtitle D. The first alternative involved using NPDES permits rather than RCRA regulations to address dam safety and structural integrity. The second strategy would eliminate the structural integrity requirements from the RCRA subtitle D rule and, instead, have EPA establish and fund a program for conducting annual (or at some other frequency) structural stability assessments of CCR surface impoundments having a ''high'' or ''significant'' hazard potential rating as defined by criteria developed by the USACE for the NID. EPA would conduct these assessments and, using appropriate authorities already available under RCRA, CERCLA, and/or the Clean Water Act, would require facilities to respond to issues identified with their CCR surface impoundments. The rationale behind this suggested approach was that annual inspections would be far more cost effective than the phase-out of CCR surface impoundments—approximately $3.4 million annually for annual assessments, as compared to the $876 million annual cost of a rule that also phased out CCR. EPA also solicited comments on the effectiveness of this approach in ensuring the structural integrity of CCR surface impoundments. (See for example: 75 FR at 35176, 35223.)

On October 21, 2010, EPA published a NODA announcing that EPA intended to consider the information that had been developed through the Agency's Assessment Program as part of the CCR rulemaking. The NODA described the Assessment Program, and solicited comment on ''the extent to which both the CCR surface impoundment information collection request responses and assessment materials on the structural integrity of these impoundments should be factored into EPA's final rule on the Disposal of Coal Combustion Residuals from Electric Utilities.'' (See 75 FR 35128.) This included the responses to information requests that EPA originally sent to electric utilities, as well as reports and materials related to the site assessments developed through the Assessment Program. At that time, EPA had completed the assessments and the final reports for 53 units. On August 2, 2013, EPA published another NODA soliciting public comment on the additional assessments that had been completed since the 2010 NODA. In all, this included draft and final reports for a total of 522 units and 209 facilities. EPA again solicited comment on the extent to which this information should be taken into account as part of this rulemaking.

EPA received numerous comments on the proposed structural stability requirements. Many of these fell within two general areas: (1) EPA's approach of

[77] In the proposed rule under proposed § 257.71—Design criteria for existing CCR surface impoundments, the Agency only required the hazard potential classification for which the facility is designed and a detailed explanation of the basis for the classification (§ 257.71(d)(1)) ''as may be available'' (§ 257.71(d)). Similarly the computed minimum factor of safety for slope stability of the CCR retaining structure(s) and the analyses used in the determination (§ 257.71(d)(11) ''as may be available'' (§ 257.71(d)).

establishing the structural stability requirements, along with EPA's proposed reliance on MSHA's size thresholds to determine the applicability for the majority of structural stability requirements; and (2) the level of detail laid out in the technical criteria themselves.

With respect to the overall regulatory approach, the majority supported both the concept of structural stability requirements for existing and new CCR surface impoundments, and the adoption of the MSHA size threshold for complying with the majority of the structural stability requirements. EPA received comments from a number of state entities (the Association of State Dam Safety Officials (ASDSO) and the Association of State and Territorial Solid Waste Management Officials (ASTSWMO)) suggesting that EPA incorporate federal dam safety guidelines rather than rely solely on MSHA's dam safety guidelines. Commenters were concerned that the MSHA regulations ''only exist to protect miners on mine property, and not the downstream public.'' They urged that any EPA regulation also include consideration of hazards to the downstream public. These commenters also requested that EPA ''incorporate specific safety standards consistent with the Federal Guidelines for Dam Safety,'' referencing standards contained in FEMA documents 93, 333, 64, 94 and 65.

Little support was expressed for the alternative strategies presented in the proposal for addressing structural stability. Some comments were received suggesting additional alternatives. One commenter suggested that EPA consider limiting the volume of ''primary containment ponds'' to 10 acre-feet, reasoning that this provision would likely eliminate much of the concern regarding catastrophic failures, like TVA, and actually reduce the amount of slurry released in the event of a structural failure. Other commenters argued that EPA should limit the structural requirements to CCR surface impoundments both meeting the proposed size threshold and having a hazard potential classification of ''high'' or ''significant'' hazard potential rating based on FEMA's criteria for dam safety.[78] Commenters argued that a failure of a CCR surface impoundment with a ''low hazard potential classification'' posed only a low risk for on-site economic or environmental losses and would avoid the imposition of costly, arbitrary and unnecessary regulatory burdens on the owner or operator. In addition, commenters contended that this regulatory approach would be consistent with many state dam regulatory programs that apply dam integrity standards only to ''high'' or ''significant'' potential hazard facilities and would promote consistency with existing state controls.[79] Several commenters also suggested that EPA consider adding regulatory language or preamble discussion to assist owners or operators of CCR surface impoundments in interpreting the specific technical requirements in the regulation.

EPA disagrees with the suggestion that the Agency finalize a mandatory size limitation for operating CCR surface impoundments. While limiting the volume of CCR surface impoundments to ten acre-feet would limit the volume of CCR released in the event of a structural failure, limiting the size of CCR surface impoundments to 10 acre-feet may not always be practicable; nor does EPA believe that such a restriction is truly necessary to ensure that the section 4004(a) standard will be met. Many CCR surface impoundments are much larger than ten acre-feet and have been operating for many years without a structural failure. While EPA acknowledges that this fact in no way guarantees that a failure will not occur, the Agency is convinced that the implementation of all of the combined regulatory requirements in this rule (*e.g.,* location criteria, structural integrity, inflow design flood controls and inspection requirements) provides the necessary safeguards that will ensure that CCR surface impoundments are designed, constructed, operated, and maintained to minimize the risks associated with a catastrophic release of impounded CCR due to structural failure. While limiting the size of CCR surface impoundments will reduce risks because there will be a lower volume of waste in the unit, the Agency is not convinced that, in practice, such a requirement would meaningfully reduce the risks at many facilities. EPA expects that such a restriction would only cause facilities to construct either several small units or a multi-unit system. Failure of one unit can lead to progressive failure of other units in the system, and thus, ultimately this may not reduce the total volume of waste that could be released into the environment. EPA also disagrees that structural stability requirements should only apply to ''high'' or ''significant'' potential hazard facilities. Similarly, EPA disagrees with commenters that structural integrity requirements should only apply to owners or operators of CCR surface impoundments that both meet the specified size criteria and have either a high hazard or significant hazard potential classification. Even for CCR units with a low hazard potential classification, EPA is still concerned with the risk to human health and the environment from any structural failure of a CCR unit. As discussed previously in Unit VI.C of this document, the environmental effects of the failure of even a low hazard potential impoundment can still be significant, given the size of these units, the nature of the material in the unit, and the potential volumes that could be released. Contamination of surface waters and groundwater resources is still a significant threat when CCR units of this size fail, irrespective of the lower likelihood that a release will affect human health, as reflected in the low hazard potential classification. Consequently, one focus of this rule is preventing any release, catastrophic or otherwise, of CCR to the environment, and limiting all structural stability requirements commenters suggested would be inconsistent with this goal.

The Agency agrees that the final regulation should incorporate provisions that address the hazards to the downstream public. Accordingly, the final rule incorporates a number of provisions consistent with the FEMA Guidelines, including a requirement that owners and operators know each CCR unit's hazard potential classification, as this is part of owners and operators' responsibility to actively ensure the integrity of their CCR unit(s) and that their operations do not endanger human health or the environment. EPA also agrees that the requirements should be differentiated based on the potential severity of the consequence posed by the unit's failure, and therefore the hazard potential can be relevant in determining the stringency of particular requirements. However, the hazard potential is, at best, only an indicator of the potential damage that may be incurred from the

[78] See: *Federal Guidelines for Dam Safety: Hazard Potential Classification for Dams,* Federal Emergency Management Agency (''FEMA'') (reprinted January 2004). Under the FEMA dam safety classification system, a ''low hazard potential classification'' means that failure or mis-operation of the impoundment ''results in no probable loss of human life and low economic and/or environmental losses. Losses are principally limited to owner's property.''

[79] See *e.g.,* New Mexico Rules and Regulations Governing Dam Design, Construction and Dam Safety (*e.g.,* requiring dam site security, an instrumentation plan for monitoring and evaluating dam performance, and an operation and maintenance manual and emergency action plan only for dams with a high or significant hazard potential); see also NMAC sections 19.25.12.11(G)–(J).

structural failure of the unit, and so EPA has generally not relied on hazard potential as the sole basis for determining the structural integrity requirements that are necessary for a CCR unit.[80] Although the hazard potential classification can serve as a proxy for the amount of water and CCR that could potentially be released to the environment in the event of a CCR surface impoundment failure, the amount of water and CCR potentially released is more directly correlated to the actual height and storage volume of the CCR surface impoundment. In addition, it is widely recognized that the hazard potential classification of an individual unit can often fail to encompass the overall magnitude of a release on human health and the environment. CCR surface impoundments can frequently be part of a facility's run-off system that is responsible for routing surface waters to a drainage basin or watershed. As previously discussed, the failure of a CCR unit that is part of such a system has the potential to inundate downstream surface water units and water bodies, resulting in progressive failures of other units, including other CCR surface impoundments at the facility, which in turn can have a much greater environmental impact than the failure of just the one unit for which a hazard potential classification was made. Using a ''height and/or volume'' threshold to determine the applicability of the structural integrity criteria ensures that CCR units with the potential to cause these progressive failures in downstream surface water management units are appropriately overseen and regulated. CCR surface impoundments exceeding a specified height and/or capacity threshold also pose a higher degree of risk of release of CCR to the environment than other types of CCR surface impoundments (*e.g.,* incised or ''small'' CCR units). For all of these reasons, the size of the CCR unit, rather than the hazard potential classification, is the best indicator of potential severity of release of CCR to the environment and should therefore be the primary basis on which structural integrity criteria are applied. As such, EPA is promulgating, as proposed, a regulatory strategy that establishes some requirements for all CCR surface impoundments, but relies primarily on size as the basis for determining the majority of the specific technical criteria for minimizing risk from structural failure.

Regarding the second major issue presented in the comments, as noted previously, EPA received comments requesting the Agency to provide either more specific regulatory language or further guidance in the preamble, so that parties could certify that the CCR surface impoundment met the rule's overall performance standard. Commenters contended that guidance would be particularly critical if EPA did not establish more specific technical criteria, as owners or operators will be vulnerable to lawsuits for non-compliance. In addition, state officials requested that EPA adopt more specific standards consistent with those adopted under FEMA's Federal Guidelines for Dam Safety. As discussed throughout this section in more detail, EPA has adopted clarifications to the regulation, particularly in the sections on structural stability and safety factors, to more precisely lay out the specific technical standards that are considered to be the ''generally accepted and recognized good engineering practices'' that must be met. EPA relied extensively on existing MSHA requirements, FEMA's Federal Guidelines for Dam Safety, and guidance issued by the U.S. Army Corps of Engineers, as they were applied throughout EPA's Assessment Program, to supplement the technical detail originally contained in the proposed rule. EPA has also modified the criteria, where necessary, so they better reflect the information and experience developed through the Assessment Program, *e.g.,* the engineering criteria used to evaluate the CCR surface impoundments and to make recommendations to improve the structural stability of the units.

In this rule, the Agency is finalizing structural integrity criteria to ensure that CCR surface impoundments are designed, constructed, operated, and maintained in a manner that ensures the structural integrity of the CCR surface impoundment throughout its active life (*i.e.,* through closure of the CCR unit), detects actual or potential releases of CCR as early as practicable, and prevents catastrophic failures. Many of the requirements have been adopted without revision from the proposed rule for some requirements, however, as noted EPA has provided additional language to clarify the final regulation. These clarifications have been made in response to comments urging EPA to finalize regulatory requirements that were more precise or sufficiently objective (*i.e.,* a specific standard of performance) to allow a qualified professional engineer to reasonably certify that the requirements of the rule have been met. These specific regulatory clarifications are discussed throughout this section.

A further change is that the final rule requires facilities to periodically reassess several elements of the structural integrity performance standards (*i.e.,* re-assess every five years). Finally, in contrast to the programs established by MSHA and FEMA, the final rule establishes certain minimum requirements for all CCR surface impoundments. This is based on the fact that, unlike the dams regulated under other federal programs, the material in all CCR units is harmful, so even small releases can present environmental and human health concerns. But the majority of the structural integrity requirements vary depending on whether the CCR surface impoundment or lateral expansion exceeds particular size thresholds. The rulemaking record clearly demonstrates that these larger CCR surface impoundments present a greater risk of catastrophic failure, and therefore require a more robust set of regulatory requirements to ensure their continued structural integrity. The final rule's implementation of a size threshold for structural integrity requirements is consistent with the approach taken by the majority of dam safety programs and regulation.

These modifications are being made to better reflect the protections necessary to ensure that: (1) Structural integrity is maintained throughout the operational life of a CCR unit; and (2) the risk of catastrophic failure is minimized. The changes being made in this rule have been directly influenced by comments received, the observations and the conclusions drawn from EPA's Assessment Program, and the recommendations made by both MSHA and FEMA regarding dam safety. They are also generally consistent with the regulatory requirements of many other state and other federal agencies regulating dam safety.

1. Overview of Technical Criteria

Except for incised units, owners or operators of all existing and new CCR surface impoundments and any lateral expansion of these CCR units are required to: (1) Place a permanent identification marker on or immediately adjacent to the CCR units with the name associated with the CCR unit and the name of the owner or operator of the CCR unit; (2) conduct an initial hazard potential assessment to determine the current hazard potential classification of

[80] For example, EPA relied on hazard potential to trigger the requirement for an Emergency Action Plan, which will identify the actions necessary to minimize damage to life and property. As damage to life and property are the factors directly addressed in hazard potential classification, reliance on the classification is an appropriate determinant for this requirement.

the CCR unit; (3) conduct periodic (*i.e.,* every five years) hazard potential re-assessments; (4) develop an Emergency Action Plan (EAP) if the hazard potential classification of the CCR unit is classified as either a high- or significant hazard potential; and (5) maintain the CCR unit with vegetated slopes or other forms of slope protection.

Owners or operators of CCR surface impoundments that either have a height of five feet or more and a storage volume of 20 acre feet or more, or a height of 20 feet or more are required to comply with the following additional structural integrity criteria: (1) Document the design and construction of the CCR surface impoundment; (2) conduct an initial structural stability assessment; (3) conduct an initial safety factor assessment; and (4) conduct periodic (not to exceed five years) structural stability and safety factor assessments.[81] Owners and operators of CCR units that fail to make the safety factor assessment or fail to meet the factors of safety specified in the rule must stop placing CCR in the unit and initiate closure.

The structural integrity requirements of the final rule require the compilation of construction history of the existing CCR surface impoundment within one year of the effective date of the rule.

Within two months of the effective date of the rule, the structural integrity requirements (§ 257.73) state that the owner or operator must install a permanent marker on the existing CCR surface impoundment. This timeframe is being promulgated as proposed, as EPA did not receive comments on the timeframe for installation of a permanent marker.

2. Structural Integrity Requirements Applicable to All CCR Surface Impoundments

a. Hazard Potential Classification Assessments

A hazard potential classification provides an indication of the potential for danger to life, development, or the environment in the event of a release of CCR from a surface impoundment. In this rule, an owner or operator of any existing or new CCR surface impoundment or any lateral expansion of a CCR surface impoundment must determine which of the following hazard potential classifications characterizes their particular CCR unit.[82] These classifications are: a high hazard potential CCR surface impoundment, a significant hazard potential CCR surface impoundment; and a low hazard potential CCR surface impoundment and are defined as follows:

- *High hazard potential CCR surface impoundment* means a diked surface impoundment where failure or mis-operation will probably cause loss of human life.
- *Significant hazard potential CCR surface impoundment* means a diked surface impoundment where failure or mis-operation results in no probable loss of human life, but can cause economic loss, environmental damage, disruption of lifeline facilities, or impact other concerns.
- *Low hazard potential CCR surface impoundment* means a diked surface impoundment where failure or mis-operation results in no probable loss of life and low economic and/or environmental losses. Losses are principally limited to the surface impoundment's owner's property.

Owners and operators of all CCR surface impoundments must determine each unit's hazard potential classification through a hazard potential classification assessment. Hazard potential classification assessments must be certified by a qualified professional engineer and documentation must be provided that supports the basis for the current hazard potential rating. An initial hazard potential assessment must be conducted within one year of the effective date of the rule for existing units and prior to the initial receipt of CCR in the unit for new units or lateral expansions. Hazard potential classifications, structural stability assessments, and safety factor assessments require significant planning and coordination, such as detailed site-work and investigations, modeling and analysis, design and construction planning and implementation, and post-construction investigation. Many of these efforts take several months to complete, compounded by the fact that much of the work cannot be completed in cold-weather or heavy-rain seasons.

As commenters noted, it is imperative that the owner or operator maintain a current assessment of a unit's hazard potential classification, rather than develop a single one-time classification ''for which the facility was designed.'' (See proposed § 257.71(d)(10).) Moreover, FEMA recommends that a unit's hazard potential classification should be reviewed no less frequently than every five years in order to take into account changes in the factors that are the basis for which a hazard potential classification is made (*e.g.,* changed reservoir or downstream development).[83] Based on this information, EPA determined that a periodic reassessment of a CCR surface impoundment's hazard potential classification is a necessary component in maintaining the accuracy of the unit's hazard potential classification, as well as the overall safety of the unit. Consequently, EPA is requiring the owner or operator of a CCR surface impoundment to reassess the hazard potential classifications of their CCR unit and to have that classification, certified by a qualified professional engineer, at least every five years.

EPA has continued to rely on FEMA requirements as the basis for general CCR surface impoundment safety requirements, *e.g.,* inflow design flood selection, inspection criteria, earthquake analyses and design for several reasons: (1) Structural failure risks for CCR surface impoundments are similar to the risks from the larger dam universe for which FEMA intends its guidance; and (2) risks to downstream development from CCR surface impoundment failures are equal or similar to those presented by other types of dams' failures.

In this rule, hazard potential classifications define the consequences in the event of a failure of a CCR surface impoundment. The classification is separate from the structural stability of a CCR unit or the likelihood of the impoundment failing. A surface impoundment that meets or exceeds all of the structural stability criteria and safety factors of this rule would still be classified as ''high hazard potential'' if, in the event of failure, loss of life would be likely to occur.

[81] *Height* means the vertical measurement from the downstream toe of the CCR surface impoundment at its lowest point to the lowest elevation of the crest of the CCR surface impoundment.

[82] Incised CCR surface impoundments are not required to perform a hazard potential classification assessment because hazard potential classifications are based on the failure of a dam, diked surface impoundment, or other water-retaining structure and the adverse incremental impacts that may result from the failure. Because incised CCR surface impoundments, as defined in this rule, do not have a diked portion which may fail, the incised CCR surface impoundment cannot have a hazard potential classification. This final rule covers CCR surface impoundment failures and releases due to other potential failure modes (*i.e.,* which do not pose an immediate catastrophic threat to human health or the environment), such as a release through the liner of the unit or through failure of underlying structures, in the location restrictions, design criteria, and operating criteria of the rule.

[83] See: *Federal Guidelines for Dam Safety: Hazard Potential Classification for Dams,* Federal Emergency Management Agency (''FEMA'') (reprinted January 2004). Under the FEMA dam safety classification system, a ''low hazard potential classification'' means that failure or mis-operation of the impoundment ''results in no probable loss of human life and low economic and/or environmental losses. Losses are principally limited to owner's property.''

The hazard potential classification of the CCR surface impoundments is an essential element in determining how to properly design, construct, operate, and maintain a CCR surface impoundment. As such, the final rule bases the stringency of some technical requirements, in part, on the potential for adverse impacts on the failure of the CCR unit, as quantified by the hazard potential classification of this rule. Specifically, the requirements become more stringent as the potential for loss of life and/or property damage increases. This is reflected in both the criteria established under the structural stability assessments, *.e.g.,* where the combined capacity of all spillways must adequately manage flow during and following peak discharge from the specified inflow design flood based on the hazard potential classification of the unit—and in the hydrologic and hydraulic capacity requirements, which are similarly specified based on the hazard potential classification of the CCR unit (see §§ 257.73(d)(2)(v); 257.74(d)(2)(v) and 257.82 respectively).[84] Additionally, high and significant hazard potential CCR surface impoundments must develop a written Emergency Action Plan which establishes emergency action procedures in the event of a previously defined emergency.

b. Emergency Action Plan

An Emergency Action Plan (EAP) is a document that identifies potential emergency conditions at a CCR surface impoundment and specifies actions to be followed to minimize loss of life and property damage. Typically an EAP includes: (1) Actions the owner or operator will take to moderate or alleviate a problem at the CCR unit; (2) actions the owner or operator will take, in coordination with emergency management authorities, to respond to incidents or emergencies related to the CCR surface impoundment; (3) procedures owner or operators will follow to issue early warning and notification message to responsible downstream emergency management authorities; (4) inundation maps to allow owners and operators of the CCR unit and emergency management authorities to identify critical infrastructure and population-at-risk sites that may require protective measures, warning and evacuation planning; and (5) delineation of the responsibilities of all those involved in managing an incident or emergency and how the responsibilities should be coordinated and implemented.[85] As FEMA guidance suggests, and EPA reiterates here, the level of detail in the EAP should be commensurate with the potential impact of a surface impoundment failure or other operational incident (*e.g.,* its hazard potential classification). A surface impoundment with low potential hazard impact should not require an extensive evaluation or be subject to an extensive planning process, while high-hazard and significant hazard surface impoundments would typically require a much larger emergency planning effort. In addition, high hazard and significant hazard surface impoundments tend to involve more entities that must coordinate responsibilities and greater efforts would generally be necessary to effectively respond to an incident with such a surface impoundment than to a similar incident involving a low-hazard surface impoundment. As such, every EAP must be tailored to specific site conditions.

EPA is promulgating, as proposed, a provision that requires any CCR surface impoundment that is determined by the owner or operator, through the certification by a qualified professional engineer, to be either a high hazard potential CCR surface impoundment or a significant hazard potential CCR surface impoundment to prepare and maintain a written EAP. While EPA agrees that the level of detail contained in an EAP should be commensurate with its hazard potential rating, EPA has concluded that at a minimum, the EAP must: (1) Define responsible persons and the actions to be taken in the event of a CCR surface impoundment-safety emergency; (2) provide contact information for emergency responders, including a map which delineates the downstream area which would be affected in the event of a failure and a physical description of the CCR surface impoundment; (3) include provisions for an annual face-to-face meeting or exercise between representatives of the owner or operator of the CCR unit and the local emergency responders; and (4) define conditions that initiate implementation of the EAP and define emergency response actions which must be implemented upon the detection of these conditions, including all persons responsible for the implementation of the emergency response actions. The first three of these four requirements were proposed as part of the EAP and are being promulgated without revision. The fourth requirement, which requires facilities to explicitly define the conditions by which the EAP is activated, was inadvertently omitted from the proposal, and is being added to the final rule to ensure that the EAP includes at least the basic requirements necessary to function effectively.

The owner or operator must amend the written EAP whenever there is a change in conditions that would substantially affect the written EAP in effect, *e.g.,* change in personnel, change in emergency responder contact information, a change in the CCR surface impoundments' designation from a significant-hazard potential classification to a high-hazard potential classification, or the vertical expansion of the CCR unit (*i.e.,* increase in the amount of CCR that potentially could be released.) Consistent with the requirements for hazard potential classification reassessments, the Agency is requiring, at a minimum that the EAP be reassessed at least every five years. If an owner or operator determines that, as part of it periodic hazard potential re-assessment that the unit no longer is classified as a high-hazard or a significant-hazard potential classification, but is now classified as a low hazard potential CCR surface impoundment, then the owner or operator of the CCR unit is no longer subject to the requirement to prepare and maintain an EAP, effective when such documentation is placed into the facility's operating record. If, however, during the reassessment effort it is determined that an existing CCR unit classified as a low hazard potential has been re-classified as either a significant-hazard or high-hazard potential, the owner or operation must prepare an EAP for the CCR unit within six months of completing such a periodic hazard potential re-assessment.

Although the owner or operator is responsible for developing and maintaining the EAP, which must be certified by a qualified professional engineer, the plan should be developed and implemented in close coordination with all applicable emergency management authorities, including the appropriate local, state, and federal authorities. Generally, these coordination efforts, along with the EAP, provide emergency management authorities with the necessary information to facilitate the implementation of their responsibilities, and so, it is vital that the development of the EAP be coordinated with emergency responders and other entities, agencies, and jurisdictions, as

[84] A high-hazard potential impoundment, for example, must be designed with sufficient spillway capacity to manage flow from the probable maximum flood, whereas a low hazard potential unit need only account for a 100 year flood.

[85] See: ''Federal Guidelines for Dam Safety: Emergency Action Planning for Dams,'' FEMA 64/ July 2013.A.

appropriate. After the initial EAP has been developed and placed in the operating record and on the owner or operator's internet site, it should be periodically reviewed and updated on a regular basis, as it can become outdated and ineffective. While the Agency is only requiring the EAP to be re-assessed every five years, it is recommended that the EAP be reviewed at least annually for appropriateness, accuracy, and adequacy so as to remain current. EPA recommends that the EAP be promptly updated to address changes in personnel, contact information and/or significant changes to the facility or emergency procedures. Even if no revisions are necessary, the review should be documented.

The initial EAP must be prepared within 18 months from the effective date of the rule. In order to prepare an EAP, the owner or operator must accurately and comprehensively identify potential failure modes and at-risk development, and therefore completion of the emergency action plan needs to follow the completion of the initial hazard potential classification, structural stability assessment, and safety factor assessments, during which this information will be generated.

c. Vegetated Slopes of Dikes and Surrounding Areas

EPA proposed to require both new and existing CCR surface impoundments that exceed the MSHA size thresholds to document the slope protection measures that have been adopted and to compute the minimum factors of safety for slope stability, in order to support the certification from an independent professional engineer that the unit has been designed in accordance with ''generally accepted engineering standards.'' EPA is promulgating the requirement that all CCR surface impoundments have adequate slope protection because EPA determined through the Assessment Program that slope protection is an essential element in preventing slope erosion and subsequent deterioration of CCR unit slopes. EPA is requiring slope protection for all units, not just units exceeding the size threshold of the final rule, because EPA has identified that slope protection on CCR units is a generally accepted good practice which reduces the occurrence of erosion, degradation of surface waters due to run-off from the CCR unit, enhances slope stability, and that vegetated cover is an easily accomplished practice in the vast majority of climates where CCR surface impoundments are located. In conducting the Assessment Program, the protective cover of slopes of the CCR surface impoundment was determined to be relevant to the overall condition rating of all units, irrespective of size. This is consistent with FEMA guidance, which also lays out specifications for the ideal vegetative cover for a dam. EPA has adopted this requirement to be consistent with its findings from the Assessment Program, and in response to comments, and has elaborated on the slope protection measures necessary to achieve the factors of safety. The final rule provides performance standards drawn primarily from FEMA guidance, as applied during the Assessment Program.

All CCR surface impoundments are required to be designed, constructed, operated, and maintained with adequate slope protection to protect against surface erosion at the site. Slope protection is necessary to ensure that dike or embankment erosion does not occur. Additionally, slope protection is required of all CCR surface impoundments to maintain the stability of the CCR surface impoundment slope under rapid drawdown events [86] and low pool conditions of water bodies that may abut the CCR surface impoundment and are outside the control of the owner or operator, *e.g.,* a natural river which the slopes of the CCR surface impoundment run down to and abut. The slope protection can act as a stabilizer in the slope of the embankment during rapid drawdown events. Adequate slope protection can be achieved in most climates through simple vegetation, typically a healthy, dense stand of low-growing grass, or other similar vegetative cover. In arid climates where the upkeep of vegetation is inhibited, alternate forms of slope protection, including rip-rap, or rock-armor is typically used. Additional slope protective measures are available and effective in certain circumstances, including but not limited to rock, wooden pile, or concrete revetments, vegetated wave berms, concrete facing, gabions, geotextiles, or fascines.

The owner or operator must ensure that the slopes of the CCR surface impoundment are protected from erosion by appropriate engineering slope protection measures. It is recommended throughout embankment technical literature that vegetative cover not be permitted to root too deeply, precipitating internal embankment issues. The rule requires a vegetative cover limit to prevent the establishment of rooted vegetation, such as a tree or a bush on the CCR surface impoundment slope. EPA has concluded that a vegetative cover of no more than six inches above the face of the embankment is adequate and is the uppermost limit for vegetative cover height for this final rule. In developing this requirement, EPA was strongly influenced by information contained in the FEMA document entitled, ''Technical Manual for Dam Owners: Impacts of Plants on Earthen Dams'' [87] in determining an appropriate vegetative cover height for CCR surface impoundments. Six inches represents a vegetative height which prevents any trees, bushes, or shrubbery from rooting deeply enough to warrant additional removal measures outside of simple mowing. Furthermore, the height prescribed by the final rule represents a maximum height of vegetative cover to allow for adequate observation of the slope of the CCR unit during inspection. Vegetative cover in excess of six inches above the slope of the dike would prevent the adequate observation of the slope of the CCR unit and detection of structural concerns such as animal burrows and minor sloughs, amongst others concerns. Consistent with FEMA guidance, as applied during the Assessment Program, other slope protection, such as rock armoring or vegetated berms, would also be considered adequate.[88]

3. Structural Integrity Criteria Applicable to CCR Surface Impoundments Exceeding a Specific Size Threshold

The structural integrity criteria discussed in this section of the preamble apply to existing and new CCR surface impoundments and any lateral expansion with: (1) A height of five feet or more and a storage volume of 20 acre-feet or more; or (2) a height of 20 feet or more. The rule defines *height* as the vertical measurement from the downstream toe of the CCR surface impoundment at its lowest point to the lowest elevation of the crest of the CCR surface impoundment. The *downstream toe* is defined as the junction of the downstream slope or face of the CCR surface impoundment with the ground surface. This final rule considers the lowest elevation of the crest of the CCR

[86] This rapid drawdown is not included in the rule's factors of safety assessments. The protection against rapid drawdown requirement of this provision is concerned with the rapid drawdown of adjacent water bodies acting upon the downstream slope of the CCR surface impoundment rather than the rapid drawdown of the impounded reservoir of the CCR surface impoundment acting upon the upstream slope of the CCR surface impoundment.

[87] *http://www.fema.gov/media-library-data/20130726-1446-20490-2338/fema-534.pdf.*

[88] *http://www.fema.gov/media-library-data/20130726-1446-20490-2338/fema-534.pdf.*

surface impoundment to be the maximum storage elevation of the reservoir or pool of the CCR unit, *e.g.,* the invert of the lowest-elevation spillway. EPA is implementing this size threshold because it comports with thresholds established by other federal and state agencies regulating dam integrity and/or safety. Specifically, for the implementation of the size threshold of this final rule, EPA relied on the identical size parameters, *i.e.,* height of five feet and capacity of 20 acre-feet, which is promulgated in MSHA coal slurry impoundment regulations in 30 CFR 77.216.

In the proposed rule, EPA used the size cut-off promulgated by MSHA in their dam safety requirements for coal slurry impoundments at 30 CFR part 77. In proposing this cut-off, EPA reasoned that the MSHA requirements affecting coal slurry impoundments were directly applicable and relevant to CCR surface impoundments and provided a size threshold that, when applied to the rule's structural integrity criteria, would generally meet RCRA's mandate to ensure protection of human health and the environment by minimizing the potential for catastrophic failure. Specifically, EPA proposed that surface impoundments: (1) Impounding CCR to an elevation of five feet or more above the upstream toe of the structure and can have a storage volume of 20 acre-feet or more; or (2) impounding CCR to an elevation of 20 feet or more above the upstream toe of the structure would be subject to the structural stability criteria. EPA also proposed to define *upstream toe* as the junction of the upstream slope of the dam with the ground surface, with the height of the CCR unit measured from the upstream toe or water-borne toe of the CCR unit.

While little comment was received on adopting this size threshold or the accompanying definition of *upstream toe,* the Agency was concerned that the size threshold presented in the proposed rule did not reflect standard measuring protocols used by other federal agencies and the dam sector in determining the size of a dam or, in the case of this rule, surface impoundment. Of particular concern to the Agency was the fact that EPA's own Assessment Program was measuring the height of a CCR unit from the downstream toe rather than the upstream toe, which was specified in the MSHA regulatory requirement and the subsequent CCR proposed rule.

A review of MSHA, FEMA and the USACE regulations and guidance, as well as the guidance of several state agencies that oversee dam safety, revealed that dam or surface impoundment height is more appropriately measured from the downstream and not the upstream toe of the unit. EPA based this conclusion on the near-universal position of dam safety guidance that the downstream slope height of the dike is of primary concern in the design, construction, operation, and maintenance of the dam or surface impoundment. Virtually all of the dam safety regulations, including state and federal guidance and regulations, that EPA reviewed considered measured dam height to be taken from the downstream slope of the dike. Some of these guidance and regulations include FEMA ''Federal Guidelines for Dam Safety,'' U.S. Army Corps ''National Inventory of Dams,'' and MSHA Metal and Nonmetal Tailings and Water Impoundment Inspection requirements in 30 CFR part 56 and § 57.20010.[89] This information, coupled with the information on the methodology used in the Assessments Program, convinced the Agency that a revised description of the CCR surface impoundment size cutoff was necessary, specifically requiring the height of the CCR unit to be measured from the downstream toe.

a. Design and Construction Information

The first element of the structural integrity criteria applicable to CCR units exceeding the specified size threshold requires the owner or operator to compile and place in the operating record design and construction information pertaining to the CCR unit. Among other things, this provision requires the following documentation to be provided by the owner or operator: (1) The name of the owner or operator of the unit; (2) the name of the unit; and (3) any identification number assigned by the state. In addition, it requires that the owner or operator identify: (5) The location of the CCR unit on a U.S. Geological Survey Map or a topographic map of equivalent scale; (6) provide dimensional drawings of the CCR unit with pertinent engineering structures and appurtenances identified; (7) describe the purpose of the CCR unit; and (8) identify the name and size of the watershed affecting the CCR unit, if any. Detailed information is also required documenting: (9) The design and construction of the unit including dates and descriptions of each zone or stage constructed; (10) instrumentation used to monitor the operation of the CCR unit, (11) spillway and diversion design descriptions and construction specifications; and (12) provisions for surveillance, maintenance and repair of the CCR unit.

While these requirements apply to both existing and new CCR surface impoundments, existing CCR surface impoundments are required to compile this information only ''to the extent available,'' within one year of the effective date of the rule. Conversely, new CCR surface impoundments or any lateral expansion must compile all of the information listed prior to the initial receipt of CCR. For existing CCR surface impoundments, EPA acknowledges that much of the construction history of the surface impoundment maybe unknown or lost. EPA's Assessment Program confirmed that many owners or operators of CCR units did not possess documentation on the construction history or operation of the CCR unit. Information regarding construction materials, expansions or contractions of units, operational history, and history of events was frequently difficult for the owners or operators to obtain. The Assessment Program also confirmed the Agency's initial assumption that this information, in many instances, will be difficult to compile. Therefore, in this rule, EPA is using the phrase ''to the extent available'' and clarifying that the term requires the owner or operator to provide information on the history of construction only to the extent that such information is reasonably and readily available. EPA intends facilities to provide relevant design and construction information only if factual documentation exists. EPA does not expect owners or operators to generate new information or provide anecdotal or speculative information regarding the CCR surface impoundment's design and construction history.

There are several other requirements under the design and construction criteria requiring clarification. First, the Agency is amending the requirement that all dimensional drawings of the CCR unit (see § 257.73(b)(vii) and § 257.74(b)(vii)) use a uniform scale of one inch equals 100 feet. After further consideration, EPA has deleted this requirement and has replaced the proposed scale of 1 inch equals 100 feet with the phrase ''at a scale that details engineering structures and appurtenances relevant to the design, construction, operation, and maintenance of the CCR unit.'' EPA made this change in response to comments arguing that this level of detail was unnecessary. EPA agrees that, given the extremely large variety in the size of CCR units, a prescriptive scale for all drawings of all CCR units is not necessary in many cases; this level of detail would be excessive for most

[89] *http://www.msha.gov/regs/complian/PILS/2013/PIL13-IV-01.asp.*

units. The Agency is also clarifying, (see § 257.73(b)(2) and § 257.74(b)(2)) that if an owner or operator determines that a significant change has occurred in the information/documentation previously compiled under this provision, the owner or operator must update the relevant information and place it in the operating record.

b. Types of Assessments

A second element of the structural integrity criteria is the requirement for specific technical assessments of the CCR unit. Consistent with the requirements outlined in the proposed rule, two technical assessments are required for all CCR units exceeding the specified size threshold: (1) A structural stability assessment; and (2) a safety factor assessment. The owner or operator of an existing CCR surface impoundment is required to conduct an initial assessment addressing both structural stability and safety factors within one year of the effective date of the rule. New CCR surface impoundments or any lateral expansion of a CCR unit are required to complete the initial assessment prior to placing CCR into the unit. Following the initial assessments, EPA is also requiring periodic re-assessments of both a CCR surface impoundment's structural stability and factors of safety. EPA proposed to require an annual recertification, but in a departure from the proposed rule, EPA is only requiring these re-assessments to be conducted on a regular basis, not to exceed once every five years. In making this regulatory change, the Agency has relied heavily on the dam safety guidance established by FEMA in the document titled, *Federal Guidelines for Dam Safety* that a formal inspection, including ''. . . a review to determine if the structures (*i.e.,* CCR surface impoundments) meet current accepted design criteria and practices . . .'' be taken at an interval not to exceed five years. EPA has interpreted this guidance to be applicable to both the structural stability assessment and the safety factor assessment.

A demonstration must be completed within the assessment period for the specific type of assessment. This means that, within this timeframe the owner or operator must demonstrate that the CCR unit meets all of the requirements of each type of assessment, as certified by a qualified professional engineer. It also means that the owner or operator must have taken all measures necessary to bring the unit into compliance with all of the requirements for assessments of this final rule within the assessment period. If the owner or operator cannot demonstrate that the unit meets these factors of safety (or otherwise fails to comply with the structural stability requirements) within the appropriate timeframe, the unit must initiate closure.

i. Periodic Structural Stability Assessments

In order to ensure the proper upkeep and operation of the CCR unit, the owner or operator must demonstrate that the CCR surface impoundment has been designed, constructed, operated and maintained to provide structural stability. Specifically, consistent with the proposal, the final rule requires the owner or operator to demonstrate that the design, construction, operation, and maintenance of the CCR surface impoundment is consistent with recognized and generally accepted good engineering practices for the maximum volume of CCR and water that can be impounded therein. As discussed previously, EPA has elaborated on this overall performance standard in response to comments from the engineers who would be required to make these certifications, urging EPA to specify more precisely the standards that must be met. Specifically the final rule focuses on the critical structural aspects of the CCR surface impoundment that EPA identified in the proposed rule, and identifies the minimum elements that a professional engineer must provide engineering details on or otherwise address. In certain cases, the final criteria identify specific engineering performance standards. EPA relied on existing MSHA requirements, FEMA dam safety guidance, and guidance issued by the USACE, as applied throughout EPA's Assessment Program to develop these criteria. Consistent with the proposal, these demonstrations must be certified by a qualified professional engineer. Each of these criteria is discussed in more detail below.

In addition to implementing adequate slope protection against erosion, which is a structural stability requirement applicable to all CCR units, the owner or operator of a CCR surface impoundment exceeding the specified size threshold must demonstrate that the unit, including any vertical and lateral expansions, is constructed with ''stable foundations and abutments.'' A stable foundation is an essential element of surface impoundment construction and prevents differential settlement of the embankment which can result in adverse internal stresses with the embankment cross-section. Soils tend to consolidate when subjected to loadings for extended periods, which can lead to strain incompatibility, a phenomena which prevents the full development of peak strength of the foundation. The stability of foundations and abutments can be determined by engineering monitoring, representative soil sampling, and modeling. Similarly, cohesion between the abutments of the CCR surface impoundment and the embankment of the CCR surface impoundment is critical. Frequently, CCR surface impoundments are subject to cracking and excessive seepage and piping in the groins where the abutment and embankment meet. These adverse conditions may lead to further structural deficiencies which threaten the safety of the CCR surface impoundment.

Consistent with general engineering construction methodologies, the structural stability assessment also requires the owner or operator to determine whether the CCR surface impoundment has been mechanically compacted to a density sufficient to withstand the range of loading conditions in the CCR unit.[90] Compaction of a dike or embankment is considered essential, as the compaction of soils leads to an increase in density and subsequently strength. Soil mechanics theory has established that the density of a soil corresponds to the moisture content and strength of the soil. The rule requires the owner or operator make this determination for all dikes of a CCR surface impoundment.

EPA notes that a number of existing voluntary consensus standards are available that can be useful in making this determination. For example, ASTM D 698 establishes a performance standard of 95% of the maximum standard Proctor density. Similarly, ASTM D 1557 establishes a standard of 90% of the maximum modified Proctor density. Alternatively, in certain instances, such as soils consisting of more than 30% material retained on the ¾ in. sieve, Proctor testing is not appropriate and the relative density criteria can be met. In such cases, EPA recommends a 70% relative density. These specific soil compaction criteria are ubiquitous throughout engineering construction as sufficient to support engineered works based on the requirements. They are also consistent with the standards promulgated by the state of New Mexico's dam safety program in order to ensure proper compaction during construction of new CCR surface impoundments.

EPA recognizes that it would be highly difficult for owners or operators

[90] *http://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-2300.pdf.*

of older units to certify with any certainty that the unit's construction meets the specific numeric compaction criteria found in the ASTM standards. New units, however, can easily meet these standards, and should therefore be designed and constructed to meet the numeric compaction criteria.

The owner or operator must also design, construct, operate, and maintain the CCR surface impoundment spillway or spillways with appropriate material so as to prevent the degradation of the spillway, as well as to ensure that the CCR surface impoundment has adequate spillway capacity to manage the outflow from a specific inflow design flood. In addition, a demonstration must be made that the CCR surface impoundment has been designed, constructed, operated, and maintained with inflow design flood controls and/or spillway capacity to manage peak discharge during and following inflow design floods. This demonstration is required to ensure the CCR surface impoundments will have adequate hydrologic and hydraulic capacity to prevent such failures as overtopping and excessive internal seepage and erosion. Spillways must be designed to withstand discharge from the inflow design flood without losing their structural form and leading to discharge issues, such as erosion or overtopping of the embankment. This requirement is covered in more detail in the hydrologic and hydraulic capacity requirements for CCR surface impoundments section of this rule.

EPA is not requiring a facility to include any demonstration relating to the potential for rapid, or sudden, drawdown loading condition. Rapid or sudden drawdown is a condition in earthen embankments in which the embankment becomes saturated through seepage in an extended high pool elevation in the reservoir. A threat to the embankment emerges when the reservoir pool is drawn down or lowered at a rate significantly higher than the excess poor water pressure within the embankment can diminish. Typically, rapid drawdown scenarios are considered for embankments with reservoirs used for water supply and management, emergency reservoirs, or agricultural supply, in which the reservoir is rapidly discharged from the structure. In these scenarios, a high pool elevation is maintained in the reservoir in storage months. Subsequently, the water supply is drawn on in months where there is a high demand for the reservoir's contents. This drawing down of the pool can affect the structural stability of the unit. However, the management of CCR surface impoundments differs from that of conventional water supply, emergency, and agricultural reservoirs. The only instance of a rapid drawdown of a CCR surface impoundment which EPA has identified is in the event of a massive release of the reservoir of the CCR surface impoundment due to a failure of the dike of the CCR surface impoundment. In this instance, a massive release has occurred or is occurring. A subsequent failure of the upstream or internal embankment due to this rapid drawdown would only precipitate further embankment failure and not any further release of the contents of the impoundment, as the contents of the surface impoundment would have already been released. In these instances, remediation of a failure in a rapidly drawn-down section would be necessary prior to filling of the unit, but is not a concern precipitating a release of impounded contents.

A second consideration regarding rapid drawdown, however, is the rapid drawdown of a water body adjacent to the slope of the CCR surface impoundment which may periodically inundate the slope. Many CCR surface impoundments are located in areas in which the downstream slope of the CCR surface impoundment runs down to a lake, stream, or river. In such instances, rapid drawdown must be considered for the stability of the downstream slope of the embankment in the event of a rapid drawdown in the lake, stream, or river pool elevation or stage. Because the water ponded against the downstream slope of the CCR surface impoundment provides a stabilizing load on the slope of the CCR surface impoundment, the rapid or gradual loss of this stabilizing force must be considered in the analysis of the CCR surface impoundment. The rule, therefore, requires that existing and new CCR surface impoundments and any lateral expansions of such units with a downstream slope that can be inundated by an adjacent water body, such as rivers, streams, or lakes, be constructed with downstream slopes that will maintain structural integrity in events of low pool or rapid drawdown of the adjacent water body. This ensures that the structural integrity of the downstream slope of the CCR surface impoundment will be maintained, even though the conditions of an adjacent surface water body may be outside the owner or operator's control.

ii. Periodic Safety Factor Assessments

As previously discussed, EPA received comment requesting the Agency to supplement the proposed technical criteria to assist owners or operators of CCR surface impoundments in interpreting the factor of safety determination required by proposed § 257.71(d)(12). EPA proposed that facilities compute ''a minimum factor of safety for slope stability of the CCR retaining structure(s),'' and to provide the methods and calculations used to determine each factor of safety. In reviewing the proposed requirement, the Agency agrees that further elaboration on the requirement is necessary to ensure that engineers can accurately assess a CCR unit's structural stability using factor of safety calculations, and would be valuable to ensure a consistent national standard. EPA has therefore revised the criteria to be consistent with the criteria developed and used to assess these impoundments as part of the Assessment Program.

Accordingly, the final rule requires demonstrations of structural integrity using accepted engineering methodologies under specific loading conditions. Owners or operators must conduct and have certified by a qualified professional engineer, an initial assessment, supported by the appropriate engineering calculations, documenting whether the CCR unit achieves the following minimum factors of safety: (1) The calculated static factor of safety under the long-term, maximum storage pool loading condition, which must equal or exceed 1.50; (2) the calculated static factor of safety under the maximum surcharge pool loading condition, which must equal or exceed 1.40; (3) the calculated seismic factor of safety, which must equal or exceed 1.00; and (4) the calculated liquefaction factor of safety, which must equal or exceed 1.20. In addition to the safety factors specified for existing CCR surface impoundments, new CCR surface impoundments and any lateral expansion must also comply with a fifth safety factor, the calculated static factor of safety under the end-of-construction loading condition, which must equal or exceed 1.30.

The minimum static factors of safety are adopted directly from the USACE's Engineer Manual EM 1110–2–1902 entitled, ''Slope Stability.'' As discussed in more detail in Unit III of this document, EPA relied heavily on this manual and applied these specific factors of safety during its Assessment Program, and it is widely considered the benchmark in the dam engineering community for slope stability and methodology and analysis.

The seismic factor of safety is adopted from review of several dam safety guidance documents, including USACE guidance Engineer Circular 1110–2–6061: Safety of Dams-Policy and Procedures 2204, Engineer Circular

1110–2–6000: Selection of Design Earthquakes and Associated Ground Motions 2008, and Engineer Circular 1110–2–6001: Dynamic Stability of Embankment Dams 2004. EPA also reviewed MSHA's 2009 Engineering and Design Manual for Coal Refuse Disposal Facilities, in particular Chapter 7, ''Seismic Design: Stability and Deformation Analyses.'' These documents are viewed by ASDSO, FEMA and MSHA as generally accepted guidance on how to conduct seismic stability analyses. EPA chose the factor of safety of 1.00 because the 1.00 quantity represents the condition of the slope in which the strength of resistance to loading is equal to the anticipated loading stress acting upon the embankment, or the value which represents stability under the appropriate loading condition.

The liquefaction factor of safety is adopted from review of several dam safety guidance and liquefaction guidance, including ''Soil Liquefaction During Earthquakes,'' Idriss and Boulanger, Earthquake Engineering Research Institute, 2008,[91] ''Geotechnical and Stability Analyses for Ohio Waste Containment Facilities,'' Ohio EPA, Sept. 14, 2004, Chapter 5,[92] and *Federal Guidelines for Dam Safety: Earthquake Analyses and Design of Dams,* Document 65, FEMA May 2005.[93] EPA also reviewed several technical resources regarding soil liquefaction, including ''Ground Motions and Soil Liquefaction During Earthquakes,'' Seed and Idriss, 1982,[94] ''Liquefaction Resistance of Soils: Summary report from the 1996 and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils,'' Youd and Idriss, 2001,[95] and *Seismic Design Guidance for Municipal Solid Waste Landfill Facilities,* US EPA, Office of Research and Development, 1995. EPA chose a liquefaction factor of safety of 1.20, identifying that consideration of liquefaction potential and post-liquefaction residual strength slope stability included several uncertainties in assumptions and analysis which must be accounted for in a factor of safety above unity (*i.e.,* 1.00). FEMA guidance explicitly states that ''post-liquefaction factors of safety are generally required to be a minimum of 1.2 to 1.3.''

In conjunction with this requirement, EPA continues to require periodic re-assessments of the safety factor calculations, but as discussed, has modified the frequency to be no less than once every five years for all affected CCR units. Periodic reassessments are necessary to account for factors that are subject to change and can adversely affect the structural stability of a CCR unit, *e.g.,* age, use, volume of material contained within, and to reflect the dynamic nature of a CCR surface impoundment and the loads to which the dikes of the CCR surface impoundment may reasonably be expected to become subject to both the requirement to periodically reassess safety factor calculations and the five-year timeframes are consistent with the guidance set forth by other federal agencies in assessing dam safety, including MSHA, FEMA, and the USACE. For example, FEMA's Federal *Guidelines for Dam Safety* explicitly recommends that a dam be formally reassessed at an interval not to exceed every five years, and EPA has adopted this minimum frequency of assessment in this final rule.

(a) General Safety Factor Assessment Considerations

Generally accepted engineering methodologies specify that the determination of the structural stability factors of safety specified above is to be calculated by the qualified professional engineer using conventional analysis procedures or, if necessary, special analysis procedures. Conventional analysis procedures include, but are not limited to, limit equilibrium methods of slope stability analysis, whereas, special analysis procedures include, but are not limited to, finite element methods, finite difference methods, three-dimensional methods, or probabilistic methods. Whichever methodology is used to determine the factors of safety of the CCR surface impoundment, the qualified professional engineer must document the methodology used, as well as the basis for using that methodology, and the analysis must be supported by appropriate engineering calculations.

Limit equilibrium methods compare forces, moments, and stresses which cause instability of the mass of the embankment to those which resist that instability. The principle of the limit equilibrium method is to assume that if the slope under consideration were about to fail, or at the structural limit of failure, then one must determine the resulting shear stresses along the expected failure surface. These determined shear stresses are then compared with the shear strength of the soils along the expected failure surface to determine the factor of safety. Limit equilibrium methods include, but are not limited to, methods of slices. The most commonly applicable method of slices are the ordinary method of slices or Modified Swedish Method, Bishop's Modified Method, force equilibrium methods, Janbu's method, Morgenstern and Price's method, or Spencer's Method.

If conventional analysis procedures yield results that indicate complex failure mechanisms or the need for estimation of displacements, such as the need to determine internal stresses or displacements in an embankment or account for 3-dimensional effects in an embankment, special analysis procedures may be necessary to calculate factors of safety. Special analysis procedures include, but are not limited to: (1) The finite element method; (2) the finite difference method; (3) the three-dimensional limit equilibrium analysis method; or (4) the probabilistic method.[96]

Structural stability factors of safety need to be met in all cross-sections of the CCR surface impoundment since the failure of any cross-section of the CCR surface impoundment can result in the loss of the reservoir and stored CCR material in the CCR surface impoundment. However, it is not necessary to require the facility to fully analyze and calculate factors of safety for all cross sections under the specific loading conditions identified above. Rather, it is sufficient to calculate the factors of safety under both static, seismic, and liquefaction loading conditions only for the critical cross section of the CCR surface impoundment embankment, provided the facility carefully analyzes each cross section to properly identify the critical cross section. EPA has adopted this approach because the critical cross-section(s) represents a ''most-severe'' case and it is reasonably anticipated that all other cross-sections of the embankment will exceed the calculated factors of safety of the critical cross-section(s). The final rule therefore adopts this approach. The final rule

[91] *https://www.eeri.org/products-page/monographs/soil-liquefaction-during-earthquakes-3/.*

[92] *http://epa.ohio.gov/portals/34/document/guidance/gd_660.pdf.*

[93] *http://www.ferc.gov/industries/hydropower/safety/guidelines/fema-65.pdf.*

[94] Seed, H.B., and Idriss, I.M., 1982, ''Ground Motions and Soil Liquefaction During Earthquakes,'' Monograph No. 5, Earthquake Engineering Research Institute, Berkeley, California, pp. 134.

[95] Youd, T.L., Idriss, I.M., 2001, ''Liquefaction Resistance of Soils: Summary report from the 1996 and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils.'' Journal of Geotechnical and Geoenvironmental Engineering, ASCE.

[96] Additional information regarding special analysis methodologies can be found in publications from the U.S. Army Corps of Engineers Engineering Publications or geotechnical journals and scholarly articles.

defines the critical cross section of the embankment of a CCR surface impoundment to be that which is anticipated to be most susceptible amongst all cross sections of the embankment to structural failure based on several engineering considerations for the given loading condition, such as soil composition of the cross-section, phreatic surface level within the cross section, grade of the upstream and downstream slopes of the cross section, and presence or lack of reinforcing measures in the cross-section as opposed to other cross-sections, such as buttressing or slope protection on the slopes of the cross section. Due to the variance of qualitative and quantitative properties of embankment structural strength, EPA expects that a prudent engineering analysis will need to consider multiple cross sections to ensure proper selection of a critical cross section.

(b) The Calculated Static Factor of Safety Under the Long-Term, Maximum Storage Pool Loading Condition

It is generally accepted practice to analyze the stability of the downstream slope of the dam embankment for steady-state seepage (or steady seepage) conditions with the reservoir at its normal operating pool elevation (usually the spillway crest elevation) since this is the loading condition the embankment will experience most. This condition is called steady seepage with maximum storage pool. The maximum storage pool loading is the maximum water level that can be maintained that will result in the full development of a steady-state seepage condition. Maximum storage pool loading conditions need to be calculated to ensure that the CCR surface impoundment can withstand a maximum expected pool elevation with full development of saturation in the embankment under long-term loading. The final rule requires that the calculated static factor of safety for the critical cross section of the CCR surface impoundment under the long-term maximum storage pool loading condition meet or exceed 1.5. The generally accepted methodology for determining the long-term, maximum storage pool loading condition considers conditions at the CCR surface impoundment that exist for a length of time sufficient for steady-state seepage or hydrostatic conditions to fully develop within the embankment of the CCR unit.[97] The maximum storage pool loading needs to consider a pool elevation in the CCR unit that is equivalent to the lowest elevation of the invert of the spillway, *i.e.,* the lowest overflow point of the perimeter of the embankment. The generally accepted methodology for the calculation of the factors of safety uses shear strengths expressed as effective stress and with pore water pressures that correspond to the long-term condition. Pore-water pressures should be estimated from the most reliable of the following sources: (1) Field measurements of pore pressures in existing slopes; (2) past experience and judgment of the qualified professional engineer; (3) hydrostatic pressure computation for conditions of no flow; or (4) steady-state seepage analysis using flow nets or finite element analyses.

(c) The Calculated Static Factor of Safety Under the Maximum Surcharge Pool Loading Condition

The maximum surcharge pool loading condition is calculated to evaluate the effect of a raised level (*e.g.,* flood surcharge) on the stability of the downstream slope. This ensures that the CCR surface impoundment can withstand a temporary rise in pool elevation above the maximum storage pool elevation for which the CCR surface impoundment may normally be subject under inflow design flood stage, for a short-term until the inflow design flood is passed through the CCR surface impoundment. The final rule requires that the calculated static factor of safety for the critical cross section of the CCR surface impoundment under the long-term maximum surcharge pool loading condition meet or exceed 1.4.

Similar to the long-term, maximum loading condition, a prudent evaluation of the maximum surcharge pool loading condition needs to consider conditions at the CCR unit to exist for a length of time sufficient for steady-state seepage or hydrostatic conditions to fully develop within the embankment of the CCR surface impoundment. The maximum surcharge pool is considered a temporary pool that is higher than the maximum storage pool; the maximum surcharge loading condition should therefore consider a temporary condition in the pool at which the pool exists temporarily above the maximum storage pool elevation in the event of an inflow design flood and spillway discharge condition in the reservoir, *i.e.,* above the lowest invert of the spillway during the anticipated inflow design flood.

(d) The Calculated Seismic Factor of Safety

All CCR surface impoundments, including any lateral expansions that exceed the size threshold must meet a seismic factor of safety equal to or greater than 1.0. EPA has included this requirement because the mechanics and response phenomena of geotechnical structures vary radically under dynamic loading from those under static loading. Consequently, reliance on the factors of safety under static loading is not sufficient to evaluate the structural stability of a CCR surface impoundment. Standard engineering methodology and guidance support EPA's conclusion that adequate seismic analysis of embanked structures is essential to ensure the continued structural stability of a geotechnical structure under dynamic, or seismic, loading is warranted.[98]

As discussed in the section of this preamble addressing the location criteria, all CCR surface impoundments must also be capable of withstanding a design earthquake without damage to the foundation or embankment that would cause a discharge of its contents. To further support the location criteria established in this rule, CCR surface impoundments and any lateral expansion exceeding a specific height and/or volume threshold must be assessed under seismic loading conditions for a seismic loading event with a 2% probability of exceedance in 50 years, equivalent to a return period of approximately 2,500 years, based on the USGS seismic hazard maps for seismic events with this return period for the region where the CCR unit is located. EPA chose the 2% exceedance probability in 50 years event based on its common use in seismic design criteria throughout engineering. See for example, ASCE 7 *Minimum Design Loads for Buildings and Other Structures, International Building Code.* Moreover, USGS seismic hazard maps, dictate that the life of a structure and the realistic probability of event occurrence be considered in the design of lateral force resisting systems for structures. As discussed in the Regulatory Impact Assessment, the expected life of a CCR surface impoundment can exceed 50 years. Consistent with the location criteria for seismic impact zones, EPA adopted 2% as a reasonable probability of occurrence.

Under standard engineering methodologies, seismic analysis includes several procedures to adequately analyze the structural

[97] U.S. Army Corps of Engineers ''Slope Stability'' manual.

[98] *E.g.,* FEMA's *Federal Guidelines for Dam Safety: Earthquake Analyses and Design of Dams.*

strength of a CCR surface impoundment during dynamic, *i.e.,* seismic, loading. Such analyses would typically need to include the appropriate characterization of ground motions at the site of the CCR surface impoundment for the 2% probability in 50 years seismic event.[99] In addition, the peak ground acceleration (PGA), velocity, and displacement should be selected using historic records, site-specific observations, or magnitude-distance attenuation relations. Additionally, the analysis would need to include an appropriate duration of earthquake, considering accelerograms for the anticipated event. Appropriate elastic response spectra should be selected using engineering methodology for selection, such as the Newmark-Hall Spectrum or other appropriate published spectra, USGS Probabilistic Maps, or site-specific response spectra.

(e) The Calculated Liquefaction Factor of Safety

All CCR surface impoundments, including any lateral expansions that exceed the size threshold and have been determined to contain soils susceptible to liquefaction must meet a liquefaction factor of safety equal to or greater than 1.20. A prudent engineering analysis of structural stability also includes a liquefaction potential analysis and analysis of post-liquefaction static factors of safety. As discussed previously, liquefaction is a phenomenon which typically occurs in loose, saturated or partially-saturated soils in which the effective stress of the soils reduces to zero, corresponding to a total loss of shear strength of the soil. The most common occurrence of liquefaction is in loose soils, typically sands. The liquefaction FOS determination in the final rule is used to determine if a CCR unit would remain stable if the soils of the embankment of the CCR unit were to experience liquefaction. Liquefaction analysis is only necessary in instances where CCR surface impoundments show, through representative soil sampling, construction documentation, or anecdotal evidence from personnel with knowledge of the CCR unit's construction, that soils of the embankment are susceptible to liquefaction.

EPA has included this requirement because the mechanics and response phenomena of geotechnical structures vary radically following induced liquefaction, *i.e.,* post-liquefaction. Similar to the requirement for seismic factors of safety, liquefaction factors of safety are necessary because reliance on static loading is not sufficient to evaluate the structural stability of a CCR surface impoundment. Standard engineering methodology and guidance support EPA's conclusion that adequate liquefaction potential analyses and post-liquefaction residual strength slope stability analyses of embanked structures is essential to ensure the continued structural stability of a geotechnical structure following dynamic loading.

Under standard engineering methodologies, liquefaction potential analysis and post-liquefaction stability analysis includes several procedures to adequately analyze the structural strength of a CCR surface impoundment. Because only certain soils, such as loose sands, are susceptible to liquefaction, the rule requires only embankments constructed of such soils identified through liquefaction potential analysis to meet liquefaction factors of safety. Such liquefaction potential analysis would need to include proper soil characterization of the embankment soils for soil age and origin, fines content and plasticity index, water content, saturation, and maximum current, past, and anticipated future phreatic surface levels within the embankment, foundation, or abutments, location beneath the natural ground surface, and penetration resistance whether through standard penetration testing (SPT) or, ideally, cone penetration testing (CPT). Post-liquefaction stability analysis would need to include detailed characterization of the site conditions, identification of the minimum liquefaction-inducing forces based on soil characterization, determination of seismic effect on liquefied layers of the embankment, and calculation of factors of safety against each liquefied layer of the embankment.

(f) The Calculated Static Factor of Safety Under the End-of-Construction Loading Condition

The End-of-Construction loading condition must be calculated for new CCR surface impoundments to ensure that the CCR surface impoundment can withstand a ''first-filling'' of the embankment, during which time the embankment first become saturated and is subject to phreatic flow through the cross-section.

Embankments are typically constructed in layers with soils at or above their optimum moisture content that undergo internal consolidation because of the weight of the overlying layers. Embankment layers may become saturated during construction as a result of consolidation of the layers or by rainfall. Because of the low permeability of fine-grained soils of which many embankments are constructed and the relatively short time for construction of the embankment, there can be little drainage of the water from the soil during construction: resulting in the development of significant pore pressures. Soils with above optimum moisture content will develop pore pressures more readily when compacted than soils with moisture contents below optimum. In general, the most severe construction loading condition is at the end of construction.

The final rule requires that the calculated static factor of safety for the critical cross section of the CCR surface impoundment under end of construction loading conditions meet or exceed 1.30. The End-of-Construction loading condition is analyzed for new construction under their initial filling condition, following the completion of construction. Undrained shear strength conditions are typically assumed for the End-of-Construction loading condition. Both the upstream and downstream slopes of the embankment are analyzed for this condition

(g) Failure To Demonstrate Minimum Safety Factors or Failure To Complete a Timely Safety Factor Assessment

As previously discussed, the rule requires an owner or operator to document that the calculated factors of safety for each CCR surface impoundment achieve the minimum safety factors specified in the rule. For any CCR surface impoundment that does not meet these requirements, the owner or operator must either take any engineering measure necessary to ensure that the unit meets the requirements by the rule's deadlines, or cease placement of CCR and non-CCR waste into the unit and initiate closure of such CCR unit as provided in section 257.102 within six months. Similarly, if an owner or operator fails to complete the initial safety factor assessment or any subsequent periodic factor safety assessment by the deadlines established in the rule, the owner or operator must cease placing CCR and non-CCR waste into the unit and initiate closure within six months.

(h) Vertical Expansions of CCR Surface Impoundments and Structural Integrity Criteria

It is not uncommon for the owner or operator to raise the crest of a CCR surface impoundment to accommodate the additional capacity needs of the

[99] FEMA Doc. 65 ''Earthquake Analyses and Design of Dams;'' *http://www.ferc.gov/industries/hydropower/safety/guidelines/fema-65.pdf.*

facility. The record documents that CCR surface impoundments are commonly expanded from the original design or as-built construction, through such ''vertical expansions,'' including where a CCR surface impoundment changes from a ''small'' CCR unit (*i.e.,* below the height and/or volume threshold) to a ''large'' CCR unit (*i.e.,* exceeding the height and/or volume threshold). In these situations, the owner or operator of the CCR unit becomes subject to additional structural integrity requirements as a result of the vertical expansion. Realizing that these newly created CCR units will require some time to meet the structural integrity requirements, the Agency is allowing one year from the completion of the vertical expansion for the owner or operator to comply with the requirements of §§ 257.73 or 257.74, as applicable.

F. Operating Criteria—Air Criteria

EPA proposed to require CCR landfills, CCR surface impoundments and any lateral expansion to control the creation of fugitive dust. Specifically, EPA proposed that facilities must ensure that fugitive dust either not exceed the standard of 35 μg/m^3, established as the level of the 24-hour National Ambient Air Quality Standards (NAAQS) for fine particulate matter (PM–2.5), or any alternative standard established pursuant to applicable requirements developed under a State Implementation Plan (SIP) approved or promulgated by the Administrator pursuant to section 110 of the CAA (see 75 FR 55175). Consistent with the numerical standard, EPA proposed to require that CCR units be managed to control the wind dispersal of dust, and that CCR landfills also be required to emplace wet conditioned CCR (*i.e.,* wetting CCR with water to a moisture-content that prevents wind dispersal and facilitates compaction, but does not result in free liquids) into the unit. EPA also required that documentation of the measures taken to comply with the requirements be certified by an independent registered professional engineer. EPA proposed these requirements based on the results of a screening level analysis of the risks posed by fugitive dust from CCR landfills, which showed that without fugitive dust controls, levels at nearby locations could exceed 35 μg/m^3, established as the level of the 24-hour PM 2.5 NAAQS for fine particulate. These measures were also intended to reduce the excessive cancer risks associated with the inhalation of hexavalent chromium. This potential risk would apply to over six million people who live within the census population data ''zip code tabulation areas'' for the 495 rule-affected electric utility plant locations. (See 75 FR 35215.)[100]

As part of the proposal, EPA solicited comments on the following fugitive dust issues: (1) The location of air monitoring stations near CCR landfills or CCR surface impoundments; and (2) information on any techniques, such as wetting, compaction, or daily cover that are or can be employed to reduce exposures to fugitive dust. The Agency received no information from commenters on either of these issues.

The majority of comments received, however, took issue with the proposed technical standard of 35 ug/m^3. Commenters argued that, as proposed, the standard would be impossible to implement because the Agency provided no information on particle size, form of the standards, whether an averaging period is available, point of compliance or how one considers upwind sources. More generally, however, commenters argued that the proposed provisions were unnecessary because fugitive dust issues were adequately addressed by existing air rules through the development and implementation of NAAQS, such as PM_{10} and $PM_{2.5}$. These same commenters acknowledged, however, that if the Agency established a criterion to control fugitive dusts, a more appropriate and reasonable standard could be based on best management practices or BMPs. To that end, commenters offered information suggesting that CCR landfills typically used compaction, regular wetting and temporary covers in conjunction with visual air monitoring to effectively control fugitive dust at their facilities, and that these practices were included in facility operating plans.

As discussed in the proposed rule, EPA's decision to address fugitive dust was based on a peer review of the 2010 draft Risk Assessment, 2007 NODA stakeholder comments, photographic documentation of fugitive dust associated with the management of CCR, Agency actions to control fugitive emissions during the clean-up of the December 2008 TVA Kingston spill, and OSHA's Material Safety Data Sheets (now *Safety Data Sheets* (*SDS*)) requirements for coal ash. These lines of evidence have been bolstered since the proposal, by evidence collected during the eight 2010 CCR public hearings, where stakeholders provided extensive feedback about fugitive dust impacts associated with CCR management at facilities adjacent to their residences, and by documented reports on fugitive dust issues provided by citizen groups.[101] The stakeholders called for federal oversight to address those instances where complaints were seemingly ignored by state regulators and/or where state administrative enforcement measures failed to compel the utilities to effectively amend their dust emission control management practices. The Agency followed up on the complaints with state agencies and compiled a preliminary database on documented and alleged fugitive dust damage cases.[102]

In support of this rule, EPA compiled records of over 20 documented fugitive dust cases, in addition to several alleged cases that could not be verified. The documented cases indicate that fugitive dust concerns arise in all phases of the CCR life cycle—from conveyor belt transfer at the coal-fired power plant, through stockpiling and transport for disposal/beneficial use, and up to final disposition. Fugitive dust also is a potential concern associated with both—landfills and surface impoundments. Whereas a nexus between fugitive dust impacts and CCR landfill operations was to be expected, EPA discovered that fugitive dust was also of concern at CCR surface impoundments, either under conditions of windy winter spells affecting CCR exposed above or next to the CCR surface impoundment boundary, or due to the total CCR surface impoundment evaporation in arid areas.

Very few studies have been undertaken to test the health impacts caused by fugitive dust emissions, and of those few, due to inherent limitations, all failed to prove that fugitive dust was the cause of the documented health concerns. For example, in the wake of the January

[100] As evidenced in 42 U.S.C. 6971(f), Congress intended that the Occupational Safety and Health Administration (OSHA) be able to enforce its regulations to protect workers exposed to hazardous waste and that EPA and OSHA would work together to ensure that. EPA is clarifying that it intends that the CCR disposal rule not preempt applicable OSHA standards designed to protect workers exposed to CCRs; thus EPA's final rule on CCR disposal will apply in addition to any applicable OSHA standards. The Agency has added specific regulatory language in this section to address this intent.

[101] For instance, photographic evidence provided by Susan Holmes, the Bokoshe Environmental Cause Group (B.E. Cause), Bokoshe, Oklahoma. See Earthjustice's brief background coverage at: *http://earthjustice.org/blog/2011-april/not-having-fun-in-bokoshe-ok*, and ABC News' *Oklahoma Town Fears Cancer, Asthma May Be Linked to Dump Site,* March 29, 2011: *http://abcnews.go.com/US/oklahoma-town-fears-cancer-asthma-linked-dump-site/story?id=13240312*.

[102] A compilation of damage cases can be found in the docket supporting this rule.

2005 coal ash pile collapse at the Rostosky Ridge Road, in Allegheny County, Pennsylvania, both the federal and county studies [103] failed to test during this period and missed the narrow exposure window that would have possibly demonstrated a link between the event and the short-term health symptoms (*e.g.,* sore throat, cough, fever, nausea, fatigue, diarrhea, and headaches) contracted by residents who ultimately removed approximately 1,500 tons of fly ash from their properties immediately after the incident without the benefit of any protective respiratory gear. The federal and county studies also found no evidence of long-term arsenic poisoning of the tested individuals. For recurring instances of CCR dispersion in the air at the Indian River Power Plant, Millsboro, Delaware, three consecutive state studies tentatively established other risk factors as the probable cause for a lung cancer cluster in a down-wind location of the presumable source term (CCR fugitive dust blowing of a landfill and stack emissions).[104] Critics claim that these studies used too small of a sample, and were not designed to capture the impact of long-term exposure to pollution.[105]

Nevertheless, in eleven other cases, states adopted measures to address concerns from fugitive dust emissions; these included conducting lung-cancer cluster and other health studies, conducting particle dispersion studies, issuing Notices of Violation and Consent Orders to the responsible facilities, waiving landfill cover exemptions, and requiring dust management plans for newly permitted CCR landfills. In addition, in several instances, citizens filed lawsuits or reached an out-of-court settlement with the primary responsible party; and in one case, OSHA imposed a steep fine on the owners of a facility manufacturing abrasive blasting and roofing materials from slag produced at a nearby coal-fired power plant, for willfully exposing their workers to dangerously high levels of hazardous dust, and for failing to provide adequate breathing protection and training for workers at the facility. According to stakeholder allegations, fugitive dusts generated by these same materials also adversely impacted residents in the facility's immediate vicinity.

As previously stated, many commenters argued that the proposed numeric particulates standard was incompatible with the air quality requirements established under the States' Implementation Plans (SIPs) or with provisions set up by the states in their Title V Clean Air Permits to the power producers. In addition, the commenters argued that the proposed standard lacked technical details to facilitate effective implementation, and that implementation of the standard required specialized equipment and advanced training to carry out a judicious reading and interpretation of opacity, a proxy measure for the level of fugitive dust emissions. In light of these comments, EPA re-evaluated the existing CAA standards applicable to these units; 40 CFR 70.2 identifies fossil-fuel-fired steam electric plants of more than 250 million BTU/hour heat input as potential sources of fugitive dust (PM sources) that must be covered by state permitting, and 40 CFR 70.3 stipulates that fugitive emissions from a part 70 source shall be included in the permit application and the part 70 permit in the same manner as stack emissions, regardless of whether the source category is included in the list of sources contained in the definition of major source. Based on these applicable CAA requirements, the Agency agrees that the adoption of a PM standard under the final rule would entail a potential for duplication or inconsistency with applicable state-established standards in SIP permits.

EPA also acknowledges the challenges involved in measuring the proposed compliance standard. Because fugitive dust is emitted from non-point sources, it cannot be easily measured by conventional methods. Usually, regulations developed by the states to control fugitive dust stipulate that no person or source shall cause or allow, from any activity, any emissions of fugitive particulate matter that are visible to an observer who looks horizontally along the source's property line. A quantitative measurement of fugitive dust levels (EPA's Reference Method 9) would require measuring opacity, which, as the commenters noted, necessitates specialized technical training, trainee certification, and judicious application of instrumentation.

Therefore, rather than requiring a potentially redundant and challenging-to-implement quantitative standard, EPA is substituting a performance standard for fugitive dust control. This standard requires owners or operators of a CCR unit to adopt measures that will effectively minimize CCR from becoming airborne at the facility, including CCR fugitive dust originating from CCR units, CCR piles, roads, and other CCR management activities. The Agency considers this standard to be consistent with the intent of the proposed rule, with the added advantage of allowing facilities the flexibility to determine the appropriate measures to achieve regulatory compliance at their individual site. This standard and the accompanying regulatory requirements supporting its implementation, will achieve the statutory obligation of ''*no reasonable probability of adverse effects on human health and the environment.''*

As in the proposal, the Agency is also requiring documentation of the measures taken to comply with the technical standard in a ''CCR fugitive dust control plan'' (herein referred to as ''plan''). Consistent with the proposal, the plan must be certified by a qualified professional engineer and placed in the operating record and on the owner or operators publicly accessible internet site. The plan requires owners or operators to elaborate on the types of activities applicable and appropriate for the conditions at the facility that will be employed to minimize CCR from becoming airborne at the facility. Examples of control measures that may be appropriate include: Locating CCR inside an enclosure or partial enclosure; operating a water spray or fogging system; reducing fall distances at material drop points; using wind barriers, compaction, or vegetative covers; establishing and enforcing reduced vehicle speed limits; paving and sweeping roads; covering trucks transporting CCR; reducing or halting operations during high wind events; or applying a daily cover.

The initial plan must be completed by the effective date of the rule (*i.e.,* within six months of publication). Because this is an initial plan, and because it must be completed within a short timeframe, EPA acknowledges that the facility may only be able to present its initial judgment of the measures that it anticipates are likely to be effective based on the information that is readily available within this six month

[103] (i) *Coal Fly Ash Landslide, Forward Township, Allegheny County, Pennsylvania,* ASTDR Health Consultation June 1, 2006: *http://www.atsdr.cdc.gov/HAC/pha/CoalFlyAshLandslide/CoalFlyAshLandslideHC060106.pdf* (ii) *Results of the Health Investigation Following Fly Ash Contamination in Forward Township, Allegheny County, Pennsylvania,* Allegheny County Health Department, July 2005: *http://www.achd.net/air/pubs/pdf/Forward%20Fly%20Ash%20Study%202005.pdf.*

[104] *Millsboro Inhalation Exposure and Biomonitoring Study.* State of Delaware Department of Natural Resources and Environmental Control, Department of Health and Social Services, Dover (RTI Project 0213061), DE, May 2013: *http://www.dnrec.delaware.gov/Admin/Documents/Millsboro_Inhalation_Exposure_and_Biomonitoring_Study_Final_Repor_05282013.pdf.*

[105] *Critic chides cancer study: Indian River plant results called lame.* Delawareonline, May 28, 2013: *http://www.delawareonline.com/article/20130528/NEWS/305280081/.*

timeframe. EPA anticipates that owners or operators may need to revise the plan as they gain additional information and experience implementing the regulations. In recognition of this, the final rule also requires that the CCR fugitive dust control plan include a description of the procedures the owner or operator will follow to periodically assess the effectiveness of the control plan. Consistent with other plans required in this rule, the owner or operator may amend the written CCR fugitive dust control plan at any time. However, the owner or operator must amend the written plan whenever there is a change in conditions that would substantially affect the written plan in effect, such as the construction and operation of a new CCR unit. The plan and any subsequent amendments must be certified by a qualified professional engineer.

In addition, the Agency is promulgating with a slight modification the requirement for owners and operators of all CCR landfills and any lateral expansion to emplace CCR as conditioned CCR, as well as the definition of conditioned CCR. *Conditioned CCR* has been defined to mean CCR wetted with water to a moisture content that will prevent wind dispersal, but will not result in free liquids, consistent with the definition in the proposed rule. In response to several commenters' requests, and upon further evaluation the Agency is allowing that in lieu of water, CCR conditioning may be accomplished with an appropriate chemical dust suppression agent.[106] As with other requirements of this rule, in order to ensure that the provisions of the fugitive dust criteria are maintained throughout the operating life of the CCR unit, the Agency is requiring that the owner or operator prepare an annual CCR fugitive dust control report, describing the actions taken to control CCR fugitive dust, a record of all citizen complaints, and a summary of any corrective measures taken. The first annual report must be completed no later than 14 months after placing the initial CCR fugitive dust control plan in the facility's operating record. The owner or operator has completed the annual CCR fugitive dust control report when the plan has been placed in the facility's operating record.

The general public, as well as the Agency, is highly concerned with potential risks associated with CCR fugitive dusts. This was readily apparent during the public hearings and from the many comments received on this issue. The Agency continues to receive information regarding this human health and environmental concern. While the subtitle D provisions of this rule lack permitting oversight mechanisms to control fugitive dust from CCR units, it is clear to the Agency that additional substantive actions was needed to facilitate citizen suit enforcement of this criteria. Consequently, the Agency are adding a specific requirement to the CCR fugitive dust control plan to require owners and operators of all CCR units to develop and implement formal procedures to log citizen complaints involving CCR fugitive dust events. These complaints must, then, be included as part of the annual CCR fugitive dust control report. This report must be placed in the operating record and on the owner or operator's publicly accessible internet site. Promulgation of these measures will subject the owner or operator of the CCR disposal facility to public and state scrutiny, and create an incentive for the owner or operator of the CCR disposal facility to improve compliance with the fugitive dust control requirements.

G. Operating Criteria—Run-On and Run-Off Controls for CCR Landfills

EPA's proposal required owners or operators of CCR landfills and all lateral expansions to design, construct and maintain a run-on control system to prevent flow onto the active portion of these units during the peak discharge from a 24-hour, 25-year storm. As described in the proposed rule, run-on controls are designed to prevent erosion, which may damage the physical structure of the landfill, prevent the surface discharge of CCR in solution or suspension; and to minimize the downward percolation of run-on through wastes, creating leachate. Similarly, EPA proposed run-off controls in order to collect and control, at a minimum, the water volume resulting from a 24-hour, 25-year storm. This standard was proposed in order to protect surface waters from contamination. Under the existing 40 CFR part 257 requirements, to which CCR units are currently subject, run-off must not cause a discharge of pollutants into waters of the United States that is in violation of the National Pollutant Discharge Elimination System (NPDES) under section 402 of the Clean Water Act. EPA did not propose to revise the existing requirement, but merely incorporated it for ease of the regulated community.

The Agency proposed the 24-hour period because it was a timeframe that included storms of high intensity with short duration and storms of low intensity with long duration. EPA believed that this was a widely used standard that had been incorporated into the hazardous waste landfills and MSW landfills regulatory requirements. At the time, EPA had no information that warranted a more restrictive standard for CCR landfills. EPA received no significant comment on the proposed requirements, and for the most part, is adopting the proposed requirements without revision. However, in an effort to clarify and provide more direction to the owner or operator and the certifying qualified professional engineer, the Agency has added additional regulatory language that more specifically describes the technical criteria established under this section of the rule.

The run-on and run-off controls of the final rule require that the owner or operator prepare the initial run-on and run-off control system plan within 18 months of publication of the rule. Run-on and run-off control system plan reporting may require design, construction, and post-construction implementation. In instances where run-on and run-off capacity is insufficient, installing additional capacity may involve construction of diversion structures such as swales or ditches. Many of these efforts may require several months of design and construction, compounded by the fact that much of the work cannot be completed in cold-weather or heavy-rain seasons.

1. Run-On and Run-Off Controls for CCR Landfills and All Lateral Expansions[107]

All CCR landfills and all lateral expansions must be designed, constructed, operated, and maintained with a run-on control system to prevent flow onto the active portion of the CCR unit from the peak discharge from a 24-hour, 25-year storm and a run-off control system to collect and control at

[106] Spray-on adhesives, surfactants, aqueous foamers, humectants (calcium, magnesium, ad sodium chloride and their mixtures), and polymer solutions and emulsions. See, for instance ''The Role of Chemicals in Controlling Coal Dust Emissions'' Benetech, Inc. available at *http://pdf.ebooks6.com/download.php?id=139860* or Peterson, Edwin. ''An Aid to Fugitive Materials Control in Coal Ash Applications'' presented at the World of Coal Ash (WOCA) conference—May 9–12, 2011 in Denver, Colorado.

[107] In the proposed rule under the RCRA subtitle D option, EPA jointly proposed run-on and run-off requirements for CCR landfills and CCR surface impoundments under proposed § 257.81. In this final rule, EPA has modified the ''run-on and run-off'' requirements and is providing separate requirements for CCR landfills and CCR surface impoundments. CCR surface impoundments are now subject to the hydrologic and hydraulic capacity requirements at § 257.82. This new section of the rule more appropriately addresses flow management issues at CCR surface impoundments.

least the volume of water resulting from a 24-hour, 25-year storm from the active portion of the CCR unit.[108]

Consistent with the proposal, the rule requires the owner or operator of a CCR landfill or lateral expansion to prepare an initial run-on and run-off control system plan for the CCR unit. For existing CCR landfills, the plan must be prepared by the owner or operator no later than one year from the effective date of the rule. For new CCR landfills and any lateral expansion of a CCR landfill, the plan must be prepared no later than the date of initial placement of CCR in the landfill or lateral expansion. The plan must document how the run-on and run-off control systems have been designed and constructed to meet the requirements of rule and must be supported by appropriate engineering calculations. The run-on and run-off control system plan must be certified by a qualified professional engineer and is considered prepared when the owner or operator has placed the plan in the facility's operating record.

The rule also provides for the owner or operator to amend the plan at any time (*e.g.,* prior to receipt of CCR in the CCR unit, during the operating life of the CCR unit, during closure of the CCR unit, or following closure of the CCR unit) provided the revised plan is placed in the facility's operating record. The owner or operator must, however revise the plan whenever there is a change in the conditions that would substantially affect the written plan in effect (*e.g.,* closure of an existing portion or cell of the CCR landfill, resulting in a possible change in the size of the ''active portion'' of the CCR landfill).

In addition, consistent with other provisions in this rule, the Agency is requiring that the run-on and run-off control system plan be reviewed, and where necessary, revised or updated at least every five years. The Agency is specifying this periodic review in order to address factors having the potential to influence the run-on and run-off control system. Among other things, CCR landfills can be subject to build-out, operational changes, and surface cover changes, all of which have the potential to significantly alter run-on and run-off flows to and from the active portion of the CCR landfill. Changes in storm intensity and duration, as well as upstream catchment area characteristics, can alter flows that may significantly affect a previously adequate run-on and run-off control system. A mandated five year review of a control system plan is consistent with accepted good engineering practices and protocols for proper maintenance of operational systems supporting the overall performance of a CCR landfill. It is also consistent with the proposed requirement that an owner or operator ''maintain'' the run-on and run-off control system. EPA interprets this to require the owner or operator to ensure that the run-on and run-off control system is kept in a condition that meets the requirements of the rule, *i.e.,* that the run-on and run-off control system both prevents flow onto the active portion of the unit during the peak discharge from a 24-hour, 25-year storm and collects and controls at least the water volume resulting from a 24-hour, 25-year storm event for the duration of the CCR landfill's operational life. A requirement to conduct a review of the control plan at least once every five years merely provides an explicit mechanism to ensure this occurs in a manner that facilitates citizen and state oversight.

The date of preparing the initial plan is the basis for establishing the deadline to complete the first subsequent plan; *i.e.,* the subsequent plan must be completed within five years of the prior plan. The owner or operator may complete any required plan prior to the required deadline and must place the completed plan into the facility's operating record within the five year timeframe. A qualified professional engineer must certify that the run-on and run-off control system plan, including any subsequent amendments, meets the run-on and run-off control system requirements of this final rule.

a. Run-On Control

Consistent with the proposal, EPA is defining *run-on* to mean any liquid that drains over land onto any part of a CCR landfill or any lateral expansion of a CCR landfill. In surface water hydrology, run-on is a quantity of surface run-off, or excess rain, snowmelt, or other sources of water, which flows from an upstream catchment area onto a specific downstream location. This rule requires that the CCR landfill be designed, constructed, operated, and maintained to prevent flow onto the active portion of the CCR landfill during the peak discharge from a 24-hour, 25-year storm. EPA has adopted this requirement to minimize the amount of surface water entering the CCR landfill and to minimize disruption of the CCR landfills operation due to storm water inflow. Uncontrolled or undesirable storm water run-on may have significant impacts on the stability of the slopes of a CCR landfill and continued safe operation of the CCR landfill, due to such phenomena as erosion and infiltration.

b. Run-Off Control

EPA has adopted the definition of run-off from the proposal without revision. *Run-off* means any liquid that drains over land from any part of the CCR landfill. Effectively, run-off is the portion of rainwater, snowmelt, or other liquid which does not undergo abstraction, such as infiltration, and travels overland. Typically, run-off is the product of the inability of water to infiltrate into soil due to saturation or infiltration rate capacity being exceeded. The rule requires that the CCR landfill be designed, constructed, operated, and maintained to collect and control at least the water volume resulting from a 24-hour, 25-year storm. The owner or operator must design, construct, operate, and maintain the CCR landfill in such a way that any run-off generated from at least a 24-hour, 25-year storm must be collected through hydraulic structures, such as drainage ditches, toe drains, swales, or other means, and controlled so as to not adversely affect the condition of the CCR landfill. EPA has promulgated these requirements to minimize the detention time of run-off on the CCR landfill and minimize infiltration into the CCR landfill, to dissipate storm water run-off velocity, and to minimize erosion of CCR landfill slopes. An additional concern with run-off from CCR landfills is the water quality of the run-off, which may collect suspended solids from the landfill slopes. EPA acknowledges that the run-off requirements will also minimize the amount of run-off related pollution generated by the landfill run-off.

c. Run-On and Run-Off Control System Plan

The owner or operator of any CCR landfill must prepare an initial run-on and run-off control system plan documenting, with supporting engineering calculations, how the control systems have been designed and constructed to meet the requirements of the rule. This has been adopted without revision from the proposal. In most cases, EPA expects this documentation will include in addition to the supporting engineering calculations, references and drawings regarding the

[108] Under existing part 257 requirements, to which CCR units are currently subject, runoff must not cause a discharge of pollutants into waters of the United States that is in violation of the National Pollutant Discharge Elimination System (NPDES) under section 402 of the Clean Water Act (40 CFR 257.3–3). EPA did not propose to revise this requirement but is merely incorporating it here for ease of the regulated community.

identification of the 24-hour, 25-year storm for the location of the CCR landfill, a characterization of the rainfall abstractions, including but not limited to depression storage and infiltration, the selection and basis of an appropriate run-off model, the selection and basis of an appropriate run-on or run-off routing model, and the selection and design of an appropriate run-on and run-off management system (*e.g.,* swales, ditches, retention or detention ponds). Consideration of the above factors would generally constitute a comprehensive review of the hydraulic and hydrologic processes associated with the design of a run-on and run-off control system plan. EPA recognizes that over time, any number of factors, *e.g.,* expansion of the facility, could affect a change in the run-on and run-off control system plan. Consequently in the final rule EPA is providing for flexibility in this area by stating that the plan can be amended by the owner or operator at any time during the life of the CCR landfill, provided the amendments are placed in the operating record and on the facility's publicly accessible Internet site.

H. Operating Criteria—Hydrologic and Hydraulic Capacity Requirements for CCR Surface Impoundments

As discussed in the previous section, EPA proposed to require owners or operators of CCR landfills to design, construct, operate, and maintain: (1) A run-on control system to prevent flow onto the active portion of the unit during the peak discharge from a 24-hour, 25-year storm; and (2) a run-off control system to collect and control, at a minimum, the water volume resulting from the same 24-hour, 25-year storm. EPA also proposed to apply these same run-on and run-off requirements to all CCR surface impoundments and lateral expansions.

Commenters overwhelmingly disagreed with EPA's decision to apply the same run-on and run-off requirements to both CCR landfills and CCR surface impoundments, arguing that a ''control system to prevent flow onto the active portion of the surface impoundment'' was at odds with a commonly employed practice of using CCR surface impoundments to manage incoming storm water and other inflow. While some commenters reasoned that preventing run-on may be appropriate for CCR landfills and CCR surface impoundments surrounded by above-ground dikes, the proposed requirement was entirely inappropriate for units specifically designed to retain storm water from an adjoining watershed or to operate as part of a facility's overall storm water management system. Numerous commenters suggested that instead of the run-on prevention provision for CCR surface impoundments, EPA adopt a requirement specifying that CCR surface impoundments be designed to accommodate ''peak discharge events.'' Other commenters argued that storm water run-on controls were only appropriate during and after the closure of CCR surface impoundments; while still other commenters suggested that EPA remove entirely the run-on and run-off requirements because CCR surface impoundments were typically designed to impound and discharge storm water flow far in excess of a 25-year/24-hour storm event.

In evaluating the arguments against the requirements to prevent flow onto the CCR surface impoundment, the Agency was strongly influenced by guidance developed by FEMA for selecting and accommodating hydraulic and hydrologic inflow and outflow as well as the application of this guidance to the CCR surface impoundments evaluated as part of EPA's Assessment Program.[109] A review of FEMA guidance confirmed commenters' contentions that managing flow both to and from dams and impoundments was a widely used practice, and a preferable management strategy for accommodating storm water flows. This was further confirmed by observations made during EPA's Assessment Program; EPA frequently observed units designed to detain or retain storm water inflows of an upstream catchment area to manage CCR, and/or to receive storm water inflow as part of the facility's overall storm water management system. Moreover, EPA relied on the same FEMA guidance to assess the adequacy of the hydrologic and hydraulic capacity of the CCR surface impoundments. In conducting these assessments, EPA considered a number of factors including operating freeboard, catchment area, hydrologic structures' inflow and outflow ratings, design precipitation event, spillway presence and capacity, and unit operating procedures to make this determination. The adequacy of the capacity was determined using FEMA guidance for selecting and accommodating inflow design floods (IDF) for dams. (Note: The use of the terminology related to ''inflow design flood'' for CCR surface impoundments rather than ''run-on'' and ''run-off'' is more directly applicable to the hydraulic and hydrologic capacity of CCR surface impoundments to adequately manage both the inflow and outflow from a design flood.)

During its assessment effort, EPA also found that, contrary to commenter's arguments CCR surface impoundments were often not designed to address floods in excess of a 24-hour, 25-year storm event. Rather many CCR surface impoundments were deficient in their hydrologic and hydraulic capacity requirements due to factors such as lack of operating freeboard, misunderstanding of the actual contributory area, lack of documentation, undersized decant structures, undersized spillways, and lack of spillways.

EPA also disagrees with the comment asserting that storm water controls are only appropriate during and after closure of CCR surface impoundments. Hydrologic and hydraulic capacity, as determined by an effective design flood control system, is an essential element of the overall structural integrity and safety of a CCR surface impoundment. CCR surface impoundments are subject to any number of stresses throughout their operational life; one of the most common causes of a dike or embankment failure being the inability of the CCR unit to adequately pass or manage flood flows resultant from direct or indirect precipitation. These failures can occur at any point in the CCR unit's life, not solely during and after closure, and are usually due to inadequate hydrologic and hydraulic capacity, leading to internal erosion due to seepage and piping, erosion of spillways, overtopping erosion, and overstressing of the embankment. Furthermore, according to the U.S. Bureau of Reclamation, a common dam failure mode is due to overtopping, accounting for 30% of the failures in the U.S. over the last 75 years.[110] Overtopping is the direct result of lack of adequate hydrologic and hydraulic capacity of a dam or surface impoundment. Therefore, EPA is not modifying the regulation as suggested by the commenter.

In light of comments received, observations made during EPA's Assessment Program, and guidance developed by FEMA, EPA has concluded that it was inappropriate to propose to prohibit all run-on discharge or inflow from storm water to CCR surface impoundments. EPA has also

[109] EPA referred to FEMA's ''Federal Guidelines for Dam Safety: Selecting and Accommodating Inflow Design Floods for Dams'' in evaluating the adequacy of the CCR surface impoundment's hydrologic and hydraulic capacity during its assessment effort.

[110] *http://www.usbr.gov/ssle/damsafety/Risk/BestPractices/16-FloodOvertoppingPP20121126.pdf.*

concluded that run-on and run-off criteria are inappropriate for CCR surface impoundments, and that a more appropriate standard involves determining the hydrologic and hydraulic capacity of a unit, measured by its inflow design flood or IDF. Therefore, EPA is amending the proposed run-on and run-off requirements for CCR surface impoundments to require owners or operators of all CCR surface impoundments to design, construct, operate, and maintain hydraulic and hydrologic capacity to adequately manage flow both into and from a CCR surface impoundment during and after the peak discharge resulting from the inflow design flood, based on the Hazard Potential Classification of the CCR surface impoundment.

The final rule requires the preparation of the initial inflow design flood control system plan within 18 months of publication of the final rule. In many cases, inflow design flood control system plan reporting may require design, construction, and post-construction implementation in order to provide sufficient hydrologic and hydraulic (H/H) capacity for the CCR unit. In instances where H/H capacity is insufficient, installing additional capacity may involve spillway construction or decant structure construction or installation. Many of these efforts may require several months of design and construction, compounded by the fact that much of the work cannot be completed in cold-weather or heavy-rain seasons.

1. Inflow Design Flood Controls for CCR Surface Impoundments and All Expansions

The Agency has concluded that the proposed requirement preventing run-on to a CCR surface impoundment was both impractical and unwarranted and could possibly disrupt effective storm water management systems operating at CCR facilities. Therefore, consistent with FEMA guidance, the Agency is modifying this requirement to require an owner or operator of an existing or new CCR surface impoundment or any lateral expansion to design, construct, operate, and maintain H/H capacity of CCR surface impoundments to: (1) Adequately manage flow into the CCR surface impoundment during and following the peak discharge of the inflow design flood; and (2) adequately manage flow from the CCR unit to collect and control the peak discharge resulting from the inflow design flood. The inflow design flood is based on the hazard potential classification of the unit as required by § 257.73 and § 257.74 of this rule.[111] The inflow design floods for specific hazard potential classifications are as follows: (1) The probable maximum flood (PMF) for high hazard potential CCR surface impoundments; (2) the 1000-year flood for significant hazard potential CCR surface impoundments; (3) the 100-year flood for low hazard potential CCR surface impoundments; and (4) the 25-year flood for incised CCR surface impoundments.[112]

EPA has based this revised requirement on the FEMA's guidance entitled, ''Selecting and Accommodating Inflow Design Floods for Dams,'' which represents current and accepted practices in dam engineering and provides a consistent and uniform standard that has been adopted throughout dam engineering.

Incised CCR surface impoundments, as defined in this rule, are also required to meet inflow design flood requirements.[113] While incised units do not pose the same potential for release as a diked unit, *i.e.,* breach of dike and release of CCR, overtopping of an incised unit does represent a potential environmental hazard warranting control. EPA acknowledges, however, that overtopping of an incised unit would result in a release of CCR material through a surcharge flow, *i.e.,* flow of a temporary stage overtopping the ''crest'' of the incised CCR surface impoundment, and would not precipitate the degradation of a dike and potential subsequent breach of a dike and massive release of contents of the CCR surface impoundment. To reflect the lower risks associated with such releases, and because incised CCR surface impoundments are not required to determine their hazard potential classification, the Agency is requiring that incised CCR surface impoundments only must accommodate a 25-year flood for the hydrologic and hydraulic capacity requirements of the rule. EPA chose the 25-year flood for incised CCR surface impoundments to maintain consistency with the proposed rule, which required that all units accommodate a 25-year storm event. As part of these requirements, EPA is also finalizing a definition of *inflow design flood* and *flood hydrograph. Inflow design flood* has been defined to mean the flood hydrograph that is used to design or modify the CCR surface impoundment and its appurtenant works, and *flood hydrograph* has been defined to mean the temporal distribution of inflow into a CCR surface impoundment.

2. Inflow Design Flood Control Systems

Controlling the inflow and outflow of the CCR surface impoundment reduces the risks of hydrologic failure, which include overtopping erosion, internal excessive seepage and piping, erosion of spillways, and overstressing of the structural components of the CCR surface impoundment. The CCR surface impoundment's H/H capacity is to be designed based on the unit's hazard potential classification as determined by a qualified professional engineer. To meet the performance standard in the rule, the CCR surface impoundment must be designed to have adequate H/H capacity to ensure that rainfall and watershed characteristics have been accounted for, the hydraulic ratings of all intake structures are adequate and free of obstruction, operating freeboard is adequate, all spillways and decant structures have adequate capacity, and all downstream hydraulic structures have adequate capacity. While not required, an antecedent flood study may be necessary to characterize the condition of the CCR surface impoundment under normal operating conditions.

EPA recognizes that in many impoundment configurations, an inflow design flood may be limited to the direct precipitation that falls within the perimeter of the CCR surface impoundment during a storm event, due to the lack of storm water inflow routing from adjacent catchment areas. Other CCR surface impoundments may have storm water or other hydrologic contributions from various catchment areas or other sources. The final rule's hydraulic and hydrologic capacity standards require all CCR surface impoundments to have adequate hydraulic and hydrologic capacity to accommodate all contributory inflow to CCR surface impoundments, regardless of the inflow's origin.

The hydraulic and hydrologic capacity requirements will minimize the potential for overtopping to occur from normal or abnormal operations, overfilling, wind and wave action, rainfall, and run-on, and will ensure that the unit is operated with appropriate consideration of these potentially adverse conditions. The Agency notes, however, that the operating freeboard of a CCR surface

[111] *Federal Guidelines for Dam Safety: Selecting and Accommodating Inflow Design Floods for Dams.* August 1, 2013. FEMA P–94.

[112] All discharge from the CCR surface impoundment must be handled in accordance with the surface water requirements under § 257.3–3.

[113] *Incised CCR surface impoundment* means a CCR surface impoundment which is constructed by excavating entirely below the natural ground surface, holds an accumulation of CCR entirely below the adjacent natural ground surface, and does not consist of any constructed diked portion.

impoundment is subject to fluctuations, deviating from original design assumptions and specifications. Additionally, EPA notes that routine maintenance and alterations of hydraulic structures associated with the CCR surface impoundments, *e.g.,* decant structures and spillways, can adversely impact the hydrologic and hydraulic capacity of the CCR surface impoundment. At no point should the inflow design flood exceed the capacity of the CCR surface impoundment, regardless of fluctuations in freeboard, maintenance of hydraulic structures, or other potential obstructions to the hydraulic and hydrologic capacity of the unit. The owner or operator must account for operational changes or diminished capacity in the calculation of hydraulic and hydrologic capacity of the CCR unit.

3. Inflow Design Flood Control System Plan

The owner or operator of an existing CCR surface impoundment must prepare an initial inflow design flood control system plan to document that the design and construction of the system will achieve the rule's performance standards no later than 18 months after the publication of this rule in the **Federal Register**. New CCR surface impoundments or lateral expansions of CCR surface impoundments must prepare an initial inflow design flood control system plan no later than the date of initial receipt of CCR in the unit. The owner or operator must obtain a certification from a qualified professional engineer that the plan meets all applicable requirements of the rule for inflow design flood control system plans. The plan must also be supported by appropriate engineering calculations. This documentation should also include references, and drawings regarding the identification of the design storm for the catchment area affecting the CCR surface impoundment and the CCR surface impoundment itself, a characterization of the rainfall abstractions, including but not limited to depression storage and infiltration in the upstream catchment area affecting the CCR surface impoundment. In addition, EPA expects supporting documentation to address the selection and basis of an appropriate run-off model and an appropriate run-on or run-off routing model; the identification and characterization of any intake or decant structures of the CCR surface impoundment; an appropriate characterization of the spillway(s) of the CCR surface impoundment and their capacity; and characterization of downstream hydraulic structures which ultimately receive the discharge from the CCR surface impoundment. Finally, the owner or operator must comply with the recordkeeping, notification and internet requirements specified in the rule for the plan.

The owner or operator may amend the written inflow design flood control system plan at any time prior to receipt of CCR in the CCR unit, during the operating life of the CCR unit, during closure of the CCR unit, or following closure of the CCR unit provided the revised plan is placed in the facility's operating record. The owner or operator must amend the written inflow design flood control system plan whenever there is a change in the conditions that would substantially affect the written plan in effect. The owner or operator of the CCR surface impoundment must also periodically update the inflow design flood control system plan. The owner or operator must review or update an existing plan at a frequency no less than every five years. Changes in storm characteristics (*e.g.,* intensity and duration) and upstream catchment area characteristics, hazard potential classifications, as well as build-out, operational changes, and diminishing available capacity, all have the potential to influence inflow design flood volumes and therefore the effectiveness of the existing inflow design flood control systems. A periodic review of the plan to address these and other factors is necessary to ensure that the hydrologic and hydraulic capacity of the unit is maintained over time. An update of the inflow design flood control system plan should document any modifications pertinent to the inflow design flood control system.

The owner or operator may amend the written inflow design flood control system plan at any time and must place the revised plan in the facility's operating record. However, the owner or operator must amend the written inflow design flood control system plan whenever there is a change in the conditions that would substantially affect the written plan in effect. The owner or operator of the CCR unit must also review and, where necessary, update an inflow design flood control system plan every five years. As part of this review, the owner or operator must obtain certification from a qualified professional engineer must certify that the inflow design flood control system plan, and any subsequent amendments continues to meet the requirements of the rule. The date of completion of the initial plan is the basis for establishing the deadline to complete the first subsequent plan. The owner or operator may complete any required plan prior to the required deadline, and must place the completed plan into the facility's operating record within a reasonable amount of time.

I. Operating Criteria—Inspection Requirements for CCR Surface Impoundments

EPA proposed structural stability requirements for CCR surface impoundments based on the long-standing MSHA requirements, with only minor modifications. These structural stability requirements were covered in various sections of the proposed rule (see specifically proposed §§ 257.71, 257.72, 257.83, and 257.84). Section 257.83 addressed requirements for periodic inspections of CCR surface impoundments. In proposing these requirements, the Agency concluded that periodic inspections were critical to ensure that any problems relating to structural stability are quickly identified and remedied to prevent catastrophic releases, such as occurred at Martins Creek, Pennsylvania and TVA's Kingston, Tennessee facility. The proposed rule required owners or operators to conduct: (1) Weekly inspections to detect potentially hazardous conditions or structural weakness; and (2) annual inspections to assure that the design, operation, and maintenance of the surface impoundment was in accordance with generally accepted engineering standards. EPA proposed that weekly inspections be conducted by a person qualified to recognize specific signs of structural instability and other hazardous conditions by visual observation and, if applicable, to monitor instrumentation. The proposed rule also required annual inspection reports from an independent registered professional engineer, certifying that the design, operation, and maintenance of the CCR surface impoundment was in accordance with generally accepted engineering standards. Consistent with the annual inspection requirements, EPA, as part of its recordkeeping requirements also proposed that owners or operators of CCR surface impoundments annually document and report on, among other things: (1) Changes in the geometry of the impounding structure; (2) location and type of instrumentation monitoring the unit; (3) the minimum, maximum and present depth and elevation of the impounded water, sediment or slurry for the reporting period; and (4) storage capacity of the impounding structure (see 75 FR at 35246).

The annual inspection provisions also required that if a potentially hazardous

condition developed, the owner or operator must immediately take several actions: Eliminate the potentially hazardous condition; notify potentially affected persons and state and local first responders; notify and prepare to evacuate, if necessary, all personnel from the property who may be affected by the potentially hazardous condition(s); and direct a qualified person to monitor all instruments and examine the structure at least once every eight hours, or more often as required by an authorized representative of the state. Finally, the proposed rule required that inspection and monitoring reports be maintained in the facility operating record and placed on the facility's publicly accessible Internet site as well as promptly reporting the results of the inspection or monitoring to the state.

EPA specifically requested comment on whether to cover all CCR impoundments for stability (including the inspection requirements), regardless of height and storage volume, whether to use the cut-offs in the MSHA regulations, or whether other regulations, approaches, or size cut-offs should be used. The Agency further requested commenters who believed that other regulations or size cut-offs should be used (and not the size cut-offs established in the MSHA regulations) to provide the basis and technical support for their position. (75 FR 35176, 35223). In response to EPA's general solicitation for alternative size cut-offs, the Agency received little response. However, many commenters questioned EPA's decision to require inspections for all CCR surface impoundments, given that the other structural stability requirements were triggered only if the CCR unit exceeded the proposed size threshold (consistent with MSHA requirements). Commenters argued that there was no basis to require inspections of all CCR surface impoundments given that units below the specified size threshold had a much lower risk of catastrophic failure. A more limited requirement the commenter's argued, was supported by MSHA's decision to regulate only those ''larger'' sized units. Other commenters argued that inspection timeframes should take into account site specific conditions at the site and be based on the recommendations of an independent registered professional engineer. Commenters reasoned that while, in theory, a short inspection interval (*i.e.,* a weekly inspection) should increase the chances of finding an adverse condition, the judgment of a qualified professional engineer to establish the frequency and focus, as well as the purpose of the dam safety inspection was a far more effective method for detecting and preventing the development of a potentially adverse situation. Still other commenters questioned the overall value of a weekly inspection if, as proposed, no documentation of the results was required.

In reviewing the proposed regulatory language, it appears an error was made. Although the preamble generally stated that the proposed regulatory requirements addressing stability (which included inspections) applied only to those CCR surface impoundments exceeding the specified size threshold established by the MSHA regulations, the regulatory text required inspections for all CCR units. The final rule requires weekly general inspections and monthly instrumentation inspections to be conducted for all CCR surface impoundments. Periodic inspections of all CCR units are a necessary practice to ensure that the overall structural integrity of the CCR unit is maintained and that actual and potential structural weaknesses and other hazardous conditions are quickly identified and remediated throughout the active life of the unit. All CCR surface impoundments pose some risk of release—whether from a catastrophic failure or from a more limited structural failure, such as occurred at Duke Energy's Dan River plant. Periodic inspections are a generally accepted, prudent engineering practice that will significantly reduce the risks of such failures; during the Assessment Program, EPA discovered that many facilities routinely conduct some sort of periodic inspection and monitoring, although the frequency varied widely between facilities. The final rule merely codifies this practice, by establishing a consistent minimum timeframe. EPA is therefore requiring that all CCR surface impoundments be inspected by a qualified person both weekly (for visual signs of a potentially adverse condition) and monthly (for instrumentation monitoring). Consistent with the proposed rule, EPA is also requiring annual inspections for all CCR surface impoundments that exceed the specified size threshold of: (1) A height of five feet and a storage capacity of 20 acre-feet; or (2) a height of 20 feet, must also be inspected no less than annually by a qualified professional engineer. These inspection requirements are generally being promulgated as proposed, with minor technical clarifications.

The final inspection requirements have been drawn heavily from guidelines established by FEMA for dam safety, under which maintaining structural integrity involves continuous evaluation of the unit, based on periodic inspections. To be most effective, FEMA suggests, and EPA concurs, that inspections be varied with respect to both the time interval between inspections and the level of detail of the inspection. FEMA guidance, in part, suggests that inspections can be categorized as either: Visual observations to identify abnormal conditions (*i.e.,* informal inspections); field inspections by a professional engineer (*i.e.,* intermediate inspections); and a technical review to determine if the unit meets current and accepted design criteria and practices (*i.e.,* formal inspection).[114] In general, FEMA recommends that inspections focusing on visual observations should be conducted often (*e.g.,* weekly) while more substantive technical evaluation should be conducted every year to every five years depending on the engineering analyses required. (See also the preamble discussion on the requirements specified in §§ 257.73 and 257.74 of this rule, in particular the discussion addressing the five year time interval for structural stability and factor of safety reassessments.)

For the reasons discussed above, EPA has concluded, consistent with FEMA guidelines, that routine inspections of all CCR units are necessary to ensure that the units are safely operated and that issues that could disrupt the safety and continuing operation of these units are promptly identified and remediated. Accordingly, the final rule requires both weekly inspections and monthly instrumentation inspections to be conducted at all CCR surface impoundments to confirm that they are operating safely. These inspections must be conducted by a qualified person trained to recognize specific signs of structural instability and other hazardous conditions by visual observation and if, applicable monitor instrumentation. EPA is also retaining the annual inspection requirement for CCR surface impoundments exceeding the specified size threshold established in this rule. This inspection must be conducted and certified by a qualified professional engineer. Units exceeding this size threshold pose a higher degree of risk of release of CCR to the environment than other types of CCR surface impoundments (*e.g.,* incised or ''small'' CCR units) and as such warrant additional regulatory control and oversight.

[114] See ''*Federal Guidelines for Dam Safety*'' Federal Emergency Management Agency. (Reprinted April 2004).

The final rule requires that both weekly inspections of the CCR unit and monthly monitoring of CCR unit instrumentation be initiated within 6 months of the publication of the rule.

Within nine months of the publication of the rule, the owner or operator must complete the initial annual inspection of the CCR unit. Initial annual inspection requires the retaining of a professional engineer along with the familiarization of the engineer with the facility and CCR units. Additionally, the annual inspection should not be conducted unless weekly inspection and monthly instrumentation monitoring has been initiated and established in order to generate a body of information for the professional engineer to consider. Furthermore, in some cold-weather regions of the United States, weather may inhibit adequate inspection of CCR units, whether through snow or ice cover. EPA is establishing a timeframe of nine months after the publication of the rule so as to allow for adequate weather conditions for inspection.

1. Surface Impoundment Inspection Requirements

a. Weekly Inspections

As presented in the proposed rule and finalized here, this rule requires all CCR surface impoundments to be examined by a qualified person at least once every seven days for any appearance of actual or potential structural weakness or other conditions that are disrupting or that have the potential to disrupt the operation or safety of the CCR unit. The results of the inspection by a qualified person must be recorded in the facility's operating record.

Weekly inspections are intended to detect, as early as practicable, signs of distress in a CCR surface impoundment that may result in larger, more severe conditions. They are also designed to identify potential issues with hydraulic structures that may affect the structural safety of the CCR surface impoundment and impact the hydraulic and hydrologic capacity of the CCR surface impoundment. The early detection of signs of structural weaknesses is an essential preventative measure which helps to impede structural failure. The required weekly inspections are designed to identify such signs of structural weakness before they develop into larger, debilitating concerns in the structural stability of the dike.

Appearances of structural weakness may include, but are not limited to: (1) Excessive, turbid, or sediment-laden seepage; (2) signs of piping and other internal erosion; (3) transverse, longitudinal, and desiccation cracking; (4) slides, bulges, boils, sloughs, scarps, sinkholes, or depressions: (5) Abnormally high or low pool levels; (6) animal burrows; (7) excessive or lacking vegetative cover; (8) slope erosion; and (9) debris.

In addition, EPA is also adopting a new provision that requires the qualified person to inspect the discharge of all outlets of hydraulic structures which pass underneath the base of the CCR surface impoundment or through the dike of the CCR unit for abnormal discoloration, flow, or discharge of debris or sediment. The requirement is being added to aid in the identification of any internal or sub-surface issues which cannot be reasonably identified in a routine visual inspection. Abnormal discharges from hydraulic structures are often an indication of potential issues with the sub-surface or internal integrity of the structure. Hydraulic structures, particularly corrugated metal pipe, are subject to deterioration and corrosion over time and, as deterioration proceeds, the hydraulic structure becomes more susceptible to collapse, translation, or malfunction. Issues with hydraulic structures within the dike may exacerbate structural or operational issues with the CCR surface impoundment due to the significant internal deterioration of the dike via the hydraulic structure. As an example, on February 2, 2014, Duke Energy's Dan River Fossil Plant experienced a structural collapse of a corrugated metal storm water discharge pipe which passed underneath the interior of a CCR surface impoundment. The subsequent collapse of the base of the CCR surface impoundment led to a massive release of CCR to the environment. Additionally, the adjacent dike of the CCR surface impoundment was severely damaged due to the erosion of the upstream slope.

Further, an owner or operator may want to consider inspections outside of the weekly, seven-day schedule if an unanticipated event, such as a flood, earthquake, or vandalism occurs on the site. While rare in occurrence, these events may increase the chances that a potential structural stability issue has arisen. Prudent CCR management practices dictate that a visual assessment is warranted after such events. For example, after a large flood (considered a flood with a return period of equal or greater frequency of ten years) there is potential for damage, including structural damage to the CCR surface impoundment, caused by increased reservoir levels that inundate areas infrequently inundated. The slopes of the dike should be inspected to ensure that no significant erosion has occurred due to the flood, or that any large debris or sediment has been deposited on the dike. An inspection should also be conducted following an earthquake where earthquake damage is observed or can be reasonably expected, where ground motion is felt at the CCR surface impoundment or in nearby locations, or following established magnitude-epicenter distance relationships.[115]

b. Monthly Instrumentation Inspection

In a departure from the proposed rule, EPA is requiring the monitoring of all instrumentation supporting the operation of the CCR unit to be conducted by a qualified person no less than once per month. This is a change from the proposal which required instrumentation to be monitored no less than every seven days.

Many commenters argued that requiring inspections every seven days was excessive, and that, based on FEMA guidelines for dam safety, a more reasonable timeframe would be once per month for CCR surface impoundments with a hazard potential rating of ''high'' and quarterly for those CCR surface impoundments with a hazard potential rating of ''significant.'' In considering these comments, the Agency was influenced by a number of factors including the FEMA guidelines suggested by the commenters. Also weighing heavily in EPA's decision were the observations made as part of the Assessment Program, which revealed that many CCR units are equipped with only ''basic'' measuring devices such as piezometers and pool elevation and freeboard instrumentation and not the more sophisticated (*i.e.,* sensitive) measuring devices for measuring pressure, seepage, internal movement, slope movement; and vibration. These findings strongly suggested to the Agency that, given the status of current instrumentation employed at CCR facilities, weekly monitoring would be excessive, impractical, and—of greatest significance—unlikely to indicate any measurable changes in structural stability in such a short timeframe. EPA, therefore, agrees that a monthly timeframe is a more appropriate interval for detecting discernible or significant changes in the operation of the CCR

[115] The U.S. Army Corps of Engineers have developed useful criteria for post-earthquake inspections, specifically their published magnitude-epicenter distance criteria in Table 11.1 of ''Safety of Dams—Policy and Procedures,'' ER 1110–2–1156, 31 March 2014.[115] The criteria stipulate when the dam (or in the case of this rule, CCR surface impoundment) should be inspected.

unit. EPA has not, however, differentiated between high, significant, and low hazard potential CCR surface impoundments in the requirement that instrumentation be monitored monthly, as commenters suggested. Through the assessment effort, EPA identified that typically low hazard potential CCR surface impoundments were monitored less frequently than high- or significant hazard potential CCR surface impoundments by the owner or operator. Additionally, these low hazard potential CCR surface impoundments less commonly were equipped with sophisticated monitoring instrumentation, including remote monitoring instrumentation which would allow the owner or operator to monitor the unit from a remote location. Based on these observations, along with the limited burden that instrumentation monitoring places on the owner or operator, the rule requires all CCR surface impoundments with instrumentation to be monitored monthly.

c. Annual Inspections

The rule requires owners or operators of any CCR surface impoundments exceeding the MSHA size threshold (*i.e.,* a height of five feet or more and a storage volume of 20 acre-feet or more; or a height of 20 feet or more) to conduct annual inspections of the CCR unit throughout its operating life. These annual inspections are focused primarily on the structural stability of the CCR surface impoundment and must ensure that the operation and maintenance of the CCR surface impoundment is in accordance with recognized and generally accepted good engineering standards. Inspections must be conducted and certified by a qualified professional engineer.[116] Incised CCR surface impoundments, as defined in § 257.53 are not subject to the annual inspection requirements. Incised units present lower risks of structural failure, and so weekly inspections are sufficient to address any risks associated with these CCR units.

Annual inspections of any CCR surface impoundment must include, at a minimum: (1) A review of all previously generated information regarding the status and condition of the CCR unit, including, but not limited to, all operating records and publicly accessible internet site entries, design and construction drawings and other documentation; (2) a thorough visual inspection to identify indications of distress, unusual or adverse behavior, or malfunction of the CCR unit and appurtenant structures; and (3) a thorough visual inspection of hydraulic structures underlying the base of the CCR unit and passing through the dike of the CCR unit for structural integrity and continued safe and reliable operation. Additionally, following each inspection, the qualified professional engineer must prepare an inspection report which documents the following: (1) Any changes in geometry of the impounding structure since the previous annual inspection; (2) the location and type of existing instrumentation and the maximum recorded readings of each instrument since the previous annual inspection; (3) the approximate minimum, maximum, and present depth and elevation of the impounded water and CCR since the previous annual inspection; (4) the storage capacity of the impounding structure at the time of inspection; (5) the approximate volume of the impounded water and CCR at the time of the inspection; and (6) any appearances of an actual or potential structural weakness of the CCR unit, in addition to any existing conditions that are disrupting or have the potential to disrupt the operation and safety of the CCR unit and appurtenant structures; and (7) any other change(s) which may have affected the stability or operation of the impounding structure since the previous annual inspection.

This last set of requirements was originally presented in § 257.84 of the proposed rule (*i.e.,* recordkeeping requirements), however, the Agency has moved these requirements to the annual inspection section of the rule because (1) these requirements apply only to CCR surface impoundments exceeding the specified size threshold, rather than all CCR surface impoundments, as proposed; (2) must be reported annually; and (3) are more appropriately housed in the inspection section.

The owner or operator of existing CCR surface impoundments must ensure that the initial annual inspection by a qualified professional engineer is completed and documented with a report no later than nine months after the publication of the rule. EPA established this timeframe for completing an initial annual inspection based on its experience with the Assessment Program. In an effort similar to conducting an initial annual inspection, the following tasks were generally completed within three months: Retaining the services of a qualified professional engineer, developing a scope of work, reviewing existing documentation on the CCR unit, conducting a thorough field inspection, and completing an inspection report. Owners and operators of new CCR surface impoundment must commence annual inspections no later than one year from the initial placement of CCR into the new unit. An annual inspection is not required in any calendar year in which the five year structural stability reassessment is also required to be completed. (See §§ 257.73 and 257.74.) The report which the qualified professional engineer has certified must be placed in the facility's operating record and placed on the facility's publicly accessible internet site. An annual inspection is considered complete when the inspection report has been placed in the facility's operating record. Finally, if a deficiency is identified during an inspection, the owner or operator must take immediate measures to remedy the structural weakness or disrupting condition as soon as feasible.

J. Operating Criteria—Inspections for CCR Landfills

Under 40 CFR part 258, EPA does not require specific inspection requirements for MSWLFs. Rather, EPA relies on states to establish their own inspection criteria and frequency of inspections to ensure protection of human health and the environment. It is the Agency's understanding that many states require owners or operators of MSWLFs to conduct either daily, weekly, quarterly and annual inspections of these units to ensure that the design, construction, operation, and maintenance complies with all requirements. In addition, based on a review of selected state regulations most states conduct state inspections of operating landfills no less than annually.

Under the proposed subtitle D option, EPA did not propose to require mandatory inspections of new or existing landfills or any lateral expansion. However, under the subtitle C option, EPA proposed to apply the requirements of § 264.303 to permitted CCR landfills. Specifically, these requirements stated that CCR landfills while in operation would be required to be inspected weekly and after storms to detect evidence of any of the following: (1) Deterioration, malfunctions, or improper operation of run-on and run-off control systems; (2) proper functioning of wind dispersal control systems, where present; and (3) the presence of leachate in and proper functioning of the leachate collection and removal system where present. (See proposed § 264.1306, 75 FR 35257).

[116] For purposed of this requirement, qualified means an individual experienced in the operation and maintenance of dams and who has been trained to recognize signs of concern and structural weakness by visual observation, and if applicable, to monitor instrumentation.

Upon further evaluation, the Agency has decided, consistent with the weekly inspection requirements proposed for CCR landfills under the subtitle C option, as well as many state requirements for MSWLFs, to require all existing and new CCR landfills and any lateral expansion to conduct, at intervals not exceeding seven days, inspections by a qualified person for any appearances of actual or potential structural weakness or any other conditions which are disrupting or have the potential to disrupt the operation or safety of the CCR landfill. In addition, EPA is also requiring inspections by a qualified professional engineer at intervals not exceeding one year to ensure that the design, construction, operation, and maintenance of the CCR landfill is consistent with recognized and generally accepted good engineering standards. This inspection must include a review of all data in the operating record as well as a visual inspection of the unit to identify signs of distress or malfunction that is or potentially could affect the safe operation of the unit. The qualified professional engineer must then also prepare a report to identify and discuss the findings of the inspection as well as a discussion of potential remedies for addressing any deficiencies discovered during the inspection. The Agency has concluded that all CCR landfills should be routinely inspected to ensure that they are operating as designed and are being maintained in compliance with the federal criteria.

The Agency is promulgating these inspection requirements based on: (1) A review of state municipal landfill inspection requirements; and (2) comments from parties that clearly supported inspections of all CCR landfills. The Agency reviewed MSWLF inspection checklists in a selected number of states to assess the scope of these inspections. The Agency also conducted a preliminary review of state MSWLF regulations for New York, Pennsylvania, Ohio, Wisconsin, Illinois, Missouri, North Dakota and California. All of these states require MSWLF owners or operators to conduct a either daily, weekly, monthly, quarterly and annual inspections addressing the following: (1) Proper placement of the waste; (2) slope stability and erosion control; (3) surface water percolation is minimized (*i.e.* reduce ponding); (4) liner systems and leachate collection systems are properly operated and maintained; (5) water quality monitoring systems are maintained and operating; (6) dust is controlled; and (7) a plan is in place to promptly address and correct problems and deficiencies discovered during the inspection. The Agency also noted during its review of state regulations that states reserve the right to inspect landfills at any time and routinely conduct state inspections on a no less than annual basis. CCR landfills present at least the same level of risks as MSWLFs, and while the operations may differ, both operating systems are equally susceptible to malfunction. Weekly inspections of all CCR landfills by a qualified person are therefore equally necessary to ensure that groundwater monitoring, run-on and run-off controls, liner systems, and leachate collection systems are operated and maintained to reduce adverse environmental and human health impacts.

This rule also requires that owners or operators of all existing and new CCR landfills and any lateral expansion conduct an annual inspection, certified by a qualified professional engineer, to assure that these units are designed, constructed, operated, and maintained throughout their operating life to ensure protection of human health and the environment. The Agency finds that annual inspections for these units are justified for a number of reasons. First, CCR landfills are large engineered units that require that a variety of design and operating parameters be assessed to assure that the CCR landfill is operating as designed. Of particular concern to the Agency is the fact that coal ash is a fine grained material that may have the potential to compact and clog leachate collection systems (see: ''Operations and Maintenance Guidelines for Coal Ash Landfills'' Christopher Hardin, et. al. 2011 World of Coal Ash Conference. May 2011). It is reasonable therefore that the rule requires annual inspections to assure that these liner and leachate systems are assessed to assure that they are performing their functions as designed. Second, a formal annual inspection would review data collected during weekly inspections and determine if any remedial actions are need to address deficiencies. Third, the annual review by a qualified professional engineer ensures that a detailed level of engineering analysis of operating conditions are evaluated which could lead to recommendations to address design or operating issues that need attention.

K. Groundwater Monitoring and Corrective Action

EPA is finalizing groundwater monitoring and corrective action requirements to ensure that groundwater contamination at new and existing CCR units will be detected and cleaned up as necessary to protect human health and the environment. These requirements reflect Congressional intent that protection of groundwater be a prime objective of any new solid waste regulations. As stated in the proposal, EPA's damage cases and risk assessments indicate there is significant potential for CCR landfills and CCR surface impoundments to leach hazardous constituents into groundwater, impair drinking water supplies and cause adverse impacts on human health and the environment. Indeed, groundwater contamination is one of the key environmental and human health risks EPA has identified with CCR landfills and CCR surface impoundments. Groundwater monitoring is a key mechanism for facilities to verify that the existing containment structures, such as liners and leachate collection and removal systems, are functioning as intended. Thus, in order for a CCR landfill or CCR surface impoundment to show no reasonable probability of adverse effects on health or the environment, a system of routine groundwater monitoring to detect any contamination from a CCR unit, and corrective action requirements to address identified contamination, are essential.

EPA proposed to require that a system of monitoring wells be installed at all new and existing CCR units. The regulation would also provide procedures for sampling these wells and methods for statistical analysis of the analytical data derived from the well samples to detect the presence of hazardous constituents released from these CCR units. The Agency proposed a groundwater monitoring program consisting of detection monitoring and assessment monitoring, and a corrective action program. This phased approach to groundwater monitoring and corrective action programs provides for a graduated response over time to the problem of groundwater contamination as the evidence of such contamination increases. This allows for proper consideration of the transport characteristics of CCR constituents in groundwater, while protecting human health and the environment.

EPA largely based these proposed groundwater monitoring requirements on those for MSWLFs in the 40 CFR part 258 criteria, albeit with certain modifications to tailor the requirements to the case at hand. In particular, the possibility that a state may lack a permit program for CCR units made it impossible to include some of the alternatives available in 40 CFR part 258, which establish alternative standards that allow a state, as part of

its permit program to tailor the default requirements to account for site specific conditions at the individual facility. EPA also sought to tailor the proposed requirements for CCR units, by incorporating certain provisions from the interim status regulations, which operate in the absence of a permit, and by including in several of the proposed requirements, a certification by an independent registered professional engineer that the rule's requirements had been met.

In the proposed rule, the Agency required facilities to install a groundwater monitoring system that met a specified performance standard and that consisted of a minimum of one upgradient and three downgradient wells at all CCR units. EPA acknowledged in the proposal that the design of an appropriate groundwater monitoring system is particularly dependent on site conditions relating to groundwater flow, and on the development of a system that has a sufficient number of wells, installed at appropriate locations and depths, to yield groundwater samples from the uppermost aquifer that represent the quality of background groundwater that has not been affected by contaminants from a CCR unit. EPA's existing requirements under 40 CFR parts 258 and 264 recognize this, and because they operate in a permitting context, these requirements provide more flexibility in establishing groundwater monitoring systems. But because the same guarantee of permit oversight is not available under the criteria developed for the proposal, EPA proposed to establish a minimum requirement based on the part 265 interim status regulations, which are self-implementing. Long experience demonstrates that these monitoring requirements will be protective of a wide variety of conditions and wastes, and that facilities can feasibly implement these requirements. EPA also noted that in many instances a more detailed groundwater monitoring system will need to be in place, and EPA therefore proposed requiring a certification by the independent registered professional engineer that the groundwater monitoring system is designed to detect all significant groundwater contamination.

EPA also proposed to require that owners and operators of CCR units establish consistent sampling and analysis procedures to determine whether a statistically significant increase in the level of a hazardous constituent(s) has occurred, indicating the presence of groundwater contamination.

As noted, EPA proposed a phased approach to monitoring. The first phase is detection monitoring where indicators would be monitored to determine whether groundwater was potentially being contaminated. The parameters EPA proposed to be used as indicators of groundwater contamination were the following: Boron, chloride, conductivity, fluoride, pH, sulfate, sulfide, and total dissolved solids (TDS). In selecting the parameters for detection monitoring, EPA chose constituents that are present in CCR and would rapidly move through the subsurface, and thus provide an early detection of whether contaminants were migrating from the CCR unit. Under the proposed rule, monitoring would be required no less frequently than semiannually.

When a statistically significant increase over background levels is detected for any of these parameters, the proposed rule required the facility to begin an assessment monitoring program to determine if releases of CCR constituents of concern had occurred. The parameters that were proposed for assessment monitoring were aluminum, antimony, arsenic, barium, beryllium, boron, cadmium, chloride, chromium, copper, fluoride, iron, lead, manganese, mercury, molybdenum, pH, selenium, sulphate (sic), sulfide, thallium, and total dissolved solids.

The proposed rule also required that whenever monitoring results indicate a statistically significant level exceeding the groundwater protection standard for any of these parameters, the owner or operator must start the process for cleaning up the contamination, and initiate an assessment of corrective action remedies. The proposed rule required that the assessment of correction action remedies be initiated within 90 days and then completed within 90 days.

EPA proposed that the assessment of corrective measures must consider a number of factors, including the effectiveness, performance, and time needed for the potential remedies. As part of the assessment of corrective measures, the owner or operator was required to identify the source of the release. The owner or operator was also required to gather data on plume definition, fate of the contaminants, stratigraphy and hydraulic properties of the aquifer. The owner or operator also was required to consider whether immediate measures to limit further plume migration or measures to minimize further introduction of contaminants to groundwater would be necessary. EPA also proposed to require the owner or operator to provide notification of the corrective measures assessment to the State Director, place the corrective measures assessment in the operating record and on the owner's or operator's publicly accessible internet site, and discuss the results of the corrective measures assessment in a public meeting with interested and affected parties.

Based on the results of the corrective measures assessment, EPA proposed to require the owner or operator to select a remedy based on a number of factors, including: the long- and short-term effectiveness and protectiveness of the potential remedy, along with the degree of certainty that the remedy will prove successful; the effectiveness of the remedy in controlling the source to reduce further releases; the ease or difficulty of implementing a potential remedy; the degree to which community concerns are addressed by a potential remedy; and potential risks to human health and the environment from exposure to contamination prior to completion of the remedy. The owner or operator was also required to specify as part of the selected remedy a schedule for initiating and completing remedial activities.

Under the proposed rule, implementing the corrective action program required the owner or operator to establish and implement a corrective action groundwater monitoring program; implement the corrective action remedy selected; and take any interim measures necessary to ensure the protection of human health and the environment, all according to the schedule the owner or operator developed during the assessment of corrective measures.

The proposed rule also required that the owner or operator must demonstrate that concentrations of constituents have not exceeded the groundwater protection standards for three consecutive years in order to support a determination that the remedy is complete.

The majority of the commenters supported ''appropriate groundwater monitoring standards for CCR waste management units'' and the development of such standards under a RCRA subtitle D framework. Comments were received on various parts of the groundwater monitoring scheme laid out in the proposed rule. The majority of comments received requested EPA to provide ''more flexibility'' to the proposed requirements. Many commenters wanted the states to be more involved with the process and provided comments suggesting that additional ''flexibility,'' such as is provided in the 40 CFR part 258

regulations for MSWLFs as part of the permitting process, be extended to CCR units. For example, commenters wanted states to have the authority to add or drop monitoring constituents; approve alternative schedules; modify the number of wells needed; allow variances; allow alternatives to the point of compliance specified in the rule; employ alternative methods to detect potential groundwater contamination, such as leak detection systems; allow alternatives to the statistical methods used to determine whether groundwater contamination has occurred; and to replace the qualified professional engineer role in the certification process.

For the final rule, EPA has developed a groundwater monitoring program that is flexible and allows facilities to design a system that accounts for site specific conditions within specific parameters. The final rule establishes an overall performance standard that the system must meet, lays out the minimum requirements of an effective system, and requires the owner or operator to design a system that achieves that overall performance standard based on a full characterization of site conditions.

As described in more detail below, in certain cases, EPA was able to develop performance standards to serve as ''more flexible'' alternatives to the technical specifications laid out in the proposal. In these instances, the available information allowed the Agency to develop performance standards that were sufficiently objective and determinate that EPA could conclude that the 4004(a) standard would be met nationwide.

However, many of the commenters' requests related to alternatives that would be less stringent than the minimum criteria laid out in the proposal and were based on arguments that state regulators (or facilities) should be allowed to ''tailor'' those requirements to sites that did not need those particular requirements. As explained at length in the proposal, EPA is concerned that provisions allowing such modifications are particularly susceptible to abuse, since in many cases the provisions could allow substantial cost avoidance. In the absence of a mandated state oversight mechanism to ensure that the suggested modifications are technically appropriate, these kinds of provisions can operate at the expense of protectiveness. In Unit II of this preamble, EPA explains the extent of our authority to establish criteria under RCRA sections 1008(a)(3) and 4004(a), including the implications associated with the lack of any authority to establish a program analogous to part 258, which relies on approved states to implement the federal criteria through a permitting program. As a result of the statutory structure, this rule is self-implementing and is designed to operate to ensure that facilities will manage CCR in a manner that achieves the 4004(a) standard even in the absence of any regulatory entity available to judge the reasonableness of the desired alternatives. While some states currently do have programs for the regulation of CCR, which in some cases may be more stringent than this final rule, the federal program must be defensible on the record in place at the time the final rule is adopted. Based on the current rulemaking record, in most cases EPA lacked the information necessary to defend the commenters' less stringent alternatives (*i.e.,* the commenters' requested ''flexibilities'') to the minimum technical criteria specified in this rule for these units. Under both the subtitle C and part 258 programs, EPA can rely on subsequent proceedings to develop the information necessary to support such tailoring. This is clearly neither contemplated nor authorized under the regulatory program relevant to this rule.

In addition, given the extremely technical nature of these requirements, EPA remains concerned that such provisions would render the requirements appreciably more difficult for citizens to effectively enforce. Nevertheless, working within these constraints this rule specifically allows the qualified PE to design a system that accounts for site conditions within the parameters of the minimum technical criteria, and EPA has added language to the regulation that expressly clarifies this. Moreover, states that have programs can continue to impose more stringent requirements, and thus can require, for example, additional monitoring wells, monitoring of additional aquifers, and inclusion of additional parameters to the detection monitoring list or the assessment monitoring list. The following discussion addresses in more detail the technical requirements under groundwater monitoring and corrective action in the final rule.

1. Applicability

Consistent with the provisions in the proposed rule, the final rule requires a system of monitoring wells to be installed at all CCR landfills, CCR surface impoundments and lateral expansions. Existing CCR units must install the groundwater monitoring system, develop their groundwater sampling and analysis procedures, develop background levels for appendix III and appendix IV constituents, and begin detection monitoring (§ 257.90 through § 257.94) within two years of the effective date of this rule. The proposed rule required that existing CCR units comply with the groundwater monitoring requirements within one year of the effective date. EPA proposed one year believing that it would be feasible for facilities to install the necessary systems. EPA also believed that a one year timeframe would ensure that existing CCR disposal facilities begin monitoring groundwater as soon as possible, so that releases from existing CCR units are detected and addressed. Comments received on this issue argued that the one-year timeframe was not sufficient to complete a hydrogeologic study and develop a monitoring plan. Several commenters requesting more time mentioned staffing shortages and limited contractor and lab resources. One state, referencing its experience relating to development and implementation of groundwater monitoring systems, said that a one year timeframe to investigate, design and submit and obtain approval for the installation of an effective groundwater monitoring system was unreasonable. Most commenters thought that a timeframe of two years was reasonable. After review of the comments received on this issue and careful reexamination of the actual requirements in the final rule, EPA agrees that a one-year timeframe is not feasible, and has decided to extend the timeframes for completing installation of the system, including background monitoring, to two years. As important as it is to begin detecting and addressing releases to groundwater, it is equally important that these complex systems be designed and installed correctly. That generally entails a number of activities, many of which must occur sequentially, including: determining the uppermost aquifer, deciding whether to install a single or multi-unit monitoring system, collecting and evaluating hydrogeological information that can be used to model the site, characterizing the site geology, characterizing the groundwater flow beneath the site, determining the flow direction and hydraulic gradient, establishing horizontal and vertical flow direction, determining hydraulic conductivity, determining groundwater flow rate, determining the monitoring wells placement, selecting the drilling method, designing the monitoring wells, developing sampling and analysis procedures, choosing a statistical method for evaluating the data and

beginning detection monitoring. We also recognize that in some states, the state may require the owner or operator to receive state approval before they can install a groundwater monitoring system. Two years is a more reasonable timeframe in which to carry out these activities. New CCR landfills, new CCR surface impoundments and any lateral expansion must comply with these same requirements (§§ 257.90 through 257.94) before any CCR can be placed in the CCR unit.

Consistent with the proposal, the final rule also requires that the owner or operator of the CCR facility annually certify that each CCR unit is in compliance with the groundwater monitoring and corrective action provisions and provide a copy of this certification to the State Director. Because this is a self-implementing rule that relies on citizen enforcement, it is important for the owner or operator of the facility to periodically document that they are in compliance with the existing groundwater monitoring requirements, and an annual certification is the easiest and most effective way to achieve this. While the groundwater monitoring data will be made available on the owner or operator's publicly accessible Web site and in the operating record of the facility, the analysis of these data is complicated and requires a certain level of scientific expertise to analyze the data correctly. As such, a document that serves as both an interpretative record of scientific analysis and regulatory compliance is critically important to the successful implementation of a self-implementing rule that is to be enforced exclusively by citizens and the states. For similar reasons, the certification must also be placed in the operating record, provided to the State Director, and posted on the owner or operator's publicly accessible Web site.

The groundwater monitoring requirements must be met throughout the active life of the CCR unit, as well as during the closure and post-closure care period.

EPA has added a new provision to § 257.90 to address the corrective action requirements that apply when CCR have been released into the environment, such as from the kind of structural failure that occurred with TVA's Kingston Fossil Fuel plant release, or from the kind of release that occurred in North Carolina at the Dan River. EPA inadvertently drafted the corrective action requirements in the proposed rule to apply exclusively upon detection of groundwater contamination caused by a leaking unit. However, there is no reason to establish different corrective action provisions for conducting clean-up operations for different kinds of releases; the same general process is applicable to all kinds of releases.

The new provision requires that in the event of a release from a CCR unit, the owner or operator must immediately take all necessary measures to control the source(s) of releases so as to reduce or eliminate, to the maximum extent practicable, further releases of contaminants into the environment. The owner or operator of the CCR unit is also required to comply with all of the relevant corrective action requirements in §§ 257.96, 257.97, and 257.98.

2. Groundwater Monitoring System Requirements

EPA received comments that supported establishing more prescriptive requirements for the design of the groundwater monitoring system. For example, one commenter argued that three downgradient wells are insufficient to ensure detection of leakage from the very large disposal units typically used for CCR; due to uncertainty in flow directions, the perimeter of the CCR unit must be monitored on its cross-gradient, as well as downgradient sides. The commenter suggested that the minimum number of non-background monitoring wells should instead be three, plus one for every 500 feet of downgradient and cross-gradient perimeter of the CCR unit (*i.e.,* if the perimeter length adds up to 1200 feet, the minimum number of wells would be five), and that wells should be spaced no more than 500 feet apart along the downgradient and cross-gradient perimeter. EPA also received many comments arguing that the minimum requirements were overly prescriptive, and that the final rule should instead allow a professional engineer or hydrologist to design ''an alternative, but equally effective, groundwater monitoring program.'' The majority of comments on groundwater monitoring systems requested that EPA not promulgate requirements that would be incompatible with state requirements.

The final rule provisions are fundamentally the same as those in the proposal, although EPA has also added language to the regulations to better clarify how the requirements in the various sections collectively operate. The final rule establishes a general performance standard that all groundwater monitoring systems must meet: All groundwater monitoring systems must consist of a sufficient number of appropriately located wells (at least one upgradient and three downgradient wells) in order to yield groundwater samples from the uppermost aquifer that represent the quality of background groundwater and the quality of groundwater passing the waste boundary. This is the same performance standard included in the proposed rule. The objective of a groundwater monitoring system is to intercept groundwater to determine whether the groundwater has been contaminated by the CCR unit. Early contaminant detection is important to allow sufficient time for corrective measures to be developed and implemented before sensitive receptors are significantly affected. To accomplish this, the rule requires that wells be located to sample groundwater from the uppermost aquifer at the waste boundary. These requirements have been adopted without fundamental change from the proposal.

Because hydrogeologic conditions vary so widely from one site to another, the rule does not prescribe the exact number, location and depth of monitoring wells needed to achieve the general performance standard. Rather, the rule requires the owner or operator to install a minimum of one upgradient and three downgradient wells, and any additional monitoring wells necessary to achieve the general performance standard of accurately representing the quality of the background groundwater and the groundwater passing the waste boundary. The number, spacing, and depths of the monitoring wells must be determined based on a thorough characterization of the site, including a number of specifically identified factors relating to the hydrogeology of the site (*e.g.,* aquifer thickness, groundwater flow rates and direction). Further, any owner or operator who determines that the specified minimum number of wells is adequate must provide a factual justification for that decision. Factors that may substantiate a reduced density of groundwater monitoring wells includes simple geology (*i.e.,* horizontal, thick, homogenous strata that are continuous across site, with no fractures, faults, folds, or solution channels), a flat and constant hydraulic gradient, uniform hydraulic conductivity, low seepage velocity, and high dispersivity potential.

In essence, the rule establishes a presumption that the minimum of one upgradient and three downgradient wells is not sufficient, and requires the owner or operator to rebut that presumption in order to install only this minimum. This is fundamentally consistent with the proposed rule, which required the installation of a system that would achieve the general performance standard, as well as the

''minimum'' of one upgradient and three downgradient wells. The final regulation merely makes more explicit that both of these requirements must be met.

EPA considered establishing a more prescriptive set of requirements, including a specified number, location, and design of monitoring wells, but because of the highly site specific nature of developing an adequate groundwater monitoring system, determined that it lacked sufficient information to be able to design a single groundwater monitoring system that would be nationally protective at all sites. A properly designed system must account for many variables, most of which are highly dependent on the individual characteristics of the unit and the facility site. Consequently, the final rule leaves the exact system design to be determined by those at the site, including a qualified professional engineer, who can tailor the design of the system to the unit and site conditions.

Nevertheless, EPA is confident that the parameters laid out in the regulation will ensure that the design of groundwater monitoring systems at CCR facilities will be protective. As a practical matter, EPA expects that there will be few cases, if any, where four wells will be sufficient, given that this requirement was originally developed for hazardous waste management units that are typically much smaller than CCR units. As mentioned above, a small unit with simple geology, a flat and constant hydraulic gradient, uniform hydraulic conductivity, low seepage velocity, and high dispersivity potential would be the type of unit for which the minimum number of wells could be sufficient to meet the overall performance standard. Although EPA is finalizing a requirement for one upgradient and three downgradient wells as a regulatory minimum, the Agency expects large CCR units to have many more wells because most CCR sites have hydrologic settings that are too complex for the regulatory minimum to be adequate. Facilities with large CCR units could have as many as thirty or more downgradient wells. This is because the placement and spacing of detection monitoring wells along the downgradient perimeter of the CCR unit must be based on the abundance, extent, and physical/chemical characteristics of the potential contaminant pathways. All potential pathways need to be monitored.

Therefore, even though EPA is not requiring a specific number of wells, the Agency is confident that the combination of the requirements will ensure that protective groundwater monitoring systems will be installed. The owner or operator is required to install a sufficient number of wells to meet the performance standard in § 257.91(a)(1) and (2), provide a justification if they determine the required minimum is adequate, and have a qualified professional engineer certify that their groundwater monitoring system has been designed and constructed to ensure that the groundwater monitoring will meet this performance standard—*i.e.,* accurately represent the quality of groundwater that has not been affected by leakage from any CCR unit—that is, groundwater from background wells and the quality of groundwater passing the waste boundary.

The final rule establishes certain parameters regarding the location of the wells. Upgradient background wells must be located beyond the upgradient extent of potential contamination. However, groundwater quality in areas where the geology is complex can be difficult to characterize. If the facility is new, groundwater samples collected from both upgradient and downgradient locations prior to waste disposal can be used to establish background water quality. Downgradient wells to monitor for any contaminants leaking into the groundwater must be located at the hydraulically downgradient perimeter (*i.e.,* the edge) of the CCR unit or at the closest practical distance from this location.

Determining background groundwater quality by sampling wells that are not hydraulically upgradient may be necessary where hydrogeologic conditions do not allow the owner or operator to determine which wells are hydraulically upgradient (*e.g.,* floodplains, where nearby surface water can influence groundwater). In such cases, the rule allows the owner or operator to establish groundwater quality at existing units by locating wells that are not upgradient under certain conditions (§ 257.91(a)(1)). This provision may be used when hydrogeologic conditions do not allow the owner or operator to determine which wells are hydraulically upgradient and when sampling at other wells will provide data establishing background groundwater quality that is equally or more representative than that provided by upgradient wells. These conditions could include one or more of the following:

- The facility is located above an aquifer in which groundwater flow directions change seasonally.
- The facility is located near production wells that influence the direction of groundwater flow.
- Upgradient groundwater quality is affected by a source of contamination other than the CCR unit.
- The proposed or existing CCR unit overlies a groundwater divide or local source of recharge.
- Geologic units present at downgradient locations are absent at upgradient locations.
- Karst terrain or fault zones modify flow.
- Nearby surface water (*e.g.,* rivers) influences groundwater flow directions.

Additionally, there is nothing in the rule that would prevent the owner or operator from monitoring multiple aquifers in addition to the uppermost significant aquifer. Certain site conditions warrant more extensive monitoring requirements, as discussed in ''Technical Manual Solid Waste Disposal Facility Criteria'', EPA530–R–93–017, USEPA, November, 1993, Chapter 5, Subpart E, Ground-Water Monitoring and Corrective Action.

Each CCR unit must have its own groundwater monitoring system, unless the owner or operator chooses to install a multiunit groundwater monitoring system. The final rule specifies that if a multiunit system is installed, it must be based on the consideration of several factors, including the number, spacing, and orientation of the CCR units, the hydrogeologic setting, the site history and the engineering design of the CCR units. A multiunit groundwater monitoring system must be equally capable of detecting background and groundwater contamination at the waste boundary as an individual monitoring system. This documentation must be certified by a qualified professional engineer. Whether a single or multi-unit system has been installed, the monitoring wells must be cased in a manner maintaining the integrity of the borehole and must be maintained so as to meet design specifications. Both of these provisions have been adopted from the proposal without revision.

3. Sampling and Analysis Requirements

EPA received comment on several aspects of its proposed requirements for conducting groundwater sampling and analyses. Specifically mentioned here, commenters raised concern about the number of samples required to establish background concentrations and about the statistical test methodologies specified in the proposal. As discussed below, EPA has modified the rule to account for the issues raised by these commenters. The sampling and analysis requirements in the final rule have

otherwise been adopted from the proposed rule with only minor clarifications.

The rule provides procedures for sampling monitoring wells and methods for the statistical analysis of groundwater monitoring of appendix III (detection monitoring) and appendix IV (assessment monitoring) constituents that may be released from CCR units. The sampling and analysis program must include procedures and documentation for sample collection (including the frequency, water level measurements, well purging, field analyses, and sample withdrawal and collection); sample preservation and handling (including sample containers, sample preservation, sample storage and shipment); chain of custody control; analytical procedures (appropriate methods can be found in ''*Test Methods for Evaluating Solid Waste, Physical/Chemical Methods,*'' SW–846 (USEPA, 1986), *http://www.epa.gov/waste/hazard/testmethods/sw846/online/index.htm*); and quality assurance/quality control. More information and guidance can be found in ''*Technical Manual Solid Waste Disposal Facility Criteria,*'' EPA530–R–93–017, USEPA, November, 1993, Chapter 5, Subpart E, Ground-Water Monitoring and Corrective Action, as well as the ''*Unified Guidance Document: Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities,*'' March 2009, EPA 530/R–09–007.

Similar to the approach used in designing a groundwater a number of system, the final rule adopts a combination of a general performance standard for groundwater sampling and analytical methods, along with particular technical specifications that must be met. The general performance standard requires that the method used must accurately measure hazardous constituents and other monitoring parameters. In addition, the rule specifies that groundwater elevations must be measured in each monitoring well immediately prior to sampling. Also, the rate and direction of the groundwater flow in the uppermost aquifer must be determined each time groundwater is sampled. Further, the rule specifies that the background groundwater quality must be established at a hydraulically upgradient well for each of the monitoring parameters or constituents required by the applicable groundwater monitoring program, except as provided in § 257.91. The number of samples collected to establish groundwater quality data must be consistent with the appropriate statistical procedures determined for the specific statistical method chosen. The sampling must also be conducted to account for both seasonal and spatial variability in groundwater quality.

To establish background levels, the proposed rule required that ''a minimum of four independent samples from each background and downgradient well must be collected and analyzed . . .'' 75 FR 35247–35248 (proposed §§ 257.93(f) and 257.94(b)). This is the same sampling protocol that EPA adopted for both the subtitle C and part 258 groundwater monitoring requirements.

EPA received comments criticizing this sampling protocol. Several commenters stated that more than the required four samples were needed in order to adequately represent background water quality and reduce the number of false negatives. For example, one commenter argued that EPA should require a minimum of one year of monthly monitoring of background concentrations to characterize fluctuations in parameters that will be evaluated statistically. The commenter claimed that this would also help to ensure that quarterly monitoring events are properly timed. Another comment stated that more data points and time were needed to ensure statistical confidence in the data. By contrast, another commenter objected to the requirement to obtain four independent samples, arguing that this requirement was unnecessary and should be deleted. The commenter argued that this requirement was inconsistent with EPA's Unified Guidance (EPA, 2009) for Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities, which specifies that replicate samples (*i.e.,* multiple samples from the same location during a given sampling event) should typically be limited to the collection of two samples from the same location, rather than four. Another commenter requested clarification on the number of samples required when establishing background levels that would serve as the point of comparison in determining whether a statistically significant increase over background levels had occurred.

In response to these comments, EPA reviewed the available information to determine whether revisions to the proposed requirements were warranted.

More recent information developed since the promulgation of the subtitle C and part 258 groundwater monitoring requirements indicates that statisticians now generally consider sample sizes of four or less to be insufficient for good statistical analysis because the observations are too few to adequately characterize the parameters of the population. Tests utilizing a small background sample size have low statistical performance in terms of power and per-test false positive rates. In 2009, EPA issued a guidance document that accounts for more recent scientific developments, ''*Unified Guidance Document: Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities,*'' March 2009, EPA 530/R–09–007. This guidance recommends a minimum of eight to ten independent background observations be collected before performing the first statistical test. Sample sets of 20 are considered optimal.

RCRA regulations are predicated on having appropriate and representative background measurements. Samples should be tested against data which best represent current uncontaminated conditions. In addition, as discussed further in Unit VI.K.5 below, the detection of a statistically significant increase over background concentrations of the constituents of concern will have serious implications for unlined surface impoundments, as these units will be required to close whenever the facility makes such a finding. EPA is also cognizant of the significant differences between the subtitle C and part 258 regulations and the final regulations being promulgated for CCR units. Both the subtitle C and the part 258 MSWLF requirements are implemented under permit programs, under which regulatory authorities are specifically authorized to establish more stringent requirements to account for scientific advances (among other things). EPA expects that current permits generally specify a greater number of samples than the minimum laid out in the regulations (*i.e.,* more than four) to determine background concentrations. And because of this it is less critical that those regulations (subtitle C and part 258) reflect the most current science. By contrast, as previously discussed, the provisions adopted under this rule are self-implementing, and will only be updated through a subsequent rulemaking. Accordingly, the Agency agrees with the comments that four samples would be insufficient and has amended the rule to require the owner or operator to collect, at a minimum, eight statistically independent and identically distributed (spatially invariant) samples from each well for each monitoring parameter. Although still a small sample size by statistical standards, eight independent observations allows for minimally acceptable estimates of variability and evaluation of trend and goodness-of fit. While more samples, including a full

year of background monitoring, would be scientifically ideal, the Agency selected eight samples by balancing the minimum number needed to ensure the scientific accuracy of the results against the need to expedite initiating the groundwater monitoring process of detecting exceedances, along with any necessary corrective action at these facilities.

Background sampling (*i.e.,* the requirement to collect eight statistically independent samples from each well) must be completed for all appendix III and IV constituents by the end of the 24 month period to begin implementation of the groundwater monitoring program.

EPA has also revised the regulatory text relating to the number of samples that must be collected during subsequent sampling events after background concentrations have been established to clarify how the various provisions collectively operate. Consistent with the proposal, the final rule requires the owner or operator to collect and analyze the number of samples from each well necessary to be consistent with the statistical test selected under § 257.93(e) and with the unique characteristics of the site, but at minimum, to collect at least one sample from each background and downgradient well. In cases where the groundwater is ''well-behaved'' one sample from each compliance well could be all that the owner or operator would need to conduct the necessary comparisons. But if statistical assumptions are not met (*e.g.,* the observations are not statistically independent or background well data show trends) a comparison based on a single observation will not yield a significant result, and will likely result in a false positive. Further, detection monitoring tests, such as Student's t-test, look at the difference between the sample means (*e.g.,* upgradient vs downgradient) to determine when an observed difference should be considered more than a chance fluctuation. Every t-test assumes that the observations that make up each data group meet the requirements of statistical independence and stationarity. Therefore, the larger the sample size the more significant the result. In other words, a facility can choose to use only one observation (a group size of one), but the chances are good that the result derived would be non-significant, since there are many reasons sample means can vary. Consequently, it is likely to be in the facility's best interest to take more samples than the minimum, particularly in the early stages of monitoring. As monitoring continues, each successive sample will be added to the sampling data base, which will increase the confidence in the statistical analyses performed. Additional guidance on sample size can be found in the ''*Unified Guidance Document: Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities,*'' March 2009, EPA 530/R–09–007.

The requirements for applying statistical procedures in the rule are the same as those included in the proposed rule, which were based on the statistical procedures used in the MSWLF regulations. The rule requires the owner or operator to select from among the listed statistical procedures based on a determination that the test is appropriate for evaluating groundwater at that site. The statistical method chosen must be appropriate for the distribution of chemical parameters or hazardous constituents. The rule has been revised to include the clarification that normal distributions of data values shall use parametric methods and non-normal distributions shall use non-parametric methods. The rule identifies four statistical procedures, along with an alternative procedure that must meet the performance standard of § 257.93(g). The four specific statistical procedures provided in this final rule are: (1) A parametric analysis of variance followed by multiple comparison procedures to identify statistically significant evidence of contamination; (2) an analysis of variance based on ranks followed by multiple comparison procedures to identify statistically significant evidence of contamination; (3) a tolerance or prediction interval procedure; and (4) a control chart approach. The performance standard for the alternative method in subsection (g) is the same as the performance standard in the proposal, with minor revisions. EPA has deleted the performance standard ''protect human health and the environment'' in subsections (3), (4) and (5). While that standard is perfectly appropriate in a context in which a regulatory authority will apply the standard, EPA is concerned that a qualified professional engineer will be unable to certify that any alternative statistical method meets that standard. EPA received comments from professional engineers raising concern about their ability to certify that many of the requirements in the proposed rule had been met without further specification or clarification. To address those concerns, in those three provisions EPA has substituted a more objective performance standard that more precisely defines the relevant issues to be considered. Specifically, the subsections now specify that those approaches must be ''at least as effective as any other approach in this section for evaluating groundwater.''

The data objectives of the monitoring, in terms of the number of samples collected and the frequency of collection, must be consistent with the statistical method selected. Guidance on selecting a specific method is described in ''*Unified Guidance Document: Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities,*'' March 2009, EPA 530/R–09–007. The owner or operator must indicate in the operating record the statistical method that will be used in the analysis of groundwater monitoring results.

The owner or operator must conduct the statistical comparisons between upgradient and downgradient wells within 90 days of completion of each sampling event and receipt of validated data. The statistical comparison must be conducted in order to determine if a statistically significant increase has occurred over background levels for each parameter or constituent required in the particular groundwater monitoring program that applies to the unit as determined under §§ 257.94(a) or 257.95(a). This has been adopted without revision from the proposal.

EPA is finalizing as proposed the prohibition in § 257.93(b) on field filtering groundwater samples because filtration of samples for metals analyses will not provide accurate information concerning the mobility of metals contaminants, the primary objective of groundwater sampling. Metal contaminants may move through fractured and porous media not only as dissolved species, but also as precipitated phases, polymeric species, or adsorbed to particles of colloidal dimensions (<10 microns). For an assessment of mobility, all mobile species must be considered, including suspended or colloidal particles acting as absorbents for contaminants. Filtration of groundwater samples for metals analyses will not provide accurate information concerning the mobility of metal contaminants because some mobile species in solution are likely to be removed by filtration before chemical analysis. Significant underestimations of mobility may result if filters (typically 0.45 micron) are used to separate dissolved and particulate phases.

In its approach to sampling EPA is specifying in the final rule that owners and operators use 'total recoverable metals' concentrations in measuring groundwater quality. Measurement of total recoverable metals captures both the particulate fraction and dissolved

fraction of metals in natural waters. Exceedances of ambient water criteria on a total recoverable basis are an indication that metal loadings could be a stress to an ecosystem.

One commenter argued that to prohibit field filtering would potentially bias the results artificially high, particularly at sites where low yielding formations or naturally high levels of turbidity in groundwater are encountered. However, high turbidity can also be the consequence of faulty well design and/or construction, which causes the introduction of foreign materials (high turbidity) through created fracture pathways. A properly designed well should allow for sufficient groundwater flow for sampling, minimize the passage of materials into the well, and exhibit sufficient structural integrity to prevent collapse of the intake structure. It is vital that the well provide a representative hydraulic connection to the geologic formation of interest. Otherwise the water chemistry information cannot be correctly interpreted in relation to groundwater flow or transport of chemical constituents.

Sampling with no filtration means that increased importance is placed on proper well construction and purging sampling procedures to eliminate or minimize sources of sampling artifacts. There should be nothing in the well design that will lead to high levels of turbidity. Groundwater sampling should be conducted utilizing EPA protocol low stress (low-flow) purging and sampling methodology, including measurement and stabilization of key indicator parameters prior to sampling. For purposes of sampling, this final rule presumes that a properly constructed well is capable of yielding groundwater samples with low turbidity (≤5 Nephelometric Turbidity Units (NTU)), and by knowing the cause of turbidity the qualified professional engineer will be able to optimize well performance and reduce turbidity levels, eliminating the need for filtration.

EPA is revising § 257.93(i)(2) to specify a time period of 90 days to determine if a statistically significant increase over background concentrations of one of more of the contaminants has been detected. As proposed, this section specified: ''Within a reasonable period of time after completing sampling and analysis, the owner or operator of the CCR landfill or surface impoundment must determine whether there has been a statistically significant increase over background at each monitoring well.'' Commenters pointed out that this section of the regulation was very vague, and potentially unenforceable. Several commenters suggested that once sampling and analysis had been completed, 90 days would be a reasonable amount of time to complete the statistical analysis to determine whether an exceedance had occurred. No commenter suggested a longer period of time was necessary and that timeframe is consistent with the Agency's experience of the timeframes necessary to complete such analyses. Accordingly, we have revised the provision to require the determination of a statistically significant increase to be made within 90 days of sampling and analysis.

4. Detection Monitoring Program

With three exceptions, EPA is finalizing the regulatory provisions relating to detection monitoring as proposed. The three revisions are the appendix III list of monitoring parameters; the required number of samples to determine background concentrations; and the availability of an option to conduct detection monitoring on a less frequent basis due to a lack of groundwater.

The detection monitoring phase of the groundwater monitoring program in this rule requires that the owners or operators of CCR units establish background concentrations for all monitoring parameters (appendix III and IV of part 257) and sample at least semiannually during the active life of the facility, closure, and post closure periods for a set of detection monitoring indicator parameters (appendix III of part 257).

In response to comments, EPA has revised appendix III to delete conductivity and sulfide from the list of monitoring parameters and to add calcium. Thus, the list of parameters included on the detection monitoring list is boron, calcium, chloride, fluoride, pH, sulfate and total dissolved solids (TDS). The Agency has deleted conductivity from the detection monitoring program because it is merely a proxy for TDS, which is already included on the list of parameters to analyze during detection monitoring. The Agency has also deleted sulfide because it occurs in groundwater only under strongly reducing conditions, and such conditions are rather rare at CCR disposal facilities. Calcium is being added to appendix III because it is an indicator of the extent of leaching from fly ash and FGD gypsum and because of the strong demonstrated link between the leaching of calcium and arsenic, which is one of the primary risk drivers identified in the risk assessment.

As discussed in the preceding section, in detection monitoring, a minimum of eight independent samples from each background and downgradient well must be collected and analyzed for the appendix III and IV parameters no later than 24 months from the effective date of the rule. During subsequent sampling events, at least one sample from each background and downgradient well must be collected and analyzed, although the total number of samples must be consistent with the statistical procedures selected and with the performance standard in § 257.93(g). See discussion above in section 3. Sampling and Analysis Requirements.

Under the proposed rule, monitoring would be required no less frequently than semiannually. In the final rule, semiannual sampling remains the general requirement; however, in response to comments, EPA has decided to include a provision that would allow an alternative sampling frequency if there is not adequate groundwater to flow to sample wells semiannually. Specifically, EPA received comment stating that there may be instances where there simply is not enough water available to collect and analyze on a semiannual basis, especially in western climates where the rate of groundwater recharge may be too slow or a lack of precipitation exists. The commenter also provided an example demonstrating that mining practices in adjacent areas can greatly alter the groundwater flow. Accordingly, EPA has included a provision to address the situations where there is insufficient groundwater available to collect and analyze samples around CCR units on a semiannual basis.

An owner or operator seeking to establish an alternative frequency must demonstrate that less frequent monitoring is necessary based on the following three factors: (1) Lithology of the aquifer and the unsaturated zone; (2) hydraulic conductivity of the aquifer and the unsaturated zone; and (3) groundwater flow rates. In addition, the rule requires the owner or operator to demonstrate that any alternate sampling frequency would be no less effective in ensuring that any leakage from the CCR unit will be discovered within a timeframe that does not materially delay the initiation of any necessary remediation measures. The owner or operator must have a qualified professional engineer certify that the alternative (*i.e.,* less frequent) monitoring will achieve this performance standard. The final rule also specifies that any alternate frequency during the active life (including closure) and the post-closure

care period shall be no less than annual. As noted, the owner or operator will bear the burden of justifying an alternate frequency under this regulation, and in any court proceeding brought to enforce these requirements. This means that any uncertainty or lack of information will be weighed against the entity seeking to justify the alternate frequency.

Consistent with the proposed rule, if the owner or operator determines that there is a statistically significant increase (SSI) over background for one or more of the parameters listed in appendix III at any monitoring well at the waste boundary, the owner or operator must place a notice in the operating record and on the facility's internet site indicating which parameters have shown statistically significant changes from background levels and notify the State Director.

The facility must also then establish an assessment monitoring program and begin monitoring within 90 days. The owner or operator has the opportunity to demonstrate that a source other than the CCR unit caused the statistically significant increase or that the statistically significant increase resulted from error in sampling, analysis, statistical evaluation or a natural variation in groundwater quality. Within 90 days, the owner or operator must prepare a report documenting this demonstration which must then be certified by a qualified professional engineer verifying the accuracy of the information in the report. If a successful demonstration is made within 90 days, the owner or operator may continue detection monitoring. If a successful demonstration is not made within 90 days, the owner or operator must initiate assessment monitoring.

Commenters raised concern that 90 days would not be sufficient to complete all of the activities necessary to determine whether the detection of an SSI was from another source than the CCR unit or was based on inaccurate results. The Agency recognizes that in some circumstances it could take more than 90 days to resample and have laboratories conduct new analyses, or to conduct field investigations to determine that another source is causing the contamination. As a result, § 257.94(e)(3) does not place an ultimate time limit for owners and operators to complete the demonstration. However, if after 90 days the owner or operator has not made a successful demonstration, (s)he must begin an assessment monitoring program. At this stage, there is evidence to indicate that a release has occurred from the CCR unit, and while EPA agrees that the facility may want to confirm that the information is accurate, it is critical that the facility not delay indefinitely the more targeted monitoring to determine whether a constituent of concern is contaminating groundwater. It would not be consistent with the statutory standard to allow a facility unlimited time to delay taking reasonable steps to assess, and if necessary, address potential contamination by continuing to resample until they obtain a ''better'' answer. Moreover, initiation of an assessment monitoring program does not involve an irretrievable commitment of resources or even a significant investment by the facility, but only requires the facility to begin more targeted sampling for constituents of concern. This represents a reasonable first step to address a potential threat to groundwater. This requirement is also in the MSWLF part 258 regulations. For more information see 56 FR 51078 (October 9, 1991).

Subsequent to initiating the assessment monitoring program, if an owner or operator demonstrates that the statistically significant increase resulted from an error in sampling, analysis, statistical evaluation, or natural variation in groundwater quality, or was caused by a source other than the CCR unit, the owner or operator may cease assessment monitoring and return to detection monitoring. If the demonstration is successful, the owner or operator must have the demonstration certified by a qualified professional engineer, and is required by § 257.94(e)(3) to place a notice in the operating record, and on publicly accessible Internet site and send a copy of the report to the State Director.

5. Assessment Monitoring Program

EPA is adopting an assessment monitoring program that is largely identical to the program laid out in the proposal. However, as discussed in more detail below, some revisions have been made; some were made in response to comments, but most are conforming changes made to be consistent with changes adopted in other provisions, such as the detection monitoring program described previously.

Consistent with the proposed rule, if any of the detection monitoring parameters are detected at a statistically significant level over the established background concentrations, the owner or operator must proceed to the next step, assessment monitoring. Assessment monitoring requires annual sampling and analysis for the full list of constituents included in appendix IV. The number and frequency of samples required for assessment monitoring are the same as those established for detection monitoring. See discussion above in 3. Sampling and Analysis Requirements.

EPA has also revised the list of constituents in appendix IV by deleting the following constituents and parameters: Aluminum, boron, chloride, copper, iron, manganese, pH, sulfate, sulfide, and TDS; and adding the following constituents: Cobalt, lithium, and radium 226 and 228 combined. The following constituents and parameters are being removed from appendix IV because they are on appendix III and therefore will continue to be monitored throughout assessment monitoring: Boron, chloride, pH, sulfate and TDS. Although fluoride is on appendix III, we are also retaining it on appendix IV because it does have an MCL and was found to pose risks in the 2014 risk assessment, and therefore is appropriately considered to be a constituent that is relevant for purposes of corrective action. Aluminum, copper, iron, manganese, and sulfide have been removed because they lack maximum contaminant levels (MCLs) and were not shown to be constituents of concern based on either the risk assessment conducted for this rule or the damage cases (see Units X and XI of this document). Cobalt has been added to appendix IV because cobalt was found to be a risk driver in the 2014 risk assessment, based on certain waste management disposal practices that lead to highly acidic wastes conditions. Lithium is being added to appendix IV because it has been detected in several proven and potential damage cases at levels exceeding EPA's Regional Screening Level (RSL) of soil to groundwater and has been determined as potentially toxic if consumed concurrently with certain drug types.[117] Radium 226 and 228 combined (the sum of the radioactive isotopes radium-226 and radium-228) is being added because there is evidence from several damage cases of exceedances of gross alpha, indicating that radium from the disposal of CCR may be problematic. Appendix IV now contains antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, fluoride, lead, lithium, mercury, molybdenum,

[117] *EPA's Regional Screening Level (RSL) Soil to Groundwater Supporting Table (TR = 1E–6, HQ = 1)* May 2014/Mid-atlantic Risk assessment: *http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/Generic_Tables/index.htm; and Health Consultation: Chesapeake ATGAS 2H Well Site Leroy Hill Road, Leroy, Leroy Township, Bradford County, Pennsylvania,* October 29, 2013. U.S. Department of Health and Human Services, Agency for Toxic Substances and Disease Registry Division of Community Health Investigations Atlanta, Georgia. *http://www.atsdr.cdc.gov/.*

selenium, thallium and radium 226 and 228 combined.

If any appendix IV constituents are detected in any appendix IV analyses, the owner or operator must notify the State Director and continue to monitor, at least semiannually, for both the specific constituents in appendix IV that were detected and all parameters in appendix III. EPA has decided to also include a provision to allow an alternative sampling frequency if there is not adequate groundwater to flow to sample wells semiannually, consistent with the revised provision adopted for the detection monitoring program. If the owner or operator demonstrates at any time during assessment monitoring that all of the detected appendix III and IV constituents are at or below background values for two consecutive sampling events, (s)he must notify the state and may return to detection monitoring. In general, EPA expects that appendix III constituents are unlikely to remain elevated once measures have been taken to address the release of the detected appendix IV constituents. But should appendix III constituent levels remain elevated, detection monitoring continues to be necessary to determine whether another source of contamination is present.

After obtaining the sampling results the owner or operator must place a notice in the operating record and on the facility's internet site indicating which appendix IV constituents have been detected and notify the State Director. Within 90 days and on at least a semiannual basis thereafter, the owner or operator must resample all wells, conduct analyses for all parameters in appendix III and for those constituents in appendix IV that were detected in the initial assessment monitoring sampling event. The results of this resampling must be placed in the owner or operator's operating record, as well as its publicly accessible internet site. The results of the resampling must also be sent to the State Director. These provisions have been adopted without change from the proposal.

For each appendix IV constituent that is detected, a groundwater protection standard must be set. The groundwater protection standards must be the MCL or the background concentration level for the detected constituent, whichever is higher. If there is no MCL promulgated for a detected constituent, then the groundwater protection standard must be set at background. The proposed rule would have allowed the owner or operator to establish an alternative groundwater protection standard for constituents for which MCLs have not been established provided that the alternative groundwater protection standard has been certified by an independent registered professional engineer and the state has been notified that the alternative groundwater protection standard has been placed in the operating record and on the owner's or operator's publicly accessible internet site. This provision had been adopted from the part 258 regulations, but was determined to be inappropriate in a self-implementing rule, as it was unlikely that a facility would have the scientific expertise necessary to conduct a risk assessment, and was too susceptible to potential abuse. Additionally, numerous comments were received suggesting that only those constituents with MCLs be included in appendix IV. The commenters were concerned that only MCLs are enforceable. With the exception of cobalt, lead, lithium and molybdenum (included on appendix IV because of their relevance in the risk assessment and damage cases), all appendix IV constituents have an MCL. In the proposed rule, as stated above, owner or operators were allowed to establish certain types of alternative groundwater protection standards. In the final rule, if a constituent has no MCL (*i.e.,* cobalt, lead, lithium and molybdenum), their groundwater protection standards will be their background levels. These background standards are sufficiently precise that they are enforceable.

The owner or operator must compare the levels of any detected appendix IV constituents to the appropriate groundwater protection standard. If the concentrations of all appendix IV constituents are shown to be at or below background values for two consecutive sampling events using the statistical procedures required by § 257.93, the owner or operator of the CCR disposal facility must place that information in the operating record and on the facility's publicly accessible internet site and notify the State Director. The owner or operator may then return to detection monitoring.

If the concentrations of any appendix III or IV constituents are above background values, but all concentrations are determined to be below the groundwater protection standard using the statistical procedures required by this rule, the owner or operator must continue assessment monitoring program.

If, however, the monitoring indicates a statistically significant increase for any appendix IV constituent over the groundwater protection standard, the owner or operator is required to notify the State Director and local officials of this finding and place a notice in the operating record and on the owner or operator's publicly accessible internet site.

The owner or operator also must characterize the nature and extent of the release. As part of characterizing the nature and extent of the release, the owner or operator must install additional wells, as necessary to define the contaminant plume(s) and collect data on the nature and estimated quantity of the material released. Adequate characterization of the release is critical in designing and effectively implementing a protective corrective action program if groundwater remediation is necessary. The purpose of these additional wells is to delineate the contaminant plume boundary and to eventually demonstrate the effectiveness of corrective action in meeting the groundwater protection standard.

Because the requirements for additional monitoring are entirely specific to the site conditions and the size and nature of the release, the Agency is not able to set requirements that precisely specify the location or the number of additional wells that must be installed. Instead EPA has adopted an approach that corresponds to the approach to designing the original groundwater monitoring system under § 257.91. The regulations establish a general performance standard (''install additional wells as necessary to define the contaminant plume'') and specify a true minimum of installing at least one well at the facility boundary in the direction of contaminant migration in order to ascertain whether the contaminants have migrated past the facility boundary. The regulations also establish a rebuttable presumption that this minimum is insufficient, requiring the owner or operator to justify a decision to install only this minimum. The requirement to justify the decision to only install the minimum number of additional wells is a revision from the proposal that has been adopted to be consistent with the Agency's overall approach to developing an effective groundwater monitoring system.

The Agency has also added some clarification to the proposed requirement to characterize the nature and extent of the release, by requiring the owner or operator to collect data on the nature and estimated quantity of material released, including specific information on the constituents listed in appendix IV and the levels at which they are present in the material released. This information will be necessary to help the owner or operator characterize the release and assist in ultimately deciding on a remedy.

If contamination has migrated off-site, the owner or operator must notify individuals who own land or reside on land overlying the plume.

In addition to characterizing the nature and extent of the release, the owner or operator must initiate an assessment of corrective measures within 90 days of finding a statistically significant increase over background concentrations, and select the appropriate remedy. During this phase, the owner or operator is required to continue at least semiannual monitoring (or an alternative frequency, no less than annually) for all appendix III constituents and for those appendix IV constituents exceeding the groundwater protection standard. To be consistent with the provisions in detection monitoring, EPA has included a provision that would allow the owner or operator to demonstrate that a source other than their CCR unit caused the contamination or that the statistically significant increase above groundwater protection standards resulted from error in sampling, analysis, statistical evaluation, or natural variation in groundwater quality. This alternative option will not delay compliance with the next phase of the groundwater monitoring and corrective action program. Thus, until such a demonstration is made, the owner or operator must comply with the other requirements of this section, including initiating the assessment of corrective measures. At this stage, the evidence that the CCR unit is leaking is stronger, and the owner or operator has previously had the opportunity to demonstrate that the finding was made in error under the detection monitoring program, so no further delay in initiating measures to address any groundwater contamination is warranted.

Another change since the proposal is that in addition to complying with all of the corrective action requirements—*i.e.,* initiating an assessment of corrective measures, followed by selection of a remedy and implementation of a corrective action program—if the unit is an unlined surface impoundment, it must either retrofit or initiate closure. Further, where the facility has chosen to install a multi-unit groundwater monitoring system, the detection of an SSI of an appendix IV constituent would trigger the corrective action and closure (or retrofit) of all of the unlined surface impoundments covered by that monitoring system, as there will be no way to isolate a particular unlined unit as the source of the contamination. These requirements are discussed in more detail in the Closure section.

6. Assessment of Corrective Measures

This section of the regulations also largely mirrors the analogous provisions in the proposed rule. EPA added some language to reflect that this section is not limited to the remediation of groundwater from a leaking CCR unit but will also apply to contamination caused by any kind of release from a CCR unit. EPA also made some minor revisions in response to comments, and some editorial changes to conform this provision to changes made in other sections of the rule.

Consistent with the proposal, § 257.96(a) specifies that the assessment of corrective measures must be initiated within 90 days of detecting a statistically significant increase of any of the constituents listed in appendix IV, at a level exceeding the groundwater protection standard(s), or of otherwise documenting a release of contaminants from the CCR unit. The regulation also requires the assessment of corrective measures to be completed in 90 days of such a finding, but in response to comments, EPA is adopting a provision that will allow for a single 60 day extension. Multiple commenters argued that 90 days was not adequate to complete the assessment of corrective measures. Commenters stated that for situations with complex hydrogeology, additional studies and sampling may be required in order to assess potential contributing offsite sources, background levels, and possible remedies. They stated that identification of remedy alternatives, collection and analysis of data used to evaluate remedy alternatives, and discussions with vendors/contractors regarding availability of labor and materials are all critical steps in the remedy selection process. As explained in the ''Technical Manual Solid Waste Disposal Facility Criteria,'' EPA530–R–93–017, USEPA, November, 1993, Chapter 5, Subpart E, Ground-Water Monitoring and Corrective Action, the owner or operator will need to: (1) Identify and remediate the source of contamination; and (2) identify and remediate the known contamination. The factors that must be considered in assessing corrective measures include source evaluation, plume delineation, groundwater assessment and source control. Based on the comments received, as well as the Agency's own experience, EPA recognizes that there may be complex situations that require more time to develop a careful and well-thought out corrective measures assessment. Therefore, the final rule has been modified to allow up to an additional 60 days to complete the assessment of corrective measures, provided that a qualified professional engineer certifies that the additional time is necessary. The initial 90 days plus the additional 60 days, which is within the range of time suggested by the commenters, would provide the owner or operator up to 150 days to complete the corrective measures assessment, which EPA expects will be sufficient. The certification must be placed in the operating record, on the owner's or operator's publicly accessible internet site and submitted to the proper state official.

The rule requires the owner or operator to assess the effectiveness of potential remedies in meeting the objectives of § 257.97 by addressing at least: (1) Performance, reliability, ease of implementation and potential impacts; (2) time requirements; and (3) institutional requirements. The proposed rule also included consideration of the costs of remedy implementation. However, that language came directly from the MSWLF rule in part 258. Because Congress did not authorize the consideration of costs in establishing minimum national standards under RCRA section 4004(a), we have removed this factor. In evaluating the performance, reliability, ease of implementation, and potential impacts of each remedy, the owner or operator should evaluate whether specific remedial technologies are appropriate to the problem and the ability of those technologies to achieve the groundwater protection standards. Analysis of a remedy's reliability should include an assessment of the effectiveness of the remedy in controlling the source of the release and its long-term reliability. Source control measures need to be evaluated to limit the migration of the plume, and to ensure an effective remedy. The regulation does not limit the definition of source control to exclude any specific type of measure to achieve this. Remedies must control the source of the contamination to reduce or eliminate further releases by identifying and locating the cause of the release. Source control measures may include the following: Modifying the operational procedures (*e.g.,* banning waste disposal); undertaking more extensive and effective maintenance activities (*e.g.,* excavate waste to repair a liner failure); or, in extreme cases, excavation of deposited wastes for treatment and/or offsite disposal. Construction and operation requirements also should be evaluated. The analysis of the timing of potential remedies should include an evaluation of construction, start-up, and

completion time. Timing is particularly important if contamination has migrated off-site. Institutional requirements such as local permit or public health requirements may affect implementation of the remedies evaluated and should be assessed by the owner or operator.

The proposed rule included a provision that would allow an owner or operator to determine that compliance cannot be reasonably achieved with any currently available methods. This has been deleted from the final rule. The Agency determined that without state oversight or a permitting program, that provision was potentially subject to abuse and thus, inappropriate to include in a self-implementing rule.

As part of evaluating potential remedies, the owner or operator must hold a public meeting to discuss the remedies under consideration (prior to selecting a final remedy). Once the owner or operator has selected a remedy, he must place a description of the selected remedy in the operating record, on the owner or operator's publicly accessible internet site and notify the State Director.

7. Selection of Remedy

This section of the final rule has been adopted with only minor changes from the proposal. As in the prior section, EPA has revised certain provision to reflect that this section will also apply to the cleanup of contamination caused by a release from a CCR unit. EPA also deleted a provision that had been adopted from the part 258 regulations, but that was determined to be inappropriate in a self-implementing rule as it was too susceptible to potential abuse.

Based on the results of the corrective measures assessment conducted, the owner or operator must select a remedy. The selected remedy must attain all of the performance standards listed in subsection (b). Specifically, the remedy must protect human health and the environment, attain the groundwater protection standards, control the sources of releases so as to reduce or eliminate, to the maximum extent practicable, further releases of appendix IV constituents into the environment, and comply with any relevant standards for management of wastes generated as a result of the remedial activities. EPA included an additional criterion more directly related to remediation of contamination associated with a release, such as from a collapse or structural failure of a CCR unit, which requires the remedy to ''remove from the environment as much of the contaminated material that was released from the CCR unit as is feasible, taking into account factors such as avoiding the inappropriate disturbance of sensitive ecosystems.'' Together, these criteria reflect the major technical components of any kind of clean up remedy.

The rule also specifies decision criteria to be considered by the owner or operator in selecting the most appropriate remedy. These include: (1) Long and short term effectiveness, and degree of certainty of success; (2) effectiveness of remedy in controlling the source to reduce further releases; (3) ease or difficulty of implementation; and (4) community concerns. Additionally, the rule requires the owner or operator to specify a schedule for implementing and completing the remedial activities. The rule requires the owner or operator to set the schedule because it is impossible for EPA to establish a single schedule appropriate for all possible situations; the schedule will necessarily depend on the nature and size of the contamination, among other factors. The rule outlines six factors to be considered in establishing a schedule for completing remedies (§§ 257.97(d)(1–6)). These factors are: (1) Extent and nature of contamination; (2) reasonable probabilities of remedial technologies in achieving compliance with the groundwater protection standards; (3) availability of treatment or disposal capacity for CCR managed during implementation of the remedy; (4) potential risks to human health and the environment; (5) resource value of the aquifer; and (6) other relevant factors. EPA had included one additional factor in the proposal: ''The desirability of utilizing technologies that are not currently available, but which may offer significant advantages over already available technologies in terms of effectiveness, reliability, safety, or ability to achieve remedial objectives.'' EPA considered that this provision, which could be used to justify delaying remediation measures, was potentially subject to abuse and thus, inappropriate to be included in a self-implementing rule.

For similar reasons, EPA deleted the provisions in the proposal, subsections (e) and (f) that would authorize a facility to determine that remediation of a release is not necessary. These sections which came from the MSWLF rule in part 258 are appropriate where there is state oversight. The preamble to the final MSWLF rule specifically discusses situations in which an approved state may decide not to require cleanup of hazardous constituents released to groundwater from a MSWLF (see 56 FR 51090). However, there is no similar guarantee that an individual facility will act in the public interest.

8. Implementation of the Corrective Action Program

The proposed rule required the owner or operator to include a schedule for initiating the remedial activities in the schedule for implementing the remedy (§ 257.97(d)). The Agency understands that selecting a remedy is closely related to the assessment process and cannot be accomplished unless a sufficiently thorough evaluation of alternatives has been completed. The process of documenting the rationale for selecting a remedy requires that a report be placed in the operating record that clearly defines the corrective action objectives and demonstrates why the selected remedy is anticipated to meet those objectives. The report must identify how the remedy will be protective of human health and the environment, attain the groundwater protection standards (either background or MCLs), attain source control objectives, and comply with waste management standards.

The selection of a remedy also involves a public meeting with interested parties before finally selecting a remedy. For these reasons, the Agency is not establishing a deadline for completing the remedy selection process, but rather expects it to be completed as soon as practicable. Once the assessment of corrective measures has been completed within the timeframe specified in this rule, and the public meeting has occurred, the facility owner or operator must select a remedy and begin implementing that remedy as soon as is practicable. It is vitally important that the facility selects a remedy as soon as practicable and begins designing and implementing that remedy, so that releases to groundwater are addressed without unnecessary delay. EPA understands that there are a variety of activities that may be necessary in order to select the appropriate remedy (*e.g.,* discussions with affected citizens, state and local governments; conducting on-site studies or pilot projects); and, once selected, to implement the remedy (*e.g.,* securing on-site utilities if needed, obtaining any necessary permits, etc.). That is why EPA does not find it appropriate to set specific timeframes for selecting the remedy or to begin implementing the selected remedy. However, in order to ensure that the community is kept informed as to the progress of selecting and implementing the remedy, EPA is requiring that the facility owner or operator, on a semiannual basis, post status reports/updates on their progress

to their publicly accessible internet site and submit these to the state.[118]

However, the Agency has concluded that it is reasonable to require that once a remedy has been chosen, the owner or operator of the CCR unit must begin to implement that remedy within a specified period of time. Consistent with the timeframes throughout this section, the final rule requires that within 90 days of selecting a remedy, the owner or operator must have initiated corrective measures, including any interim measures determined to be appropriate, and have established a corrective action groundwater monitoring program (and begin following it). (§ 257.98). This is a reasonable timeframe in which to begin these activities based on EPA's long experience in conducting and overseeing cleanup activities.

The remedy would be considered complete when the owner or operator demonstrates compliance with the groundwater protection standards for a period of three consecutive years, and all other actions required to meet the performance standards in § 257.97(b) have been satisfied (*e.g.,* source control). The owner or operator must obtain certification that the remedy is complete from a qualified professional engineer, and must notify the State Director. The certification must also be placed in the operating record and on the owner or operator's publicly accessible Internet site.

The Agency deleted the provision that allows an owner or operator to determine that compliance cannot be reasonably achieved with any currently available methods. The Agency determined that without state oversight or a permitting program, that provision was potentially subject to abuse and thus, inappropriate to be included in a self-implementing rule.

9. Timing Overview

The groundwater monitoring regulations require that the owner or operator of existing CCR units must comply with § 257.90–§ 257.94 within 30 months of the date of publication of the rule. Essentially, that means that by the end of 30 months, the owner or operator must (1) install the groundwater monitoring system; (2) document the sampling and analysis procedures; (3) establish which statistical tests will be used to determine exceedances; (4) sample all wells to have a minimum of 8 samples for all appendix III and IV parameters; and (5) determine if there is a statistically significant exceedance of any appendix III parameter, which would trigger assessment monitoring.

New CCR units must comply with §§ 257.90–257.93, including the requirement under § 257.94(b) to collect and analyze eight independent samples from each well for the parameters listed in appendix III and IV to this part to determine background levels for all appendix III and IV constituents, before commencing operation. Essentially, that means that before receiving CCR waste, the owner or operator must (1) install the groundwater monitoring system; (2) document the sampling and analysis procedures; (3) establish which statistical tests will be used to determine exceedances; and (4) sample all wells to have a minimum of eight samples for all appendix III and IV parameters.

If assessment monitoring is triggered, within three months the owner or operator must sample all wells for all appendix IV constituents (minimum of one sample) and resample (minimum of one sample) all wells for all appendix III parameters and those appendix IV constituents that were detected in the first round of sampling. The owner or operator could also simultaneously use this three month timeframe to demonstrate that the statistically significant increase found in detection monitoring was due to another source or sampling and analysis error. While conducting assessment monitoring, the owner or operator must continue sampling for all appendix III constituents and any appendix IV detected constituents semiannually. The owner or operator must sample for all appendix IV constituents annually.

The owner or operator must also establish groundwater protection standards (MCL or background levels) for all appendix IV constituents detected during sampling.

If one or more appendix IV constituents are detected at statistically significant levels above the groundwater protection standards established, or a release from a CCR unit has been detected, corrective action is triggered. The owner or operator must characterize the nature and extent of the release by installing additional monitoring wells, collecting data on the quantity and concentration levels of regulated constituents in the released material, sampling and notifying the State Director, local government officials, and any persons who own land or reside on the land that overlies the plume if the plume has migrated off site. The owner or operator must also place the notification in their operating record and on their publicly accessible Internet site.

If corrective action is triggered, within three months the owner or operator must initiate an assessment of corrective measures. If the CCR unit is an unlined surface impoundment, the unit must stop receiving CCR and non-CCR wastes and initiate closure of the unit or begin to retrofit the unit within six months. The owner or operator could also simultaneously use these three months to initiate an assessment of corrective measures to demonstrate that the statistically significant increase found during assessment monitoring was due to another source or sampling and analysis error.

The assessment of corrective measures must be completed in three months, with the possibility of an additional two months if the owner or operator demonstrates the need for additional time. The owner or operator must continue assessment monitoring and provide notification of the corrective measures assessment to the State Director and place the assessment in the operating record and on the owner's or operator's publicly accessible Internet site. The owner or operator also must discuss the results of the corrective measures assessment at least one month prior to selection of remedy in a public meeting.

Within three months of selecting a remedy, the owner or operator must initiate remedial activities. Corrective action is completed when the owner or operator demonstrates compliance with the groundwater protection standards for three consecutive years.

L. Closure of Inactive Units.

As discussed in Unit VI.A of this document, EPA proposed that inactive CCR surface impoundments that had not completed closure in accordance with specified standards by the effective date would be subject to all of the requirements applicable to existing CCR surface impoundments. EPA adopted this approach to create an incentive to expedite the closure of these units, with all of the significant risk mitigation that such a measure would entail. EPA is retaining this general approach in the final rule, but has revised the provision to grant inactive CCR surface impoundments more time to complete closure, consistent with the other closure provisions in the final rule. The

[118] As evidenced in 42 U.S.C. 6971(f), Congress intended that the OSHA be able to enforce its regulations to protect workers exposed to hazardous waste and that EPA and OSHA would work together to ensure that. EPA is clarifying that it intends that the CCR disposal rule not preempt applicable OSHA standards designed to protect workers exposed to CCRs; thus EPA's final rule on CCR disposal will apply in addition to any applicable OSHA standards. The Agency has added specific regulatory language in this section to address this intent.

final rule extends the deadline to three years from publication of the rule in the **Federal Register**.

The proposal was based on EPA's belief that the timeframes between publication of the final rule and the effective date would be sufficient for facilities to close inactive CCR surface impoundments. This was particularly true under the subtitle C option, where the timeframe between publication and the effective date could be as long as 18 months, due to the need for subsequent action by authorized states. Under the proposed rule, the maximum amount of time a facility would have to initiate and complete closure of a disposal unit was seven months. However, as discussed elsewhere in this preamble, EPA received numerous comments raising concern that these timeframes would essentially be ''impossible to meet'' for surface impoundments located in certain geographic and climatic conditions, as well as for all of the larger units. These comments convinced EPA that it had not adequately accounted for the complexities inherent in electric generating facility operations, and the different characteristics of CCR surface impoundments in designing the closure provisions in the proposal. EPA has revised the timeframes applicable to closures in the final rule accordingly in light of these issues. See Unit VI.M of this document. These same considerations apply with respect to this provision, and additional time is therefore necessary to make this option truly viable.

EPA selected three years based primarily on two factors. EPA initially focused on the minimum amount of time necessary to close a CCR surface impoundment. As discussed in more detail in Unit VI.M of this document, there can be a substantial range in the amount of time needed to close a surface impoundment, depending on, for example, the size and location of the unit.

However, a critical factor in EPA's decision is that under this approach these units will not be subject to the rule's groundwater monitoring or structural stability requirements (provided they complete closure within three years). Moreover, based on the information in the record, it appears highly unlikely that groundwater monitoring is currently being conducted at these units (as discussed in Unit IV.A of this document, the information on groundwater monitoring requirements applicable to existing units was extremely sparse, but many older units appear to lack effective groundwater monitoring systems). EPA considered that allowing these inactive units to remain in place without taking measures to address the continuing threat that these units present for a substantial amount of time could not be justified. EPA therefore focused on the amount of time authorized under the rule for implementation of the groundwater monitoring requirements (*i.e.,* 2 years from the effective date) and for key structural stability requirements (*i.e.,* 18 months to complete key analyses).

As discussed in more detail in the next section, the information in the record demonstrates that it is feasible to complete the closure of CCR surface impoundments within three years. EPA recognizes that larger CCR surface impoundments (*i.e.,* above 40 acres) may not be able to close within this timeframe. However, to be able to support this provision, EPA must balance the risk mitigation achieved by closure of CCR surface impoundments against the risks inherent in allowing inactive CCR surface impoundments to remain in place for longer periods of time. The longer inactive CCR impoundments remain without all of the protections provided by the final rule, the greater the potential for significant health and environment impacts. Larger units are also the ones more likely to present the highest risks, and so warrant the greater oversight provided by application of all of the technical criteria to their operation (and closure). Consequently, EPA is unable to justify expanding this option to include the longer timeframes available under §§ 257.102 or 257.103.

The criteria for conducting the closure of inactive CCR surface impoundments are essentially the same as those applicable to active CCR units. Inactive units can either clean close units, or close with waste in place, subject to same performance standards in § 257.102 for all other CCR units. If an inactive CCR surface impoundment is completely closed within the three year timeframe, no other requirements apply to that unit. This means that no groundwater monitoring or other post-closure care requirements would apply to these units. Once an inactive CCR surface impoundment has been breached and dewatered, the risks are essentially the same as the risks associated with an inactive CCR landfill, which are not subject to any requirements under the final rule.

However, owners or operators of inactive CCR surface impoundments that have not completed closure within this timeframe must comply with all of the requirements applicable to existing CCR impoundments. If the facility intends to maintain the inactive unit indefinitely, whether to provide potential future capacity, or to continue to dredge the unit to provide material for beneficial use, or with the idea that it may be repurposed for other facility operations (*e.g.,* to manage stormwater), there is no basis for distinguishing between these units and actively managed units on the basis of the potential risks. Thus, such units would need, for example, to meet all of the location and structural stability criteria (which could independently compel closure of the unit), install the groundwater monitoring system, and begin to monitor within the timeframes established in the final rule. This also means that any facility that initiates closure under this provision but fails to complete it within this timeframe, must comply with all groundwater monitoring requirements in §§ 257.90–98 (*e.g.,* install groundwater monitoring wells) as well as all of the post-closure care requirements.

M. Closure and Post-Closure Care

Closure and post-closure care are an integral part of the design and operation of CCR landfills and CCR surface impoundments.[119] EPA solicited public comment on closure and post-closure care requirements under a subtitle D approach in the proposed rule and sought additional comment on specific closure requirements in a subsequent notice of data availability.

For CCR landfills, the proposed closure and post-closure care requirements were modeled on current regulations that apply to municipal solid waste landfills, which are codified in part 258. In some cases, the proposed requirements were modified to reflect the lack of a mandatory permitting mechanism (see Unit V.A. of this preamble for additional information), in addition to other changes EPA believed were appropriate to ensure that there would be no reasonable probability of adverse effects from the wastes that remain after a CCR unit had closed. For CCR surface impoundments, the Agency modeled the proposed requirements on current regulations that apply to interim status hazardous waste surface impoundments, which are codified in part 265. Some additional proposed provisions were based on requirements currently applicable to water, sediment, or slurry impoundments and

[119] As discussed in the proposed rule, EPA's ''Guide for Industrial Waste Management'' documents the general consensus on the need for effective closure and post-closure care requirements (Chapter 11). This guide can be accessed at *http://www.epa.gov/epawaste/nonhaz/industrial/guide/.*

impounding structures that are regulated by the MSHA. See 30 CFR part 77, subpart C.

The proposed rule included a number of closure and post-closure criteria, including: (1) Requirements to prepare closure and post-closure plans; (2) requirements for conducting closure of a CCR unit when the CCR is removed and when the CCR is left in place, including design criteria for a final cover system; (3) timeframes to commence and complete closure activities; (4) closure and post-closure care certification requirements; and (5) requirements for conducting post-closure care. The Agency received numerous comments on the proposed closure and post-closure criteria, with the majority of comments pertaining to the proposed timeframes for closure (*i.e.,* timeframes for commencing and completing closure) of a CCR surface impoundment. As a result of these comments, EPA solicited additional comments on the timeframes for closure in a NODA published on August 2, 2013 (NODA 3). See 78 FR at 46944. The sections below explain the approach and rationale for the final rule closure and post-closure care criteria based on the comments received in response to the proposed rule and the NODA.

1. Closure Plan

The Agency proposed to require that the owners or operators of CCR landfills and CCR surface impoundments prepare a written closure plan describing the closure of the unit and providing a schedule for implementation of the plan. 75 FR at 35207–08. The closure plan would describe the steps necessary to close the CCR unit at any point during the active life based on recognized and generally accepted good engineering practices. The proposal also identified the minimum information necessary to include in the closure plan. This information included: (1) An estimate of the largest area of the CCR unit that would ever require a final cover during the active life of the CCR unit; (2) an estimate of the maximum inventory of CCR that would ever be present on-site over the active life of the CCR unit; (3) a description of the final cover and the procedures to be used to install the final cover; (4) a description of how the facility will provide for major slope stability following closure; (5) a description of the measures the owner or operator will adopt to preclude the probability of future impoundment of water, sediment, or slurry; and (6) a schedule for the implementation of the closure plan. See proposed § 257.100(a) and (g). The proposed rule would also have required each owner or operator to develop the closure plan by the effective date of the final rule. Finally, EPA proposed to require the owner or operator to have the closure plan certified by an independent registered professional engineer, in addition to complying with all of the notification and posting requirements under the rule.

EPA received few public comments on either the proposal to develop a closure plan or the individual elements of the closure plan. Some commenters generally supported the requirement for an owner or operator to develop a closure plan for the CCR unit, and no commenters opposed it. However, one commenter requested that EPA include more specific requirements for slope stability in the regulatory language beyond the general requirement to address major slope stability in the closure plan for units that close with waste in place.

The Agency agrees that the proposed regulatory language should provide more specific criteria defining the expectations with regard to major slope stability. The proposed regulation merely required the owner or operator to ''provide for major slope stability'' in the closure plan, or in other words, to include measures to ensure that slope stability issues will be accounted for in designing the final cover. See 75 FR 35252.

EPA explained that unit closure must provide for major slope stability to prevent the sloughing of the cover system over the wastes that will remain in the CCR unit over the long term. Sloughing of a land slope can occur when the earth material becomes saturated with water and incapable of maintaining the slope resulting in the movement or sliding of the earth material. 75 FR at 35209. Slope stability is a critical issue in the design of final cover systems for both surface impoundments and landfills because cover system slope instability has been attributed to a number of final cover system failures.[120] More specifically, the primary causes of final cover system slope failure during construction have been identified as: (1) Placing soil over the sideslope geosynthetics from the top of the slope downward, rather than the toe of the slope upward; (2) using presumed values for critical interface shear strengths that were not conservative; and (3) using interface shear strength values from laboratory tests performed under conditions not representative of the actual field conditions. For final cover system slope failures after rainfall or thaw, the primary causes of failure have been identified as: (1) Not accounting for seepage forces; (2) clogging of the internal drainage layer, which leads to increased seepage forces; and (3) not accounting for moisture at the geomembrane and compacted clay liner interface (which weakened the interface) due to both rain falling on the compacted clay liner surface during construction and freeze-thaw effects.

Given that slope stability is a critical issue in the design and eventual performance of a final cover system, EPA has adopted a new criterion in the performance standard that all closures must meet: The owner or operator must ensure that the CCR unit is closed in a manner that will ''provide for major slope stability to prevent the sloughing or movement of the final cover system during closure and throughout the post-closure care period.'' See § 257.102(d)(1)(iii). Or in other words, the owner or operator must design a final cover system with any measures necessary to ensure that the major slopes of the closed CCR unit remain stable. Consistent with the proposal, the closure plan must discuss how the final cover system will achieve the performance standards specified in the regulation, which will necessarily include how the measures taken to address major slope stability. As explained in the proposed rule, the original provision was based on existing MSHA standards, specifically the requirements under 30 CFR 77.216–5 which apply to abandoned water, sediment or slurry impoundments and impounding structures.[121] 75 FR 35208–09. Under these requirements major slope stability includes long term stability considerations, such as ''erosion control, drainage, etc.'' These issues are equally relevant to the closure of CCR units, and EPA expects facilities to account for these factors in their final closure plans.

The remaining information elements of the closure plan have been adopted without revision (although EPA has reorganized the final regulatory text for greater clarity). These are briefly summarized below:

a. An estimate of the largest area of the CCR unit ever requiring a final cover during the active life of the CCR unit. If

[120] USEPA, ''Assessment and Recommendations for Improving the Performance of Waste Containment Systems,'' EPA/600/R–02/099, December 2002.

[121] The term ''abandoned'' is defined in the MSHA regulations under 30 CFR 77.217, and as applied to an impoundment or impounding structure such term means that work on the structure has been completed in accordance with a plan for abandonment approved by the District Manager.

the owner or operator routinely closes portions of a CCR unit as the design capacity is reached, the closure plan should indicate the largest area of the CCR unit that will be open (and requiring a final cover) at one time.

b. An estimate of the maximum inventory of CCR ever on-site over the active life of the CCR unit. If the owner or operator routinely closes portions of a CCR unit as the design capacity is reached, the closure plan should indicate the maximum inventory of CCR that will be open (and requiring a final cover) at one time.

c. A description of the final cover and the procedures to be used to install the final cover. The closure plan should also discuss how the closure performance standard will be achieved.

d. A description of the provisions to preclude the probability of future impoundment of water, sediment, or slurry. The final grades of the final cover system should promote surface water run-off and minimize erosion. The closure plan should also discuss the steepness of the slopes of the final cover system, in addition to the vertical spacing and width of benches.

e. A schedule for the implementation of the closure plan.

This rule also provides new procedures for amending an existing written closure plan. While the proposed rule did not specifically allow or require the owner or operator to revise an existing closure plan, EPA recognizes that available information and conditions known at the time the closure plan is prepared may very well change during the active life of the CCR unit, which could be decades in some cases. In order to eliminate any potential confusion over whether an owner or operator is allowed under this rule to revise the closure plan to reflect a change in conditions or circumstances, the final rule adopts new procedures for amending a written closure plan. These new procedures allow the owner or operator to revise the closure plan at any time provided the revised plan is placed in the facility's operating record, in addition to complying with all of the notification and posting requirements under the rule. Furthermore, the final rule requires the closure plan be amended any time there is a change in conditions that would substantially affect the written closure plan in effect.

Finally, in a departure from the proposed rule, the final rule provides owners and operators one year from the rule's effective date to prepare the initial written closure plan, which is one year longer than proposed. EPA made this change as part of its effort to coordinate the compliance and implementation timeframes in the CCR rule with another Agency rulemaking—the Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category (ELG) rulemaking—that may affect owners and operators of CCR units. See 78 FR 34442. As explained in that proposal, consistent with RCRA section 1006(b), EPA has sought to effectively coordinate any final RCRA requirements with the ELG requirements, to minimize the overall complexity of these two regulatory structures, and to facilitate the implementation of engineering, financial and permitting activities. EPA's goal is to ensure that the two rules work together to effectively address the discharge of pollutants from steam electric generating facilities and the human health and environmental risks associated with the disposal of CCRs, without creating avoidable or unnecessary burdens.

EPA proposed to require facilities to complete a closure plan by the rule's effective date, or six months following the rule's publication. However, this would have required owners or operators to prepare closure plans approximately three months prior to publication of the ELG final rule. Given that an understanding of the ELG rule would likely affect the details and content of a closure plan, the Agency concluded that it would make no sense to require an owner or operator to prepare a closure plan within six months, only to have them update it months later, after the owner or operator understands the requirements of both the CCR and ELG final rules. No measureable environmental or health benefit would be gained by having a closure plan in place for those three months. Moreover, EPA wants to ensure that closure plans are well considered, and the knowledge that a plan may need to be substantially revised in the near future could create a contrary incentive.

By extending the deadline for preparation of the closure plan by one year, owner or operators will have slightly more than six months after the ELG rule is published to complete a closure plan. This is consistent with the six month timeframe EPA originally proposed, which as noted, would have required completion of the closure plan within six months of publication of the final CCR rule.

2. Closure of a CCR Unit Through Removal and Decontamination

The proposed rule would have allowed facilities to close a CCR unit either through CCR removal and decontamination of all areas affected by releases from the CCR unit (''clean closure'') or with CCR in place with a final cover system. The Agency proposed that if the owner or operator elects to clean close a CCR unit, CCR removal and decontamination are complete when constituent concentrations throughout the CCR unit and any areas affected by releases from the CCR unit do not exceed the numeric cleanup levels for those constituents found in CCR established by the state in which the CCR unit is located, to the extent that the state has established cleanup levels. 75 FR 35208. In the absence of state cleanup levels, the proposal stated that metals should be removed to either statistically equivalent background levels, or to maximum contaminant levels or health-based numbers. Once a facility had completed clean closure of a CCR unit, EPA proposed that post-closure care would not be required for that unit. EPA also noted that it was considering whether to adopt a further incentive for clean closure, under which the owner or operator could remove the deed notation required under the proposed rule, once all CCR has been removed from the facility and notification provided to the state.

Several commenters urged EPA to not require clean closure as the only method of closing a CCR unit, arguing that clean closure is not feasible or not necessary. Others acknowledged that clean closure is not only a viable option for their CCR units, but in some cases it would be ''the only prudent closure option.'' A few commenters suggested criteria to determine the conditions under which clean closure would be appropriate. For example, one commenter agreed with EPA that the risk-based corrective action process (RBCA) would be useful in determining whether waste removal is appropriate at the site.

EPA received relatively few comments on the specific standards for conducting clean closure. One commenter identified six criteria that should be included in any final regulation in order to allow a facility to have been deemed to have completed clean closure of a CCR surface impoundment and thereby avoid post-closure care. Some of the commenter's suggestions were comparable to requirements in the proposal. However the commenter also included requirements to ensure that adequate engineering controls were used to prevent contamination of soil and groundwater during excavation, and requirements for quarterly monitoring of shallow groundwater beneath the surface impoundment for a period of five years to demonstrate that no

residual CCR was left in place. Finally, a number of commenters supported a provision that would allow the owner or operator to remove the deed notation required provided all CCR is removed from the site.

EPA did not propose to require clean closure nor to establish restrictions on the situations in which clean closure would be appropriate. As EPA acknowledged in the proposal, most facilities will likely not clean close their CCR units given the expense and difficulty of such an operation. Because clean closure is generally preferable from the standpoint of land re-use and redevelopment, EPA has explicitly identified this as an acceptable means of closing a CCR unit. However, both methods of closure (*i.e.,* clean closure and closure with waste in place) can be equally protective, provided they are conducted properly. Thus, consistent with the proposal, the final rule allows the owner or operator to determine whether clean closure or closure with the waste in place is appropriate for their particular unit. EPA agrees that the RBCA process, using recognized and generally accepted good engineering practices such as the ASTM Eco–RBCA process, can be a useful tool to evaluate whether waste removal is appropriate at the site. It is, however, not a necessary prerequisite.

EPA has adopted the provisions governing clean closure from the proposed rule with only one revision. The final provisions consist of two performance standards: First, the owner or operator must remove all CCR from the unit and decontaminate all areas affected by releases from the CCR landfill or surface impoundment. As part of meeting this performance standard, the final rule requires facility owners or operators to remove all wastes from the closing unit, and remove all liners contaminated with CCR waste and CCR waste leachate. The final rule also requires the owner or operator to remove and decontaminate all areas affected by releases from the CCR unit. This would require removal or decontamination of the underlying and surrounding soils and flushing, pumping, and/or treating the aquifer. The Agency interprets the term ''soil'' broadly to include both unsaturated soils and soils containing groundwater.

Second, the final rule specifies that closure has been completed when all CCR in the unit and any areas affected by releases from the CCR unit have been removed and groundwater monitoring demonstrates that all concentrations of the assessment monitoring constituents listed in appendix IV to part 257 do not exceed either statistically equivalent background levels or MCLs. This standard encompasses both saturated and unsaturated soils, as well as the groundwater. As part of attaining this standard, facility owners and operators will need to document that any contaminants left in the subsoils (*i.e.,* contaminated groundwater left in soils below the former landfill or impoundment) will not impact any environmental media including groundwater, surface water, or the atmosphere in excess of Agency-recommended limits or factors. Typically, any metals in these ''subsoils'' in excess of background levels are allowed to either naturally attenuate, or are removed by flushing. Once the facility has removed all of the assessment monitoring constituents listed in appendix IV down to background levels or MCLs the groundwater is considered to be ''clean'' and closure is complete.

EPA disagrees that specific provisions requiring the use of adequate engineering controls to prevent contamination of soil and groundwater during excavation are necessary to ensure that closure will be protective. To the extent that any contamination of soil or groundwater has occurred during CCR removal, this would constitute a release (or an ''area affected by a release'') from the CCR unit, and the final performance standard requires the facility to ensure that this has been removed before closure is deemed to be complete.

Contrary to the commenter's suggestion that quarterly monitoring for five years is necessary to demonstrate that no residual CCR was left in place, the rule requires a facility to document that all appendix IV concentrations are below MCL or background levels for two consecutive sampling events, using the statistical procedures in § 257.93(g). This is the same sampling required to demonstrate under the groundwater monitoring program that there is no longer a reason to suspect a source of contamination, and that consequently assessment monitoring can cease. EPA selected these provisions as the most factually analogous to the circumstances surrounding the clean closure of a CCR unit. Once a facility has removed the waste and any liner, the presumption is that the source of contamination has been removed as well. Although there may be site-specific factors that could support the need for a longer monitoring period, there is no factual basis to require a longer minimum period of sampling on a national basis.

This represents a change from the proposal. EPA proposed a performance standard that required decontamination to either any state established numeric cleanup levels for CCR constituents, or in the absence of state cleanup levels, the removal of metals to either statistically equivalent background levels, or to MCLs, or health-based numbers. This was taken directly from the current part 258 standards for MSWLFs. EPA has deleted both of these standards as inappropriate for these units.

The reference to state established clean up levels was inadvertently carried over from the existing part 258 regulations. As explained throughout this preamble, EPA is unable to rely on state programs to establish the specific standards under this rule; the record does not contain information on all state cleanup standards, and there is no mechanism for states to operate approved programs in lieu of federal programs.

EPA determined that the requirement to clean all soils to background levels was equally inappropriate. In practice, EPA does not routinely require complete removal of all contamination (that is, cleanup to 'background') from a closing unit even for hazardous waste units. Requiring CCR units to clean up soils to levels before the site was contaminated, would be more stringent than current hazardous waste policies. There is no basis in the current record to impose provisions for the remediation of CCR units that are more stringent than those imposed on hazardous wastes.

Upon completion, the unit is exempt from the groundwater monitoring and any other post-closure care requirements. In addition, the final rule adopts the proposal to allow the owner or operator to remove the deed notation required under § 257.102(i)(4), upon certification that clean closure has been completed. EPA proposed this option to create a further incentive for clean closure, and it is clear from the commenters, who uniformly supported this option, that it does so. Some commenters raised concern about the effect this option will have on state laws, which may not allow the deed notation to be removed. EPA notes that these criteria do not preempt state laws; to the extent state law requires the facility to retain a deed notation despite the completion of clean closure, those requirements will remain in place, notwithstanding this final rule.

3. Closure of a CCR Unit With CCR in Place

The proposed rule would have also allowed facilities to close a CCR unit by leaving the CCR in place and installing a final cover system. The final cover

system would have been required to be designed and constructed to a have a permeability less than or equal to the permeability of any bottom liner system or the natural subsoils present, or a permeability no greater than 1×10^{-5} centimeters per second (cm/sec), whichever is less. The proposal would have also required an infiltration layer that contains a minimum of 18 inches of earthen material and an erosion layer containing a minimum of six inches of earthen material that is capable of sustaining native plant growth to help minimize erosion of the final cover. These proposed requirements were generally modeled after the performance standard and technical requirements contained in § 258.60 for MSWLFs. 75 FR 35208. EPA also proposed that the final cover system would have to be designed to minimize the disruption of the final cover through a design that accommodates settling and subsidence and provides for major slope stability to prevent the sloughing of the closed CCR unit over the long term. These last two criteria are based on existing requirements for interim status units under RCRA part 265 and MSHA requirements under 30 CFR part 77, subpart C, respectively.

As proposed, CCR surface impoundments would have been subject to an additional set of performance standards. The owner or operator of a CCR surface impoundment would have been required to either drain the CCR unit or solidify the remaining wastes. In addition, the owner or operator would have been required to stabilize the wastes to a bearing capacity to support the final cover. The proposed criteria would also have required that the final cover for all CCR units be designed to minimize the migration of liquids through the closed CCR surface impoundment over the long term; promote drainage, and accommodate settling and subsidence so that the final cover's integrity is maintained. Finally, closure of the CCR unit would also have been subject to the general performance standard that the probability of future impoundment of water, sediment, or slurry be precluded.

The Agency also proposed to allow owners or operators of CCR units to select an alternative final cover design. As proposed, the alternative final cover design would have required an infiltration layer that achieves an equivalent reduction in infiltration, and an erosion layer that would provide equivalent protection from wind and water erosion, as the infiltration and erosion layers specified for final covers described above. In addition, the proposed approach for alternative final cover designs would have also required certification by an independent registered engineer, notification being provided to the state that the alternative final cover design has been placed in the facility's operating record, and placement of the alternative final cover design on the owner or operator's publicly accessible Internet site.

a. Final Cover System Design

EPA received comments supporting the proposed approach, while other commenters opposed the proposed final cover system design requirements. One state commenter generally supported using the part 258 final cover design requirements as a general model for CCR units. This commenter also requested that the Agency clarify whether new CCR units would be required to install a composite final cover system given that it was proposed that new CCR units would be required to designed and constructed with a composite bottom liner. Another state indicated that its state regulations allow final cover designs similar to that proposed by EPA, although the state requires a 24 inch infiltration layer and a 12 inch erosion layer. Another commenter referenced current research showing that soil-only covers may not be effective in minimizing infiltration over the long term under certain climates. This commenter recommended that a geomembrane should be made a standard component of the cover system. Other commenters stated that the final cover system should be a composite system consisting of a synthetic component and a low permeability clay component. A state commenter offered that post-closure maintenance of composite cap system incorporating a geomembrane has been challenging in that state. Another commenter stated that a compacted clay liner should not be used as a final cover for landfills due to the potential for settlement cracking, desiccation cracking, and root and animal penetration. Instead, it was suggested that if a single barrier system is used, then a benefit-cost analysis favors a geomembrane, and if a composite barrier is to be used, a benefit-cost analysis favors a composite system of a geomembrane and geosynthetic clay liner.

The Agency also received many comments on the proposed approach to allow the use of alternative final cover systems. Most commenters supported allowing the use of alternative covers. One commenter stated that the use of geosynthetic clay liners in lieu of 18 inches of earthen material for the infiltration layer is a commonly accepted for cover systems for MSWLFs. This commenter also noted that that geosynthetic clay liners have documented permeability characteristics on the order of 1×10^{-9} cm/sec. Another commenter supported allowing the use of alternative cover systems because a one-size-fits-all approach is not appropriate for final cover system designs. A state also offered that appropriately designed alternative final covers such as capillary barrier covers and evapotranspiration covers are being successfully used at facilities in the state.

After considering comments received regarding final covers, the Agency is essentially finalizing the approach in the proposed rule with minor revisions. The final rule allows owners or operators to use a final cover system consisting of an infiltration layer and an erosion layer, provided the infiltration layer has a permeability less than or equal to the bottom liner or natural subsoils. However, regardless of the bottom liner or natural subsoils present, the final cover must have a permeability no greater than 1×10^{-5} cm/sec.

To address the commenters' concerns that the final cover system may not function effectively as designed over the long term under certain circumstances, the rule also includes a performance standard that any final cover system must meet. This standard is modeled after the closure performance standard applicable to interim status hazardous waste units under § 265.111. The final rule requires that any final cover system control, minimize or eliminate, to the maximum extent practicable, post-closure infiltration of liquids into the waste and releases of leachate (in addition to CCR or contaminated run-off) to the ground or surface waters. Thus, a facility must ensure that in designing a final cover for a CCR unit they account for any condition that may cause the final cover system not to perform as designed. This could include accounting for site conditions that may increase the likelihood that a cover would be susceptible to desiccation cracking or settlement cracking. Under this performance standard, if the cover system results in liquids infiltration or releases of leachate from the CCR unit, the final cover would not be an appropriate cover. The final rule requires the final cover system design to be certified by a qualified professional engineer that the design meets both the performance standard and cover system criteria.

The final rule does not require the use of composite final covers, such as a geomembrane underlain by a compacted soil infiltration layer. This is also the

case in situations for a CCR unit that is designed with a composite bottom liner or if the permeability of the soil underlying the unit is comparable to the permeability of a geomembrane. As EPA has concluded for municipal solid waste landfills, in certain site-specific situations it may be possible to construct an infiltration layer that achieves an equivalent reduction in infiltration without matching the permeability in the bottom liner material. 62 FR 40710.

Nonetheless, in certain locations, composite cover systems may be necessary to achieve the rule's performance standards. EPA acknowledges that under certain circumstances issues can arise with compacted clay barriers, particularly when used alone. These can include desiccation, freeze-thaw sensitivity, and distortion due to total and differential settlement of the underlying wastes. These issues can generally be addressed through proper maintenance of the cover system; and in fact the final rule requires as part of post-closure care that the owner or operator maintain the integrity and effectiveness of any final cover, including making repairs to the final cover to correct the effects of settlement, subsidence, erosion, or other events, and preventing run-on and run-off from eroding or otherwise damaging the final cover. Consequently, EPA is not mandating the installation of a composite liner system.

However, fewer problems are typically seen with the use of composite cover systems. And while ongoing oversight and proper maintenance is necessary to ensure the efficacy of any cover system, less effort is generally involved to ensure the continued performance of a composite cover system. EPA therefore generally recommends that facilities install a composite cover system, rather than a compacted clay barrier, as the composite system has often proven to be more effective (and cost effective) over the long term. For these reasons, EPA also anticipates that composite cover systems will be recommended in many circumstances by qualified professional engineers.

The final rule also allows the use of an alternative final cover. The rule requires that the alternative final cover must include infiltration and erosion layer that achieve equivalent performance as the minimum designs specified for final cover systems as discussed above. As discussed in the proposed rule, EPA included this provision to increase the flexibility for an owner or operator of a CCR unit to account for site-specific conditions. Moreover, these provisions will provide an opportunity to incorporate future technology improvements that would be missed if the rule required prescriptive design measures. In addition, these requirements would not supersede more stringent state requirements. Thus, if a state either has more prescriptive or more stringent standards in its state regulations applicable to CCR units, those state requirements would control any final cover system or alternative final cover system design.

While the rule provides the owner or operator flexibility in selecting the final cover for the unit, EPA remains concerned about the lack of guaranteed state oversight on final cover selection. A final cover system that does not perform as designed may result in unacceptable infiltration of water into the closed CCR unit that may lead to leachate and releases from the unit. To address this concern, as well as the concerns raised by commenters regarding the long-term performance of certain cover systems by providing further assurance that the final cover system will perform over the long term, EPA has deleted the proposed provision that would have allowed owners or operators to shorten the length of the post-closure care period. As discussed in Unit M.9 below, the final rule requires facilities to conduct post-closure care for all CCR units for 30 years.

b. Performance Standards When Leaving CCR in Place

EPA received no significant comments on the proposed performance standards. The Agency is therefore finalizing these requirements without revision from the proposal (although EPA has reorganized the final regulatory text for greater clarity). The performance standards are summarized below:

i. As discussed in the previous section, the CCR unit must be closed in a manner that will control, minimize or eliminate, to the maximum extent practicable, post-closure infiltration of liquids into the waste and releases of CCR, leachate, or contaminated run-off to the ground or surface waters.

ii. The CCR unit must be closed in a manner that will preclude the probability of future impoundment of water, sediment, or slurry.

iii. The CCR unit must be closed in a manner that will provide for major slope stability, which is discussed is Unit M.1 of this document for closure plans above.

iv. The CCR unit must be closed in a manner that will minimize the need for further maintenance of the unit.

v. The CCR unit must be closed in the shortest amount of time consistent with recognized and generally accepted good engineering practices. The Agency added this performance standard to be consistent with the final provisions applicable for the timeframes for initiating and completing the closure of CCR units.

4. Timeframes for Closure

The Agency proposed that closure of a CCR landfill or CCR surface impoundment must be initiated by the owner or operator no later than 30 days following the known final receipt of CCR. To address concerns about ''inactive'' or abandoned units, the proposed rule also provided that a CCR unit must initiate closure no later than one year after the most recent receipt of CCR if the CCR unit had remaining capacity and there was a reasonable likelihood that the CCR unit would receive additional CCR (*i.e.,* the rule would have forced the facility to close the CCR unit). See 77 FR at 35209 and proposed § 257.100(j). In addition, the proposed rule would have required an owner or operator to complete closure activities within 180 days of initiating closure. See proposed § 257.100(k). Thus, the maximum amount of time a facility would have had to initiate and complete closure of a CCR unit was seven months.

While the existing closure criteria for MSWLFs allow the Director of an approved State to grant time extensions for closure (both to initiate and to complete closure) if steps are taken to prevent threats to human health and the environment from the unclosed unit, EPA proposed not to include similar provisions for owners or operators of CCR units. At proposal, the Agency believed that extending the closure deadlines was inappropriate because, in the absence of an approved state program, the owner or operator could unilaterally decide to extend the time for closure of a CCR unit, without any basis, or oversight by a regulatory authority. 75 FR 35209.

EPA received numerous comments in response to the proposed deadlines under the subtitle D proposed approach. Industry and state commenters stated that the proposed deadlines to begin and complete closure activities (30 and 180 days, respectively) are technically impracticable and simply too short for the vast majority of CCR units, especially for CCR surface impoundments to complete closure. Commenters stated that a 30-day deadline to initiate closure activities may not be workable in situations such as when there are construction

limitations due to seasonal or climatic conditions, and should not be required in circumstances when a coal-fired generating unit is temporarily idled (*e.g.,* maintenance related outages or an outage corresponding with a CCR handling system conversion). Regarding the amount of time needed to close a unit, numerous commenters noted that it would be impossible to properly complete closure activities within the proposed 180 days at most CCR surface impoundments due to the length of time needed to dewater an impoundment and stabilize the wastes prior to constructing the final cover system. For example, commenters pointed out that dewatering of a surface impoundment alone can take several years to complete because impoundments can be hundreds of acres in size. One commenter provided information related to an ongoing CCR surface impoundment closure where the dewatering and ash stabilizing phases of closure took two years to complete. Commenters also stated that because a large number of CCR units will have to be closed during roughly the same timeframe, facilities may not be able to obtain the necessary specialized personnel, equipment, and materials (*e.g.,* clay or fill material, liner materials) to close multiple units simultaneously. This issue may be further complicated in locations where multiple facilities are competing for the same limited resources. Commenters further argued that adopting the same closure deadlines applicable to MSWLFs is not appropriate given differences in size, design, and operation (*e.g.,* CCR surface impoundments contain large volumes of water, MSWLFs typically close each component cell when it reaches its disposal capacity). As a result of these concerns, commenters recommended that EPA extend the deadlines both to commence and complete closure activities. The majority of the these commenters, however, urged EPA not to establish specific deadlines for closure and instead require facilities to close a CCR unit consistent with a closure plan approved by a state, or developed and certified by a qualified professional, such as a professional engineer.

In a subsequent NODA, the Agency solicited additional public comment on several different options to address these concerns. 78 FR at 46944–46. With respect to the deadline to initiate closure, EPA presented several examples of routine and legitimate circumstances in which CCR units would not receive CCR for periods longer than one year, even though the facility intended to continue to use the unit. For example, EPA discussed circumstances in which the facility alternates between two surface impoundments, only one of which is operational at a time. Once the impoundment has reached capacity, the facility dewaters the unit, and begins to send CCR to the second impoundment. Once the unit is dewatered, the CCR is excavated and disposed in an adjacent landfill. The time to fill these units has varied over the years as demand has fluctuated, but a typical time to fill a unit with CCR is two years, perhaps longer, during which the other unit is ''idle,'' in that it does not ''receive CCR,'' but it remains operational.

The Agency also solicited comment on a revised approach to the deadline to initiate closure. The approach entailed establishing a rebuttable presumption that if the CCR unit has not received waste within a particular period of time (*e.g.,* 18–24 months), the CCR unit would be considered inactive and unit closure would be required to begin within a specified time. However, if the facility could substantiate that there was a reasonable likelihood that the CCR unit would again receive CCR in the future and also was able to document certain findings, the owner or operator would not need to immediately commence closure of the CCR unit. In the NODA, EPA discussed several examples of situations that could support a demonstration that immediate closure of the CCR unit was not necessary. One example was if an owner or operator could document that a CCR unit had been dedicated to a temporarily idled coal-fired generating unit and there was a reasonable likelihood that CCRs would be disposed in the CCR unit once the coal-fired generating unit resumed operation. Another situation presented was a CCR unit dedicated to a coal-fired generating unit that was not burning coal at the time (*e.g.,* electricity was being generated with other fuels such as natural gas), but the facility needed the CCR unit following resumption of coal burning. A final example involved normal facility operations that include periods during which the CCR unit does not receive CCR for extended periods (*e.g.,* the alternating use of two CCR surface impoundments discussed above). As part of this approach, the Agency solicited comment on whether to limit the length of time an owner or operator can maintain an idle CCR unit.

With respect to the deadline for completing closure, EPA acknowledged in the NODA that different deadlines, at least for the larger CCR units, were warranted. Information that the Agency has obtained throughout the rulemaking confirmed commenters' claims that the timeframes originally proposed to complete closure of CCR surface impoundments will be practicably infeasible for the larger impoundments. However, the Agency cautioned that any ultimate timeframe provided in the rule that would be practicable for the largest CCR units would be far too long to justify as timeframes for closure of the smaller impoundments. EPA explained that it intended to examine available closure plans for CCR surface impoundments to determine whether there are consistent timeframes or other factors that EPA could adopt as part of the regulations. EPA specifically identified two closure plans of CCR units that were scheduled to close as a possible source of useful information. These plans projected that closure would take multiple years to complete for modestly-sized CCR surface impoundments (*i.e.,* less than 50 acres).

a. Deadlines To Initiate Closure

In response to the NODA, most utility commenters stated that the time to initiate closure should be tied to reasonable triggers that account for the diverse uses of CCR surface impoundments and CCR landfills. In particular, these commenters recommended that closure not be initiated for an idled CCR unit if the CCR unit was expected to receive additional waste in the future, whether CCR or any other waste the unit may be authorized to manage. These commenters also supported the scenarios EPA described in the NODA as examples of legitimate situations that could warrant delaying the immediate closure of a CCR unit. Many of these commenters generally agreed that the rebuttable presumption alternative discussed in the NODA could be an appropriate approach for closure, in particular for CCR units not covered by a state-approved operating plan, provided the regulatory approach would be implemented in a manner that did not restrict other legitimate uses of the CCR unit. Many of these commenters also asserted that a limit on the length of time a CCR unit can remain idle is not practical because the owner or operator will not be able to predict with any degree of certainty how long a CCR unit will be idled. Several of these commenters also urged EPA to specify in the final rule what EPA intended by the phrase ''initiation of closure;'' that is, that EPA define the activities or actions the owner or operator must take by the deadlines specified in the rule.

A trade organization and other commenters warned that strict restraints on the initiation (and completion) of

closure of CCR units would pre-empt opportunities for reclaiming CCR from these CCR units for beneficial use of CCR. These commenters recommended that the final rule create meaningful incentives for the beneficial use of CCR already in CCR units which will become unavailable to reclamation once a final cover system is put in place. For example, one commenter suggested that an incentive could be deferring deadlines for closure of a CCR unit if an owner or operator reduces its net tonnage by a set amount, such as 10,000 tons per year, if the CCR is beneficially used. EPA also received comments from several states that generally supported the rebuttable presumption concept. One state supported a longer rebuttable presumption time period of three years that could be extended if approved by the state on a case-by-case basis.

After consideration of all of the public comments, the Agency is adopting an approach that largely mirrors the approach outlined in the NODA. Closure of a CCR unit is triggered in one of three ways. The first is upon the known final receipt of waste (CCR or otherwise), or when an owner or operator removes the known final volume of CCR from the CCR unit for the purpose of beneficial use of CCR. Under these scenarios, the final rule requires an owner or operator to commence closure of the CCR unit within 30 days of such known final receipt or known final volume removal, whichever date is later.

The second way closure can be triggered relates to ''idled'' CCR units. This applies to situations in which the CCR unit has remaining disposal, treatment, or storage capacity, or there has been a temporary pause in the removal activities of CCR from the CCR unit. In these situations, the rule establishes a presumption that the owner or operator must initiate closure of the CCR unit no later than two years after the most recent receipt of CCR or any non-CCR waste stream, or no later than two years after the most recent date that CCR was removed from the CCR unit for the purpose of beneficial use, whichever date is later. The rule, however, provides procedures for an owner or operator of the CCR unit to rebut this presumption and obtain additional time, provided the owner or operator can make the prescribed demonstrations.

The final way closure is triggered is when a CCR unit fails to meet certain of the technical criteria. Specifically, an owner or operator may be compelled to close a CCR unit in the following circumstances: (1) If the CCR unit has been sited inappropriately; *i.e.,* cannot meet the applicable location criteria; (2) if an unlined CCR surface impoundment is found to contaminate groundwater in excess of a groundwater protection standard; or (3) if a CCR surface impoundment cannot demonstrate the minimum factors of safety regarding structural integrity of the CCR unit. When closure is triggered under these circumstances, the owner or operator must initiate closure of the CCR unit within six months. Each of these is discussed in more detail below.

i. ''Known Final Receipt'' of CCR

Several commenters suggested that the rule not link the deadlines to initiate closure solely to when a CCR unit ceases to receive CCR. Many of these commenters provided information that CCR units also serve functions other than managing CCR, including the management of other wastes or water treatment. Thus, while there are periods of time that certain CCR units will receive both CCR and non-CCR wastes, there are also other times when the same CCR unit will only receive non-CCR wastes or perform other forms of active waste management in the unit, *e.g.,* specific water treatment functions. EPA agrees that these are legitimate waste management activities, and EPA is aware of no risks that would warrant cessation of such activities simply because the unit is no longer receiving CCR. Therefore, in response to these comments, the final rule no longer requires closure based solely upon the receipt of CCR. Instead, the final rule requires closure to be initiated after the CCR unit ceases to receive any waste or waste stream into the CCR unit. See § 257.102(e)(1) and (e)(2) in the rule.

The Agency also agrees with those commenters that supported delaying the commencement of closure of a CCR unit if substantial quantities of CCR are removed from the CCR unit for the beneficial use of the waste. This could include, for example, removal of CCR from a CCR unit followed by its use as a partial replacement for Portland cement. As discussed in Unit IV.B of this preamble, EPA has identified significant benefits from reducing the disposal volumes of CCR in CCR landfills and CCR surface impoundments, including reduced risks associated with the practice of CCR disposal, benefits from reducing the need to mine and process virgin materials, and energy and greenhouse gas benefits. EPA finds these potential benefits compelling and is therefore revising the closure requirements in the rule to accommodate the removal and beneficial use of CCR. EPA has therefore revised the rule to provide that closure of an otherwise idled CCR unit is not immediately triggered, as long as the owner or operator is removing substantial quantities of CCR from the unit. However, once removal of CCR for beneficial use is no longer taking place, the rule would require the owner or operator to initiate closure of the CCR unit. See § 257.102(e)(1) and (e)(2) in the rule.

After considering comments received regarding the specific timeframe by which closure must be initiated following known final receipt of wastes, the Agency is finalizing the 30 day timeframe from the proposed rule. Several commenters expressed concern that 30 days is too short because it does not account for the potential that weather or seasonal concerns may interfere or cause substantial delay. The Agency acknowledges that weather or seasonal effects can delay certain activities, but disagrees that the rule provision needs to be revised to account for those. This provision does not require that specific actions or activities must be initiated during this 30-day period. For example, the rule does not require the installation of the final cover system (or the commencement of removal of CCR from the CCR unit) necessarily begin within this 30-day period. Instead, the provision is more flexible; the owner or operator can initiate closure by taking other actions necessary to implement the closure plan that are not weather or seasonal dependent, such as turning off pumps supporting sluice lines or taking any steps necessary to comply with any state or other agency standards that are a prerequisite to initiating closure. Provided the owner or operator has started to take the measures to implement the closure plan that can be feasibly undertaken, the facility will have complied with this requirement.

The 30-day period remains equally appropriate under the wider provision that allows closure to be triggered either by the known final receipt of all wastes in the unit, or upon the known final volume removal of CCR for beneficial use of CCR. There are no facts unique to these circumstances that would necessitate an extension beyond the 30 day timeframe. Furthermore, as the terms ''known final receipt'' and ''known final volume removal'' suggest, the owner or operator has made the determination to cease managing waste in the CCR unit, or to cease removing CCR from the CCR unit for beneficial use purposes. This will likely occur in situations where the CCR unit is reaching its disposal capacity (or treatment capacity when the CCR unit is receiving non-CCR waste streams) or the

owner or operator intends to close the CCR unit for other purposes (*e.g.,* the closing of a CCR surface impoundment following conversion to dry handling of CCR). Given that these situations can generally be anticipated and planned for in advance, EPA is not aware of circumstances that would prevent owners or operators from at least commencing closure within this 30-day period. In summary, the owner or operator must commence closure of the CCR unit with 30 days of known final receipt of CCR or any non-CCR waste stream, or within 30 days of known final removal of CCR for beneficial use, whichever date is later.

ii. Temporarily Idled Units

This situation involves CCR units with remaining CCR disposal or storage capacity (or treatment capacity for non-CCR waste streams) that may sit idle for extended periods of time (*e.g.,* potentially years at a time); however, the owner or operator intends to continue to maintain the idled unit to receive CCR or non-CCR waste streams in the future. EPA proposed that these CCR units could remain idle for up to one year, but that closure of the CCR unit would have to be initiated no later than one year after the most recent receipt of CCRs. See 75 FR 35252 (proposed § 257.100(j)). The majority of commenters claimed that one year was too short and would require the premature closure of CCR units that would be needed in the future. In response to these comments and new information documenting examples of legitimate circumstances in which CCR units were idled for more than one year, EPA solicited comment on a revised approach to establish longer timeframes to initiate closure for temporarily idled CCR units. As discussed previously, this approach entailed establishing a rebuttable presumption that if the CCR unit has not received waste within a specified period of time (*i.e.,* 18 months to two years), the CCR unit would be considered inactive and closure of the CCR unit would be required. However, this time could be extended beyond the 18 months or two years if the facility could substantiate certain findings. See 78 FR at 46945.

After considering comments received, the Agency is essentially finalizing the approach presented in the 2013 NODA. Specifically, in situations where the CCR unit has remaining disposal or storage capacity (or treatment capacity for non-CCR wastestreams) and there is a reasonable likelihood that the CCR unit will receive additional CCR or non-CCR waste in the future, the final rule allows the owner or operator to keep the CCR unit available for use for up to two years. However, if the CCR unit has not received CCR or any non-CCR waste within two years of the last receipt of CCR or any non-CCR waste, whichever date is later, the rule requires closure of the CCR unit unless the owner or operator can document that additional time is necessary to accommodate routine operations and legitimate waste management activities.

The Agency agrees that it is not necessary to require closure of temporarily idled CCR units after one year. Information in the record documents numerous examples of legitimate circumstances in which CCR units were idled for more than one year. In most of the examples provided CCR units are temporarily idled for periods that can last more than one year, but typically use of the CCR units resumes within approximately two years. Based on this information EPA has concluded that a two year timeframe before presumptively requiring closure of a CCR unit would be more consistent with current practice, and is better supported by the available information.

This same information documented that there can be situations in which a CCR unit is idled for longer periods of time (*e.g.,* a coal-fired boiler may be idled for years during which another fossil fuel is burned (*e.g.,* natural gas), and the CCR unit will be needed when the utility returns to coal burning. In order to obtain additional time beyond two years, the owner or operator must document in writing both that the CCR unit has remaining disposal or storage capacity and the facts that support a conclusion that there is a reasonable likelihood that the CCR unit will accept CCR or non-CCR waste in the foreseeable future. The facility would need to substantiate those findings, including the specific reasons the owner or operator believes ''that there is a reasonable likelihood that CCR will be disposed in the waste disposal unit.'' These findings would need to be certified by the owner or operator of the CCR unit.

The rule identifies examples of specific scenarios that would support a determination that there is a continuing need for the unit to support future waste management activities (*e.g.,* that the CCR will resume receiving CCR or non-CCR waste in the future). These are intended to be illustrative rather than an exclusive list; there may well be additional circumstances in which routine operations or legitimate waste management practices would support the necessary determination. The particular situations identified in the rule generally match those discussed in the NODA or reflect situations identified in public comments. Specifically, the rule identifies four particular circumstances: (1) Normal plant operations include periods during which the CCR unit does not receive wastes (CCR or non-CCR waste streams). This may include the alternating use between one CCR unit that receives CCR while dewatering or removing CCR from a second unit. (2) The CCR unit is dedicated to a coal-fired boiler unit that is temporarily idled (*i.e.,* CCR is not being generated) and there is a reasonable likelihood that the coal-fired boiler will resume operations in the future. (3) The CCR unit is dedicated to an operating coal-fired boiler (*i.e.,* CCR is being generated); however, no CCR is being placed in the CCR unit because the CCR is being entirely diverted to beneficial uses, but there is a reasonable likelihood that the CCR unit will again be used in the foreseeable future. (4) The CCR unit currently receives only non-CCR waste streams and those non-CCR waste streams are not generated for an extended period of time, but there is a reasonable likelihood that the CCR unit will again receive non-CCR waste streams in the future. As noted, a facility must substantiate these findings; it is not sufficient to merely repeat the words of the regulation and conclude that additional time is warranted.

The final rule allows an owner or operator to obtain additional two-year time extensions for as long as the owner or operator continues to be able to provide a factual basis to justify the need for additional time via a written demonstration. Because these idled units must continue to comply with all applicable technical requirements, including those for groundwater monitoring, corrective action, and structural stability, a fixed or definitive limit on the amount of time that a CCR unit can sit idle is not necessary.

In addition, the Agency agrees that the final rule should better define the actions or activities that constitute ''initiation of closure'' of a CCR unit. A clear definition will assist in the implementation and understanding of the rule. Commenters suggested a number of actions or activities, any one of which would be sufficient to show that closure of the CCR unit has been initiated. Examples provided by the commenters included the removal of CCR sluice lines; beginning the necessary permitting processes (*i.e.,* submitting a completed permit application); turning off pumps supporting the sluice lines; preparing a bid for contractors; or procuring capping materials such as clay or top soil.

The final rule specifies that closure has been initiated when the owner or operator takes two actions. The first action is that the owner or operator must have permanently ceased placing CCR and non-CCR waste streams in the CCR unit. As suggested by commenters, permanent removal of CCR sluice lines or inactivation of the pumping system supporting the sluicing operation would be evidence that placement of CCR and non-CCR waste streams has ceased. The second action is that the owner or operator must have taken steps to implement the written closure plan required by the rule. This second action would include submitting a completed application for any required state or agency permit or permit modification in order to implement closure of the CCR unit, or taking any steps necessary to comply with any state or other agency standards or regulations that are a prerequisite to initiating or completing the closure of the CCR unit. Once the owner or operator has completed both of these actions, closure of the CCR unit has been initiated for purposes of this rule. See § 257.102(e)(3) in this rule.

iii. Closure for Cause

Finally, the Agency is clarifying that the closure initiation timeframes specified above—the 30 day period for known final receipt or known final volume removal and the 2 year period for temporarily idled CCR units—do not apply to closures initiated for cause. As discussed elsewhere in the preamble, the final rule requires certain CCR surface impoundments and CCR landfills to close. The situations include: Unlined CCR surface impoundments whose groundwater monitoring shows an exceedance of a groundwater protection standard; existing CCR surface impoundments that do not comply with the location criteria; CCR surface impoundments that are not designed and operated to achieve minimum safety factors; and existing CCR landfills that do not comply with the location criteria for unstable areas. In these situations, the final rule specifies that the owner or operator must initiate closure activities within six months of making the relevant determination that the CCR unit must close.

b. Deadlines To Complete Closure

In response to the August 2013 NODA, many utility commenters stated that the time period to complete closure must be sufficiently flexible to account for the inherent uncertainties in predicting a closure schedule. These commenters pointed to potentially innumerable complications and circumstances beyond the control of the owner or operator that render it nearly impossible to predict with precision when the closure of a CCR unit will be completed. These commenters also believe it is impractical and unrealistic for the rule to subject the closure of CCR units to any type of fixed regulatory structure. They maintained their position from the proposed rule that it would be impossible to properly complete closure of most CCR surface impoundments within 180 days. Their recommendation is to allow closure timeframes to be governed by the a state-approved closure process, which would include the owner or operator developing and submitting a closure plan to the state and mechanisms for the state to verify and enforce compliance with all closure requirements, including the closure plan. Under this approach, the owner or operator's compliance with the requirements of the state-approved closure process (including following the closure plan, completing mitigation, etc.) would represent compliance with this rule's closure requirements. For CCR units not subject to a state-approved closure process, these commenters recommended that the owner or operator should demonstrate compliance with the CCR closure requirements by submitting a closure plan to the state that is certified by an independent professional engineer. In this case, because there is not direct state oversight and administration of the closure process, the timelines in the closure plan could be subject to a modified set of tiered timeframes for completing closure, provided owners or operators could demonstrate that more time is needed to close the unit on a case-by-case basis.[122] These commenters also opposed any closure approach with firm and inflexible timeframes because no single factor (*e.g.,* the acreage of the CCR unit or the volume of CCR in the unit) is determinative in all instances of how long it will take to complete closure of the CCR unit. Commenters also cautioned that pre-closure closure plans (and the closure schedules contained therein) may not be an actual reflection of the time it will take to close the unit due to unforeseen or variable conditions. Finally, these commenters also generally opposed the idea discussed in the NODA of petitioning the Agency for a site-specific rule to vary from a generally applicable deadline.

Many commenters described the numerous factors that could affect timeframes for closure of a CCR unit. Most comments were specific to CCR surface impoundments where closures are typically more complex as compared to CCR landfills due to the presence of water in impoundments. Factors most often cited by the commenters that may affect the time required to close a CCR unit included: (1) The size and volume of CCR in the unit; (2) the geotechnical characteristics of the CCR; (3) the type or design of the surface impoundment (*i.e.,* diked, incised, valley fill, and side hill); (4) the need to coordinate or obtain approvals from state permitting officials; (5) the availability of qualified engineers, contractors, and materials since closing a CCR unit is a specialized activity, especially given that many units may be required to close simultaneously; (6) climate and weather that can affect dewatering operations and the length of a construction season; (7) the time needed to obtain replacement disposal capacity for a closing unit that would ensure ongoing facility operations; and (8) dam safety considerations during closure. Many of commenters identified that the dewatering process (an early necessary step in the closure process) as being a site-specific issue, as the time that will be needed to dewater an impoundment can vary considerably depending on the type of CCR unit, the volume of CCR in unit, and the geotechnical properties of the CCR. Several commenters also cited that closure times for some CCR units will require substantial volumes of fill material to properly grade a closing surface impoundment to facilitate positive drainage from the closed unit. These commenters provided estimates on the volumes of fill material needed and showed that the earthmoving aspect of this step alone can take many years to complete in some cases.

Several state commenters generally supported the tiered closure alternative discussed in the NODA. However, these commenters urged EPA to include provisions in the rule to provide flexibility for closing units to demonstrate the need for additional time on a case-by-case basis.

i. Timeframes for Completing Closure

In the August 2013 NODA the Agency solicited comment on ways to establish categories of timeframes that would adequately account for the various factors that can affect the amount of

[122] The tiered timeframes for completing closure could be based on the size of the CCR unit (after obtaining necessary state and local approvals): (1) Within 3 years for an impoundment with an area less than 20 acres; (2) Within five years for an impoundment between 20 and 50 acres; (3) Within 8 years for an impoundment between 50 and 75 acres; (4) Within 10 years for an impoundment with an area of 75 acres or more; and (5) Within 180 days for a landfill. Under this approach, the owner or operator could demonstrate the need for additional time to close the CCR unit.

time needed to properly close a CCR surface impoundment. One approach discussed in the NODA was called the ''tiered approach'' that was based on comments received in response to the proposed rule. Under that approach, the final rule would establish fixed timeframes to complete closure that varied depending on the size of the impoundment (*i.e.,* surface area acreage). The Agency stated in the NODA that the concept of a tiered approach was appealing; however, the precise basis for the distinctions (*i.e.,* unit size cutoffs) and timeframes were not clear. EPA further explained its concern that factors other than size (*e.g.,* climate, geography, unit configuration) would also appear to be relevant, and that any timeframes should account for those other factors. EPA encouraged commenters interested in supporting a tiered approach to provide the rationale and data to support any suggested categories of timeframes. 78 FR 46946. Most commenters opposed the tiered approach by itself (*i.e.,* an approach without an accompanying process by which an owner or operator could obtain additional time due to site-specific circumstances) because they felt there simply are too many factors that can affect closure timeframes. These commenters concluded that basing closure timeframes on a subset of factors would not be appropriate. As one commenter noted, a 20 acre impoundment 10 feet deep can likely be dewatered and closed more quickly than a 20 acre impoundment 30 feet deep.

After considering comments and information available on closure timeframes, EPA has concluded that there are insufficient data and information to adopt the kind of tiered approach discussed in the NODA. EPA is convinced that the available information does not support an approach that would establish fixed and definitive timeframes for closure, based on a select subset of factors that distinguish between surface impoundments (*e.g.,* a 50 acre diked impoundment holding 500 acre-feet of CCR with a hydraulic conductivity of 1×10^{-5} centimeters per second located in a state in the southwest with a permitting program would be required to close in four and one-half years, while a 50 acre cross valley impoundment holding 1,500 acre-feet of CCR with a hydraulic conductivity of 1×10^{-6} centimeters per second located in a state in the upper midwest with a permitting program would be required to close in seven years, etc.). While information is available for surface impoundments on certain factors, such as the size and type of the unit and geographic information, the Agency has little to no data for a number of other key factors. For example, EPA has no information on the geotechnical properties of the CCR that can affect the time needed to dewater a unit, the volumes of clays, soils, and other materials that will be needed for closure, and information on the time needed to obtain state approvals (in accordance with state CCR programs) related to closure of a unit.

In discussing the tiered approach EPA noted that commenters had suggested that the largest CCR surface impoundments (*i.e.,* those having a surface area greater than 75 acres) should be subject to a site-specific deadline to complete closure. In the NODA, the Agency explained that a site-specific deadline may not be practicable unless the rule were to establish a ''variance'' process as part of the rule. 78 FR 46946. Under a variance approach, EPA would establish a specific deadline (*e.g.,* closure must be completed no later than five years from the date closure activities are initiated), but would allow facilities to petition EPA for a site-specific rule to establish an alternate deadline. In response to the NODA, some commenters expressed interest in such an approach, but other commenters found the approach not practicable since each owner or operator would need to petition the Agency for a site-specific rule. Some commenters believed that a site-specific rule process, which would necessarily involve a notice and comment process, would be an unwieldy process leading to unnecessary delays. The Agency agrees that this is also not a practical alternative to establish timeframes to complete closure.

Recognizing the numerous factors that can affect the amount of time needed to close an impoundment, many commenters suggested EPA not establish any type of fixed regulatory deadline for closure. Instead, these commenters recommended that the rule allow closure timeframes to be governed by a state-approved closure process. Under this process suggested by commenters, an adequate state-approved closure process would include one where the owner or operator developing and submitting a closure plan to the state and mechanisms for the state to verify and enforce compliance with all closure requirements, including the closure plan. Under the commenter's recommendation, compliance with the requirements of the state-approved closure process would not be compliance with the closure requirements of this rule. As discussed elsewhere in this preamble, under subtitle D of RCRA, the Agency cannot rely on the existence of a state permitting authority to implement the subtitle D requirements.

Some other commenters suggested EPA not establish any type of fixed regulatory deadline for closure in the rule, and instead rely on the closure plan developed and certified by a professional engineer. The Agency disagrees that this approach would meet the protectiveness standard of RCRA section 4004(a). CCR units present significant risks, and it is critical that facilities complete closure expeditiously—particularly those that are closing because they are structurally unsound or are contaminating groundwater. To be able to determine that the rule will be protective, the final rule must limit the discretion of individual facilities, many of whom may have significant incentives for delay, and avoid the potential for abuse. Moreover, in contrast to corrective action, where EPA was truly unable to establish an outer limit on the necessary timeframes—including even a presumptive outer bound—closures, while complex, do not vary to the same degree as site remediation actions. Consequently, as discussed later in this section, the available data were sufficient to support the establishment of definitive timeframes.

Most commenters, however, were generally supportive of an approach that would establish timeframes for closure, whether in a tiered-like approach (*i.e.,* timeframes for closure based on one or more characteristics of the unit) or under a ''rebuttable presumption'' approach, so long as the rule would provide the owner or operator a process or procedures to demonstrate the need for additional time. As explained in the NODA, such an approach could be implemented by establishing a presumption that facilities complete closure within a specified timeframe, such as five years, unless the facility could document that closure is not feasible to complete within the presumptive timeframe.

After consideration of all of the public comments, EPA is adopting an approach that takes elements from two of the alternatives discussed in the NODA: The concept of tiered timeframes based primarily on the size of the surface impoundment, and the concept of a rebuttable presumption. The final rule establishes a presumption that the owner or operator must complete the closure of a CCR surface impoundment within five years of initiating closure activities. For CCR landfills the presumption is that the owner or

operator must complete closure within six months of initiating closure activities. The rule, however, provides procedures for an owner or operator to rebut either presumption and obtain additional time, provided the owner or operator can make the prescribed demonstrations. For CCR surface impoundments, the amount of additional time beyond the five years varies based on the size (using surface area acreage of the CCR unit as the surrogate of size) of the unit. For impoundments 40 acres or smaller, the maximum time extension is two years. For impoundments greater than 40 acres, the maximum time extension is five two-year extensions (ten years) and the owner or operator must substantiate the factual circumstances demonstrating the need for each two year extension. For a CCR landfill, the amount of additional time beyond the six months does not vary according to the size of the landfill, rather the maximum time extension is two one-year extensions (two years) for any CCR landfill. The owner or operator must substantiate the factual circumstances demonstrating the need for each one-year extension.

ii. CCR Surface Impoundment Timeframes

To develop these timeframes the Agency began by identifying the period of time in which most surface impoundments could feasibly complete closure. EPA intended this period of time to serve as the basis for the rebuttable presumption of the rule. As EPA recognized in the NODA, a timeframe that would be feasible for the largest units would grant more time than could be justified to complete the closure of smaller units. The closure of CCR units, and particularly the closure of CCR units that are compelled to close because they fail to comply with the rule's requirements (*e.g.,* are structurally unstable or are contaminating groundwater), needs to occur as expeditiously as is feasible. While these units (and particularly the larger CCR surface impoundments) are in the process of closing, they continue to present risks to human health and the environment. On the other hand a presumptive time period that is feasible for a small percentage of units would simply result in a greater number of facilities that would need to obtain time extensions. It is well established that the law cannot compel actions that are physically impossible, ''*lex non cogit ad impossibilia,*'' and it is incumbent on EPA to develop a regulation that does not in essence establish such a standard.

The available information shows that CCR surface impoundments can vary in size by orders of magnitude (*i.e.,* from less than one acre to nearly 1,000 acres). EPA evaluated the information on the size distribution of CCR surface impoundments in its database of survey results from EPA's 2009 Information Request.[123] Through this effort, EPA received a substantial amount of factual information from 240 facilities covering 676 surface impoundments, including surface area information on over 650 impoundments. The database of survey responses shows that the median surface impoundment is approximately 14 acres in size, 75 percent of impoundments are 50 acres or smaller, 80 percent of impoundments are 66 acres or smaller, and 90 percent of impoundments are 111 acres or smaller.

Available information on actual and projected timeframes needed to close CCR surface impoundments of varying sizes (using surface area as the surrogate for size) is summarized below. Much of this information came from public comments from utilities. The largest CCR surface impoundment in this data set that has actually completed closure is a 40-acre unit that closed over a period of approximately five years (*i.e.,* the surface impoundment at PPL Corporation's Martins Creek Power Plant).[124] This facility closed with waste in place, and included installation of a final cover system. According to the facility, this CCR unit ceased receiving wastewater in January 2008, and the closure work began with dewatering the unit and preparing the revised closure plan and permit modification applications. Installation of the final cover, in addition to final soil grading and seeding of the unit was completed in spring 2012. By early 2013, all remaining closure actions were completed and state regulators issued final approvals in July 2013. EPA gave substantial weight to this information because (1) it was a CCR surface impoundment—the units of greatest relevance to the issue at hand; (2) the closure was recently completed, and so would accurately reflect current and available engineering practices; and (3) the facility actually completed closure of the unit. See EPA–HQ–RCRA–2012–0028–0103 and EPA–HQ–RCRA–2012–0028–0113.

As another example, American Electric Power (AEP) provided some information on the recent closure of a CCR surface impoundment in 2013. This 21-acre unit had been inactive for several years and was closed over the course of two construction seasons. The impoundment was closed by leaving CCR in place and installing a composite cap, in addition to the installation of hydraulic appurtenances to control the design storm events. See EPA–HQ–RCRA–2012–0028–0067.

Cleco Corporation provided planned closure timeframes contained in existing permits for its CCR surface impoundments. For three of its CCR surface impoundments, which in aggregate totaled 66 acres, Cleco Corporation estimated that it could take approximately one year to complete closure, which would be accomplished by leaving CCR in place and installing a final cover system. Cleco Corporation also estimated that it would take approximately nine months to complete closure of two additional CCR surface impoundments, with an aggregate acreage of 5.5 acres, by removing CCR from the CCR units, (*i.e.,* clean closure of the units). Information on the size of any of the five CCR units was not provided, which complicates the Agency's ability to assess the closure of any of the individual CCR units. In addition, the time period appears to begin when dewatering operations are initiated and the comments do not discuss how much time may be needed to obtain any necessary approvals from the state prior to commencing closure activities. See EPA–HQ–RCRA–2012–0028–0106.

Similarly, Xcel Energy stated in its comments to the NODA that it closed four CCR surface impoundments at its Northern States Power of Minnesota's Minnesota Valley Plant by removing all of their contents. See EPA–HQ–RCRA–2012–0028–0079. While the commenter did not provide any information on the time needed to close the four CCR units, other information available to the Agency indicated that closure took place sometime after May 2009 and was completed prior to September 2013. Based on information obtained from Xcel Energy in response to EPA's request for information from May 2009, the four CCR units at the Minnesota Valley Plant each have a surface area less than one acre. In addition, the response to the information request showed that one CCR surface impoundment was nearly full of ash, a second was more than half full, and the final two CCR units were less than one quarter full.

In the August 2013 NODA, the Agency solicited comment on a draft plan to close two CCR surface

[123] More information on EPA's Information Request, including a data base of survey responses, can be accessed at *http://www.epa.gov/epawaste/nonhaz/industrial/special/fossil/surveys/index.htm.*

[124] EPA included information on the planned closure of this CCR surface impoundment in the NODA. 78 FR 46945. The closure plan estimated that the closure process would take approximately three years to complete.

impoundments at Santee Cooper's Grainger Generating Station in South Carolina. 78 FR 46945. The plan estimated that closure of the two CCR units, approximately 42 and 39 acres in surface area, could be accomplished during a three year period. This original estimate was based on closing the unit with waste in place and installing a final cover. However, Santee Cooper has since amended its draft plan and is now pursuing closure by removal of CCR and transport off-site for either disposal or beneficial use.[125] The revised draft envisions the complete removal of CCR from both CCR units and also one foot of underlying soil beneath the units. In total, the draft closure plan estimates that approximately 1.3 million cubic yards of CCR and underlying soil will be removed from both units—approximately 900,000 cubic yards from one unit and 400,000 cubic yards from the second—over a period of six to ten years.

The Florida Electric Power Coordinating Group (FCG) claimed that, based on FGC member experience, closing a 30 acre CCR surface impoundment is expected to take approximately two years to complete, but provided no additional information or details. See EPA–HQ–RCRA–2012–0028–0064.

The Utility Solid Waste Activities Group (USWAG) provided another projected closure schedule for a 20 acre CCR surface impoundment operated by Luminant. This facility was in the process of closing the unit when the comments were prepared. The schedule estimated that completion of all closure activities, would take approximately 45 months (3 years, 9 months) to complete. However, the commenter also states that, when complete, the ''full closure period will take approximately 84 months (seven years) due to the unique circumstances of that closure.'' No other information was provided on this closure to explain the ''unique circumstances'' that warrant such an extended period of time. See EPA–HQ–RCRA–2012–0028–0113.

There is other information in these data that indicates that larger impoundments may be able to complete closure within approximately the same timeframes as smaller units. For example, the data included the projected closure of a 100-acre CCR surface impoundment over a four and one-half year period, which seems to indicate that larger units may be able to close in approximately the same period of time. However, the Agency gave substantially less weight to this information for a number of reasons. Most critically, this information merely demonstrated projected timeframes for CCR surface impoundments, not actual timeframes that had been achieved. In addition, for some of these data, it was unclear whether the circumstances that allowed for completion within this timeframe were generally applicable to the majority of CCR surface impoundments. In one instance, the commenter noted that the time to complete closure was shorter than would normally be expected because the impoundment was being closed well before it reached full capacity and because water in the impoundment could be pumped into an adjacent impoundment. The commenter also noted that the impoundment had been built with a leachate collection system to facilitate dewatering at closure. See EPA–HQ–RCRA–2012–0028–0113.

Moreover, the majority of commenters claimed that it would take substantially longer than five years to close the largest impoundments. For example, USWAG stated that one of its members obtained ''approval for a closure plan for a 343-acre surface impoundment that provided for a twelve-year closure period to ensure adequate time to complete dewatering of the impoundment, assure the stability of the dewatered CCRs, and uniformly construct the slope of the final cover materials.'' No other information was provided on this closure example. See EPA–HQ–RCRA–2009–0640–10483. USWAG also provided information on the closure of the CCR surface impoundment at First Energy's Little Blue Run Disposal Area. This 950 acre surface impoundment, which is the largest CCR surface impoundment in the country, has a projected closure period of 15 years.

Similarly, to illustrate the time required simply for earthmoving operations to close a large CCR surface impoundment (in their example, 350 acres), Duke Energy Corporation estimated that the time needed in the schedule to deliver and place the necessary volume of materials for construction of the final cover and the sub-base to the cover system could take between nine and 12 years. This estimate is based on the need for approximately 10 to 11 million cubic yards of fill to construct and shape the sub-base of the final cover and the cover system itself that would require nearly 500,000 truckloads to deliver. See EPA–HQ–RCRA–2012–0028–0095.[126]

Collectively, this information formed the basis for the five year presumptive default. As noted the median size of CCR surface impoundments is approximately 14 acres, and 75 percent of impoundments are 50 acres or smaller. The information presented by the utilities documents that impoundments as large as 66 acres under normal circumstances can close within two to three years. EPA therefore expects that most, if not all, units should be able to complete closure within five years. For all but the very largest units, this timeframe would even accommodate potential delays caused by weather or any other unpredictable variables. This is clearly demonstrated by the examples presented by public comments, and by the recent example of the 40-acre CCR surface impoundment in Martins Creek that closed within five years.

EPA also notes that five years is the timeframe Congress mandated for the completion of open dumps to close or upgrade. While the closure times apply generally to all units—both those whose closure is mandated by this final rule and those that close because the facility decides to do so—the statutory directive provides further support for EPA's decision.

But as many commenters stated, initial estimates can and often do vary from actual closure times due to unforeseen or variable conditions. EPA acknowledges that a host of variables can, and frequently do, delay closure activities, such that the initial time estimates to complete closure of the unit are ultimately exceeded. For example, the 40 acre impoundment at Martins Creek Power Plant discussed above was initially scheduled in its closure plan to be completed within three years; however, closure ultimately took five years to complete. The additional two

[125] ''Amended Closure Plan Wastewater Ash Ponds, Grainger Generating Station, Conway, South Carolina,'' January 2014.

[126] EPA also received information from Consumers Energy Company on the closure of three former fly ash surface impoundments at the JR Whiting plant. These surface impoundments (combined) totaled approximately 52 acres and are scheduled to be closed with a final cover over an approximately 12-year period. The commenter claimed that the extended time for closure ''was necessary to allow dewatering and the filling of numerous voids, but principally to allow the generation of fly ash to allow the placement of structurally placed, low permeability ash to provide minimal required slopes for closure and to serve as the select layer for the flexible membrane liner.'' See EPA–HQ–RCRA–2012–0028–0068. Information on the individual size of any of the three CCR units was not provided in the comments, which complicates any assessment of the time needed to complete closure of any single CCR unit. Because the facility appears to be continuing to use the unit to actively manage waste, EPA does not consider this to be representative of a typical closure process.

years was due to the need to obtain approval of a modified closure plan from the state, as well as modifications to three permits, in addition to obtaining other local planning approvals. Further time was also needed to accommodate the public notice and comment processes for several of the permits and approvals.

EPA recognizes that there are a number of unpredictable or variable conditions that can affect the time needed to close a CCR unit and that those conditions are not within the control of the owner or operator. For example, some states require review and approval of a closure plan prior to initiating of closure activities. See, for example, 25 Pa. Code sections 288.292(b) and 289.311(b) for CCR landfills and CCR surface impoundments, respectively. Another commenter noted that in Illinois, permits from several different authorities may need to be obtained to commence closure, including the Illinois Department of Natural Resources, the U.S. Army Corps of Engineers, and the U.S. Fish and Wildlife Services.

Climate and weather can also impact the time needed to complete closure. For example, an unusually wet or short construction season can result in schedule delays; one commenter noted that in certain regions of the Midwest, it is possible for as much as 40 inches of rain to fall in a given season.

To account for these conditions, a substantial majority of commenters requested that the final rule include the potential for time extensions, and several specifically referenced the need for a ''force majeure'' provision. One commenter also recommended that a ''force majeure'' clause specifically include delays caused by court order (*i.e.,* appeals of permits issued by state agencies causing judgments in court). Another commenter provided an example of a ''force majeure'' provision that could serve as a model:

> An extension shall be granted for any scheduled activity delayed by an event of force majeure which shall mean any event arising from causes beyond the control of the owner that causes a delay in or prevents the performance of any of the conditions under this rule including but not limited to: acts of God, fire, war, insurrection, civil disturbance, explosion; adverse weather conditions that could not be reasonably anticipated causing unusual delay in transportation and/or field work activities; restraint by court order or order of public authority; inability to obtain, after exercise of reasonable diligence and timely submittal of all applicable applications, any necessary authorizations, approvals, permits, or licenses due to action or inaction of any governmental agency or authority; and delays caused by compliance with applicable statutes or regulations governing contracting, procurement or acquisition procedures, despite the exercise of reasonable diligence by representatives of the owner.
>
> Events which are not force majeure include by example, but are not limited to, unanticipated or increased costs of performance, changed economic circumstances, normal precipitation events, or failure by the owner to exercise due diligence in obtaining governmental permits or performing any other requirement of this rule or any procedure necessary to provide performance pursuant to the provisions of this rule.

EPA agrees that the rule should include procedures to obtain extensions of time to complete closure of the unit, based on the complexity of the activity. As previously noted, the law, including a regulation, cannot compel the impossible. However, because the record demonstrates that most units, even the larger units, can close within that five year timeframe, the rule establishes a high threshold to obtain additional time. To account for those instances of true physical impossibility, the rule limits extensions to circumstances in which the owner or operator can demonstrate that the additional time is needed due to factors that are truly beyond the facility's control—*i.e.,* could fairly be characterized as an example of ''force majeure.'' To obtain additional time, the owner or operator of the CCR unit must document in writing the exact reasons why additional time is needed. The regulation specifies that such reasons could include: (1) Complications stemming from the climate and weather, such as unusual amounts of precipitation or a significantly shortened construction season; (2) the time required to dewater a surface impoundment due to the volume of CCR contained in the CCR unit or the geotechnical characteristics of the CCR in the unit; (3) the geology and terrain surrounding the CCR unit will affect the amount of material needed to close the CCR unit; or (4) the time required or delays caused by the need to obtain State permits and/or to comply with other State requirements. These findings would need to be certified by the owner or operator of the unit, as well as by a qualified professional engineer.

The final rule limits the amount of time that closure can be extended based on the size of the CCR unit. Specifically, the rule allows CCR surface impoundments 40 acres or smaller a time extension of up to two years, while CCR surface impoundments larger than 40 acres can obtain up to five two-year extensions. The 40 acre size demarcation is based on the available information showing that surface impoundments of 40 acres or smaller routinely have either completed closure or are projected to be able to complete closure within a timeframe shorter than five years. EPA expects that facilities will account for all potential delays that can reasonably be foreseen in planning their closure activities, and that this is feasible within this five year timeframe. Consequently the final rule restricts facilities with units of this size to a single extension to account for truly exception circumstances (*e.g.,* Acts of God).

The Agency also recognizes that there is increased uncertainty for CCR surface impoundments larger than 40 acres. First, while available information documents that some CCR surface impoundments larger than 40 acres can be closed within this same five year period, the Agency has other information indicating that closure of units larger than 40 acres can be expected to take much longer than five years. For example, the largest surface impoundment in the country is approximately 950 acres and is scheduled to cease receiving CCR by December 31, 2016 and commence closure in 2017. The facility's projected closure period is 15 years. However, EPA currently has no data (anecdotal or otherwise) on the actual timeframes in which a surface impoundment of that size has completed closure. Given that closure for the largest of surface impoundments could reasonably be expected to take more than five years to complete, the Agency has concluded that surface impoundments larger than 40 acres need to be provided with the possibility of additional time extensions beyond the two years provided to impoundments less than 40 acres. Based on available information, in particular the current estimates of the time needed to close the largest unit in the country, the rule authorizes a facility to obtain a maximum of five time extensions, totaling as much as ten years in two year increments to close a CCR surface impoundment greater than 40 acres. However, the owner or operator must substantiate the factual circumstances demonstrating the need for each two-year extension.

Several commenters also urged EPA to specify in the final rule what EPA intended by the phrase ''completion of closure;'' and to define the activities or actions the owner or operator must complete to satisfy the closure requirements. For purposes of this rule, closure of a CCR unit is complete when the unit meets all of the requirements of this rule and the owner or operator

obtains certification from a qualified professional engineer verifying that closure has indeed been completed, consistent with all of the performance standards in the rule. While EPA recognizes that under some state programs closure is not considered complete until the owner or operator receives certification from the state, this is not a prerequisite to completion of closure under these federal rules.

iii. Closure Timeframes for CCR Landfills

Similar to the approach for CCR surface impoundments, EPA recognizes that there can be unforeseen and extraordinary circumstances that warrant additional time to close a CCR landfill. Accordingly, the rule adopts procedures analogous to those for CCR surface impoundments that allow the owner or operator to obtain additional time to complete the closure of a CCR landfill, provided the owner or operator can make the prescribed demonstrations. However, the amount of additional time the facility can obtain beyond the presumptive six month timeframe does not depend on the size of the landfill; rather the maximum time extension is two one-year extensions (two years) for any CCR landfill. As with the procedures for CCR surface impoundments, the owner or operator must substantiate the factual circumstances demonstrating the need for each one-year extension.

EPA developed this timeframe based on its review of the available information in the record regarding the timeframes for completing the closure of CCR landfills, some of which is summarized below. Additional information may also be found in the comment response document.

In response to the August 2013 NODA, Nebraska Public Power District (NPPD) provided information documenting that it completed closure of a 10 acre CCR landfill within 180 days after the final volume of fly ash and bottom ash was placed in the CCR landfill. Closure was accomplished by leaving CCR in place and installing a final cover system. NPPD's comments do not indicate what year closure of this CCR landfill was completed. See EPA–HQ–RCRA–2012–0028–0076.

The Florida Electric Power Coordinating Group (FCG) stated in its comments that FCG member experience with CCR landfill closure has ''demonstrated the need for a period of time greater than 180 days to complete closure activities.'' However, the commenter did not provide any information indicating how long such closures actually took, nor any information to substantiate their claim. See EPA–HQ–RCRA–2012–0028–0064.

Overall, the closure of CCR landfills is less complex than the closure of CCR surface impoundments. Portions of the CCR landfills that reach final grade can be closed as other areas of the CCR landfill continue to receive CCR, which is typically not possible at CCR surface impoundments. Nor does the owner or operator need to dewater the unit, which appears to be the aspect of closure most likely to be a source of unanticipated circumstances. Finally, there is substantially less uncertainty with respect to the timeframes to complete the closure of CCR landfills, which are not all that different (in this respect) than landfills containing other forms of solid or hazardous waste. EPA therefore has greater confidence that a fixed period of two years will be adequate to account for the vast majority of circumstances.

c. Alternative Closure Requirements

The Agency is finalizing alternative closure requirements in two narrow circumstances for a CCR landfill or CCR surface impoundment that would otherwise have to cease receiving CCR and close, consistent with the requirements of § 257.101(a), (b)(1), or (d). The first is where the owner or operator can certify that CCR must continue to be managed in that CCR unit due to the absence of both on-site and off-site alternative disposal capacity. § 257.103(a). The second is where the owner or operator of a facility certifies that the facility will cease operation of the coal-fired boilers no later than the dates specified in the rule, but lacks alternative disposal capacity in the interim. § 257.103(b). Under either of these alternatives, CCR units may continue to receive CCR under the specified conditions explained below. In addition, under either alternative, the owner or operator must continue to comply with all other requirements of the rule, including the requirement to conduct any necessary corrective action.

1. No alternative CCR disposal capacity (§ 257.103(a)).

The Agency recognizes that the circumstance may arise where a facility's only disposal capacity, both on-site and off-site, is in a CCR unit that has triggered the closure requirements in § 257.101(a), (b)(1), or (d). As a result, the facility may be faced with either violating the closure requirements in § 257.101 by continuing to place CCR in a unit that is required to close, or having to cease generating power at that facility because there is no place in which to dispose of the resulting waste. For example, while it is possible to transport dry ash off-site to alternate disposal facility that simply is not feasible for wet-generated CCR. Nor can facilities immediately convert to dry handling systems. As noted previously, the law cannot compel actions that are physically impossible, and it is incumbent on EPA to develop a regulation that does not in essence establish such a standard.

Should a facility choose to comply with the regulation and stop generating power, there would be significant risks to human health that would arise if a community would be left without power for an extended period of time. As information in the record demonstrates, obtaining alternative capacity can sometimes require a substantial amount of time (*e.g.,* if the facility needs to construct alternative capacity, including potentially the need to locate an alternative site or purchase additional property). EPA recognizes that there are also significant risks to human health and the environment, as demonstrated throughout this preamble, from a leaking or improperly sited CCR unit, and that these risks justify requiring those units to either retrofit to meet the federal criteria established in the final rule or close. EPA also acknowledges that in the interim period while the owner or operator seeks to obtain additional capacity, the risks associated with the continued use of these units will be significant. However, the Agency believes that the risks to the wider community from the disruption of power over the short-term outweigh the risks associated with the increased groundwater contamination from continued use of these units. This conclusion is further buttressed by the fact that during this interim period the risks associated with allowing these units to continue to receive CCR are mitigated by all of the other requirements of the rule with which the facility must continue to comply, including the requirements to continue groundwater monitoring and corrective action.

Under § 257.103(a)(1), a CCR unit that would otherwise be required to cease receiving CCR under § 257.101(a), (b)(1), or (d), may continue to receive CCR provided the owner or operator certifies that the CCR generated at that facility must continue to be managed in that unit due to the absence of alternative disposal capacity both on-site and off-site. The rule also requires the owner or operator to document this claim, and the claim must be based on the real absence of an alternative and not justified based on the costs or inconvenience of alternative disposal capacity. § 257.103(a)(1)(i). The owner

or operator must also remain in compliance with all other requirements of this rule, including the requirement to take any necessary corrective action. § 257.103(a)(1)(ii). Because this alternative is only available as long as the absence of disposal capacity exists, the owner or operator must document its efforts to obtain additional capacity. If any additional capacity is identified, the owner or operator must arrange to use it as soon as is feasible. § 257.103(a)(1)(iii). The owner or operator is also required to prepare an annual progress report documenting the continued absence of disposal capacity and must also document the progress made toward developing alternative capacity. § 257.103(a)(1)(iv).

Once alternative disposal capacity is available, the CCR unit must cease receiving CCR and must initiate closure following the timeframes in § 257.102(e) and (f). Finally, if the owner or operator has not identified alternative capacity within five years after the initial certification the CCR unit subject to this section must cease receiving CCR and must initiate closure following the timeframes in § 257.102(e) and (f). As discussed elsewhere in this preamble, several commenters provided information to document the length of time needed to obtain additional capacity. Based on this information, the five year timeframe provided for under this alternative is expected to provide sufficient time to obtain alternative disposal capacity and to avoid the consequences of a forced immediate closure of a power plant.

2. Permanent cessation of a coal-fired boiler by a date certain. (§ 257.103(b)).

Under this provision, the Agency addresses the circumstance where a facility's only disposal capacity, both on-site and off-site, is in a CCR unit that has triggered the closure requirements in § 257.101(a), (b)(1), or (d), but the owner or operator of coal-fired power plant has decided to permanently cease operation of that plant within one of two timeframes specified in the regulation. For the same reasons discussed immediately above, EPA has concluded that the provisions of § 257.103(b) represent the most reasonable balance between the competing risks.

Additionally, EPA anticipates that some owners or operators will decide to permanently cease operation of a coal-fired power plant in response to the combined effects of new and/or existing statutory or regulatory requirements promulgated under the Clean Air Act and under the Clean Water Act (*e.g.* the proposed Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category. See 78 FR 34442, in combination with market dynamics. As discussed earlier in this preamble, RCRA section 1006(b) directs EPA to integrate the provisions of RCRA for purposes of administration and enforcement and to avoid duplication, to the maximum extent practicable, with the appropriate provisions of other EPA statutes, including the CAA and the CWA. As noted earlier, section 1006(b) conditions EPA's authority to reduce or eliminate RCRA requirements on the Agency's ability to demonstrate that the integration meets RCRA's protectiveness mandate (42 U.S.C. 6005(b)(1)). *See Chemical Waste Management* v. *EPA,* 976 F.2d 2, 23, 25 (D.C. Cir. 1992). The provisions of § 257.103(b) are fully consistent with the direction in section 1006(b) to account for the provisions of other EPA statutes which may lead an owner or operator to close a coal-fired power plant.

EPA has also concluded that the provisions of § 257.103(b) meet RCRA's protectiveness mandate. As stated above, EPA recognizes that there are long-term risks to human health and the environment, as demonstrated throughout this preamble, from a leaking CCR unit and those risks justify requiring those units to either meet the federal criteria established in this rule or close. However, the risks associated with allowing these units to continue to receive CCR are mitigated by the requirement that the facility must comply with all other requirements of the rule, including initiating groundwater monitoring and corrective action where necessary. And a critical factor is that facilities that choose to rely on this alternative will be required to *complete* closure of their disposal unit in an expedited timeframe. Thus, the risks from these units will be fully addressed sooner. Consequently, while over the short term the risks will be higher, overall, the risks will be at least equivalent to, or potentially lower than if the CCR unit had closed in accordance with the normal closure timeframes.

Under § 257.103(b)(1), a CCR unit that would otherwise be required to cease receiving CCR under § 257.101(a), (b)(1), or (d), may continue to receive CCR provided the owner or operator of the facility certifies that the facility will cease operation of the coal-fired boilers within the timeframes specified in paragraphs (b)(2) through (b)(4) and that the CCR generated at that facility (before the plant ceases to operate) must continue to be managed in that unit due to the absence of alternative disposal capacity both on-site and off-site. The rule also requires the owner or operator to document the facts that support this claim. The regulation specifies that the claim must be based on the real absence of alternative disposal capacity, and not justified based on the costs or inconvenience of alternative disposal capacity. § 257.103(b)(1)(i). The owner or operator must also remain in compliance with all other requirements of this rule, including the requirement to take any necessary corrective action. § 257.103(b)(1)(ii). The owner or operator is also required to prepare an annual progress report documenting the continued absence of disposal capacity and must also document the progress made toward the closing of the coal-fired boiler. § 257.103(b)(1)(iii).

Under § 257.103(b)(1), the owner or operator does not need to demonstrate any efforts to develop alternative capacity because of the impending closure of the power plant itself.

Consistent with the general timeframes provided for the closure of CCR surface impoundments, EPA has established different timeframes based on the size of the CCR unit. Under § 257.103(b)(2), where the disposal unit is a CCR surface impoundment 40 acres or smaller in size, the coal-fired boiler must cease operation and the disposal unit must have completed closure within 8.5 years of the publication date of the rule. Where the disposal unit is a CCR surface impoundment larger than 40 acres in size, the coal-fired boiler must cease operation and the disposal unit must have completed closure within 13.5 years of the publication date of the rule. § 257.103(b)(3). Finally, under § 257.103(b)(4), where the disposal unit is a CCR landfill, the coal-fired boiler must cease operation and the disposal unit must have completed closure within 6 years of the publication date of the rule. These timeframes were selected to ensure that closure of these units will be completed in a measurably shorter timeframe, and that overall the risks will be lower, or at least equivalent to, the level of risk that would be achieved under the rule's ''standard'' closure provisions.

5. Notation on the Deed to Property

The proposed rule would have required, following closure of the CCR unit, the owner or operator to record a notation on the deed or some other instrument normally examined during a title search. This notation would notify any potential purchaser in perpetuity that the property has been used as a CCR landfill or CCR surface impoundment and that use of the land is restricted under the rule's post-closure care provisions. After the

notation was completed, the proposed rule would have required the owner or operator to notify the state that the notation has been recorded and a copy has been placed in the facility's operating record and on its publicly accessible internet site. In addition, the Agency solicited public comment on adding a provision to the rule to allow removal of the deed notation once all CCR are removed from the CCR unit, and notification is provided to the state of this action. The EPA solicited comment on this potential approach as a way to create a further incentive for clean closure of the facility. 75 FR at 35208–09. The proposal further encouraged commenters who are interested in supporting such an option to suggest alternatives to state oversight to provide for facility accountability.

EPA received few public comments on the proposed requirement to record a deed notation to the property (or some other instrument that is normally examined during title search). One commenter provided general support for the proposed requirement to record a deed notation to the property. Another commenter urged EPA to ensure that any deed notation requirements should not interfere or conflict with existing state property laws that provide for environmental covenants.

EPA did receive several comments in response to the Agency's solicitation of comment on adding a provision to the rule to allow removal of the deed notation when all CCR are removed from the facility, and notification is provided to the state of this action. One commenter supported the addition of this provision, stating that the licensure requirements of the Professional Engineer provide an assurance of integrity because the Professional Engineer would be required to verify that closure has been completed in accordance with the closure plan. This commenter also stated that it would be sufficient to allow removal of a deed notation upon an application to the state agency supported by a declaration of a licensed professional, subject to state agency review and approval. Another commenter supported providing the incentive for clean closure and allowing the facility to demonstrate the ''cleanliness of the closure.'' The commenter also recommended that the information provided by the facility should be followed by a review from an independent third party with knowledge of the industry and associated environmental issues.

After considering comments, the final rule requires an owner or operator to record a notation on the deed or some other instrument normally examined during a title search. This notation notifies any potential purchaser in perpetuity that the property has been used as a CCR landfill or CCR surface impoundment and that use of the land is restricted under the rule's post-closure care provisions. See § 257.102(i). In response to the commenter that urged EPA to ensure that any deed notation requirements should not interfere or conflict with existing state property laws, the Agency has no information that the proposed requirement would create such a conflict. In addition, the commenter did not provide any information or suggest that EPA's proposed approach would actually interfere or conflict with existing state property laws. Therefore, the Agency is finalizing the deed notation requirement as proposed.

In addition, regarding the Agency's solicitation of comment on adding a provision to the rule to allow removal of the deed notation when all CCR are removed from the facility, as discussed in Unit VI.M.2 of this preamble, the final rule adopts the proposal to allow the owner or operator to remove the deed notation required under § 257.102(i)(4), upon certification that clean closure has been completed. The rationale for this decision is discussed in that unit of the preamble.

6. Notification of Intent To Close and Certification of Closure Completion

The Agency proposed to require owners or operators to notify the state that a notice of intent to close a CCR unit has been placed in the facility's operating record and on the publicly accessible internet site. This notification had to be completed prior to beginning closure of the CCR unit. Following closure of a CCR unit, the proposed rule would also have required the owner or operator to obtain a certification from an independent registered professional engineer verifying that closure has been completed in accordance with the written closure plan. As proposed, this certification would be placed in the facility's operating record and on the publicly accessible Internet site.

The Agency received no public comments on the proposed requirements to develop a notification of intent to close or the certification of completion of closure. Therefore, the Agency is finalizing these requirements as proposed. See § 257.102(g) and (h).

7. Post-Closure Care Plan

The Agency proposed to require that the owners or operators of CCR landfills and CCR surface impoundments prepare a written post-closure care plan describing how the CCR unit would be maintained after closure. See proposed § 257.101(c). The proposal also identified the minimum information necessary to include in the post-closure care plan. This information included: (1) A description of the monitoring and maintenance activities for the CCR unit and the frequency at which these activities would be performed; (2) the name, address, and telephone number of the person or office to contact about the facility during the post-closure care period; and (3) a description of the planned uses of the property during the post-closure care period.

The proposed rule further provided that the post-closure use of the property shall not disturb the integrity of the final cover, liner(s), or any other components of the containment system, or the function of the post-closure monitoring systems unless necessary to comply with the requirements of the rule. The proposal would have allowed a disturbance if the owner or operator of the CCR unit demonstrated that disturbance of the final cover, liner, or other component of the containment system, including any removal of CCR, would not increase the potential threat to human health or the environment. A professional engineer would have been required to certify such a demonstration.

The Agency received no significant comments on the proposed post-closure care requirements. The Agency's responses to these comments are addressed in the closure comment response document, which is available in the rulemaking docket. Therefore, the Agency is finalizing these requirements substantially as proposed. See § 257.102(g) and (h).

8. Post-Closure Care Activities

Following closure of a CCR landfill or CCR surface impoundment, EPA proposed that the owner or operator would be required to conduct post-closure care of the closed unit. At a minimum, the proposal would have required the owner or operator to conduct at least the following: (1) Maintain the integrity and effectiveness of any final cover, including making repairs to the final cover to correct the effects of settlement, subsidence, erosion, or other events, and preventing run-on and run-off from eroding or otherwise damaging the final cover; (2) maintain the integrity and effectiveness of the leachate collection and removal system and operating the leachate collection and removal system in accordance with applicable requirements under the design criteria for such systems; and (3) maintain the groundwater monitoring system in

accordance with applicable requirements under the groundwater monitoring and corrective action rule provisions.

EPA received few public comments on the proposed activities to conduct during the post-closure care period. These commenters were supportive of the activities and specifically urged the rule to require the monitoring of groundwater throughout the post-closure care period. The Agency received no comments opposing the proposed post-closure care activities. Therefore, EPA is finalizing the same post-closure care activities in this rule. See § 257.104(b). In addition, consistent with the proposal, the rule clarifies that certain CCR units are not subject to these post-closure care activities. Specifically, owners or operators that elect to close a CCR unit by removing CCR (*i.e.,* clean close the CCR unit) are not subject to any post-closure care requirements. See § 257.104(a)(2) and Unit M.2 of this preamble. In addition, owners or operators of inactive CCR surface impoundments that elect to complete closure of the unit within 30 months of the rule's effective date are not subject to any post-closure care requirements. See § 257.104(a)(3).

9. Length of Post-Closure Care Period

The Agency proposed that the owner or operator of a CCR unit conduct post-closure care for 30 years. EPA also proposed to allow utilities to conduct post-closure care for a decreased length of time if the owner or operator demonstrates that the reduced period is sufficient to protect human health and the environment. The owner or operator would have been required to have this demonstration certified by a professional engineer, in addition to complying with all of the notification and posting requirements under the proposed rule. The proposed rule would also have allowed an increase in the post-closure care period if the owner or operator of the CCR unit determined that it is necessary to protect human health and the environment. EPA also recognized in the proposed rule that state oversight can be critical to ensure that post-closure care is conducted for the length of time necessary to protect human health and the environment; however the Agency also recognized that there is no set length of time for post-closure care that will be appropriate for all possible sites, and all possible conditions. Therefore, EPA solicited comment on alternative methods to account for different conditions, yet still provide methods of oversight to assure facility accountability.

Some commenters supported the proposed approach because it provided flexibility to increase or decrease the post-closure care period of 30 years. EPA also received comments from a number of states documenting the current state requirements; some states require a post-closure care period of less than 30 years, some require 30 years, and one state currently requires 40 years for CCR units. Other commenters opposed the shortening of the 30-year period without state involvement and approval.

After considering public comments, and in a departure from the proposed rule, the Agency is requiring that post-closure care be conducted for a minimum of 30 years. EPA is making this change due to the lack of guaranteed state oversight for this rule. The Agency has concluded that providing the owner or operator the flexibility to shorten the post-closure care period is no longer appropriate, particularly given the flexibility being provided for the selection of a final cover system or alternative final cover system. As discussed in Unit M.3 above, the information available to the Agency supports the need to proceed cautiously. By not allowing the post-closure care period to be shortened, EPA better ensures that the final cover system will be properly maintained. In addition, a mandatory 30 year period ensures that if problems do arise with respect to a final cover system, the groundwater monitoring and corrective action provisions of the rule will detect and address any releases from the CCR unit, at least during the post-closure care period.

10. Notification of Completion of Post-Closure Care Period

The Agency proposed to require owners or operators of CCR units to notify the state that a notice of completion of the post-closure care period has been placed in the facility's operating record and on the publicly accessible Internet site. The proposed approach would have required the owner or operator to obtain a certification from an independent registered professional engineer verifying that post-closure care has been completed in accordance with the written post-closure care plan.

The Agency received no public comments on the proposed requirement to develop a notification of completion of the post-closure care period. Therefore, the Agency is finalizing these requirements as proposed. See § 257.104(e).

N. Recordkeeping, Notification and Posting of Information to the Internet

In response to EPA's lack of authority to require a state permit program or to oversee state programs, EPA has sought to enhance the protectiveness of the regulatory requirements by providing for state and public notifications of the third party certifications, as well as requiring a robust set of other information that documents the decisions made or actions taken to comply with the technical requirements of the rule. Consistent with the proposed rule, owners or operators of CCR units are required to document how the various provisions of the rule have been met by placing information (*e.g.,* plans, records, notifications, reports) in the operating record and providing notification of these actions to the State Director/or appropriate Tribal authority. The owner or operator is also required to establish and maintain a publicly accessible Internet site that posts documentation that has, in many instances, also been entered into the operating record. The owner or operator is required to maintain a copy of the current Emergency Action Plan, the current fugitive dust control plan, and the current written closure plan as long as the facility remains active. EPA believes that the establishment and maintenance of this information in both the operating record and on a publicly accessible Internet site is appropriate so as to allow states and citizens access to all of the information necessary to show that the rule has been implemented in accordance with the regulatory requirements.

With regard to the specific recordkeeping and reporting requirements outlined in the proposal, the Agency received very little comment. Commenters were primarily concerned not with the specific recordkeeping requirements but rather how the recordkeeping requirements aligned with the overall approach of the RCRA subtitle D regulatory scheme. These comments and the Agency's responses are discussed in Unit V of this preamble.

The combined mechanisms of recordkeeping, notifications, and maintaining a publicly accessible Internet site will serve to provide interested parties with the information necessary to determine whether the owner or operator is implementing and is operating in accordance with the requirements of the rule. As stated in the proposal and reiterated here, EPA believes that it cannot conclude that the RCRA subtitle D regulations will ensure there is no reasonable probability of

adverse effects on health or the environment, unless there are mechanisms for states and citizens to monitor the situation, such as when groundwater monitoring shows exceedances above the groundwater protection standard specified in the rule, so they can determine when intervention is appropriate. EPA also believes that the recordkeeping and notification requirements will minimize the danger of owners or operators abusing the self-implementing system being established in this rule through increased transparency and by facilitating the citizen suit enforcement provisions applicable to the rule.

In contrast to the proposed rule, the Agency has identified for ease of implementation each recordkeeping, notification and Internet posting required in this rule. The proceeding section provides a summary of the requirements for each reporting mechanism.

1. Recordkeeping Requirements

This rule requires the owner or operator of a CCR landfill or CCR surface impoundment and any lateral expansion to maintain files of all required information (*e.g.,* demonstrations, plans, notifications, and reports) that supports the implementation of this rule in an operating record located at the facility. Each file must be maintained in the operating record for a period of at least five years following submittal of the file into the operating record. In certain instances, however, files must be maintained until the CCR unit completes closure. For example, the initial and periodic structural stability assessments as required under section § 257.73(d) and § 257.74(d) must be maintained for five years consistent with the timeframe for periodic reassessments. Whereas, information on the construction of a CCR surface impoundment must be maintained until the CCR unit completes closure (see 257.73(c) and 257.102.) These timeframes are generally consistent with the timeframes required for maintaining hazardous waste compliance records under subtitle C of RCRA and with the timeframes outlined in the proposed subtitle C option for the regulation of CCR. (See specifically 40 CFR 264.73 and 265.73.)

Owners or operators with more than one CCR unit may elect to consolidate all files into one operating record provided that each unit is identified and files for that unit are maintained separately in different sections of the operating record. The owner or operator of the CCR unit must place files documenting compliance with the location restrictions; design criteria; operating criteria; groundwater monitoring and corrective action; closure and post closure care, into the operating record, with the specific documentation requirements found in § 257.105. In the development of this final rule, the Agency has included in the regulatory language a comprehensive listing of each recordkeeping and notification required by the rule. The Agency anticipates that this effort will facilitate owners or operators efforts in complying with the reporting provisions of the rule, and will provide other interested parties with a guide to the reporting provisions of the rule.

2. Notification Requirements

As previously discussed, owners or operators are required to notify State Directors and/or the appropriate Tribal authority when specific documentation has been placed in the operating record and on the owner or operator's publicly accessible Web site. In most instances these notifications must be certified by a qualified professional engineer and may, in certain instances will be accompanied with additional information and or data supporting the notification. For example under § 257.106(f)(1), within 60 days of commencing construction of a new CCR unit, a notification of the availability of the design criteria specified under § 257.105(f)(1) or (f)(3) in the operating record and on the owner or operator's publicly accessible Internet site. If however, the owner or operator of the CCR units elects to install an alternative composite liner, the owner or operator must also submit to the State Director and/or appropriate Tribal authority a copy of the alternative composite liner design which has been certified by a qualified professional engineer.

Notification requirements can be found in § 257.106, and are required for location criteria, design criteria, operating criteria, groundwater monitoring and corrective action and closure and post closure care.

3. Publicly Accessible Internet Site Requirements

The Agency is finalizing, as proposed a requirement for owners and operators of any CCR unit to establish and maintain a publicly accessible Internet site, titled ''CCR Rule Compliance Data and Information.'' As with the operating record, owners or operators that maintain multiple CCR units may elect to use one Internet site in order to comply with these requirements, provided that the Web site clearly and distinctly identifies information from each of the CCR units by name and location. Unless provided otherwise in the rule, information posted to the Internet site must be available for a period no less than three years from the initial posting date. Posting of information must be completed no later than 30 days from submittal of the information to the operating record. This timeframe is consistent with the notification requirements of the rule. As with the other criteria in this section, Internet postings are required for various elements identified in the following sections: Location restrictions; design criteria; operating criteria; groundwater monitoring and corrective action; closure and post closure care. These requirements are enforceable by citizen suits.

VII. Summary of Major Differences Between the Proposed and Final Rules

The basic regulatory framework outlined in the proposed rule under the subtitle D option, is being adopted in this final rule for the regulation of CCR landfills and CCR surface impoundments and any lateral expansion. However, as discussed in Unit VI of this document, the Agency has made a number of revisions to several of the provisions in the proposed rule, including (1) the timeframes for closure; (2) locations restrictions—placement above the uppermost aquifer; (3) the use of an alternative composite liner design; (4) revisions to align the structural stability criteria with the experience and data generated by the Assessment Program; and (5) air criteria. These changes have been made in response to public comments and additional information collected and analyses conducted by EPA in the course of responding to those comments. These are discussed in greater detail below. Under the proposed rule, all new CCR landfills and all CCR surface impoundments that had not completed closure would be required to retrofit to a composite liner or close within five years. However, after reviewing comments and further evaluation, the Agency has concluded that this regulatory approach was unnecessary in light of the protections afforded by the other technical provisions of the rule (*e.g.,* groundwater monitoring, corrective action). In the final rule, EPA is allowing unlined CCR surface impoundments to continue to operate for the remainder of the active life, provided that the facility documents through groundwater monitoring that the CCR surface impoundment is not contaminating groundwater. However, if groundwater

monitoring at the facility demonstrates that the unlined CCR surface impoundment has exceeded any groundwater protection standard, the owner or operator must initiate corrective action, and either remove all CCR from the unit and install a composite liner (*i.e.,* ''retrofit'') or close within five years. In a departure from the proposed rule, CCR surface impoundments less than 40 acres may receive one two-year extension, providing for a maximum of seven years to complete closure. Units greater than 40 acres may receive up to five two-year extensions providing a maximum of 15 years to complete closure. These units are also eligible for alternative closure timeframes to account for site specific operational constraints.

In addition, under the proposed rule, CCR surface impoundments that had not closed in accordance with the rule would be subject to all the provisions of the rule. After further evaluation, EPA has revised the provision to allow an inactive CCR surface impoundment three years from publication of the rule in the **Federal Register** to complete closure. Owners or operators of inactive CCR surface impoundments that have not completed closure within this timeframe are subject to all the applicable requirements of the rule.

In response to comment and upon further evaluation the Agency is amending the location restriction relating to the placement of the CCR unit above the natural water table. Under the proposal, new landfills, any CCR surface impoundment, and all lateral expansions would have been required to have a base located a minimum of two feet above the upper limit of the natural water table. In the final rule, the Agency has amended this requirement to require that new CCR landfills and all CCR surface impoundments, and all lateral expansions be constructed with a base no less than 1.52 meters (five feet) above the uppermost aquifer or must demonstrate that there will not be an intermittent, recurring, or sustained hydraulic connection between any portion of the base of the CCR unit and the uppermost aquifer due to normal fluctuations in groundwater elevations (including the seasonal high water table.) EPA has made this change in response to comments and further evaluation demonstrating that this standard is the minimum distance necessary to demonstrate that no reasonable probability of adverse effects on human health and the environment will occur.

EPA proposed to require all new CCR landfills, CCR surface impoundments and any lateral expansion to be constructed with a composite liner. A composite liner was defined as a system consisting of two components; the upper component consisting of a minimum 30-mil FML and the lower component consisting of at least two feet of compacted soil. Based on public comments and further evaluation, the Agency is finalizing a new requirement that allows an owner or operator to install an alternative composite liner provided it meets the performance standard established in the rule. EPA has concluded that this alternative composite liner affords the same protection to groundwater resources as a composite liner.

Under the proposed rule, all CCR landfills and CCR surface impoundments would have been required to manage fugitive dusts in a manner not to exceed 35 μg/m3. The proposal also required owners or operators to control the wind dispersal of dusts consistent with the standard, and to document the measures taken to comply with the requirements. In response to comments and upon further evaluation, the Agency has removed the numerical standard of 35 μg/m3 from the rule and is establishing a performance standard for fugitive dust control. This standard requires owners or operators of any CCR unit to adopt measures that will effectively minimize CCR from becoming airborne at the facility. The Agency considers this standard to be generally consistent with the proposed rule with the added advantage of allowing for flexibility in achieving compliance. The owner or operator must also prepare an annual CCR fugitive dust control report that describes actions taken by the owner or operator to control CCR fugitive dust and to present a record of all citizen complaints during the previous year, as well as a summary of the corrective action measures taken.

VIII. Implementation Timeframes for Minimum National Criteria and Coordination With Steam Electric ELG Rule

The final rule generally establishes timeframes for the technical criteria based on the amount of time determined to be necessary to implement the requirements (*e.g.,* installing the groundwater monitoring wells). In establishing these timeframes, EPA also accounted for other Agency rulemakings that may affect owners or operators of CCR units, namely the Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category (ELG) (78 FR 34432 (June 7, 2013)) and the Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units (Clean Power Plan) (79 FR 34830 (June 18, 2014)). Specifically, the implementation timeframes in this rule will not require owners or operators of CCR units to make decisions about those CCR units without first understanding the implications that such decisions would have for meeting the requirements of each rule. For example, this final rule requires the closure and post-closure plans to be prepared following the anticipated publication of the ELG and Clean Power Plan final rules so that owners or operators of CCR units can take into consideration those final rules as they prepare the closure and post-closure care plans.

This is also particularly true in the situation where the minimum criteria in the CCR rule could potentially require a surface impoundment to either undergo RCRA closure or retrofit with a composite liner. A decision on what action to take with that unit may ultimately be directly influenced by the requirements of the ELG rule; for example, if the final ELG rule requires a conversion to dry handing of fly ash, then it may not make economic sense for an electric utility to retrofit a surface impoundment that contains wet-handled fly ash since it would be required to cease that practice under the ELG rule. Thus, under the final timeframes in this rule, any such decision will not have to be made by the owner or operator of a CCR unit until well after the ELG rule is final and the regulatory requirements are well understood. In this example, the earliest date that a CCR surface impoundment may be triggered into a retrofit or closure decision is approximately February 2017 (the exact date would be 24 months following publication of this final rule), which would apply to a CCR surface impoundment that fails to achieve minimum safety factors for the CCR unit. This is due to the fact that the owner or operator must complete the initial safety factor assessment within 18 months of the publication of this rule plus an additional six months to initiate closure of the CCR unit if the minimum factors or safety are not achieved. The ELG rule is scheduled to be finalized in September 2015 and its effective date is 60 days following its publication. Thus, there is ample time for the owners and operators of CCR units to understand the requirements of both regulations and to make the appropriate business decisions.

The tables below summarize the implementation timeframes for the minimum criteria for existing CCR

surface impoundments and for existing CCR landfills being promulgated in this rule.

IMPLEMENTATION TIMEFRAMES FOR THE MINIMUM CRITERIA FOR EXISTING CCR SURFACE IMPOUNDMENTS

Requirement	Implementation timeframe (number of months after publication of rule)	Description of requirement to be completed
Location Restrictions (§ 257.60–§ 257.64)	42 months	—Complete demonstration for placement above the uppermost aquifer. —Complete demonstrations for wetlands, fault areas, seismic impact zones, and unstable areas.
Design Criteria (§ 257.71)	18 months	—Document whether CCR unit is either a lined or unlined CCR surface impoundment.
Structural Integrity (§ 257.73)	8 months	—Install permanent marker.
	18 months	—Compile a history of construction, complete initial hazard potential classification assessment, initial structural stability assessment, and initial safety factor assessment.
	24 months	—Prepare emergency action plan.
Air Criteria (§ 257.80)	6 months	—Prepare fugitive dust control plan.
Hydrologic and Hydraulic Capacity (§ 257.82)	18 months	—Prepare initial inflow design flood control system plan.
Inspections (§ 257.83)	6 months	—Initiate weekly inspections of the CCR unit.
	6 months	—Initiate monthly monitoring of CCR unit instrumentation.
	9 months	—Complete the initial annual inspection of the CCR unit.
Groundwater Monitoring and Corrective Action (§ 257.90–§ 257.98).	30 months	—Install the groundwater monitoring system; develop the groundwater sampling and analysis program; initiate the detection monitoring program; and begin evaluating the groundwater monitoring data for statistically significant increases over background levels.
Closure and Post-Closure Care (§ 257.103–§ 257.104).	18 months	—Prepare written closure and post-closure care plans.
Recordkeeping, Notification, and Internet Requirements (§ 257.105–§ 257.107).	6 months	—Conduct required recordkeeping. —Provide required notifications. —Establish CCR website.

IMPLEMENTATION TIMEFRAMES FOR THE MINIMUM CRITERIA FOR EXISTING CCR LANDFILLS

Requirement	Implementation timeframe (number of months after publication of rule)	Description of requirement to be completed
Location Restrictions (§ 257.64)	42 months	—Complete demonstration for unstable areas.
Air Criteria (§ 257.80)	6 months	—Prepare fugitive dust control plan.
Run-On and Run-Off Controls (§ 257.81).	18 months	—Prepare initial run-on and run-off control system plan.
Inspections (§ 257.83)	6 months	—Initiate weekly inspections of the CCR unit.
	9 months	—Complete the initial annual inspection of the CCR unit.
Groundwater Monitoring and Corrective Action (§ 257.90–§ 257.98).	30 months	—Install the groundwater monitoring system; develop the groundwater sampling and analysis program; initiate the detection monitoring program; and begin evaluating the groundwater monitoring data for statistically significant increases over background levels.
Closure and Post-Closure Care (§ 257.103—§ 257.104).	18 months	—Prepare written closure and post-closure care plans.
Recordkeeping, Notification, and Internet Requirements (§ 257.105—§ 257.107).	6 months	—Conduct required recordkeeping. —Provide required notifications. —Establish CCR website.

IX. Implementation of the Minimum Federal Criteria and State Solid Waste Management Plans

As explained earlier in this document, the final regulations EPA is promulgating under RCRA subtitle D impose minimum federal criteria with which CCR units must comply without any additional action by a state or federal regulator. As discussed previously in this document, under the provisions of subtitle D applicable to solid waste, states are not required to adopt or implement these regulations, to develop a permit program, or submit a program covering these units to EPA for approval and there is no mechanism for EPA to officially approve or authorize a state program to operate ''in lieu of'' the federal regulations.

EPA has, however, received numerous comments regarding the potential implementation challenges that this statutory and resulting regulatory structure may pose, particularly in states that already have a comprehensive regulatory program governing CCR units. These concerns include the fact that facilities may need to comply with two sets of potentially differing regulations, perhaps resulting in confusion for the regulated community and the general public, and also potentially resulting in inconsistent results from citizens seeking enforcement of the criteria. The

commenters were also concerned that there is no explicit mechanism for EPA to officially approve a state program (as there is in subtitle C or in the municipal solid waste provisions of subtitle D). In addition, in states without a current formal program for overseeing CCR landfills and surface impoundments at coal fired electric utilities, stakeholders have expressed a preference for a state mechanism for implementing the federal requirements. Finally, many stakeholders expressed a strong preference for a permit program with its opportunities for public input and transparency.

Moreover, EPA recognizes the critical role that our state partners play in implementation and ensuring compliance with environmental regulations. This is particularly important in complex situations, such as presented by CCR landfills and surface impoundments that involve corrective action and requirements and timelines for closure of units. EPA expects that states will be active partners in overseeing the regulation of CCR landfills and CCR surface impoundments, and has adopted a number of provisions to ensure that States have the information necessary to undertake this role. First, the final regulations require owners or operators of regulated CCR units to notify the state of actions taken to comply with the requirements of the rule (see § 257.106). Facilities will also be required to maintain a publicly accessible internet site that will document the facility's compliance with the requirements of the rule; states (along with other members of the public) will be able to access this site to monitor facility activities (see § 257.107). (For a detailed discussion of these requirements, please see Unit VI.N of this document.)

In order to ease implementation the regulatory requirements for CCR landfills and CCR surface impoundments, EPA strongly encourages the states to adopt at least the federal minimum criteria into their regulations. EPA recognizes that some states have already adopted requirements that go beyond the minimum federal requirements; for example, some states currently impose financial assurance requirements for CCR units, and require a permit for some or all of these units. This rule will not affect these state requirements. The federal criteria promulgated today are minimum requirements and do not preclude States' from adopting more stringent requirements where they deem to be appropriate.

As noted above, commenters on the proposal voiced concerns that because EPA does not have the authority to approve a state program under subtitle D of RCRA, there is no document in which EPA formally provides its judgment that a state solid waste program substantially incorporates the minimum federal criteria. However, a mechanism for this has been available for many years through the solid waste management planning process already in the regulations at 40 CFR part 256 ''Guidelines for Development and Implementation of state Solid Waste Management Plans.'' This process, designed early in the development of the waste management infrastructure, was structured to encourage states to effectively plan for and manage their solid wastes, including upgrading or closing any units that were considered ''open dumps'' through the development of SWMPs. Currently most states have SWMPs that have previously been submitted to and approved by EPA. EPA strongly recommends that states take advantage of this process by revising their SWMPs to address the issuance of the revised federal requirements in this final rule, and to submit revisions of these plans to EPA for review, using the provisions contained in 40 CFR part 256. To be clear, EPA is not suggesting that states revise their entire SWMPs, but only that states revise their plans to address the revised federal requirements being promulgated today. EPA would then review and approve the revised SWMPs provided they demonstrate that the minimum federal requirements in this final rule will be met. In this way, EPAs approval of a revised SWMP signals EPA's opinion that the state SWMP meets the minimum federal criteria.

As noted above, the part 256 regulations established the system for the development and approval of initial SWMPs as well as their revisions. For the convenience of the reader, we describe these regulations in the following paragraphs. The regulations lay out a series of requirements that a plan must meet to be approved, as well as a number of recommendations that should also be reflected in the solid waste management plan. (*e.g.,* 40 CFR 256.01–256.04 and 256.20–256.27.) For example, § 256.02 sets out the scope of the SWMPs, requiring that the plans address ''all solid waste in the state that poses potential adverse effects on public health or the environment or provides an opportunity for resource conservation or resource recovery.'' The regulations also specify that the plan must require that all solid waste shall be disposed of in ''sanitary landfills,''—*i.e.,* units that meet any federal requirements promulgated under RCRA section 4004(a)—or otherwise disposed of in an environmentally sound manner. 40 CFR 256.01(a)(2). The plan must also prohibit the establishment of new open dumps, and provide for the closing or upgrading of all existing open dumps within the state, pursuant to the requirements of RCRA section 4005. 40 CFR 256.01(a)(2)–(3). State plans must also ''set forth an orderly and manageable process for achieving the objectives of the Act and meeting the requirements of these guidelines.'' 40 CFR 256.02(d). The regulations further specify that the plan ''shall describe as specifically as possible the activities to be undertaken, including detailed schedules and milestones.'' Id.

The part 256 regulations further require a SWMP to identify the state's legal authorities, and regulatory powers, including any revisions that may be necessary to implement the plan. 40 CFR 256.02(e). The plan must also identify and set out the responsibilities of state, local, and regional authorities that will implement the state plan. 40 CFR 256.10(a). Thus, the SWMP is the comprehensive compendium, developed and adopted with public participation, setting forth how solid waste is managed in a particular state. As such, SWMPs have been a key component of solid waste programs for many years. As stated above, states that have approved plans will only need to address these requirements for CCR landfills and surface impoundments.

In addition to the substantive requirements, the part 256 regulations impose a number of procedural obligations. Before submission to EPA, the SWMP must be adopted by the state pursuant to state administrative processes and developed in accordance with the public participation requirements set out in § 256.60. In addition, all SWMPs were to contain procedures for revisions. 40 CFR 256.03(e). EPA anticipates that states would rely on their existing procedures to revise their SWMPs to implement the new federal criteria.

Currently, most states have approved SWMPs. These approvals were based on the requirements applicable to solid waste management that were in force at the time of approval. Now, because EPA is promulgating revised federal criteria, the facilities that will be considered to be ''sanitary landfills'' and ''open dumps'' is changing. Thus, EPA expects that SWMPs in many states will need to be revised to account for these revised Federal requirements. Consistent with the provisions in § 256.01(a)(2)–(3) and with the requirement in § 256.03(e) that such plans are to be revised where

necessary, in order to maintain approval of these plans EPA expects that states will revise their SWMPs to account for the promulgation of revised federal criteria for CCR landfills and surface impoundments.

As fully explained later in this section, the plans are generally the best tool available for demonstrating how CCR units will be regulated in a state, including how the state intends its state requirements to relate to the federal regulations. In addition, EPA anticipates that the public participation processes will have substantial benefit, by involving all sectors of the community in addressing the management of CCR in a particular state.

EPA believes that the revised SWMPs will have significant benefits and provide the best mechanism available to respond to the concerns expressed by commenters regarding the role of states in management of this waste. First, the revised plans will enable states to set out, as part of their overall solid waste program, how the State intends to regulate CCR landfills and surface impoundments; that is, these plans can demonstrate how, if at all, the state program has incorporated the minimum national criteria and can highlight those areas where the state regulations are more stringent than or otherwise go beyond the federal minimum criteria. For example, the plan can describe the actions the state will take to oversee CCR units, particularly those units undergoing closure or corrective action, and how the State intends to review or use the notices and other information pertaining to the units that the facility owners will be providing to the state (as required in the federal regulations). Providing this detail can greatly assist the regulated community to understand the regulatory structure under which they will be operating. It can also assist the general public in understanding the regulations and thereby their ability to monitor industry's compliance with the rule.

Second, substantial benefits will be gained through the public participation process required as part of revising the state plans. See 40 CFR 256.60. At a minimum, these processes will promote greater awareness of the federal regulatory requirements, as well as how these fit into the overall context of solid waste management in the State, which will be very valuable as the new minimum criteria for CCR are implemented. In addition, these processes will provide the public and communities near CCR landfills and surface impoundments with an opportunity to participate in the decision making about how CCR are managed in their state. Finally, the record generated by the public participation process has an inherent value to states, the utilities, and the general public in that it can demonstrate explicitly the manner in which issues related to the regulation of CCR landfills and surface impoundments were raised and resolved in the state. This record would be a value in any later proceedings seeking enforcement of the rule.

Third, once EPA has approved a SWMP that incorporates or goes beyond the minimum federal requirements, EPA expects that facilities will operate in compliance with that plan and the underlying state regulations. In those circumstances, EPA's view is that facilities adhering to the requirements of a state program that is identical to or more stringent than an approved SWMP will meet or exceed the minimum federal criteria. In addition, EPA anticipates that a facility that operates in accord with an approved SWMP will be able to beneficially use that fact in a citizen suit brought to enforce the federal criteria; EPA believes a court will accord substantial weight to the fact that a facility is operating in accord with an EPA-approved SWMP. In addition, as noted above, the record generated by the public participation process in developing the SWMP has an inherent value to the states, the utilities, and the general public in any such litigation. The more specific the record is on the public process regarding how the SWMP would incorporate the minimum federal requirements and any state oversight the more valuable it would be in any court proceedings to complement EPA's approval of the SWMP. As fully explained earlier, EPA approval of a state SWMP does not mean that the state program operates ''in lieu of'' the federal program as EPA does not have the authority to make such a determination.

The process and criteria for approval of SWMPs are set out in 40 CFR part 256. The part 256 regulations state that EPA has six months from submittal of a plan to either approve or disapprove it. The regulations further state that EPA will approve a plan if the agency determines that the plan: (a) Meets the requirement set out in RCRA Section 4003(a)(1), (2), (3), and (5); (b) and contains provisions for revisions. Those requirements of 4003(a) are: The identification of the responsibilities of state, local, and regional authorities in the implementation of the plan and the means for coordinating regional planning and implementation; prohibition on the establishment of new open dumps and the requirement that all solid waste be utilized for resource recovery or disposed of in landfills meeting the minimum federal criteria; provision of the closing or upgrading of all existing open dumps; and no prohibition on negotiating or entering into contracts for the supply of solid waste to resource recovery facilities. In this rule, EPA has established minimum national criteria for CCR disposal facilities, which effectively define when CCR disposal facilities are open dumps. In order for EPA to approve a revised state SWMP, it must determine that the state plan provides enforceable regulatory requirements for the closing or upgrading of CCR disposal facilities that constitute open dumps. A state SWMP can do so through direct incorporation and implementation of the minimum federal criteria established by this rule or through incorporation of alternative requirements that are at least as protective of public health and the environment.

EPA anticipates that it will be able to review and approve state SWMPs that adopt the federal regulations in total or go beyond the federal minimum criteria very quickly; EPA's review of plans that do not adopt the federal minimum criteria or alter them substantially is likely to be more difficult and therefore more time consuming. EPA's review of and decision to approve or disapprove a state solid waste management plan will be based on the record before the Agency at the time of that decision. This record includes the record developed during the public participation process in which the state engaged prior to submitting the revised SWMP to EPA for approval. Should information come to EPA's attention at a later date that a state is not implementing its approved plan or taking actions at variance with the plan's provisions, EPA will take appropriate steps including potentially withdrawing approval of the SWMP.

Because SWMPs form a critical part of the implementation of this rule, EPA intends to engage the states very soon after promulgation of the minimum criteria to develop a streamlined, efficient process for review and approval of these revised plans. EPA also intends to develop both guidance for states to use to submit revisions and for EPA to use in its review of the revisions.

In addition, EPA is exploring options for developing and publishing the statutorily required inventory of open dumps. Specifically, within one year of the promulgation of federal criteria under RCRA section 4004(a), section 4005(b) directs EPA ''to assist the states in complying'' with the directive in section 4003(a)(3) that state SWMPs

shall provide for closure and upgrading of open dumps (*i.e.,* facilities that do not meet the revised federal criteria) by publishing an inventory of all ''open dumps'' in the US. 42 U.S.C. 6945(b). Because the minimum criteria promulgated today include implementation timelines, it is possible for a facility to become an open dump in the future for failure to meet the minimum criteria. Thus, EPA anticipates publishing an initial inventory and likely subsequent periodic updates.

Finally, in addition to benefits just described of a revised SWMP, RCRA Section 4005 provides an incentive in certain circumstances for states to obtain EPA approval on revised SWMPs. Under section 4005, States with approved SWMPs can provide additional time for facilities that do not meet the national minimum criteria (*i.e.,* ''open dumps''), to come into compliance. As noted above, within one year of the promulgation of federal criteria under RCRA section 4004(a), section 4005(b) directs EPA ''to assist the states in complying'' with the directive in section 4003(a)(3) that state SWMPs shall provide for closure and upgrading of open dumps (*i.e.,* facilities that do not meet the revised Federal criteria) by publishing an inventory of all ''open dumps'' in the US. 42 U.S.C. 6945(b). Facilities on this inventory are eligible to obtain a ''schedule of compliance'' from a state with an approved management plan, provided certain additional criteria have been met. Specifically, the facility must demonstrate that it is unable to use other ''public or private alternatives'' to manage its waste in the non-compliant unit. In such cases, the state may establish a schedule of remedial measures that includes ''an enforceable sequence of actions or operations'' which must lead to compliance within a ''reasonable time (not to exceed five years from the date of publication of criteria).'' 42 U.S.C. 6945(a). Such a schedule would shield the facility from any suit brought to enforce the criteria. Thus, if a State receives EPA approval on its revised plan, it can offer facilities additional time, albeit limited, to come into compliance with the federal requirements. EPA expects, however, that few facilities will either be eligible for or need to take advantage of this flexibility. First, as a practical matter, only a limited number of facilities or units will fall into the category of open dumps within the relevant timeframes. As noted, an open dump is defined as a solid waste facility that does not meet the federal minimum criteria. 42 U.S.C. 6903(14). As also explained, the final criteria establish timeframes for facilities to implement the technical requirements, ranging between six months to several years, including certain provisions that authorize extensions. Until those deadlines pass, the facility is not an open dump and therefore would not be eligible for or need a compliance schedule under section 4005. Because the statute limits the states' ability to set compliance schedules to five years from the publication of the criteria, if a facility is out of compliance with the criteria either shortly before or after this time five-year timeframe, from a purely practical perspective, compliance schedules are no longer a viable option. Thus for certain of the provisions (*e.g.,* closure, which generally must be completed within five years) compliance schedules would never be available.

Second, the timeframes in the regulation reflect EPA's considered judgment of the amount of time that would realistically be needed under normal circumstances for a facility to come into compliance, based on standard engineering practices used throughout the industry. Most facilities will, in fact, be able to comply with the federal criteria within the specified timeframes, and so will not need to seek a compliance schedule. For example, as part of its Dam Safety Assessment program, EPA evaluated all CCR surface impoundments with a dam hazard potential rating of ''high'' or ''significant,'' using criteria that were essentially the same as the technical criteria adopted in the final rule. As of the completion of that program, all units were either rated satisfactory, or were taking steps to ensure the structural stability of the unit. EPA acknowledges that ensuring the structural stability of these units requires continued maintenance and oversight, so past compliance is no guarantee of future compliance. However, our experience from the Assessment Program leads us to expect that the vast majority of CCR surface impoundments will be able to demonstrate compliance with the structural stability requirements in the final criteria within the specified timeframes. Any facility that seeks to justify an extension would have a heavy burden to demonstrate that anything longer than a minor amount of time is needed to implement the structural stability requirements would meet the statutory standard (*i.e.,* be ''reasonable''). Similarly, absent factors beyond the facility's control (i.e, ''Acts of God'') EPA is unable to envision the circumstances that would support a decision that additional time beyond the 30 months already provided in the criteria to comply with the groundwater monitoring requirements would be ''reasonable.''

Third, RCRA section 4005(a) imposes a number of requirements that will further limit both the circumstances in which a compliance schedule may be granted, and the amount of time that states will ultimately be authorized to grant. 42 U.S.C. 6945(a). Section 4005(a) requires that to obtain a compliance schedule, the facility must first demonstrate that it has considered other public or private alternatives to comply with the prohibition on open dumping and is unable to utilize such alternatives.[127] At a minimum, this means that the facility must demonstrate that there are no alternative units that meet the federal requirement, either on-site or off-site, that can be used to dispose of the CCR. EPA also interprets this provision to require the facility to demonstrate that it has made a good faith effort to comply with the criteria, which would include documenting the actions that had been taken, along with the facts demonstrating the reasons that compliance was not feasible within the criteria's timeframes. As has been previously discussed, cost is not a factor that is appropriately considered under sections 1008(a)(3), 4004(a), or 4005(a), and so would not provide an adequate justification for these purposes either.

Further, the statute requires that a schedule for compliance specify ''a schedule of remedial measures, and an enforceable sequence of actions, leading to compliance within a reasonable time.'' Id. This means that any compliance schedule must lay out precisely the activities that remain to be completed, along with clear and enforceable deadlines for each. Again, this will effectively serve to limit the ultimate amount of time that would be granted in any individual case.

Finally, as stated earlier, the statute requires that any schedule to bring an open dump into compliance is to be limited to a ''reasonable time,'' that is not to exceed five years from the date of publication of the federal criteria. Whether a particular period of time is ''reasonable'' depends on the facts of the particular situation, but, generally speaking, it should take into account the technical complexity of the requirement, the activities that remain

[127] Upon promulgation of criteria under sections 1008(a)(3) and 4004(a), the continued use of any unit that does not comply with these criteria is prohibited, as ''open dumping,'' unless a compliance schedule has been established.

to be completed, the reasons for the lack of compliance, and other particular factors such as geology, geography, weather, and engineering circumstances. For example, EPA expects that a significantly lower amount of time would be reasonable for a facility that simply chose to delay implementation than for a facility whose compliance was complicated by factors beyond its control. Overall, to be consistent with the statute, EPA expects that facilities seeking to establish an alternative compliance schedule would need to provide a factual justification that not only documents the reasons that compliance within the criteria's timeframes was not feasible, but carefully documents the facts that would support a determination that any significant extension of time to come into compliance is ''reasonable.''

EPA expects that as part of any revised solid waste management plans, a state would explain the criteria it intended to use to determine whether and how much additional time to comply with the federal criteria should be granted. See 40 CFR 256.04(f) and 256.26. Consistent with the statute's directives, EPA expects that any extension would be limited to the time absolutely necessary to bring a unit into compliance, and that five years would not automatically be granted. Nor would a revised solid waste management plan that granted all ''open dumps'' an additional five years generally meet the regulatory criteria for approval. Id. EPA also expects that states would consider the original timeframes laid out in the criteria. As previously discussed, in developing these time frames EPA sought to achieve a balance between the minimum amount of time that would realistically be needed to properly and adequately implement the technical requirements, and the need to expeditiously address the significant risks associated with CCR units. EPA therefore expects that in granting additional time under compliance schedules, states will be guided by the same considerations. As documented throughout this preamble, CCR disposal units do pose significant risks to public health and the environment; it is therefore critical that actions to implement these criteria be taken expeditiously to address these risks. EPA intends to closely review those portions of a state solid waste management plan that address the processes and criteria for establishing compliance schedules.

In conclusion, EPA believes that the use of the solid waste management plan revision process is the best mechanism available under RCRA subtitle D to address the states' interest in obtaining formal EPA ''approval'' of their solid waste management plans. EPA will continue to work with the states as the rules are implemented to ensure that this process is streamlined and efficient.

X. Risk Assessment

EPA revised and updated the 2010 draft risk assessment using mathematical models to determine the rate at which chemical constituents may be released from different waste management units (WMUs), to predict the fate and transport of these constituents through the environment, and to estimate the resulting risks to human and ecological receptors. Modeling was conducted in a step-wise fashion, with more refined analyses used at each subsequent step. Below, EPA discusses how the risk assessment was revised and updated in response to the various public comments received. The Agency also provides a summary of the analyses conducted as part of the risk assessment and the final conclusions drawn from these analyses. For further discussion, see the revised risk assessment and response to comments documents available in the docket.

A. Response to Public Comments

EPA received numerous, general comments on both the draft risk assessment and subsequent NODAs. These comments tended to express general support or disapproval for the risk assessment methodology, data, or results. However, these comments did not provide any specific technical recommendations or data that could be used to improve the risk assessment. EPA appreciates the overwhelming interest of the public regarding the Agency's risk assessment. However, without any substantive critique that could be acted upon, EPA could not alter the risk assessment in response to these more general comments. To the extent that any commenter mentioned substantive issues regarding a specific aspect of the risk assessment, these comments are further addressed in subsequent sections of this preamble.

1. Comments Related to Fate and Transport Modeling

COMMENT: Commenters wondered how realistic results may be using a risk assessment model that assumes current conditions will be maintained for 10,000 years. Specifically, commenters were concerned about the assumption that constituent concentrations in the leachate remain constant throughout that timeframe. In addition, commenters questioned the assumption that well use and climate conditions will remain constant for 10,000 years.

EPA RESPONSE: EPA acknowledges that the 10,000-year groundwater modeling time horizon required further clarification in the revised risk assessment. Thus, the text in the revised risk assessment has been updated to make it clear that the selection of a *maximum* 10,000-year time horizon does not mean that all model simulations continue for the full 10,000 years. Specifically, Section 4 states:

EPA ran the model until either the observed groundwater concentration of a constituent at the receptor point reached a peak and then fell below a model-specified minimum concentration (10^{-16} mg/L), or the model had been run for a time period of 10,000 years.

Although groundwater concentrations are modeled beyond the observed peak or maximum average concentrations, these post-peak or post-maximum average predictions are not used in estimates of risk. In many cases the leachate plume reaches the receptor point much sooner than 10,000 years. As discussed in Section 5 and appendix K of the revised risk assessment, on a national scale, both unlined and clay-lined surface impoundments consistently pose peak risks within 100 years. Meanwhile, composite liners show much longer peak arrival times, close to 10,000 years for most surface impoundment runs. Peak arrival times are longer for landfills, and more than 10,000 years for composite-lined landfills. Under such timeframes, EPA acknowledges that surface conditions may change significantly, compounding the uncertainty associated with the predicted exposures and risks. However, EPA also notes that the time to first exceedance of selected risk criteria is typically considerably less than the time to the greatest exceedance.

EPA acknowledges that future groundwater use patterns may shift as the number and location of receptors changes, and that it is unknown whether future changes in receptor locations and other surface conditions would result in greater, lesser, or the same risk as predicted in this analysis. However, no known data exist that would allow EPA to do more than speculate about future population dynamics. Thus, the Agency relied on the best available data on the current population to conduct the revised risk assessment. The approach used to place residential groundwater wells is further discussed in Section 4 and appendix B of the revised risk assessment, and the associated uncertainties are discussed in Section 5.

COMMENT: Comments related to the specifics of the groundwater transport modeling were received from commenters. Issues covered in their comments included the following:

Geochemical Modeling:

- The way that soil and aquifer K_d values were determined and used, including the fact that the risk assessment did not explicitly model oxidation/reduction reactions and precipitation-dissolution processes that may influence the chemical fate and transport.
- Whether hydrogeologic settings were assigned correctly.

Selection of Sorbents:

- The selection of iron oxides, and dissolved organic matter (DOM) and particulate organic matter (POM) to represent all sorbents in soil and aquifer materials.
- The selection of goethite as the iron oxide mineral used to estimate sorption to vadose zone and aquifer materials.
- The treatment of POM and DOM in the MINTEQA2 modeling used to generate the K_d values (sorption isotherms) used in the analysis.
- The adequacy of sensitivity and uncertainty analyses for the MINTEQA2 modeling.

K_d Values:

- The approach used to determine the value of pH in the aquifer for selecting K_d.
- The subsequent calculation of the retardation factor.

Arsenic Speciation:

- The assumption that arsenic III is the only or dominant form of arsenic is too conservative, as arsenic III readily converts to the less mobile arsenic V species under aerobic conditions.
- A commenter requested time to exceedance results for arsenic species and other constituents, as well as distance versus concentration output from EPACMTP.

EPACMTP Assumptions and Simplifications:

—The appropriateness of EPACMTP and its various assumptions and simplifications for groundwater modeling, including:
—Not altering the chemistry of the aquifer receiving leachate.
—Not simulating variable oxidation-reduction potential conditions or multiple chemical species during a model run.
—Not evaluating the potential mobilization of non-waste related metals from soils when exposed to leachate with potentially different geochemistry compared to ambient conditions.
—Not considering the potential occupation of adsorption sites by naturally occurring metals or competition from multiple contaminants.
—Not considering mounding-induced reduction of the unsaturated zone thickness or other cases where the groundwater table is in direct contact with the bottom of the WMU.
—Not considering fractured rock, karst, and other complex hydrogeologic settings.

The comments also addressed the general need for more transparency in the data and methods used in the analysis and the need for validation and/or comparison of model inputs and results to site-specific field data.

EPA RESPONSE: The following is EPA's response broken out by subtopic.

Geochemical Modeling:

EPA recognizes that explicit reactive/geochemical modeling would be more realistic than using linear and nonlinear partitioning coefficients. EPA considered the use of the Objects Representing Chemical Speciation and Transport (ORCHESTRA) model during revisions to the risk assessment because it can account for geochemical interactions, such as aqueous complexation, precipitation, surface complexation, and ion exchange.[128] However, such modeling is not a practical approach for a nationwide analysis because the data collection effort necessary to populate such a model on a nationwide, location-based level would be prohibitively expensive. Even assuming such data were available to populate ORCHESTRA or a similar model, the complexity of the algorithms necessary to account for highly variable geochemical and hydrogeologic conditions nationwide and the time required to run such a model would also be impractical. Furthermore, the use of K_d as a surrogate for dilution/sorption/precipitation processes is a widely used and accepted method in both the scientific literature and the groundwater modeling community, provided the values of K_d used are appropriate to account for the range of potential attenuation processes.[129] Therefore, for a nationwide analysis, the use of K_d is a practical and necessary simplification. EPA has added discussion to the risk assessment to clarify K_d-related issues raised by the commenters. Appendix H of the revised risk assessment displays select percentiles of the K_d values used in the analysis. These values were derived from the isotherm sampling performed by EPACMTP and used in the modeling (including effective K_d values for the unsaturated zone). A listing of all individual K_d values available in the MINTEQA2 isotherms used in these analyses would not be practicable. Instead, the full input and output files are available to the public in the docket.

Some commenters suggested that EPA should focus on the effect of redox potential in the groundwater on fate and transport. While this is possible, it would take significant effort to set up this type of approach for every inorganic constituent considered in the risk assessment, and it was determined not to be necessary. EPA did indirectly account for some of the major effects of redox potential when modeling arsenic and other constituents for which speciation is known to have a significant impact on mobility. For these constituents, a model run was conducted for each species under the assumption that all of the constituent mass was present as that speciation. Therefore, EPA did not evaluate redox, and acknowledges this is a source of uncertainty for the groundwater transport modeling approach. Commenters expressed concern about the assumption of a single speciation, noting that it is likely that constituents will be present as some combination of the different species. EPA acknowledges that this approach is a simplification of real world conditions; however, the Agency believes this approach is useful because it provide bounding estimates that can inform the risk assessment.

Regarding the concern that there were possible errors in hydrogeological assignments, these assignments have been updated in the revised risk assessment based on a more robust and accurate dataset for waste management units (WMU) and facility locations. These data are discussed in Section 3 and appendix B of the revised risk assessment. Because these assignments were based on more complete GIS coverages of soils and aquifers across the U.S., they are more consistent and reliable than the previous ones in representing the spatial variability in hydrogeologic environments needed by the EPACMTP model.

Selection of Sorbents:

In recent years, databases of equilibrium sorption reactions have been compiled in the literature for several of the dominant potential sorbents in the environment, including two common iron oxide minerals: hydrous ferrous oxides (HFO) and

[128] Meeussen, J.C.L. 2003. ORCHESTRA: An Object-Oriented Framework for Implementing Chemical Equilibrium Models. *Environmental Science & Technology* 37(6):1175–1182.

[129] U.S. EPA. 1999. *Understanding Variation In Partition Coefficient, Kd, Values Volume I: The Kd Model, Methods of Measurement, and Application of Chemical Reaction Codes.* EPA 402–R–99–004A. OAR. Washington, DC. August.

goethite.[130] [131] Because of the availability of these data and their prevalence in the environment, these are the sorbent types available for MINTEQ2 modeling used to develop constituent sorption isotherms. Other common hydrous oxides that can sorb chemicals include hydrous oxides of aluminum, manganese, and silicon (Dzombak and Morel, 1990); however, there were insufficient data on these to consider their use. To determine the most appropriate iron oxide sorbent, EPA chose goethite as the most appropriate form of hydrous iron oxide for the risk assessment to avoid an underestimation of risk. While both goethite and HFO are common forms of iron oxide in soils, goethite is a much poorer adsorbent than HFO, thereby leading to relatively greater groundwater plume concentrations. EPA acknowledges that HFOs are common as well and there is the potential for HFOs with greater sorption affinities than goethite to be present at some CCR disposal sites. In reaching this conclusion, EPA consulted experts who published on this subject (specifically, Dr. David Dzombak, Dr. Samir Mathur and Dr. Jerry Allison), developer of MINTEQA2. EPA agrees that this was a necessary assumption.

EPA also recognizes that limiting MINTEQA2 to two types of sorptive materials (iron oxide and organic matter [DOM and POM]) is a simplification given the wide range or soil and aquifer materials that actually adsorb metals (*e.g.,* clay and other soil minerals). However, given that the extensive sorption databases needed to perform MINTEQA2 are available for POM, DOM, and goethite, they are the best representation of subsurface sorption processes active in soils and aquifer materials. This decision and the actual approaches used to model DOM, POM, and goethite are described in detail in MINTEQA2 background documents and the associated Response to Peer Review Comments for those documents.

Finally, with respect to the adequacy of sensitivity and uncertainty analyses for MINTEQA2, EPA notes that the 2009 sensitivity analysis showed that only results for strongly sorbing constituents were sensitive to the K_d values output from MINTEQA2. In contrast, the three risk drivers identified in the revised risk assessment (arsenic, lithium, and molybdenum) all tend to be weakly sorbing, with the exception of arsenic in the pentavalent state. Furthermore, to the extent K_d affects the risks, Section 5 of the revised risk assessment evaluated these effects by examining alternate speciation (*e.g.,* trivalent and pentavalent arsenic) as well as the effect of waste type and waste pH. For these reasons, EPA finds that sufficient sensitivity and uncertainty analyses were conducted.

K_d Values:

The approach adopted in the risk assessment to determine the value of pH in the aquifer (used to select K_d) and the subsequent calculation of the retardation factor assumed that, after entering the aquifer, the leachate plume would thoroughly mix with the ambient, uncontaminated groundwater. One commenter stated that the mixing zone would only be present at the periphery of the groundwater plume. This is consistent with the general conceptual model used in this risk assessment of uniform subsurface flow with recharge. However, EPACMTP requires a constant groundwater pH in each model run to model transport with nonlinear sorption isotherms. EPA assumed full mixing as a more conservative approach to selecting pH because, for most metals, sorption/precipitation tends to increase (*i.e.,* K_d goes up) with higher pH, which is characteristic of much CCR leachate (*i.e.,* assuming full mixing lowers the groundwater pH and, thus, decreases sorption). To characterize the potential effect of this simplifying assumption on calculated risk results, EPA conducted an uncertainty analysis that is presented in Section 5 of the revised risk assessment.

EPA considered comparing the modeled K_d values to available estimates in the published literature, but did not do so for three reasons. First, there are many individual values within each K_d isotherm that depend both on constituent concentrations and MINTEQA2 master variables, such as pH, organic carbon, and iron oxide concentrations. Second, measured values are limited to specific sites where conditions that may not be fully documented, and because such variables can vary from site to site, it can be very difficult to determine exactly how well the collected values represent conditions across the country. Third, field and laboratory methods for measuring K_d vary greatly and are not easy to compare, adding a significant measurement uncertainty to the variability issues mentioned above. Therefore, not only would this comparison be complicated to perform, it would also be subject to its own numerous uncertainties and unknown biases, making it unlikely to provide a basis for definitive conclusions about the representativeness of the current approach.

With respect to comments on the calculation of the retardation factor, EPA points commenters to U.S. EPA (2003) [132] which discusses how EPA uses K_d values to model sorption in the subsurface environment.

Arsenic Speciation:

Commenters also pointed out that literature on arsenic V often shows that it is orders of magnitude less soluble than arsenic III, which appears inconsistent with the results of the 2010 Draft Risk Assessment. The draft assessment found similar exposure concentrations for both arsenic species. As a result of a combination of different updates to the revised risk assessment, the modeled concentrations of arsenic III and V are now generally an order of magnitude different, although the specific results vary between pathways. One cause of this difference is likely the increased distances to receptors in the revised risk assessment. The increased distance would lead to additional arsenic V attenuation because this species sorbs more readily (*i.e.,* has greater K_d values) than arsenic III. Section 5 of the revised risk assessment discusses the uncertainty associated with modeling both species of arsenic. For the specific concentrations at various distances, EPA directs the commenter to review the input and output files available in the docket.

EPA did not model the time to first exceedance of risk criteria, but did conduct a sensitivity analysis for the time to peak groundwater concentration. The time to peak results for arsenic species and other select constituents are presented in Section 5 of the revised risk assessment. The distance to nearest well receptors is also discussed in Section 5 of the revised risk assessment. The relation of distance versus concentration was not explicitly evaluated on a per simulation basis, rather all receptor well locations within one mile from the WMU footprint were included in the analysis to provide a conservative risk estimate.

EPACMTP Assumptions and Simplifications:

Comments on the treatment of dispersivity within EPACMTP highlighted the need for greater transparency about the model's

[130] Dzombak, D.A and F.M.M. Morel. 1990. Wiley-Interscience, New York, 393 pp.

[131] Mathur, Samir S. 1995. *Development of a Database for Ion Sorption on Goethite using Surface Complexation Modeling.* Carnegie Mellon University, M.S. Thesis, Department of Civil and Environmental Engineering.

[132] U.S. EPA (Environmental Protection Agency). 2003. *EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP).* Technical Background Document. EPA 53–R–03–002. Office of Solid Waste, Washington, DC.

underlying assumptions and input data sources. The documentation for the 2010 Draft Risk Assessment did not include comprehensive tables detailing model input parameters, their values or distributional characteristics, and the sources of the data used. These values are, in many cases, publicly available in the EPACMTP Background and Parameters/Data Background documents.[133] [134] EPA still finds it inappropriate to duplicate this large amount of data. Instead, the revised risk assessment includes an increase in the number of references to these documents, and directs readers to refer to these documents for further information. Additionally, the full input and output files are available to the public in the docket.

With respect to the fundamental questions raised about the assumptions and simplifications built into EPACMTP, EPA acknowledges some limitations within the model. Some simplifications are necessary to complete a large, national scale risk assessment, and the model provides the most appropriate available tool to complete this type of analysis. As discussed in Section 5 of the revised risk assessment, EPACMTP has been thoroughly peer reviewed and tested for application in large-scale risk assessments. This section also provides additional documentation on these internal and external reviews of the model, its limitations, and the associated uncertainties. With respect to particular criticisms levied:

- EPA alters the chemistry of the aquifer receiving leachate by changing the aquifer pH in response to full mixing. Alternatively, EPA conducts an analysis in Section 5 using the alternate assumption of partial mixing;
- EPA evaluates alternative species in separate model runs. As described in the revised risk assessment, EPA believes that presentation of these two results bound the range of possible risks from a constituent. To the extent that EPA does not model oxidation-reduction potential, EPA notes that this would require geochemical modeling, which was not feasible for the reasons discussed above;
- Full mixing of the leachate plume did not demonstrate significant potential to affect aquifer pH. Thus, since pH is one of the most significant factors affecting constituent mobilization EPA does not believe significant constituent mass from the underlying soils will be mobilized in most cases. Instead, it is a site-specific consideration that is not possible to include in a nationwide risk assessment.
- A discussion of sorbent competition as a limitation of the analysis is discussed in Attachment H–1 of appendix H in the revised risk assessment.
- EPA did not consider groundwater mounding, groundwater in contact with the waste management unit, fractured rock, karst, and other complex hydrogeologic settings as these are site-specific considerations that could not be accommodated in a nationwide risk assessment.

COMMENT: Several commenters discuss the use of site-specific analysis to increase confidence in the risk assessment results. They expressed concern that the results are difficult to evaluate given the significant variability and uncertainty associated with the national scope of the analysis, and that validation or calibration of EPACMTP results with actual data is needed, including the potential use of damage cases.

EPA RESPONSE: Commenters expressed concern about validation of the EPACMTP model with actual field data and some commenters suggested that EPA should use actual monitoring data rather than modeling to assess potential risks. EPA recognizes the importance of monitoring data in characterizing specific sites. EPA agrees with the commenters that confidence in the results of an environmental fate and transport model increase significantly when model predictions can be compared favorably with measured field results. However, site-specific modeling involves extensive data collection and detailed modeling (representing site-specific conditions and processes), which was not possible for this large, national-scale risk assessment. Available site-specific data are limited to a relatively small fraction of locations and settings. This risk assessment was intended to represent a broad range of potential conditions. Consequently, EPA validated the model results with actual field data by comparing the results of the national probabilistic, Monte Carlo analysis to proven/potential damage cases from across the United States. These damage cases represent real-world instances of contamination from CCR WMUs that provide the best available comparison for the results of the risk assessment. This comparison is presented in Section 5 of the revised risk assessment. EPA also provided extensive EPACMTP validation results relative to theoretical models and field data in appendix D of the EPACMTP technical background document (U.S. EPA, 2003a,b).[135]

COMMENT: Comments relating to the number of wells contaminated, the realistic risk of exposure, well placement within the plume, distance to receptor wells, identification of surface water receptors, surface water interception modeling, the appropriateness of receiving water reaches (*e.g.* the nearest surface water body), and other receptor or well-related issues were received from public commenters.

Surface Water Interception Modeling:

Regarding surface water interception, many comments were supportive of EPA's approach for simulating the interception of groundwater by surface water bodies, which has been added to the revised risk assessment. However, some commenters indicated that a meaningful allocation of the groundwater plume between a surface water body and a downgradient well receptor can only be determined reliably with assessment of the system at a local scale.

Commenters also raised questions regarding the specific surface water interception methodology, including the base data and algorithms used to calculate stream base flow, net groundwater flow, and the contaminant mass loss to groundwater. Concern was expressed about the large range of possible values used for Monte Carlo sampling without calibrating models to site specific conditions and the potential to mismatch parameters. Additionally, concerns were raised that the assessment assumed transport directly to the nearest water body without reflecting complexities that are often present and could lead to longer transport pathways or to pathways to water bodies other than the nearest.

Commenters noted that the vicinity of many WMUs is serviced by a municipal water supply, and; therefore, there would be no drinking water receptors associated with these WMUs. Comments were also received that the one mile distance considered by the transport model is not sufficient, because actual receptor wells in many cases are further than one mile from facilities. Comments also highlighted the possibility that modeled receptor well concentrations may incorrectly represent actual

[133] U.S. EPA. 2003. *EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP): Parameters/Data Background Document.* EPA 530–R–03–003. Office of Solid Waste, Washington, DC. April.

[134] U.S. EPA. 2003. *EPACMTP Technical Background Document.* Office of Solid Waste, Washington, DC.

[135] U.S. EPA (Environmental Protection Agency). 2003a. *EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP).* Technical Background Document. EPA 53–R–03–002. Office of Solid Waste, Washington, DC.

exposures by sampling from a single aquifer depth. Comments on dispersivity noted the need for greater transparency in the report.

Placement of Receptor Wells, EPACMTP Well Inputs and Assumptions:

Comments related to the risk assessment's use of water well distances from MSWLFs and the Agency's belief that these distances would be protective for CCR WMUs. Additional comments focused on the assumption that the wells used in this assessment are contaminated (*i.e.,* located within the plume), even if the well location used reflects a deeper well that may be screened in an uncontaminated aquifer; the manner in which the assessment handles uncontaminated wells, plume characteristics, groundwater-surface water interactions, vertical contaminant concentration across a screened interval in an aquifer; and the values used for plume dispersivity.

EPA RESPONSE: The following is EPA's response broken out by subtopic.

Surface Water Interception Modeling:

In cases where receptor wells are located downgradient from a surface water body that intersects the groundwater table, some or all of the groundwater, along with the mass of constituents contained therein, is intercepted by the water body before it can reach the well. This interception was not modelled in the 2010 Draft Risk Assessment. However, a review of the input database for the 2010 Draft Risk Assessment found that such a water body was present in approximately two-thirds of the Monte Carlo runs. Furthermore, ignoring the loss of constituent mass had the effect of overestimating exposures. Thus, in the revised risk assessment an EPACMTP model post-processor was created to account for surface water interception by removing constituent mass flowing into the water body from the groundwater plume, and leaving only the remaining groundwater available to migrate to a drinking water receptor. The approach used to account for interception is discussed in further detail in Section 4 and appendix J of the revised risk assessment.

While commenters were generally supportive of the proposed approach, some indicated that a meaningful allocation of constituent mass from groundwater into a surface water body required site-specific data. Concerns were raised about the assumption that transport occurred directly to the nearest water body without reflecting complexities that are often present and could lead to longer transport pathways or to pathways to water bodies other than the nearest. EPA acknowledges that local conditions can make groundwater flow conditions complex, and detailed, local-scale assessments would be required to describe these conditions accurately. While EPA agrees that local-scale conditions must be considered for precise estimation for specific systems, it was impractical for EPA to characterize, simulate, and calibrate models for the numerous locations across the nation. Discussion of the uncertainties associated with this approach has been added to Section 5 of the revised risk assessment.

Several questions about the surface water interception methodology were raised by the public. The qBaseflow input parameter was derived from the NHDplus mean recharge parameter (MEAN_RCHRG) [136] and the size of the water body catchment and reach (see appendix B of the revised risk assessment). The approach assumes that all streams intersect the shallow aquifer and that all streams either gain water from the aquifer or do not interact with the aquifer at all (for simplicity and conservatism). As the commenter indicates, qNetflow is a key result calculated by subtracting the stream baseflow from the average groundwater flow upgradient of the stream. The qNetflow value becomes the adjusted groundwater flow beyond the stream, reflecting groundwater losses to the stream. One commenter raised a specific question about how the methodology handles cases where qNetflow is less than zero, but greater than the average groundwater flow. This case does not occur with the methodology adopted by EPA, because qNetflow is always equal to or less than the average groundwater flow (*i.e.* streams are assumed not to be losing). If qNetflow is negative (*i.e.,* a losing stream), all of the groundwater is assumed to migrate to any wells on the opposite side of the stream.

Model Validation/Calibration:

Concern was expressed about the large range of possible values used in the probabilistic analysis for certain parameters and the potential for this to result in a mismatch of input parameters without proper site-specific calibration. EPA notes that the revised risk assessment is not intended to capture the exact risks at each disposal site. Instead, the revised assessment combines the best resolution of site-based, regional and national data available to provide an estimate of potential risks that may occur from current disposal practices. While the assigned data for any given model iteration may not reflect the exact conditions at a real-world site, the resulting sum of all model iterations reflect the range of potential conditions near each WMU, weighted by prevalence, across the conterminous United States.

Placement of Receptor Wells, EPACMTP Well Inputs and Assumptions:

Comments regarding placement of receptor wells in the probabilistic analysis (also known as the appropriateness of receiving water reaches) are the result of a fundamental misinterpretation regarding the constraints placed on groundwater receptor location to be, as described in the 2010 Draft Risk Assessment, ''within the contaminant plume.'' This constraint is more fully explained in Section 4.4.3.6 of the EPACMTP technical background document.[137] A citation referring readers to that document has been placed in Section 4 of the revised risk assessment. Because the comment resulted from a misunderstanding, EPA does not believe the sensitivity analysis suggested by the commenter is necessary.

Some commenters were concerned that many residents in the vicinity of some WMUs may be serviced by a municipal water supply. Because these residents would not be exposed to groundwater, the risk assessment could overestimate exposures. EPA acknowledges that there may be a large percentage of the population that does not rely on groundwater as a source of potable water; however, the aim of the risk assessment is to estimate the magnitude of potential risk to the exposed population. Thus, this does not represent a significant source of uncertainty in the risk assessment.

Comments were also received that the one-mile distance considered by the transport model is not sufficient, because actual receptor wells in many cases are further distant than one mile from facilities. EPA conducted a sensitivity analysis, discussed in Section 5 of the revised risk assessment, which indicates that risks beyond the one-mile distance are appreciably lower than risks within one mile. Given that the highly exposed population was adequately captured by a one-mile radius, the significant additional effort required to extend the analysis further downgradient was unjustified.

[136] Available online at: *water.usgs.gov/GIS/metadata/usgswrd/XML/nhd_recharge.xml.*

[137] U.S. EPA (Environmental Protection Agency). 2003a. *EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP).* Technical Background Document. EPA 53–R–03–002. Office of Solid Waste, Washington, DC.

With respect to comments related to the placement of wells within deeper aquifers, EPA has a policy of addressing uncertainty by erring in favor of the protection of human health and environmental quality. Consistent with this practice, wells screened within vulnerable, surficial aquifers (*i.e.,* the top 10 meters of the saturated zone) continue to be the primary focus of the Agency's national-scale modeling efforts. Comments also highlighted the possibility that modeled receptor well concentrations may incorrectly represent actual exposures by sampling from a single aquifer depth. Wells are typically screened across an extended depth, and may capture both contaminated and pristine groundwater. Due to the constraints of EPACMTP, EPA maintained the current approach of modeling exposures at a single depth. A discussion of the uncertainties associated with this approach has been added to Section 5 of the revised risk assessment.

In response to comments on the use of MSW landfill data to predict the distance to private wells, EPA did not use the MSW data in the revised risk assessment. Instead, EPA used synthetic population representations of U.S. Census data to place each household and its occupants at discrete points across the landscape surrounding CCR WMUs. Synthetic populations are realistic representations of households and individual residents and their attributes in a given census area, and are based on methods that identify realistic locations within each block by using LandScan 90-meter night-time population distributions to place each household across the landscape.[138] From these households, a distribution of the distances to the nearest well was created. This approach is discussed in more detail in appendix B of the revised risk assessment. Some commenters suggested that EPA develop site-specific estimates of actual populations around facilities rather than relying on synthetic populations to determine potential receptor locations. The synthetic approach provides the maximum spatial resolution possible for publically available population data from the U.S. Census. More site-specific estimates would be costly, but not necessarily more accurate.

Some commenters were also concerned that the assessment did not consider direct discharges from surface impoundments to surface water. This pathway was outside the scope of the assessment, because it is regulated by the NPDES program. However, this pathway was evaluated in *Environmental Assessment for the Proposed Effluent Limitation Guidelines and Standards for the Steam Electric Power Generating Point Source Category,*[139] which will be revised in support of final effluent limitation guidelines due to be released in September of 2015.

2. Comments Related to Source Modeling

COMMENT: The majority of the public commentary in this subcategory was dominated by the assertion that Toxicity Characteristic Leaching Procedure (TCLP), Synthetic Precipitation Leaching Procedure (SPLP) and other laboratory leachate test data are not applicable to CCR wastes. Comments specifically regarding the use of Leaching Environmental Assessment Framework (LEAF) data for modeling leaching behavior noted that the data should be applied appropriately and pointed out the following: (1) That the range of conditions (*i.e.,* range of pH) encompassed by the LEAF data is broader than those conditions found in the field for CCR disposal; (2) high pH limits the mobility of leaching constituents; (3) the need for validating LEAF leachate concentrations against field data if available; and (4) the reliability of the LEAF data is questionable as a result of inconsistencies identified in the LeachXS Lite™ database.

EPA RESPONSE: Only pore water and impoundment water data were used to characterize surface impoundments. Therefore, the comments received on the use of laboratory leachate data are not relevant for the surface impoundment scenario. For landfills, EPA agrees that TCLP, SPLP and other single pH test methods may not be the most appropriate leachate extraction methods for all waste streams and all disposal scenarios. The 2010 Draft Risk Assessment relied on a hierarchy of dissolved concentration data to characterize leaching from landfills, ranging in order of preference from field leachate data to TCLP. However, new data collected using the LEAF test methods have been made available through a series of EPA reports.[140] [141] [142] LEAF were collected with three LEAF methods, specifically:

- SW–846 Method 1313 (and its predecessor, Method SR02);
- SW–846 Method 1314; and
- SW–846 Method 1316 (and its predecessor, Method SR03).[143]

With the availability of the LEAF data, EPA no longer relied on other data sources to model landfills because the inability to identify trends in leaching behavior from single pH tests made it impossible to link these data together with the LEAF data in the probabilistic analysis. The LEAF data provide information on the leaching behavior of CCR for a range of pH values observed in CCR landfills, as well as the liquid-to-solid ratio of the pore water. The data from these three methods were used in conjunction to characterize landfill leaching. While the natural pH range for any individual sample may be narrower than the full range analyzed with the LEAF methods, many facilities burn a range of coal types under varying operating conditions, and co-dispose with other materials, so the range of pH for a specific CCR sample may be exposed to is wider than the pH estimated based on one sample alone.

EPA agrees that appropriate use of the data is needed to ensure that data represent likely conditions of leaching occurring at range of facilities nationwide taking into account local specific environmental conditions, the geometry of monofill, type of coal, air pollution control, and other factors that affect leaching. Since the NODAs were released, a report comparing leachate from field and laboratory analyses has been completed.[144] The report includes the use of geochemical speciation modeling as needed to reflect site-

[138] Bhaduri, B., E. Bright, P. Coleman, and M. Urban. 2007. LandScan USA: A high resolution geospatial and temporal modeling approach for population distribution and dynamics. *GeoJournal 69*:103–117.

[139] U.S. EPA. 2013. Environmental Assessment for the Proposed Effluent Limitation Guidelines and Standards for the Steam Electric Power Generating Point Source Category. EPA–821–R–13–003. Office of Water. Washington, DC. 20460. April.

[140] U.S. EPA. 2006. *Characterization of Mercury-Enriched Coal Combustion Residues from Electric Utilities Using Enhanced Sorbents for Mercury Control. EPA–600/R–06/008.* Prepared by F. Sanchez, R. Keeney, D. Kosson, and R. DeLapp for the U.S. Environmental Protection Agency, Air Pollution Prevention and Control Division. February.

[141] U.S. EPA. 2008. *Characterization of Coal Combustion Residues from Electric Utilities Using Wet Scrubbers for Multi-Pollutant Control. EPA/600/R–08/077.* Prepared by F. Sanchez, D. Kosson, R. Keeney, R. DeLapp, L. Turner, and P. Kariher for the U.S. Environmental Protection Agency, Air Pollution Prevention and Control Division. July.

[142] U.S. EPA. 2009. *Characterization of Coal Combustion Residues from Electric Utilities—Leaching and Characterization Data.* EPA–600/R–09/151. Office of Research and Development, National Risk Management Research Laboratory, Research Triangle Park, NC. December.

[143] Methods SR02 and SR03 are predecessor methods to SW–846 Methods 1313 and 1316.

[144] U.S. EPA. 2014. *Leaching Test Relationships, Laboratory-to-Field Comparisons and Recommendations for Leaching Evaluation using the Leaching Environmental Assessment Framework (LEAF).* EPA–600/R–14/061. EPA Office of Research and Development, National Risk Management Research Laboratory, Research Triangle Park, NC 27711. November.

specific factors affecting leaching, and shows that LEAF methods provide realistic predictions of environmental releases across the range of pH.

All three LEAF methods are summarized in appendix C, with the leachate data provided in Attachment C–5 of the revised risk assessment. Additionally, the inter-laboratory validation for these methods are described in U.S. EPA (2012a, b) [145] [146] while Kosson et al. (2002) [147] provides the detailed test methodology for the predecessor methods, SR02 and SR03. The noted discrepancies and classification errors within LeachXS Lite have been corrected.

COMMENT: Public comments focused on the general relevance of the facility data based on age and noted that newer data should be used to more accurately reflect the current state of CCR management. Related comments cited that the grouping of waste and liner types by facility is not representative of current conditions. Another commenter suggested that the outcomes for different liner types were not comparable and should not be used to make relative conclusions about liner performance. It was also suggested that the assumed three-foot clay layer underlying composite liners is too thick, and two feet would be more representative of current practice. Commenters also described existing management controls required in some geographical locations that mitigate potential risks (*e.g.,* liners, leachate collection) and requested that EPA reflect the existence of those controls in their analysis, as well as mismanagement scenarios when these controls are not in place.

EPA RESPONSE: Since the purpose of the risk assessment was to evaluate risks for the universe of currently operating facilities and WMUs, EPA generally agrees with the commenter that the 1995 EPRI and 2006 DOE survey data relied on in the 2010 Draft Risk Assessment may be outdated. Thus, EPA collected data from several new sources of information on the facilities, WMUs, and liners that are present at the time of this analysis. Further discussion of these data sources is available in Section 2 and appendix A of the revised risk assessment.

Regarding the inclusion of mismanagement scenarios, EPA reviewed the high-end pore water concentrations and determined that these data represent actual CCR samples and therefore represent possible high-end risks from current management practices. To better understand which practices may lead to the highest risks, EPA conducted sensitivity analyses that consider the influence of liner type, liner design, waste type and other variables on model results. The results of these analyses are presented in Section 5 of the revised risk assessment.

Several commenters described existing management controls required in some geographical locations that mitigate potential risks (*e.g.,* liners, leachate collection) and requested that EPA reflect the existence of those controls in the final risk analysis. The Agency's analysis reflects the presence of different management scenarios at WMUs to the extent the available data allowed (*e.g.,* WMUs were assumed to have liners if the information indicated such). A key objective of the analysis was to compare the effectiveness of management options (*e.g.,* liners; surface impoundments versus landfills) at preventing potential releases and exposures. Because the population of WMUs considered in the analysis included a range of management controls, the analysis does provide such comparative results between management options. The uncertainties associated with the updated facility, WMU and liner data are discussed in Section 5 of the revised risk assessment.

COMMENT: One commenter suggested that the risk assessment applied risk results for fly ash to bottom ash, FGD sludge, and other CCR wastes, which may result in an incorrect estimate of risks for these other wastes. Other commenters called for EPA to evaluate each CCR waste independently. A public commenter expressed concern about whether the risk assessment adequately considered alternative CCR disposal scenarios. Specifically, it was noted that CCR codisposed with coal refuse generate more acidic conditions (*i.e.,* lower pH) due to higher-levels of sulfide minerals, which may significantly impact the mobility of metals.

EPA RESPONSE: In the revised risk assessment, EPA modeled a combined ash waste types for the majority of surface impoundments and all landfills. Although commenters are correct that different CCR wastes may behave differently when monofilled, the 2009/2010 EPA survey data indicates that the CCR are codiposed in a majority of units. Thus, EPA believes this approach appropriately reflects current disposal practices.

With regard to the evaluation of CCR codisposed with coal refuse, EPA notes that the pore water data used to characterize surface impoundments were broken out separately for this waste type evaluation. These data reflect samples collected in the field and are representative of the pH at which these samples are managed. While some ash and coal refuse samples are highly acidic, others are more neutral or slightly basic (full pH range of 1.7 to 8.2). The development and application of these waste types is discussed in Section 3, Section 4 and appendix H of the revised risk assessment, while the associated uncertainties are discussed in Section 5. For landfills, waste pH, which is the major driver of variations in K_d values used to distinguish waste types, was known with great accuracy for CCR nationwide because U.S. EPA (2009a) [148] compiled a full, nationwide distribution of CCR pH. In this distribution, disposal of ash with coal refuse is reflected is the acidic tail of the distribution. For the national probabilistic analysis, EPA aggregated model runs for ash and coal refuse (surface impoundments) and acidic waste (landfills) with other wastes so that risks reflected the prevalence of these disposal practices. However, EPA also performed sensitivity analyses to understand the extent that the lower pH of co-managed wastes could affect risks, which is discussed in Section 5 of the revised risk assessment.

COMMENT: Commenters stated that it is unclear why EPA chose to approximate infiltration through composite liner systems based on leak detection system flow rates from industrial landfills that use a different construction design than projected for CCR landfills.

EPA RESPONSE: The composite liner leakage rates used for this risk assessment correspond to leakage rates developed for the peer-reviewed Industrial Waste Management

[145] U.S. EPA. 2012. *Interlaboratory Validation of the Leaching Environmental Assessment Framework (LEAF) Method 1314 and Method 1315.* EPA/600/R–12/624. Prepared by A.C. Garrabrants, D.S. Kosson, R. DeLapp, P. Kariher, P.F.A.B. Seignette, H.A. van der Sloot, L. Stefanski, and M. Baldwin for the U.S. EPA Office of Research and Development, Air Pollution Control Division. September.

[146] U.S. EPA. 2012b. *Interlaboratory Validation of the Leaching Environmental Assessment Framework (LEAF) Method 1313 and Method 1316. EPA/600/R–12/623.* Prepared by A.C. Garrabrants, D.S. Kosson, L. Sefanski, R. DeLapp, P.F.A.B. Seignette, H.A. van der Sloot, P. Kariher, and M. Baldwin for the U.S. EPA Office of Research and Development, Air Pollution Control Division. September.

[147] Kosson, D.S., H.A. van der Sloot, F. Sanchez and A.C. Garrabrants. 2002. An integrated framework for evaluating leaching in waste management and utilization of secondary materials. *Environmental Engineering Science 19*(3):159–204.

[148] U.S. EPA. 2009. *Characterization of Coal Combustion Residues from Electric Utilities—Leaching and Characterization Data.* EPA–600/R–09/151. Office of Research and Development, National Risk Management Research Laboratory, Research Triangle Park, NC. December.

Evaluation Model (IWEM).[149] The types of synthetic liners used are likely to be the same, regardless of the type of waste present. EPA is unaware of any factors specific to CCR that would exacerbate leakage rates, nor did the commenter provide any. Thus, in the absence of any information to the contrary, EPA finds these to be the best available data.

Because there is currently no approach for differentiating between flow from unimpacted water released by the consolidation of clay and from contaminated leakage through the liner, EPA excluded data on the subset of composite liners constructed with natural clay from the distribution of composite liner leakage rates. EPA did consider the potential impact of incorporating these additional data into the risk assessment as part of sensitivity analysis, presented in Section 5 of the revised risk assessment.

COMMENT: Concerning the treatment of non-detect values in the risk assessment, one commenter recognized that the use of one half the detection limit in calculations has become an accepted protocol. However, it was suggested that this approach may not be appropriate in all cases, and that newer or more straightforward methods can be applied to improve precision and minimize biasing of the dataset. Another commenter noted that mercury was excluded from the analysis due to the high number of non-detects.

EPA RESPONSE: Additional constituent data measured with lower detection limits have been made available to EPA since completion of the 2010 Draft Risk Assessment. However, the overall CCR constituent database still contains a large number of non-detect data for some constituents. EPA continues to incorporate all available with the use half the reported detection limit as the most appropriate method to account for these non-detects. The commenter is correct that much of the pre-2010 mercury data has high detection limits and a large proportion of non-detects. In this one instance, EPA relied only on the newer data made available to the Agency since the 2010 Risk Assessment, which was collected through newer methods with significantly lower detection limits. A more detailed rationale for this approach is provided in Section 3 of the revised risk assessment, along with further discussion of the uncertainty in Section 5.

COMMENT: Comments received related to the effect of waste compaction in landfills focused on changes to hydrologic properties of waste materials, such as porosity and hydraulic conductivity. These changes may result from compaction, consolidation, hydration or geochemical changes, and have the potential to result in either an underestimation or overestimation of risks.

EPA RESPONSE: EPA acknowledges that the landfill source model does not consider the compaction of CCR waste that may occur over time as a result of anthropogenic activities, gravity or infiltrating water. However, no data on either the rate or degree to which these processes may occur were provided by commenters or identified elsewhere. EPA considered the impacts of this uncertainty in Section 5 of the revised risk assessment.

COMMENT: Public comments focused on assumptions relating to the variability of unlined landfill design, landfill clay liner materials, and construction of landfill cover materials and construction. Specific comments emphasized that the clay liner and cover thickness assumptions (three feet) were too conservative and not conservative enough, respectively. Commenters also questioned why composite covers and leachate collection systems were not considered for clay-lined landfills. Additionally, commenters stated that there was a high degree of variability in the material and design and construction for unlined landfills that was not accounted for in the HELP modeling. One commenter also pointed out that the assessment may overestimate percolation rates from landfills by underestimating the use of engineering controls. In addition, a commenter stated that the assessment assumes that States will require liners in all cases which may not be the case, thereby weakening the regulation.

EPA RESPONSE: For both unlined and clay-lined landfills, EPA used Hydrologic Evaluation of Landfill Performance (HELP) model-derived infiltration rates. These infiltration rates assume that the cap placed on top of the landfill at the end of its useful life will remain intact for the duration of the risk assessment, up to a maximum 10,000 years of modeling. A commenter pointed out that hydraulic conductivity of a clay liner is likely to increase by orders of magnitude due to desiccation resulting from natural temperature cycles. Additionally, commenters stated that there was a high degree of variability in the material and design and construction for unlined landfills that was not accounted for in the HELP modeling. EPA has adopted the use of the HELP model, which was subject to both peer and administrative review, as the source of unlined and clay-lined infiltration rates for landfill for nearly two decades. EPA acknowledges that there are limitations in using HELP. However, the model has been tested and verified as discussed in the EPACMTP Parameter/Data Background Document.[150] To the extent that the performance of the cap will decrease over time, EPA acknowledges that unlined and clay-lined infiltration rates calculated by HELP may be underestimated, however the degree of that underestimate is unknown. Discussion of this uncertainty has been added to Section 5 of the revised risk assessment.

COMMENT: One commenter expressed concern over the fact that the assessment modeled all disposal sites above the water table. The commenter indicated that many surface impoundments and landfills are deep and can come in direct contact with the water table. This will result in an underestimation of peak concentrations, arrival times and risks for these WMUs. Furthermore, the commenter emphasized that the use of the unsaturated zone flow module to calculate infiltration from the bottom of impoundments underestimates true risks in the consolidated sediment, and noted that clogged soil layers should be treated as saturated rather than unsaturated.

EPA RESPONSE: EPA acknowledges that EPACMTP is not designed to handle scenarios where the water table is above the bottom of the landfill. However, EPACMTP can accommodate surface impoundments in direct contact with the water table. If unit geometry and the selected depth to the water table create a scenario where the bottom of the unit is in contact with the water table, then the entire soil column is considered saturated. Otherwise, even for very high infiltration rates, regions beneath impoundments will remain partially saturated when there is sufficient distance between the unit and the water table. EPA has added a discussion of the uncertainties associated with WMU source terms and EPACMTP in Section 5 of the revised risk assessment.

EPA believes the commenter misunderstood how the sediments were modeled for surface impoundments. The EPACMTP unsaturated zone

[149] U.S. EPA. 2002. *Industrial Waste Management Evaluation Model (IWEM) Technical Background Document.* EPA530–R–02–012. Office of Solid Waste, Washington, DC. August.

[150] U.S. EPA. 2003. *EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP): Parameters/Data Background Document.* EPA 530–R–03–003. Office of Solid Waste, Washington, DC. April.

module assumes that the 0.2 m of consolidated sediments at the bottom of a surface impoundment are always saturated whereas the 0.5 m of clogged native soil are assumed to be unsaturated when the bottom of the surface impoundment is above the water table.

COMMENT: Public commenters recommended that EPA address the future increase in mercury and NO_X compounds levels in CCR that will result from mercury capture from flue gas under new emission control regulations. Commentary pointed out that the recent Vanderbilt study should provide data that could be used to expand the risk assessment in this area.

EPA RESPONSE: The risk assessment was designed to evaluate the risks associated with current management practices and, as such, draws no conclusions about the potential for future air pollution technologies to alter the composition or leaching behavior of CCR wastes. However, it has been shown that newer mercury pollution control technologies currently in place have the potential to affect leaching behavior.[151] [152] [153] Thus, EPA conducted a sensitivity analysis to evaluate the risks associated with existing units that dispose of this waste; however, the data were too few to allow EPA to draw conclusions about the effect of pollution control technologies on the risks. This sensitivity analysis is presented in Section 5 of the revised risk assessment.

COMMENT: Multiple public commenters noted that additional pore water will improve the risk assessment, but TCLP and SPLP data are not appropriate for use as source concentrations. Additionally, commenters stated that EPA applies the LEAF data to pH conditions that are not realistic to CCR disposal scenarios. Although LEAF provides a more representative and scientifically sound approach, it must be correctly adapted. Alternative statistical methods to represent the input data as a range is certainly feasible and could enhance the risk assessment if the range of data is used as an input to the risk assessment.

Commenters agree that the LEAF data does provide useful information, but point out that it is associated with the potential for leaching and does not represent actual leaching of a specific CCR under actual field conditions. Commenters argues that field leaching data should not be mixed with laboratory data, and that EPA's field leachate dataset (for landfills and impoundments) is not adequate for use in the CCR risk assessment. Specific efforts recommended to properly utilize the LEAF data include: Use of probability density functions for leachate concentrations based on pH and/or L/S ratios in the Monte Carlo process; selection of leachate concentrations based on pH and L/S and tied to the geographic location of the WMU and CCR type; and geochemical modeling to incorporate reactions once leachate impacts groundwater.

A few commenters pointed out that the pore water data are generally representative, although concerns were raised about the highest arsenic concentration (81 mg/L) in the dataset. One commenter believed that although the addition of new data is an improvement, EPA could greatly improve the accuracy of the model's results by removing the extreme and unsubstantiated outlier data driving its high risk cases. Another commenter believed the assumption that concentration of contaminants in the sediment pores (applicable to a post closure scenario) would be equal to the concentration assigned to in the impoundment water would result in underestimated risks. Additionally, commenters noted that EPA should classify the data according to CCR type and coal type.

Overall, commenters support updates to the pore water data and the use of statistical method to normalize the data curve. However, one commenter noted that EPA should not use commenter-submitted CCR pore water data unless it meets requisite applicable data quality requirements. Another commenter stated that EPA needs to provide better clarity on these solicited comments (on the use of older pore water data) and provide these documents in the docket. Without these documents, the reader does not have a complete understanding of co-managed material containing CCR. Another comment noted that properly collected field pore water (freely draining) samples should take priority over any of the laboratory generated data and freely draining pore water is more representative of leachate releases than tightly held pore water.

EPA RESPONSE: The use of pore water data is still considered the most appropriate approach to estimate constituent fluxes to groundwater for CCR surface impoundments. This is because pore water better represents the leachate seeping from the bottom of the impoundment than impoundment water samples. EPA did not use available LEAF data for surface impoundments because a national distribution of pH was not available to allow the Agency to probabilistically assign LEAF concentrations to these units, and because there was no way to account for partitioning of the leachate into wastewater versus porewater. Thus, EPA has continued to rely on pore water data, supplemented with data from the 2010 comments. EPA appreciates commenter support on the use of pore water data and statistical methods for data analysis for surface impoundments. EPA agrees that data available for minefill sites may not be representative of disposal in surface impoundments. Thus, these data were not considered in the revised risk assessment. The specific handling of pore water concentration data with site quartiles, rather than site averages, is discussed in Section 4 and Section 5 of the revised risk assessment report.

EPA agrees that TCLP and SPLP data are less appropriate for CCR disposal scenarios and no longer uses these data in the revised risk assessment. EPA adapted the LEAF methods and data for landfills, as this is the best available approach and data to represent CCR landfill leachates, and does not mix or use field data with LEAF laboratory results for landfill leachate. The LEAF data are considered the most robust and technically defensible data available. As noted in the 2010 Environmental Science and Technology publication,[154] the data represents the largest collection of comprehensive characteristic leaching data to date.

A commenter noted that the LEAF data provide the potential for leaching and not actual leaching of a specific CCR under actual field conditions. The commenter suggests using probability distribution of key factors affecting leaching behavior [*i.e.,* pH and liquid/solid ratio (L/S)] and site specific data tied to the geographic location of the management unit and the type of CCR being managed. In the revised risk assessment, pH is expressed as a

[151] U.S. EPA. 2006. *Characterization of Mercury-Enriched Coal Combustion Residues from Electric Utilities Using Enhanced Sorbents for Mercury Control. EPA–600/R–06/008.* Prepared by F. Sanchez, R. Keeney, D. Kosson, and R. DeLapp for the U.S. Environmental Protection Agency, Air Pollution Prevention and Control Division. February.

[152] U.S. EPA. 2008. *Characterization of Coal Combustion Residues from Electric Utilities Using Wet Scrubbers for Multi-Pollutant Control. EPA/600/R–08/077.* Prepared by F. Sanchez, D. Kosson, R. Keeney, R. DeLapp, L. Turner, and P. Kariher for the U.S. Environmental Protection Agency, Air Pollution Prevention and Control Division. July.

[153] U.S. EPA. 2009. *Characterization of Coal Combustion Residues from Electric Utilities—Leaching and Characterization Data.* EPA–600/R–09/151. Office of Research and Development, National Risk Management Research Laboratory, Research Triangle Park, NC. December.

[154] Thorneloe, S., D. Kosson, F. Sanchez, A. Garrabrants, and G. Helms. 2010. Evaluating the Fate of Metals in Air Pollution Control Residues from Coal-Fired Power Plants. *Environ. Sci. Technol. 44:*7351–7356.

national distribution for selecting leachate concentrations developed to represent CCR nationally, and L/S is considered in estimating washout leachate concentrations based on field data observations. The use of the pH distribution developed in U.S. EPA (2009) [155] does capture the range of potential variability in pH conditions at CCR sites nationwide and is the best approach possible given the current availability of information on site-specific coal ash chemistry. Although leachate concentrations were selected considering pH and L/S conditions that are nationally representative, EPA does not have the detailed and extensive site-specific measurements that would be needed to tie CCR and leachate concentrations to specific WMU locations. Instead, EPA adopted a national probabilistic approach that is site-based and representative of risks to human and ecological health across the country. The revised risk assessment also provides details regarding how the LEAF data are used in combination of geographical specific data such as hydrology, precipitation, fill configuration, CCR type, pH, L/S ratio, and other factors that take the leaching potential as an input to fate and transport models accounting for attenuation and dilution. Additionally, an effort was made to collect CCR samples that characterize the range and quantity of coal usage in the U.S. along with likely air pollution control configurations. While the data is not statistically representative on a site-specific basis, it is adequate to identify trends in leaching behavior that relate to differences in materials types, APC technology, and coal rank. Geochemical speciation modeling was not conducted because the source term as measured and interpreted is conservative, provided that oxidizing conditions occur.

Regarding the number and concentration of pore water samples, EPA reviewed the high-end pore water concentrations and determined that these represent actual CCR samples that therefore represent possible high-end risks if CCR is inadequately regulated and managed. EPA recognizes that more pore water data would potentially improve the representativeness of the dataset, but is convinced that the current dataset adequately captures the possible high end risks that are of most interest in the rulemaking, including risks from the mismanagement of CCR through codisposal with coal refuse.

The assumption that saturated contaminant concentrations in surface impoundment sediments are at equilibrium with the impoundment waters is a conservative assumption that is unlikely to significantly underestimate risks. This assumption is further discussed in Section 5 of the revised risk assessment report.

Regarding commenter-submitted pore water data, EPA conducted a review of the additional datasets provided by the commenters with respect to relevance and data quality. Based on the available information, EPA determined that the selected datasets were relevant and acceptable in terms of data quality requirements. However, EPA does not have sufficient data to distinguish between freely draining and tightly bound pore water data at this time. Overall, EPA agrees that the use of these data introduces some uncertainty into the analysis, which is discussed in Section 5 of the revised risk assessment.

COMMENT: One commenter questioned the assumption that there will be no net addition of waste into a surface impoundment during and after the operational life, noting that impoundments are frequently deepened. Additionally, many surface impoundment wastes are left in place at the time of closure, so that the waste behaves more as a landfill than a surface impoundment (and increasingly, with new landfills being constructed on top of previous surface impoundments). Another commenter questioned why the conceptual model assumes that impoundments are always full during their operating life, which overestimates releases to the subsurface. Additionally, a commenter noted that the assumption of only 0.2 m of sediment accumulation underestimates the amount of sedimentation and subsequently overestimates the amount of percolation to the subsurface. The commenter stated that in actual operation, ash thickness can increase up to 30 feet or more, eventually filling the impoundment, which results in a significant decrease in percolation through the base. Furthermore, the commenter questioned the assumption that post-closure percolation continues at the same rate as during active operations.

EPA RESPONSE: Based on the 2009/2010 EPA surveys, it was assumed that the majority of the surface impoundments are storage impoundments, which are continuously dredged. Because these facilities have other units (whether onsite or offsite) established for disposition, it likely that the majority of waste in the dredged impoundments would be removed by the end of the unit's operating life. Regardless, an uncertainty analysis provided in appendix K demonstrates that the risks during the operating life of surface impoundments are greater because the higher hydraulic head drives leachate into underlying soils with greater force than gravity alone post-closure. Therefore, EPA did not explicitly model the post-closure phase of surface impoundments. The uncertainties resulting from this decision are discussed in Section 5 of the revised risk assessment.

EPA acknowledges that EPACMTP is restricted to modeling flow as steady state with the assumption that an impoundment always has a fixed depth of wastewater. EPA further acknowledges that such an assumption may overestimate infiltration. The surface impoundment conceptual model assumes that sediments are periodically dredged and removed and that the long-term average thickness of the sediment is approximately 0.4 m, with half of that layer consolidated. EPA has used EPACMTP and its predecessor model versions for a longstanding time period and it has undergone multiple rounds of internal and external review. The reviews associated with EPACMTP and its limitations are further discussed in Section 5 of the revised risk assessment report.

COMMENT: Public commenters suggested that risks from operating landfills should be considered along with those that occur post-closure. These commenters questioned whether greater risks may occur during site operations when wastes are uncovered and exposed directly to precipitation. Additional commenters noted that complete leaching of all constituent mass at a constant concentration is overly conservative.

EPA RESPONSE: The landfill source model used in this risk assessment is not able to address landfills during operation because the non-linear sorption isotherms used require a constant, annualized infiltration rate throughout the duration of leaching. Instead, the revised risk assessment assumed that the full footprint of the landfill is filled to capacity with a cap no less permeable than the soil or liner underlying the WMU is present at the start of leaching. EPA acknowledges that this approach introduces some uncertainty into the analysis, the potential impacts of which are discussed in Section 5 of the revised risk assessment.

With respect to comments that complete leaching of all constituent mass is overly conservative, EPA now

[155] U.S. EPA. 2009. *Characterization of Coal Combustion Residues from Electric Utilities—Leaching and Characterization Data*. EPA–600/R–09/151. Office of Research and Development, National Risk Management Research Laboratory, Research Triangle Park, NC. December.

models landfills using leachable mass as discussed in Section 4 and appendix C of the revised risk assessment. Alternatively, EPA presents a sensitivity analysis of these results compared with the results generated using total mass in Section 5.

3. Comments Related to Exposure Scenarios

COMMENT: The commenter emphasized that the risk assessment does not consider direct discharges to ground and surface water systems other than groundwater infiltration (*e.g.,* direct injection to groundwater, point and nonpoint discharges to surface water systems). It was recommended that EPA consider combining contributions from these sources with CCR groundwater leaching impacts to calculate the full load of CCR constituents to groundwater and surface water systems. The commenter continues by suggesting that the use of liners in impoundments does not reduce overall hazards if direct discharges are considered in the risk assessment.

EPA RESPONSE: RCRA waste disposal risk assessments do not address direct discharges from impoundments to surface waters because they are regulated as permitted point source discharges under the Clean Water Act by EPA's Office of Water. Since this pathway is outside the scope of the risk assessment, the revised risk assessment does not consider these releases. However, this pathway was evaluated in the Environmental Assessment for the Proposed Effluent Limitation Guidelines and Standards for the Steam Electric Power Generating Point Source Category,[156] which will be revised in support of final effluent limitation guidelines (ELG) due to be released in September of 2015. The revised risk assessment was updated to note this fact.

EPA is not aware of any CCR disposal where waste is directly injected into groundwater aquifers, and absent any data on this practice declines to evaluate it.

COMMENT: Public comments were received on the methodology applied to evaluate exposure to fugitive dust during landfill operations (before closure). The majority of these comments focused on the fugitive analysis as presented in *Inhalation of Fugitive Dust: A Screening Assessment of the Risks Posed by Coal Combustion Waste Landfills,*[157] and EPA's proposed approach for refining the analysis. Comments received on the initial fugitive dust analysis methodology and modeling ranged from emphasizing that the approach was overly conservative in some cases to underestimating risk in other cases.

Multiple comments were provided on the proposed methodology for refining the fugitive dust analysis that was applied in the revised risk assessment. One commenter recommended that 2010/2011 EPA survey data should be used to refine the fugitive dust analysis for landfills. Specifically, the current OW data indicate that active portions of the landfills are significantly smaller than the landfills identified in the 1995 EPRI survey. Several comments were received that pointed out that the application of AERSCREEN and AERMOD is appropriate if representative or realistic inputs are used including meteorological data, material silt content, source areas for subcells of ash management units and consideration of common operating and control practices, which are in some cases defined by the states (*e.g.,* Virginia). However, one commenter expressed concern that no previous or current EPA regulatory model; including SCREEN3, AERSCREEN or AERMOD; has been rigorously tested and evaluated for performance in modeling fugitive emissions associated with CCR landfills.

In general, the commenters supported or recommended the use of appropriate AP–42 factors and other techniques to estimate emissions. Others noted that consideration of deposition impacts and constituent-specific modeling is appropriate. One commenter recommended that EPA should conduct a full-scale assessment that considers fugitive dust as well as emissions from landfills and emissions of diesel particulate matter from haul trucks, on-site heavy-duty landfill equipment, and diesel-powered pumps and generators, with potential receptors of interest as residents and sensitive subpopulations living near the power plant, along the transportation route and at the landfill. Another commenter expressed concern over the lack of metal speciation data, while another comment concerned gas emissions from the landfills (*e.g.,* hydrogen sulfide). One final commenter voiced concern that insufficient information was provided on the modeling approach and the model inputs to support evaluation and allow comments on the overall validity or propriety of the suggested modeling.

EPA RESPONSE: The majority of the comments received concerning exposures during landfill operation (before closure) focused on the assessment of fugitive dust. EPA acknowledges that the 2010 Draft Risk Assessment did not evaluate the inhalation pathway, relying instead on the findings of a previous evaluation, *Inhalation of Fugitive Dust: A Screening Assessment of the Risks Posed by Coal Combustion Waste Landfills.*[158] This previous evaluation only considered releases from windblown emissions and the potential to exceed national ambient air quality standards (NAAQS) for particulate matter.

Based on the comments received, EPA updated the screening analysis of fugitive dust. EPA agrees that there are potential risks posed by fugitive emissions from sources beyond wind and revised the analysis to consider emissions from a range of activities, such as vehicular activity, unloading operations and spreading/compacting operations. Emissions from these sources were calculated using techniques that have undergone extensive peer-review, including *AP–42: Compilation of Air Pollutant Emission Factors.*[159] Screening level modeling was performed with a combination of AERSCREEN and AERMOD to estimate dust dispersion and deposition rates. Model inputs were selected to be representative of current landfills, environmental settings (*e.g.,* meteorological conditions) and common dust management practices. Estimated air concentrations were used to screen acute and chronic health risks from inhalation, as well as the potential to exceed NAAQS standards. Furthermore, EPA considered exposures that may result from the offsite deposition on and accumulation in downgradient media. This was done for all relevant metal species. In contrast, EPA did not evaluate emissions of hydrogen sulfide to air as EPA has no data on the extent to which this constituent is present in CCR or released into the surrounding environment. Further discussion of this screening analysis is presented in

[156] U.S. EPA. 2013. Environmental Assessment for the Proposed Effluent Limitation Guidelines and Standards for the Steam Electric Power Generating Point Source Category. EPA–821–R–13–003. Office of Water. Washington, DC 20460. April.

[157] U.S. EPA. 2010. *Inhalation of Fugitive Dust: A Screening Assessment of the Risks Posed by Coal Combustion Waste Landfills.* OSWER. Washington, DC. September.

[158] U.S. EPA. 2010. *Inhalation of Fugitive Dust: A Screening Assessment of the Risks Posed by Coal Combustion Waste Landfills.* OSWER. Washington, DC. September.

[159] U.S. EPA. 1985. *Compilation of Air Pollutant Emission Factors. Volume I: Stationary Point and Area Sources (Fourth Edition).* AP–42. U.S. Environmental Protection Agency, Office of Air and Radiation and Office of Air Quality Planning and Standards, Research Triangle Park, NC. September.

Section 3 and appendix F of the revised risk assessment.

COMMENT: Comments both supported and disagreed with the appropriateness of a screening analysis to eliminate pathways from consideration in the full-scale probabilistic analysis. One commenter pointed out that the EPA conducted a very conservative, but appropriate, screen to identify constituents to include in the full-scale probabilistic analysis. Another commenter emphasized that a full-scale risk assessment should be conducted that assesses exposures concurrently through all pathways (*e.g.,* including surface pathways with inhalation exposure) for all chemical constituents. In particular, they emphasized that inhalation exposures to human carcinogens, such as hexavalent chromium, as well as noncarcinogens may occur through the aboveground pathway. Although the commenters disagreed over the use of a screening approach, both expressed concerns over the use of risk attenuation factors to scale screening risks to the full-scale risks for the subset of constituents that did not pass the screen and were not evaluated under the full scale assessment. Both commenters believe that this approach ignores the unique fate and transport properties of the omitted constituents and that the use of a simplistic, attenuation factor is not an appropriate way to estimate risk.

EPA RESPONSE: By first conducting the screening analysis presented in Section 3 of the revised risk assessment, EPA was able to focus available resources on the characterization of risks for exposure routes and constituents with the greatest potential to pose risks. The screening analysis conducted for the revised risk assessment considered all of the potential exposure routes identified in the conceptual models for surface impoundments and landfills, which included aboveground exposures to ambient air, soil, sediment, produce, and animal products. Each exposure pathway was evaluated for all constituents (and individual species, as appropriate) for which both concentration and toxicity data were available.

The screening analysis was developed to be protective of highly exposed individuals. Due to the conservative nature of the screening, the calculated risks represent a protective, but unlikely, combination of conditions that most likely reflect an upper bound on potential exposures for each individual constituent. The revised screening assessment did not rely on risk attenuation factors to screen out constituents. All constituents that resulted in screening-level risks above human health or ecological criteria, and for which characterization of fate and transport could be refined, were carried forward for further consideration in the probabilistic analysis, described in Section 4 of the revised risk assessment. It is possible that consideration of exposure to multiple constituents through a single pathway or to the same constituent through multiple pathways may have resulted in the retention of some additional constituents. However, it is highly unlikely that these additional constituents would remain risk drivers once more realistic dilution and attenuation in the environment is considered.

COMMENT: Multiple commenters noted that there may be additional constituents present in CCR wastes beyond those quantitatively evaluated in the risk assessment. In particular, multiple commenters referenced organics and radionuclides. Some commenters called on EPA to quantify the risks associated with these additional constituents. Others claimed that these constituents are present in low levels and do not pose risk to receptors.

EPA RESPONSE: In the *Report to Congress: Wastes from the Combustion of Fossil Fuels: Volume 2—Methods, Findings, and Recommendations,*[160] EPA reviewed the available data on organic constituents, such as polyaromatic hydrocarbons and dioxins. These data indicated that concentrations of all organics are near or below analytical detection limits both in CCR and in the leachate released from CCR. Based on the findings of this report, the Agency concluded that organic constituents were not risk drivers and did not require further evaluation. In the absence of additional data that demonstrate the organic composition of CCR wastes have markedly changed, EPA continues to rely on these findings.

EPA acknowledges that, like other inorganic constituents, naturally-occurring radionuclides may be concentrated in CCR waste through the combustion of coal. However, due to a lack of data that could be used to characterize leachate concentrations for individual radionuclides, a quantitative evaluation of risk was not conducted. To address this data gap, EPA has included radionuclides in the list of constituents for groundwater monitoring. Furthermore, potential transport of these constituents downgradient by windblown dust and storm run-off are addressed through requirements for fugitive dust controls and run-on/run-off controls.

4. Comments Related to Human Exposure and Toxicity

COMMENT: Some commenters argued that EPA underestimated risks by not considering combined chemical effects, additive risk and concurrent exposures through multiple pathways. One commenter indicated that EPA should conduct a full scale assessment that considers concurrent exposure from ingestion of fish and groundwater. Commenters also raised concerns that some chemical constituents share a common mechanism of toxicity and may affect the same body organ or system, resulting in greater risks than predicted through the consideration of each constituent separately.

One commenter noted that the combination of risks from different constituents would not change the overall results of the risk assessment. Constituents concentrations found to result in an HQ less than 1 in the screening analysis are unlikely to make a meaningful contribution to overall risk regardless of whether multiple compounds share the same toxicological endpoints. Additionally, the commenter expressed that it would be inappropriate to add the risks from different constituents as modeled because the constituents do not all arrive at a hypothetical receptor at the same time, due to differing mobility in the subsurface environment.

EPA RESPONSE: EPA acknowledges that this risk assessment considered potential risks to human health from individual constituents and individual pathways. EPA acknowledges that not explicitly evaluating cumulative risk is a source of uncertainty that may result in some underestimation of risks. It is possible that an individual could be exposed to risks from drinking contaminated groundwater, as well as eating contaminated fish from a local surface water body, but it is unlikely that these two exposure pathways would occur simultaneously with any appreciable frequency in the real world. It is even more unlikely that a receptor would be exposed to both media at the high-end concentrations modeled. Therefore, the magnitude of the uncertainty introduced into the risk assessment is likely to be small. It is also possible for an individual to be exposed to multiple constituents through a single pathway. This is a more likely scenario because, as demonstrated

[160] U.S. EPA (Environmental Protection Agency). 1999b. Report to Congress: Wastes from the Combustion of Fossil Fuels: Volume 2—Methods, Findings, and Recommendations (EPA 530–R–99–010). Office of Solid Waste and Emergency Response. Washington, DC.

by the available data, CCR typically leach multiple inorganic constituents. Where exposure to multiple constituents is likely to occur, EPA policy is to assume that the risks resulting from these exposures are additive.[161] The current probabilistic analysis identified individual constituents above risk criteria. Many of the other constituents modeled resulted in risks an order of magnitude or more below risk criteria. Thus, the consideration of additive risk, even with the high-end risks modeled in this risk assessment, is unlikely alter the principal results of the probabilistic analysis. Similarly, because the risks for individual constituents were found to be above levels of concern, consideration of additive risk is unlikely to meaningfully change the results of the analysis. EPA updated the revised risk assessment to include a discussion of the associated uncertainties in Section 5.

COMMENT: Some commenters identified incorrect and inconsistent reporting of toxicity benchmark values and recommended conducting a thorough review of literature to ensure the use of the most current values were used. One commenter expressed concern over the use of the current IRIS value for arsenic carcinogenic effects and believes it underestimates risk. Other commenters emphasized that it would be inappropriate for EPA to consider using the draft oral cancer slope factor (CSF) for arsenic and the oral CSF for hexavalent chromium [chromium (VI)] published by the New Jersey Department of Environmental Protection (NJDEP). Concerning lead, one commenter supported a peer reviewer's recommendation to use the Integrated Exposure Uptake Biokinetic (IEUBK) model to calculate human health risks, especially for young children. Additionally, a commenter requested chemical-specific information on toxicity criteria derivation, as well as information on the relationship between environmental exposures to specific chemicals and adverse health effects. The commenter emphasized that this information would provide an uncertainty discussion regarding toxicity values, facilitate communication with the public, and provide a balanced perspective on risk.

EPA RESPONSE: Human health benchmarks were chosen based on the Office of Solid Waste and Emergency Response hierarchy (OSWER Directive 9285.7–53).[162] EPA reviewed the benchmarks to confirm their accuracy and determine whether newer values have become available from EPA or other sources used by EPA since the CCR draft risk assessment was conducted. The current, updated list of human health benchmarks is provided in appendix E of the revised risk assessment, and the references cited in that appendix provide further information on the potential adverse effects and derivation of toxicity criteria.

For lead, EPA used the drinking water maximum contaminant level (MCL) to estimate risks from drinking water exposure in the draft risk assessment. In the revised risk assessment EPA continued to rely on the MCL, but also used IEUBK model for lead in children as described in Section 5 of the revised risk assessment. While lead failed the screening assessment, risks from lead exposure in the probabilistic assessment were well below the risk criterion, and did not drive risks in either the probabilistic or any sensitivity analyses.

COMMENT: The commenters questioned why the cancer benchmark of 1×10^{-5} was selected while the typical range used by OSWER and EPA guidance is a range from 1×10^{-4} to 1×10^{-6}. The commenters suggested that an explanation is necessary. In particular, one commenter requests clarification on the phrase ''point of departure'' when supporting the use of the cancer benchmark of 1×10^{-5}. Concerning non-cancer criteria, a commenter suggested that non-cancer risks should be report as follows: Worst Case—Assume maximum exposure scenarios including exposure 24-hours/day, 365 days/year for 70 years; High End—95th percentile based on national human activity pattern distributions; Central Tendency—50th percentile (or median) risk based on national human activity pattern distributions. Furthermore, another commenter believed that it is more appropriate to consider 95th percentiles, rather than 90th percentile, of exposure and risk estimates for humans and ecological receptors.

EPA RESPONSE: The rationale for the selected cancer and non-cancer risk criteria, based on Agency policy, is discussed in Section 2 of the revised risk assessment. A citation to the where ''point of departure'' was originally defined is provided for reference. The rationale for use of 90th percentile risk generated by a Monte Carlo simulation is discussed in Section 4 of the revised risk assessment.

COMMENT: Commenters questioned the evaluation of only the reasonable maximum exposure scenario. Specifically, it was noted that the receptor placement downgradient of an unlined management unit does not represent the entire population exposure distribution. One commenter suggested that EPA clearly define the exposed population of interest.

EPA RESPONSE: In risk assessments used to develop regulations under RCRA, EPA has historically assessed potential risks resulting from a reasonable maximum exposure (RME) scenario in order to ensure that the resulting regulation is adequately protective of human health without being excessively conservative. The types of data necessary to define the exact population that relied on groundwater wells as a source of drinking water or consumes fish from impacted water bodies are not available. EPA believes that consideration of RME is a reasonable and protective alternative, given the available data. Uncertainties associated with the revised risk assessment are further discussed in Section 5 of the revised risk assessment.

COMMENT: The commenters questioned the use of data from the 1997 Exposure Factors Handbook in the development of intake rate distributions for various exposures, because more current data are currently available. Commenters recommended that EPA make updates to these parameters using more current sources of information, including the recently released 2011 Exposure Factors Handbook.[163] In addition, some commenters pointed out the potential for the available exposure factor data to underestimate or overestimate exposures. One commenter noted that the risk assessment did not fully account for the dependence of input variables (*e.g.,* the interdependence of body weight and water ingestion rates for children and link between the rate of fish consumed from a water body). Another commenter suggested that a sensitivity analysis of human health exposure factors be conducted to add to the sensitivity analysis conducted by EPA in 2009.

Regarding fish consumption rates, commenters questioned the representativeness of a fixed fish consumption rate drawn from a single

[161] U.S. EPA. 2000. *Supplementary Guidance for Conducting Health Risk Assessment of Chemical Mixtures.* Risk Assessment Forum, Washington, DC. August.

[162] U.S. EPA. 2003. *Human Health Toxicity Values in Superfund Risk Assessments.* Office of Solid Waste and Emergency Response Directive 9285.7–53. December.

[163] U.S. EPA. 2011. *Exposure Factors Handbook: 2011 Edition.* EPA/600/R–090/052F. National Center for Environmental Assessment, Office of Research and Development, Washington, DC. September.

study. It was suggested for transparency that the risk assessment provide the results of the chi-square tests to demonstrate how well the fish consumption rate data fit a log normal distribution. Additionally, it was suggested that fish consumption rates should be determined from other studies and more robust data sets. One commenter suggested the incorporation of fish consumption rates representative of subsistence fishers, such as Native American populations that harvest and consume fish as part of their native traditions and culture.

Regarding drinking water ingestion rates, one commenter voiced concern about the assumption that groundwater is the source of all drinking water. The commenter indicated that this is an overly conservative and atypical assumption, as a majority of individuals will consume liquids from other sources (*e.g.,* milk, juice, sodas, bottled water, sports and energy drinks).

EPA RESPONSE: This revised risk assessment relied on both the 1997 *Exposure Factors Handbook (EFH)* [164] and the 2008 *Child-Specific Exposure Factors Handbook* (*CSEFH*) [165] for information on human exposure factors for the U.S. population. The 2011 *Exposure Factors Handbook* [166] has been completed and updates some of the data from the 1997 EFH. During the finalization of this risk assessment, EPA released *OSWER Directive 9200.1–120.*[167] Although this document provides default exposure factors to use for point estimates, EPA is still in the process of updating the full distributions necessary for probabilistic analysis. Therefore, this risk assessment does not incorporate the data from the 2011 EFH.

Exposure data used for the fish ingestion rates are described in appendix D of the revised risk assessment. Data on site-specific fish consumption rates were not available for use in this analysis. Instead, the full distribution of fish consumption rates were drawn from a study of adult anglers from Maine that fished from streams, rivers, and ponds. Because age-specific data for children were not available, all child cohorts were assumed to consume fish at the same rate as the adult cohort. Data on fish ingestion rates for Native American subsistence fishers are currently limited and can vary widely geographically, to the point that the 2011 EFH makes no recommendation for representative values. EPA acknowledges that these issues introduce uncertainty into the analysis, which are further discussed in Section 5 of the revised risk assessment.

COMMENT: Commenters emphasized the need to update exposure factors for childhood exposures and recommended that updates include data from the 2011 EFH. One commenter stated that the risk assessment appropriately considered the potential fish exposures for children. However, they pointed out that the fish consumption rates for children should be lower than those applied for adults. Another commenter suggested that the risk assessment should provide a clear description of how the exposure duration of child cohorts were used in the risk calculations. Specifically, the commenter questioned whether exposure durations were truncated at the end of each age cohort or aged through the different cohorts.

EPA RESPONSE: The revised risk assessment makes use of the 1997 EFH [168] and the 2008 CSEFH [169] for information on human exposure factors for the U.S. population. Although, as discussed in the preamble sections above, the revised risk assessment does not incorporate data from the recent 2011 EFH,[170] all child data included in this document was derived from the 2008 EFH. In addition to child ingestion of drinking water, EPA's evaluation has been revised to also account for infant exposures that may occur from formula mixed with contaminated groundwater. These data are presented in appendix D of the revised risk assessment. Consistent with the commenter's recommendation for cohort aging, the risk assessment aged receptors through each age cohort using age-specific data for exposure factors and physical characteristics that were weighted proportionally by the corresponding time period and then summed. Specific discussion of truncation values is provided in later in this preamble.

COMMENT: Public commenters recommended updating BCF values with more current references. One commenter questioned why bioconcentration factors were zero for some constituents that are essential nutrients (*i.e.,* cobalt and copper). Another commenter voiced concern that EPA had not fully considered the appropriateness of using BCFs to describe metals bioaccumulation, suggesting that current science (including EPA guidance documents) indicates that BCFs are poor predictors of tissue metal concentrations due to wide variation in uptake patterns governed by several chemical and biological factors. Another commenter recommended the use of an approach that would be more robust than the single BCF approach, establishing and applying distributions of BCFs. This commenter also recommended that the assessment adhere to the EPA policy of using dissolved metals in the calculating the bioconcentration of metals in fish, or should provide the rationale for using a different approach.

EPA RESPONSE: EPA recognizes that the use of BCFs may not represent the most current approaches available to estimate metal bioaccumulation at individual sites, where fish tissue data can be collected. However, as noted by public commenters, BCFs are useful in a screening-level assessment and EPA believes they are also appropriate for a national-level risk assessment, where site-specific data are not available and collection of site-specific data is not viable.

In some cases, insufficient data to determine a BCF value meant that these constituents could not be quantitatively evaluated for this pathway. Regarding the concern expressed with respect to zero BCF values, the commenter did not provide alternative BCFs that EPA could consider for the constituents at issue. Additionally, EPA agrees that, given the latest scientific information, distributions of BAFs/BCFs may be better than single BAFs/BCFs because they account for changes in bioaccumulation/bioconcentration at different water concentrations. EPA is working to develop BAF/BCF distributions for several CCR pollutants of concern but does not yet have a robust enough dataset for use for the final CCR Rule. In lieu of this, EPA is proceeding with the single BAF/BCF approach for the current analysis. EPA does recognize this issue as a limitation for the BCF calculations and considers it as an uncertainty in the risk

[164] U.S. EPA. 1997. *Exposure Factors Handbook, Volume III, Activity Factors.* EPA/600/P–95/002Fa. Office of Research and Development, Washington, DC. August.

[165] U.S. EPA. 2008. *Child-Specific Exposure Factors Handbook.* EPA/600/R–06–096F. National Center for Environmental Assessment, Cincinnati, OH.

[166] U.S. EPA. 2011. *Exposure Factors Handbook: 2011 Edition.* EPA/600/R–090/052F. National Center for Environmental Assessment, Office of Research and Development, Washington, DC. September.

[167] U.S. EPA. 2014. *Human Health Evaluation Manual, Supplemental Guidance: Update of Standard Default Exposure Factors.* OSWER Directive 9200.1–120. February.

[168] U.S. EPA. 1997. *Exposure Factors Handbook, Volume III, Activity Factors.* EPA/600/P–95/002Fa. Office of Research and Development, Washington, DC. August.

[169] U.S. EPA. 2008. *Child-Specific Exposure Factors Handbook.* EPA/600/R–06–096F. National Center for Environmental Assessment, Cincinnati, OH.

[170] U.S. EPA. 2011. *Exposure Factors Handbook: 2011 Edition.* EPA/600/R–090/052F. National Center for Environmental Assessment, Office of Research and Development, Washington, DC. September.

characterization. Overall, EPA agrees that the use of this older data introduces some uncertainty into the analysis. These uncertainties are discussed in greater detail in Section 5 of the revised risk assessment.

With the exception of mercury, EPA evaluated bioconcentration based on water column concentrations that include contributions from dissolved and solid phases because available BCFs represent contributions from both. Because a BAF based only on dissolved-phase concentrations was available for mercury, EPA evaluated this constituent using only dissolved concentrations. Applying this conservative approach for most constituents ensured protection of human health. Even with this conservative assumption, the 90th percentile risks for the probabilistic analysis (Section 4) did not exceed risk criteria for the fish ingestion pathway. Therefore, this approach is unlikely to have affected the principal findings of the risk assessment.

For the revised risk assessment, EPA reviewed the available literature and identified BCFs for additional constituents that previously had no values. As noted in appendix G of the revised risk assessment, the following source hierarchy was used for fish BCFs:

- Primary literature: These are generally papers focused on a single chemical [171] [172] [173] [174] or may contain data on multiple chemicals.[175] [176]
- U.S. EPA databases/publications: These included ECOTOX [177] and the Mercury Report to Congress.[178]
- Other government agency resources: These included ATSDR Toxicological Profiles [179] and the Hazardous Substances Data Bank.[180]

EPA also finds that the references provided by commenters provided primarily phytotoxicity and accumulation data for terrestrial plants, and were therefore not relevant to EPA's explicit solicitation on whether the bioconcentration factors drawn from Baes et al. (1984) should be considered in the final risk assessment.[181]

5. Comments Related to Ecological Exposure and Toxicity

COMMENT: Public commenters emphasized the potential importance of cumulative ecological risk, whereby an ecological receptor may be exposed to multiple constituents and/or pathways concurrently. For example, amphibians may be subject to both dermal and ingestion exposure. Public commenters noted that ecological risks were underestimated because the following scenarios were not considered for ecological receptors: Aboveground pathways, contaminant transport to nearby uncontaminated environments, and the inclusion of field data in the analysis.

EPA RESPONSE: EPA acknowledges that cumulative effects can be important for ecological receptors. However, just as EPA did not consider cumulative human health risks from exposures to groundwater (discussed in the previous sections of this preamble), they were not modeled for ecological receptors. In the national, probabilistic analysis (Section 4 of the revised risk assessment), risks for all constituents fell below the ecological criteria. Even the sum of modeled risks for all constituents fell below the ecological criteria. In sensitivity analyses (Section 5 of the revised risk assessment), which considered different subsets of national disposal practices that may drive risks, boron and cadmium were the two constituents found to result in risks above ecological criteria. To the extent that cumulative exposures were not evaluated, EPA acknowledges that ecological risk could be underestimated to some degree. However, these uncertainties are unlikely to affect the principal findings of the risk assessment. In addition, EPA also notes that all surface water risks are orders of magnitude lower than the risks resulting from direct discharges modeled in U.S. EPA (2013).[182]

In contrast to the surface water and sediment exposures, ecological risks for individual constituents were appreciably above risk criteria for direct exposure to impoundment wastewater. As a result, it is clear that CCR disposal in surface impoundments have the potential to pose risk to ecological receptors, even without consideration of cumulative exposures.

COMMENT: Public commenters stated that the risk assessment does not consider sensitive habitats or species. Commenters requested additional consideration of threatened and endangered species and the inclusion of ecological field data.

EPA RESPONSE: EPA did not evaluate these sensitive habitats and sensitive/endangered ecological receptors because these are inherently site-specific issues for which data on potential impacts are often not available and can be difficult to quantify, even on a site-specific basis. EPA acknowledges that the inability to quantitatively evaluate the potential for these adverse effects represents a source of uncertainty. Discussion of these uncertainties is presented in Section 5 of the revised risk assessment.

COMMENT: Public commenters were concerned that a more conservative approach was needed to derive the ecological benchmarks. Multiple commenters also stated that the use of risk attenuation factors to scale the screening risks to full-scale risks was inappropriate. Several commenters noted that the ecological boron benchmark used for surface water exposures contained incorrect units based on an incorrect transcription in the peer-reviewed article. Another commenter noted that the ecological

[171] Eisler, R. 1989. *Molybdenum Hazards to Fish, Wildlife, and Invertebrates: A Synoptic Review.* Contaminant Hazard Reviews, Report No. 19, Biological Report 85(1.19). Laurel, MD. August.

[172] Kumada, H., et al. 1973. Acute and chronic toxicity, uptake and retention of cadmium in freshwater organisms. Bull. *Freshwater Fish.* Res. Lab. 22: 157

[173] Lemly AD. 1985. Toxicology of selenium in a freshwater reservoir: implications for environmental hazard evaluation and safety. *Ecotoxicology and Environmental Safety.* 10(3): 314–338.

[174] Murphy, B.R., G.J. Atchison, and A.W. McIntosh. 1978. Cadmium and zinc in muscle of bluegill (Lepomis macrochirus) and largemouth bass (Micropterus salmoides) from an industrially contaminated lake. *Environmental Pollution* 17:253–257.

[175] Barrows ME, Petrocelli SR, Macek KJ, Carroll JJ. 1980. Bioconcentration and elimination of selected water pollutants by bluegill sunfish (Lepomis macrochirus). In: Haque R, ed. Dynamics, exposure and hazard assessment of toxic chemicals. Ann Arbor, Michigan, U.S.A.: American Chemical Society. p. 379–392.

[176] Stephan, C.E. 1993. Derivation of Proposed Human Health and Wildlife Bioaccumulation Factors for the Great Lakes Initiative. Draft. Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Duluth, MN. March.

[177] U.S. EPA (Environmental Protection Agency). 2009b. E*COTOX User Guide: ECOTOXicology Database System*. Version 4.0. Available online at *www.epa.gov/ecotox/*.

[178] U.S. EPA (Environmental Protection Agency). 1997d. *Mercury Study Report to Congress. Volume III—Fate and Transport of Mercury in the Environment.* EPA 452/R–97/005. Office of Air Quality Planning and Standards and Office of Research and Development, Washington, DC.

[179] ATSDR (Agency for Toxic Substances and Disease Registry). 2008. Minimal Risk Levels (MRLs) for Hazardous Substances. Available at *www.atsdr.cdc.gov/mrls.html*.

[180] U.S. NLM (National Library of Medicine). 2011. *Hazardous Substances Data Bank (HSDB).* Available online at: *toxnet.nlm.nih.gov/cgi-bin/sis/htmlgen?HSDB*.

[181] Baes, C.F., III, R.D. Sharp, A.L. Sjoreen, and R.W. Shor. 1984. *A Review and Analysis of Parameters for Assessing Transport of Environmentally Released Radionuclides Through Agriculture.* ORNL–5786. Oak Ridge National Laboratory, Oak Ridge, TN. September.

[182] U.S. EPA. 2013. Environmental Assessment for the Proposed Effluent Limitation Guidelines and Standards for the Steam Electric Power Generating Point Source Category. EPA–821–R–13–003. Office of Water. Washington, DC 20460. April.

cadmium benchmark used for direct contact with surface water was incorrect.

EPA RESPONSE: Ecological benchmarks were obtained for CCR constituents when available and compared with the modeled media concentrations (*e.g.,* surface water, sediment) to estimate the HQs used to characterize ecological risk. These benchmarks represent the best available estimates of receptor responses based ''no effects'' (NOAEL) or ''lowest effects'' (LOAEL) study data. In some scenarios, these benchmarks may represent species not actually present in the field. In others, these benchmarks may not capture the most sensitive possible receptor at every site or for each constituent. While some benchmarks have factors of safety included to account for these or other uncertainties, there remains the potential for these ecological benchmarks to underestimate risks for the specific species and communities that live in surface waters impacted by CCR WMUs. The magnitude of this uncertainty is unknown. Consideration of any additional sensitive species not captured by the current benchmarks may result in some additional constituents above risk criteria in the probabilistic analysis. EPA notes that ecological risks to some of these additional sensitive receptors may be reflected in damage cases. However, this site-specific uncertainty is unlikely to affect the national conclusions of the risk assessment.

Regarding incorrect benchmark values, an updated boron benchmark was used in the revised risk assessment. The units in the fish study from which the previous SCV was derived [183] had been erroneously transcribed in Suter and Tsao (1996) [184] as µg/L instead of mg/L. The updated SCV was recalculated using the corrected units. The revised value has been corroborated with the authors. Additionally, a continuous criteria concentration (CCC) was used for the cadmium surface water benchmark in the revised risk assessment, replacing the previous value. The updated values are presented in appendix E of the revised risk assessment report.

[183] Hamilton, S.J. 1995. Hazard assessment of inorganics to three endangered fish in the Green River, Utah. *Ecotoxicol Environ Saf 30*:134–142.

[184] Suter, G.W., and C.L. Tsao. 1996. *Toxicological Benchmarks for Screening Potential Contaminants of Concern for Effects on Aquatic Biota: 1996 Revision.* U.S. Department of Energy, Oak Ridge National Laboratory, Oak Ridge, TN. June.

6. Comments Related to the Monte Carlo Analysis Approach

COMMENT: While some public commenters stated that the human health probability distributions appeared appropriate, others expressed concern regarding a conservative bias in input parameter probability distributions used and the resulting potential for overestimation of risks. These commenters noted that the ideal approach would be to estimate the actual risk and associated uncertainty rather than weighting the results conservatively.

EPA RESPONSE: The revised risk assessment conducted a full-scale, probabilistic Monte Carlo analysis to quantify human and ecological risks. EPA agrees it would be ideal to produce best estimates of actual risk. All input data distributions (*e.g.,* aquifer data, soil type, WMU data, climate data, distance to groundwater wells, distance to surface water bodies, constituent concentrations, water flow data, human exposure factors) were developed in line with this objective. However, these distributions were developed from available data and are subject to the limitations of these data. In cases where data were not sufficient to fully characterize the input distribution, conservative values and assumptions were used to fill data gaps to remain protective of human health and the environment. Further discussion of these uncertainties has been added to Section 5 of the revised risk assessment.

COMMENT: Public commenters pointed out that the risk assessment does not formally differentiate variability from uncertainty or show confidence limits for risk results, which makes it challenging to identify opportunities to reduce uncertainty. One commenter requested that EPA discuss the implications of the relatively wide risk distributions, including the reasons why some risk distributions are larger than others based on the Monte Carlo results.

EPA RESPONSE: EPA acknowledges it would be ideal to separate variability from uncertainty when possible in a probabilistic risk assessment. EPA was able to reduce a substantial number of the uncertainties in the revised risk assessment through the acquisition of additional data on facilities, environmental parameters, and constituent concentrations. Variability and uncertainty are still comingled in a large number of cases due to remaining data gaps; however, EPA conducted multiple sensitivity analyses to determine the potential for different inputs to affect risk results. Additional discussion of the differences between parameter variability, data uncertainty, and model error, as well as discussions of the sensitivity and uncertainty analyses, is presented in Section 5 of the revised risk assessment.

EPA disagrees that there are wide risk distributions. While the commenter correctly points to other risk assessments that had closer central tendency and high-end results, those were either site-specific assessments or involved no fate or transport modeling. National-scale risk assessments will necessarily have wider variability in their results compared to risk assessments that are specific to a single site. Thus, the ''wider'' risk distributions simply reflect the fact that different sites with different CCR can have very disparate impacts on human health and the environment.

7. Miscellaneous Comments

COMMENT: Some commenters stated that the documentation is incomplete and that an independent reviewer could not reproduce the analysis. Another commenter performed an independent review and cancer risk estimate and noted that the EPA used a reasonable approach for calculating cancer cases in the risk assessment.

EPA RESPONSE: EPA acknowledges that the documentation of the inputs and intermediate outputs could have been more transparent for the 2010 Draft Risk Assessment. In the revised risk assessment, many of the inputs EPA used are directly discernible from the appendices. A summary of the data available in each appendix is presented in Section 1 of the revised risk assessment. EPA also acknowledges that the additions and discussions of inputs in the document were not sufficient for complete duplication of the results. Thus, the input and output files for the draft risk assessment were made available in the docket of the proposed rule via an FTP site,[185] and final input and output files are being placed in the docket for the final rule.

COMMENT: Commenters requested improvement on the graphical presentation of risk results. Additionally, commenters requested further explanation of the minimum and maximum truncating values, as truncated values may reduce risk estimates.

EPA RESPONSE: While EPA did not provide a graphical presentation of the risk results, this information is more clearly discernible from the full input and output files. For discussion of the

[185] Available online at: *ftp://ftp.epa.gov/coal-combustion-residues.*

full inputs and outputs files, see the responses in the preamble section above. With regard to truncation, EPA no longer manually truncates input distributions for the human exposure factors. Instead, exposure factor distributions in the revised risk assessment were generated with the @ Risk software (Palisade Co., Newfield, NY),[186] as described in appendix D. EPA has also added further discussion of the cohorts to revised risk assessment, with tables comparing each cohort's risk presented in Section 5 of the revised risk assessment.

COMMENT: Commenters requested more complete documentation of the sensitivity analysis. Other comments included a request to add human health exposure factor variables to the sensitivity analysis, and to conduct additional sensitivity analyses on different topics (*e.g.,* well distance distribution).

EPA RESPONSE: EPA acknowledges the omission of the original sensitivity analysis from the docket. EPA updated the sensitivity analysis [187] so that it clearly describes the methodology that underlies the results summarized in Section 5 of the revised risk assessment. This sensitivity analysis was placed in the docket for the proposed rule.

Human health exposure factor variables were not evaluated in the sensitivity analysis. Human exposure factor variables have well-established, peer-reviewed, national distributions that are regularly used in probabilistic risk analyses conducted by EPA based on Agency policy. Therefore, the contribution of variability in the exposure factors to the variability in risk was not particularly useful for understanding the aspects of CCR disposal practices that may drive risk. Additional sensitivity analyses such as leachate duration versus leachable content and liner performance by thickness were conducted in the revised risk assessment and are summarized in Section 5.

B. Summary of Risk Assessment and Results

1. Problem Formulation

EPA first developed conceptual models to illustrate a general layout of surface impoundments and landfills, the chemical constituents that may be released from these WMUs, the routes through which these constituents may migrate through environmental media, and the types of exposures that may result. These conceptual models were used as the basis for all subsequent data collection efforts. EPA first collected data on the coal-fired power plants and CCR WMUs located across the United States. EPA then collected regional and national data to characterize the environment and receptor population surrounding each WMU. The data assembled represent the most current and comprehensive information available to the Agency at the time this risk assessment was conducted. Using the data collected, EPA first conducted a simplified hazard identification to determine which constituents warranted further evaluation. At this stage, EPA considered the presence of a constituent in CCR waste, combined with the availability of at least one toxicity benchmark, sufficient evidence of hazard potential. Table 1 presents a summary of the different chemical constituents retained as constituents of potential concern (COPCs) for further analysis.

TABLE 1—LIST OF CHEMICAL CONSTITUENTS EVALUATED IN THE CCR RISK ASSESSMENT

Aluminum
Ammonia
Antimony
Arsenic
Barium
Beryllium
Boron
Cadmium
Calcium
Chloride
Chromium
Cobalt
Copper
Fluoride
Iron
Lanthanum
Lead
Lithium
Magnesium
Manganese
Mercury
Molybdenum
Nickel
Nitrate/Nitrite
Selenium
Silicon
Silver
Sodium
Strontium
Sulfate
Sulfide
Thallium
Uranium
Vanadium
Zinc

All risks identified in subsequent analyses were compared against risk criteria of cancer risk greater than 1×10^{-5} or a noncancer hazard quotient (HQ) greater than 1. EPA typically relies on a risk range to determine the point at which regulation is appropriate. EPA uses as an initial cancer risk ''level of concern'' a calculated risk level of 1×10^{-5} (one in one hundred thousand) or an HQ above 1.0 for any noncarcinogens. For example, waste streams for which the calculated high-end individual cancer-risk level is 1×10^{-5} or higher generally are considered candidates for regulation. Waste streams whose risks are calculated to be 1×10^{-4} or higher generally will be considered to pose a substantial present or potential hazard to human health and the environment and generally will be regulated. Waste streams for which these risks are calculated to be 1×10^{-6} or lower, and lower than 1.0 HQs or EQs for any noncarcinogens, generally will be considered not to pose a substantial present or potential hazard to human health and the environment and generally will not regulated. See 59 FR 66075–66077, December 22, 1994.

2. Screening Analysis

EPA conducted separate screening analyses for each exposure pathway to identify which COPCs are most likely to pose risk to receptors. The results of this screening generally do not provide a precise characterization of individual risks that may occur, but rather identify those COPCs that are most likely to exceed risk criteria. In cases where well established, post-construction management practices (''controls'') have been shown to minimize releases from WMUs, EPA considered exposures for both an uncontrolled and controlled management scenario.

This screening analysis identified potential risks to human and ecological receptors resulting from the releases of particulate matter and the chemical constituents contained therein through wind and run-off. Under an uncontrolled management scenario, risks to human receptors resulted from the inhalation of windblown particulates in ambient air and the ingestion of soil and animal products (*i.e.,* meat and dairy), while risks to ecological receptors resulted from exposures to soil and sediment. Under a controlled management scenario, which consisted of fugitive dust controls and run-on/run-off controls, all risks associated with these exposure pathways decreased to below the criteria. Due to the conservative nature of the screening, there is a great deal of uncertainty surrounding the specific risks calculated for these exposure pathways. These risks represent a protective, but unlikely, combination of conditions that reflect at least an upper

[186] Available online at: *www.palisade.com/risk/*.

[187] U.S. EPA. 2009. *Sensitivity Analysis for the Coal Combustion Waste Risk Assessment.* Draft Technical Report. Prepared by RTI International for U.S. EPA, Office of Solid Waste, Washington, DC.

bound on potential exposures. Thus, the cumulative effect of these uncertainties results in an overestimation of nationwide risks to most or all receptors. Therefore, EPA makes no direct findings concerning the magnitude of the risks that may occur under either an uncontrolled or controlled management scenario, but concludes with a high degree of confidence that the reductions achievable with standard management practices are sufficient to be protective even under this conservative screening assessment. Based on these lines of evidence, EPA concluded that no further characterization was warranted for these exposure pathways.

These screening analyses identified potential risks to human and ecological receptors from leaching of chemical constituents from CCR waste into surrounding environmental media. Risks to human health resulted from ingestion of groundwater and fish, while risks to ecological receptors resulted from exposure to surface water. There was no simple method to estimate the effect controls may have for these pathways. However, considerable dilution and attenuation may occur before COPCs reach downgradient private wells and surface water bodies. Therefore, EPA retained all of the COPCs found to be above risk criteria in groundwater and surface water for further characterization. In addition, EPA used the uncontrolled screening results for the above ground sediment pathway as a conservative proxy for the groundwater to surface water sediment pathway. As a result, sediment exposures of four COPCs were retained for further characterization. Table 2 presents a summary of the chemical constituents retained as COPCs for each pathway.

TABLE 2—LIST OF CHEMICAL CONSTITUENTS RETAINED FOR PROBABILISTIC ANALYSIS

Human health		Ecological	
Ingestion of groundwater	Ingestion of fish	Surface water exposure	Sediment exposure
Antimony	Arsenic	Aluminum	Antimony
Arsenic	Cadmium	Arsenic	Arsenic
Boron	Mercury	Barium	Silver
Cadmium	Selenium	Beryllium	Vanadium
Cobalt	Thallium	Boron	
Fluoride		Cadmium	
Lead		Chloride	
Lithium		Chromium	
Molybdenum		Cobalt	
Thallium		Copper	
		Iron	
		Lead	
		Molybdenum	
		Nickel	
		Selenium	
		Silver	
		Vanadium	
		Zinc	

These screening analyses also identified potential risks to ecological receptors from direct exposure to impoundment wastewater. Unlike the other exposure pathways, no dilution or attenuation will occur within impoundment wastewater prior to ecological exposures. Thus, the direct exposures considered in the screening analysis provide a reasonable estimate of the relative magnitude of risks. Based on the screening analyses, EPA concluded that HQs for ecological receptors exceeded 1 for the following constituents (listed from highest to lowest potential): Arsenic (100), barium (50), aluminum (30), boron (30), selenium (20), cadmium (10), vanadium (10), beryllium (2), chloride (2) and chromium (2). Because the screening analysis provides sufficient characterization of these exposures, this pathway was not carried forward for further analysis.

3. Probabilistic Analysis

EPA conducted a national-scale, probabilistic analysis to better characterize the potential risks to human and ecological receptors associated with leachate released from surface impoundments and landfills. The specific exposure routes evaluated for these releases were human ingestion of groundwater used as a source of drinking water and fish caught from freshwater lakes or streams, as well as ecological contact with and ingestion of surface water and sediment. A combination of models was used to predict COPC fate and transport through the environment, receptor exposures, and the resulting risks. Site-specific data were used, supplemented by regional and national data sets, to capture the national variability of disposal practices, environmental conditions and receptor behavior. EPA modeled risks for both highly exposed individuals (90th percentile risks) and more moderately exposed individuals (50th percentile risks). In instances where the speciation of a COPC has been shown to greatly affect fate and transport, EPA modeled multiple species to provide a bounding on potential exposures.

Table 3 shows the 90th percentile human health risks to the most sensitive age cohorts for constituents that exceeded the risk criteria. Risks are presented for arsenic modeled entirely as two different species (III and V) to provide a bounding on potential risks. Values that exceed the selected risk criteria are shown in bold. No 90th percentile risks above ecological criteria were identified for either surface impoundment or landfills. No 50th percentile risks above human health or ecological criteria were identified for either surface impoundment or landfills.

TABLE 3—90TH PERCENTILE NATIONWIDE PROBABILISTIC RISK RESULTS

COPC	Ingestion of groundwater	
	Surface impoundments	Landfills
Cancer Risks		
Arsenic III	2×10^{-4}	5×10^{-6}
Arsenic V	1×10^{-5}	7×10^{-8}
Noncancer Risks		
Arsenic III	5	0.1
Arsenic V	0.4	<0.01
Lithium	2	[a]
Molybdenum	2	<0.01

[a] Leachate data were not available to model this COPC for landfills.

• Surface Impoundments:

Ingestion of groundwater was the only exposure pathway that resulted in risks above 1×10^{-5}. 90th percentile cancer risks above 1×10^{-5} were identified for arsenic III (2×10^{-4}). The 90th percentile noncancer risks above an HQ of 1 were identified for arsenic III (5), lithium (2), and molybdenum (2).

• Landfills:

All 90th percentile cancer and noncancer risks were below human health criteria.

High-end risks identified for surface impoundments are consistently higher than those for landfills. These results are attributed to the higher infiltration rates through surface impoundments, which are driven by the hydraulic head of the ponded water. Median risks for both surface impoundments and landfills were substantially lower than both the high-end risks in this risk assessment and the median risks modeled in the 2010 Risk Assessment. This decrease is attributed primarily to the interception of groundwater by surface water bodies, which is accounted for in the revised risk assessment to provide a more accurate mass balance of constituent mass during transport. It is common for coal-fired utilities to be located near water bodies, which are used as a source of cooling water and conveyance of waste. As a result, in the majority of model iterations, the interception of groundwater by surface water bodies resulted in negligible downstream well concentrations.

Based on the results of the probabilistic analysis, EPA concludes that leaching from CCR waste management units has the potential to pose risk to receptors. Arsenic, lithium, and molybdenum are the chemical constituents found to pose the greatest risks from surface impoundments, while arsenic posed the greatest risks from landfills. Available toxicological profiles indicate that risks from arsenic ingestion are linked to an increased likelihood of cancer in the skin, liver, bladder and lungs, as well as nausea, vomiting, abnormal heart rhythm, and damage to blood vessels;[188] risks from lithium ingestion are linked to neurological and psychiatric effects, decreased thyroid function, renal effects, cardiovascular effects, skin eruptions, and gastrointestinal effects;[189] and risks from molybdenum ingestion are linked to higher levels of uric acid in the blood, gout-like symptoms, and anemia.[190]

4. Sensitivity and Uncertainty Analysis

The modeled probabilistic risks capture the range of current, nationwide CCR disposal practices. However, because of the broad scope of the analysis, there are a number of sources of variability and uncertainty present. Therefore, to confirm the results of the probabilistic analysis and to better understand whether any particular subset of disposal practices drives the risks identified, EPA conducted additional sensitivity and uncertainty analyses.

EPA reviewed the models used, as well as the data and assumptions input into these models, to better understand the sources of variability and uncertainty inherent in the probabilistic analysis. The Agency then qualitatively and, to the extent possible, quantitatively analyzed these sources to understand the potential effects each may have on the modeled risk results. During this review, specific attention was focused on the parameters shown to have the greatest influence on model results. As a further method of validation, EPA compared the results of the sensitivity and uncertainty analyses with proven and potential damage cases. Together these analyses and comparisons show that there is a high degree of confidence in the principal findings of the probabilistic analysis. However, the review of sensitive parameters revealed some specific disposal practices that may result in greater risks than identified in the probabilistic modeling.

Through these additional sensitivity and uncertainty analyses, which explored different subsets of national disposal practices, EPA identified the potential for higher risks than those identified in the broader, national analysis. In particular, consideration of different waste pH values showed higher risks for arsenic at more acidic and basic pH values, as well as additional risks for boron, cobalt, fluoride and mercury at these more extreme pH values. Consideration of specific liner types showed that groundwater risks are driven by disposal in unlined units and, in particular, unlined surface impoundments. For these units, EPA identified higher risks for arsenic, lithium, and molybdenum, as well as additional risks for thallium. Clay-lined units were found to pose lower risks than unlined units. Composite-lined units were found to be the most protective disposal practice, resulting in risks far below all criteria identified in this risk assessment.

C. Conclusions

Based on the analyses presented in this document, EPA concludes that current management practice of placing CCR waste in surface impoundments and landfills poses risks to human health and the environment within the range that OSWER typically regulates. On a national scale, surface impoundments presented higher risks than landfills. Risks to ecological receptors were identified from exposures to aluminum, arsenic, barium, beryllium, boron, cadmium, chloride, chromium, selenium and vanadium through direct exposure to impoundment wastewater. Risks to residential receptors were identified primarily from exposures to arsenic, lithium, and molybdenum in groundwater used as a source of drinking water, but additional risks from boron, cadmium, cobalt, fluoride, mercury and thallium were identified for specific subsets of national disposal practices.

Sensitivity analyses on liner type indicate that disposal of CCR wastes in unlined surface impoundments and landfills presents the greatest risks to human health and the environment. As modeled, the national risks from clay-lined units are lower than those for unlined units, but such units can exceed risk criteria at individual sites. Composite liners were the only liner type modeled that effectively reduced risks from all pathways and constituents far below human health and ecological criteria in every sensitivity analysis conducted. Sensitivity analyses on waste type indicate that the acidic conditions that result from codisposal of CCR waste with coal refuse and the basic conditions that result from disposal of FGD waste result in higher

[188] Profile for arsenic available online at: *www.epa.gov/iris/subst/0278.htm* and *www.atsdr.cdc.gov/toxprofiles/tp2.pdf.*

[189] Profile for lithium available online at: *hhpprtv.ornl.gov/issue_papers/Lithium.pdf.*

[190] Profile for molybdenum available online at: *www.epa.gov/iris/subst/0425.htm.*

risks from arsenic and other constituents than CCR waste disposed alone.

The risk results are consistent with the groundwater damage cases compiled by EPA. These damage cases were primarily associated with unlined units and were most frequently associated with releases of arsenic. Recent surveys of the industry indicate the majority of newly constructed units are lined, and that that the practice of codisposal with coal refuse has declined. However, this risk assessment presents a static snapshot of current disposal practices. While newer units may be managed in a more protective manner, older units, which still comprise the majority of current units, continue to operate in a manner that poses risks to human health and the environment that OSWER typically regulates.

XI. Summary of Damage Cases

EPA has a long history of considering damage cases in its regulatory decisions under RCRA. As discussed earlier in this preamble, the statute specifically directs EPA to consider ''documented cases in which danger to human health and the environment from surface run-off or leachate has been proved,'' in reaching its Regulatory Determination for these wastes, demonstrating that such information is to carry great weight in decisions under this section. 42 U.S.C. 6982(n)(4). Damage cases, even if only potential damage cases, are also relevant under the third Bevill factor: ''potential danger, if any, to human health and the environment from the disposal and reuse of such materials.'' 42 U.S.C. 6982(n)(4). In addition, damage cases are among the criteria EPA must consider under its regulations for determining whether to list a waste as a ''hazardous waste.'' See 40 CFR 261.11(a)(3)(ix). Damage cases generally provide extremely potent evidence in hazardous waste listings. In this regard, EPA notes that the number of damage cases collected for this rulemaking (157) is by far the largest number of documented cases in the history of the RCRA program.

EPA considers that both proven and potential damage cases provide information directly relevant to this rulemaking. First, damage cases provide evidence of both the extent and nature of the potential risks to human health and the environment. The primary difference between a proven and a potential damage case is whether the contamination has migrated off-site of the facility. But the mere fact that groundwater contamination has not yet migrated off-site does not change the fact that a potentially harmful constituent has leached from the unit into groundwater. Whether the constituent ultimately causes further damage by migrating into drinking water wells does not diminish the significance of the environmental damage caused to the groundwater under the site, even where it is only a future source of drinking water. As EPA explained in the preamble to the original 1979 open dumping criteria, which are currently applicable to these facilities, EPA is concerned with groundwater contamination even if the aquifer is not currently used as a source of drinking water. Sources of drinking water are finite, and future users' interests must also be protected. (See 44 FR 53445–53448.) (''The Act and its legislative history clearly reflect Congressional intent that protection of groundwater is to be a prime concern of the criterion. . . . EPA believes that solid waste activities should not be allowed to contaminate underground drinking water sources to exceed established drinking water standards. Future users of the aquifer will not be protected unless such an approach is taken.'')

In the June 21, 2010 proposed rule, EPA presented for public comment an assessment of CCR damage cases, and requested comments and other information related to damage cases EPA had previously received from industry, environmental groups, and citizen groups. EPA later requested public comment on additional damage case information in a Notice of Data Availability (NODA) published in the **Federal Register** on October 12, 2011 (76 FR 63252). As discussed in Section IV of this preamble, the Agency is deferring making a Bevill determination; however, EPA is still presenting its findings with regard to damage cases (including information submitted during the comment periods for the June 2010 proposal and the October 2011 NODA) because as described above, this information supports actions taken in the present final rule.[191]

A. Damage Cases Presented in June 21, 2010 Proposed Rule

In the June 2010 proposed rule, the Agency summarized its database on damage cases that had expanded since the May 2000 Regulatory Determination.[192] This summary included two cases of CCR slurry spill caused by surface impoundment dike failures (the 2005 Martins Creek, Pennsylvania, and the 2008 TVA Kingston, Tennessee), and two cases involving structural fill (the use, between 1995–2007, of CCR in the reclamation of two sand and gravel pits in Gambrills, Maryland; and for contouring the Battlefield Golf Course, in Chesapeake, Virginia, in the early 2000s). In the June 2010 proposed rule, the Battlefield Golf Course site was designated as a potential damage case, whereas the other three sites were designated as proven damage cases.[193]

B. Additional Information and Studies

Shortly prior to the publication of the June 2010 proposed rule and immediately thereafter, several stakeholder groups provided the Agency with new information on damage cases. In November 2009, the Electric Power Research Institute (EPRI) issued a two-volume draft report [194] analyzing the 24 proven and 43 potential damage cases established in EPA's 2007 damage case report [195] accompanying the August 2007 Notice of Data Availability (NODA).[196] EPRI claimed that in the great majority of damage cases there is no record of primary MCL contaminants migrating off-site that would justify designating them as proven damage cases. EPRI also disagreed with several ecologic damage cases that had been predicated on fish advisories in Texas, on the grounds that the selenium toxicity standard that triggered these fish advisories was later revised by the state, and subsequently the fish advisories were rescinded. In February and August 2010, The Environmental Integrity Project (EIP), jointly with other citizen groups, issued two reports, identifying 70 alleged damage cases.[197] [198] Fifty of these cases were submitted to EPA for the first time.

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[191] Damage Case Compendium (Technical Support Document on Damage Cases), U.S. EPA, December 2014.

[192] See June 21, 2010 **Federal Register**—Appendix to the Preamble: Documented Damages from CCR Management Practices (75 FR 35230).

[193] See 75 FR at 35131 for definitions of ''proven'' and ''potential'' damage cases.

[194] *Evaluations of CCP Damage Cases:* These two volumes were finalized in July and September 2010, respectively: *http://my.epri.com/portal/server.pt?open=512&objID=413&&PageID=230509&mode=2&cached=true.*

[195] *Coal Combustion Waste Damage Case Assessments,* July 9, 2007. EPA–HQ–RCRA–2006–0796–0015.

[196] Notice of Data Availability on the Disposal of Coal Combustion Wastes in Landfills and Surface Impoundments, 72 FR 49714, August 29, 2007.

[197] *In Harm's Way: Lack of Federal Coal Ash Regulations Endangers Americans and Their Environment.* Environmental Integrity Project, Earthjustice, and Sierra Club: *http://www.environmentalintegrity.org/news_reports/08_26_10.php.*

[198] *Out of Control: Mounting Damages from Coal Ash Waste Sites.* Environmental Integrity Project and EarthJustice: *http://www.environmentalintegrity.org/news_reports/news_02_24_10.php.*

In response to EPRI's report, EPA reassessed the 24 proven damage cases identified in EPA's 2007 Damage Case report, as well as three additional proven damage cases cited in the proposed rule. In addition, in response to EIP's reports, the Agency assessed the 70 alleged damage cases, to independently confirm the allegations in the report. In reviewing [199] these alleged damage cases, EPA took a number of measures. First, to the extent the information was available, EPA consulted tabulated monitoring well data to validate the exceedance data presented in comments; and studied well- and waste-unit location maps, geohydrologic studies, and groundwater potentiometric maps to validate both whether the wells were up-gradient or down-gradient wells and instances of groundwater mounding. EPA also contacted state regulators to confirm the reports' claims of contamination, particularly contamination exceeding state or federal water quality standards, and conducted internet research (focusing on state regulatory information) pertaining to the sites in question. EPA also thoroughly assessed state comments submitted to EPA in response to the June 2010 proposed rule and the October 2011 NODA. Third, EPA identified state or federal administrative measures applied to utilities (*e.g.,* consent orders, notices of violation, penalties for non-compliance, etc.) and/or legal motions (*e.g.,* law-suits, motions for injunctive relief, and out-of-court settlements) filed by the states or citizen groups in order to identify any instances of non-compliance by the utilities that have resulted in documented impacts to water resources.

EPA's review confirmed that 13 of the 27 damage cases previously designated as proven did meet the criteria used by EPA for identifying proven damage cases; however, EPA also found that six of the 27 cases only meet the criteria for a potential damage case, while the remaining eight cases were altogether rejected (*i.e.,* EPA determined that a damage case has not occurred, and/or test of proof criteria were not satisfied, and/or CCR was not the only or predominant waste component). Regarding the 70 alleged damage cases in the two EIP reports, EPA concluded that ten of them qualify as proven damage cases, 45 as potential damage cases, and the remainder were either rejected or, due to the lack of adequate information, defined as indeterminate.

In November 2011, the Utility Solid Waste Activities Group (USWAG) submitted to the docket of the October 2011 NODA a critical review of EIP's 70 alleged damage cases from 2010. USWAG's review concluded that ''the overwhelming majority of the allegations regarding the 70 sites . . . fail to provide the requisite 'test of proof' documentation necessary for EPA to characterize virtually any of the sites as proven damage cases.'' Also, in November 2011 EIP submitted to the docket of the October 2011 NODA a report alleging 20 new damage cases.[200]

Following review of the comments on the proposed rule and the October 2011 NODA, EPA has revisited some of its earlier damage case findings. Our post-proposal studies have resulted in: (1) Rejection of 17 of the previously-established and newly-alleged damage cases, either due to inappropriate scope (*e.g.,* oil combustion waste, non-utility CCR, or CCR disposed-off in abandoned coal mine pits), co-mingling with non-CCR waste, or inadequate information to ascertain that contaminants are derived from CCR; (2) two of the damage cases that had been previously designated as 'rejected' in EPA's 2007 damage case report were re-categorized as proven damage cases and six others were re-categorized as potential damage cases; and (3) one damage case site reported in *Risky Business* occurred next to a site that had already been previously reported.

In summary, at the present time the Agency has established 40 proven and 113 potential damage cases. In addition, the rulemaking docket contains four additional, state-endorsed damage cases from Wisconsin. While EPA has insufficiently-detailed information (including the extent, if any, that the contaminants have migrated off site) to designate these four additional sites as potential or proven, because the state has identified them to us as damage cases, we have included them in our overall total of 157.

C. Stakeholder Comments on Damage Cases

All of the comments submitted by stakeholders to the dockets of the proposed rule and the October 2011 NODA, as well as EPA's responses, are included in the Technical Support Document to CCR Damage Cases which is available in the RCRA docket supporting this rule. The following is a summary of the salient comments submitted by the various stakeholder groups.

1. Utility Industry's Comments

EPA received several comments from utilities arguing that an incident should not be considered to be a ''damage case'' if the environmental damage has been addressed or is no longer occurring and/or if the State Director is satisfied that no further action is required. (Note: For those damage cases known to the Agency prior to EIP's 2010 reports, remediation is completed or underway at *all* sites where remediation was known to be required.) These commenters also argued that EPA should disregard cases in which there are no downstream contaminant receptors to be harmed by the contamination. These commenters also alleged that only ''proven'' damage cases should be considered to be relevant as only these are ''*documented cases in which danger to human health or the environment from surface runoff or leachate has been proved,*'' 42 U.S.C. 6982(n)(4).

Industry commenters also made a number of other points. They stated that most damage cases occurred in older facilities commissioned before current state landfill regulations were promulgated, where most waste units lack liners and leachate collection systems, and that in most cases, exceedances of state or federal water quality standards were contained on site, and these exceedances are mostly for constituents (*e.g.,* sulfate and boron) that do not have federal, health-based drinking water quality standards. These commenters also claimed that the number of proven damage cases is very sparse: Of the 24 proven damage cases in EPA's 2007 report,[201] they argued that only three had documented off-site groundwater exceedances of health-based MCLs that can be attributed to CCR impacts. They also claimed that of the 70 alleged damage cases in EIP's 2010 reports (*In Harm's Way* and *Out of Control*), 64 did not meet EPA's ''test of proof'' criteria for characterizing the site as a proven damage case. For the remaining six sites, where the allegations on their face arguably met EPA's definition of a proven damage case, these commenters claimed that these cases should be discounted because they involved sites that are either no longer active or where the damages had been already remediated

[199] See *Assessment of Previously Identified Proven Damage and Recently Alleged Damage Cases,* October 2010.

[200] EPA–HQ–RCRA–2011–0392–0259. Nineteen of the cases involve groundwater impact, and one involves soil contaminated by the placement of coal ash and clinkers from train engine boilers for railroad tracks bed. A hard copy of the report, *Risky Business: Coal Ash Threatens America's Groundwater Resources at 19 More Sites,* was issued on December 12, 2011.

[201] *Coal Combustion Waste Damage Case Assessments,* ibid.

or are undergoing remediation with federal/state oversight. These commenters also said that 12 of the 70 EIP-alleged damage cases were previously addressed in EPA's 2007 Damage Case report, and of these, five sites had been rejected by the EPA due to lack of evidence of damage or lack of evidence of damage uniquely associated with CCR, and seven sites had been characterized as indeterminate due to insufficient information. According to these commenters, no new information regarding these 12 sites was contained in the two EIP reports that warrants their designation as proven damage cases.[202]

2. Individual State Comments

EPA also received a significant number of comments from individual states. In their comments, many of the states addressed selected damage cases that occurred within their jurisdiction, subject to their authority. Several states agreed with EPA's assessment of the damage cases; for instance, Wisconsin and Michigan complimented EPA's database of damage cases. Other commenters agreed with some of the newly alleged damage cases' reports of groundwater contamination exceeding regulatory standards, but disagreed with EIP's conclusions that enforcement was inadequate, tardy, or absent. According to some state commenters, enforcement was not necessary or appropriate in those instances. For example, some states (*e.g.,* North Carolina, Oklahoma, Tennessee, and Florida) argued that the contamination did not pose public health risks because the contaminants were confined to state-established Compliance Boundaries (known also as Groundwater Mixing Zones) [203] and/or because there was no evidence the contamination had migrated off-site. Several other states (*e.g.,* Maryland, Virginia, and Texas) confirmed EPA's established damage cases as well as some of the newly alleged damage cases, but claimed that these cases were associated with presently outdated practices, and that regulatory requirements have since been revised to prohibit such practices. Two states (South Dakota and Pennsylvania) confirmed that contamination above federal or state regulatory standards had occurred, but attributed the contaminant(s) to sources other than CCR units, *e.g.,* coal mining pits associated with coal refuse; and/or nearby, up-gradient unlined MSWLFs, cooling water evaporation ponds, or natural background soil compositions. For certain cases, the states explained that required assessment monitoring was still ongoing to establish the source, scope, and extent of the contamination, and so had reached no conclusions about the specific allegations (North Carolina, North Dakota, and Tennessee). Finally Ohio acknowledged that the extent of groundwater contamination risk within the state is poorly-documented due to the scarcity of monitoring wells down gradient from unlined disposal units.

3. State Association Comments

The Association of State and Territorial Solid Waste Management Officials (ASTSWMO) argued that the 24 proven damage cases reported in EPA's 2007 Damage Case report do not reflect current land disposal practices, and so are irrelevant to the proposed rule. For example, disposal ''units'' involved in several damage cases included five sand and gravel pits, two quarries, and one lake impoundment. ASTSWMO commented that half of these sites began operating in 1970 or earlier, including at least six sites that began operating in the early 1950s. ASTSWMO claimed that much of the information cited in the two EIP 2010 alleged damage case reports is incomplete, incorrect and/or misleading. For example, their comments alleged that EIP failed to provide pertinent information on specific monitoring wells, sample/analytical dates, and hydrogeological data. ASTSWMO also claimed that many of the assumptions about groundwater flow were based on a topographic maps rather than on potentiometric maps that are based on subsurface groundwater flow data. They also claim that data in state files contradicted claims in the reports, and that EIP's reports contained numerous technical errors, such as reporting values for naturally occurring constituents as contamination, reported data without distinguishing between down-gradient and up-gradient wells, ignoring the potential contribution from sources other than CCR-related units (*e.g.,* coal mining legacy), and claims that information provided by state program staff was misconstrued/misrepresented.

4. Citizens Group Comments

Citizen groups generally argued that the fact that damage has occurred should be part of the weight of evidence documenting the potential for harm at all CCR disposal sites, without regard to whether the damage cases were categorized as ''proven'' or ''potential.'' These commenters also raised a number of arguments in direct response to the comments provided by the utilities and the states. For example, these commenters argued that the presence of downstream receptors is a valid factor to consider when setting priorities for mitigating damage, but does not justify allowing contamination to migrate off of the disposal site. These commenters claimed that about one-fifth of EPA's damage cases preceding the 2010 EIP reports show evidence of contamination of private and public drinking water wells. In addition, these commenters allege that state regulatory agencies have done little to respond to contamination from CCR disposal sites, and, even in those cases where action has been taken, rarely is any action taken beyond assessment monitoring. According to these commenters, off-site monitoring has only occurred at a limited number of sites, and mostly such monitoring was performed voluntarily by the utilities and was not reported to state regulators. These commenters also claimed that although less than half of EPA's damage cases preceding the 2010 EIP reports involve active landfills, almost three-quarters of the newly alleged damage cases (EIP's 2010 reports) involve active landfills. They further alleged that a large majority of EPA's surface impoundment damage cases preceding the 2010 EIP reports are active sites, indicating that the absence of liners is contributing to the contamination problems. They noted that one quarter of the damage cases in EIP's 2010 reports involved units with liners, indicating that the mere presence of any liner provides no assurance that migration of contaminated groundwater from a waste unit is not occurring. Overall, they claimed that surface impoundments remain ''woefully unregulated'' when compared to landfills. Over one third of EIP's alleged groundwater damage cases show migration of contamination off-site. Also, a quarter of EPA's damage cases preceding the 2010 EIP reports involve contamination of surface water, and 15 percent of these damage cases show ecologic damage. Finally, these commenters note that several of the Secondary Contaminant Maximum Levels (SMCLs) constituents still might

[202] EPA–HQ–RCRA–2011–0392–0211, ibid.

[203] A Zone of Discharge or Zone of Mixing is a three dimensional region containing groundwater being managed to mitigate impairment caused by the release of contaminants from a waste disposal site; by definition, it is inside the detection boundary area, hence it is exempt from compliance with MCL and SMCL standards (*e.g.,* in Florida, Illinois, South Carolina, Tennessee, North Carolina, and Pennsylvania).

cause harm to recipients residing next to CCR disposal sites.[204]

D. Response to Key Stakeholder Comments

In many instances EPA did not have access to information that would either substantiate or refute the claims in EIP's reports. In many instances public commenters submitted information that clarifies, rebuts or otherwise calls into question some of the allegations contained in the various damage case reports. For example, there are instances in which claims were made that a contaminant plume had migrated offsite even though there were no offsite monitoring wells to confirm the claim. Due to the dearth of groundwater monitoring on facilities' boundaries (or beyond) EPA could not identify offsite plume migration for most sites, except in the rare instances drinking water wells had been contaminated. Consequently, only 10 of the 70 alleged cases submitted by EIP in 2010 were designated as proven damage cases.

In addition, factual errors were identified in certain instances; for example, certain allegations of groundwater contamination were based on surface water standards (rather than groundwater standards). Corrections or updated facts are reflected in EPA's damage case assessment. Nevertheless, EPA was able to validate a significant number of EIP's claims; for example, as of 2011, EPA was able to confirm that a significant portion of the damage cases in EIPs 2010 report involved both landfills and surface impoundments, most of which involved units with either no liner or a substandard liner system. And for many of EIP's damage cases, EPA was able to confirm sufficient details to classify them as potential damage cases.

However, EPA disagrees with most of the arguments minimizing the significance of the damage case record. First, cases where contamination has been remediated remain relevant to this rulemaking. EPA is relying on the damage cases to evaluate the extent and nature of the risks associated with particular CCR management practices. Facts demonstrating the consequences from particular activities therefore remain relevant, particularly (although not solely) where the management practices continue to occur. In other words, what matters in this regard are facts that provide information on the reasons that unit leaked, the particular contaminants that were present, the levels of those contaminants, and the nature of any impacts caused by that contamination. None of these facts are affected by whether the damage is ultimately mitigated or remedied. This is entirely consistent with RCRA section 8002(n), which requires EPA to evaluate the ''potential danger, if any, to human health and the environment from the disposal and reuse of such materials'' in addition to ''documented'' damage cases. 42 U.S.C. 6982(n)(3)–(4). Accordingly, the fact that any contamination has subsequently been remediated is not a basis for disregarding a damage case. Moreover, EPA is not relying on these damage cases to evaluate the adequacy of state programs, although it may ultimately provide information relevant to such findings. Therefore the adequacy of the state's response, or the lack thereof, is also not relevant to whether particular damage cases are appropriately considered as part of this rulemaking.

EPA also disagrees that only the presence of receptors within the impact sphere of a contaminating facility merits consideration of a particular damage case. EPA's longstanding and consistent policy across numerous regulatory programs has been that groundwater contamination is a significant concern that merits regulatory action in its own right, whether or not the aquifer is not currently used as a source of drinking water. Sources of drinking water are finite, and future users' interests must also be protected. The absence of current receptors is therefore also not an appropriate basis on which to discount damage cases. And for all of the reasons discussed above, EPA also disagrees that only exceedances of health-based standards of contaminants that have migrated off-site (*i.e.,* only proven damage cases) should be accounted for as part of this rulemaking.

The Agency also disagrees with the claims that the number of damage cases is ''sparse,'' the majority of which involve only ''outdated CCR management practices'' in older facilities, and therefore are not relevant to determining the current risks from CCR mismanagement. Even assuming that only ''proven'' damage cases were relevant, to date, EPA has confirmed a total of 40 proven damage cases, which is hardly ''sparse.'' And when ''potential'' damage cases are considered, the totals rise to 157; this is the largest number of damage cases in the history of the RCRA program. Further, these numbers likely underestimate the true number of cases in which CCR units are contaminating groundwater. In reality, the damage case record represents only a subset of those CCR waste units that have effective groundwater monitoring. As discussed in Unit IV.A of this document, a significant portion of CCR surface impoundments still lack groundwater monitoring, and only approximately 80% of the recently commissioned impoundments (*i.e.,* since about 1994) have groundwater monitoring.

In addition, under many state programs existing impoundments are exempt from groundwater monitoring and once monitoring is put in place, new damage cases quickly emerge. This is illustrated by two lines of evidence: First, in the wake of the 2008 TVA Kingston CCR spill two states required utilities for the first time to install groundwater monitoring. Illinois required facilities to install groundwater monitoring down gradient from their surface impoundments. As a result, within only about two years, Illinois detected seven new instances of primary MCL exceedances and five additional instances with exceedances of SMCLs. The data for all twelve sites were gathered from onsite; it appears none of these facilities had been required to monitor groundwater off-site, so whether the contamination had migrated off-site is currently unknown.[205] Similarly, North Caroline required facilities to install additional down gradient wells. In January 2012, officials from the North Carolina Department of Environment and Natural Resources disclosed that elevated levels of metals have been found in groundwater near surface impoundments at all of the State's 14 coal-fired power plants.[206]

Second, states with effective programs for groundwater monitoring tend to have a larger record of damage cases (*e.g.,* Wisconsin, nationally ranked as the 32nd CCR disposer in 2011, has 14 damage cases) as compared to states with less stringent groundwater

[204] Examples include boron's One-Day and Ten-Day Health Advisory (3.0 mg/L) and the Longer Term Health Advisory (2.0 mg/L) levels for children; manganese's Long Term Health Advisory (LTHA: 0.3 mg/L) level; and sulfate's Drinking Water Advisory (DWA: 500 mg/L) level in groundwater have been exceeded each in between over 60 and close to 80 of both the alleged and damage case sites and those sites preceding the 2010 EIP reports.

[205] See EIP's December 2011 *Risky Business: Coal ash Threatens America's Groundwater Resources at 19 More Sites,* docket document EPA–HQ–RCRA–2011–0392–0259, appendix A3. *www.environmentalintegrity.org/.../121311EIPThirdDamageReport.pdf* and *Illinois EPA's Ash Impoundment Strategy Progress Reports,* February 10 and October 2011, accessed Online July 15, 2014: *http://www.epa.state.il.us/water/groundwater/publications/ash-impoundment-progress.pdf and http://www.epa.state.il.us/water/ash-impoundment/documents/ash-impoundment-progress-102511.pdf.*

[206] Groundwater Monitoring Data for Coal Ash Ponds, NC DENR: *http://portal.ncdenr.org/web/wq/hot-topics/coalashregulation/gwatermonitoring.* Accessed Online July 15, 2014.

monitoring requirements (*e.g.,* Texas, nationally ranked as the second largest CCR disposer in 2011, has only three confirmed, potential damage case).

Nor is it accurate that the majority of these damage cases involve older units that no longer reflect current management practices or state requirements. The commenters point to the fact that the majority of cases involve units constructed before current state landfill regulations were promulgated, and thus lack liners and leachate collection systems. EPA agrees that the majority of cases do involve such units, but this hardly reflects ''outdated'' or irrelevant management practices. As discussed in Unit IV.A of this document, the majority of CCR continues to be managed in older (*i.e.,* constructed pre-1994) units that lack liners and leachate collection systems, and will in fact continue to be managed in such units for at least the near future.

Approximately six percent of the waste units associated with groundwater impacts have been constructed from 1990 onwards. Considering there is a lag time between the construction of many of the disposal units and the first detection of their groundwater impact by subsequently installed groundwater monitoring wells, the absence of damage cases associated with newer units is neither unexpected nor dispositive as to the level of risk such units pose.

Finally, a number of other factors support the conclusion that the current number of damage cases likely underestimate the current risks. First, the combined effect of a number of current state regulatory provisions is to decrease the instances in which off-site contamination will be detected (or on-site contamination will need to be remediated). For example, several states have adopted ''buffer zones'' where certain standards may not apply; Florida designates certain areas as a ''Zone of Discharge'' (ZOD), in which numerical primary and secondary drinking water standards do not apply; this exemption extends even beyond the ZOD, unless ordered specifically by the state. In addition, secondary maximum contaminant levels (SMCLs) are not applicable to existing industrial facilities discharging to groundwater in the state.[207] In other instances, states grant waivers to certain facilities that exceed health-based standards several-fold.[208] Certain states (*e.g.,* Indiana) consider surface impoundments as temporary storage facilities as long as they are dredged on a periodic basis (*e.g.,* annually). Under these states' rules, such impoundments are exempt from any solid waste regulations that would require groundwater monitoring, and from requirements for corrective action.[209] Such requirements are likely to decrease the instances in which contamination above an MCL has migrated off-site will be detected. Second, the record documents several instances where, once the contaminant plume has migrated off-site and impacted private water wells, the utility has purchased these properties, thereby rendering the off-site contamination, ''on-site.'' At times, this practice (which is condoned by the state) has expanded the ZOD to well beyond its original boundary. Once the status of the contaminant plume changes from off-site migration, which typically requires remedial action, back to onsite containment, this can affect the kind of corrective action the state requires of the utility (or indeed whether any will be required).

E. Characterization of Impacts Associated With CCR Units

1. CCR Waste Unit Types Associated With Damage Cases

EPA's documented record of confirmed damage cases is dominated by wet-disposal and treatment modes: Surface impoundments, cooling ponds, and artificial wetlands constitute close to half of the total number of implicated waste units. In comparison, dry disposal modes such as landfills, sand and gravel pits, storage piles for coal ash and FGD, and certain structural fills account for about one third of the confirmed damage cases.[210] Sand and gravel pits and quarries as well as structural fills, comprise about ten percent of all the unit types that are associated with damage cases.

2. Contaminants of Concern (COCs)

Because the list of constituents to be monitored in groundwater varies from permit to permit and among states, accurate estimates of the frequency of constituents associated with groundwater impacts nationwide cannot be made with confidence. Based on the available monitoring records, the most prevalent contaminant among the primary MCLs identified in damage cases is arsenic, whereas the most prevalent contaminants identified among the secondary MCLs are sulfate and boron. Similarly, disparities from one permit to another as to which constituents are monitored in NPDES discharges from CCR impoundments limit EPA's ability to identify trends associated with contaminants of concern. Based on the Agency's record of all of the confirmed damage cases, it can be only established that the most prevalent COCs with respect to Primary Water Quality Criteria (WQCs) exceedances in surface water, and/or of cleanup standards in sediments and soils are selenium and arsenic, and for Secondary WQCs or cleanup standard exceedances, are boron and iron.[211]

The high mobility of boron and sulfate explains the prevalence of these constituents in damage cases that are associated with groundwater impacts. Damage cases impacting surface water that have also a documented ecologic impact comprise the largest subset of proven damage cases (over 40 percent). The most prevalent COC here is selenium, the bioaccumulative effects of which have caused abnormal mortality rates and sublethal effects such as histopathological changes and damage to reproductive and developmental success, adversely impacting aquatic populations and communities of fish and amphibians. Such impacted communities, residing both in lentic (*e.g.,* cooling water lakes) and lotic (*e.g.,* small to medium-size streams) settings that receive regulated (*i.e.,* via permitted outfalls) and unregulated (*i.e.,* via seepage) discharge from CCR impoundments were documented and rather extensively studied in several sites (*e.g.,* in Texas, North Carolina, and South Carolina).[212] [213]

[207] Illinois uses a similar concept: Groundwater Mixing Zone; North Carolina waives any compliance requirements for constituents in exceedance of the state's groundwater standards that are confined to monitoring wells within the Compliance Boundary; and in Pennsylvania and Tennessee, state laws do not require state response to onsite exceedances of secondary MCLs.

[208] The observations cited in the following pertain to groundwater quality. Regarding surface water quality, NPDES permits in many states commonly have very limited requirements for monitoring discharge constituents, excluding all or most of the heavy metals.

[209] E.g., Duke Energy's Gibson Generating Station, Princeton, Indiana, a proven damage case.

[210] Facilities with both wet and dry disposal waste units are implicated in less than twenty percent of the cases.

[211] For a list of the key metals found in CCR wastewater and examples of the environmental concerns associated with them, see *Steam Electric Power Generating Point Source Category: Final Detailed Study Report;* EPA 821–R–09–008, October 2009: *http://water.epa.gov/scitech/wastetech/guide/steam-electric/upload/Steam-Electric_Detailed-Study-Report_2009.pdf.*

[212] In validation of the findings of the Risk Assessment accompanying this rule, EPA has documented numerous damage cases where selenium in CCR wastewater discharge into surface waters triggered the issuance of fish-consumption advisories as well as selenium MCL exceedances in groundwater, suggesting that selenium concentrations in CCR wastewater constitute a human health risk.

[213] According to the draft Steam Industry's Effluent Guidelines EA, the steam electric power

There are fewer recorded instances of surface water damage cases involving the heavy metal COCs such as antimony, beryllium, mercury, and thallium than of groundwater damage cases. It is unclear whether this genuinely reflects lower potential risks via this route of exposure. Intrinsic differences between the chemical and physical parameters of surface water and groundwater (*e.g.,* the higher redox potential and the larger flow-rate of the former) would accelerate the removal of many metals from surface water through precipitation and/or adsorption and facilitate a greater dilution. However, as noted, NPDES permits in many states commonly have very limited requirements for monitoring discharge constituents, excluding all or most of the heavy metals, so this cannot be ruled out as at least a contributing factor.[214]

3. Failure/Impact Modes

The CCR damage case record shows the following prevalent impact modes (more than one possible impact type per generating facility site is possible): Slightly over half of the recorded impact cases are associated with groundwater; about ten percent are associated with surface water, which quite frequently is also accompanied by documented ecological impacts and/or with the contamination of soils and/or river sediments; over one third are associated with both groundwater and surface water impacts; and about four percent are associated with catastrophic surface impoundment failures.

The established damage case record includes ten sites involving exceedances of primary MCLs that have impacted drinking water wells. In all of these cases, the implicated utility provided alternative potable water to well water users.[215] Three of the damage cases were listed on the National Priority List as Superfund sites,[216] and one is a Superfund Alternative (SA) site.[217] In the course of reassessing the pre-EIP 2010 damage cases and vetting EIP's alleged damage cases, the Agency rejected two other Superfund damage cases, because in addition to CCR, these site had also accepted large volume of non-CCR waste.[218]

Four major releases of CCR sludge associated with surface impoundment dike or pipe failure resulted in significant coal slurry releases,[219] causing fish kills and other ecologic damage, and in some instances damage to infrastructure. In the Clinch River spill, for instance, it was estimated that 217,000 fish were killed in a 90-mile stretch of the river in Virginia and Tennessee. The Clinch River plant coal ash had a high free lime content, which reacted with water in the settling pond to form an alkaline calcium hydroxide. As a result, during the release, pH was elevated to levels as high as 12.7. The high-toxicity shock also decimated benthic macro-invertebrate populations for a distance of over three miles below the spill site, and snails and mussels were eliminated for over 11 miles below the Clinch River power plant.

As demonstrated in the aftermath of the 2008 coal ash spill in TVA Kingston, Tennessee, large impoundment dike breach incidents result in impacts to soil and river sediments. In a study conducted few months after the spill, Emory River's downstream sediments showed high mercury concentrations similar to those detected in the coal ash (115–130 µg/kg).[220] According to this study, the ecological effects of mercury in the coal ash and sediments depend on the chemical mobility of mercury in the solids and the potential for mercury methylation in the impacted area. Previous studies have shown that sulfate addition can promote methylation in freshwater ecosystems by stimulating sulfate reducing bacteria, the primary organisms responsible for producing methylmercury in the environment. In coal-ash-containing waters, a 10- to 20-fold increase in SO_4^{-2} concentrations was observed in the Emory River Cove area relative to unaffected upstream sites. Therefore, the methylation potential of mercury from this material could be high because the coal ash also provides an essential nutrient (SO_4^{-2}) that encourages microbial methylation. In addition, leaching of contaminants from the coal ash caused contamination of surface waters in areas of restricted water exchange and slight elevation down gradient. The accumulation of arsenic-rich fly ash in bottom sediment in the Emory River's aquatic system could cause fish poisoning via both food chains and decrease of benthic fauna that is a vital food source. Another recent study estimates that the damage to fish and other wildlife incurred by both permitted and unpermitted CCR effluent discharge at some 22 sites amounts to over $2.3 billion.[221]

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sector is responsible for a significant fraction of the toxic pollutants reported to be discharged in industrial National Pollutant Discharge Elimination System (NPDES) permits.

[214] This issue is illustrated by the very limited monitoring record on mercury exceedances in surface water as compared to the extensive documentation of mercury impacts revealed in studied surface water that receive steam industry effluents. These studies have documented fish and invertebrates exposed to mercury from CCR wastewater exhibiting elevated levels of mercury in their tissues and developing sublethal effects such as reduced growth and reproductive failure. For an excellent summary of surface water ecologic and human health risks and impacts study results, see the cited Steam Electric Power study report.

[215] These proven damage cases include eight cases where the utility was directed by the state to provide an alternative water supply (NIPSCO Yard 520, IN; Constellation Energy Gambrills, MD; Don Frame Trucking, NY; Bruce Mansfield, PA; Trans Ash Landfill, TN; VEPCO Chisman Creek, VA; Stoneman, WI; and WEPCO Highway 59, WI); and two instances in which the utility provides substitute water to residents on a voluntary basis (Gibson Station, IN, and Colstrip, MT). In three additional, potential damage cases (Oak Creek, WI; Battlefield Golf Course, VA; and Joliet Station 9, IL), the utilities provide substitute water—out of abundance caution—to adjacent residential properties whose water wells were impacted by secondary MCL exceedances, and in two additional cases, the electrical utility was instructed by state regulators to provide substitute water to residential properties which either have had their drinking water wells impacted by trace amounts of thallium, within the State and the federal standards (Asheville, NC) or by exceedances of boron (Sutton, NC). Finally, in one case (Belews Creek, NC) the electric utility agreed to co-fund upgrading of potable water treatment plants in two municipalities to eliminate trihalomethanes, a carcinogenic by-product of power plant scrubber, bromide-containing river water subject to water treatment employing chlorine.

[216] OU–12, Oak Ridge, Tennessee (an NPL site between 1989 and 1997); VEPCO, Chisman Creek, Virginia (an NPL site between 1983 and 1988); and the Lemberger Landfill, Wisconsin (1986 to present).

[217] Town of Pines Groundwater Plume, Indiana (SA: 2003–Present): *http://www.epa.gov/region5/superfund/npl/sas_sites/INN000508071.htm.* The Site is not listed on the National Priority List (NPL) although it qualifies for such listing. The SA approach uses the same investigation and cleanup process and standards that are used for sites listed on the NPL, while it can potentially save the time and resources associated with listing a site on the NPL. As long as a PRP enters into an SA approach agreement with EPA, there is no need for EPA to list the site on the NPL.

[218] These are the formerly proven damage case of Salem Acres, Massachusetts (originally addressed in the 2007 *Coal Combustion Waste Damage Case Assessments* Report), and Industrial Excess Landfill, Uniontown, Ohio, an alleged damage case submitted by EIP in *In Harm's Way,* 2010.

[219] These catastrophic releases involved the release of 1.1×10^9, 2.7×10^8, 1.3×10^8, and 1×10^8 gallons of CCR slurry at the spills of the 2008 Kingston TVA, Tennessee; the 2014 Dan River, North Carolina; the 1967 Clinch River, Virginia; and the 2005 Martins Creek, Pennsylvania, respectively.) In addition, the possible ecologic impacts of two consecutive, 30 million gallons each, of CCR slurry releases (in 2007 and 2008) by the Eagle Valley power plant in Indiana have not been assessed.

[220] *Survey of the Potential Environmental and Health Impacts in the Immediate Aftermath of the Coal Ash Spill in Kingston, Tennessee.* Laura Ruhl et al., Environ. Sci. Technol. Published online on May 4, 2009. Volume *43* (16), pp 6326–6333: *http://pubs.acs.org/doi/abs/10.1021/es900714p.*

[221] A. Dennis Lemly and Joseph P. Skorupa: *Wildlife and the Coal Waste policy Debate: Proposed Rules for Coal Waste Disposal Ignore Lessons from 45 Years of Wildlife Poisoning.* Environ. Sci. Technol., 27 July, 2012.

a. Construction Year and First Detection Year

Slightly over half of the CCR waste units identified as the source of groundwater contamination in the damage cases were commissioned in the 1970s and 1980s, two boom decades of coal-fueled power generation growth in the U.S. Whereas the majority of the CCR waste units associated with damage cases were constructed before 1990, approximately six percent of the units in the damage cases (where the commissioning date is known) became operational after 1990. For 61 units with known commissioning dates, the median lag time between commissioning and the first detection of impact to groundwater is about 20 years. However, considering the large range of lag time values (between less than one year and 50 years) the recorded median lag time most probably reflects additional variables. Possible variables include monitoring wells that were installed after many of the waste units were already well into their operating stage, and the variable hydraulic conductivity of the impoundment's substrate (including the effectiveness of its liner, if any), both of which will determine how quickly groundwater contamination is first detected. Overall, the evidence about the lag time between the commissioning of a waste unit and the first detection of the impact of its leakage implies that most likely there are prospective damage cases that have not yet been identified, challenging industry's claims that the damage cases represent the legacy of a bygone regulatory regime.

b. Liners

Of the waste units implicated in damage cases to groundwater with information on liners, over 90 percent have either no liners, some sort of ash-based liners (*e.g.,* Poz-O-Tec, an FGD/lime-conditioned liner), or only partial- or high-permeability (*e.g.,* concrete) liners. The majority of the remaining CCR waste units is either clay-lined and/or has a recognizably-failed liner. Considering that over a half of CCR waste units associated with groundwater impacts were constructed in the 1970s and 1980s, historic information on liner prevalence and composition is highly pertinent. According to the February 1988 Report to Congress on coal combustion wastes (''RTC I''), before 1975 less than 20 percent of all generating facility units managed their CCR in lined disposal units, and in generating facility units constructed since 1975, the share of lined units grew to over 40 percent.[222] However, as late as in the mid-1980s, about three-quarters of all CCR units (87 percent of surface impoundments and 39 percent of landfills) were still unlined.[223]

In the mid-1990s, the estimated prevalence of unlined landfills still ranged between 43–57 percent, and between 71–72 percent for surface impoundments.[224] According to the March 1999 Report to Congress on wastes from the combustion of fossil fuels (RTC II), the most prevalent liner type was compacted clay (about one-half of all lined landfills, and about 80-percent of all lined surface impoundments). Composite and/or synthetic liners were significantly more prevalent in landfills than in surface impoundments. Based on recent EPA data,[225] the use of liners is still more prevalent in landfills than in surface impoundments.

c. Geographic Distribution

Close to 70 percent of all the established damage cases occur in EPA Regions 5, 4, and 3 (in descending frequency, Region 5: 34 percent; Region 4: 28 percent; and Region 3: seven percent).[226] This distribution correlates well with the regional distribution of *unlined* CCR units in the mid-1980s.[227]

d. Current CCR Waste Unit Status

As of mid-2011, close to half of the combined (proven and potential) damage case CCR waste units were still active; about a quarter were inactive due to either closure of the individual disposal unit, a fuel switch (*e.g.,* from coal to gas) by the generating facility, or the decommissioning of the facility. Another quarter or so represented power generating facilities where CCR waste units (primarily impoundments) that failed to comply with state requirements had been closed and replaced by other, new disposal units, and/or the generating facilities switched from wet- to dry disposal. Since mid-2011, the percentage of inactive CCR units associated with groundwater damage cases has further increased, due to the continued drop in power demand during the economic recession, which has resulted in power station temporary removal from active service (*i.e.,* mothballing) and closures, combined with an increasing switch by many facilities to a more cost-effective fossil fuel (*i.e.,* natural gas).

F. Conclusions

EPA now has a significantly better understanding of CCR damage cases than when the proposed rule was issued. First, damage cases are more numerous than previously contemplated and as more monitoring well systems are installed, the number of damage cases is likely to increase. Second, the CCR damage case record corroborates the findings of the risk analysis by demonstrating the greater vulnerability of groundwater (and surface water) to wet disposal (*i.e.,* surface impoundments). Third, the damage cases show a direct correlation between the absence of liners and groundwater impacts, and illustrate that whereas in general the design of waste units—particularly surface impoundments—has improved over time, a notable portion of CCR impoundments constructed in the last two decades still lack a protective liner, thus presenting a potential threat to groundwater. Finally, a recent CCR spill incident[228] demonstrates that inactive surface impoundments that have not been properly decommissioned (*i.e.,* by breaching, dewatering, and capping or by clean-closing) continue to pose a

[222] Wastes from the Combustion of Coal by Electric Utility Power Plants (First Report to Congress), EPA/530–SW–88–002, February, 1988, pages 4–30 to 4–33: *http://www.epa.gov/osw/nonhaz/industrial/special/fossil/coal-rtc.pdf*.

[223] These statistics are based on about 42 percent of the total CCR units at that time, for which liner information was available. RTC I attributes this low percentage to the common practice of disposal in off-site units, for which liner information was not available.

[224] Based on three different partial surveys cited in the Second Report to Congress (RTC II, 1999): *Wastes from the Combustion of Fossil Fuels, Volume 2—Methods, Findings, and Recommendations* (Second Report to Congress), EPA 530–R–99–010, March 1999: *http://www.epa.gov/osw/nonhaz/industrial/special/fossil/volume_2.pdf*.

[225] EPA compiled the baseline use of bottom liners by CCR landfills and surface impoundments from the following sources: (1) Impoundment data from EPA/OSWER's 2009–2011 impoundment dam integrity site inspections; *http://www.epa.gov/waste/nonhaz/industrial/special/fossil/surveys2/index.htm*; (2) Impoundment data from ORCR's 2009 Information Collection Request (ICR) addressing power plants with impoundments; *http://www.epa.gov/waste/nonhaz/industrial/special/fossil/coalashletter.htm*; and (3) Landfill and impoundment data from EPA Office of Water's 2010 ICR addressing power plants to be affected by the Steam Electric Power Generating Effluent Guidelines: *http://water.epa.gov/scitech/wastetech/guide/steam_index.cfm#point6*.

[226] See *http://www.epa.gov/aboutepa/#regional* for a list of states covered by each EPA Regional office.

[227] According to the Report to Congress I (1988), in the mid-1980s, the distribution of unlined CCR waste units across EPA regions was as follows: For surface impoundments: 31.7 percent (Region 4); 18.6 percent (Region 5); 6.2 percent (Region 7); and 3.5 percent (Region 3). For landfills: 11.1 percent (Region 5); 2.9 percent (Region 3); and 2.4 percent (Region 4).

[228] The Duke Energy's Dan River, North Carolina, February 2, 2014 CCR slurry spill.

significant risk to human health and the environment.

XII. Summary of Regulatory Impact Analysis

EPA estimated the costs and benefits of the final rule. The Regulatory Impact Analysis (RIA) is available to the public in the docket for this action.

A. Costs of the Final Rule

The estimated costs of the final rule are summarized in Table XII–A below. These are the incremental costs above the ''baseline.'' *i.e.,* the current costs for managing CCR absent this regulation. The baseline takes into account existing state regulations for managing CCR now and into the future. To the extent that some states may have granted waivers or variances for certain provisions of State requirements, or in other instances may have added extra pollution control requirements above existing regulatory requirements to some specific permits issued to electric utility plants for operating CCR management units, the RIA did not take those actions into account.

EPA used the following data sources to create a model for the RIA that estimates the costs and benefits of the rule: (1) 2012 DOE EIA–923 database; (2) ORCR's 2009–2012 CCR impoundment site inspections; (3) impoundment data from ORCR's 2009 mail survey to plants with CCR impoundments; (4) landfill and impoundment data from EPA Office of Water's 2010 mail survey to power plants in support of the 2013 proposed Steam Electric Power Generating Effluent Limitation Guidelines; (5) Integrated Planning Model (IPM) v. 5.13 (for the future projection of coal consumption by electric utility plants); and (6) the 1995 Electric Power Research Institute (EPRI) Co-management Survey.

TABLE XII–A—ESTIMATED COST OF POLLUTION CONTROLS REQUIRED BY THE CCR FINAL RULE

[Millions 2013$]

CCR pollution control	@ 3% discount rate		@ 7% discount rate	
	Annualized values	Present values	Annualized values	Present values
1. Groundwater monitoring	$4.79	$151	$2.80	$39.9
2. Bottom liners	491	15,500	297	4,230
3. Leachate collection system (landfills only)	51.6	1,630	18.4	263
4. Fugitive CCR dust controls	7.09	224	3.36	48.0
5. Stormwater run-on/run-off controls	18.8	594	13.0	186
6. Location restrictions	43.6	1,380	20.0	285
7. Closure capping	20.1	630	12.0	171
8. Post-closure groundwater monitoring (30 years)	0.08	2.40	0.04	0.61
9. Impoundment structural integrity requirements	10.9	344	11.1	158
10. Corrective action (CCR contaminated groundwater cleanup)	19.0	600	19.1	273
11. Reporting and recordkeeping	26.3	831	27.3	389
12. Conversion to dry CCR handling	29.0	916	57.3	818
13. Inactive impoundments (dewater and closure cap)	12.0	380	26.7	381
14. Subtotal industry costs (1+...+13)	734	23,200	508	7,240
State Agency Burden Costs				
15. Impoundment structural integrity requirements	0.22	6.88	0.22	3.16
16. Corrective action	0.38	12.0	0.38	5.45
17. Reporting and recordkeeping	0.53	16.6	0.55	7.78
18. Subtotal State agency burden costs (15+16+17)	1.12	35.5	1.15	16.4
19. Total cost (14+18)	735	23,200	509	7,260

B. Benefits of the Final Rule

The RIA contains two categories of benefits (1) benefits that are monetized and (2) non-monetized benefits. The RIA estimates 11 categories of expected future human health and environmental benefits for the CCR rule. These include reduced future CCR impoundment structural failure releases; reduced future CCR groundwater contamination; improved air quality from reduced power plant air pollution; and surface water quality benefits. The estimated value of each of the 11 monetized benefits is presented in Table XII–B below.

TABLE XII–B—EPA ESTIMATED MONETIZED BENEFITS FOR THE CCR FINAL RULE

[Millions 2013$ over 100-year period of analysis 2016–2114]

	3% discount rate		7% discount rate	
	Annualized	Present value	Annualized	Present value
1. Reduced CCR impoundment structural failure releases	$156	$4,910	$143	$2,040
2. Reduced CCR landfill & impoundment groundwater contamination	12.8	405	9.86	141
3. Induced increase in future annual CCR beneficial uses	117	3,130	79.0	1,120
4. Reduced incidence of cancer from CCR exposure	<0.1	0.17	<0.1	<0.1
5. Avoided IQ losses from mercury in CCR	0.28	8.80	<0.1	0.35
6. Avoided IQ losses from lead in CCR	0.186	5.87	<0.1	0.23
7. Reduced need for specialized education (associated with 5 & 6 above)	<0.1	<0.1	<0.1	<0.1
8. Non-market surface water quality benefits	2.26	71.4	1.89	27.0

TABLE XII–B—EPA ESTIMATED MONETIZED BENEFITS FOR THE CCR FINAL RULE—Continued

[Millions 2013$ over 100-year period of analysis 2016–2114]

	3% discount rate		7% discount rate	
	Annualized	Present value	Annualized	Present value
9. Protection of threatened & endangered species near CCR impoundments	0.91	28.7	0.76	10.8
10. Improved air quality from induced changes to power plant emissions	4.66	147	2.04	29.1
11. Reduced power plant groundwater withdrawals	<0.1	<0.1	<0.1	<0.1
12 Total monetized benefits (1 + . . . + 11)	294	8,710	236	3,360

In addition to the monetized benefit categories, the RIA describes 11 additional non-monetized benefit categories. Due to uncertainties and weaknesses in supporting documentation for quantifying and monetizing these benefits, the RIA presents these benefits separately from the benefits listed above, and does not include them in the quantified comparison of benefits and costs. These non-monetized benefits include:

1. Financial market benefits
2. Reduced community dread of CCR impoundment structural failure releases
3. Reduced health and property nuisance impacts from CCR fugitive dust
4. Cancer and non-cancer human health benefits from reduced CCR contamination of fish consumed by recreational anglers and subsistence fisher households in surface waters near power plants (additional to monetized avoided health effects)
5. Cancer and non-cancer human health benefits from reduced CCR exposure by other recreational users of surface waters near power plants (additional to monetized avoided health effects)
6. Avoided CCR contamination of sediments in surface waters near power plants
7. Water quality benefits from avoided CCR contamination treatment costs for use of surface waters for drinking and irrigation water supply
8. Commercial fisheries benefit in surface waters near power plants
9. Increased participation in water-based recreation near power plants
10. Avoided fish impingement and entrainment mortality from power plant water intakes (induced conversion to dry CCR handling reduces future water demand for CCR sluicing)
11. Increased property values surrounding electric utility plants (from closure capping and re-vegetation of CCR surface impoundments)

The total monetized benefits less the total costs of the rule provide the net monetized benefits of the rule. Table XII–C summarizes the total costs and benefits as well as the net benefits of the rule.

TABLE XII–C—EPA ESTIMATED INCREMENTAL COSTS & BENEFITS OF THE CCR RULE

[Millions 2013$ over 100-year period of analysis 2015–2114]

	3% discount rate	7% discount rate
A. Annualized Values.		
A1. Total Costs	$735	$509
A2 Total monetized benefits	294	236
A3. Net Benefits (A2–A1)	(441)	(273)
A4. Benefit to Cost Ratio (A3/A1)	0.40	0.46
B. Present Value.		
B1. Total Costs	23,200	7,260
B2 Total monetized benefits	8,710	3,360
B3. Net Benefits (B2–B1)	(14,490)	(3, 900)
B4. Benefit to Cost Ratio (B2/B1)	0.38	0.46

XIII. Uniquely Associated Wastes

By way of this rule, EPA is codifying in § 261.4(b)(4) a list of low volume waste that when co-disposed with CCR are not subject to hazardous waste regulations. These wastes are also referred to as uniquely associated wastes. However, these uniquely associated wastes are subject to hazardous waste regulations when they are not co-disposed with CCR.

In a letter to EPA dated October 10, 1980 the Utility Solid Waste Activities Group (USWAG) suggested interpretive language that EPA should adopt regarding the amendments to the Solid Waste Disposal Act Amendments of 1980 which address fossil fuel combustion wastes. EPA replied to USWAG by letter dated January 13, 1981 (known as the 1981 Dietrich letter), and addressed, among other issues, other associated wastes generated in conjunction with the burning of fossil fuels.[229] EPA stated that ''We believe it is appropriate, in the light of Congressional intent, to interpret the § 261.4(b)(4) exclusion to include other wastes that are generated in conjunction with the burning of fossil fuels and mixed with and co-disposed or co-treated with fly ash, bottom ash, boiler slag and flue gas emission control wastes.'' When amendments to the 1980 Solid Waste Disposal Act were introduced, Congressmen Bevill and Rahall stated, respectively:

It is the sponsor's intention that this list of waste materials in the amendment be read broadly, to incorporate the waste products generated in the real world as a result of the combustion of fossil fuels. We do not believe that these terms should be narrowly read and thus impose regulatory burdens upon those who seek to assist the Nation by burning coal. EPA should recognize that these ''waste streams'' often include not only the

[229] See letter from Gary N. Dietrich to Paul Elmer, USWAG, available in the docket for this rule.

byproducts of the combustion of coal and other fossil fuels, but also relatively small proportions of other materials produced in conjunction with the combustion, even if not derived directly from these fuels. EPA should not regulate these waste streams because of the presence of these materials, if there is no evidence of any substantial environmental danger from these mixtures. *(126 Cong. Rec. H1102).*

In the real world, these waste materials do not include solely fly ash, bottom ash, slag, or scrubber sludge. Quite often, other materials are mixed with these large volume waste streams, with no environmentally harmful effects, and often with considerable benefit-as when, for example, boiler cleaning-acids are neutralized by being mixed with alkaline fly ash. These appear to me to be environmentally beneficial practices, which EPA should encourage. At the very least, however, the Agency should take no steps to discourage them until it has developed a full factual understanding of the situation. This amendment would assure that EPA allows all persons burning coal to avoid unnecessary regulation of the byproducts produced by that combustion, as those byproducts are currently being managed in the real world, by real people, with real sense. *(126 Cong. Rec. H1104).*

As such, EPA interpreted 40 CFR 261.4(b)(4) (the Bevill exemption) to mean that wastes produced in conjunction with the combustion of fossil fuels, which are necessarily associated with the production of energy, and which traditionally have been, and which actually are, mixed with and co-disposed or co-treated with fly ash, bottom ash, boiler slag, or flue gas emission control wastes from coal combustion are not hazardous wastes. In the Deitrich letter EPA stated that these other associated wastes include, but are not limited to the following wastes: (1) Boiler cleaning solutions; (2) boiler blowdown; (3) demineralizer regenerant; (4) pyrites; and (5) cooling tower blowdown.

In a February 1988 Report to Congress on Wastes from the Combustion of Coal by Electric Utility Power Plants EPA listed the following low-volume wastes commonly produced in conjunction with the burning of fossil fuels to produce electricity: (1) Boiler blowdown; (2) coal pile run-off; (3) cooling tower blowdown; (4) demineralizer regenerants and rinses; (5) metal and boiler cleaning wastes; (6) pyrites; and (7) sump effluents. Presented for each type of low-volume waste is a brief description of how the waste is generated, typical quantities produced, and the physical and chemical composition of the waste.[230] The source of this information was primarily an August 1981 USWAG/Edison Electric Institute report in response to a request for information in the 1981 Dietrich letter.

In an August 1, 1993 Regulatory Determination the Agency emphasized that co-management of low-volume wastes and large-volume wastes (fly ash, bottom ash, boiler slag, or flue gas emission control wastes from coal combustion) makes the combined waste stream a remaining waste that would be subject to a subsequent Regulatory Determination and provided the list below of management practices that result in combined waste streams that are remaining wastes.[231]

- Discharge of boiler blowdown to a large-volume waste impoundment,
- Discharge of demineralizer regenerant to a large-volume waste impoundment,
- Discharge of metal cleaning wastes to a large-volume waste impoundment,
- Discharge of boiler chemical cleaning wastes to a large-volume waste impoundment,
- Discharge of plant wastewater treatment effluent to a large-volume waste impoundment,
- Discharge of coal mill rejects to a large-volume waste impoundment,
- Disposal of oil ash in a large-volume waste landfill or impoundment,
- Disposal of plant wastewater treatment sludge in a large-volume waste landfill.

In a 1999 Report to Congress on wastes from the combustion of fossil fuels [232] EPA stated that low-volume wastes are generated as a result of supporting processes that are ancillary to, but a necessary part of, the combustion and power generation processes and provided the following list of low-volume wastes.

- Coal pile run-off
- Coal mill rejects/pyrites
- Boiler blowdown
- Cooling tower blowdown and sludge
- Water treatment sludge
- Regeneration waste streams
- Air heater and precipitator washwater
- Boiler chemical cleaning waste
- Floor and yard drains and sumps
- Laboratory wastes
- Wastewater treatment sludge

The concept of uniquely associated wastes with respect to CCR was first introduced in the May 22, 2000 Regulatory Determination. Prior to this, these wastes were referred to as other wastes, remaining wastes, or low-volume wastes, that are generated in conjunction with the burning of fossil fuels and mixed with and co-disposed or co-treated with fly ash, bottom ash, boiler slag and flue gas emission control wastes. For the May 22, 2000 Regulatory Determination, the Agency proposed the uniquely associated wastes concept with the intent of being consistent with other wastes covered under the Bevill Amendment (a.k.a., the Bevill exemption), such as mining and mineral processing wastes that the Agency refers to as uniquely associated wastes, and under the Bentsen Amendment for oil and gas exploration and production wastes which are referred to as associated wastes. The Agency recognized that determining whether a particular waste is uniquely associated with fossil fuel combustion involves an evaluation of the specific facts of each case. In the Agency's view, the following qualitative criteria should be used to make such determinations on a case-by-case basis:

(1) Wastes from ancillary operations are not ''uniquely associated'' because they are not properly viewed as being ''from'' fossil fuel combustion.

(2) In evaluating a waste from non-ancillary operations, one must consider the extent to which the waste originates or derives from the fossil fuels, the combustion process, or combustion residuals, and the extent to which these operations impart chemical characteristics to the waste.

EPA proposed the following list of wastes that the Agency considered to be uniquely associated wastes (*i.e.,* uniquely associated with the combustion of coal for the generation of electricity at electric utilizes and independent power producers and, therefore, covered by the Bevill exemption).

- Coal Pile Run-off
- Coal Mill Rejects and Waste Coal
- Air Heater and Precipitator Washes
- Floor and Yard Drains and Sumps
- Wastewater Treatment Sludges
- Boiler Fireside Chemical Cleaning Wastes

EPA also proposed the following list of wastes that would not be considered uniquely associated wastes.

- Boiler Blowdown
- Cooling Tower Blowdown and Sludges
- Intake or Makeup Water Treatment and Regeneration Wastes
- Boiler Waterside Cleaning Wastes
- Laboratory Wastes
- General Construction and Demolition Debris

[230] See *http://www.epa.gov/osw/nonhaz/industrial/special/fossil/coal-rtc.pdf,* pages 3–41 to 3–62. This report addressed wastes generated from the combustion of coal by electric utility power plants, and did not address comanaged utility coal combustion wastes, other fossil fuel combustion wastes, and wastes from non-utility boilers.

[231] *http://www.epa.gov/osw/nonhaz/industrial/special/mineral/080993.pdf.*

[232] *http://www.epa.gov/osw/nonhaz/industrial/special/fossil/volume_2.pdf.*

- General Maintenance Wastes

EPA requested comments on these proposed lists and received several comments from states, industry, and the environmental community. Industry opposed the ''uniquely associated'' waste framework, and favors retaining the 1981''Dietrich Policy.''

Many commenters argued that the Dietrich policy has provided clear guidance on the scope of the Bevill exemption for the past 20 years, and that appropriate waste management practices have been implemented for these wastes. The Dietrich Policy has proven itself effective in furthering congressional intent to recognize certain historic co-management practices provided they are not environmentally harmful. The Association of State and Territorial Solid Waste Management Officials recommended that EPA contact States that have management programs for fossil fuel combustion wastes to determine how to best manage the waste that are uniquely associated or not uniquely associated with fossil fuel combustion wastes. The Hoosier Environmental Council opposed exempting coal wastes and stated that ''coal mill rejects and coal pile run-off would not be uniquely associated wastes . . . because neither of these wastes is derived from coal combustion.''

EPA acknowledges that the Deitrich letter has been longstanding policy with regard to CCR uniquely associated wastes and that the Agency has not sought input from States on the issue. Moreover, as evident from the Congressional Record, the Congressional intent was to ''include not only the byproducts of the combustion of coal and other fossil fuels, but also relatively small proportions of other materials produced in conjunction with the combustion, even if not derived directly from these fuels.'' These other materials would include many of those listed in the Dietrich letter as well as many of those listed in the May 2000 Regulatory determination.

After considering the 1981 Dietrich letter, a copy of which is included in the docket for this rule, the proposed guidance in the May 2000 Regulatory Determination, comments received on the May 2000 Regulatory Determination and the July 2010 proposed rule, EPA has concluded that the 1981 Dietrich letter accurately reflects the intent of Congress when they exempted CCR from hazardous waste regulations. EPA also believes that many of the wastes listed as uniquely associated wastes in the May 22, 2000 Regulatory Determination are also consistent with the Congressional intent. Therefore, the Agency is finalizing the following list of uniquely associated wastes that includes materials from both the Dietrich letter and the May 2000 Regulatory Determination.

- Coal pile run-off
- Boiler cleaning solutions
- Boiler blowdown
- Process water treatment and demineralizer regeneration wastes
- Cooling tower blowdown
- Air heater and precipitator washes
- Effluents from floor and yard drains and sumps, and
- Wastewater treatment sludges

This list is being codified in 40 CFR 261.4(b): Solid wastes which are not hazardous wastes.

XIV. Statutory and Executive Order Reviews

A. Executive Order 12866: Regulatory Planning and Review and Executive Order 13563: Improving Regulation and Regulatory Review

Under section 3(f)(1) of Executive Order 12866 (58 FR 51735, October 4, 1993), this action is an ''economically significant regulatory action'' because it is likely to have an annual effect on the economy of $100 million or more. The total annual cost of this final rule is estimated to be $509 million a year using a 7% discount rate. Accordingly, EPA submitted this action to the Office of Management and Budget (OMB) for review under Executive Orders 12866 and 13563 (76 FR 3821, January 21, 2011) and any changes made in response to OMB recommendations have been documented in the docket for this action.

In addition, EPA prepared an analysis of the potential costs and benefits associated with this action. The Regulatory Impact Analysis (RIA) estimated the costs and benefits for this action. The RIA estimated 12 regulatory costs: (1) Groundwater monitoring; (2) bottom liner installation; (3) leachate collection system installation and management; (4) fugitive dust controls; (5) rain and surface water run-on/run-off controls; (6) disposal unit location restrictions (including water tables, floodplains, wetlands, fault areas, seismic zones, and karst terrain); (7) closure capping to cover units; (8) post-closure groundwater monitoring requirements; and (9) impoundment structural integrity requirements; (10) corrective actions (CCR contaminated groundwater cleanup); (11) paperwork reporting/recordkeeping; and (12) impoundment closures and conversion to dry handling. Using a 7% discount rate, the annualized costs are estimated at $509 million, and using a 3% discount rate, annualized costs are estimated to be $735 million. Using a 7% discount rate, the total present value costs are estimated at $7.3 billion, and using a 3% discount rate the present value of estimated costs is $23.2 billion.

The RIA estimated 11 monetized benefits: (1) CCR impoundment release prevention; (2) CCR landfill & impoundment groundwater contamination prevention; (3) induced increase in CCR beneficial uses (*e.g.,* concrete, wallboard); (4) reduced incidence of cancer from CCR exposure; (5) avoided IQ losses from mercury; (6) avoided IQ losses from lead; (7) reduced need for specialized education; (8) non-market surface water quality benefits; (9) protection of threatened & endangered species near CCR impoundments; (10) improved air quality from induced changes to power plant emissions and (11) reduced power plant groundwater withdrawals. The annualized monetized benefits are estimated at $294 million (@ 3% discount rate) and $236 million (@ 7% discount rate). The total present value monetized benefits are estimated at $8.7 billion (@ 3% discount rate) and $3.4 billion (@ 7% discount rate).

B. Paperwork Reduction Act (PRA)

The information collection activities in this rule will be submitted for approval to the Office of Management and Budget (OMB) under the PRA. The Information Collection Request (ICR) document that the EPA prepared has been assigned EPA ICR number 1189.25, OMB control number 2050–0053. You can find a copy of the ICR in the docket for this rule, which will be available in the docket once the ICR has been submitted to OMB for review, and it is briefly summarized here. The information collection requirements are not enforceable until OMB approves them.

These regulations, promulgated under subtitle D of RCRA, constitute national minimum criteria with which facilities must comply without oversight or intervention by a federal or state authority. To address concerns about the absence of regulatory oversight under a subtitle D regulation, EPA has developed a combination of mechanisms, including recordkeeping, notification, and maintaining a publicly accessible Internet site. The increased transparency resulting from these requirements will minimize the potential for owners or operators to abuse the self-implementing system established in this rule. In addition, these requirements provide interested parties the information necessary to

determine whether the owner or operator is operating in compliance with the requirements of the rule and thus will facilitate enforcement by States and private citizens. EPA has consolidated the recordkeeping, notification, and Internet posting requirements into a single section of the regulations in an effort to make these requirements easier to follow. It is important to note that EPA will not be collecting any information under this rule—instead, facilities must keep records, notify the state, and post information on a publicly available Web site. EPA has taken steps to minimize the burden to the regulated community while at the same time achieving the transparency needed to ensure proper implementation of this rule. In addition to the burden to owner and operators of CCR landfills, in an effort to ease implementation, EPA has reporting and recordkeeping requirements for certain beneficial uses and states. For beneficial use that meets the fourth criteria, the user must maintain records and provide documentation upon request. For states, states are encouraged to voluntarily adopt at least the federal minimum criteria through the revision of SWMPs. In addition, EPA estimated the burden on state government agencies associated with the receipt of various notification requirements in the rule.

The respondents/affected entities are the owners/operators of electric utilities and independent power producers that fall within the NAICS code 221112. Specifically, these regulations apply to owners and operators of new and existing landfills and new and existing surface impoundments, including lateral expansions that of all landfills and surface impoundments that dispose or otherwise engage in solid waste management of CCR generated from the combustion of coal at electric utilities. The rule also applies to CCR units located off-site of the electric utilities' or independent power producers' facilities that receive CCR for disposal. The rule applies to certain inactive CCR surface impoundments at active electric utilities' or independent power producers' facilities, if the CCR unit still contains CCR and liquids. Finally, the rule applies to certain beneficial users of CCR. The rule may also impact States that choose to revise their SWMPs.

Respondents are obligated to keep records, make the required notifications, and maintain the publicly available Internet site. These requirements are part of the minimum federal criteria under 40 CFR part 257 and promulgated under the authority of sections 1006(b), 1008(a), 2002(a), 3001, 4004, and 4005(a) of the Solid Waste Disposal Act of 1970, as amended by the Resource Conservation and Recovery Act of 1976 (RCRA), as amended by the Hazardous and Solid Waste Amendments of 1984 (HAS), 42 U.S.C. 6906(b), 6907(a), 6912(a), 6944, and 6945(a).

Respondents/affected entities: EPA estimates the total number of respondents to be 486. This number represents the estimated number of coal-fired electric utility plants that will be affected by the rule.

Respondent's obligation to respond: The recordkeeping, notification, and posting are part of the minimum national criteria being promulgated under Sections 1008, 4004, and 4005(a) of RCRA.

Estimated number of respondents: 486.

Frequency of response: The frequency of response varies.

Total estimated burden: EPA estimates the total annual burden to respondents to be approximately 358,957 hours with a three year total estimated burden of 1,076,871 hours. Burden is defined at 5 CFR 1320.3(b).

Total estimated cost: The total estimated annual cost is approximately $64,007,121; this is composed of approximately $22,894,608 in annualized labor costs and $41,112,513 in annualized capital or operation and maintenance costs. The three year total estimated costs are $192,021,364 composed of $68,683,824 in labor costs and $123,337,540 in operations and maintenance.

In addition, developing a state SWMP (see Unit IX of this preamble) is not a requirement under this rule, however, EPA is encouraging states to develop these plans and has developed a burden estimate associated with this activity. The estimate for this one-time activity has been annualized over the three-year period covered by the ICR. The total estimated annual burden (for the 47 states and Puerto Rico where CCR are generated) is approximately 10,880 hours, and approximately $429,414 in annualized labor costs; this estimate assumes no annualized capital or operations and maintenance costs.

An agency may not conduct or sponsor, and a person is not required to respond to, a collection of information unless it displays a currently valid OMB control number. The OMB control numbers for the EPA's regulations in 40 CFR are listed in 40 CFR part 9. When OMB approves this ICR, the Agency will announce that approval in the **Federal Register** and publish a technical amendment to 40 CFR part 9 to display the OMB control number for the approved information collection activities contained in this final rule.

C. Regulatory Flexibility Act

The Regulatory Flexibility Act (RFA) generally requires an agency to prepare a regulatory flexibility analysis of any rule subject to notice and comment rulemaking requirements under the Administrative Procedure Act or any other statute unless the agency certifies that the rule will not have a significant economic impact on a substantial number of small entities (SISNOSE). Small entities include small businesses, small organizations, and small governmental jurisdictions.

For purposes of assessing the impacts of this rule on small entities, small entity is defined as: (1) A small business, based on the U.S. Small Business size standard for NAICS code 221112 (fossil fuel electric utility plants), with fewer than 750 employees; (2) a small government jurisdiction, based on the RFA/SBREFA's definition (5 U.S. Code section 601(5)), is the government of a city, county, town, township, village, school district, or special district with population under 50,000; (3) a small organization that is any not-for-profit enterprise which is independently owned and operated and is not dominant in its field.

After considering the economic impacts of this final rule on small entities, I certify that this action will not have a significant economic impact on a substantial number of small entities.

The small entities directly regulated by this final rule consist of one small county, 31 small cities, 32 small companies, and 13 small cooperative owner entities that own at least one coal-burning power plant. There are 91 coal-burning power plants that are owned by the 77 small owner entities. Those plants fall into the following categories: One small county plant, 31 small city plants, 42 plants owned by small companies, and 17 small cooperative plants.

The RIA estimated CCR compliance costs as a percentage of revenues for each entity and found that for almost all small entities affected by the rule the estimated annualized costs were less than 1% of revenues.

Although this final rule will not have a significant economic impact on a substantial number of small entities, EPA nonetheless has tried to reduce the impact of this rule on small entities.

D. Unfunded Mandates Reform Act (UMRA)

Title II of the Unfunded Mandates Reform Act of 1995 (UMRA), 2 U.S.C. 1531–1538, requires Federal agencies, unless otherwise prohibited by law, to assess the effects of their regulatory

actions on state, local, and tribal governments and the private sector. This rule contains a federal mandate that may result in expenditures of $100 million or more for state, local, and tribal governments, in the aggregate, or the private sector in any one year. Accordingly, EPA has prepared under section 202 of the UMRA a written statement which is summarized below.

The RIA estimates the rule may affect 414 coal-fired electric utility plants, and may have a nationwide average annualized cost of approximately $509 million per year (at a 7% discount rate). Of this amount, average annualized costs to State/local governments total $36 million, and the average annualized cost to the private sector totals approximately $436 million per year (the remainder of the total costs are the costs associated with compliance at federally-owned electric utility plants.)

Consistent with the intergovernmental consultation provisions of section 204 of the UMRA, EPA initiated pre-proposal consultations with governmental entities affected by this rule. In developing the regulatory options for the CCR rule, EPA consulted with small governments according to EPA's UMRA interim small government consultation plan developed pursuant to section 203 of UMRA. EPA's interim plan provides for two types of possible small government input: Technical input and administrative input. According to this plan, and consistent with section 204 of UMRA, early in EPA's 2009 process for developing the CCR rule, EPA implemented a small government consultation process consisting of two consultation components: (1) A series of meetings in 2009 for purposes of acquiring technical input from State government officials, and (2) letters to 10 organizations representing elected State and local government officials to inform and seek input for the rule's development, as well as to invite them to a meeting held September 16, 2009 in Washington DC to provide input on the rule. Following are the meetings held with state officials in 2009: (1) February 27 with the Association of State and Territorial Solid Waste Management Officials (ASTSWMO) Coal Ash Workgroup (Washington DC), (2) March 22–24 with the Environmental Council of States (ECOS) Spring Meeting (Alexandria VA), (3) April 15–16 with the ASTSWMO Mid-Year Meeting (Columbus OH), (4) May 12–13 with the EPA Region IV State Directors Meeting (Atlanta, GA), (5) June 17–18 with the ASTSWMO Solid Waste Managers Conference (New Orleans, LA), (6) July 21–23 with the ASTSWMO Board of Directors Meeting (Seattle, WA), and (7) August 12 with the ASTSWMO Hazardous Waste Subcommittee Meeting (Washington DC). ASTSWMO is an organization with a mission to work closely with the EPA to ensure that its state government members are aware of the most current developments related to state waste management programs. ECOS is a national non-profit, non-partisan association of state and territorial environmental agency leaders. As a result of these meetings EPA received letters in mid-2009 from 22 state governments as well as a letter from ASTSWMO expressing their stance on CCR regulatory options.

On August 24, 2009 letters were mailed to the following 10 organizations, which include representation from small government elected officials, to inform and seek input for the rule development, as well as to invite them to a meeting held September 16, 2009 in Washington DC: (1) National Governors Association, (2) National Conference of State Legislatures, (3) Council of State Governments, (4) National League of Cities, (5) U.S. Conference of Mayors, (6) County Executives of America, (7) National Association of Counties, (8) International City/County Management Association, (9) National Association of Towns and Townships, and (10) Environmental Council of the States. These 10 organizations representing State and local government officials are identified in EPA's November 2008 Federalism guidance as the ''Big 10'' organizations appropriate to contact for purpose of consultation with small government elected officials.

Consistent with section 205, EPA identified and considered a reasonable number of regulatory alternatives in the June 2010 proposed rule, and is adopting the least-costly approach (*i.e.* a modified version of the ''D Prime'' least costly approach presented in the 2010 proposed CCR rule).

This rule is not subject to the requirements of section 203 of UMRA because it contains no regulatory requirements that might significantly or uniquely affect small governments. The threshold amount established for determining whether regulatory requirements could significantly affect small governments is $100 million annually. The RIA estimates a $1.2 million annual cost for state/local government implementation of the rule and $36 million in annual direct compliance costs on 57 state or local governments. These estimates are well below the $100 million annual threshold established under UMRA. However this rule does have over a $100 million dollar impact on industry. EPA selected one of the lower industry cost options for the final rule by selecting a RCRA subtitle D rule instead of a RCRA subtitle C rule.

E. Executive Order 13132—Federalism

The EPA has concluded that this action may have federalism implications because it imposes substantial direct compliance costs on state or local governments, and the Federal government will not provide the funds necessary to pay those costs. Based on the estimates in EPA's RIA for this action, the final rule, if promulgated, may impose a $1.2 million annual cost for state/local government implementation of the rule and $36 million in annual direct compliance costs on 57 state or local governments. This amount exceeds the $25 million per year ''substantial compliance cost'' threshold defined in section 1.2(A) (1) of EPA's November 2008 ''Guidance on Executive Order 13132: Federalism.'' There are 57 State and local governments which own 68 coal-burning power plants or 16% of the 414 electric utility plants expected to be affected by this rule. These 57 local governments consist of 7 state governments, 31 small municipality governments, 18 non-small municipal governments and 1 (small) county government owner.

The EPA provides the following federalism summary impact statement. The EPA consulted with state and local officials early in the process of developing the proposed action to permit them to have meaningful and timely input into its development. In developing the regulatory options described in this final action, EPA consulted with 10 national organizations representing state and local elected officials to ensure meaningful and timely input by state/local governments, consisting of two consultation components. This consultation is described and summarized in the UMRA section above.

In the spirit of Executive Order 13132, and consistent with EPA policy to promote communications between EPA and state and local governments, EPA specifically solicited comment on the proposed action from state and local officials. EPA received comments from over two hundred (200) entities representing state and local governments. The comments submitted primarily addressed the issue presented in the proposal of which approach to regulating CCR was appropriate—a regulation under subtitle C or under subtitle D of RCRA. The state and local government commenters overwhelming

voiced their opposition to a regulation under subtitle C, citing impacts to state programs if EPA were to bring such a large number of facilities and a large volume of waste into the subtitle C universe. State governments were very concerned with the resources which would be required to issue subtitle C permits to these facilities and to develop and obtain EPA approval of revisions to their authorized RCRA subtitle C programs. They also expressed concerns about the limits in the existing hazardous waste disposal capacity in the United States to absorb such a large volume of new wastes, also citing the financial burden and potential liability problems for cities and towns that operate landfills or use landfills to dispose of waste that might include coal ash.

In addition, states and local governments expressed concern that a subtitle C rule would have a negative effect on beneficial use of CCR and on state beneficial use programs. State and local governments fully supported continued beneficial use of CCR and continuation of the Bevill exemption for CCR beneficial use. They requested that EPA establish standards to ensure that beneficial uses are protective of human health and the environment and ensure consistency in management of these materials throughout the country. They specifically cited the use of CCR in cement and concrete applications, highway construction projects and wallboard manufacture (among other uses) and the impacts to municipalities through increased costs and potential job loss if CCR is classified as a hazardous waste. They also noted an expectation that utility rates would rise as a result of CCR being disposed of in landfills rather than being used for beneficial purposes, due to limited availability of commercial hazardous waste disposal facilities and costs of transporting high volumes of CCR to these facilities. State Departments of Transportation expressed particular concern that a subtitle C rule would negatively affect the use of CCR in road bed. Commenters further supported continued beneficial use of CCR to reduce the need for mining for substitute products in cement and concrete. Finally, should CCR be classified as a hazardous waste, they indicated the need for EPA to clarify that products made using CCR are new products and not considered hazardous wastes, and may be treated in the same manner as similar products made without CCR.

Since EPA is promulgating this regulation under subtitle D, the concerns over the potential effect of a subtitle C regulation on beneficial use are moot. Moreover in this final rule, EPA has established a definition for beneficial use which we believe makes clear the distinction between beneficial use and disposal. This is fully discussed in Unit VI of this document.

While States supported a rule under subtitle D, they also voiced concern about the need for flexibility to address site-specific situations, as would be available under a state permitting program, and concern about potential inconsistencies between the new federal requirements and existing State programs. States suggested that regulation under subtitle D should embrace the existing state permitting programs—allowing state permitting programs as the foundation for regulating CCR disposal—and requested financial incentives to implement federal criteria through state solid waste programs. They also emphasized the need to allow time for states to make necessary changes in existing state rules and statutes to incorporate federal criteria. A few expressed the desire that financial assurance for closure, post closure care, and corrective action should be included in the final rule as a mechanism to ensure that funds will be provided by owners and operators to carry out these activities.

As fully explained earlier in this document, EPA is promulgating this rule under subtitle D of RCRA. As such, these regulations constitute the minimum federal requirements which apply to CCR units. States are not required to adopt these regulations or to revise their state programs to incorporate the new federal requirements. As fully discussed in Unit V of this document, ''Development of the RCRA Subtitle D Regulatory Approach,'' sections 1008(a), 4004, and 4005(a) of RCRA (*i.e.,* subtitle D) does not provide EPA with the ability to require states to issue permits, to approve state programs to operate in lieu of the federal program, or to enforce any of the requirements addressing the disposal of CCR. Consequently EPA designed the final rule to ensure protection of public health and the environment within these limitations. In addition, to help address potential implementation challenges that this statutory and resulting regulatory structure impose, as fully set out in Section IX of this document, EPA is encouraging states to revise their Solid Waste Management Plans and to submit these to EPA for approval.

A complete list of the comments from state and local governments has been provided to the Office of Management and Budget and has been placed in the docket for this rulemaking. In addition, the detailed response to comments from these entities is contained in EPA's response to comments document on this rulemaking.

As required by section 8(a) of Executive Order 13132, EPA included a certification from its Federalism Official stating that EPA had met the Executive Order's requirements in a meaningful and timely manner when it sent the draft of this final action to OMB for review pursuant to Executive Order 12866. A copy of this certification is included in the public version of the official record for this final action.

F. Executive Order 13175—Consultation and Coordination With Indian Tribal Governments

Subject to the Executive Order 13175 (65 FR 67249, November 9, 2000) EPA may not issue a regulation that has tribal implications, that imposes substantial direct compliance costs, and that is not required by statute, unless the Federal government provides the funds necessary to pay the direct compliance costs incurred by tribal governments, or EPA consults with tribal officials early in the process of developing the proposed regulation and develops a tribal summary impact statement.

EPA has concluded that this action may have tribal implications. However, it will neither impose substantial direct compliance costs on tribal governments, nor preempt Tribal law. As identified in EPA's Regulatory Impact Analysis for this action, there are no known tribal owner entities of the coal-fired electric utility plants affected by this action. Although there are three of the 414 coal-fired electric utility plants (in operation as of 2012) which are located on tribal lands, they are not owned by tribal governments. These are: (1) Navajo Generating Station in Coconino County, owned by the Arizona Salt River Project; (2) Bonanza Power Plant in Uintah County, Utah, owned by the Deseret Generation and Transmission Cooperative; and (3) Four Corners Power Plant in San Juan County, New Mexico owned by the Arizona Public Service Company. The Navajo Generating Station and the Four Corners Power Plant are on lands belonging to the Navajo Nation, while the Bonanza Power Plant is located on the Uintah and Ouray Reservation of the Ute Indian Tribe.

EPA consulted with tribal officials early in the process of developing this regulation to permit them to have meaningful and timely input into its development.

G. Executive Order 13045: Protection of Children From Environmental Health Risks and Safety Risks

This action is subject to E.O. 13045 (62 FR 19885, April 23, 1997) because it is an economically significant regulatory action as defined by E.O. 12866, and EPA believes that the environmental health or safety risks addressed by this action may have a disproportionate effect on children. Accordingly, we have evaluated the environmental health or safety effects of Coal Combustion Residual constituents of potential concern on children. The results of this evaluation are contained in the *Human and Ecological Risk Assessment of Coal Combustion Wastes* available in the docket for this action.

As ordered by E.O. 13045 Section 1–101(a), EPA identified and assessed environmental health risks and safety risks that may disproportionately affect children in the revised risk assessment. Pursuant to U.S. EPA's Guidance on Selecting Age Groups for Monitoring and Assessing Childhood Exposures to Environmental Contaminants, children are divided into seven distinct age cohorts: 1 to <2 yr, 2 to <3 yr, 3 to <6 yr 6 to <11 yr, 11 to <16 yr, 16 to <21 yr, and infants (<1 yr). Using exposure factors for each of these cohorts, EPA calculated cancer and non-cancer risk results in both the screening and probabilistic phases of the assessment. In general, risks to infants tended to be higher than other childhood cohorts, and also higher than risks to adults. However, for drinking water cancer risks, the longer exposures for adults led to the highest risks. Screening risks exceeded EPA's human health criteria for children exposed to contaminated air, soil, and food resulting from fugitive dust emissions and run-off. Similarly, 90th percentile child cancer and non-cancer risks exceeded the human health criteria for the groundwater to drinking water pathway under the full probabilistic analysis (Table 5–17 in the *Human and Ecological Risk Assessment of Coal Combustion Wastes*). As ordered by E.O. 13045 Section 101(b) EPA has ensured that the standard addresses disproportionate risks to children that result from environmental health risks. The results of the screening assessment finds that risks fell below the criteria when wetting and run-on/runoff controls required by the rule are considered. Under the full probabilistic analysis, composite liners required by the rule for new waste management units showed the ability to reduce the 90th percentile child cancer and non-cancer risks for the groundwater to drinking water pathway to well below EPA's criteria. Additionally, the groundwater monitoring and corrective action required by the rule will reduce risks from current waste management units. Thus, EPA believes that this rule will be protective of children's health.

In general, because the pollution control requirements under the CCR rule will reduce health and environmental exposure risks at all coal-fired electric utility plants, the CCR rule is not expected to create additional or new risks to children.

H. Executive Order 13211: Actions Concerning Regulations That Significantly Affect Energy Supply, Distribution, or Use

Executive Order 13211 (66 FR 28355 (May 22, 2001)) requires EPA to prepare and submit a Statement of Energy Effects to the Administrator of the Office of Information and Regulatory Affairs, Office of Management and Budget (OMB), for actions identified as ''significant energy actions.'' This action, which is a significant regulatory action under Executive Order 12866, is not likely to have a significant adverse effect on the supply, distribution, or use of energy based on the results of the electricity price impact estimates of the Regulatory Impact Analysis (RIA) for this action. We have prepared a Statement of Energy Effects for this action.

According to Executive Order 13211, the statement should address (i) any adverse effects on energy supply, distribution, or use, (including a shortfall in supply, price increases, and increased use of foreign supplies) should the proposal be implemented, and (ii) reasonable alternatives to the action with adverse energy effects and the expected effects of such alternatives on energy supply, distribution, and use.

The potential impact of the final CCR rule on electricity prices is analyzed relative to the ''in excess of one percent'' threshold which is one of nine alternative numerical indicators established by OMB for defining ''significant adverse effect'' under Executive Order 13211.[233] The integrated planning model (IPM) estimates potential increases in wholesale electricity prices for 22 National Energy Modeling System (NEMS) regions. In addition, the analysis focuses on potential changes in electricity prices in 2020, 2025, and 2030. The analysis focuses on these relatively early year in the analytic time horizon examined in the RIA to minimize uncertainty in the estimated electricity price impacts. In addition, under the provisions of the rule, the year 2018 is when impoundments begin to undergo closure or wet/dry conversion if they are found to be leaking. Therefore, 2020, 2025, and 2030 represent high-cost year relative to other years in the analytic time horizon, and the analysis presented here will likely yield conservative estimates of the rule's impact on electricity prices.

Using IPM, the weighted average nationwide potential increase in the wholesale price of electricity is not expected to exceed one percent (between .18% and 0.19% in the years 2020 through 2030). However, for one of the 22 NEMS regions (AZNM), the RIA projects a potential price increase above one percent (between 0.78% and 1.05% in the years 2020 through 2030).

Finally, any retail electricity price increases, if they occur, would have the effect of offsetting a portion of the compliance costs to electric utilities estimated in the RIA, as the utilities would be recovering costs through price increases to customers. Therefore, these impacts are not additive to total rule costs, but would instead offset costs to utilities estimated in the RIA.

Only one region may slightly exceed a one percent electricity price increase, which the RIA estimated without considering the potential reduction in such impact with the compliance deadline flexibility of this action for CCR surface impoundments. Thus all regions are likely to experience less than one percent electricity price impacts of this action. Therefore, this statement does not address reasonable alternatives to the action because EPA does not expect this action to have adverse energy effects as defined by OMB.

I. National Technology Transfer and Advancement Act

Section 12(d) of the National Technology Transfer and Advancement Act of 1995 (''NTTAA''), Public Law 104–113, 12(d) (15 U.S.C. 272 note) directs EPA to use voluntary consensus standards in its regulatory activities unless to do so would be inconsistent with applicable law or otherwise impractical. Voluntary consensus standards are technical standards (*e.g.,* materials specifications, test methods, sampling procedures, and business practices) that are developed or adopted by voluntary consensus standards bodies. NTTAA directs EPA to provide Congress, through OMB, explanations when the Agency decides not to use

[233] OMB defines nine alternative numerical indicators of ''significant adverse effect'' on energy supply, distribution, or use in Section 4 of its ''Memorandum for Heads of Executive Departments and Agencies, and Independent Regulatory Agencies,'' M–01–27, July 13, 2001.

available and applicable voluntary consensus standards.

This rulemaking involves technical standards. EPA has decided to use the following technical standards in this rule: (1) RCRA Subpart D, Section 257.70 liner design criteria for new CCR landfills and any lateral expansion of a CCR landfill includes voluntary consensus standards developed by ASTM International and EPA test methods such as SW–846, (2) Section 257.71 liner design criteria for existing CCR surface impoundments include voluntary consensus standards developed by ASTM International and EPA test methods such as SW–846, (3) Section 257.72 liner design criteria for new CCR surface impoundments and any lateral expansion of a CCR surface impoundment include voluntary consensus standards developed by ASTM International and EPA test methods such as SW–846, and (4) Section 257.73 structural stability standards for new and existing surface impoundments use the ASTM D 698 and 1557 standards for embankment compaction.

J. Executive Order 12898: Federal Actions To Address Environmental Justice in Minority Populations and Low-Income Populations

Executive Order (E.O.) 12898 (59 FR 7629, Feb. 16, 1994) establishes federal executive policy on environmental justice. Its main provision directs federal agencies, to the greatest extent practicable and permitted by law, to make environmental justice part of their mission by identifying and addressing, as appropriate, disproportionately high and adverse human health or environmental effects of their programs, policies, and activities on minority populations and low-income populations in the United States.

EPA has determined that this final rule will not have disproportionately high and adverse human health or environmental effects on minority or low-income populations because it increases the level of environmental protection for all affected populations without having any disproportionately high and adverse human health or environmental effects on any population, including any minority or low-income population.

EPA's risk assessment for this action did not separately evaluate either minority or low income populations. However, to evaluate the demographic characteristics of communities that may be affected by the CCR rule, the RIA compares the demographic characteristics of populations surrounding coal-fired electric utility plants with broader population data for two geographic areas: (1) One-mile radius from CCR management units (*i.e.,* landfills and impoundments) likely to be affected by groundwater releases from both landfills and impoundments; and (2) watershed catchment areas downstream of surface impoundments that receive surface water run-off and releases from CCR impoundments and are at risk of being contaminated from CCR impoundment discharges (*e.g.,* unintentional overflows, structural failures, and intentional periodic discharges).

For the population as a whole 24.8% belong to a minority group and 11.3% falls below the Federal Poverty Level. For the population living within one mile of plants with surface impoundments 16.1% belong to a minority group and 13.2% live below the Federal Poverty Level. These minority and low-income populations are not disproportionately high compared to the general population. The percentage of minority residents of the entire population living within the catchment areas downstream of surface impoundments is disproportionately high relative to the general population, *i.e.,* 28.7%, versus 24.8% for the national population. Also, the percentage of the population within the catchment areas of surface impoundments that is below the Federal Poverty Level is disproportionately high compared with the general population, *i.e.,* 18.6% versus 11.3% nationally.

Comparing the population percentages of minority and low income residents within one mile of landfills to those percentages in the general population, EPA found that minority and low-income residents make up a smaller percentage of the populations near landfills than they do in the general population, *i.e.,* minorities comprised 16.6% of the population near landfills versus 24.8% nationwide and low-income residents comprised 8.6% of the population near landfills versus 11.3% nationwide. In summary, although populations within the catchment areas of plants with surface impoundments appear to have disproportionately high percentages of minority and low-income residents relative to the nationwide average, populations surrounding plants with landfills do not. Because landfills are less likely than impoundments to experience surface water run-off and releases, catchment areas were not considered for landfills.

Because the CCR rule is risk-reducing, with reductions in risk occurring largely within the surface water catchment zones around, and groundwater beneath, coal-fired electric utility plants, the rule will not result in new disproportionate risks to minority or low-income populations.

K. Congressional Review Act

The Congressional Review Act, 5 U.S.C. 801 *et seq.,* as added by the Small Business Regulatory Enforcement Fairness Act of 1996, generally provides that before a rule may take effect, the agency promulgating the rule must submit a rule report, which includes a copy of the rule, to each House of the Congress and to the Comptroller General of the United States. EPA will submit a report containing this rule and other required information to the U.S. Senate, the U.S. House of Representatives, and the Comptroller General of the United States prior to publication of the rule in the **Federal Register**. A Major rule cannot take effect until 60 days after it is published in the **Federal Register**. This action is a ''major rule'' as defined by 5 U.S.C. 804(2). This rule will be effective 180 days after its publication in the **Federal Register**.

List of Subjects

40 CFR Part 257

Environmental protection, Beneficial use, Coal combustion products, Coal combustion residuals, Coal combustion waste, Disposal, Hazardous waste, Landfill, Surface impoundment.

40 CFR Part 261

Environmental protection, Hazardous waste, Recycling, Reporting and recordkeeping requirements.

Dated: December 19, 2014.

Gina McCarthy,

Administrator.

For the reasons set out in the preamble, title 40, chapter I, of the Code of Federal Regulations is amended as follows:

PART 257—CRITERIA FOR CLASSIFICATION OF SOLID WASTE DISPOSAL FACILITIES AND PRACTICES

■ 1. The authority citation for part 257 continues to read as follows:

Authority: 42 U.S.C. 6907(a)(3), 6912(a)(1), 6944(a); 33 U.S.C. 1345(d) and (e).

■ 2. Section 257.1 is amended by:

■ a. Adding a sentence at the end of paragraph (a) introductory text;

■ b. Revising paragraphs (a)(1) and (2); and

■ c. Adding paragraph (c)(12).

The revisions and additions read as follows:

§ 257.1 Scope and purpose.

(a) * * * Unless otherwise provided, the criteria in §§ 257.50 through 257.107 are adopted for determining which CCR landfills and CCR surface impoundments pose a reasonable probability of adverse effects on health or the environment under sections 1008(a)(3) and 4004(a) of the Act.

(1) Facilities failing to satisfy any of the criteria in §§ 257.1 through 257.4 or §§ 257.5 through 257.30 or §§ 257.50 through 257.107 are considered open dumps, which are prohibited under section 4005 of the Act.

(2) Practices failing to satisfy any of the criteria in §§ 257.1 through 257.4 or §§ 257.5 through 257.30 or §§ 257.50 through 257.107 constitute open dumping, which is prohibited under section 4005 of the Act.

* * * * *

(c) * * *

(12) Except as otherwise specifically provided in subpart D of this part, the criteria in subpart A of this part do not apply to CCR landfills, CCR surface impoundments, and lateral expansions of CCR units, as those terms are defined in subpart D of this part. Such units are instead subject to subpart D of this part.

■ 3. Section 257.2 is amended by adding in alphabetical order definitions for ''CCR landfill'' and ''CCR surface impoundment'' to read as follows:

§ 257.2 Definitions.

* * * * *

CCR landfill means an area of land or an excavation that receives CCR and which is not a surface impoundment, an underground injection well, a salt dome formation, a salt bed formation, an underground or surface coal mine, or a cave. For purposes of this subpart, a CCR landfill also includes sand and gravel pits and quarries that receive CCR, CCR piles, and any practice that does not meet the definition of a beneficial use of CCR.

CCR surface impoundment means a natural topographic depression, man-made excavation, or diked area, which is designed to hold an accumulation of CCR and liquids, and the unit treats, stores, or disposes of CCR.

* * * * *

■ 4. Part 257 is amended by:

■ a. Adding and reserving subpart C; and

■ b. Adding subpart D.

The additions read as follows:

Subpart C—[Reserved]

Subpart D—Standards for the Disposal of Coal Combustion Residuals in Landfills and Surface Impoundments

General Provisions

Sec.
257.50 Scope and purpose.
257.51 Effective date of this subpart.
257.52 Applicability of other regulations.
257.53 Definitions.

Location Restrictions

257.60 Placement above the uppermost aquifer.
257.61 Wetlands.
257.62 Fault areas.
257.63 Seismic impact zones.
257.64 Unstable areas.

Design Criteria

257.70 Design criteria for new CCR landfills and any lateral expansion of a CCR landfill.
257.71 Liner design criteria for existing CCR surface impoundments.
257.72 Design criteria for new CCR surface impoundments and any lateral expansion of a CCR surface impoundment.
257.73 Structural integrity criteria for existing CCR surface impoundments.
257.74 Structural integrity criteria for new CCR surface impoundments and any lateral expansion of a CCR surface impoundment.

Operating Criteria

257.80 Air criteria.
257.81 Run-on and run-off controls for CCR landfills.
257.82 Hydrologic and hydraulic capacity requirements for CCR surface impoundments.
257.83 Inspection requirements for CCR surface impoundments.
257.84 Inspection requirements for CCR landfills.

Groundwater Monitoring and Corrective Action

257.90 Applicability.
257.91 Groundwater monitoring systems.
257.92 [Reserved]
257.93 Groundwater sampling and analysis requirements.
257.94 Detection monitoring program.
257.95 Assessment monitoring program.
257.96 Assessment of corrective measures.
257.97 Selection of remedy.
257.98 Implementation of the corrective action program.

Closure and Post-Closure Care

257.100 Inactive CCR surface impoundments.
257.101 Closure or retrofit of CCR units.
257.102 Criteria for conducting the closure or retrofit of CCR units.
257.103 Alternative closure requirements.
257.104 Post-closure care requirements.

Recordkeeping, Notification, and Posting of Information to the Internet

257.105 Recordkeeping requirements.
257.106 Notification requirements.
257.107 Publicly accessible internet site requirements.

Subpart D—Standards for the Disposal of Coal Combustion Residuals in Landfills and Surface Impoundments

§ 257.50 Scope and purpose.

(a) This subpart establishes minimum national criteria for purposes of determining which solid waste disposal facilities and solid waste management practices do not pose a reasonable probability of adverse effects on health or the environment under sections 1008(a)(3) and 4004(a) of the Resource Conservation and Recovery Act.

(b) This subpart applies to owners and operators of new and existing landfills and surface impoundments, including any lateral expansions of such units that dispose or otherwise engage in solid waste management of CCR generated from the combustion of coal at electric utilities and independent power producers. Unless otherwise provided in this subpart, these requirements also apply to disposal units located off-site of the electric utility or independent power producer. This subpart also applies to any practice that does not meet the definition of a beneficial use of CCR.

(c) This subpart also applies to inactive CCR surface impoundments at active electric utilities or independent power producers, regardless of the fuel currently used at the facility to produce electricity.

(d) This subpart does not apply to CCR landfills that have ceased receiving CCR prior to October 19, 2015.

(e) This subpart does not apply to electric utilities or independent power producers that have ceased producing electricity prior to October 19, 2015.

(f) This subpart does not apply to wastes, including fly ash, bottom ash, boiler slag, and flue gas desulfurization materials generated at facilities that are not part of an electric utility or independent power producer, such as manufacturing facilities, universities, and hospitals. This subpart also does not apply to fly ash, bottom ash, boiler slag, and flue gas desulfurization materials, generated primarily from the combustion of fuels (including other fossil fuels) other than coal, for the purpose of generating electricity unless the fuel burned consists of more than fifty percent (50%) coal on a total heat input or mass input basis, whichever results in the greater mass feed rate of coal.

(g) This subpart does not apply to practices that meet the definition of a beneficial use of CCR.

(h) This subpart does not apply to CCR placement at active or abandoned underground or surface coal mines.

(i) This subpart does not apply to municipal solid waste landfills that receive CCR.

§ 257.51 Effective date of this subpart.

The requirements of this subpart take effect on October 19, 2015.

§ 257.52 Applicability of other regulations.

(a) Compliance with the requirements of this subpart does not affect the need for the owner or operator of a CCR landfill, CCR surface impoundment, or lateral expansion of a CCR unit to comply with all other applicable federal, state, tribal, or local laws or other requirements.

(b) Any CCR landfill, CCR surface impoundment, or lateral expansion of a CCR unit continues to be subject to the requirements in §§ 257.3–1, 257.3–2, and 257.3–3.

§ 257.53 Definitions.

The following definitions apply to this subpart. Terms not defined in this section have the meaning given by RCRA.

Acre foot means the volume of one acre of surface area to a depth of one foot.

Active facility or *active electric utilities or independent power producers* means any facility subject to the requirements of this subpart that is in operation on October 14, 2015. An electric utility or independent power producer is in operation if it is generating electricity that is provided to electric power transmission systems or to electric power distribution systems on or after October 14, 2015. An off-site disposal facility is in operation if it is accepting or managing CCR on or after October 14, 2015.

Active life or *in operation* means the period of operation beginning with the initial placement of CCR in the CCR unit and ending at completion of closure activities in accordance with § 257.102.

Active portion means that part of the CCR unit that has received or is receiving CCR or non-CCR waste and that has not completed closure in accordance with § 257.102.

Aquifer means a geologic formation, group of formations, or portion of a formation capable of yielding usable quantities of groundwater to wells or springs.

Area-capacity curves means graphic curves which readily show the reservoir water surface area, in acres, at different elevations from the bottom of the reservoir to the maximum water surface, and the capacity or volume, in acre-feet, of the water contained in the reservoir at various elevations.

Areas susceptible to mass movement means those areas of influence (*i.e.,* areas characterized as having an active or substantial possibility of mass movement) where, because of natural or human-induced events, the movement of earthen material at, beneath, or adjacent to the CCR unit results in the downslope transport of soil and rock material by means of gravitational influence. Areas of mass movement include, but are not limited to, landslides, avalanches, debris slides and flows, soil fluctuation, block sliding, and rock fall.

Beneficial use of CCR means the CCR meet all of the following conditions:

(1) The CCR must provide a functional benefit;

(2) The CCR must substitute for the use of a virgin material, conserving natural resources that would otherwise need to be obtained through practices, such as extraction;

(3) The use of the CCR must meet relevant product specifications, regulatory standards or design standards when available, and when such standards are not available, the CCR is not used in excess quantities; and

(4) When unencapsulated use of CCR involving placement on the land of 12,400 tons or more in non-roadway applications, the user must demonstrate and keep records, and provide such documentation upon request, that environmental releases to groundwater, surface water, soil and air are comparable to or lower than those from analogous products made without CCR, or that environmental releases to groundwater, surface water, soil and air will be at or below relevant regulatory and health-based benchmarks for human and ecological receptors during use.

Closed means placement of CCR in a CCR unit has ceased, and the owner or operator has completed closure of the CCR unit in accordance with § 257.102 and has initiated post-closure care in accordance with § 257.104.

Coal combustion residuals (CCR) means fly ash, bottom ash, boiler slag, and flue gas desulfurization materials generated from burning coal for the purpose of generating electricity by electric utilities and independent power producers.

CCR fugitive dust means solid airborne particulate matter that contains or is derived from CCR, emitted from any source other than a stack or chimney.

CCR landfill or landfill means an area of land or an excavation that receives CCR and which is not a surface impoundment, an underground injection well, a salt dome formation, a salt bed formation, an underground or surface coal mine, or a cave. For purposes of this subpart, a CCR landfill also includes sand and gravel pits and quarries that receive CCR, CCR piles, and any practice that does not meet the definition of a beneficial use of CCR.

CCR pile or pile means any non-containerized accumulation of solid, non-flowing CCR that is placed on the land. CCR that is beneficially used off-site is not a CCR pile.

CCR surface impoundment or impoundment means a natural topographic depression, man-made excavation, or diked area, which is designed to hold an accumulation of CCR and liquids, and the unit treats, stores, or disposes of CCR.

CCR unit means any CCR landfill, CCR surface impoundment, or lateral expansion of a CCR unit, or a combination of more than one of these units, based on the context of the paragraph(s) in which it is used. This term includes both new and existing units, unless otherwise specified.

Dike means an embankment, berm, or ridge of either natural or man-made materials used to prevent the movement of liquids, sludges, solids, or other materials.

Displacement means the relative movement of any two sides of a fault measured in any direction.

Disposal means the discharge, deposit, injection, dumping, spilling, leaking, or placing of any solid waste as defined in section 1004(27) of the Resource Conservation and Recovery Act into or on any land or water so that such solid waste, or constituent thereof, may enter the environment or be emitted into the air or discharged into any waters, including groundwaters. For purposes of this subpart, disposal does not include the storage or the beneficial use of CCR.

Downstream toe means the junction of the downstream slope or face of the CCR surface impoundment with the ground surface.

Encapsulated beneficial use means a beneficial use of CCR that binds the CCR into a solid matrix that minimizes its mobilization into the surrounding environment.

Existing CCR landfill means a CCR landfill that receives CCR both before and after October 14, 2015, or for which construction commenced prior to October 14, 2015 and receives CCR on or after October 14, 2015. A CCR landfill has commenced construction if the owner or operator has obtained the federal, state, and local approvals or permits necessary to begin physical

construction and a continuous on-site, physical construction program had begun prior to October 14, 2015.

Existing CCR surface impoundment means a CCR surface impoundment that receives CCR both before and after October 14, 2015, or for which construction commenced prior to October 14, 2015 and receives CCR on or after October 14, 2015. A CCR surface impoundment has commenced construction if the owner or operator has obtained the federal, state, and local approvals or permits necessary to begin physical construction and a continuous on-site, physical construction program had begun prior to October 14, 2015.

Facility means all contiguous land, and structures, other appurtenances, and improvements on the land, used for treating, storing, disposing, or otherwise conducting solid waste management of CCR. A facility may consist of several treatment, storage, or disposal operational units (*e.g.,* one or more landfills, surface impoundments, or combinations of them).

Factor of safety (Safety factor) means the ratio of the forces tending to resist the failure of a structure to the forces tending to cause such failure as determined by accepted engineering practice.

Fault means a fracture or a zone of fractures in any material along which strata on one side have been displaced with respect to that on the other side.

Flood hydrograph means a graph showing, for a given point on a stream, the discharge, height, or other characteristic of a flood as a function of time.

Freeboard means the vertical distance between the lowest point on the crest of the impoundment dike and the surface of the waste contained therein.

Free liquids means liquids that readily separate from the solid portion of a waste under ambient temperature and pressure.

Groundwater means water below the land surface in a zone of saturation.

Hazard potential classification means the possible adverse incremental consequences that result from the release of water or stored contents due to failure of the diked CCR surface impoundment or mis-operation of the diked CCR surface impoundment or its appurtenances. The hazardous potential classifications include high hazard potential CCR surface impoundment, significant hazard potential CCR surface impoundment, and low hazard potential CCR surface impoundment, which terms mean:

(1) *High hazard potential CCR surface impoundment* means a diked surface impoundment where failure or mis-operation will probably cause loss of human life.

(2) *Low hazard potential CCR surface impoundment* means a diked surface impoundment where failure or mis-operation results in no probable loss of human life and low economic and/or environmental losses. Losses are principally limited to the surface impoundment owner's property.

(3) *Significant hazard potential CCR surface impoundment* means a diked surface impoundment where failure or mis-operation results in no probable loss of human life, but can cause economic loss, environmental damage, disruption of lifeline facilities, or impact other concerns.

Height means the vertical measurement from the downstream toe of the CCR surface impoundment at its lowest point to the lowest elevation of the crest of the CCR surface impoundment.

Holocene means the most recent epoch of the Quaternary period, extending from the end of the Pleistocene Epoch, at 11,700 years before present, to present.

Hydraulic conductivity means the rate at which water can move through a permeable medium (*i.e.,* the coefficient of permeability).

Inactive CCR surface impoundment means a CCR surface impoundment that no longer receives CCR on or after October 14, 2015 and still contains both CCR and liquids on or after October 14, 2015.

Incised CCR surface impoundment means a CCR surface impoundment which is constructed by excavating entirely below the natural ground surface, holds an accumulation of CCR entirely below the adjacent natural ground surface, and does not consist of any constructed diked portion.

Indian country or *Indian lands* means:

(1) All land within the limits of any Indian reservation under the jurisdiction of the United States Government, notwithstanding the issuance of any patent, and including rights-of-way running throughout the reservation;

(2) All dependent Indian communities within the borders of the United States whether within the original or subsequently acquired territory thereof, and whether within or without the limits of the State; and

(3) All Indian allotments, the Indian titles to which have not been extinguished, including rights of way running through the same.

Indian Tribe or *Tribe* means any Indian tribe, band, nation, or community recognized by the Secretary of the Interior and exercising substantial governmental duties and powers on Indian lands.

Inflow design flood means the flood hydrograph that is used in the design or modification of the CCR surface impoundments and its appurtenant works.

In operation means the same as *active life.*

Karst terrain means an area where karst topography, with its characteristic erosional surface and subterranean features, is developed as the result of dissolution of limestone, dolomite, or other soluble rock. Characteristic physiographic features present in karst terranes include, but are not limited to, dolines, collapse shafts (sinkholes), sinking streams, caves, seeps, large springs, and blind valleys.

Lateral expansion means a horizontal expansion of the waste boundaries of an existing CCR landfill or existing CCR surface impoundment made after October 14, 2015.

Liquefaction factor of safety means the factor of safety (safety factor) determined using analysis under liquefaction conditions.

Lithified earth material means all rock, including all naturally occurring and naturally formed aggregates or masses of minerals or small particles of older rock that formed by crystallization of magma or by induration of loose sediments. This term does not include man-made materials, such as fill, concrete, and asphalt, or unconsolidated earth materials, soil, or regolith lying at or near the earth surface.

Maximum horizontal acceleration in lithified earth material means the maximum expected horizontal acceleration at the ground surface as depicted on a seismic hazard map, with a 98% or greater probability that the acceleration will not be exceeded in 50 years, or the maximum expected horizontal acceleration based on a site-specific seismic risk assessment.

New CCR landfill means a CCR landfill or lateral expansion of a CCR landfill that first receives CCR or commences construction after October 14, 2015. A new CCR landfill has commenced construction if the owner or operator has obtained the federal, state, and local approvals or permits necessary to begin physical construction and a continuous on-site, physical construction program had begun after October 14, 2015. Overfills are also considered new CCR landfills.

New CCR surface impoundment means a CCR surface impoundment or lateral expansion of an existing or new CCR surface impoundment that first receives CCR or commences construction after October 14, 2015. A

new CCR surface impoundment has commenced construction if the owner or operator has obtained the federal, state, and local approvals or permits necessary to begin physical construction and a continuous on-site, physical construction program had begun after October 14, 2015.

Operator means the person(s) responsible for the overall operation of a CCR unit.

Overfill means a new CCR landfill constructed over a closed CCR surface impoundment.

Owner means the person(s) who owns a CCR unit or part of a CCR unit.

Poor foundation conditions mean those areas where features exist which indicate that a natural or human-induced event may result in inadequate foundation support for the structural components of an existing or new CCR unit. For example, failure to maintain static and seismic factors of safety as required in §§ 257.73(e) and 257.74(e) would cause a poor foundation condition.

Probable maximum flood means the flood that may be expected from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in the drainage basin.

Qualified person means a person or persons trained to recognize specific appearances of structural weakness and other conditions which are disrupting or have the potential to disrupt the operation or safety of the CCR unit by visual observation and, if applicable, to monitor instrumentation.

Qualified professional engineer means an individual who is licensed by a state as a Professional Engineer to practice one or more disciplines of engineering and who is qualified by education, technical knowledge and experience to make the specific technical certifications required under this subpart. Professional engineers making these certifications must be currently licensed in the state where the CCR unit(s) is located.

Recognized and generally accepted good engineering practices means engineering maintenance or operation activities based on established codes, widely accepted standards, published technical reports, or a practice widely recommended throughout the industry. Such practices generally detail approved ways to perform specific engineering, inspection, or mechanical integrity activities.

Retrofit means to remove all CCR and contaminated soils and sediments from the CCR surface impoundment, and to ensure the unit complies with the requirements in § 257.72

Representative sample means a sample of a universe or whole (*e.g.,* waste pile, lagoon, and groundwater) which can be expected to exhibit the average properties of the universe or whole. See EPA publication SW–846, Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, Chapter 9 (available at *http://www.epa.gov/epawaste/hazard/testmethods/sw846/online/index.htm*) for a discussion and examples of representative samples.

Run-off means any rainwater, leachate, or other liquid that drains over land from any part of a CCR landfill or lateral expansion of a CCR landfill.

Run-on means any rainwater, leachate, or other liquid that drains over land onto any part of a CCR landfill or lateral expansion of a CCR landfill.

Sand and gravel pit or quarry means an excavation for the extraction of aggregate, minerals or metals. The term sand and gravel pit and/or quarry does not include subsurface or surface coal mines.

Seismic factor of safety means the factor of safety (safety factor) determined using analysis under earthquake conditions using the peak ground acceleration for a seismic event with a 2% probability of exceedance in 50 years, equivalent to a return period of approximately 2,500 years, based on the U.S. Geological Survey (USGS) seismic hazard maps for seismic events with this return period for the region where the CCR surface impoundment is located.

Seismic impact zone means an area having a 2% or greater probability that the maximum expected horizontal acceleration, expressed as a percentage of the earth's gravitational pull (g), will exceed 0.10 g in 50 years.

Slope protection means engineered or non-engineered measures installed on the upstream or downstream slope of the CCR surface impoundment to protect the slope against wave action or erosion, including but not limited to rock riprap, wooden pile, or concrete revetments, vegetated wave berms, concrete facing, gabions, geotextiles, or fascines.

Solid waste management or management means the systematic administration of the activities which provide for the collection, source separation, storage, transportation, processing, treatment, or disposal of solid waste.

State means any of the fifty States in addition to the District of Columbia, the Commonwealth of Puerto Rico, the Virgin Islands, Guam, American Samoa, and the Commonwealth of the Northern Mariana Islands.

State Director means the chief administrative officer of the lead state agency responsible for implementing the state program regulating disposal in CCR landfills, CCR surface impoundments, and all lateral expansions of a CCR unit.

Static factor of safety means the factor of safety (safety factor) determined using analysis under the long-term, maximum storage pool loading condition, the maximum surcharge pool loading condition, and under the end-of-construction loading condition.

Structural components mean liners, leachate collection and removal systems, final covers, run-on and run-off systems, inflow design flood control systems, and any other component used in the construction and operation of the CCR unit that is necessary to ensure the integrity of the unit and that the contents of the unit are not released into the environment.

Unstable area means a location that is susceptible to natural or human-induced events or forces capable of impairing the integrity, including structural components of some or all of the CCR unit that are responsible for preventing releases from such unit. Unstable areas can include poor foundation conditions, areas susceptible to mass movements, and karst terrains.

Uppermost aquifer means the geologic formation nearest the natural ground surface that is an aquifer, as well as lower aquifers that are hydraulically interconnected with this aquifer within the facility's property boundary. Upper limit is measured at a point nearest to the natural ground surface to which the aquifer rises during the wet season.

Waste boundary means a vertical surface located at the hydraulically downgradient limit of the CCR unit. The vertical surface extends down into the uppermost aquifer.

Location Restrictions

§ 257.60 Placement above the uppermost aquifer.

(a) New CCR landfills, existing and new CCR surface impoundments, and all lateral expansions of CCR units must be constructed with a base that is located no less than 1.52 meters (five feet) above the upper limit of the uppermost aquifer, or must demonstrate that there will not be an intermittent, recurring, or sustained hydraulic connection between any portion of the base of the CCR unit and the uppermost aquifer due to normal fluctuations in groundwater elevations (including the seasonal high water table). The owner or operator must demonstrate by the dates specified in paragraph (c) of this section

that the CCR unit meets the minimum requirements for placement above the uppermost aquifer.

(b) The owner or operator of the CCR unit must obtain a certification from a qualified professional engineer stating that the demonstration meets the requirements of paragraph (a) of this section.

(c) The owner or operator of the CCR unit must complete the demonstration required by paragraph (a) of this section by the date specified in either paragraph (c)(1) or (2) of this section.

(1) For an existing CCR surface impoundment, the owner or operator must complete the demonstration no later than October 17, 2018.

(2) For a new CCR landfill, new CCR surface impoundment, or any lateral expansion of a CCR unit, the owner or operator must complete the demonstration no later than the date of initial receipt of CCR in the CCR unit.

(3) The owner or operator has completed the demonstration required by paragraph (a) of this section when the demonstration is placed in the facility's operating record as required by § 257.105(e).

(4) An owner or operator of an existing CCR surface impoundment who fails to demonstrate compliance with the requirements of paragraph (a) of this section by the date specified in paragraph (c)(1) of this section is subject to the requirements of § 257.101(b)(1).

(5) An owner or operator of a new CCR landfill, new CCR surface impoundment, or any lateral expansion of a CCR unit who fails to make the demonstration showing compliance with the requirements of paragraph (a) of this section is prohibited from placing CCR in the CCR unit.

(d) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(e), the notification requirements specified in § 257.106(e), and the internet requirements specified in § 257.107(e).

§ 257.61 Wetlands.

(a) New CCR landfills, existing and new CCR surface impoundments, and all lateral expansions of CCR units must not be located in wetlands, as defined in § 232.2 of this chapter, unless the owner or operator demonstrates by the dates specified in paragraph (c) of this section that the CCR unit meets the requirements of paragraphs (a)(1) through (5) of this section.

(1) Where applicable under section 404 of the Clean Water Act or applicable state wetlands laws, a clear and objective rebuttal of the presumption that an alternative to the CCR unit is reasonably available that does not involve wetlands.

(2) The construction and operation of the CCR unit will not cause or contribute to any of the following:

(i) A violation of any applicable state or federal water quality standard;

(ii) A violation of any applicable toxic effluent standard or prohibition under section 307 of the Clean Water Act;

(iii) Jeopardize the continued existence of endangered or threatened species or result in the destruction or adverse modification of a critical habitat, protected under the Endangered Species Act of 1973; and

(iv) A violation of any requirement under the Marine Protection, Research, and Sanctuaries Act of 1972 for the protection of a marine sanctuary.

(3) The CCR unit will not cause or contribute to significant degradation of wetlands by addressing all of the following factors:

(i) Erosion, stability, and migration potential of native wetland soils, muds and deposits used to support the CCR unit;

(ii) Erosion, stability, and migration potential of dredged and fill materials used to support the CCR unit;

(iii) The volume and chemical nature of the CCR;

(iv) Impacts on fish, wildlife, and other aquatic resources and their habitat from release of CCR;

(v) The potential effects of catastrophic release of CCR to the wetland and the resulting impacts on the environment; and

(vi) Any additional factors, as necessary, to demonstrate that ecological resources in the wetland are sufficiently protected.

(4) To the extent required under section 404 of the Clean Water Act or applicable state wetlands laws, steps have been taken to attempt to achieve no net loss of wetlands (as defined by acreage and function) by first avoiding impacts to wetlands to the maximum extent reasonable as required by paragraphs (a)(1) through (3) of this section, then minimizing unavoidable impacts to the maximum extent reasonable, and finally offsetting remaining unavoidable wetland impacts through all appropriate and reasonable compensatory mitigation actions (*e.g.,* restoration of existing degraded wetlands or creation of man-made wetlands); and

(5) Sufficient information is available to make a reasoned determination with respect to the demonstrations in paragraphs (a)(1) through (4) of this section.

(b) The owner or operator of the CCR unit must obtain a certification from a qualified professional engineer stating that the demonstration meets the requirements of paragraph (a) of this section.

(c) The owner or operator of the CCR unit must complete the demonstrations required by paragraph (a) of this section by the date specified in either paragraph (c)(1) or (2) of this section.

(1) For an existing CCR surface impoundment, the owner or operator must complete the demonstration no later than October 17, 2018.

(2) For a new CCR landfill, new CCR surface impoundment, or any lateral expansion of a CCR unit, the owner or operator must complete the demonstration no later than the date of initial receipt of CCR in the CCR unit.

(3) The owner or operator has completed the demonstration required by paragraph (a) of this section when the demonstration is placed in the facility's operating record as required by § 257.105(e).

(4) An owner or operator of an existing CCR surface impoundment who fails to demonstrate compliance with the requirements of paragraph (a) of this section by the date specified in paragraph (c)(1) of this section is subject to the requirements of § 257.101(b)(1).

(5) An owner or operator of a new CCR landfill, new CCR surface impoundment, or any lateral expansion of a CCR unit who fails to make the demonstrations showing compliance with the requirements of paragraph (a) of this section is prohibited from placing CCR in the CCR unit.

(d) The owner or operator must comply with the recordkeeping requirements specified in § 257.105(e), the notification requirements specified in § 257.106(e), and the Internet requirements specified in § 257.107(e).

§ 257.62 Fault areas.

(a) New CCR landfills, existing and new CCR surface impoundments, and all lateral expansions of CCR units must not be located within 60 meters (200 feet) of the outermost damage zone of a fault that has had displacement in Holocene time unless the owner or operator demonstrates by the dates specified in paragraph (c) of this section that an alternative setback distance of less than 60 meters (200 feet) will prevent damage to the structural integrity of the CCR unit.

(b) The owner or operator of the CCR unit must obtain a certification from a qualified professional engineer stating that the demonstration meets the requirements of paragraph (a) of this section.

(c) The owner or operator of the CCR unit must complete the demonstration

required by paragraph (a) of this section by the date specified in either paragraph (c)(1) or (2) of this section.

(1) For an existing CCR surface impoundment, the owner or operator must complete the demonstration no later than October 17, 2018.

(2) For a new CCR landfill, new CCR surface impoundment, or any lateral expansion of a CCR unit, the owner or operator must complete the demonstration no later than the date of initial receipt of CCR in the CCR unit.

(3) The owner or operator has completed the demonstration required by paragraph (a) of this section when the demonstration is placed in the facility's operating record as required by § 257.105(e).

(4) An owner or operator of an existing CCR surface impoundment who fails to demonstrate compliance with the requirements of paragraph (a) of this section by the date specified in paragraph (c)(1) of this section is subject to the requirements of § 257.101(b)(1).

(5) An owner or operator of a new CCR landfill, new CCR surface impoundment, or any lateral expansion of a CCR unit who fails to make the demonstration showing compliance with the requirements of paragraph (a) of this section is prohibited from placing CCR in the CCR unit.

(d) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(e), the notification requirements specified in § 257.106(e), and the Internet requirements specified in § 257.107(e).

§ 257.63 Seismic impact zones.

(a) New CCR landfills, existing and new CCR surface impoundments, and all lateral expansions of CCR units must not be located in seismic impact zones unless the owner or operator demonstrates by the dates specified in paragraph (c) of this section that all structural components including liners, leachate collection and removal systems, and surface water control systems, are designed to resist the maximum horizontal acceleration in lithified earth material for the site.

(b) The owner or operator of the CCR unit must obtain a certification from a qualified professional engineer stating that the demonstration meets the requirements of paragraph (a) of this section.

(c) The owner or operator of the CCR unit must complete the demonstration required by paragraph (a) of this section by the date specified in either paragraph (c)(1) or (2) of this section.

(1) For an existing CCR surface impoundment, the owner or operator must complete the demonstration no later than October 17, 2018.

(2) For a new CCR landfill, new CCR surface impoundment, or any lateral expansion of a CCR unit, the owner or operator must complete the demonstration no later than the date of initial receipt of CCR in the CCR unit.

(3) The owner or operator has completed the demonstration required by paragraph (a) of this section when the demonstration is placed in the facility's operating record as required by § 257.105(e).

(4) An owner or operator of an existing CCR surface impoundment who fails to demonstrate compliance with the requirements of paragraph (a) of this section by the date specified in paragraph (c)(1) of this section is subject to the requirements of § 257.101(b)(1).

(5) An owner or operator of a new CCR landfill, new CCR surface impoundment, or any lateral expansion of a CCR unit who fails to make the demonstration showing compliance with the requirements of paragraph (a) of this section is prohibited from placing CCR in the CCR unit.

(d) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(e), the notification requirements specified in § 257.106(e), and the Internet requirements specified in § 257.107(e).

§ 257.64 Unstable areas.

(a) An existing or new CCR landfill, existing or new CCR surface impoundment, or any lateral expansion of a CCR unit must not be located in an unstable area unless the owner or operator demonstrates by the dates specified in paragraph (d) of this section that recognized and generally accepted good engineering practices have been incorporated into the design of the CCR unit to ensure that the integrity of the structural components of the CCR unit will not be disrupted.

(b) The owner or operator must consider all of the following factors, at a minimum, when determining whether an area is unstable:

(1) On-site or local soil conditions that may result in significant differential settling;

(2) On-site or local geologic or geomorphologic features; and

(3) On-site or local human-made features or events (both surface and subsurface).

(c) The owner or operator of the CCR unit must obtain a certification from a qualified professional engineer stating that the demonstration meets the requirements of paragraph (a) of this section.

(d) The owner or operator of the CCR unit must complete the demonstration required by paragraph (a) of this section by the date specified in either paragraph (d)(1) or (2) of this section.

(1) For an existing CCR landfill or existing CCR surface impoundment, the owner or operator must complete the demonstration no later than October 17, 2018.

(2) For a new CCR landfill, new CCR surface impoundment, or any lateral expansion of a CCR unit, the owner or operator must complete the demonstration no later than the date of initial receipt of CCR in the CCR unit.

(3) The owner or operator has completed the demonstration required by paragraph (a) of this section when the demonstration is placed in the facility's operating record as required by § 257.105(e).

(4) An owner or operator of an existing CCR surface impoundment or existing CCR landfill who fails to demonstrate compliance with the requirements of paragraph (a) of this section by the date specified in paragraph (d)(1) of this section is subject to the requirements of § 257.101(b)(1) or (d)(1), respectively.

(5) An owner or operator of a new CCR landfill, new CCR surface impoundment, or any lateral expansion of a CCR unit who fails to make the demonstration showing compliance with the requirements of paragraph (a) of this section is prohibited from placing CCR in the CCR unit.

(e) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(e), the notification requirements specified in § 257.106(e), and the Internet requirements specified in § 257.107(e).

Design Criteria

§ 257.70 Design criteria for new CCR landfills and any lateral expansion of a CCR landfill.

(a)(1) New CCR landfills and any lateral expansion of a CCR landfill must be designed, constructed, operated, and maintained with either a composite liner that meets the requirements of paragraph (b) of this section or an alternative composite liner that meets the requirements in paragraph (c) of this section, and a leachate collection and removal system that meets the requirements of paragraph (d) of this section.

(2) Prior to construction of an overfill the underlying surface impoundment must meet the requirements of § 257.102(d).

(b) A *composite liner* must consist of two components; the upper component

consisting of, at a minimum, a 30-mil geomembrane liner (GM), and the lower component consisting of at least a two-foot layer of compacted soil with a hydraulic conductivity of no more than 1×10^{-7} centimeters per second (cm/sec). GM components consisting of high density polyethylene (HDPE) must be at least 60-mil thick. The GM or upper liner component must be installed in direct and uniform contact with the compacted soil or lower liner component. The composite liner must be:

(1) Constructed of materials that have appropriate chemical properties and sufficient strength and thickness to prevent failure due to pressure gradients (including static head and external hydrogeologic forces), physical contact with the CCR or leachate to which they are exposed, climatic conditions, the stress of installation, and the stress of daily operation;

(2) Constructed of materials that provide appropriate shear resistance of the upper and lower component interface to prevent sliding of the upper component including on slopes;

(3) Placed upon a foundation or base capable of providing support to the liner and resistance to pressure gradients above and below the liner to prevent failure of the liner due to settlement, compression, or uplift; and

(4) Installed to cover all surrounding earth likely to be in contact with the CCR or leachate.

(c) If the owner or operator elects to install an alternative composite liner, all of the following requirements must be met:

(1) An *alternative composite liner* must consist of two components; the upper component consisting of, at a minimum, a 30-mil GM, and a lower component, that is not a geomembrane, with a liquid flow rate no greater than the liquid flow rate of two feet of compacted soil with a hydraulic conductivity of no more than 1×10^{-7} cm/sec. GM components consisting of high density polyethylene (HDPE) must be at least 60-mil thick. If the lower component of the alternative liner is compacted soil, the GM must be installed in direct and uniform contact with the compacted soil.

(2) The owner or operator must obtain certification from a qualified professional engineer that the liquid flow rate through the lower component of the alternative composite liner is no greater than the liquid flow rate through two feet of compacted soil with a hydraulic conductivity of 1×10^{-7} cm/sec. The hydraulic conductivity for the two feet of compacted soil used in the comparison shall be no greater than 1×10^{-7} cm/sec. The hydraulic conductivity of any alternative to the two feet of compacted soil must be determined using recognized and generally accepted methods. The liquid flow rate comparison must be made using Equation 1 of this section, which is derived from Darcy's Law for gravity flow through porous media.

$$\text{(Eq. 1)} \qquad \frac{Q}{A} = q = k\left(\frac{h}{t} + 1\right)$$

Where,

Q = flow rate (cubic centimeters/second);
A = surface area of the liner (squared centimeters);
q = flow rate per unit area (cubic centimeters/second/squared centimeter);
k = hydraulic conductivity of the liner (centimeters/second);
h = hydraulic head above the liner (centimeters); and
t = thickness of the liner (centimeters).

(3) The alternative composite liner must meet the requirements specified in paragraphs (b)(1) through (4) of this section.

(d) The *leachate collection and removal system* must be designed, constructed, operated, and maintained to collect and remove leachate from the landfill during the active life and post-closure care period. The leachate collection and removal system must be:

(1) Designed and operated to maintain less than a 30-centimeter depth of leachate over the composite liner or alternative composite liner;

(2) Constructed of materials that are chemically resistant to the CCR and any non-CCR waste managed in the CCR unit and the leachate expected to be generated, and of sufficient strength and thickness to prevent collapse under the pressures exerted by overlying waste, waste cover materials, and equipment used at the CCR unit; and

(3) Designed and operated to minimize clogging during the active life and post-closure care period.

(e) Prior to construction of the CCR landfill or any lateral expansion of a CCR landfill, the owner or operator must obtain a certification from a qualified professional engineer that the design of the composite liner (or, if applicable, alternative composite liner) and the leachate collection and removal system meets the requirements of this section.

(f) Upon completion of construction of the CCR landfill or any lateral expansion of a CCR landfill, the owner or operator must obtain a certification from a qualified professional engineer that the composite liner (or, if applicable, alternative composite liner) and the leachate collection and removal system has been constructed in accordance with the requirements of this section.

(g) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(f), the notification requirements specified in § 257.106(f), and the Internet requirements specified in § 257.107(f).

§ 257.71 Liner design criteria for existing CCR surface impoundments.

(a)(1) No later than October 17, 2016, the owner or operator of an existing CCR surface impoundment must document whether or not such unit was constructed with any one of the following:

(i) A liner consisting of a minimum of two feet of compacted soil with a hydraulic conductivity of no more than 1×10^{-7} cm/sec;

(ii) A composite liner that meets the requirements of § 257.70(b); or

(iii) An alternative composite liner that meets the requirements of § 257.70(c).

(2) The hydraulic conductivity of the compacted soil must be determined using recognized and generally accepted methods.

(3) An existing CCR surface impoundment is considered to be an existing unlined CCR surface impoundment if either:

(i) The owner or operator of the CCR unit determines that the CCR unit is not constructed with a liner that meets the requirements of paragraphs (a)(1)(i), (ii), or (iii) of this section; or

(ii) The owner or operator of the CCR unit fails to document whether the CCR unit was constructed with a liner that meets the requirements of paragraphs (a)(1)(i), (ii), or (iii) of this section.

(4) All existing unlined CCR surface impoundments are subject to the requirements of § 257.101(a).

(b) The owner or operator of the CCR unit must obtain a certification from a qualified professional engineer attesting that the documentation as to whether a CCR unit meets the requirements of paragraph (a) of this section is accurate.

(c) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(f), the notification requirements specified in § 257.106(f), and the Internet requirements specified in § 257.107(f).

§ 257.72 Liner design criteria for new CCR surface impoundments and any lateral expansion of a CCR surface impoundment.

(a) New CCR surface impoundments and lateral expansions of existing and new CCR surface impoundments must

be designed, constructed, operated, and maintained with either a composite liner or an alternative composite liner that meets the requirements of § 257.70(b) or (c).

(b) Any liner specified in this section must be installed to cover all surrounding earth likely to be in contact with CCR. Dikes shall not be constructed on top of the composite liner.

(c) Prior to construction of the CCR surface impoundment or any lateral expansion of a CCR surface impoundment, the owner or operator must obtain certification from a qualified professional engineer that the design of the composite liner or, if applicable, the design of an alternative composite liner complies with the requirements of this section.

(d) Upon completion, the owner or operator must obtain certification from a qualified professional engineer that the composite liner or if applicable, the alternative composite liner has been constructed in accordance with the requirements of this section.

(e) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(f), the notification requirements specified in § 257.106(f), and the Internet requirements specified in § 257.107(f).

§ 257.73 Structural integrity criteria for existing CCR surface impoundments.

(a) The requirements of paragraphs (a)(1) through (4) of this section apply to all existing CCR surface impoundments, except for those existing CCR surface impoundments that are incised CCR units. If an incised CCR surface impoundment is subsequently modified (*e.g.,* a dike is constructed) such that the CCR unit no longer meets the definition of an incised CCR unit, the CCR unit is subject to the requirements of paragraphs (a)(1) through (4) of this section.

(1) No later than, December 17, 2015, the owner or operator of the CCR unit must place on or immediately adjacent to the CCR unit a permanent identification marker, at least six feet high showing the identification number of the CCR unit, if one has been assigned by the state, the name associated with the CCR unit and the name of the owner or operator of the CCR unit.

(2) *Periodic hazard potential classification assessments.* (i) The owner or operator of the CCR unit must conduct initial and periodic hazard potential classification assessments of the CCR unit according to the timeframes specified in paragraph (f) of this section. The owner or operator must document the hazard potential classification of each CCR unit as either a high hazard potential CCR surface impoundment, a significant hazard potential CCR surface impoundment, or a low hazard potential CCR surface impoundment. The owner or operator must also document the basis for each hazard potential classification.

(ii) The owner or operator of the CCR unit must obtain a certification from a qualified professional engineer stating that the initial hazard potential classification and each subsequent periodic classification specified in paragraph (a)(2)(i) of this section was conducted in accordance with the requirements of this section.

(3) *Emergency Action Plan (EAP)*—(i) *Development of the plan.* No later than April 17, 2017, the owner or operator of a CCR unit determined to be either a high hazard potential CCR surface impoundment or a significant hazard potential CCR surface impoundment under paragraph (a)(2) of this section must prepare and maintain a written EAP. At a minimum, the EAP must:

(A) Define the events or circumstances involving the CCR unit that represent a safety emergency, along with a description of the procedures that will be followed to detect a safety emergency in a timely manner;

(B) Define responsible persons, their respective responsibilities, and notification procedures in the event of a safety emergency involving the CCR unit;

(C) Provide contact information of emergency responders;

(D) Include a map which delineates the downstream area which would be affected in the event of a CCR unit failure and a physical description of the CCR unit; and

(E) Include provisions for an annual face-to-face meeting or exercise between representatives of the owner or operator of the CCR unit and the local emergency responders.

(ii) *Amendment of the plan.* (A) The owner or operator of a CCR unit subject to the requirements of paragraph (a)(3)(i) of this section may amend the written EAP at any time provided the revised plan is placed in the facility's operating record as required by § 257.105(f)(6). The owner or operator must amend the written EAP whenever there is a change in conditions that would substantially affect the EAP in effect.

(B) The written EAP must be evaluated, at a minimum, every five years to ensure the information required in paragraph (a)(3)(i) of this section is accurate. As necessary, the EAP must be updated and a revised EAP placed in the facility's operating record as required by § 257.105(f)(6).

(iii) *Changes in hazard potential classification.* (A) If the owner or operator of a CCR unit determines during a periodic hazard potential assessment that the CCR unit is no longer classified as either a high hazard potential CCR surface impoundment or a significant hazard potential CCR surface impoundment, then the owner or operator of the CCR unit is no longer subject to the requirement to prepare and maintain a written EAP beginning on the date the periodic hazard potential assessment documentation is placed in the facility's operating record as required by § 257.105(f)(5).

(B) If the owner or operator of a CCR unit classified as a low hazard potential CCR surface impoundment subsequently determines that the CCR unit is properly re-classified as either a high hazard potential CCR surface impoundment or a significant hazard potential CCR surface impoundment, then the owner or operator of the CCR unit must prepare a written EAP for the CCR unit as required by paragraph (a)(3)(i) of this section within six months of completing such periodic hazard potential assessment.

(iv) The owner or operator of the CCR unit must obtain a certification from a qualified professional engineer stating that the written EAP, and any subsequent amendment of the EAP, meets the requirements of paragraph (a)(3) of this section.

(v) *Activation of the EAP.* The EAP must be implemented once events or circumstances involving the CCR unit that represent a safety emergency are detected, including conditions identified during periodic structural stability assessments, annual inspections, and inspections by a qualified person.

(4) The CCR unit and surrounding areas must be designed, constructed, operated, and maintained with vegetated slopes of dikes not to exceed a height of 6 inches above the slope of the dike, except for slopes which are protected with an alternate form(s) of slope protection.

(b) The requirements of paragraphs (c) through (e) of this section apply to an owner or operator of an existing CCR surface impoundment that either:

(1) Has a height of five feet or more and a storage volume of 20 acre-feet or more; or

(2) Has a height of 20 feet or more.

(c)(1) No later than October 17, 2016, the owner or operator of the CCR unit must compile a history of construction, which shall contain, to the extent feasible, the information specified in

paragraphs (c)(1)(i) through (xi) of this section.

(i) The name and address of the person(s) owning or operating the CCR unit; the name associated with the CCR unit; and the identification number of the CCR unit if one has been assigned by the state.

(ii) The location of the CCR unit identified on the most recent U.S. Geological Survey (USGS) 7½ minute or 15 minute topographic quadrangle map, or a topographic map of equivalent scale if a USGS map is not available.

(iii) A statement of the purpose for which the CCR unit is being used.

(iv) The name and size in acres of the watershed within which the CCR unit is located.

(v) A description of the physical and engineering properties of the foundation and abutment materials on which the CCR unit is constructed.

(vi) A statement of the type, size, range, and physical and engineering properties of the materials used in constructing each zone or stage of the CCR unit; the method of site preparation and construction of each zone of the CCR unit; and the approximate dates of construction of each successive stage of construction of the CCR unit.

(vii) At a scale that details engineering structures and appurtenances relevant to the design, construction, operation, and maintenance of the CCR unit, detailed dimensional drawings of the CCR unit, including a plan view and cross sections of the length and width of the CCR unit, showing all zones, foundation improvements, drainage provisions, spillways, diversion ditches, outlets, instrument locations, and slope protection, in addition to the normal operating pool surface elevation and the maximum pool surface elevation following peak discharge from the inflow design flood, the expected maximum depth of CCR within the CCR surface impoundment, and any identifiable natural or manmade features that could adversely affect operation of the CCR unit due to malfunction or mis-operation.

(viii) A description of the type, purpose, and location of existing instrumentation.

(ix) Area-capacity curves for the CCR unit.

(x) A description of each spillway and diversion design features and capacities and calculations used in their determination.

(xi) The construction specifications and provisions for surveillance, maintenance, and repair of the CCR unit.

(xii) Any record or knowledge of structural instability of the CCR unit.

(2) *Changes to the history of construction.* If there is a significant change to any information compiled under paragraph (c)(1) of this section, the owner or operator of the CCR unit must update the relevant information and place it in the facility's operating record as required by § 257.105(f)(9).

(d) *Periodic structural stability assessments.* (1) The owner or operator of the CCR unit must conduct initial and periodic structural stability assessments and document whether the design, construction, operation, and maintenance of the CCR unit is consistent with recognized and generally accepted good engineering practices for the maximum volume of CCR and CCR wastewater which can be impounded therein. The assessment must, at a minimum, document whether the CCR unit has been designed, constructed, operated, and maintained with:

(i) Stable foundations and abutments;

(ii) Adequate slope protection to protect against surface erosion, wave action, and adverse effects of sudden drawdown;

(iii) Dikes mechanically compacted to a density sufficient to withstand the range of loading conditions in the CCR unit;

(iv) Vegetated slopes of dikes and surrounding areas not to exceed a height of six inches above the slope of the dike, except for slopes which have an alternate form or forms of slope protection;

(v) A single spillway or a combination of spillways configured as specified in paragraph (d)(1)(v)(A) of this section. The combined capacity of all spillways must be designed, constructed, operated, and maintained to adequately manage flow during and following the peak discharge from the event specified in paragraph (d)(1)(v)(B) of this section.

(A) All spillways must be either:

(*1*) Of non-erodible construction and designed to carry sustained flows; or

(*2*) Earth- or grass-lined and designed to carry short-term, infrequent flows at non-erosive velocities where sustained flows are not expected.

(B) The combined capacity of all spillways must adequately manage flow during and following the peak discharge from a:

(*1*) Probable maximum flood (PMF) for a high hazard potential CCR surface impoundment; or

(*2*) 1000-year flood for a significant hazard potential CCR surface impoundment; or

(*3*) 100-year flood for a low hazard potential CCR surface impoundment.

(vi) Hydraulic structures underlying the base of the CCR unit or passing through the dike of the CCR unit that maintain structural integrity and are free of significant deterioration, deformation, distortion, bedding deficiencies, sedimentation, and debris which may negatively affect the operation of the hydraulic structure; and

(vii) For CCR units with downstream slopes which can be inundated by the pool of an adjacent water body, such as a river, stream or lake, downstream slopes that maintain structural stability during low pool of the adjacent water body or sudden drawdown of the adjacent water body.

(2) The periodic assessment described in paragraph (d)(1) of this section must identify any structural stability deficiencies associated with the CCR unit in addition to recommending corrective measures. If a deficiency or a release is identified during the periodic assessment, the owner or operator unit must remedy the deficiency or release as soon as feasible and prepare documentation detailing the corrective measures taken.

(3) The owner or operator of the CCR unit must obtain a certification from a qualified professional engineer stating that the initial assessment and each subsequent periodic assessment was conducted in accordance with the requirements of this section.

(e) *Periodic safety factor assessments.* (1) The owner or operator must conduct an initial and periodic safety factor assessments for each CCR unit and document whether the calculated factors of safety for each CCR unit achieve the minimum safety factors specified in paragraphs (e)(1)(i) through (iv) of this section for the critical cross section of the embankment. The critical cross section is the cross section anticipated to be the most susceptible of all cross sections to structural failure based on appropriate engineering considerations, including loading conditions. The safety factor assessments must be supported by appropriate engineering calculations.

(i) The calculated static factor of safety under the long-term, maximum storage pool loading condition must equal or exceed 1.50.

(ii) The calculated static factor of safety under the maximum surcharge pool loading condition must equal or exceed 1.40.

(iii) The calculated seismic factor of safety must equal or exceed 1.00.

(iv) For dikes constructed of soils that have susceptibility to liquefaction, the calculated liquefaction factor of safety must equal or exceed 1.20.

(2) The owner or operator of the CCR unit must obtain a certification from a qualified professional engineer stating

that the initial assessment and each subsequent periodic assessment specified in paragraph (e)(1) of this section meets the requirements of this section.

(f) *Timeframes for periodic assessments*—(1) *Initial assessments.* Except as provided by paragraph (f)(2) of this section, the owner or operator of the CCR unit must complete the initial assessments required by paragraphs (a)(2), (d), and (e) of this section no later than October 17, 2016. The owner or operator has completed an initial assessment when the owner or operator has placed the assessment required by paragraphs (a)(2), (d), and (e) of this section in the facility's operating record as required by § 257.105(f)(5), (10), and (12).

(2) *Use of a previously completed assessment(s) in lieu of the initial assessment(s).* The owner or operator of the CCR unit may elect to use a previously completed assessment to serve as the initial assessment required by paragraphs (a)(2), (d), and (e) of this section provided that the previously completed assessment(s):

(i) Was completed no earlier than 42 months prior to October 17, 2016; and

(ii) Meets the applicable requirements of paragraphs (a)(2), (d), and (e) of this section.

(3) *Frequency for conducting periodic assessments.* The owner or operator of the CCR unit must conduct and complete the assessments required by paragraphs (a)(2), (d), and (e) of this section every five years. The date of completing the initial assessment is the basis for establishing the deadline to complete the first subsequent assessment. If the owner or operator elects to use a previously completed assessment(s) in lieu of the initial assessment as provided by paragraph (f)(2) of this section, the date of the report for the previously completed assessment is the basis for establishing the deadline to complete the first subsequent assessment. The owner or operator may complete any required assessment prior to the required deadline provided the owner or operator places the completed assessment(s) into the facility's operating record within a reasonable amount of time. In all cases, the deadline for completing subsequent assessments is based on the date of completing the previous assessment. For purposes of this paragraph (f)(3), the owner or operator has completed an assessment when the relevant assessment(s) required by paragraphs (a)(2), (d), and (e) of this section has been placed in the facility's operating record as required by § 257.105(f)(5), (10), and (12).

(4) *Closure of the CCR unit.* An owner or operator of a CCR unit who either fails to complete a timely safety factor assessment or fails to demonstrate minimum safety factors as required by paragraph (e) of this section is subject to the requirements of § 257.101(b)(2).

(g) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(f), the notification requirements specified in § 257.106(f), and the internet requirements specified in § 257.107(f).

§ 257.74 Structural integrity criteria for new CCR surface impoundments and any lateral expansion of a CCR surface impoundment.

(a) The requirements of paragraphs (a)(1) through (4) of this section apply to all new CCR surface impoundments and any lateral expansion of a CCR surface impoundment, except for those new CCR surface impoundments that are incised CCR units. If an incised CCR surface impoundment is subsequently modified (*e.g.,* a dike is constructed) such that the CCR unit no longer meets the definition of an incised CCR unit, the CCR unit is subject to the requirements of paragraphs (a)(1) through (4) of this section.

(1) No later than the initial receipt of CCR, the owner or operator of the CCR unit must place on or immediately adjacent to the CCR unit a permanent identification marker, at least six feet high showing the identification number of the CCR unit, if one has been assigned by the state, the name associated with the CCR unit and the name of the owner or operator of the CCR unit.

(2) *Periodic hazard potential classification assessments.* (i) The owner or operator of the CCR unit must conduct initial and periodic hazard potential classification assessments of the CCR unit according to the timeframes specified in paragraph (f) of this section. The owner or operator must document the hazard potential classification of each CCR unit as either a high hazard potential CCR surface impoundment, a significant hazard potential CCR surface impoundment, or a low hazard potential CCR surface impoundment. The owner or operator must also document the basis for each hazard potential classification.

(ii) The owner or operator of the CCR unit must obtain a certification from a qualified professional engineer stating that the initial hazard potential classification and each subsequent periodic classification specified in paragraph (a)(2)(i) of this section was conducted in accordance with the requirements of this section.

(3) *Emergency Action Plan (EAP)*—(i) *Development of the plan.* Prior to the initial receipt of CCR in the CCR unit, the owner or operator of a CCR unit determined to be either a high hazard potential CCR surface impoundment or a significant hazard potential CCR surface impoundment under paragraph (a)(2) of this section must prepare and maintain a written EAP. At a minimum, the EAP must:

(A) Define the events or circumstances involving the CCR unit that represent a safety emergency, along with a description of the procedures that will be followed to detect a safety emergency in a timely manner;

(B) Define responsible persons, their respective responsibilities, and notification procedures in the event of a safety emergency involving the CCR unit;

(C) Provide contact information of emergency responders;

(D) Include a map which delineates the downstream area which would be affected in the event of a CCR unit failure and a physical description of the CCR unit; and

(E) Include provisions for an annual face-to-face meeting or exercise between representatives of the owner or operator of the CCR unit and the local emergency responders.

(ii) *Amendment of the plan.* (A) The owner or operator of a CCR unit subject to the requirements of paragraph (a)(3)(i) of this section may amend the written EAP at any time provided the revised plan is placed in the facility's operating record as required by § 257.105(f)(6). The owner or operator must amend the written EAP whenever there is a change in conditions that would substantially affect the EAP in effect.

(B) The written EAP must be evaluated, at a minimum, every five years to ensure the information required in paragraph (a)(3)(i) of this section is accurate. As necessary, the EAP must be updated and a revised EAP placed in the facility's operating record as required by § 257.105(f)(6).

(iii) *Changes in hazard potential classification.* (A) If the owner or operator of a CCR unit determines during a periodic hazard potential assessment that the CCR unit is no longer classified as either a high hazard potential CCR surface impoundment or a significant hazard potential CCR surface impoundment, then the owner or operator of the CCR unit is no longer subject to the requirement to prepare and maintain a written EAP beginning on the date the periodic hazard potential assessment documentation is

placed in the facility's operating record as required by § 257.105(f)(5).

(B) If the owner or operator of a CCR unit classified as a low hazard potential CCR surface impoundment subsequently determines that the CCR unit is properly re-classified as either a high hazard potential CCR surface impoundment or a significant hazard potential CCR surface impoundment, then the owner or operator of the CCR unit must prepare a written EAP for the CCR unit as required by paragraph (a)(3)(i) of this section within six months of completing such periodic hazard potential assessment.

(iv) The owner or operator of the CCR unit must obtain a certification from a qualified professional engineer stating that the written EAP, and any subsequent amendment of the EAP, meets the requirements of paragraph (a)(3) of this section.

(v) *Activation of the EAP.* The EAP must be implemented once events or circumstances involving the CCR unit that represent a safety emergency are detected, including conditions identified during periodic structural stability assessments, annual inspections, and inspections by a qualified person.

(4) The CCR unit and surrounding areas must be designed, constructed, operated, and maintained with vegetated slopes of dikes not to exceed a height of six inches above the slope of the dike, except for slopes which are protected with an alternate form(s) of slope protection.

(b) The requirements of paragraphs (c) through (e) of this section apply to an owner or operator of a new CCR surface impoundment and any lateral expansion of a CCR surface impoundment that either:

(1) Has a height of five feet or more and a storage volume of 20 acre-feet or more; or

(2) Has a height of 20 feet or more.

(c)(1) No later than the initial receipt of CCR in the CCR unit, the owner or operator unit must compile the design and construction plans for the CCR unit, which must include, to the extent feasible, the information specified in paragraphs (c)(1)(i) through (xi) of this section.

(i) The name and address of the person(s) owning or operating the CCR unit; the name associated with the CCR unit; and the identification number of the CCR unit if one has been assigned by the state.

(ii) The location of the CCR unit identified on the most recent U.S. Geological Survey (USGS) 7½ minute or 15 minute topographic quadrangle map, or a topographic map of equivalent scale if a USGS map is not available.

(iii) A statement of the purpose for which the CCR unit is being used.

(iv) The name and size in acres of the watershed within which the CCR unit is located.

(v) A description of the physical and engineering properties of the foundation and abutment materials on which the CCR unit is constructed.

(vi) A statement of the type, size, range, and physical and engineering properties of the materials used in constructing each zone or stage of the CCR unit; the method of site preparation and construction of each zone of the CCR unit; and the dates of construction of each successive stage of construction of the CCR unit.

(vii) At a scale that details engineering structures and appurtenances relevant to the design, construction, operation, and maintenance of the CCR unit, detailed dimensional drawings of the CCR unit, including a plan view and cross sections of the length and width of the CCR unit, showing all zones, foundation improvements, drainage provisions, spillways, diversion ditches, outlets, instrument locations, and slope protection, in addition to the normal operating pool surface elevation and the maximum pool surface elevation following peak discharge from the inflow design flood, the expected maximum depth of CCR within the CCR surface impoundment, and any identifiable natural or manmade features that could adversely affect operation of the CCR unit due to malfunction or mis-operation.

(viii) A description of the type, purpose, and location of existing instrumentation.

(ix) Area-capacity curves for the CCR unit.

(x) A description of each spillway and diversion design features and capacities and calculations used in their determination.

(xi) The construction specifications and provisions for surveillance, maintenance, and repair of the CCR unit.

(xii) Any record or knowledge of structural instability of the CCR unit.

(2) *Changes in the design and construction.* If there is a significant change to any information compiled under paragraph (c)(1) of this section, the owner or operator of the CCR unit must update the relevant information and place it in the facility's operating record as required by § 257.105(f)(13).

(d) *Periodic structural stability assessments.* (1) The owner or operator of the CCR unit must conduct initial and periodic structural stability assessments and document whether the design, construction, operation, and maintenance of the CCR unit is consistent with recognized and generally accepted good engineering practices for the maximum volume of CCR and CCR wastewater which can be impounded therein. The assessment must, at a minimum, document whether the CCR unit has been designed, constructed, operated, and maintained with:

(i) Stable foundations and abutments;

(ii) Adequate slope protection to protect against surface erosion, wave action, and adverse effects of sudden drawdown;

(iii) Dikes mechanically compacted to a density sufficient to withstand the range of loading conditions in the CCR unit;

(iv) Vegetated slopes of dikes and surrounding areas not to exceed a height of six inches above the slope of the dike, except for slopes which have an alternate form or forms of slope protection;

(v) A single spillway or a combination of spillways configured as specified in paragraph (d)(1)(v)(A) of this section. The combined capacity of all spillways must be designed, constructed, operated, and maintained to adequately manage flow during and following the peak discharge from the event specified in paragraph (d)(1)(v)(B) of this section.

(A) All spillways must be either:

(*1*) Of non-erodible construction and designed to carry sustained flows; or

(*2*) Earth- or grass-lined and designed to carry short-term, infrequent flows at non-erosive velocities where sustained flows are not expected.

(B) The combined capacity of all spillways must adequately manage flow during and following the peak discharge from a:

(*1*) Probable maximum flood (PMF) for a high hazard potential CCR surface impoundment; or

(*2*) 1000-year flood for a significant hazard potential CCR surface impoundment; or

(*3*) 100-year flood for a low hazard potential CCR surface impoundment.

(vi) Hydraulic structures underlying the base of the CCR unit or passing through the dike of the CCR unit that maintain structural integrity and are free of significant deterioration, deformation, distortion, bedding deficiencies, sedimentation, and debris which may negatively affect the operation of the hydraulic structure; and

(vii) For CCR units with downstream slopes which can be inundated by the pool of an adjacent water body, such as a river, stream or lake, downstream slopes that maintain structural stability

during low pool of the adjacent water body or sudden drawdown of the adjacent water body.

(2) The periodic assessment described in paragraph (d)(1) of this section must identify any structural stability deficiencies associated with the CCR unit in addition to recommending corrective measures. If a deficiency or a release is identified during the periodic assessment, the owner or operator unit must remedy the deficiency or release as soon as feasible and prepare documentation detailing the corrective measures taken.

(3) The owner or operator of the CCR unit must obtain a certification from a qualified professional engineer stating that the initial assessment and each subsequent periodic assessment was conducted in accordance with the requirements of this section.

(e) *Periodic safety factor assessments.* (1) The owner or operator must conduct an initial and periodic safety factor assessments for each CCR unit and document whether the calculated factors of safety for each CCR unit achieve the minimum safety factors specified in paragraphs (e)(1)(i) through (v) of this section for the critical cross section of the embankment. The critical cross section is the cross section anticipated to be the most susceptible of all cross sections to structural failure based on appropriate engineering considerations, including loading conditions. The safety factor assessments must be supported by appropriate engineering calculations.

(i) The calculated static factor of safety under the end-of-construction loading condition must equal or exceed 1.30. The assessment of this loading condition is only required for the initial safety factor assessment and is not required for subsequent assessments.

(ii) The calculated static factor of safety under the long-term, maximum storage pool loading condition must equal or exceed 1.50.

(iii) The calculated static factor of safety under the maximum surcharge pool loading condition must equal or exceed 1.40.

(iv) The calculated seismic factor of safety must equal or exceed 1.00.

(v) For dikes constructed of soils that have susceptibility to liquefaction, the calculated liquefaction factor of safety must equal or exceed 1.20.

(2) The owner or operator of the CCR unit must obtain a certification from a qualified professional engineer stating that the initial assessment and each subsequent periodic assessment specified in paragraph (e)(1) of this section meets the requirements of this section.

(f) *Timeframes for periodic assessments*—(1) *Initial assessments.* Except as provided by paragraph (f)(2) of this section, the owner or operator of the CCR unit must complete the initial assessments required by paragraphs (a)(2), (d), and (e) of this section prior to the initial receipt of CCR in the unit. The owner or operator has completed an initial assessment when the owner or operator has placed the assessment required by paragraphs (a)(2), (d), and (e) of this section in the facility's operating record as required by § 257.105(f)(5), (10), and (12).

(2) *Frequency for conducting periodic assessments.* The owner or operator of the CCR unit must conduct and complete the assessments required by paragraphs (a)(2), (d), and (e) of this section every five years. The date of completing the initial assessment is the basis for establishing the deadline to complete the first subsequent assessment. The owner or operator may complete any required assessment prior to the required deadline provided the owner or operator places the completed assessment(s) into the facility's operating record within a reasonable amount of time. In all cases, the deadline for completing subsequent assessments is based on the date of completing the previous assessment. For purposes of this paragraph (f)(2), the owner or operator has completed an assessment when the relevant assessment(s) required by paragraphs (a)(2), (d), and (e) of this section has been placed in the facility's operating record as required by § 257.105(f)(5), (10), and (12).

(3) *Failure to document minimum safety factors during the initial assessment.* Until the date an owner or operator of a CCR unit documents that the calculated factors of safety achieve the minimum safety factors specified in paragraphs (e)(1)(i) through (v) of this section, the owner or operator is prohibited from placing CCR in such unit.

(4) *Closure of the CCR unit.* An owner or operator of a CCR unit who either fails to complete a timely periodic safety factor assessment or fails to demonstrate minimum safety factors as required by paragraph (e) of this section is subject to the requirements of § 257.101(c).

(g) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(f), the notification requirements specified in § 257.106(f), and the internet requirements specified in § 257.107(f).

Operating Criteria

§ 257.80 Air criteria.

(a) The owner or operator of a CCR landfill, CCR surface impoundment, or any lateral expansion of a CCR unit must adopt measures that will effectively minimize CCR from becoming airborne at the facility, including CCR fugitive dust originating from CCR units, roads, and other CCR management and material handling activities.

(b) *CCR fugitive dust control plan.* The owner or operator of the CCR unit must prepare and operate in accordance with a CCR fugitive dust control plan as specified in paragraphs (b)(1) through (7) of this section. This requirement applies in addition to, not in place of, any applicable standards under the Occupational Safety and Health Act.

(1) The CCR fugitive dust control plan must identify and describe the CCR fugitive dust control measures the owner or operator will use to minimize CCR from becoming airborne at the facility. The owner or operator must select, and include in the CCR fugitive dust control plan, the CCR fugitive dust control measures that are most appropriate for site conditions, along with an explanation of how the measures selected are applicable and appropriate for site conditions. Examples of control measures that may be appropriate include: Locating CCR inside an enclosure or partial enclosure; operating a water spray or fogging system; reducing fall distances at material drop points; using wind barriers, compaction, or vegetative covers; establishing and enforcing reduced vehicle speed limits; paving and sweeping roads; covering trucks transporting CCR; reducing or halting operations during high wind events; or applying a daily cover.

(2) If the owner or operator operates a CCR landfill or any lateral expansion of a CCR landfill, the CCR fugitive dust control plan must include procedures to emplace CCR as conditioned CCR. Conditioned CCR means wetting CCR with water to a moisture content that will prevent wind dispersal, but will not result in free liquids. In lieu of water, CCR conditioning may be accomplished with an appropriate chemical dust suppression agent.

(3) The CCR fugitive dust control plan must include procedures to log citizen complaints received by the owner or operator involving CCR fugitive dust events at the facility.

(4) The CCR fugitive dust control plan must include a description of the procedures the owner or operator will

follow to periodically assess the effectiveness of the control plan.

(5) The owner or operator of a CCR unit must prepare an initial CCR fugitive dust control plan for the facility no later than October 19, 2015, or by initial receipt of CCR in any CCR unit at the facility if the owner or operator becomes subject to this subpart after October 19, 2015. The owner or operator has completed the initial CCR fugitive dust control plan when the plan has been placed in the facility's operating record as required by § 257.105(g)(1).

(6) *Amendment of the plan.* The owner or operator of a CCR unit subject to the requirements of this section may amend the written CCR fugitive dust control plan at any time provided the revised plan is placed in the facility's operating record as required by § 257.105(g)(1). The owner or operator must amend the written plan whenever there is a change in conditions that would substantially affect the written plan in effect, such as the construction and operation of a new CCR unit.

(7) The owner or operator must obtain a certification from a qualified professional engineer that the initial CCR fugitive dust control plan, or any subsequent amendment of it, meets the requirements of this section.

(c) *Annual CCR fugitive dust control report.* The owner or operator of a CCR unit must prepare an annual CCR fugitive dust control report that includes a description of the actions taken by the owner or operator to control CCR fugitive dust, a record of all citizen complaints, and a summary of any corrective measures taken. The initial annual report must be completed no later than 14 months after placing the initial CCR fugitive dust control plan in the facility's operating record. The deadline for completing a subsequent report is one year after the date of completing the previous report. For purposes of this paragraph (c), the owner or operator has completed the annual CCR fugitive dust control report when the plan has been placed in the facility's operating record as required by § 257.105(g)(2).

(d) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(g), the notification requirements specified in § 257.106(g), and the internet requirements specified in § 257.107(g).

§ 257.81 Run-on and run-off controls for CCR landfills.

(a) The owner or operator of an existing or new CCR landfill or any lateral expansion of a CCR landfill must design, construct, operate, and maintain:

(1) A run-on control system to prevent flow onto the active portion of the CCR unit during the peak discharge from a 24-hour, 25-year storm; and

(2) A run-off control system from the active portion of the CCR unit to collect and control at least the water volume resulting from a 24-hour, 25-year storm.

(b) Run-off from the active portion of the CCR unit must be handled in accordance with the surface water requirements under § 257.3–3.

(c) *Run-on and run-off control system plan*—(1) *Content of the plan.* The owner or operator must prepare initial and periodic run-on and run-off control system plans for the CCR unit according to the timeframes specified in paragraphs (c)(3) and (4) of this section. These plans must document how the run-on and run-off control systems have been designed and constructed to meet the applicable requirements of this section. Each plan must be supported by appropriate engineering calculations. The owner or operator has completed the initial run-on and run-off control system plan when the plan has been placed in the facility's operating record as required by § 257.105(g)(3).

(2) *Amendment of the plan.* The owner or operator may amend the written run-on and run-off control system plan at any time provided the revised plan is placed in the facility's operating record as required by § 257.105(g)(3). The owner or operator must amend the written run-on and run-off control system plan whenever there is a change in conditions that would substantially affect the written plan in effect.

(3) *Timeframes for preparing the initial plan*—(i) *Existing CCR landfills.* The owner or operator of the CCR unit must prepare the initial run-on and run-off control system plan no later than October 17, 2016.

(ii) *New CCR landfills and any lateral expansion of a CCR landfill.* The owner or operator must prepare the initial run-on and run-off control system plan no later than the date of initial receipt of CCR in the CCR unit.

(4) *Frequency for revising the plan.* The owner or operator of the CCR unit must prepare periodic run-on and run-off control system plans required by paragraph (c)(1) of this section every five years. The date of completing the initial plan is the basis for establishing the deadline to complete the first subsequent plan. The owner or operator may complete any required plan prior to the required deadline provided the owner or operator places the completed plan into the facility's operating record within a reasonable amount of time. In all cases, the deadline for completing a subsequent plan is based on the date of completing the previous plan. For purposes of this paragraph (c)(4), the owner or operator has completed a periodic run-on and run-off control system plan when the plan has been placed in the facility's operating record as required by § 257.105(g)(3).

(5) The owner or operator must obtain a certification from a qualified professional engineer stating that the initial and periodic run-on and run-off control system plans meet the requirements of this section.

(d) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(g), the notification requirements specified in § 257.106(g), and the internet requirements specified in § 257.107(g).

§ 257.82 Hydrologic and hydraulic capacity requirements for CCR surface impoundments.

(a) The owner or operator of an existing or new CCR surface impoundment or any lateral expansion of a CCR surface impoundment must design, construct, operate, and maintain an inflow design flood control system as specified in paragraphs (a)(1) and (2) of this section.

(1) The inflow design flood control system must adequately manage flow into the CCR unit during and following the peak discharge of the inflow design flood specified in paragraph (a)(3) of this section.

(2) The inflow design flood control system must adequately manage flow from the CCR unit to collect and control the peak discharge resulting from the inflow design flood specified in paragraph (a)(3) of this section.

(3) The inflow design flood is:

(i) For a high hazard potential CCR surface impoundment, as determined under § 257.73(a)(2) or § 257.74(a)(2), the probable maximum flood;

(ii) For a significant hazard potential CCR surface impoundment, as determined under § 257.73(a)(2) or § 257.74(a)(2), the 1,000-year flood;

(iii) For a low hazard potential CCR surface impoundment, as determined under § 257.73(a)(2) or § 257.74(a)(2), the 100-year flood; or

(iv) For an incised CCR surface impoundment, the 25-year flood.

(b) Discharge from the CCR unit must be handled in accordance with the surface water requirements under § 257.3–3.

(c) *Inflow design flood control system plan*—(1) *Content of the plan.* The owner or operator must prepare initial

and periodic inflow design flood control system plans for the CCR unit according to the timeframes specified in paragraphs (c)(3) and (4) of this section. These plans must document how the inflow design flood control system has been designed and constructed to meet the requirements of this section. Each plan must be supported by appropriate engineering calculations. The owner or operator of the CCR unit has completed the inflow design flood control system plan when the plan has been placed in the facility's operating record as required by § 257.105(g)(4).

(2) *Amendment of the plan.* The owner or operator of the CCR unit may amend the written inflow design flood control system plan at any time provided the revised plan is placed in the facility's operating record as required by § 257.105(g)(4). The owner or operator must amend the written inflow design flood control system plan whenever there is a change in conditions that would substantially affect the written plan in effect.

(3) *Timeframes for preparing the initial plan*—(i) *Existing CCR surface impoundments.* The owner or operator of the CCR unit must prepare the initial inflow design flood control system plan no later than October 17, 2016.

(ii) *New CCR surface impoundments and any lateral expansion of a CCR surface impoundment.* The owner or operator must prepare the initial inflow design flood control system plan no later than the date of initial receipt of CCR in the CCR unit.

(4) *Frequency for revising the plan.* The owner or operator must prepare periodic inflow design flood control system plans required by paragraph (c)(1) of this section every five years. The date of completing the initial plan is the basis for establishing the deadline to complete the first periodic plan. The owner or operator may complete any required plan prior to the required deadline provided the owner or operator places the completed plan into the facility's operating record within a reasonable amount of time. In all cases, the deadline for completing a subsequent plan is based on the date of completing the previous plan. For purposes of this paragraph (c)(4), the owner or operator has completed an inflow design flood control system plan when the plan has been placed in the facility's operating record as required by § 257.105(g)(4).

(5) The owner or operator must obtain a certification from a qualified professional engineer stating that the initial and periodic inflow design flood control system plans meet the requirements of this section.

(d) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(g), the notification requirements specified in § 257.106(g), and the internet requirements specified in § 257.107(g).

§ 257.83 Inspection requirements for CCR surface impoundments.

(a) *Inspections by a qualified person.* (1) All CCR surface impoundments and any lateral expansion of a CCR surface impoundment must be examined by a qualified person as follows:

(i) At intervals not exceeding seven days, inspect for any appearances of actual or potential structural weakness and other conditions which are disrupting or have the potential to disrupt the operation or safety of the CCR unit;

(ii) At intervals not exceeding seven days, inspect the discharge of all outlets of hydraulic structures which pass underneath the base of the surface impoundment or through the dike of the CCR unit for abnormal discoloration, flow or discharge of debris or sediment; and

(iii) At intervals not exceeding 30 days, monitor all CCR unit instrumentation.

(iv) The results of the inspection by a qualified person must be recorded in the facility's operating record as required by § 257.105(g)(5).

(2) *Timeframes for inspections by a qualified person*—(i) *Existing CCR surface impoundments.* The owner or operator of the CCR unit must initiate the inspections required under paragraph (a) of this section no later than October 19, 2015.

(ii) *New CCR surface impoundments and any lateral expansion of a CCR surface impoundment.* The owner or operator of the CCR unit must initiate the inspections required under paragraph (a) of this section upon initial receipt of CCR by the CCR unit.

(b) Annual i*nspections by a qualified professional engineer.* (1) If the existing or new CCR surface impoundment or any lateral expansion of the CCR surface impoundment is subject to the periodic structural stability assessment requirements under § 257.73(d) or § 257.74(d), the CCR unit must additionally be inspected on a periodic basis by a qualified professional engineer to ensure that the design, construction, operation, and maintenance of the CCR unit is consistent with recognized and generally accepted good engineering standards. The inspection must, at a minimum, include:

(i) A review of available information regarding the status and condition of the CCR unit, including, but not limited to, files available in the operating record (*e.g.,* CCR unit design and construction information required by §§ 257.73(c)(1) and 257.74(c)(1), previous periodic structural stability assessments required under §§ 257.73(d) and 257.74(d), the results of inspections by a qualified person, and results of previous annual inspections);

(ii) A visual inspection of the CCR unit to identify signs of distress or malfunction of the CCR unit and appurtenant structures; and

(iii) A visual inspection of any hydraulic structures underlying the base of the CCR unit or passing through the dike of the CCR unit for structural integrity and continued safe and reliable operation.

(2) *Inspection report.* The qualified professional engineer must prepare a report following each inspection that addresses the following:

(i) Any changes in geometry of the impounding structure since the previous annual inspection;

(ii) The location and type of existing instrumentation and the maximum recorded readings of each instrument since the previous annual inspection;

(iii) The approximate minimum, maximum, and present depth and elevation of the impounded water and CCR since the previous annual inspection;

(iv) The storage capacity of the impounding structure at the time of the inspection;

(v) The approximate volume of the impounded water and CCR at the time of the inspection;

(vi) Any appearances of an actual or potential structural weakness of the CCR unit, in addition to any existing conditions that are disrupting or have the potential to disrupt the operation and safety of the CCR unit and appurtenant structures; and

(vii) Any other change(s) which may have affected the stability or operation of the impounding structure since the previous annual inspection.

(3) *Timeframes for conducting the initial inspection*—(i) *Existing CCR surface impoundments.* The owner or operator of the CCR unit must complete the initial inspection required by paragraphs (b)(1) and (2) of this section no later than January 18, 2016.

(ii) *New CCR surface impoundments and any lateral expansion of a CCR surface impoundment.* The owner or operator of the CCR unit must complete the initial annual inspection required by paragraphs (b)(1) and (2) of this section is completed no later than 14 months

following the date of initial receipt of CCR in the CCR unit.

(4) *Frequency of inspections.* (i) Except as provided for in paragraph (b)(4)(ii) of this section, the owner or operator of the CCR unit must conduct the inspection required by paragraphs (b)(1) and (2) of this section on an annual basis. The date of completing the initial inspection report is the basis for establishing the deadline to complete the first subsequent inspection. Any required inspection may be conducted prior to the required deadline provided the owner or operator places the completed inspection report into the facility's operating record within a reasonable amount of time. In all cases, the deadline for completing subsequent inspection reports is based on the date of completing the previous inspection report. For purposes of this section, the owner or operator has completed an inspection when the inspection report has been placed in the facility's operating record as required by § 257.105(g)(6).

(ii) In any calendar year in which both the periodic inspection by a qualified professional engineer and the quinquennial (occurring every five years) structural stability assessment by a qualified professional engineer required by §§ 257.73(d) and 257.74(d) are required to be completed, the annual inspection is not required, provided the structural stability assessment is completed during the calendar year. If the annual inspection is not conducted in a year as provided by this paragraph (b)(4)(ii), the deadline for completing the next annual inspection is one year from the date of completing the quinquennial structural stability assessment.

(5) If a deficiency or release is identified during an inspection, the owner or operator must remedy the deficiency or release as soon as feasible and prepare documentation detailing the corrective measures taken.

(c) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(g), the notification requirements specified in § 257.106(g), and the internet requirements specified in § 257.107(g).

§ 257.84 Inspection requirements for CCR landfills.

(a) *Inspections by a qualified person.* (1) All CCR landfills and any lateral expansion of a CCR landfill must be examined by a qualified person as follows:

(i) At intervals not exceeding seven days, inspect for any appearances of actual or potential structural weakness and other conditions which are disrupting or have the potential to disrupt the operation or safety of the CCR unit; and

(ii) The results of the inspection by a qualified person must be recorded in the facility's operating record as required by § 257.105(g)(8).

(2) *Timeframes for inspections by a qualified person*—(i) *Existing CCR landfills.* The owner or operator of the CCR unit must initiate the inspections required under paragraph (a) of this section no later than October 19, 2015.

(ii) *New CCR landfills and any lateral expansion of a CCR landfill.* The owner or operator of the CCR unit must initiate the inspections required under paragraph (a) of this section upon initial receipt of CCR by the CCR unit.

(b) *Annual inspections by a qualified professional engineer.* (1) Existing and new CCR landfills and any lateral expansion of a CCR landfill must be inspected on a periodic basis by a qualified professional engineer to ensure that the design, construction, operation, and maintenance of the CCR unit is consistent with recognized and generally accepted good engineering standards. The inspection must, at a minimum, include:

(i) A review of available information regarding the status and condition of the CCR unit, including, but not limited to, files available in the operating record (*e.g.,* the results of inspections by a qualified person, and results of previous annual inspections); and

(ii) A visual inspection of the CCR unit to identify signs of distress or malfunction of the CCR unit.

(2) *Inspection report.* The qualified professional engineer must prepare a report following each inspection that addresses the following:

(i) Any changes in geometry of the structure since the previous annual inspection;

(ii) The approximate volume of CCR contained in the unit at the time of the inspection;

(iii) Any appearances of an actual or potential structural weakness of the CCR unit, in addition to any existing conditions that are disrupting or have the potential to disrupt the operation and safety of the CCR unit; and

(iv) Any other change(s) which may have affected the stability or operation of the CCR unit since the previous annual inspection.

(3) *Timeframes for conducting the initial inspection*—(i) *Existing CCR landfills.* The owner or operator of the CCR unit must complete the initial inspection required by paragraphs (b)(1) and (2) of this section no later than January 18, 2016.

(ii) *New CCR landfills and any lateral expansion of a CCR landfill.* The owner or operator of the CCR unit must complete the initial annual inspection required by paragraphs (b)(1) and (2) of this section no later than 14 months following the date of initial receipt of CCR in the CCR unit.

(4) *Frequency of inspections.* The owner or operator of the CCR unit must conduct the inspection required by paragraphs (b)(1) and (2) of this section on an annual basis. The date of completing the initial inspection report is the basis for establishing the deadline to complete the first subsequent inspection. Any required inspection may be conducted prior to the required deadline provided the owner or operator places the completed inspection report into the facility's operating record within a reasonable amount of time. In all cases, the deadline for completing subsequent inspection reports is based on the date of completing the previous inspection report. For purposes of this section, the owner or operator has completed an inspection when the inspection report has been placed in the facility's operating record as required by § 257.105(g)(9).

(5) If a deficiency or release is identified during an inspection, the owner or operator must remedy the deficiency or release as soon as feasible and prepare documentation detailing the corrective measures taken.

(c) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(g), the notification requirements specified in § 257.106(g), and the internet requirements specified in § 257.107(g).

Groundwater Monitoring and Corrective Action

§ 257.90 Applicability.

(a) Except as provided for in § 257.100 for inactive CCR surface impoundments, all CCR landfills, CCR surface impoundments, and lateral expansions of CCR units are subject to the groundwater monitoring and corrective action requirements under §§ 257.90 through 257.98.

(b) *Initial timeframes*—(1) *Existing CCR landfills and existing CCR surface impoundments.* No later than October 17, 2017, the owner or operator of the CCR unit must be in compliance with the following groundwater monitoring requirements:

(i) Install the groundwater monitoring system as required by § 257.91;

(ii) Develop the groundwater sampling and analysis program to include selection of the statistical

procedures to be used for evaluating groundwater monitoring data as required by § 257.93;

(iii) Initiate the detection monitoring program to include obtaining a minimum of eight independent samples for each background and downgradient well as required by § 257.94(b); and

(iv) Begin evaluating the groundwater monitoring data for statistically significant increases over background levels for the constituents listed in appendix III of this part as required by § 257.94.

(2) *New CCR landfills, new CCR surface impoundments, and all lateral expansions of CCR units.* Prior to initial receipt of CCR by the CCR unit, the owner or operator must be in compliance with the groundwater monitoring requirements specified in paragraph (b)(1)(i) and (ii) of this section. In addition, the owner or operator of the CCR unit must initiate the detection monitoring program to include obtaining a minimum of eight independent samples for each background well as required by § 257.94(b).

(c) Once a groundwater monitoring system and groundwater monitoring program has been established at the CCR unit as required by this subpart, the owner or operator must conduct groundwater monitoring and, if necessary, corrective action throughout the active life and post-closure care period of the CCR unit.

(d) In the event of a release from a CCR unit, the owner or operator must immediately take all necessary measures to control the source(s) of releases so as to reduce or eliminate, to the maximum extent feasible, further releases of contaminants into the environment. The owner or operator of the CCR unit must comply with all applicable requirements in §§ 257.96, 257.97, and 257.98.

(e) *Annual groundwater monitoring and corrective action report.* For existing CCR landfills and existing CCR surface impoundments, no later than January 31, 2018, and annually thereafter, the owner or operator must prepare an annual groundwater monitoring and corrective action report. For new CCR landfills, new CCR surface impoundments, and all lateral expansions of CCR units, the owner or operator must prepare the initial annual groundwater monitoring and corrective action report no later than January 31 of the year following the calendar year a groundwater monitoring system has been established for such CCR unit as required by this subpart, and annually thereafter. For the preceding calendar year, the annual report must document the status of the groundwater monitoring and corrective action program for the CCR unit, summarize key actions completed, describe any problems encountered, discuss actions to resolve the problems, and project key activities for the upcoming year. For purposes of this section, the owner or operator has prepared the annual report when the report is placed in the facility's operating record as required by § 257.105(h)(1). At a minimum, the annual groundwater monitoring and corrective action report must contain the following information, to the extent available:

(1) A map, aerial image, or diagram showing the CCR unit and all background (or upgradient) and downgradient monitoring wells, to include the well identification numbers, that are part of the groundwater monitoring program for the CCR unit;

(2) Identification of any monitoring wells that were installed or decommissioned during the preceding year, along with a narrative description of why those actions were taken;

(3) In addition to all the monitoring data obtained under §§ 257.90 through 257.98, a summary including the number of groundwater samples that were collected for analysis for each background and downgradient well, the dates the samples were collected, and whether the sample was required by the detection monitoring or assessment monitoring programs;

(4) A narrative discussion of any transition between monitoring programs (*e.g.,* the date and circumstances for transitioning from detection monitoring to assessment monitoring in addition to identifying the constituent(s) detected at a statistically significant increase over background levels); and

(5) Other information required to be included in the annual report as specified in §§ 257.90 through 257.98.

(f) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(h), the notification requirements specified in § 257.106(h), and the internet requirements specified in § 257.107(h).

§ 257.91 Groundwater monitoring systems.

(a) *Performance standard.* The owner or operator of a CCR unit must install a groundwater monitoring system that consists of a sufficient number of wells, installed at appropriate locations and depths, to yield groundwater samples from the uppermost aquifer that:

(1) Accurately represent the quality of background groundwater that has not been affected by leakage from a CCR unit. A determination of background quality may include sampling of wells that are not hydraulically upgradient of the CCR management area where:

(i) Hydrogeologic conditions do not allow the owner or operator of the CCR unit to determine what wells are hydraulically upgradient; or

(ii) Sampling at other wells will provide an indication of background groundwater quality that is as representative or more representative than that provided by the upgradient wells; and

(2) Accurately represent the quality of groundwater passing the waste boundary of the CCR unit. The downgradient monitoring system must be installed at the waste boundary that ensures detection of groundwater contamination in the uppermost aquifer. All potential contaminant pathways must be monitored.

(b) The number, spacing, and depths of monitoring systems shall be determined based upon site-specific technical information that must include thorough characterization of:

(1) Aquifer thickness, groundwater flow rate, groundwater flow direction including seasonal and temporal fluctuations in groundwater flow; and

(2) Saturated and unsaturated geologic units and fill materials overlying the uppermost aquifer, materials comprising the uppermost aquifer, and materials comprising the confining unit defining the lower boundary of the uppermost aquifer, including, but not limited to, thicknesses, stratigraphy, lithology, hydraulic conductivities, porosities and effective porosities.

(c) The groundwater monitoring system must include the minimum number of monitoring wells necessary to meet the performance standards specified in paragraph (a) of this section, based on the site-specific information specified in paragraph (b) of this section. The groundwater monitoring system must contain:

(1) A minimum of one upgradient and three downgradient monitoring wells; and

(2) Additional monitoring wells as necessary to accurately represent the quality of background groundwater that has not been affected by leakage from the CCR unit and the quality of groundwater passing the waste boundary of the CCR unit.

(d) The owner or operator of multiple CCR units may install a multiunit groundwater monitoring system instead of separate groundwater monitoring systems for each CCR unit.

(1) The multiunit groundwater monitoring system must be equally as capable of detecting monitored constituents at the waste boundary of

the CCR unit as the individual groundwater monitoring system specified in paragraphs (a) through (c) of this section for each CCR unit based on the following factors:

(i) Number, spacing, and orientation of each CCR unit;

(ii) Hydrogeologic setting;

(iii) Site history; and

(iv) Engineering design of the CCR unit.

(2) If the owner or operator elects to install a multiunit groundwater monitoring system, and if the multiunit system includes at least one existing unlined CCR surface impoundment as determined by § 257.71(a), and if at any time after October 19, 2015 the owner or operator determines in any sampling event that the concentrations of one or more constituents listed in appendix IV to this part are detected at statistically significant levels above the groundwater protection standard established under § 257.95(h) for the multiunit system, then all unlined CCR surface impoundments comprising the multiunit groundwater monitoring system are subject to the closure requirements under § 257.101(a) to retrofit or close.

(e) Monitoring wells must be cased in a manner that maintains the integrity of the monitoring well borehole. This casing must be screened or perforated and packed with gravel or sand, where necessary, to enable collection of groundwater samples. The annular space (*i.e.,* the space between the borehole and well casing) above the sampling depth must be sealed to prevent contamination of samples and the groundwater.

(1) The owner or operator of the CCR unit must document and include in the operating record the design, installation, development, and decommissioning of any monitoring wells, piezometers and other measurement, sampling, and analytical devices. The qualified professional engineer must be given access to this documentation when completing the groundwater monitoring system certification required under paragraph (f) of this section.

(2) The monitoring wells, piezometers, and other measurement, sampling, and analytical devices must be operated and maintained so that they perform to the design specifications throughout the life of the monitoring program.

(f) The owner or operator must obtain a certification from a qualified professional engineer stating that the groundwater monitoring system has been designed and constructed to meet the requirements of this section. If the groundwater monitoring system includes the minimum number of monitoring wells specified in paragraph (c)(1) of this section, the certification must document the basis supporting this determination.

(g) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(h), the notification requirements specified in § 257.106(h), and the internet requirements specified in § 257.107(h).

§ 257.92 [Reserved]

§ 257.93 Groundwater sampling and analysis requirements.

(a) The groundwater monitoring program must include consistent sampling and analysis procedures that are designed to ensure monitoring results that provide an accurate representation of groundwater quality at the background and downgradient wells required by § 257.91. The owner or operator of the CCR unit must develop a sampling and analysis program that includes procedures and techniques for:

(1) Sample collection;

(2) Sample preservation and shipment;

(3) Analytical procedures;

(4) Chain of custody control; and

(5) Quality assurance and quality control.

(b) The groundwater monitoring program must include sampling and analytical methods that are appropriate for groundwater sampling and that accurately measure hazardous constituents and other monitoring parameters in groundwater samples. For purposes of §§ 257.90 through 257.98, the term *constituent* refers to both hazardous constituents and other monitoring parameters listed in either appendix III or IV of this part.

(c) Groundwater elevations must be measured in each well immediately prior to purging, each time groundwater is sampled. The owner or operator of the CCR unit must determine the rate and direction of groundwater flow each time groundwater is sampled. Groundwater elevations in wells which monitor the same CCR management area must be measured within a period of time short enough to avoid temporal variations in groundwater flow which could preclude accurate determination of groundwater flow rate and direction.

(d) The owner or operator of the CCR unit must establish background groundwater quality in a hydraulically upgradient or background well(s) for each of the constituents required in the particular groundwater monitoring program that applies to the CCR unit as determined under § 257.94(a) or § 257.95(a). Background groundwater quality may be established at wells that are not located hydraulically upgradient from the CCR unit if it meets the requirements of § 257.91(a)(1).

(e) The number of samples collected when conducting detection monitoring and assessment monitoring (for both downgradient and background wells) must be consistent with the statistical procedures chosen under paragraph (f) of this section and the performance standards under paragraph (g) of this section. The sampling procedures shall be those specified under § 257.94(b) through (d) for detection monitoring, § 257.95(b) through (d) for assessment monitoring, and § 257.96(b) for corrective action.

(f) The owner or operator of the CCR unit must select one of the statistical methods specified in paragraphs (f)(1) through (5) of this section to be used in evaluating groundwater monitoring data for each specified constituent. The statistical test chosen shall be conducted separately for each constituent in each monitoring well.

(1) A parametric analysis of variance followed by multiple comparison procedures to identify statistically significant evidence of contamination. The method must include estimation and testing of the contrasts between each compliance well's mean and the background mean levels for each constituent.

(2) An analysis of variance based on ranks followed by multiple comparison procedures to identify statistically significant evidence of contamination. The method must include estimation and testing of the contrasts between each compliance well's median and the background median levels for each constituent.

(3) A tolerance or prediction interval procedure, in which an interval for each constituent is established from the distribution of the background data and the level of each constituent in each compliance well is compared to the upper tolerance or prediction limit.

(4) A control chart approach that gives control limits for each constituent.

(5) Another statistical test method that meets the performance standards of paragraph (g) of this section.

(6) The owner or operator of the CCR unit must obtain a certification from a qualified professional engineer stating that the selected statistical method is appropriate for evaluating the groundwater monitoring data for the CCR management area. The certification must include a narrative description of the statistical method selected to evaluate the groundwater monitoring data.

(g) Any statistical method chosen under paragraph (f) of this section shall comply with the following performance standards, as appropriate, based on the statistical test method used:

(1) The statistical method used to evaluate groundwater monitoring data shall be appropriate for the distribution of constituents. Normal distributions of data values shall use parametric methods. Non-normal distributions shall use non-parametric methods. If the distribution of the constituents is shown by the owner or operator of the CCR unit to be inappropriate for a normal theory test, then the data must be transformed or a distribution-free (non-parametric) theory test must be used. If the distributions for the constituents differ, more than one statistical method may be needed.

(2) If an individual well comparison procedure is used to compare an individual compliance well constituent concentration with background constituent concentrations or a groundwater protection standard, the test shall be done at a Type I error level no less than 0.01 for each testing period. If a multiple comparison procedure is used, the Type I experiment wise error rate for each testing period shall be no less than 0.05; however, the Type I error of no less than 0.01 for individual well comparisons must be maintained. This performance standard does not apply to tolerance intervals, prediction intervals, or control charts.

(3) If a control chart approach is used to evaluate groundwater monitoring data, the specific type of control chart and its associated parameter values shall be such that this approach is at least as effective as any other approach in this section for evaluating groundwater data. The parameter values shall be determined after considering the number of samples in the background data base, the data distribution, and the range of the concentration values for each constituent of concern.

(4) If a tolerance interval or a predictional interval is used to evaluate groundwater monitoring data, the levels of confidence and, for tolerance intervals, the percentage of the population that the interval must contain, shall be such that this approach is at least as effective as any other approach in this section for evaluating groundwater data. These parameters shall be determined after considering the number of samples in the background data base, the data distribution, and the range of the concentration values for each constituent of concern.

(5) The statistical method must account for data below the limit of detection with one or more statistical procedures that shall at least as effective as any other approach in this section for evaluating groundwater data. Any practical quantitation limit that is used in the statistical method shall be the lowest concentration level that can be reliably achieved within specified limits of precision and accuracy during routine laboratory operating conditions that are available to the facility.

(6) If necessary, the statistical method must include procedures to control or correct for seasonal and spatial variability as well as temporal correlation in the data.

(h) The owner or operator of the CCR unit must determine whether or not there is a statistically significant increase over background values for each constituent required in the particular groundwater monitoring program that applies to the CCR unit, as determined under § 257.94(a) or § 257.95(a).

(1) In determining whether a statistically significant increase has occurred, the owner or operator must compare the groundwater quality of each constituent at each monitoring well designated pursuant to § 257.91(a)(2) or (d)(1) to the background value of that constituent, according to the statistical procedures and performance standards specified under paragraphs (f) and (g) of this section.

(2) Within 90 days after completing sampling and analysis, the owner or operator must determine whether there has been a statistically significant increase over background for any constituent at each monitoring well.

(i) The owner or operator must measure ''total recoverable metals'' concentrations in measuring groundwater quality. Measurement of total recoverable metals captures both the particulate fraction and dissolved fraction of metals in natural waters. Groundwater samples shall not be field-filtered prior to analysis.

(j) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(h), the notification requirements specified in § 257.106(h), and the Internet requirements specified in § 257.107(h).

§ 257.94 Detection monitoring program.

(a) The owner or operator of a CCR unit must conduct detection monitoring at all groundwater monitoring wells consistent with this section. At a minimum, a detection monitoring program must include groundwater monitoring for all constituents listed in appendix III to this part.

(b) Except as provided in paragraph (d) of this section, the monitoring frequency for the constituents listed in appendix III to this part shall be at least semiannual during the active life of the CCR unit and the post-closure period. For existing CCR landfills and existing CCR surface impoundments, a minimum of eight independent samples from each background and downgradient well must be collected and analyzed for the constituents listed in appendix III and IV to this part no later than October 17, 2017. For new CCR landfills, new CCR surface impoundments, and all lateral expansions of CCR units, a minimum of eight independent samples for each background well must be collected and analyzed for the constituents listed in appendices III and IV to this part during the first six months of sampling.

(c) The number of samples collected and analyzed for each background well and downgradient well during subsequent semiannual sampling events must be consistent with § 257.93(e), and must account for any unique characteristics of the site, but must be at least one sample from each background and downgradient well.

(d) The owner or operator of a CCR unit may demonstrate the need for an alternative monitoring frequency for repeated sampling and analysis for constituents listed in appendix III to this part during the active life and the post-closure care period based on the availability of groundwater. If there is not adequate groundwater flow to sample wells semiannually, the alternative frequency shall be no less than annual. The need to vary monitoring frequency must be evaluated on a site-specific basis. The demonstration must be supported by, at a minimum, the information specified in paragraphs (d)(1) and (2) of this section.

(1) Information documenting that the need for less frequent sampling. The alternative frequency must be based on consideration of the following factors:

(i) Lithology of the aquifer and unsaturated zone;

(ii) Hydraulic conductivity of the aquifer and unsaturated zone; and

(iii) Groundwater flow rates.

(2) Information documenting that the alternative frequency will be no less effective in ensuring that any leakage from the CCR unit will be discovered within a timeframe that will not materially delay establishment of an assessment monitoring program.

(3) The owner or operator must obtain a certification from a qualified

professional engineer stating that the demonstration for an alternative groundwater sampling and analysis frequency meets the requirements of this section. The owner or operator must include the demonstration providing the basis for the alternative monitoring frequency and the certification by a qualified professional engineer in the annual groundwater monitoring and corrective action report required by § 257.90(e).

(e) If the owner or operator of the CCR unit determines, pursuant to § 257.93(h) that there is a statistically significant increase over background levels for one or more of the constituents listed in appendix III to this part at any monitoring well at the waste boundary specified under § 257.91(a)(2), the owner or operator must:

(1) Except as provided for in paragraph (e)(2) of this section, within 90 days of detecting a statistically significant increase over background levels for any constituent, establish an assessment monitoring program meeting the requirements of § 257.95.

(2) The owner or operator may demonstrate that a source other than the CCR unit caused the statistically significant increase over background levels for a constituent or that the statistically significant increase resulted from error in sampling, analysis, statistical evaluation, or natural variation in groundwater quality. The owner or operator must complete the written demonstration within 90 days of detecting a statistically significant increase over background levels to include obtaining a certification from a qualified professional engineer verifying the accuracy of the information in the report. If a successful demonstration is completed within the 90-day period, the owner or operator of the CCR unit may continue with a detection monitoring program under this section. If a successful demonstration is not completed within the 90-day period, the owner or operator of the CCR unit must initiate an assessment monitoring program as required under § 257.95. The owner or operator must also include the demonstration in the annual groundwater monitoring and corrective action report required by § 257.90(e), in addition to the certification by a qualified professional engineer.

(3) The owner or operator of a CCR unit must prepare a notification stating that an assessment monitoring program has been established. The owner or operator has completed the notification when the notification is placed in the facility's operating record as required by § 257.105(h)(5).

(f) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(h), the notification requirements specified in § 257.106(h), and the Internet requirements specified in § 257.107(h).

§ 257.95 Assessment monitoring program.

(a) Assessment monitoring is required whenever a statistically significant increase over background levels has been detected for one or more of the constituents listed in appendix III to this part.

(b) Within 90 days of triggering an assessment monitoring program, and annually thereafter, the owner or operator of the CCR unit must sample and analyze the groundwater for all constituents listed in appendix IV to this part. The number of samples collected and analyzed for each well during each sampling event must be consistent with § 257.93(e), and must account for any unique characteristics of the site, but must be at least one sample from each well.

(c) The owner or operator of a CCR unit may demonstrate the need for an alternative monitoring frequency for repeated sampling and analysis for constituents listed in appendix IV to this part during the active life and the post-closure care period based on the availability of groundwater. If there is not adequate groundwater flow to sample wells semiannually, the alternative frequency shall be no less than annual. The need to vary monitoring frequency must be evaluated on a site-specific basis. The demonstration must be supported by, at a minimum, the information specified in paragraphs (c)(1) and (2) of this section.

(1) Information documenting that the need for less frequent sampling. The alternative frequency must be based on consideration of the following factors:

(i) Lithology of the aquifer and unsaturated zone;

(ii) Hydraulic conductivity of the aquifer and unsaturated zone; and

(iii) Groundwater flow rates.

(2) Information documenting that the alternative frequency will be no less effective in ensuring that any leakage from the CCR unit will be discovered within a timeframe that will not materially delay the initiation of any necessary remediation measures.

(3) The owner or operator must obtain a certification from a qualified professional engineer stating that the demonstration for an alternative groundwater sampling and analysis frequency meets the requirements of this section. The owner or operator must include the demonstration providing the basis for the alternative monitoring frequency and the certification by a qualified professional engineer in the annual groundwater monitoring and corrective action report required by § 257.90(e).

(d) After obtaining the results from the initial and subsequent sampling events required in paragraph (b) of this section, the owner or operator must:

(1) Within 90 days of obtaining the results, and on at least a semiannual basis thereafter, resample all wells that were installed pursuant to the requirements of § 257.91, conduct analyses for all parameters in appendix III to this part and for those constituents in appendix IV to this part that are detected in response to paragraph (b) of this section, and record their concentrations in the facility operating record. The number of samples collected and analyzed for each background well and downgradient well during subsequent semiannual sampling events must be consistent with § 257.93(e), and must account for any unique characteristics of the site, but must be at least one sample from each background and downgradient well;

(2) Establish groundwater protection standards for all constituents detected pursuant to paragraph (b) or (d) of this section. The groundwater protection standards must be established in accordance with paragraph (h) of this section; and

(3) Include the recorded concentrations required by paragraph (d)(1) of this section, identify the background concentrations established under § 257.94(b), and identify the groundwater protection standards established under paragraph (d)(2) of this section in the annual groundwater monitoring and corrective action report required by § 257.90(e).

(e) If the concentrations of all constituents listed in appendices III and IV to this part are shown to be at or below background values, using the statistical procedures in § 257.93(g), for two consecutive sampling events, the owner or operator may return to detection monitoring of the CCR unit. The owner or operator must prepare a notification stating that detection monitoring is resuming for the CCR unit. The owner or operator has completed the notification when the notification is placed in the facility's operating record as required by § 257.105(h)(7).

(f) If the concentrations of any constituent in appendices III and IV to this part are above background values, but all concentrations are below the groundwater protection standard

established under paragraph (h) of this section, using the statistical procedures in § 257.93(g), the owner or operator must continue assessment monitoring in accordance with this section.

(g) If one or more constituents in appendix IV to this part are detected at statistically significant levels above the groundwater protection standard established under paragraph (h) of this section in any sampling event, the owner or operator must prepare a notification identifying the constituents in appendix IV to this part that have exceeded the groundwater protection standard. The owner or operator has completed the notification when the notification is placed in the facility's operating record as required by § 257.105(h)(8). The owner or operator of the CCR unit also must:

(1) Characterize the nature and extent of the release and any relevant site conditions that may affect the remedy ultimately selected. The characterization must be sufficient to support a complete and accurate assessment of the corrective measures necessary to effectively clean up all releases from the CCR unit pursuant to § 257.96. Characterization of the release includes the following minimum measures:

(i) Install additional monitoring wells necessary to define the contaminant plume(s);

(ii) Collect data on the nature and estimated quantity of material released including specific information on the constituents listed in appendix IV of this part and the levels at which they are present in the material released;

(iii) Install at least one additional monitoring well at the facility boundary in the direction of contaminant migration and sample this well in accordance with paragraph (d)(1) of this section; and

(iv) Sample all wells in accordance with paragraph (d)(1) of this section to characterize the nature and extent of the release.

(2) Notify all persons who own the land or reside on the land that directly overlies any part of the plume of contamination if contaminants have migrated off-site if indicated by sampling of wells in accordance with paragraph (g)(1) of this section. The owner or operator has completed the notifications when they are placed in the facility's operating record as required by § 257.105(h)(8).

(3) Within 90 days of finding that any of the constituents listed in appendix IV to this part have been detected at a statistically significant level exceeding the groundwater protection standards the owner or operator must either:

(i) Initiate an assessment of corrective measures as required by § 257.96; or

(ii) Demonstrate that a source other than the CCR unit caused the contamination, or that the statistically significant increase resulted from error in sampling, analysis, statistical evaluation, or natural variation in groundwater quality. Any such demonstration must be supported by a report that includes the factual or evidentiary basis for any conclusions and must be certified to be accurate by a qualified professional engineer. If a successful demonstration is made, the owner or operator must continue monitoring in accordance with the assessment monitoring program pursuant to this section, and may return to detection monitoring if the constituents in appendices III and IV to this part are at or below background as specified in paragraph (e) of this section. The owner or operator must also include the demonstration in the annual groundwater monitoring and corrective action report required by § 257.90(e), in addition to the certification by a qualified professional engineer.

(4) If a successful demonstration has not been made at the end of the 90 day period provided by paragraph (g)(3)(ii) of this section, the owner or operator of the CCR unit must initiate the assessment of corrective measures requirements under § 257.96.

(5) If an assessment of corrective measures is required under § 257.96 by either paragraph (g)(3)(i) or (g)(4) of this section, and if the CCR unit is an existing unlined CCR surface impoundment as determined by § 257.71(a), then the CCR unit is subject to the closure requirements under § 257.101(a) to retrofit or close. In addition, the owner or operator must prepare a notification stating that an assessment of corrective measures has been initiated.

(h) The owner or operator of the CCR unit must establish a groundwater protection standard for each constituent in appendix IV to this part detected in the groundwater. The groundwater protection standard shall be:

(1) For constituents for which a maximum contaminant level (MCL) has been established under §§ 141.62 and 141.66 of this title, the MCL for that constituent;

(2) For constituents for which an MCL has not been established, the background concentration for the constituent established from wells in accordance with § 257.91; or

(3) For constituents for which the background level is higher than the MCL identified under paragraph (h)(1) of this section, the background concentration.

(i) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(h), the notification requirements specified in § 257.106(h), and the Internet requirements specified in § 257.107(h).

§ 257.96 Assessment of corrective measures.

(a) Within 90 days of finding that any constituent listed in appendix IV to this part has been detected at a statistically significant level exceeding the groundwater protection standard defined under § 257.95(h), or immediately upon detection of a release from a CCR unit, the owner or operator must initiate an assessment of corrective measures to prevent further releases, to remediate any releases and to restore affected area to original conditions. The assessment of corrective measures must be completed within 90 days, unless the owner or operator demonstrates the need for additional time to complete the assessment of corrective measures due to site-specific conditions or circumstances. The owner or operator must obtain a certification from a qualified professional engineer attesting that the demonstration is accurate. The 90-day deadline to complete the assessment of corrective measures may be extended for no longer than 60 days. The owner or operator must also include the demonstration in the annual groundwater monitoring and corrective action report required by § 257.90(e), in addition to the certification by a qualified professional engineer.

(b) The owner or operator of the CCR unit must continue to monitor groundwater in accordance with the assessment monitoring program as specified in § 257.95.

(c) The assessment under paragraph (a) of this section must include an analysis of the effectiveness of potential corrective measures in meeting all of the requirements and objectives of the remedy as described under § 257.97 addressing at least the following:

(1) The performance, reliability, ease of implementation, and potential impacts of appropriate potential remedies, including safety impacts, cross-media impacts, and control of exposure to any residual contamination;

(2) The time required to begin and complete the remedy;

(3) The institutional requirements, such as state or local permit requirements or other environmental or public health requirements that may substantially affect implementation of the remedy(s).

(d) The owner or operator must place the completed assessment of corrective measures in the facility's operating record. The assessment has been completed when it is placed in the facility's operating record as required by § 257.105(h)(10).

(e) The owner or operator must discuss the results of the corrective measures assessment at least 30 days prior to the selection of remedy, in a public meeting with interested and affected parties.

(f) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(h), the notification requirements specified in § 257.106(h), and the Internet requirements specified in § 257.107(h).

§ 257.97 Selection of remedy.

(a) Based on the results of the corrective measures assessment conducted under § 257.96, the owner or operator must, as soon as feasible, select a remedy that, at a minimum, meets the standards listed in paragraph (b) of this section. This requirement applies to, not in place of, any applicable standards under the Occupational Safety and Health Act. The owner or operator must prepare a semiannual report describing the progress in selecting and designing the remedy. Upon selection of a remedy, the owner or operator must prepare a final report describing the selected remedy and how it meets the standards specified in paragraph (b) of this section. The owner or operator must obtain a certification from a qualified professional engineer that the remedy selected meets the requirements of this section. The report has been completed when it is placed in the operating record as required by § 257.105(h)(12).

(b) Remedies must:

(1) Be protective of human health and the environment;

(2) Attain the groundwater protection standard as specified pursuant to § 257.95(h);

(3) Control the source(s) of releases so as to reduce or eliminate, to the maximum extent feasible, further releases of constituents in appendix IV to this part into the environment;

(4) Remove from the environment as much of the contaminated material that was released from the CCR unit as is feasible, taking into account factors such as avoiding inappropriate disturbance of sensitive ecosystems;

(5) Comply with standards for management of wastes as specified in § 257.98(d).

(c) In selecting a remedy that meets the standards of paragraph (b) of this section, the owner or operator of the CCR unit shall consider the following evaluation factors:

(1) The long- and short-term effectiveness and protectiveness of the potential remedy(s), along with the degree of certainty that the remedy will prove successful based on consideration of the following:

(i) Magnitude of reduction of existing risks;

(ii) Magnitude of residual risks in terms of likelihood of further releases due to CCR remaining following implementation of a remedy;

(iii) The type and degree of long-term management required, including monitoring, operation, and maintenance;

(iv) Short-term risks that might be posed to the community or the environment during implementation of such a remedy, including potential threats to human health and the environment associated with excavation, transportation, and re-disposal of contaminant;

(v) Time until full protection is achieved;

(vi) Potential for exposure of humans and environmental receptors to remaining wastes, considering the potential threat to human health and the environment associated with excavation, transportation, re-disposal, or containment;

(vii) Long-term reliability of the engineering and institutional controls; and

(viii) Potential need for replacement of the remedy.

(2) The effectiveness of the remedy in controlling the source to reduce further releases based on consideration of the following factors:

(i) The extent to which containment practices will reduce further releases; and

(ii) The extent to which treatment technologies may be used.

(3) The ease or difficulty of implementing a potential remedy(s) based on consideration of the following types of factors:

(i) Degree of difficulty associated with constructing the technology;

(ii) Expected operational reliability of the technologies;

(iii) Need to coordinate with and obtain necessary approvals and permits from other agencies;

(iv) Availability of necessary equipment and specialists; and

(v) Available capacity and location of needed treatment, storage, and disposal services.

(4) The degree to which community concerns are addressed by a potential remedy(s).

(d) The owner or operator must specify as part of the selected remedy a schedule(s) for implementing and completing remedial activities. Such a schedule must require the completion of remedial activities within a reasonable period of time taking into consideration the factors set forth in paragraphs (d)(1) through (6) of this section. The owner or operator of the CCR unit must consider the following factors in determining the schedule of remedial activities:

(1) Extent and nature of contamination, as determined by the characterization required under § 257.95(g);

(2) Reasonable probabilities of remedial technologies in achieving compliance with the groundwater protection standards established under § 257.95(h) and other objectives of the remedy;

(3) Availability of treatment or disposal capacity for CCR managed during implementation of the remedy;

(4) Potential risks to human health and the environment from exposure to contamination prior to completion of the remedy;

(5) Resource value of the aquifer including:

(i) Current and future uses;

(ii) Proximity and withdrawal rate of users;

(iii) Groundwater quantity and quality;

(iv) The potential damage to wildlife, crops, vegetation, and physical structures caused by exposure to CCR constituents;

(v) The hydrogeologic characteristic of the facility and surrounding land; and

(vi) The availability of alternative water supplies; and

(6) Other relevant factors.

(e) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(h), the notification requirements specified in § 257.106(h), and the Internet requirements specified in § 257.107(h).

§ 257.98 Implementation of the corrective action program.

(a) Within 90 days of selecting a remedy under § 257.97, the owner or operator must initiate remedial activities. Based on the schedule established under § 257.97(d) for implementation and completion of remedial activities the owner or operator must:

(1) Establish and implement a corrective action groundwater monitoring program that:

(i) At a minimum, meets the requirements of an assessment monitoring program under § 257.95;

(ii) Documents the effectiveness of the corrective action remedy; and

(iii) Demonstrates compliance with the groundwater protection standard pursuant to paragraph (c) of this section.

(2) Implement the corrective action remedy selected under § 257.97; and

(3) Take any interim measures necessary to reduce the contaminants leaching from the CCR unit, and/or potential exposures to human or ecological receptors. Interim measures must, to the greatest extent feasible, be consistent with the objectives of and contribute to the performance of any remedy that may be required pursuant to § 257.97. The following factors must be considered by an owner or operator in determining whether interim measures are necessary:

(i) Time required to develop and implement a final remedy;

(ii) Actual or potential exposure of nearby populations or environmental receptors to any of the constituents listed in appendix IV of this part;

(iii) Actual or potential contamination of drinking water supplies or sensitive ecosystems;

(iv) Further degradation of the groundwater that may occur if remedial action is not initiated expeditiously;

(v) Weather conditions that may cause any of the constituents listed in appendix IV to this part to migrate or be released;

(vi) Potential for exposure to any of the constituents listed in appendix IV to this part as a result of an accident or failure of a container or handling system; and

(vii) Other situations that may pose threats to human health and the environment.

(b) If an owner or operator of the CCR unit, determines, at any time, that compliance with the requirements of § 257.97(b) is not being achieved through the remedy selected, the owner or operator must implement other methods or techniques that could feasibly achieve compliance with the requirements.

(c) Remedies selected pursuant to § 257.97 shall be considered complete when:

(1) The owner or operator of the CCR unit demonstrates compliance with the groundwater protection standards established under § 257.95(h) has been achieved at all points within the plume of contamination that lie beyond the groundwater monitoring well system established under § 257.91.

(2) Compliance with the groundwater protection standards established under § 257.95(h) has been achieved by demonstrating that concentrations of constituents listed in appendix IV to this part have not exceeded the groundwater protection standard(s) for a period of three consecutive years using the statistical procedures and performance standards in § 257.93(f) and (g).

(3) All actions required to complete the remedy have been satisfied.

(d) All CCR that are managed pursuant to a remedy required under § 257.97, or an interim measure required under paragraph (a)(3) of this section, shall be managed in a manner that complies with all applicable RCRA requirements.

(e) Upon completion of the remedy, the owner or operator must prepare a notification stating that the remedy has been completed. The owner or operator must obtain a certification from a qualified professional engineer attesting that the remedy has been completed in compliance with the requirements of paragraph (c) of this section. The report has been completed when it is placed in the operating record as required by § 257.105(h)(13).

(f) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(h), the notification requirements specified in § 257.106(h), and the internet requirements specified in § 257.107(h).

Closure and Post-Closure Care

§ 257.100 Inactive CCR surface impoundments.

(a) Except as provided by paragraph (b) of this section, inactive CCR surface impoundments are subject to all of the requirements of this subpart applicable to existing CCR surface impoundments.

(b) An owner or operator of an inactive CCR surface impoundment that completes closure of such CCR unit, and meets all of the requirements of either paragraphs (b)(1) through (4) of this section or paragraph (b)(5) of this section no later than April 17, 2018, is exempt from all other requirements of this subpart.

(1) *Closure by leaving CCR in place.* If the owner or operator of the inactive CCR surface impoundment elects to close the CCR surface impoundment by leaving CCR in place, the owner or operator must ensure that, at a minimum, the CCR unit is closed in a manner that will:

(i) Control, minimize or eliminate, to the maximum extent feasible, post-closure infiltration of liquids into the waste and releases of CCR, leachate, or contaminated run-off to the ground or surface waters or to the atmosphere;

(ii) Preclude the probability of future impoundment of water, sediment, or slurry;

(iii) Include measures that provide for major slope stability to prevent the sloughing or movement of the final cover system; and

(iv) Minimize the need for further maintenance of the CCR unit.

(2) The owner or operator of the inactive CCR surface impoundment must meet the requirements of paragraphs (b)(2)(i) and (ii) of this section prior to installing the final cover system required under paragraph (b)(3) of this section.

(i) Free liquids must be eliminated by removing liquid wastes or solidifying the remaining wastes and waste residues.

(ii) Remaining wastes must be stabilized sufficient to support the final cover system.

(3) The owner or operator must install a final cover system that is designed to minimize infiltration and erosion, and at a minimum, meets the requirements of paragraph (b)(3)(i) of this section, or the requirements of an alternative final cover system specified in paragraph (b)(3)(ii) of this section.

(i) The final cover system must be designed and constructed to meet the criteria specified in paragraphs (b)(3)(i)(A) through (D) of this section.

(A) The permeability of the final cover system must be less than or equal to the permeability of any bottom liner system or natural subsoils present, or a permeability no greater than 1×10^{-5} centimeters/second, whichever is less.

(B) The infiltration of liquids through the CCR unit must be minimized by the use of an infiltration layer that contains a minimum of 18 inches of earthen material.

(C) The erosion of the final cover system must be minimized by the use of an erosion layer that contains a minimum of six inches of earthen material that is capable of sustaining native plant growth.

(D) The disruption of the integrity of the final cover system must be minimized through a design that accommodates settling and subsidence.

(ii) The owner or operator may select an alternative final cover system design, provided the alternative final cover system is designed and constructed to meet the criteria in paragraphs (b)(3)(ii)(A) through (C) of this section.

(A) The design of the final cover system must include an infiltration layer that achieves an equivalent reduction in infiltration as the infiltration layer specified in paragraphs (b)(3)(i)(A) and (B) of this section.

(B) The design of the final cover system must include an erosion layer that provides equivalent protection from wind or water erosion as the erosion layer specified in paragraph (b)(3)(i)(C) of this section.

(C) The disruption of the integrity of the final cover system must be minimized through a design that accommodates settling and subsidence.

(4) The owner or operator of the CCR surface impoundment must obtain a written certification from a qualified professional engineer stating that the design of the final cover system meets either the requirements of paragraphs (b)(3)(i) or (ii) of this section.

(5) *Closure through removal of CCR.* The owner or operator may alternatively elect to close an inactive CCR surface impoundment by removing and decontaminating all areas affected by releases from the CCR surface impoundment. CCR removal and decontamination of the CCR surface impoundment are complete when all CCR in the inactive CCR surface impoundment is removed, including the bottom liner of the CCR unit.

(6) The owner or operator of the CCR surface impoundment must obtain a written certification from a qualified professional engineer that closure of the CCR surface impoundment under either paragraphs (b)(1) through (4) or (b)(5) of this section is technically feasible within the timeframe in paragraph (b) of this section.

(7) If the owner or operator of the CCR surface impoundment fails to complete closure of the inactive CCR surface impoundment within the timeframe in paragraph (b) of this section, the CCR unit must comply with all of the requirements applicable to existing CCR surface impoundments under this subpart.

(c) *Required notices and progress reports.* An owner or operator of an inactive CCR surface impoundment that closes in accordance with paragraph (b) of this section must complete the notices and progress reports specified in paragraphs (c)(1) through (3) of this section.

(1) No later than December 17, 2015, the owner or operator must prepare and place in the facility's operating record a notification of intent to initiate closure of the CCR surface impoundment. The notification must state that the CCR surface impoundment is an inactive CCR surface impoundment closing under the requirements of paragraph (b) of this section. The notification must also include a narrative description of how the CCR surface impoundment will be closed, a schedule for completing closure activities, and the required certifications under paragraphs (b)(4) and (6) of this section, if applicable.

(2) The owner or operator must prepare periodic progress reports summarizing the progress of closure implementation, including a description of the actions completed to date, any problems encountered and a description of the actions taken to resolve the problems, and projected closure activities for the upcoming year. The annual progress reports must be completed according to the following schedule:

(i) The first annual progress report must be prepared no later than 13 months after completing the notification of intent to initiate closure required by paragraph (c)(1) of this section.

(ii) The second annual progress report must be prepared no later than 12 months after completing the first progress report required by paragraph (c)(2)(i) of this section.

(iii) The owner or operator has completed the progress reports specified in paragraph (c)(2) of this section when the reports are placed in the facility's operating record as required by § 257.105(i)(2).

(3) The owner or operator must prepare and place in the facility's operating record a notification of completion of closure of the CCR surface impoundment. The notification must be submitted within 60 days of completing closure of the CCR surface impoundment and must include a written certification from a qualified professional engineer stating that the CCR surface impoundment was closed in accordance with the requirements of either paragraph (b)(1) through (4) or (b)(5) of this section.

(d) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(i), the notification requirements specified in § 257.106(i), and the internet requirements specified in § 257.107(i).

§ 257.101 Closure or retrofit of CCR units.

(a) The owner or operator of an existing unlined CCR surface impoundment, as determined under § 257.71(a), is subject to the requirements of paragraph (a)(1) of this section.

(1) Except as provided by paragraph (a)(3) of this section, if at any time after October 19, 2015 an owner or operator of an existing unlined CCR surface impoundment determines in any sampling event that the concentrations of one or more constituents listed in appendix IV to this part are detected at statistically significant levels above the groundwater protection standard established under § 257.95(h) for such CCR unit, within six months of making such determination, the owner or operator of the existing unlined CCR surface impoundment must cease placing CCR and non-CCR wastestreams into such CCR surface impoundment and either retrofit or close the CCR unit in accordance with the requirements of § 257.102.

(2) An owner or operator of an existing unlined CCR surface impoundment that closes in accordance with paragraph (a)(1) of this section must include a statement in the notification required under § 257.102(g) or (k)(5) that the CCR surface impoundment is closing or retrofitting under the requirements of paragraph (a)(1) of this section.

(3) The timeframe specified in paragraph (a)(1) of this section does not apply if the owner or operator complies with the alternative closure procedures specified in § 257.103.

(4) At any time after the initiation of closure under paragraph (a)(1) of this section, the owner or operator may cease closure activities and initiate a retrofit of the CCR unit in accordance with the requirements of § 257.102(k).

(b) The owner or operator of an existing CCR surface impoundment is subject to the requirements of paragraph (b)(1) of this section.

(1) Except as provided by paragraph (b)(4) of this section, within six months of determining that an existing CCR surface impoundment has not demonstrated compliance with any location standard specified in §§ 257.60(a), 257.61(a), 257.62(a), 257.63(a), and 257.64(a), the owner or operator of the CCR surface impoundment must cease placing CCR and non-CCR wastestreams into such CCR unit and close the CCR unit in accordance with the requirements of § 257.102.

(2) Within six months of either failing to complete the initial or any subsequent periodic safety factor assessment required by § 257.73(e) by the deadlines specified in § 257.73(f)(1) through (3) or failing to document that the calculated factors of safety for the existing CCR surface impoundment achieve the minimum safety factors specified in § 257.73(e)(1)(i) through (iv), the owner or operator of the CCR surface impoundment must cease placing CCR and non-CCR wastestreams into such CCR unit and close the CCR unit in accordance with the requirements of § 257.102.

(3) An owner or operator of an existing CCR surface impoundment that closes in accordance with paragraphs (b)(1) or (2) of this section must include a statement in the notification required under § 257.102(g) that the CCR surface impoundment is closing under the requirements of paragraphs (b)(1) or (2) of this section.

(4) The timeframe specified in paragraph (b)(1) of this section does not apply if the owner or operator complies with the alternative closure procedures specified in § 257.103.

(c) The owner or operator of a new CCR surface impoundment is subject to the requirements of paragraph (c)(1) of this section.

(1) Within six months of either failing to complete the initial or any subsequent periodic safety factor assessment required by § 257.74(e) by the deadlines specified in § 257.74(f)(1) through (3) or failing to document that the calculated factors of safety for the new CCR surface impoundment achieve the minimum safety factors specified in § 257.74(e)(1)(i) through (v), the owner or operator of the CCR surface impoundment must cease placing CCR and non-CCR wastestreams into such CCR unit and close the CCR unit in accordance with the requirements of § 257.102.

(2) An owner or operator of an new CCR surface impoundment that closes in accordance with paragraph (c)(1) of this section must include a statement in the notification required under § 257.102(g) that the CCR surface impoundment is closing under the requirements of paragraph (c)(1) of this section.

(d) The owner or operator of an existing CCR landfill is subject to the requirements of paragraph (d)(1) of this section.

(1) Except as provided by paragraph (d)(3) of this section, within six months of determining that an existing CCR landfill has not demonstrated compliance with the location restriction for unstable areas specified in § 257.64(a), the owner or operator of the CCR unit must cease placing CCR and non-CCR waste streams into such CCR landfill and close the CCR unit in accordance with the requirements of § 257.102.

(2) An owner or operator of an existing CCR landfill that closes in accordance with paragraph (d)(1) of this section must include a statement in the notification required under § 257.102(g) that the CCR landfill is closing under the requirements of paragraph (d)(1) of this section.

(3) The timeframe specified in paragraph (d)(1) of this section does not apply if the owner or operator complies with the alternative closure procedures specified in § 257.103.

§ 257.102 Criteria for conducting the closure or retrofit of CCR units.

(a) Closure of a CCR landfill, CCR surface impoundment, or any lateral expansion of a CCR unit must be completed either by leaving the CCR in place and installing a final cover system or through removal of the CCR and decontamination of the CCR unit, as described in paragraphs (b) through (j) of this section. Retrofit of a CCR surface impoundment must be completed in accordance with the requirements in paragraph (k) of this section.

(b) *Written closure plan*—(1) *Content of the plan.* The owner or operator of a CCR unit must prepare a written closure plan that describes the steps necessary to close the CCR unit at any point during the active life of the CCR unit consistent with recognized and generally accepted good engineering practices. The written closure plan must include, at a minimum, the information specified in paragraphs (b)(1)(i) through (vi) of this section.

(i) A narrative description of how the CCR unit will be closed in accordance with this section.

(ii) If closure of the CCR unit will be accomplished through removal of CCR from the CCR unit, a description of the procedures to remove the CCR and decontaminate the CCR unit in accordance with paragraph (c) of this section.

(iii) If closure of the CCR unit will be accomplished by leaving CCR in place, a description of the final cover system, designed in accordance with paragraph (d) of this section, and the methods and procedures to be used to install the final cover. The closure plan must also discuss how the final cover system will achieve the performance standards specified in paragraph (d) of this section.

(iv) An estimate of the maximum inventory of CCR ever on-site over the active life of the CCR unit.

(v) An estimate of the largest area of the CCR unit ever requiring a final cover as required by paragraph (d) of this section at any time during the CCR unit's active life.

(vi) A schedule for completing all activities necessary to satisfy the closure criteria in this section, including an estimate of the year in which all closure activities for the CCR unit will be completed. The schedule should provide sufficient information to describe the sequential steps that will be taken to close the CCR unit, including identification of major milestones such as coordinating with and obtaining necessary approvals and permits from other agencies, the dewatering and stabilization phases of CCR surface impoundment closure, or installation of the final cover system, and the estimated timeframes to complete each step or phase of CCR unit closure. When preparing the written closure plan, if the owner or operator of a CCR unit estimates that the time required to complete closure will exceed the timeframes specified in paragraph (f)(1) of this section, the written closure plan must include the site-specific information, factors and considerations that would support any time extension sought under paragraph (f)(2) of this section.

(2) *Timeframes for preparing the initial written closure plan*—(i) *Existing CCR landfills and existing CCR surface impoundments.* No later than October 17, 2016, the owner or operator of the CCR unit must prepare an initial written closure plan consistent with the requirements specified in paragraph (b)(1) of this section.

(ii) *New CCR landfills and new CCR surface impoundments, and any lateral expansion of a CCR unit.* No later than the date of the initial receipt of CCR in the CCR unit, the owner or operator must prepare an initial written closure plan consistent with the requirements specified in paragraph (b)(1) of this section.

(iii) The owner or operator has completed the written closure plan when the plan, including the certification required by paragraph (b)(4) of this section, has been placed in the facility's operating record as required by § 257.105(i)(4).

(3) *Amendment of a written closure plan.* (i) The owner or operator may amend the initial or any subsequent written closure plan developed pursuant to paragraph (b)(1) of this section at any time.

(ii) The owner or operator must amend the written closure plan whenever:

(A) There is a change in the operation of the CCR unit that would substantially affect the written closure plan in effect; or

(B) Before or after closure activities have commenced, unanticipated events necessitate a revision of the written closure plan.

(iii) The owner or operator must amend the closure plan at least 60 days prior to a planned change in the operation of the facility or CCR unit, or no later than 60 days after an unanticipated event requires the need to revise an existing written closure plan. If a written closure plan is revised after closure activities have commenced for a CCR unit, the owner or operator must amend the current closure plan no later than 30 days following the triggering event.

(4) The owner or operator of the CCR unit must obtain a written certification from a qualified professional engineer that the initial and any amendment of

the written closure plan meets the requirements of this section.

(c) *Closure by removal of CCR.* An owner or operator may elect to close a CCR unit by removing and decontaminating all areas affected by releases from the CCR unit. CCR removal and decontamination of the CCR unit are complete when constituent concentrations throughout the CCR unit and any areas affected by releases from the CCR unit have been removed and groundwater monitoring concentrations do not exceed the groundwater protection standard established pursuant to § 257.95(h) for constituents listed in appendix IV to this part.

(d) *Closure performance standard when leaving CCR in place*—(1) The owner or operator of a CCR unit must ensure that, at a minimum, the CCR unit is closed in a manner that will:

(i) Control, minimize or eliminate, to the maximum extent feasible, post-closure infiltration of liquids into the waste and releases of CCR, leachate, or contaminated run-off to the ground or surface waters or to the atmosphere;

(ii) Preclude the probability of future impoundment of water, sediment, or slurry;

(iii) Include measures that provide for major slope stability to prevent the sloughing or movement of the final cover system during the closure and post-closure care period;

(iv) Minimize the need for further maintenance of the CCR unit; and

(v) Be completed in the shortest amount of time consistent with recognized and generally accepted good engineering practices.

(2) *Drainage and stabilization of CCR surface impoundments.* The owner or operator of a CCR surface impoundment or any lateral expansion of a CCR surface impoundment must meet the requirements of paragraphs (d)(2)(i) and (ii) of this section prior to installing the final cover system required under paragraph (d)(3) of this section.

(i) Free liquids must be eliminated by removing liquid wastes or solidifying the remaining wastes and waste residues.

(ii) Remaining wastes must be stabilized sufficient to support the final cover system.

(3) *Final cover system.* If a CCR unit is closed by leaving CCR in place, the owner or operator must install a final cover system that is designed to minimize infiltration and erosion, and at a minimum, meets the requirements of paragraph (d)(3)(i) of this section, or the requirements of the alternative final cover system specified in paragraph (d)(3)(ii) of this section.

(i) The final cover system must be designed and constructed to meet the criteria in paragraphs (d)(3)(i)(A) through (D) of this section. The design of the final cover system must be included in the written closure plan required by paragraph (b) of this section.

(A) The permeability of the final cover system must be less than or equal to the permeability of any bottom liner system or natural subsoils present, or a permeability no greater than 1×10^{-5} cm/sec, whichever is less.

(B) The infiltration of liquids through the closed CCR unit must be minimized by the use of an infiltration layer that contains a minimum of 18 inches of earthen material.

(C) The erosion of the final cover system must be minimized by the use of an erosion layer that contains a minimum of six inches of earthen material that is capable of sustaining native plant growth.

(D) The disruption of the integrity of the final cover system must be minimized through a design that accommodates settling and subsidence.

(ii) The owner or operator may select an alternative final cover system design, provided the alternative final cover system is designed and constructed to meet the criteria in paragraphs (f)(3)(ii)(A) through (D) of this section. The design of the final cover system must be included in the written closure plan required by paragraph (b) of this section.

(A) The design of the final cover system must include an infiltration layer that achieves an equivalent reduction in infiltration as the infiltration layer specified in paragraphs (d)(3)(i)(A) and (B) of this section.

(B) The design of the final cover system must include an erosion layer that provides equivalent protection from wind or water erosion as the erosion layer specified in paragraph (d)(3)(i)(C) of this section.

(C) The disruption of the integrity of the final cover system must be minimized through a design that accommodates settling and subsidence.

(iii) The owner or operator of the CCR unit must obtain a written certification from a qualified professional engineer that the design of the final cover system meets the requirements of this section.

(e) *Initiation of closure activities.* Except as provided for in paragraph (e)(4) of this section and § 257.103, the owner or operator of a CCR unit must commence closure of the CCR unit no later than the applicable timeframes specified in either paragraph (e)(1) or (2) of this section.

(1) The owner or operator must commence closure of the CCR unit no later than 30 days after the date on which the CCR unit either:

(i) Receives the known final receipt of waste, either CCR or any non-CCR waste stream; or

(ii) Removes the known final volume of CCR from the CCR unit for the purpose of beneficial use of CCR.

(2)(i) Except as provided by paragraph (e)(2)(ii) of this section, the owner or operator must commence closure of a CCR unit that has not received CCR or any non-CCR waste stream or is no longer removing CCR for the purpose of beneficial use within two years of the last receipt of waste or within two years of the last removal of CCR material for the purpose of beneficial use.

(ii) Notwithstanding paragraph (e)(2)(i) of this section, the owner or operator of the CCR unit may secure an additional two years to initiate closure of the idle unit provided the owner or operator provides written documentation that the CCR unit will continue to accept wastes or will start removing CCR for the purpose of beneficial use. The documentation must be supported by, at a minimum, the information specified in paragraphs (e)(2)(ii)(A) and (B) of this section. The owner or operator may obtain two-year extensions provided the owner or operator continues to be able to demonstrate that there is reasonable likelihood that the CCR unit will accept wastes in the foreseeable future or will remove CCR from the unit for the purpose of beneficial use. The owner or operator must place each completed demonstration, if more than one time extension is sought, in the facility's operating record as required by § 257.105(i)(5) prior to the end of any two-year period.

(A) Information documenting that the CCR unit has remaining storage or disposal capacity or that the CCR unit can have CCR removed for the purpose of beneficial use; and

(B) Information demonstrating that that there is a reasonable likelihood that the CCR unit will resume receiving CCR or non-CCR waste streams in the foreseeable future or that CCR can be removed for the purpose of beneficial use. The narrative must include a best estimate as to when the CCR unit will resume receiving CCR or non-CCR waste streams. The situations listed in paragraphs (e)(2)(ii)(B)(*1*) through (*4*) of this section are examples of situations that would support a determination that the CCR unit will resume receiving CCR or non-CCR waste streams in the foreseeable future.

(*1*) Normal plant operations include periods during which the CCR unit does not receive CCR or non-CCR waste

streams, such as the alternating use of two or more CCR units whereby at any point in time one CCR unit is receiving CCR while CCR is being removed from a second CCR unit after its dewatering.

(*2*) The CCR unit is dedicated to a coal-fired boiler unit that is temporarily idled (*e.g.,* CCR is not being generated) and there is a reasonable likelihood that the coal-fired boiler will resume operations in the future.

(*3*) The CCR unit is dedicated to an operating coal-fired boiler (*i.e.,* CCR is being generated); however, no CCR are being placed in the CCR unit because the CCR are being entirely diverted to beneficial uses, but there is a reasonable likelihood that the CCR unit will again be used in the foreseeable future.

(*4*) The CCR unit currently receives only non-CCR waste streams and those non-CCR waste streams are not generated for an extended period of time, but there is a reasonable likelihood that the CCR unit will again receive non-CCR waste streams in the future.

(iii) In order to obtain additional time extension(s) to initiate closure of a CCR unit beyond the two years provided by paragraph (e)(2)(i) of this section, the owner or operator of the CCR unit must include with the demonstration required by paragraph (e)(2)(ii) of this section the following statement signed by the owner or operator or an authorized representative:

I certify under penalty of law that I have personally examined and am familiar with the information submitted in this demonstration and all attached documents, and that, based on my inquiry of those individuals immediately responsible for obtaining the information, I believe that the submitted information is true, accurate, and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment.

(3) For purposes of this subpart, closure of the CCR unit has commenced if the owner or operator has ceased placing waste and completes any of the following actions or activities:

(i) Taken any steps necessary to implement the written closure plan required by paragraph (b) of this section;

(ii) Submitted a completed application for any required state or agency permit or permit modification; or

(iii) Taken any steps necessary to comply with any state or other agency standards that are a prerequisite, or are otherwise applicable, to initiating or completing the closure of a CCR unit.

(4) The timeframes specified in paragraphs (e)(1) and (2) of this section do not apply to any of the following owners or operators:

(i) An owner or operator of an inactive CCR surface impoundment closing the CCR unit as required by § 257.100(b);

(ii) An owner or operator of an existing unlined CCR surface impoundment closing the CCR unit as required by § 257.101(a);

(iii) An owner or operator of an existing CCR surface impoundment closing the CCR unit as required by § 257.101(b);

(iv) An owner or operator of a new CCR surface impoundment closing the CCR unit as required by § 257.101(c); or

(v) An owner or operator of an existing CCR landfill closing the CCR unit as required by § 257.101(d).

(f) *Completion of closure activities.* (1) Except as provided for in paragraph (f)(2) of this section, the owner or operator must complete closure of the CCR unit:

(i) For existing and new CCR landfills and any lateral expansion of a CCR landfill, within six months of commencing closure activities.

(ii) For existing and new CCR surface impoundments and any lateral expansion of a CCR surface impoundment, within five years of commencing closure activities.

(2)(i) *Extensions of closure timeframes.* The timeframes for completing closure of a CCR unit specified under paragraphs (f)(1) of this section may be extended if the owner or operator can demonstrate that it was not feasible to complete closure of the CCR unit within the required timeframes due to factors beyond the facility's control. If the owner or operator is seeking a time extension beyond the time specified in the written closure plan as required by paragraph (b)(1) of this section, the demonstration must include a narrative discussion providing the basis for additional time beyond that specified in the closure plan. The owner or operator must place each completed demonstration, if more than one time extension is sought, in the facility's operating record as required by § 257.105(i)(6) prior to the end of any two-year period. Factors that may support such a demonstration include:

(A) Complications stemming from the climate and weather, such as unusual amounts of precipitation or a significantly shortened construction season;

(B) Time required to dewater a surface impoundment due to the volume of CCR contained in the CCR unit or the characteristics of the CCR in the unit;

(C) The geology and terrain surrounding the CCR unit will affect the amount of material needed to close the CCR unit; or

(D) Time required or delays caused by the need to coordinate with and obtain necessary approvals and permits from a state or other agency.

(ii) *Maximum time extensions.* (A) CCR surface impoundments of 40 acres or smaller may extend the time to complete closure by no longer than two years.

(B) CCR surface impoundments larger than 40 acres may extend the timeframe to complete closure of the CCR unit multiple times, in two-year increments. For each two-year extension sought, the owner or operator must substantiate the factual circumstances demonstrating the need for the extension. No more than a total of five two-year extensions may be obtained for any CCR surface impoundment.

(C) CCR landfills may extend the timeframe to complete closure of the CCR unit multiple times, in one-year increments. For each one-year extension sought, the owner or operator must substantiate the factual circumstances demonstrating the need for the extension. No more than a total of two one-year extensions may be obtained for any CCR landfill.

(iii) In order to obtain additional time extension(s) to complete closure of a CCR unit beyond the times provided by paragraph (f)(1) of this section, the owner or operator of the CCR unit must include with the demonstration required by paragraph (f)(2)(i) of this section the following statement signed by the owner or operator or an authorized representative:

I certify under penalty of law that I have personally examined and am familiar with the information submitted in this demonstration and all attached documents, and that, based on my inquiry of those individuals immediately responsible for obtaining the information, I believe that the submitted information is true, accurate, and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment.

(3) Upon completion, the owner or operator of the CCR unit must obtain a certification from a qualified professional engineer verifying that closure has been completed in accordance with the closure plan specified in paragraph (b) of this section and the requirements of this section.

(g) No later than the date the owner or operator initiates closure of a CCR unit, the owner or operator must prepare a notification of intent to close a CCR unit. The notification must include the certification by a qualified professional engineer for the design of the final cover system as required by § 257.102(d)(3)(iii), if applicable. The

owner or operator has completed the notification when it has been placed in the facility's operating record as required by § 257.105(i)(7).

(h) Within 30 days of completion of closure of the CCR unit, the owner or operator must prepare a notification of closure of a CCR unit. The notification must include the certification by a qualified professional engineer as required by § 257.102(f)(3). The owner or operator has completed the notification when it has been placed in the facility's operating record as required by § 257.105(i)(8).

(i) *Deed notations.* (1) Except as provided by paragraph (i)(4) of this section, following closure of a CCR unit, the owner or operator must record a notation on the deed to the property, or some other instrument that is normally examined during title search.

(2) The notation on the deed must in perpetuity notify any potential purchaser of the property that:

(i) The land has been used as a CCR unit; and

(ii) Its use is restricted under the post-closure care requirements as provided by § 257.104(d)(1)(iii).

(3) Within 30 days of recording a notation on the deed to the property, the owner or operator must prepare a notification stating that the notation has been recorded. The owner or operator has completed the notification when it has been placed in the facility's operating record as required by § 257.105(i)(9).

(4) An owner or operator that closes a CCR unit in accordance with paragraph (c) of this section is not subject to the requirements of paragraphs (i)(1) through (3) of this section.

(j) The owner or operator of the CCR unit must comply with the closure recordkeeping requirements specified in § 257.105(i), the closure notification requirements specified in § 257.106(i), and the closure Internet requirements specified in § 257.107(i).

(k) *Criteria to retrofit an existing CCR surface impoundment.* (1) To retrofit an existing CCR surface impoundment, the owner or operator must:

(i) First remove all CCR, including any contaminated soils and sediments from the CCR unit; and

(ii) Comply with the requirements in § 257.72.

(iii) A CCR surface impoundment undergoing a retrofit remains subject to all other requirements of this subpart, including the requirement to conduct any necessary corrective action.

(2) *Written retrofit plan*—(i) *Content of the plan.* The owner or operator must prepare a written retrofit plan that describes the steps necessary to retrofit the CCR unit consistent with recognized and generally accepted good engineering practices. The written retrofit plan must include, at a minimum, all of the following information:

(A) A narrative description of the specific measures that will be taken to retrofit the CCR unit in accordance with this section.

(B) A description of the procedures to remove all CCR and contaminated soils and sediments from the CCR unit.

(C) An estimate of the maximum amount of CCR that will be removed as part of the retrofit operation.

(D) An estimate of the largest area of the CCR unit that will be affected by the retrofit operation.

(E) A schedule for completing all activities necessary to satisfy the retrofit criteria in this section, including an estimate of the year in which retrofit activities of the CCR unit will be completed.

(ii) *Timeframes for preparing the initial written retrofit plan.* (A) No later than 60 days prior to date of initiating retrofit activities, the owner or operator must prepare an initial written retrofit plan consistent with the requirements specified in paragraph (k)(2) of this section. For purposes of this subpart, initiation of retrofit activities has commenced if the owner or operator has ceased placing waste in the unit and completes any of the following actions or activities:

(*1*) Taken any steps necessary to implement the written retrofit plan;

(*2*) Submitted a completed application for any required state or agency permit or permit modification; or

(*3*) Taken any steps necessary to comply with any state or other agency standards that are a prerequisite, or are otherwise applicable, to initiating or completing the retrofit of a CCR unit.

(B) The owner or operator has completed the written retrofit plan when the plan, including the certification required by paragraph (k)(2)(iv) of this section, has been placed in the facility's operating record as required by § 257.105(j)(1).

(iii) *Amendment of a written retrofit plan.* (A) The owner or operator may amend the initial or any subsequent written retrofit plan at any time.

(B) The owner or operator must amend the written retrofit plan whenever:

(*1*) There is a change in the operation of the CCR unit that would substantially affect the written retrofit plan in effect; or

(*2*) Before or after retrofit activities have commenced, unanticipated events necessitate a revision of the written retrofit plan.

(C) The owner or operator must amend the retrofit plan at least 60 days prior to a planned change in the operation of the facility or CCR unit, or no later than 60 days after an unanticipated event requires the revision of an existing written retrofit plan. If a written retrofit plan is revised after retrofit activities have commenced for a CCR unit, the owner or operator must amend the current retrofit plan no later than 30 days following the triggering event.

(iv) The owner or operator of the CCR unit must obtain a written certification from a qualified professional engineer that the activities outlined in the written retrofit plan, including any amendment of the plan, meet the requirements of this section.

(3) *Deadline for completion of activities related to the retrofit of a CCR unit.* Any CCR surface impoundment that is being retrofitted must complete all retrofit activities within the same time frames and procedures specified for the closure of a CCR surface impoundment in § 257.102(f) or, where applicable, § 257.103.

(4) Upon completion, the owner or operator must obtain a certification from a qualified professional engineer verifying that the retrofit activities have been completed in accordance with the retrofit plan specified in paragraph (k)(2) of this section and the requirements of this section.

(5) No later than the date the owner or operator initiates the retrofit of a CCR unit, the owner or operator must prepare a notification of intent to retrofit a CCR unit. The owner or operator has completed the notification when it has been placed in the facility's operating record as required by § 257.105(j)(5).

(6) Within 30 days of completing the retrofit activities specified in paragraph (k)(1) of this section, the owner or operator must prepare a notification of completion of retrofit activities. The notification must include the certification by a qualified professional engineer as required by paragraph (k)(4) of this section. The owner or operator has completed the notification when it has been placed in the facility's operating record as required by § 257.105(j)(6).

(7) At any time after the initiation of a CCR unit retrofit, the owner or operator may cease the retrofit and initiate closure of the CCR unit in accordance with the requirements of § 257.102.

(8) The owner or operator of the CCR unit must comply with the retrofit recordkeeping requirements specified in

§ 257.105(j), the retrofit notification requirements specified in § 257.106(j), and the retrofit Internet requirements specified in § 257.107(j).

§ 257.103 Alternative closure requirements.

The owner or operator of a CCR landfill, CCR surface impoundment, or any lateral expansion of a CCR unit that is subject to closure pursuant to § 257.101(a), (b)(1), or (d) may continue to receive CCR in the unit provided the owner or operator meets the requirements of either paragraph (a) or (b) of this section.

(a)(1) *No alternative CCR disposal capacity.* Notwithstanding the provisions of § 257.101(a), (b)(1), or (d), a CCR unit may continue to receive CCR if the owner or operator of the CCR unit certifies that the CCR must continue to be managed in that CCR unit due to the absence of alternative disposal capacity both on-site and off-site of the facility. To qualify under this paragraph (a)(1), the owner or operator of the CCR unit must document that all of the following conditions have been met:

(i) No alternative disposal capacity is available on-site or off-site. An increase in costs or the inconvenience of existing capacity is not sufficient to support qualification under this section;

(ii) The owner or operator has made, and continues to make, efforts to obtain additional capacity. Qualification under this subsection lasts only as long as no alternative capacity is available. Once alternative capacity is identified, the owner or operator must arrange to use such capacity as soon as feasible;

(iii) The owner or operator must remain in compliance with all other requirements of this subpart, including the requirement to conduct any necessary corrective action; and

(iv) The owner or operator must prepare an annual progress report documenting the continued lack of alternative capacity and the progress towards the development of alternative CCR disposal capacity.

(2) Once alternative capacity is available, the CCR unit must cease receiving CCR and initiate closure following the timeframes in § 257.102(e) and (f).

(3) If no alternative capacity is identified within five years after the initial certification, the CCR unit must cease receiving CCR and close in accordance with the timeframes in § 257.102(e) and (f).

(b)(1) *Permanent cessation of a coal-fired boiler(s) by a date certain.* Notwithstanding the provisions of § 257.101(a), (b)(1), and (d), a CCR unit may continue to receive CCR if the owner or operator certifies that the facility will cease operation of the coal-fired boilers within the timeframes specified in paragraphs (b)(2) through (4) of this section, but in the interim period (prior to closure of the coal-fired boiler), the facility must continue to use the CCR unit due to the absence of alternative disposal capacity both on-site and off-site of the facility. To qualify under this paragraph (b)(1), the owner or operator of the CCR unit must document that all of the following conditions have been met:

(i) No alternative disposal capacity is available on-site or off-site. An increase in costs or the inconvenience of existing capacity is not sufficient to support qualification under this section.

(ii) The owner or operator must remain in compliance with all other requirements of this subpart, including the requirement to conduct any necessary corrective action; and

(iii) The owner or operator must prepare an annual progress report documenting the continued lack of alternative capacity and the progress towards the closure of the coal-fired boiler.

(2) For a CCR surface impoundment that is 40 acres or smaller, the coal-fired boiler must cease operation and the CCR surface impoundment must have completed closure no later than October 17, 2023.

(3) For a CCR surface impoundment that is larger than 40 acres, the coal-fired boiler must cease operation, and the CCR surface impoundment must complete closure no later than October 17, 2028.

(4) For a CCR landfill, the coal-fired boiler must cease operation, and the CCR landfill must complete closure no later than April 19, 2021.

(c) Required notices and progress reports. An owner or operator of a CCR unit that closes in accordance with paragraphs (a) or (b) of this section must complete the notices and progress reports specified in paragraphs (c)(1) through (3) of this section.

(1) Within six months of becoming subject to closure pursuant to § 257.101(a), (b)(1), or (d), the owner or operator must prepare and place in the facility's operating record a notification of intent to comply with the alternative closure requirements of this section. The notification must describe why the CCR unit qualifies for the alternative closure provisions under either paragraph (a) or (b) of this section, in addition to providing the documentation and certifications required by paragraph (a) or (b) of this section.

(2) The owner or operator must prepare the periodic progress reports required by paragraphs (a)(1)(iv) or (b)(1)(iii), in addition to describing any problems encountered and a description of the actions taken to resolve the problems. The annual progress reports must be completed according to the following schedule:

(i) The first annual progress report must be prepared no later than 13 months after completing the notification of intent to comply with the alternative closure requirements required by paragraph (c)(1) of this section.

(ii) The second annual progress report must be prepared no later than 12 months after completing the first annual progress report. Additional annual progress reports must be prepared within 12 months of completing the previous annual progress report.

(iii) The owner or operator has completed the progress reports specified in paragraph (c)(2) of this section when the reports are placed in the facility's operating record as required by § 257.105(i)(10).

(3) An owner or operator of a CCR unit must also prepare the notification of intent to close a CCR unit as required by § 257.102(g).

(d) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(i), the notification requirements specified in § 257.106(i), and the Internet requirements specified in § 257.107(i).

§ 257.104 Post-closure care requirements.

(a) *Applicability.* (1) Except as provided by either paragraph (a)(2) or (3) of this section, § 257.104 applies to the owners or operators of CCR landfills, CCR surface impoundments, and all lateral expansions of CCR units that are subject to the closure criteria under § 257.102.

(2) An owner or operator of a CCR unit that elects to close a CCR unit by removing CCR as provided by § 257.102(c) is not subject to the post-closure care criteria under this section.

(3) An owner or operator of an inactive CCR surface impoundment that elects to close a CCR unit pursuant to the requirements under § 257.100(b) is not subject to the post-closure care criteria under this section.

(b) *Post-closure care maintenance requirements.* Following closure of the CCR unit, the owner or operator must conduct post-closure care for the CCR unit, which must consist of at least the following:

(1) Maintaining the integrity and effectiveness of the final cover system, including making repairs to the final

cover as necessary to correct the effects of settlement, subsidence, erosion, or other events, and preventing run-on and run-off from eroding or otherwise damaging the final cover;

(2) If the CCR unit is subject to the design criteria under § 257.70, maintaining the integrity and effectiveness of the leachate collection and removal system and operating the leachate collection and removal system in accordance with the requirements of § 257.70; and

(3) Maintaining the groundwater monitoring system and monitoring the groundwater in accordance with the requirements of §§ 257.90 through 257.98.

(c) *Post-closure care period.* (1) Except as provided by paragraph (c)(2) of this section, the owner or operator of the CCR unit must conduct post-closure care for 30 years.

(2) If at the end of the post-closure care period the owner or operator of the CCR unit is operating under assessment monitoring in accordance with § 257.95, the owner or operator must continue to conduct post-closure care until the owner or operator returns to detection monitoring in accordance with § 257.95.

(d) *Written post-closure plan*—(1) *Content of the plan.* The owner or operator of a CCR unit must prepare a written post-closure plan that includes, at a minimum, the information specified in paragraphs (d)(1)(i) through (iii) of this section.

(i) A description of the monitoring and maintenance activities required in paragraph (b) of this section for the CCR unit, and the frequency at which these activities will be performed;

(ii) The name, address, telephone number, and email address of the person or office to contact about the facility during the post-closure care period; and

(iii) A description of the planned uses of the property during the post-closure period. Post-closure use of the property shall not disturb the integrity of the final cover, liner(s), or any other component of the containment system, or the function of the monitoring systems unless necessary to comply with the requirements in this subpart. Any other disturbance is allowed if the owner or operator of the CCR unit demonstrates that disturbance of the final cover, liner, or other component of the containment system, including any removal of CCR, will not increase the potential threat to human health or the environment. The demonstration must be certified by a qualified professional engineer, and notification shall be provided to the State Director that the demonstration has been placed in the operating record and on the owners or operator's publicly accessible Internet site.

(2) *Deadline to prepare the initial written post-closure plan*—(i) *Existing CCR landfills and existing CCR surface impoundments.* No later than October 17, 2016, the owner or operator of the CCR unit must prepare an initial written post-closure plan consistent with the requirements specified in paragraph (d)(1) of this section.

(ii) *New CCR landfills, new CCR surface impoundments, and any lateral expansion of a CCR unit.* No later than the date of the initial receipt of CCR in the CCR unit, the owner or operator must prepare an initial written post-closure plan consistent with the requirements specified in paragraph (d)(1) of this section.

(iii) The owner or operator has completed the written post-closure plan when the plan, including the certification required by paragraph (d)(4) of this section, has been placed in the facility's operating record as required by § 257.105(i)(4).

(3) *Amendment of a written post-closure plan.* (i) The owner or operator may amend the initial or any subsequent written post-closure plan developed pursuant to paragraph (d)(1) of this section at any time.

(ii) The owner or operator must amend the written closure plan whenever:

(A) There is a change in the operation of the CCR unit that would substantially affect the written post-closure plan in effect; or

(B) After post-closure activities have commenced, unanticipated events necessitate a revision of the written post-closure plan.

(iii) The owner or operator must amend the written post-closure plan at least 60 days prior to a planned change in the operation of the facility or CCR unit, or no later than 60 days after an unanticipated event requires the need to revise an existing written post-closure plan. If a written post-closure plan is revised after post-closure activities have commenced for a CCR unit, the owner or operator must amend the written post-closure plan no later than 30 days following the triggering event.

(4) The owner or operator of the CCR unit must obtain a written certification from a qualified professional engineer that the initial and any amendment of the written post-closure plan meets the requirements of this section.

(e) *Notification of completion of post-closure care period.* No later than 60 days following the completion of the post-closure care period, the owner or operator of the CCR unit must prepare a notification verifying that post-closure care has been completed. The notification must include the certification by a qualified professional engineer verifying that post-closure care has been completed in accordance with the closure plan specified in paragraph (d) of this section and the requirements of this section. The owner or operator has completed the notification when it has been placed in the facility's operating record as required by § 257.105(i)(13).

(f) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(i), the notification requirements specified in § 257.106(i), and the Internet requirements specified in § 257.107(i).

Recordkeeping, Notification, and Posting of Information to the Internet

§ 257.105 Recordkeeping requirements.

(a) Each owner or operator of a CCR unit subject to the requirements of this subpart must maintain files of all information required by this section in a written operating record at their facility.

(b) Unless specified otherwise, each file must be retained for at least five years following the date of each occurrence, measurement, maintenance, corrective action, report, record, or study.

(c) An owner or operator of more than one CCR unit subject to the provisions of this subpart may comply with the requirements of this section in one recordkeeping system provided the system identifies each file by the name of each CCR unit. The files may be maintained on microfilm, on a computer, on computer disks, on a storage system accessible by a computer, on magnetic tape disks, or on microfiche.

(d) The owner or operator of a CCR unit must submit to the State Director and/or appropriate Tribal authority any demonstration or documentation required by this subpart, if requested, when such information is not otherwise available on the owner or operator's publicly accessible Internet site.

(e) *Location restrictions.* The owner or operator of a CCR unit subject to this subpart must place the demonstrations documenting whether or not the CCR unit is in compliance with the requirements under §§ 257.60(a), 257.61(a), 257.62(a), 257.63(a), and 257.64(a), as it becomes available, in the facility's operating record.

(f) *Design criteria.* The owner or operator of a CCR unit subject to this subpart must place the following

information, as it becomes available, in the facility's operating record:

(1) The design and construction certifications as required by § 257.70(e) and (f).

(2) The documentation of liner type as required by § 257.71(a).

(3) The design and construction certifications as required by § 257.72(c) and (d).

(4) Documentation prepared by the owner or operator stating that the permanent identification marker was installed as required by §§ 257.73(a)(1) and 257.74(a)(1).

(5) The initial and periodic hazard potential classification assessments as required by §§ 257.73(a)(2) and 257.74(a)(2).

(6) The emergency action plan (EAP), and any amendment of the EAP, as required by §§ 257.73(a)(3) and 257.74(a)(3), except that only the most recent EAP must be maintained in the facility's operating record irrespective of the time requirement specified in paragraph (b) of this section.

(7) Documentation prepared by the owner or operator recording the annual face-to-face meeting or exercise between representatives of the owner or operator of the CCR unit and the local emergency responders as required by §§ 257.73(a)(3)(i)(E) and 257.74(a)(3)(i)(E).

(8) Documentation prepared by the owner or operator recording all activations of the emergency action plan as required by §§ 257.73(a)(3)(v) and 257.74(a)(3)(v).

(9) The history of construction, and any revisions of it, as required by § 257.73(c), except that these files must be maintained until the CCR unit completes closure of the unit in accordance with § 257.102.

(10) The initial and periodic structural stability assessments as required by §§ 257.73(d) and 257.74(d).

(11) Documentation detailing the corrective measures taken to remedy the deficiency or release as required by §§ 257.73(d)(2) and 257.74(d)(2).

(12) The initial and periodic safety factor assessments as required by §§ 257.73(e) and 257.74(e).

(13) The design and construction plans, and any revisions of it, as required by § 257.74(c), except that these files must be maintained until the CCR unit completes closure of the unit in accordance with § 257.102.

(g) *Operating criteria.* The owner or operator of a CCR unit subject to this subpart must place the following information, as it becomes available, in the facility's operating record:

(1) The CCR fugitive dust control plan, and any subsequent amendment of the plan, required by § 257.80(b), except that only the most recent control plan must be maintained in the facility's operating record irrespective of the time requirement specified in paragraph (b) of this section.

(2) The annual CCR fugitive dust control report required by § 257.80(c).

(3) The initial and periodic run-on and run-off control system plans as required by § 257.81(c).

(4) The initial and periodic inflow design flood control system plan as required by § 257.82(c).

(5) Documentation recording the results of each inspection and instrumentation monitoring by a qualified person as required by § 257.83(a).

(6) The periodic inspection report as required by § 257.83(b)(2).

(7) Documentation detailing the corrective measures taken to remedy the deficiency or release as required by §§ 257.83(b)(5) and 257.84(b)(5).

(8) Documentation recording the results of the weekly inspection by a qualified person as required by § 257.84(a).

(9) The periodic inspection report as required by § 257.84(b)(2).

(h) *Groundwater monitoring and corrective action.* The owner or operator of a CCR unit subject to this subpart must place the following information, as it becomes available, in the facility's operating record:

(1) The annual groundwater monitoring and corrective action report as required by § 257.90(e).

(2) Documentation of the design, installation, development, and decommissioning of any monitoring wells, piezometers and other measurement, sampling, and analytical devices as required by § 257.91(e)(1).

(3) The groundwater monitoring system certification as required by § 257.91(f).

(4) The selection of a statistical method certification as required by § 257.93(f)(6).

(5) Within 30 days of establishing an assessment monitoring program, the notification as required by § 257.94(e)(3).

(6) The results of appendices III and IV to this part constituent concentrations as required by § 257.95(d)(1).

(7) Within 30 days of returning to a detection monitoring program, the notification as required by § 257.95(e).

(8) Within 30 days of detecting one or more constituents in appendix IV to this part at statistically significant levels above the groundwater protection standard, the notifications as required by § 257.95(g).

(9) Within 30 days of initiating the assessment of corrective measures requirements, the notification as required by § 257.95(g)(5).

(10) The completed assessment of corrective measures as required by § 257.96(d).

(11) Documentation prepared by the owner or operator recording the public meeting for the corrective measures assessment as required by § 257.96(e).

(12) The semiannual report describing the progress in selecting and designing the remedy and the selection of remedy report as required by § 257.97(a), except that the selection of remedy report must be maintained until the remedy has been completed.

(13) Within 30 days of completing the remedy, the notification as required by § 257.98(e).

(i) *Closure and post-closure care.* The owner or operator of a CCR unit subject to this subpart must place the following information, as it becomes available, in the facility's operating record:

(1) The notification of intent to initiate closure of the CCR unit as required by § 257.100(c)(1).

(2) The annual progress reports of closure implementation as required by § 257.100(c)(2)(i) and (ii).

(3) The notification of closure completion as required by § 257.100(c)(3).

(4) The written closure plan, and any amendment of the plan, as required by § 257.102(b), except that only the most recent closure plan must be maintained in the facility's operating record irrespective of the time requirement specified in paragraph (b) of this section.

(5) The written demonstration(s), including the certification required by § 257.102(e)(2)(iii), for a time extension for initiating closure as required by § 257.102(e)(2)(ii).

(6) The written demonstration(s), including the certification required by § 257.102(f)(2)(iii), for a time extension for completing closure as required by § 257.102(f)(2)(i).

(7) The notification of intent to close a CCR unit as required by § 257.102(g).

(8) The notification of completion of closure of a CCR unit as required by § 257.102(h).

(9) The notification recording a notation on the deed as required by § 257.102(i).

(10) The notification of intent to comply with the alternative closure requirements as required by § 257.103(c)(1).

(11) The annual progress reports under the alternative closure requirements as required by § 257.103(c)(2).

(12) The written post-closure plan, and any amendment of the plan, as required by § 257.104(d), except that only the most recent closure plan must be maintained in the facility's operating record irrespective of the time requirement specified in paragraph (b) of this section.

(13) The notification of completion of post-closure care period as required by § 257.104(e).

(j) *Retrofit criteria.* The owner or operator of a CCR unit subject to this subpart must place the following information, as it becomes available, in the facility's operating record:

(1) The written retrofit plan, and any amendment of the plan, as required by § 257.102(k)(2), except that only the most recent retrofit plan must be maintained in the facility's operating record irrespective of the time requirement specified in paragraph (b) of this section.

(2) The notification of intent that the retrofit activities will proceed in accordance with the alternative procedures in § 257.103.

(3) The annual progress reports required under the alternative requirements as required by § 257.103.

(4) The written demonstration(s), including the certification in § 257.102(f)(2)(iii), for a time extension for completing retrofit activities as required by § 257.102(k)(3).

(5) The notification of intent to initiate retrofit of a CCR unit as required by § 257.102(k)(5).

(6) The notification of completion of retrofit activities as required by § 257.102(k)(6).

§ 257.106 Notification requirements.

(a) The notifications required under paragraphs (e) through (i) of this section must be sent to the relevant State Director and/or appropriate Tribal authority before the close of business on the day the notification is required to be completed. For purposes of this section, *before the close of business* means the notification must be postmarked or sent by electronic mail (email). If a notification deadline falls on a weekend or federal holiday, the notification deadline is automatically extended to the next business day.

(b) If any CCR unit is located in its entirety within Indian Country, the notifications of this section must be sent to the appropriate Tribal authority. If any CCR unit is located in part within Indian Country, the notifications of this section must be sent both to the appropriate State Director and Tribal authority.

(c) Notifications may be combined as long as the deadline requirement for each notification is met.

(d) Unless otherwise required in this section, the notifications specified in this section must be sent to the State Director and/or appropriate Tribal authority within 30 days of placing in the operating record the information required by § 257.105.

(e) *Location restrictions.* The owner or operator of a CCR unit subject to the requirements of this subpart must notify the State Director and/or appropriate Tribal authority that each demonstration specified under § 257.105(e) has been placed in the operating record and on the owner or operator's publicly accessible internet site.

(f) *Design criteria.* The owner or operator of a CCR unit subject to this subpart must notify the State Director and/or appropriate Tribal authority when information has been placed in the operating record and on the owner or operator's publicly accessible internet site. The owner or operator must:

(1) Within 60 days of commencing construction of a new CCR unit, provide notification of the availability of the design certification specified under § 257.105(f)(1) or (3). If the owner or operator of the CCR unit elects to install an alternative composite liner, the owner or operator must also submit to the State Director and/or appropriate Tribal authority a copy of the alternative composite liner design.

(2) No later than the date of initial receipt of CCR by a new CCR unit, provide notification of the availability of the construction certification specified under § 257.105(f)(1) or (3).

(3) Provide notification of the availability of the documentation of liner type specified under § 257.105(f)(2).

(4) Provide notification of the availability of the initial and periodic hazard potential classification assessments specified under § 257.105(f)(5).

(5) Provide notification of the availability of emergency action plan (EAP), and any revisions of the EAP, specified under § 257.105(f)(6).

(6) Provide notification of the availability of documentation prepared by the owner or operator recording the annual face-to-face meeting or exercise between representatives of the owner or operator of the CCR unit and the local emergency responders specified under § 257.105(f)(7).

(7) Provide notification of documentation prepared by the owner or operator recording all activations of the emergency action plan specified under § 257.105(f)(8).

(8) Provide notification of the availability of the history of construction, and any revision of it, specified under § 257.105(f)(9).

(9) Provide notification of the availability of the initial and periodic structural stability assessments specified under § 257.105(f)(10).

(10) Provide notification of the availability of the documentation detailing the corrective measures taken to remedy the deficiency or release specified under § 257.105(f)(11).

(11) Provide notification of the availability of the initial and periodic safety factor assessments specified under § 257.105(f)(12).

(12) Provide notification of the availability of the design and construction plans, and any revision of them, specified under § 257.105(f)(13).

(g) *Operating criteria.* The owner or operator of a CCR unit subject to this subpart must notify the State Director and/or appropriate Tribal authority when information has been placed in the operating record and on the owner or operator's publicly accessible internet site. The owner or operator must:

(1) Provide notification of the availability of the CCR fugitive dust control plan, or any subsequent amendment of the plan, specified under § 257.105(g)(1).

(2) Provide notification of the availability of the annual CCR fugitive dust control report specified under § 257.105(g)(2).

(3) Provide notification of the availability of the initial and periodic run-on and run-off control system plans specified under § 257.105(g)(3).

(4) Provide notification of the availability of the initial and periodic inflow design flood control system plans specified under § 257.105(g)(4).

(5) Provide notification of the availability of the periodic inspection reports specified under § 257.105(g)(6).

(6) Provide notification of the availability of the documentation detailing the corrective measures taken to remedy the deficiency or release specified under § 257.105(g)(7).

(7) Provide notification of the availability of the periodic inspection reports specified under § 257.105(g)(9).

(h) *Groundwater monitoring and corrective action.* The owner or operator of a CCR unit subject to this subpart must notify the State Director and/or appropriate Tribal authority when information has been placed in the operating record and on the owner or operator's publicly accessible internet site. The owner or operator must:

(1) Provide notification of the availability of the annual groundwater

monitoring and corrective action report specified under § 257.105(h)(1).

(2) Provide notification of the availability of the groundwater monitoring system certification specified under § 257.105(h)(3).

(3) Provide notification of the availability of the selection of a statistical method certification specified under § 257.105(h)(4).

(4) Provide notification that an assessment monitoring programs has been established specified under § 257.105(h)(5).

(5) Provide notification that the CCR unit is returning to a detection monitoring program specified under § 257.105(h)(7).

(6) Provide notification that one or more constituents in appendix IV to this part have been detected at statistically significant levels above the groundwater protection standard and the notifications to land owners specified under § 257.105(h)(8).

(7) Provide notification that an assessment of corrective measures has been initiated specified under § 257.105(h)(9).

(8) Provide notification of the availability of assessment of corrective measures specified under § 257.105(h)(10).

(9) Provide notification of the availability of the semiannual report describing the progress in selecting and designing the remedy and the selection of remedy report specified under § 257.105(h)(12).

(10) Provide notification of the completion of the remedy specified under § 257.105(h)(13).

(i) *Closure and post-closure care.* The owner or operator of a CCR unit subject to this subpart must notify the State Director and/or appropriate Tribal authority when information has been placed in the operating record and on the owner or operator's publicly accessible Internet site. The owner or operator must:

(1) Provide notification of the intent to initiate closure of the CCR unit specified under § 257.105(i)(1).

(2) Provide notification of the availability of the annual progress reports of closure implementation specified under § 257.105(i)(2).

(3) Provide notification of closure completion specified under § 257.105(i)(3).

(4) Provide notification of the availability of the written closure plan, and any amendment of the plan, specified under § 257.105(i)(4).

(5) Provide notification of the availability of the demonstration(s) for a time extension for initiating closure specified under § 257.105(i)(5).

(6) Provide notification of the availability of the demonstration(s) for a time extension for completing closure specified under § 257.105(i)(6).

(7) Provide notification of intent to close a CCR unit specified under § 257.105(i)(7).

(8) Provide notification of completion of closure of a CCR unit specified under § 257.105(i)(8).

(9) Provide notification of the deed notation as required by § 257.105(i)(9).

(10) Provide notification of intent to comply with the alternative closure requirements specified under § 257.105(i)(10).

(11) The annual progress reports under the alternative closure requirements as required by § 257.105(i)(11).

(12) Provide notification of the availability of the written post-closure plan, and any amendment of the plan, specified under § 257.105(i)(12).

(13) Provide notification of completion of post-closure care specified under § 257.105(i)(13).

(j) *Retrofit criteria.* The owner or operator of a CCR unit subject to this subpart must notify the State Director and/or appropriate Tribal authority when information has been placed in the operating record and on the owner or operator's publicly accessible Internet site. The owner or operator must:

(1) Provide notification of the availability of the written retrofit plan, and any amendment of the plan, specified under § 257.105(j)(1).

(2) Provide notification of intent to comply with the alternative retrofit requirements specified under § 257.105(j)(2).

(3) The annual progress reports under the alternative retrofit requirements as required by § 257.105(j)(3).

(4) Provide notification of the availability of the demonstration(s) for a time extension for completing retrofit activities specified under § 257.105(j)(4).

(5) Provide notification of intent to initiate retrofit of a CCR unit specified under § 257.105(j)(5).

(6) Provide notification of completion of retrofit activities specified under § 257.105(j)(6).

§ 257.107 Publicly accessible Internet site requirements.

(a) Each owner or operator of a CCR unit subject to the requirements of this subpart must maintain a publicly accessible Internet site (CCR Web site) containing the information specified in this section. The owner or operator's Web site must be titled ''CCR Rule Compliance Data and Information.''

(b) An owner or operator of more than one CCR unit subject to the provisions of this subpart may comply with the requirements of this section by using the same Internet site for multiple CCR units provided the CCR Web site clearly delineates information by the name or identification number of each unit.

(c) Unless otherwise required in this section, the information required to be posted to the CCR Web site must be made available to the public for at least five years following the date on which the information was first posted to the CCR Web site.

(d) Unless otherwise required in this section, the information must be posted to the CCR Web site within 30 days of placing the pertinent information required by § 257.105 in the operating record.

(e) *Location restrictions.* The owner or operator of a CCR unit subject to this subpart must place each demonstration specified under § 257.105(e) on the owner or operator's CCR Web site.

(f) *Design criteria.* The owner or operator of a CCR unit subject to this subpart must place the following information on the owner or operator's CCR Web site:

(1) Within 60 days of commencing construction of a new unit, the design certification specified under § 257.105(f)(1) or (3).

(2) No later than the date of initial receipt of CCR by a new CCR unit, the construction certification specified under § 257.105(f)(1) or (3).

(3) The documentation of liner type specified under § 257.105(f)(2).

(4) The initial and periodic hazard potential classification assessments specified under § 257.105(f)(5).

(5) The emergency action plan (EAP) specified under § 257.105(f)(6), except that only the most recent EAP must be maintained on the CCR Web site irrespective of the time requirement specified in paragraph (c) of this section.

(6) Documentation prepared by the owner or operator recording the annual face-to-face meeting or exercise between representatives of the owner or operator of the CCR unit and the local emergency responders specified under § 257.105(f)(7).

(7) Documentation prepared by the owner or operator recording any activation of the emergency action plan specified under § 257.105(f)(8).

(8) The history of construction, and any revisions of it, specified under § 257.105(f)(9).

(9) The initial and periodic structural stability assessments specified under § 257.105(f)(10).

(10) The documentation detailing the corrective measures taken to remedy the

deficiency or release specified under § 257.105(f)(11).

(11) The initial and periodic safety factor assessments specified under § 257.105(f)(12).

(12) The design and construction plans, and any revisions of them, specified under § 257.105(f)(13).

(g) *Operating criteria.* The owner or operator of a CCR unit subject to this subpart must place the following information on the owner or operator's CCR Web site:

(1) The CCR fugitive dust control plan, or any subsequent amendment of the plan, specified under § 257.105(g)(1) except that only the most recent plan must be maintained on the CCR Web site irrespective of the time requirement specified in paragraph (c) of this section.

(2) The annual CCR fugitive dust control report specified under § 257.105(g)(2).

(3) The initial and periodic run-on and run-off control system plans specified under § 257.105(g)(3).

(4) The initial and periodic inflow design flood control system plans specified under § 257.105(g)(4).

(5) The periodic inspection reports specified under § 257.105(g)(6).

(6) The documentation detailing the corrective measures taken to remedy the deficiency or release specified under § 257.105(g)(7).

(7) The periodic inspection reports specified under § 257.105(g)(9).

(h) *Groundwater monitoring and corrective action.* The owner or operator of a CCR unit subject to this subpart must place the following information on the owner or operator's CCR Web site:

(1) The annual groundwater monitoring and corrective action report specified under § 257.105(h)(1).

(2) The groundwater monitoring system certification specified under § 257.105(h)(3).

(3) The selection of a statistical method certification specified under § 257.105(h)(4).

(4) The notification that an assessment monitoring programs has been established specified under § 257.105(h)(5).

(5) The notification that the CCR unit is returning to a detection monitoring program specified under § 257.105(h)(7).

(6) The notification that one or more constituents in appendix IV to this part have been detected at statistically significant levels above the groundwater protection standard and the notifications to land owners specified under § 257.105(h)(8).

(7) The notification that an assessment of corrective measures has been initiated specified under § 257.105(h)(9).

(8) The assessment of corrective measures specified under § 257.105(h)(10).

(9) The semiannual reports describing the progress in selecting and designing remedy and the selection of remedy report specified under § 257.105(h)(12), except that the selection of the remedy report must be maintained until the remedy has been completed.

(10) The notification that the remedy has been completed specified under § 257.105(h)(13).

(i) *Closure and post-closure care.* The owner or operator of a CCR unit subject to this subpart must place the following information on the owner or operator's CCR Web site:

(1) The notification of intent to initiate closure of the CCR unit specified under § 257.105(i)(1).

(2) The annual progress reports of closure implementation specified under § 257.105(i)(2).

(3) The notification of closure completion specified under § 257.105(i)(3).

(4) The written closure plan, and any amendment of the plan, specified under § 257.105(i)(4).

(5) The demonstration(s) for a time extension for initiating closure specified under § 257.105(i)(5).

(6) The demonstration(s) for a time extension for completing closure specified under § 257.105(i)(6).

(7) The notification of intent to close a CCR unit specified under § 257.105(i)(7).

(8) The notification of completion of closure of a CCR unit specified under § 257.105(i)(8).

(9) The notification recording a notation on the deed as required by § 257.105(i)(9).

(10) The notification of intent to comply with the alternative closure requirements as required by § 257.105(i)(10).

(11) The annual progress reports under the alternative closure requirements as required by § 257.105(i)(11).

(12) The written post-closure plan, and any amendment of the plan, specified under § 257.105(i)(12).

(13) The notification of completion of post-closure care specified under § 257.105(i)(13).

(j) *Retrofit criteria.* The owner or operator of a CCR unit subject to this subpart must place the following information on the owner or operator's CCR Web site:

(1) The written retrofit plan, and any amendment of the plan, specified under § 257.105(j)(1).

(2) The notification of intent to comply with the alternative retrofit requirements as required by § 257.105(j)(2).

(3) The annual progress reports under the alternative retrofit requirements as required by § 257.105(j)(3).

(4) The demonstration(s) for a time extension for completing retrofit activities specified under § 257.105(j)(4).

(5) The notification of intent to retrofit a CCR unit specified under § 257.105(j)(5).

(6) The notification of completion of retrofit activities specified under § 257.105(j)(6).

■ 5. Amend part 257 by adding ''Appendix III to Part 257'' and ''Appendix IV to Part 257'' to read as follows:

Appendix III to Part 257—Constituents for Detection Monitoring

Common name [1]
Boron
Calcium
Chloride
Fluoride
pH
Sulfate
Total Dissolved Solids (TDS)

[1] Common names are those widely used in government regulations, scientific publications, and commerce; synonyms exist for many chemicals.

Appendix IV to Part 257—Constituents for Assessment Monitoring

Common name [1]
Antimony
Arsenic
Barium
Beryllium
Cadmium
Chromium
Cobalt
Fluoride
Lead
Lithium
Mercury
Molybdenum
Selenium
Thallium
Radium 226 and 228 combined

[1] Common names are those widely used in government regulations, scientific publications, and commerce; synonyms exist for many chemicals.

PART 261—IDENTIFICATION AND LISTING OF HAZARDOUS WASTE

■ 6. The authority citation for part 261 continues to read as follows:

Authority: 42 U.S.C. 6905, 6912(a), 6921, 6922, 6924(y) and 6938.

■ 7. Section 261.4 is amended by revising paragraph (b)(4) to read as follows:

§ 261.4 Exclusions.

* * * * *

(b) * * *

(4)(i) Fly ash waste, bottom ash waste, slag waste, and flue gas emission control waste generated primarily from the combustion of coal or other fossil fuels, except as provided by § 266.112 of this chapter for facilities that burn or process hazardous waste.

(ii) The following wastes generated primarily from processes that support the combustion of coal or other fossil fuels that are co-disposed with the wastes in paragraph (b)(4)(i) of this section, except as provided by § 266.112 of this chapter for facilities that burn or process hazardous waste:

(A) *Coal pile run-off.* For purposes of paragraph (b)(4) of this section, coal pile run-off means any precipitation that drains off coal piles.

(B) *Boiler cleaning solutions.* For purposes of paragraph (b)(4) of this section, boiler cleaning solutions means water solutions and chemical solutions used to clean the fire-side and water-side of the boiler.

(C) *Boiler blowdown.* For purposes of paragraph (b)(4) of this section, boiler blowdown means water purged from boilers used to generate steam.

(D) *Process water treatment and demineralizer regeneration wastes.* For purposes of paragraph (b)(4) of this section, process water treatment and demineralizer regeneration wastes means sludges, rinses, and spent resins generated from processes to remove dissolved gases, suspended solids, and dissolved chemical salts from combustion system process water.

(E) *Cooling tower blowdown.* For purposes of paragraph (b)(4) of this section, cooling tower blowdown means water purged from a closed cycle cooling system. Closed cycle cooling systems include cooling towers, cooling ponds, or spray canals.

(F) *Air heater and precipitator washes.* For purposes of paragraph (b)(4) of this section, air heater and precipitator washes means wastes from cleaning air preheaters and electrostatic precipitators.

(G) *Effluents from floor and yard drains and sumps.* For purposes of paragraph (b)(4) of this section, effluents from floor and yard drains and sumps means wastewaters, such as wash water, collected by or from floor drains, equipment drains, and sumps located inside the power plant building; and wastewaters, such as rain runoff, collected by yard drains and sumps located outside the power plant building.

(H) *Wastewater treatment sludges.* For purposes of paragraph (b)(4) of this section, wastewater treatment sludges refers to sludges generated from the treatment of wastewaters specified in paragraphs (b)(4)(ii)(A) through (F) of this section.

* * * * *

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Document 25

U.S. EPA, Office of Solid Waste and Emergency Response, OSWER Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor in Indoor Air, June 2015.

OSWER Publication 9200.2-154

OSWER TECHNICAL GUIDE FOR ASSESSING AND MITIGATING THE VAPOR INTRUSION PATHWAY FROM SUBSURFACE VAPOR SOURCES TO INDOOR AIR

U.S. Environmental Protection Agency

Office of Solid Waste and Emergency Response

June 2015

DISCLAIMER

This document presents current technical recommendations of the U.S. Environmental Protection Agency (EPA) based on our current understanding of vapor intrusion into indoor air from subsurface vapor sources. This guidance document does not impose any requirements or obligations on the EPA, the states or tribal governments, or the regulated community. Rather, the sources of authority and requirements for addressing subsurface vapor intrusion are the relevant statutes and regulations. Decisions regarding a particular situation should be made based upon statutory and regulatory authority. EPA decision-makers retain the discretion to adopt or approve approaches on a case-by-case basis that differ from this guidance document, where appropriate, as long as the administrative record supporting its decision provides an adequate basis and reasoned explanation for doing so.

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ACRONYMS AND ABBREVIATIONS

ACH	air changes per hour (air exchanges per hour)
ADT	active depressurization technology
AER	air exchange rate
ANSI	American National Standards Institute
ASQ	American Society for Quality
ASTM	American Society for Testing and Materials
ASTSWMO	Association of State and Territorial Solid Waste Management Officials
ATSDR	Agency for Toxic Substances and Disease Registry
BTEX	benzene, toluene, ethylbenzene, xylenes
BWD	block-wall depressurization
CalEPA	California Environmental Protection Agency
CASRN	Chemical Abstracts Service Registry Number
CEI	Community Engagement Initiative
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CHC	chlorinated hydrocarbon
CIC	Community Involvement Coordinator
CIO	Chief Information Officer
CIP	community involvement plan
CMS	corrective measures study
CSM	conceptual site model
DCE	dichloroethylene, or equivalently dichloroethene
DNAPL	dense non-aqueous-phase liquid
DoD	U.S. Department of Defense
DoN	U.S. Department of Navy
DQO	data quality objective
DTD	drain-tile depressurization
EI	environmental indicator
EPA	U.S. Environmental Protection Agency
ERT	Environmental Response Team
FR	Federal Register
FS	feasibility study

FYR	five-year review
HI	Hazard Index
HQ	Hazard Quotient
HVAC	heating, ventilation and air conditioning
IC	institutional control
ICIAP	Institutional Controls Implementation and Assurance Plan
IDLH	immediately dangerous to life or health
ITRC	Interstate Technology and Regulatory Council
LCR	lifetime cancer risk
LEL	lower explosive limit
LEP	limited English proficiency
LNAPL	light non-aqueous-phase liquid
LTS	long-term stewardship
MADEP	Massachusetts Department of Environmental Protection
NAPL	non-aqueous-phase liquid
NAS	National Academy of Sciences
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NFA	No Further Action
NIST	National Institute of Standards and Technology
NPL	National Priorities List
NRC	National Research Council
NIOSH	National Institute for Occupational Safety and Health
NYSDOH	New York State Department of Health
O&M	operation and maintenance
OIG	Office of the Inspector General
OSC	on-scene coordinator
OSHA	Occupational Safety and Health Administration
OSWER	Office of Solid Waste and Emergency Response
OUST	Office of Underground Storage Tanks
PAH	polycyclic aromatic hydrocarbon
PCB	polychlorinated biphenyl
PCE	tetrachloroethylene, or equivalently tetrachloroethene
PEM	preemptive mitigation
PID	photoionization detector

P.E.	Professional Engineer
ppbv	parts per billion by volume
PRP	potentially responsible party
QAPP	quality assurance project plan
QMP	quality management plan
RCRA	Resource Conservation and Recovery Act
RfC	inhalation reference concentration
RFI	RCRA facility investigation
RI	remedial investigation
RME	reasonable maximum exposure
ROD	Record of Decision
RPM	remedial project manager
SMD	sub-membrane depressurization
SSD	sub-slab depressurization
TAGA	trace atmospheric gas analyzer
TCE	trichloroethylene, or equivalently trichloroethene
UFP-QAPP	Uniform Federal Policy for Quality Assurance Project Plans
UECA	Uniform Environmental Covenants Act
USPS	U.S. Postal Service
UST	underground storage tank
UU/UE	unlimited use/unrestricted exposure
VI	vapor intrusion
VISL	vapor intrusion screening level
VOC	volatile organic compound

EXECUTIVE SUMMARY

Definition and Description of Vapor Intrusion

Vapor intrusion is the general term given to migration of hazardous vapors from any subsurface vapor source, such as contaminated soil or groundwater, through the soil and into an overlying building or structure. These vapors can enter buildings through cracks in `basements and foundations, as well as through conduits and other openings in the building envelope. Vapors can also enter structures that are not intended for human occupancy (e.g., sewers, drain lines, access vaults, storage sheds, pump houses) through cracks and other openings.

All types of buildings, regardless of foundation type (e.g., basement, crawl space, slab-on-grade), have openings that render them potentially vulnerable to vapor intrusion. Buildings subject to vapor intrusion include, but are not limited to, residential buildings (e.g., detached single-family homes, trailer or 'mobile' homes, multi-unit apartments and condominiums), commercial workplaces (e.g., office buildings, retail establishments), educational and recreational buildings (e.g., schools and gyms), and industrial facilities (e.g., manufacturing plants).

Vapor intrusion is a potential human exposure pathway -- a way that people may come into contact with hazardous vapors while performing their day-to-day indoor activities. For purposes of this Technical Guide, the vapor intrusion pathway is referred to as "complete" for a specific building or collection of buildings when the following five conditions are met under current conditions:

1) A subsurface source of vapor-forming chemicals is present (e.g., in the soil or in groundwater) underneath or near the building(s) (see Sections 2.1, 5.3, 6.2.1, and 6.3.1);

2) Vapors form and have a route along which to migrate (be transported) toward the building (see Sections 2.2 and 6.3.2);

3) The building(s) is(are) susceptible to soil gas entry, which means openings exist for the vapors to enter the building and driving 'forces' (e.g., air pressure differences between the building and the subsurface environment) exist to draw the vapors from the subsurface through the openings into the building(s) (see Sections 2.3 and 6.3.3);

4) One or more vapor-forming chemicals comprising the subsurface vapor source(s) is(are) present in the indoor environment (see Sections 6.3.4 and 6.4.1); and

5) The building(s)[1] is(are) occupied by one or more individuals when the vapor-forming chemical(s) is(are) present indoors.

[1] For purposes of this Technical Guide and its recommendations for evaluating human health risk posed by vapor-forming chemicals, "building" refers to a structure that is intended for occupancy and use by humans. This would include, for instance, homes, offices, stores, commercial and industrial buildings, etc., but would not normally include sheds, carports, pump houses, or other structures that are not intended for human occupancy.

A complete vapor intrusion pathway indicates that there is an opportunity for human exposure, which warrants further analysis (see Section 7.4) to determine whether there is a basis for undertaking a response action(s) (see Section 7.7). Depending upon building- and site-specific circumstances, concentrations of chemical vapors indoors arising from a complete vapor intrusion pathway may threaten the health of building occupants (e.g., residents, workers, etc.), which may warrant a response action(s).

On the other hand and for purposes of this Technical Guide, if one (or more) of the five foregoing conditions is currently absent and is reasonably expected to be absent in the future (e.g., vapor migration is significantly and persistently impeded by natural geologic, hydrologic, or biochemical (e.g., biodegradation) processes and conditions), the vapor intrusion pathway is referred to as "incomplete." EPA recommends that any determination that the vapor intrusion pathway is incomplete be supported by site-specific evidence to demonstrate that the nature and extent of vapor-forming chemical contamination in the subsurface has been well characterized (Section 6.3.1) and the types of vapor sources and the conditions of the vadose zone and surrounding infrastructure do not present opportunities for unattenuated or enhanced transport of vapors (Sections 5.4 and 6.5.2) toward and into any building (see Section 7.3 for further discussion). When the vapor intrusion pathway is determined to be incomplete, then vapor intrusion mitigation is not generally warranted.

EPA recommends that site managers also evaluate whether subsurface vapor sources that remain have the potential to pose unacceptable human health risks due to vapor intrusion in the future[2] if site conditions were to change. The vapor intrusion pathway is referred to as 'potentially complete' for a building when:

- a subsurface source of vapor-forming chemicals is present underneath or near an existing building or a building that is reasonably expected to be constructed in the future;
- vapors can form from this source(s) and have a route along which to migrate (be transported) toward the building; and
- three additional conditions are reasonably expected to all be met in the future, which may not all be met currently; i.e.,
    - the building is susceptible to soil gas entry, which means openings exist for the vapors to enter the building and driving forces exist to draw the vapors from the subsurface through the openings into the building;
    - one or more vapor-forming chemicals comprising the subsurface vapor source(s) is (or will be) present in the indoor environment; and
    - the building is or will be occupied by one or more individuals when the vapor-forming chemical(s) is (or are) present indoors.

[2] "Both current and reasonably likely future risks need to be considered in order to demonstrate that a site does not present an unacceptable risk to human health and the environment." (EPA 1991a).

In addition to their toxicity threats, methane and certain other vapor-forming chemicals can also pose explosion hazards depending upon structure-, building-, and site-specific circumstances. Explosion hazards may pose an imminent and substantial danger to human health and public welfare.

Technical Guide Development and Recommended Uses

To help assess the subsurface vapor intrusion pathway, the Office of Solid Waste and Emergency Response (OSWER) released in November 2002 for comment EPA's *Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils* ("Draft VI Guidance"). Since the Draft VI Guidance was released, EPA's knowledge of and experience with assessment and mitigation of the vapor intrusion pathway has increased considerably, leading to an improved understanding of and enhanced approaches for evaluating and managing vapor intrusion. In addition, EPA received hundreds of comments from the public since 2002 on the Draft VI Guidance, on a public review draft issued in April 2013, and on emerging practices and science considerations.

This Technical Guide presents current technical recommendations of the EPA based on our current understanding of vapor intrusion into indoor air from subsurface vapor sources. One of its main purposes is to promote national consistency in assessing the vapor intrusion pathway.[3] At the same time, it provides a flexible science-based approach to assessment that accommodates the different circumstances (e.g., stage of the cleanup process) in which vapor intrusion is first considered at a site and differences among pertinent EPA programs. This Technical Guide is intended for use at any site (and any building or structure on a site) being evaluated by EPA pursuant to the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) or the corrective action provisions of the Resource Conservation and Recovery Act (RCRA), EPA's brownfield grantees, or state agencies acting pursuant to CERCLA or an authorized RCRA corrective action program where vapor intrusion may be of potential concern. This document and the accompanying *Technical Guide For Addressing Petroleum Vapor Intrusion At Leaking Underground Storage Tank Sites* (EPA 2015b)[4] supersede and replace the Draft VI Guidance.

Although this Technical Guide is intended for use at any site subject to federal statutes, regulations, and rules, it is not intended to alter existing requirements, guidance, or practices among OSWER's programs about development, selection, or documentation of final remediation[5] plans (addressing subsurface vapor sources, for example).

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[3] If EPA staff wish to consider using any specific guidance that is not explicitly recommended in this Technical Guide, they should consult with Headquarters.

[4] For petroleum hydrocarbons that arise from petroleum that has been released from Subtitle I UST systems, EPA has developed a companion to this Technical Guide (*Technical Guide For Addressing Petroleum Vapor Intrusion At Leaking Underground Storage Tank Sites* (EPA 2015b)), which provides information and guidance about how EPA recommends vapor intrusion be assessed for petroleum hydrocarbons in these settings.

[5] For purposes of this Technical Guide, "remediation" is intended to apply to interim and final cleanups, whether conducted pursuant to RCRA corrective action, the CERCLA removal or remedial programs, or using EPA brownfield grant funds with oversight by state and tribal response programs. In addition to permanent remedies for subsurface vapor sources, site remediation may also entail implementation of institutional controls and construction and operation of engineered systems for exposure control.

Document Content and Key Recommendations

This document is comprised of eleven sections and three appendices, including a list of acronyms, which precedes this summary, and a glossary of terms in Section 10. Section 3 provides an overview of the entire Technical Guide and can be further summarized as follows:

- Broadly speaking, two general levels of vapor intrusion assessments can be distinguished:

  1) A preliminary analysis, which utilizes available and readily ascertainable information to develop an *initial* understanding of the potential for human health risks to be posed by vapor intrusion, which would typically be performed as part of an initial site assessment (Section 5).

  2) A detailed investigation (Section 6), which is generally recommended when the preliminary analysis (e.g., Section 5.3) indicates that subsurface contamination with vapor-forming chemicals may be present underlying or near buildings. A detailed investigation of the vapor intrusion pathway is typically performed as part of the site investigation stage.

  The approach for assessing vapor intrusion will vary from site to site, because each site will differ in the available data when vapor intrusion is being evaluated. This Technical Guide, therefore, recommends a framework for planning and conducting vapor intrusion investigations, rather than a prescriptive step-by-step approach to be applied at every site.

- Response actions to address vapor intrusion when it poses unacceptable human health risks (Sections 7.7 and 8) typically entail a combination of:

  - remediation to reduce or eliminate subsurface vapor sources (Section 8.1);
  - engineered exposure controls for specific buildings to reduce vapor intrusion or reduce concentrations of vapor-forming chemicals that have already entered the building (Section 8.2);
  - monitoring to assess and verify the performance and effectiveness of the remediation systems and engineered exposure controls (Section 8.4); and
  - institutional controls (ICs) to restrict land use and/or to alert parties (e.g., prospective developers, owners, and municipalities) of the presence of subsurface sources of vapor-forming chemicals and to foster operation, maintenance, and monitoring of the remediation systems and engineered exposure controls (Section 8.6).

  Additional response actions to avoid or reduce human exposure may also warrant consideration in circumstances where “early” or prompt response action is appropriate to address indoor air exposure conditions or a potential for explosion hazards.

Additional key recommendations and policies comprising this document include the following:

Planning, Scoping and Conducting Investigations (see Sections 5.4 and 6.2 for further information)

- Consider site and building access agreements, equipment security, and locations of underground utilities and piping, such as storm and sewer lines within buildings, when planning vapor intrusion investigations (Section 6.2).

- Develop an initial conceptual site model, use this model to guide planning and scoping of the investigation, and update this model as additional information and insights are generated (Sections 5.4, 7.1, and 7.2).

- Generally limit chemical analyses to those vapor-forming chemicals known or reasonably expected to be present in the subsurface environment.

- Consider a "worst first" approach to prioritize buildings for investigation at sites where numerous buildings are potentially subject to vapor intrusion (Section 6.2.2).

- To the extent practical, plan and implement investigations within buildings and on individual properties with the goal of limiting return visits, which can cause disruption and inconvenience for building occupants and owners (Section 6.2).

- Generally assess the vapor intrusion pathway by collecting, weighing, and evaluating multiple lines of evidence (Sections 6.3, 7.1, and 7.2).

- Utilize 100 feet to define an initial lateral inclusion zone for vapor intrusion assessment (i.e., for identifying buildings that are 'near' a subsurface vapor source and generally warrant assessment) for purposes of a preliminary analysis). Investigate soil vapor migration distance (e.g., define inclusion zone(s) for assessing vapor intrusion in specific buildings) on a site-specific basis. That is, distances larger or smaller than 100 feet (i.e., beyond or within an initial 100-foot inclusion zone) may need to be considered when developing objectives for detailed vapor intrusion investigations and interpreting the resulting data (Section 6.2.1).

- To support evaluations of sources of indoor air concentrations, identify in individual buildings known or suspected indoor sources of the vapor-forming chemicals also found in the subsurface and characterize ambient air quality in the site vicinity for these same chemicals (Sections 6.3.5 and 6.4).

- Select sampling and analytical methods that are capable of obtaining reliable analytical detections of concentrations less than project-appropriate, risk-based screening levels (e.g., vapor intrusion screening levels, or VISLs).

- When groundwater is a subsurface source of vapors, collect groundwater samples from wells screened across the top of the water table to characterize the source strength for vapor intrusion (Sections 6.3.1 and 6.4.5).

- Collect indoor air samples to characterize exposure levels in indoor air, account for seasonal variations in climate and the habits of building occupants, and ensure that

related risk management decisions are based upon a consideration of a reasonable maximum vapor intrusion condition for a given building (Sections 6.3.4 and 6.4.1).

- When sampling indoor air,
  - employ time-integrated sampling methods (e.g., evacuated canisters, sorbent-based sampling devices). Indoor air concentrations can be temporally variable and time-integrated exposure estimates over appropriate exposure durations (e.g., chronic typically; less-than-chronic in some cases) are generally most useful for exposure and human health risk assessment (Sections 6.4.1 and 7.4);
  - remove potential indoor sources[6] of vapor-forming chemicals from the building to strive to ensure that the concentrations measured in the indoor air samples are attributable to the vapor intrusion pathway (Sections 6.3.5 and 6.4.1); and
  - measure the pressure difference between the indoors and the subsurface, which provides a complementary line of evidence to support data evaluation and interpretation (Section 6.4.1) and is a more direct means of assessing building under-pressurization than is monitoring weather/climate factors (e.g., air temperature, wind speed).
- Mathematical modeling of vapor intrusion is most appropriately used in conjunction with other lines of evidence (Section 6.6).
- Confirm the reliability of modeling results, especially when limited site-specific data are available as inputs (Section 6.6).
- Collect and evaluate appropriate site-specific information to demonstrate that the property fulfills the conditions and assumptions of the generic conceptual model underlying the vapor intrusion screening levels (Section 6.5.2).

Data Evaluation and Decision-making

- Assess (and seek) concordance among the lines of evidence to more confidently support decision-making (Sections 7.1, 7.2, and 7.3).[7] Multiple lines of evidence are generally recommended for supporting conclusions, such as the following:
  - The subsurface vapor source(s) at a specific site has the potential to pose an unacceptable vapor intrusion exposure under current or reasonably expected future conditions, due to its vapor strength (Section 6.5) and proximity relative to one or more existing buildings or a building that may be constructed in the future (Section 6.2.1).

[6] As mentioned in Section 6.3.5, indoor sources can sometimes be identified and located using portable instruments.

[7] Confidence in the assessment and risk management decisions is expected to be higher when multiple independent lines of evidence come together to provide mutually supporting evidence for a common understanding of the site conditions/scenarios and the potential for vapor intrusion (EPA 2010b).

- The vapor intrusion pathway is complete for one or more buildings under current or reasonably expected future conditions (Section 7.3).

- The vapor intrusion pathway is incomplete for one or more buildings near a subsurface source of vapor-forming chemicals (Section 7.3), due to

  - inadequate source strength (i.e., chemicals comprising subsurface contamination and/or their potential vapor concentrations cannot pose an unacceptable human health risk via the vapor intrusion pathway) (Section 6.5); or

  - geologic, hydrologic, and/or biochemical (e.g., biodegradation) processes that provide substantial and persistent attenuation of vapors extending laterally over large distances relative to the footprint of the building(s) and the extent of the vapor source (Section 6.3.2).

- Indoor air concentrations attributable to vapor intrusion pose (or, alternatively, are unlikely to pose) an unacceptable human health risk in one or more existing buildings under current or reasonably expected future conditions, based upon currently available information about a chemical's toxicity (Section 7.4).

- Indoor air concentrations measured in one or more buildings can (or alternatively, cannot) be reasonably attributed to indoor or ambient air sources (i.e., background – see Glossary) (Sections 6.3.5 and 7.4.2).

Multiple lines of evidence are particularly important for supporting "no-further-action" decisions regarding the vapor intrusion pathway (e.g., pathway incomplete determinations) to reduce the chance of reaching a false-negative conclusion (i.e., concluding vapor intrusion does not pose unacceptable human health risk, when it actually poses an unacceptable human health risk). Collecting and weighing multiple lines of evidence can also reduce the chance of reaching a false-positive conclusion (i.e., concluding vapor intrusion poses unacceptable human health risk, when it does not). On the other hand, parties may implement engineered exposure controls for vapor intrusion, even though only limited lines of evidence or measurements may be available to characterize the overall vapor intrusion pathway.

- Consider reasonably expected future conditions, in addition to current conditions, when reaching conclusions about the vapor intrusion pathway (Sections 3.2 and 7.3). For example, EPA recommends that vapor intrusion be evaluated for reasonably expected future land use conditions, including new building construction and new uses and occupants for uninhabited buildings.

- Identify any conditions that warrant prompt action (Section 7.5) and respond, consistent with applicable statutes and regulations and considering EPA guidance, with actions that eliminate, avoid, reduce or otherwise address the human health risk posed by vapor intrusion (Sections 7.7 and 8.2):

  - Explosive conditions and threats that warrant prompt action (Section 7.5.1) are reasonably suspected to exist when measured concentrations of vapors in the building, utility conduits, sumps, subsurface drains, or other structure directly

connected to the building exceed one-tenth (10%) of the lower explosive limit (LEL).[8] EPA recommends evacuation of buildings with potential explosion and fire hazards, along with notification to the local fire department about the situation.

- o Conditions posing health concerns that warrant prompt action are reasonably suspected to exist when estimated exposure concentrations of vapors in the building exceed health-protective concentrations for short-term or acute exposure (Section 7.5.2).

- When making decisions pertaining to the assessment of vapor intrusion at nonresidential buildings, consider the characteristics of the populations potentially exposed to vapor-forming chemicals in the indoor air, the relative contributions of vapors from background (including anthropogenic background), and any existing or planned engineering or institutional controls for the building, in addition to the potential for vapor intrusion (Sections 4, 6.3.5, 6.4.1 and 7.4.2).

- When evaluating environmental sampling results to assess the vapor intrusion pathway, first determine that the samples were collected appropriately (Sections 5.5 and 6.4).

- Before conducting risk-based screening, verify that the site fulfills the conditions and assumptions of the generic conceptual model underlying the VISLs (Section 6.5.2).

- Compare groundwater concentrations to the VISLs (Section 6.5) for groundwater to estimate the boundaries of the plume, when contaminated groundwater is the subsurface vapor source for vapor intrusion (Section 6.2.1).

- Generally support the decision to collect indoor air data (Section 6.4.1) by lines of site- or building-specific evidence that demonstrate vapor intrusion has the potential to pose a significant human exposure [e.g., data on strength and proximity of subsurface vapor source(s) (Sections 6.2.1, 6.3.1, and 6.5), or preferential vapor migration in the vadose zone or into buildings (Sections 5.4, 6.3.2, and 6.3.3)].

- Consider variability in laboratory analyses when evaluating sampling data.

- Generally conduct a human health risk assessment to determine whether the potential human health risks posed to building occupants are within or exceed acceptable levels consistent with applicable statutes and considering EPA guidance (Section 7.4).

- Consider the potential for adverse non-cancer health effects from short-duration exposures (i.e., acute, short-term, or subchronic exposure durations), as well as longer term exposure (i.e., chronic exposure) conditions, and select toxicity values considering OSWER's preferred hierarchy of sources (EPA 2003) (Sections 7.4 and 7.5.2).

[8] The Occupational Safety and Health Administration of the U.S. Department of Labor (OSHA) considers concentrations in excess of one-tenth of the LEL to be a hazardous atmosphere in confined spaces [29 CFR 1910.146(b)]. The National Institute for Occupational Safety and Health (NIOSH) has designated such concentrations as immediately dangerous to life or health (IDLH).

- Consider collecting multiple rounds of indoor air samples,[9] using time-integrated measurements (Section 6.4.1) to estimate exposure concentrations appropriate for the exposure (occupancy) scenario being evaluated (e.g., residential versus commercial), when the risk assessment for an existing building would support a conclusion that the human health risks are acceptable (Section 7.4).[10]

- In the risk characterization of the human health risk assessment, discuss 'background' contributions to indoor air exposure and associated human health risks (Section 7.4.2). (For purposes of this Guide, 'background' refers to a vapor-forming chemical(s) or location(s) that is(are) not influenced by the releases from a site – see Glossary). Information on 'background' contributions of site-related, vapor-forming chemicals in indoor air is important to risk managers because generally EPA does not clean up to concentrations below natural or anthropogenic background levels[11] (EPA 2002e).

- If data are available, distinguish the contribution of 'background' to total exposure concentration(s). With such information, EPA can help advise affected individuals about the environmental and human health risks they face. Other parties, including building owners and operators, may help with risk communication.

- If background vapor sources (see Glossary) are found to be primarily responsible for indoor air concentrations (see Section 6.3.5), then response actions for vapor intrusion would generally not be warranted for current conditions.

<u>Engineered Exposure Controls and Building Mitigation</u>

- When vapor intrusion has been determined to pose unacceptable human health risks,

    - Aim to achieve a permanent remedy by eliminating or substantially reducing the level(s) of vapor-forming chemical(s) in the subsurface source medium (e.g., groundwater, subsurface soil, sewer lines) (Sections 7.7 and 8.1); and
    - In cases where subsurface vapor sources cannot be remediated quickly, implement engineered exposure controls to reduce or eliminate vapor intrusion in buildings (i.e., "mitigate" vapor intrusion) or reduce indoor air exposure levels (Sections 7.7 and 8.2).

[9] Because weather conditions and building operations can lead to time-variable contributions from vapor intrusion and ambient air infiltration, indoor air concentrations of vapor-forming chemicals can be expected to vary over time (see, for example, Section 2.6). An individual sample (or single round of sampling) would be insufficient to characterize seasonal variability, or variability at any other time scale.

[10] EPA recommends basing the decision about whether to undertake response action for vapor intrusion (i.e., a component of risk management; see Section 7.4) on a consideration of a reasonable maximum exposure (e.g., EPA 1989, 1991a), which is a semi-quantitative term, referring to the lower portion of the high end of the exposure distribution (see Glossary).

[11] With respect to vapor intrusion mitigation (see Sections 3.5 and 8.2), some options for reducing indoor air exposure levels (e.g., ventilation, indoor air treatment) unavoidably act on background concentrations arising from indoor or outdoor sources, as well as vapor concentrations arising from vapor intrusion. Most options for interrupting the vapor intrusion pathway (e.g., active depressurization technologies – see Section 8.2) unavoidably interrupt the intrusion of naturally occurring radon also. It should also be noted that some EPA regulations (e.g., indoor radon standards under 40 CFR 192.12) are inclusive of background.

- When developing monitoring programs to assess effectiveness of building mitigation, consider the degree of human health risk or hazard being mitigated, the building use, the technology used to mitigate vapor intrusion, and coordination with site remediation efforts.

- Establish cleanup levels and criteria for terminating engineered exposure controls and other building mitigation methods, institutional controls, and remediation systems for subsurface vapor sources (Sections 7.6 and 8.7).

Document Activities and Decisions

- Document objectives and methods of vapor intrusion investigations, preferably in a vapor intrusion work plan (Section 6.2).

- Base decisions upon data and information in the administrative record.

- Base decisions to undertake response actions on lines of site- or building-specific evidence (e.g., characterization of subsurface vapor source(s) strength and proximity to building(s); building conditions) that demonstrate that vapor intrusion has the potential to pose an unacceptable human health risk (Section 7).

- Document, consistent with statutory requirements and considering prevailing guidance for the respective land restoration program (e.g., CERCLA, RCRA corrective action, brownfields, etc.), any and all decisions pertaining to vapor intrusion, including decisions to undertake (or not to undertake) investigation or mitigation of specific buildings at a contaminated site.

- Prepare and publish system manuals to document building mitigation and remediation systems (Section 8.5).

- Prepare and implement operations and maintenance manuals and practices to foster continued effective operation and performance of engineered exposure controls and remediation systems for subsurface vapor sources (Section 8.5).

- Document monitoring programs that assess the performance and effectiveness of remediation and mitigation systems.

Community Outreach and Involvement (Section 9)

- Develop or refine a community involvement or public participation plan while planning a vapor intrusion investigation and implement this plan throughout the assessment, remediation, and mitigation phases.

- Conduct building-by-building contact and communication as means of educating the community and obtaining access needed to assess, mitigate, and monitor the vapor intrusion pathway. Personal contact is further recommended to establish a good working relationship with each building owner or occupant and to build trust.

- Generally provide validated results and interpretations (e.g., chemicals of concern, associated risk assessment implications) to property owners and occupants in a timely manner (e.g., within approximately 30 days of receiving these results).

- Provide adequate opportunities for public participation (including potentially affected landowners and communities) when considering appropriate use of ICs.

The science and technology to assess and mitigate vapor intrusion have evolved significantly over the past decade. EPA will continue to monitor these evolving developments and will update these recommendations in the future, if and as appropriate.

1.0 INTRODUCTION

This technical guide was prepared by the U.S. Environmental Protection Agency (EPA) through the cooperative efforts of a team of EPA Headquarters and Regional staff, known as the Vapor Intrusion Intra-Agency Workgroup (Workgroup). Drafts of this document were subjected to a comprehensive, consultative peer-input process in 2012, as described in EPA's *Peer Review Handbook* (EPA-SPC 2006), which included comments and other contributions from Workgroup members representing several EPA offices and the EPA's Vapor Intrusion Forum.[12] Public comments submitted from 2002 through 2013 and recommendations of the Office of Inspector General (OIG) were also considered in developing this document.

This document comprises EPA's 'final' vapor intrusion technical guide[13] and is referred to herein as "this Technical Guide." It describes a recommended framework for assessing vapor intrusion that relies upon collecting and evaluating multiple lines of evidence to support risk management decisions. It also provides technical recommendations about monitoring and terminating building mitigation systems.

This Technical Guide relied upon a large body of scientific information found in the peer-reviewed literature. Additionally, EPA developed three technical support documents that were externally peer reviewed (EPA 2011a, 2012a, 2012b). This approach is consistent with EPA's peer review handbook and policy (EPA-SPC 2006). Peer-reviewed literature, peer-reviewed technical reports, existing and relevant EPA guidance (e.g., for conducting human health risk assessment; for planning and conducting investigations of environmental contamination), and other pertinent information that support development or implementation of this Technical Guide are cited within.

This introductory section: defines the term "vapor intrusion"; summarizes EPA's statutory authorities to protect human health from vapor intrusion; summarizes the intended uses of this Technical Guide, including its applicability to petroleum hydrocarbons and other potentially biodegradable chemicals and to nonresidential buildings; identifies key technical resources that facilitate consideration of its recommendations; provides a concise historical accounting of its development; describes how the public was involved in its development; and provides an overview of its organization.

1.1 Definition of Vapor Intrusion

Certain chemicals that are released into the subsurface[14] as liquids or solids may form hazardous vapors that migrate or are transported through the vadose zone[15] and eventually

[12] The EPA Vapor Intrusion Forum is an intra-Agency group engaged in sharing information, technical resources, and perspectives pertaining to vapor intrusion assessment and mitigation.

[13] This document is intended to fulfill EPA's commitment to the OIG to issue "updated, revised, and finalized" vapor intrusion guidance (EPA 2009a, Appendix B; EPA 2010b).

[14] For purposes of this Technical Guide, the phrases 'released into the subsurface' and 'release to the subsurface' are intended to encompass any and all mechanisms by which chemical contamination arises in the subsurface, including, for example, spills and releases above the ground surface that result in subsurface (e.g., soil and groundwater) contamination.

enter buildings as a component of a gas[16] by migrating (being transported) through cracks, seams, interstices, and gaps in basement floors, walls, or foundations ("adventitious openings"), through intentional openings (e.g., perforations due to utility conduits, sump pits), and/or within conduits (e.g., drain and sewer lines). Vapor intrusion is the general term given to migration of hazardous vapors from any subsurface contaminant source, such as contaminated soil or groundwater or contaminated conduit(s), into an overlying building or unoccupied structure via any opening or conduit.

Recognition of soil vapor intrusion to buildings and other enclosed spaces occurred in the 1980s with concerns over radon intrusion.[17] Subsequently, there was an increasing awareness that anthropogenic chemicals (e.g., petroleum hydrocarbons and chlorinated solvents) in soil and ground water could also pose threats to indoor air quality via the vapor intrusion pathway (Little et al. 1992; Moseley and Meyer 1992).

Vapor intrusion can occur in a broad range of land use settings, including residential, commercial, and industrial, and affect buildings with virtually any foundation type (e.g., basement, crawl space(s), or slab on grade). In the last 20 years, vapor intrusion impacts have been demonstrated in occupied buildings at a number of sites across the country (e.g., Little et al. 1992). As a result, vapor intrusion is widely recognized as a potential pathway of human exposure to "volatile" hazardous chemicals in indoor spaces. When and where vapor intrusion occurs, concentrations of vapors can increase gradually in amount in buildings or structures as time passes (i.e., "accumulate"). Depending upon site- and building-specific circumstances, vapors of potentially toxic chemicals may accumulate to a point where the health of the occupants (e.g., residents, workers, etc.) in those buildings could be threatened.

In addition to their toxicity threats, methane and certain other vapor-forming chemicals can pose explosion hazards depending upon structure-, building-, and site-specific circumstances. Explosion hazards may pose an imminent and substantial danger to human health and public welfare.

Careful consideration of the vapor intrusion pathway is warranted at all sites where vapor-forming chemicals are present in the soil or groundwater aquifer (NRC 2013).

Section 2.0 describes the vapor intrusion pathway in greater detail.

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[15] The 'vadose zone' is the soil zone between land surface and the groundwater table within which the moisture content is less than saturation (except in the capillary fringe). It is also referred to as the "unsaturated zone."

[16] The terms 'gas' and 'vapor' refer the gaseous state, as distinguished from the liquid or solid state, of matter. Whereas "vapor' refers to a volatile chemical that may comprise only a portion of the total volume, 'gas' refers to the entire volume. For economy of words, this Technical Guide refers to vapor concentrations in soil gas as "soil gas concentrations."

[17] Radon is a colorless, odorless, radioactive gas that is formed from the decay of radium, a radioactive element that occurs naturally in the soil and bedrock in many areas of the United States. Radon can also be emitted from certain uranium- or radium-containing products and wastes. For more information about radon, see: http://www.epa.gov/radon/index.html.

1.2 Statutory Authorities

Protection of human health is a critical mandate underlying several federal statutes, including the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended,[18] and the Resource Conservation and Recovery Act (RCRA), as amended.[19] Protection of human health is also a critical objective of the National Oil and Hazardous Substances Pollution Contingency Plan (NCP), which is the federal government's blueprint for responding to oil spills and releases of hazardous substances, pollutants, or contaminants.

The sources of authority and requirements for addressing subsurface vapor intrusion are the relevant statutes and regulations. On this basis, the EPA has broad authority and distinct responsibilities[20] to assess and, if warranted, mitigate vapor intrusion in residential and nonresidential[21] settings arising from a chemical release that causes subsurface contamination by volatile hazardous chemicals.[22] These actions may include sampling indoor air to assess exposure levels of building occupants to subsurface vapors and implementing interim mitigation measures to control, reduce, or eliminate exposure indoors to vapors emanating from subsurface vapor sources. Where such subsurface contamination includes vapor-forming chemicals (see Section 3.1) and underlies or is near buildings, EPA recommends that the potential for human health risk from vapor intrusion be evaluated throughout the cleanup life

[18] Amendments to CERCLA include the Small Business Liability Relief and Brownfields Revitalization Act.

[19] Application of these statutory authorities to a particular situation generally entails site- and fact-specific analysis.

[20] On January 23, 1987, the President of the United States signed Executive Order 12580 entitled, "Superfund Implementation," which delegates to a number of Federal departments and agencies the authority and responsibility to implement certain provisions of CERCLA. The policies and procedures for implementing these provisions (e.g., carrying out response actions) are spelled out in the NCP. The provisions of Executive Order 12580 appear at 52 *Federal Register* 2923.

[21] The EPA and the Occupational Safety and Health Administration (OSHA) of the Department of Labor each have a distinct statutory responsibility to ensure the safety and health of America's workforce through the timely and effective implementation of a number of federal laws and implementing regulations. On November 23, 1990, the Secretary of the Department of Labor and Administration of the EPA signed a Memorandum of Understanding (MOU) with the goal of establishing a program for improved environmental and workplace health and safety, which continues in effect. Implementation of the MOU is intended "to improve the combined efforts of the agencies to achieve protection of workers, the public, and the environment at facilities subject to EPA and OSHA jurisdiction; to delineate the general areas of responsibility of each agency; and to provide guidelines for coordination of interface activities between the two agencies with the overall goal of identifying and minimizing environmental or workplace hazards." An additional MOU was signed in February 1991 to establish a process and framework for notification, consultation and coordination between EPA and OSHA to aid both agencies in identifying environmental and workplace health and safety problems and to more effectively implement enforcement of their respective national environmental and workplace statutes. For additional information, see https://www.osha.gov/pls/oshaweb/owasrch.search_form?p_doc_type=MOU&p_toc_level=1&p_keyvalue=Agency&p_status=CURRENT.

EPA's recommended approach for evaluating vapor intrusion exposures is based upon its existing risk assessment guidance, as summarized in Section 7.4.

[22] Section 3.1 of this Technical Guide describes technical criteria for identifying which specific chemicals are sufficiently volatile and hazardous to generally warrant routine evaluation during vapor intrusion assessments, when they are present as subsurface contaminants. These sufficiently volatile and hazardous chemicals are referred to as "vapor-forming chemicals" for purposes of this Technical Guide.

cycle (i.e., initial site assessment, site investigation, interim and final response actions,[23] and periodic reviews of the selected remedy), as described in Sections 5 and 6 of this Guide.

Although this Technical Guide is intended for use at any site subject to federal statutes, regulations, and rules, it is not intended to alter existing requirements, guidance, or practices among OSWER's programs about development, selection, or documentation of final remediation[24] plans (addressing subsurface vapor sources, for example).

EPA may need access to private property to conduct investigations, studies and response actions pursuant to CERCLA and RCRA, as amended. The Superfund Amendments and Reauthorization Act of 1986 and RCRA explicitly grant EPA the authority to enter property for these purposes (EPA 1986, 1987, 2010a). EPA generally prefers to obtain access through consent and cooperation. If consent is denied, however, EPA can use the judicial process or an administrative order to gain access. Application of legal doctrines to a particular access situation warrants site- and fact-specific analysis.

Provisions under CERCLA, RCRA, federal regulations, and federal guidance also provide authority and support for taking early actions to mitigate actual and potential human health risks, as discussed below. In the context of vapor intrusion, "early action" may include response measures such as engineered exposure controls to reduce or eliminate vapor intrusion in buildings (i.e., "mitigate" vapor intrusion) or reduce indoor air exposure levels (see Sections 7.8 and 8.2) and 'prompt' response actions to address more urgent threats to human health or public welfare (see Section 7.5).

1.2.1 Taking Action with Limited Data under CERCLA and the NCP

CERCLA and the NCP both contain provisions that support and encourage taking early actions to mitigate actual and potential threats to human health associated with vapor intrusion. For example, CERCLA sections 104 and 106 provide the federal government with broad authority to take response action(s) to address a release or threatened release of hazardous substances that "may present" a human health risk. Similarly, the preamble to the final NCP issued in the *Federal Register* on March 8, 1990 (55 FR 8704), states, "EPA expects to take early action at sites where appropriate, and to remediate sites in phases using operable units as early actions to eliminate, reduce or control the hazards posed by a site or to expedite the completion of total site cleanup. In deciding whether to take early actions, EPA balances a number of considerations, including the desire to definitively characterize site risks and analyze alternative remedial approaches for addressing those threats in great detail with the desire to implement protective measures quickly. EPA intends to perform this balancing with a bias for initiating

[23] The words "response action" or "response" are used generically in this Technical Guide to include remedial and removal actions under CERCLA as amended and similar actions under RCRA as amended.

[24] For purposes of this Technical Guide, "remediation" is intended to apply to interim and final cleanups, whether conducted pursuant to RCRA corrective action, the CERCLA removal or remedial programs, or using EPA brownfield grant funds with oversight by state and tribal response programs. In addition to permanent remedies for subsurface vapor sources, site remediation may also entail implementation of institutional controls and construction and operation of engineered systems.

response actions necessary or appropriate to eliminate, reduce, or control hazards posed by a site as early as possible."[25]

For sites that are not on the National Priorities List (NPL), EPA may use its removal authority under CERCLA to undertake early action to mitigate vapor intrusion threats. For sites that are on the NPL, EPA's Superfund program may use its remedial or removal authority under CERCLA to undertake early action to ensure the protection of human health during existing or future property uses that could be affected by vapor intrusion. Building mitigation, control of subsurface vapor source(s), and associated ICs could be part of a final remedy selected for the site, or where appropriate, could represent an early action that (1) is evaluated and selected on a faster track and (2) complements the anticipated final remedial action for the site.

Because of state cost-share consequences, EPA recommends that state concurrence be sought for any Fund-lead mitigation under CERCLA where there is a reasonable expectation that the state will need to take over responsibility for operations and maintenance (O&M) as part of a long-term, final remedy.

EPA's guidance for preparing Superfund decision documents states: "An interim action is limited in scope and only addresses areas/media that also will be addressed by a final site/operable unit ROD [Record of Decision]….Early actions can be taken throughout the RI/FS [remedial investigation/feasibility study] process to initiate risk reduction activities…. "Early" in this case is simply a description of when the action is taken in the Superfund process. Thus, an early action is one that is taken before the RI/FS for the site or operable unit has been completed. Hence, early actions may be either interim or final" (EPA 1999b). The primary goals of an early action are to "achieve prompt risk reduction and increase the efficiency of the overall site response" (EPA 1992b). Although preparation of an RI/FS Report is not essential for an early action, documentation that supports the rationale for the action and becomes part of Administrative Record is recommended, consistent with the NCP and CERCLA. For interim actions, EPA's guidance for preparing Superfund decision documents states: "A summary of site data collected during field investigations should be sufficient to document a problem in need of response. In addition, a short analysis of remedial alternatives considered, those rejected, and the basis for the evaluation (as is done in a focused FS) should be summarized to support the selected action" (EPA 1999b).

For response actions selected in an Action Memorandum or Record of Decision which are carried out by potentially responsible parties (PRPs), and where the PRP(s) agree to implement preemptive mitigation (PEM) for vapor intrusion, EPA recommends that PRP commitments to proceed with response action (including early action) be obtained through settlements or other enforcement documents (for example, administrative orders). Such response action commitments could include performance of O&M and monitoring. EPA recommends that settlement with PRPs concerning PEM/early action response actions specify that PRPs agree not to challenge the basis of the response based on inadequate characterization.

[25] So, for example, EPA cited the NCP in its *Compilation of Information Relating to Early/Interim Actions at Superfund Sites and the TCE IRIS Assessment* (EPA 2014b).

1.2.2 Taking Action with Limited Data under RCRA Corrective Action

EPA has emphasized the importance of interim actions and site stabilization in the RCRA corrective action program to control or abate "ongoing risks" to human health and the environment while site characterization is underway or before a final remedy is selected (see the *Federal Register* of May 1, 1996 [61 FR 19446]). Interim actions encompass a wide range of institutional and physical corrective action activities to achieve stabilization and can be implemented at any time during the corrective action process. EPA recommends that interim actions, including PEM, be employed as early in the corrective action process as possible, consistent with the human health and environmental protection objectives and priorities for the site. EPA recommends that, as further information is collected, program implementers continue to look for opportunities to conduct additional interim response actions.

1.3 Scope and Recommended Uses of this Technical Guide

This Technical Guide presents EPA's current recommendations for how to identify and consider key factors when assessing vapor intrusion, making risk management decisions, and implementing mitigation pertaining to this potential human exposure pathway. This Technical Guide and the accompanying *Technical Guide For Addressing Petroleum Vapor Intrusion At Leaking Underground Storage Tank Sites* (EPA 2015b) supersede and replace EPA's *Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils* (EPA 2002c) ("Draft VI Guidance"). One of the main purposes of this Technical Guide is to promote national consistency in assessing the vapor intrusion pathway.[26] At the same time, it provides a flexible science-based approach to assessment that accommodates the different circumstances (e.g., stage of the cleanup process) at a site and differences among pertinent EPA programs.

This Technical Guide is intended for use at any site[27] being evaluated by EPA pursuant to CERCLA or RCRA corrective action, EPA's brownfield grantees, or state agencies acting

[26] If EPA staff wish to consider using any specific guidance that is not explicitly recommended in this Technical Guide, they should consult with Headquarters.

[27] The term "site" is used generically in this Technical Guide to represent areas of contamination managed in a cleanup project under CERCLA as amended, under RCRA as amended, at a federal facility, or pursuant to an EPA Brownfields grant.

pursuant to CERCLA or an authorized RCRA corrective action program[28] where vapor intrusion may be of potential concern. EPA recommends consideration of this Technical Guide when:

- Making "Current Human Exposures Under Control" environmental indicator (EI) determinations at RCRA corrective action facilities (EPA 1999a, 2002b)[29] and National Priorities List (NPL) sites under CERCLA (EPA 2008b);

- Undertaking removal actions, remedial actions, pre-remedial investigations,[30] remedial investigations, and five-year reviews (FYRs)[31] and selecting remedies under CERCLA; and

- Undertaking RCRA facility investigations and corrective actions and site investigations and cleanups at federal facilities and brownfield sites.

This Technical Guide addresses both residential and nonresidential buildings that may be impacted by vapor intrusion from subsurface vapor sources.

The broad concepts of this Technical Guide generally may be appropriate when evaluating any of a large number and broad range of vapor-forming chemicals— described in Section 3.1 — that potentially can provide subsurface sources for vapor intrusion into buildings. These chemicals include, for example, chlorinated hydrocarbons (CHCs), petroleum hydrocarbons, other types of both halogenated and non-halogenated volatile organic compounds (VOCs),

[28] EPA believes that states, tribes, and local governments will find this Technical Guide useful for their respective programs. EPA recommends that state agencies that have delegated authority to implement CERCLA or RCRA consider this Technical Guide when implementing their state-specific guidance for vapor intrusion assessment and mitigation, if any, (e.g., ensure they incorporate features such as: using multiple lines of evidence to support pathway-incomplete determinations and "no-further-action" decisions; collecting multiple rounds of indoor air sampling to characterize exposure levels in indoor air in existing buildings and reduce the chance of reaching a false-negative conclusion (i.e., concluding exposure is at an acceptable risk level when it is not) or a false-positive conclusion (i.e., concluding vapor intrusion poses unacceptable human health risk, when it does not); focusing lab analyses of indoor air, ambient air, and sub-slab soil gas samples on vapor-forming chemicals known or suspected to be released to the subsurface environment; invoking the recommended criteria described in Section 6.5.2 as a condition for using risk-based screening levels for vapor intrusion; assessing human health risk posed by less-than-chronic exposure durations; and considering reasonably expected future conditions, as well as current conditions, when making risk management decisions and selecting cleanup and building mitigation plans).

[29] Also see http://www.epa.gov/osw/hazard/correctiveaction/eis/faqs.htm.

[30] CERCLA authorizes the EPA to identify and prioritize which sites warrant further investigation to ascertain whether remedial action is needed. The Hazard Ranking System (HRS) is the statutorily required method for evaluating and identifying sites for placement on the NPL.

[31] Section 121 of CERCLA specifies that remedial actions that result in any hazardous substances, pollutants, or contaminants remaining at the site be re-evaluated every five years to ensure that the remedy is and will continue to be protective of human health and the environment. OSWER Directive 9200.2-84 (*Assessing Protectiveness at Sites for Vapor Intrusion: Supplemental Guidance to the Comprehensive Five-Year Review Guidance* (EPA 2012c)) provides supplemental guidance for considering vapor intrusion while evaluating remedy protectiveness in the context of the Superfund five-year review process (even if vapor intrusion was not addressed as part of the original remedial action).

elemental mercury, and radon when it arises from uranium- or radium-bearing solid wastes in the subsurface.[32]

This Technical Guide addresses risk management (e.g., exposure control or avoidance methods) for indoor air contamination that arises from vapor intrusion from subsurface sources of these vapor-forming chemicals. It is not intended as a guide for assessing or mitigating indoor air exposures that arise solely from other sources (e.g., indoor use and storage of certain consumer products[33]).

The exposure route of general interest for vapor intrusion is inhalation[34] of vapors present in indoor air that have entered via soil gas entry from the subsurface.[35] Other human exposure routes that may warrant consideration during site investigations of subsurface contamination (e.g., ingestion of soil or water, dermal contact with soil or water, inhalation of particulate material, inhalation of vapors while outdoors, and inhalation of vapors while showering or washing with contaminated groundwater while indoors) are not addressed in this Technical Guide.

EPA recommends that risk management and response action decisions for the vapor intrusion pathway generally consider reasonably expected future conditions, which may differ from current conditions due to changes in land use, building and infrastructure construction and conditions, and vadose zone hydrology and oxygenation, among other factors. This Technical Guide provides general information regarding how these factors may enhance or impede vapor intrusion. It also provides recommendations for institutional controls and monitoring where a subsurface vapor source(s) is(are) present and has the potential to pose unacceptable human health risks.

Although this Technical Guide is intended for use at any site subject to federal statutes, regulations, and rules, it is not intended to alter existing requirements, guidance, or practices among OSWER's programs about circumstances for reviewing past risk management and cleanup decisions. As noted, remedy reviews are required by Section 121 of CERCLA when

[32] Radon emanating from natural geological materials may also affect indoor air quality in occupied buildings, but is not a subject of this Technical Guide. According to EPA estimates, inhalation of toxic radon decay products is the leading cause of lung cancer among non-smokers. For more information about radon emanating from natural geological materials, see: http://www.epa.gov/radon/index.html.

[33] Indoor air in most buildings will contain detectable levels of a number of volatile compounds, whether or not the building overlies a subsurface source of vapor-forming chemicals (EPA 2011a). As discussed further in Section 2.7 of this Technical Guide, these chemicals originate from indoor uses of chemical-containing products (e.g., household or consumer products) and from outdoor (ambient) air. EPA's indoor air quality program provides useful advice for control of indoor air exposures (see http://www.epa.gov/iaq/).

[34] Among human exposure pathways involving contamination of land and water, vapor intrusion is distinct. Whereas contact with contaminated surface soil, contaminated fish, and contaminated drinking water generally can be readily avoided for prolonged periods, breathing cannot.

[35] In addition, certain hazardous chemicals (e.g., methane) can pose explosion hazards when they gradually increase in amount in structures (e.g., confined spaces) or buildings as time passes to a point where there is an imminent and substantial danger to human health and public welfare.

hazardous substances remain on site.[36] EPA's other land restoration programs (e.g., RCRA corrective action, brownfield redevelopment) will continue to rely upon their existing, respective practices to address the need, if any, for periodic reviews of cleanup decisions, including consideration of the vapor intrusion pathway.

Finally, this Technical Guide does not aim or intend to:

- Offer recommendations for vapor intrusion assessments that private parties choose to conduct as part of real estate transactions;
- Modify existing guidance regarding landowner liability protection (e.g., all appropriate inquiries, the *bona fide* prospective purchaser provision); or
- Offer recommendations for responding to leaks from natural gas transmission lines.

1.3.1 Petroleum Hydrocarbons

The approaches in this Technical Guide are recommended for evaluating the vapor intrusion pathway pursuant to CERCLA or RCRA corrective action for petroleum hydrocarbons that are mixed with other types of volatile hazardous chemicals or are the result of releases from sources other than Subtitle I underground storage tank (UST) systems.[37] For petroleum hydrocarbons that arise from petroleum that has been released from Subtitle I UST systems, EPA has developed a companion to this Technical Guide (*Technical Guide For Addressing Petroleum Vapor Intrusion At Leaking Underground Storage Tank Sites* (EPA 2015b)), which provides information and guidance about assessing vapor intrusion from petroleum hydrocarbons in these settings and may also be useful in informing decisions about vapor intrusion and petroleum hydrocarbons at non-UST sites that are similar in size to a typical Subtitle I UST release.

Many petroleum hydrocarbons may naturally biodegrade in the vadose zone through the actions of microorganisms found naturally in soil. When oxygen supply from the atmosphere is sufficient, biodegradation of petroleum hydrocarbons can occur relatively quickly, will generally produce less harmful compounds (i.e., biodegradation products), and can result in substantial attenuation of petroleum hydrocarbon vapors over relatively short distances in the vadose zone.

Numerous site-specific factors can influence the biodegradation rate of petroleum hydrocarbons (and other biodegradable vapor-forming chemicals) in the vadose zone. These factors include quantities, distribution, types, and mixtures of vapor-forming chemicals, which can differ substantially among sites where petroleum hydrocarbons are released to the subsurface

[36] The NCP states [40 *CFR* 300.430(f)(4)(ii)]: "If a remedial action is selected that results in hazardous substances, pollutants, or contaminants remaining at the site above levels that allow for unlimited use and unrestricted exposure, the lead agency shall review such action no less often than every five years after initiation of the selected remedial action." For further information, see, for example, http://www.epa.gov/superfund/cleanup/postconstruction/5yr.htm

[37] For example, the approaches in this Technical Guide are recommended for evaluating the vapor intrusion pathway associated with subsurface releases of petroleum, petroleum derivatives, and petroleum hydrocarbons from refineries, bulk storage facilities, oil exploration and production sites, pipelines and transportation, chemical manufacturing facilities, former manufactured gas plants, creosote (wood-treating) facilities, large-scale fueling and storage operations at federal facilities, and dry cleaners that use petroleum solvents.

environment. This Technical Guide allows site-specific observations of the effects of biodegradation to be considered in its approach for petroleum hydrocarbons (and any other biodegradable, vapor-forming chemical). Sections 6.3.2 and 7.3 expand on EPA's recommended approach to evaluating biodegradation of vapor-forming chemicals in the vadose zone at sites with subsurface contamination.

1.3.2 Nonresidential Buildings

EPA has broad authority and distinct responsibilities to assess and, if warranted, mitigate vapor intrusion in nonresidential settings arising from a chemical release that causes subsurface contamination by volatile hazardous chemicals (see Section 1.2). EPA[38] is authorized to take all appropriate actions to protect human health and the environment from subsurface vapor sources of chemical exposure consistent with applicable federal statutes[39,40] and regulations and considering EPA guidance,[41] taking into account the nonresidential setting. These actions may include sampling indoor air to assess exposure levels of building occupants to subsurface vapor sources and implementing interim mitigation measures to control, reduce, or eliminate exposure indoors to vapors emanating from a subsurface vapor source(s).

As used in this Technical Guide, the phrase "nonresidential buildings" may include, but is not limited to, institutional buildings (e.g., schools, libraries, hospitals, community centers and other enclosed structures for gathering, gyms and other enclosed structures for recreation); commercial buildings (e.g., hotels, office buildings, many (but not all) day care facilities, and retail establishments); and industrial buildings where vapor-forming chemicals may or may not be routinely used or stored. Section 4.0 expands on EPA's recommended approach to evaluating and mitigating vapor intrusion in nonresidential buildings.

1.4 Companion Documents and Technical Resources

Technical information pertaining to vapor intrusion has also been prepared to support development of and facilitate implementation of the technical approaches and recommendations in this Technical Guide. Key technical information is described in this section and can be found on OSWER's vapor intrusion website (see Section 11.0 for citations and internet links).

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[38] On January 23, 1987, the President of the United States signed Executive Order 12580 entitled, "Superfund Implementation," which delegates to a number of Federal departments and agencies the authority and responsibility to implement certain provisions of CERCLA. The policies and procedures for implementing these provisions (e.g., carrying out response actions) are spelled out in the NCP. The provisions of Executive Order 12580 appear at 52 *Federal Register* 2923. At federal facilities on the NPL, EPA may not be the lead agency, but does have oversight responsibilities pursuant to CERCLA Section 120.

[39] CERCLA and RCRA authorize EPA to protect human health and the environment, as summarized in Section 1.2 of this Technical Guide. The NCP also addresses protection of human health and the environment.

[40] See, for example, CERCLA Section 101(22).

[41] See, for example, OSWER Directive 9355.0-30 (*Role of the Baseline Risk Assessment in Superfund Remedy Selection Decisions*) (EPA 1991a) and *Rules of Thumb for Superfund Remedy Selection,* OSWER Directive 9355.0-69, August 1997 (EPA 1997).

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1.4.1 Vapor Intrusion Screening Level Calculator

The Vapor Intrusion Screening Level (VISL) Calculator (2015a) is a technical resource, developed by EPA that:

(1) Identifies chemicals considered to be typically vapor-forming and known to pose a potential cancer risk or noncancer hazard through the inhalation pathway (as described further in Section 3.1 herein);

(2) Provides generally recommended screening-level concentrations for groundwater, near-source soil gas (exterior to buildings), sub-slab soil gas, and indoor air based upon default residential or nonresidential exposure scenarios, a target cancer risk level of one per million (10^{-6}), and a target hazard quotient of one for potential non-cancer effects; and

(3) Facilitates calculation of site-specific screening levels (see Section 6.5) and/or candidate cleanup levels (see Section 7.6) based on user-defined target risk levels, exposure scenarios, and semi-site-specific (Appendix A) or site-specific (Section 7.6) attenuation factors.

The VISL Calculator is comprised of an MS Excel workbook. It can be used in evaluating whether the vapor intrusion pathway has the potential to pose a human health risk by helping to:

(1) Identify whether volatile hazardous chemicals that can pose a threat through vapor intrusion are present;

(2) Determine if those volatile hazardous chemicals are present at potentially explosive levels;

(3) Compare subsurface or indoor data against recommended screening levels provided in the VISL Calculator; and

(4) Prioritize buildings and sites for investigation and response action.

The recommended screening-level concentrations in the spreadsheet are calculated using the recommended approaches in existing EPA guidance for human health risk assessment, as described further in Sections 6.5.2 and 6.5.3 herein, and are based on current understanding of the vapor intrusion pathway.

1.4.2 Technical Support Documents

Key technical documents supporting development of the technical approaches and recommendations in this Technical Guide include:

Background Indoor Air Concentrations of Volatile Organic Compounds in North American Residences (1990-2005): A Compilation of Statistics for Assessing Vapor Intrusion (EPA 2011a): This technical report presents (1) a summary of indoor air studies that measured background concentrations of VOCs in the indoor air of thousands of North American residences and (2) an evaluation and compilation of the statistical information reported in these studies. The objective of this compilation is to illustrate the ranges and variability of

VOC concentrations in indoor air during the study period (1990-2005), resulting from sources other than vapor intrusion. This technical report was externally peer reviewed, consistent with EPA's peer review policy (EPA-SPC 2006) for scientific and technically based work products that are intended to inform Agency decisions.

EPA's Vapor Intrusion Database: Evaluation and Characterization of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings (EPA 2012a): This technical report presents technical information about sites in the U.S. that have been investigated for vapor intrusion. The primary focus of the report is the evaluation of concentrations of chlorinated VOCs in and underneath residential buildings based upon the EPA's vapor intrusion database as of 2010. This report provides the technical basis for the generic and semi-site-specific attenuation factors recommended in this Technical Guide to calculate vapor intrusion screening levels (see Section 6.5 and Appendix A). This technical report was externally peer reviewed, consistent with EPA's peer review policy (EPA-SPC 2006) for scientific and technically based work products that are intended to inform Agency decisions.

Conceptual Model Scenarios for the Vapor Intrusion Pathway (EPA 2012b): This technical report provides simplified simulation examples to illustrate graphically how subsurface conditions and building-specific characteristics determine: (1) the distribution of vapor-forming chemicals in the subsurface; and (2) the indoor air concentration relative to a source concentration. It was prepared to help environmental practitioners gain insights into the processes and variables involved in the vapor intrusion pathway and to provide a theoretical framework with which to draw inferences about and better understand the complex vapor fate and transport conditions typically encountered at actual, contaminated sites. This technical report was externally peer reviewed, consistent with EPA's peer review policy (EPA-SPC 2006) for scientific and technically based work products that are intended to inform Agency decisions.

These technical tools and documents, as well as others, can be found at http://www.epa.gov/oswer/vaporintrusion, a website developed to support the development of this Technical Guide and enhance public communication about the topic. This website also allows certain sections of this Technical Guide to be more dynamic and facilitates updates to information.

Technical documents intended to facilitate consideration of the recommendations in the *Technical Guide For Addressing Petroleum Vapor Intrusion At Leaking Underground Storage Tank Sites* (EPA 2015b) can be found at http://www.epa.gov/oust/cat/pvi/.

1.5 Historical Context

To help assess the subsurface vapor intrusion pathway, the Office of Solid Waste and Emergency Response (OSWER) released in November 2002 for comment EPA's Draft VI Guidance, which presents EPA's technical information and recommendations for evaluating subsurface vapor intrusion, based on the understanding of vapor intrusion at that time (EPA 2002c). This Technical Guide and the accompanying *Technical Guide For Addressing Petroleum Vapor Intrusion At Leaking Underground Storage Tank Sites* (EPA 2015b) supersede and replace the Draft VI Guidance.

Since the Draft VI Guidance was released, EPA's knowledge of and experience with assessment and mitigation of the vapor intrusion pathway has increased considerably, leading to an improved understanding of and enhanced approaches for evaluating and managing vapor intrusion. In addition:

- Other federal agencies with responsibilities and obligations for environmental cleanup or for response to reports of vapor intrusion have developed vapor intrusion guides for their respective programs (e.g., ATSDR 2008; DoD 2009; DoN 2011a; USPS 2009).

- A number of state agencies involved with environmental quality or public health protection have developed vapor intrusion guides for their programs, which they may continue to implement under their respective statutory authorities (e.g., see ASTSWMO [2009], a compilation).

- The Interstate Technology & Regulatory Council (ITRC), a state-led coalition of environmental regulatory professionals, prepared three guidelines for assessing the vapor intrusion pathway (ITRC 2007ab, 2014).

EPA has considered these guides in developing this Technical Guide.

In addition, in December 2009, the OIG made recommendations regarding EPA's Draft VI Guidance, which are documented in the evaluation report *Lack of Final Guidance on Vapor Intrusion Impedes Efforts to Address Indoor Air Risks* (Report No. 10-P-042; EPA 2009a). Among other things, the OIG recommended that the final guidance incorporate:

- Updated toxicity values.

- A recommendation(s) to collect and weigh multiple lines of evidence in evaluating and making decisions about human health risks posed by vapor intrusion.

- How risks from petroleum hydrocarbon vapors should be addressed.

- How the guidance applies to Superfund FYRs.

- When or whether preemptive mitigation is appropriate.

- Operations, maintenance, and termination of mitigation systems.

- When institutional controls are appropriate.

In its response letter dated March 11, 2010, OSWER generally agreed with OIG's recommendations to finalize guidance on vapor intrusion. In addition, the OIG recommended

that EPA identify and publicly report the portions of its Draft VI Guidance that remain valid and the portions that would be updated.[42]

This Technical Guide and the companion documents identified in Sections 1.3 and 1.4 fulfill EPA's commitment to address the OIG's recommendations. Table 1-1 identifies specific updates prepared by EPA in response to OIG's specific recommendations. Table 1-2 describes additional updates identified and publicly announced by EPA (EPA 2010b).

TABLE 1-1
DIRECTORY TO UPDATES IN THIS TECHNICAL GUIDE ADDRESSING RECOMMENDATIONS OF EPA OFFICE OF INSPECTOR GENERAL (EPA 2009A)

Topics to Be Addressed	Location Within This Technical Guide	Companion Documents
Update toxicity values		*VISL Calculator* (EPA 2015a)
Use of multiple lines of evidence in evaluating and making decisions about risks from vapor intrusion	Sections 5, 6, and 7	
How risks from petroleum hydrocarbon vapors should be addressed	Sections 1.3.1, 6.3.2 and 7.3	*Technical Guide for Addressing Petroleum Vapor Intrusion at Leaking Underground Storage Tank Sites* (EPA 2015b)
How this Technical Guide applies to Superfund Five-year Reviews (FYRs)		*Assessing Protectiveness at Sites for Vapor Intrusion: Supplemental Guidance to the Comprehensive Five-Year Review Guidance* (EPA 2012c)
When or whether preemptive mitigation/early action is appropriate	Sections 3.3 and 7.8	
Operations and maintenance of mitigation systems	Section 8.3	
Termination of mitigation systems	Section 8.7	
When ICs and deed restrictions are appropriate.	Section 8.6	

[42] OSWER carried out this recommendation by issuing a memorandum in August 2010, entitled *Review of the Draft 2002 Subsurface Vapor Intrusion Guidance* (EPA 2010b). The guidance reflected in this memorandum is incorporated in this Technical Guide.

TABLE 1-2
DIRECTORY TO ADDITIONAL UPDATES IN THIS TECHNICAL GUIDE PUBLICLY IDENTIFIED BY OSWER (EPA 2010B)

Topics to Be Updated, Including References to the Draft VI Guidance	Location Within This Technical Guide	Companion Technical Document or Resource
Updated a few chemical-specific physical parameters used for identifying the vapor-forming chemicals of concern.	Section 3.1	VISL Calculator (EPA 2015a)
Updated the toxicity-based criteria in Table D-1 in the draft guidance.	Section 3.1	VISL Calculator (EPA 2015a)
Observation-based conservative attenuation factors have been updated with a larger database. The generic attenuation factor for external soil gas has been updated, as well as the Reliability Assessment, using the newer available data.	Section 6.5.3 and Appendix A	*U.S. EPA's Vapor Intrusion Database: Evaluation of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings* (EPA 2012a)
Observational data since 2002 indicates that the "single line of evidence" approach with site-estimated attenuation factors is generally not appropriate for external soil gas samples.	Section 6.4.4 and Appendix A	
Experiences since 2002 illustrate the value of collecting indoor air samples earlier in the investigations. The "indoor air last" approach has been updated, which will allow more flexibility in the sequencing of subsurface and interior/indoor sample collection.	Sections 6.3.4 and 6.3.6	
The portions addressing background contamination have been updated. EPA also updated with more specific methodologies for evaluating and/or decision-making and managing background contamination.	Sections 6.3.5, 7.4 and 7.6	*Background Indoor Air Concentrations of Volatile Organic Compounds in North American Residences (1990-2005): A Compilation of Statistics for Assessing Vapor Intrusion* (EPA 2011a)
The portion of this Technical Guide focusing on testing indoor air has been updated to allow more flexibility in the duration of sampling to take advantage of other sampling durations and methods.	Section 6.4.1	
The Draft VI Guidance allows site-specific decisions to be made based on indoor air concentrations in a relatively few representative buildings. This portion of this Technical Guide has been updated to increase the confidence that the approach fully addresses building-by-building variability.	Sections 6.2.2 and 7.8	
Updated and expanded the community involvement information to be more specific to vapor intrusion sites, including guidelines for effective risk communication and available resources, outreach products and tools for outreach.	Section 9	

1.6 Public Involvement in Developing this Vapor Intrusion Technical Guide

On November 29, 2002, EPA published a notice in the *Federal Register* (67 FR 71169) announcing and soliciting comment on its Draft VI Guidance. Since that time, EPA continued to gather information and learn more about vapor intrusion, in part by convening periodic forums where practitioners, regulated parties, and regulators could discuss the emerging science and engineering pertaining to vapor intrusion assessment and mitigation. In addition, on March 17, 2011, EPA published a notice in the *Federal Register* (76 FR 14660) re-opening the docket and soliciting additional comment on its development efforts for this Technical Guide. The docket was re-opened again in March 2012 to receive comments about specific technical documents that were prepared to support development of this Technical Guide; these technical documents are listed in Section 1.4. Finally, another review draft was released on April 16, 2013 for public comment. In developing and refining this Technical Guide, EPA considered all public comments and input received since 2002.

EPA also proactively engaged communities beyond the traditional outreach practices, especially environmental justice communities and communities subject to multiple stressors.[43] Aspects of this engagement have included:

- Conducting public listening sessions in communities impacted by vapor intrusion to solicit input on developing this Technical Guide.

- Using Internet sites and other communication tools to update stakeholders on the progress of developing this Technical Guide.

Table 1-3 identifies specific vapor intrusion topics that have received substantive public comment as a result of EPA's outreach efforts.

1.7 Organization

The next nine sections of this Technical Guide are as follows:

- Section 2.0 Conceptual Model of Vapor Intrusion further describes vapor intrusion and identifies many of the variables that influence vapor migration in the vadose zone and soil gas entry into buildings.

- Section 3.0 Overview of this Vapor Intrusion Technical Guide provides an overview of this Technical Guide and the general recommended framework for vapor intrusion assessment and response action.

- Section 4.0 Considerations for Nonresidential Buildings provides information regarding EPA roles, responsibilities, and risk management decision-making in nonresidential settings, including those (e.g., manufacturing facilities) where workers handle volatile hazardous chemicals similar to or different from those contaminating the subsurface.

[43] For more information about the Community Engagement Initiative visit: http://www.epa.gov/oswer/engagementinitiative/

TABLE 1-3
VAPOR INTRUSION TOPICS RECEIVING SUBSTANTIVE PUBLIC COMMENT

Topics	Location Within This Technical Guide	Companion Document(s)
Applicability to petroleum hydrocarbons	Sections 1.3.1, 6.3.2 and 7.3	*Technical Guide for Addressing Petroleum Vapor Intrusion at Leaking Underground Storage Tank Sites* (EPA 2015b)
Applicability to nonresidential buildings	Sections 1.3.2, 4.0 and 7.4.3	
Conditions warranting prompt response action	Sections 5.2, 7.5 and 8.2.1	
Planning investigations and applying data quality objectives	Section 6.2 and Appendix B	
Sampling and monitoring methods for indoor air	Section 6.4.1	
Attenuation factors and risk-based screening	Section 6.5 and Appendix A	*U.S. EPA's Vapor Intrusion Database: Evaluation of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings* (EPA 2012a)
Semi-site-specific screening and application of mathematical models	Sections 6.5 and 6.6	
Use of conceptual site models and multiple lines of evidence in evaluating risks posed by vapor intrusion	Sections 2, 3.2, 5.4, 6.3 and 7	
Risk management benchmarks and decision-making	Section 7	
Use of institutional controls for building mitigation	Section 8.6	
Monitoring and termination of mitigation systems	Sections 8.4 and 8.7	
Risk communication	Section 7.4 and 9	

- Section 5.0 Preliminary Analysis of Vapor Intrusion provides technical information for situations where only limited site-specific data may be available (e.g., initial site assessment).

- Section 6.0 Detailed Investigation of Vapor Intrusion provides technical information for conducting site-specific vapor intrusion assessments emphasizing multiple lines of evidence, including consideration of background concentrations.

- Section 7.0 Risk Assessment and Management Framework provides general recommendations about data evaluations and risk-informed decision-making pertaining to vapor intrusion, including consideration of background concentrations.

- Section 8.0 Building Mitigation and Subsurface Remediation provides technical information for mitigating vapor intrusion and describes how subsurface vapor source remediation and other final cleanup actions are combined with engineered and non-engineered exposure controls to ensure protection of human health.

- Section 9.0 Planning for Community Involvement provides information and describes available resources for engaging affected communities and communicating risk-related information.

- Section 10.0 Glossary provides definitions and descriptions of key terms used in this document.

This Technical Guide concludes with Section 11.0, Citations and References, and three supporting appendices:

- Appendix A: Recommended Subsurface-to-Indoor-Air Attenuation Factors.

- Appendix B: Data Quality Assurance Considerations.

- Appendix C: Calculating Vapor Source Concentration from Groundwater Sampling Data.

2.0 CONCEPTUAL MODEL OF VAPOR INTRUSION

This section presents a general (i.e., not site-specific) conceptual model of vapor intrusion, borrowing from published depictions (EPA 2008a; EPA 2012b; ITRC 2007a; McAlary et al. 2011; DoD 2009). It identifies and describes the 'what', 'where', 'how' and 'why' of vapor intrusion, to provide insights about the many of the lines of evidence pertinent to evaluating vapor intrusion on a site-specific basis, which are discussed further in Sections 5, 6, and 7 of this Technical Guide.[44] It concludes with several general observations that may assist practitioners when planning and conducting detailed vapor intrusion investigations at specific sites, which is the subject of Section 6 of this Technical Guide.

Vapor intrusion is a potential human exposure pathway — a way that people may come into contact with hazardous vapors while performing day-to-day indoor activities. Figure 2-1 summarizes the vapor intrusion pathway for soil gas entry. For purposes of this Technical Guide, the vapor intrusion pathway is referred to as "complete" [45] for a specific building or collection of buildings when the following five conditions are met under current conditions:

1. A subsurface source of vapor-forming chemicals is present (e.g., in the soil or in groundwater) underneath or near the building(s);

2. Vapors form and have a route along which to migrate (be transported) toward the building(s);

3. The building(s) is(are) susceptible to soil gas entry, which means openings exist for the vapors to enter the building and driving 'forces' exist to draw the vapors from the subsurface through the openings into the building(s);

4. One or more vapor-forming chemicals comprising the subsurface vapor source(s) is (or are) also present in the indoor environment; and

5. The building(s) is (or are) occupied by one or more individuals when the vapor-forming chemical(s) is (or are) present indoors.[46]

If one (or more) of these conditions is currently absent and is reasonably expected to be absent in the future (e.g., vapor migration is significantly and persistently impeded by natural geologic, hydrologic, or biochemical (e.g., biodegradation) processes and conditions), the vapor intrusion pathway is referred to as "incomplete."

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[44] In general, a conceptual site model integrates all lines of site-specific evidence into a three-dimensional conceptualization of site conditions that includes contaminant sources, release mechanisms, vapor migration route(s), and potential receptors. Section 5.4 provides additional information about developing conceptual site models.

[45] A complete vapor intrusion pathway indicates that there is an opportunity for human exposure in the subject building(s), whereas an incomplete pathway would not provide an opportunity for human exposure,

[46] The exposure route of general interest for vapor intrusion is inhalation of toxic vapors present in indoor air. Because breathing is not avoidable for prolonged periods, individuals in occupied buildings are presumed to be exposed by the inhalation route to any hazardous vapors present in indoor air. Hence, the presence of a human exposure route is implied in the fifth condition.

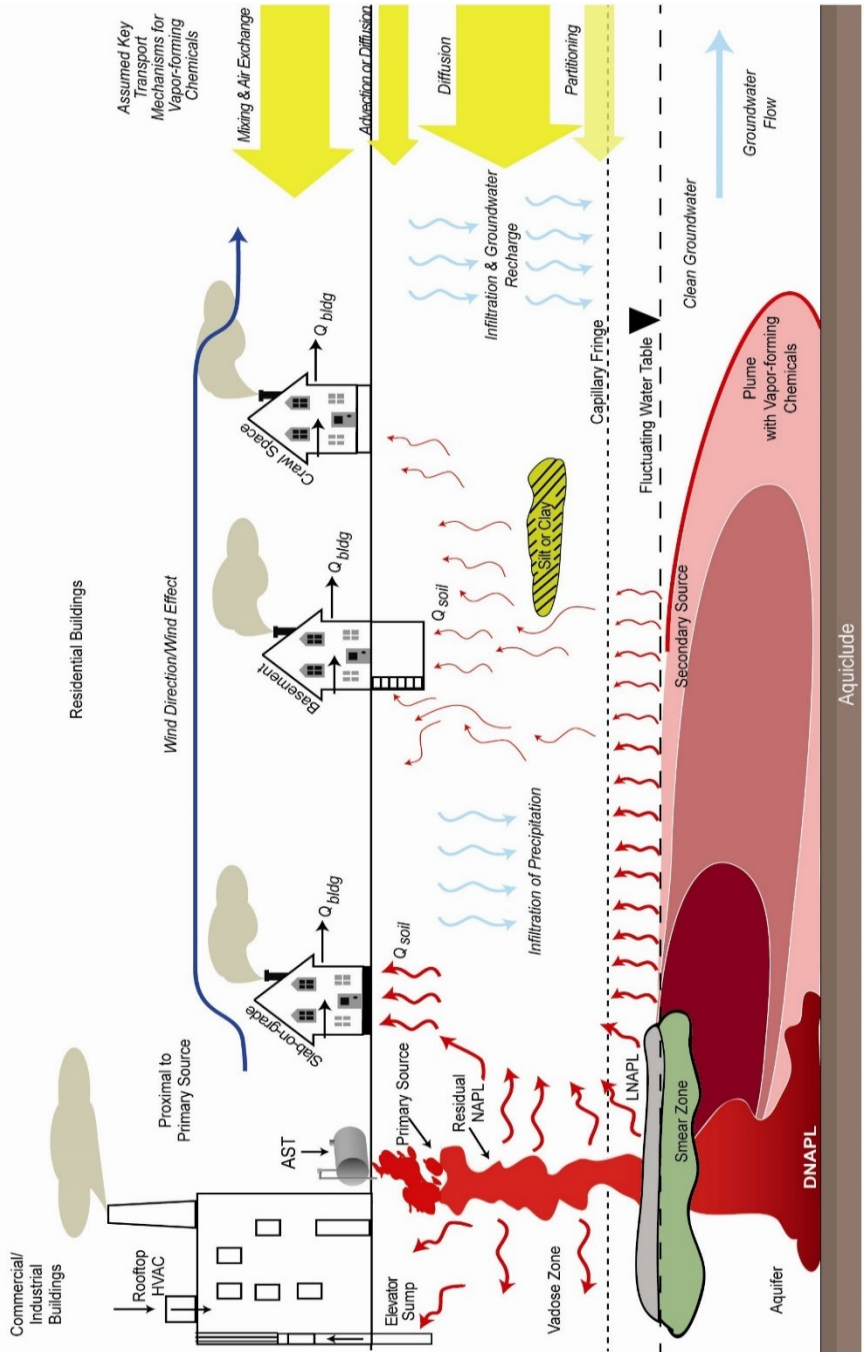

Figure 2-1 Illustration of Key Elements of the Conceptual Model of Soil Vapor Intrusion
Note: Q_{soil} represents soil gas entry; Q_{bldg} represents air exchange.

The first three of these five conditions are further discussed in the next three subsections. Knowledge of potential vapor sources and vapor fate and transport mechanisms is essential for interpreting the data collected during a site-specific investigation of vapor intrusion. Knowledge of the factors that influence the vapor intrusion pathway is also invaluable for identifying, prioritizing, and sequencing data collection activities, which allows a phased and efficient overall investigation plan to be developed. Practitioners are encouraged to refer to quantitative discussions of these subjects, which are provided in *Conceptual Model Scenarios for the Vapor Intrusion Pathway* (EPA 2012b).

The human population of primary interest is comprised of individuals living in, working in, or otherwise occupying a building subject to vapor intrusion. All types of buildings have openings and conduits that render them potentially vulnerable to vapor intrusion. This includes residential buildings (e.g., single-family homes, trailer or 'mobile' homes, multi-unit apartments and condominiums), commercial workplaces (e.g., office buildings, retail establishments), industrial facilities (e.g., manufacturing plants), and educational and recreational buildings (e.g., schools and gyms). Vapor intrusion can occur in buildings with any foundation type (e.g., basement, crawl space, slab-on-grade).

As noted previously, methane and certain other vapor-forming chemicals can also pose explosion hazards in buildings and unoccupied structures,[47] depending upon building-, structure-, and site-specific circumstances. The discussion in the next three sections pertains also to methane and other vapor-forming chemicals that can pose explosion hazards, because similar processes and conditions are involved in explosive vapors migrating towards the interior of buildings or non-occupied structures from the subsurface environment; i.e.,

1) A subsurface source of vapor-forming chemicals is present (i.e., in the soil or in groundwater) underneath or near the structure(s) or building(s).

2) Vapors form and have a route along which to migrate (be transported) toward the structure(s) or building(s).

3) The structure(s) or building(s) is (or are) susceptible to soil gas entry, which means openings exist for the vapors to enter the structure(s) or building(s) and driving 'forces' exist to draw the vapors from the subsurface through the openings into the structure(s) or building(s).

[47] For purposes of evaluating potential explosion hazards, non-occupied structures, in addition to buildings, are relevant structures for intrusion and accumulation of vapors.

2.1 Subsurface Vapor Sources

The originating (i.e., primary) source(s) of subsurface contamination may include, but are not limited to, leaking tanks (above or below ground), discharges to sewer lines[48], septic tanks, and floor drains, landfills and other land disposal management units, fire-training areas, spills, discharge areas, and vapor leaks from pressurized tanks and pipelines. The resulting subsurface contamination may be comprised of non-aqueous-phase liquids (NAPLs) [49] (e.g., solvents; petroleum-related products, such as gasoline) and contaminated soil. These are often referred to as the source zone(s). Groundwater and sewer lines[50] flowing through or underneath[51] the source zone(s) can become contaminated and in turn become a (secondary or derivative) subsurface vapor source of contaminant vapors at locations distant from the source zone.

Contaminants in soil, NAPLs, and groundwater can become sources for vapor intrusion if they are likely to volatilize under normal temperature and pressure conditions. Water solubility is also a factor for chemicals in source zones that come into contact with migrating groundwater. Common classes of chemicals of concern for vapor intrusion that exhibit the foregoing characteristics are VOCs, such as tetrachloroethylene (PCE), trichloroethylene (TCE), vinyl chloride, carbon tetrachloride, and benzene, toluene, ethylbenzene and xylenes (collectively, BTEX). Other compounds that are not as volatile as these VOCs (e.g., so-called semi-volatile organic compounds), but that may be cause for concern, include some polycyclic aromatic hydrocarbons (PAHs) (e.g., naphthalene), some polychlorinated biphenyl (PCB) congeners, and elemental mercury, a dense NAPL (DNAPL).[52]

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[48] Historically, sanitary sewers and septic tanks have been common disposal points for aqueous and chemical wastes from commercial and industrial operations. Contaminated water, non-aqueous phase liquid (NAPL), and VOC vapors can leak from sewer lines through cracks, joints, or breaks. A study of solvent contamination in California arising from dry cleaning operations concluded that discharges to and leakage from sewer lines is an important source of PCE contamination of soil and groundwater: "Where a source investigation has been done in connection with PCE contamination, the … data strongly indicate that leakage through the sewer lines is the major avenue through which PCE is introduced to the subsurface." (Izzo 1992). In the South Weber neighborhood near the Hill Air Force Base in Utah, sewer lines carrying discharged contaminated groundwater to the municipal treatment system were identified as a source of vapor intrusion in homes [Source: *EnviroNews* - Updating environmental issues and activities at Hill Air Force Base, Utah (March 2011); Currently available on-line at: http://www.hillrab.org/news.aspx]

[49] EPA's Contaminated Site Cleanup Information website (http://www.clu-in.org/) provides information describing NAPLs that are denser than water (DNAPLs) or less dense than water (LNAPLs), and methods for their detection and remediation in the subsurface environment.

[50] In addition to receiving direct discharges, sewers can be indirect receptacles of subsurface contamination via infiltration of NAPL, soil gas, or contaminated groundwater through cracks in piping and manholes. For example, Vroblesky et al (2011) found that infiltration of contaminated groundwater into sewers and its transport via and exfiltration from sewers caused complex and unanticipated patterns of groundwater contamination at a site in South Carolina.

[51] Figure 2-1 illustrates a NAPL release/source (near the commercial/industrial building on the left) that fully penetrates the vadose zone. A partially penetrating NAPL release/source may also cause groundwater contamination, however, as infiltrating water passes through the source zone and migrates to the groundwater table.

[52] Once volatilized into soil or sewer gas from a subsurface vapor source(s), these less volatile chemicals will migrate under the influence of diffusion and advection (see Section 2.2) as do more volatile chemicals, although there may be chemical-specific differences in their susceptibility to biodegradation in the vadose zone.

Landfill gases, such as methane and hydrogen sulfide, also can be associated with the vapor intrusion pathway for buildings located near current or former landfills or other degrading wastes. These gases are actively produced as a result of anaerobic biodegradation processes. Methane can also be associated with the vapor intrusion pathway for buildings located near degrading petroleum hydrocarbons or fuel-grade ethanol released into the subsurface environment (Ma et al. 2014, 2012; Sihota et al. 2013).

Properties with potential contamination by vapor-forming chemicals can be found in many industrial and commercial areas. These properties include current and former manufacturing and chemical processing plants, warehouses, landfills and other land disposal units, coal gasification plants, chemical handling or transfer facilities and areas (e.g., train yards), dry cleaners, and retail fueling outlets (also known as gas stations). Use, storage, or transport of chemicals at these facilities may have resulted in a release of vapor-forming chemicals to the environment creating the potential for future vapor intrusion issues. In addition to industrial and commercial activities, roadside dumping, pesticide spraying, or even disposal of household chemicals via a septic field may also release volatile chemicals that may eventually migrate to the subsurface environment.

The primary contamination source need not, however, be on the property of interest to pose a vapor intrusion problem.[53] As illustrated in Figure 2-1, the primary source(s) of vapor intrusion (e.g., contaminated soil, or leaked tanks) may be present on a neighboring property or on a property some distance away. Even "greenspace" properties that have not previously been occupied or developed may contain contamination by vapor-forming chemicals due to migrating plumes of contaminated groundwater or migrating soil gases.[54]

In the case of groundwater as a subsurface vapor source for vapor intrusion, the source strength will be influenced by the vertical distribution of contaminant concentrations in the upper reaches (e.g., top foot) of the water table and by seasonal fluctuations in the groundwater table groundmass flux of vapors. If vapor-forming chemicals are not present in the upper reaches (e.g., within the uppermost foot) of the groundwater table (e.g., due to the presence of an overlying zone of clean water from recharge; i.e., "fresh water lens"),[55] vapor transport to the overlying vadose zone will be impeded due to the slower diffusion of volatile chemicals in water

[53] Depending on the geology and amount and form of contamination in the source zone(s), contaminated groundwater plumes can be long and narrow and can flow beneath a property located a mile or more away from the primary source. Soil gas plumes tend to extend in both lateral directions and can be larger in lateral extent relative to groundwater plumes.

[54] See Section 6.2.1 for further discussion on which buildings and non-occupied structures are considered "near" for purposes of a preliminary analysis.

[55] Infiltrating precipitation is important in recharging aquifers with fresh water, as well as in wetting vadose zone soils. At locations distant from "source zones," infiltrated water that reaches the upper surface of a plume of contaminated groundwater (i.e., recharges groundwater) in an unconfined aquifer will tend to dilute concentrations of vapor-forming chemicals and may form a lens of relatively "clean" water at the groundwater table, which overlies the plume. Because diffusion of dissolved-phase volatile chemicals will tend to control the mass transfer of vapors into the soil gas at the groundwater table, the presence of a lens of clean water as little as a foot in thickness overlying a plume may be sufficient to impede vapor flux to the vadose zone (McAlary et al. 2011). This condition is less likely to occur where fluctuations of the groundwater table are large, relative to local recharge, and would not generally be expected in arid climates.

than in soil gas. For this reason, Figure 2-1 does not show vapors emanating from the leading (i.e., right-most) edge of the plume.

If the vapor-forming chemicals are present in the upper reaches of the groundwater table (i.e., volatile chemicals are in the uppermost reaches of an unconfined – "water table" – aquifer), fluctuations in the water table will tend to transport the volatile chemicals upward (during periods of rising water table) or expose impacted water above the water table to soil gas (during periods of falling water table). The latter will facilitate the episodic formation of vapors in the vadose zone. Rising water tables also will bring the vapor source closer to the building(s).

2.2 Subsurface Vapor Migration

At many sites, the subsurface vapor source (e.g., in soil or groundwater) is not in contact with the bottom of the subject building. Under these circumstances, vapors emanating from the source medium enter the pore space around and between the subsurface soil particles in the soil column above the groundwater table, which is called the unsaturated soil zone or vadose zone. If the subsurface vapor source is in the vadose zone, the vapors have the potential to migrate radially in all directions from the source via diffusion (i.e., upward toward the atmosphere, laterally outward, and downward toward the water table; downward migration may eventually lead to groundwater contamination). If the subsurface vapor source is in the upper-most zone of groundwater, the vapors have the potential to migrate upwards toward the atmosphere via diffusion. Figure 2-1 illustrates these conditions and this process.

Regardless of source type, soil gas concentrations emanating from a subsurface vapor source generally attenuate, or decrease, as the volatile chemicals move from the source through the soil and into indoor air. If and when soil vapor monitoring data at a given site are not consistent with this trend, the conceptual site model may be incomplete (e.g., additional, unrecognized sources or a preferential migration route(s) may exist at the site) and/or bias or error may have been imparted by the sampling and analysis techniques.

Diffusion, which is caused by the random motion of molecules, affects the distribution of soil vapors when there are spatial differences in chemical concentrations in the soil gas. The net direction of diffusive transport is toward the direction of lower concentrations.

Advection occurs in the vadose zone when there is bulk movement of soil gas induced by spatial differences in soil gas pressure. The direction of advective vapor transport is always toward the direction of lower air pressure. Advection is generally expected to occur in the vicinity of buildings, because differences in temperature between the building interior and the subsurface environment or the operation of combustion units or fans within the building can create driving forces for soil gas entry (See Section 2.3). Advection of soil gas may also occur:

- near the ground surface due to fluctuations in barometric (atmospheric) pressure, which can either release soil gas into the atmosphere (Clements and Wilkening 1974) or

introduce ambient air into the subsurface environment (the latter process may be important in oxygenating surface soil horizons);[56]

- wherever methane generation from anaerobic degradation is sufficiently high (e.g., near some landfills, some locations with degrading fuels).

Advection may be hindered where extensive surface barriers, such as asphalt, concrete, or frozen soil are present.

Vapors also can migrate via advection (and diffusion) along a preferential subsurface pathway, such as a utility corridor or more porous zones of soil or rock, or beneath surface barriers that limit the direction(s) of vapor migration, such as frozen ground or asphalt.[57]

Vapor migration in the vadose zone can be impeded by several factors, including high soil moisture, low-permeability (generally fine-grained) soil, and biodegradation:

- High moisture levels in the vadose zone can significantly reduce the effective rate of diffusive transport, owing to the substantially smaller diffusion coefficient of vapor-forming chemicals in water compared to air. Where ground covers, such as asphalt or concrete, are absent, soil cores taken external to building structures can reasonably be expected to show greater soil moisture than underneath buildings (Tillman and Weaver 2007), particularly after episodes of precipitation and infiltration. Fluctuations in the elevation of the groundwater table can also contribute to temporal changes in soil moisture profiles, in addition to changing the thickness of the vadose zone.

- A low-permeability layer in the vadose zone, particularly one with high moisture content or perched water, may impede or prevent upward migration of vapors from deeper sources in the vadose zone. Figure 2-1 illustrates partial impedance due to a silty or clay layer of limited lateral extent.[58] In some cases, soil or rock can impose sufficient resistance to vapor migration to make the vapor intrusion pathway insignificant, because low-permeability layers are laterally extensive over distances that are large compared to the size of the building(s) or the extent of subsurface contamination with vapor-forming chemicals.

[56] Under certain conditions, such as periods during which indoor–outdoor pressure differences are small, atmospheric pressure fluctuations may contribute to the vapor flux into a building (Robinson and Sextro, 1997).

[57] Whether the subsurface vapor source is contaminated soil or groundwater, soil gas concentrations emanating from a subsurface source generally attenuate, or decrease, as the vapors move from the source through the soil and into indoor air due to diffusion and advection and are subject to any degradation. If and when soil vapor monitoring data at a given site are not consistent with this trend, the possible existence of a preferential migration route(s) warrants consideration. Sewer lines also warrant consideration as potential sources of vapors, as well as conduits for preferential (e.g., unattenuated) transport of vapors towards buildings. Preferential migration routes are discussed further throughout this Technical Guide, including in Sections 5.4, 6.3.2, and 6.5.2.

[58] Low-permeability layer(s) overlying contaminated groundwater (i.e., "aquicludes") can, likewise, impede the flux of vapors from the contaminated plume to the vadose zone. The aquiclude shown at the base of Figure 2-1 would not impede the flux of vapors from the contaminated plume to the vadose zone, however, because the aquiclude is below both. The aquiclude would impede vapor flux from any additional contaminated plume located below it.

- Some chemicals (e.g., benzene, methane, and other petroleum hydrocarbons; vinyl chloride (Patterson et al. 2013) and some other chlorinated hydrocarbons) may experience reductions in their soil gas concentrations due to biodegradation in the vadose zone under certain conditions. Depending upon the potential for oxygen to migrate into the subsurface and underneath buildings from the ambient air, biodegradation may be anaerobic or aerobic. The rate of biodegradation *in situ* will be chemical-specific (i.e., chemicals have different degradation rates even within a similar microbial environment), will be site-specific (i.e., the microbial environment will depend upon soil moisture, nutrient and oxygen levels, and the chemical mixture,[59] among other factors (Holden and Fierer 2005)), and may be location-specific (i.e., the microbial environment can change over time and space due to variations in soil moisture,[60] nutrient and oxygen[61] levels). In some cases, biodegradation in the vadose zone can impede vapor migration significantly.

Demonstrating the extent, if any, to which these processes act as a barrier to vapor transport at specific sites may entail intensive testing or investigative methods that are very different from the sampling and analysis techniques for indoor air and soil gas (see, for example, Sections 6.3.2 and 6.4). Where and when it occurs, biodegradation may result in the formation of by-products that are potentially hazardous (e.g., methane from ethanol, vinyl chloride from PCE or TCE).

The distribution and magnitude of soil gas concentrations immediately beneath a building are expected to reflect the interplay between vapor transport toward the building (via diffusion and advection) in the vadose zone and vapor withdrawal due to soil gas entry into the building (in the case where the building is under-pressurized), which may be spatially and temporally variable (Section 2.3). Likewise, soil vapor may become contaminated as a result of over-pressurized buildings forcing contaminated indoor air through openings in the foundation into nearby soil.

2.3 Openings and Driving Forces for Soil Gas Entry into Buildings

Hazardous vapors in the vadose zone may eventually enter buildings as a component of a gas by migrating through cracks, seams, interstices, and gaps in basement floors, walls, or foundations ("adventitious openings") or through intentional openings, such as perforations due to utility conduits and sump pits. Figure 2-2 illustrates some of these types of openings. Buildings can be expected to vary, even within a single community, in the amount of opening

[59] For example, aerobic biodegradation of benzene may be impeded by the presence of methane, due to competition for oxygen by methane-oxidizing ("methanotrophic") bacteria, depending upon site-specific conditions (Ma et al. 2012).

[60] Moisture plays a particularly important role for microorganisms in the vadose zone. Microbial growth and activity can decrease rapidly with depth, coincident with the soil moisture profile, and increase again in the capillary fringe (Holden and Fierer 2005).

[61] Site-specific infrastructure and soil conditions, climate, and other factors will determine the extent to which oxygen levels underneath a building will be different compared to locations outside the building footprint. In addition to buildings, surface covers, such as asphalt or concrete, can impede oxygenation of the vadose zone, relative to the case where the ground surface is in contact with the atmosphere, all other factors being equal.

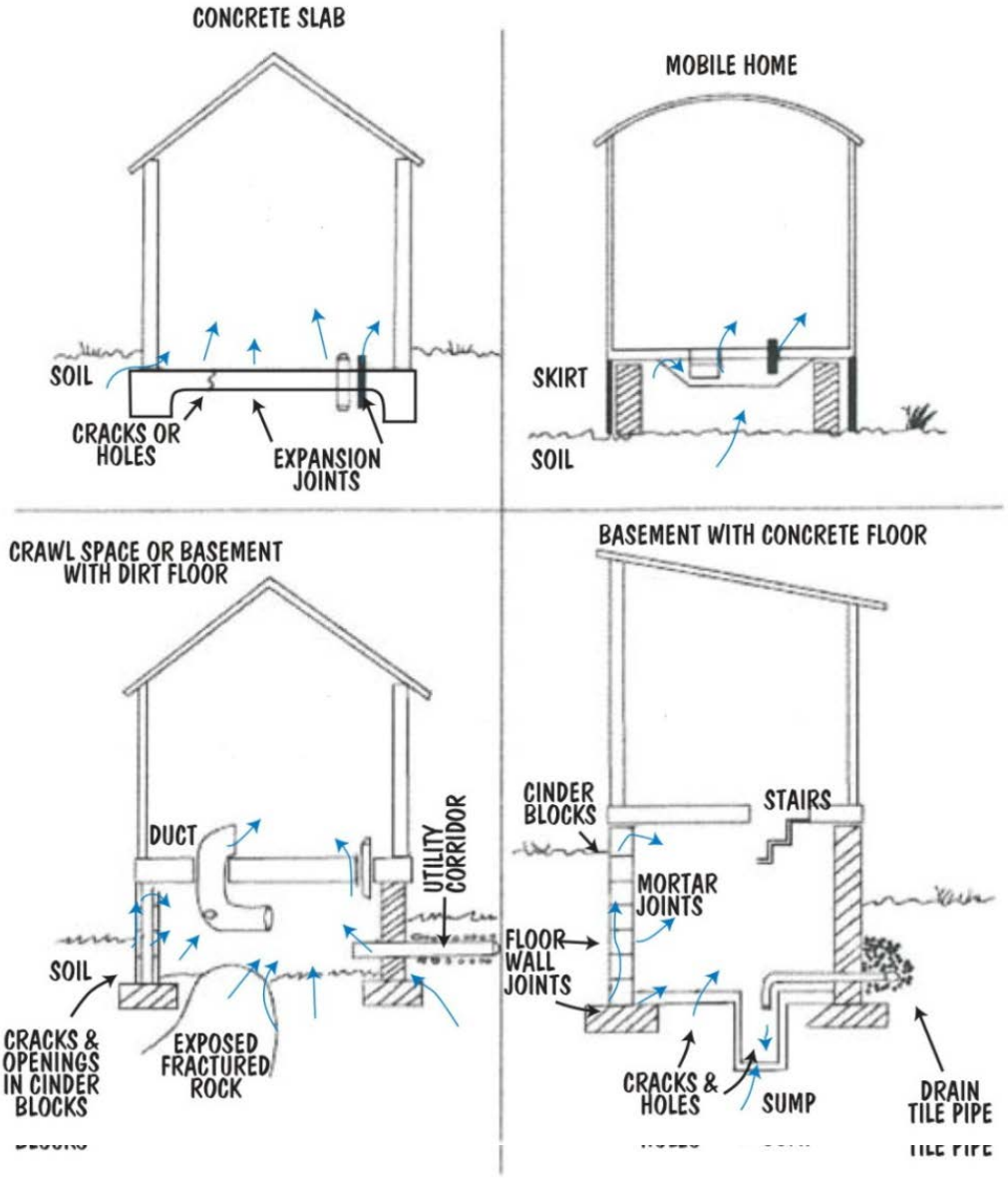

Figure 2-2 Illustration of Potential Openings in Various Building Types
Note: Blue arrows represent soil gas migration or entry. Source: EPA (2008)

area available for soil gas entry; for example, buildings with deteriorating basements and foundations or dirt floors are more susceptible to soil gas entry.

As mentioned in Section 2.2, advection in the vadose zone can arise in the vicinity of buildings whenever there is a difference between the air pressure within a building and the subsurface environment. The air pressure within a building can be lower than in the subsurface due to:

- Temperature differences between indoor and subsurface locations (e.g., the winter-time "stack effect," when buildings are commonly heated, leading to convection cells driven by heated air that rises to upper levels and leaks through roofs and upper-floor windows).

- The operation of mechanical devices, such as exhaust fans for ventilation, air conditioners, and clothes dryers, with vents to the outdoors.

- The operation of fireplaces that vent combustion (exhaust) gases to the outdoors.

- The operation of furnaces in basements of centrally heated buildings, which can incrementally depressurize the basement (EPA 1993a).

- Wind load on the building walls.[62]

Even small pressure differences may cause advective flow of soil gas into or out of the building through pores, cracks, or openings in the building floor or basement walls[63] or gas present in drain lines, sumps, and sewer lines that do not have adequate vapor traps.[64]

[62] The wind effect is caused by differences in building pressure on a building's surfaces. The outdoor air pressure will be higher on the windward side of the building, than on the leeward side, as ambient air flows around the building. The net effect of this pressure difference will vary from building to building, depending upon the location of the primary openings for soil gas entry (and the primary opening for air infiltration through the building envelope –see Section 2.4) (EPA 1993a, Section 2.3 therein).

[63] As a result of the construction of foundation walls and floor slabs, a perimeter crack (i.e., space between the floor slab and walls) may be created and serve as an entry location for soil vapors. This perimeter crack is often obscured by wall coverings, and may not be accessible for inspection or direct testing. Vapors have been observed to migrate through what appears to be intact concrete floors and walls, which may, in fact, have small unobserved fractures or porous areas from improper curing. In addition, conduits may be present that facilitate soil gas entry into buildings. These conduits may include utility (e.g., sewer, water, or electrical) penetrations and floor drains

[64] Where sewers or other conduits contain volatile contaminants, lateral lines connecting buildings to these conduits may facilitate vapor intrusion into indoor air. Although floor drains are designed to allow water to drain away from the building, they are usually not designed or constructed to eliminate gas entry. At a test house in Indianapolis, elevated levels of PCE and chloroform were found in gas in a laundry drain line, which was suspected of serving as a source of vapors found in indoor air (EPA 2012f). Although building construction codes and toilet designs are intended to prevent sewer gas from entering homes, inadequate maintenance (e.g., plumbing fixture seals) can result in loss of the intended protection. Pennell et al (2013), for example, found sewer gas entry to be a significant source of PCE in indoor air at a home in Massachusetts. In addition, sewer gas was a suspected source of benzene in indoor air in many buildings near a gasoline spill site in Hazleton, Pennsylvania (www.epa.gov/reg3hwmd/npl/PA0001409671.htm), where sewer vent traps were subsequently installed to mitigate intrusion of gasoline vapors into homes.

To date, most analytical and computational models of vapor intrusion have been predicated on the assumption that residences and other small buildings experience a constant under-pressurization (i.e., lower pressure in the building than in the subsurface), which fosters vapor intrusion. Whereas this assumption facilitates analyses and may be reasonable for some purposes (see, for example, Section 2.5), it is highly idealized. To illustrate: fluctuations in subslab-to-building pressure difference (and, hence, soil gas entry rates) over time can be reasonably expected due to:

- diurnal (daily) and seasonal changes in the temperature of ambient air, whereas indoor temperatures may be more stable, particularly during periods when mechanical heating and cooling systems are in use;
- changes in ambient air pressure;
- non-instantaneous response (i.e., lag or delay in response) of subsurface soil gas to changes in ambient air pressure (EPA 1993a, Section 2.3 therein), particularly where low-permeability soil is in direct contact with a building foundation (e.g., basement) below the ground surface;[65]
- changes in wind direction and speed; and
- intermittent operation of mechanical ventilation systems and combustion devices that vent exhaust gases to the outside.

Theoretically, these processes and variables suggest that soil gas entry rates can be expected:

- to vary over different time scales (e.g., within an day, and between seasons);
- to differ geographically due to differences in ambient air temperature, pressure, wind, and building conditions (e.g., leakage area and its distribution over the building envelope); and
- to be discontinuous over some time periods.

[65] On the other hand, where granular fill is present underneath a building, there is potential for preferential soil gas flow through the fill, especially in locations where the gas permeability of the surrounding soil is low. Where granular materials have differentially settled, air voids (also highly permeable to soil gas flow) may form beneath the foundation. Utility penetrations and other conduits may be connected to the granular fill, accentuating the potential pathway for soil gas entry into a building. Adding to the complexity, pressure differentials caused by wind flows conceivably could create a cross-flow through granular fill underneath the foundation, which may episodically dilute vapor concentrations (and oxygenate soil gas) in the building vicinity.

2.4 Air Exchange and Mixing

Air exchange refers to the flows into and out of a building, which are generally in balance, and is composed of three processes:

1) infiltration—air leakage through random cracks, interstices, and other unintentional openings in the building envelope;

2) natural ventilation—airflows through open windows, doors, and other designed (intentional) openings in the building envelope; and

3) mechanical ventilation—air movement controlled and driven by fans.

For the vapor intrusion exposure scenario, air exchange by each of these processes will generally tend to mitigate the effects of vapor intrusion (i.e., reduce indoor air concentrations) via dilution, while air inflows will also transport indoors any vapor-forming chemicals in ambient air (see Section 2.7).[66]

The air exchange rate is conventionally defined as the ratio of the airflow rate (e.g., cubic meters per second) to the building volume (e.g., cubic meters) and is generally expressed in terms of exchanges per hour (i.e., overall units of $hour^{-1}$). Values for residential air exchange rates are typically on the order of approximately 0.18 to 1.26 air changes per hour (ACH) (EPA 2011b, see Table 19-24 therein, 10^{th} and 90^{th} percentiles).[67,68] Values for non-residential buildings are highly-dependent upon building use and can range widely (on the order of approximately 0.3 to 4.1 ACH) (EPA 2011b, see Table 19-27 therein, 10^{th} and 90^{th} percentiles).

[66] The potential diluting effect of air exchange arises when ambient air has negligible presence of the volatile chemicals found in site-related contamination in the subsurface environment. In some situations, site-related contamination has the potential to impact ambient air with the same vapor-forming chemicals that pose a threat from vapor intrusion. For example, contamination of shallow soil or groundwater may release site-related vapor-forming chemicals to ambient air. In such situations, air exchange would contribute to the presence of site-related contamination in indoor air, rather than only dilute any impacts from vapor intrusion.

[67] EPA's Office of Research and Development evaluated eight studies of air exchange rate for residential buildings and selected a 1995 EPA study as the basis for recommending values for risk assessment (EPA 2011b, Table 19-24). The key study analyzed almost 3,000 time-averaged measurements of exchange rate in occupied homes in the United States, which were generally obtained using a tracer-release method. Median values ranged from 0.35 $hour^{-1}$ in the mid-western region to 0.49 $hour^{-1}$ in the northeast and southern regions. Tenth percentile values ranged from 0.16 $hour^{-1}$ in the mid-western and southern regions of the U.S. to 0.23 $hour^{-1}$ in the northeast region. Regional differences in exchange rate reflect differences in weather (e.g., temperature and wind speed), prevailing building conditions (e.g., house 'leakiness'), and the time periods (e.g., season) in which measurements were made.

[68] EPA's Office of Research and Development (EPA 2011b, Section 19.5.1.2.7) also summarized a study that conducted approximately 500 indoor-outdoor air exchange rate (AER) calculations based on residences in three urban locations (metropolitan Elizabeth, NJ; Houston, TX; and Los Angeles, CA). This study highlights how climate and season can influence air exchange rate. In Texas, the measured AERs were lower in the summer cooling season (median = 0.37 ACH) than in the winter heating season (median = 0.63 ACH), likely because windows were closed while air conditioners were in use. The measured AERs in California were higher in summer (median = 1.13 ACH) than in winter (median = 0.61 ACH), because summers in Los Angeles County are less humid than NJ or TX and residents are more likely to utilize natural ventilation through open windows and screened doors. In New Jersey, air exchange rates in the heating and cooling seasons were similar.

To date, most analytical and computational models of vapor intrusion have been predicated on the assumption that residences and other small buildings are well mixed spaces throughout which concentrations of vapor-forming chemicals are uniform. Whereas this assumption facilitates analyses and may be reasonable for some purposes (see Section 2.5), it is highly idealized. To illustrate: airflow within a building (i.e., inter-zonal airflow) can be impeded by doors, walls, and other partitions that separate rooms and other building areas. Whereas airflows within a building can be facilitated by mechanical means, spatial variation of temperature and humidity suggest that air mixing is not necessarily complete even in buildings that benefit from centralized systems for heating, air condition, and ventilation. Furthermore, many residences do not have such mechanical systems. Therefore, buildings subject to vapor intrusion may exhibit differences in concentration of vapor-forming chemicals among building areas (e.g., rooms) as a result of the differential proximity to openings for soil gas entry (see Section 2.3) and openings for air leakage and ventilation and the magnitude and balance of inter-zonal airflows. For example, rooms with perforations through the foundation (e.g., bathrooms or utility rooms) may have greater concentrations of vapor-forming chemicals in air compared to rooms that do not. Generally, basements can reasonably be expected to exhibit greater concentrations of vapor-forming chemicals than upper occupied levels.

Buildings constructed over a crawl space with a dirt floor may benefit from the dilution of soil gas by any ventilation of crawl space air, but would not have the impedance to vapor intrusion that concrete slabs can provide. Trailers enclosed at the bottom by a skirt are expected to have greater potential for vapor intrusion than would non-enclosed trailers. Wind movement between the ground surface and the bottom of the non-enclosed trailer would tend to minimize vapor buildup and associated potential for vapor flux into the building. Similarly, the existence of underground parking for a multi-story building (or other modifications to the foundation that enhance subsurface ventilation) would tend to minimize the potential for vapor intrusion.

2.5 Conceptual Model Scenarios

Based upon the foregoing conceptual model, numerous factors can influence the potential indoor air concentration arising from vapor intrusion. Some of these significant factors are illustrated in Figure 2-3.

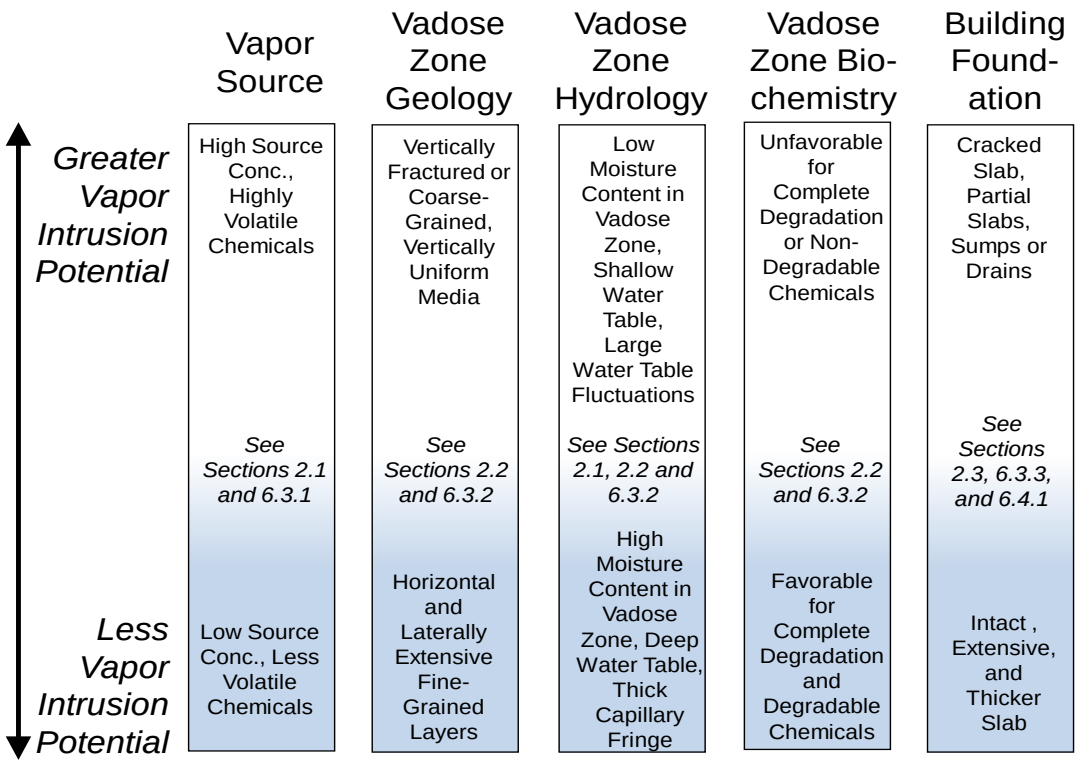

Figure 2-3 Some Factors That Affect Vapor Intrusion

The document *Conceptual Model Scenarios for the Vapor Intrusion Pathway* (EPA 2012b) provides simplified simulation examples[69] to illustrate graphically how several of the subsurface and building-specific factors work together to determine the distribution of volatile contaminants in the subsurface and the indoor air concentration relative to a source concentration. The conceptual model scenarios document offers insights into the factors influencing the vapor intrusion pathway. It provides a theoretical framework with which to draw inferences about and better understand the complex vapor fate and transport conditions typically encountered at actual, non-idealized contaminated sites. The following general observations can be made from these simplified simulation examples, and may be useful when considering the vapor intrusion pathway at a particular site:

- The horizontal and vertical distance over which vapors may migrate in the subsurface depends on the source concentration, source depth, soil matrix properties (e.g., porosity and moisture content), and time since the contaminant release to the environment occurred. Months or years of volatilization and vapor migration may be required to fully develop vapor distributions in the vadose zone at sites with deep vapor sources or with impedances to vapor migration arising from hydrologic or geologic conditions.

- Vapor concentrations, including oxygen, in the vadose zone (i.e., soil gas concentrations) may not be uniform in sub-slab soil gas or in soil gas at similar depths exterior to the building of interest. Therefore, soil gas concentrations at exterior locations (i.e., outside a building's footprint) may be substantially different from the concentration underneath the building (e.g., the sub-slab concentration), depending on site-specific conditions and the location and depth of the exterior soil gas sample.

- Simulations assuming an idealized, constructed ground cover suggest that shallow soil gas concentrations can be greater under low-permeability ground covers (e.g., asphalt) than under soil open to the atmosphere.

- The soil gas distribution beneath a building is not the only factor that determines the indoor air concentration. The indoor air concentration is also influenced by building conditions, including the presence of openings (e.g., cracks, utility penetrations) in the foundation, building pressurization, and the air exchange rate.

- Advective flow into buildings, which is presumed to occur predominantly near cracks and openings in the foundation slab, may affect the distribution of vapor-forming chemicals directly beneath the structure. Heterogeneities in the permeability of geologic materials and backfill, along with wind effects and building and atmospheric pressure temporal variation, may also contribute to the spatial and temporal variability of vapor concentrations in sub-slab soil gas and indoor air.

[69] Two important simplifications are the assumptions of constant values for the driving force for vapor intrusion (i.e., subslab to indoor air pressure difference) and air exchange rate, whereas time-variable values are reasonably expected as a result of changing weather and other conditions (as summarized in Sections 2.3 and 2.4, respectively).

- Subsurface heterogeneities in site geology, such as layering and moisture content, can influence the extent and rate of vapor migration from a contaminant source towards overlying or adjacent buildings.

- The soil gas distribution of aerobically biodegradable chemicals (e.g., BTEX) can be significantly different than that of other chemicals that are not biodegradable (i.e., are recalcitrant) in similar settings. Specifically, the soil gas concentrations of aerobically biodegradable chemicals exhibit greater attenuation than those of recalcitrant chemicals when the subsurface availability of oxygen is adequate.

2.6 Variability in Exposure Levels

Given the foregoing conceptual model of vapor intrusion and summary of modeled scenarios (EPA 2012b), the degree to which vapor intrusion is a pathway of concern can vary widely from site to site and from building to building within a site. Adding to the complexity, theoretical considerations (i.e., soil gas entry rates, air exchange rates, interior compartmentalization and inter-zonal airflows) suggest that indoor air concentrations arising from vapor intrusion can be expected to vary over time and within a building. Field observations and measurements demonstrate that indoor air concentrations can exhibit significant temporal variation within a day and between days and seasons in an individual residential building (EPA 2012a; Holton et al. 2013ab).

2.7 Consideration of Indoor and Outdoor Sources of VOCs

Indoor air in many buildings will contain detectable levels of a number of vapor-forming chemicals whether or not the building overlies a subsurface source of vapors (EPA 2011a), because indoor air can be impacted by a variety of indoor and outdoor sources. Indoor sources of volatile contaminants include the use and storage of consumer products (e.g., cleaners, air fresheners, aerosols, mothballs, scented candles, insect repellants, or other household products), combustion processes (e.g., smoking, cooking, and home heating), occupant activities (e.g., craft hobbies, home improvements, automotive repairs), and releases from interior building materials (e.g., carpets, insulation, paint, and wood-finishing products). Outdoor sources of volatile chemicals may arise due to releases from nearby sources such as industrial facilities, vehicles, yard maintenance equipment, fuel storage tanks, and paint or pesticide applications; regional sources such as air emissions from regional industry, vehicle exhaust, agricultural activities, and fires; or global sources, such as distant air emissions. The outdoor air surrounding a building is referred to as “ambient air” throughout this Technical Guide.

The contribution of indoor and outdoor sources of vapors (or both) to indoor air concentrations, which do not arise from site-related contamination,[70] is referred to as “background” throughout this Technical Guide (see, for example, Sections 2.7, 6.3.5, and 7.4.2 and the Glossary). In

[70] In some situations, site-related contamination has the potential to impact indoor or ambient air (EPA 1993c) with the same vapor-forming chemicals that pose a threat from vapor intrusion. For example, contaminated groundwater in building sumps or intruding into the building via groundwater seepage could provide an indoor source of site-related contamination. Contamination of shallow soil or groundwater may also release site-related vapor-forming chemicals to ambient air. In such situations, neither of these sources of indoor air contamination would be considered ‘background.’

some buildings, “background” sources by themselves can cause building occupants and visitors to experience significant exposures to vapor-forming chemicals.

In contrast to “background” concentrations in soil arising from naturally occurring minerals, “background” concentrations in indoor air often are not uniform in time. For example, concentrations of vapor-forming chemicals in ambient air may exhibit temporal variation over several time scales (e.g., daily, seasonal, longer term) and spatial differences across urban, suburban, and rural land use areas, reflecting differences in emission sources and rates and environmental factors that transport, disperse, and remove these pollutants (Jia et al. 2012 and citations therein). Concentrations of vapor-forming chemicals arising in indoor air in residential buildings due to indoor sources have been observed to depend upon season and other factors. Available studies suggest complex (e.g., patchy) spatial patterns in exposure concentration, which has led some researchers to refer to “microplumes” in the indoor air environment (McBride et al., 1999 and citations therein).

3.0 OVERVIEW OF THIS VAPOR INTRUSION TECHNICAL GUIDE

This section provides an overview of this Technical Guide and the general recommended framework for vapor intrusion assessment and response action, which is illustrated in Figure 3-1. This section opens with a description of subsurface contaminants that have the greatest potential to pose a health concern via vapor intrusion, based upon their volatility and potential hazards.

3.1 Contaminants of Potential Concern

Several physicochemical criteria may be considered for defining and screening for volatility.[71] For purposes of this Technical Guide, a chemical generally is considered to be "volatile" if:

1) Vapor pressure is greater than 1 millimeter of mercury (mm Hg), or

2) Henry's law constant (ratio of a chemical's vapor pressure in air to its solubility in water) is greater than 10^{-5} atmosphere-meter cubed per mole (atm m^3 mol^{-1}) (EPA 1991b, Section 3.1.1; EPA 2002c, Appendix D).

Various other criteria may be considered for identifying when volatile chemicals are present at levels of potential health concern. For purposes of this Technical Guide, a volatile chemical generally is considered to be "potentially toxic" via vapor intrusion if:

1) the vapor concentration of the pure component exceeds the indoor air target risk level, when the subsurface vapor source is in soil, or

2) the saturated vapor concentration exceeds the target indoor air risk level, when the subsurface vapor source is in groundwater.

Each of the chemicals with one or more toxicity values used to derive Regional Screening Levels (http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/Generic_Tables/index.htm) were evaluated for volatility and toxicity, according to the foregoing recommended criteria. These criteria do not include a consideration of whether these chemicals are regulated pursuant to CERCLA, as amended, or RCRA, as amended. The universe of chemicals evaluated and the results of the evaluation are provided in EPA's on-line VISL Calculator (EPA 2015a), which is described further in Sections 1.4.1 and 6.5.2 of this Technical Guide.

Chemicals which satisfy the foregoing screening criteria for volatility and toxicity are designated as "vapor-forming chemicals" for purposes of this Technical Guide. In addition:

[71] In chemistry and physics, volatility refers to the tendency of a substance to form vapors, which are molecules in a gaseous state, and escape from a liquid or solid. Volatility is directly related to a substance's vapor pressure and Henry's law constant. EPA (1991b) also cites molecular weight as a necessary criterion for assessing volatility. Molecular weight is not retained for this Technical Guide as a volatility criterion, because it is a relatively weak predictor of volatility.

- cis-1,2-dichloroethylene, a volatile chemical that lacks sufficient toxicity information (to apply the toxicity criteria above), is identified as a vapor-forming chemical due to its potential use as an indicator of vapor intrusion when it is present as a subsurface contaminant;[72]

- methane is identified as a vapor-forming chemical due to its potential to pose an explosion hazard and to be formed via anaerobic biodegradation processes in the subsurface environment;[73] and

- radon is identified as a vapor-forming chemical when it arises from uranium- or radium-bearing solid wastes in the subsurface.[74]

Chemicals that meet these recommended screening criteria are referred hereafter in this Technical Guide as "vapor-forming chemicals." EPA recommends that these chemicals be evaluated during vapor intrusion assessments, when they are present as subsurface contaminants due to a site-related release(s). EPA recommends that chemical analyses be limited to those vapor-forming chemicals known or reasonably expected to be present in the subsurface environment due to a site-related release(s). The list of vapor-forming substances warranting consideration for potential vapor intrusion may be modified in the future.[75]

3.2 Vapor Intrusion Assessment

The approach for assessing vapor intrusion will vary from site to site, due to site-specific factors. For example, the information available for evaluating vapor intrusion potential will vary depending upon when vapor intrusion is first considered during a site's investigation-and-cleanup life cycle. Many sites can be evaluated for potential vapor intrusion during the normal course of an initial site assessment. Examples include brownfield sites that are intended for redevelopment and buildings where chemical odors have been reported. The data available for evaluating vapor intrusion may be very limited at the outset for these situations. At the other end of the investigation and cleanup life cycle, certain sites with long- term cleanups underway for contaminated groundwater may be evaluated for vapor intrusion during periodic reviews, if any,

[72] EPA (2011a) and DoN (2011a) report that cis-1,2-dichloroethylene (cis-1,2-DCE) is "rarely detected in background indoor air." When they are subsurface contaminants, volatile chemicals, such as cis-1,2-DCE, that are rarely or never present in indoor sources can be inferred to arise in indoor air via vapor intrusion "without further explanation" (DoN 2011a). Brenner (2010), for example, employed this principle to identify buildings susceptible to vapor intrusion and to diagnose the relative contributions of vapor intrusion and infiltration to indoor air concentrations.

[73] As noted previously, methane in soil gas may produce two other undesirable consequences: (1) it can exacerbate migration and intrusion of other vapors if it is generated at rates sufficient to foster advective flow of soil gas (see Section 2.3); and (2) its biodegradation in the vadose zone can reduce the oxygen available for biodegradation of other hydrocarbons (Ma et al. 2012).

[74] Radon emanating from natural geological materials may also affect indoor air quality in occupied buildings, but is not a subject of this Technical Guide. For more information about radon emanating from natural geological materials, see: http://www.epa.gov/radon/index.html.

[75] For example, inhalation toxicity values for additional volatile chemicals may become available in the future.

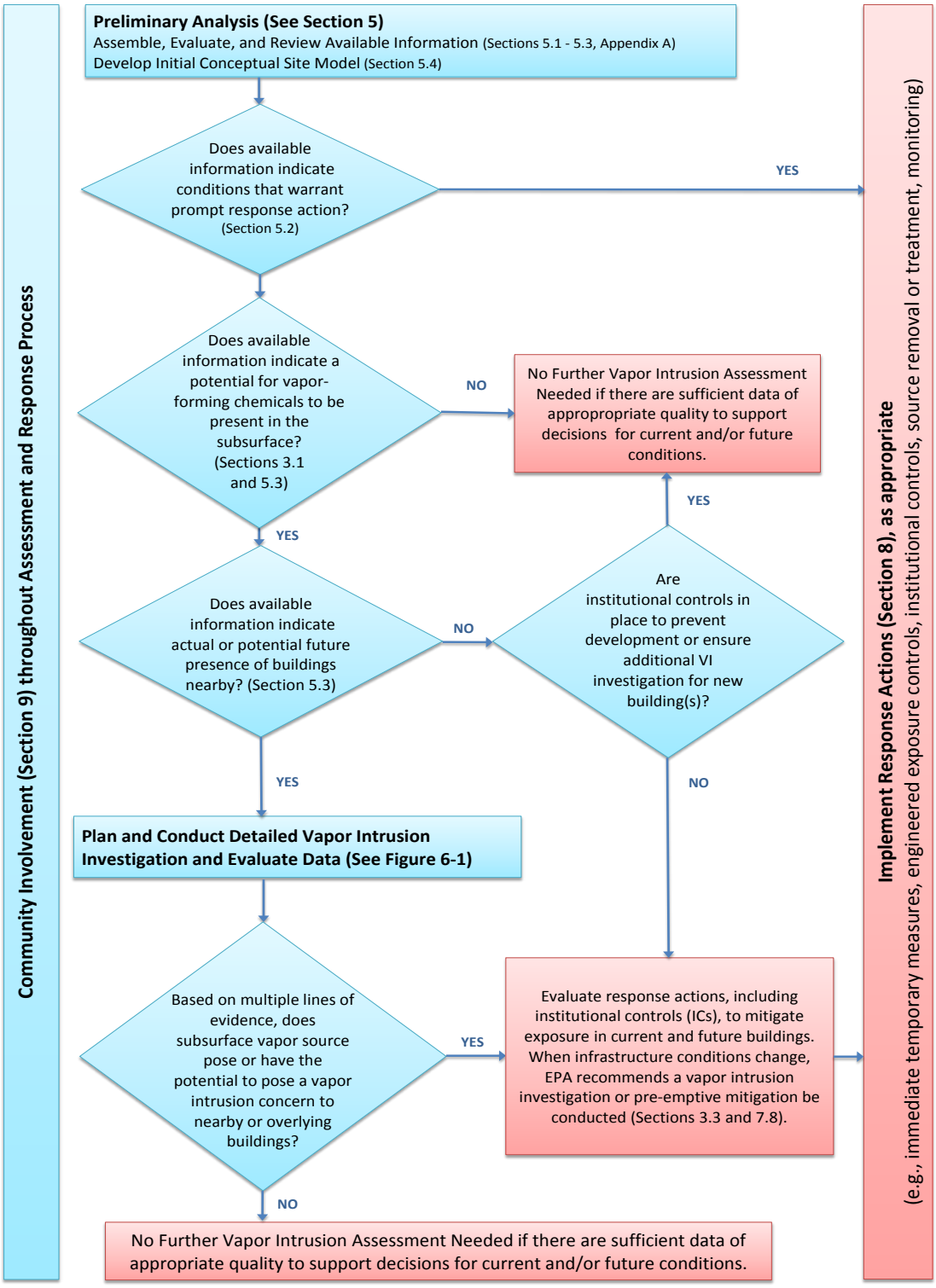

Figure 3-1 Overview of Recommended Framework for Vapor Intrusion Assessment and Response Action

of remedy performance and groundwater monitoring data.[76] In such situations, detailed information about the nature and extent of subsurface contamination and the relevant hydrogeologic conditions may already exist. In addition, there are different scenarios for vapor intrusion (EPA 2012b), depending on characteristics of the source (e.g., types, chemicals of concern, mass, distribution, and distance from building(s)), subsurface conditions and vapor migration routes (e.g., soil types and layering, existence of preferential migration routes due to geology or infrastructure, and existence of any impediments to vapor migration), building susceptibility (e.g., age, design, construction, condition), lifestyle factors (e.g., keeping windows open or closed), and regional climate. For these reasons, every site (and every building) will not warrant the same approach to or intensity of assessment for vapor intrusion. This Technical Guide, therefore, recommends a framework for planning and conducting vapor intrusion investigations, rather than a prescriptive step-by-step approach to be applied at each and every site.

Broadly speaking, two general levels of vapor intrusion assessments can be distinguished:

1) A preliminary analysis utilizes available and readily ascertainable information to develop an *initial* understanding of the potential for human health risk that are or may be posed by vapor intrusion, which would typically be performed as part of an initial site assessment. The recommended information, approaches, and practices for conducting a preliminary analysis and its potential outcomes are described in Section 5.0.

2) A detailed investigation is generally recommended when the preliminary analysis indicates that subsurface contamination with vapor-forming chemicals may be present underlying or near buildings. A detailed investigation of the vapor intrusion pathway is typically performed as part of the site investigation stage. The recommended approaches and practices for conducting detailed vapor intrusion investigations are described in Section 6.0.

Considerable information, primarily empirical, has been generated regarding evaluation of the vapor intrusion pathway since the pathway emerged as a national issue in the late 1990s and especially in the past ten years. Broadly speaking, this information demonstrates that the vapor intrusion pathway can be complex. (The conceptual model of vapor intrusion provided in Section 2.0 identifies many of the factors, variables, and conditions that warrant consideration on a site-specific basis.) As a result, current practice suggests that the vapor intrusion pathway generally be assessed using multiple lines of evidence.[77]

Specific conclusions that EPA recommends be based upon multiple lines of evidence include:

[76] These situations can arise, for example, if the groundwater remedy was selected in the 1980s (long before vapor intrusion became recognized as a potentially significant exposure pathway), or if supplemental groundwater data indicate that the plume is migrating toward new inhabited areas.

[77] As discussed further in Section 7.2, confidence in the assessment and risk management decisions is expected to be higher when multiple independent lines of appropriate site- or building-specific evidence from, for example, multiple types samples of environmental media (e.g., groundwater, soil-gas, sub-slab vapor, crawlspace, and indoor air) and/or other data come together to provide mutually supporting evidence for a common understanding of the site conditions/scenarios and the potential for vapor intrusion (EPA 2010b) (i.e., the various lines of evidence are in agreement with each other).

- The subsurface vapor source(s) at a specific site has (or, alternatively, does not have) the potential to pose an unacceptable vapor intrusion exposure under current or reasonably expected future conditions, due to its strength (e.g., concentration and mass of vapor-forming chemicals) and proximity relative to one or more existing buildings or a building that may be constructed in the future.

- The vapor intrusion pathway is complete for one or more buildings under current conditions or is potentially complete under reasonably expected future conditions.

- The vapor intrusion pathway is incomplete for one or more buildings near a subsurface source of vapor-forming chemicals, due to geologic, hydrologic, and/or biochemical (e.g., biodegradation) processes that provide substantial and persistent attenuation of vapors extending laterally over large distances relative to the footprint of the building(s) and the extent of the vapor source.

- Indoor air concentrations attributable to vapor intrusion pose (or, alternatively, are unlikely to pose) an unacceptable human health risk in one or more existing buildings under current or reasonably expected future conditions.

- Indoor air concentrations measured in one or more buildings can (or alternatively, cannot) be reasonably attributed to indoor or ambient air sources (i.e., background).

Multiple lines of evidence are particularly important for supporting "no-further-action" decisions regarding the vapor intrusion pathway (e.g., pathway incomplete determinations) to reduce the chance of reaching a false-negative conclusion (i.e., concluding vapor intrusion does not pose unacceptable human health risk, when it actually poses an unacceptable human health risk). Collecting and weighing multiple lines of evidence can also help avoid reaching a false-positive conclusion (i.e., concluding vapor intrusion poses an unacceptable human health risk, when it does not.

In summary, EPA recommends that site assessors generally collect and weigh multiple lines of evidence, including qualitative information, to support decision-making regarding the vapor intrusion pathway. Lines of appropriate evidence to evaluate the vapor intrusion pathway were identified in Section 2 and are discussed further in Sections 5 through 7.

As noted in Section 1.3, Figure 3-1, and the preceding discussion of lines of evidence, EPA recommends that site assessors consider reasonably expected future conditions, in addition to current conditions, when reaching conclusions about the vapor intrusion pathway.[78] For this reason, this Technical Guide includes recommendations for evaluating whether subsurface vapor sources that remain have the potential to pose unacceptable human health risks in the future if current conditions were to change. For example:

- Section 6.3.3 recommends that site assessors consider investigating vapor intrusion in non-residential buildings under conditions when the heating, ventilation, and air-conditioning system is not operating; and

[78] "Both current and reasonably likely future risks need to be considered in order to demonstrate that a site does not present an unacceptable risk to human health and the environment." (EPA 1991a).

- Section 7.3 identifies some factors and processes that can make the characteristics of the vadose zone (e.g., soil moisture) transitory.

EPA also recommends that vapor intrusion be evaluated for reasonably expected future land use conditions, including new building construction and new uses and occupants for any uninhabited buildings.

3.3 Building Mitigation and Subsurface Remediation

The NCP expresses the preference for response actions that eliminate or substantially reduce the level of contamination in the source medium to acceptable levels, thereby achieving a permanent remedy. In the case of vapor intrusion, such a response action would generally entail eliminating or substantially reducing the level of vapor-forming chemicals in the subsurface (e.g., in contaminated groundwater, soil, and/or sewer lines) via treatment or removal (i.e., "remediation"). Section 8 discusses source remediation to achieve a permanent remedy and associated institutional controls (ICs) and monitoring for vapor intrusion mitigation, including criteria for their termination.

Comprehensive remediation[79] of the subsurface environment often occurs over a prolonged period (e.g., several years) to attain cleanup levels. In the interim, problems of unacceptable vapor intrusion are often addressed by also installing engineered exposure controls to reduce or eliminate vapor intrusion in buildings (i.e., "mitigate" vapor intrusion) or reduce indoor air exposure levels. Engineered exposure controls can generally be deployed and generally become effective relatively quickly. They can be considered as "interim" or "early" response actions, which are also authorized by the NCP (Section 1.2), as necessary and appropriate to promptly reduce threats to human health. Section 8 summarizes technical information about specific exposure controls and provides information about their operation, maintenance and monitoring and associated ICs, including criteria for their termination.

Functionally, engineered exposure controls can be categorized into two basic strategies:

- Those that seek to prevent or reduce vapor entry into a building (e.g., active depressurization technologies). These methods are more commonly implemented when response actions are needed.[80]

- Those that seek to reduce or eliminate vapors that have entered into a building (e.g., indoor air treatment, ventilation).

[79] For purposes of this Technical Guide, "remediation" is intended to apply to interim and final cleanups, whether conducted pursuant to RCRA corrective action, the CERCLA removal or remedial programs, or using EPA brownfield grant funds with oversight by state and tribal response programs. In addition to permanent remedies for subsurface vapor sources, site remediation may also entail implementation of ICs and construction and operation of engineered systems to reduce risks to human health and the environment posed by environmental pathways other than vapor intrusion. Although this Technical Guide is intended for use at any site subject to federal statutes, regulations, and rules, it is not intended to alter existing requirements, guidance, or practices in OSWER's programs about development, selection, or documentation of final "remediation" plans (addressing subsurface vapor sources, for example) – see, for example, Sections 7.6 and 7.7.

[80] Mitigation methods that prevent or reduce vapor entry into a building from subsurface vapor sources would generally also be expected to reduce radon entry.

Neither strategy entails reducing the level of vapor-forming contamination in the subsurface source medium.[81]

As reflected in the foregoing conceptual model of vapor intrusion (Section 2.0), entry of the vapors into a building may be prevented or reduced by any of several techniques, which have the following objectives:

- Remove or reverse the driving forces for vapor intrusion into the building (e.g., install and operate an active depressurization technology to mitigate vapor intrusion from contaminated soil or groundwater; establish over-pressurization within and throughout the footprint of a nonresidential building).

- Eliminate or minimize identified openings for vapor entry into the building (e.g., caulking, grouting, or otherwise sealing all holes, cracks, sumps and other foundational openings or creating a barrier between the soil and the building that blocks openings for entry of soil gas into the building; install, repair, and/or maintain vapor traps in sewer and drain lines).

Engineered exposure controls that entail mechanical systems and forces (e.g., sub-slab depressurization or ventilation systems; building over-pressurization) are often referred to as "active." Engineered exposure controls that do not involve mechanical operations (e.g., installing a sub-slab barrier to chemical vapor entry) are often referred to as "passive." Many building mitigation systems rely on both active and passive strategies.

Engineered exposure controls that seek to reduce or eliminate vapors that have entered into a building can also be effective. In some instances, they can be implemented more readily than engineered exposure controls that reduce or eliminate entry of the vapors into a building. Typically, the simplest approach to limiting the concentration levels in occupied indoor spaces is to increase building ventilation (i.e., increase the rate at which indoor air is replaced with outdoor air), thereby diluting indoor air concentrations (see Section 2.4).[82] Alternatively, vapor-forming chemicals are removed from indoor air using an adsorbing material (such as activated carbon) that can be either properly disposed of or recycled. Building mitigation methods that act upon vapor-forming chemicals in indoor air (i.e., rely upon enhanced ventilation or treatment) are generally capable of reducing background levels of chemicals, in addition to reducing indoor levels of vapor-forming chemicals that intrude from subsurface sources.

[81] Even when operated for prolonged periods, engineered exposure controls are considered 'interim' remedies for purposes of this Technical Guide, because their implementation does not substitute for remediation of the subsurface source(s) of vapor-forming chemicals. Engineered exposure controls may, nevertheless, become part of a final cleanup plan.

[82] It can be difficult to establish a ventilation rate that mitigates vapor intrusion and yields an environment conducive to human occupancy (e.g., considering air temperature or moisture). In addition, ventilation may affect the driving forces for vapor intrusion. For example, mechanically exhausting air from the building will generally contribute to building under-pressurization (see Section 2.3), which may result in increased intrusion of soil gas into the building, which may offset the intended dilution effect of ventilation. On the other hand, introducing outdoor air at a rate slightly greater than the exhaust rate can create over-pressurization, which opposes the primary driving force for vapor intrusion.

Selection of an interim response action from these options may depend upon building- and site-specific factors (EPA 2008). For example, building-specific factors may include:

- Use (e.g., single-family residential, multi-family residential, commercial, educational, recreational, governmental, religious, industrial)
- Type of foundation/basement (e.g., basements with concrete slab floors or dirt floors, slab on grade, slab below grade) and other construction features
- Type of heating/cooling/ventilation systems (e.g., some systems will tend to increase pressure, whereas others will tend to decrease pressure, inside the building).

Each of these characteristics can influence the choice of mitigation methodology and, therefore, they are commonly identified during building surveys during a site-specific vapor intrusion investigation. Site-specific considerations may include the degree of risk or hazard being addressed and whether the subsurface vapor source(s) is stable in extent and concentration or is undergoing remediation.

Temporary relocation may warrant consideration in instances where explosion hazards are present (see Section 7.5.1), which may pose an imminent and substantial danger to human health and public welfare. Prompt response action may also be warranted where short-term or acute exposures may pose unacceptable human health risk (see Section 7.5.2) that cannot be addressed timely or feasibly by implementing engineered exposure controls. Section 8.2 discusses various prompt response actions for such situations, which may include temporary relocation.

There may be situations where a party may wish to implement mitigation or control measures for vapor intrusion, even though only limited lines of evidence or measurements may be available to characterize the overall vapor intrusion pathway. For example, a party may be aware that vapor intrusion has been documented at neighboring structures, where measures are being implemented to mitigate the vapor intrusion pathway. A party may conclude there is a reasonable basis to take action, but each building presents a fact-specific situation that calls for its own individual judgment. Likewise, it may be appropriate and cost-effective to design, install, operate, and monitor engineered exposure controls for individual buildings to mitigate vapor intrusion in newly constructed buildings, or in buildings to be constructed in the future, that are located in areas of vapor-forming subsurface contamination, rather than potentially allow vapor intrusion to occur later and assess vapor intrusion after the fact. The term “preemptive mitigation/early action” is used in this Technical Guide to describe these situations.[83]

The decision for preemptive mitigation/early action arises from precaution and from recognizing that:

- Installing engineered exposure controls in buildings is typically a cost-effective means of protecting human health and normally can be implemented relatively quickly in many buildings while subsurface contamination is being delineated or remediated.

[83] The term ‘preemptive’ has been used to describe the use of various types of controls that can prevent vapor intrusion from occurring prior to having fully demonstrated that unacceptable vapor intrusion currently exists in specific buildings being considered (EPA 2010a).

- Conventional vapor intrusion investigations can be disruptive for building occupants (residents, workers, etc.) and owners.

- Comprehensive subsurface characterization and investigation of vapor intrusion can entail prolonged study periods, during which time building occupants and owners and others may have questions and concerns about human health risk that are or may be posed via vapor intrusion.

Early action and interim action are allowed by federal environmental protection statutes, regulations, and guidance, including CERCLA, as amended, and RCRA, as amended – see Section 1.2 of this Technical Guide, for example. Other aspects of preemptive mitigation/early action are also discussed in Section 7.8, including situations and criteria for decision-makers to consider.

As noted in Figure 3-1, EPA recommends that risk managers consider reasonably expected future conditions, in addition to current conditions, when making risk management decisions about the vapor intrusion pathway. For this reason, this Technical Guide includes recommendations for response actions at sites where subsurface vapor sources remain into the future, but do not pose unacceptable human health risk under current conditions (e.g., no building is present nearby). For example, institutional control s are generally recommended to restrict land use and/or alert parties (e.g., prospective developers, owners, and municipalities) of the presence of subsurface sources of vapor-forming chemicals at levels that pose a continuing threat via vapor intrusion (see Sections 7.3, 7.4, and 8.6). When infrastructure conditions change above or near an area of known contamination with vapor-forming chemicals, EPA recommends a vapor intrusion investigation or pre-emptive mitigation be conducted, particularly if a building is constructed for human occupancy (see Section 8.2.3).

3.4 Community Outreach and Involvement

EPA is committed to transparency and upfront collaboration with community stakeholders regarding land cleanup, emergency preparedness and response, and management of hazardous chemicals and wastes. OSWER's Community Engagement Initiative (CEI), in particular, is designed to enhance OSWER's and the Regional offices' engagement with local communities and stakeholders (e.g., state and local governments, tribes, academia, private industry, other federal agencies, and nonprofit organizations) to help them participate meaningfully in government decisions regarding OSWER's nationwide programs.

Meaningful and sustained community outreach and engagement efforts are critical to the implementation of work plans for site-specific vapor intrusion assessment and mitigation. Because assessing the vapor intrusion pathway may involve sampling in a home or workplace, as well as other temporary inconveniences (e.g., assisting in reducing indoor sources of contaminants), individual, one-on-one communication with each property owner or renter generally warrants consideration. Building-by-building contact and communication are recommended as the most effective means of educating the community and obtaining access needed to assess, mitigate, and monitor the vapor intrusion pathway. Personal contact is further recommended to establish a good working relationship with each building owner or occupant and to build trust. In many instances, local religious and cultural organizations, and other community groups can be sought for assistance in reaching out to affected community members.

Vapor intrusion education and training are important components of meaningful community outreach and engagement efforts. Informing stakeholders about the vapor intrusion pathway and the cleanup process can help to build trust and can foster community participation in the overall assessment and risk management process.

Recognizing the importance of community outreach and engagement efforts, EPA staff are highly encouraged to consult with colleagues experienced in community outreach and utilize available EPA planning resources, including those discussed in Section 9, which provides OSWER's community involvement planning guide for vapor intrusion projects. Like EPA, the ITRC also recommends implementing a community outreach program that provides timely information to concerned community members and property owners.

4.0 CONSIDERATIONS FOR NONRESIDENTIAL BUILDINGS

The approach for investigating and, if necessary, mitigating vapor intrusion can vary from site to site, and from building to building, due to site- and building-specific factors and circumstances, including: the nature (e.g., mixture of vapor-forming chemicals and form), locations, and extent of subsurface contamination; geologic, hydrologic, and biochemical factors in the vadose zone; and the size, structural conditions and uses of buildings and background levels of vapor-forming chemicals in the building. Information on 'background' contributions of site-related, vapor-forming chemicals in indoor air is important to risk managers because generally EPA does not clean up to concentrations below natural or anthropogenic background levels (EPA 2003e). These statements hold true for residential and non-residential buildings.

Section 6.3.5 of this Technical Guide provides specific recommendations about how to evaluate background concentrations. Section 7.4 of this Technical Guide provides clarifications and recommendations about applying the methods in Section 6.3.5 to informing risk management decisions and recommendations. The Glossary in this Technical Guide defines various terms and types of vapor sources to foster a common understanding of EPA's approach and recommendations.

This section summarizes EPA's general recommendations to consider in making decisions about evaluating and addressing potential vapor intrusion for nonresidential buildings[84] pursuant to CERCLA and RCRA, including decisions that a response action or corrective action is not currently warranted.

When evaluating nonresidential buildings at sites that have subsurface contamination with vapor-forming chemicals, EPA generally recommends that building owners or operators (e.g., lessees) be contacted for information about vapor-forming chemicals used or stored or otherwise present in the building, the types of building occupants potentially exposed to subsurface vapor intrusion, as well as any training, equipment, or engineering controls to mitigate inhalation exposures. EPA recommends that information be provided to building owners concerning the potential for vapor intrusion so that this information can be communicated to building employees, tenants, and other occupants. Building occupants include, but are not limited to, facility employees, visitors, customers, suppliers, and building maintenance personnel.

Generally, EPA recommends the following factors be considered when making decisions pertaining to vapor intrusion at nonresidential buildings, including as to whether indoor air sampling, soil gas sampling underneath the building, or interim measures to mitigate vapor intrusion to reduce associated indoor air exposures for a nonresidential building may be warranted:

[84] As used in this Technical Guide, the phrase "nonresidential buildings" may include, but is not limited to, institutional buildings (e.g., schools, libraries, hospitals, community centers and other enclosed structures for gathering, gyms and other enclosed structures for recreation), commercial buildings (e.g., hotels, office buildings, many (but not all) day care facilities, and retail establishments); and industrial buildings where vapor-forming substances may or may not be routinely used or stored.

1) The types of populations potentially exposed to vapor-forming chemicals in the indoor air of the nonresidential building, including, for example, whether:

   a) Individuals are or may be present under current or reasonably expected future conditions who would not likely anticipate any chemical exposures (e.g., office workers, visitors, customers, suppliers, and other members of the general public) and may not benefit fully from hazard communication programs and other work practices in place to foster protection of workers who use chemicals, if any.

   b) Sensitive populations are or may be present under current or reasonably expected future conditions, who may have increased susceptibility or vulnerability.

2) The potential for vapor intrusion versus background vapor sources (See Glossary) to contribute to indoor air concentrations of vapor-forming chemicals found in the subsurface. Questions to consider include, for example:

   a) Can subsurface vapor intrusion be identified as a potential cause of unacceptable human health risk to building occupants (see Section 5 for further discussion about the preliminary analysis stage and Section 7 for further discussion and definition of acceptable versus unacceptable human health risk)? [85]

   b) Can subsurface remediation (e.g., excavation of contaminated soil or soil vapor extraction beneath the subject building) that is planned or underway reduce human health risk from vapor intrusion within a time frame that is protective for any potential current or near-term exposures in the building?

   c) Is there a known source(s) of one or more vapor-forming chemical(s) – see Section 3.1 – in indoor air in the nonresidential building other than vapor intrusion (e.g., indoor use and storage of chemicals, which would constitute a 'background' vapor source(s) and contribute to indoor air exposure concentrations; see Sections 2.7 and 6.3.5 for further discussion and recommendations about background sources and concentrations)? If such a vapor-forming chemical(s) is (or are) present:

      i. Is(are) it the same as the vapor-forming chemical(s) found in the subsurface?

      ii. How does the indoor air exposure concentration(s) arising from the indoor vapor source(s) compare to the indoor air concentration(s) estimated or reasonably expected to arise from vapor intrusion? [86]

   Information on 'background' contributions of site-related, vapor-forming chemicals in indoor air is important to risk managers because generally EPA does not clean up to concentrations below natural or anthropogenic background levels (EPA 2002e).

[85] EPA's recommended approaches to human health risk assessment are provided in Sections 7.4 and 7.5 of this Technical Guide.

[86] EPA's recommended approaches to distinguishing and considering 'background' are provided in Sections 6.3.5 and 7.4.2 of this Technical Guide.

3) Any existing or planned engineering or institutional control(s) in the building or any industrial hygiene/occupational health program that addresses workplace inhalation exposures and its scope. Questions to consider include, for example:

    a) Do work practices and engineering controls currently in place ensure protection[87] of all building occupants who may be exposed via the vapor intrusion pathway?

    b) Are enforceable institutional controls (ICs) or other control mechanisms in place to ensure that current land use and workplace practices will be sustained and will remain protective regarding indoor air exposures from vapor intrusion to all building occupants? Have these ICs and control mechanisms been communicated to all appropriate parties and documented to EPA? Can they be readily monitored and, if necessary, be enforced?

EPA recommends documenting any decision not to undertake investigation or mitigation for vapor intrusion in a nonresidential building, as well as any decision to pursue such activities. EPA may consider reviewing these decisions, as appropriate and consistent with applicable statutes and regulations and considering EPA guidance,[88] if the land use changes or new information becomes available that suggests circumstances supporting past risk management decisions have changed and prompt the need to revisit those decisions. It is recommended that EPA request from property owners and building tenants/operators timely notification of significant changes in building ownership, uses, access by the general public, or building construction (e.g., renovations), which may affect exposure of occupants and related risk management decisions pertaining to potential vapor intrusion assessment and mitigation, subsurface remediation, or ICs.

Regardless of decisions about indoor air sampling, soil gas sampling underneath the building, or interim measures to mitigate vapor intrusion, EPA[89] may proceed, consistent with applicable federal statutes and regulations (see Section 1.2) and considering EPA guidance, with activities such as the following, where appropriate:

- Subsurface investigation to delineate the areal extent of a subsurface vapor plume.
- Subsurface remediation to reduce or eliminate subsurface sources of vapors-forming chemicals to protect human health and the environment.

[87] EPA's recommended approaches to risk management are provided in Sections 7.4 and 7.5 of this Technical Guide.

[88] For the Superfund five-year review process, OSWER Directive 9200.2-84 (EPA 2012c) provides a recommended framework for considering vapor intrusion while evaluating remedy protectiveness.

[89] On January 23, 1987, the President of the United States signed Executive Order 12580 entitled, "Superfund Implementation," which delegates to a number of Federal departments and agencies the authority and responsibility to implement certain provisions of CERCLA. The policies and procedures for implementing these provisions (e.g., carrying out response actions) are spelled out in the NCP. The provisions of Executive Order 12580 appear at 52 *Federal Register* 2923. At federal facilities on the NPL, EPA may not be the lead agency, but does have oversight responsibilities pursuant to CERCLA Section 120.

5.0 PRELIMINARY ANALYSIS OF VAPOR INTRUSION

When a site is first identified and evaluated for vapor intrusion,[90] the amount, utility, and reliability of available information may be limited. A preliminary analysis utilizes available and readily ascertainable information to develop an *initial* understanding of the potential for human health risk to be posed by vapor intrusion, which would typically be performed as part of an initial site assessment.

This section describes EPA's recommended information, approaches, and practices for conducting preliminary analyses for vapor intrusion using pre-existing and readily ascertainable information to develop an initial understanding of the vapor intrusion potential at a site. This section:

- Explains the recommended types of information that generally can be obtained when a site is first considered for vapor intrusion (see Sections 5.1, 5.3, 5.4, and 5.5).
- Identifies some of the site conditions for which prompt action is generally warranted (see Section 5.2).
- Illustrates some of the site conditions for which further evaluation of the vapor intrusion pathway might be warranted (see Sections 5.3, 5.4, and 5.5).
- Describes the recommended approaches to evaluating the reliability of pre-existing information, including any sampling data (see Sections 5.1 and 5.5).

Depending upon the nature and reliability of the available information, it may be possible to determine whether a vapor intrusion investigation (see Section 6) or a response action (see Sections 7 and 8) is warranted. If the available information is not reliable or adequate for these purposes, however, additional data collection generally is recommended.

5.1 Assemble, Evaluate, and Review Available Information

The recommended first step in a preliminary analysis generally entails assembling and reviewing relevant information that is available at the time for the site. At a minimum, EPA recommends that information about potential subsurface sources of vapors and the presence and current use(s) of nearby buildings be developed and evaluated. For some sites, such as sites being evaluated for redevelopment (EPA 2008a), information about contiguous or nearby facilities also may be relevant, because vapors can encroach from nearby facilities due to migration of contaminated groundwater or soil gas, even though vapor-forming chemicals may not have been used at the subject site.

The following recommended types of information are often available through documents (e.g., federal, state, tribal and local government records) or through interviews with individuals

[90] A site may be identified, for example, based on reports to the National Response Center, citizen complaints or inquiries, state agency referrals, or other information (e.g., site history, land use, site inspections) obtained by EPA. At a brownfield site subject to an EPA grant, subsurface contamination may be discovered as a result of pre-acquisition investigation by prospective purchasers, during site redevelopment, or at other project stages.

knowledgeable about the facility or site and surrounding area (e.g., past and present owners, operators and occupants; area residents or workers):

- History and descriptions of the types of operations and activities that occurred on or near the site and nearby properties.
- Information or records about the types of chemicals that may have been used or disposed of at the site and nearby properties or are currently used and disposed at the site.
- Information about the site and nearby properties, such as the occurrence of odors, reports of dumping liquids, observations of unreported waste disposal practices, or other indications of chemical presence and release.
- Adverse physiological effects reported by building occupants (e.g., dizziness, nausea, vomiting, confusion).
- Evidence of subsurface intrusion of groundwater (e.g., wet basements) reported by building owners or occupants.

Such information usually can be reviewed and weighed together to assess whether vapor-forming chemicals (see Section 3.1) were or are being used, stored, or handled at or near the site and were or may have been released to the subsurface environment.

In addition, the following types of information may be available through documents, interviews with individuals knowledgeable about the facility or site, or reconnaissance and site inspection:

- Locations, ownership, occupancy, and intended and actual use(s) of buildings on or near the site.
- Current and reasonably anticipated future land use on and near the site.
- Location of subsurface utility corridors.

Evaluation of such information usually can help determine whether humans are present currently or are reasonably expected to be present in the future, and who may become exposed to any intrusion of vapors from the subsurface into a building(s). Zoning, land use planning, and related information may also need to be consulted to identify reasonably anticipated future land use and building types in areas where buildings do not exist or to ascertain whether reasonably anticipated uses of existing buildings are likely to change (EPA 2010c).

EPA recommends evaluating the available data to identify any data gaps for purposes of the preliminary analysis. For example, has the history of operations and primary activities been established for the site and all contiguous properties, including currently vacant land? To the extent that there are significant data gaps, EPA recommends that additional data gathering (e.g., interviews, records review) generally be planned and conducted.

EPA also recommends evaluating the available data to assess its reliability and internal consistency. For example, if the available information about operations and activities at a specific property comes only from area residents, EPA recommends additional efforts to

identify, contact, and interview current and past owners to obtain and corroborate this information. Also, if anecdotal information about current activities at a specific property is in conflict with common knowledge about local zoning, EPA recommends that additional data gathering and evaluation be identified (e.g., contact property owner), planned, and conducted to resolve the inconsistency.

Section 5.5.1 describes additional considerations for evaluating the reliability of sampling data that may be available for some sites at the preliminary analysis stage.

5.2 Identify and Respond to Conditions that Warrant Prompt Action

The following conditions may indicate a need for prompt action, including follow-up evaluations to determine whether urgent intervention is warranted to eliminate, avoid, reduce, or otherwise address a human health hazard:

- Odors reported by occupants, particularly if described as "chemical," "solvent," or "gasoline." The presence of odors does not necessarily correspond to an unacceptable human health risk due to vapor intrusion, and the odors could be the exclusive result of indoor vapor sources; however, it is generally prudent to investigate any reports of odors as the odor threshold for some vapor-forming chemicals exceeds their respective lower explosive limit (LEL) or health-protective concentrations for short-term or acute exposure.

- Physiological effects reported by occupants (e.g., dizziness, nausea, vomiting, confusion, etc.). These effects may or may not be due to subsurface vapor intrusion (or even indoor vapor sources); however, it is generally prudent to investigate any such reports.

- Wet basements in areas where groundwater is known to contain vapor-forming chemicals (see Section 3.1) and the associated water table is shallow enough that the basements are prone to groundwater intrusion or flooding. This condition is particularly important where there is evidence of light NAPL (LNAPL) on the water table directly below the building or direct evidence of intrusion of liquid-phase contamination (i.e., liquid chemical or dissolved in water) inside the building.

EPA generally recommends testing of indoor air (see Sections 6.4.1 and 6.3.4) as soon as practical in buildings where:

- chemical odors or physiologic effects are reported and there is a credible information to suggest that a release to the subsurface environment may be a contributing factor, or

- intruding contaminated groundwater is reported and observed.

Likewise, EPA generally recommends testing of unoccupied structures for explosive gases as soon as practical where chemical odors are reported and there is a credible information to suggest that a release to the subsurface environment may be a contributing factor.

Section 7.4 provides EPA's approach and recommendations for identifying when human health risks are "unacceptable." Section 7.5.2 describes EPA's recommended approaches to identifying concentration levels indicating a potential need for prompt response action. Section

8.2.1 identifies potential response actions to reduce or avoid these threats promptly, when the results of testing reveal threats or potential threats warranting prompt response action.

EPA recommends health and safety planning for all building- or site-specific actions, as discussed further in Section 6.2, which considers expected work conditions and anticipated hazards.

5.3 Determine Presence of Structures and Vapor-forming Chemicals

For purposes of this Technical Guide and as reflected in the conceptual model of vapor intrusion (Section 2), the vapor intrusion pathway is referred to as "complete" for a specific building or collection of buildings when the following five conditions are met under current conditions:

1) A subsurface source of vapor-forming chemicals is present underneath or near the building(s) (see Sections 2.1, 6.2.1, and 6.3.1);

2) Vapors form and have a route along which to migrate (be transported) toward the building(s) (see Sections 2.2 and 6.3.2);

3) The building(s) is (or are) susceptible to soil gas entry, which means openings exist for the vapors to enter the building(s) and driving 'forces' exist to draw the vapors from the subsurface through the openings into the building(s) (see Sections 2.3 and 6.3.3);

4) One or more vapor-forming chemicals comprising the subsurface vapor source(s) is (or are) present in the indoor environment (see Sections 6.3.4 and 6.4.1); and

5) The building(s) is (or are) occupied by one or more individuals when the vapor forming chemical(s) is (or are) present indoors.

EPA recommends that site managers also evaluate whether subsurface vapor sources that remain have the potential to pose a complete vapor intrusion pathway in the future if site conditions were to change (e.g., reasonably expected occupancy or construction in the future of a building above or near a subsurface vapor source). A complete vapor intrusion pathway indicates that there is an opportunity for human exposure, which warrants further analysis (see Section 7.4) to determine whether there is a basis for undertaking a response action(s) (see Section 7.7).

At the preliminary assessment stage, the available information may not be sufficient to evaluate whether all five conditions are present under current or reasonably expected future conditions. EPA recommends, however, that readily ascertainable information be reviewed for purposes of assessing whether the first and fifth conditions are present; that is:

- A subsurface source of vapor-forming chemicals is present or is reasonably expected to be present (e.g., in contaminated groundwater, soil, or sewer lines or from a primary

vapor release).[91] Section 3.1 describes chemicals that have the potential to pose an unacceptable human health risk through the vapor intrusion pathway. In the absence of environmental sampling data, the potential presence of vapor-forming chemicals in the subsurface may be inferred from site information, as identified in Section 5.1 (e.g., site history).

- At least one building is present or is reasonably expected to be constructed in the future above or "near" the subsurface vapor source(s), which is or could be occupied by humans. For purposes of this Technical Guide and its recommendations for evaluating human health risk posed by vapor-forming chemicals, "building" refers to a structure that is intended for occupancy and use by humans. This would include, for instance, homes, offices, stores, commercial and industrial buildings, etc., but would not normally include sheds, carports, pump houses, or other structures that are not intended for human occupancy. However, where the assessment identifies the potential for methane or other potentially explosive vapors to be present in the subsurface, EPA recommends reviewing readily ascertainable information for purposes of assessing whether non-occupied structures (including, but not limited to, sewers, pits, and subsurface drains) are present, which may also accumulate vapors, in addition to occupied and non-occupied buildings. Existing buildings (and non-occupied structures) can be identified during inspections of the land areas overlying and near subsurface vapor sources. The potential presence of buildings in the future may be inferred from site information, such as identified in Section 5.1. See Section 6.2.1 for further discussion on which buildings and non-occupied structures are considered "near" for purposes of a preliminary analysis.

If the available information is deemed reliable, well documented, and sufficient (see Section 5.1) and indicates that neither of these conditions is met, then further vapor intrusion assessments are not generally warranted.[92]

Example: From 1920 to 1931, the ABC Mining Company obtained and shipped iron ore from a local deposit. Ore from the mine was shipped by rail to a different location where it was milled and processed to extract the metal. Although no company records are available for the mine, a review of mining techniques indicates that solvents and other vapor-forming chemicals were not used in the mining process during the 1920s and 1930s. Former mining structures have been removed, and the site is currently vacant. The city has proposed redeveloping the site with bike and hiking trails but no buildings or other structures for storage or site maintenance support. Based on the information and

[91] As noted in Section 2.1, the primary contamination source need not be on the property of interest to pose a vapor intrusion problem. The primary source(s) of vapor-forming chemicals (e.g., contaminated soil, leaking tanks) may be present on a neighboring property or on a property some distance away. Even "greenspace" properties that have not previously been occupied or developed may contain subsurface contamination by vapor-forming chemicals due to migrating plumes of contaminated groundwater or migrating soil gases. Therefore, EPA recommends that the potential for vapor intrusion be considered at all properties being considered for redevelopment (EPA 2008a) or proximate to industrial and commercial use areas.

[92] Consistent with federal environmental protection statutes, regulations, and OSWER guidance, a subsurface investigation may still be warranted for non-volatile substances or for other potential exposure pathways such as those identified in Section 1.3.

findings, the need for further assessment of the vapor intrusion pathway due to mining-related contamination is not indicated.

If, on the other hand, there is reliable evidence to indicate that a release of vapor-forming chemicals to the subsurface has occurred (e.g., environmental sampling data indicate detectable levels of a vapor-forming chemical(s) in potential source media)[93] or may have occurred underneath or near a property, then EPA recommends further vapor intrusion assessment in areas where buildings are present or future buildings could be constructed, including development of a conceptual site model (see Section 5.4) and investigation of site-specific conditions (see Section 6).

Example: The XYZ Recycling Center site was used from 1963 to 1984 for the collection and recycling of industrial solvents and other fluids. The site was repeatedly cited by the state and city for improper handling and disposal of solvents, and was closed in 1985. Groundwater data indicate the presence of multiple chlorinated hydrocarbons. Buildings overlying the contaminated groundwater are currently used mainly for storage of non-chemical goods, but the site has been proposed for future residential or commercial redevelopment. Based on the foregoing information and findings, further assessment of the potential for vapor intrusion is warranted, possibly including risk-based screening of the groundwater data (see Section 6.5).

If a release of vapor-forming chemicals to the subsurface is known or suspected to have occurred at or near the site, but buildings are not present and none are reasonably anticipated in the future (e.g., the contaminated source underlies an open space, recreational area, or wildlife refuge), then further vapor intrusion assessments may not be appropriate under current conditions. It may be appropriate, however, to establish an institutional control (IC) requiring a vapor intrusion investigation or building mitigation[94] in the future, in case land use changes. ICs for building mitigation and subsurface vapor source remediation are discussed further in Sections 3.3 and 8.6 of this Technical Guide.

Existing guidance and practice pursuant to CERCLA and RCRA corrective action (CA) recognize and entail various phases of subsurface or site characterization, including a site investigation to determine the full nature and extent of contamination at a site, quantify risks posed to human health and the environment, and gather information to support the selection and implementation of appropriate remedies. On this basis, a subsurface investigation may be warranted at some point to characterize subsurface contamination and assess the need for subsurface remediation to protect the environment and human health for potential exposure pathways other than vapor intrusion (such as those identified in Section 1.3). For example, site investigations to characterize the nature and extent of groundwater contamination and support assessments of risk to human health through the ingestion pathway are typically conducted, consistent with federal statutes and regulations (e.g., CERCLA and RCRA) and considering EPA guidance.

[93] Section 6.5 provides information on how such data may be used in a quantitative fashion to screen the site further.

[94] If, for example, a developer is considering acquiring and building on land that contains subsurface contamination with vapor-forming chemicals, the developer could retrofit existing buildings or build new buildings with vapor mitigation systems without first conducting an extensive vapor intrusion investigation (see Sections 3.3 and 7.8). Section 8.2.3 identifies additional approaches and considerations for new buildings.

5.4 Develop Initial Conceptual Site Model

EPA recommends that the planning and data review team develop an initial conceptual site model (CSM) for vapor intrusion when the preliminary analysis indicates the presence of subsurface contamination with vapor-forming chemicals underlying or near buildings. The initial CSM (and any subsequent refined CSM) can be used to support evaluations of the adequacy of the available site-specific information, to guide any vapor intrusion investigations (see Sections 6.2 and 6.3), and to support data selection for risk-based screening (see Section 6.5). The CSM can also provide useful information for supporting prompt development of a strategy for early/interim response actions (see Sections 7.8 and 8.2).

The remainder of this section discusses recommended information that can be useful for developing a CSM. Note that some of the recommended information may not be readily available when a site is first considered for vapor intrusion. Although the CSM may be updated iteratively (and interim mitigation measures may be undertaken) as the vapor intrusion investigation unfolds, EPA recommends completing the CSM before making final risk management decisions for a given site (see Section 7).

As discussed in Section 5.3, the available information may not be sufficient at the preliminary analysis stage to evaluate whether the vapor intrusion pathway is complete under current or future conditions. Therefore, the initial CSM for vapor intrusion is likely to be incomplete. EPA recommends, however, that the initial CSM for vapor intrusion portray the current understanding of site-specific conditions pertaining to the vapor intrusion pathway. Ideally, at a minimum, the initial CSM will address:

- Nature (i.e., type, chemical composition), location, and spatial extent of the source(s) of vapor-forming chemicals in the subsurface (see Sections 2.1 and 6.3.1, for example). For example, it is useful to know which vapor-forming chemical(s) primarily comprise the subsurface vapor source[95] and whether it is also capable of posing explosion hazards. It is also useful to know whether vapor-forming chemicals are present in groundwater, vadose zone soils, sewer lines, and/or some other source underneath or near buildings.

- Location, use, occupancy, and basic construction (e.g., foundation type) of existing buildings.

The CSM can be updated as additional information is obtained through investigation (Section 6) and building surveys (Section 6.4.1).

EPA recommends the CSM also portray the current understanding of the hydrologic and geologic setting in and around the subsurface vapor source(s) and the buildings, which is expected to influence vapor migration and attenuation in the vadose zone (see Sections 2.2 and 6.3.2, for example). When these conditions are not well established from existing information, and the preliminary analysis indicates the presence of subsurface contamination with vapor-

[95] EPA also recommends that the CSM identify any site-specific chemicals of concern that may be biodegradable and identify and summarize information and data pertaining to the possible role of biodegradation *in situ* in limiting vapor migration in the vadose zone (see Section 6.3.2) or generating hazardous, volatile degradation products (e.g., methane from anaerobic biodegradation, vinyl chloride as a byproduct of PCE or TCE biodegradation).

forming chemicals underlying or near buildings, EPA recommends that a detailed vapor intrusion investigation be scoped and conducted to address these data gaps (see Section 6.3).

Furthermore, EPA recommends the CSM identify known or suspected preferential migration routes that could facilitate vapor migration to greater distances and at higher concentrations than otherwise expected. EPA recommends that buildings with significant preferential migration routes be evaluated closely. For the purposes of this Technical Guide, a preferential migration route is a naturally occurring subsurface feature or anthropogenic (human-made) subsurface conduit that is expected to exhibit little resistance to vapor flow in the vadose zone (i.e., exhibits a relatively high gas permeability) or groundwater flow (i.e., exhibits a relatively high hydraulic conductivity), depending upon its location and orientation relative to the water table and ground surface, thereby facilitating the migration of vapor-forming chemicals in the subsurface and/or into buildings.[96] Naturally occurring examples include fractures and macropores, which may facilitate a preferential route for either the vertical or horizontal migration of source materials and/or vapors. Anthropogenic examples include sewer lines and manholes,[97] utility vaults and corridors, elevator shafts, subsurface drains, permeable fill, and underground mine workings that intersect subsurface vapor sources or vapor migration routes. In highly developed residential areas, extensive networks of subsurface utility corridors may be present, which can significantly influence the migration of contaminants. A preferential migration route can be a "significant" influence on vapor intrusion when it is of sufficient volume and proximity to a building that it may be reasonably anticipated to influence vapor migration towards or vapor intrusion into the building. Significant vertical routes of preferential migration may result in higher than anticipated concentrations in the overlying near-surface soils, whereas significant horizontal routes of preferential migration may result in elevated concentrations in areas on the periphery of subsurface contamination (see Section 6.2.1).

CSMs for vapor intrusion assessments often need to consider two distinct exposure situations:

1) At some sites and contaminated locations, there are concerns as to whether vapor intrusion may pose a human health risk to current occupants of an existing building(s). For this situation, EPA recommends that building-specific information be available to support the CSM, which may be obtained through a building survey (see Section 6.4.1, for example) .

2) At other sites and contaminated locations, buildings are not present, but are expected to be constructed, and building-specific information may not be available to support the CSM. For this situation, the CSM may need to consider a hypothetical building constructed anywhere over (or near) the subsurface vapor source.

[96] For purposes of this Technical Guide, preferential migration routes are distinguished from adventitious and intentional openings in a building that may also facilitate vapor entry from the subsurface (see Section 2.3), but which are expected to typically be present in all buildings (e.g., cracks, seams, interstices, and gaps in basement floors and walls or foundations; perforations due to utility conduits).

[97] In addition to receiving direct discharges of aqueous and chemical wastes from commercial and industrial operations, sewers can be indirect receptacles of subsurface contamination via infiltration of NAPL, soil gas, or contaminated groundwater through cracks in piping and manholes (see Section 2 of this Technical Guide, for example, for further discussion).

In general, CSMs identify the potentially exposed populations, potential exposure routes, and potential adverse health effects (i.e., toxicity) arising from these exposures. As such, EPA recommends the CSM also identify and consider sensitive populations, including but not limited to:

- Elderly,
- Women of child-bearing age,
- Infants and children,
- People suffering from chronic illness, or
- Disadvantaged populations (i.e., an environmental justice situation).

By definition and as noted in Section 2, the exposure route of general interest for vapor intrusion is inhalation of vapors in indoor air and the human population of primary interest is comprised of individuals living or working in or otherwise occupying a building subject to vapor intrusion. However, EPA also recommends that the CSM identify any site-specific chemicals of concern that have potential for explosion hazards (e.g., methane) or for posing other routes of exposure (e.g., dermal exposure to shallow contaminated groundwater seeping into a basement).

EPA recommends that the CSM also identify and characterize suspected sources of site-related, vapor-forming chemicals that are also found in ambient air in the site vicinity. In some situations, site-related contamination has the potential to impact ambient air with the same vapor-forming chemicals that pose a threat from vapor intrusion. For example, contamination of shallow soil or groundwater may release site-related vapor-forming chemicals to ambient air. EPA recommends the CSM identify any such conditions, which have implications for the scope and objectives of the overall site investigation, as well as for data evaluation and the human health risk assessment.

To document current site conditions, EPA recommends that a CSM be supported by maps, cross sections, and site diagrams, to the extent practical, and that the narrative description clearly distinguish what aspects are known or determined and what assumptions have been made in its development.

EPA generally recommends that developing a CSM be incorporated into the first step in EPA's data quality objective (DQO) process (EPA 2006a). It is rare for a site to have readily available sources of sufficient information to develop a complete CSM when the vapor intrusion potential is first considered. For example, a detailed site-specific investigation may be necessary to characterize the full extent of subsurface vapor sources and geologic conditions underlying nearby buildings (see Sections 6.3.1 and 6.3.2) and to demonstrate the absence of preferential routes for vapor migration and intrusion. The CSM normally warrants updating as new information is developed and new questions are framed and answered. A well-defined, detailed CSM may also facilitate the identification of additional data needs and development of appropriate detection limits for laboratory and field analyses, which can support planning of the detailed vapor intrusion investigation (see Section 6.2) and site-specific human health risk assessment, if any (see Section 7.4). Sections 6.3, 6.4, 7.1, and 7.2 provide additional information about data collection and evaluation for purposes of supporting the CSM.

5.5 Evaluating Pre-Existing and Readily Ascertainable Sampling Data

Sites and adjacent facilities that have been the subject of previous environmental investigations or regulatory actions may already have data on contaminant concentrations in site media (i.e., sampling data) when the vapor intrusion pathway is first considered and evaluated. Some of these sites and facilities may be undergoing remediation but warrant a vapor intrusion assessment as a result, for example, of changing toxicity information for vapor-forming chemicals, as part of a periodic review of remediation effectiveness and protectiveness (if any), or for other reasons.

If the pre-existing environmental data are deemed reliable and other conditions are met (as described in the remainder of this subsection and in Section 6.5.2), the sampling data may be compared to recommended generic vapor intrusion screening criteria (see Section 6.5) for purposes of developing some preliminary insights about the potential level of exposure and risk posed by vapor intrusion. Such a screening can, for example, help focus a subsequent vapor intrusion investigation (see Section 6) or provide support for considering building mitigation as an early action (see Section 7.8.2), depending upon building- and site-specific circumstances. Note that some of the site-specific information generally recommended for supporting a risk-based screening (see Section 6.5.2) may not be available when a site is first considered for vapor intrusion.

5.5.1 Evaluate Sampling Data Reliability and Quality

To the extent that environmental sampling data are identified for the site or nearby properties, EPA recommends that these data be evaluated to determine whether they are of sufficient quality and reliability to support a comparison to recommended generic vapor intrusion screening criteria (see Section 6.5). Some questions that could be considered when reviewing historical sampling data include:

- How were the samples collected and analyzed? EPA recommends using pre-existing data when they have been collected and analyzed by methods considered reliable by today's standards.

- How old are the data? Were analyses conducted for all vapor-forming chemicals known or suspected to be present and reasonably expected degradation products? EPA recommends using pre-existing data when they can be considered representative of current conditions.

- Were the reporting limits sufficiently low for comparison with vapor intrusion screening criteria? EPA recommends use of pre-existing data with non-detect results only when they can be considered reliable on this basis.

- Were multiple locations sampled to assess spatial variability of the results? Were multiple sampling events conducted to assess temporal variability of the results? EPA recommends characterizing spatial and temporal variability to increase confidence in

data evaluation and decision-making and ensure consideration of a reasonable maximum vapor intrusion condition.[98]

EPA also recommends that the reliability of any historical sampling data be assessed by considering the principles for collecting subsurface and indoor air samples that are described in Sections 6.3.1 and 6.4 of this Technical Guide. In addition, the EPA's *Guidance for Data Usability in Risk Assessment, Part A* (EPA 1992a) outlines a recommended approach for evaluating whether the data are useable for the human health risk assessment. As such, its recommended approach is also worthwhile and complementary for evaluating the quality and usefulness of historical data collected at a site.

5.5.2 Evaluate Applicability of the VISLs and Adequacy of the Initial CSM

Before performing any comparison of existing sampling data to recommended generic vapor intrusion screening levels (VISLs) (see Section 6.5), it is important to verify that site-specific conditions reflect the conditions and assumptions of the generic model underlying the VISLs, which are summarized in Section 6.5.2. To verify that the generic vapor intrusion model applies, there is a need for basic knowledge of the subsurface source of vapors (e.g., location, form, and extent of site-specific vapor-forming chemicals) and subsurface conditions (e.g., soil type in the vadose zone, depth to groundwater for groundwater sources), which are important elements of the CSM (see Section 5.4). When these subsurface data are not available, EPA recommends they be collected (i.e., initiate a vapor intrusion investigation; see Section 6.3.2, for example) before relying upon risk-based screening using pre-existing sampling data.

5.5.3 Preliminary Risk-based Screening

If reliable pre-existing sampling data are available and an adequate CSM has been developed (i.e., sufficient subsurface characterization information exists to adequately characterize the locations, forms, and extent of site-specific vapor-forming chemicals and general subsurface conditions (e.g., hydrologic and geologic setting in and around the source(s) and the buildings)), then a risk-based screening may be useful to obtain some preliminary insights about the potential level of exposure and risk posed by vapor intrusion.

Example: A prospective developer of a vacant lot with no history of onsite chemical use is interested in evaluating the potential for vapor intrusion in the future due to potential migration onto the lot of a plume of contaminated groundwater emanating from another property. The extent and nature of this off-property plume have been adequately and recently characterized and geologic conditions near (but not on) the lot have been characterized, as documented in a publicly available report(s). In this circumstance, it may be possible to support a preliminary screening and obtain some useful insights. For example, if the maximum concentration of each chemical of concern in the off-property plume of contaminated groundwater currently and in the future is less than the generic chemical-specific screening level for groundwater, then vapor intrusion may not be a future

[98] EPA recommends basing the decision about whether to undertake response action for vapor intrusion (i.e., a component of risk management; see Section 7.4) on a consideration of a reasonable maximum exposure (e.g., EPA 1989, 1991a), which is intended to be a semi-quantitative phrase, referring to the lower portion of the high end of the exposure distribution (see Glossary).

concern on the vacant lot, provided there are sufficient data to document that conditions on the vacant lot are consistent with the generic model behind the vapor intrusion screening levels, as described in Section 6.5.2.

Depending upon lot-specific circumstances, additional data collection or evaluation, possibly including on-lot site characterization, may be warranted (i.e., proceed to a detailed vapor intrusion investigation) to verify that the expected conditions hold true (e.g., hydrogeologic conditions on the vacant lot are consistent with the generic model behind the vapor intrusion screening levels). EPA generally also recommends consideration of the vapor intrusion pathway during the development planning or initial post-construction stage (e.g., pre-emptive mitigation – Sections 3.3 and 7.8; mathematical modeling, where parameters are chosen to represent conditions that give a high-impact case – Section 6.6; indoor air testing – Section 6.4.1 -- to confirm the screening results based upon the groundwater source data) before making final risk management decisions.

This example reinforces the following general recommended guidelines:

- EPA generally recommends that site-specific data be collected and evaluated to verify that the subject property reflects the conditions and assumptions of the generic model underlying the VISLs (see Section 6.5.2).

- EPA generally recommends that multiple lines of evidence (e.g., hydrogeologic information in addition to sampling data) be collected and weighed together in supporting assessments of the vapor intrusion pathway (see Sections 7.1, 7.2, and 7.3 for further information).

- Multiple rounds of groundwater (or soil gas) sampling results can be useful in supporting conclusions that a specific vapor source is stable or shrinking and/or is not expected to pose a vapor intrusion concern (see Sections 6.3.1 and 6.4.5) under reasonably expected future, as well as current, conditions.

Similar recommended guidelines may be appropriate in situations where vapor intrusion potential is being evaluated as part of a periodic review of an existing remedy (prompted, for example, by recent construction of a new building over a contaminated plume that is undergoing remediation) (EPA 2002b, 2012c).

6.0 DETAILED INVESTIGATION OF VAPOR INTRUSION

EPA recommends that the planning and data review team plan and conduct a site investigation for vapor intrusion when the preliminary analysis (Section 5.3) indicates the presence of subsurface contamination with vapor-forming chemicals underlying or near buildings.

This section describes EPA's generally recommended approaches and practices for conducting detailed vapor intrusion investigations, which typically entail collecting and weighing multiple lines of evidence to characterize the vapor intrusion pathway. Specifically, this section:

- Identifies that a wide variety of scenarios may be encountered among sites investigated for potential vapor intrusion, which necessitates site-specific approaches to scoping investigations and sequencing investigation phases and objectives (Section 6.1);
- Provides EPA's recommendations for planning, scoping, and conducting vapor intrusion investigations (Sections 6.2, 6.3, and 6.4);
- Presents EPA's recommended screening levels for vapor intrusion and describes EPA's recommended uses of risk-based screening and suggested interpretation of the results (Section 6.5); and
- Provides recommendations for developing and using mathematical models in vapor intrusion assessments (Section 6.6).

Section 7 describes EPA's generally recommended approaches and practices for determining, on the basis of the investigation results, whether the vapor intrusion pathway poses a potential human health risk to building occupants under current and reasonably expected future conditions and whether response actions are warranted for vapor intrusion mitigation at individual facilities, buildings, or sites.

6.1 Common Vapor Intrusion Scenarios

Vapor intrusion scenarios can be quite varied, owing to the possible combinations of:

- Multiple hazardous chemicals that can form vapors.
- Multiple forms in which these chemicals may be released to or present as contaminants in the subsurface, for example:
    - Residual NAPL and adsorbed-phase chemicals, including LNAPLs that are less dense than water and DNAPLs that are denser than water.
    - Dissolved-phase chemicals in groundwater or soil moisture.
    - Primary vapor releases (e.g., from chemical vapor transmission lines).
- The variety of geologic and hydrologic characteristics and conditions in the subsurface environment in which this contamination may occur.

- The variety of buildings (in terms of size, age, condition, and use) and current or expected land use settings (e.g., residential, commercial, industrial) that may be subject to vapor intrusion from such subsurface contamination.

- Circumstances under which subsurface contamination is found or suspected and investigated (e.g., brownfield redevelopment, citizen reports/complaints, reported release)

- The variety of sources that may contribute to vapor concentrations in ambient air and may serve as indoor vapor sources unrelated to vapor intrusion.

A few of the possible scenarios are illustrated in Figure 2-1. Many more can be inferred from the conceptual model of vapor intrusion discussed in Section 2. Some of the common scenarios where vapor intrusion has been documented to occur include:

- Groundwater contaminant plumes in shallow aquifers underlying residential and nonresidential buildings. Many well-known vapor intrusion sites are in this category, in part because there is generally a greater opportunity to have multiple buildings overlying the vapor source. Specific sites and buildings normally can be prioritized and distinguished based upon their potential for vapor intrusion, which generally would depend upon a number of site-specific factors, such as:

    - strength, proximity, and extent of the vapor source emanating from shallow groundwater (see Sections 2.1 and 5.4);

    - the potential for significant attenuation of vapor migration due to geologic, hydrologic, or biochemical conditions in the vadose zone (see Sections 2.2 and 5.4);

    - the potential for significant attenuation of the contaminant plume due to geologic, hydrologic, or biochemical conditions in the saturated zone; and

    - type(s), characteristics and structural condition of the overlying building(s) (see Sections 2.3, 2.4, and 5.4).

- Soil contamination in the vadose zone underlying commercial or industrial buildings. Typically, one or a few buildings may be threatened by potential vapor intrusion. Specific buildings and sites normally can be prioritized and distinguished based upon their potential for vapor intrusion, which generally would depend upon a number of site-specific factors, such as:

    - strength, proximity, and extent of the vadose zone source (see Sections 2.1 and 5.4);

    - the potential for attenuation of vapor migration due to geologic, hydrologic, or biochemical conditions in the vadose zone (see Sections 2.2 and 5.4); and

    - type(s), characteristics and structural condition of the overlying building(s) (see Sections 2.3, 2.4, and 5.4).

- Sites with residual wastes (e.g., landfills, former manufactured gas plants, former oil production fields) underlying or near buildings. The potential for methane formation may more frequently warrant additional consideration for sites with residual wastes than for contaminated groundwater plumes.

EPA's recommended approaches and practices for vapor intrusion investigations aim to be flexible and adaptable to a wide range of reasonably expected scenarios and are not intended to be prescriptive or exhaustive for any specific scenario.

6.2 Planning and Scoping

Before information or data are collected, EPA generally recommends conducting systematic and thorough planning during which performance or acceptance criteria are developed for the collection, evaluation, or use of these data (EPA 2006a).[99] EPA recommends the data quality objective (DQO) process as the appropriate systematic planning process for its decision-making and has issued guidance for its application to hazardous waste site investigations pursuant to CERCLA and RCRA (EPA 2000a).[100] When appropriately conducted, planning provides greater assurance that the data collected will fulfill specific project needs and that mitigation and subsurface remediation options will be considered early in the process.[101] A clear and logical plan will often facilitate communication with building owners, occupants, and other stakeholders.

Given these considerations, a thorough planning process, guided by a CSM, is usually advisable for detailed vapor intrusion investigations. Figure 6-1 provides a diagram to illustrate such planning and scoping. The initial stages of planning would typically entail gathering readily available existing information and formulating an initial CSM, as described in Section 5.4. The CSM portrays the current understanding of site-specific conditions, including the nature and extent of contamination, contaminant fate and transport routes, potential "receptors" and contaminant exposure pathways. The term "conceptual" merely reflects that the model need not be entirely quantitative and mathematical; it does not, however, denote a simplistic or incomplete understanding of site conditions. The CSM normally warrants updating as new information is developed and new investigatory questions are framed and answered.

Subsequent to formulating an initial CSM based on readily available information, the scope for an initial phase of vapor intrusion investigation would be developed, preferably along with a logical plan for future directions in response to the reasonably expected outcomes of the initial investigatory phases and in coordination with the objectives and phasing of the broader site

[99] In situations where imminent threats (see Section 5.2) are known or reasonably expected, the initial planning process may be more truncated and focused, but careful and thoughtful planning is still recommended.

[100] Appendix B provides additional information about EPA's quality system and DQO process.

[101] *Science and Decisions: Advancing Risk Assessment* was prepared by the National Academy of Sciences (NAS) Committee on Improving Risk Analysis Approaches Used by the U.S. EPA (NRC 2009) and is commonly referred to as the "Silver Book." Among other recommendations, the NAS Committee encouraged EPA to focus greater attention on design in the formative stages of risk assessment, specifically on planning and scoping and problem formulation, and to view risk assessments as a method for evaluating the relative merits of various options for managing risk, rather than as an end in itself. Consistent with these recommendations, plausible mitigation and subsurface remediation options (see Section 8) may warrant consideration during development of vapor intrusion investigation plans.

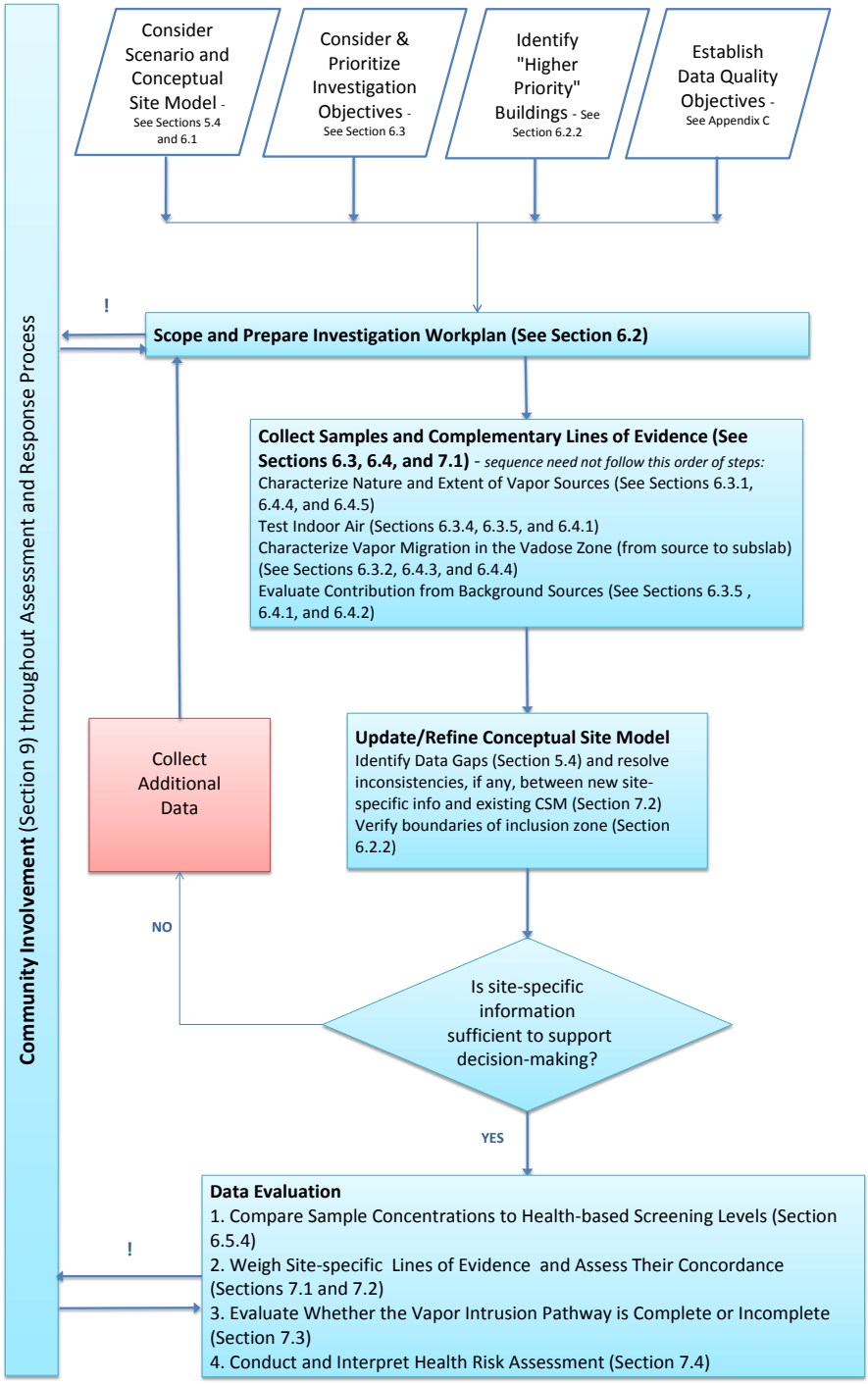

Figure 6-1 Overview of Planning, Scoping, and Conducting Vapor Intrusion Investigations

characterization. Initial plans may warrant periodic updates and refinements, particularly when data outcomes are unexpected and prompt the need to reevaluate the CSM. In each case, EPA recommends that the investigation work plan include the identification of and basis for the indoor air screening levels (such as the vapor intrusion screening levels (VISLs)) and/or indoor air action levels (i.e., level of each vapor-forming chemical of potential concern that would trigger a response action if exceeded), which would dictate the DQOs for the sampling and analysis methods. In general, EPA recommends the plan also include a rationale or logic for where and how the data will be collected and over what duration(s), how the data will be interpreted (e.g., weighed with other lines of evidence, compared to risk-based benchmarks), whether confirmatory sampling will be needed if all sample concentrations are less than the action levels, whether response action(s) would be triggered if sample concentrations exceed the target levels, and similar considerations. EPA recommends considering potential health effects and relevant exposure periods (e.g., chronic versus short-term effects and exposure durations and scenarios; see Section 7.4) for site-related, vapor-forming chemicals when developing DQOs and sampling plans for indoor air (see Section 6.4.1, for example). Sections 6.3 through 6.6 below provide additional information for planning and scoping site-specific investigations for vapor intrusion assessment.

EPA's fundamental approach to evaluating contaminated sites calls for proceeding in a stepwise fashion with early data collection efforts usually limited to developing a basic understanding of the site, as reflected in the CSM.[102] Subsequent data collection efforts focus on filling gaps in the understanding of the CSM and gathering information necessary to evaluate the relative merits of various options for managing risk. Therefore, EPA generally recommends developing and implementing an overall vapor intrusion investigation plan in multiple stages or phases. Such a phased approach encourages the identification of key data needs early in the process to better ensure that data collection provides information relevant to decision-making (e.g., interim action to mitigate vapor intrusion and selection of a cleanup plan for subsurface contamination). In this way, the overall site characterization effort can be scoped to prioritize data collection and minimize the collection of unnecessary data and maximize data quality.

EPA recommends that the objectives and methods of the investigation be documented, preferably in a vapor intrusion work plan. An individual work plan may address a single phase or stage or may address the overall investigation. The vapor intrusion work plan(s) may be

[102] Investigations under CERCLA and RCRA corrective action (CA) explicitly recognize phasing. In these cleanup programs, the first investigatory phase is an *initial site assessment.* The purpose of this activity is to gather information on site conditions (current and historical), releases, potential releases, and exposure pathways. Investigators use this information to determine whether a response action (e.g., removal action or interim cleanup measure) may be needed or to identify areas of concern for further study. Information collected during this phase usually forms the basis for determining whether the next stage, site investigation, is warranted. In the RCRA CA program, the initial site assessment is called the RCRA facility assessment. Under CERCLA, this phase is called the preliminary assessment/site inspection. The purpose of the second phase, site investigation, is to determine the nature and extent of contamination at a site, quantify risks posed to human health and the environment, and gather information to support the selection and implementation of appropriate remedies. In the RCRA CA program, this phase is known as the RCRA facility investigation. Under the CERCLA remedial program, this phase is referred to as the remedial investigation. In addition, the site investigation may itself be conducted in multiple stages (or phases).

incorporated as part of a comprehensive site investigation work plan or as a stand-alone document, depending upon site-specific circumstances.[103]

At a minimum, EPA recommends that the components of the work plan(s) include or reference:

- Narrative description of the rationale, objective(s), and scope of the investigation.
- Summary of the CSM, based upon the current understanding of site conditions.
- Scaled map(s) illustrating known extent of subsurface contamination and readily identifiable landmarks (e.g., streets and buildings).
- Media to be sampled.
- Number, type, and location of and rationale for proposed sampling locations.
- Sampling methods and procedures for each medium.
- Analytic method(s) to be used to obtain chemical concentrations and a statement about whether a stationary or mobile laboratory will be used.
- Standard operating procedures of the laboratory and for field instruments.
- Quality assurance project plan (QAPP).
- Health and safety plan.[104]

EPA recommends that planning for vapor intrusion investigations also consider site and building access agreements, equipment security, and locations of underground utilities.

EPA recommends that the planning, data collection, and data review team(s) for vapor intrusion investigations generally include:

- Individuals with expertise in characterizing subsurface environmental conditions and interpreting and communicating environmental data.
- On-site (field) personnel with appropriate training and experience in hazard identification, workplace practices to foster health and safety, and recommended sampling protocols.

[103] EPA recommends that monitoring programs (see Section 8.4) that assess the performance and effectiveness of remediation and mitigation systems (see Sections 8.1 and 8.2, respectively) also be documented, preferably in work plans similar to those recommended herein for characterizing and assessing the vapor intrusion pathway.

[104] All governmental agencies and private employers are directly responsible for the health and safety of their employees. This general rule applies to many parties involved in the assessment and cleanup of Superfund sites, RCRA corrective action sites, and brownfield redevelopment sites. Standards established pursuant to the Occupational Safety and Health Act are found in Title 29 of the Code of Federal Regulations (29 CFR), which include standards for training, hazard communication, and site-specific health and safety plans.

- Individuals with expertise in human health risk assessment to characterize risks posed by the vapor intrusion pathway.

- Individuals with expertise in community involvement and outreach.

Depending upon the complexity of the CSM (see Section 5.4) and site-specific data evaluations, decision-makers may also find valuable input from individuals with expertise in hydrogeology, inferential statistics, laboratory analysis methods, and building construction, ventilation, and operations and individuals knowledgeable about land use planning, zoning, and land development.

EPA recommends that the scope of investigations within buildings and on individual properties be contemplated, planned, and implemented with the goal of limiting, to the extent practical, return visits, which can cause disruption and inconvenience for building occupants and owners. For example, it may be preferable to collect a comprehensive set of data (e.g., indoor air, sub-slab soil gas, and ambient air samples; pressure readings; see Section 6.4) and confirm information about building occupancy, building usage, heating, cooling, and ventilation (see Section 6.4.1) in a single mobilization, rather than over separate visits, when the investigation objectives include indoor air sampling (see Section 6.3.4) or evaluating contributions of 'background' sources on levels of vapor-forming chemicals in indoor air (see Section 6.3.5).

6.2.1 Vapor Intrusion Inclusion Zones

Soil gas concentrations generally decrease with increasing distance from a subsurface vapor source, and eventually at some distance the concentrations become negligible. The distance at which soil gas concentrations become negligible is a function of the strength and dimensions of the vapor source, the type of vapor source, the soil types and layering in the vadose zone, the presence of physical barriers (e.g., asphalt covers or ice) at the ground surface, and the presence of preferential migration routes, among other factors (see, for example, EPA 2012b). The extent of the site-specific "inclusion zone" for vapor intrusion may also expand in the future, depending upon:

- The age of the chemical release and whether sufficient time has elapsed to allow soil gas to migrate from the source to its maximum potential extent.[105]

- Whether the subsurface vapor source is expanding (i.e., is migrating) or rising in concentration, including hazardous byproducts of any biodegradation.

Because these factors vary among sites, the distance beyond which structures will not be affected by vapor intrusion should be a site-specific determination.

Recommended Distance for Initial Evaluation. There are limited published empirical data relating observed indoor air concentrations of subsurface contaminants to distance from a well-

[105] EPA (2012b, Section 6.1) presents some information about transient vapor migration after a subsurface vapor source is released. Sites with shallow vapor sources (e.g., less than one meter deep) may take only a few hours to a few days for soil gas to migrate to its maximum potential extent. Sites with deeper vapor sources (e.g., greater than 10 meters deep) may take months or years for soil gas to migrate to its maximum potential extent.

defined source boundary. However, a buffer zone of approximately 100 feet (laterally or vertically from the "boundary" of subsurface vapor concentrations of potential concern) generally has been used in determining which buildings to include in vapor intrusion investigations (i.e., which buildings are 'near' a subsurface vapor source for purposes of a preliminary analysis) when significant surface covers are not present, under the assumption that preferential vapor migration routes are absent.[106] Specifically, a buffer zone of 100 feet (or approximately two houses wide) has been suggested by several states for initial evaluation and is supported, in general, by:

- theoretical analyses that assume the absence of a preferential vapor migration route(s) and that diffusion is the predominant mechanism of vapor migration in the vadose zone (Lowell and Eklund 2004); and

- reports that vapor intrusion impacts generally have not been observed "at distances greater than one or two houses beyond the estimated extent of the groundwater plume", at sites where contaminated groundwater is the subsurface vapor source (Folkes et al. 2009).

However, we would note that vapor source types for which use of a 100-foot buffer would typically be inappropriate include:

- Landfills where methane is generated in sufficient quantities to induce advective transport in the vadose zone.[107]

- Commercial or industrial settings where a vapor-forming chemical(s) has been released within an enclosed space at a density that may result in significant advective transport of the vapor(s) downward through cracks or openings in floors and into the vadose zone.

- Leaking vapors from pressurized gas transmission lines.

In each of these cases, the diffusive transport of vapors may be overridden by advective transport and the vapors may be transported in the vadose zone several hundred feet from the source of contamination.[108]

Moreover, we would also note that anecdotal evidence indicates that in some settings buildings greater than 100 feet from a plume "boundary" are affected by vapor intrusion, even when

[106] Preferential migration routes are defined and discussed in Section 5.4. When present, they may facilitate subsurface vapor migration over distances greater than 100 feet.

[107] EPA has also published *Guidance for Evaluating Landfill Gas Emissions from Closed or Abandoned Facilities* (EPA 2005), which provides procedures and a set of tools for evaluating landfill gas emissions to ambient air and soil gas migration due to pressure gradients.

[108] For example, Little et al (1992) describe a landfill in southern California, where methane was detected in enclosed spaces in nearby homes at concentrations approaching 1% by volume and chlorinated hydrocarbons had migrated into a house 180 meters from the landfill.

diffusion is the presumed mechanism of vapor migration.[109] Furthermore, the presence of conduits (e.g., sewer and drain lines that intercept and carry subsurface contamination (Vroblesky et al. 2011), as well as permeable bedding for sewer lines or other utilities) or preferential hydrogeologic pathways that facilitate unattenuated vapor migration in the vadose zone, and other factors (e.g., presence of extensive surface covers, uncertainties in delineating the boundaries) may extend the recommended inclusion distance for a vapor intrusion investigation. For these reasons, EPA recommends investigating soil vapor migration distance on a site-specific basis. That is, larger or smaller distances may need to be considered when developing objectives for detailed vapor intrusion investigations and interpreting the resulting data. Data from sub-slab and exterior soil gas sampling (see, for example, Sections 6.4.3, and 6.4.4, respectively)[110] and indoor air testing (see, for example, Sections 6.3.4 and 6.4.1) can be collected and evaluated to delineate or confirm areas at specific sites within which buildings are potentially subject to vapor intrusion.

Criteria for Establishing "Boundaries" of the Plumes that Contain Vapor-forming Chemicals. This Technical Guide is intended to be applied to existing groundwater plumes as they are currently defined (e.g., Maximum Contaminant Levels, state standards, or risk-based concentrations). However, it is important to recognize that some non-potable aquifers may have plumes that have been defined by threshold concentrations significantly higher than drinking-water concentrations. In these cases, contamination that is not technically considered part of the plume may still have the potential to pose unacceptable human health risk via the vapor intrusion pathway. Consequently, the plume definition may need to be expanded for purposes of defining an inclusion zone for a vapor intrusion investigation. When groundwater is the subsurface vapor source, EPA generally recommends comparing groundwater concentrations to the VISLs to estimate the boundaries of the plume, when contaminated groundwater is a subsurface vapor source, for purposes of establishing the boundaries of the vapor intrusion inclusion zone.

Criteria for Establishing "Boundaries" of NAPL Plumes that Contain Vapor-forming Chemicals. EPA generally recommends comparing soil gas concentrations to the respective VISLs to estimate the boundaries of the vapor plume, when residual or free-phase NAPL is a subsurface vapor source, for purposes of establishing the boundaries of the vapor intrusion inclusion zone.

6.2.2 Prioritizing Investigations with Multiple Buildings

At sites where numerous buildings are potentially subject to vapor intrusion (e.g., developed areas with an extensive plume of contaminated groundwater), it may not be feasible or practical at the outset to sample indoor air in each building or soil gas underneath or near each building. In such circumstances, EPA generally recommends a "worst first" approach to prioritize

[109] Among other possibilities, vapor intrusion impacts observed to occur at distances greater than 100 feet in the absence of a preferential migration route(s) may reflect imprecision in the interpolated edge of a plume, based upon sampling data from sparse monitoring wells, and/or use of screening levels for drinking water, rather than for vapor intrusion (i.e., VISLs), to delineate a plume's extent.

[110] For assessing the extent of soil gas migration from the subsurface vapor source, EPA generally recommends measuring soil gas concentrations, either sub-slab soil gas (preferably) or exterior soil gas, with a sufficient density to characterize and understand spatial variability (Section 6.3.2).

buildings for investigation. Factors that, if known, may warrant consideration in prioritizing buildings for investigation include:

- Source strength and proximity. Buildings overlying and near a source of vapors in the vadose zone would generally be expected to have a greater potential for vapor intrusion than buildings that do not overlie this same vapor source. Where the subsurface vapor source is groundwater, buildings located over higher concentrations or shallower water levels would generally be expected to have a greater potential for vapor intrusion than buildings located over lower concentrations and deeper groundwater plumes.

- Building types and conditions. Buildings that are continuously occupied may pose a more immediate concern than buildings that are not currently occupied, if all other factors (e.g., source strength and proximity) are equivalent. Nonresidential buildings with bay-style doors that are routinely open may be better ventilated than other types of nonresidential buildings, providing greater potential for dilution of vapor-forming chemicals that enter the building via vapor intrusion.

- Vapor migration ease. Buildings overlying vadose zones comprised of coarse geological materials (e.g., gravel, boulders) generally would be expected to have a greater potential for vapor intrusion than buildings overlying vadose zones comprised of fine-grained materials (e.g., silts, clays), provided significant preferential migration routes (e.g., geologic fractures, utility corridors) are not present in the fine-grained layers.

Interviews and building surveys during development of the investigation work plan (or during the preliminary analysis – see Section 5) also can provide useful information for prioritizing buildings, when phased testing is chosen or indicated. Sections 6.3 and 6.4 provide additional examples of survey information that can support planning, in addition to supporting data interpretation.

In situations where "higher-priority" buildings and locations are investigated initially, investigation of locations of other buildings may still be warranted, for example, to ensure that the CSM is complete and accurate and that variability in the subsurface conditions and building conditions is understood. There usually is substantial spatial variability in the concentrations of subsurface vapors, caused by heterogeneities in the subsurface materials and other factors, that can result in variability among buildings in vapor flux and indoor air concentrations arising from vapor intrusion. Additionally, building construction, building age and maintenance, and occupants' activities that affect soil gas entry and air exchange rate will vary from building to building, further adding to the variability in indoor air concentrations between buildings. Therefore, it may be difficult to identify *a priori* either a "representative" or "reasonable worst case"[111] building or group of buildings, when it is determined that sampling all buildings is not practical.

[111] For purposes of this Technical Guide, "reasonable worst case" is intended to be a semi-quantitative phrase, referring to the upper portion of the high end of the exposure distribution, but less than the absolute maximum exposure (see Glossary). Because EPA generally recommends a "worst first" approach to prioritize buildings for investigation of the vapor intrusion pathway, "reasonable worst case" buildings would warrant a "higher priority" than "representative" or typical buildings.

When sampling all buildings is not practical, but other lines of evidence suggest that vapor intrusion may be occurring, the site management team may wish to consider installing engineered exposure controls for vapor intrusion mitigation in buildings without baseline indoor air data (i.e., building mitigation as an early action – see Sections 3.3 and 7.8).

6.2.3 Planning for Community Involvement

Community involvement is an important component of any vapor intrusion investigation. EPA recommends that a community involvement or public participation plan (see Section 9.1) be developed or refined while planning a vapor intrusion investigation. Proper and sustained community outreach and engagement efforts are critical to effectively implementing work plans for vapor intrusion investigations, particularly when they involve sampling in a home or workplace or on private property. Resuming and conducting community involvement at legacy sites (i.e., sites that have a past history of agency involvement; see Section 9.6) can be particularly complex. The site planning team is encouraged to consult with appropriate EPA colleagues experienced in community outreach and involvement efforts and utilize available EPA planning resources, including those discussed in Section 9.

6.3 Characterize the Vapor Intrusion Pathway

As discussed in Section 2, the vapor intrusion pathway entails emanation of volatile chemicals from a subsurface source(s) in a vapor form that migrates in the vadose zone, gradually increases in amount underneath buildings as time passes, and enters buildings through openings and conduits. As a result, detailed vapor intrusion investigations designed to develop or enhance the CSM for a specific site will typically address one or more of the following objectives, often in phases:[112]

- Characterize the nature and extent of subsurface sources of vapors.
- Characterize the subsurface migration paths between vapor sources and buildings (potential “receptors”).
- Assess building(s) for their susceptibility to soil gas entry.
- Evaluate the presence and concentration of a site-related subsurface contaminant(s) in indoor air.
- Identify and evaluate contributions of indoor and ambient air sources to concentrations of hazardous vapors in indoor air.

[112] The order of presentation is not intended to convey a suggested sequencing of objectives; rather, it follows the presentation of the conceptual model of vapor intrusion in Section 2.

These objectives are described in the following subsections for purposes of identifying the primary lines of evidence typically developed and evaluated for each objective and describing how the objectives fit together in developing and enhancing the CSM for a specific site an characterizing vapor intrusion potential. This information is provided to assist the site planning team in selecting and sequencing objectives for vapor intrusion investigations.

6.3.1 Characterize Nature and Extent of Subsurface Vapor Sources

Where the preliminary analysis indicates that subsurface contamination with vapor-forming chemicals may be underlying or near buildings, EPA recommends that the nature and extent of such contamination be well characterized. Source characterization data are critical to developing a sound CSM and supporting confident, final decisions about the vapor intrusion pathway.

Investigations to characterize the nature and delineate the extent of potential sources of vapors may rely upon the results of groundwater sampling, soil sampling, or soil gas sampling, as dictated by the site-specific source(s) and subsurface conditions.

Groundwater Sources:

Where contaminated groundwater is a vapor source located near buildings, EPA recommends that groundwater observation wells (i.e., monitoring wells) be installed at strategic locations and used to assess groundwater flow and contaminant concentrations; i.e., verify the nature and extent of groundwater contamination through groundwater sampling and analysis.[113] Groundwater samples obtained from the uppermost portion of the aquifer[114] that underlies the study area of interest (i.e., where buildings are located) are recommended for characterizing representative vapor source concentrations for vapor intrusion assessment. For this purpose, wells (or multi-level samplers) that are screened across the water table interface are preferred and EPA recommends samples be collected as close as possible to the top of the water table using approved sampling methods designed to minimize loss of volatiles while sampling (EPA 2002a, EPA-ERT 2001a).[115] Ideally, the plume can be shown as stable or shrinking (i.e., is not migrating or rising in concentration, including hazardous byproducts of any biodegradation), through multiple rounds of sampling, so that vapor source concentrations can be confidently evaluated under reasonably expected future, as well as current, conditions. Otherwise, the inclusion zone for vapor intrusion (see Section 6.2.1) may expand over time and/or current sample concentrations in or beneath a given building may under-estimate the reasonable maximum vapor intrusion condition in the future.

For purposes of assessing vapor intrusion for specific buildings, groundwater samples from wells nearer to buildings are generally recommended over those from more distant wells. Interpolation of the results obtained from two or more wells in the uppermost portion of the aquifer may be warranted for these purposes when the spatial pattern suggests significant lateral gradients in contaminant concentrations within the area of interest. However, for purposes of determining whether contaminated groundwater poses acceptable human health risk from vapor intrusion on an area-wide basis, it may be more appropriate to utilize sampling results for the most greatly impacted well within the area of interest.

In addition, EPA generally recommends that a soil gas sample be collected immediately above the groundwater table (and above the capillary fringe) (i.e., "near-source" soil gas sample)[116] to help characterize the subsurface vapor source. The results of such "near

[113] Although a soil gas survey can also be employed as a screening tool to assist with the delineation of a plume of contaminated groundwater, EPA recommends that plume delineation ultimately be supported by the collection and analysis of confirmatory groundwater samples at appropriate locations.

[114] EPA recommends that, to the extent practical, groundwater samples be collected over a narrow interval (e.g., a few feet or less) just below the water table when the data are to be used for assessing the potential for vapor intrusion. Of course, the broader objectives of a site characterization will generally necessitate installation and sampling of additional wells, from other depth intervals, to accurately characterize the full nature and extent of groundwater contamination. Such wells and the broader topic of site characterization are not discussed in this Technical Guide, which is focused instead on recommended guidelines that are pertinent specifically to vapor intrusion.

[115] If available groundwater data do not meet these criteria, the site data review team may consider whether they are nevertheless representative of potential vapor source concentrations emanating from groundwater.

[116] In this context and for purposes of this Technical Guide, "near" means "within a practically short distance." Site- and location-specific circumstances and project-specific objectives typically will influence the quantitative definition of "near" for purposes of collecting "near-source" soil gas samples.

source" soil gas samples can be compared to calculations of the vapor concentration expected when the soil gas is in equilibrium with the concentrations measured in shallow groundwater (see Appendix C). A favorable comparison (i.e., the two concentrations are equivalent for each vapor-forming chemical in groundwater) would help to support the results of the groundwater characterization. On the other hand, a "fresh water lens" (or other site-specific conditions; see, for example, Section 6.3.2) could account for measured soil gas concentration(s) being significantly lower than the calculated equilibrium concentration(s).

Because fluctuations in water table elevation can lead to elevated vapor concentrations in the vadose zone, EPA also recommends that "near source" soil gas sampling (and possibly a soil gas survey) be considered in different seasons that coincide with groundwater fluctuations.

Vadose Zone Sources:

Where contaminated soil or non-aqueous-phase liquid (NAPL) in the vadose zone is a subsurface vapor source, soil sampling using coring techniques for sample retrieval or using sensors, such as a membrane interface probe, can be used to characterize the chemical composition and general location of contamination; that is, bulk soil concentration data can be used in a qualitative sense for this purpose. For example, high soil concentrations generally would indicate impacted soil. Unfortunately, the converse is not always true. Non-detect results for soil samples cannot be interpreted to indicate the absence of a subsurface vapor source, because of the potential for vapor loss due to volatilization during soil sampling, preservation, and chemical analysis.

Alternatively or in addition, a soil gas survey can be used to locate the primary source zone and delineate the areal and vertical extent of the vapor-affected area. Generally, EPA recommends that the soil gas survey include a soil gas sample collected immediately above each contaminant source in the vadose zone (i.e., "near-source" soil gas samples) to help characterize the vapor source.

Although a soil gas survey can generally be used to characterize many other subsurface vapor sources (e.g., sewer and drain lines; landfills and other land-based disposal units; impoundments and other land-based storage and/or treatment units, pressurized tanks and pipelines), additional approaches tailored to the specific source type may also warrant consideration.

These sampling options are generally coupled with an understanding of the site-specific subsurface conditions that control the location and extent of contamination (e.g., geologic properties, including stratigraphy and level of heterogeneity; hydrogeologic conditions; sewers, drains, and other conduits that lie underneath or intersect areas of groundwater and soil contamination). Such understanding is generally developed by interpreting the data obtained through borehole logging (i.e., visually inspecting soil cores and determining soil texture) or geophysical tools.

EPA generally recommends sample locations be of sufficient density to adequately account for spatial variability and heterogeneity in subsurface conditions. EPA generally recommends consulting with individuals who have expertise in characterizing subsurface environmental conditions (e.g., a geologist) when determining appropriate sampling locations and spacing.

When combined with the data demonstrating that the property reflects the conditions and assumptions of the generic model invoked in the VISLs (see Section 6.5.2), groundwater and "near-source" soil gas samples can be compared to medium-specific screening levels to develop an initial quantitative perspective about the potential level of exposure and human health risk posed by vapor intrusion. Section 6.5 provides additional information about risk-based screening of vapor source concentrations.

6.3.2 Characterize Vapor Migration in the Vadose Zone

As described in Section 2, geologic, hydrologic, biochemical factors in the vadose zone, as well as elapsed time since the environmental release, can influence vapor migration and attenuation in soil gas concentrations between subsurface vapor sources and nearby building(s).[117] As noted in Section 5.4, EPA recommends the CSM portray the current understanding of these vadose zone conditions in and around the subsurface vapor source(s) and nearby building(s). Furthermore, EPA recommends the CSM identify known or suspected preferential migration routes that could facilitate vapor migration to greater distances and at higher concentrations than otherwise expected. When these conditions are not well established from existing information, EPA recommends that a detailed investigation be scoped to address these data gaps.

When combined with other data, as discussed further in Section 7.3, information about subsurface vapor migration can support determinations that the vapor intrusion pathway is complete under current conditions or may be complete under future conditions. In some cases, vadose zone conditions may impose sufficient resistance to vapor migration to make the vapor intrusion pathway insignificant. In these circumstances, information about subsurface vapor migration, combined with other lines of evidence, can support determinations that the vapor intrusion pathway is incomplete under current conditions, as discussed further in Section 7.3.

Investigations seeking to characterize vapor migration in the vadose zone generally entail, at a minimum, a soil gas survey. Because soil gas concentrations can exhibit considerable spatial variability, due to a variety of factors,[118] EPA generally recommends that soil gas surveys collect soil gas samples at multiple locations and depth intervals between the vapor source and building(s) (potential "receptors"). As a result, the soil gas survey may include samples collected immediately outside the building ("exterior soil gas") at various depths or several depth intervals,

[117] The horizontal and vertical distance over which vapors may migrate in the subsurface depends on the source concentration, source depth, soil matrix properties (e.g., porosity and moisture content), and time since the release occurred. For example, months or years of volatilization and vapor migration may be required to fully develop vapor distributions in the vadose zone at sites with deep vapor sources or with impedances to vapor migration arising from hydrologic or geologic conditions (Section 2.5; EPA 2012b). Under such circumstances, soil gas surveys conducted soon after an environmental release may not yield data indicating the maximum extent of vapor migration.

[118] Modeling of idealized scenarios provides additional demonstrations about spatial variability of soil gas concentrations. For example, vertical profiles of soil gas concentration(s) can be very different underneath buildings compared to locations exterior to the building and soil gas concentrations may not be uniform laterally, particularly in the vicinity of the building, even when the vapor source is a laterally extensive plume of contaminated groundwater (EPA 2012b). These simulation results indicate why EPA recommends that soil gas generally be sampled in multiple sampling locations, when assessing subsurface vapor migration routes.

as well as immediately beneath it (e.g., sub-slab soil gas sampling).[119] If any shallow soil gas samples are collected, EPA recommends they be collected as close as possible to the building and at depths below the respective building foundation and no less than five feet below ground surface, depending on site-specific conditions. Where crawl spaces are present, crawl space air sampling may also be conducted.

Generally, EPA recommends that the soil gas survey include a "near-source" soil gas sample collected immediately above each source of contamination to help characterize the subsurface vapor source (see Section 6.3.1). The results of such "near source" soil gas samples can be compared to calculations of the vapor concentration expected when the soil gas is in equilibrium with the concentrations measured in shallow groundwater (see Appendix C), when the subsurface vapor source is in the groundwater. Geologic, hydrologic, or biologic impedances to vapor migration may be indicated if the measured "near source" soil gas concentrations are significantly lower than the calculated equilibrium concentrations.

To characterize subsurface migration in the vadose zone, soil gas survey data are generally coupled with an understanding of the site-specific subsurface conditions that influence vapor migration and attenuation (e.g., geologic properties, including stratigraphy and level of heterogeneity; hydrologic conditions, including groundwater elevation and soil moisture;[120] and biological properties, including availability of oxygen to support aerobic biodegradation).[121] Such geologic understanding is generally developed by interpreting the data obtained through borehole logging and geophysical tools. Soil permeability to air flow can be measured in the field (McHugh et al. 2013) and would be used to corroborate inferences based upon borehole logging data. Hydrologic conditions can be characterized by analyzing soil samples for porosity and moisture content and by hydrologic modeling. For potentially biodegradable contaminants, an intensive soil gas survey to establish current vertical profiles for contaminant vapors and oxygen (and, in some cases, biodegradation products, such as carbon dioxide or methane)[122] may be able to demonstrate that biodegradation is responsible for attenuating vapor migration

[119] EPA recommends that spacing of soil gas sampling locations generally consider the extent and location of the subsurface vapor source, distance between the building and the source, and other site-specific factors.

[120] Tillman and Weaver (2007) conducted hydrologic modeling and collected field data, which showed that moisture content determined from soil cores taken external to a building may over-estimate soil moisture underneath the building. They inferred that vapor intrusion assessments based upon moisture content in soil from open areas between buildings may under-estimate vapor intrusion potential.

[121] As noted in Section 2, vapor migration in the vadose zone can be impeded by several factors, including soil moisture, low-permeability (generally fine-grained) soils, and biodegradation. Significant characterization of the vadose zone may be needed to demonstrate that such geologic, hydrologic, and biologic features are laterally extensive over distances that are large compared to the footprint of the building and the extent of the subsurface vapor source at a specific site.

[122] Interpretation of profiles for carbon dioxide and methane can be challenging, due to the presence of natural sources unrelated to contaminant biodegradation (Holden and Fierer 2005).

to a greater extent than can be attributed to advection and diffusion in the vadose zone.[123, 124] For both purposes, samples collected directly underneath the building will tend to be more representative of conditions influencing vapor intrusion potential than samples collected outside the building footprint, all else being equal.

When conducted contemporaneously for multiple buildings, a soil gas survey and characterization of the vadose zone can help identify distances from subsurface vapor sources beyond which threats from vapor intrusion are not reasonably expected, as mentioned in Section 6.2.1. At sites with a limited number of potentially affected buildings, it may be feasible to characterize the subsurface vapor migration near and surrounding all of them. However, at sites where a large number of buildings may be affected, this approach is not likely to be feasible; in these cases, EPA generally recommends that the site manager seek the advice of an individual familiar with the site-specific subsurface conditions (typically a geologist) to help guide selection of appropriate sampling locations and assess whether "representative" or "reasonable worst case" locations can be identified, as appropriate to the objectives of the investigation. Because there usually is substantial spatial variability in the concentrations of subsurface vapors, caused partially by heterogeneities in the subsurface materials, it may be difficult to identify *a priori* locations that are either "representative" or are "reasonable worst case" subsurface conditions.

Subsurface investigations of vapor intrusion also generally warrant an evaluation of utility corridors, which can facilitate unattenuated vapor transport over longer-than-anticipated distances and/or vapor migration towards and into buildings that are serviced by the utility. EPA also recommends subsurface investigations of vapor intrusion consider whether sewers and other man-made conduits have the potential to transport NAPLs, contaminated groundwater, and/or vapors (through soil) towards and/or directly into buildings. Public and facility records may be useful sources of information about utility and sewer locations, which may provide maps, "as built diagrams," or construction specifications. Depending upon the CSM, sampling of vapors within the utility corridor (or within a sewer, if present) may be warranted to characterize vapor migration in the subsurface (or characterize a secondary source of vapors – see Sections 6.3.1 and Section 2.1).

Reasonably expected future risks posed by the subsurface vapor source(s) warrant consideration, in addition to risks posed under current conditions, "in order to demonstrate that a site does not present an unacceptable risk to human health and the environment" (EPA 1991a). For example, when evaluating subsurface vapor migration and attenuation in locations where buildings do not exist, it is important to recognize that the conditions in the vadose zone and soil

[123] At sites where aerobic biodegradation is limiting the upward migration of petroleum hydrocarbon vapors, for example, the vertical concentration profile will typically show higher concentrations of petroleum hydrocarbons and lower (or non-detect) concentrations of oxygen in deeper soil gas samples. At these same sites, the vertical concentration profile will typically show lower (or non-detect) concentrations of petroleum hydrocarbons and higher concentrations of oxygen in shallower soil gas samples. Because weather events can affect rates of oxygen replenishment in the vadose zone (Lundegard et al. 2008), multiple rounds of such sampling are recommended to demonstrate that biodegradation consistently poses a significant impedance to upward vapor migration. This recommendation is particularly apt where the subsurface vapor source is strong (e.g., unweathered NAPL in the vadose zone) relative to time-variable processes supplying oxygen to the vadose zone.

[124] In this context, mathematical modeling (see Section 6.6) can be employed to characterize vapor migration attributable to advection and diffusion in the vadose zone.

gas concentrations may be changed as a result of constructing a new building and/or supporting infrastructure. The moisture content may decrease and the moisture profile change in the vadose zone as a result of reduced infiltration of rainwater below a building footprint (Tilman and Weaver 2007). The permeability to vapor flow in the vadose zone may be altered in the foundation vicinity due to construction. Finally, the future presence of extensive surface covers and/or utility corridors may also modify the vertical and horizontal profile of soil gas concentrations in the subsurface (EPA 2012b). As a result, EPA recommends that appropriate lines of evidence in addition to a soil gas survey (e.g., mathematical modeling, where parameters are chosen to represent conditions that give a high-impact case – Section 6.6) be developed and considered to support any determination that a future building will not be subject to vapor intrusion or will not pose unacceptable human health risk for occupants. Owing to the potentially unpredictable plans for building construction and site redevelopment, as well as potentially unpredictable changes in the transitory soil characteristics (e.g., soil moisture) and soil gas concentrations, institutional controls may be warranted (e.g., to inform the need for a confirmatory evaluation of the vapor intrusion pathway) when new buildings are constructed in areas where the subsurface vapor source(s) has(have) significant potential to pose a vapor intrusion threat.

6.3.3 Assess Building Susceptibility to Soil Gas Entry

When elevated concentrations of vapor-forming chemicals accumulate in the soil gas immediately underneath the foundation, surrounding the basement, or within the crawl space of a vulnerable building, then soil gas entry (i.e., vapor intrusion) can lead to unacceptable levels of subsurface contaminants in indoor air, depending upon building- and site-specific circumstances. As discussed in Section 2.3, soil gas can enter a building when openings are present and driving ‘forces’ exist to draw the vapors from the subsurface through the openings into the indoor environment.

Single-family detached homes can generally be presumed to have openings for soil gas entry; as such, they will generally be susceptible to soil gas entry unless a mitigation system (e.g., radon mitigation system) is present and operating as intended. Some buildings are more susceptible to soil gas entry than others. For example, buildings with significant openings, such as:

- buildings with deteriorating basements or dirt floors, which generally provide poor barriers to vapor (soil gas) entry; and
- buildings with sumps (or other openings to the subsurface) that can facilitate transport of vapors via soil gas entry.

EPA recommends that appropriate lines of evidence be employed to assess susceptibility to soil gas entry, when this objective is selected as part of a site-specific investigation plan for vapor intrusion assessment. Vulnerability to soil gas entry can be assessed for a specific building by using any of several methods, including:

- Concurrently monitoring indoor air samples for presence of radon and finding radon in indoor air at levels greater than in ambient air.[125]

- Concurrently monitoring indoor air and ambient air (see Section 6.3.5) and finding cis-1,2-dichloroethylene, vinyl chloride, 1,1-dichloroethylene, or 1,1-dichloroethane in indoor air at levels greater than in ambient air, when and where they are present in the subsurface vapor source(s), but are not used indoors.[126]

- Employing a photoionization detector (PID) or other real-time in-field device, capable of detecting parts per billion by volume (ppbv) levels, to directly survey suspected locations of soil gas entry (e.g., utility penetrations, sumps) and finding elevated readings of vapors.

- Conducting a visual inspection for cracks and holes in concrete foundation slabs, basement walls, or any floor drain(s). (Openings for soil gas entry will not necessarily be visible or accessible for inspection, so the absence of visible openings, by itself, is insufficient to demonstrate that a building is not susceptible to soil gas entry.)

- Monitoring pressure differences between the building and subsurface environment to characterize the 'driving force' for soil gas entry and the effects of the heating, ventilation, and air-conditioning (HVAC) systems.

- Injecting tracers into the subsurface at selected concentrations and subsequently finding it in indoor air samples.

Certain complementary information obtained for the building, as identified in Section 6.4.1, can also support such assessments. Relevant information includes the operating characteristics of HVAC systems.

In many commercial buildings, the HVAC system brings outdoor air into the building, potentially creating building over-pressurization relative to the outdoor environment. When the building is

[125] Because vapor intrusion and radon intrusion entail similar mechanisms for subsurface vapor migration and gas entry into buildings and structures (Section 2.3), naturally occurring radon may serve as a tracer to help identify those buildings that are more susceptible to soil gas entry than others. Buildings with radon concentrations greater than levels in ambient air are likely susceptible to soil gas intrusion and would likely be susceptible to intrusion of any chemical vapors in the subsurface. On the other hand, the radon concentration in a building is not generally expected to be a good quantitative indicator of indoor air exposure concentrations of vapor-forming chemicals arising from sub-surface contamination. Hence, radon measurement is not generally recommended as a proxy for directly measuring vapor-forming chemicals in indoor air. Among other factors, the distribution of radon-emanating rock and soil and the spatial and temporal variability of their source strength are generally expected to be very different (e.g., tending to be broader and more uniform) than the distribution and source strength variability for subsurface sources of chemical vapors.

[126] EPA (2011a) reports that "vinyl chloride, 1,1-dichoroethylene, cis-1,2-dichloroethylene, and 1,1-dichloroethane are rarely detected in background indoor air." DoN (2011a) also reports that vinyl chloride and cis-1,2-dichloroethylene "are rarely detected in background indoor air." When they are subsurface contaminants, volatile chemicals that are rarely or never present in indoor sources can be inferred to arise in indoor air via vapor intrusion "without further explanation" (DoN 2011a). Brenner (2010), for example, employed this principle (and cis-1,2-dichloroethylene) to identify buildings susceptible to vapor intrusion and to diagnose the relative contributions of vapor intrusion and infiltration to indoor air concentrations.

over-pressurized sufficiently to eliminate the driving force for soil gas entry over at least a portion of the building foundation, vapor intrusion potential is diminished.[127]

Reasonably expected future risks posed by subsurface contamination warrant consideration, in addition to risks posed under current conditions, "in order to demonstrate that a site does not present an unacceptable risk to human health and the environment" (EPA 1991a). For example, current building use and HVAC systems might not be sustained perpetually. Therefore, when the subsurface vapor source(s) underneath or near a building with an over-pressurizing HVAC system has(have) significant potential to pose a vapor intrusion threat, it may be useful to assess susceptibility to soil gas entry and diagnose vapor intrusion (also see Sections 6.3.4 and 6.4.1) in such buildings under conditions when the HVAC system is not operating. (In addition, indoor air testing could be conducted during periods when the HVAC system operates with diminished flows, such as weekends or evenings.) The results of such testing can be used to support determinations about whether the vapor intrusion pathway is "potentially complete" and is reasonably expected to pose unacceptable human health risk (see Section 7.4) in the future,[128] in which case a response action(s) may be warranted (see Section 7.7). For example, if the results indicate susceptibility to soil gas entry when the HVAC system is not in operation and vapor intrusion under these conditions has the potential to pose a health concern, then the building may warrant future monitoring (e.g., continuous monitoring of the pressure gradient across the foundation or indoor air testing) and/or engineered exposure controls, which may be enforceable through an institutional control (IC) (see Section 8.6).

Likewise, well-designed and operated radon mitigation systems generally should diminish vapor intrusion via soil gas entry under current conditions. Therefore, buildings with pre-existing radon mitigation systems, which overlie or are near subsurface vapor sources, could be tested under conditions where the radon mitigation system is temporarily not operated to support decisions about monitoring and ICs as part of a vapor intrusion remedy.[129]

6.3.4 Evaluate Presence and Concentration of Subsurface Contaminants in Indoor Air

Indoor air sampling (see Section 6.4.1) using time-integrated sampling methods or grab samples can confirm the presence, if any, of a site-related vapor-forming chemical (i.e., one comprising the subsurface vapor source(s)) in the indoor environment. When combined with data characterizing subsurface vapor migration and demonstrating the building is (or is not) susceptible to soil gas entry, indoor air sampling data can support determinations that the vapor intrusion pathway is (or is not) complete for a given building, as discussed further in Section 7.3. When conducted contemporaneously in multiple buildings, indoor air sampling can, in concert with soil gas survey data and data delineating subsurface vapor sources, help identify the boundaries of the land area(s) within which buildings are known or suspected to have indoor air concentrations of subsurface contaminants arising from vapor intrusion (also see Section 6.2.1).

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[127] Over-pressurization may not be uniform throughout a building, particularly in large buildings. Over-pressurization in portions of a building will not necessarily mitigate all openings for soil gas entry.

[128] "Both current and reasonably likely future risks need to be considered in order to demonstrate that a site does not present an unacceptable risk to human health and the environment." (EPA 1991a).

[129] EPA recommends that state and local laws be researched before any such testing is conducted. Some areas have local ordinances governing operation and maintenance of radon mitigation systems.

Indoor air sampling is most commonly conducted using time-integrated sampling methods, when characterizing exposure concentrations for building occupants (see Section 6.4.1), which may include contributions from "indoor" or ambient air sources of these chemicals (see Section 2.7). For example, time-integrated concentrations of hazardous vapors in samples of indoor air can be compared to appropriate, risk-based screening criteria (see Section 6.5) to obtain some preliminary insights about the potential level of exposure and risk posed by vapor intrusion or can be used to support a human health risk assessment (Section 7.4) about vapor-forming chemicals found in the subsurface environment.[130]

When sampling indoor air (or sub-slab soil gas) to characterize exposure concentrations arising from vapor intrusion, EPA recommends removing potential indoor sources of vapor-forming chemicals (see Section 2.7 and 6.4.1) from the building to strive to ensure that the concentrations measured in the indoor air samples are attributable to the vapor intrusion pathway. However, even after removing indoor sources, their effects may linger depending on source strength, relative humidity in the building, the extent to which the contaminants have been absorbed by carpets and other fabrics or "sinks," and air exchange rate. In addition, field experience suggests that it may not be possible to remove all indoor sources. It may be particularly impractical to do so in industrial settings where vapor-forming materials are used or stored.

6.3.5 Identify and Evaluate Contributions from Indoor and Ambient Air Sources

As noted in Section 2.7 herein, indoor air is likely to contain detectable levels of a number of vapor-forming chemicals regardless of whether the building overlies a subsurface vapor source, because indoor air can be impacted by a variety of indoor and outdoor vapor sources unrelated to site contamination. The contribution of indoor and outdoor vapor sources (or both) to indoor air concentrations is referred to as "background" throughout this Technical Guide, when they do not arise from site-related contamination (see Glossary). Information on 'background' contributions of site-related, vapor-forming chemicals in indoor air is important to risk managers because generally EPA does not clean up to concentrations below natural or anthropogenic background levels (EPA 2002e).

To determine if a subsurface vapor source(s) is (or are) responsible for indoor air contamination, EPA recommends that such background sources of site-specific analytes be identified and distinguished from vapor-forming chemicals arising from vapor intrusion. A comprehensive investigation of all background substances found in the environment is usually not recommended. For example, sub-slab soil gas and ambient air samples typically would not be analyzed for radon for purposes of characterizing 'background' exposures *per se*, whereas EPA would recommend analyzing for radon if its precursor was part of a regulated release to the subsurface environment (EPA 2002e).[131] Generally, EPA recommends the site planning and

[130] In certain cases, depending in part on the results (e.g., concentrations exceed risk-based screening levels), indoor air sampling data may be a sufficient basis for supporting decisions to undertake pre-emptive mitigation/early action (see Sections 3.3 and 7.8) in lieu of additional rounds of sampling and analysis or an evaluation of the contribution of background sources to indoor air concentrations.

[131] Sub-slab soil gas and indoor air samples might also be analyzed for radon, where its precursor was not part of a release to the subsurface environment, for purposes of diagnosing vulnerability to soil gas entry (see, for example, Section 6.3.3), depending upon the objectives of the vapor intrusion investigation.

data evaluation team limit chemical analyses to those vapor-forming chemicals known (based upon subsurface contaminant characterization) or reasonably expected (based upon site history) to be present as a result of a release to the subsurface environment.

To support evaluations of sources of indoor air concentrations, EPA recommends conducting a building survey (see Section 6.4.1) that identifies in individual buildings known or suspected indoor sources of the vapor-forming chemicals also found in the subsurface (see Section 2.7) and characterizing ambient air quality (see Section 6.4.2) in the site vicinity for these same chemicals. Key supporting information includes: (1) the locations and types of known or potential indoor vapor sources; (2) information about outdoor vapor sources related to the site (e.g., locations of chemical storage, use, and/or release to the environment); (3) information about outdoor vapor sources un-related to the site, such as nearby commercial or industrial facilities and mobile sources (e.g., cars, trucks, and other equipment); and (4) data on the local ambient air quality.

Interviews of building occupants and inspections of buildings can be helpful initial sources of information about indoor uses and storage of vapor-forming consumer and commercial products.[132] In addition, vapor-detecting field instruments and in-field gas chromatographs[133] can be used to locate indoor vapor sources. Grab (essentially short-duration) samples of indoor air, as described in Section 6.4.1, can be useful for identifying specific vapor-forming chemicals emanating from indoor vapor sources of consumer or commercial products. When the objective is to quantitatively distinguish contributions to indoor air concentrations from vapor intrusion versus contributions from indoor and ambient air sources, as described below, EPA recommends obtaining indoor air concentrations using time-integrated sampling methods (see Section 6.4.1) instead of grab samples.

If the subsurface vapor source(s) is (or are) comprised of multiple vapor-forming chemicals and the subsurface source medium (e.g., soil, groundwater) and location are identical for these chemicals, then contemporaneous samples of sub-slab soil gas (see Section 6.4.3) and indoor air (see Section 6.4.1) can be compared, potentially supporting one of the following conclusions:

> Results indicating vapor intrusion as solely responsible for vapor concentrations in indoor air. The predominant vapor-forming chemicals in the sub-slab soil gas and their relative proportions in indoor air and sub-slab vapor samples would be expected to be similar, whereas their concentrations in sub-slab soil gas would be expected to be substantially higher than in indoor air,[134] if vapor intrusion is solely responsible for indoor air

[132] Information about the chemical composition of commonly encountered products is provided by the U.S. Navy (DoN 2011a, Appendix A) in its guidance for background analysis for the vapor intrusion pathway.

[133] Gorder and Dettenmaier (2011) reported on the use of a field-portable gas chromatograph and mass spectrometer to identify specific sources of vapor-forming chemicals and estimate their mass emission rate(s). EPA's Environmental Response Team has employed the Trace Atmospheric Gas Analyzer (TAGA) mobile laboratory for similar purposes.

[134] Based upon the generic sub-slab attenuation factor identified in Section 6.5.3 herein, sub-slab soil gas concentrations can be expected to typically exceed indoor air concentrations by 33 times or more in residences that are impacted by vapor intrusion (i.e., 33 is the inverse of an attenuation factor of 0.03), when background sources are negligible and the building is under-pressurized relative to the subsurface during indoor air sampling.

concentrations.[135] If recalcitrant (i.e., not subject to biodegradation in the vadose zone), the predominant vapor-forming chemicals and their relative proportions in the subsurface vapor source would likewise tend to be similar to those in indoor air if vapor intrusion is solely responsible for indoor air concentrations.[136]

Results indicating indoor vapor sources as primarily responsible for indoor air concentrations. If a vapor-forming chemical is present with an elevated concentration in indoor air, but is not present or is negligibly present in sub-slab soil gas samples (or representative samples of the subsurface vapor source), then the presence of this contaminant in indoor air may not arise from the vapor intrusion pathway, but rather from indoor sources or other background sources (e.g., ambient air). In these circumstances, EPA recommends considering additional attempts to identify and temporarily eliminate indoor sources, where practical, and re-sample indoor air and sub-slab soil gas after doing so.

Likewise, outdoor (ambient) air samples can be collected (see Section 6.4.2) contemporaneously with indoor air (see Section 6.4.1) and sub-slab soil gas (see Section 6.4.3) samples, as recommended in Section 6.4.

Results indicating outdoor vapor sources as primarily responsible for indoor air concentrations. If a vapor-forming chemical(s) is(are) detected in outdoor air and indoor air at similar concentrations, but is(are) not present in sub-slab soil gas samples (or representative samples of the subsurface vapor source) or is present in the subsurface samples at concentration(s) similar to indoor air),[137] then the presence of this contaminant(s) in indoor air may not arise from the vapor intrusion pathway, but rather from outdoor sources (i.e., ambient air).

Concentrations of vapor-forming chemicals in indoor air, sub-slab soil gas, and ambient air can be compared, as described above, using an individual time-integrated sample for each medium. Recognizing that weather conditions and building operations can lead to variable contributions from vapor intrusion and ambient air infiltration over time, EPA recommends, however, that such

[135] Conversely, if there is an interior source of a vapor-forming chemical in indoor air samples, the relative proportion of this chemical in indoor air will be greater than its respective proportion in the sub-slab soil gas, even where vapor intrusion is occurring, assuming that the other vapor-forming chemicals in the sub-slab soil gas do not have 'background' sources.

[136] Conversely, if there is an interior source of a vapor-forming chemical in indoor air samples, the relative proportion of this chemical in indoor air will be greater than its respective proportion in the subsurface vapor source or in "near-source" soil gas samples (see Section 6.3.1), even where vapor intrusion is occurring, assuming that the other vapor-forming chemicals in the sub-surface do not have 'background' sources.

[137] Sample concentrations of vapor-forming chemicals in indoor air and sub-slab soil gas can be compared to conservative, risk-based screening levels to provide a complementary line of evidence. Generally, vapor-forming chemicals with concentrations that consistently fall below screening levels (see Section 6.5) through multiple sampling events (see Section 6.4) warrant no further action or study, so long as the exposure assumptions match those taken into account by the calculations and the site fulfills the conditions and assumptions of the generic conceptual model underlying the screening levels (see Section 6.5.2).

comparisons be made for multiple sets of paired samples, collected in different seasons,[138] to support any conclusion that vapor intrusion is not a significant contributor to indoor air concentrations, which can instead be attributed to indoor and outdoor sources unrelated to the subject site. Even with a few sets of such samples, rigorous statistical tests may not be feasible. Nevertheless, comparing contemporaneously measured concentrations and proportions of vapor-forming chemicals in indoor air, subsurface media, and ambient air can be effective for this investigation objective, particularly when one (or more) of the analytes is known to be present only in the subsurface or in ambient air.

The following hypothetical example illustrates how site-specific sampling data might inform conclusions about the relative contributions of indoor versus subsurface vapor sources in a building overlying contaminated groundwater:

Example: Time-integrated samples of indoor air, outdoor air, and subslab soil gas were collected contemporaneously for a building that overlies shallow groundwater that is contaminated with a suite of vapor-forming chemicals (designated as VFCA, VFCB, VFCC, and VFCD). The sampling results are summarized as follows:

Vapor-forming Chemical in Groundwater	Time-weighted Sample Concentrations ($\mu g/m^3$)			Ratio of Subslab Concentration to Indoor Air Concentration
	Subslab Soil Gas	Indoor Air	Outdoor Air	
VFCA	*1*	*0.65*	*0.75*	*3*
VFCB	*33,000*	*26*	*0.18*	*1,300*
VFCC	*5,200*	*5.8*	*0.14*	*900*
VFCD	*15,000*	*15*	*0.51*	*1,000*

Based upon the conceptual site model, the presence of these vapor-forming chemicals in outdoor (ambient) air is believed to be due to anthropogenic sources that are not associated with the environmental release responsible for the subsurface contamination. The building is presumed to be susceptible to vapor intrusion, as indicated by pressure monitoring data that indicate building under-pressurization, relative to the subsurface environment, during the sampling event (as discussed further in Section 6.4.1).

Based upon these findings, the presence of VFCB, VFCC, and VFCD in indoor air appears to be solely or primarily attributable to vapor intrusion. The relative proportions

[138] A goal of collecting multiple samples is to observe and characterize a reasonable maximum vapor intrusion condition for the respective building. Because weather conditions and building operations can lead to time-variable contributions from vapor intrusion (e.g., driving forces for vapor intrusion; see Section 2.3) and ambient air infiltration (see Sections 2.4), indoor air concentrations of vapor-forming chemicals can be expected to vary over time. An individual sample, collected at a randomly chosen time, may under-estimate or over-estimate average and reasonable maximum exposure conditions (see Section 6.4.1) to different degrees, depending upon the season of sample collection and other factors.

of these subsurface contaminants in indoor air and sub-slab vapor samples are similar, as indicated by a similar ratio of subslab to indoor air concentration, considering analytical uncertainty. In addition, their indoor air concentrations exceed those found in the paired sample of ambient air.

By contrast, the presence of VFCA in indoor air may be entirely attributable to infiltration of ambient air, as the sample concentrations in indoor air and outdoor are similar, considering analytical uncertainty.

Recommended next steps in the investigation might include a human health risk assessment (see Section 7.4) and a review of the conceptual site model (see Section 5.4) to evaluate whether the different conclusion for VFCA can be reasonably explained (e.g., by vapor attenuation in the vadose zone that is expected to be substantially greater than for VFCB, VFCC, and VFCD).

EPA has compiled and published an evaluation of studies pertaining to indoor air concentrations of volatile organic compounds in North American residences in 1990-2005 (EPA 2011a), which can be employed to identify whether measured indoor air concentrations in residences exceed the historical range of background concentrations. Specifically, if measured indoor air concentrations are found to greatly exceed the historical range of background levels, there is a greater likelihood that the indoor air concentrations are the result of vapor intrusion. This conclusion is supported by the expectation that current levels of vapor-forming chemicals in ambient air and in indoor air due to indoor and ambient air sources are likely to be lower than those observed historically,[139] due to regulations and business practices fostering less use of toxic chemicals in consumer products and industrial processes and reduced emissions from mobile and stationary sources. As a result of this expectation, EPA does not recommend the use of generic values of historical background concentrations, even those cited in peer-reviewed publications or available from databases maintained by regulatory agencies, to characterize current levels in any building, for purposes of supporting conclusions that indoor air concentrations are due to 'background' sources. Rather, EPA recommends that site-specific data (e.g., sub-slab, indoor air and ambient air sampling data) be obtained (as described in Sections 6.4.1, 6.4.2, and 6.4.3), and evaluated, as described above, when the investigation objectives include determining whether indoor air concentrations arise from indoor or ambient air sources.

The following additional approaches for identifying and characterizing 'background' sources may warrant consideration in special situations:

- McHugh et al. (2012) have demonstrated the principle that building over-pressurization can be employed temporarily to minimize vapor intrusion and facilitate measuring indoor

[139] McCarthy et al. (2007), for example, analyzed ambient air data for 25 toxic substances collected in the United States from 1990 through 2005 and found that concentrations of many halogenated volatile organic compounds were declining at most sites and evaluation periods (i.e., 1990-2005, 1995-2005, and 2000-2005). They found that concentrations of petroleum hydrocarbons, such as benzene, associated with mobile sources were all consistently decreasing over the three evaluation periods at most sites.

air concentrations under conditions where only indoor sources may be contributing.[140] At this time, however, there are no standard practices for using over-pressurization to assess 'background' contributions, which is a research and development need (SERDP-ESTCP 2014).

- Forensic and multi-variate statistical methods have been described and illustrated by the U.S. Navy (DoN 2011a) in its guidance for background analysis for the vapor intrusion pathway.

6.3.6 Select, Prioritize, and Sequence Investigation Objectives

Site-specific investigations of potential vapor intrusion frequently begin with pursuing one or more of the objectives presented in Sections 6.3.1 through 6.3.5. Criteria potentially warranting consideration by the site planning team when making decisions about prioritizing and sequencing investigation objectives include, but are not limited to: site scenario (see Section 6.1); building occupants who may be particularly sensitive to the potentially toxic effects of vapors; buildings that are more susceptible to soil gas entry (e.g., buildings with deteriorating basements or dirt floors; whether there are any significant data gaps in the CSM (see Section 5.4); and relationships with and perspectives of the owners and occupants of potentially impacted buildings.

Characterizing subsurface vapor sources (Section 6.3.1), characterizing subsurface vapor migration (Section 6.3.2), and evaluating the presence of subsurface contaminants in indoor air (Section 6.3.4) – are frequently candidates for an initial objective and each can be pursued separately. For example, characterizing subsurface vapor sources (Section 6.3.1) may be a useful initial choice when responding to an initial report about a release of hazardous, vapor-forming chemicals to the subsurface from a commercial or industrial operation or when buildings do not exist currently, but are expected in the future. Characterizing subsurface vapor sources may also be a useful initial choice when building owners or occupants are reluctant to grant access for indoor air testing. In this situation, the site planning team may need to pursue subsurface investigations more intensely to characterize vapor intrusion potential before being granted building access. On the other hand, testing indoor air is recommended as an initial objective when responding to reports of odors in buildings or clusters of inhalation-related symptoms and there is credible information to suggest that a subsurface environmental release may be a contributing factor (see Section 5.2).

In a different scenario, characterizing subsurface vapor migration (Section 6.3.2) may be a useful starting point when addressing sources that are comprised of potentially biodegradable chemicals or that are suspected to occur below an extensive geologic layer that might impede upward diffusive migration. For large buildings with HVAC systems that may over-pressurize the interior relative to the subsurface environment, EPA generally recommends: a building assessment early in the investigation, which obtains and weighs the complementary information

[140] Indoor air concentrations measured after sufficient periods of over-pressurization may be indicative of 'background' levels, whereas indoor air concentrations detected before and after a sufficient period of "rebound" from temporary over-pressurization may be indicative of joint contributions from 'background' sources and any vapor intrusion from the subsurface.

identified in Section 6.4.1, to support investigation planning; and an evaluation of susceptibility to soil gas entry under conditions when the HVAC system is not operating (see Section 6.3.3).

Each of the investigation objectives described in Sections 6.3.1 through 6.3.5 may, in some cases, be conducted iteratively with increasing complexity as the investigation proceeds and the CSM is refined. For example, field instruments can be useful for locating potential background sources (e.g., household or commercial cleaning products) (see Section 6.3.5) and grab (essentially short-duration) samples of indoor air, as described in Section 6.4.1, can be useful for characterizing the chemical composition of identified indoor sources of vapors during an initial building reconnaissance while potential background sources are surveyed. These activities might be followed by indoor air and sub-slab soil gas sampling, using time-integrated sampling methods as described in Section 6.4.1 and 6.4.2, to distinguish subsurface contributions from indoor sources. More advanced methods of distinguishing the various potential contributions to indoor air might be utilized, if warranted, in intermediate phases of the investigation under such an iterative approach.

6.4 General Principles and Recommendations for Sampling

Sampling of indoor air, outdoor air, soil gas, and groundwater and analysis for vapor-forming chemicals can play an important role in vapor intrusion investigations for one or more of the objectives identified in Section 6.3. This subsection summarizes for indoor air, outdoor air, sub-slab soil gas, exterior soil gas, and groundwater the following:

- Principal methods for collecting samples.
- Potential uses of the resulting sampling data.
- Recommended practices for sample collection.
- Unique or frequently encountered logistical issues.

We would note that soil and NAPL sampling has been and may be used to characterize the nature (e.g., chemical composition) and general location of subsurface vapor sources (see Section 6.3.1). Information about soil sampling can be found in *Standard Operating Procedures, Soil Sampling* (EPA-ERT 2001b). However, bulk soil (as opposed to soil gas) sampling and analysis is not currently recommended for estimating the potential for vapor intrusion to pose unacceptable human health risk in indoor air, because of the potential for vapor loss due to volatilization during soil sampling, preservation, and chemical analysis. In addition, there are uncertainties associated with soil partitioning calculations.

To ensure that the sampling data will meet the site-specific data quality needs, EPA recommends that the sampling and analytical methods selected by the site planning team be capable of obtaining reliable analytical detections of concentrations less than project-appropriate, risk-based screening levels (e.g., VISLs). Towards that end, EPA recommends that, as part of establishing site-specific data quality objectives (DQOs), the planning and data collection team(s) consult with a laboratory skilled in the analysis of air and soil gas samples and choose sampling and analytical methods capable of routinely attaining the desired detection sensitivity for each medium.

EPA also recommends that the site planning team identify and utilize appropriate sampling locations and durations and address spatial and temporal variability to fulfill the specific objectives of the investigation, which may include obtaining data to characterize the potential human exposure in a building(s). EPA recommends the CSM, the objective(s) of the investigation, and other site-specific information be considered in determining the number and types of samples used at a specific site.

The sampling duration depends on the type of medium being sampled (for example, soil gas, sub-slab soil gas, and indoor or outdoor air) and analytical methods (for example, Method TO-15). Some of the key recommended considerations are provided in the following subsections. Several rounds of sampling are recommended to develop an understanding of temporal variability[141] to ensure that final risk management decisions are based upon a consideration of a reasonable maximum vapor intrusion condition.[142]

6.4.1 Indoor Air Sampling

Indoor air sampling results are used to assess the presence of and level of human health risk posed by vapor-forming chemicals in indoor air (see Sections 6.3.4 and 7.4), and to diagnose whether vapor intrusion is occurring (see Sections 6.3.3, 6.3.5, and 7.3). These two uses of indoor air sampling in vapor intrusion investigations are discussed further below with recommended methods for each. As discussed further in Sections 8.4 and 8.7, indoor air sampling may also be useful for supporting performance evaluations of vapor intrusion mitigation systems and verifying the health protectiveness of subsurface remediation systems.

EPA recommends that the decision to collect indoor air data be supported by lines of site- or building-specific evidence (e.g., characterization of subsurface vapor source(s) strength and proximity to building(s), vadose zone conditions, and building conditions) that demonstrate that vapor intrusion has the potential to pose a significant human exposure. Confidence in the assessment is expected to be higher when multiple lines of site- or building-specific evidence, in addition to indoor air data, come together to provide mutually supporting evidence for a common understanding of the site conditions/scenarios and the potential for vapor intrusion (i.e., the various lines of evidence are in agreement with each other).

A potential shortcoming of indoor air testing is that indoor sources and outdoor sources unrelated to subsurface contamination and to releases from the subject site – “background” (see Glossary) – may contribute to the presence of volatile chemicals in occupied buildings (see Section 2.7), particularly if these sources cannot be removed from the building prior to and throughout the duration of sampling indoors. This shortcoming of indoor air testing is

[141] Seasonally variable conditions (e.g., moisture levels, depth to groundwater) can lead to seasonally variable concentrations and distributions of vapors in the vadose zone. Likewise, weather conditions and building operations can lead to time-variable contributions from vapor intrusion (e.g., driving forces for vapor intrusion; see Section 2.3) and ambient air infiltration (see Sections 2.4). Collectively, these processes cause indoor air concentrations of vapor-forming chemicals to vary over time (see Section 2.6). An individual sample (or single round of sampling) would be insufficient to characterize seasonal variability, or variability at any other time scale.

[142] EPA recommends basing the decision about whether to undertake response action for vapor intrusion (i.e., a component of risk management; see Section 7.4) on a consideration of a reasonable maximum exposure (e.g., EPA 1989, 1991a), which is intended to be a semi-quantitative phrase, referring to the lower portion of the high end of the exposure distribution (see Glossary).

unavoidable when the subsurface environment contains the very same volatile chemicals that contemporaneously arise in indoor air due to background sources, which is common for some chemicals and relatively rare for others (EPA 2011a). In this circumstance, additional lines of evidence, possibly including special procedures and analyses, may warrant evaluation to distinguish background contributions from those originating from vapor intrusion (see Section 6.3.5).

After discussing recommended sampling methods and practices for the primary uses of indoor air sampling data, this sub-section concludes by discussing:

- Recommended measures to reduce the impact of indoor sources of vapor-forming chemicals.
- Recommended approach to establishing analyte lists for indoor air samples.
- Complementary, building-specific data (i.e., additional lines of evidence) that can be collected contemporaneously while indoors.

Characterize Human Exposure Levels. Indoor air sampling and analysis provide a direct approach to obtaining concentrations of vapor-forming chemicals in indoor air to which building occupants can be exposed. For this purpose, EPA generally recommends time-integrated sampling methods, since indoor air concentrations can be temporally variable[143] and time-integrated exposure estimates over appropriate exposure durations (e.g., chronic typically; less-than-chronic in some cases) are generally most useful for assessing human exposure and human health risk (see Section 7.4).

Because of variability, a single indoor air sample, collected at a randomly chosen time, is insufficient information to estimate an average exposure. On the other hand, it is impractical to collect indoor air samples continuously over a chronic exposure period (i.e., up to 30 years for a reasonable maximum exposure duration in a residence (EPA 2014a)), which would also entail deferring risk management decisions for a prolonged period while human exposures from vapor intrusion could occur unabated. Hence, current and past practice has generally relied upon collecting multiple indoor air samples for purposes of estimating long-term average (i.e., chronic) exposures and assessing human health risk (see Section 7.4). All else being equal, a longer collection period for each individual sample would be expected to yield a more reliable basis for estimating long-term, time-average exposure than would a one-day sample collection period.

When investigating short-term exposure conditions that might warrant prompt response action to protect human health (see, for example, Sections 5.2 and 7.5.2), time-integrated indoor air samples can provide useful estimates of exposure for the location and time period of sample collection. (A short-term exposure is defined as a “repeated exposure for more than 24 hours,

[143] Because weather conditions and building operations can lead to time-variable contributions from vapor intrusion (e.g., driving forces for vapor intrusion; see Section 2.3) and ambient air infiltration (see Sections 2.4), indoor air concentrations of vapor-forming chemicals can be expected to vary over time (see Section 2.6). Field observations indicate that indoor air concentrations arising from vapor intrusion can be temporally variable within a day and between days and seasons in an individual residential building (EPA 2012f; Holton et al., 2013ab).

up to 30 days" – see Glossary.) All else being equal, a longer collection period for an individual sample would be expected to yield a more reliable basis for estimating time-average short-term exposure than a one-day sample.

As noted above, EPA also recommends considering potential health effects and relevant exposure periods for site-related, vapor-forming chemicals when developing DQOs and sampling plans for indoor air.

Variability in laboratory analyses can be considered when evaluating these data in support of risk management decisions.[144]

Time-integrated samples provide a direct measurement of the average chemical concentration over a fixed period of time (e.g., ranging from 8 hours to several weeks, depending upon the sampling method, its capabilities, and its deployment). Time-integrated samples can be collected using either evacuated canisters, which collect gas in a container, or sorbent samplers, which collect vapor-forming chemicals on a sorbent material.

Evacuated canisters

Evacuated canisters are spherical- or cylindrical-shaped stainless steel or silica-lined containers that are prepared to be under negative pressure relative to the environment and certified by the laboratory to be clean and leak-free.[145] As described in EPA Method TO-14A (EPA 1999c), evacuated canisters can be used as passive (sub-atmospheric pressure sampling) or active (pressurized sampling) samplers. In both cases, the canister is initially evacuated to a standard vacuum in preparation for sampling. For sub-atmospheric sampling, when the canister is opened for sample collection, the differential pressure causes air to flow into the canister without use of a pump. In this case, sampling must end before the vacuum is fully dissipated, else the sample collection period will be unknown. For pressurized sampling, a pump is used to pass air into the canister until a specified pressure (up to two atmospheres) is reached. In both cases, a flow-control device is used to maintain a constant flow into the canister over the desired sample period. To ensure that the canisters are filling at the proper rate, EPA recommends checking the flow rate periodically during sample collection. EPA Methods TO-14A and TO-15 provide further information on measuring and controlling flow rates into canister-type samplers.

[144] For a recently published study, EPA's ORD determined "The acceptance criterion to demonstrate equivalency is ±30% … based on what is defined as acceptable reproducibility in vapor intrusion field studies" (EPA 2012f).

[145] Canisters are cleaned and re-used because they are too expensive to dispose routinely. The certification process entails cleaning the interior of the container using a combination of dilution, heat, and high vacuum. Canisters are then analyzed for a large suite of vapor-forming chemicals to establish that they are free of detectable chemicals at a suitably low (sensitive) detection level. The cleanliness of canisters can be certified individually (i.e., direct testing of each canister, or 100% certification), which is generally desirable in instances where the data are to be used for exposure/risk assessment purposes. Alternatively, canisters can be certified by batch (or lot), in which a subset of the canisters are tested directly (e.g., 10%) and results are extrapolated to the remainder of the batch. Batch-certified canisters may be sufficient when concentrations of target analytes are expected to be high, relative to potential levels of residual contamination in the canister after cleaning. EPA recommends that flow controllers also be cleaned between uses to avoid artificial contamination.

Typically, for vapor intrusion investigations, indoor air samples are collected using six-liter canisters using sub-atmospheric pressure sampling over a 24-hour period in residences or over an 8-hour period (or workday equivalent) in commercial and industrial settings, when using these devices. Larger canisters (i.e., 15-liter) allow higher flow rates and may be preferable for longer sampling events or to collect a larger volume of sample.[146] A capillary flow controller has been developed and demonstrated for use in industrial hygiene applications (Rossner et al. 2002; Rossner and Wick 2005), which may hold promise for extending sampling time periods for indoor air with standard-sized canisters.

Details for selecting and utilizing sampling canisters are provided in EPA Methods TO-14A (EPA 1999c) and TO-15 (EPA 1999d). EPA's Environmental Response Team has developed a standard operating procedure for sampling air with evacuated canisters (EPA-ERT 1995).

An advantage of using evacuated canisters for sample collection is the capability of analyzing multiple sub-samples from the same canister (because these canisters obtain a "whole air" sample). They are also reasonably easy to deploy and retrieve. However, sample recovery and representativeness can be affected by ambient conditions; for example, low humidity conditions in the sample may lead to losses of certain volatile compounds on the canister walls (EPA 1999c).

Fourteen days is the most commonly cited hold time for air samples in canisters. Some analytes, however, may be stable in canisters for up to 30 days.

Sorbent Samplers

Sorbent sampling devices are hollow containers that hold one or more adsorbent media that can bind vapor-forming chemicals. They have been developed and tested over several decades for industrial hygiene monitoring and have more recently been employed for other purposes, including vapor intrusion investigations. Sorbent samplers can be used in an active or passive mode.

In the active mode, a pump is used to draw air at a known rate through the device. The flow rate and sampling volume are determined based on the type of sorbent used, the target constituent(s), and the amount of sorbent contained in the device. Care must be taken to ensure that the volume of air drawn through the tube does not exceed the "breakthrough" volume[147] (i.e., the volume of air which may be passed through the sorbent tube before a detectable level of the analyte concentration elutes from the non-sampling end), else the time-weighted average concentration will be biased low by an unknown amount.

In the passive mode, no pump is used, and vapor-forming chemicals enter the device due to diffusion. Consequently, passive (diffusion) samplers may be placed in locations of interest without consideration of power availability.

[146] Alternatively, two (or more) large canisters can be connected together to allow collection of time-integrated samples over longer durations, which is generally desirable for characterizing long-term average exposure levels.

[147] For this reason, sample volumes in the one- to four-liter range are generally recommended for this method (EPA 1999e).

Although passive (diffusion) samplers have been less commonly used to quantify indoor air concentrations, their use may grow as a result of recent demonstrations that they can yield results comparable to those obtained using evacuated canisters (EPA-Region 9 2010; EPA 2012f; Odencrantz et al. 2009; Odencrantz et al. 2008),[148] and a recognition that they may be less intrusive for some building owners and occupants and more convenient for field staff (EPA-Region 9 2010). Passive samplers are also capable of being deployed for longer durations than evacuated canisters, thereby providing a more economic means of obtaining average indoor air concentrations over longer periods of exposure. Time-integrated samples of indoor air over longer periods than one day are also indicated by field observations demonstrating that indoor air concentrations arising from vapor intrusion can be temporally variable within a day and between days and seasons (EPA 2012f; Holton et al., 2013a).

The basic configuration of a passive sampler is a solid, typically granular, sorbent contained in a metal, glass of plastic container with openings of known dimensions. Several different containers and a wide range of adsorptive media are commercially available, which function similarly. After sample collection, adsorbed mass is measured in a laboratory for each analyte; the two most common analytical methods involve thermal desorption or solvent extraction combined with gas chromatography/mass spectrometry. The air concentration for each analyte is calculated from the adsorbed mass, the duration of sampling, and the uptake rate.

The uptake rate is dependent upon the geometry of the sampling device and the diffusion coefficient of the analyte. The uptake rate is the most critical variable for accurately measuring air concentrations with passive samplers, since the sampling duration and adsorbed mass can generally be measured very accurately. Fortunately, most commercially available passive samplers have published uptake rates for several compounds, which collectively address many of the vapor-forming chemicals described in Section 3.1.[149] Once the target analyte(s) and uptake rate(s) are known, the sample duration needed to attain data quality objectives (i.e., reporting limit equal to or lower than the risk-based screening level or risk-based action level) can be calculated for each analyte.

Uptake rates of deployed samplers can be affected by ambient conditions (e.g., temperature, because chemical-specific diffusion rates are temperature-dependent; and humidity, which influences the uptake of water vapor, which may interfere with retention and stability of the analyte and/or with laboratory analysis). EPA, therefore, recommends that ambient conditions be recorded during deployment of passive samplers.

One potential advantage of passive samplers is that they can be left unattended for relatively longer durations, thereby conveniently providing estimates of longer-term time-

[148] For example, EPA's National Exposure Research Laboratory found that Radiello™ charcoal passive samplers performed well for sampling periods up to 28 days for TCE (EPA 2012f). In that study, one-week (7-day) Radiello™ passive samplers were utilized as a primary measurement tool and the resulting data were used as a basis of comparison to longer-duration samples (e.g., two-week, four-week (monthly), and 13-week (quarterly) samples).

[149] Standard methods for determining uptake rates have been published by a few organizations. Ideally, the selected passive sampling device will have vendor-supplied uptake rates supported by controlled chamber tests or a considerable body of field-calibrated uptake rates for most, if not all, of the target compounds.

weighted average concentrations. However, similar to active sorbent sampling, the duration of passive sampling must be such that the adsorptive capacity of the media is not approached or exceeded, else the time-weighted average concentration will be biased low by an unknown amount.

One potential disadvantage of sorbent sampling, compared to canister sampling, is that only one analysis is possible from an individual device, because it does not collect a "whole air" sample. Thus, if an error occurs in laboratory handling or there is an instrument malfunction, the sample is lost. Such errors generally are not common. Therefore, this potential disadvantage will not generally offset the benefits of sorbent sampling, the foremost of which is the ability to obtain time-integrated samples over longer periods (i.e., up to a few months for some compounds) than with evacuated canisters.

For a typical-size residential building or a commercial building less than 1,500 square feet, EPA recommends that the site teams generally collect one time-integrated sample in the area directly above the foundation floor (basement or crawl space) and one from the first floor living or occupied area, at least for the initial sampling round.[150] In general, EPA recommends samples be collected at the breathing zone level for the most sensitive exposed population.[151]

EPA recommends the site planning and data evaluation team discuss the number of sample locations per building for atypical situations, which include: (1) very large homes or buildings;[152] (2) multi-use buildings, particularly ones with segmented areas that are occupied by different populations (e.g., day care with young children versus office with adult workers) or have different occupancy patterns over time. Additional samples may also be warranted, depending on internal building partitions, HVAC layout, contaminant distribution in the subsurface, and occurrence of observable locations of potential soil gas entry (e.g., basement sumps or drains, relatively large holes or spaces in the foundation floor, entry points for utilities). Closed rooms located below ground may have appreciably higher contaminant concentrations originating from vapor intrusion. Closed rooms may warrant sampling to characterize the reasonably maximum exposure levels, if occupied, or to diagnose vapor intrusion (e.g., see below), even if not occupied.

[150] Placement of indoor air sampling devices may entail compromises. Whereas the ideal location may be a central location that is unobstructed and representative of the actual used area of a room, placement at breathing zone height in a heavily used area well away from any wall is likely to interfere with normal occupant activities.

[151] The "most sensitive" exposed population may be identifiable by combining information about the types of human occupants in a given building and the types of potential toxic effects for vapor-forming chemicals found in the subsurface environment. For example, the 'most sensitive' exposed population could be children, pregnant women, or elderly adults, depending upon building- and chemical-specific characteristics.

[152] Larger commercial and residential buildings (e.g., multi-family residences) may warrant additional discussion with the site planning team and perhaps a statistician to select the appropriate number and placement of indoor air samples to meet DQOs.

Indoor air concentrations vary over time, due to time-dependent changes in soil gas entry rates, exchange rates, intra-building mixing, among other factors (see Section 2).[153] Therefore, multiple rounds (and often several rounds) of indoor air sampling is generally recommended in order to reduce the chance of reaching a false-negative conclusion (i.e., concluding exposure is at an acceptable risk level when it is not) or reaching a false-positive conclusion (i.e., concluding exposure is at an unacceptable risk level when it is not).[154] Also, multiple sampling events generally are considered necessary to account for seasonal variations in climate and the habits of building occupants and ensure that related risk management decisions are based upon a consideration of a reasonable maximum vapor intrusion condition.[155] In many geographic areas in the continental United States, indoor air sampling during the heating season may yield higher indoor air concentrations than at other periods, because stack effects are generally more significant and, therefore, higher rates of soil gas entry are reasonably expected. Another scenario that may yield higher indoor air concentrations is when a building is sealed and the ventilation system is not operating.

When sampling indoor air (or sub-slab soil gas), EPA generally recommends removing potential indoor sources of vapor-forming chemicals (see Section 2.7) from the building to strive to ensure that the concentrations measured in the indoor air samples are attributable to the vapor intrusion pathway.[156] After removal of indoor sources, their effects may linger longer depending on source strength, relative humidity inside the building, the extent to which the contaminants have been absorbed by carpets and other fabrics or "sinks," and air exchange rate of the building. In residential settings, EPA generally recommends that potential indoor sources be removed from the structure and stored in a secure location at least 24 to 72 hours prior to the start of sampling, based on an approximate air exchange rate of 0.25 to 1.0 per hour in

[153] Because weather conditions and building operations can lead to time-variable contributions from vapor intrusion (e.g., driving forces for vapor intrusion; see Section 2.3) and ambient air infiltration (see Sections 2.4), indoor air concentrations of vapor-forming chemicals can be expected to vary over time. Holton et al. (2013ab) obtained and reported a set of long-term, high-frequency, indoor air data for an unoccupied house (except for periodic visits by researchers) in Utah overlying a plume of chlorinated hydrocarbons. TCE concentrations in indoor air varied by approximately two to three orders of magnitude, exceeding variations in measured air exchange rate.

[154] An individual sample, collected at a randomly chosen time, may under-estimate average and reasonable maximum exposure conditions. From their high-frequency, measured data, Holton et al. formulated a synthetic data set (simulating one-day-average concentrations), which they used to estimate that a single, randomly drawn, one-day sample had a forty percent chance of being less than the true mean (Holton et al. 2013b; see Table 1 therein). When the true mean was assumed to exceed the risk-based action level ("target concentration" in their parlance) by two or five times, they estimated that a single, randomly drawn, one-day sample had a twenty percent or six percent chance, respectively, of not detecting the exceedance. These data support EPA's recommendation to collect multiple rounds of indoor air sampling to reduce the chance of reaching a false-negative conclusion. Collecting multiple rounds of indoor air sampling can also reduce the chance of reaching a false-positive conclusion (i.e., concluding that vapor intrusion poses unacceptable human health risk when it does not), because an individual sample, collected at a randomly chosen time, may over-estimate the average exposure condition.

[155] Given EPA's over-arching duty to protect human health and recognizing the disruption to building owners and occupants caused by indoor air sampling, risk managers may choose to pursue pre-emptive mitigation (i.e., early action) at some buildings (see Sections 3.3 and 7.8) rather than, for example, conduct multiple rounds of sampling over a few years to establish an estimate of long-term average exposure concentration and characterize temporal variability.

[156] Vapor-detecting field instruments and in-field gas chromatographs can be used to locate indoor sources of vapors. For example, Gorder and Dettenmaier (2011) reported on the use of a field-portable gas chromatograph and mass spectrometer to identify specific sources of vapor-forming chemicals. EPA's Environmental Response Team has employed the Trace Atmospheric Gas Analyzer (TAGA) mobile laboratory for similar purposes.

residential buildings. In residences with attached garages, keeping the door(s) between the garage and the living space closed prior to and during indoor air sampling may also be warranted, in situations where the site-specific chemicals of potential concern include petroleum hydrocarbons or are components of products stored in the garage.

Diagnose Vapor Intrusion and Background Sources. When access is granted for indoor air sampling, EPA generally recommends concurrently collecting samples of sub-slab soil gas (see Section 6.4.3) and outdoor (ambient) air (see Section 6.4.4) over similar durations using the same methods. Comparing these results to each other and to results for subsurface vapor sources can foster insights and support findings about the relative contribution of vapor intrusion and background sources to indoor air concentrations (as described in Section 6.3.5). In this case, time-integrated sampling methods are recommended for indoor air, because concentrations of vapor-forming chemicals can vary significantly over time (see Section 2.6).

Grab (essentially short-duration) samples can, however, be useful for:

- confirming the presence of a subsurface contaminant in indoor air[157] (see Section 6.3.4) or in gas in a drain line or sewer lateral that enters a building,
- identifying specific vapor-forming chemicals emanating from indoor sources of consumer or commercial products[158] (see Section 6.3.5), and
- identifying specific vapor-forming chemicals emanating from suspected openings for soil gas entry into buildings (see Section 6.3.3).

Grab samples can provide a convenient and less intrusive means of confirming the presence, if any, of a site-related subsurface contaminant(s) in the indoor environment. However, an individual grab sample is not reliable for purposes of demonstrating that vapor intrusion is not occurring in a specific building; among other considerations, vapor intrusion and indoor air concentrations can exhibit significant temporal variability (EPA 2012f, Holton et al., 2013ab). Consequently, EPA recommends collecting multiple time-integrated samples to support any such building-specific determination.

Indoor air samples can also be concurrently collected for radon testing, which may be useful in evaluating building susceptibility to soil gas entry (see Section 6.3.3).

Evaluate and Develop Analyte Lists. EPA recommends the site planning and data evaluation team generally limit chemical analyses to those vapor-forming chemicals known (based upon subsurface contaminant characterization) or reasonably expected (based upon site history) to be present in the subsurface environment. For example, if the site history and reliable subsurface sampling data do not identify benzene as a subsurface contaminant, it would be appropriate for site managers to exclude benzene as a target analyte for indoor air samples. Benzene could originate indoors as a result of a car, lawnmower, or snow blower in a garage. In

[157] For this purpose, EPA generally recommends collecting one sample directly above the foundation floor (e.g., basement or crawlspace) and one from the first floor living or occupied area.

[158] For characterizing indoor sources or openings for soil gas entry, one round of grab sampling of indoor air may be sufficient.

this hypothetical case, benzene would not typically be amenable to reduction by vapor mitigation systems or subsurface remediation efforts. In fact, requesting an extensive list of analytes that are not related to subsurface contamination may unnecessarily complicate risk communication if indoor air testing reveals volatile chemicals unrelated to vapor intrusion.

Collect Complementary Data While Indoors. A variety of useful information can be gathered during a building survey conducted in advance of or during indoor air sampling. EPA recommends that the following complementary data be gathered by observation, interviews, or reports (e.g., mechanical test-and-balance reports) when buildings are to be sampled to analyze indoor air:

- Building Occupancy
    - Characteristics and locations of building occupants (e.g., residents, including children or other sensitive populations; expectations for presence of general public in commercial or industrial settings; presence of multiple exposure units – due to different uses or activities and occupants – within a building other than a single-family residence).
    - Hours of building occupancy under current conditions (and reasonably expected future conditions, as appropriate), particularly for a nonresidential setting. Because this information is pertinent to the human health risk assessment and data evaluation, EPA recommends considering hours of building occupancy when establishing the sampling duration for characterizing indoor air exposure levels.
- Susceptibility to Soil Gas Entry Under Current Conditions
    - EPA recommends that the pressure difference between the indoors and the subsurface be measured whenever indoor air samples are collected. Ideally, differential pressure data would be collected continuously starting several days before sampling and throughout the sample collection period.[159] The magnitude and direction of the pressure difference during sampling can support insights about whether a 'driving force' for vapor intrusion is present during indoor air sampling; if not, then the resulting sampling data are unlikely to characterize a reasonable maximum vapor intrusion exposure condition. Differences in driving forces (direction or magnitude) among indoor air sampling events may help to explain any significant differences in observed indoor air concentrations over time.[160] Measuring pressure difference between the indoors and the subsurface

[159] These data can be collected using portable pressure monitors installed in a dedicated sub-slab probe at one or more locations. Pressure transducers were employed for this purpose during high-frequency sampling as part of a research study in Indianapolis (EPA 2012f, see Section 3.6.6 therein); readings were recorded every 15 minutes. Technical information about pressure-measuring instruments (e.g., description, operation, and calibration) can be found in Section 4 of *Technical Guidance Document: Compliance Assurance Monitoring* (EPA 1998).

[160] Pre-mitigation measurements of the pressure difference between indoors and the subsurface may also be useful for supporting design of active depressurization technologies to reduce vapor intrusion (EPA 1993a, see Section 3 therein).

is a more direct means of assessing building under-pressurization than is monitoring weather/climate factors (e.g., air temperature, wind speed). Pressure difference monitoring in large buildings can help identify any areas with significant under-pressurization.

- Presence and operation of a mitigation system, which would generally be expected to mitigate intrusion of vapor-forming chemicals even if designed for radon.

- Physical conditions that indicate potential openings to soil gas entry (e.g., potential conduits, such as cracks or floor drains; presence of structures such as utility pits, sumps, and elevators; basements or crawl spaces; modifications to the original foundation).

- Building Heating, Ventilation, and Cooling

  - Building ventilation, including zones of mechanical influence and stagnation. As noted in Section 2.4, greater ventilation is intended to result in smaller vapor concentrations in indoor air. Any non-ventilated or passively ventilated rooms (such as mechanical rooms) may be subject to greater accumulation of vapors. For commercial and industrial buildings, each distinct zone of influence may warrant sampling, when indoor air testing is selected as part of a site-specific investigation plan for vapor intrusion assessment.

  - Operating characteristics of HVAC systems. In many commercial buildings, the HVAC system brings outdoor air into the building, potentially creating building over-pressurization relative to the outdoor environment. EPA recommends noting any areas with significant over-pressurization, relative to the outdoors.

- Indoor and Outdoor Sources of Vapor-Forming Chemicals

  - Chemicals and consumer products used or stored within the building that can act as potential sources of toxic vapors. Vapor-forming chemicals are used in many commercial and most industrial buildings.[161] As noted in Section 2.7, consumer products that can emit vapors may be common in residential buildings. In some circumstances, a photoionization detector (PID) can be used to directly screen the building for locations with vapor-forming chemicals and materials; however, the PID may not be sensitive enough for very low concentration sources. More sensitive options include use of the HAPSITE gas chromatograph/mass spectrometer (Gorder and Dettenmaier 2011) or the TAGA Mobile Laboratory (EPA-ERT 2012).

  - HVAC systems that bring outdoor air into the building potentially bring contaminated outdoor air into the building, depending on the location of the vent and exhaust with regard to other spaces. For example, HVAC intakes adjacent to

[161] Depending upon it history of uses and operations, buildings undergoing renovation, redevelopment or reuse may have lingering presence of vapor-forming chemicals due to a past release(s) also.

or near a dry-cleaning facility may introduce vapors of the dry-cleaning solvent into the building.

- In some cases, contaminated groundwater seeps into or actively collects in the building (for example, in sumps), possibly serving as a direct source of vapors. It may be appropriate to collect water samples concurrently with indoor air (and any sub-slab) samples in these circumstances.

- Presence and operation of any indoor air treatment system (e.g., in-line carbon adsorption) that can reduce indoor exposure levels of vapor-forming chemicals.

In general, EPA recommends that the foregoing complementary information be collected during investigation planning and scoping to help determine where to sample and prioritize or sequence buildings for testing. Then, the information can be confirmed during indoor sampling.

Field experience in residential settings suggests that it may not be possible to remove all indoor sources of vapor-forming chemicals. It may be particularly impractical to do so in industrial settings where vapor-forming materials are used or stored. It may also be impractical when deploying passive samplers, owing to their longer deployment period. Therefore, EPA recommends asking building occupants to document indoor sources (and relevant building operations) during indoor air sampling, using an activity log or questionnaire.

6.4.2 Outdoor Air Sampling

Outdoor air concentration data can be useful in identifying potential contributions to indoor air concentrations from ambient air sources (see Section 6.3.5). Therefore, EPA generally recommends collecting ambient air samples using similar sampling and analysis methods, whenever indoor air samples are collected. Normally, EPA recommends one or two outdoor air sample locations to characterize the conditions surrounding a single or a few buildings.[162] Additional outdoor air samples may be warranted if the investigation is assessing multiple buildings over a wide area. EPA also recommends that sample locations be designed to characterize representative conditions in the absence of site-related subsurface contamination (e.g., avoid collecting ambient air samples near locations of known or suspected chemical release(s), including any atmospheric releases from remediation equipment). It also is suggested that observable potential outdoor sources of pollutants (e.g., air emissions from nearby commercial or industrial facilities) be recorded during all building surveys.

Because concentrations of vapor-forming chemicals in ambient air can vary with time, EPA recommends that ambient air samples generally be collected over the same sampling period as indoor air, which will facilitate data evaluations when contaminant concentrations are compared between media. For residential buildings, EPA generally recommends beginning ambient air sampling at least one hour, but preferably two hours, before indoor air monitoring begins and continuing to sample until at least 30 minutes before indoor monitoring is complete. EPA recommends this practice because most residential buildings have an hourly air exchange rate in the range of 0.25 to 1.0, causing air that enters the building before indoor air sampling to

[162] For buildings where outdoor air is mechanically brought into the building, an outdoor sample may be co-located near the HVAC intake.

remain in the building for a long time (for example, see Section D.10, ITRC 2007a). Recommended lag times may warrant adjusting for nonresidential buildings.

Evaluate and Develop Analyte Lists. To characterize potential concentrations entering a building via ambient air, EPA generally recommends that chemical analyses for ambient air samples be limited to those vapor-forming chemicals known (based upon subsurface testing) or suspected (based upon site history) to be present in the subsurface environment. Requesting an extensive list of analytes that are not related to subsurface contamination, as discussed previously, may unnecessarily complicate risk communication.

Consider Collecting Complementary Data. Monitoring air exchange during ambient air sampling events can provide useful complementary data. Ideally, these data would be collected continuously starting before sampling and throughout the sample collection period. Information about air exchange can support insights about the amount of ambient air infiltration during sampling.

6.4.3 Sub-slab Soil Gas Sampling

Sub-slab sampling is intended to draw soil gas from the air space immediately below the floor slab of a building. Depending upon building construction and condition, this air space may be an air gap that forms beneath a concrete foundation due to differential settlement over time or a pore space within a granular layer that may have been placed below the concrete slab. Access to this air space is generally provided by drilling or coring through the concrete and inserting a probe, which is sealed into the floor. EPA's Environmental Response Team has developed a standard operating procedure for constructing and installing sub-slab soil gas sampling probes (EPA-ERT 2007).

Sub-slab soil gas samples can provide useful data for characterizing the levels of hazardous, vapor-forming chemicals that can enter a building via soil gas intrusion. When combined with other soil gas data, sub-slab soil gas data can be used to assess whether the subsurface vapor migration route is complete (i.e., subsurface vapor migration is capable of transporting hazardous vapors from the source to building; see Section 6.3.2). When combined with an appropriate attenuation factor (e.g., a conservative generic value – see Section 6.5.3), sub-slab soil gas data can be used to estimate a potential upper-bound indoor air concentration[163] that may arise from vapor intrusion. In this way, sub-slab data can be used to assess the potential for the vapor intrusion pathway to pose a health concern.[164]

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[163] For purposes of this Technical Guide, the term "upper bound indoor air concentration" is intended to be a semi-quantitative phrase, referring to the high end of the exposure distribution. EPA recommends basing the decision about whether to undertake response action for vapor intrusion (i.e., a component of risk management) on a consideration of a "reasonable maximum exposure" (e.g., EPA 1989, 1991a), which is intended to be a semi-quantitative phrase, referring to the lower portion of the high end of the exposure distribution (see Glossary). Alternatively, a "worst case" or "reasonable worst case" (see Glossary) indoor air concentration would refer to the upper portion of the exposure distribution. Section 6.6, which discusses mathematical modeling of vapor intrusion, notes that consideration of a "worst case" exposure condition may be particularly useful where the predicted "worst case" indoor air concentrations can be shown to pose acceptable human health risk.

[164] The sub-slab soil gas concentration provides only half of the information for estimating vapor flux into a building. The other information needed is the soil gas flow rate (Q_{soil}), which is embodied in the attenuation factor. The soil gas flow rate can also be explicitly calculated using a model.

Field experience indicates there may be substantial spatial variability in sub-slab soil gas concentrations even over an average-sized footprint of a residential building. EPA, therefore, recommends site planning and data review teams consider collecting multiple samples per building when sub-slab soil gas sampling is conducted.[165] Three sub-slab samples have been collected in a number of EPA investigations of a typical size residential building or commercial building less than 1,500 square feet in area. EPA recommends the site planning and data evaluation team discuss the number of sample locations per building for atypical situations, which include: (1) very large or small homes or buildings;[166] (2) buildings with more than one foundation floor type;[167] (3) subsurface structures or conditions that might facilitate or mitigate vapor intrusion; and 4) multi-use buildings with distinct segmented areas that differ significantly by occupying population or exposure frequency. In addition, EPA recommends multi-point sub-slab samples be considered to support data interpretation and resolve uncertainties that may arise when:

- There are fewer surrounding buildings that are being sampled (that could have helped the understanding of typical sub-slab values and variability).[168]

- The indoor and sub-slab concentrations for a specific building(s) are out of line with expectations based on data from neighboring homes and other information.

EPA generally recommends that sub-slab sampling include centrally located sub-slab samples in buildings identified for testing when the subsurface vapor source is laterally extensive relative to the building footprint (e.g., a broad plume of contaminated groundwater).[169] In addition, EPA recommends that site teams consider internal building partitions, HVAC layout, contaminant distribution, utility conduits, and openings for preferential soil gas entry in selecting any additional locations for collecting sub-slab samples.

Several rounds of sampling are generally recommended to develop an understanding of temporal variability of sub-slab soil gas concentrations, particularly when these data are used with the recommended attenuation factor (see Section 6.5.3) to estimate a potential upper-bound indoor air concentration that may arise from vapor intrusion.

[165] An individual sample, collected at a randomly chosen time, may under-estimate or over-estimate average subslab conditions. Collecting multiple subslab soil gas samples can, therefore, reduce the chance of reaching a false-negative conclusion (i.e., concluding subsurface vapor source strength is limited, when vapor intrusion actually poses an unacceptable human health risk) or a false-positive conclusion (i.e., concluding subsurface vapor source strength is unacceptably elevated, when vapor intrusion actually poses an acceptable human health risk).

[166] For larger structures, a statistician may assist in identifying the number and placement of sampling ports to meet the desired DQOs.

[167] In basements with a partial slab, but one large enough to allow vapors to accumulate (for example, if the slab covers more than 50 percent of the building footprint), EPA generally recommends that one sub-slab port be installed on the slab portion and an indoor air sample be collected directly over the dirt portion.

[168] In these cases, EPA recommends multiple ports be installed in a specific percentage (e.g., more than 10 percent) of the buildings sampled to provide a check for variability in the study area.

[169] Based on work conducted in New York as of the spring of 2010, it appears that the sub-slab concentrations beneath the central area of a home are usually (75 percent of the time) higher than (or as high as) the concentrations closer to the perimeter of the home. This field observation is supported by modeling results for idealized scenarios, which show greater sub-slab soil gas concentrations near foundation centers in under-pressurized residential buildings when the vapor source is laterally extensive relative to the building footprint (EPA 2012b).

If a site team decides to proceed with sub-slab sampling, EPA recommends that leak-testing be performed to ensure the hole is properly sealed, for example through the use of a helium tracer gas shroud. Because installing soil gas probes can disturb subsurface conditions, EPA recommends that the site team allow some time after the sampling probe has been installed for the subsurface to return to equilibrium conditions. An EPA study of the time needed for the subsurface conditions to come back to equilibrium (equilibration rate) after they have been disturbed by installation of the soil gas probes found that an equilibration time of two hours generally was sufficient because most sub-slab material consists of sand or a sand-gravel mixture—even for buildings built directly on clay (Section 5.0, EPA 2006b).

There also may be special considerations for sub-slab soil gas samples because of either a unique construction (for example, pretension concrete slab) or environmental situation. Key EPA recommendations include, but are not limited to:

- Identify the location of cables in post-tensioned concrete (e.g., using ground-penetrating radar) before sub-slab sampling, as drilling through a cable poses a significant health and safety concern and may damage the slab.

- Avoid locating sub-slab samples in areas where groundwater might intersect the slab.

- Identify and avoid the location(s) of underground utilities and structures (for example, electric, gas, water, or sewer lines) to prevent damage to these lines; however, sample collection in close proximity to these lines may be warranted as building penetrations for these lines may pose openings for soil gas entry.

- Consider whether to augment sub-slab samples with samples through the basement walls, as the primary entry points for vapors in basements might be through the sidewalls rather than from below the floor slab.

Evaluate and Develop Analyte Lists. To characterize potential concentrations entering a building via soil gas, EPA generally recommends that chemical analyses for sub-slab soil gas samples be limited to those vapor-forming chemicals known (based upon subsurface testing) or suspected (based upon site history) to be present in the subsurface environment. Requesting an extensive list of analytes that are not related to subsurface contamination, as discussed previously, may unnecessarily complicate risk communication.

Collect Complementary Data While Indoors. When sub-slab soil gas samples are collected, EPA recommends that the following complementary information be gathered by observation or interviews:

- Physical conditions and characteristics that are pertinent to assessing the building's susceptibility to soil gas entry, if any (e.g., potential conduits, such as cracks or floor drains; presence of structures, such as utility pits and elevators; basements or crawl spaces). Such information may help interpret spatial differences in sub-slab or indoor air concentrations within a building.

- Areas with potentially significant over- or under-pressurization relative to the outdoors. Such information may assist in interpreting spatial differences in sub-slab or indoor air concentrations within a building.

- Where outdoor air is mechanically brought into the building by the HVAC system and building(s) interiors are over-pressurized, it may be helpful to also collect ambient air samples to support interpretations of the sub-slab sampling results. If the predominant vapor-forming substances and their respective concentrations in sub-slab soil gas and outdoor air samples are similar, then ambient air may be influencing sub-slab soil gas conditions.

EPA recommends that the pressure difference between the indoors and the subsurface be measured whenever sub-slab soil gas samples are collected. Ideally, differential pressure data would be collected continuously starting several days before sampling and throughout the sample collection period.[170] EPA recommends measuring pressure at locations away from where sub-slab sampling probes are installed to avoid any pressure artifacts caused during purging and sampling. The magnitude and direction of the pressure difference during sampling can support insights about whether a driving force for vapor intrusion is present during sampling.

When any sub-slab soil gas sample is collected, EPA recommends that relevant meteorological data that can influence soil gas concentration patterns at the time of sampling, such as wind speed, snow or ice cover, significant recent precipitation, and changes in barometric pressure, be recorded, using direct observation (e.g., for snow or ice cover) or readily available data sources (e.g., regional weather stations). These data may be helpful qualitatively in data interpretation; for example, in reconciling soil gas data collected on multiple occasions.

A potential shortcoming of sub-slab soil gas testing is that gaining access may be difficult (or, in some cases, infeasible). This difficulty can often be overcome by implementing a program of community outreach and engagement that fosters trust and good relationships (see Section 9.0).

When access is granted for indoor sampling, EPA recommends collecting sub-slab and indoor air samples contemporaneously using similar sampling and analysis methods and sampling durations to allow for data comparison. The sub-slab sampling ports can be installed after the indoor air sample is deployed and collected (8 - 24 hours later) to avoid biasing the indoor air concentrations with potentially higher sub-slab gas infiltration rates during port installation. Alternatively, the sub-slab ports may be installed prior to indoor air sampling and sampled concurrently with the indoor air samples, provided sufficient time is allowed for the indoor air concentrations to return to “normal” after installation of the sub-slab port.[171]

[170] These data can be collected using portable pressure monitors installed in a dedicated sub-slab probe at one or more locations. Pressure transducers were employed for this purpose during high-frequency sampling as part of a research study in Indianapolis (EPA 2012f, see Section 3.6.6 therein); readings were recorded every 15 minutes. Technical information about pressure-measuring instruments (e.g., description, operation, and calibration) can be found in Section 4 of *Technical Guidance Document: Compliance Assurance Monitoring* (EPA 1998).

[171] EPA generally recommends delaying indoor air testing for at least 24 to 72 hours based on an approximate air exchange rate of 0.25 to 1.0 per hour. Note that the effects of any ‘spike’ in indoor air concentration may linger depending on source strength, relative humidity inside the building, and the extent to which the contaminants have been absorbed by carpets and other fabrics or “sinks.”

6.4.4 Soil Gas Sampling

Data obtained from a soil gas survey can be used to identify, locate, and characterize subsurface vapor sources (see Section 6.3.1) and characterize subsurface vapor migration routes, including any impedances from geologic, hydrologic, or biochemical conditions (see Section 6.3.2). Soil gas survey data can also be useful in supporting the design of soil vapor extraction systems and other subsurface remediation systems and the performance assessment of these systems (see Section 8.1). For each of these purposes, EPA recommends that soil gas survey data be supported by site-specific geologic information (i.e., site geology and subsurface lithology).

Soil gas sampling generally consists of installing a probe into the ground, drawing gas out of the probe, and collecting the gas for transport to a location for analysis. Inert materials (e.g., stainless steel, copper, brass, polyvinyl chloride, high-density polyethylene) are recommended for constructing soil gas probes. To ensure that data collected are representative of conditions *in situ* (e.g., are not adversely impacted by artificial infiltration of ambient air), a reliable seal of the annulus between the probe and the probe housing and leak testing for the seal are generally recommended. In addition, purging of the probe before collecting the soil gas sample is recommended, analogous to purging of monitoring wells before collecting groundwater samples. EPA's Environmental Response Team has developed a standard operating procedure for soil gas sampling, including constructing and installing sampling probes (EPA-ERT 2001c).

Typically, grab (rather than time-integrated) samples are collected when sampling soil gas. EPA recommends that the site team allow some time after the sampler has been installed for the subsurface to return to equilibrium conditions because installing temporary or permanent soil gas probes can disturb subsurface conditions. The equilibration time may depend on the degree of soil disturbance during installation, which is influenced by the type of drilling techniques used to install the soil gas probes (e.g., with more time needed for auger drilling compared with hand drilling). For example, the California Environmental Protection Agency recommends an equilibration time of two hours for temporary driven probes and 48 hours for probes installed using augered borings (CalEPA 2012).

EPA recommends documenting wind direction, precipitation information, temperature, and other site-specific information that can influence soil gas concentration patterns at the time of sampling, using readily available data sources. These data may be helpful qualitatively in data interpretation; for example, in reconciling soil gas data collected on multiple occasions or assessing concordance of sampling data from various media, when not collected contemporaneously.

EPA recommends that soil gas samples be taken as close to the areas of interest as possible and preferably from directly beneath the building structure. As vapors are likely to migrate upward through the coarsest or driest material in the vadose zone, EPA recommends that soil gas samples be collected from these materials.

Using vertical boring or drilling techniques, it is generally practical to collect soil gas samples only in locations exterior or adjacent to a building's footprint ("exterior" soil gas samples). Modeling results for idealized scenarios show that, in homogeneous soil, soil gas concentrations tend to be greater beneath the building than at the same depth in adjacent open areas when the vapor source is underneath the building, even if the source is laterally extensive relative to the building footprint (e.g., broad plume of contaminated groundwater) (EPA 2012b). Given these

predictions and supporting field evidence (EPA 2012a, see Figure 6; Luo et al. 2009; Patterson and Davis 2009, see Figure 1), individual exterior soil gas samples cannot generally be expected to accurately estimate sub-slab or indoor air concentrations. This potential limitation may be particularly valid for shallow soil gas samples collected exterior or adjacent to a building footprint. On the other hand, when the subsurface vapor source is not underneath the building, "exterior" soil gas samples collected from depths below a building's foundation and along the side of the building closest to the source may be useful for characterizing a reasonable worst case condition underneath the building in the absence of routes for preferential vapor migration or soil gas entry.

Deeper soil gas samples collected in the vadose zone immediately above the source of vapor contamination (i.e., "near-source" soil gas samples; see Section 6.3.1) can reasonably be expected to be less susceptible to the diluting effects of ambient air, compared to shallow soil gas samples. On this basis, deeper soil gas samples collected in the vadose zone immediately above the source of vapor contamination will tend to be more suitable than will be shallow soil gas samples for assessing vapor concentrations that may be in contact with the building's sub-slab.[172] Several rounds of sampling are generally recommended to develop an understanding of temporal variability of "near-source" soil gas concentrations, particularly when these data are used with the recommended attenuation factor (e.g., a conservative generic value – see Section 6.5.3) to estimate a potential upper-bound indoor air concentration that may arise from vapor intrusion.[173]

6.4.5 Groundwater Sampling

Groundwater sampling and analysis also feature prominently in many vapor intrusion investigations, for example, to help characterize plumes that can serve as vapor sources. Groundwater sampling methods are not discussed here because practitioners typically are relatively experienced and trained to collect samples that meet site-specific data quality needs (see, for example, EPA-ERT 2001a). However, Section 6.3.1 provides a few recommended guidelines for groundwater sampling that are pertinent for characterizing representative vapor source concentrations for vapor intrusion assessment. One key consideration in sampling groundwater for vapor intrusion investigations is focusing on characterizing water table

[172] Luo et al. (2009) also point to the shortcomings of relying on exterior sampling data, citing significant differences in vapor concentrations and soil gas composition between interior and exterior sampling locations at a maintenance warehouse located at a former refinery. They also observed that the spatial variability in the soil-gas distribution was smaller for soil-gas samples drawn from the source zone, suggesting greater confidence in the assessment of source zone or "near source" vapor concentrations.

[173] For purposes of this Technical Guide, the term "upper bound indoor air concentration" is intended to be a semi-quantitative phrase, referring to the high end of the exposure distribution. EPA recommends basing decisions about whether to undertake response action for vapor intrusion (i.e., a component of risk management) on a consideration of a reasonable maximum exposure (e.g., EPA 1989, 1991a), which is intended to be a semi-quantitative phrase, referring to the lower portion of the high end of the exposure distribution (see Glossary). Alternatively, a "worst case" or "reasonable worst case" (see Glossary) indoor air concentration would refer to the upper portion of the exposure distribution. Section 6.6, which discusses mathematical modeling of vapor intrusion, notes that consideration of a "worst case" exposure condition may be particularly useful where the predicted "worst case" indoor air concentrations can be shown to pose acceptable human health risk.

concentrations. EPA recommends that groundwater samples be taken from wells screened (preferably over short intervals) across the top of the water table.[174]

Groundwater data can be compared to the groundwater VISLs (see Section 6.5).[175] When combined with an appropriate attenuation factor (see Section 6.5.3), groundwater data can be used to estimate a potential upper-bound indoor air concentration that may arise from vapor intrusion.[176] In these ways, groundwater data can be used to assess the potential for vapor intrusion from groundwater sources to pose a health concern.

6.4.6 Planning for Building and Property Access

Vapor intrusion investigations generally entail gaining legal access to buildings and properties to conduct sampling. To address this practical and logistical concern during the planning stage, EPA recommends that an access agreement be executed between the property owner, any occupants, and the investigating entity. Section 9.3 provides additional information for addressing building and property access for sampling.

Obtaining and scheduling access to a property and building can be difficult, whether the structure is a commercial or institutional building or a private residence. This potential difficulty can often be overcome by implementing a program of community outreach and engagement that fosters trust and good relationships. EPA recommends conducting public outreach and communication for this purpose considering the site-specific community involvement plan (See Section 9.1).

6.5 Overview of Risk-Based Screening

Risk screening for vapor intrusion generally is performed using site-specific data collected via appropriate methods, as described in Section 6.4. In some cases, pre-existing data identified during a preliminary analysis can be deemed reliable and adequate for use in risk-based screening (see Section 5.5).

6.5.1 Objectives of Screening

The primary objective of risk-based screening is to identify sites or buildings unlikely to pose a health concern through the vapor intrusion pathway. Generally, at properties where subsurface concentrations of vapor-forming chemicals (e.g., groundwater or "near source" soil gas concentrations) fall below screening levels (i.e., VISLs), no further action or study is warranted, so long as the exposure assumptions match those taken into account by the calculations and the site fulfills the conditions and assumptions of the generic conceptual model underlying the

[174] EPA recommends that, to the extent practical, groundwater samples be collected over a narrow interval (e.g., a few feet or less) just below the water table when the data are to be used for assessing the potential for vapor intrusion.

[175] If available groundwater data do not meet the criteria set forth in Section 6.4.5, the site data review team may judge whether they are nevertheless representative of potential vapor source concentrations emanating from groundwater.

[176] EPA recommends basing decisions about whether to undertake response action for vapor intrusion (i.e., a component of risk management) on a consideration of a reasonable maximum exposure (e.g., EPA 1989, 1991a).

screening levels. In a similar fashion, the results of risk-based screening can help the data review team identify areas, buildings, and/or chemicals that can be eliminated from further assessment.

Subsurface concentrations of vapor-forming chemicals that exceed the VISL for the respective medium (e.g., groundwater, soil gas, subslab soil gas) would not automatically trigger mitigation or subsurface remediation (i.e., they are not offered as response action levels or cleanup levels). Exceeding a subsurface screening level generally suggests, however, that further evaluation of the vapor intrusion pathway is appropriate. In this way, risk-based screening, along with other lines of evidence, can help focus a subsequent site-specific investigation, the results of which would provide support for considering building mitigation and other risk management options (see Section 8.0). For example, the results of vapor source strength screening can help identify and prioritize buildings for indoor testing.

Finally, risk-based screening can also support:

- a preliminary evaluation of human health risk using individual building data (e.g., indoor air concentrations), which would consider the magnitude of the concentration exceedance of the indoor air screening level and site-specific risk management benchmarks (see Section 7.4.1); and

- identification of buildings and structures that may warrant prompt action due to potential explosion threats (see Section 7.5.1).

6.5.2 Scope and Basis for Health-based, Vapor Intrusion Screening Levels

EPA developed VISLs for human health protection that are generally recommended, medium-specific, risk-based screening-level concentrations intended for use in identifying areas or buildings that may warrant further investigation of the vapor intrusion pathway. These VISLs are calculated and documented in the VISL Calculator and are based on:

- Current toxicity values selected considering OSWER's hierarchy of sources for toxicity values (EPA 2003).

- Physical-chemical parameters for vapor-forming chemicals.

- EPA-recommended approaches for human health risk assessment (e.g., EPA 2009c, 2014a).

The VISLs for human health protection include indoor air screening levels for long-term (i.e., chronic) exposures, which consider the potential for cancer and noncancer effects of vapor-forming chemicals.[177] The VISLs for human health protection also include subsurface screening levels for comparison to sub-slab soil gas, "near-source" soil gas, and groundwater sampling

[177] The VISL Calculator does not include information about radon. Information about characterizing the human health risk posed by radon can be found on-line at: http://epa-prgs.ornl.gov/radionuclides/

results. These screening levels are derived from the indoor air screening levels for chronic exposures using medium-specific, generic attenuation factors described further in Section 6.5.3 and Appendix A. The user's guide for the VISL Calculator provides additional information about derivation of the indoor air and subsurface screening levels (EPA 2015a).

The medium-specific VISLs for human health protection are intended to be compared to:

- Building-specific data, such as results from sub-slab soil gas samples, crawl space samples, or indoor air samples; or
- Site- or building-specific data that characterize subsurface vapor sources (e.g., groundwater samples, "near-source" soil gas concentrations)

to determine if there is a potential for the vapor intrusion pathway to pose a health concern to building occupants.

The medium-specific VISLs for health protection are developed considering a generic conceptual model for vapor intrusion consisting of:

- A source of vapors underneath the building(s) either in the vadose zone or in the uppermost, continuous zone of groundwater.
- Vapor migration via diffusion upwards through unsaturated soils from these sources toward the ground surface and overlying buildings.
- Buildings with poured concrete foundations (e.g., basement or slab-on-grade foundations) that are susceptible to soil gas entry.

A critical assumption for this generic model is that site-specific subsurface characteristics will tend to reduce or attenuate soil gas concentrations as vapors migrate upward from the source and into overlying structures. Specific factors that may result in relatively unattenuated or enhanced transport of vapors into a building include the following:

- Significant openings to the subsurface that facilitate soil gas entry into the building (e.g., sumps, unlined crawl spaces, earthen floors) other than typical utility penetrations. [178]
- Very shallow groundwater sources (e.g., depths to water less than five feet below foundation level) (see, for example, EPA (2012a), Section 5.2).
- Significant routes for preferential, subsurface vapor migration whether naturally-occurring (e.g., fractured bedrock) or anthropogenic (see Sections 5.4 and 6.3.2).

[178] For purposes of this Technical Guide, the term "significant openings" is intended to refer to forms and amounts of openings, other than adventitious and intentional openings in a building that are expected to typically be present in all buildings (e.g., cracks, seams, interstices, and gaps in basement floors and walls or foundations; perforations due to utility conduits). Such an atypical opening would be "significant" when it is of sufficient volume and proximity to a building that it may be reasonably anticipated to influence vapor migration towards or soil gas entry into the building.

These specific factors are likely to render inappropriate the use of the recommended attenuation factors and the sub-slab, groundwater, and soil gas VISLs for purposes of identifying sites or buildings unlikely to pose a health concern through the vapor intrusion pathway. On the other hand, further evaluation of the vapor intrusion pathway is still appropriate when the sub-slab, groundwater, and soil gas VISLs are exceeded for samples from a building or site where these specific factors are present.

Vapor source types that typically make the use of the recommended attenuation factors and health-based VISLs for groundwater and soil gas inappropriate include:

- Those originating in landfills where methane is generated in sufficient quantities to induce advective transport in the vadose zone.

- Those originating in commercial or industrial settings where vapor-forming chemicals can be released within an enclosed space and the density of the chemicals' vapor may result in significant advective transport of the vapors downward through cracks and openings in floors and into the vadose zone.

- Leaking vapors from pressurized gas transmission lines.

In each case, the diffusive transport of vapors may be overridden by advective transport, and the vapors may be transported in the vadose zone several hundred feet from the source of contamination with little attenuation in concentration.

In general, EPA recommends considering whether the assumptions underlying the generic conceptual model are attained at a given site. If they are not attained, then EPA recommends that the medium-specific VISLs not be relied upon as a line of evidence for identifying sites or buildings unlikely to pose a health concern through the vapor intrusion pathway. Where the assumptions regarding the subsurface attenuation factors do not or may not apply, EPA generally recommends collecting indoor air samples.

As noted in Section 6.5.1, these VISLs are not automatically response action levels, although EPA recommends that similar calculation algorithms be employed to derive cleanup levels (see Section 7.6)**.** Comparison of sample concentrations to the VISLs is only one factor recommended for use in determining the need for a response action at a site. As discussed further in Section 6.5.4, an individual subsurface sampling result that exceeds the respective, chronic screening level does not establish that vapor intrusion will pose an unacceptable human health risk to building occupants. Conversely, these generic, single-chemical VISLs do not account for the cumulative effect of all vapor-forming chemicals that may be present. Thus, if multiple chemicals that have a common, non-cancer toxic effect are present, a significant health threat may exist at a specific building or site even if none of the individual substances exceeds its VISL (see discussion of non-cancer hazard index in Section 7.4.1).

6.5.3 Recommended Attenuation Factors for Health-based Screening

Vapor attenuation refers to the reduction in volatile chemical concentrations that occurs during vapor migration in the subsurface, coupled with the dilution that can occur when the vapors enter a building and mix with indoor air (Johnson and Ettinger 1991). The aggregate effect of these physical and chemical attenuation mechanisms can be quantified through the use of a vapor intrusion attenuation factor, which is defined as the ratio of the indoor air concentration

arising from vapor intrusion to the soil gas concentration at the source or a depth of interest in the vapor migration route (EPA 2012a).[179]

EPA compiled a database of empirical attenuation factors for chlorinated VOCs and residential buildings through review of data from 913 buildings at 41 sites with indoor air concentrations paired with sub-slab soil gas, groundwater, exterior soil gas, or crawl space concentrations (EPA 2012a). After removing data that do not meet quality criteria and data likely to be influenced by background sources, the distributions of the remaining attenuation factors were analyzed graphically and statistically.[180] Based upon these analyses, the attenuation factors in Table 6-1 are recommended by EPA to derive the VISLs for health protection.

With the exception of the "near-source" exterior soil gas attenuation factor, the recommended values for residential buildings are the estimated 95th percentile values, rounded to one significant figure.[181] The rationale for these recommendations and related analyses are provided in Appendix A. These recommended values are proposed to apply to all vapor-forming chemicals for use in estimating potential upper-bound concentrations in indoor air that may arise from vapor intrusion.[182] The recommended groundwater and "near-source" soil gas attenuation factors do not, however, include the effects of biodegradation.[183] On the other hand, because biodegradation is not expected to occur indoors (i.e., in indoor air in the absence of an air treatment system), the sub-slab soil gas and crawl space attenuation factors are expected to apply equally to vapor-forming chemicals that biodegrade in the vadose zone and those that do not.

As with the medium-specific VISLs, EPA recommends considering whether there are site- or building-specific factors that may result in unattenuated or enhanced transport of vapors toward and into a building, such as the presence of preferential migration route(s) as described in Sections 5.4 and 6.3.2. The presence of such factors is likely to render inappropriate the use of any of these generic attenuation factors.

[179] As defined here, the vapor attenuation factor is an inverse measurement of the overall dilution that occurs as vapors migrate from a subsurface vapor source into a building; i.e., lower attenuation factor values indicate lower vapor intrusion impacts and greater dilution; higher values indicate greater vapor intrusion impacts and less dilution (EPA 2012a, b). Johnson and Ettinger (1991) utilized the symbol α for the vapor intrusion attenuation factor. For example, the subslab soil gas attenuation factor is intended to account for concentration dilution arising during migration through openings in the foundation and from mixing of subsurface contaminants inside the building. The groundwater attenuation factor is intended to account for concentration dilution arising during vapor migration from the groundwater table through the vadose zone, in addition to concentration dilution arising during migration through openings in the foundation and from mixing of subsurface contaminants inside the building.

[180] A summary of the resulting distributions is provided in Appendix A of this document.

[181] The recommended "near-source" exterior soil gas attenuation factor corresponds to approximately the estimated 75th percentile value.

[182] EPA recommends basing decisions about whether to undertake response action for vapor intrusion (i.e., a component of risk management) on a consideration of a reasonable maximum exposure (e.g., EPA 1989, 1991a).

[183] Appropriate data can be collected and evaluated, as described in Section 6.3.2, to characterize and document the occurrence of biodegradation in the vadose zone and its effects in attenuating vapor concentrations of biodegradable vapor-forming chemicals.

TABLE 6-1
RECOMMENDED VAPOR ATTENUATION FACTORS FOR RISK-BASED SCREENING OF THE VAPOR INTRUSION PATHWAY[184]

Sampling Medium	Medium-specific Attenuation Factor for Residential Buildings
Groundwater, generic value, except for shallow water tables (less than five feet below foundation) or presence of preferential vapor migration routes in vadose zone soils	1E-03 (0.001)
Groundwater, specific value for fine-grained vadose zone soils, when laterally extensive layers are present[185]	5E-04 (0.0005)
Sub-slab soil gas, generic value	3E-02 (0.03)
"Near-source" exterior soil gas, generic value except for sources in the vadose zone (less than five feet below foundation) or presence of routes for preferential vapor migration in vadose zone soils	3E-02 (0.03)
Crawl space air, generic value	1E-00 (1.0)

The VISL Calculator (http://www.epa.gov/oswer/vaporintrusion/guidance.html) also facilitates calculation of groundwater screening levels based on the recommended attenuation factor for fine-grained soil. EPA recommends that any use and application of this semi-site-specific groundwater attenuation factor be supported by site-specific geologic information (i.e., site geology and subsurface lithology). Significant characterization of the vadose zone may be needed to demonstrate that fine-grained layers are laterally extensive over distances that are large compared to the size of the building(s) or the extent of vapor contamination at a specific site, which is the recommended support for using the semi-site-specific attenuation factor for

[184] Use of these attenuation factors for estimating indoor air concentrations is contingent upon site conditions fitting the generic model of vapor intrusion described in Section 6.5.2 and subsurface conditions being characterized considering the recommendations in Sections 6.3 and 6.4.

[185] The Draft VI Guidance allowed for the modification of VISLs for groundwater by incorporating a lower attenuation factor, based upon "some site-specific inputs", which estimates a greater reduction in vapor concentrations in the vadose zone than the generic value (EPA 2002c, 2010b). In the Draft VI Guidance, graphs were provided from which such "semi-site-specific" attenuation factors could be selected and justified based upon site-specific soil type and depth to the water table. Based upon analysis of EPA's expanded database, a single groundwater attenuation factor is provided in this Technical Guide for fine-grained soils.

fine-grained soil.[186] For purposes of applying the groundwater attenuation factors, EPA recommends the depth to groundwater be estimated relative to the bottom of the building foundation and be based upon the seasonal high groundwater table.

6.5.4 Comparing Sample Concentrations to Health-based Screening Levels

When evaluating environmental sampling results to assess the vapor intrusion pathway, it is important to first determine that the samples were collected appropriately. Section 6.4 provides information about recommended sampling locations and procedures for vapor intrusion investigations. In addition, EPA recommends collecting and evaluating appropriate site-specific information to demonstrate that the property fulfills the conditions and assumptions of the generic conceptual model underlying the VISLs, as described in Section 6.5.2.

After verifying that the CSM justifies the use of the VISLs, the individual sample concentrations may be compared to the appropriate medium-specific screening levels. In order to select the appropriate target media concentrations for comparison, it generally is important to identify whether a source of vapors for a building or a developed area occurs in the unsaturated zone, which is an important aspect of the CSM. This allows the site data to be segregated into two categories:

- Data representing areas where contaminated groundwater is the only source of contaminant vapors.

  In this first case, groundwater VISLs are generally appropriate to use to evaluate groundwater concentrations (also see sampling recommendations in Sections 6.3.1 and 6.4.5). Under these circumstances, EPA recommends that the plume be shown to be stable or shrinking (i.e., is not migrating or rising in concentration, including hazardous byproducts of any biodegradation) to establish that the potential for vapor intrusion to pose a human health risk from vapor intrusion will not increase in the future. "Near-source" soil gas data (i.e., soil gas samples collected immediately above the water table) could also be compared to the soil gas VISLs to obtain a corroborating line of evidence (see recommendations in Section 6.3.1).

  When the anticipated outcome of the screening is a finding that groundwater poses acceptable human health risk from vapor intrusion on an area-wide basis, it may be appropriate to compare sampling results for the most greatly impacted well within the area of interest and show that these results are less than the groundwater VISLs.

- Data representing areas where the underlying vadose zone soil contains a source of vapors (e.g., residual NAPL).

  In this second case, EPA recommends that only soil gas VISLs be used and compared to results from "near-source" soil gas samples collected near the vapor source zone

[186] The general soil type assigned to paired vapor intrusion data in the EPA's database "generally represents the coarsest soil described in the vadose zone near the sample location" unless "sufficient stratigraphic information was available to indicate finer sediments are laterally continuous" (EPA 2012a). EPA recommends that similar criteria be applied to justifying the use of the semi-site-specific attenuation factor for groundwater (or selection of soil-related parameters for modeling); see Section 6.6. For these purposes, soil classified as clay, silty clay, silty clay loam, or silt consistent with the U.S. Soil Conservation Service classification system can be considered to be "fine-grained."

(also see sampling recommendations in Sections 6.3.1 and 6.4.4). In this situation, the groundwater VISLs (and vapor attenuation factors for groundwater) are not recommended for estimating potential upper-bound indoor air concentrations, because they have been derived assuming no other vapor sources exist between the water table and the building foundation.

In both cases, because of the complexity of the vapor intrusion pathway, EPA recommends that professional judgment be used when applying the VISLs.

Generally, if all subsurface sample concentrations for a given building or area are less than the respective medium-specific screening level, then vapor intrusion is less likely to pose an unacceptable human health risk to building occupants. On the other hand, when individual sample concentrations exceed the respective screening level, additional assessments may be warranted. So, for example, if a groundwater or "near-source" soil gas concentration exceeds the respective screening level, it is recommended that sub-slab soil gas testing and indoor air testing be conducted.

However, we would note that any individual subsurface sampling result that exceeds the respective, chronic screening level does not establish that vapor intrusion will pose an unacceptable human health risk to building occupants. For one, the subsurface screening levels are expected to be conservative (i.e., are likely to over-estimate the contribution to indoor air levels arising from vapor intrusion) for many buildings due to the use of a high-end attenuation factor (see Section 6.5.3). In many cases, indoor air concentrations arising from vapor intrusion would be expected to be lower than those estimated using the recommended generic attenuation factors. For carcinogens, the screening levels are set using a one-per-million lifetime cancer risk (i.e., 10^{-6}), whereas EPA recommends consideration of a cancer risk range when making risk management decisions (see Section 7.4.1). Finally, sampling results can be expected to be variable spatially and temporally and these screening levels assume a long period of exposure at the stated concentration.

Owing to the temporal variability in building-specific data and the potential temporal and spatial variability in soil gas vapor concentrations, EPA generally recommends multiple samples be collected (see Section 6.4) and compared to the respective medium-specific screening level. In addition, the results of risk-based screening are generally most useful when they can be evaluated for indoor air and subsurface vapor sources concurrently and in the context of the CSM. EPA, therefore, generally recommends that multiple lines of evidence be developed and their results weighed together when evaluating and making risk-informed decisions pertaining to vapor intrusion. EPA generally recommends that concordance among the multiple lines of evidence be obtained, particularly when considering a determination that the vapor intrusion pathway is incomplete or does not pose an unacceptable human health risk. Sections 7.1, 7.2, and 7.3 provide additional information and recommendations about developing and using multiple lines of evidence and risk management decision-making.

6.5.5 Planning for Communication of Sampling Results

EPA recommends the community involvement or public participation plan (See Section 9.1) describe and address community questions, concerns, and preferences for participation regarding sampling results. Generally, EPA recommends that the site planning team provide validated results to property owners and occupants. These results can be transmitted to relevant parties in a letter, along with a description of what future actions, if any, may be

warranted. In addition, the site planning team may choose to hold a community meeting to discuss the sampling results in general terms and EPA's plans, if any, for response actions. Section 9.4 provides additional information for communicating sampling results.

6.6 General Principles and Recommendations for Mathematical Modeling

When suitably constructed, documented, and verified, mathematical models can provide an acceptable line of evidence supporting risk management decisions pertaining to vapor intrusion. In certain situations (e.g., for future construction on vacant properties), it is particularly useful to employ mathematical modeling to predict reasonable maximum indoor air concentrations, because indoor air testing is not possible.

Mathematical modeling is most appropriately used in conjunction with other lines of evidence. For example, in the brownfield development case (i.e., yet-to-be-constructed building), EPA generally recommends these additional lines of evidence include, at a minimum, data that characterize potential subsurface vapor sources and associated geologic and hydrologic conditions in the vadose zone (see Sections 6.3.1 and 6.3.2).

Generally, mathematical models transform empirical values of input parameters into predictions of chemical concentrations in environmental media. The model input parameters are equally as important to the results as the mathematical components of the model (i.e., governing equations and solution algorithms). As a consequence, the results critically depend on the choices for the inputs.

Historically, to assure confidence in predictions of mathematical models, they have been compared to measured, site-specific values. When measured and predicted values do not reasonably match, model input parameters are adjusted through calibration. For example, calibration is commonly used in groundwater flow modeling, in which model-predicted groundwater levels are matched to measured groundwater levels for a baseline condition to gain insight into hydrogeologic properties. The calibrated input parameters must reasonably represent the underlying phenomena and the characteristics of the model must reasonably match the field situation. Calibration of mathematical models is known to be non-unique, so that different sets of parameters can be used to fit the same observed data. This means that calibration does not produce a theoretically correct set of parameters. Because various values of input parameters could be used in the calibrated model, there will always be uncertainty as to the actual values.

Three approaches exist for applying mathematical models in these circumstances:

1) Calibrating the mathematical model to the measured indoor air concentration (and, possibly, the sub-slab soil gas concentration) considered to be representative of vapor intrusion (i.e., background vapor sources have been identified and removed prior to sampling and data evaluation indicates that the concentration is reasonably attributable to vapor intrusion). Calibration entails adjusting the input parameters within plausible and realistic ranges so that the predicted indoor air concentrations (or sub-slab soil gas concentrations) are similar to the measured vapor concentrations. The adjusted input parameters can then be compared to site-specific conditions and data to verify that the CSM and calibrated model are coherent and sound.

2) Conducting an uncertainty analysis (perhaps using an automated uncertainty analysis (see http://www.epa.gov/athens/learn2model/part-two/onsite/uncertainty-vi.html as only one example)) to understand where, within the probability distribution of results, model results with pre-selected default parameters lie. This approach may be particularly useful where indoor air concentrations have not been measured or non-site-specific inputs have been used.

3) Using a bounding case analysis, where parameters are chosen to represent conditions that give a high-impact (e.g., "reasonable worst") case – see Glossary – or "worst" (maximum plausible)[187] case. This approach may be particularly useful where the predicted indoor air concentrations for the bounding case can be shown to pose acceptable human health risk.[188] The range of predicted indoor air concentrations can be established if the analysis also includes a low-impact ("best") case.

Unless site-specific parameter values are obtained for input parameters and the mathematical model is calibrated to field data, use of default input parameter values will generate model results that lie at an unknown point within an uncertainty band of the model outcomes. Because the combined effect of parameter uncertainty is large, a one- or two-order of magnitude error might be made unknowingly. To reduce these errors, sub-slab vapor sampling could be used to characterize the vapor concentration(s) beneath a building. Model results (i.e., predicted sub-slab soil gas concentrations) that match measured values would have increased confidence. Alternately, using bounding estimates of parameter values could provide a conservative model result that would be expected to represent the reasonable worst case of potential exposure.

Three examples follow where differing applications of mathematical models would be useful in vapor intrusion assessment:

- Verify General Magnitude. Modeling using site-specific inputs can be useful for verifying the general magnitude of measured indoor air sample concentrations, which may allow risk managers to reach supportable conclusions not to conduct additional indoor air testing. In this situation, the model could be calibrated to indoor air measurements and the plausibility of the calibrated input parameters evaluated. If the calibrated model input parameters are plausible, then they can be considered an additional line of evidence supporting risk management decisions.

- Explore Range of Outcomes through Uncertainty Analysis. In certain situations, indoor air testing is not possible (e.g., for future construction on vacant properties) or feasible.

[187] For purposes of this Technical Guide, the phrase "worst case indoor air concentration" is intended to be a semi-quantitative phrase, referring to the high end of the exposure distribution. "No-further-action" decisions can normally be supported more confidently when the "worst case indoor air concentration" can be shown to pose acceptable health risks. Under these conditions, the "reasonable maximum exposure" (see Glossary) typically would also pose acceptable health risks.

[188] "Bounding estimates" purposely overestimate the exposure or dose in an actual population for the purpose of developing a statement that the risk is "not greater than..." (EPA 1992c).

Here the range of possible outcomes could be explored with the model through an uncertainty analysis. For example, model input parameters, including building and vadose zone soil properties, could be varied within plausible ranges to determine the parameters to which the model is most sensitive to guide field investigations. Uncertainty analyses can also be used to ascertain whether the subsurface vapor source concentrations are such that indoor air samples would not be expected to contain detectable levels of vapor-forming chemicals arising from vapor intrusion.

- Generate Bounding Estimates. If the range of parameter values is known with confidence for the site, then parameters can be chosen to represent the bounding case of maximum plausible vapor intrusion (i.e., worst case).

In each of these examples, model parameters might vary in space and time because of subsurface heterogeneity, transient hydrologic conditions, or variation in building operation. Thus, there is a need for characterizing spatial and temporal variability.

Mathematical models provide opportunities to predict conditions that cannot be observed directly, but the reliability of the results need to be confirmed, especially when limited site-specific data are available and the model is not calibrated to observed indoor air concentrations. Use of a generic, conservative attenuation factor (see Section 6.5.3) to predict potential, upper-bound indoor air concentrations (based upon soil gas concentrations – see Sections 6.4.3 and 6.4.4) implicitly represents use of a mathematical model, even when the attenuation factor is selected from an empirical data set. Whether the mathematical model is implicit (e.g., generic, conservative attenuation factor) or explicit (e.g., mathematical model that generates a bounding estimate), both analytic approaches make the assumption that site-specific attenuation is likely to be greater and the indoor air concentration(s) is (are) likely to be lower than predicted value(s).

The use of extreme and non-representative assumptions or parameter values is the most common weakness of mathematical modeling for environmental assessments. Mathematical modeling typically yields more reliable results when used with high-quality, site-specific data inputs (that is, representative groundwater or soil gas concentrations, depth to groundwater, soil type and moisture content underneath the building, and the building conditions (e.g., air exchange rate, building mixing height), for example); in these cases, the site-specific data inputs and CSM provide additional lines of evidence supporting the use of mathematical modeling as a line of evidence.

Whenever mathematical modeling is used to make predictions pertaining to vapor intrusion, EPA recommends that the site planning and data team:

- Identify the underlying mathematical model and include appropriate references to document that it has been peer-reviewed.
- Verify that the selected model fits the CSM and is appropriate for the chosen purpose.
- Document all inputs and outputs in a readily recognizable and understandable format.
- Identify the critical parameters and conduct a sensitivity analysis for the most critical parameters.

- Determine and document the appropriate modeling approach (e.g., calibration, uncertainty analysis, bounding case analysis).

- Perform new individual measurements (i.e., field sampling) to confirm one or more results of the modeling.

A critical assumption underlying almost all mathematical models of vapor intrusion is that site-specific subsurface characteristics will tend to reduce or attenuate soil gas concentrations as vapors migrate upward from the source and into overlying structures. Mathematical modeling of vapor intrusion is, therefore, not generally recommended for sites and buildings where unattenuated or enhanced transport of vapors toward and into a building is reasonably expected. Sections 5.4, 6.3.2, and 6.5.2 identify several factors that may result in unattenuated or enhanced transport of vapors toward and into a building.

7.0 RISK ASSESSMENT AND MANAGEMENT FRAMEWORK

This section provides general recommendations about risk-informed decision-making pertaining to vapor intrusion. The risk management information described herein presumes that a sound CSM has been developed (see Sections 5.4 and 6.3), which is supported by multiple lines of evidence, and that subsurface vapor sources have been characterized (see Section 6.3.1) sufficiently to support the risk management decisions for the site. EPA also notes that temporal and spatial variability of sampling data can span at least an order of magnitude and often more.

Site-specific decisions potentially supported by the information described in this section include:

- Whether to install engineered exposure controls to prevent or reduce the impacts of vapor intrusion in specific buildings.
- Whether to remediate subsurface vapor sources for the site to reduce risks posed by vapor intrusion.
- Whether the vapor intrusion pathway is incomplete and there is no potential for unacceptable human exposure under current or future conditions.
- Whether to collect additional information as part of the detailed vapor intrusion investigation or monitor indoor air as part of an overall vapor intrusion remedy.

As conditions warrant and resources allow, EPA generally recommends that officials responsible for overseeing cleanups pursuant to RCRA and CERCLA ensure that past decisions pertaining to vapor intrusion continue to be supported by current conditions (EPA 2002b).

Finally, EPA encourages systematic approaches to decision-making, which can foster scientific rigor, consistency, and transparency.

7.1 Collect Site-specific Lines of Evidence

Current practice suggests that the vapor intrusion pathway generally be assessed using multiple lines of evidence. As discussed in Sections 5.1, 5.4, 5.5.2, 6.3, 6.4, and 6.5, appropriate lines of evidence to support development of the CSM and evaluate the vapor intrusion pathway may include, but are not limited to:

Subsurface Vapor Sources

- Site history and source of the contaminants to demonstrate that vapor-forming chemicals have been or may have been released to the underlying and surrounding subsurface environment and identify the type of vapor source (e.g., vapor-forming chemicals dissolved in groundwater or present in a NAPL).
- Groundwater data (generally recommended from more than one sampling event), as appropriate, to confirm the presence of a water-table aquifer, if present, as a source of vapors and establish its chemical and hydrogeologic characteristics.

- Soil gas data, bulk soil sampling data,[189] and/or NAPL sampling data to confirm the presence of contamination in the vadose zone, if present, as a source of vapors and establish its chemical and physical characteristics.

- Sub-slab (or crawl space) soil gas data to assess concentrations potentially available for entry with any intruding soil gas (generally recommended from multiple sampling events and in multiple locations to reduce the chance of reaching a false-negative conclusion (i.e., concluding subsurface vapor source strength is limited when vapor intrusion actually poses an unacceptable human health risk) or a false-positive conclusion.

- Comparison of groundwater and/or soil gas concentrations to VISLs to evaluate source strength and potential for a health concern if the vapor intrusion pathway is complete.

Vapor Migration and Attenuation in the Vadose Zone

- Soil gas survey data, including some level of vertical and spatial profiling, as appropriate, to confirm soil gas migration and attenuation along anticipated routes in the vadose zone between sources and buildings.

- Data on site geology and hydrology (e.g., soil moisture and porosity) to support the interpretation of soil gas profiles, the characterization of gas permeability, and the identification of anticipated soil gas migration routes in the vadose zone or the identification and characterization of impeded migration.

- Vertical profiles of chemical vapors, electron acceptors for microbial transformations (e.g., oxygen), and degradation products (e.g., methane, vinyl chloride) to characterize attenuation due to biochemical (e.g., biodegradation) processes.

- Utility corridor assessment to identify preferential migration routes, if any, that facilitate subsurface vapor migration between sources and towards and into buildings

Building Foundation Assessment, Including Susceptibility to Soil Gas Entry

- Building construction and current conditions, including utility conduits or other preferential routes or openings for soil gas entry, heating and cooling systems in use, and any segmentation of ventilation and air handling.

- Instrumental (e.g., PID) readings to locate and identify potential openings for soil gas entry into buildings.

[189] As noted in Section 6.4, bulk soil sampling and analysis can be used to characterize the chemical composition and general location of contamination; for example, high soil concentrations generally would indicate impacted soil. On the other hand, non-detect results for soil samples cannot be interpreted to indicate the absence of a subsurface vapor source, because of the potential for vapor loss due to volatilization during soil sampling, preservation, and chemical analysis. Therefore, bulk soil (as opposed to soil gas) sampling and analysis is not currently recommended for estimating the potential for vapor intrusion to pose unacceptable human health risk in indoor air.

- Grab samples of soil gas or indoor air near openings to characterize the composition of presumptive soil gas entering buildings.

- Pressure data to assess the driving force for soil gas entry into building(s) via advection.

- Tracer-release data to verify openings in building foundations for soil gas entry or assess fresh air exchange within buildings.

Interior Assessment

- Indoor air sampling data (Section 6.4.1) to assess the presence of subsurface contaminants in indoor air (Section 6.3.4), estimate potential exposure levels to building occupants to support site-specific human exposure and human health risk assessments (see Section 7.4), and otherwise diagnose vapor intrusion and characterize background concentrations (Section 6.3.5).[190]

Indoor and Outdoor Sources of Vapor-forming Chemicals Found in the Subsurface

- Building-specific indoor sources of volatile chemicals (Section 2.7).

- Concurrent outdoor air data to assess potential contributions of ambient air to indoor air concentrations (Sections 6.3.5 and 6.4.2).

- Comparative evaluations of indoor air and sub-slab soil gas data (e.g., Section 6.3.5), including calculation and comparison of building-specific, empirical attenuation factors (EPA 2012a, Section 3.0) (e.g., to assess their consistency among subsurface contaminants to assist in identifying indoor vapors arising from vapor intrusion).

Additional Supporting Lines

- Results of statistical analyses (e.g., data trends, contaminant ratios) to support data interpretation.

- Results of mathematical modeling that rely upon site-specific inputs (Section 6.6).

The relative utility of these and other individual lines of evidence will depend on site-specific factors, as described and documented in the CSM (Section 5.4), and the objectives of the investigation (Section 6.3). For example:

- When the primary subsurface vapor source is residual NAPL in the vadose zone, bulk soil data would typically be collected to characterize the chemical composition and general location of contamination; for example, high soil concentrations generally would

[190] In certain cases, depending in part on the results (e.g., concentrations exceed risk-based screening levels), indoor air sampling data may be a sufficient basis for supporting decisions and recommendations to undertake pre-emptive mitigation (see Sections 3.3 and 7.8) in lieu of additional rounds of sampling and analysis or an evaluation of the contribution of background sources to indoor air concentrations.

indicate impacted soil in the vadose zone, as discussed in Sections 6.3.1 and 6.4.[191] In this situation, "near source" soil gas data, rather than groundwater data, would be recommended for assessing the potential for vapor intrusion to pose an unacceptable human health risk to occupants of any building overlying the NAPL zone. On the other hand, when the subsurface vapor source underneath a building is shallow groundwater, groundwater sampling data from the uppermost hydrogeologic unit would be an appropriate line of evidence for purposes of assessing the potential for vapor intrusion to pose an unacceptable human health risk, unlike the previous example.

- In both of the preceding cases, information about the soil conditions (e.g., soil type and moisture) *underlying the buildings* would be useful for characterizing the subsurface vapor migration route between the subsurface vapor source and the building. Sub-slab soil gas samples and indoor air samples (if background sources are removed or accounted for), in concert with other lines of evidence, can provide a strong line of evidence regarding whether the vapor intrusion pathway is complete.

- For an industrial building, indoor air testing while the HVAC system is not operating (see Section 6.3.3) could be useful for diagnosing vapor intrusion. On the other hand, single-family detached homes can generally be presumed susceptible to soil gas entry when heating or cooling systems are operating.

7.2 Weigh and Assess Concordance Among the Lines of Evidence

To the risk manager, the ideal outcome from collecting multiple lines of appropriate evidence is a concordant set of site-specific information that unambiguously supports decisions that can be made confidently. However, based upon observations at many buildings and sites, the vapor intrusion site where all available information is in agreement and is unambiguous may be the exception rather than the rule. Some lines of evidence may not be definitive (e.g., indoor air and subsurface concentrations can be greatly variable temporally and spatially). At worse, some individual lines of evidence may be inconsistent with other lines of evidence. In general, when lines of evidence are not concordant and the weight of evidence does not support a confident decision, EPA recommends re-evaluating the CSM, which may warrant adjusting the CSM to better represent the weight of the available evidence.

For example, a building overlying contaminated shallow groundwater may have high concentrations of vapor-forming chemicals in the sub-slab soil gas samples, but lower concentrations in soil gas samples collected exterior to the building at intermediate depths. In this example, the exterior soil gas data suggest there may not be a connected vapor migration path between the groundwater source and the building that exhibits continuous attenuation along the path. Nevertheless, the data review team may conclude that vapor migration is capable of transporting hazardous vapors from the source to building(s) if the groundwater and sub-slab soil gas samples share common contaminants that are known or suspected to have been released at the site (for example, samples of both groundwater and

[191] Because of the large uncertainties associated with measuring concentrations of volatile contaminants introduced during soil sampling, preservation, and chemical analysis, bulk soil (as opposed to soil gas) sampling and analysis is not currently recommended for estimating the potential for vapor intrusion to pose unacceptable human health risk in indoor air. In addition, there are uncertainties associated with soil partitioning calculations.

the sub-slab soil gas contain TCE). In this circumstance, the data review team may wish to consider whether the occurrence of a higher TCE concentration in the sub-slab soil gas than in the exterior soil gas sample(s) can be explained by: (1) a previously unknown or unrecognized utility corridor or other preferential migration route that provides relatively unattenuated vapor transport between the groundwater and the building; (2) a previously unknown or unrecognized source of TCE in the vadose zone; or (3) the possibility that the exterior soil gas samples were not well located for purposes of characterizing subsurface vapor migration. This example also underscores the importance of developing an adequate CSM (e.g., identify all sources and preferential routes of subsurface vapor migration) and illustrates why EPA generally recommends that the vapor intrusion pathway not be deemed incomplete based upon any single line of evidence (EPA 2010b), such as exterior soil gas in this example.

When lines of evidence are not concordant and the weight of evidence does not support a confident decision, it may also be appropriate to collect additional lines of evidence, possibly including additional samples, depending upon the CSM. For example:

- Appropriate site-specific testing (see Section 6.3.5) can be conducted to assess the contribution of background sources of vapor-forming chemicals, including comparisons among chemicals of their relative concentrations in indoor air, outdoor air, and soil gas. Background sources of vapor-forming chemicals may help to explain situations where the indoor air concentration is higher than can be accounted for by the subsurface vapor source or the sub-slab soil gas data.

- Diagnostic testing of indoor air (see Section 6.4.1), building condition assessments or utility surveys, or supplemental hydrogeologic characterization (see Section 6.3.2) can be used to investigate the suspected presence of preferential migration routes, such as those described in Sections 5.4 and 6.3.2. Such investigations may help to explain situations where the sub-slab or indoor air concentration appears to reflect unattenuated vapor transport from the subsurface vapor source.

- Building susceptibility to vapor intrusion can be tested (see Section 6.3.3), which may help to explain situations where the indoor air concentration is significantly lower than expected based upon the sub-slab soil gas data.

- Vapor migration in the vadose zone can be further characterized to identify impedances to vapor migration (see Section 6.3.2), appropriate semi-site specific attenuation factors can be considered (see Section 6.5.3), and appropriate modeling can be conducted (see Section 6.6) to investigate site-specific vapor attenuation. Such data and analyses may help to explain situations where the sub-slab soil gas concentration is significantly lower than expected based upon groundwater source or “near-source” soil gas concentrations and the respective medium-specific attenuation factor (Section 6.5.2 and Appendix A). In some of these situations, the vapor intrusion pathway may be impeded, or perhaps even incomplete, due to geologic, hydrologic, or microbial characteristics in the vadose zone (see Sections 6.3.2 and 7.3).

Recognizing the temporal and spatial variability of indoor air and subsurface concentrations and the potentially episodic nature of vapor intrusion at some sites (Section 2), EPA generally recommends collecting multiple rounds of sampling in the respective media from multiple locations (see Section 6.4) to reduce the chance of reaching a false-negative or false-positive

conclusion. Considerable judgment may be necessary when evaluating multiple data sets from individual sampling events to support decision-making.

In summary, EPA recommends the appropriate use and evaluation ("weighing") of multiple lines of evidence for determining whether the vapor intrusion pathway is complete or not, whether any elevated levels of contaminants in indoor air are likely caused by subsurface vapor intrusion versus an indoor source or an ambient (outdoor) air source, whether concentrations of subsurface contaminants in indoor air may pose a health concern, and whether interim response measures to mitigate vapor intrusion are warranted.

7.3 Evaluate Whether the Vapor Intrusion Pathway is Complete or Incomplete

For purposes of this Technical Guide, and as reflected in the conceptual model of vapor intrusion (see Section 2), the vapor intrusion pathway is referred to as "complete" for a specific building or collection of buildings when the following five conditions are met under current conditions:

1) A subsurface source of vapor-forming chemicals is present underneath or near the building(s) (see Sections 2.1, 5.3, 6.2.1, and 6.3.1);

2) Vapors form and have a route along which to migrate (be transported) toward the building(s) (see Sections 2.2 and 6.3.2);

3) The buildings are susceptible to soil gas entry, which means openings exist for the vapors to enter the building and driving 'forces' exist to draw the vapors from the subsurface through the openings into the building(s) (see Sections 2.3 and 6.3.3);

4) One or more vapor-forming chemicals comprising the subsurface vapor source(s) is (or are) present in the indoor environment (see Sections 6.3.4 and 6.4.1); and

5) The building is occupied by one or more individuals when the vapor-forming chemical(s) is (or are) present indoors.

Considerable scientific and professional judgment will likely be needed when weighing lines of evidence to determine whether the vapor intrusion pathway is complete or incomplete. Each of the first four conditions generally entails obtaining and weighing multiple lines of evidence, whereas the fifth condition generally can be confidently determined by direct observation. EPA recommends considering and evaluating together the various lines of evidence in determining completeness of the vapor intrusion pathway under current conditions.

As noted previously (e.g., Section 3.2), EPA recommends that risk management decisions also consider whether the vapor intrusion pathway is 'potentially complete' under reasonably expected future conditions. The vapor intrusion pathway is referred to as 'potentially complete' for a building when:

- a subsurface source of vapor-forming chemicals is present underneath or near an existing building or a building that is reasonably expected to be constructed in the future;

- vapors can form from this source(s) and have a route along which to migrate (be transported) toward the building; and

- three additional conditions are reasonably expected to all be met in the future, which may not all be met currently; i.e.,

    - the building is susceptible to soil gas entry, which means openings exist for the vapors to enter the building and driving forces exist to draw the vapors from the subsurface through the openings into the building;

    - one or more vapor-forming chemicals comprising the subsurface vapor source(s) is (or will be) present in the indoor environment (see Sections 6.3.4 and 6.4.1); and

    - the building is or will be occupied by one or more individuals when the vapor-forming chemical(s) is (or are) present indoors.

This determination also generally entails obtaining and weighing multiple lines of evidence.

A complete pathway indicates that there is an opportunity for human exposure, which warrants further analysis to determine whether there is a basis for undertaking a response action(s). Specifically, a complete exposure pathway does not necessarily mean that an unacceptable human health risk exists due to vapor intrusion. Rather, specific exposure conditions, such as the magnitude, frequency, and duration of exposures, and the contribution from background concentrations warrant examination; hence, EPA recommends additional analyses be conducted to assess and characterize human health risk to building occupants where the vapor intrusion pathway is determined to be complete (see, for example, Sections 7.4 and 6.3.5). On the other hand, human exposure, and hence human health risk, from the vapor intrusion pathway would not exist if the pathway is incomplete.

The conceptual model described in Section 2 identifies the characteristics of the vadose zone that could render the vapor intrusion pathway incomplete under current and future conditions. These individual characteristics include, but are not limited to:

- Soil layers that significantly and persistently impede vapor transport due to geologic or hydrologic conditions (e.g., fine-grained soil, soil with high moisture content) and are laterally extensive over distances that are large compared to the size of the building(s) or the extent of subsurface contamination with vapor-forming chemicals; and

- A biologically active vadose zone that can significantly and persistently attenuate soil gas concentrations due to biodegradation, in which all appropriate conditions (e.g., nutrients, moisture, and electron acceptors, such as dissolved oxygen in the case of aerobic biodegradation) are readily available over a laterally extensive area.

EPA recommends demonstrating these characteristics, when present, by collecting, evaluating, and documenting multiple lines of evidence, as identified in Section 6.3.2. In addition, EPA recommends that any determination that the vapor intrusion pathway is incomplete be supported by site-specific evidence to demonstrate that:

- The nature and extent of vapor-forming chemical contamination in the subsurface has been well characterized, as discussed in Sections 6.3.1 and 6.4. Ideally, where groundwater is the source of vapors, the plume has been shown to be stable or

shrinking to establish that the potential for vapor intrusion to pose a health concern will not increase in the future.

- The types of vapor sources and the conditions of the vadose zone and surrounding infrastructure do not present opportunities for unattenuated or enhanced transport of vapors toward and into any building (e.g., via a preferential migration route(s)), as discussed in Sections 5.4, 6.2.1, 6.3.2, and 6.5.2.

When the vapor intrusion pathway is determined to be incomplete, then vapor intrusion mitigation is not generally warranted under current conditions. EPA recommends that site managers also evaluate whether subsurface vapor sources that remain have the potential to pose a complete vapor intrusion pathway and unacceptable human health risk due to vapor intrusion in the future if site conditions were to change. For example, potentially unpredictable changes in the transitory soil characteristics (e.g., soil moisture) and soil gas concentrations may occur as a result of constructing a new building or supporting infrastructure. Either type of change could result in the potential for unacceptable human health risk due to vapor intrusion in the future.

Response actions may, therefore, be warranted to protect human health wherever and as long as subsurface vapor sources remain that have the potential to pose unacceptable human health risk in the future due to vapor intrusion. These response actions (see Section 7.7) may include institutional controls (see Section 8.6) (e.g., to record and alert parties about the presence of subsurface vapor sources and/or to inform the need for a confirmatory vapor intrusion investigation in case infrastructure or geologic conditions are modified in the future). In addition, subsurface remediation may be warranted to protect human health or the environment via other exposure pathways (e.g., groundwater discharge to surface water bodies), consistent with applicable statutes and considering EPA guidance.

7.4 Conduct and Interpret Human Health Risk Assessment

EPA generally recommends that a human health risk assessment be conducted to determine whether the potential human health risk posed to building occupants by a complete or potentially complete vapor intrusion pathway are within or exceed acceptable levels, consistent with applicable statutes[192] and considering EPA guidance (EPA 1991a, 2009c). The primary purpose of this risk assessment is to provide risk managers with an understanding of the actual and potential risks to human health posed by vapor intrusion under current and reasonably expected future conditions. This information may be useful in determining whether a current or potential future threat to human health exists, as described in Sections 7.4.1, 7.4.2, and 7.5.2,[193] which warrants response action(s), as described in Sections 7.7 and 8.

[192] In the RCRA corrective action program, any human health risk assessment would typically be conducted during the RCRA facility investigation, if a release to the environment is identified. Under the CERCLA remedial program, a human health risk assessment would typically be conducted during the remedial investigation and is generally referred to as a baseline (i.e., pre-cleanup) risk assessment.

[193] In appropriate circumstances (e.g., where time is of the essence to ensure protection of human health; see, for example, Section 7.5.2), a formal human health risk assessment need not be completed and documented before taking a response action, but a preliminary evaluation of human health risk using individual building data or aggregated community data is generally recommended (also see Section 7.8).

The human health risk posed to building occupants by intrusion of a given vapor-forming chemical will depend upon its toxicity, its concentration in indoor air, the amount of time the occupants spend in the building, and other variables (e.g., human life stage (e.g., child) can matter for some chemicals (e.g., those with a mutagenic mode of action for carcinogenicity)). EPA recommends that its risk assessment guidance (e.g., EPA 2009c, EPA 2003) be used to identify, develop, and combine information about these variables and characterize human health risk due to vapor intrusion from subsurface contaminant sources.

For the vapor intrusion pathway, the inhalation route is the primary means of human exposure. Therefore, the human health risk assessment uses estimates of indoor air exposure concentrations, exposure duration and frequency for building occupants, and the potential toxicity of the vapor-forming chemicals found in the subsurface (e.g., inhalation unit risk and noncancer reference concentration) to characterize risks of cancer and noncancer effects (EPA 2009c). Generally, exposure concentrations in existing buildings can be estimated using direct measurements of indoor air (see Sections 6.3.4 and 6.4.1). EPA recommends that time-integrated measurements from multiple sampling events be used to estimate exposure concentrations appropriate for the exposure (occupancy) scenario being evaluated (e.g., residential versus commercial), when the risk assessment for an existing building would support a conclusion that the human health risk is acceptable (see Section 7.4.1).[194,195] Generally, modeling would be used to conservatively estimate exposure concentrations under future conditions in buildings yet to be constructed in areas with subsurface contamination by vapor-forming chemicals (see Section 6.6). EPA recommends the noncancer assessment consider the potential for adverse health effects from short-duration inhalation exposures (i.e., acute, short-term, or subchronic exposure durations),[196] as well as longer term inhalation exposure (i.e., chronic exposure) conditions. EPA recommends that inhalation toxicity values be selected

[194] An individual sample, collected at a randomly chosen time, may under-estimate (or over-estimate) average and reasonable maximum exposure conditions. From their high-frequency, measured data, Holton et al. formulated a synthetic data set (simulating one-day-average concentrations), which they used to estimate that a single, randomly drawn, one-day sample had a forty percent chance of being less than the true mean (Holton et al. 2013b; see Table 1 therein). When the true mean was assumed to exceed the risk-based action level ("target concentration" in their parlance) by two or five times, they estimated that a single, randomly drawn, one-day sample had a twenty percent or six percent chance, respectively, of not detecting the exceedance. These data support EPA's recommendation to collect multiple rounds of indoor air sampling data to reduce the chance of reaching a false-negative conclusion (i.e., concluding exposure is at an acceptable risk level when it is not). Collecting multiple rounds of indoor air sampling can also reduce the chance of reaching a false-positive conclusion (i.e., concluding that vapor intrusion poses unacceptable human health risk when it does not), because an individual sample, collected at a randomly chosen time, may over-estimate the average and reasonable maximum exposure conditions.

[195] Given EPA's assigned mission to protect human health from environmental contamination and recognizing the disruption to building owners and occupants caused by indoor air sampling, risk managers may choose to pursue pre-emptive mitigation (i.e., early action) at some buildings (see Sections 3.3 and 7.8) rather than, for example, conduct multiple rounds of sampling over a few years to establish an estimate of long-term average exposure concentration and characterize temporal variability.

[196] The inhalation reference concentration (RfC) (expressed in units of mass concentration in air) is defined as an estimate (with uncertainty spanning perhaps an order of magnitude) of a continuous inhalation exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. Reference values may be derived for acute (≤24 hours), short-term (>24 hours, up to 30 days), subchronic (>30 days, up to approximately 10% of the life span), and chronic (greater than 10% of the life span) exposure durations, all of which are derived based on an assumption of continuous exposure throughout the duration specified. See http://www.epa.gov/ncea/iris/help_ques.htm#whatiris

considering OSWER's hierarchy of sources (EPA 2003) and that relevant existing guidance (e.g., EPA 2009c) be followed in situations where a desired toxicity value is not available.

When a single vapor-forming chemical is present in the subsurface and intrudes as a vapor into occupied building spaces, the noncancer human health risk can be characterized by calculating the noncancer hazard quotient (HQ) (EPA 2009c,Chapter 8). When multiple vapor-forming chemicals are present in the subsurface and intrude as vapors into occupied building spaces, the HQ estimates for each chemical are aggregated (as a simple sum, which is the Hazard Index (HI)), based upon the assumption that each chemical acts independently (i.e., there are no synergistic or antagonistic toxicity interactions among the chemicals). If the HI exceeds one, there may be concern for potential adverse non-cancer effects and risk assessors should consider segregating the chemicals by target organ or toxic effect to derive separate hazard index (HI) values for each (EPA 2009c, Chapter 8). EPA recommends that noncancer HQ and HI values be estimated for each type of exposure period identified in the conceptual site model or indicated by measurements of indoor air levels of vapor-forming chemicals (e.g., chronic, subchronic, short-term, acute), evaluating inhalation reference concentrations that "match the characterization of the exposure scenario" (EPA 2009c, Chapter 4).[197]

The carcinogenic risks can be characterized by calculating the excess cancer risk over a lifetime (LCR) and, if multiple vapor-forming chemicals are present, aggregating the LCR estimates for each carcinogen (as a simple sum), based upon the assumption that each chemical acts independently (EPA 2009c, Chapter 8).

A well-crafted risk characterization section (EPA 1992c, 1995ab, 2000b, 2009c) puts risk calculations into context for risk managers, so that they may effectively weigh and interpret risk assessment results and recognize key uncertainties (e.g., in the exposure and dose-response assessments and risk estimation).[198] Additional recommendations for promoting and increasing the utility and transparency of human health risk assessments can be found in *Framework for Human Health Risk Assessment to Inform Decision Making* (EPA-RAF, 2014).

[197] For example, when evaluating situations in which vapor concentrations in indoor air exceed the chronic reference concentration (see Section 7.4.1), and there are shorter periods of significantly higher vapor intrusion exposure, EPA recommends that noncancer risks for the shorter periods also be characterized using toxicity values appropriate for the respective period(s). On the other hand, if vapor concentrations in indoor air are consistently less than benchmarks for acceptable chronic exposure, then exposures for less-than-chronic scenarios are unlikely to pose unacceptable human health risk.

[198] For example, EPA recommends that the risk characterization for existing buildings describe the uncertainty in the exposure assessment arising from: (i) inherent variability of indoor air exposures over time and space; (ii) the match between the sampling data [e.g., sampling frequency (i.e., number of samples and time intervals between samples); and time period over which each sample was collected] and the exposure period represented by the selected toxicity value (e.g., chronic); and (iii) the ability to distinguish and apportion the contribution to indoor air concentrations arising from vapor intrusion versus background sources. EPA recommends that the risk characterization for future buildings describe the principal uncertainties in the exposure assessment, which may be associated with the type(s) of building use, building construction and operations (e.g., HVAC system), frequency and duration of occupancy, vapor concentrations in indoor air, or other factors.

EPA recommends that any human health risk assessment be documented; a summary in a decision document is also generally warranted.[199] EPA also recommends that human health risk information for individual buildings be communicated to building occupant(s) and owners. Section 9.4 provides additional information for communicating sampling results.

7.4.1 Risk Management Benchmarks

EPA recommends that OSWER programs make the risk management determination to take response action consistent with their statutes and regulations and considering existing program guidance.[200] The carcinogenic risk and non-cancer HI values used in this determination generally are the "cumulative risks" that include all exposure pathways that a given population may consistently face.[201] In making such risk management determinations, EPA generally recommends reporting the HQ and HI to one significant figure.

EPA generally uses a cancer risk range of 10^{-6} to 10^{-4} as a "target range" within which to manage human health risk as part of site cleanup. For judging whether indoor air exposures may pose acceptable health risk based upon potential non-cancer effects, EPA generally recommends that the target HQ or HI not exceed 1.

Once a decision has been made to undertake a response action, EPA has expressed a preference for cleanups that are at the more protective end of the cancer risk range. Thus, EPA recommends using an individual lifetime cancer risk of 10^{-6} as a point of departure for establishing cleanup levels based upon potential cancer effects (see Section 7.6).[202] The EPA risk manager may determine that a response action achieving reductions in human health risk

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[199] Devices that have been found to improve comprehension and retention of textual materials include a table of contents, clear section headings, and a summary (Morgan et al. 1992). It is most helpful to provide a summary that translates the risk assessment into relatively simple language that non-expert risk managers, stakeholders, and wider audiences can understand (Lundgren and McMakin, 2013). Hazards and risks posed by vapor intrusion are more likely to be misunderstood or misinterpreted if they are not explained in simple terms.

[200] See, for example: *The Role of the Baseline Risk Assessment in Superfund Remedy Selection Decisions*, OSWER Directive 9355.0-30, April 22, 1991 (EPA 1991a); *Rules of Thumb for Superfund Remedy Selection,* OSWER Directive 9355.0-69, August 1997 (EPA 1997); and Advanced Notice of Proposed Rulemaking: Corrective Action for Solid Waste Management Units at Hazardous Waste Management Facilities (61 *Federal Register* 19432, May 1, 1996). So, for example, EPA cited OSWER Directive 9355.0-30 (EPA 1991a) in its *Compilation of Information Relating to Early/Interim Actions at Superfund Sites and the TCE IRIS Assessment* (EPA 2014b).

[201] In some site-specific situations, a population might be exposed to a substance or combination of substances through several exposure pathways (i.e., not only the vapor intrusion pathway). For example, individuals might be exposed to substance(s) from a contaminated site by consuming contaminated drinking water from a groundwater supply, as well as from vapor intrusion. Once reasonably expected exposure pathways have been identified, EPA recommends examining whether it is likely that the same individuals would consistently face the reasonable maximum exposure for each pathway or a combination of some of these pathways. Under such circumstances, the total exposure to each chemical would equal the sum of the exposures by all consistently faced pathways (EPA 1989, Section 8.3) and EPA recommends that the risk assessor clearly identify those exposure pathway combinations for which a total risk estimate or hazard index is being developed. When characterizing human health risk arising from multiple pathways and posed by a vapor-forming chemical(s) with potential adverse noncancer effects, EPA recommends that the toxicity values for each pathway "match the characterization of the exposure scenario" (EPA 2009c, Chapter 4).

[202] See: National Oil and Hazardous Substances Pollution Contingency Plan (55 *Federal Register* 8717); and Advanced Notice of Proposed Rulemaking: Corrective Action for Solid Waste Management Units at Hazardous Waste Management Facilities (61 *Federal Register* 19432, May 1, 1996).

within the 10^{-6} to 10^{-4} cancer risk range is acceptable, however, depending on site-specific conditions or remedial factors.

For establishing cleanup levels based upon potential non-cancer effects, EPA generally recommends that the target HI not exceed 1 (see Section 7.6).

7.4.2 Accounting for Background Contributions

As noted previously, EPA recommends including in the human health risk assessment vapor-forming chemicals that are related to releases to the subsurface environment. Some of these vapor-forming chemicals may be present in indoor air due to 'background' sources (see Section 2.7). If data are available, EPA recommends that the contribution of 'background' to total exposure concentration(s) be distinguished in the human health risk assessment (EPA 2002e). If background vapor sources (see Glossary) are found to be primarily responsible for indoor air concentrations (see Section 6.3.5), then response actions for vapor intrusion would generally not be warranted for current conditions. In any event, EPA recommends that the risk characterization include a discussion of 'background' contributions to indoor air exposure and associated human health risk. With such information, EPA can help advise affected individuals about the environmental and public health risks they face that are within their control (e.g., indoor sources of vapor-forming chemicals in residences).[203] Other parties, including building owners and operators, may help with risk communication.

If 'background' contributions are unknown and such data are sought to support risk management decisions, EPA recommends that additional data be collected (see, for example, Section 6.3.5). Information on 'background' contributions of site-related, vapor-forming chemicals in indoor air is also important to risk managers because generally EPA does not clean up to concentrations below natural or anthropogenic background levels (EPA 2002e).

7.4.3 Occupational Exposure Limits

Permissible exposure limits (PELs) are enforceable occupational exposure standards developed by the Occupational Safety and Health Administration (OSHA) in the U.S. Department of Labor. Most of OSHA's PELs were adopted in 1971 from then-existing secondary guidance levels, such as Threshold Limit Values (TLVs) developed by the American Conference of Governmental Industrial Hygienists (ACGIH) to protect workers from adverse effects of occupational exposure to airborne chemicals. They were intended to protect workers against catastrophic effects (such as cardiovascular, liver, kidney, and lung damage), as well as more subtle effects (such as narcosis, central liver system damage, and sensory irritation).

PELs (and TLVs), however, are not intended to protect sensitive workers, may not incorporate the most recent toxicological data, and may differ from EPA derivations of toxicity values with respect to weight-of-evidence considerations and use of uncertainty factors. For these and other

[203] In cases where 'background' contamination (e.g., due to indoor use of a consumer product or household chemical in a residence) may pose a human health risk, but its remediation is beyond the authority of the applicable statute, risk communication to the public may be most effective when coordinated with public health agencies (EPA 2002e).

reasons, [204] EPA does not recommend using OSHA's PELs (or TLVs) for purposes of assessing human health risk posed to workers (EPA 1991c, Appendix C) by the vapor intrusion pathway or supporting final "no-further-action" determinations for vapor intrusion arising in nonresidential buildings. Rather, EPA's recommendations for assessing human health risk posed by vapor intrusion are set forth herein in Sections 7.4.1 and 7.4.2.

7.5 Concentration Levels Indicating Potential Need for Prompt Response Action

In some circumstances, human health risk arises from vapor intrusion, which warrants prompt response action. This Section provides some recommendations for identifying such circumstances.

7.5.1 Potential Explosion Hazards

EPA recommends using the chemical-specific LELs[205] to identify potential explosion hazards (e.g., for methane and other petroleum hydrocarbons). Whenever building-specific data (such as results from sub-slab soil gas samples and crawl space samples for any building type, indoor air samples from sheds or pump houses, or gas samples from confined or semi-confined spaces (e.g., sewers)) exceed one-tenth (10%) of the LEL for any chemical, a hazard is indicated that generally warrants prompt action.[206,207] EPA recommends to building owners and occupants the evacuation of buildings with potential explosion and fire hazards, along with immediate notification to the local fire department about the threat. Construction and operation of engineered systems that can reduce or eliminate intrusion of explosive vapors into existing buildings or unoccupied structures may also warrant consideration to reduce the potential for future explosion hazards.

7.5.2 Considering Short-term and Acute Exposures

EPA may identify health-protective concentration levels for vapor-forming chemicals based upon potential noncancer health effects that can be posed by air exposures over short-term or acute exposure durations, considering EPA guidance for human health risk assessment (e.g., EPA

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[204] OSHA's website (May 2015) currently states: "OSHA recognizes that many of its permissible exposure limits (PELs) are outdated and inadequate for ensuring protection of worker health. Most of OSHA's PELs were issued shortly after adoption of the Occupational Safety and Health (OSH) Act in 1970, and have not been updated since that time. Since 1970, OSHA promulgated … new PELs for 16 agents, and standards without PELs for 13 carcinogens. Industrial experience, new developments in technology, and scientific data clearly indicate that in many instances these adopted limits are [also] not sufficiently protective of worker health. This has been demonstrated by the reduction in allowable exposure limits recommended by many technical, professional, industrial, and government organizations, both inside and outside the United States." [On-line source: https://www.osha.gov/dsg/annotated-pels/] On October 10, 2014, OSHA issued a Chemical Management Request for Information (79 FR 61384), in which it acknowledges many of its PELs are not sufficiently protective and seeks comment on strategies to address this problem; available on-line at: https://www.osha.gov/FedReg_osha_pdf/FED20141010.pdf

[205] The Vapor Intrusion Screening Level Calculator (EPA 2015a) provides LELs for vapor-forming chemicals to facilitate identification of potential explosion hazards.

[206] NIOSH has designated such concentrations as immediately dangerous to life or health (IDLH).

[207] Although the building-specific data may vary temporally, any short-term exceedance of one-tenth of the LEL indicates vapor concentrations that, given an ignition source and available oxygen, may be capable of causing an explosion.

2009c) and using sources of toxicity information considering OSWER's hierarchy (EPA 2003). For example, subchronic reference concentrations, developed by the EPA Office of Research and Development/National Center for Environmental Assessment/ Superfund Health Risk Technical Support Center (STSC), are currently available for some vapor-forming chemicals as Provisional Peer Reviewed Toxicity Values (PPRTVs), which are designated as a Tier 2 source of toxicity values by OSWER (EPA 2003). Acute and intermediate Minimal Risk Levels (MRLs)[208] adopted by the Agency for Toxic Substances and Disease Registry (ATSDR) are currently available for some vapor-forming chemicals and are designated as a Tier 3 source of toxicity values by OSWER (EPA 2003). PPRTVs and ATSDR MRLs are peer reviewed and are publicly available (see, http://hhpprtv.ornl.gov/ and http://www.atsdr.cdc.gov/mrls.html).

Historically, toxicity values for short-term or acute exposure durations have not been derived or published in EPA's IRIS, which otherwise is EPA's preferred source of toxicity values (EPA 2003). EPA, under its authority, will work to develop expanded science policy direction to address short-term exposures and develop and identify appropriate toxicity values for additional chemicals for consideration for vapor intrusion assessment and related OSWER regulatory frameworks. EPA recommends that relevant existing guidance (e.g., EPA 2009c) be followed in situations where a desired toxicity value is not available, using sources of toxicity information considering OSWER's hierarchy (EPA 2003).

Although the indoor air concentrations may vary temporally, an appropriate exposure concentration estimate (e.g., time-integrated or time-averaged indoor air concentration measurement in an occupied space – see Section 6.4.1) that exceeds the health-protective concentration levels for acute or short-term exposure (i.e., generally considered to be a hazard quotient (HQ) greater than one for an acute or short-term exposure period)[209] indicates vapor concentrations that are generally considered to pose an unacceptable human health risk.[210]

As noted in Section 7.4 of this Technical Guide, a well-crafted risk characterization section (EPA 1992c, 1995ab, 2000b, 2009c) puts risk calculations into context for risk managers, so that they may effectively weigh and interpret risk assessment results and recognize key uncertainties (e.g., in the exposure and dose-response assessments and risk estimation). Uncertainties include the derivation of an RfC, which is defined as "…an estimate (with uncertainty spanning perhaps an order of magnitude)…" (See http://www.epa.gov/ncea/iris/help_ques.htm#whatiris). Sections 3.3 and 7.7 identify other EPA-recommended considerations for risk managers.

When indoor air concentrations in an occupied space exceed health-protective concentration levels for short-term or acute inhalation exposures arising from a complete vapor intrusion

[208] Minimal Risk Levels (MRLs) published by ATSDR are estimates of the daily human exposure to a hazardous substance that is likely to be without appreciable risk of adverse non-cancer health effects over a specified duration of exposure. The ATSDR MRLs are peer reviewed and are publicly available (http://www.atsdr.cdc.gov/mrls.html).

[209] See Glossary for definitions of "acute" and "short-term" exposure durations.

[210] See, for example: *The Role of the Baseline Risk Assessment in Superfund Remedy Selection Decisions*, OSWER Directive 9355.0-30, April 22, 1991 (EPA 1991a); and *Rules of Thumb for Superfund Remedy Selection,* OSWER Directive 9355.0-69, August 1997 (EPA 1997). In addition, the NCP states "For systemic toxicants, acceptable exposure levels shall represent concentration levels to which the human population, including sensitive subgroups, may be exposed without adverse effect during a lifetime or part of a lifetime, incorporating an adequate margin of safety" [40 *CFR* 300.430(e)(2)(i)(1)].

pathway, ventilation, indoor air treatment, temporary relocation, and other response actions may be implemented to reduce or avoid these threats promptly (see Section 8.2.1). Construction and operation of engineered systems that can reduce or eliminate vapor intrusion into existing buildings (see Section 8.2) may also warrant consideration after urgent threats to human health have been addressed.

7.6 Risk-based Cleanup Levels

When response action is determined to be warranted to reduce or eliminate indoor air exposures from vapor intrusion (see Sections 7.4 and 7.5), EPA recommends that cleanup levels be established and documented consistent with statutes and regulations and considering guidance for the respective OSWER program.[211] These cleanup levels would be used to evaluate when building mitigation measures, subsurface remediation, and associated monitoring can be terminated and to assess cleanup progress in the meantime (see Section 8.7).

Candidate risk-based cleanup levels can be calculated using information from the risk assessment (Section 7.4). Results of the human health risk assessment indicate, for example, which site-related vapor-forming chemicals warrant building mitigation and subsurface remediation. The exposure factors and toxicity values used in the human health risk assessment can be used to calculate chemical-specific cleanup levels, considering EPA risk assessment methods (e.g., EPA 2009c, EPA 2003). Candidate cleanup levels are usually developed for potential cancer and non-cancer effects. The lower (or lowest if there are multiple potential non-cancer effects) of the candidate values, based upon cancer risk and non-cancer HQ/HI targets, is generally recommended for selection as the cleanup level (EPA 1991c, Section 3.4 therein).[212] The VISL Calculator (http://www.epa.gov/oswer/vaporintrusion/guidance.html) can be used to support these calculations, including input of alternative attenuation factor(s) based upon site- or building-specific information.

Calculating candidate cleanup levels based upon potential cancer effects entails selecting a target cancer risk. As noted above (Section 7.4.1), once a decision has been made to undertake a response action, EPA has expressed a preference for cleanups achieving the lower end of the cancer risk range (i.e., 10^{-6}) (EPA 1991a). Response actions achieving reductions in human health risk anywhere within the cancer risk range may be deemed acceptable by the EPA risk manager, however.

To protect human health from potential noncancer effects, EPA generally recommends using a target value of one for the non-cancer HQ (if there is a single vapor-forming chemical of health concern for vapor intrusion) or for the non-cancer HI (if there are multiple vapor-forming chemicals of health concern for vapor intrusion acting by a common effect).

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[211] See, for example: *RCRA Corrective Action Plan (Final),* OSWER Directive 9902.3-2A (EPA 1994); and *A Guide to Preparing Superfund Proposed Plans, Records of Decision, and Other Remedy Selection Decision Documents,* OSWER Directive 9200.1-23P (EPA 1999b).

[212] An exception arises when 'background' sources pose elevated exposures, because generally EPA does not clean up to concentrations below natural or anthropogenic background levels (EPA 2002e).

Cleanup levels for indoor air can be readily calculated, as described above, without additional assumptions or modeling about vapor intrusion processes. On the other hand, cleanup levels for groundwater and/or soil gas in the vadose zone will entail developing a medium-specific vapor attenuation factor, which EPA recommends be conservatively estimated based upon site-specific information. The cleanup level for soil gas can be calculated by dividing the chemical-specific indoor air cleanup level by the site-specific soil gas vapor attenuation factor. The cleanup level for groundwater can be calculated by dividing the chemical-specific indoor air cleanup level by the site-specific vapor attenuation factor for groundwater vapors and assuming equilibrium between the aqueous and vapor phases at the groundwater table. EPA recommends that site-specific attenuation factors intended to be protective of chronic exposure conditions: be conservatively estimated when based upon mathematical models; and be based upon multiple measurements of indoor air concentration in different seasons, which have negligible influences from 'background' sources, when based upon site-specific measurements.

EPA recommends that cleanup levels be documented with at most two significant figures, even though some of the input values may carry additional significant figures (EPA 1991b, see page 19).

7.7 Options for Response Action

When response action is determined to be warranted to reduce or eliminate indoor air exposures from vapor intrusion (see Sections 7.4 and 7.5), EPA recommends that OSWER programs select, recommend, and document response action(s) consistent with statutes and regulations and considering their existing program guidance.[213]

The selection of a health-protective interim response action(s) for existing buildings will generally depend on site-specific considerations, which can include: nature of subsurface vapor source (e.g., groundwater, vadose zone soils, sewer lines), magnitude of the exposure above cleanup levels; the severity of the potential adverse health effects or health hazard; building features and conditions (e.g., construction; heating, ventilation, and air conditioning equipment); climate and season (which influence the feasibility of ventilation, for example); the quality of ambient air in the vicinity; and the feasibility of implementing a given option quickly.[214] In general, EPA recommends that response actions limit the amount of time individuals are exposed to concentrations that correspond to unacceptable human health risk, as described in Sections 7.4 and 7.5.

[213] See, for example: *RCRA Corrective Action Plan (Final),* OSWER Directive 9902.3-2A (EPA 1994); and *A Guide to Preparing Superfund Proposed Plans, Records of Decision, and Other Remedy Selection Decision Documents,* OSWER Directive 9200.1-23P (EPA 1999b).

[214] Most response actions cannot be implemented immediately upon determining that a response is warranted. For example, engineered exposure controls ordinarily entail from two to four weeks of lead time (at a minimum) for planning, design, any permit acquisition, material acquisition and construction. In many circumstances, ventilation measures to reduce exposure can be implemented more quickly, but local climate or air quality may render this option less attractive during some seasons.

TABLE 7-1
MATRIX OF OPTIONS TO RESPOND TO HUMAN HEALTH RISK POSED BY THE VAPOR INTRUSION PATHWAY

Option for Response Action	Applicability of Response Action for Common Sources of Sub-surface Vapors		
	Groundwater	Vadose Zone Soil	Sewer & Drain Lines
Remediation of Source*	•	•	•
Removal of contaminated soil via excavation	#	•	
Treatment of contaminated soil *in situ*	#	•	
Treatment of contaminated groundwater *in situ*	•		
Removal of contaminated groundwater (e.g., pump-and-treat)	•		
Decontaminating and/or rehabilitating sewer and drain lines			•
Interim Measures to Reduce or Eliminate Vapor Intrusion*	•	•	•
Subslab de-pressurization and ventilation systems	•	•	
Sealing major openings for soil gas entry, where known and identified+	•	•	
Building over-pressurization	•	•	
Installing, repairing, or maintaining vapor traps			•
Interim Measures to Reduce or Avoid Exposure to Vapors	•	•	•
Notification to local fire department about potential explosion hazards+	•	•	•
Notification and risk communication to building occupants and owners, including institutional controls (e.g., deed notices)	•	•	•
Increasing building ventilation*	•	•	•
Treating indoor air*	•	•	•
Temporary relocation+	•	•	•
Monitoring Indoor Air to Characterize Human Exposure	•	•	•

KEY: • designates potentially appropriate response action for indicated vapor source

FOOTNOTES:

* includes: associated institutional controls to maintain operations and provide public notification of residual contamination; and associated monitoring to assess effectiveness and protectiveness of the response action

\# remediation of soil may also be warranted for purposes of protecting groundwater from further contamination, even if contaminated soil in the vadose zone is not a source for vapor intrusion directly (e.g., due to the absence of an existing building near the contaminated soil)

\+ response option primarily applies to existing buildings

Table 7-1 presents an overview of key candidate response options for the vapor intrusion pathway, which are discussed further in Section 8. Response actions that may be recommended for and implemented in existing buildings include:

- Interim measures that can be implemented relatively quickly (see Section 8.2.1), if prompt action is warranted to reduce or eliminate exposures to vapor-forming chemicals (see Sections 5.2 and 7.5.2) or to mitigate explosion hazards (see Section 7.5.1);
- Engineered exposure controls (see Section 8.2.2) with associated monitoring and institutional controls (see Section 8.6), as an interim (but potentially long-term) measure to reduce or eliminate vapor intrusion into buildings; and
- Remediation of the subsurface vapor source (see Section 8.1) with associated monitoring and institutional controls (see Section 8.6).

Response actions that may be warranted in buildings that may be constructed in the future include:

- Remediation of the subsurface vapor source (see Section 8.1) with associated monitoring and institutional controls (see Section 8.6); and
- Institutional controls (see Section 8.6) to inform the need for building mitigation (see Section 8.2.2) and/or a confirmatory vapor intrusion investigation before the building is occupied, in case the building is to be or may be constructed before subsurface vapor sources are remediated to cleanup levels.

Indoor air monitoring has frequently been selected as a response action in circumstances where subsurface vapor sources are present and the vapor intrusion pathway has not been shown to be incomplete. Indoor air monitoring may be deemed warranted, for example:

- To better characterize spatial or temporal variability;
- To address uncertainty in the characterization of the vapor intrusion pathway when subsurface vapor sources have the potential to pose a health concern in overlying or nearby buildings (e.g., incomplete pathway characterization, concern about the potential for changes in building conditions, discordant lines of evidence); or
- For other site-specific or situation-specific reasons.

EPA generally prefers to obtain building access and undertake response actions through consent and cooperation from building owners, tenants, and other stakeholders (see Section 1.2).

7.8 Pre-emptive Mitigation/Early Action

It may be appropriate to implement mitigation of the vapor intrusion pathway as an early action, even though all pertinent lines of evidence have not yet been completely developed to characterize the vapor intrusion pathway for the subject building(s), when sufficient site-specific data indicate that vapor intrusion: (1) is occurring or may occur due to subsurface contamination that is being addressed by federal statutes, regulations, or guidance for environmental protection; and (2) is posing or may pose a health concern to occupants of an existing

building(s). Likewise, it may be appropriate and cost-effective to design, install, operate, and monitor mitigation systems (including passive barrier systems) in newly constructed buildings (or buildings planned for future construction) that are located in areas of vapor-forming subsurface contamination, rather than allow vapor intrusion (if any) to occur and address vapor intrusion after the fact. As described in Section 3.3, preemptive mitigation/early action is the term used to describe both situations.

Preemptive mitigation (PEM) is recognized as an early action that is intended to ensure protectiveness of human health. In this context and as described further in Section 8.2, mitigation refers to methods that seek to:

- Prevent or reduce vapor entry into a building.
- Reduce or eliminate vapors that have entered a building.

Note that the selection and implementation of PEM, when it occurs, is not necessarily intended to pre-judge final decisions about remediation of subsurface vapor sources; however, EPA generally recommends that decision-making about PEM include a consideration of the O&M and monitoring obligations. In addition, EPA recommends that the selection of PEM be based upon data and information in the administrative record and be documented in the administrative record, consistent with statutes and regulations and considering EPA guidance for the respective land restoration program (e.g., CERCLA, RCRA corrective action, brownfields, etc.), in order to provide an adequate basis for actions undertaken.

7.8.1 Rationale

In ensuring protectiveness of human health, PEM generally may be an appropriate approach to consider for buildings with potential vapor intrusion for a number of reasons, including:

- Building mitigation typically is an effective means of protecting human health and is cost effective for many buildings.
- The potential exposure scenario (e.g., inhalation of potentially toxic vapors) cannot generally be readily avoided by building occupants.
- Involuntary and unavoidable exposures and hazards are generally sources of anxiety and concern for affected building occupants and the general public, particularly when they occur in homes and in the workplace.
- Comprehensive subsurface characterization and investigations of vapor intrusion (to conclusively characterize unacceptable, but variable, levels of vapor-forming chemicals in soil, groundwater, and indoor air, as described in Section 6) can entail prolonged study periods, during which building occupants may be exposed and owners and environmental stewardship groups may remain anxious and concerned about potential indoor air exposures to subsurface vapors in the absence of mitigation.
- Conventional vapor intrusion investigations in and of themselves can be disruptive, particularly when indoor access is sought to acquire interior samples and assess interior building conditions.

- Mitigation can typically be implemented relatively quickly, while subsurface contamination is being more fully delineated or remediated.

- EPA's experience with residential communities suggests that many affected residents seek and prefer that mitigation systems be installed when vapor intrusion is suspected.

- Mitigation can be a cost-effective approach to help ensure protectiveness of human health during ongoing vapor intrusion investigations to acquire multiple lines of evidence and characterize spatial and temporal variability in subsurface and indoor air concentrations, as well as while subsurface remediation is being planned and conducted to reduce or eliminate subsurface vapor sources.

In summary, PEM, based on limited but credible subsurface and building data, can be an appropriate approach to begin to implement response actions quickly and ensure protectiveness of current building occupants. In such circumstances, resources can be used appropriately to focus first on mitigation of buildings and subsurface remediation, rather than site and building characterization efforts, which may be prolonged. Although PEM may be an effective tool to reduce the human exposure and human health risk, building mitigation is not generally intended to address the subsurface vapor source; as such, EPA recommends that it typically be used in conjunction with remediation of the subsurface source of vapor-forming chemicals (e.g., source removal or treatment), as discussed in Section 8.1.

7.8.2 General Decision Framework

To consider PEM, EPA recommends that reliable data supporting a preliminary analysis, as described in Section 5.0, and risk-based screening, as described in Section 6.5, be obtained and documented in the administrative record. In appropriate circumstances (e.g., where time is of the essence to ensure protection of human health; see, for example, Section 7.5.2), a formal human health risk assessment need not be conducted and documented before selecting PEM, but a preliminary evaluation of human health risk using individual building data or aggregated community data is generally recommended. If there are insufficient data to perform a preliminary risk analysis, but subsurface vapor sources are known to be present near buildings (see Section 5.3), EPA recommends that an appropriate vapor intrusion investigation (see Section 6) be conducted to obtain sufficient data.

EPA generally recommends that the decision to undertake building mitigation be supported by appropriate lines of site- or building-specific evidence (e.g., characterization of subsurface vapor source(s) strength and proximity to building(s); building conditions) that demonstrate that vapor intrusion has the potential to pose an unacceptable human health risk. Sections 5, 6, and 7 herein provide information about the types of evidence obtained and relied upon in assessing vapor intrusion potential and the types of analyses that can support determinations of whether the vapor intrusion pathway is complete for a specific building or collection of buildings and poses or has the potential to pose a health concern to building occupants. This information is equally pertinent for supporting final remediation and mitigation decisions and for supporting PEM consistent with applicable statutes and regulations. The premise of PEM, however, is to protect human health first without necessarily waiting to collect all lines of pertinent evidence or multiple rounds of sampling data.

Certain types of subsurface conditions may have greater potential to facilitate vapor intrusion when subsurface sources of vapors are present. These conditions include, but are not limited to:

- Shallow aquifers (for example, five feet or less from the building foundation to the seasonal high water table).

- High-permeability (e.g., gravelly) vadose zone soils that are fairly dry, which are favorable to upward migration of gases.

- Preferential migration routes, such as fractured sediments or bedrock, buried streambeds, subsurface drains, and utility conduits, as they can facilitate vertical or lateral migration of vapor with limited attenuation of chemical concentrations.

Under these conditions, it may be easier to determine that PEM may be warranted if a structure is located near a subsurface vapor source that has the potential to pose an unacceptable human health risk. Other factors to consider include the following:

- Susceptibility to soil gas entry. Some buildings have greater potential for vapor intrusion (i.e., are more susceptible to soil gas entry; see Section 2.3) than others. For example, buildings with deteriorating basements or dirt floors generally provide poor barriers to vapor (soil gas) entry. Buildings with sumps or other openings to the subsurface that can facilitate soil gas entry are also more susceptible to vapor intrusion.

- Actions undertaken or planned to address the subsurface source of vapors. For example, if the source of vapors (e.g., contaminated soil in the vadose zone) is being removed (e.g., excavation of contaminated soil or soil vapor extraction underneath the building) or is to be removed within a time frame that is protective for any potential current or near-term exposures in the overlying or nearby building, then PEM may not be warranted.

7.8.3 Some General Scenarios Where Pre-emptive Mitigation May be Warranted

Three general scenarios where PEM may be warranted are summarized below. The first two scenarios address situations where building(s) currently exist, while the third scenario addresses a situation where building(s) may be constructed in the future.

Site with High Potential to Facilitate Vapor Intrusion. In this scenario, indoor air concentration data have not been collected, but other lines of evidence support a conclusion that the vapor intrusion pathway is likely complete and may pose an unacceptable human health risk. Figure 7-1 shows a hypothetical residential area located near a shopping center that contains an active dry-cleaning facility. In this hypothetical example, a sufficient number of appropriately screened monitoring wells have been installed throughout the neighborhood to characterize a historical groundwater plume emanating from the dry cleaner that has migrated under eight homes and continues to migrate. Groundwater is encountered at approximately five feet below ground surface, and site geology consists of dry gravel and sands. “Near-source” soil gas samples have also been collected from several locations throughout the neighborhood and found to corroborate a high-strength vapor source near the buildings. All homes have crawl spaces with dirt floors. In this hypothetical example, PEM may be warranted for the eight buildings located above, near, or downgradient of the groundwater plume, based on the groundwater concentration and soil gas data available (i.e., PCE concentrations significantly exceeding

screening levels in this example),[215] and the likelihood that the proximity of the groundwater table, characteristics of the vadose zone, and building conditions will collectively facilitate vapor migration and intrusion.

Note that if a groundwater restoration system is constructed and operated and plume migration is thereby controlled, additional buildings downgradient of the plume may not warrant PEM in the future. In the meantime, an IC may be appropriate for the undeveloped parcel hydraulically down-gradient of the current leading edge of the plume.

Site with Indoor Air Data for Some Buildings but Not for All Buildings. Depending on individual owners and occupants in the affected community, it may be difficult to obtain adequate data for all buildings within a specified area. Challenges include gaining timely access into each building and other practical considerations. In such circumstances, it may be appropriate to characterize a limited number of buildings under a reasonable maximum vapor intrusion condition,[216] by collecting and weighing multiple lines of evidence, and then extrapolating those findings to similar buildings nearby. The following hypothetical scenario describes one such situation, which is represented in Figure 7-2. In this hypothetical example, a sufficient number of appropriately screened monitoring wells have been installed throughout the neighborhood to characterize a historical groundwater plume. "Near-source" soil gas samples have also been collected from several locations throughout the neighborhood and found to corroborate the measured groundwater concentrations. Indoor air has been sampled and analyzed for a few homes and found to exhibit concentrations that pose an unacceptable human health risk. In this scenario, the assumption can be made that buildings with similar construction and built about the same time may have similar susceptibility to soil gas entry. As a result, it may be determined to use a PEM approach to offer mitigation systems to all buildings within a specified area of subsurface contamination.

[215] Several site-specific factors render inappropriate the use of the recommended attenuation factors and groundwater and soil gas VISLs for purposes of identifying sites or buildings unlikely to pose a health concern through the vapor intrusion pathway, as discussed in Section 6.5.2. Nevertheless, response actions for vapor intrusion can be supported when the groundwater and soil gas VISLs are exceeded for samples from a building or site where these specific factors are present.

[216] EPA recommends basing decisions about whether to undertake response action for vapor intrusion (i.e., a component of risk management) on a consideration of a reasonable maximum exposure (e.g., EPA 1989, 1991a), which is intended to be a semi-quantitative phrase, referring to the lower portion of the high end of the exposure distribution (see Glossary).

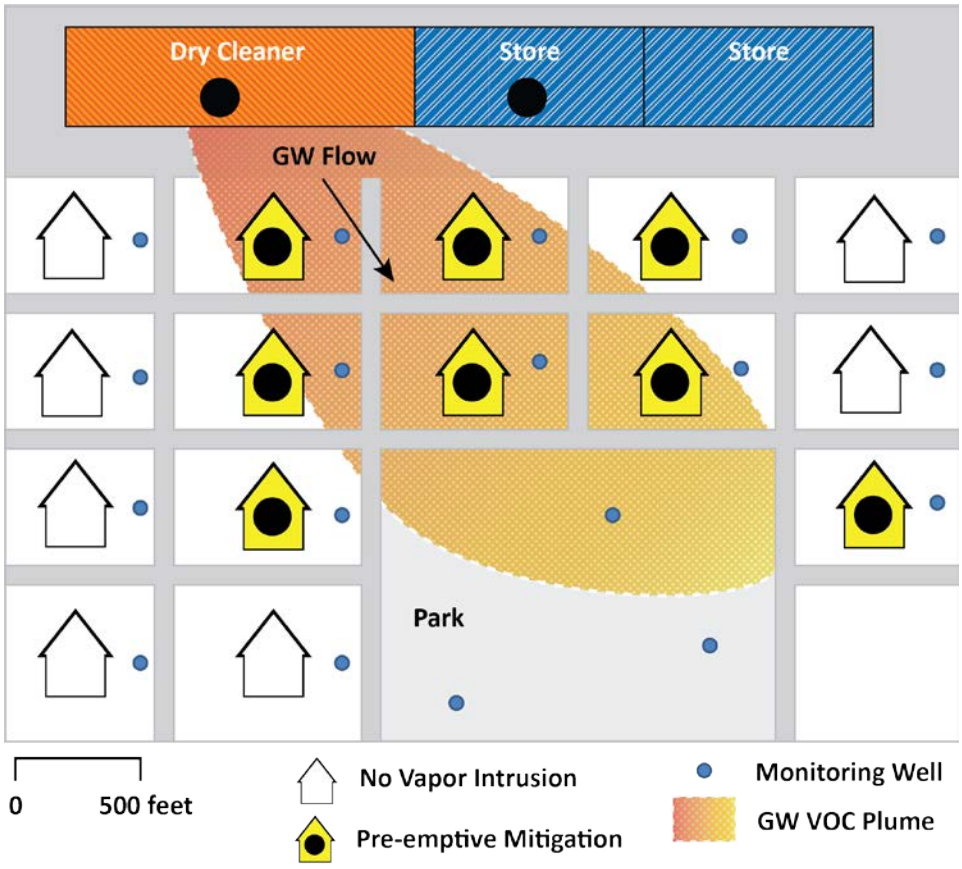

Figure 7-1 Sample Depiction of Subsurface Vapor Source and Data to Support Pre-emptive Mitigation/Early Action for Multiple Buildings, Each with Limited Data

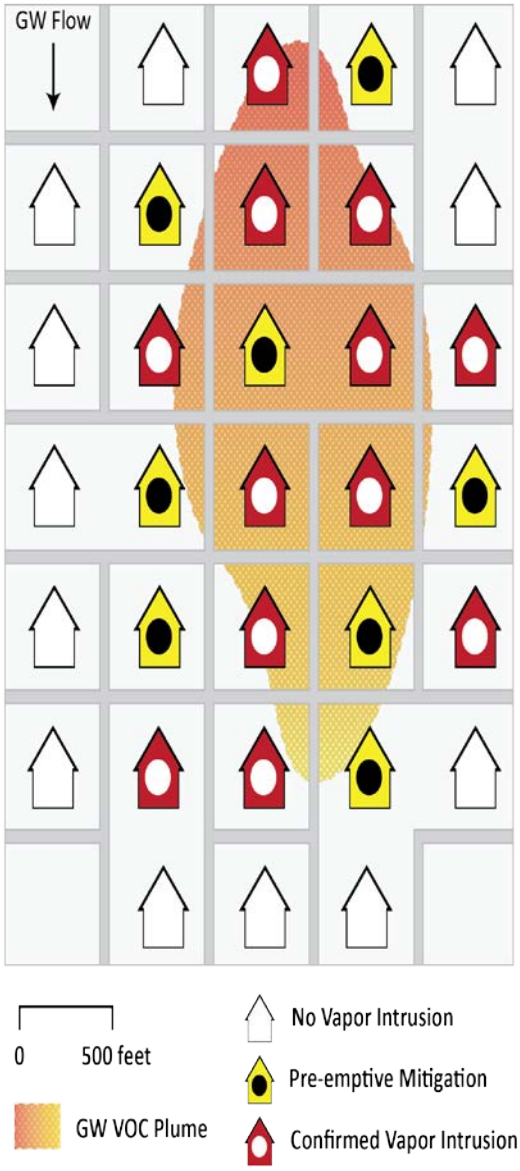

Figure 7-2 Sample Depiction of Subsurface Vapor Source and Data to Support Pre-emptive Mitigation/Early Action for Multiple Buildings, Some with Only Limited or No Data

Future Construction and Development. If current data (e.g., "near-source" soil gas) indicate that there is potential for unacceptable human health risk arising from vapor intrusion in an area where a building(s) is expected to be constructed in the future, EPA recommends that the remediation decision document record the known facts and data analyses and clearly state that vapor intrusion mitigation or site re-evaluation may be needed when the property is developed or occupied. EPA generally recommends appropriate ICs to ensure enforcement of such remediation decisions.[217]

Prior site use (see Section 5) can be particularly relevant where residential development is planned or occurring on property formerly used for commercial or industrial purposes. In these situations, it is not uncommon for residual NAPLs or shallow plumes to remain. Under this circumstance, PEM may be warranted for new construction as a precautionary measure without direct evidence of a vapor intrusion pathway. Incorporating mitigation systems into newly constructed buildings is generally easier to implement and incurs lower cost when compared with retrofitting existing structures.

On the other hand, if response actions to treat or remove the subsurface vapor source(s) are being conducted or will be conducted before a building is constructed and occupied, then building mitigation for the vapor intrusion pathway may not be warranted in the future.

7.8.4 Additional Considerations

EPA recommends that the following factors also be considered in evaluating PEM and determining whether to implement it.

Weighing Relative Costs of Characterization versus Engineered Exposure Controls. EPA recommends that cost not be the primary criterion for deciding whether or how to mitigate vapor intrusion because protection of human health could be compromised. On the other hand, cost effectiveness is addressed by CERCLA and the NCP and can be an important consideration when evaluating response alternatives. Cost can be a factor in deciding when and whether to pursue PEM, in relation to continuing to investigate and assess actual or potential vapor intrusion, and in ensuring effective human health protection through installing and operating a vapor intrusion mitigation system. At PRP-lead sites, for example, PEM may be viewed favorably where the costs associated with a complete site characterization or continued monitoring are estimated to easily exceed the cost of installing a mitigation system (and associated system monitoring). The number of buildings that would need to be characterized, or the order of priority, may be a factor in considering whether to implement PEM.

Institutional Controls. For existing vapor intrusion mitigation systems, ICs may be warranted to ensure that the system is operated, maintained, and monitored. Maintenance and monitoring of the mitigation system, which are discussed in Sections 8.3 and 8.4 of this document, are generally appropriate to ensure that the system is performing as intended. In addition, ICs may facilitate access to property to conduct routine maintenance and monitoring activities, although

[217] At undeveloped sites, or at sites where land use may change in the future, ICs may be important to ensure that the vapor intrusion pathway is effectively addressed in the future. ICs at undeveloped sites could include mechanisms to inform the need for PEM in new buildings. Selecting and implementing PEM for new buildings avoids some of the difficulties associated with attempting to predict the potential for vapor intrusion prior to building construction.

separate access agreements also warrant consideration. Additional information regarding ICs is provided in Section 8.6 of this document.

Community Input and Preferences. Community acceptance of early action may vary widely, depending on the human health risk to building occupants and past experiences at the site, including interaction with site stakeholders and regulators and perceptions of the site. Some owners and occupants may view PEM as a precautionary measure and be willing to have mitigation systems installed; some may even request them before characterization is completed. On the other hand, some home owners may not agree to have a mitigation system installed unless the pathway is demonstrated to be complete.

Others may be reluctant to install mitigation systems because of the operation costs or the inconvenience associated with the installation and subsequent monitoring. Although some owners may view mitigation systems as an advantage when they sell a property, others may be concerned with the possible negative effect on property values.

Issues and concerns about equity and fairness can also arise when some homes within a neighborhood receive mitigation systems and others do not. In some situations, it may be easier to persuade property owners to install vapor intrusion mitigation systems if the entire street, block, or neighborhood is found to warrant early action.

Public meetings and one-on-one meetings provide opportunities to discuss PEM with affected property owners and building occupants and obtain information and input. Section 9.0 of this document provides additional information about community involvement and engagement.

Refined Conceptual Site Model

Decisions to undertake pre-emptive mitigation may warrant re-evaluation as additional monitoring and/or site and/or building characterization data become available and are evaluated in the context of the conceptual site model. If and when such data shift the weight of evidence towards a conclusion that the vapor intrusion pathway is incomplete or otherwise does not pose unacceptable health risk, then EPA recommends re-considering whether continued operation, maintenance, and monitoring of the interim response action (Section 8.2) is warranted.

8.0 BUILDING MITIGATION AND SUBSURFACE REMEDIATION

This section summarizes information and recommendations on potential response options to mitigate and manage vapor intrusion. It is organized as follows:

- Section 8.1 summarizes the role of subsurface remediation in mitigating vapor intrusion.
- Section 8.2 provides an overview of engineered exposure controls (i.e., building mitigation technologies) for existing and new buildings.
- Sections 8.3 and 8.4 summarize information about operating and monitoring building mitigation systems, respectively.
- Section 8.5 summarizes information about documenting building mitigation systems.
- Section 8.6 describes and provides information about institutional controls (ICs).
- Section 8.7 provides information about exit strategies (e.g., termination of: subsurface remediation for vapor source control; building mitigation system operation; and associated ICs).

Sections 5.2, 7, and 9 discuss potential bases for deciding to implement response options for vapor intrusion. Sections 3.3 and 7.7 introduced some of the response options and policies discussed in the remainder of this Section regarding components and development of cleanup plans.

8.1 Subsurface Remediation for Vapor Source Control

The preferred long-term response to the intrusion of vapors into buildings is to eliminate or substantially reduce the level of contamination in the subsurface vapor source (e.g., groundwater, subsurface soil, sewer lines) by vapor-forming chemicals to acceptable-risk levels, thereby achieving a permanent remedy. Remediation of the groundwater plume or a source of vapor-forming chemicals in the vadose zone will eventually eliminate potential exposure pathways and can include the following actions, among others:

- Removal of contaminated soil via excavation;
- Removal of contaminated groundwater with pump-and-treat approaches;
- Decontaminating and/or rehabilitating sewer lines that harbor vapor-forming chemicals; and
- Treatment of contaminated soil and groundwater *in situ*, using technologies such as soil vapor extraction, multiphase extraction, and bioremediation, or natural attenuation.

Because there is a substantial body of EPA and other guidance on selection, design, construction, and operation of technologies for remediation of subsurface vapor sources (e.g., EPA 1993b, 2006c; NRC 2004), these topics are not discussed further here.

When monitoring to assess the performance and effectiveness of remediation technologies for subsurface vapors, EPA recommends employing the methods, approaches, and recommendations described in Sections 5.4, 6.2, 6.4 and 7.0 of this Technical Guide.

ICs may be necessary to help ensure the continued integrity of the cleanup. In some cases, therefore, ICs such as zoning or deed restrictions, may accompany implementation of vapor source remediation methods. Section 8.6 provides information about ICs and their application to the vapor intrusion pathway.

8.2 Building Mitigation for Vapor Intrusion

In cases where subsurface vapor sources cannot be remediated quickly, it may be appropriate to also undertake (interim) measures in individual occupied buildings (i.e., building mitigation for vapor intrusion) to reduce threats to human health more quickly. EPA recommends that building mitigation for vapor intrusion be regarded as an interim action that can provide effective human health protection, which may become part of a final cleanup plan. Mitigation of vapor intrusion in specific buildings generally is not a substitute for remediation of subsurface vapor sources. Thus, EPA recommends that building mitigation generally be conducted in conjunction with vapor source remediation where at all possible.

The purpose of this section is to provide an overview of vapor intrusion mitigation for new and existing buildings where response action is determined to be warranted. Section 8.2.1 summarizes response options that generally can be implemented relatively quickly to reduce indoor air concentrations. Section 8.2.2 identifies and summarizes the most commonly implemented engineered control methods for reducing vapor intrusion into existing buildings. Section 8.2.3 identifies and describes some approaches and considerations for addressing vapor intrusion for new buildings. Additional detailed information about technologies for reducing vapor intrusion into buildings and their selection, design, operation, and monitoring is provided in other EPA documents (EPA 1993a, 2008c). Building owners and occupants may find EPA's *Consumer's Guide to Radon Reduction* (EPA 2013b) a useful source of additional information, in light of similarities in technologies for reducing vapor intrusion and radon intrusion.

ICs may be necessary to help ensure the continued integrity of building mitigation systems. In many cases, therefore, ICs may accompany implementation of engineered exposure controls, for example to ensure that an active system remains operational and passive membranes are not disturbed (EPA 2008c). Additional information about ICs is provided in Section 8.6.

8.2.1 Prompt Response Options for Existing Buildings

For buildings with potential explosion and fire hazards, EPA recommends evacuation, along with notification of the local fire department about the threat. If, on the other hand, prompt action is warranted to reduce or eliminate vapor intrusion exposures in an existing building (e.g., measured indoor air concentrations pose an unacceptable human health risk for an acute or short-term exposure scenario (see Section 7.5.2)), it may be appropriate to implement response options such as the following:

- Sealing major openings for soil gas entry, where known and identified;
- Over-pressurizing nonresidential buildings by adjusting the HVAC system;

- Installing, repairing, or maintaining vapor traps for sewer or drain lines that are sources of vapor intrusion;

- Increasing building ventilation, for example using fans or natural ventilation;

- Treating indoor air (e.g., adsorption using activated carbon); and

- Temporary relocation

The fore-going response actions may take several days to a few weeks to plan (e.g., arrange, design) and implement, which generally is quicker than other interim response actions (e.g., active depressurization technologies). The first three options seek to reduce or eliminate vapor entry into the building. The last three options seek to reduce, eliminate, or avoid vapors that have entered the building by vapor intrusion. Specifically:

- Vapor intrusion into the building via soil gas entry from vadose zones soils can be reduced by sealing foundational openings using products such as synthetic rubbers, acrylics, oil-based sealants, asphalt/bituminous products, swelling cement, silicon, epoxy or elastomeric polymers. EPA recommends screening the selected sealant(s) (e.g., checking the composition, relying upon manufacturer's data) to ensure they do not contain or emit vapor-forming chemicals that might pose a human health risk to building occupants. This interim mitigation approach is among the easiest and least expensive to implement; however, its effectiveness relies upon being able to identify and access openings for soil gas entry. EPA recommends appropriate monitoring of indoor air concentrations be conducted to ensure that sealing attains and sustains sufficient reduction in vapor intrusion. In some cases, however, sealing openings may not be capable of reducing indoor air concentrations to acceptable levels and/or some openings may not be visible and accessible. EPA recommends that this response option generally be supplemented by installing, operating, and maintaining an engineered exposure control (e.g., an active depressurization technology) that reduces or eliminates vapor entry into the building until remediation of subsurface vapor sources is complete and terminated.

- For commercial and industrial buildings where HVAC units blow air into the building and are well maintained, it may be advantageous to increase pressurization in the building to prevent or reduce vapor intrusion. In some cases (e.g., buildings with few doors and other openings), relatively small increases in building pressure may be sufficient, which may be accomplished by increasing the air flow rate and using specialized equipment to monitor and balance air flow rates. EPA recommends appropriate monitoring of pressure and other indicators (e.g., indoor air monitoring) be conducted to ensure that adequate pressurization is sustained throughout areas of the building that could be subject to vapor intrusion. In some climates and for some buildings, this response option may be impractical or prohibitively expensive.

- Vapor intrusion into the building via gas entry from sewer and drain lines can be reduced or eliminated by installing, repairing, and maintaining vapor traps.

- Increasing building ventilation (i.e., increasing the rate at which indoor air is replaced with outdoor air) can reduce the buildup of indoor air contaminants within a structure. Natural ventilation may be accomplished by opening windows, doors, and vents. Forced

or mechanical ventilation may be accomplished by using a fan to blow air into or out of the building. Increased ventilation is easiest and least costly to implement in locations where the air is not conditioned (heated or cooled). If indoor air is conditioned, increased ventilation can be a costly option because the conditioned air is ventilated to the outdoors. This drawback can be partly overcome by use of heat exchangers, but they are also costly. Another concern is that exhausting air from the building will generally contribute to under-pressurization of the building, relative to the subsurface, thereby potentially resulting in an increased rate of soil gas entry (i.e., vapor intrusion) unless ambient air entry into the building is increased equivalently. EPA recommends appropriate monitoring of indoor air concentrations be conducted to ensure that ventilation attains and sustains sufficient reduction in exposures to vapor-forming chemicals. In some cases, ventilation may not be capable of reducing indoor air concentrations to acceptable levels. In addition, building occupants may find it uncomfortable to increase the air exchange rate by more than a factor of three or four. EPA generally recommends that this response option be supplanted, when feasible, by installing, operating, and maintaining an engineered exposure control that reduces or eliminates vapor entry into the building until remediation of subsurface vapor sources is complete and terminated.

- Commercially available indoor air cleaners, which include both in-duct models and portable air cleaners, is another response option. These devices operate on various principles, including zeolite and carbon sorption and photocatalytic oxidation. Methods that rely on adsorption generate a waste that must be disposed of appropriately or regenerated and warrant periodic replacement of the adsorption medium. EPA recommends appropriate monitoring of indoor air concentrations be conducted to ensure that adequate treatment is sustained throughout the building. EPA generally recommends that this response option be supplanted, when feasible, by installing, operating, and maintaining an engineered exposure control that reduces or eliminates vapor entry into the building until remediation of subsurface vapor sources is complete and terminated.

- Temporary relocation may be implemented for buildings where conditions warranting prompt response action (see Section 7.5) and cannot be adequately addressed by other means.[218]

None of these options entails reducing the level of vapor-forming contamination in the subsurface medium (see Section 8.1). EPA generally recommends that these response options be supplanted, when feasible, by installing, operating, and maintaining an engineered exposure

[218] For response actions carried out under Sections 104(a) and 106(a) of CERCLA, OSWER Directive 9230.0-97 (*Superfund Response Actions: Temporary Relocations Implementation Guidance* (EPA 2002d)) states: "Temporary relocation should not be selected if health and safety risks or circumstances that pose an unreasonable inconvenience can be adequately addressed by other means without significantly increasing the overall cost or duration of the response action." Similarly, OSWER Directive 9355.0-71P (*Interim Policy on the Use of Permanent Relocations as Part of Superfund Remedial Actions* (EPA 1999f)) states: "EPA's preference is to address the risks posed by the contamination by using well-designed methods of cleanup which allow people to remain safely in their homes and business." OSWER Directive 9230.0-97 provides recommended procedures and other policies for temporarily relocating residents when this response action is selected and implemented under Sections 104(a) and 106(a) of CERCLA.

control that reduces or eliminates vapor entry into the building (see Section 8.2.2), until remediation of subsurface vapor sources is complete and terminated.

8.2.2 Active Depressurization Technologies for Existing Buildings

This section provides a brief overview of engineered systems that can be used to reduce or eliminate soil vapor intrusion in existing buildings, along with a summary of steps and considerations for selecting an appropriate technology for a given building. The focus is on active depressurization technologies most commonly employed for reducing soil vapor intrusion into buildings. This focus does not mean, however, that active depressurization technologies are always preferred over other mitigation methods or that they will be the best option for every site. More detailed information on vapor intrusion mitigation systems for existing buildings, including sub-membrane ventilation systems and passive technologies,[219] can be found in several EPA publications (e.g., EPA 2008c).

Active depressurization technologies (ADT) have been used successfully to mitigate the intrusion of radon into buildings and have also been successfully installed and operated in residential, commercial, and school buildings to control vapor intrusion from subsurface vapor-forming chemicals. ADT systems are widely considered the most practical vapor intrusion mitigation strategy for most existing buildings, including those with basement slabs or slab-on-grade foundations. ADT systems are generally recommended for consideration for vapor intrusion mitigation because of their demonstrated capability to achieve significant concentration reductions in a wide variety of buildings[220] and their moderate cost.

Sub-slab depressurization (SSD) systems, a common type of ADT system, function by creating a pressure difference across the building slab to prevent soil gas entry into the building (i.e., overcoming the building's natural under-pressurization, which is the 'driving force' for vapor intrusion; see Section 2.3). Creating this pressure difference is accomplished by extracting soil gas from beneath the slab and venting it to the atmosphere.[221] For the system to be effective by this mechanism,[222] this soil depressurization must be established and maintained at least near the primary openings for soil gas entry (EPA 1993a). Construction of SSD systems entails opening one or more holes in the existing slab, removing soil from beneath the slab to create a "suction pit" (6–18 inch radius), placing vertical suction pipes into the holes, and sealing the

[219] As noted in Section 3.3, engineered exposure controls that do not involve mechanical operations (e.g., creating a barrier between the soil and the building that blocks openings from soil gas entry into the building) are referred to as "passive."

[220] Folkes and Kurz (2002) describe a case study of a vapor intrusion mitigation program in Denver, Colorado. Sub-slab depressurization systems and/or sub-membrane depressurization systems were installed in 337 residential homes to control indoor air concentrations of 1,1-dichloroethylene (DCE) resulting from migration of vapors from groundwater with elevated 1,1-DCE concentrations. Over three years of monitoring data for 301 homes have shown that these systems are capable of achieving the very substantial reductions in concentrations in indoor air. Approximately one quarter of the systems warranted minor adjustment or upgrading after initial installation in order to achieve the state standards established for indoor air exposure.

[221] Depending, in part, upon location and prevailing statutes and regulations, governmental permits or authorizations may be required for venting systems that exhaust to the atmosphere.

[222] A second mechanism by which ADT systems can function is diluting the vapor concentrations beneath the slab and foundation (EPA 1993a, 2008c). Engineered controls designed and operated to use this mechanism predominately are often referred to as sub-slab ventilation systems.

openings around the pipes. These pipes are then connected together to a fan, which draws soil gas from the sub-slab area through the piping and vents it to the outdoors.[223] Sealing known and accessible openings in the slab and foundation can reduce the flow rate of conditioned indoor air that can be pulled into the sub-slab region by the suction wells and the sub-slab depressurization (EPA 2008).

SSD systems were first developed for radon reduction (EPA 1993a) and operate under similar design principles as radon mitigation methods. Figure 8-1 illustrates such an SSD system.

When sumps and associated drain tile systems are present, they may also be depressurized to prevent soil gas entry into the building (again, overcoming the building's natural under-pressurization). This variation on active depressurization is often referred to as drain-tile depressurization (DTD). Depressurization of drain tiles located near a foundation wall can help control soil gas entry at the joint between the foundation wall and slab. Figure 8-2 illustrates such a DTD system.

If the building has hollow block walls, the usual sub-slab suction point may not adequately mitigate the wall cavities, which may be particularly important if the outside surfaces are in contact with the soil. In these situations, the void network within the wall may be depressurized by drawing air from inside the wall and venting it to the outside. This method, called "block-wall depressurization" (BWD) is often used in combination with SSD. Because uniform depressurization of block walls can be difficult, BWD is generally recommended only when sub-slab or DTD prove inadequate to control vapor intrusion. Figure 8-3 illustrates such a BWD system.

In buildings with a crawl space foundation or a basement with a dirt floor, a flexible membrane may be installed over the floor to facilitate depressurization of the soil gas beneath the membrane, which prevents vapors from intruding into the crawl space or basement air. To maximize the effectiveness of a sub-membrane depressurization (SMD) system, EPA recommends the membrane cover the entire floor area and be sealed at all seams and penetrations. Figure 8-4 illustrates such an SMD system.

Extensive guidance is available for the design, sizing, installation, and testing of ADT systems for radon control in existing and new homes and large institutional (e.g., school) and commercial buildings. EPA recommends that ADT systems be designed and installed by qualified persons, typically environmental professionals and licensed radon contractors. EPA guidance for design of ADT systems can be found in several publications (e.g., EPA 1993a, 2008c). EPA recommends documenting each constructed ADT system via a system manual, as described further in Section 8.5.

The Vapor Intrusion Mitigation Quick Guide provided in Table 8-1 summarizes a list of steps for selecting and implementing a vapor intrusion mitigation system in existing buildings.

[223] A central issue that determines the design and effectiveness of ADT systems is the ease with which suction at one location can extend to other subsurface areas underneath the building. Where a good and uniform layer of aggregate (e.g., gravel or crushed rock) was placed underneath a slab foundation during construction, for example, such hydraulic control and communication can generally be expected to be good (EPA 1993a). Where the layer of aggregate under a slab is interrupted or uneven to a significant degree, additional suction pipes will generally be needed and their location will be increasingly important.

TABLE 8-1
VAPOR INTRUSION MITIGATION QUICK GUIDE FOR EXISTING BUILDINGS

Step 1: Consider Prompt Response Actions

It may be appropriate to implement certain interim measures before engineered controls are constructed and operated, as warranted and feasible. For example, building ventilation can be increased, cracks and other openings in the floor or foundation (that otherwise allow soil gas entry) can be sealed, or indoor air treatment can be conducted (refer to Section 8.2.1).

Step 2: Select a Building Mitigation System

The initial step in selecting the appropriate vapor intrusion mitigation technology is to conduct a visual inspection of an existing building. The selection of a vapor intrusion mitigation system primarily depends on building characteristics and contaminant concentrations. In the majority of cases, a type of active depressurization technology (ADT) can be an efficient, reliable, and cost-effective vapor intrusion mitigation technique. In some cases, however, other approaches may be preferable.

Factors that may prompt consideration of vapor intrusion mitigation approaches other than ADT include foundation conditions that prevent development and extension of a suction field below the building.

If there are no factors that would rule out an ADT technology, appropriate systems that can be considered include:

- Sub-slab depressurization (SSD) systems, particularly in houses having slabs (basements and slabs on grade) where drain tiles are not present.
- Drain-tile depressurization (sump/DTD or remote discharge/DTD) when drain tiles are present.
- Sub-membrane depressurization (SMD) in buildings with a crawlspace foundation or a basement with a dirt floor,
- Block-wall depressurization (BWD), usually used only as a supplement to SSD, DTD, or SMD to better mitigate vapors found to be migrating through the wall.

Step 3: Design Building Mitigation System

EPA recommends the final detailed design of the selected vapor intrusion mitigation technology specify the number and location of suction points, location and size of piping, suction fan, piping network and exhaust system, and sealing options to be used in conjunction with the ADT technology. Pre-mitigation diagnostic testing can provide information about the suction field underneath a building and pressure differences that will need to be overcome (EPA 1993a) if the ADT system is to be effective. Diagnostic testing during installation can also help verify the adequacy of the design.

Step 4: Install Building Mitigation System

EPA recommends that the vapor intrusion mitigation system be installed consistent with design specifications by equipment manufacturers, local permit conditions and regulations, and relevant industry standards.

Step 5: Confirm the Installed System is Operating Properly

EPA recommends a visual inspection of the installed system as a routine quality assurance step to confirm that all construction details have been completed. Post-construction monitoring is recommended (refer to Section 8.4) to demonstrate the ADT system is operating appropriately and effectively. Where a vapor intrusion mitigation system is not performing adequately, post-construction diagnostic tests can be helpful in trouble-shooting (EPA 1993a).

Step 6: Ensure Proper Operation and Maintenance of Vapor Intrusion Mitigation System (refer to Sections 8.3 and 8.4)

EPA recommends proper system maintenance and periodic inspections and monitoring to ensure the system is operating as designed and is effective at reducing indoor air concentrations to (or below) target levels. EPA recommends that site managers provide the building owner/occupant with information to help ensure proper operation and maintenance of the system.

EPA recommends that periodic inspections include periodic measurements to confirm that the building mitigation system is continuing to perform adequately.

The U.S. Navy has issued a concise fact sheet that contains useful technical information (DoN 2011b).

8.2.3 Approaches and Considerations for New Buildings

The ADT systems described above are generally available for new buildings also. However, a wider array of approaches and technical options is typically available to mitigate or avoid vapor intrusion for new buildings, compared to existing buildings. These options potentially include the choice of building location and opportunities to modify the building design and construction, which are not available for existing buildings. For example:

- At some sites, contaminated areas most likely to produce unacceptable vapor intrusion exposures can be avoided and designated for another purpose, such as recreational space or undeveloped landscape.

- Mitigation needs can also be considered in the selection of heating and cooling systems, which are normally selected based only on economics, aesthetics, preference, and custom. A system design that avoids creating under-pressurization inside the structure and maintains over-pressurization inside the structure may be effective in mitigating vapor intrusion.

- Passive barriers, such as a low-permeability membrane, can be more readily installed between the soil and the building during new building construction. Passive barriers are intended to reduce vapor intrusion by limiting openings for soil gas entry. However, passive barriers as stand-alone technologies may not adequately reduce vapor intrusion owing to difficulties in their installation and the potential for perforations of the barrier during or after installation. They are commonly combined with ADT systems or with sub-membrane ventilation systems to help improve their efficiency.

- Venting layers can be more readily installed between the soil and the building during new building construction.[224]

- New buildings may be designed to include a highly ventilated, low-occupancy area at ground level, such as an open parking garage.

Steps 2-6 of the Vapor Intrusion Mitigation Quick Guide provided in Table 8-1 are also pertinent to newly constructed buildings. EPA guidance for selecting, designing, and installing vapor intrusion mitigation systems for new buildings can be found in several publications (e.g., EPA 2008c). The U.S. Navy has issued a concise fact sheet that contains useful technical information (DoN 2011c).

[224] Constructed sub-slab ventilation systems typically consist of: a venting layer (e.g., filled with porous media such as sand or pea gravel; or suitably fabricated with continuous voids) below a floor slab to allow soil gas to move laterally to a collection piping system for discharge to the atmosphere; and a sub-slab liner that is installed on top of the venting layer to reduce entry points for vapor intrusion. These and other sub-slab ventilation systems function by drawing outside air into and through the sub-slab area, which dilutes and reduces concentrations of vapor-forming chemicals, and provides a route for soil gas to vent to the atmosphere or migrate outside the building footprint, rather than into a building.

8.2.4 Owner/Occupant Preferences and Building Access

Building owners and occupants can initially be notified in various ways that their home or building warrants construction and operation of a building mitigation system. Section 9.5 provides information regarding such notifications and other messages pertaining to building mitigation.

Whereas EPA managers and mitigation system designers may be primarily concerned with the performance, cost-effectiveness, and reliability of any mitigation system, the building owners and occupants may have additional perspectives and opinions that warrant consideration during technology selection, design, construction, and operation. For example, owners and tenants will often have strong opinions about where fans and piping are located, what level of fan noise is acceptable, and what quality of construction craftsmanship is satisfactory. When there are multiple mitigation options (for example, at a large commercial building), EPA recommends these options be presented fairly to the building owner and tenants, explaining the advantages and disadvantages associated with each and describing the rationale for the preferred alternative.

In some cases, obtaining and scheduling access to a building can be difficult, whether the structure is a commercial or institutional building or a private residence. Commercial building tenants may not want construction activities disrupting business operations. Some homeowners/tenants may resist granting access to their home. Other homeowners/tenants may prefer to schedule tests before or after their work-day. To address these practical and logistical concerns, EPA recommends that an access agreement(s) be executed between the property owner, any tenants, and the mitigating entity to ensure appropriate access as needed to operate, maintain, and monitor the engineered exposure controls in each impacted building.

8.3 Operation and Maintenance of Vapor Intrusion Mitigation Systems

For purposes of this Technical Guide, operation and maintenance (O&M) is used generically to refer to periodic inspections, component maintenance or replacements, repairs, and related activities that are generally necessary to ensure continued operation and effectiveness of engineered exposure controls to mitigate vapor intrusion. EPA generally recommends that such O&M activities be conducted routinely, be documented in an O&M plan (as described further in Section 8.5), and consider recommendations of equipment manufacturers, if any, and site-specific factors. Additional information about ensuring continued effectiveness of systems is available in EPA (2009b).

Design specifications for vapor migration systems may include (1) a maintenance frequency that varies over the operating period of the mitigation system and/or (2) a provision to evaluate and modify the frequency based on data or information obtained during monitoring and maintenance. For example, it may be acceptable to reduce inspection or maintenance frequency once efficient system operation has been demonstrated for at least an initial year, with triggers for additional, unscheduled inspections following alarms (from warning devices) and floods, earthquakes, and building modifications, if any.

Typical O&M activities for either passive or active systems may include, but are not limited to:

- Routine inspection of all visible components of the vapor intrusion mitigation system, including fans, piping, seals, membranes and collection points, to ensure there are no

signs of degradation or blockage. EPA recommends that the as-built drawing for the vapor intrusion mitigation system be examined to verify the system configuration has not been modified.

- Visual inspection of the building to evaluate whether any significant changes were made (such as remodeled basement, new furnace) that would affect the design of the vapor intrusion mitigation system or the general environment in which it is operated. A crawl space SMD membrane, for example, may warrant repair or replacement if its integrity is compromised.

- Visual inspection of the area of concern (including basement floor and wall seals, sumps, floor drains and utility penetrations) to ensure there are no significant changes in conditions that would warrant modification of the system design.

- Routine monitoring of vent risers for flow rates and pressures generated by the fan to confirm the system is working and moisture is draining correctly.

- Routine maintenance, calibration and testing of functioning components of the venting system consistent with the manufacturers' specifications.

    - Pressure readings for both active and passive depressurization systems as well as positive pressurization systems (e.g., periodic verification of measurable pressure differences across the slab).

    - Confirmation that the extraction fan is operating.

    - SSD system fans generally can function well for prolonged periods without maintenance; however, EPA recommends fans be replaced periodically throughout the operating life of the system (e.g., every 4 to 10 years) to avoid breakdowns and associated problems.

- Inspection of external electrical components to identify undesirable conditions, such as excessive noise, vibration, moisture, or corrosion, and to verify that the fan cut-off switch is operable.

    - Inspection of the fan(s) is important throughout the operating period but may be particularly important near the end of its expected lifespan. Noisy fans typically indicate problems with ball bearings and warrant replacement on that basis.

    - Confirmation of adequate operation of the warning device or indicator.

- Confirmation that building owner/occupants are knowledgeable about how to maintain system operation. Confirmation that a copy of the O&M manual is present in the building and has been updated as necessary.

EPA also recommends that the site team determine if there has been any change in ownership/occupant. If such a change has occurred, EPA recommends the site manager work with the new owner/occupant to ensure continued integrity and operation of the vapor intrusion mitigation system.

8.4 Monitoring of Vapor Intrusion Mitigation Systems

Regardless of the type of system selected for mitigating vapor intrusion in a given building, EPA recommends monitoring to demonstrate that performance standards are achieved at the time of installation and that those performance standards continue to be met throughout the operating period of the mitigation system. EPA recommends that any monitoring program developed for a building mitigation system be based upon site-specific considerations, including the degree of risk or hazard being mitigated, the building use, the technology used to mitigate vapor intrusion, whether the subsurface vapor source(s) is stable in extent and concentration, and coordination with site remediation efforts. For example:

- An older building with highly volatile chemicals at high concentrations may need a more intense level of monitoring than a new building with lower concentrations of less volatile chemicals.

- Passive systems are generally less predictable and less efficient at preventing vapor intrusion than active systems and, therefore, typically warrant more intensive monitoring, all else being equal.

- When contaminated groundwater plumes are migrating to new areas (i.e., expanding) or concentrations in shallow groundwater are increasing, increased frequency and intensity of mitigation monitoring may be warranted.

- During start-up, some remediation methods have the potential to alter soil gas conditions in ways and to a degree that may be difficult to predict. Increased frequency and intensity of mitigation monitoring may be warranted when such remediation methods are implemented near buildings undergoing mitigation.

Mitigation monitoring will generally entail two phases: (i) an initial post-construction phase, which is generally more intensive; and (ii) a subsequent phase, which may be comprised of fewer diagnostic tests to be conducted periodically. As with radon mitigation systems (EPA 1993a, Section 11.1.2), results of indoor air sampling during initial post-construction monitoring may be used to demonstrate that the occupant's exposure to vapor-forming subsurface contaminants has been reduced as anticipated. In addition, pressure field measurements in the subslab region can be used to demonstrate that the system has attained hydraulic control and communication (e.g., depressurization in the case of an ADT system) over the footprint of the building (or portion of a large building, as appropriate, considering the extent of subsurface contamination). Adjustments to the mitigation system and/or additional diagnostic testing (EPA 1993a, 1993c) may be warranted if the results of such testing do not clearly demonstrate that the system is achieving its intended performance and effectiveness. Once an adequate demonstration of effectiveness has been made for the vapor intrusion mitigation system, periodic monitoring is recommended to verify that this performance is sustained; for this purpose, monitoring may be comprised of fewer types of tests than during the immediate post-construction (i.e., start-up) phase at the discretion of EPA when the subsurface vapor source(s) is stable. Examples of various monitoring scenarios for these two phases are provided in Table 4 of CalEPA (2011), Table 6-2 of NJDEP (2012), and Table 3-1 of MADEP (2011). Additional information about ensuring continued effectiveness is available in the *Operational and Functional Determination and the Transfer of Fund-lead Vapor Intrusion Mitigation Systems to the State* (EPA 2009b).

When monitoring to assess the performance and effectiveness of building mitigation technologies, EPA recommends employing the methods, approaches described in Sections 5.4, 6.2, 6.4 and 7.0 of this Technical Guide. EPA also recommends that monitoring programs that assess the performance and effectiveness of remediation and mitigation systems be documented, preferably in work plans similar to those recommended herein for characterizing and assessing the vapor intrusion pathway (see Section 6.2). Such vapor intrusion monitoring plans may be incorporated as part of a comprehensive remedial design and operations manual or as a stand-alone document, depending upon site-specific circumstances. In addition, EPA recommends that data and other results obtained through such monitoring programs be documented (e.g., in the administrative record), as they become available.

The remainder of this section identifies and further discusses some elements commonly incorporated in monitoring programs for active depressurization technologies.

Pressure Measurements

Sub-slab probes can be used to monitor differential pressures for a direct indication of the hydraulic performance of ADT systems (i.e., the pressure difference across the slab prevents soil gas entry); see Section 2.3. For basements, the walls that are underground become part of the critical building envelope that must prevent soil gas entry. For subsurface depressurization systems, EPA recommends that the pressure gauge be monitored quarterly to verify the system is operating efficiently. A reduced monitoring frequency may be appropriate after one year of successful operation of the remedial system.

Tracer Testing

Openings within the building or leaks in the mitigation system can affect system performance. Tracers can be used either for leak detection through barriers, building materials or system components (piping, for example) or to measure the air exchange rate in the building.

Smoke testing is a qualitative form of tracer testing used to detect leaks (e.g., at seams and seals of membranes in SMD systems or at potential leakage points (openings) through floors above sealed crawl space systems or through conduits that facilitate preferential vapor migration), or to test airflow patterns. A limitation of smoke testing in existing structures is that non-noxious smokes can be expensive, and cheaper high-volume smoke sources can leave undesirable residues. The efficacy of smoke testing in some applications has been questioned on the grounds that many leaks are too small for visual detection using this method (Maupins and Hitchins 1998, Rydock 2001), and that leaks large enough to detect using smoke could be detected other ways. More quantitative methods have been recommended, such as tracer testing with instrumentation for quantitative results.

Air Sampling

Once an adequate demonstration of vapor intrusion mitigation system effectiveness has been made, indoor air quality generally will be acceptable as long as an adequate pressure difference is maintained throughout the footprint of the building. Periodic or intermittent sampling of indoor air, nevertheless, warrants consideration, since indoor air data can provide direct confirmation that the system is reducing exposure levels of vapor-forming chemicals and because depressurization technologies can be expected to alter the distribution of vapors in the vadose zone and available for soil gas entry, if any.

Weather-Related Considerations

EPA recommends that weather conditions be noted during monitoring activities (EPA 1993a). Weather conditions, such as temperature and precipitation, can affect the performance of a vapor intrusion mitigation system. For example, cold temperatures may increase the building depressurization created by the thermal stack effect and thus increase the driving force for soil gas entry, depending upon the height of the house and the temperature difference between indoors and outdoors (see Section 2.3). As a result, the ADT system may need to overcome more building depressurization than originally considered when designed. Precipitation may also increase moisture in the fill under the slab, which may affect the performance of the system, and is a factor to consider in developing a monitoring program.

Alarms

Alarms generally are used as part of a monitoring program to ensure that malfunctions of vapor intrusion mitigation systems are timely and readily detected and addressed. According to ASTM (2003), "All active radon mitigation systems shall include a mechanism to monitor system performance (air flow or pressure) and provide a visual or audible indication of system degradation and failure" (i.e., an 'alarm'). ASTM goes on to say, "The mechanism shall be simple to read or interpret and be located where it is easily seen or heard. The monitoring device shall be capable of having its calibration quickly verified on site." Such devices may indicate operational parameters (such as on/off or pressure indicators) or hazardous gas buildup (such as percent LEL indicators). EPA concurs with the cited advice from ASTM and recommends it be considered when monitoring and maintaining mitigation systems for vapor-forming chemicals and sites addressed by this Technical Guide.

In particular, EPA recommends that system failure alarms be installed on active depressurization systems, and appropriate responses to alarms be communicated by the building owner/occupants. EPA also recommends that alarms be placed in readily visible, frequently trafficked locations within the respective building and their proper operation be confirmed on installation and monitored periodically.

Placards

EPA also recommends that permanent placards be placed on the system to describe the system's purpose and operational requirements (e.g., power source) and instructions on what to do if the system does not operate as designed (for example, a phone number to call for corrective action). EPA recommends the placard provide information about how to read and interpret the monitoring instruments or warning devices provided. EPA also recommends that these placards be placed as close to the monitoring/alarm part of the system as possible, as well as close to the fan or other active parts of the system.

8.5 Documentation of Engineered Exposure Controls for Vapor Intrusion Mitigation

EPA recommends that documentation be provided to building owners and occupants and appropriate regulatory agencies[225] describing the vapor intrusion mitigation system (i.e., a 'system manual') and its associated O&M (i.e., an 'O&M plan'). The system manual provides a detailed record about the mitigation system, including as-built drawings, permits (if any), copies of agreements, and construction/layout plans, whereas the O&M manual describes the O&M activities to be conducted routinely and identifies which party is responsible for these O&M activities. Additional information about ensuring continued effectiveness is available in *Operational and Functional Determination and the Transfer of Fund-lead Vapor Intrusion Mitigation Systems to the State* (EPA 2009b).

O&M Plan

O&M plans generally are prepared on a site-specific basis, and they often are particularly useful at sites where:

- Monitoring is needed to verify remedial effectiveness.
- The remedial system warrants periodic adjustments and maintenance.
- Human health risk would result if the system fails or if site conditions change.
- Conditions that would trigger specific contingent response may occur sporadically or episodically.

Some site remedial systems may also warrant the use of a regulatory agency-approved contingency plan or similar corrective response document approved by the regulatory agency to identify conditions that may trigger the need for additional maintenance, collection of additional data, modifications of monitoring frequency, or other responses to ensure the remedy remains effective.

Communication with building owners and occupants about vapor intrusion and the O&M of a vapor intrusion mitigation system is critically important. For example, building owners may be concerned about some aspect of system operation and decide to turn it off. It is important to communicate that turning off the system may result in harmful indoor air concentrations inside the building.

System Manual

The specific contents of the system manual will depend on the type of system. EPA recommends, however, that the system manual generally include at least the following information or items:

- Cover/transmittal letter;

[225] For example, EPA recommends the potentially responsible party (PRP) provide a system manual and O&M plan to EPA at PRP-lead Superfund sites.

- Description and diagram of final as-built system layout with components labeled;
- Building permits for a vapor intrusion mitigation system;
- Pre- and post-mitigation air and gas sampling data;
- Pre- and post-mitigation diagnostic test data;
- Copies of contracts and warranties;
- Proper operating procedures of the system;
- Contact information of the contractor or installer;
- Copy of signed access agreement;
- Copy of vapor mitigation system O&M agreement;
- Copy of pre-mitigation sample result letter (see Section 9.4);
- Copy of post-construction sample result letter;
- Contact information in case of future questions; and
- Inspection and maintenance guidelines.

User's Guide

Documentation typically is also provided to the property owner and occupant in the form of a user's guide suitable to keep lay persons informed about the system and to provide a summary reference in case questions or issues arise pertaining to the system.

A user's guide is a brief summary of why a vapor intrusion mitigation system was installed at a property and how the system works, and may include the following: (1) a brief description of the system and its proper range of operation; (2) contact information for the party responsible for responding to malfunctions and ensuring the system performs properly; and (3) information about routine maintenance to be conducted by the owner/occupant, if any. EPA recommends that a user's guide be placed near the system for quick access and easy reference (e.g., into a clear protective sleeve and attached to the main extraction pipe of the ADT system). An easy-to-read user's guide may be especially helpful at rental properties because the guide informs each new tenant about what the system is and why it was installed.

8.6 Use of Institutional Controls

ICs may be used to restrict certain land uses, buildings, or activities that could otherwise pose an unacceptable human exposure via the vapor intrusion pathway.

Response actions for vapor intrusion may include ICs to restrict land use for protection of human health regardless of whether a vapor intrusion mitigation system provides interim measures to control (i.e., reduce, limit) human exposures. ICs can be used as either an interim

response until site cleanup goals are reached or as part of a long-term response where vapor-forming waste remains in place.

General EPA guidance on ICs is provided in *Institutional Controls: A Guide to Planning, Implementing, Maintaining, and Enforcing Institutional Controls at Contaminated Sites* ("PIME IC Guidance") (EPA 2012d). As discussed in the PIME IC Guidance, ICs are non-engineered instruments, such as administrative or legal controls, that help to minimize the potential for human exposure to contamination and protect the integrity of a response action. ICs typically operate by imposing land or resource use restrictions at a given site or by conveying notice to stakeholders regarding subsurface contamination or the possible need to refrain from certain actions that may result in human exposure to hazardous chemicals. For example, ICs may be used to restrict the development and use of properties for certain land uses (e.g., prohibiting residential housing, hospitals, schools, and day care facilities).

In some situations, ICs can be used to restrict access to a property, facilitate response activities conducted by a responsible party or EPA, such as the installation or maintenance of vapor intrusion mitigation systems, or help ensure the integrity of vapor mitigation systems. ICs may also be used to help inform the need for vapor intrusion mitigation for future construction where vapor-forming waste remains in place and may pose unacceptable human health risk due to vapor intrusion.

As described further in Section 2.2 of the PIME IC Guidance, ICs can be described in four general categories:

- Proprietary controls.
- Governmental controls.
- Enforcement and permit tools with IC components.
- Informational devices.

The first three categories (i.e., proprietary controls, governmental controls, and enforcement and permit tools with IC components) typically memorialize and prescribe substantive use restrictions concerning the land or resource use, while informational devices generally operate to provide notice of contamination and any remedial activities to parties. Depending on the nature of the site and the particular jurisdiction in which it is located, certain instruments may not be available or feasible for a particular site. Certain ICs may help facilitate how interim response actions and subsurface remediation are carried out, such as provisions addressing access, O&M of vapor intrusion mitigation systems, and design specifications for buildings (see Example #3 box below).

8.6.1 Evaluating ICs in the Overall Context of Response Selection

As a site moves through a program's response selection process (for example, a Superfund remedial investigation/feasibility study [RI/FS] or RCRA facility investigation/corrective measures study [RFI/CMS]), EPA recommends that site managers develop information about reasonably anticipated future land uses and infer reasonably expected exposure pathways related to land use. This information may be incorporated in the conceptual site model and often can be used to evaluate whether ICs will be needed to ensure protectiveness of current and

reasonably anticipated future land uses over time. EPA's land use guidance (EPA 1995a, 2010c) recommends that the site manager discuss reasonably anticipated future land uses of the site with local land use planning authorities, local officials, property owners, and the public, as appropriate, as early as possible during the scoping phase of the RI/FS, RFI/CMS, or equivalent phase under other cleanup programs.

EPA recommends that the Region's decisions to implement ICs be documented in proposed cleanup plans and in final cleanup decision documents. For example, for CERCLA cleanups, the proposed restriction, and need for ICs would normally be identified in the Proposed Plan for notice and opportunity to comment by potentially affected landowners and the public. Such use restrictions or notices typically are then selected and memorialized in the Record of Decision (ROD).

In some cases, unanticipated changes in land use may occur after the response action is implemented, which may impact the protectiveness of a completed response action and raise questions concerning the effectiveness of the ICs. As a result, vapor intrusion may be identified as a potential human exposure pathway in a subsequent periodic review. In this case, EPA recommends that site managers evaluate options for modifying the original response decision, including the need for new or additional ICs consistent with existing and reasonably anticipated future land uses and other response selection considerations.

8.6.2 Common Considerations and Scenarios Involving ICs

The evaluation of whether an IC is needed at a contaminated site, including one where the vapor intrusion pathway poses a current or potential threat to human health, is a site-specific determination. When evaluating whether an IC will be needed, EPA recommends that EPA Regional staff consider whether the site meets unlimited use and unrestricted exposure (UU/UE), among other factors. UU/UE is generally the level of cleanup at which all exposure pathways present an acceptable level of human health risk for all land uses, including reasonably anticipated future land use scenarios that are considered during response selection.

Common scenarios where ICs may be a useful instrument for fostering protectiveness at a site involving vapor intrusion threats include, but are not limited to, the following:

1. Existing buildings overlie soil or groundwater contamination, or a migrating groundwater plume that is moving toward existing buildings potentially poses a future vapor intrusion threat;

2. Future construction is planned or is reasonably anticipated on a site that overlies subsurface contamination with vapor-forming chemicals;

3. Changes to building construction/design (such as remodeling or ventilation changes) or building use (such as commercial building converted for residential use) potentially affect exposure to the vapor intrusion pathway;

4. Vapor intrusion mitigation systems are needed in buildings, or existing ventilation systems are being utilized for vapor intrusion mitigation, and continued access is sought to facilitate their O&M;

5. Response actions to reduce source contamination will not immediately meet response objectives; and

6. Response actions to reduce or eliminate source contamination will not be taken (for example, where it is technically impracticable to treat groundwater that is the source of vapor intrusion).

Informational ICs may also serve to provide notice to parties, including prospective purchasers, about what land or building uses are compatible with human health risk that may be posed by vapor intrusion at the site. For example, modifications to a building's ventilation or air conditioning system may affect building under-pressurization in a way that fosters a greater potential vapor intrusion threat. Various ICs can be tailored to address construction and design specifications of both existing and future buildings—a local ordinance, for example, may require parties to submit a building design to its building department that incorporates mitigation measures as determined appropriate by a Professional Engineer (P.E.) (see IC Example #1).

In addition to restricting land, building, or resource use, some types of ICs may provide an effective means for addressing O&M at vapor intrusion sites consistent with decision documents and enforcement documents. This could happen, for instance, when an IC specifies that mitigation systems be installed and maintained in future construction or if the use of an existing building changes (e.g., industrial building use changes to mixed commercial or residential uses). Provisions regarding access to and periodic maintenance and testing of the mitigation systems, and other site-specific obligations may be incorporated into the IC (see IC Example #2).

IC EXAMPLE 1:

City of Mandan, North Dakota Ordinance No. 1002 (City of Mandan 2006)

In 2006, the City of Mandan, North Dakota, enacted an ordinance that created an Environmental Institutional Control Zoning District to define an area of downtown Mandan impacted by petroleum contaminated soil and groundwater and to establish ICs for the protection of human health and the environment. Among other provisions, the ordinance requires any person proposing redevelopment, demolition, excavation, grading, or construction activities at properties within the District to submit to the city administrator or their appointee a contingency plan, approved by the North Dakota Department of Health, to evaluate and manage any petroleum contaminated soils or groundwater and any potential petroleum vapor impacts. The contingency plan must be prepared by a P.E. with experience in the environmental field, and the plan must consider and protect against, among other things, the vapor intrusion pathway. In addition, the ordinance also provides for restrictions on construction of new structures within the District. In pertinent part, the ordinance provides:

"Any person proposing to construct a new structure within the District shall submit a design for that structure that incorporates engineered controls to mitigate the effects of the potential presence of petroleum in the subsurface to the city administrator or their appointee. The design must be prepared by a P.E. and the design must be approved by the North Dakota Department of Health and must meet additional applicable codes and standards relative to the presence of petroleum. The design shall protect the public health and the environment by considering, at a minimum a) historic water/product intrusion; b) historic petroleum vapor/odor issues; c) potential future water/product intrusion; and d) potential future petroleum vapor/intrusion. The design shall incorporate vapor barriers, venting system, groundwater suppression/collection, and specialized HVAC as determined appropriate by a P.E."

IC EXAMPLE 2: State IC Legislation

Some states have enacted statutes that directly authorize proprietary controls for the purpose of preventing use in conflict with environmental contamination or remedies. These state statutes divide into ones modeled after the Uniform Environmental Covenants Act (UECA)[226] and other non-UECA statutes.[227] These UECA and non-UECA state statutes tend to provide advantages over traditional common law proprietary controls by reducing certain legal and management complications associated with their use. The Model UECA, for instance, contemplates that the grantee or "holder" of the "environmental covenant" may be given specific rights or obligations with respect to future implementation of the environmental covenant.[228] This ability to oblige parties to undertake affirmative actions at a site, such as long-term maintenance of a cap or O&M of a vapor intrusion mitigation system, through a UECA environmental covenant, is different from traditional common law proprietary controls.

Proprietary controls that bind current and subsequent landowners (that is, the proprietary control "runs with the land") to use restrictions at properties, as well as oblige them to undertake affirmative obligations, may have utility at vapor intrusion sites. For instance, at a contaminated site in Bucks County, Pennsylvania, an environmental covenant executed pursuant to the Pennsylvania Uniform Environmental Covenants Act contained provisions to address vapor intrusion threats. In addition to provisions for access, annual inspections, compliance reporting, and other specifications related to cleanup activities, parties to the environmental covenant agreed to construct slab-on-grade buildings without basements and install vapor barriers as an engineered control to mitigate the potential for vapor intrusion as part of the eventual development of the property. Further, the environmental covenant provided that engineering plans for the vapor barriers first be submitted to and approved by EPA prior to construction. For examples of environmental covenants executed pursuant to the Pennsylvania Uniform Environmental Covenants Act, Act No. 68 of 2007, 27 Pa. C.S. §§ 6501-6517: http://www.depweb.state.pa.us/portal/server.pt/community/land_recycling_program/20541/uniform_environmental_covenants_act/1034860

[226] UECA was developed by the National Conference of Commissioners on Uniform State Laws. See: www.uniformlaws.org.

[227] See, for example, Colo. Rev. Stat. § 25-15-320 (2011); Cal. Civ. Code § 1471 (2011).

[228] "Grantee" is a traditional property law term describing a person to whom property is conveyed. States that have passed legislation based on UECA have created different legal concepts specific to those jurisdictions. For example, UECA jurisdictions typically define "holder" and "environmental covenant" to reflect, respectively, the grantee and the servitude that imposes the land or resource use restrictions. The model UECA provides that "[h]older means the grantee of an environmental covenant…" See definition 6 in Section 2.0 of the model UECA.

8.6.3 Selecting the Right Instrument(s)

When evaluating potential IC instruments, EPA recommends that site managers and site attorneys balance the relative advantages and limitations of IC instruments under consideration—for example, consider legal implementation issues, jurisdictional questions, permanence and enforceability concerns—and select those that best achieve the response objectives. (IC Example #3 describes how these factors were considered at the Middlefield-Ellis-Whisman Study Area.)

EPA guidance on ICs provides detailed considerations regarding the selection of ICs and the relative strengths of the different categories of IC instruments.[229] Ultimately, the selection of ICs is a site-specific evaluation based on the characteristics of the site (for example, the nature and extent of the vapor intrusion threat) and the particular jurisdiction in which it is located. There are times when multiple IC instruments can be "layered" to best ensure protectiveness of the response action while meeting the response objectives outlined in the decision documents.[230]

Because many ICs are created pursuant to state and other non-federal laws, the authority to implement and otherwise oversee these ICs resides with government entities other than EPA. Units of local governments, for instance, typically have jurisdiction to implement, maintain, enforce, and terminate certain governmental controls, such as zoning ordinances and building permit conditions. Therefore, it is important to evaluate the capacity (financial, technical, etc.) and willingness of the entity ultimately responsible for taking over IC responsibilities prior to IC selection.[231] Site managers and site attorneys are encouraged to coordinate early with IC stakeholders so that adequate assurances may be acquired and then subsequently maintained as necessary over time.

Given the potential role of non-EPA entities, it may be appropriate for EPA to facilitate or recommend a process by which IC stakeholders provide similar assurances or otherwise reach a common understanding[232] regarding their respective IC responsibilities to ensure that selected ICs are effectively implemented, maintained, and enforced. At a vapor intrusion site, for example, a zoning ordinance may be effective in preventing or ensuring responsible future development of properties overlying a contaminated groundwater plume that presents a vapor intrusion pathway threat. Such zoning ordinances generally are designed and enacted by the local government. Once enacted, the ordinance must be followed and enforced for it to serve as an effective IC over its lifespan. One inherent limitation of governmental controls, however, is that their implementation, modification, and termination generally follow a legislative process

[229] See Site Manager's IC Guide and Section 3.2 of the PIME IC Guide for a framework to consider when deciding among available ICs.

[230] See Section 3.2 of the PIME IC Guide for more discussion on layering ICs.

[231] See Section 3.8 of the PIME IC Guide on IC stakeholder capacity considerations.

[232] Parties may be able to provide assurances or otherwise reach a common understanding regarding their respective IC roles and responsibilities through various mechanisms that may be available under state law (for example, a Memorandum of Understanding, Memorandum of Agreement, Administrative Order on Consent, contract, City Resolution, or enforceable agreement, etc.). For additional discussion about obtaining or memorializing IC assurances, see Sections 3.3, 3.8, and 4.3 of the PIME IC Guide.

IC EXAMPLE 3: Efforts to Address VI at the Middlefield-Ellis-Whisman Study Area

The Middlefield-Ellis-Whisman (MEW) Study Area is composed of four separate CERCLA sites—Raytheon Corp., Intel Corp. (Mountain View Plant), Fairchild Semiconductor Corp. (Mountain View Plant), and portions of the former Naval Air Station Moffett Field Superfund site—and many distinct parcels with land uses including residential, commercial, and light industrial. In 2009, EPA finalized a Supplemental FS for the MEW Study Area that presented an evaluation of a variety of remedial alternatives that could be used to mitigate potential vapor intrusion into current and future buildings overlying the shallow plume of contaminated groundwater. The FS provided an analysis of ICs using the NCP evaluation criteria: overall protection of human health and the environment; long-term protectiveness and permanence; compliance with applicable or relevant and appropriate requirements; reduction of toxicity, mobility, or volume through treatment; short-term effectiveness; implementability; and cost. The other two NCP evaluation criteria, state acceptance and community acceptance, were evaluated in the ROD Amendment for the vapor intrusion pathway remedy at the MEW Study Area.

In 2009, EPA published the Proposed Plan for the MEW Study Area that identified EPA's preferred alternatives for the vapor intrusion remedy. The Proposed Plan identified the adoption of a municipal ordinance as EPA's preferred IC, but the City of Mountain View and concerned property owners raised concerns that this was not necessary. Instead, EPA worked with the City of Mountain View, California, to have the City formalize its permitting procedures that apply to future construction. These permitting procedures oblige those proposing new building construction within the MEW Study Area to obtain EPA approval of construction plans to ensure that, where necessary, the appropriate vapor intrusion control system is integrated into building construction. In a 2010 ROD Amendment, EPA presented its selected remedy for the vapor intrusion pathway for the MEW Study Area. The ROD Amendment identified a combination of ICs for use at the site. In place of a municipal ordinance as called for in the Proposed Plan, the ROD Amendment selected reliance upon the internally modified permitting procedures by the City of Mountain View's Building, Planning, and Permitting Departments. The City will also implement remedy requirements for projects subject to the California Environmental Quality Act through that law's procedures. With regard to existing commercial buildings where an active remedy is necessary, EPA selected the use of recorded agreements that will help provide notice to current and future owners and occupants, notice to EPA and the MEW Companies when there is a change in building ownership or configuration, and the necessary access to install, maintain and operate the vapor intrusion remedy. These agreements will be binding on and enforceable against future property owners. Additionally, EPA selected the use of a tracking service to provide notice when changes are made to properties within the MEW Study Area. Additional controls that will be implemented by the City of Mountain View include creation of a mapping database to help ensure that parties interested in properties within the MEW Study Area are informed of the appropriate construction specifications when making inquiries with the City.

For more information on the MEW Study Area, see the *Final Supplemental Feasibility Study for the Vapor Intrusion Pathway* (June 2009), *Proposed Plan for the Vapor Intrusion Pathway* (July 2009), and *Record of Decision Amendment for the Vapor Intrusion Pathway* (August 2010), available at: www.epa.gov/region9/mew

outside the authority of EPA that may raise questions regarding the reliability and continued sustainability of the IC. Obtaining early and continued assurances from a local government specifying its commitment to the governmental control is recommended to help address this limitation prior to its selection as part of a final cleanup plan.

Certain IC instruments may not be available for use at a site, depending on federal, state, local, tribal, or other applicable laws. Therefore, after determining the universe of ICs available for use at a particular site, the practical and legal limitations can be evaluated. For example, large sites with widespread contamination pose unique IC challenges. These challenges could arise, for instance, where a contaminated groundwater plume underlies many distinct parcels with multiple property owners/occupants and vapor intrusion is the exposure pathway of concern. Negotiating and implementing proprietary controls with many property owners, some of whom may not be PRPs, may present legal, administrative, and other challenges.[233]

8.6.4 Long-term Stewardship

Long-term stewardship (LTS) activities are intended to help ensure that cleanups remain protective of human health and the environment over time and that reuse activities remain compatible with residual site contamination and associated human health risk potentially posed by the vapor intrusion pathway. LTS procedures vary widely, but they generally are intended to help assure compliance with the response actions at the site, including IC compliance, by providing relevant information in a timely manner to stakeholders who may use the property (e.g., owners, excavators, developers, prospective purchasers or tenants) or to parties who otherwise have IC responsibilities (i.e., an entity with enforcement authority). LTS procedures, for example, may entail provisions to monitor and then inform those responsible for the response actions of potential changes in land use, ownership, tenancy, or building construction at a site. Also, LTS procedures may facilitate monitoring IC(s) so that they remain effective and reliable over time. EPA guidance on ICs generally speaks to LTS procedures in terms of IC maintenance[234] and enforcement activities.[235]

Periodic Reviews

A key part of IC maintenance is a periodic process over the IC life cycle to critically review and evaluate the IC instrument(s). Site managers and other stakeholders can evaluate the status of IC implementation, maintenance and enforcement activities at a site and address any potential IC deficiencies during the periodic review. The CERCLA FYR process,[236] for example, allows site managers to evaluate overall protectiveness of the remedy, including ICs.[237]

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[233] See Section 4.4 of the PIME IC Guide for strategies for implementing proprietary controls.

[234] The term "maintenance" generically refers to those activities, such as monitoring and reporting, that ensure ICs are implemented properly and functioning as intended.

[235] See Sections 8 and 9 of the PIME IC Guide discussing IC maintenance and enforcement activities.

[236] See CERCLA section 121(c).

[237] For general FYR guidance, see *Comprehensive Five-Year Review Guidance* (EPA 2001) at www.epa.gov/superfund/cleanup/postconstruction/5yr.htm. For a more detailed discussion on IC considerations during the CERCLA FYR process, see *Recommended Evaluation of Institutional Controls: Supplement to the "Comprehensive Five-Year Review Guidance,"* (EPA 2011c).

A list of possible IC-specific issues arising from any periodic review of a vapor intrusion site may include:

- ICs that are specified by the decision documents but are not yet in place;
- ICs that are in place but are not attaining compliance with the use restrictions specified by the decision documents (e.g., land use not compatible with IC-specified use restrictions);
- ICs are not identified in the decision documents but are necessary for the remedy to be protective of human health because of the vapor intrusion pathway; and
- Response selection assumptions change (e.g., toxicity values, potential exposure pathways, or land uses change) and warrant the need for new or different response actions, including additional IC(s).

IC Planning Documents

Responsibilities to monitor and report on IC compliance, among other obligations, may be documented in an Institutional Controls Implementation and Assurance Plan (ICIAP)[238] or other IC-related planning documents.[239] An ICIAP can serve to: (1) document the activities necessary to implement and ensure the long-term effectiveness and permanence of ICs (that is, the IC life cycle); and (2) identify the person(s) or organization(s) who, under state or local law, are responsible for conducting those activities. Some ICs generally fall within the jurisdiction of a particular category of stakeholders. Therefore, in addition to developing a comprehensive planning document, such as an ICIAP, it may be useful for parties who share IC responsibilities (e.g., a PRP and local government regarding the use of governmental controls, such as an ordinance or permitting system) to reach a common understanding and acknowledge various IC roles and responsibilities in a formalized manner. Where possible, EPA recommends that these types of arrangements among IC stakeholders be documented to describe commonly understood roles and responsibilities for proper and effective monitoring, reporting, and other IC maintenance and enforcement activities.

8.6.5 Community Involvement and ICs

EPA recommends that site managers and site attorneys provide adequate opportunities for public participation (including potentially affected landowners and communities) when considering appropriate use of ICs (EPA 2012e). Those opportunities may include providing appropriate notice and soliciting comments about cleanup plans. Community acceptance of the need for ICs to provide protection from residual contamination and public understanding of the legal and administrative steps for maintaining ICs often are important to the long-term effectiveness of ICs.

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[238] For further guidance on developing ICIAPs, EPA developed *Institutional Controls: A Guide to Preparing Institutional Control Implementation and Assurance Plans at Contaminated Sites* (EPA 2012e).

[239] For example, other types of documents may address IC-related activities and responsibilities at a site, such as a ROD, O&M plan, and land use control and implementation plan for federal facility sites.

8.7 Termination/Exit Strategy

This sub-section focuses on the termination/exit strategy for vapor mitigation response actions. Termination for vapor mitigation activities implemented under CERCLA, RCRA, Brownfields, and federal facilities cleanups can occur when the objectives of these cleanup activities have been met. For purposes of this sub-section, termination refers to the cessation of all activities related to building mitigation, control of subsurface vapor source(s), ICs, and monitoring.

When mitigating vapor intrusion through subsurface source remediation, building mitigation, and ICs, it is important to develop termination criteria, including the rationale for their selection, early in the remedy planning (e.g., alternatives development) process. (Termination criteria generally refer to numeric cleanup levels for each site-specific contaminant and narrative cleanup objectives that are to be attained by the response actions.) EPA recommends that these termination criteria be recorded in decision documents, in any other planning reports, and in monitoring reports. EPA generally recommends also developing and documenting an exit strategy, which clarifies how it will be determined that the termination criteria have been attained (e.g., monitoring data and associated statistics that will be used to demonstrate attainment). This document could be developed in conjunction with the O&M plan and monitoring program so that all stakeholders are provided with a clear and comprehensive set of termination criteria for the remediation and mitigation systems and ICs. If site conditions (e.g., building usage, vapor flux) change during the cleanup activities, it may become necessary to modify the termination criteria and/or strategy.

When reviewing vapor intrusion activities, considerations for evaluating termination activities may include:

- Termination of subsurface remediation activities;
- Termination of engineered exposure controls (building mitigation);
- Termination of the associated ICs; and
- Termination of monitoring.

8.7.1 Termination of Subsurface Remediation Activities

Where feasible, the preferred response to address vapor intrusion is to eliminate or substantially reduce the level of volatile chemical contamination in the source media (e.g., groundwater and subsurface soil) to levels that eliminate the need to mitigate or monitor vapor intrusion, as noted in Section 8.1 of this Technical Guide. If subsurface remediation activities are being conducted at the site, termination of these activities will be contingent on demonstrating that the chemical-specific cleanup levels for the subsurface media have been attained. EPA recommends that the termination criteria and exit strategy for these remediation activities be documented to foster collection and evaluation of appropriate data to support eventual termination of these subsurface activities.

EPA recommends that site-specific monitoring data be evaluated to determine if the termination criteria have been met. Typically, monitoring will continue until the source(s) are remediated to cleanup levels that eliminate the need to mitigate vapor intrusion at the point of exposure. As appropriate, the exit strategy may provide criteria for phased remediation, resulting in a

termination evaluation as source cleanup levels are achieved in parts of the contaminated area. If the subsurface vapor source(s) is not remediated, it is generally anticipated that remediation (and monitoring and any building mitigation) will continue.

Monitoring, in part, could be based on data similar to those that were used in a multiple-lines-of-evidence approach for characterizing the pathway and human health risk or for supporting the decision to undertake preemptive mitigation/early action (e.g., soil gas sampling, sub-slab sampling, or vapor sampling within potentially affected structures). EPA recommends identifying and documenting target concentration(s) that would allow for remediation termination, along with recommended monitoring/sampling frequencies.

If evaluation of the site-specific data indicates an increase in subsurface vapor concentrations during the monitoring period, it may be appropriate to evaluate whether the subsurface remediation plan and the CSM are adequate and appropriate.

Typically, once it is preliminarily determined that the subsurface remediation system(s) may be terminated, EPA recommends a period of attainment monitoring. During the attainment period, EPA recommends that the remediation system (e.g., reagent delivery equipment, soil vapor extraction wells) not be operated for a sufficient period to allow subsurface vapors reach equilibrium and indicate post-remediation conditions. The type and frequency of data collected during attainment monitoring entails a site-specific determination. Additionally, EPA recommends that criteria be described and documented, as part of exit strategy development, to determine when ending the attainment monitoring period is appropriate. To develop an exit termination strategy, site-specific fate and transport data may be used to identify an appropriate time period to allow the vapor concentrations to equilibrate. In addition, the termination of the attainment monitoring period may involve an evaluation of the contaminant attenuation in the vadose zone.

8.7.2 Termination of Building Mitigation

For purposes of this Technical Guide, “termination of building mitigation” refers to ending the use of an engineered exposure control(s) that reduces or eliminates human exposure via the vapor intrusion pathway. Typically, vapor mitigation is implemented when it is determined that (1) unacceptable human health risk to inhabitants is identified, or (2) the system(s) was(were) installed as part of an early action strategy (see Sections 3.3 and 7.8 for a discussion of building mitigation as an early action).

As described in Section 8.2, vapor intrusion can be mitigated in specific buildings using either an active or passive vapor mitigation system (or a combination thereof).

Active Building Mitigation

Generally, building mitigation systems are implemented in conjunction with the investigation and remediation of subsurface vapor source(s). Typically, building mitigation systems will be operated until the source(s) are remediated to attain the cleanup levels (e.g., for the subsurface vapor source(s)) that eliminate the need to mitigate vapor intrusion at the point of exposure. If subsurface vapor source(s) are not remediated, it is generally anticipated that mitigation activities will continue indefinitely. As appropriate, the termination strategy may provide criteria for phased evaluation of system cessation as source cleanup levels are achieved in parts of the contaminated area.

Generally, once the subsurface vapor source(s) is remediated to levels that meet the remedial objectives and protect human health from the vapor intrusion pathway, EPA recommends that the site-specific monitoring data be evaluated to determine if the termination criteria for the building mitigation system have been met. These monitoring data, in part, could be based on data similar to those that were used for characterizing human health risk or for supporting the decision to undertake preemptive mitigation/early action during the vapor intrusion investigation (e.g., sub-slab soil gas sampling and/or indoor air sampling). EPA recommends identifying and documenting target concentration(s) that would allow for system termination, along with recommended monitoring/sampling frequencies. In addition, certain site-specific performance assessment data (e.g., standpipe vapor sampling) may also warrant consideration to make this determination.

Typically, once it is determined that the building mitigation system may be terminated, EPA recommends a period of attainment monitoring. During the attainment period, EPA recommends that the mitigation system (e.g., subslab suction wells or ventilation fans) be offline for a sufficient period to allow vapors beneath the structure reach equilibrium and indicate post-remediation conditions. The type and frequency of data collected during attainment monitoring entails a site-specific determination. Additionally, EPA recommends that criteria be established in the exit strategy to determine when ending the attainment monitoring period is appropriate. To develop an exit termination strategy, site-specific fate and transport data may be used to identify an appropriate time period to allow the vapor concentrations to equilibrate. In addition, the termination of the attainment monitoring period may involve an evaluation of the contaminant attenuation in the vadose zone.

If the attainment criteria evaluation indicates that cleanup levels and objectives are not being met, it may be necessary to continue or resume subsurface remediation and mitigation activities. Once it is determined that the cleanup levels and objectives have been met, the active components of the system may be removed from the building; on the other hand, the building owner may elect to continue to operate the mitigation system under their own discretion and for their own purposes (e.g., radon reduction and moisture control). Once the cleanup levels and objectives have been met, all O&M and monitoring of active mitigation systems specified by EPA can cease.

Passive Building Mitigation

The termination of passive vapor mitigation systems will typically be similar to the criteria established for the termination of active mitigation systems. In summary:

- Like active mitigation systems, passive mitigation systems are typically implemented in conjunction with the investigation and remediation of subsurface vapor source(s).

- Generally, once the subsurface vapor source(s) is remediated to levels that meet the cleanup levels and objectives that will protect human health from the vapor intrusion pathway, EPA recommends that the site-specific monitoring data be evaluated to determine if the termination criteria have been met.

If the site-specific criteria evaluation indicates that cleanup levels and objectives are not being met, it may be appropriate to evaluate the current system's effectiveness or the possible application of an active mitigation system. Once it is determined that contaminant cleanup levels and objectives have been met, all O&M and monitoring specified by EPA can cease. EPA

generally does not have a need to seek removal of barriers or seals that comprise a passive mitigation system as part of termination activities.

8.7.3 Termination of ICs

"Termination of ICs," as used in this Technical Guide, refers to discontinuing any and all ICs specified by EPA because restrictions on land or resource use and/or notices and other informational devices are no longer necessary to help ensure protectiveness of human health (i.e., human health risk from exposures to vapor intrusion, if any, are expected to be acceptable in the absence of all IC(s)). Generally, ICs are implemented in conjunction with the investigation and remediation of source(s). It is anticipated that ICs selected and implemented will be needed until (1) subsurface vapor source(s) are adequately remediated, or (2) restrictions on land, resource, or building use are no longer necessary based on current and reasonably anticipated future exposure scenarios. Therefore, when developing a termination strategy for ICs that have been selected as part of a response action, the strategy is typically based on data collected from the affected media.

EPA recommends that the exit strategy consider and identify cleanup levels for the subsurface vapor source(s). As long as the subsurface vapor source exceeds such cleanup levels, it is generally anticipated that the associated ICs will continue. As appropriate, the termination/exit strategy may provide criteria for a phased IC termination evaluation as source cleanup levels are achieved in parts of the contaminated area.

If the site-specific criteria evaluation indicates that terminating the ICs is appropriate, EPA may conclude that site conditions no longer warrant ICs being used as part of the response action for the vapor intrusion pathway. At this point, EPA could notify the appropriate entity(s), such as local or state government, tribe, affected landowner, or responsible parties, in writing that EPA's response objectives have been met and that the IC need not be maintained. As such, EPA's oversight of the IC(s) can cease.

8.7.4 Termination of Monitoring

For purposes of this Technical Guide, monitoring includes activities conducted to verify that the vapor intrusion pathway does not pose a health concern to building inhabitants while remediation and mitigation activities are underway and in the event that the remediation and mitigation activities are terminated. "Termination of monitoring," for purposes of this Technical Guide, refers to ending any monitoring that was needed to verify that no further response action, including IC-related activity, is necessary to protect human health from indoor air exposures posed by vapor intrusion. When developing termination criteria for monitoring, the decision is generally based on data collected from all the affected media.

As noted above, monitoring is generally implemented in conjunction with the remediation of subsurface vapor sources(s). EPA recommends that the exit strategy consider cleanup levels for all contaminated media. Typically, monitoring will continue until the source(s) are remediated to cleanup levels that eliminate the need to mitigate vapor intrusion at the point of exposure (i.e., allow building mitigation systems to be terminated). If the subsurface vapor source is not remediated, it is generally anticipated that any associated monitoring will continue. As appropriate, the exit strategy may provide criteria for phased monitoring, resulting in a termination evaluation as source cleanup levels are achieved in parts of the contaminated area.

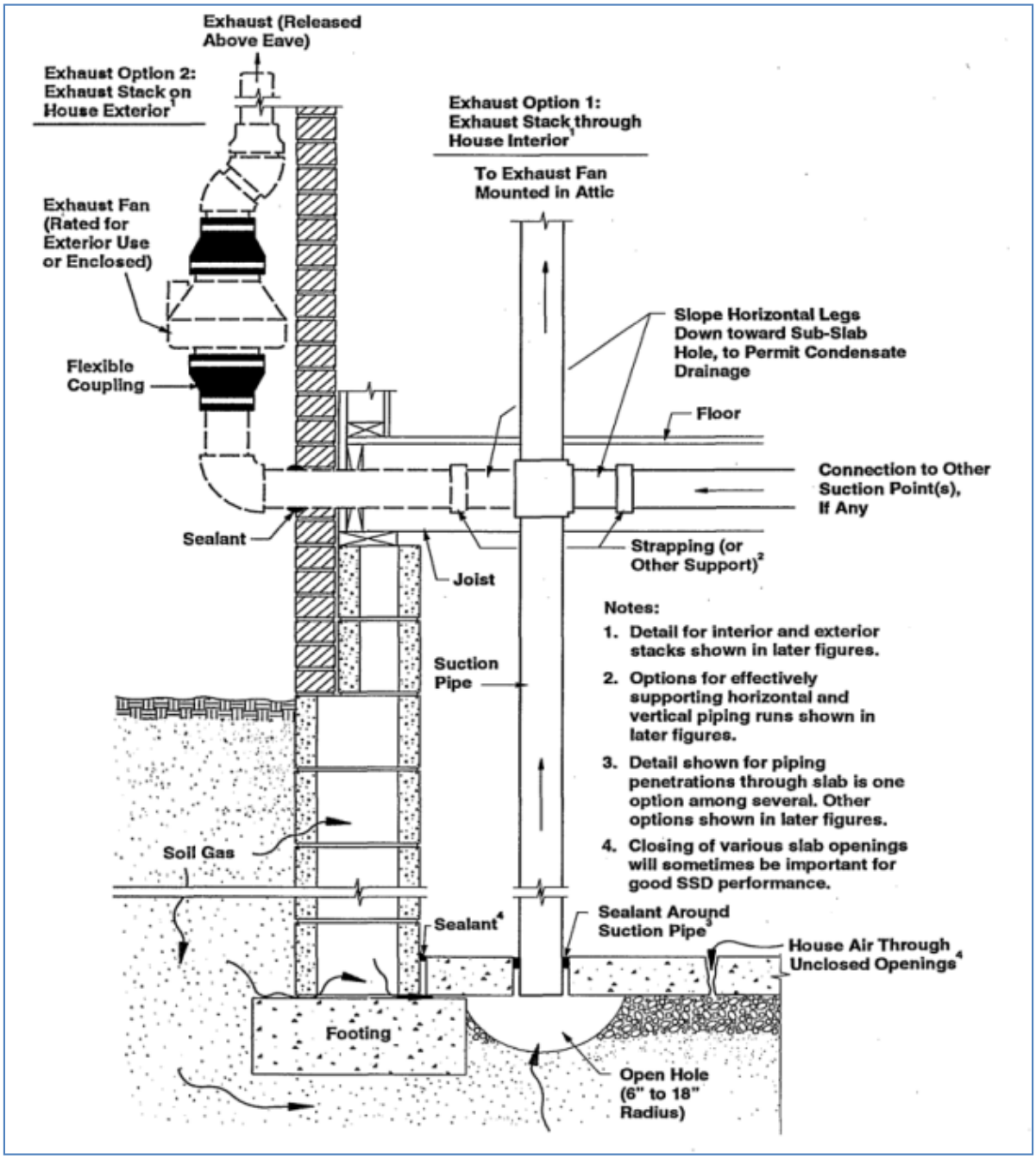

Figure 8-1 Illustration of Sub-slab Depressurization (SSD) System

Note: Shows one example of how a sub-slab depressurization system might be constructed. In this case, the example suction pipe has been inserted vertically downward through the slab from inside the house. Two options are indicated for location of the exhaust fan: one exterior to the building; and the other within an attic. In both of these cases, the exhaust gas stream is to be vented outside and above the building.

Source: EPA (1993a; Figure 1)

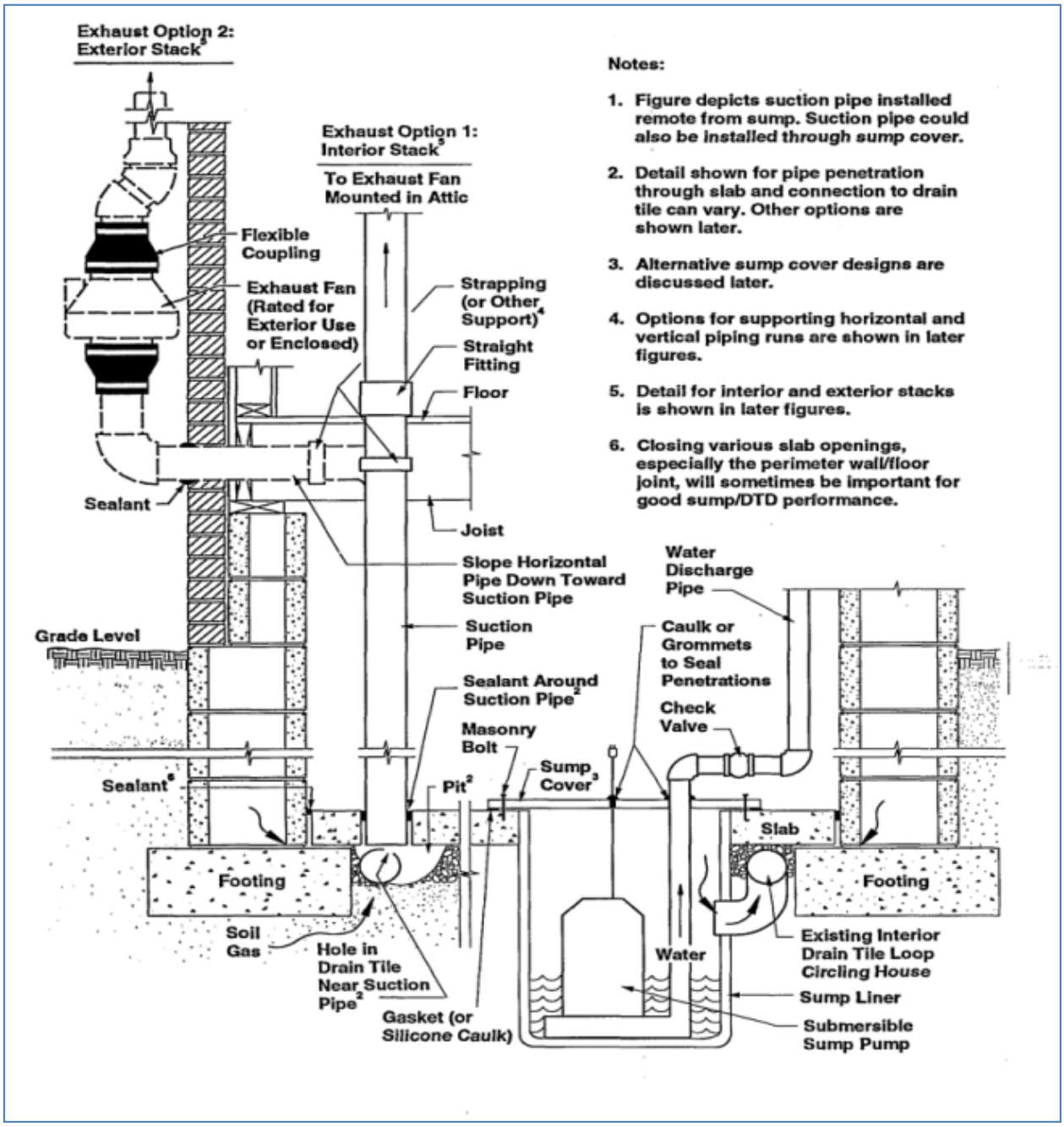

Figure 8-2 Illustration of Drain-tile Depressurization (DTD) System

Note: Shows one example of how a drain-tile depressurization system might be constructed. In this case, tiles are shown draining to a sump in the basement, to which an air-tight cover is sealed. The example suction pipe has been inserted vertically downward through the slab at a location remote from the sump. Two options are indicated for location of the exhaust fan: one exterior to the building; and the other within an attic. In both of these cases, the exhaust gas stream is to be vented outside and above the building.
Source: EPA (1993a; Figure 3)

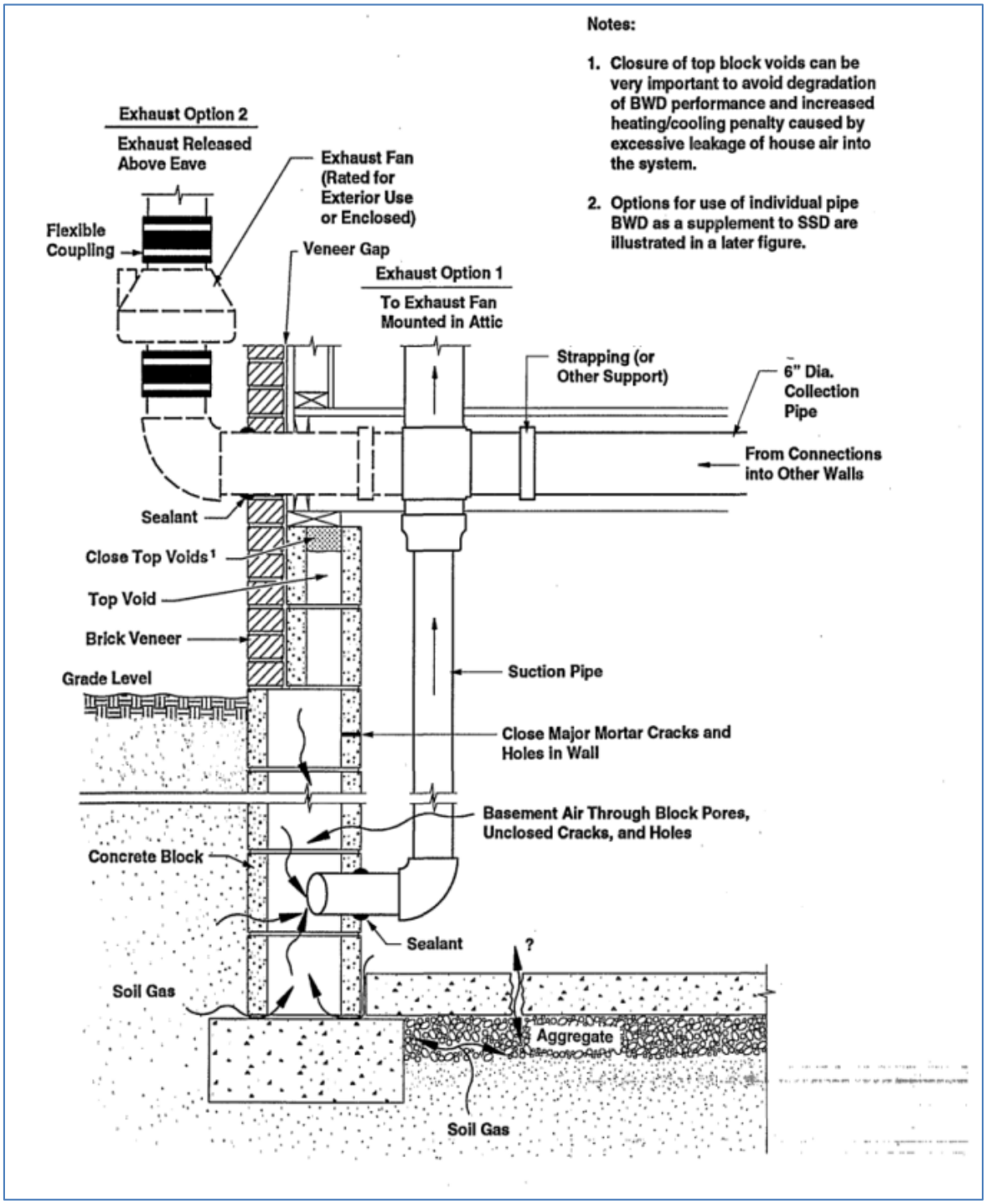

Figure 8-3 Illustration of Block-wall Depressurization (BWD) System

Note: Shows one example of how a block-wall depressurization system might be constructed. In this case, individual suction pipes are inserted into the void space in the basement wall, which are connected to one or more fans. Source: EPA (1993a; Figure 5)

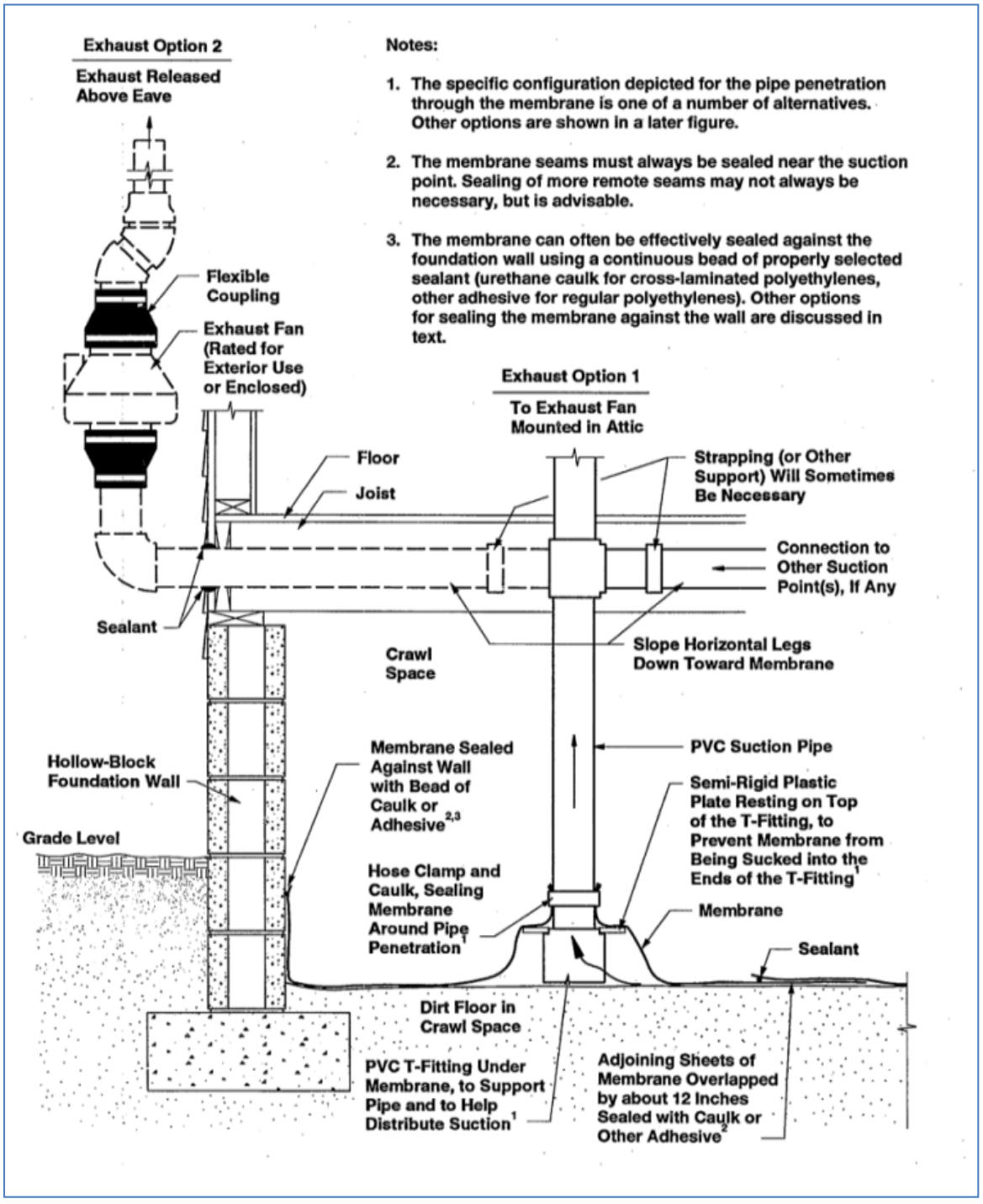

Figure 8-4 Illustration of Sub-membrane Depressurization (SMD) System

Note: Shows one example of how a sub-membrane depressurization system might be constructed. In this case, the example suction pipe penetrates the membrane overlying a dirt floor.

Source: EPA (1993a; Figure 6)

9.0 PLANNING FOR COMMUNITY INVOLVEMENT

Communicating information about environmental risk is one of the most important responsibilities of site managers and community decision-makers. Simply stated, risk communication, whether written, verbal, or visual statements concerning risk, is the process of informing people about potential and perceived hazards to their person, property, or community.

EPA recommends that human health risk be described in context, recognizing there are personal, cultural and societal dimensions of risk. EPA also recommends providing advice about risk-reduction behavior and encouraging a dialogue between the sender and receiver of the message. The best risk communication occurs in contexts in which the participants are informed about risks they are concerned about, the process is fair, and the participants are free and able to solve whatever communication difficulties arise. *Risk Communication in Action: The Risk Communication Workgroup* (EPA 2007) is one of several resources available that explain the elements of successful risk communication and describe communication tools and techniques.

Thus, community involvement is a key component of any site investigation or other EPA response action. Members of the public affected by environmental contamination can be made aware of what EPA is doing in their community and have a say in the decision-making process. Stakeholder and community involvement is particularly important for sites with vapor intrusion issues, in part because the exposure to toxic vapors may pose a significant human health risk that is unknown to inhabitants (in the absence of mitigation systems), as they potentially arise in homes, workplaces, schools, and places of commerce and gathering. Because of the potentially intrusive nature of assessment and mitigation for vapor intrusion, stakeholder involvement is important throughout the process.

EPA generally recommends that stakeholder and community involvement be conducted from the earliest stage of the site assessment and risk assessment process, with on-going education, two-way communication, and discussion throughout the entire process to create community trust and acceptance. For example, EPA recommends initiating community involvement activities as soon as possible after determining that vapor intrusion may exist at a particular site.

Informing the community about vapor intrusion concerns and plans to conduct an assessment, including sampling, can be resource intensive. Thus, EPA recommends evaluating each project, in coordination with appropriate state and tribal officials, to assess the level of stakeholder interest and need for community involvement during various stages of the decision-making process.

Public Participation and Risk Communication

A meaningful community involvement process is founded upon knowledge of effective public participation and risk communication practices. Public participation refers to the full range of activities that EPA uses to engage communities in the Agency's decision-making process. In 2003, EPA updated its Public Involvement Policy.[240] Its foundation includes seven basic steps to support effective public participation:

[240] EPA Public Involvement Policy (2003): http://www.epa.gov/publicinvolvement/policy2003/index.htm.

1) Plan and budget.

2) Identify those to involve.

3) Consider providing assistance.

4) Provide information.

5) Conduct involvement.

6) Review and use input and provide feedback to the public.

7) Evaluate involvement.

To help implement the steps, EPA developed a series of brochures[241] on effective public participation that outline how to budget for, plan, conduct, and evaluate public participation.

EPA Program-Specific Community Involvement Guidance and Recommendations

CERCLA and other EPA regulations[242] identify specific community involvement activities that are appropriate at certain points throughout the cleanup process. Specifically, in 2005, OSWER published the *Community Involvement Handbook*[243] (EPA 540-K-05-003). The handbook presents legal and policy motivations for Superfund community involvement and includes additional suggestions for involving the community in the Superfund process. In addition, EPA's *Proposed Guidelines for Brownfields Grants* encourages applicants to describe their plans for involving community-based organizations in site cleanup and reuse decisions.[244] The *Grant Funding Guidelines for State and Tribal Response Programs* for brownfields funding also encourage programs to establish, at a minimum, "mechanisms and resources to provide meaningful opportunities for public participation."[245] In addition, in 1995, EPA promulgated the *RCRA Expanded Public Participation* rule (60 FR 63417-34, December 11, 1995)[246] which created additional opportunities for public involvement in the permitting process and increased access to permitting information.[247]

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[241] EPA Public Involvement Brochures: http://www.epa.gov/publicinvolvement/brochures/index.htm

[242] 40 CFR §300.155 http://edocket.access.gpo.gov/cfr_2003/julqtr/pdf/40cfr300.155.pdf

[243] EPA *Superfund Community Involvement Handbook*: http://www.epa.gov/superfund/community/cag/pdfs/ci_handbook.pdf

[244] EPA Brownfields Grants website: http://www.epa.gov/brownfields/cleanup_grants.htm

[245] EPA Brownfields State and Tribal Response Program Grants website: http://www.epa.gov/brownfields/state_tribal/fund_guide.htm

[246] Section 7004(b) of the Resource Conservation and Recovery Act provides EPA broad authority to encourage and assist public participation in the development, revision, implementation, and enforcement of any regulation, guideline, or program under RCRA.

[247] EPA *RCRA Public Participation Manual*: http://www.epa.gov/osw/hazard/tsd/permit/pubpart/manual.htm

At sites with vapor intrusion issues, EPA recommends that the site planning team (i.e., the remedial project manager (RPM) or on-scene coordinator (OSC); community involvement coordinator (CIC); risk assessor; the enforcement case team; EPA contractor; state, tribal, or local agency staff; federal agency staff relevant to the site; or others) to consider the following:

- Develop a community involvement plan (CIP) or update the existing CIP.
- Learn about the site and the community to foster development of a CIP that highlights key community needs, concerns and expectations.
- Commit to ongoing, sustained communication activities throughout vapor mitigation and site cleanup efforts.
- Develop a communication strategy[248] and conduct outreach to inform stakeholders about the facts and findings pertaining to the site.
- Obtain written permission, if appropriate and necessary, for building/property access, and involve the property owner/occupant in identifying or removing potential indoor air contamination sources, including inspection of residence and completing an occupant survey.
- Fully communicate and interpret sampling results, and evaluate mitigation options, if any are warranted.
- Recognize preference of owners and occupants for confidentiality with regards to property-specific data.

When considering the most effective community involvement strategies, EPA recommends that its previous involvement be considered, as well as the existence of community or neighborhood groups and the phase of the regulatory process in which vapor intrusion is being addressed. Additional resources for planning and implementing effective community involvement activities are discussed in Section 9.2: Communication Strategies and Conducting Community Outreach.

9.1 Developing a Community Involvement or Public Participation Plan

A CIP is a site-specific strategy to enable meaningful community involvement throughout the cleanup process.[249] CIPs specify EPA-planned community involvement to address community needs, concerns, and expectations that are identified through community interviews and other means. A CIP will enable community members to understand the ways in which they can participate in decision-making throughout the cleanup process. That is, the CIP is a way for EPA to plan for informing and involving the community in the cleanup process and can be a powerful

[248] A communication strategy can be one component of a CIP, but it addresses a specific event, issue, or concern, such as an emergency response to a release, or communicating risk at a site. The CIP, on the other hand, describes an overall strategy for conveying information throughout the cleanup process at a site.

[249] Community involvement plans available at: http://www.epa.gov/superfund/community/pdfs/toolkit/ciplans.pdf

way to communicate EPA's commitment to listening and responding to community concerns, and provide timely information and opportunities for community involvement.

The CIP is intended to be a "living" document and is most effective when it is updated or revised as site conditions change. When developing the CIP document, EPA recommends that the site planning team consider the following steps:

Describe the Environmental Setting and Cleanup Process

Describe the release and affected areas (the site). This includes information about the site, its history, the key issues related to site contamination, and how vapor intrusion fits into EPA's overall cleanup effort at the site.

Describe and Learn about the Community

Describe the community. The community profile is a description of the affected community that summarizes demographic information and identifies significant subgroups in the population, languages spoken, and other important characteristics of the affected community, such as whether the site is located in an area with environmental justice concerns or includes sensitive populations. EPA recommends that the community profile also document information sources and describe how the profile was developed.

Learn about community needs, concerns and expectations: Issues of concern to residents and business owners can be identified through community interviews, informal discussions and interactions, local media reports, and other insights about the affected community. Questions may include:

- What are public perceptions and opinions of EPA and the cleanup process?
- How do people want to be kept informed (i.e., mechanisms to deliver information)?
- How do people want to be included in the decision-making process?
- What are the perceived barriers to effective public participation?
- Are there other sources of pollution that affect the community?
- Have there been past experiences of mistrust or any unique concerns?

This information can be used to recommend any special services to be provided, including technical assistance, formation of a Community Advisory Group, facilitation/conflict resolution, or translation services.

Write and Compile the CIP

Once the site planning team has learned about the community, it is time to put the information together in a way that will be useful to EPA and the community. In addition to the site description, community description, and community needs and concerns, the CIP also may include a reference listing of contacts (name, address, phone, email) useful for the

community or the site planning team. EPA recommends that the contact list generally include contact information for:

- The site planning team.
- Community groups and community leaders.
- Local elected officials.
- Local, state, tribal, and federal agency staff relevant to the site.
- Media contacts (including social media outlets and community journalists).
- Others, as appropriate.

To ensure that the CIP is indeed informed by the community, EPA recommends that a draft of the CIP be shared with the community, and their input and feedback be invited as it evolves. Again, the CIP is intended to be a "living" document and is most effective when it is updated or revised as site conditions change. In some cases, particularly when the CIP is updated or revised for a FYR or where community interest is minimal, a short CIP outlining EPA's plan for community involvement may be all that is needed. For most sites, EPA recommends that the CIP be written to address the community directly, and their active involvement be invited at each stage of the cleanup process.

9.2 Communication Strategies and Conducting Community Outreach

EPA recommends that community outreach activities be initiated as soon as possible after determining that vapor intrusion may exist at a particular site. Informing and educating the community includes distributing information and providing opportunities for EPA to listen to community concerns. EPA recommends community outreach activities be tailored to the community based on information gleaned from community interviews and other methods used in developing the CIP. Public health officials from state, tribal, or local agencies may be helpful in communicating risk information and answering questions from the community.

Communication Strategies

Communication strategies are plans for communicating information related to a specific issue, event, situation, or audience. They serve as the blueprints for communicating with the public, stakeholders, or even colleagues. EPA recommends that communication strategies:

- Outline the objective and goals of the communication.
- Identify stakeholders.
- Define key messages.
- Pinpoint potential communication methods and vehicles for communicating information and obtaining information from the community for a specific purpose.

When developing a communication strategy, the first step is to determine why the communication is necessary and define its desired objectives, and then to focus on defining the audiences and how to reach them. Keep in mind that the demographics, knowledge, and concerns of the audiences play an important role in defining the key messages. Once the key messages are defined, the outreach vehicle can be determined.

Conducting Community Outreach

The site planning team likely will use several different outreach techniques during the course of the cleanup process. When planning community outreach, EPA generally recommends that the site planning team collaborate with internal and external partners, such as local, state, and tribal officials and departments of health; faith-based organizations; and community groups. It is important to accommodate hearing-impaired or limited English proficiency (LEP)[250] persons in all outreach efforts by providing spoken or sign language interpreters at meetings and translating printed outreach materials. It also is important to ensure that the community understands the concept of vapor intrusion.

Examples of community outreach techniques to consider are described below.

Public Meetings/Gatherings

Public meetings are a useful opportunity to explain environmental conditions at the site, potential health impacts, intended indoor air sampling, and remediation strategies. It may be helpful to hold meetings prior to and following key sampling events to describe sampling strategies and consequent results, respectively. EPA recommends that the meeting include a period to address specific questions from the public regarding sampling results or any other specific concerns, as well as visual aids and maps and spoken or sign language interpreters to facilitate communication and discussion. The use of a CSM, for example, is useful in public meetings to graphically reinforce the messages. It may be helpful to follow up with meeting participants to inquire about the effectiveness of the meeting and whether it met their needs. Other meeting follow-up activities could include responding to requests for information, distributing meeting notes, and creating a mailing list.

Additional opportunities for the site planning team to communicate with the community in a group setting include public availability sessions and public forums or poster sessions at community group meetings or neighborhood board meetings. These options are a more informal way of interacting with community members and they allow a casual “question and answer” or discussion format as compared to the more formal presentation at a public meeting.

Mass Media

The media can be the best means of reaching a large audience quickly. Extending invitations to the media for important meetings, providing opportunities for media questions

[250] Executive Order 13166, *Improving Access to Services for Persons with Limited English Proficiency*, directs federal agencies to examine the services they provide, identify any need for services to those with LEP, and develop and implement a system to provide those services so LEP persons can have meaningful access to them.

to be addressed in a timely manner, and recognizing that the media control the content of their publications all are important considerations when working with the media. The site planning team can work with the Agency's regional site press officer to foster a relationship with the media by sharing the Agency's rationale for its plans and actions. It is appropriate to use the media to publicize a site-related decision, an upcoming meeting, changes in schedule, or changes in activities or expectations. Press releases can be used to inform the media of major site-related milestones.

Fact Sheets

Communities appreciate concise, easy-to-understand, and technically accurate fact sheets on the history of the contamination, chemicals of concern, human health risk, planned cleanup activities, and the vapor intrusion assessment and response actions. Be sure to include who to contact for more information.

Because sites involving vapor intrusion can be complex, it may be useful to include additional information in the fact sheets for home owners and renters, including information about household products that may be potential sources of indoor air contamination, as well as steps that can be taken to minimize these sources. EPA recommends preparing and distributing periodic status updates and fact sheets to concerned community members throughout the cleanup process.

Letters

Whenever there are plans to conduct indoor air sampling, EPA recommends sending a letter to each building owner and renter explaining plans to conduct indoor air sampling and requesting written permission for voluntary access to do so. In addition, a one-on-one meeting with the building owner or renter is generally recommended to discuss sampling efforts and access agreements in detail (see Section 9.3).

EPA also recommends that letters be sent to each building owner and renter to report sampling results in a timely manner (see Section 9.4). These letters and meetings often are part of a larger effort that also includes use of other communication strategies, such as community meetings and in-person visits.

In-person Visits

EPA recommends individual, one-on-one communication with each property owner and renter whenever possible.

- Try to schedule in-person visits with individual property owners and renters. These visits also may include owners and renters of properties located outside the planned investigation area. The initial visit can be used to explain sampling plans in more detail, answer questions, and obtain written permission to sample.

- During the visit, the property owner or renter can be briefed about any instructions to follow during sampling activities (for example, keep doors and windows closed during sampling). A general survey of the building could be conducted to determine likely sources of indoor air contaminants.

- EPA recommends the site planning team also describe to owners and renters the sampling devices that will be used, what they look like, where they will be located, and any restrictions or impediments to daily activities that may arise from the ongoing sampling activities.

Information Repository

An information repository can be established and maintained prior to, during, and following site activities, which is generally required for sites where remedial action or removal actions (where on-site action is expected to exceed 120 days) are undertaken pursuant to CERCLA. The information repository is intended to include the administrative record, fact sheets, question-and-answer sheets, and other site-related documents and be located reasonably near the site. However, given the tremendous change in information technology, it may also be appropriate to set up an Internet-based or digital repository (webpages) to share key information. This depends on the community's ability to access and utilize this technology. EPA recommends that community members be made aware of the information repository through the other public outreach mechanisms described above (e.g., local media, newsletters, and public meetings).

Electronic Notification

It also may be useful to establish a registration capability that allows interested community members to sign up for automatic alerts to updates posted on the site website or email listserv.

9.3 Addressing Building Access for Sampling and Mitigation

EPA recommends that all requests for access, as well as provision of access, be in writing in order to document EPA's due diligence to protect human health at the site. EPA recommends that the site planning team provide building owners and occupants with information about the sampling device(s)) being used, including what they look like, where they will be located and any restrictions or impediments to daily activities that may arise due to ongoing sampling.

In the case of an initial refusal to provide access, additional attempts for access are generally recommended, although regional practices may vary. EPA recommends documenting all attempts to gain access, for example using telephone conversation records, emails, or letters sent to home or building owners.

Gaining access to owner-occupied residences for vapor intrusion sampling and mitigation may be handled differently than for commercial buildings or rental properties.

Owner-Occupied Residences: Allowing EPA to sample or install mitigation systems in an owner-occupied residence is a voluntary action. EPA generally encourages owners to take advantage of an offer for an assessment and mitigation system, if necessary.

Rental Properties: Access may be voluntary or involuntary. Site planning teams often deal with both owners and renters when there is a need to sample on, in, or under a rental property. There are different legal and communication issues for owners and renters. For example, the owner is responsible for granting access for sampling and for installation of mitigation measures, if they are necessary; however, if the owner grants access, logistics normally are

arranged with the renter. EPA recommends apprising both the owner and the renter of human health risk that may be posed by vapor intrusion, which includes providing building-specific sampling results to both parties when available. If the owner of a rental property refuses access, EPA may, nevertheless, pursue access, in the interest of protecting the occupants, for determining the need for response, choosing a response action, taking a response action, or otherwise enforcing CERCLA or RCRA (EPA 1986, 1987, 2010a). Notifying the owner of a rental property of this statutory authority may help to avoid the need for legal action.

Nonresidential Buildings: Site managers also may need to sample on, in, or under nonresidential buildings, such as schools, libraries, hospitals, hotels, and stores. In these situations, broader outreach to the public may be appropriate in addition to maintaining direct contact with the property owner. Similar to rental properties, access for sampling and for implementation of mitigation methods, if they are necessary, may be voluntary or involuntary. If the owner of a nonresidential building refuses access, EPA may, nevertheless, pursue access, in the interest of protecting the occupants, for determining the need for response, choosing a response action, taking a response action, or otherwise enforcing CERCLA or RCRA (EPA 1986, 1987, 2010a).

Property Ownership Changes: For owners of homes or buildings who did not provide access for assessment sampling or installation of a mitigation system, EPA recommends that the site planning team make reasonable attempts to track ownership changes, although the appropriate state, tribal, or local agency or PRP may be in a better position to track this information. For example, reasonable attempts to make contact can be done by annually conducting drive-bys or inspections and noting homes or buildings for sale, periodically checking on-line real estate sales or title insurance listings, or using other mechanisms. Homes that were initially targeted but not sampled can be reconsidered during the review or if there are major changes to the toxicity values for the site contaminants of concern. Annually mailing notifications to buildings not previously sampled is a means to foster reconsideration of testing with a change in ownership. If ownership changes are noted, appropriate follow-up can be conducted with the new home owner or building owner.

Federal statutory authority to access private property to conduct investigations, studies and cleanups pursuant to CERCLA and RCRA is discussed in Section 1.2 of this Technical Guide.

9.4 Communication of Indoor Sampling Efforts and Results

The community involvement plan or public participation plan is intended to address community concerns and participation regarding indoor air and sub-slab sampling. In addition to the general community involvement activities occurring throughout the cleanup process (see Section 9.2), the site planning team may choose to hold a community meeting to discuss indoor sampling efforts and results. EPA recommends sending a letter to each home or building owner and renter explaining plans to conduct sampling or providing sampling results. EPA recommends that this letter be in addition to a one-on-one meeting with the building or home owner to discuss access agreements, sampling efforts, and sampling results. Prompt communication of sampling results to building or home owners is important as some people may choose to make precautionary decisions prior to regulatory decisions on remediation or mitigation measures.

EPA recommends the site planning team inquire about stakeholder preferences for confidentiality with regards to property-specific data. It may be appropriate to segregate data for private residential properties versus community properties (e.g., schools, daycare centers,

commercial buildings) or provide different types of property identifiers for these respective building types in reports and maps and tables displayed at public meetings or otherwise made available to the community.

Letters Transmitting Sampling Results[251]

EPA recommends that the site planning team provide validated sampling results and interpretations (e.g., chemicals of concern, associated risk assessment implications) in plain English (and translations, if necessary) to property owners and renters in a timely manner (e.g., within approximately 30 days of receiving the results). EPA also recommends the transmittal letter indicate what future actions (e.g., mitigation options), if any, are contemplated,[252] based on the sampling results, and contain additional site-specific and possibly building-specific information, including, but not limited to:

- Site and Home/Building Information.
  - Site name and location of contamination.
  - Date of sampling.
  - Address of sampled home or building.
  - Locations sampled (both indoor and outdoor).

- Sampling Results
  - Sampling results for site-related, vapor-forming chemical(s) and for any other chemicals, if detected, including an explanation of results believed to be attributable to background sources, if known.[253]
  - Risk-based screening levels (for example, VISLs described in Section 6.5) or other risk-based benchmarks used to explain and interpret the sampling results.
  - Explanation and interpretation of sampling results, if known, which may include a summary of the human health risk assessment, if available (see Section 7.4).[254]

[251] Within the community of risk professionals, the phrase 'risk communication' has come to mean communication that supplies lay people with the information they need to make informed independent judgments about human health risk or public safety (Morgan et al. 1992). In this case about vapor intrusion, the ultimate goal of risk communication is to assist stakeholders and the general public in understanding the investigation data and the rationale behind any risk-informed decision, so they may arrive at a balanced judgement that reflects the factual evidence in relation to their own interests and values.

[252] This section may include an explanation of mitigation process and responsibilities and a timeline for further contact regarding system installation and options. If a building mitigation system is recommended on the basis of a human health risk assessment, EPA recommends that the site planning team explain that the risk calculation reflects conservative, health-protective factors.

[253] With such information, EPA can help advise citizens about the environmental and public health threats they face that are within their control (e.g., from indoor sources). In cases where 'background' contamination may pose a human health risk, but its remediation is beyond the authority of the applicable statute, risk communication to the public may be most effective when coordinated with public health agencies (EPA 2002e). The public may also be advised about the scope and limits of EPA's statutory authorities.

[254] Assessment uncertainty is generally an important factor in deciding how to act (Frewer 2004); i.e., whether to reduce risk through response action or reduce uncertainty (e.g., through additional monitoring and data collection). Risk professionals, therefore, generally recommend that risk communication to stakeholders and the general public characterize the sources of uncertainty, as well as the magnitude of uncertainty associated with a particular hazard (see, for example, Frewer (2004) and Markon and Lemyre 92013)).

  - Simple tabulated and color-coded results (representing exceedances of human health risk levels or no exceedance).

- Diagrams/Illustrations
  - Diagrams and illustrations of sampling devices.
  - Diagrams and illustrations of sampling locations
  - Diagrams of specific mitigation systems (e.g., how a SSD system works and looks).

- Next Steps
  - Actions that property owners and occupants can take to reduce vapor intrusion exposure until mitigation systems are in place.

- Information Sources
  - Contact information for a person who can answer questions or supply further explanations.
  - The location of the site information repository or site website can be included as a resource for public access to more detailed information and site documents.

9.5 Transmitting Messages Regarding Mitigation Systems

The initial notification to residents or building owners about mitigating vapor intrusion can be delivered in various ways. A primary mechanism is a face-to-face meeting with the building owner or occupant to explain the sampling results and discuss next steps, including installation of a vapor intrusion mitigation system. EPA recommends that this meeting include a member of the site planning team (RPM or OSC and risk assessor, for example), a representative from the local health department or the Agency for Toxic Substances and Disease Registry (ATSDR), and the mitigation contractor scheduler. This meeting could discuss topics such as:

- Sampling Results: Describe where samples were taken and the chemicals of concern, and explain the results as related to site action levels. Any questions related to human health risk can be answered by the risk assessor or public health representative at this time. For questions or concerns regarding personal health, EPA recommends that residents and building owners contact their medical professional.

- Mitigation System Details: Describe the need for a mitigation contractor to visit the residence to identify potential locations for the mitigation system. The property owner will need to be present for the visit and will have input about where the system is installed, if they agree to install such a system. Photos of a mitigation system (piping, system fan, number of holes drilled in the slab, height of the vent on the outside of the residence, etc.) may be helpful. EPA recommends that plans and schedules for periodic inspection, maintenance, and monitoring also be described.

- Access: EPA recommends advance planning to ensure building access to install, monitor and maintain any mitigation system. Arrangements could be made at this meeting to sign an additional access agreement for these activities, if needed.

- Cost of the Mitigation System: Identify which party will pay for installation of the mitigation system and anticipated property-owner costs. For example, EPA or a PRP may pay for the

system installation, and the property owner or PRP may take responsibility to pay for the monthly costs associated with the mitigation system.

- Project Schedule and Next Steps: The meeting may be concluded by giving an overview of the overall project timeline, including the appointment for the mitigation contractor visit and system installation.

Notification also can be provided through the data transmittal letter. In many cases, however, the decision to install mitigation systems will not have been made prior to the transmittal of sampling results. In these situations, data transmittal letters can convey that EPA is reviewing all data results for the affected area and considering appropriate next steps. Once the decision document is signed, the site planning team can develop and mail a fact sheet to all community members in the affected area, followed by a community meeting.

In addition, if a vapor intrusion mitigation system is installed, EPA recommends that the property owner or renter be informed that the system normally is designed to protect the home or building only against vapor-forming chemicals coming from the subsurface. A vapor intrusion mitigation system generally will not protect the home against continuing indoor sources because vapor intrusion mitigation systems typically are not indoor air filtration systems.

EPA recommends that current owner-occupants be advised that if they decline or waive an offer to install a vapor mitigation system, they might be responsible for the costs of installing and maintaining their own system if they decide to do so at a later time. EPA also recommends documenting any declination or waiver.

9.6 Addressing Community Involvement at Legacy Sites

Ongoing site activities with assessment components, such as remedial investigations and monitoring, allow EPA to continually evaluate site conditions and adjust cleanup actions as warranted. During periodic reviews or conducting other site activities, such as the FYR pursuant to CERCLA, EPA has evaluated vapor intrusion where appropriate. In some instances, EPA has newly identified vapor intrusion as an exposure pathway. These mature or “legacy” sites present a unique challenge to site planning teams.

Conducting community involvement at legacy sites may be complicated by several factors including:

- A remedy for the control of exposure to volatile chemicals already has been installed, proposed, or is under construction as part of the cleanup plan.

- Ownership of properties previously exposed to VOCs has changed hands through resale, foreclosure, or assumption of the property by second-generation homeowners. These owners were not part of any original resolution of exposure issues and in many cases may not be aware that a remediation or treatment was put in place.

- Property owners and other community members who participated in prior cleanup efforts may be reluctant to fully engage with efforts to reopen lines of investigation at their properties.

In these and similar circumstances, the challenge for Agency representatives is to resume contact with communities who have put past difficulties behind them. In many cases, mailing lists are outdated, previous reliable contacts no longer are available, and elected officials may not have institutional memory of the events that prompted the remediation.

Strategies for Revitalizing Community Involvement at Legacy Sites

Every legacy re-entry will be a site-specific situation. Therefore, EPA recommends that events and activities be planned to acknowledge and accommodate the inevitable changes in the makeup of a community. In addition to the communication strategies and community involvement techniques described in Sections 9.1 through 9.5, additional suggestions to ease re-entry and revitalize community involvement at a legacy site include:

- Reassess the community and the site by revisiting the site and the surrounding areas and taking note of new construction.
- Reintroduce yourself and the Agency to current municipal staff and check previously used public venues for viability. Determine if new venues may be closer or more accessible to the community.
- If contacts within the community are still extant, reconnect; ask for updates on the growth and stability of the community. If no viable contacts exist, attempt to cultivate new ones.
- Revise and update mailing lists and fact sheets.

As with all sites affected by vapor intrusion issues, be prepared to meet with property owners door to door and to hold public meetings or forums to explain the current investigation and its importance to protecting human health.

9.7 Property Value Concerns for Current and Prospective Property Owners

EPA recognizes that vapor intrusion impacts may have implications for property values. In some instances, mitigation systems and other clean-up measures may help to restore property values.

Nevertheless, property value issues are outside the scope of Agency authority. In general, if asked, EPA recommends that regional staff suggest that prospective buyers and sellers contact real estate professionals and lenders from the local area with questions about property values. If a home owner or renter has questions about vapor intrusion mitigation systems, EPA regions can provide information that explains how vapor intrusion systems are designed to reduce exposure to chemicals found in indoor air and to avert human health-related problems.

9.8 Additional Community Involvement Resources

EPA's Superfund Community Involvement Program:

EPA's Superfund Community Involvement website contains many resources that may be helpful for planning community involvement activities for other cleanup programs. This resource includes a list of regional Superfund community involvement points of contact, a list of technical

assistance and training resources, and descriptions and links to community involvement policies, guidance and publications (see http://www.epa.gov/superfund/community/).

EPA's Superfund Community Involvement Toolkit (CI Toolkit):

While targeted to a Superfund Program audience, the CI toolkit may be helpful to a wide variety of users because it is a practical, easy-to-use aid for designing and enhancing community involvement activities and contains tips on how to avoid some of the pitfalls common to the community involvement process. The toolkit enables users to quickly review and adapt a variety of community involvement tools to engage the community during all stages of the cleanup process. Relevant tools include tips for conducting public availability and poster sessions and public meetings, developing fact sheets, working with the media, planning communication strategies, developing a Community Involvement Plan, and establishing an information repository (see http://www.epa.gov/superfund/community/toolkit.htm).

EPA's Community Engagement Initiative:

The OSWER CEI is designed to enhance OSWER and regional offices' engagement with local communities and stakeholders to help them participate meaningfully in government decisions on land cleanup, emergency preparedness and response, and the management of hazardous substances and waste (see http://www.epa.gov/oswer/engagementinitiative/).

10.0 GLOSSARY

The following definitions are provided for purposes of this Technical Guide:

accumulate ..... Increase gradually in amount as time passes. Note that there will be a finite maximum amount, which will be determined by site- and building-specific conditions and will reflect a balance among physical processes (e.g., soil gas entry, air exchange).

active ..... Involving mechanical operations; Compare with *passive*.

active depressurization technology..... Vapor intrusion mitigation method that creates a driving force for air flow from the building into the subsurface by lowering the pressure below the slab, thereby reducing vapor intrusion (soil gas entry into a building).

acute ..... Refers to repeated or single exposure for 24 hours duration or less. Compare with *short-term* and *subchronic*.

advection ..... As it pertains to soil gas, refers to bulk movement in the vadose zone induced by spatial differences in soil gas pressure. The direction of advective vapor transport is always toward the direction of lower air pressure.

aerobic ..... Describes a process or activity requiring oxygen. Compare with *anaerobic*.

air exchange rate ..... Rate of air infiltration into a building through windows, doorways, intakes and exhausts, 'adventitious openings' (e.g., cracks and seams that combine to form the building envelope), plus natural and mechanical ventilation.

ambient air ..... The outdoor air surrounding a building or site.

anaerobic ..... Describes a process or activity requiring the absence of oxygen. Compare with *aerobic*.

analyte..... A substance for which identification (of presence) and/or quantification (of amount, such as concentration) is/are sought by instrumental measurement.

attenuation ..... Decrease in vapor concentration in soil gas emanating from a subsurface vapor source along the migration route towards and into a building (indoor air)

attenuation factor..... The ratio of the indoor air concentration arising from vapor intrusion to the soil gas concentration at the source or a depth of interest in the vapor migration route.

background ..... Refers to a vapor-forming chemical(s) or location(s) that is(are) not influenced by the releases from a site, and is usually described (EPA 1989, 1995c, 2002e) as naturally occurring or anthropogenic: 1) *Anthropogenic* – natural

	and human-made substances present in the environment as a result of human activities and not specifically related to the site-related release in question; and, 2) *Naturally occurring* – substances present in the environment in forms that have not been influenced by human activity. Background may include a vapor-forming chemical(s) present in indoor air due to human activities that is(are) not related to vapor intrusion or site-related contamination.
background vapor concentration	This term may include the concentration of a vapor-forming chemical in indoor air that fits within the definition of "background" above. Information on background concentrations of vapor-forming chemicals in indoor air "is important to risk managers because generally EPA does not clean up to concentrations below natural or anthropogenic background levels" (EPA 2002e).[255]
background vapor source.....	The origin(s) and location(s) of a vapor-forming chemical(s), other than vapor intrusion, and not associated with or emanating from a site-related release(s) to the environment. Background vapor sources may include indoor or outdoor sources. See also *indoor vapor source, outdoor vapor source,* and *background vapor concentration;* compare to *subsurface vapor source*.
biodegradation.....	Decomposition or breakdown of a substance through the action of microorganisms (such as bacteria or fungi).
brownfield	A parcel of real estate that is abandoned or inactive or may not be operated at its fully beneficial use and on which expansion or redevelopment is contemplated or reasonably expected; distinguished from "greenfield" because expansion or redevelopment may be complicated by the presence of vapor-forming chemicals in the subsurface environment.
building.....	a structure that is intended for human occupancy and use. This would include, for instance, homes, offices, stores, commercial and industrial buildings, etc., but would not normally include sheds, carports, pump houses, or other structures that are not intended for human occupancy.
building survey.....	Refers generically to gathering -- by observation, interviews, reviewing documents and records or other means -- information about existing buildings, including,

[255] It should, however, be noted that some EPA regulations (e.g., indoor radon standards under 40 CFR 192.12) are inclusive of background.

	but not limited to, location, use, occupancy, basic construction (e.g., foundation type), heating ventilation and cooling systems, potential indoor sources of vapor-forming chemicals, and anticipated susceptibility to soil gas entry (e.g., presence of radon mitigation system).
capillary fringe	The porous material just above the ground water table which may hold water by capillarity (a property of surface tension that draws water upwards) in the smaller void spaces.
chlorinated hydrocarbon (CHC)	Compound comprised solely of the elements chlorine, hydrogen and carbon. Includes dry-cleaning solvents such as tetrachloroethylene (PCE) and degreasing solvents such as trichloroethylene (TCE) and 1,1,1-trichloroethane (TCA).
chronic	Refers to repeated exposure for more than approximately 10% of the life span (approximately seven years) in humans. Compare with *subchronic*.
concentration	Amount (mass) of a vapor-forming chemical contained in a unit quantity (e.g., volume) of a specific medium (e.g., air, soil gas).
conceptual site model (CSM)	Narrative description of the current understanding of the site-specific conditions, which, in the case of vapor intrusion, include the nature, location, and spatial extent of the source(s) of vapor-forming chemicals in the subsurface and the location, use, occupancy, and basic construction of existing buildings. A CSM represents an adaptation of a general *conceptual model* to account for and reflect site- and/or building-specific conditions. See also *model*.
crawl space	A type of basement in which one cannot stand up — the height may be as little as one foot, and the bottom surface is often bare soil.
complete (vapor intrusion) pathway	The vapor intrusion pathway is referred to as “complete” for a building or collection of buildings when five conditions are met under current conditions: (1) a subsurface source of vapor-forming chemicals is present underneath or near the building(s); (2) vapors form and have a route along which to migrate (be transported) toward the building(s); (3) the building(s) is (or are) susceptible to soil gas entry, which means openings exist for the vapors to enter the building(s) and driving forces exist to draw the vapors from the subsurface into the building(s); (4) one or more vapor-forming chemicals comprising the subsurface vapor source(s) is (or are) present in the indoor environment; and (5) the building(s)

	is (or are) occupied by one or more individuals when the vapor-forming chemical(s) is (or are) present indoors.
data objectivity	Refers to the accuracy, reliability, and absence of bias in the information; scientific information will generally attain this criterion when the original or supporting data are generated using sound research, investigatory, or statistical methods.
data quality objective (DQO)	Performance and acceptance criteria that clarify study objectives, define the appropriate type of data, and specify tolerable levels of potential decision errors that will be used as the basis for establishing the quality and quantity of data needed to support decisions.
data utility	Refers to the usefulness (e.g., relevance, importance) of the information to reaching a conclusion or judgment (e.g., is the vapor intrusion pathway complete or incomplete? Does the vapor-forming chemical in indoor air arise from background sources or vapor intrusion? Does vapor intrusion pose an unacceptable human health risk in a specific building?)
diffusion	Random motion that affects the distribution of molecules when there are spatial differences in chemical concentrations in the fluid (e.g., soil gas, indoor air, groundwater). The net direction of diffusive transport is toward the direction of lower concentrations.
driving force	refers to the combination of: (i) pressure differences between a building interior and the subsurface or ambient air, which foster vapor intrusion and infiltration, respectively, via advection; and (ii) concentration differences between a building interior and the subsurface or ambient air, which foster vapor transport via diffusion.
early action	Refers to a response action undertaken early in the cleanup process to achieve prompt risk reduction. Also see *response action* and *pre-emptive mitigation.*
evidence	A fact or other information (i.e., datum) ascertainable by direct observation, interviews, review of records and documents, instrumental analysis in a lab or field setting, research and testing, sampling of environmental media (e.g., indoor air, soil gas, groundwater), statistical analysis, or other means, which is useful for forming a conclusion or judgment; each distinguishable datum is referred to as a line of evidence, which may be categorized into scientific realms (e.g., geology, biology, physics) or investigatory objectives (e.g., characterization of subsurface vapor source, accounting for background sources)

exposure	Opportunity to come into contact with vapor-forming chemicals (via inhalation, in the case of vapor intrusion).
exposure assessment	Process of characterizing the magnitude, frequency, and duration of exposure to a vapor-forming chemical, along with the characteristics of the population exposed.
exposure control	Modification of a property or building intended to reduce or eliminate human exposure to hazardous vapors in buildings or explosive vapors in structures, which arise from the vapor intrusion; such controls may include engineered methods (e.g., active depressurization technologies, mechanical ventilation, indoor air treatment) or non-engineered methods (e.g., institutional controls, such as deed notices and land use restrictions)
exposure pathway	The physical course a vapor-forming chemical takes from its source (e.g., groundwater) to the individual (in a building in the case of vapor intrusion).
exposure route	The way in which a vapor-forming chemical enters a human body (i.e., inhalation in the case of vapor intrusion).
flux	The rate of movement of mass through a unit cross-sectional area per unit time in response to a concentration gradient or a driving force for advection.
gas	A fluid (as air) that has neither independent shape nor volume but tends to expand indefinitely; a state of matter in which the matter concerned occupies the whole of its container irrespective of its quantity.
grab sample	A sample of air collected over a short (practically instantaneous) duration. Compare with *time-integrated sample*.
hazard index (HI)	The sum of hazard quotients for substances that affect the same target organ or organ system. Because different pollutants can cause similar adverse health effects, it is often appropriate to combine hazard quotients associated with different substances.
hazard quotient (HQ)	The ratio of the potential exposure to the substance and the level at which no adverse effects are expected. If the HQ is calculated to be equal to or less than 1, then no adverse health effects are expected as a result of exposure. If the HQ is greater than 1, then adverse health effects are possible.
hazardous	Involving or exposing one to threat of adverse health effects (due to toxicity) or loss of loss of life or welfare (due to explosiveness).

Henry's Law Coefficient or Constant	Ratio of a chemical's vapor pressure in air to its solubility in water. Generally reported for standard reference temperature, such as 25 °C.
human exposure pathway	A way that people may come into contact with environmental contaminants while performing their day-to-day indoor activities.
human health risk assessment	The evaluation of scientific information on the hazardous properties of vapor-forming chemicals (hazard assessment and characterization), the dose-response relationship, and the extent of human exposure to those agents. The product of the risk assessment is a statement regarding the probability that populations or individuals so exposed will be harmed and to what degree and describing the principal technical uncertainties (i.e., risk characterization).
hydrocarbon	Compound comprised solely of the elements hydrogen and carbon. See also *chlorinated hydrocarbon* and *petroleum hydrocarbon*.
inclusion zone	Land area within which EPA recommends assessing the vapor intrusion pathway, which extends beyond the aggregate boundaries of the site-specific source(s) of vapor-forming chemicals.
indoor vapor source	Refers to a vapor-forming chemical(s) in indoor air which originates within a building. Indoor sources of vapor-forming chemicals may include, but are not limited to, use and storage of consumer or household products, use or storage of industrial materials or products, combustion processes, activities or operations within a building, and releases from interior building materials (e.g., off-gases from furniture or clothing); for example, operational use or storage of chemicals in an industrial building may represent an indoor vapor source separate from a site-related release. Also see *background vapor source;* compare to *subsurface vapor source*.
infiltration	Air leakage into a building through random cracks, interstices, and other unintentional openings in the building envelope.
institutional control (IC)	Non-engineering measures intended to affect human activities in such a way as to prevent or reduce exposure to hazardous substances. For example, ICs may be used to restrict certain land uses, buildings, or activities that could otherwise result in unacceptable exposure to the vapor intrusion pathway. Generally, four categories of ICs are recognized: governmental controls; proprietary controls; enforcement tools; and informational devices. They are almost always used in conjunction with, or as a

	supplement to, other cleanup measures such as treatment or containment.
interim action	Refers to a response action that is undertaken to protect human health, but is limited in scope and objective (e.g., does not accomplish complete or final remediation of subsurface vapor sources). Also see *response action.*
interzonal air flow	Movement or transport of air through doorways, ductwork, and service chaseways that interconnect rooms or zones within a building.
lines of evidence	Data collected and weighed together in supporting assessments of the vapor intrusion pathway, which are identified and described throughout Sections 2 through 7 inclusive. See also *evidence*.
lower explosive limit (LEL)	The lowest concentration at which a gas or vapor is flammable or explosive at ambient conditions.
mitigation	Interim actions taken to reduce or eliminate human exposure to vapor-forming chemicals in a specific building arising from the vapor intrusion pathway; compare with *remediation.*
model	Refers to a description of a system. In the case of vapor intrusion the 'system' will generally consist of a subsurface source of vapors, one or more buildings potentially subject to soil gas entry, and the soil underlying the building(s). *Conceptual models* (i.e., models that are conceptual) are comprised of narrative descriptions that identify the primary physical elements and processes of the system and the interactions between and relationships among them; for example, Section 2 of this document provides a general conceptual model of how vapor intrusion can arise and why it may be variable over time and in space. A *mathematical model* is an expression of a conceptual model, which uses mathematical symbols and language to identify key elements (e.g., variables) and processes. Generally, mathematical models are highly idealized or simplified descriptions, compared to the complex systems they represent. For example, Johnson and Ettinger (1991) formulated an idealized mathematical model of vapor intrusion. In the case of a *physical model,* the description is provided using physical objects, which may or may not have full functionality; for example, a physical model of a construction project might differ from a planned system in its scale, but would necessarily show significant elements in relationship to each other.

near-source	Refers to a soil gas sample collected within a practically short distance from subsurface vapor source
nonresidential building	Refers to a building other than a home; includes, but is not limited to, institutional buildings (e.g., schools, libraries, hospitals, community centers and other enclosed structures for gathering, gyms and other enclosed structures for recreation); commercial buildings (e.g., hotels, office buildings, many (but not all) day care centers, and retail establishments); and industrial buildings where vapor-forming chemicals may or may not be routinely used or stored. Compare with *residential building*; see also *building*.
outdoor vapor source	Refers to a vapor-forming chemical(s) present in outdoor (ambient) air. Sources of vapor-forming chemicals in outdoor air may include, but are not limited to, releases from industrial facilities, vehicle exhaust, yard maintenance equipment, fuel storage tanks, paint or pesticide applications, agricultural activities, and fires, as well as site-related contamination, activities, and operations (e.g., emissions from remediation equipment). Also see *background vapor source;* compare to *subsurface vapor source*.
passive	Not involving mechanical operations; Compare with *active*.
petroleum hydrocarbon (PHC)	Hydrocarbons derived from petroleum and present in various refined products of petroleum (such as automotive gasoline, diesel fuel, lubricating oils). See also *hydrocarbon*.
potentially complete (vapor intrusion pathway)	The vapor intrusion pathway is referred to as 'potentially complete' for a building when: a subsurface source of vapor-forming chemicals is present underneath or near an existing building or a building that is reasonably expected to be constructed in the future; vapors can form from this source(s) and have a route along which to migrate (be transported) toward the building; and three additional conditions are reasonably expected to all be met in the future, which may not all be met currently (i.e., the building is susceptible to soil gas entry, which means openings exist for the vapors to enter the building and driving forces exist to draw the vapors from the subsurface through the openings into the building; one or more vapor-forming chemicals comprising the subsurface vapor source(s) is (or will be) present in the indoor environment; and the building is or will be occupied by one or more individuals when the vapor-forming chemical(s) is (or are) present indoors.

preemptive mitigation (PEM)	Implementation of systems or control measures to mitigate the vapor intrusion pathway as an early action, even though all pertinent lines of evidence have not yet been completely developed to characterize the vapor intrusion pathway for the subject building(s). Also see *early action* and *response action.*
preferential migration route	Naturally occurring subsurface feature (e.g., gravel lens, fractured rock) or anthropogenic (human-made) subsurface conduit (e.g., utility corridor or vault, subsurface drain) that is expected to exhibit little resistance to vapor flow in the vadose zone (i.e., exhibits a relatively high gas permeability) or groundwater flow (i.e., effectively exhibits a relatively high hydraulic conductivity), depending upon its location and orientation relative to the water table and ground surface, thereby facilitating the migration of vapor-forming chemicals in the subsurface and towards or into buildings
pressure difference/differential pressure	Difference between the air pressure within a building and the subsurface environment or ambient air. Can promote advective flow of gas into or out of a building through pores, cracks, or openings in the building foundation or envelope.
radon	A radioactive gas formed during the radioactive decay of radium, which occurs naturally in many geologic settings.
reasonable maximum exposure (RME)	A semi-quantitative term, referring to the lower portion of the high end of the exposure distribution; conceptually, above the 90th percentile exposure but less than the 98th percentile exposure.
reasonable worst case	A semi-quantitative term, referring to the upper portion of the high end of the exposure distribution, but less than the absolute maximum exposure.
reference concentration (RfC)	An estimate of the continuous inhalation exposure to the human population (including sensitive subgroups) that is likely to be without appreciable risk of deleterious effects during a lifetime.
remediation	Refers to interim and final cleanups, whether conducted pursuant to RCRA corrective action, the CERCLA removal or remedial programs, or using EPA brownfield grant funds with oversight by state and tribal response programs. In addition to permanent remedies for subsurface vapor sources, site remediation may also entail implementation of institutional controls and construction and operation of engineered systems.

residential building	refers to a building used as or intended for use as a home; includes, but is not limited to, single-family detached homes with foundations, trailer homes, multi-unit apartments and condominiums. Compare with *non-residential building;* see also *building*.
response action	any action taken to reduce or eliminate human exposure to or risk posed by hazardous vapors in buildings and structures, which arise from the vapor intrusion pathway; these actions may include engineered exposure controls in a specific building(s), non-engineered exposure controls, remediation of subsurface vapor sources, and associated monitoring to assess effectiveness and protectiveness. Also see *remediation* and *mitigation.*
risk	Probability of an adverse human health effect (due to toxicity) or physical hazard (e.g., due to potential for explosion) caused under specific circumstances by a vapor-forming chemical.
risk communication	The process of exchanging information about health threats and levels or significance of human health risk.
risk management	The process of determining whether response action(s) is(are) warranted to protect human health and, if so, selecting response actions to implement.
screening	Process of comparing concentrations of vapor-forming chemicals in a specific medium (e.g., indoor air, soil gas, crawl space air, groundwater) to screening levels to identify sites, buildings, or chemicals unlikely to pose a health concern through the vapor intrusion pathway versus those warranting further investigation or analysis.
screening level	Risk-based concentrations derived from standardized equations combining exposure information and assumptions with toxicity values.
short-term	Refers to repeated exposure for more than 24 hours, up to 30 days. Compare with *acute* and *subchronic*.
significant opening	Refers to refer to an atypical form and amount of an opening in a building (e.g., a sump, an unlined crawl space, an earthen floor), which could facilitate greater amounts of soil gas entry, all else being equal. Forms of openings typically expected to be present in all buildings include cracks, seams, interstices, and gaps in basement floors and walls or foundations and perforations due to utility conduits.
site	The geographical area where investigation and evaluation of the presence of vapor-forming chemicals is desired; in many situations, it includes areas surrounding

	a facility where a release to the subsurface environment is known or suspected to have originated.
soil gas	The gas present underground in the pore spaces between soil particles.
soil gas concentration	Vapor concentration in a soil gas sample. Sub-slab soil gas is found immediately beneath a building. Near-source or exterior soil gas samples are collected at other depths and typically outside the building footprint.
source strength	Vapor concentration(s) of vapor-forming chemical(s) arising from a subsurface vapor source.
stakeholder	A person, group, community, or corporate entity with an interest in activities at a site with subsurface contamination.
subchronic	Refers to repeated exposure for more than 30 days, up to approximately 10% of the life span (approximately seven years) in humans. Compare with *short-term* and *chronic*.
subsurface remediation	Response action that eliminates or substantially reduces the level of vapor-forming chemicals in the subsurface vapor source via treatment or physical removal. Compare with *mitigation.*
subsurface vapor source	Refers to a vapor-forming chemical(s) present in the subsurface environment arising from a release(s) to the environment. A subsurface vapor source may occur as a non-aqueous-phase liquid (NAPL), adsorbed-phase contamination, or dissolved-phase contamination, which may be present in the vadose zone, in groundwater, or within sewers and other conduits. Information on subsurface vapor sources is important to risk managers because response actions are generally warranted when vapor intrusion is determined to pose unacceptable human health risks. Compare with *background vapor source* and *background vapor concentration*.
termination criteria	Refers to numeric cleanup levels for each site-specific contaminant and narrative cleanup objectives that are to be attained by the response actions.
time-integrated sample	Sample collected over an extended period of time to account for temporal variations in vapor concentrations. Compare with *grab sample*.
toxicity value	Refers to an inhalation unit risk (IUR) for potential cancer effects or an inhalation reference concentration (RfC) for potential non-cancer effects of a vapor-forming chemical.

vadose zone	The soil zone between land surface and the groundwater table within which the moisture content is less than saturation (except in the capillary fringe). Soil pore spaces not occupied by moisture contain (soil) gas. Also referred to as the "unsaturated zone."
vapor	A substance in the gaseous state as distinguished from the liquid or solid state.
vapor intrusion	The migration of potentially hazardous vapors from any subsurface contaminant source, such as contaminated soil or groundwater, through the vadose zone and into a building or structure.
vapor source	The place and form of origin of chemical vapors. Also see *background vapor source*, *indoor vapor source*, *outdoor vapor source*, and *subsurface vapor source*.
vapor-forming chemical	A volatile chemical that EPA recommends be routinely evaluated during a site-specific vapor intrusion assessment, when it is present as a subsurface contaminant.
volatile chemical	Chemical with a vapor pressure greater than 1 milliliter of mercury (mm Hg), or Henry's law constant greater than 10^{-5} atmosphere-meter cubed per mole.
volatility	The tendency of a substance to form vapors, which are molecules in a gaseous state, and escape from a liquid or solid source. This tendency is directly related to a substance's vapor pressure and Henry's law constant and is indirectly related to a substance's molecular weight (i.e., substances with lower molecular weights tend to volatilize more readily than substances with similar molecular structures that have higher molecular weights).
water table	The water surface in an unconfined aquifer at which the fluid pressure in the pore spaces is at soil gas pressure.
weight of evidence	Refers to a conceptual approach to data evaluation, in which each of several lines of evidence is critically appraised for its quality (e.g., utility, objectivity) and systematically assessed for its logical support for a particular conclusion, as well as alternative conclusions; the appraisals consider lines of evidence individually and in light of other lines of reliable evidence for purposes of determining whether a particular conclusion is supported by the preponderance of the evidence and is consistent with the conceptual site model; this 'weighing' concept does not entail a quantitative (*a priori*) scheme to score or rank the individual lines of evidence. See also *evidence*.

work plan	A site-specific document that includes a project description, project objective(s), historical information about the site.
worst case	A semi-quantitative term, referring to the absolute maximum plausible exposure (i.e., a bounding – high-impact – case).

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APPENDIX A
RECOMMENDED SUBSURFACE-TO-INDOOR AIR ATTENUATION FACTORS

A.1 INTRODUCTION

This Technical Guide includes recommended medium-specific (groundwater, soil gas, and indoor air) Vapor Intrusion Screening Levels (VISLs) that are intended to help identify those sites unlikely to pose a health concern from vapor intrusion and identify areas or buildings that may warrant further investigation of the vapor intrusion pathway. These VISLs are recommended for use in evaluating the concentrations of vapor-forming chemicals measured in groundwater, "near-source" exterior soil gas, and sub-slab soil gas in residential and nonresidential settings where the potential for vapor intrusion is under investigation.

The subsurface VISLs are developed considering a generic conceptual model for vapor intrusion consisting of a groundwater or vadose zone source of vapor-forming chemicals that diffuse upwards through unsaturated soils towards the surface and enter buildings. The underlying assumption for this generic model is that subsurface characteristics will tend to reduce or attenuate soil gas concentrations as vapors migrate upward from the source and into structures. Section 6.5.2 describes this conceptual model further. In general, EPA recommends considering whether the assumptions underlying the generic conceptual model are attained at each site. The *Vapor Intrusion Screening Level (VISL) Calculator User's Guide* (EPA 2015a) provides additional information about the technical basis for deriving the VISLs.

Comparison of sampling results to medium-specific VISLs (see Section 6.5.4) comprises one line of evidence in the multiple-lines-of-evidence approach described in this Technical Guide (see, for example, Sections 7.1 and 7.2). The subsurface (groundwater and soil gas) VISLs (C_{VISL}) are calculated using risk-based, screening levels for indoor air ($C_{target,ia}$) and a medium-specific, subsurface-to-indoor air attenuation factor (α_{VI}), as follows:

$$C_{VISL} = \frac{C_{target,ia}}{\alpha_{VI}} \qquad \text{Equation A.1}$$

The risk-based, indoor air screening levels ($C_{target,ia}$) are calculated according to the guidance provided in *Risk Assessment Guidance for Superfund (RAGS) Part F* (EPA 2009) as implemented in EPA's Regional Screening Levels (RSLs) for Chemical Contaminants at Superfund Sites (http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/). The medium-specific, attenuation factors (α_{VI}) recommended for calculating the subsurface VISLs are derived from information in *EPA's Vapor Intrusion Database: Evaluation and Characterization of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings* (EPA 2012a).

This appendix describes the technical basis for the selection of the subsurface-to-indoor air attenuation factors (α_{VI}) that are recommended for use in calculating the VISLs for groundwater, sub-slab soil gas, "near-source" exterior soil gas, and crawl space air, according to Equation A.1.

A.2 DEFINITION AND DESCRIPTION OF ATTENUATION FACTOR

Vapor attenuation refers to the reduction in concentration of vapor-forming chemicals that occurs during vapor migration in the subsurface, coupled with the dilution that can occur when the vapors enter a building and mix with indoor air (Johnson and Ettinger 1991). The aggregate effect of these physical and chemical attenuation mechanisms can be quantified through the use of a subsurface-to-indoor air vapor intrusion attenuation factor (α_{VI}), which is defined as the ratio of the indoor air concentration arising from vapor intrusion ($C_{IA\text{-}VI}$) to the subsurface vapor concentration (C_{sv}) at the source or a depth of interest in the vapor migration route (EPA 2012a):

$$\alpha_{VI} = \frac{C_{IA-VI}}{C_{SV}} \alpha_{VI} = \frac{C_{IA-VI}}{C_{SV}} \qquad \text{Equation A.2}$$

As defined here, the vapor attenuation factor is an inverse measurement of the overall dilution that occurs as vapors migrate from a point of measurement in the subsurface into a building; i.e., attenuation factor values decrease with increasing dilution of vapor concentration.

Subsurface vapor concentrations (C_{SV}) may be measured directly under a building (often called sub-slab soil gas or just sub-slab), measured exterior to a building at any depth in the unsaturated zone (often called exterior soil gas), or derived from groundwater concentrations by converting the dissolved concentration to a vapor concentration assuming equilibrium conditions (i.e., by multiplying the groundwater concentration by the chemical's dimensionless Henry's law constant for the groundwater temperature *in situ*) (EPA 2001); also see Appendix C of this Technical Guide.

Subfloor vapor concentrations may also be measured in building crawl spaces. Although crawl space samples are not strictly subsurface samples, they represent the vapor concentration underlying a building's living space. Thus, crawl space samples may be evaluated in a manner similar to subsurface vapor samples.

A.3 RECOMMENDED ATTENUATION FACTORS

This section summarizes the technical basis and rationale for EPA's recommended attenuation factors for groundwater, sub-slab soil gas, exterior soil gas, and crawl space air, as follows:

- Section A.3.1 summarizes EPA's database of empirical attenuation factor values and the results of analyzing that database.
- Section A.3.2 identifies the recommended empirically based attenuation factors for groundwater.
- Section A.3.3 identifies the recommended attenuation factor for sub-slab soil gas and presents a theoretical analysis that supports the selection of the recommended empirically based value.
- Section A.3.4 recommends a generic attenuation factor for exterior soil gas and discusses its basis, justification, and limited applications.

- Section A.3.5 identifies the recommended attenuation factor for crawlspace vapor.
- Section A.3.6 presents a reliability analysis of the recommended generic attenuation factors.

A.3.1 EPA'S VAPOR INTRUSION DATABASE (EPA 2012A)

The information in *EPA's Vapor Intrusion Database: Evaluation and Characterization of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings* (EPA 2012a) is used to derive recommended attenuation factor values for use in evaluating subsurface sample concentrations collected as part of vapor intrusion investigations. EPA's vapor intrusion database consists of numerous pairings of concentrations in indoor air and subsurface samples (groundwater, sub-slab soil gas, exterior soil gas, and crawlspace vapor) from actual sites. It represents the most comprehensive compilation of vapor intrusion data for chlorinated hydrocarbons (CHCs) available at this time.

EPA's vapor intrusion database was analyzed and screened to reduce the impacts of background sources to indoor air concentrations. The resulting data distributions are considered representative of vapor intrusion of CHCs from subsurface vapor sources into residential buildings for most conditions. These distributions serve as the basis for identifying the high-end (conservative) attenuation factors for those media.

Table A-1 and Figure A-1 (Table 19 and Figure 34, respectively, in EPA (2012a)) present and compare the distributions of the attenuation factors (groundwater, exterior soil gas, sub-slab soil gas, and crawl space) that remain after applying the respective source strength and indoor air screens considered most effective at reducing the influence of background contributions to indoor air concentrations. These data demonstrate that the attenuation factor distributions obtained for groundwater, sub-slab soil gas, and crawl spaces for multiple buildings and sites are consistent with the conceptual model for vapor intrusion, which predicts that greater attenuation is expected with greater depths to the vapor sources or vapor samples. As shown in Table A-1 and Figure A-1, the paired groundwater–indoor air data generally exhibit greater attenuation (lower attenuation factors) than the paired sub-slab soil gas–indoor air data, which in turn exhibit greater attenuation than the paired crawl space-indoor air data.

A.3.2 RECOMMENDED ATTENUATION FACTORS FOR GROUNDWATER

To account for the inherent temporal and spatial variability in indoor air and subsurface vapor concentrations, the 95th percentile value of the "source-screened" groundwater data subset in EPA 2012a is recommended as a reasonably conservative generic attenuation factor, after considering a range of values. **Thus, for groundwater, the recommended generic attenuation factor (α_{gw}) is 0.001.** This value is considered to apply for any soil type in the vadose zone (excepting where preferential vapor pathways are present; see Section 5.4) in cases where the groundwater is greater than five feet below the ground surface. If the depth to groundwater is less than five feet below the building foundation, investigation of the indoor space is recommended, as there is potential for contaminated groundwater to contact the building foundation, either because the capillary fringe intersects the building foundation or groundwater fluctuations results in groundwater wetting the foundation.

Table A-2 (Table 13 in EPA (2012a)) provides statistics and Figure A-2 (Figure 28 in EPA (2012a)) shows box-and-whisker plots for individual sites compared with the statistics for the combined set of screened groundwater attenuation factors. This table and figure show that the 95th percentile value of the combined groundwater-indoor air measurements is considered appropriate for estimating reasonable maximum indoor air concentrations that might be observed at a site due to vapor intrusion. The majority of sites and buildings would be expected to exhibit lower indoor air concentrations.

A factor that commonly results in greater attenuation (lower attenuation factors) is the presence of laterally extensive, unfractured fine-grained sediment in the vadose zone. Table A-3 (Table 14 in EPA (2012a)) provides selected statistics and Figure A-3 (Figure 29 in EPA (2012a)) shows the box-and-whisker plots for the groundwater attenuation factors for three soil types. Comparing each descriptive statistic (except for the 25th percentile values) indicates that the attenuation factor values for residences overlying soils classified as "very coarse" generally are larger than those for residences overlying soils classified as "coarse," which are larger than those for soils classified as "fine." This pattern is consistent with the conceptual model for vapor intrusion; smaller attenuation factors, which indicate greater reduction in vapor concentration, would be expected in vadose zones with finer-grained soils, when all other factors (e.g., depth to groundwater, biodegradability of the volatile chemicals) are the same. The 95th percentile value of the coarse-grained soil is equal to the generic value, as expected, since coarse-grained soil provide low resistance to vapor transport and thus would be expected to yield high-valued attenuation factors. Where fine-grained sediments underlay buildings, however, more attenuation is expected and observed in the database. **Thus, a semi-site-specific attenuation factor of 0.0005 may be used at sites where laterally extensive fine-grained sediment has been demonstrated through site-specific sampling to underlay buildings being investigated for vapor intrusion**.

A.3.3 RECOMMENDED GENERIC ATTENUATION FACTOR FOR SUB-SLAB SOIL GAS

To account for the inherent temporal and spatial variability in indoor air and subsurface vapor concentrations, the 95th percentile value of the "source-screened" sub-slab data subset in EPA (2012a) is recommended as a reasonably conservative generic attenuation factor, after considering a range of values. Thus, **for sub-slab soil gas, the recommended generic attenuation factor (α_{ss}) is 0.03.**

The selection of this value can be supported by theoretical analysis. Specifically, a simple mass balance analysis, assuming a well-mixed interior volume and steady-state conditions, indicates that the theoretical (true) sub-slab soil gas attenuation factor can be expressed as the ratio of the soil gas entry rate to the building ventilation rate (Song et al., 2011; EPA 2012a) for cases where there is no background contribution to the indoor air concentration. Using median values for residential building volume and air exchange rate (395 m^3 and 0.45 ACH, respectively) provided in the *Exposure Factors Handbook 2011 Edition* (EPA, 2011) and a mid-range value of 5 L/min for soil gas entry rate in sandy materials (EPA 2002, Appendix G), the central tendency value of the sub-slab soil gas attenuation factor (according to Equation 4a therein), is expected to be approximately 0.002. Using upper-end (10th percentile) values for residential building volume and air exchange rate (154 m^3 and 0.18 ACH, respectively (EPA 2011)) and soil gas entry rate (10 L/min), an upper-end value of 0.02 for the sub-slab soil gas attenuation factor is obtained. These values agree well with the 95th percentile and 50th percentile (median) values

(0.03 and 0.003, respectively) obtained from the source-screened data. These calculations buttress the conclusion that the sub-slab attenuation factor distributions summarized in EPA's vapor intrusion database report can be considered representative of vapor intrusion of CHCs into residential buildings for most conditions.

Table A-4 (Table 10 in EPA (2012a)) provides statistics and Figure A-4 (Figure 25 in EPA (2012a)) shows box-and-whisker plots for individual sites compared with the statistics for the combined set of screened sub-slab attenuation factors. This table and figure show that the 95th percentile value of the combined sub-slab-indoor air measurements is considered appropriate for estimating reasonable maximum indoor air concentrations that might be observed at a site due to vapor intrusion. The majority of sites and buildings would be expected to exhibit lower indoor air concentrations.

A.3.4 RECOMMENDED ATTENUATION FACTOR FOR "NEAR-SOURCE" EXTERIOR SOIL GAS

Based upon the conceptual model for vapor intrusion, the attenuation factors for exterior soil gas data would be expected to be less than those for sub-slab soil gas, because the former includes an additional contribution from attenuation through the vadose zone, and greater than those for groundwater vapors for a given building at a site where groundwater is the primary subsurface source of vapors. The distributions of exterior soil gas attenuation factors shown in Table A-1 and Figure A-1 do not exhibit this expected relationship. In addition, a comparison of exterior soil gas to sub-slab soil gas concentrations for buildings where both types of samples were collected, shown in Figure A-5 (see Figure 6 in EPA (2012a)), suggests that a substantial proportion of the exterior soil gas data in the database, particularly shallow soil gas data, may not be representative of soil gas concentrations directly underneath a building. On this basis, shallow exterior soil gas sampling data generally are not recommended for purposes of estimating indoor air concentrations and the exterior soil gas attenuation factors in Table A-1 are not recommended for use in deriving generic attenuation factors.

Based upon the data in Figure A-5, "deep" exterior soil gas data appear to more reliably reflect sub-slab concentrations beneath buildings. On this basis, "near-source" soil gas sampling data (i.e., collected in the vadose zone immediately above each vapor source) generally are allowed for purposes of assessing vapor concentrations that may be in contact with the building's sub-slab, as discussed further in Section 6.4.4. However, the same conservative attenuation factor value for sub-slab soil gas is recommended for use with "near-source" exterior soil gas data for this purpose. **Thus, for "near-source" exterior soil gas, the recommended generic attenuation factor is 0.03**.

A.3.5 RECOMMENDED ATTENUATION FACTOR FOR CRAWLSPACE VAPOR

The distribution of attenuation factors presented in Figure A-1 show that attenuation between building crawlspaces and living spaces is limited. To account for the inherent temporal and spatial variability in indoor air and crawlspace vapor concentrations, the 95th percentile value of the "indoor air-screened" crawlspace data subset in EPA (2012a) is recommended as a reasonably conservative generic attenuation factor, after considering a range of values. **Thus, for crawl space vapor the recommended generic attenuation factor is 1.0** (0.9 rounded up to 1.0).

A.3.6 RELIABILITY ANALYSIS OF THE RECOMMENDED SUBSURFACE-TO-INDOOR AIR GENERIC ATTENUATION FACTORS

An analysis was performed to determine the reliability of these recommended attenuation factors for screening in residences in EPA's vapor intrusion data base with measured indoor air concentrations exceeding target levels corresponding to a cancer risk of 10^{-6} and a hazard quotient of 1. The reliability analysis was performed separately for each medium by determining the number of correct assessments and the number of false negatives for a range of attenuation factors. The potential incidence of false negatives is a critical criterion, because the primary objective of risk-based screening is to identify sites or buildings unlikely to pose a health concern through the vapor intrusion pathway (see Section 6.5.1).

For the purposes of this analysis:

- A correct assessment is deemed to occur either: (1) when a chemical's measured indoor air concentration exceeds the target level and the measured subsurface vapor concentration also exceeds the appropriate medium-specific VISL calculated using the specified generic attenuation factor, or (2) when a chemical's measured indoor air concentration is below the target level and the measured subsurface vapor concentration also is below the appropriate medium-specific VISL calculated using the recommended generic attenuation factor. Correct assessments in this analysis represent a correct decision based on subsurface concentration data regarding the potential for vapor intrusion to pose indoor air concentrations that exceed target risk-based concentrations in affected buildings.

- A false negative is deemed to occur when a chemical's measured indoor air concentration exceeds the target level, but the measured subsurface vapor concentration does not exceed the appropriate medium-specific VISL calculated using the specified generic attenuation factor. False negatives in this analysis represent the potential for making an incorrect decision based on subsurface concentration data regarding the potential for vapor intrusion to pose indoor air concentrations that exceed target risk-based concentrations in affected buildings.

This assessment uses the Data Consistency Subset of the EPA's vapor intrusion database for residential buildings (i.e., before screening to minimize the impacts of background contributions to indoor air as described in EPA (2012a)). This subset was chosen to allow for the possibility that background indoor air contributions were incorrectly identified and removed from further analysis in the "source-screened" data subsets presented in EPA (2012a). Thus, false negatives may appear if indoor or ambient (outdoor) sources of VOCs are present and they exceed the

indoor air target level. This choice of datasets provides a conservative estimate of the frequency of false negatives identified by this reliability analysis. Even lower rates of false negatives would be obtained when considering the "source-screened" data subsets, described in EPA (2012a), in which the impacts of background contributions to indoor air are minimized.

The results of this assessment are shown in Figures A-6 through A-8 for sub-slab soil gas, groundwater, and exterior soil gas.[256] The essential results are as follows:

- The recommended generic attenuation factors yield low rates of false negatives (< 2%) for all three media when individual pairs of samples are evaluated together.

- The recommended generic attenuation factors for groundwater, exterior soil gas, and sub-slab soil gas provide generally high rates of correct assessments when individual pairs of samples are evaluated together: 78% for groundwater; 76% for exterior soil gas; and 87% for sub-slab soil gas. Higher rates of correct assessments are expected for sub-slab soil gas than for the other subsurface media, likely due to the closer spatial correspondence of building sub-slab soil gas and indoor air samples.

- The rates of correct assessments appear to level off in Figure A-6 through A-8 at about the point on the x-axis where the recommended generic attenuation factors occur.

- The rates of false positives using the Data Consistency Subset can be inferred from Figure A-6 through A-8. This analysis indicates that use of ground water data or exterior soil gas data is more likely to incorrectly identify a site or building as warranting further investigation than is use of sub-slab soil gas data.

Compared to the values estimated in Figures A-6 through A-8, significantly higher rates of a correct assessment (and, hence, lower rates of false negatives and false positives) are reasonably anticipated to be realized by following this Technical Guide. Specifically, collecting multiple samples to characterize spatial and temporal variability (see, for example, Section 6.4), collecting multiple lines of additional evidence (see, for example, Section 6.3 and 7.1), and weighing this information together (see, for example, Sections 6.3 and 7) are reasonably expected to significantly reduce the "error rates" estimated in this reliability analysis, which are based upon comparison of individual pairs of indoor air and subsurface sample concentrations.

As previously stated, this Technical Guide includes subsurface VISLs that are intended to help identify those sites with the potential to pose a vapor intrusion concern. The reliability analysis described above suggests the recommended attenuation factors, on which the recommended VISLs are based, can reasonably be expected to provide an acceptably small probability of 'screening out' sites that pose a vapor intrusion concern and a high probability of correctly identifying sites or buildings that may pose a vapor intrusion concern.

[256] The reliability assessment was not conducted for crawlspace data, because the distribution of attenuation factors presented in Figure A-1 show that attenuation between building crawlspaces and living spaces is limited.

A.4 CONSIDERATIONS FOR NONRESIDENTIAL BUILDINGS

The recommended attenuation factors (see Sections B.3.2 through B.3.5) are proposed for use for nonresidential buildings as well as residential buildings. The rationale is that, in many geographic locations, some commercial enterprises have been established in converted residential buildings. Although used for commercial purposes, such buildings can reasonably be expected to exhibit similar susceptibility to vapor intrusion and similar interior mixing and dilution (and, hence, similar attenuation factors) as residential buildings represented in EPA's vapor intrusion database. In addition, McDonald and Wertz (2007) found that sub-slab attenuation factors for commercial and institutional buildings in Endicott, New York, which were not "extraordinarily large", were not substantially different than those for residential buildings in the same area.

There are theoretical considerations to support expectations that larger nonresidential buildings that are constructed on thick slabs will have lower attenuation factors than residential buildings. These considerations include:

- Given that the size (e.g., interior height and footprint area) and air exchange rate tend to be larger for many nonresidential buildings (see, for example, Table A-5), it is expected that building ventilation rates for many nonresidential buildings would be higher than those for residential buildings. A higher ventilation rate is expected to result in greater overall vapor dilution as vapors migrate from a subsurface vapor source into a building. On this basis, many nonresidential buildings would be expected to have lower attenuation factors than those for residential buildings, all else being equal.

- Comparing buildings with slab-on-grade construction, nonresidential buildings tend to have thicker slabs than residential buildings. With thicker slabs, a given amount of differential settling would be expected to lead to less cracking in the slab and would be less likely to create cracks that extend across the entire slab thickness. Buildings with thicker slabs would, therefore, be expected to exhibit lower soil gas entry rates, all else being equal.

Where appropriate, EPA may consider appropriate building-specific data, information, and analysis when evaluating vapor intrusion into large nonresidential buildings.

A.5 CITATIONS (APPENDIX A)

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TABLE A-1.
DESCRIPTIVE STATISTICS SUMMARIZING ATTENUATION FACTOR DISTRIBUTIONS FOR GROUNDWATER, EXTERIOR SOIL GAS, SUB-SLAB SOIL GAS, AND CRAWL SPACE VAPOR AFTER APPLICATION OF THE DATABASE SCREENS CONSIDERED MOST EFFECTIVE AT MINIMIZING THE INFLUENCE OF BACKGROUND SOURCES ON INDOOR AIR CONCENTRATIONS.

Statistic	Groundwater (GW > 1,000X Bkgd)	Exterior Soil Gas (SG > 50X Bkgd)	Sub-slab Soil Gas (SS > 50X Bkgd)	Crawl Space (IA > Bkgd)
Min	1.0E-07	5.0E-06	2.5E-05	5.7E-02
5%	3.6E-06	7.6E-05	3.2E-04	1.0E-01
25%	2.3E-05	6.0E-04	1.5E-03	2.2E-01
50%	7.4E-05	3.8E-03	2.7E-03	3.9E-01
75%	2.0E-04	2.7E-02	6.8E-03	6.9E-01
95%	1.2E-03	2.5E-01	2.6E-02	9.0E-01
Max	2.1E-02	1.3E+00	9.4E-01	9.2E-01
Mean	2.8E-04	5.0E-02	9.2E-03	4.6E-01
StdDev	1.0E-03	1.7E-01	5.0E-02	2.8E-01
95UCL	3.4E-04	7.8E-02	1.3E-02	5.3E-01
Count All	774	106	431	41
Count >RL	743	106	411	41
Count <RL	31	0	20	0
No. of sites	24	11	12	4

Note: The applied database screens are groundwater (vapor) concentrations > 1,000X "background," exterior soil gas > 50X "background," sub-slab soil gas > 50X "background," and for crawl space, indoor air concentrations > 1X "background." SOURCE: Table 19 in EPA (2012a).

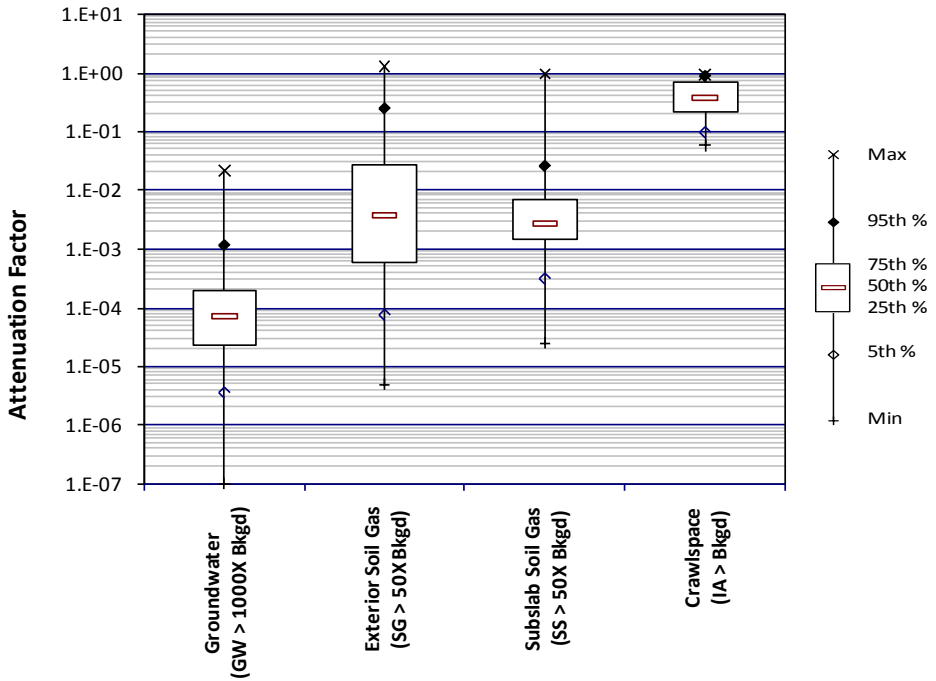

Figure A-1. Box-and-whisker plots summarizing attenuation factor distributions for groundwater, exterior soil gas, sub-slab soil gas, and crawl space vapor after application of the database screens considered most effective at minimizing the influence of background sources on indoor air concentrations. SOURCE: Figure 34 in EPA (2012a).

TABLE A-2.
DESCRIPTIVE STATISTICS SUMMARIZING GROUNDWATER ATTENUATION FACTOR DISTRIBUTIONS FOR INDIVIDUAL SITES COMPARED WITH THE COMBINED DATA SET AFTER SOURCE STRENGTH SCREEN (GROUNDWATER VAPOR CONCENTRATIONS > 1,000 TIMES "BACKGROUND").

Statistic	GW > 1,000 X Bkgd	Allepo	Alliant	BillingsPCE	CDOT	Davis	Eau Claire	Endicott	Grants	Hamilton-Sundstrand	Harcros/Tri State	Hopewell Precision	Jackson	LAFB	Lockwood	MADEP 1	MADEP 2	Moffet	Mountain View	Rapid City	Redfield	SCM - Cortlandville	Uncasville	Wall	West Side Corp.
Min	1.0E-07	9.1E-06	2.5E-06	1.0E-06	1.8E-06	4.7E-05	3.6E-06	1.9E-05	1.0E-07	9.6E-06	1.2E-06	2.5E-05		2.9E-06	8.6E-07	1.6E-04		1.3E-06	4.8E-07	9.9E-06	1.7E-06	5.9E-05	3.3E-05	1.4E-06	2.1E-06
5%	3.6E-06			1.1E-05	3.4E-06			2.8E-05	9.7E-07	1.2E-05		1.7E-04		4.0E-06	2.9E-06						7.6E-06	5.9E-05		1.7E-05	1.3E-05
25%	2.3E-05			2.1E-05	9.9E-06			2.8E-05	2.7E-06	5.8E-05		2.9E-04		1.7E-05	1.9E-05						2.8E-05	5.9E-05	3.5E-04	2.9E-05	1.5E-05
50%	7.4E-05		3.7E-06	3.9E-05	2.2E-05		2.5E-04	1.7E-04	1.2E-05	1.0E-04	2.5E-04	5.6E-04	4.7E-04	3.4E-05	8.8E-05		4.0E-05	4.0E-06	3.3E-06	3.1E-05	7.3E-05	3.1E-04	4.8E-04	8.2E-05	3.7E-05
75%	2.0E-04			8.9E-05	1.5E-04			7.0E-04	8.7E-05	1.5E-04		1.2E-03		1.4E-04	2.7E-04						1.5E-04	1.7E-03	6.5E-04	3.2E-04	2.7E-04
95%	1.2E-03			6.8E-04	5.4E-04			1.4E-03	2.9E-04	2.9E-04		7.7E-03		6.8E-04	1.3E-03						4.8E-04	4.2E-03		1.4E-03	4.3E-03
Max	2.1E-02	1.4E-05	1.1E-03	8.0E-04	5.4E-04	4.3E-04	1.9E-03	1.5E-03	2.9E-04	5.2E-04	3.7E-03	7.7E-03		2.3E-03	2.4E-03	1.0E-03		1.9E-05	3.3E-05	4.0E-05	1.8E-03	6.6E-03	1.8E-03	1.1E-02	2.1E-02
Mean	2.8E-04		1.1E-04	1.2E-04	1.1E-04	2.4E-04	7.7E-04	4.3E-04	7.5E-05	1.2E-04	7.1E-04	1.2E-03		1.6E-04	2.6E-04	6.0E-04		7.9E-06	9.7E-06	2.7E-05	1.3E-04	1.1E-03	6.0E-04	4.9E-04	1.1E-03
StdDev	1.0E-03		3.4E-04	2.1E-04	1.7E-04		8.1E-04	4.8E-04	1.1E-04	9.8E-05	1.3E-03	1.8E-03		3.6E-04	4.5E-04			9.3E-06	1.4E-05	1.6E-05	1.9E-04	1.6E-03	5.1E-04	1.7E-03	4.0E-03
95UCL	3.4E-04		2.8E-04	1.9E-04	1.8E-04		1.4E-03	5.7E-04	1.2E-04	1.5E-04	1.7E-03	2.0E-03		2.2E-04	3.5E-04			2.4E-05	2.3E-05	5.4E-05	1.5E-04	1.6E-03	9.2E-04	9.2E-04	2.3E-03
Count All	774	2	12	25	17	2	6	32	14	32	7	17	1	93	63	2	1	3	5	3	329	28	9	43	28
Count >RL	743	1	5	25	17	2	6	22	14	32	7	17	1	93	63	2	1	3	5	3	329	21	9	43	22
Count <RL	31	1	7	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	6

SOURCE: Table 13 in EPA (2012a).

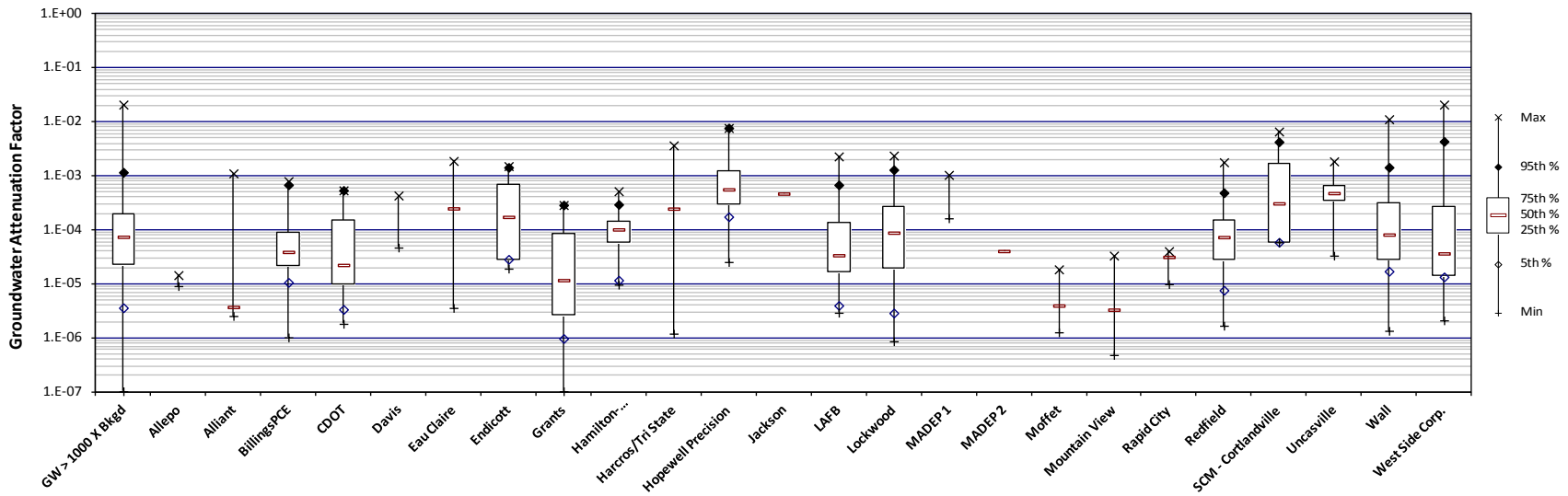

Figure A-2. Box-and-whisker plots summarizing groundwater attenuation factor distributions for individual sites compared with the combined data set after Source Strength Screen (groundwater vapor concentrations > 1,000 times "background"). SOURCE: Figure 28 in EPA (2012a).

TABLE A-3.
DESCRIPTIVE STATISTICS SUMMARIZING GROUNDWATER ATTENUATION FACTOR DISTRIBUTIONS FOR SPECIFIC SOIL TYPES AFTER SOURCE STRENGTH SCREEN.

	Soil Type Below Foundation		
Statistic	**Fine**	**Coarse**	**V.Coarse**
Min	1.0E-07	4.8E-07	2.1E-06
5%	2.3E-06	7.6E-06	1.3E-05
25%	1.9E-05	3.1E-05	2.0E-05
50%	4.6E-05	1.0E-04	1.5E-04
75%	1.4E-04	2.5E-04	6.8E-04
95%	4.5E-04	1.4E-03	4.2E-03
Max	2.4E-03	1.1E-02	2.1E-02
Mean	1.3E-04	3.3E-04	9.7E-04
StdDev	2.4E-04	8.9E-04	3.0E-03
95UCL	1.5E-04	4.1E-04	1.7E-03
Count All	353	369	52
Count >RL	344	359	40
Count <RL	9	10	12
No. of sites	10	15	3

SOURCE: Table 14 in EPA (2012a).

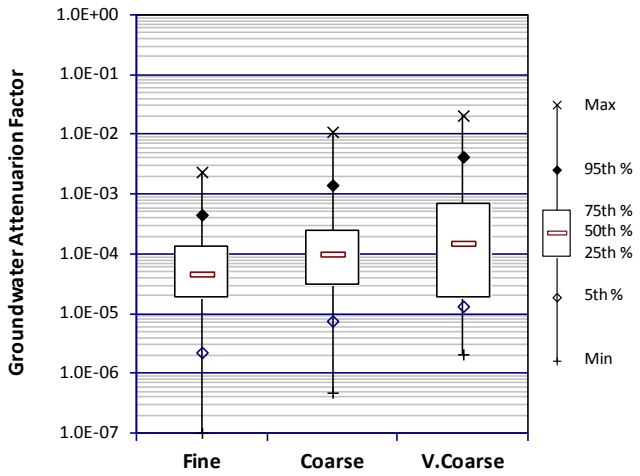

Figure A-3.Box-and-whisker plots summarizing groundwater attenuation factor distributions for specific soil types after Source Strength Screen. SOURCE: Figure 29 in EPA (2012a).

TABLE A-4.
DESCRIPTIVE STATISTICS SUMMARIZING SUB-SLAB ATTENUATION FACTOR DISTRIBUTIONS FOR INDIVIDUAL SITES COMPARED WITH THE COMBINED DATA SET AFTER SOURCE STRENGTH SCREEN (SUB-SLAB SOIL GAS CONCENTRATIONS > 50 TIMES "BACKGROUND").

Statistic	SS > 50X Bkgd	BillingsPCE	DenverPCEBB	Endicott	Georgetown	Harcros/Tri State	Hopewell Precision	Jackson	LAFB	Orion Park	Raymark	SCM-Cortlandville	West Side Corporation
Min	2.5E-05	2.5E-05	1.1E-03	2.6E-04	1.3E-03	3.8E-04	1.5E-03		3.5E-05	5.0E-04	2.5E-04	3.4E-03	2.0E-04
5%	3.2E-04	9.6E-05		6.9E-04			1.9E-03		1.4E-04		1.2E-03	3.6E-03	
25%	1.5E-03	4.6E-04		1.7E-03			5.0E-03		4.1E-04	1.8E-03	2.0E-03	7.1E-03	5.9E-04
50%	2.7E-03	7.0E-04	6.4E-03	2.6E-03	1.9E-03	4.5E-04	1.0E-02	8.4E-03	1.9E-03	2.8E-03	5.5E-03	1.8E-02	1.5E-03
75%	6.8E-03	1.5E-03		5.0E-03			1.8E-02		5.3E-03	8.8E-03	8.3E-03	4.1E-02	9.7E-03
95%	2.6E-02	2.6E-03		1.1E-02			3.4E-02		3.2E-02		2.1E-02	1.5E-01	
Max	9.4E-01	2.7E-03	4.1E-02	9.4E-01	2.9E-03	2.7E-03	3.4E-02		4.2E-02	3.3E-02	7.9E-02	1.5E-01	3.5E-01
Mean	9.2E-03	9.5E-04	1.7E-02	8.5E-03	2.0E-03	1.0E-03	1.3E-02	8.4E-03	5.0E-03	7.6E-03	7.4E-03	4.1E-02	4.3E-02
StdDev	5.0E-02	7.7E-04	1.9E-02	6.5E-02	8.4E-04	1.1E-03	1.0E-02		9.0E-03	1.1E-02	1.0E-02	5.0E-02	1.2E-01
95UCL	1.3E-02	1.2E-03	3.5E-02	1.6E-02	3.5E-03	2.3E-03	1.7E-02		7.1E-03	1.4E-02	9.2E-03	6.8E-02	1.2E-01
No. of AFs	431	27	5	207	3	4	19	1	52	9	83	12	9
No. of AFs > RL	411	27	5	188	3	4	19	1	52	9	83	12	8
No. of AFs < RL	20	0	0	19	0	0	0	0	0	0	0	0	1

SOURCE: Table 10 in EPA (2012a).

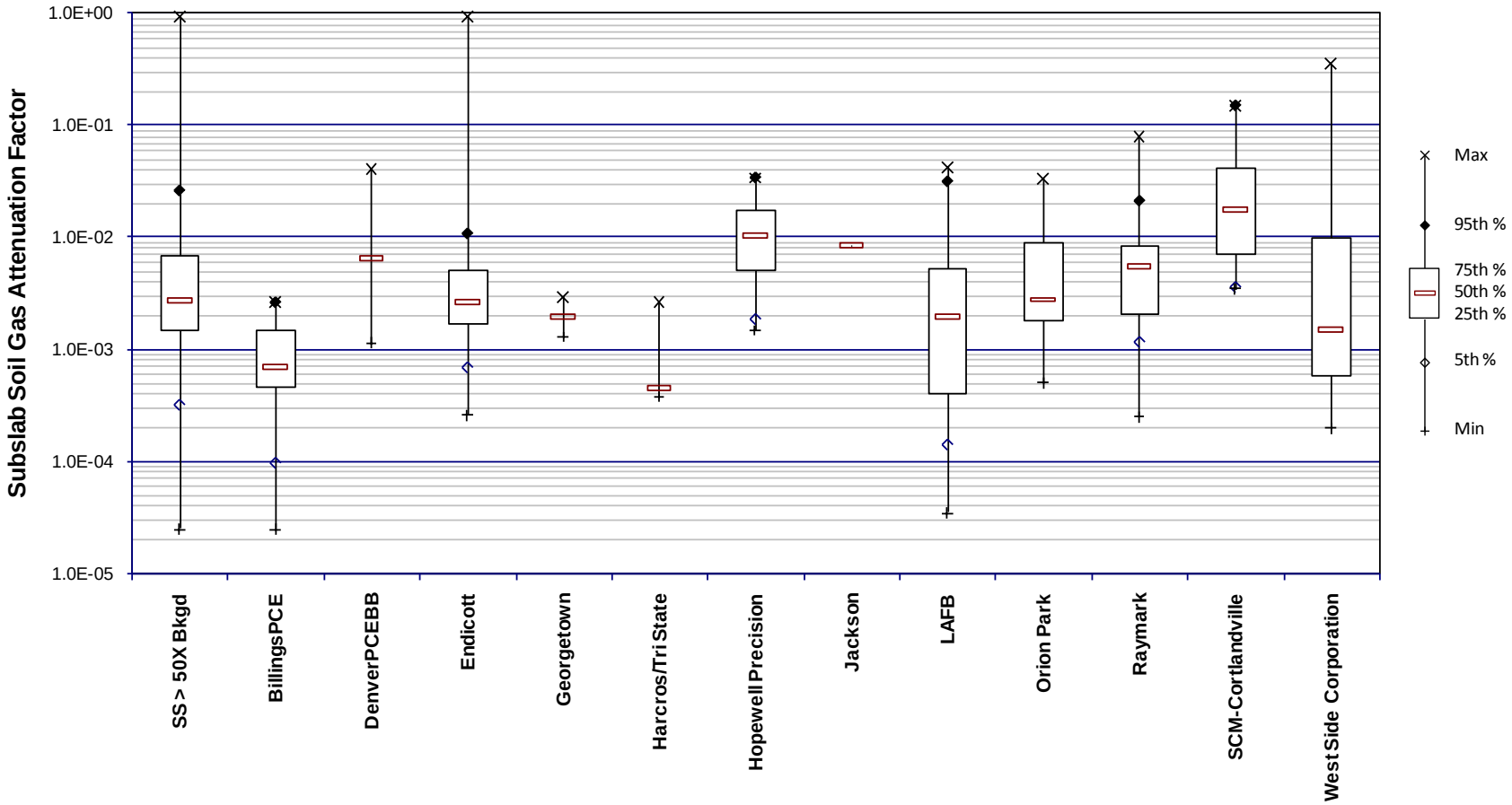

Figure A-4. Box-and-whisker plots summarizing sub-slab soil gas attenuation factor distributions for individual sites after Source Strength Screen (sub-slab soil gas concentrations > 50 times "background"). SOURCE: Figure 25 in EPA (2012a).

TABLE A-5

COMPARISON OF SIZE CHARACTERISTICS FOR RESIDENTIAL AND SOME COMMERCIAL BUILDINGS

Building Parameter and Units	Value and Source for Residential Building	Value and Source for Commercial Buildings, Other Than Warehouses and Enclosed Malls
ACH_{Bldg} (1/hr), 10th percentile	0.18 (EPA 2011, Table 19-1)	0.6 (EPA 2011, Table 19-27)
H_{Bldg} (feet)	8-feet ceiling height (EPA 2011, assumed value)	12-feet ceiling height (EPA 2011, assumed value)

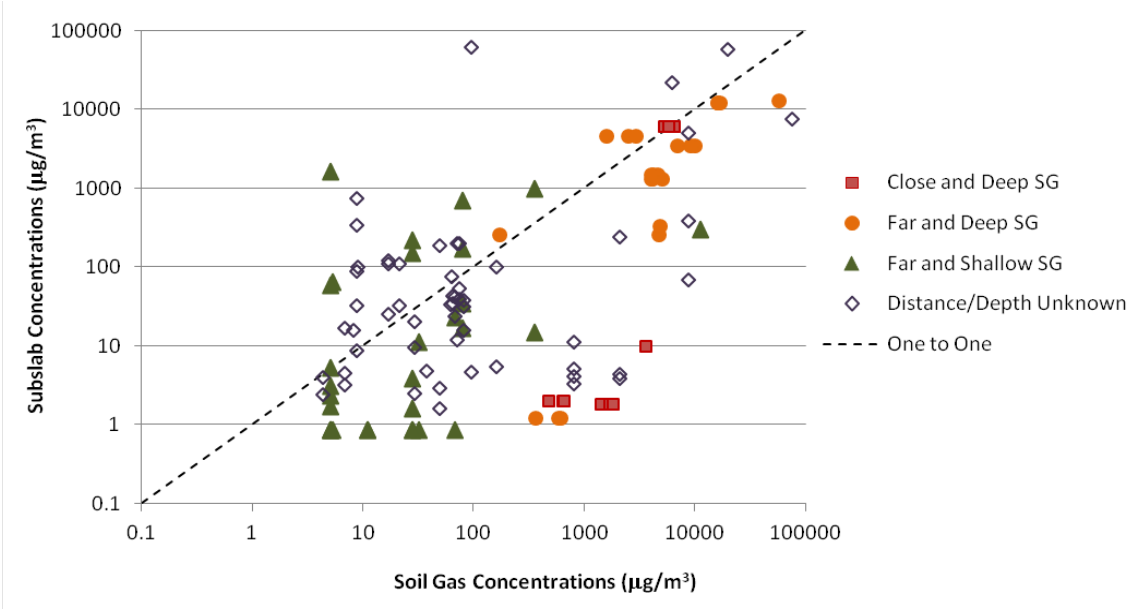

Figure A-5. Exterior soil gas versus sub-slab soil gas concentrations for buildings with both types of data in EPA's vapor intrusion database differentiated qualitatively by horizontal distance to building and depth to the exterior soil gas sample. SOURCE: Figure 6 in EPA (2012a).

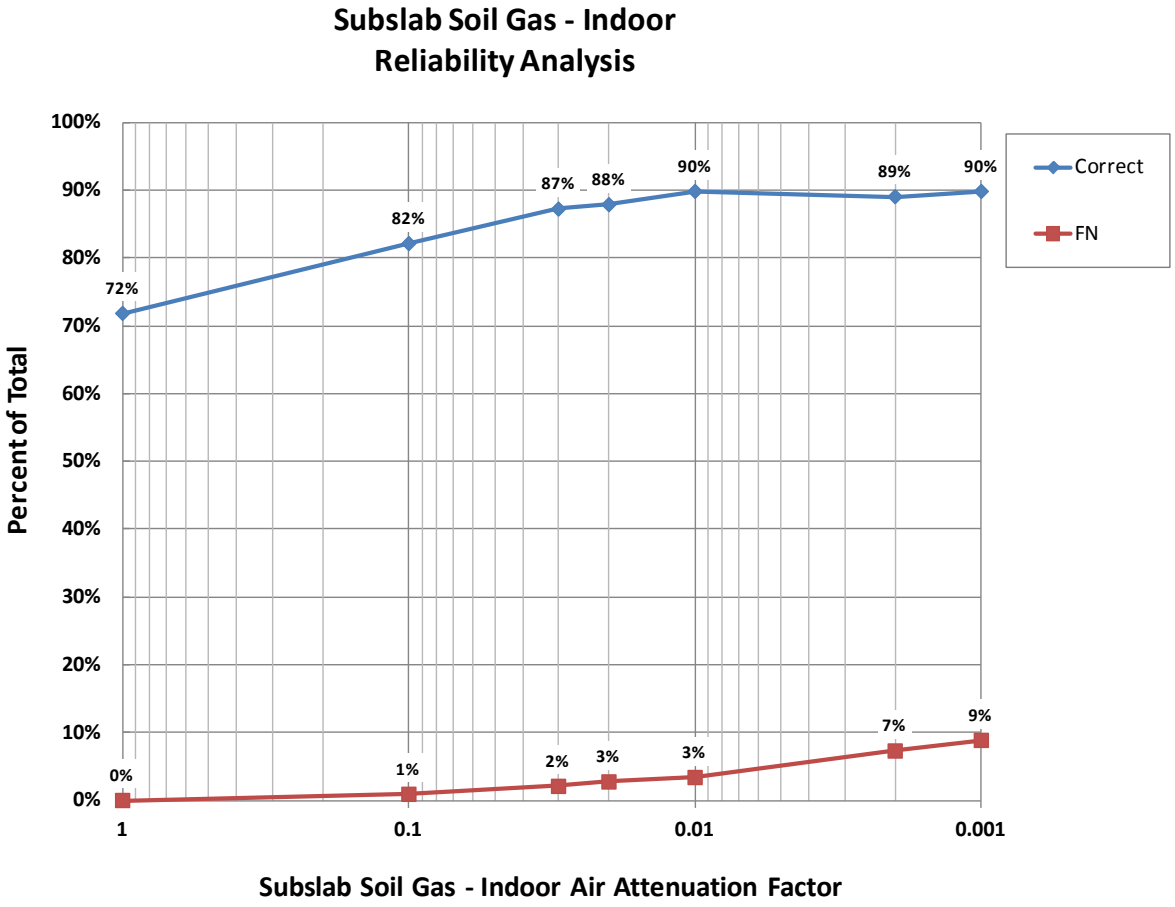

Figure A-6. Reliability Predictions for Alternative Choices of the Sub-slab Attenuation Factor Based on a Comparison of Paired Data in the Data Consistency Screen Dataset
[tabulated values shown below]

Reliability Analysis: Subslab Soil Gas - Indoor Air

Classification	SS AF = 1	SS AF = 0.1	SS AF = 0.03	SS AF = 0.02	SS AF = 0.01	SS AF = 0.002	SS AF = 0.001
Correct	551	630	669	674	689	683	689
FN	0	7	16	21	26	56	68
Total	767	767	767	767	767	767	767
SS AF	1	0.1	0.03	0.02	0.01	0.002	0.001
Correct	72%	82%	87%	88%	90%	89%	90%
FN	0%	1%	2%	3%	3%	7%	9%

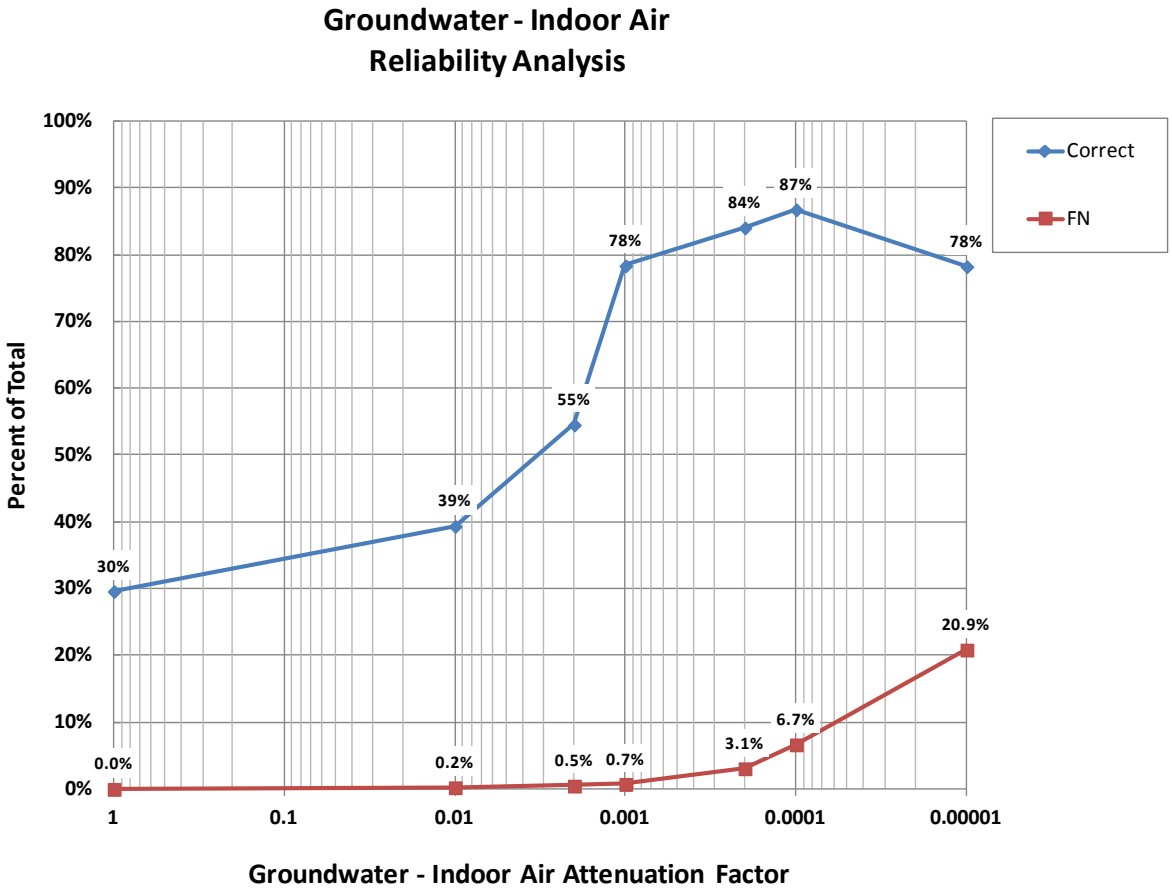

Figure A-7. Reliability Predictions for Alternative Choices of the Groundwater Attenuation Factor Based on a Comparison of Paired Data in the Data Consistency Screen Dataset
[tabulated values shown below]

Reliability Analysis: Groundwater -Indoor Air

Classification	GW AF = 1	GW AF = 0.01	GW AF = 0.002	GW AF = 0.001	GW AF = 0.0002	GW AF = 0.0001	GW AF = 0.00001
Correct	240	319	442	635	681	703	634
FN	0	2	4	6	25	54	169
Total	810	810	810	810	810	810	810
GW AF	1	0.01	0.002	0.001	0.0002	0.0001	0.00001
Correct	30%	39%	55%	78%	84%	87%	78%
FN	0.0%	0.2%	0.5%	0.7%	3.1%	6.7%	20.9%

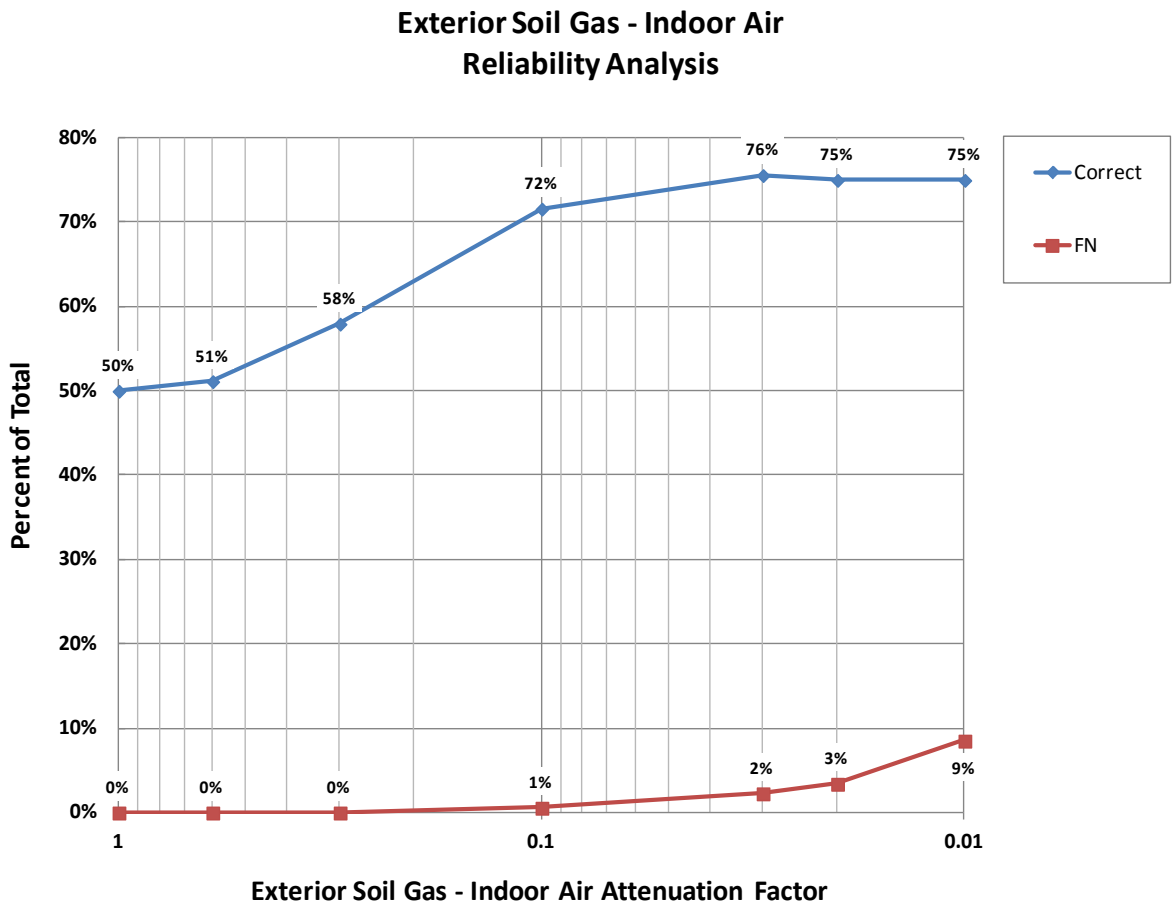

Figure A-8. Reliability Predictions for Alternative Choices of the Exterior Soil Gas Attenuation Factor Based on a Comparison of Paired Data in the Data Consistency Screen Dataset
[tabulated values shown below]

Reliability Analysis: Exterior Soil Gas - Indoor Air							
Classification	SG AF = 1	SG AF = 0.6	SG AF = 0.3	SG AF = 0.1	SG AF = 0.03	SG AF = 0.02	SG AF = 0.01
Correct	88	90	102	126	133	132	132
FN	0	0	0	1	4	6	15
Total	176	176	176	176	176	176	176
SG AF	1	0.6	0.3	0.1	0.03	0.02	0.01
Correct	50%	51%	58%	72%	76%	75%	75%
FN	0%	0%	0%	1%	2%	3%	9%

APPENDIX B
DATA QUALITY ASSURANCE CONSIDERATIONS

B.1 INTRODUCTION

Site-specific investigations of the vapor intrusion pathway will generally entail the collection and evaluation of environmental data and possibly the use of modeling. As noted in Exhibit B-1, EPA generally recommends the use of a quality assurance project plan (QAPP) for the collection of primary (and existing or secondary) data. A QAPP is a tool for project managers and planners to document the type and quality of data needed to make environmental decisions and to describe the methods for collecting and assessing the quality and integrity of those data. A QAPP is a plan or roadmap intended to help a project team document how they plan, implement, and evaluate a project. It applies the systematic planning process and the graded approach for collecting environmental data for a specific intended use. EPA standards governing the collection of data are outlined in Exhibit B-1.

Exhibit B-1. EPA Data Standards

CIO 2105 (formerly EPA Order 5360; *Policy and Program Requirements for the Agency-wide Quality System*, May 2000) is intended to promote the organization collecting or using the data to (1) establish a Quality System and prepare and approve a QAPP for each project.

For clarity, CIO 2105 will be replaced by the following two standards:

- CIO 2106-S-01 is the *Quality Standard for Environmental Data Collection, Production, and Use by EPA Organizations*, also called "Internal Standard" (EPA 2013a); and
- CIO 2106-S-02 is the *Quality Standard for Environmental Data Collection, Production, and Use by Non-EPA (External) Organizations*, also called "External Standard" (EPA 2013b).

These standards conform to *EPA Quality Policy*, CIO 2106.0, "Quality Policy" (EPA 2008a), *Procedure for Quality Policy,* CIO 2106-P-01.0, "Quality Procedure" (EPA 2008b), and the American National Standards Institute (ANSI) consensus standard, *Quality Systems for Environmental Data and Technology Programs – Requirements with Guidance for Use* (ANSI/ASQ 2004).

Two guidance documents accompany these standards:

- *EPA Guidance on Quality Management Plans* (EPA 2012b, CIO 2106-G02-QMP), documents the quality system of the organization conducting environmental data collection or using the data for EPA.
- *EPA Guidance on Quality Assurance Project Plans* (EPA 2012a, CIO 2106-G-05) focuses on projects requiring the collection of new data, projects using existing data, and projects involving modeling.

EPA also encourages the use of the *Uniform Federal Policy for Quality Assurance Project Plans (UFP-QAPP)* (EPA/DoD 2005) as a collaborative approach to fulfill the purposes of a QAPP, especially for Federal Facilities. OSWER Directive 9272.0-17, *Implementation of the Uniform Federal Policy for Quality Assurance Project Plans (UFP-QAPP) at Federal Facility Hazardous Waste Sites* (EPA 2005a) and OSWER Directive 9272.0-20 (EPA 2005b) state that QAPPs prepared and approved under the UFP conform to EPA's quality standards and are consistent with EPA Standards CIO 2106-S-0 and CIO 2106-S-02, EPA's Quality Policy (EPA 2008a), and ANSI/ASQ 2004.

B.2 RECOMMENDATIONS

This appendix provides two recommendations concerning the key components of QAPP development. These recommendations are not exhaustive, but are included as a starting point as considerations before studying or applying EPA or UFP QAPP guidance.

Recommendation 1: Using the conceptual site model (CSM), develop the project plan and QAPP through a process that involves all key players and share these materials with interested parties in draft form so that potential study weaknesses can be addressed early. The CSM is developed to portray the current understanding of site conditions, the nature and extent of contamination, routes of contaminant transport, potential contaminant pathways, and potentially exposed human population. Developing the CSM is the first step in EPA's DQO process.

Recommendation 2: Use systematic planning in developing project documents, including the QAPP. Systematic planning is a science-based, common-sense approach designed to ensure that the level of documentation and rigor of effort in planning is commensurate with the intended use of the information and available resources. DQOs are a key component of systematic planning and play a central role in the systematic planning process. DQOs generally are addressed within the QAPP and typically are a critical element in the planning for environmental investigations. *Guidance on Systematic Planning Using the Data Quality Objectives Process (QA/G-4)* (EPA 2006) provides guidance addressing implementation of DQOs and application of systematic planning to generate performance and acceptance criteria for collecting environmental data.

Table B-1 summarizes the steps in the DQO process, the purpose of each step, and provides some examples of how plans could be structured.

TABLE B-1. EXAMPLE OF STEPS IN THE DQO PROCESS

DQO Step	Purpose of the DQO Step	Example Application for Vapor Intrusion
1. State the Problem	Summarize the problem (e.g., the monitoring hypothesis, the investigation objective(s)) for which new environmental data will be collected or modeling or analysis will be performed.	Indoor air in one or more buildings overlying a shallow plume of PCE-contaminated groundwater is (are) to be sampled to determine whether PCE is present. The original PCE release occurred at an industrial site approximately 1,000 feet away from the closest building.
2. Identify the Decision	Identify the decision that will be supported by the new data, modeling or analysis.	The data will be used to support decisions about whether additional indoor air sampling or preemptive vapor intrusion mitigation will be pursued in one or more buildings.
3. Identify the Inputs to the Decision	Identify the information needed to support the decision, including data gaps that warrant collection of new information.	Indoor air sampling data for one or more buildings, in conjunction with information about measured or interpolated concentrations in groundwater near or underneath the building(s).
4. Define the Boundaries of the Study	Specify the spatial and temporal aspects of the environmental media or endpoints that the data are to represent to support the decision.	The boundaries of this initial study area extend a prescribed distance outside the lateral extent of the plume. Eventually, the boundaries of a vapor intrusion impact zone will be defined by the extent to which indoor air contamination can be associated with site-related contamination.
5. Develop a Decision Rule	Develop a logical "if…then" statement that defines the conditions that will inform the decision-maker to choose among alternative decisions.	Buildings with detectable concentrations of PCE in indoor air samples will be considered for additional indoor air sampling or preemptive vapor intrusion mitigation.
6. Specify Tolerable Limits on Decision Errors	Specify acceptable limits on decision errors, which are used to establish performance goals for limiting uncertainty in the analysis.	EPA recommends analytical limits of detection be less than risk-based screening levels for PCE to ensure that a building's indoor air concentration is not misidentified.
7. Optimize the Design for Obtaining Data	Identify the most resource-effective sampling and analysis design for generating the information needed to satisfy the DQOs.	Time-integrated samples will be collected in basements and in the first above-ground level of each building. The sampling and analysis plan and approach will be documented in a QAPP.

B.3 CITATIONS AND REFERENCES (APPENDIX B)

ANSI/ASQ. 2004. *Quality Systems for Environmental Data and Technology Programs – Requirements with Guidance for Use.* E4-2004. Currently available for purchase online at http://webstore.ansi.org/FindStandards.aspx?SearchString=ansi+e4&SearchOption=0&PageNum=0&SearchTermsArray=null|ansi+e4|null

U.S. Environmental Protection Agency (EPA). 2000. *Policy and Program Requirements for the Agency-wide Quality System*. CIO 2105. May. Currently available online at http://www.epa.gov/irmpoli8/policies/21050.pdf

U.S. Environmental Protection Agency (EPA). 2005a. *Implementation of the Uniform Federal Policy for Quality Assurance Project Plans (UFP-QAPP) at Federal Facility Hazardous Waste Sites.* OSWER Directive 9272.0-17. June 7. Currently available online at http://www.epa.gov/fedfac/pdf/oswer_qapp_directive.pdf

U.S. Environmental Protection Agency (EPA). 2005b. *Applicability of the Uniform Federal Policy for Quality Assurance project Plans.* EPA-505-04-900A, OSWER Directive 9272.0-20. December 5. Currently available online at http://www.epa.gov/fedfac/pdf/oswer_9272.0_20.pdf

U.S. Environmental Protection Agency (EPA). 2006. *Guidance on Systematic Planning Using the Data Quality Objectives Process (QA/G-4)*. EPA-240-B-06-001. February. Currently available online at http://www.epa.gov/quality/qs-docs/g4-final.pdf

U.S. Environmental Protection Agency (EPA). 2008a. *U.S. Environmental Protection Agency Quality Policy.* CIO 2106.0. Currently available online at http://www.epa.gov/irmpoli8/policies/21060.pdf

U.S. Environmental Protection Agency (EPA). 2008b. *U.S. Environmental Protection Agency Procedure for Quality Policy*. CIO 2106-P-01.0. Currently available online at http://www.epa.gov/irmpoli8/policies/21060.pdf

U.S. Environmental Protection Agency (EPA). 2012a. *U.S. Environmental Protection Agency Guidance on Quality Assurance Project Plans.* CIO 2106-G-05 QAPP. January 17.

U.S. Environmental Protection Agency (EPA), 2012b. *EPA Draft Final Guidance on Quality Management Plans.* CIO 2106-G02-QMP. January 17. Currently available online at http://www.epa.gov/oeitribalcoordination/2106-G-05%20QAPP%20Final%20Draft%2001-17-12.pdf

U.S. Environmental Protection Agency (EPA). 2013a. *Quality Standard for Environmental Data Collection, Production, and Use by EPA Organizations.* CIO 2106-S-01.

U.S. Environmental Protection Agency (EPA). 2013b. *Draft Final Quality Standard for Environmental Data Collection, Production, and Use by Non-EPA (External) Organizations.* "External Standard." CIO 2106-S-02. February 22. Currently available online at http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OEI-2012-0774-0002

U.S. Environmental Protection Agency and U.S. Department of Defense (EPA/DoD). 2005. *Uniform Federal Policy for Quality Assurance Project Plans (UFP-QAPP). Part 1: UFP-QAPP Manual.* EPA-505-B-04-900A, DTIC ADA 427785. March. Currently available online at http://www2.epa.gov/fedfac/uniform-federal-policy-quality-assurance-project-plans-evaluating-assessing-and-documenting

APPENDIX C
CALCULATING VAPOR SOURCE CONCENTRATION FROM GROUNDWATER SAMPLING DATA

Correcting the Henry's Law Constant for Groundwater Temperature

In the case of groundwater as the vapor source, the subsurface source concentration (C_{sv}) is estimated assuming that the vapor and aqueous phases are in local equilibrium according to Henry's law such that:

$$C_{sv} = H'_{TS} \times C_w \qquad \text{Equation C.1}$$

where:

C_{sv} = vapor concentration at the source of contamination (g/cm^3-v),

H'_{TS} = Henry's law constant at the system (groundwater) temperature (dimensionless), and

C_w = concentration of volatile chemical in groundwater (g/cm^3-w).

The Henry's law constants generally are reported for a temperature of 25 degrees Celsius (^{o}C). **Table C-1** provides these values for the chlorinated hydrocarbons (CHCs) in the vapor intrusion database. Average groundwater temperatures, however, are typically less than 25^{o}C. In such cases, use of the Henry's law constant at 25^{o}C may over-predict the volatility of the contaminant in water.

As described in EPA's *Soil Screening Guidance* (EPA 1996), the dimensionless form of the Henry's law constant at the average groundwater temperature (H'_{gw}) may be estimated using the Clapeyron equation:

$$H'_{gw} = \frac{\exp\left[-\frac{\Delta H_{v,gw}}{R_c} \times \left(\frac{1}{T_{gw}} - \frac{1}{T_R}\right)\right] H_R}{R \times T_{gw}} \qquad \text{Equation C.2}$$

where:

$\Delta H_{v,gw}$ = enthalpy of vaporization of the specific chemical at the groundwater temperature (cal/mol),

T_{gw} = groundwater temperature (^{o}K = ^{o}C + 273.15),

T_R = reference temperature for the Henry's law constant (298.15^{o}K),

R_C = gas constant (= 1.9872 cal/mol-^{o}K),

H_R = Henry's law constant for the specific substance at the reference temperature (atm-m^3/mol), and

R = gas constant (= 8.205 E-05 atm-m^3/mol-^{o}K).

The enthalpy of vaporization at the groundwater temperature can be approximated from the enthalpy of vaporization at the normal boiling point, as follows:

$$\Delta H_{v,gw} = \Delta H_{v,b}\left[\frac{\left(1-T_{gw}/T_C\right)}{\left(1-T_B/T_C\right)}\right]^{\eta} \qquad \text{Equation C.3}$$

where:

$\Delta H_{v,gw}$ = enthalpy of vaporization at the groundwater temperature (cal/mol),

$\Delta H_{v,b}$ = enthalpy of vaporization at the normal boiling point (cal/mol),

T_C = critical temperature for specific chemical (^oK),

T_B = normal boiling point for specific chemical (^oK),

η = exponent (unitless), and

all other symbols are as defined previously. **Table C-1** provides the chemical-specific property values used for temperature corrections to the Henry's law constant. **Table C-2** provides the value of η as a function of the ratio T_B/T_C. If site-specific data are not readily available for the groundwater temperature, then Figure 1 of the EPA fact sheet, *Correcting the Henry's Law Constant for Soil Temperature* (EPA 2001) can be used to generate an estimate.

Citations (Appendix C)

U.S. Environmental Protection Agency (EPA). 1996. *Soil Screening Guidance: Technical Background Document*. Office of Solid Waste and Emergency Response, Washington, D.C. EPA-540-R-95-128. Currently available online at: http://www.epa.gov/superfund/health/conmedia/soil/introtbd.htm

U.S. Environmental Protection Agency (EPA). 2001. *Fact Sheet, Correcting the Henry's Law Constant for Soil Temperature.* Office of Solid Waste and Emergency Response, Washington, D.C. Currently available online at http://www.epa.gov/oswer/riskassessment/airmodel/pdf/factsheet.pdf

U.S. Environmental Protection Agency (EPA). Regions 3, 6, and 9. 2011. *Regional Screening Levels for Chemical Contaminants at Superfund Sites*. Region 3, Philadelphia, PA. November. Currently available online at http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/index.htm

Lide, D.R. (Ed.). 1998. *CRC Handbook of Chemistry and Physics, 79th Ed*. Boca Raton, FL. CRC Press.

Mallard, W.G. and P.J. Linstrom (Eds.). 1998. *NIST Chemistry WebBook: NIST Standard Reference Database Number 69.* Gaithersburg, MD. National Institute of Standards and Technology. November. Currently available online at http://webbook.nist.gov/chemistry/

Table C-1. Chemical-Specific Parameters for Adjusting Henry's Law Coefficients for Groundwater Temperature

Chemical Abstracts Service Registry Number (CASRN)	Alphabetized List of Compounds	Henry's Law Constant @25°C		Henry's Law Constant @25°C[g]	Normal Boiling Point		Critical Temperature		Enthalpy of vaporization at the normal boiling point	
		H_R		H'_R	T_b		T_c		$\Delta H_{v,b}$	
		(atm-m^3/mol)	source	(unitless)	(^oK)	source	(^oK)	source	(cal/mol)	source
56-23-5	Carbon tetrachloride	2.76E-02	a	1.13E+00	3.50E+02	b	5.57E+02	h	7.13E+03	h
75-00-3	Chloroethane (ethyl chloride)	1.11E-02	a	4.54E-01	2.85E+02	b	4.60E+02	f	5.88E+03	f
67-66-3	Chloroform	3.67E-03	a	1.50E-01	3.34E+02	b	5.36E+02	h	6.99E+03	h
75-34-3	Dichloroethane,1,1-	5.62E-03	a	2.30E-01	3.30E+02	b	5.23E+02	h	6.90E+03	h
75-35-4	Dichloroethene, 1,1-	2.61E-02	a	1.07E+00	3.05E+02	b	5.76E+02	h	6.25E+03	h
156-59-2	Dichloroethene,cis-1,2-	4.08E-03	a	1.67E-01	3.28E+02	b	5.44E+02	h	7.19E+03	h
156-60-5	Dichloroethene,trans-1,2-	4.08E-03	a	1.67E-01	3.28E+02	b	5.17E+02	h	6.72E+03	h
75-09-2	Methylene chloride	3.25E-03	a	1.33E-01	3.13E+02	b	5.10E+02	h	6.71E+03	h
127-18-4	Tetrachloroethylene	1.77E-02	a	7.23E-01	3.94E+02	b	6.20E+02	h	8.29E+03	h
76-13-1	Trichloro-1,2,2-trifluoroethane,1,1,2-	5.26E-01	a	2.15E+01	3.21E+02	b	4.87E+02	f	6.46E+03	f
71-55-6	Trichloroethane, 1,1,1-	1.72E-02	a	7.03E-01	3.47E+02	b	5.45E+02	h	7.14E+03	h
79-01-6	Trichloroethylene	9.85E-03	a	4.03E-01	3.60E+02	b	5.44E+02	h	7.51E+03	h
75-01-4	Vinyl chloride (chloroethylene)	2.78E-02	a	1.14E+00	2.60E+02	b	4.32E+02	h	5.25E+03	h

Sources and Footnotes:

a Based on values reported in the U.S. EPA Regional Screening Tables. November 2011. Available online at: http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/Generic_Tables/xls/params_sl_table_run_NOV2011.xls

b Experimental values. EPA 2009. *Estimation Programs Interface Suite™ for Microsoft® Windows, v 4.00*. U.S EPA, Washington, DC, USA. Available online at: http://www.epa.gov/opptintr/exposure/pubs/episuite.htm

f *CRC Handbook of Chemistry and Physics, 76th Edition*

h EPA (2001). FACT SHEET *Correcting the Henry's Law Constant for Soil Temperature*. Attachment.

g National Institute of Standards and Technology (NIST). *Chemistry WebBook*. Available online at http://webbook.nist.gov/chemistry/

Table C-2. Values of Exponent η as a Function of T_B/T_C

Chemical-specific ratio T_B/T_C	H
< 0.57	0.30
0.57 - 0.71	0.74 (T_B/T_C) - 0.116
> 0.71	0.41

Document 26

U.S. EPA 83 FR 11584, Hazardous and Solid Waste Management system: Disposal of Coal Combustion Residuals from Electric Utilities; Amendments to the National Minimum Criteria (Phase one); Proposed Rule, March 15, 2018.

ENVIRONMENTAL PROTECTION AGENCY

40 CFR Part 257

[EPA–HQ–OLEM–2017–0286; FRL–9973–31–OLEM]

RIN 2050–AG88

Hazardous and Solid Waste Management System: Disposal of Coal Combustion Residuals From Electric Utilities; Amendments to the National Minimum Criteria (Phase One); Proposed Rule

AGENCY: Environmental Protection Agency (EPA).

ACTION: Proposed rule.

SUMMARY: On April 17, 2015, the Environmental Protection Agency (EPA or the Agency) promulgated national minimum criteria for existing and new coal combustion residuals (CCR) landfills and existing and new CCR surface impoundments. The Agency is proposing a rule that will address four provisions of the final rule that were remanded back to the Agency on June 14, 2016 by the U.S. Court of Appeals for the D.C. Circuit. The Agency is also proposing six provisions that establish alternative performance standards for owners and operators of CCR units located in states that have approved CCR permit programs (participating states) or are otherwise subject to oversight through a permit program administered by EPA. Finally, the Agency is proposing an additional revision based on comments received since the date of the final CCR rule.

DATES: *Comments.* Written comments must be received on or before April 30, 2018. Comments postmarked after the close of the comment period will be stamped ''late'' and may or may not be considered by the Agency.

Public Hearing. EPA will hold a hearing on this proposed rule on April 24, 2018 in the Washington, DC metropolitan area. Additional information about the hearing will be posted in the docket for this proposal and on EPA's CCR website (*https://www.epa.gov/coalash*).

ADDRESSES: *Comments.* Submit your comments, identified by Docket ID No. EPA–HQ–OLEM–2017–0286, at *https://www.regulations.gov.* Follow the online instructions for submitting comments. Once submitted, comments cannot be edited or removed from *Regulations.gov*. The EPA may publish any comment received to its public docket. Do not submit electronically any information you consider to be Confidential Business Information (CBI) or other information whose disclosure is restricted by statute. Multimedia submissions (audio, video, etc.) must be accompanied by a written comment. The written comment is considered the official comment and should include discussion of all points you wish to make. The EPA will generally not consider comments or comment contents located outside of the primary submission (*i.e.*, on the web, cloud, or other file sharing system). For additional submission methods, the full EPA public comment policy, information about CBI or multimedia submissions, and general guidance on making effective comments, please visit *https://www.epa.gov/dockets/commenting-epa-dockets.*

Instructions. Direct your comments on the proposed rule to Docket ID No. EPA–HQ–OLEM–2017–0286. The EPA's policy is that all comments received will be included in the public docket and may be made available online at *https://www.regulations.gov,* including any personal information provided, unless the comment includes information claimed to be CBI or other information whose disclosure is restricted by statute. Do not submit information that you consider to be CBI or otherwise protected through *https://www.regulations.gov* or email. The *https://www.regulations.gov* website is an ''anonymous access'' system, which means the EPA will not know your identity or contact information unless you provide it in the body of your comment. If you send an email comment directly to the EPA without going through *https://www.regulations.gov,* your email address will be automatically captured and included as part of the comment that is placed in the public docket and made available on the Internet. If you submit an electronic comment, the EPA recommends that you include your name and other contact information in the body of your comment and with any disk or CD–ROM you submit. If the EPA cannot read your comment due to technical difficulties and cannot contact you for clarification, the EPA may not be able to consider your comment. Electronic files should avoid the use of special characters, any form of encryption, and be free of any defects or viruses.

Docket. The EPA has established a docket for this action under Docket ID No. EPA–HQ–OLEM–2017–0286. The EPA has previously established a docket for the April 17, 2015, CCR final rule under Docket ID No. EPA–HQ–RCRA–2009–0640. All documents in the docket are listed in the *https://www.regulations.gov* index. Although listed in the index, some information is not publicly available, *e.g.*, CBI or other information whose disclosure is restricted by statute. Certain other material, such as copyrighted material, will be publicly available only in hard copy form. Publicly available docket materials are available either electronically at *https://www.regulations.gov* or in hard copy at the EPA Docket Center (EPA/DC), EPA WJC West Building, Room 3334, 1301 Constitution Ave. NW, Washington, DC. The Public Reading Room is open from 8:30 a.m. to 4:30 p.m., Monday through Friday, excluding holidays. The telephone number for the Public Reading Room is (202) 566–1744, and the telephone number for the EPA Docket Center is (202) 566–1742.

FOR FURTHER INFORMATION CONTACT: For information concerning this proposed rule, contact Mary Jackson, Office of Resource Conservation and Recovery, Environmental Protection Agency, 5304P, Washington, DC 20460; telephone number: (703) 308–8453; email address: *jackson.mary@epa.gov.* For more information on this rulemaking please visit *https://www.epa.gov/coalash.*

SUPPLEMENTARY INFORMATION:

Submitting CBI. Do not submit information that you consider to be CBI electronically through *http://www.regulations.gov* or email. Send or deliver information identified as CBI to only the following address: ORCR Document Control Officer, Mail Code 5305–P, Environmental Protection Agency, 1200 Pennsylvania Avenue NW, Washington, DC 20460; Attn: Docket ID No. EPA–HQ–OLEM–2017–0286.

Clearly mark the part or all of the information that you claim to be CBI. For CBI information in a disk or DC–ROM that you mail to the EPA, mark the outside of the disk or CD–ROM as CBI and then identify electronically within the disk or CD–ROM the specific information that is claimed as CBI. In addition to one complete version of the comment that includes information claimed as CBI, a copy of the comment that does not contain the information claimed as CBI must be submitted for inclusion in the public docket. If you submit a CD–ROM or disk that does not contain CBI, mark the outside of the disk or CD–ROM clearly that it does not contain CBI. Information marked as CBI will not be disclosed except in accordance with procedures set forth in 40 Code of Federal Regulations (CFR) part 2.

Public Hearing. This notice also announces that EPA will be holding a

public hearing on this proposed rule. A public hearing provides interested parties the opportunity to present data, views, or arguments concerning the proposed rule. EPA may ask clarifying questions during the oral presentations, but will not respond formally to any comments or the presentations made. Additional information about the hearing will be posted in the docket for this proposal and on EPA's CCR website (*https://www.epa.gov/coalash*).

I. General Information

A. Executive Summary

1. Purpose of the Regulatory Action

The EPA is proposing to amend the regulations for the disposal of coal combustion residuals (CCR) in landfills and surface impoundments in order to: (1) Address provisions of the final rule that were remanded back to the Agency on June 14, 2016; (2) to provide States with approved CCR permit programs (or EPA where it is the permitting authority) under the Water Infrastructure Improvements for the Nation (WIIN) Act the ability to set certain alternative performance standards; and (3) address one additional issue raised by commenters that has arisen since the April 2015 publication of the final rule, namely the use of CCR during certain closure situations.

2. Summary of the Major Provisions of the Regulatory Action

EPA is proposing two categories of revisions plus one additional revision to the regulations at 40 CFR 257 subpart D. The first category is associated with a judicial remand in connection with the settlement agreement entered on April 18, 2016 that resolved four claims brought by two sets of plaintiffs against the final CCR rule. See *USWAG et al.* v. *EPA,* No. 15–1219 (D.C. Cir. 2015). The second category is a set of revisions that are proposed in response to the WIIN Act. The last revision in the proposal deals with an issue that has been raised by commenters since the publication date of the final CCR rule. In the 2015 CCR final rule, EPA organized the regulations for the recordkeeping requirements, notification requirements and publicly accessible internet site requirements into 40 CFR 257.105, 257.106, and 257.107, respectively.[1] There are recordkeeping, notification and internet posting requirements associated with the revisions that are in this proposal. Those requirements have not all been added to the regulatory language. Those requirements will be added to §§ 257.105–257.107 when the final rule is developed.

a. Proposals Associated With Judicial Remand

The Agency is proposing four changes from the CCR final rule that was promulgated on April 17, 2015 associated with the judicial remand. The proposed revisions would: (1) Clarify the type and magnitude of non-groundwater releases that would require a facility to comply with some or all of the corrective action procedures set forth in 40 CFR 257.96–257.98 in meeting their obligation to clean up the release; (2) add boron to the list of constituents in Appendix IV of part 257 that trigger corrective action and potentially the requirement to retrofit or close the CCR unit; (3) determine the requirement for proper height of woody and grassy vegetation for slope protection; and (4) modify the alternative closure provisions.

b. Proposals Associated With the WIIN Act

The Agency is proposing six alternative performance standards that would apply in participating states (*i.e.*, those which have an EPA-approved CCR permit program under the WIIN Act) or in those instances where EPA is the permitting authority. Those alternative performance standards would allow a state with an approved permit program or EPA to: (1) Use alternative risk-based groundwater protection standards for constituents where no Maximum Contaminant Level exists; (2) modify the corrective action remedy in certain cases; (3) suspend groundwater monitoring requirements if a no migration demonstration can be made; (4) establish an alternate period of time to demonstrate compliance with the corrective action remedy; (5) modify the post-closure care period; and (6) allow Directors of states to issue technical certifications in lieu of the current requirement to have professional engineers issue certifications. These alternative standards are discussed in more detail later in this proposal.

Under the WIIN Act, EPA is the permitting authority for CCR units located in Indian County. EPA would also serve as the permitting authority for CCR units located in nonparticipating states subject to a Congressional appropriation to carry out that function. At this time, Congress has not provided appropriations to EPA to serve as the permitting authority in nonparticipating states. EPA is therefore proposing that in those cases where it is the permitting authority, it will have the same ability as a Director of a State with an approved CCR program to apply the alternative performance standards. In addition, EPA seeks comment on whether and how these alternative performance standards could be implemented by the facilities directly (even in States without a permit program), given that the WIIN Act provided authority for EPA oversight and enforcement.

c. Proposal To Allow CCR To Be Used During Certain Closure Situations

EPA is proposing to revise the current regulations to allow the use of CCR in the construction of final cover systems for CCR units closing pursuant to § 257.101 that are closing with waste-in-place. EPA is also proposing specific criteria that the facility would need to meet in order to allow for the use of CCR in the final cover system.

With this action EPA is not reconsidering, proposing to reopen, or otherwise soliciting comment on any other provisions of the final CCR rule beyond those specifically identified as such in this proposal. EPA will not respond to comments submitted on any issues other than those specifically identified in this proposal and they will not be considered part of the rulemaking record.

3. What are the incremental costs and benefits of this action?

This action is expected to result in net cost savings amounting to between $32 million and $100 million per year when discounting at 7 percent and annualized over 100 years. It is expected to result in net cost savings of between $25 million and $76 million per year when discounting at 3 percent and annualized over 100 years. Further information on the economic effects of this action can be found in Unit V of this preamble.

B. Does this action apply to me?

This rule applies to all CCR generated by electric utilities and independent power producers that fall within the North American Industry Classification System (NAICS) code 221112 and may affect the following entities: Electric utility facilities and independent power producers that fall under the NAICS code 221112. This discussion is not intended to be exhaustive, but rather provides a guide for readers regarding entities likely to be regulated by this action. This discussion lists the types of entities that EPA is now aware could potentially be regulated by this action. Other types of entities not listed in the table could also be regulated. To determine whether your entity is regulated by this action, you should

[1] Unless otherwise specified, all references to part 257 in this preamble are to title 40 of the Code of Federal Regulations (CFR).

carefully examine the applicability criteria found in § 257.50 of title 40 of the Code of Federal Regulations. If you have questions regarding the applicability of this action to a particular entity, consult the person listed in the **FOR FURTHER INFORMATION CONTACT** section.

II. Background

A. CCR Rule

On April 17, 2015, EPA finalized national regulations to regulate the disposal of CCR as solid waste under subtitle D of the Resource Conservation and Recovery Act (RCRA) titled, ''Hazardous and Solid Waste Management System; Disposal of Coal Combustion Residuals from Electric Utilities,'' (80 FR 21302) (CCR rule). The CCR rule established national minimum criteria for existing and new CCR landfills and existing and new CCR surface impoundments and all lateral expansions of CCR units that are codified in Subpart D of Part 257 of Title 40 of the Code of Federal Regulations. The criteria consist of location restrictions, design and operating criteria, groundwater monitoring and corrective action, closure requirements and post-closure care, and record keeping, notification and internet posting requirements. The rule also required any existing unlined CCR surface impoundment that is contaminating groundwater above a regulated constituent's groundwater protection standard to stop receiving CCR and either retrofit or close, except in limited circumstances.

The rule was challenged by several different parties, including a coalition of regulated entities and a coalition of environmental organizations. See, *USWAG et al.* v. *EPA,* No. 15–1219 (D.C. Cir. 2015). Four of the claims, a subset of the provisions challenged by the industry and environmental Petitioners, were settled. The rest were briefed and are currently pending before the U.S. Court of Appeals for the D.C. Circuit, awaiting resolution.

As part of that settlement, on April 18, 2016 EPA requested the court to remand the four claims back to the Agency. On June 14, 2016 the U.S. Court of Appeals for the D.C. Circuit granted EPA's motion.

One claim, which was settled by the vacatur of the provision allowing inactive surface impoundments to close early and thereby avoid groundwater monitoring, cleanup, and post-closure care requirements, was the subject of a recent rulemaking. See, 81 FR 51802 (August 5, 2016).

The remaining claims that were remanded back to the Agency are the subject of this proposed rule. As part of the settlement, EPA committed to issue a proposed rule or rules to: (1) Establish requirements for the use of vegetation as slope protection on CCR surface impoundments; (2) Clarify the type and magnitude of non-groundwater releases for which a facility must comply with some or all of the rule's corrective action procedures; and (3) Add Boron to the list of contaminants in Appendix IV, whose detection trigger more extensive monitoring and cleanup requirements. Each of these are discussed further in Unit III of the preamble. As specified in the settlement, EPA presently intends to take final action on these proposals by June 2019. The issue of alternative closure requirements (due to lack of capacity for non-CCR wastestreams) was also remanded, but was not part of the settlement agreement. That issue is also discussed in Unit III of this preamble.

In addition, on September 13, 2017, EPA granted petitions from the Utility Solid Waste Activities Group (USWAG) and from AES Puerto Rico LLP requesting the Agency initiate rulemaking to reconsider provisions of the 2015 final rule.[2] EPA determined that it was appropriate and in the public interest to reconsider provisions of the final rule addressed in the petitions, in light of the issues raised in the petitions as well as the new authorities in the WIIN Act.

This determination raised some questions as to how the remaining issues in the CCR litigation should be handled. In response to various motions filed with U.S. Court of Appeals for the D.C. Circuit, the court ordered EPA to submit a status report indicating which provisions of the final CCR rule were being or were likely to be reconsidered by the Agency and a timeline for this reconsideration. EPA filed that status report on November 15, 2017 indicating that the following provisions were or were likely to be reconsidered. These included issues that were before the court as well as those that were not:

Provision of the CCR rule	Description
Provisions under Reconsideration Subject to Challenge in Litigation	
§ 257.50(c), § 257.100	EPA Regulation of Inactive Surface Impoundments.
§ 257.53—definition of beneficial use	The Criteria for Determining Whether Activities Constitute Beneficial Use or Disposal.
§ 257.95(h)(2)	Use of Risk-Based Alternative Standards for Remediating Constituents Without an MCL.
§ 257.53—definition of CCR pile	The criteria for determining Whether a Pile will be Regulated as a Landfill or as Beneficial Use.
§ 257.96–98	Regulatory Procedures Used to Remediate Certain Non-Groundwater Releases.
§§ 257.73(a)(4), 257.73(d)(1)(iv), 257.74(a)(4), 257.74(d)(1)(iv).	Requirements for Slope Protection on Surface Impoundments, Including Use of Vegetation.
§ 257.103(a) and (b)	Whether to Allow Continued Use of Surface Impoundments Subject to Mandated Closure if No Capacity for Non-CCR Wastestreams.
§ 257.50(e)	Regulation of Inactive Surface Impoundments, Including Legacy Ponds.
§ 257.100	Exemption for Certain Remediation and Post-Closure Requirements for Inactive Surface Impoundments that Close by April 17, 2018. Note: EPA completed reconsideration of the issues associated with this claim. See 81 FR 51802 (August 5, 2016).
Appendix IV to Part 257; §§ 257.93(b), 257.94(b), 257.95(b), 257.95(d)(1).	Addition of Boron to the List of Constituents that Trigger Corrective Action.

[2] A copy of both rulemaking petitions are included in the docket to this proposed rule.

Provision of the CCR rule	Description
Provisions under Reconsideration Not Before the Court	
§ 257.97	Whether to Allow Modification of the Corrective Action Remedy.
§ 257.90	Whether to Suspend Groundwater Monitoring Requirements Where ''No Migration'' Demonstration is Made.
§ 257.98(c)	Whether to Allow Alternate Period of Time to Determine Remediation is Complete.
§ 257.104	Whether to Allow Modification of the Post-Closure Care Period.
§ 257.101, 257.102	Whether to Allow CCR to be Used to Close Surface Impoundments Subject to Mandated Closure.
§ 257.53	Clarify Placement of CCR in Clay Mines.

EPA further stated that it anticipates it will complete its reconsideration of all provisions identified in two phases. EPA indicated that in the first phase EPA would continue its process with respect to those provisions which were remanded back to EPA in June of 2016. These provisions are: The requirements for use of vegetation as slope protection; the provisions to clarify the type and magnitude of non-groundwater releases that would require a facility to comply with some or all of the corrective action procedures set out in §§ 257.96–257.98 in meeting its obligation to clean up the release; and provisions to add Boron to the list of contaminants in Appendix IV of the final rule that trigger corrective action. As noted elsewhere, the settlement agreement associated with the remand contemplates final action on these by June 14, 2019. EPA also indicated that as part of Phase One it would review the additional provisions to determine whether proposals to revise or amend some of these could be developed quickly enough so that they could be included in this first phase, and meet the schedule set out in the settlement agreement (*i.e.*, final action by June 2019). A number of these are associated with the WIIN Act which is discussed in detail in Unit II.B of this preamble.

EPA also indicated in its status report that it factored in two separate 90-day interagency review periods and assumed a 90-day public comment period as the minimum amount of time needed to provide comment based on the complexity of the issues involved. However, in developing this proposal, EPA now believes that a 90-day public comment period would be unnecessary. Instead, based on its assessment of the contents of the proposal, EPA will seek public comment for a period of 45 days. This proposal addresses four issues that were subject to legal challenge and included in the 2016 judicial remand. The legal authorities and policy options associated with these provisions have been addressed in comments to the 2015 CCR rule, as well as the litigation briefs filed by the United States and the industry and environmental petitioners. The remaining proposals included in this proposed rule largely reflect policy options that were discussed in the preamble to the 2015 final CCR rule and are based in large measure on the established record supporting the longstanding regulations for Municipal Solid Waste Landfills codified at 40 CFR part 258. By focusing this proposal on specific regulatory proposals that are largely rooted in existing requirements for how other nonhazardous waste is already regulated under Part 258, EPA has sought to minimize potential confusion and unnecessary burden on the public by basing many of these proposed changes to the 2015 CCR rule on well-understood legal theories and an existing scientific record.

EPA stated that it plans to complete review of all remaining matters identified on the chart and not covered in the Phase One proposal and determine whether to propose revisions to the provisions. EPA currently expects that if further revisions are determined to be warranted it will sign a Phase Two proposed rule no later than September 2018 and complete its reconsideration and take final action no later than December 2019.

Thus, this proposal includes those provisions where EPA has completed its review and has sufficient information to propose revisions. EPA continues to evaluate the other matters and will make a determination as to whether revisions are appropriate and if so anticipates signing a proposal by September of this year.

B. Water Infrastructure Improvements for the Nation Act

As noted in this preamble, the CCR rule was finalized in April 2015. As discussed in detail in the preamble to the final rule in the **Federal Register** (80 FR 21310–21311, April 17, 2015), these regulations were established under the authority of sections 1006(b), 1008(a), 2002(a), 3001, 4004, and 4005(a) of the Solid Waste Disposal Act of 1970, as amended by the Resource Conservation and Recovery Act of 1976 (RCRA), as amended by the Hazardous and Solid Waste Amendments of 1984(HSWA), 42 U.S.C. 6900(B), 6907(A), 6912(A), 6944, and 6945(a). ''Subtitle D of RCRA establishes a framework for federal, state, and local government cooperation in controlling the management of non-hazardous solid waste.'' (80 FR 21310, April 17, 2015). EPA's role is to create national minimum criteria; however, states are not required to adopt or implement them; thus under subtitle D, these self-implementing criteria operate even in the absence of a regulatory entity to oversee them. ''As a consequence of this statutory structure—the requirement to establish national criteria and the absence of any requirement for direct regulatory oversight—to establish the criteria EPA must demonstrate, through factual evidence available in the rulemaking record, that the final rule will achieve the statutory standard (''no reasonable probability of adverse effects on health or the environment'') at all sites subject to the standards based exclusively on the final rule provisions. This means that the standards must account for and be protective of all sites, including those that are highly vulnerable.'' (80 FR 21311, April 17, 2015).

Given the existing statutory authorities, the final rule provided very limited site-specific flexibilities and did not provide for a State program which could adopt and be authorized to implement the federal criteria.

In December 2016, the Water Infrastructure Improvements for the Nation (WIIN) Act was enacted, establishing new statutory provisions applicable to CCR units, including: (a) Authorizing States to implement the CCR rule through an EPA-approved permit program; and (b) authorizing EPA to enforce the rule and in certain situations to serve as the permitting authority.[3]

[3] Public Law 114–322.

The legislation amended RCRA section 4005, creating a new subsection (d) that establishes a Federal permitting program similar to other environmental statutes. States may submit a program to EPA for approval and permits issued pursuant to the approved state permit program operate in lieu of the Federal requirements. 42 U.S.C. 6945(d)(1)(A). To be approved, a State program must require each CCR unit to achieve compliance with the part 257 regulations (or successor regulations) or alternative State criteria that EPA has determined are ''at least as protective as'' the part 257 regulations (or successor regulations). State permitting programs may be approved in whole or in part. 42 U.S.C. 6945(d)(1)(B). States with approved CCR permitting programs are considered ''participating states''.

In states without an approved program, EPA is to issue permits, subject to the availability of appropriations specifically provided to carry out this requirement. 42 U.S.C. 6945(d)(2)(B). In addition, EPA must issue permits for CCR units in Indian Country. The legislation also authorized EPA to use its RCRA subtitle C information gathering and enforcement authorities to enforce the CCR rule or permit provisions, both in nonparticipating and participating States subject to certain conditions. 42 U.S.C. 6945(d)(4).

The statute expressly provides that facilities are to continue to comply with the CCR rule until a permit (issued either by an approved state or by EPA) is in effect for that unit. 42 U.S.C. 6945(d)(3), (6).

C. What is the agency's authority for taking this action?

These regulations are established under the authority of sections 1008(a), 2002(a), 4004, and 4005(a) and (d) of the Solid Waste Disposal Act of 1970, as amended by the Resource Conservation and Recovery Act of 1976 (RCRA), as amended by the Hazardous and Solid Waste Amendments of 1984 (HSWA) and the Water Infrastructure Improvements for the Nation (WIIN) Act of 2016, 42 U.S.C. 6907(a), 6912(a), 6944, and 6945(a) and (d). While the 2015 final CCR rule, and today's proposed revisions, implement EPA's authority under RCRA, as amended by HSWA and the WIIN Act, EPA does not intend for these proposed revisions to impose any other separate requirements under any other statute or regulation, including under the Clean Water Act and its implementing regulations.

III. What amendments associated with the judicial remand is EPA proposing?

A. Addition of Boron to Appendix IV of Part 257

The final CCR rule establishes a comprehensive system of groundwater monitoring and corrective action so that facilities detect and address groundwater releases. (80 FR 21396, April 17, 2015). The final rule requires facilities to employ a two-stage groundwater monitoring program. The first stage is ''detection monitoring'' for the constituents listed in Appendix III of the rule. Appendix III constituents are intended to provide an early detection as to whether contaminants are migrating from the disposal unit into groundwater.

If during detection monitoring, the facility determines there to be a statistically significant exceedance of any constituent over the established background level, the facility must begin the second stage of the monitoring program, ''assessment monitoring,'' by sampling for an expanded set of constituents, which are listed in Appendix IV of the rule. Appendix IV constituents are those that EPA has determined present risks of concern to human health or the environment. These are generally determined by risk assessment and/or damage cases, and are based on the characteristics of the wastes in the unit.

If an owner or operator determines, based on assessment monitoring, that concentrations of one or more of the constituents listed in Appendix IV have been detected at statistically significant levels above the site's established groundwater protection standards, that facility must initiate corrective action as described in the final rule. This determination (*i.e.*, that constituent concentrations are at statistically significant levels above the site's established groundwater protection standard) also triggers the requirement that an existing unlined CCR surface impoundment retrofit or close. Thus, the primary difference between listing on Appendix III and IV is that detection of a constituent on Appendix III initiates requirements for more extensive monitoring, while detection of a constituent on Appendix IV compels a facility to initiate remedial actions to clean up the contamination and, in some cases, to close the unit.

In the proposed CCR rulemaking (June 21, 2010), EPA included boron in both the detection monitoring (Appendix III) and the assessment monitoring (Appendix IV) lists, 75 FR 35253. The parameters that EPA proposed that facilities use as early indicators of groundwater contamination (Appendix III) were boron, chloride, conductivity, fluoride, pH, sulfate, sulfide, and total dissolved solids (TDS). EPA selected these constituents because they are present in CCR and would move rapidly through the subsurface and thus provide an early detection as to whether contaminants were migrating from the disposal unit. EPA also proposed a list of constituents for inclusion on Appendix IV. The list included all of the constituents found in CCR or leachate based on the data EPA had at the time: Aluminum, antimony, arsenic, barium, beryllium, boron, cadmium, chloride, chromium, copper, fluoride, iron, lead, manganese, mercury, molybdenum, selenium, sulfate, sulfide, thallium, and TDS. EPA then specifically asked for comment on this list and received a number of comments on these specific constituents.

In developing the final rule EPA generally relied on the same considerations it had relied on in the proposed rule. However, in response to comments, the final rule removed boron from Appendix IV, 80 FR 21500, April 17, 2015. The primary reason was that a Maximum Contaminant Level (MCL) had not yet been established under the Safe Drinking Water Act for boron. EPA generally preferred to include on Appendix IV only constituents that had established MCLs, as MCLs provide clear risk-based clean up levels in the event that corrective action is required. EPA also reasoned that because boron would remain on Appendix III it was unnecessary to include it on Appendix IV as facilities would be required to continue monitoring its concentration. Out of all the coal ash constituents modeled by EPA, boron has the fastest travel time, meaning that boron is likely to reach potential receptors before other constituents. Therefore, boron is expected to be one of the earliest constituents detected if releases to groundwater are occurring; consequently, EPA reasoned that retaining boron on Appendix III was more appropriate as it would function as a ''signal'' constituent that would ensure that assessment monitoring was quickly triggered in response to any release.

After the final rule was published, this decision was challenged as one claim in the multiparty litigation on the final rule. *See USWAG* v. *EPA,* No. 15–1219 (D.C. Cir.). In response to the litigation, EPA reexamined its decision to remove boron and concluded at that time that removing boron from Appendix IV had been inconsistent with other actions taken in the final rule. Specifically, fluoride had been included

on both Appendix III and Appendix IV. Removing boron from Appendix IV because of a lack of a MCL was also inconsistent with the approach to other constituents: Lead, molybdenum, cobalt and lithium were included on Appendix IV, and they lack MCLs. EPA also concluded, as discussed in greater detail below, that the facts independently warranted reconsidering the exclusion of boron from Appendix IV. In light of these conclusions, EPA settled this claim, agreeing to reconsider its decision through a new rule making. The settlement of this claim was presented to the Court without challenge, and on June 14, 2016, the Court severed this claim from the rest of the litigation over the final rule.

Accordingly, EPA is proposing to add boron to Appendix IV of part 257. This proposal is based on a number of considerations. First, the risk assessment (RA) conducted to support the final CCR rule shows that boron is one of nine constituents determined to present unacceptable risks under the range of scenarios modeled.[4] Of these constituents, boron is the only one associated with risks to both human and ecological receptors. Specifically, the 2014 risk assessment shows that boron can pose developmental risk to humans when released to groundwater and can result in stunted growth, phytotoxicity, or death to aquatic biota and plants when released to surfacewater bodies. EPA is proposing to rely on the existing 2014 risk assessment to support this part of this proposal, and EPA seeks public comment on whether this reliance is appropriate. The risks identified therein support including boron on Appendix IV along with arsenic, cadmium, cobalt, fluoride, lithium, mercury, molybdenum and thallium.

Second, when reviewing damage cases collected for the CCR rulemaking, EPA identified one or more ''contaminants of concern'' (COCs) for each damage case. Boron is a COC in more damage cases (approximately 50 percent of the total) than any Appendix IV constituent with the exception of arsenic. The damage cases reflect a range of waste types disposed in both surface impoundments and landfills. These damage cases corroborate the findings of the RA and also capture other risk scenarios that were not modeled in the RA, such as units that intersect with the groundwater table.

Third, as noted, out of all the coal ash constituents modeled by EPA, boron has one of the shortest travel times, meaning that boron is likely to reach potential receptors before other constituents. As such, including it on Appendix IV would ensure corrective action occurs soon after a potential release, prior to the appearance of slower-moving constituents hydrologically downstream from the source of contamination. Early detection and remediation would better protect human health and the environment by allowing for a response to contamination more quickly and preventing further and more extensive contamination, thereby limiting the exposures to human and ecological receptors. And although this consideration is not relevant under RCRA section 4004(a), early action will also have the benefit of reducing the costs to the facility of remediation, as the cost is necessarily greater to remediate more numerous contaminants and more extensive contamination.

Finally, inclusion of boron on Appendix IV would also be consistent with EPA's previous decisions for other constituents. EPA added cobalt, molybdenum, and lithium to Appendix IV even though these constituents do not currently have MCLs because they were found to be risk drivers in the 2014 risk assessment (80 FR 21404, April 17, 2015).

EPA included lithium on Appendix IV even though it does not have an MCL because it was detected in ''several'' damage cases (80 FR 21404, April 17, 2015). Lead was also detected in at least nine damage cases; and, as noted above, boron is a COC in approximately 51 percent of the total damage cases. By contrast, EPA removed aluminum, copper, iron, manganese and sulfide from Appendix IV because ''they lack maximum contaminant levels (MCLs)'' and were not shown to be constituents of concern based on either the risk assessment conducted for the rule or the damage cases (80 FR 21404, April 17, 2015).

In light of all of the information presented above, EPA is proposing to add boron to Appendix IV of part 257 and seeks comment on the appropriateness of including boron on Appendix IV in the absence of an MCL for the constituent.

B. Performance Standards To Increase and Maintain Slope Stability

As part of the Assessment Program [5] EPA determined that slope protection is an essential element in preventing slope erosion and subsequent deterioration of CCR unit slopes, and that the protective cover of slopes was a significant factor in determining the overall condition rating of all units.

So, in the final CCR rule EPA promulgated specific requirements for all CCR surface impoundments (except incised units) to install and maintain adequate slope protection. Specifically, the final rule required facilities to document that ''the CCR unit has been designed, constructed, operated, and maintained with . . . [adequate slope protection to protect against surface erosion, wave action, and adverse effects of sudden drawdown.'' §§ 257.73(d)(1)(ii); and 257.74(d)(1)(ii).

In developing the specific technical requirements for the final rule, EPA relied on existing dam safety technical literature, which universally recommends that vegetative cover not be permitted to root too deeply beneath the surface of the slope. Deep roots can potentially introduce internal embankment issues such as pathways for water intrusion and piping, precipitating erosion internally, or uprooting which is the disruption of the embankment due to the sudden uplifting of the root system. Based on these data, the final rule also required a vegetative cover height limitation to prevent the establishment of rooted vegetation, such as a tree, a bush, or a shrubbery, on the CCR surface impoundment slope, 80 FR 21476, April 17, 2015, and to prevent the obscuring of the slope during routine and emergency inspection. Based on the available information, EPA concluded that a vegetative cover height limitation of six inches above the face of the embankment was adequate to achieve these dual goals of preventing woody vegetation, while allowing inspectors adequate observation of the slope.

After the final rule was published, this provision was challenged on the grounds that EPA had failed to provide adequate notice of this requirement in the proposal. See, *USWAG et al.* v. *EPA,* No. 15–1219 (D.C. Cir. 2015). In response, EPA reexamined its decision, and agreed to reconsider this provision. This claim was settled, and the court vacated the requirement that vegetation on all slopes ''not . . . exceed a height of 6 inches above the slope of the dike'' within §§ 257.73(a)(4), 257.73(d)(1)(iv), 257.74(a)(4), and 257.74(d)(1)(iv). EPA is not proposing to reopen any other

[4] USEPA, ''Human and Ecological Risk Assessment of Coal Combustion Residuals'', December 2014; docket identification number EPA–HQ–RCRA–2009–0640–11993.

[5] In March 2009, the Agency's CCR Assessment Program (herein referred to as the Assessment Program) was initiated to evaluate the structural stability and safety of coal ash impoundments throughout the country. By September 2014, 559 impoundments had been assessed at over 230 coal-fired power plants. 80 FR 21313, April 17, 2015.

provisions of §§ 257.73 and 257.74, and will not respond to any comments received on those provisions. Because, as described below, slope protection is an essential element in preventing destabilization of a CCR surface impoundment, EPA is proposing to expand on the existing general performance standard with more specific slope protection requirements for existing and new surface impoundments. EPA is also proposing to establish distinct definitions and height limitations for grassy vegetation and woody vegetation to replace the vacated requirement. Finally, EPA is also proposing definitions for engineered slope protection measures, pertinent surrounding areas, slope protection, and vegetative height.

1. Performance Standards

Slope protection is an essential element in preventing destabilization of a CCR surface impoundment. Surficial and internal erosion, wave action, and rapid drawdown are some phenomena that can destabilize a surface impoundment. Surficial erosion is the removal of surface material, typically resulting from regular, intermittent physical phenomena such as surface run-off and wind action. Internal erosion, due to seepage and piping, is the removal of material beneath the surface of an embankment through the infiltration and transmission of water into and through the embankment. Wave action can cause erosion of embankment material typically caused by wave run-up in wind or storm events. Rapid drawdown is the rapid lowering of the water level of a reservoir which may precipitate slope failure due to residual high pore-water pressure in the embankment with a lack of counteracting pressure from the reservoir. In each of these phenomena, slope protection provides mitigating effects to counteract the phenomena through cohesion of the surface of the embankment. Furthermore, slope protection is necessary to ensure that dike or embankment erosion does not occur, both from the surface of the upstream or downstream slope, crest, or adjacent areas or from internal areas of the unit. Erosion of the embankment can precipitate more significant structural or operational deficiencies, such as beaching upstream from wave action, sloughing or sliding of the crest, discharge of solids to adjacent surface waters, and increased internal erosion. Finally, slope protection is necessary to maintain the stability of the CCR surface impoundment slope under rapid drawdown events [6] and low pool conditions of water bodies that may abut the CCR surface impoundment and are outside the reasonable control of the owner or operator, *e.g.,* a natural river which the slopes of the CCR surface impoundment intercept and abut. Accordingly, EPA is proposing to establish a number of new performance standards to ensure the stability of CCR surface impoundments.

First, EPA is proposing to modify the current regulation to require the owner or operator to ensure that both the slopes and the pertinent surrounding areas of any CCR surface impoundment (both existing and new) are designed, constructed, operated, and maintained with one or more of the forms of slope protection specified in the regulation. EPA has defined slope protection for this proposal as measures installed on the upstream or downstream slope of the CCR unit that protect the slope against wave action, erosion or adverse effects of rapid drawdown. Slope protection includes but is not limited to grassy vegetation, rock riprap, concrete revetments, vegetated wave berms, concrete facing, gabions, geotextiles, or fascines. EPA's proposed definition was developed from the available technical literature for dam safety, geotechnical engineering, and hydrology and hydraulics. The definition of slope protection includes examples of common modes of slope protection utilized in embankment dams, levees, dikes, and other engineering structures which interface with water or other impounded fluids.

EPA is proposing to define pertinent surrounding areas because adequate slope protection in surrounding areas is critical to the overall stability of the CCR surface impoundment. EPA has defined pertinent surrounding areas for this proposal as all areas immediately surrounding the CCR surface impoundment that have the potential to affect the structural stability and condition of the CCR surface impoundment, including but not limited to the toe of the downstream slope, the crest of the embankment, abutments, and unlined spillways. EPA intends this term to include all areas in the vicinity of the CCR unit that may influence the condition of the CCR unit. This would include all areas that good engineering practice dictates should be protected against adverse effects of erosion. See *e.g.,* Federal Emergency Management Agency's ''FEMA 534: Technical Manual for Dam Owners, Impacts of Plants on Earthen Dams'' (September 2005), a copy of which is available in the docket to this rulemaking.

However, the slope protection requirement would exclude certain areas on, adjacent, or near the CCR unit for which it is infeasible, impractical, or unsafe to maintain vegetation. These areas include specific design features of the unit that may occupy portions of the surface of the CCR unit. Such design features may include lined spillways, decant structures, access ways such as roads, paths, or stairs, or sluice pipes. Therefore, an owner or operator does not need slope protection to be designed, constructed, operated, and maintained in these areas. Furthermore, by the nature of these engineered structures, the integrity of the slope or pertinent surrounding area is typically maintained through the construction of the structure or the potential adverse effects to the integrity of the slope or pertinent surrounding area are limited by the nature of the structure. For instance, a properly designed, constructed, and maintained sluice pipe or decant structure may include preventative measures, such as a collar or a boot, which prevents the infiltration of water and potential erosion of the slope at the exit-point of the structure on the slope. An additional example of limited potential adverse effects would be that of a road or path on the crest of the embankment of the impoundment. Due to regular vehicle traffic, it may prove difficult to maintain vegetative cover on the surface of the travel path. Furthermore, due to the location and typical characteristics of the road, *e.g.,* located on the crest of the embankment with ample clearance from the edge of the upstream and downstream slopes, EPA does not anticipate substantial adverse effects due to erosion of the roadway based on its observations during the Assessment Program. Finally, the existing inspection and monitoring requirements of the final rule provide protection against the deterioration of the slopes and pertinent surrounding areas of the CCR surface impoundment in the locations where these structures are found. The integrity of these appurtenant design structures must be ensured by the professional engineer (PE) during regular assessments required in § 257.73 and § 257.74, to confirm that effects from erosion, wave

[6] In this provision, EPA is concerned with the rapid drawdown of adjacent water bodies acting upon the downstream slope of the CCR surface impoundment rather than the rapid drawdown of the impounded reservoir of the CCR surface impoundment acting upon the upstream slope of the CCR surface impoundment. Presumably, the water body of concern acting upon the downstream slope of the impoundment is outside the control of the owner or operator.

action, or other adverse phenomena are not introduced by the structures.

Similar to the original rule, EPA is proposing to require that slope protection consist of either grassy vegetation, engineered slope protection measures, or a combination of such measures. EPA is also proposing to establish specific performance standards that all slope protection measures must meet. First, the proposed rule would require that the owner or operator ensure that the slope protection measures are maintained in such a manner that allows for the adequate observation of and access to the CCR surface impoundment during routine and emergency events. Second, the regulation would require that the cover provide effective protection against surface erosion, wave action, and adverse effects of rapid drawdown.

2. Vegetative Cover

Grassy Vegetation. Adequate slope protection can be achieved in most climates through vegetation, typically a healthy, continuous dense stand of low-growing native grass species, or other similar vegetative cover. The most desirable form of slope protection, based on the technical literature, is a cover of native grass that creates cohesive coverage across the slope; this is due to its feasible maintenance, low cost of installation, and effective performance in maintaining slope integrity. In arid climates or submerged areas of the unit where the upkeep of vegetation is inhibited, alternate engineered slope protection measures, including rip-rap, or rock-armor, are typically used.

EPA is proposing to define grassy vegetation for this proposal as vegetation which develops shallow roots that do not penetrate the slope or pertinent surrounding areas of the CCR unit to a depth that introduces the potential of internal erosion or risk of uprooting and improves on the condition of the slopes and pertinent surrounding areas of the CCR unit. This definition is being proposed to provide a distinction between grassy vegetation—which EPA acknowledges can improve embankment slope stability, provided the vegetation does not inhibit adequate observation of or access to the slope or pertinent surrounding areas of the CCR unit—and woody vegetation, which can create unacceptable adverse risk to the structural stability and operational ability of the CCR unit. EPA has based the definition of grassy vegetation on ''FEMA 534: Technical Manual for Dam Owners, Impacts of Plants on Earthen Dams'' (September 2005) and the U.S. Army Corps of Engineers' ''ETL 1110–2–583: Guidelines for Landscape Planting and Vegetation Management at Levees, Floodwalls, Embankment Dams, and Appurtenant Structures'' (April 30, 2014).[7] This proposed definition helps to ensure that any vegetation installed by the owner or operator has a net positive effect on the condition of the unit. A continuous cover of grassy vegetation will prevent erosion of the surface or interior areas of the embankment, protect against the effects of wave action, and mitigate the effects of run-off from the CCR unit. EPA has identified some species of non-woody vegetation that do not provide protection against these adverse effects. These species would be considered weeds, which typically create a patch work of vegetative cover that do not provide a benefit to slope stability and are not intentionally installed by the owner or operator, and therefore do not meet the definition of grassy vegetation.

Weeds for this proposal can be wild vegetation that develops shallow-roots and are non-woody plants that do not create a contiguous cover, inhibit adequate observation of the slope and pertinent surrounding areas of the CCR unit and do not provide an advantageous effect on the condition of the slopes and pertinent surrounding areas of the CCR unit. EPA's description of weeds is based on FEMA guidance titled ''FEMA 534: Technical Manual for Dam Owners, Impacts of Plants on Earthen Dams'' (September 2005). EPA intends for all non-woody, grassy vegetation that do not provide an advantageous effect to the condition of the CCR unit to fall within this definition. Some examples of commonly found species considered to be weeds are: Herbaceous plants, vines, pigweed, ragweed, and thistle.

Woody Vegetation. EPA has defined woody vegetation for this proposal as vegetation that develops woody trunks, root balls, or root systems which can penetrate the slopes or pertinent surrounding areas of the CCR unit to a substantial depth and introduce the potential of internal erosion or risk of uprooting. Woody vegetation is not desirable when located on slopes or pertinent surrounding areas of CCR units; technical guidance consistently identifies the substantial risk of uprooting and internal erosion as a result of root system development from woody vegetation. This can lead to dam failure. Some examples of woody vegetation, as defined by the rule, include: Trees, bushes, and shrubbery.

Height Restrictions. The Assessment Program showed that the ability to adequately observe the surface of the slope and pertinent surrounding areas of the CCR surface impoundment are critical to early detection of deficiencies and overall maintaining of structural and operational integrity of the CCR units so EPA finalized height limitations in the CCR rule. However, EPA is now proposing new height limitations for any grassy and woody vegetative cover. Based on comments submitted from industry after the final rule was published, relating to the feasibility of vegetation management on CCR surface impoundments and the varied nature of technical guidance from federal agencies and organizations with jurisdiction or oversight over dam safety,[8] [9] EPA has subsequently determined that the 6 inch height limitation for grassy vegetation was overly restrictive and presented implementation problems for owners and operators.

In reviewing technical guidance from federal and state agencies and organizations, EPA found that the original 6 inch vegetative height limitation was a more conservative technical standard than is typically recommended in guidance. The U.S. Army Corps of Engineer's EM 1110–2–583 generally recommends that vegetation be limited to 12 inches in a ''vegetation free zone'' on and around embankment dams. In addition, the U.S. Army Corps of Engineer's EM 1110–2–583 recommends a minimum height of 3 inches to ensure the health of the grass species providing erosion protection and EPA agrees with this recommendation. The FEMA 534 technical manual does not prescribe a specific vegetative height limitation, but recommends that vegetation be maintained on the basis of achieving several dam safety goals, *e.g.*, permitting effective inspection and monitoring of the embankment, allowing adequate access, discouraging rodent, varmint, or other animal activity through elimination of habitat. Industry commenters have stated that maintaining a 6 inch or less vegetative cover in many regions of the United States was impractical during seasons of high precipitation, when the growth of grassy vegetation is at its greatest rate and access to the slopes of the

[7] A copy of these documents are available in the docket of this rulemaking.

[8] U.S. Army Corps of Engineers, EM 1110–2–583, ''Guidelines for Landscape Planting and Vegetation Management at Levees, Floodwalls, Embankment Dams, and Appurtenant Structures,'' April 30, 2014.

[9] Federal Emergency Management Agency, ''FEMA 534: Technical Manual for Dam Owners, Impacts of Plants on Earthen Dams,'' September 2005.

embankment is limited due to precipitation. They have also stated that when the slopes of the embankments are saturated due to precipitation, mowing may present undue risk of damaging the slopes of the embankment by mowing equipment.

In light of the above, EPA is proposing a vegetative height maximum limitation of 12 inches for grassy and woody vegetation. The 12-inch limit is drawn from the U.S. Army Corps of Engineer's EM 1110–2–583, which as previously noted, generally recommends that grassy vegetation be limited to 12 inches.

EPA is also proposing to define vegetative height as the linear distance measured between the ground surface where the vegetation penetrates the ground surface and the outermost growth point of the vegetation. This definition is being proposed in order to accurately identify the measurable height of vegetation for use in complying with the vegetative height limits of this rule. EPA intends this definition to reflect the maximum exposed length of the vegetative member along the main stalk of the member.

Woody Vegetation Maintenance. Finally, EPA is proposing to require that the vegetative cover be maintained so that all woody vegetation is removed and that any removal of woody vegetation with a diameter greater than ½ inch be directed by a qualified person, who must ensure that removal is conducted in a manner that does not introduce adverse risk to the stability and safety of the CCR unit or personnel undertaking the removal. EPA is proposing the specific numeric value of ½ inch for the maximum diameter of woody vegetation based on ease of reference and because the diameter represents the threshold for what EPA considers substantial woody vegetation. EPA seeks public comment as to whether a specific numeric value of greater than ½ inch for the maximum diameter of woody vegetation would be more appropriate.

Vegetative maintenance, particularly removal of a large tree or a shrubbery, must be undertaken with care so as not to allow for the uprooting of the root system and disturbance of substantial portions of the slope or surrounding pertinent areas of the CCR unit.[10] The removal and maintenance of such vegetation needs to be undertaken under the supervision of personnel familiar with the design and operation of the unit and in consideration of the complexities of removal of a tree or a shrubbery. Furthermore, the removal of vegetation must be conducted in a manner to ensure compliance with relevant environmental statutes, *e.g.*, National Environmental Policy Act, Endangered Species Act. EPA also seeks comment on requiring a specific timeframe in which woody vegetation must be removed.

Alternatives to Vegetative Cover. To accommodate climates or areas where it is infeasible for the owner or operator to maintain a vegetative cover, EPA is proposing to allow alternative forms of slope protection, *i.e.,* engineered cover or combination cover. EPA has proposed these alternative engineered slope protection measures to allow flexibility for owners or operators in maintaining an adequate slope protection cover system in locations where maintenance of vegetation may prove infeasible or where they do not wish to use grassy vegetation. These engineered slope protection measures, *i.e.,* engineered cover or combination cover, are available and effective in certain circumstances, and include but are not limited to rock or concrete revetments, vegetated wave berms, concrete facing, gabions, geotextiles, or fascines.

C. Clarify the Type and Magnitude of Non-Groundwater Releases That Would Require a Facility To Comply With Some or All of the Corrective Action Procedures in §§ 257.96–257.98

The CCR final rule establishes a number of requirements related to the detection and remediation of releases from a CCR unit. First, the groundwater monitoring and corrective action regulations in § 257.90 state that in the event of a release from a CCR unit, the owner or operator must immediately take all necessary measures to control the source(s) of releases so as to reduce or eliminate, to the maximum extent feasible, further releases of contaminants into the environment. The regulation specifies detailed procedures that must be followed in such cases, requiring that the owner or operator of the CCR unit comply with all applicable requirements in §§ 257.96, 257.97, and 257.98.

Section 257.96(a) also establishes two different standards for triggering corrective action, one for groundwater releases and one for non-groundwater releases. The requirement that a facility commence corrective action ''immediately upon detection of a release from a CCR unit'' applies only to non-groundwater releases. By contrast, the regulation requires corrective action for groundwater releases only upon a determination that contaminants are present in concentrations exceeding the groundwater protection standards in § 257.95(h).

In a separate section, the regulations also require that if a deficiency or release is identified during an inspection of a surface impoundment or landfill, the owner or operator must remedy the deficiency or release as soon as feasible, and prepare documentation detailing the corrective measures taken. See, §§ 257.73(d)(2), 257.74(d)(2), 257.83(b)(5), and 257.84(b)(5). However, these provisions do not require the facility to follow a particular process in cleaning up such releases.

After the final rule was published, the requirement that a facility must remediate any non-groundwater release using the same procedures applicable to the corrective action of groundwater releases in §§ 257.96–257.98 was challenged on the ground that EPA had failed to provide adequate notice of this requirement in the proposal. See, *USWAG et al.* v. *EPA,* No. 15–1219 (D.C. Cir. 2015). In response, EPA reexamined the provision and determined that some revision might be warranted to tailor the procedural requirements to the size or magnitude of the release. Specifically, EPA agreed that, in principle, for some non-groundwater releases, it may not be necessary for facilities to follow all of the corrective action procedures in §§ 257.96–257.98 in cleaning up or remedying the releases. Rather, for certain releases, such as releases that are small in scale, it might be preferable for the facility to focus primarily on the rapid remediation of these releases, consistent with §§ 257.90(d), 257.73(d)(2), and 257.83(b)(5), without requiring adherence to all of the corrective action procedures in §§ 257.96–257.98. Accordingly, EPA settled this claim by agreeing to reconsider the procedures a facility must use to clean up non-groundwater releases in a subsequent rulemaking. The settlement of this claim was presented to the Court without challenge, and on June 14, 2016, the Court severed this claim from the rest of the litigation over the final rule.

This portion of the proposed rule addresses whether the entire set of procedural requirements for corrective actions from the final CCR rule should apply to all non-groundwater releases. EPA is proposing to establish a subset of the corrective action procedures currently found in §§ 257.96–257.98 that would apply to non-groundwater releases that can be completely

[10] U.S. Department of Interior, Bureau of Reclamation, ''Water Operation and Maintenance, Bulletin No. 150'' which includes Guidelines for Removal of Trees and Vegetative Growth from Earth Dams, Dikes, and Conveyance Features, December 1989.

remediated within 180 days from the time of detection. Under these modified procedures, EPA would compress the reporting requirements into two steps: The initial notification of a release and the documentation that the release has been remediated. These revised procedures would be consolidated in a new section at § 257.99.

EPA designed many of the specific procedural requirements for non-groundwater releases in sections §§ 257.96–257.98 based on several notable ''catastrophic'' releases from CCR surface impoundments in recent history, such as the release of CCR materials from CCR surface impoundments from the Tennessee Valley Authority's (TVA) Kingston Fossil Plant in Harriman, TN, and the Duke Energy Dan River Steam Station in Eden, NC. However, EPA recognizes that all non-groundwater releases are not of a ''catastrophic'' nature, and may in some instances, be quite minor. Consequently, EPA is proposing to establish revised provisions to facilitate the most expeditious response to a release from a CCR unit from the owner or operator, and thereby to mitigate degradation.

EPA is proposing a 180-day time limit to complete remediation of the non-groundwater release. This time frame effectively serves to limit these provisions to releases that are expected to have limited potential for harm to human health and the environment. In this regard, EPA considers that the size and magnitude of the release, *i.e.,* the volume of harmful constituents released, is directly related to the time required to remedy the release.

EPA has identified a number of types of releases that may occur at CCR surface impoundments, and from those, identified the subset that EPA believes could be completely remediated under the existing performance standards within 180 days. Releases that can be cleaned up within 180 days are necessarily of a minimal volume. EPA expects that these reduced procedures are most likely to apply to incidental releases (including fugitive dust) that occur from seepage through the embankment, minor ponding of seepage at the toe of the embankment of the CCR unit, seepage at the abutments of the CCR unit, seepage from slopes, or ponding at the toe of the unit, rather than releases that of a ''catastrophic'' nature, as catastrophic releases are normally of a magnitude that remediation cannot be completed within 180 days. EPA seeks comment on whether 180 days is the appropriate timeframe in which an owner/operator would be expected to complete remediation of a non-groundwater release under this proposed provision, or whether a shorter deadline, *e.g.,* 120 days, or a longer deadline, *e.g.,* 240 days, would be more appropriate for remediating non-groundwater releases that are expected to have minimal impact to human health and the environment. EPA anticipates that these releases will typically be detected by qualified personnel or qualified professional engineers during weekly or annual inspections or during periodic assessments, as specified in the design and operating criteria of the CCR rule. These types of releases can indicate concerns regarding the structural stability of the unit and that further assessment for structural stability issues is warranted, but they do not typically constitute a substantial release of constituents to the environment in and of themselves.

On this basis, EPA has preliminarily concluded that this subset of small releases may not warrant all of the corrective action procedures specified in §§ 257.96–257.98. In these cases, it is preferable that the owner/operator focus on the rapid remediation of the release. However, EPA requests comment on whether 180-days is the appropriate time frame that best balances EPA's objective to ensure that small releases are remediated expeditiously, with the public's interest in understanding the practices occurring at the site that have the potential to affect their exposures and their groundwater.

Consistent with the proposed overall 180-day deadline for completing the cleanup, EPA is proposing to remove certain deadlines and to waive or compress certain reporting requirements found in the existing regulation, either because under the current regulation the requirement would fall due after the 180-day deadline, or because EPA considers that the benefit from the additional reporting requirement may be outweighed by the more expeditious clean-up of the site. Specifically, § 257.96 requires a facility to complete a written assessment of corrective measures within 90 days of detecting a release, place that assessment in the operating record, hold a public meeting to discuss the results of the corrective action assessment at least 30 days before selecting a remedy, and post the corrective action assessments to the publicly accessible facility website. Section 257.97 further requires a semiannual report describing the progress in selecting and designing a remedy, as well as a report upon selection of a remedy, describing the selected remedy and how it meets the standards in the regulation. Upon completion of the cleanup, section 257.98 requires the facility to prepare a report stating that the remedy has been completed, along with a certification from a qualified professional engineer attesting that the remedy has been completed in compliance with the regulation. This potentially multi-year structure was designed primarily to address releases that are large scale or that will otherwise require a substantial amount of time to remediate. It is less clear that this full process is truly necessary for smaller scale releases that could easily be completely cleaned up within a short period of time.

In lieu of the existing procedures EPA is proposing that within 15 days of discovering a non-groundwater release, the owner or operator must prepare a notification of discovery of a non-groundwater release, and place it in the facility's operating record as required by § 257.105. EPA is proposing this requirement to provide transparency, consistent with EPA's overall approach to corrective action under the existing regulations. Additionally, EPA is proposing that within 30 days of completing the corrective action of a non-groundwater release, the owner or operator must prepare a report documenting the completion of the corrective action. This report must include: (1) The facility's assessment of corrective measures to prevent further releases, to remediate any releases and to restore the affected area to original conditions; (2) the selected remedy, with an explanation of how it meets the standards specified in § 257.97; and (3) the certification by a professional engineer that the remedy has been completed in accordance with the regulation. Consistent with the existing regulation, the proposal also specifies that the remedy has been completed when the certification has been placed in the facility's operating record. The proposed rule would also require that the owner or operator comply with the recordkeeping requirements specified in § 257.105(h), the notification requirements specified in § 257.106(h), and the internet requirements specified in § 257.107(h). In the event the remedy has not been successfully completed within 180 days, the owner or operator must comply with the entire suite of corrective action requirements in §§ 257.96–257.98.

Under these modified procedures, EPA would compress the reporting requirements into two steps: The initial notification of a release and the documentation that the release has been remediated. Note that the same basic analytical steps would continue to apply—*e.g.,* the criteria for assessing the

corrective measures in § 257.96(c) and for evaluating the effectiveness of the remedy in § 257.97(b) remain in place. EPA is proposing that the facility document these analyses and solicit public input after conducting the cleanup, instead of before the cleanup. EPA is also proposing to waive the requirement in § 257.97(a) to prepare a semiannual report describing the progress in selecting and designing the remedy. Given that the remedy must be entirely completed within 180 days of discovering the release, a semiannual progress report is likely to be superfluous.

EPA recognizes that requiring public notification after the fact is different than requiring public consultation before the remedy is completed, and that in some situations the difference can be quite significant. For small or contained releases, EPA generally believes that the balance of interests is best struck in ensuring that these releases are remediated as quickly as possible, because the potential impact on the public is likewise limited. That balance shifts, however, as the potential for public impact increases. EPA therefore requests comment on whether some limited public involvement prior to completion of the clean-up would be appropriate. This could be achieved, for example, by delaying the initial notification and requiring the facility to provide details about the release and the planned remediation. Another alternative would be to require some kind of brief interim report to provide that information.

As noted, under the existing requirements, remediation is considered complete when a professional engineer has certified that the corrective action has met all the requirements of the section and the certification has been placed in the facility's operating record as required by § 257.105. Following the revisions to RCRA in the WIIN Act, EPA is proposing to expand this to allow a permitting authority in a participating state to make this determination.

As also noted previously, EPA is not proposing to modify the requirement to clean up all non-groundwater releases or the substantive performance standards that all remediation actions must meet. EPA is only proposing to revise the procedures the owner/operator must follow for non-groundwater releases that can be cleaned up within 180 days. However, in the interest of clarity, EPA is considering whether to incorporate the existing performance standards into the new subsection § 257.99 or whether it is sufficient to rely on cross-references to sections §§ 257.96–257.98. EPA specifically solicits comment on which approach would be most useful.

The provisions set forth in this rulemaking are intended solely to facilitate and expedite corrective action, without modifying the existing requirements to address all releases that occur or to ensure the protectiveness of the remedy. Therefore, no risk assessment was conducted to support this provision of the rulemaking.

D. Alternative Closure Requirements

The current regulations require that an owner or operator of a unit closing for cause pursuant to § 257.101, cease placing CCR and non-CCR wastestreams in the unit within six months of an event triggering closure. The current regulations provide a limited exception to this requirement in two narrow circumstances. First, an owner or operator may certify that CCR must continue to be managed in a CCR unit due to the absence of alternative disposal capacity. Section 257.103(a). Second, an owner or operator may certify that the facility will cease operations of the coal-fired boilers no later than dates specified in the final rule. Section 257.103(b). Under either of these alternative closure provisions, owners or operators may continue to place CCR, and only CCR, in a unit designated to close for cause for an extended period of time. Furthermore, the facility must continue to comply with all other provisions of the rule including groundwater monitoring and corrective action.

These exemptions were challenged as part of the litigation on the final rule on the ground that the exemption was too narrow. See, *USWAG et al.* v. *EPA,* No. 15–1219 (D.C. Cir. 2015). Specifically, plaintiffs alleged that during the rulemaking, commenters had informed EPA that facilities were using the same units to manage both CCR and non-CCR wastestreams, but the exemption only allowed the facility to continue to use the unit to dispose of CCR alone. The plaintiffs argued that EPA had failed to address their comments, and to provide any explanation for limiting the exemption to exclude the continued disposal of non-CCR wastestreams.

In response, EPA reexamined the record and concluded that it had failed to address these comments, and to explain the basis for its decision to restrict the exemption to the continued disposal of CCR alone. Accordingly, EPA settled this claim by agreeing to consider whether to expand this provision to situations in which a facility needs to continue to manage wastestreams other than CCR in the waste unit. The settlement of this claim was presented to the Court without challenge, and on June 14, 2016, the Court of Appeals for the D.C. Circuit remanded ''all of 40 CFR 257.103 (a) and (b)'' back to EPA to allow the Agency for further consideration.

Industry-Provided Information

On December 12, 2016, USWAG sent EPA a letter outlining the need for § 257.103 to include non-CCR wastestreams.[11] This letter has been placed in the docket of this proposed rule. The letter laid out four key premises for such an expansion of the alternative closure provisions. First, the letter explained that power plant operations produce volumes of non-CCR wastestreams in excess of the volumes of CCR wastestreams. These include boiler blowdown, boiler cleaning wastes, demineralizer regeneration washwater, cooling tower blowdown, air heater washwater, stormwater, and water treatment plant waste. Second, the letter explained that power plants do not have contingency plans in place to cover the inoperability of CCR surface impoundments. One anonymous company represented that the only time ponds are taken out of service for repairs and maintenance is during unit outages. Third, the letter provided examples of the new wastewater treatment systems that facilities would be forced to construct, including: Brine concentrators, surface impoundments, tank systems, filtration systems, chemical treatment facilities, and wastewater treatment systems. These systems were expected to take between 1.75 years and 7 years to construct. Finally, USWAG represented that 64,000 MW of coal, oil, and gas-fired capacity were at risk of shutdowns as a consequence of the current closure requirements.

USWAG followed up this letter with an executive summary of an EEI (Edison Electric Institute) reliability analysis.[12] This analysis evaluated electric reliability during peak summer electricity usage when removing the capacity of all boilers with unlined CCR impoundments receiving non-CCR wastewaters. This analysis assumed that the CCR impoundments had to be shut down, and that no alternative capacity

[11] USWAG (Utility Solid Waste Activities Group). 2016. Letter from Jim Roewer to Barnes Johnson. *Addition of Non-CCR Waste Streams to Alternative Closure Provision of Coal Combustion Residuals Rule.* December 12.

[12] EEI (Edison Electric Institute). 2017. *Potential Electric Reliability Risks Due to Cessation of Power Generation as a Result of the Closure of Unlined Surface Impoundments Under 40 CFR part 257.101 for the Failure to Meet Groundwater Protection Standards.* This document is available in the docket for this proposal.

was available for the non-CCR wastewaters. According to the executive summary, the resulting boiler shut downs would result in substantial impacts in three NERC (North American Electric Reliability Corporation) regions (SERC–E (Southeastern Electric Reliability Council-East), SERC–N (Southeastern Electric Reliability Council-North), and MISO (Midcontinent Independent System Operator)), minor impacts in three NERC regions (ERCOT (Electric Reliability Council of Texas), PJM, and SERC–SE (Southeastern Electric Reliability Council-South East)), and no impacts in remaining NERC regions. The analysis considered substantial impacts to be those where peak demand may not be met without shedding load and/or relying on imports. Minor impacts were those where reserves may fall below FERC standards.

EPA Proposal

EPA is not proposing to modify the alternative closure provisions of § 257.103(a) and will not respond to comments on those provisions. EPA is however, proposing to add a new paragraph (b) to allow facilities to qualify for the alternative closure provisions based on the continued need to manage non-CCR wastestreams in the unit. EPA is also not proposing to modify the alternative closure requirements of § 257.103(b) and will not respond to comments on those provisions (although EPA is proposing to redesignate § 257.103(b) as (c) as stated below). EPA is however, proposing to add a new paragraph (b) in this section to allow facilities to qualify for the alternative closure provisions based on the continued need to manage non-CCR wastestreams in a CCR unit that will cease operation of its coal-fired boilers within timeframes specified in the rule. Thus the facility, if it met the conditions, would be allowed to manage both CCR and non-CCR waste streams in the unit. EPA is also proposing to redesignate existing paragraphs (b) and (c) as paragraphs (c) and (e), respectively, and make conforming changes to this paragraph to reflect the non-CCR waste streams.

As noted previously, currently the alternative closure provisions remain unavailable for non-CCR wastestreams. The current regulation is explicit that the alternative closure provisions only allows for continued disposal of CCR, and therefore facilities must continue to comply with the current rule until an amendment is finalized.

EPA is proposing this exemption because substantial volumes of non-CCR wastestreams are generated at power plants, and may currently be managed in CCR surface impoundments. In the 2015 CCR rule, EPA discussed that the risks to the wider community from the disruption of power over the short-term outweigh the risk associated with the increased groundwater contamination from continued use of these units. 80 FR 21423, April 17, 2015. As it did for CCR in the 2015 CCR rule, this same concern would apply to non-CCR wastestreams if the CCR unit were unavailable for use and the community was left without power for an extended period of time. EPA solicits comment on ways to evaluate whether sustained loss of power to community will occur.

Based on the appendix provided in the December 12, 2016 letter from USWAG, these non-CCR wastestreams can range from insignificant (*e.g.,* 300 gallons per day for Company C's polisher regeneration waste) to massive (*e.g.,* 47.99 million gallons per day for Company C's stormwater). However, volumes alone do not adequately explain the difficulties that facilities may face. Some volumes are discharged to surface waters without treatment, and may be more amenable to alternative capacity or recirculation at the facility. For example, cooling water wastestreams may be recirculated.[13] Such wastestreams may be manageable through simple modifications of plant water flows and/or use of other existing capacity. However, other non-CCR wastestream volumes are treated in the CCR surface impoundments through settling of suspended solids to meet Clean Water Act permits. For example, coal pile runoff may be treated through settling in surface impoundments before being discharged.[14] These non-CCR wastestream volumes may require some level of pond or tank treatment that would not be sufficient in other existing, or easily constructible technology. Finally, some waste streams are primarily solids being sluiced for disposal, and require a long-term, permanent resting place of sufficient cumulative volume. For instance, pyrites at some power plants are combined with bottom ash in sluice conveying systems to ponds for their ultimate disposal. This wastestream may continue to be sluiced, in which case disposal impoundment volumes may still be necessary. However, it may also be managed jointly with bottom ash in wet-to-dry conversions, in which case landfill capacity may be necessary.[15]

As a result of the differences between these various non-CCR wastestreams, capacity may mean different things in different contexts. For other non-CCR wastestreams, capacity may mean the capacity to handle daily volumes of wastewater flowing between areas of the facility. Thus, EPA is proposing to provide a definition of capacity for the new section 257.103(b) which would be a basis for qualifying for the exemption. EPA solicits comment on the proposed use of this definition, as well as whether any additional clarification is warranted.

The differences discussed above also demonstrate why various non-CCR wastestreams may require more simple or more complex alternative capacity. This can impact the amount of time necessary to construct or otherwise locate that capacity. In the December 12 USWAG letter, timeframes to construct alternative capacity varied from 1.75 to 7 years. To achieve closure in the fastest practicable timeframe, owners and operators of facilities should transition each non-CCR wastestream to alternative capacity as such capacity becomes available. Thus, EPA is considering adding a condition requiring the facility to demonstrate that it lacks alternative capacity for *each* wastestream that continues to be managed under the alternative closure provisions and seeks comment on the proposed regulatory text. Under this proposed condition, any waste stream for which that finding cannot be made may not be managed in the unit. This condition would apply not only to the original determination, but to any subsequent determinations. Under the existing terms of the current regulation, the ability to continue to use the unit lasts only as long as no alternative capacity is available. Once the alternative capacity is identified, the owner or operator must arrange to use such capacity as soon as feasible. Section 257.103(a)(2)(ii). In addition, the current regulation requires the facility to annually document the continued lack of alternative capacity and the progress towards the development of alternative capacity. Section 257.103(a)(2)(iii). EPA is proposing to clarify that these

[13] ASHRAE (American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc.). 2012. *Water/Electricity Trade-Offs in Evaporative Cooling, Part 2: Power Plant Water Use.* Available online at *https://www.ashrae.org/File%20Library/docLib/Journal%20Documents/2012January/065-068_Emerging.pdf.*

[14] TVA (Tennessee Valley Authority) and U.S. EPA (Environmental Protection Agency). 1979. *Characterization of Coal Pile Drainage: Interagency Energy/Environment R&D Program Report.* EPA–600–7–79–051. February.

[15] McDonough, Kevin L. 2014. *Coal Ash Management: Understanding Your Options. Power Engineering.* February 14. Available online at: *http://www.power-eng.com/articles/print/volume-118/issue-2/abma-special-section/coal-ash-management-understanding-your-options.html.*

conditions apply to each individual waste stream that will continue to be managed in the unit and seeks comment on this approach.

In developing this provision, EPA relied on information from commenters to determine that this five-year period was feasible. The December 12, 2016 USWAG letter provides construction timeframes for a further 10 alternative disposal methods. All but one of these methods takes less than five years to construct. It appears these timeframes are therefore generally consistent with the timeframes on in the existing regulation; however, EPA solicits comment on alternative technologies and associated construction timeframes that have the potential to impact this period.

As noted previously, USWAG submitted an executive summary of an EEI reliability analysis. EPA understands that this analysis indicates that in some instances there may be an impact on electric reliability caused by surface impoundment closure. Consequently, EPA is proposing to limit the new alternative closure requirements to facilities that have the potential to impact electric reliability. Specifically, EPA is proposing to limit the expanded exemption to facilities in one of the three FERC regions that the EEI analysis concludes are likely to suffer substantial reliability impacts.

EPA notes that the EEI executive summary cautioned:

''Those reviewing the EEI findings should recognize that our findings were not part of any detailed planning study and provide a very high level review of possible worst case impacts on a regional level.''

Although EPA was able to review only the executive summary of this analysis, and therefore cannot draw definitive conclusions, EPA agrees that these impacts appear to be worst-case for several reasons that were clear from the executive summary alone. First, the EEI analysis assumes that all unlined CCR impoundments leak above the groundwater protection standards and the CCR units would have to be closed for cause. Second, the analysis assumes that non-CCR wastestreams were being managed in all of those CCR impoundments. Third, the analysis assumes that alternative capacity for those non-CCR wastestreams could not be found or constructed within the six-month period for closure to commence. Finally, the analysis assumes that the lack of capacity would cause the associated coal boilers to cease operation. EPA considered each of these assumptions to be worst-case as explained below.

First, the assumption that *all* unlined surface impoundments leak above the groundwater protection standard is contrary to EPA's 2014 risk assessment. This conclusion is further bolstered by the final risk assessment which showed that even input porewater concentrations from some surface impoundments were below the groundwater protection levels. Thus, the assumption that all surface impoundments leak above groundwater protection standards is worst-case rather than a best estimate.

Similarly, not all unlined CCR units manage non-CCR wastestreams. Rather than use either the non-CBI (confidential business information) data available from the 2010 Office of Water (OW) questionnaire or some other industry-provided data set, EEI has assumed that all unlined CCR units also manage non-CCR wastestreams. A quick scan of the information available in the non-CBI OW questionnaire reveals dozens of CCR surface impoundments that do not receive non-CCR wastewaters.[16]

Third, the assumption that no facility could construct alternative capacity within the time frames in the current regulation is contrary to other information presented in the USWAG letter. This letter documents several alternative disposal methods that take only two or three years to construct. It thus appears to generally be feasible for facilities with knowledge of leaking units to begin and complete the construction of these ponds, tanks, and other capacity in the time that the rule lays forth for closure to commence. If the facilities that believe that their units are leaking, or likely leaking, had already begun this construction when they first learned of the regulatory requirements, many would be nearing completion as of this rulemaking.

When taken as a whole, these worst-case assumptions result in an analysis may overestimate the effects to the electricity grid. In EPA's final rule Regulatory Impact Analysis (RIA),[17] EPA modeled electricity impacts using the Integrated Planning Model (IPM). This model exercise showed minimal retirements or effects on total capacity over the timeframe modeled. However, while the EEI analysis may be an overestimate of impacts on reliability, other entities have found that the combination of several environmental regulations may nevertheless contribute to regional reliability issues. For instance, in 2012 the GAO (Government Accountability Office) found that 18 percent of coal-fired capacity in the Midwest could retire.[18] Although the GAO concluded that EPA regulations were not expected to pose widespread concerns, it did find that these regulations could contribute to challenges in some regions. Similarly, NERC reviewed the potential reliability effects of combined EPA regulations on the power sector in 2010 and 2011.[19] [20] In those long-term reliability analyses, NERC made several recommendations. NERC recommended that EPA defer compliance targets and grant extensions where there is a demonstrated reliability need. NERC also recommended that industry make investments to retrofit or replace capacity that might be affected by (at the time) forthcoming EPA regulations.

While the NERC and GAO reports both took account of numerous EPA regulations that have since been stayed, EPA nevertheless acknowledges that the impacts of environmental regulations can potentially affect reliability when deadlines are not flexible. As a result, EPA is considering restricting the alternative closure provisions to facilities in the NERC regions and sub-regions showing the potential for substantial impacts in the EEI report. The three regions are MISO, SERC–E, and SERC–N. For facilities that are located in, or regularly provide the majority of generated electricity to, those regions, the facilities may qualify for the alternative closure provisions due to non-CCR wastestreams provided the other requirements are met.[21] EPA notes that to demonstrate that a facility regularly provides the majority of its generated electricity to one of these regions, it is not necessary that the facility provide such quantities with a high frequency. For instance, if a facility outside of one of these regions only provided a majority of its generation to that region during peak times in summer months, the fact that this is

[16] Available online at: *https://www.epa.gov/eg/steam-electric-power-generating-effluent-guidelines-questionnaire.*

[17] See docket item EPA–HQ–RCRA–2009–0640–12034, available at *https://www.regulations.gov.*

[18] GAO (Government Accountability Office). 2012. *EPA Regulations and Electricity: Better Monitoring by Agencies Could Strengthen Efforts to Address Potential Challenges.* GAO–12–635. July.

[19] NERC (North American Electric Reliability Corporation). 2010. *Special Reliability Scenario Assessment: Potential Resource Adequacy Impacts of U.S. Environmental Regulations.* October 5.

[20] NERC (North American Electric Reliability Corporation). 2011. *Potential Impacts of Future Environmental Regulations.* November.

[21] EPA estimates that the percentage of facilities located in the three NERC Assessment Areas showing the potential for substantial impacts is approximately 40 to 48 percent. This is based on the number of facilities with publically accessible websites.

done regularly, year after year, would be sufficient.

EPA solicits comment on the proposal to limit the exclusion under proposed new paragraphs (b) and (d) of § 257.103 for non-CCR wastestreams to the three specific NERC regions and sub-regions that have a demonstrated reliability need. Without the EEI analysis, EPA can only conservatively assume, as industry does, that the three regions and sub-regions showing substantial impacts in the EEI analysis have such a demonstrated need. EPA also solicits comment on the appropriateness of allowing facilities outside a NERC region to qualify if they provide electricity to that region, as well as other reasonable standards for determining which facilities qualify.

IV. What amendments associated with the WIIN Act is EPA proposing?

During the rulemaking for the current regulations for CCR in 40 CFR part 257, EPA received numerous comments requesting that EPA adopt alternative performance standards that would allow state regulators (or facilities) to ''tailor'' the requirements to particular site conditions. Many requested EPA adopt particular performance standards found in EPA's municipal solid waste landfill (MSWLF) regulations in 40 CFR part 258. As discussed in the preamble to the final 1991 rule establishing the part 258 requirements, EPA incorporated the concept of ''differential protection of groundwater'' as a basis for allowing regulatory flexibility depending on the quality of the groundwater source.[22] Although the CCR rule was largely modeled on the MSWLF regulations, as explained in both the proposed and final rules, under the statutory provisions relevant to the CCR rule, EPA lacked the authority to establish a program analogous to part 258, which relies on approved states to implement the federal criteria through a permitting program. In the absence of a mandated state oversight mechanism to ensure that the alternative standards would be technically appropriate, EPA concluded it could not adopt many of the ''more flexible'' performance standards in part 258 that commenters requested.

As fully explained in the preamble to the April 2015 CCR rule, the statutory structure established by Congress requires EPA to establish national minimum criteria that ensure there is ''no reasonable probability of adverse effects on health or the environment.'' States may, but are not required to adopt or implement these criteria; thus the national minimum criteria apply to all facilities even in the absence of a regulatory entity to implement or oversee them. EPA in establishing these national minimum criteria had to show through its rulemaking record that the final rule would achieve the statutory standard of ''no reasonable probability of adverse effects on health or the environment'' at all sites subject to the standards. This means that the standards must be protective of all sites, including the most highly vulnerable sites. The statute provided no mechanism for site specific flexibility as in the MSWLF program in part 258.

However, in 2016 Congress amended RCRA to establish a permit program analogous to that established for MSWLFs. See Unit II.B for additional detail. Under these new provisions, States may now apply to EPA for approval to operate a permit program to implement the CCR rule. As part of that process, a State program may also establish alternative State technical standards, provided EPA has determined they are ''at least as protective as'' the CCR regulations in part 257. 42 U.S.C. 6945(d)(1)(B), 6945(d)(1)(C).

In light of the legislation, EPA returned to the existing 40 CFR part 258 regulations to evaluate the performance standards that rely on a state permitting authority. EPA evaluated whether there was sufficient evidence in the record for those regulations to support incorporating either the part 258 MSWLF provision or an analogue into the part 257 CCR regulations. One complication is the statutory standard for the part 258 regulations is different than the standard for the CCR regulations. The CCR regulations are based on RCRA section 4004(a), which requires the regulations to ensure ''there is no reasonable probability of adverse effects on health or the environment from disposal of solid waste at such facility.'' 42 U.S.C. 6944(a). By contrast, EPA was authorized to ''take into account the [facility's] practicable capability'' in developing the part 258 regulations. 42 U.S.C. 6949a(c). As a consequence, the rulemaking record for some part 258 provisions may not fully support a determination that a particular provision meets the RCRA section 4004(a) standard or will be ''at least as protective'' as EPA's CCR regulations.

Based on the results of this evaluation, EPA is proposing to adopt several provisions modeled after the following in part 258: (1) The State Director may establish alternative risk-based groundwater protection standards for constituents for which Maximum Contaminant Levels (MCLs) have not been established (see § 258.55(i) and (j)); (2) The State Director may determine that remediation of a release of an Appendix IV constituent is not necessary under certain conditions (see § 258.57(e) and (f)); (3) The State Director may determine that groundwater monitoring requirements under §§ 257.91–257.95 may be suspended if there is evidence that there is no potential for migration of hazardous constituents to the uppermost aquifer during the active life of the unit and post-closure care (see § 258.50(b)); (4) The State Director may specify an alternative length of time to demonstrate that remedies are complete (see § 258.58(e)(2)); (5) The State Director may modify the length of the post-closure care period (see § 258.61(b)); and (6) The State Director may decide to certify that the regulatory criteria have been met in lieu of the exclusive reliance on a qualified professional engineer. These part 258 provisions in the MSWLF regulations were adopted based solely on a finding that they would protect human health and the environment, which is not appreciably different from the standard under RCRA section 4004(a). See, 75 FR 35193 (June 21, 2010). Thus, in proposing these flexibilities, EPA believes that the statutory standard under RCRA section 4004(a) is met.

In addition, under the WIIN Act, EPA is the permitting authority for CCR units located in Indian County. EPA would also serve as the permitting authority for CCR units located in nonparticipating states subject to a Congressional appropriation to carry out that function. EPA is proposing that where it is the permitting authority, it will have the same authority as the Director in an approved or participating state to apply the alternative performance standards. In order to make this clear, EPA is proposing to revise the definition of State Director in § 257.53 to clarify that the term ''State Director'' includes EPA where EPA is the permitting authority (that is on Tribal lands and in nonparticipating states if EPA were to receive appropriations specifically for the purpose of issuing permits). EPA seeks comment on this approach or on the alternative of adding the words ''or EPA where it is the permitting authority'' to each of the proposed flexibilities.

Further EPA is considering further modifications to these provisions, analogous to the 2010 proposal, and is seeking comment on whether it is appropriate and consistent with the WIIN Act for these alternative performance standards to apply directly to a facility in a nonparticipating State

[22] 56 FR 50978, 50995–96 (Oct. 9, 1991).

on the basis that the units in the nonparticipating states are subject to oversight by EPA through the enforcement authorities provided directly to EPA under the WIIN Act. As discussed below, EPA seeks comment on alternatives for implementing such flexibilities, for example, through appropriate detailed technical analyses, certification(s) by an independent professional engineer (or other appropriate technical expert or experts), reliance on state ground water standards, notifications to EPA, posting on the facility's publically available website, etc.

In addition, EPA is seeking comment on whether it would be appropriate and consistent with EPA's authority for an approved State or EPA in a nonparticipating state, or an owner or operator subject to EPA oversight, to establish alternative, risk-based location restrictions in lieu of the location restrictions found at §§ 257.60–257.64. For example, in the 2010 proposed CCR rule, EPA proposed a location restriction requiring demonstration that a CCR unit be located a minimum of two feet above the upper limit of the natural water table.[23] The final rule changed the requirement to five feet above the uppermost limit of the uppermost aquifer.[24] An owner or operator could also satisfy the location restriction by demonstrating the absence of an intermittent, recurring, or sustained hydraulic connection between the CCR unit and the uppermost aquifer.[25] EPA seeks comment on whether a State, or an owner/operator through a detailed technical analysis or certification(s) by an independent professional engineer (or other appropriate technical expert or experts), could establish alternative location restrictions that would satisfy the standard in RCRA section 4004(a). EPA also seeks comment on whether the October 17, 2018 compliance deadline for the location restrictions at §§ 257.60–257.64 is appropriate in light of the WIIN Act or whether an alternative deadline, either through a permit program established under the WIIN Act or one that applies directly to the facility itself during an interim period, would be more appropriate to facilitate implementation of the WIIN Act and any changes as a result of this rulemaking.

Moreover, for any adopted site specific performance standards (whether approved by the State, EPA, or implemented by the facility itself), EPA is requesting comments on whether the facility or owner operator should be required to post the specific details of the modification of the performance standard to the facility's publically accessible website or require any other recordkeeping options.

Finally, as described in Unit IV.G below, EPA is proposing one modification to the closure section in a certain situation to allow the use of CCR in construction of the cover system.

A. Alternative Risk-Based Groundwater Protection Standards

The current regulations at § 257.95(h) require the CCR unit owner or operator to set the groundwater protection standard (GWPS) at the MCL or background for all constituents from Appendix IV to part 257 that are detected at a statistically significant level above background. The GWPS must be set at the MCL for all Appendix IV constituents for which there is a promulgated level under section 1412 of the Safe Drinking Water Act. If no MCL exists for a detected constituent, then the GWPS must be set at background. In cases where the background level is higher than the promulgated MCL for a constituent, the GWPS must also be set at the background level.

In the 2010 proposal, EPA proposed allowing an owner or operator to establish an alternative GWPS for constituents for which an MCL has not been established provided that the alternative GWPS has been certified by an independent registered professional engineer and placed in the operating record and on the owner's or operator's publicly available website. In finalizing the GWPS requirements, EPA declined to allow a qualified professional engineer to establish alternative GWPS because EPA determined it was ''inappropriate in a self-implemented rule, as it was unlikely that a facility would have the scientific expertise necessary to conduct a risk assessment, and was too susceptible to potential abuse.'' [26]

In this rulemaking EPA is proposing to adopt a provision analogous to 40 CFR 258.55(i), the regulations applicable to MSWLFs. Under the existing part 258 provision, the Director of a state permitting authority in a state with an approved MSWLF permitting program may establish an alternative GWPS for constituents without an MCL, provided that it is an appropriate health-based level established in accordance with the specific criteria in this regulation. The only constituents listed in Appendix IV of the final CCR rule that currently have no MCL (and therefore, the only ones that fall under this proposal) are cobalt, lead, molybdenum and lithium. Boron, which is proposed for addition to Appendix IV, also does not have an MCL. First, these are ''health based levels,'' which means that the only relevant consideration is whether the alternate standard will protect potential receptors (both human and environmental); costs or any similar considerations may not be considered. In addition, 40 CFR 258.55(i) specifies that all of the following criteria must be met: (1) The level is derived in a manner consistent with Agency guidelines for assessing the health risks of environmental pollutants (51 FR 33992, 34006, 34014, 34028, Sept. 24, 1986); (2) The level is based on scientifically valid studies conducted in accordance with the Toxic Substances Control Act Good Laboratory Practice Standards (40 CFR part 792) or the equivalent; (3) For carcinogens, the level represents a concentration associated with an excess lifetime cancer risk level (due to continuous lifetime exposure) within the 1×10^{-4} to 1×10^{-6} range; and (4) For systemic toxicants (*i.e.,* chemicals that cause effects other than cancer), the level represents a concentration to which the human population (including sensitive subgroups) could be exposed to on a daily basis that is likely to be without appreciable risk of deleterious effects during a lifetime. For purposes of this subpart, systemic toxicants include toxic chemicals that cause effects other than cancer or mutation.

The Agency is proposing to allow participating states to set an alternative groundwater protection standard that is largely based on the four criteria specified in this part 258 provision. However, the criteria specified under the proposed revisions to § 257.95(h) would not be identical to those in 40 CFR 258.55(i). Rather EPA is proposing to use modified criteria in the CCR rule that would account for more recent science policies and for the specific characteristics of these wastes. EPA requests comments on the use of the modified criteria for CCR. These proposed modifications are described below.

As in the part 258 MSWLF regulation, EPA is proposing to allow the Director of a state with an EPA-approved CCR permitting program (and EPA where it is the permitting authority) to establish an alternative GWPS ''health-based level'' for constituents without an MCL. Consistent with part 258, this alternative GWPS is to be a health-based standard that will be protective of potential receptors (both human and ecological) and is not based on any non-

[23] 75 FR 35128, 35241 (June 21, 2010).

[24] 80 FR 21302, 21471–72 (April 17, 2015).

[25] Id.

[26] 80 FR at 21405 (April 17, 2015).

risk based factors, such as the cost to achieve that standard. EPA is proposing to adopt these provisions without change. As an alternative, similar to the language in the 2010 proposal for § 257.95(h), EPA is also considering further modifying this provision and is seeking comment as to whether an alternative risk-based GWPS could be established by an independent technical expert or experts (where there is no approved permitting authority, that is in a ''nonparticipating state''). That expert(s) would be required to derive the standard in a manner consistent with Agency guidelines (as described below); however, that alternative standard could be implemented by the facility without the intervention of a permitting authority, for example, through the use of a certified technical expert(s) or by reliance on state groundwater standards or other risk-based approach. EPA seeks comment on this approach and whether such an approach would satisfy the underlying statutory requirement of no reasonable probability of adverse effects on health or the environment from disposal of solid waste at such a facility and whether the new authorities provided to EPA in the WIIN Act for oversight and enforcement make such an approach feasible and adequate to address the concerns EPA identified in the preamble to the 2015 CCR rule that an owner or operator would not be expected to have the requisite experience necessary to conduct a risk assessment and that such an approach would be susceptible to abuse. Depending on the comments received and EPA's analysis thereof, EPA may ultimately adopt such an approach.

The current § 257.95 establishes the requirements for an assessment monitoring program, including a series of 90-day time periods in which an owner or operator has to perform the required analysis and demonstrations. The 90-day time periods are based on similar requirements and time periods in the part 258 requirements. However, EPA seeks comment on whether 90 days is an appropriate time period for the assessment monitoring requirements for CCR in light of the WIIN Act or whether alternative time periods, e.g., 120 days or 150 days, are necessary to perform the required analysis and demonstrations for CCR and whether such alternative time periods would be more appropriate to facilitate implementation of the WIIN Act and any changes as a result of this rulemaking.

EPA is also proposing to adopt the part 258 provision that requires an alternative groundwater protection standard to be derived in a manner consistent with Agency guidelines. However, some of the guidelines cited in part 258 have since been replaced or supplemented. Therefore, EPA is proposing to replace the citations with the updated versions. Specifically, EPA is proposing to cite to the *Supplementary Guidance for Conducting Health Risk Assessment of Chemical Mixtures,*[27] which supplements 51 FR 34014 (September 24, 1986); the *Guidelines for Developmental Toxicity Risk Assessment,*[28] which amends 51 FR 34028 (September 24, 1986); and the *Guidelines for Carcinogen Risk Assessment,*[29] which amends 51 FR 33992 (September 24, 1986). In addition, EPA proposes to add the guidance on deriving a reference dose, *Reference Dose (RfD): Description and Use in Health Risk Assessments.*[30] These are the current guidance documents that are most relevant to the constituents of concern for the wastes at issue. EPA seeks comment on this proposal.

EPA is also proposing to adopt, without modification, the part 258 provision that requires the alternative standard to be based on scientifically valid studies conducted in accordance with the Toxic Substances Control Act Good Laboratory Practice Standards (40 CFR part 792) or the equivalent. EPA requests comment on this approach.

EPA is proposing to adopt, with modifications, the part 258 provisions specifying that the alternative standard is set at a level that is associated with an excess lifetime cancer risk within the 1×10^{-4} to 1×10^{-6} range for carcinogens and that is likely to be without appreciable risk of deleterious effects from daily exposures for systemic toxicants. For carcinogens, EPA is also proposing to require that States use a cancer slope factor to establish the alternate GWPS within the relevant risk range. For non-carcinogens, EPA is proposing to require that States use a reference dose to establish the alternative GWPS, with a hazard quotient (HQ) of 1 as the upper bound on risk. This is the same methodology used to establish the technical criteria in the existing CCR regulation. Reliance on his methodology is also reasonable in this regulation as it ensures that this provision (and any alternative GWPS under this provision) will meet the requisite statutory standards. Some examples of groundwater values consistent with these requirements (indeed all of the proposed requirements) are Action Levels promulgated under the Safe Drinking Water Act and the Regional Screening Levels for Chemical Contaminants at Superfund Sites.[31] EPA requests comment on this approach.

In addition, EPA is considering requiring that for systemic toxicants (i.e., for chemicals that cause effects other than of deleterious effects during a lifetime. This is largely the same as the current part 258 requirement; however cancer), the alternate level represents a concentration to which potential receptors (including sensitive subgroups) could be exposed to on a daily basis that is likely to be without appreciable risk, EPA seeks comment on whether it should revise the relevant target from ''human population'' to ''potential receptors.''

Although this proposed rulemaking sets a target risk based on a risk range of 1×10^{-4} to 1×10^{-6} for carcinogens and an HQ = 1 for non-carcinogens, States would not be precluded from setting more stringent standards. The existing regulation in 40 CFR 258.55(j) identifies three other site-specific factors that may indicate the need to establish a risk level for a particular contaminant that is more protective than these levels. These are: (1) The presence of multiple contaminants in the groundwater; (2) exposure threats to sensitive environmental receptors; and (3) other site-specific exposure or potential exposure to groundwater. These factors are equally relevant to CCR facilities, and so EPA is proposing to incorporate them without any modifications. EPA requests comment on this approach.

Because any alternate GWPS will be based on established risk levels, it is reasonable that a state may set a level above background so long that it is equal to or lower than this alternate threshold. Thus, any alternate GWPS that meets the requirements specified in this proposal would still protect potential receptors from the reasonable

[27] USEPA, ''Supplementary Guidance for Conducting Health Risk Assessment of Chemical Mixtures'', EPA/630/R–00/002, August 2000. This document can be accessed at *https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=20533.*

[28] USEPA, ''Guidelines for Developmental Toxicity Risk Assessment'', EPA/600/FR–91/001, December 1991. This document can be accessed at *https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=23162.*

[29] USEPA, ''Guidelines for Carcinogen Risk Assessment'', EPA/630/P–03/001F, March 2005. This document can be accessed at *https://www.epa.gov/risk/guidelines-carcinogen-risk-assessment.*

[30] This document can be accessed at *https://www.epa.gov/iris/reference-dose-rfd-description-and-use-health-risk-assessments.*

[31] This document can be accessed at *https://www.epa.gov/risk/regional-screening-levels-rsls.*

maximum exposures identified in the final risk assessment.

B. Modification to Corrective Action Remedy

Once corrective action is triggered, the current regulations at § 257.97 require the CCR unit owner or operator to select a remedy for corrective action. In addition, § 257.98 requires the CCR unit owner or operator to begin implementing that remedy within 90 days of remedy selection.

EPA is proposing to adopt a provision analogous to 40 CFR 258.57(e) for municipal solid waste landfills (MSWLF). This part 258 provision allows the Director of a state permitting authority in participating states to determine that remediation of a release of an Appendix II to part 258 constituent from a MSWLF unit is not necessary if the owner or operator can make certain demonstrations to the satisfaction of the Director. Specifically, § 258.57(e) specifies that the Director may determine that remediation is not necessary if the owner or operator demonstrates to the satisfaction of the Director of a participating State that:

(1) The groundwater is additionally contaminated by substances that have originated from a source other than a MSWLF unit and those substances are present in concentrations such that cleanup of the release from the MSWLF unit would provide no significant reduction in risk to actual or potential receptors; or

(2) The constituent is present in groundwater that:

a. Is not currently or reasonably expected to be a source of drinking water; and

b. Is not hydraulically connected with waters to which the hazardous constituents are migrating or are likely to migrate in a concentration that would exceed the groundwater protection standards; or

(3) Remediation of the release is technically infeasible; or

(4) Remediation would result in unacceptable cross-media impacts.

Part 258 also states that even if the Director of a participating state does determine that remediation of the release is not necessary, this shall not affect the authority of the State to require the owner or operator to undertake source control measures or other measures that may be necessary to eliminate or minimize further releases to the groundwater, to prevent exposure to the groundwater, or to remediate the groundwater to concentrations that are technically practicable and significantly reduce threats to human health or the environment. 40 CFR 258.57(f).

EPA is proposing to adopt this same provision into part 257 with one modification. EPA is proposing that a State Director may, on a site-specific basis, decide not to require cleanup of part 257 Appendix IV constituents released to groundwater from a CCR disposal unit where: (1) The groundwater is contaminated by multiple sources and cleanup of the CCR release would provide no significant reduction of risk; or (2) the contaminated groundwater is not a current or potential source of drinking water and is not hydraulically connected with waters to which the part 257 Appendix IV constituents are migrating or likely to migrate in a concentration(s) that would exceed the groundwater protection standards; or (3) remediation is not technically feasible; or (4) remediation would result in cross-media impacts. In part 258, an owner or operator is not required to undertake source control measures unless ordered by a State Director to do so. Although today's proposal includes § 257.97(g), which would make source control measures mandatory in a departure from part 258, EPA is considering making the source control measures for CCR units discretionary, similar to part 258, and seeks comment on this approach. For example, while the Director may determine that total remediation is not required, EPA seeks comment on whether source control measures (*e.g.,* covers and/or flow control measures or closure, if triggered by § 257.101(a)–(c)) to minimize or eliminate further releases could not be waived. In other words, EPA seeks comment on whether a State or EPA as the permitting authority in a nonparticipating state, or a facility directly implementing the requirements of this rule and subject to EPA oversight and public notice, should have discretion not to require or perform source control measures, including closure, in certain situations, *e.g.,* where there is no reasonable probability of adverse effect to human health or the environment. In addition, partial remediation of groundwater to concentrations that are technically feasible and that significantly reduce risks would also be required. EPA also seeks comment on this proposed approach. EPA describes each of these in further detail below. Under part 258, these provisions are discretionary. Depending on the comments EPA receives, EPA may modify the proposed requirements at § 257.97 to more closely reflect the source control measures contained in part 258. If EPA makes any such changes to § 257.97, it may also make conforming changes to § 257.101.

As noted, the Agency is proposing that participating states may waive the clean-up requirements where the groundwater is already contaminated by multiple sources and clean-up of the CCR release would provide no significant reduction of risk. In some cases, CCR units releasing part 257 Appendix IV constituents to the groundwater may be located in areas that already are significantly contaminated by other sources. Where releases from the CCR units are minor compared to the overall area-wide contamination, or where remedial measures aimed at the CCR unit would not significantly reduce risk, EPA believes that remediation of releases from the CCR unit would not be necessary or appropriate. Proposed § 257.97(f) is intended to address such situations.

Section 258.57(e)(1) applies only where sufficient evidence exists that the groundwater is contaminated by a source other than the CCR unit. In such cases, the owner or operator must demonstrate that cleanup of a release from its unit would provide no significant reduction in risk to receptors due to concentrations of constituents from the other source. EPA has previously characterized this provision as requiring facilities to make a robust demonstration that other sources are significant contributors to the contamination; this provision is not intended to provide facilities with a general opportunity to seek a waiver from the existing cleanup requirements under part 257.

The Agency is not proposing to define ''significant reductions'' in risk in this rulemaking, but consistent with the MSWLF rules, believes the decision is best made on a case-by-case basis by the State. The Agency understands and anticipates that states may have difficulties in defining ''significant reduction of risk'' but expects that States will be able to draw from their experience in implementing the analogous requirement in § 258.57(e)(1). Consistent with that provision, participating states should take a protective approach when evaluating requests for such a waiver. As one potential example, EPA considers that where the facility could document that the risks to potential receptors from non-CCR constituents would still exceed acceptable levels of concern (*i.e.,* risks greater than 1×10^{-4} to 1×10^{-6} for carcinogens, or an HQ greater than 1 for non-carcinogens) even if all CCR constituents had been removed, the facility could demonstrate there would be no significant reduction of risk from remediation of the CCR constituents. However, EPA solicits comment on whether there are additional criteria that

would be useful in further defining the proposed regulatory provision under § 257.97(f)(1), *e.g.,* criteria that states have used in implementing the analogous provision in part 258.

Under proposed § 257.97(f)(2), the State may also determine that a hazardous constituent that has been released from a CCR unit to groundwater does not pose a threat to human health and the environment and, therefore, does not require remediation if: (1) The groundwater is not a current or potential source of drinking water and (2) the groundwater is not hydraulically connected with waters that could be a current or potential source of drinking water or are not likely to migrate in a concentration(s) that would exceed the groundwater protection standards established under § 257.95(h). EPA generally interprets this to require a determination that the quality of the water in the aquifer is such that it could not reasonably be expected to be used as drinking water, even if treated to remove the contaminants. The provision does not allow a waiver on the grounds that the cost of treating the water to remove the contaminants is too high. EPA realizes that it is difficult to predict future improvements in treatment technologies, or to determine hydraulic connection. In interpreting whether the aquifer meets these regulatory criteria, States may use the approach outlined in the Agency's Ground-Water Protection Strategy (August 1984) as guidance.[32] As described in this guidance, typically Class III groundwaters will be considered to meet the requirements specified in § 257.97(f)(2). Class III groundwaters are groundwaters not considered potential sources of drinking water. They are groundwaters with high salinity, total dissolved solids levels over 10,000 mg/l, or are otherwise contaminated beyond levels that allow cleanup using methods reasonably employed in public water system treatment. These groundwaters also must not migrate to Class I or II groundwaters or have a discharge to surface water that could cause degradation. The need to remediate Class III groundwaters should be assessed on a case-by-case basis. Under the second criterion, the owner or operator must also demonstrate that the uppermost aquifer is not hydraulically connected with a lower aquifer. The owner or operator may nevertheless seek an exemption if it can be demonstrated that attenuation, advection/dispersion or other natural processes can remove the threat to interconnected aquifers. The owner or operator may also seek the latter exemption if the contaminated zone is not a current or potential drinking water source.

EPA is also proposing under § 257.97(f)(3) and (4) to allow the State to determine that remediation of a release is not required when remediation is not technically feasible or when remediation presents unacceptable cross-media impacts. Such a determination may be made, for example, in some cases where the nature of the hydrogeologic setting would prevent installation and operation of an effective groundwater pump and treat system (or other effective cleanup technology), *e.g.,* where the installation and operation of such a system could potentially increase environmental degradation by introducing the contaminant into groundwater that was not previously affected by the release. Additional examples of factors that may affect the efficacy of groundwater remediation can be found in EPA Guidance for Evaluating the Technical Impracticability of Ground-Water Restoration (OSWER Directive 9234.2–25, September 1993).[33] The Agency is specifically soliciting comment on the types of situations that might warrant a determination that remediation of a release is technically impracticable or presents unacceptable impacts and would not, therefore, be required.

A successful demonstration that remediation is not technically feasible must document specific facts that attribute to this demonstration. Technical infeasibilities may be related to the accessibility of the groundwater to treatment, as well as the treatability of the groundwater using existing treatment technologies. If the owner or operator can demonstrate that unacceptable cross-media impacts are uncontrollable under a given remedial option (e.g., movement in response to groundwater pumping) and that the no action option is a less risky alternative, then the Director of approved participating state may determine that remediation is not necessary.

As noted, EPA is generally relying on the factual record developed for the part 258 regulations to support this rule. However, the record for that rule does not contain information that would demonstrate that removing the existing regulatory requirement that all CCR units impose source control would meet the RCRA section 4004(a) protectiveness standard. These existing CCR requirements were established to address the well-documented risks associated with CCR units, as detailed in the risk assessment and the numerous damage cases in the rulemaking record.[34] The part 258 regulations apply only to landfills, while the CCR regulations apply to both landfills and surface impoundments, the latter being of particular concern. Surface impoundments by their very nature pose a potential for releases to groundwater that is different than landfills (e.g., presence of a hydraulic head) that may impact the importance of source control for these types of units. As discussed above, EPA requests comment on whether the proposal is appropriate, and whether the record for either the existing CCR rule or the part 258 rules includes information, or whether other information exists, to support adoption of the more flexible corrective action provision based on part 258 for CCR units, which could allow an owner or operator to undertake corrective action for unlined surface impoundments in lieu if closure. Depending on comments received, EPA may revise this provision to more closely reflect the existing source control and corrective actions requirements in part 258 that would allow source control, including closure, to be discretionary in certain situations.

C. Modification of Groundwater Monitoring Requirements

The current regulations at § 257.90 require all CCR units, without exception, to comply with the groundwater monitoring and corrective action requirements of §§ 257.90–257.98. The final CCR rule at § 257.91(a)(2) requires the installation of groundwater monitoring wells at the waste boundary of the CCR unit.

EPA is proposing to adopt a provision analogous to 40 CFR 258.50(b), which allows the Director of an approved participating state to suspend the groundwater monitoring requirements under § 258.51 through § 258.55 if the

[32] In addition to federal guidance, EPA is aware that States may currently use different or more sophisticated groundwater classification systems. In the preamble to the October 9, 1991 Final Rule promulgating the MSW landfill standards, on the matter of groundwater classification EPA noted that ''States are expected to use groundwater classification and resource evaluations in making their State decisions.'' 56 FR 50995.

[33] Additional documents related to technical impracticability may be found at *https://www.epa.gov/superfund/superfund-groundwater-groundwater-response-selection#TI_anchor.*

[34] For example, risk estimates for unlined surface impoundments were the highest of all CCR unit types evaluated (80 FR 21319, April 17, 2015) and EPA's documented record of confirmed damage cases was dominated by ''wet disposal'' (e.g., impoundments; 80 FR 21456, April 17, 2015).

owner or operator can demonstrate that there is no potential for migration of hazardous constituents from that MSWLF unit to the uppermost aquifer during the active life of the unit and the post-closure care period. Under part 258, the demonstration must be certified by a qualified groundwater scientist and approved by the Director of a participating state, and must be based upon:

(1) Site-specific field collected measurements, sampling, and analysis of physical, chemical, and biological processes affecting contaminant fate and transport, and

(2) Contaminant fate and transport predictions that maximize contaminant migration and consider impacts on human health and environment.

The Agency recognizes that certain hydrogeologic settings may preclude the migration of hazardous constituents from CCR disposal units to groundwater resources. Requiring groundwater monitoring in these settings would provide little or no additional protection to human health and the environment. Therefore, EPA is proposing to incorporate a nearly identical provision into the part 257 regulations. This would allow the Director of a participating state to suspend the groundwater monitoring requirements in § 257.91 through § 257.95 for a CCR unit upon demonstration by the owner or operator that there is no potential for migration of hazardous constituents from the unit to the uppermost aquifer during the active life, closure, or post-closure periods. However, the requirements of § 257.96 through § 257.98 would not be suspended. As discussed below, the provision being proposed for the part 257 regulations would be identical to that in the part 258 regulations with the exception for the requirement to periodically demonstrate that conditions have not changed, that is, there is still no migration of Appendix III or IV constituents from the CCR unit to the uppermost aquifer.

EPA recognizes it may be difficult for many facilities to meet the ''no potential for migration'' standard in the regulations. The suspension of monitoring requirements is intended only for those CCR units that are located in hydrogeologic settings in which hazardous constituents will not migrate to groundwater during the active life of the unit, closure, and post-closure periods. The Agency reminds readers that the ''no migration'' waiver has been a component of both the part 258 and the RCRA subtitle C groundwater monitoring programs for many years, and; based on its experience under these programs, the Agency expects that cases where these criteria are met will be rare.

The part 258 requirements allow the Director of a state program to establish the relevant point of compliance; in an unapproved state, the point of compliance is set by regulation at the waste management unit boundary. EPA does not believe the record for the part 258 requirements would support an alternative means for establishing the relevant point of compliance for CCR groundwater monitoring wells under RCRA section 4004(a). EPA requests comment on whether a State Director or EPA in a nonparticipating state, or an owner/operator subject to EPA oversight and public notice, could establish an alternative point of compliance consistent with the flexibility already allowed under the part 258 rules that would satisfy the standard of no reasonable probability of adverse effect on human health or the environment under section 4004(a).

In this action, EPA is not proposing to provide waivers from groundwater monitoring requirements except where the owner or operator in a participating state can demonstrate no potential for migration of hazardous constituents to the uppermost aquifer during the active life of the unit, closure, or post-closure periods. Consistent with the part 258 regulation, the Agency is proposing to allow this waiver only under the following conditions. EPA seeks comment on the use of each of these conditions. First, the suspension of groundwater monitoring requirements in § 257.91 through § 257.95 is available only for owners and operators of CCR units located in participating states or in those instances where EPA is the permitting authority. The Agency has limited the availability of the waiver because the Agency recognizes the need for the State to review a no-migration demonstration prior to granting a waiver from groundwater monitoring. However, the Agency seeks comment on an approach where a technical expert could make this demonstration (under the criteria described in the following paragraphs) and the facility could implement without the intervention of a permitting authority. In such an approach, the facility would keep records and post its determination on its web site and EPA would use the authorities in the WIIN act to oversee such a determination.

Second, the rule requires demonstrations of no potential for migration to be supported by both predictions that maximize contaminant migration and actual field data collected at the site. Field testing is necessary to establish the site's hydrogeological characteristics and must include an evaluation of unsaturated and saturated zone characteristics to ascertain the flow rate and pathway by which contaminants will migrate to groundwater. Any demonstration must be based on site-specific field measurements and sampling and analyses to determine the physical, chemical, and biological processes affecting the fate and transport of hazardous constituents. Site-specific information must include, at a minimum, the information necessary to evaluate or interpret the effects of the following properties or processes on contaminant fate and transport:

(1) Aquifer Characteristics, including hydraulic conductivity, hydraulic gradient, effective porosity, aquifer thickness, degree of saturation, stratigraphy, degree of fracturing and secondary porosity of soils and bedrock, aquifer heterogeneity, groundwater discharge, and groundwater recharge areas;

(2) Waste Characteristics, including quantity, type, and origin;

(3) Climatic Conditions, including annual precipitation, leachate generation estimates, and effects on leachate quality;

(4) Leachate Characteristics, including leachate composition, solubility, density, the presence of immiscible constituents, Eh, and pH;

(5) Engineered Controls, including liners, cover systems, and aquifer controls (e.g., lowering the water table). These should be evaluated under design and failure conditions to estimate their long-term residual performance.

(6) Attenuation of contaminants in the subsurface, including adsorption/desorption reactions, ion exchange organic content of soil, soil water pH, and consideration of possible reactions causing chemical transformation or chelation.

(7) Microbiological Degradation, which may attenuate target compounds or cause transformations of compounds, potentially forming more toxic chemical species.

Modeling may also be useful for assessing and verifying the potential for migration of hazardous constituents. However, any models used should be based on actual field collected data to adequately predict potential groundwater contamination. When owners or operators prepare a no migration demonstration, they must use transport predictions that are based on the maximum contaminant migration (i.e., worst case scenario) both from the unit and through the subsurface media. Assumptions about variables affecting transport should be biased toward over

estimating transport and the anticipated concentrations. Assumptions and site-specific data that are used in the fate and transport predictions should conform with transport principles and processes, including adherence to mass-balance and chemical equilibria limitations. Within these physicochemical limitations assumptions should be biased toward the objective of assessing the maximum potential impact on human health and the environment.

Third, the proposed rule would require the demonstrations to be certified by a qualified professional engineer and approved by the Director of a participating state to ensure that there is a high degree of confidence that no contamination will reach the uppermost aquifer.

Finally, the proposed rule would require the owner or operator of the CCR unit to make periodic demonstrations every 10 years in order to retain the suspension of groundwater monitoring. The Agency received comments on suspending the groundwater monitoring requirements for MSWLFs in part 258 that suggested EPA require periodic demonstrations every five or ten years. See, 56 FR 51061 (October 9, 1991). The Agency decided against requiring periodic demonstrations for MSWLFs because the demonstration required must be extremely rigorous and because of the additional costs associated with the continual reapplication for the suspension. As mentioned earlier in this proposed rulemaking, the statutory standard for the part 258 regulations is different than the standard for the CCR regulations: The CCR regulations are based on RCRA section 4004(a), which requires that the regulations ensure ''there is no reasonable probability of adverse effects on health or the environment from disposal of solid waste at such facility.'' 42 U.S.C. 6944(a). This is a risk-only standard. By contrast, EPA was authorized to ''take into account the [facility's] practicable capability'' in developing the part 258 regulations. 42 U.S.C. 6949a(c). Also, the part 258 regulations apply only to landfills, while the CCR regulations apply to both landfills and surface impoundments, the latter being of particular concern. Surface impoundments by their very nature pose a potential for releases to groundwater that is different than landfills (*e.g.,* presence of a hydraulic head) that may impact the importance of source control for these types of units. The risk assessment for the CCR rule found that, even when key variables are controlled (*e.g.,* liner type, waste type) for the long-term risks from surface impoundments are greater than from landfills. This is because the high and sustained hydraulic head present in these surface impoundments drives leachate into the groundwater table at an accelerated rate. Based on these factors, EPA is proposing to require an owner or operator to conduct a new demonstration once every 10 years to show that the suspension of groundwater monitoring continues to be appropriate. See proposed § 257.90(g). This new demonstration should be submitted to the State Director one year before the existing groundwater monitoring suspension is due to expire. If the suspension expires for any reason, the unit must begin groundwater monitoring according to § 257.90(a) within 90 days.

Further guidance for conducting these evaluations can be found in the OSWER Solid Waste Disposal Facility Criteria Technical Manual for MSWLFs (EPA530–R–93–017, 1993) and the Ground-Water Monitoring Guidance Document for Owners and Operators of Interim Status Facilities (1983).

D. Alternate Period of Time To Demonstrate Compliance With Corrective Action

The current regulations at § 257.98(c)(2) require that facilities demonstrate that compliance with the groundwater protection standards (GWPS) established under § 257.95(h) have been achieved by monitoring results documenting that concentrations of constituents listed in Appendix IV to part 257 have not exceeded the groundwater protection standard(s) for a period of three consecutive years using the statistical procedures and performance standards in § 257.93(f) and (g). EPA is proposing to modify this by adopting a provision analogous to 40 CFR 258(e)(2). Both the part 258 regulation and the proposed § 257.98(c)(4) counterpart allow the Director of a participating state to specify an alternative length of time during which the owner or operator must demonstrate that concentrations of Appendix II to part 258 constituents (or in the case of the proposed part 257 counterpart, Appendix IV to part 257 constituents) have not exceeded the groundwater protection standard(s). Under the current part 258 regulations, the State must make this determination after taking into consideration: (1) The extent and concentration of the release(s); (2) behavior characteristics of the hazardous constituents in the groundwater; (3) accuracy of monitoring or modeling techniques, including any seasonal, meteorological, or other environmental variabilities that may affect the accuracy; and (4) characteristics of the groundwater.

When establishing an alternative compliance period, the proposed regulation would require a State to consider the following site-specific conditions under § 257.98(c)(4): (1) The extent and the concentration of the release; (2) the behavior characteristics (fate and transport) of the part 257 Appendix IV constituents in the groundwater (e.g., mobility, persistence, toxicity); (3) the accuracy of monitoring or modeling techniques, including any seasonal, geotechnical/geophysical, meteorological, or other environmental variabilities that may affect the accuracy; and (4) the characteristics of the groundwater (e.g., flow rate, pH). These are the same factors included in part 258; consideration of these factors will allow the State to set an appropriate time period for demonstrating compliance with the groundwater protection standards rather than relying on an arbitrary time period for all facilities or all situations at the same facility. In large part, EPA is relying on the longstanding experience with these criteria under part 258 for municipal solid waste landfills.

In summary, § 257.98(c)(2) and (4) of this proposal requires that the groundwater protection standard be achieved for a period of three consecutive years at all points within the plume of contamination unless an alternative period of time is established by a participating state. Those states may set an alternative period of compliance after taking site-specific conditions into consideration. In demonstrating compliance with the groundwater protection standard, the owner or operator would be required to use the statistical procedures in § 257.93.

E. Length of Post-Closure Care Period

The current regulations at § 257.104(c)(1) state that the owner or operator of a closed CCR unit must conduct post-closure care for 30 years unless at the end of the 30 years corrective action is on-going, or the CCR unit is operating under assessment monitoring, in which case the owner or operator must continue to conduct post-closure care until the unit has returned to detection monitoring.

EPA is proposing to adopt a provision analogous to 40 CFR 258.61(b), which allows the Director of a participating state to decrease the length of the post-closure care period if the owner or operator demonstrates that the reduced period is sufficient to protect human health and the environment and this demonstration is approved by the

Director of approved participating state. It also allows the Director of the participating state to increase the length of the post closure period if the Director determines a lengthened period is necessary to protect human health and the environment.

The Agency is proposing this provision to account for situations where a 30-year post-closure care period may be inappropriate based on site-specific conditions. Overall, providing for variances in the post-closure care period in these states allows the flexibility to accommodate differences in geology, climate, topography, resources, demographics, etc. In all cases, however, these decisions must be reviewed carefully by the State to ensure units are monitored and maintained for as long as is necessary to protect human health and the environment.

In determining whether a revised post-closure care period is warranted, one critical factor is ensuring that the cover will continue to function effectively. EPA recognizes that no final cover, however well-constructed, will last forever. In 1988, EPA stated that ''even the best liner and leachate collection system will ultimately fail due to natural deterioration . . . .'' [35] Although any impermeable barriers used in a final cover system will eventually fail, studies have shown that such natural deterioration can take thousands of years (Needham et al., 2006; Rowe & Islam, 2009).[36] [37] This is consistent with the concept of bathtub (or U shaped) failure rate in reliability analysis (Shehla & Khan, 2016).[38] This failure pattern begins with a wear-in period where failure rates are high due to design and manufacturing problems. The failure rate then decreases to a low, constant rate for a period of time before rising in the third, wear-out phase.

Though this wear-out phase may take thousands of years, the wear-in phase for waste management unit covers is much shorter. In the context of CCR units, the wear-in phase of a closed unit would be due to imperfections in covers, either from a manufacturing defect or faulty installation. Manufacturing defects may include items such as pin holes, whereas faulty installation may be the result of a tear or failure to properly seal joints (Bonaparte et al, 1989).[39]

Settlement resulting from factors, such as the gradual dissolution of more soluble components within the ash mixture, is also a potential issue. Depressions caused by settlement may lead to ponding and should be filled with soil. Excessive settlement may warrant reconstructing or adding to portions of the infiltration layer. Settlement can also damage the cover through tension cracks and tears in the synthetic membrane. For example, topographic surveys of the unit(s) may be used every few years until settlement behavior is established, to determine whether settlement has occurred.

Consequently, EPA is proposing to require that part of determining whether a shorter post-closure care period will protect human health and the environment, a state must ensure that the post-closure care period is long enough to detect such issues. This would require the state to consider not only the type of cover placed on the unit (*e.g.,* compacted soil), but also the placement of the groundwater monitoring wells with respect to the waste management unit. For instance, where a waste management unit is close to the groundwater table and the groundwater monitoring wells are located at the unit boundary, one would generally expect transit time of any contamination to be short, and thus a shorter post-closure monitoring period might be sufficient to catch wear-in defects in the cover system. However, where the unit is located further from the groundwater table, constituents may not have sufficient time to reach the monitoring wells under such a curtailed post-closure period.

In addition, under the current CCR regulations, once detection monitoring yields a statistically significant increase above background levels of any Appendix III constituent, assessment monitoring is triggered, and the unit continues to be subject to the rule's post-closure care requirements so long as the CCR unit is operating under assessment monitoring. Section 257.104(c)(2). EPA is not proposing to amend this requirement, or to allow States to do so as part of this new provision. Thus, the State could not allow a facility to end the post-closure care period, once the detection of contamination above background triggers assessment monitoring. This would hold, even if the State had previously authorized a shorter post-closure care period. EPA is proposing to include language in this provision that clarifies how these two requirements interact.

F. Allowing Directors of Participating States To Issue Certifications in Lieu of Requiring a PE Certification

To ensure that the RCRA subtitle D requirements would achieve the statutory standard of ''no reasonable probability of adverse effects on health and the environment'' in the absence of regulatory oversight, the current CCR regulations require facilities to obtain third party certifications and to provide enhanced state and public notifications of actions taken to comply with the regulatory requirements. Specifically, in the final CCR rule EPA required numerous technical demonstrations made by the owner or operator be certified by a qualified professional engineer (PE) in order to provide verification of the facility's technical judgments and to otherwise ensure that the provisions of the rule were properly applied. While EPA acknowledged that relying upon a third party certification was not the same as relying upon a state or federal regulatory authority and was not expected to provide the same level of independence as a state permit program, the availability of meaningful third party verification provided critical support that the rule would achieve the statutory standard, as it would provide a degree of control over a facility's discretion in implementing the rule. However, the situation has changed with the passage of the WIIN Act, which offers the opportunity for State oversight under an approved permit program. To reflect that, EPA is proposing to revise the regulations to allow the Director of a state with an approved CCR permit program (a participating state) to certify that the regulatory criteria have been met in lieu of the exclusive reliance on a qualified PE. EPA expects that States will generally rely on the expertise of its own engineers to evaluate whether the technical criteria have been met. Alternatively, States might choose to retain the required certification by a qualified PE and use its own expertise to evaluate that certification. Finally, EPA notes that under the existing regulations, a facility may already rely on a certification provided by a qualified PE in a State agency, who reviews the facility actions as part of a purely State-law mandated process. Thus, EPA is confident that the

[35] US EPA, ''Solid Waste Disposal Facility Criteria; Proposed Rule,'' 53 FR 33345 (August 30, 1988).

[36] Needham, A.D., Smith, J.W.N., Gallagher, E.M.G. 2006. *The service life of polyethylene geomembrane barriers. Engineering Geology* 85. 82–90.

[37] Rowe, R.K., Islam, M.Z. 2009. *Impact of landfill liner time-temperature history on the service life of HDPE geomembranes. Waste Management* 29. 2689–2699.

[38] Shehla, R., & Khan, A.A. (2016). Reliability analysis using an exponential power model with bathtub-shaped failure rate function: a Bayes study. *SpringerPlus, 5*(1), 1076. *http://doi.org/10.1186/s40064-016-2722-3.*

[39] Bonaparte, R., J.P. Giroud, and B.A. Gross. 1989. Rates of leakage through landfill liners. *Geosynthetics 1989 Conference.* San Diego, CA.

additional layer of oversight provided by the State under this proposal will be at least as protective than the status quo under the existing regulations.

G. Revision To Allow the Use of CCR During Certain Closure Situations

EPA is proposing to revise the current regulations to allow the use of CCR in the construction of final cover systems for CCR units closing pursuant to § 257.101 that are closing with waste-in-place. EPA is also proposing specific criteria that the final cover system must meet in order to allow for the placement of CCR in the final cover system. EPA is proposing two performance standards: One that applies directly to facilities in any ''non-participating state'' and a second that applies to facilities that operate in states with an approved CCR permit program (''participating'' state). Specifically, EPA is proposing to allow for the continued placement of CCR in units triggered for closure to construct a cover system under the following conditions: (1) Only CCR generated on-site may be used in the construction of the cover system; (2) CCR may be used exclusively for the purposes of grading and contouring of the cover system; (3) CCR must be placed within the vertical plane of the boundary of the unit; and (4) must be at either no steeper than a 5 percent grade or at a steeper grade, as determined by the Director of an approved program based on a stability analysis. These criteria are intended to ensure that the CCR utilized in construction of the final cover system does not exceed the necessary amount for grading and contouring.

The current CCR rules require that certain units must close for cause, as laid forth in § 257.101(a)–(c). As written, the regulation expressly prohibits ''placing CCR'' in any units required to close for-cause pursuant to § 257.101. This includes unlined CCR surface impoundments whose groundwater monitoring shows an exceedance of a groundwater protection standard (§ 257.101(a)(1)); existing CCR units that do not comply with the location criteria (§ 257.101(b)(1)); and CCR surface impoundments that are not designed and operated to achieve minimum safety factors (§ 257.101(b)(2) and (c)(1)). Note that the rule does not distinguish between placement that might be considered beneficial use and placement that might be considered disposal. All further placement of CCR into the unit is prohibited once the provisions of § 257.101 are triggered. By contrast, the regulations do not restrict further placement or use of CCR when the unit is closing under other provisions.

Proposal for Closure With CCR

After publication of the final rule, EPA received numerous requests that EPA clarify whether use of CCR in completing the closure of a unit was permitted under the regulation, either as part of a closure plan or under the theory that such an activity was ''beneficial use.'' After evaluating the issue, EPA is proposing an exemption that would allow further placement of CCR in a CCR unit closing pursuant to § 257.101 for the purposes of construction of the final cover system. EPA is not proposing any other revisions to the existing closure requirements; therefore, owners and operators who choose to place CCR as part of the final cover system as part of closure ''for cause'' will still need to comply with all of the existing closure requirements in §§ 257.101–104.

EPA is proposing this revision because there are environmental and health benefits in allowing use of CCR in this fashion, and as discussed below in more detail, provided the conditions outlined in this rule are met, the existing information demonstrate that the use of CCR in this fashion would not measurably affect the risks from the unit. Allowing the use of on-site CCR in lieu of other material to construct the cover furthers the general goal in § 257.102(d)(1)(v) of closing as quickly as possible. As EPA identified in the final rule, the process for procuring at-specification earthen material in the volumes necessary for the final cover system construction can complicate completion of closure requirements within the required time frames. This was explicitly described as a factor that could support an extension of the closure deadlines under § 257.102(f)(2)(i)(C). Thus, this proposed revision is expected to allow facilities to complete closure more quickly, and accordingly realize reduced risks more quickly.

This proposal is a narrow modification of the § 257.101 prohibition on CCR placement, and contains four requirements to ensure that the use of CCR is to accelerate closure rather than merely allow the facility continue the disposal of CCR in a deficient unit. First, the material placed under this exemption must have been generated on-site and be present at the time of closure. Second, the material may only be used for the grading and contouring of the cover system, not to fill up a partially full unit. Third, the placement of the material must be within the boundary or the vertical plane of the boundary of the waste management unit. Finally, the material may only be used to construct a cover at either no steeper than a 5 percent grade or at a steeper grade, as determined by the Director of an approved program (or EPA where it is the permitting authority). Each of these requirements is discussed further below.

On-site materials. EPA is proposing that all CCR material utilized for construction of the final cover system must have been generated by the facility, *i.e.,* by the coal-fired boilers that generated electricity at the facility and associated air pollution control devices, and that the CCR be located at the facility since the time of generation. CCR sourced exclusively from on-site will allow for timely construction of the final cover system. Moreover, EPA does not intend this proposed rule to allow owners and operators to continue disposal into a waste management unit that is closing for cause pursuant to § 257.101. Limiting the source of material will help to ensure that. Rather, the exemption is meant to allow for the genuine use of available materials for the closure of a waste management unit.

For grading and contouring. EPA is also proposing to limit the exemption to the design and construction of the final cover system. As noted previously, § 257.102(d)(2) requires that dewatering and stabilization be achieved prior to installation of a cover, and § 257.102(d)(3) requires that several protective layers be constructed at the uppermost areas of the final cover system. As a practical matter, these two existing provisions (which EPA is not proposing to modify or take comment on) would effectively limit the placement of CCR to grading and contouring. Nevertheless, to avoid confusion, EPA is proposing to include a specific condition to make this explicit. For the purposes of this rule, EPA considers grading and contouring as activities specifically related to creating elevation differences and travel pathways to encourage free drainage of liquids out of and away from the CCR surface impoundment. Accordingly, EPA is proposing to define grading to mean placement of CCR for the sole purpose of creating differences in elevation to support positive stormwater drainage. EPA is also proposing to define contouring to mean placement of material to provide a continuous downward slope on the surface of a drainage area (*i.e.,* the final cover system), except for erosion control features (*e.g.,* swales, contour banks).

This proposal would not allow placement of CCR for the purposes of waste stabilization or to otherwise fill

the unit to capacity. Placement of CCR for these purposes would involve the placement of substantial volumes of CCR into a leaking or otherwise deficient unit, and EPA lacks information that such further placement would be protective. To achieve this, EPA is proposing different criteria based on the construction of the unit. Many surface impoundments consist of an incised portion, or portion which is excavated below the surrounding grade. Incised units are units that hold an accumulation of CCR entirely below the adjacent natural ground surface, and do not consist of any constructed diked portion. For incised CCR surface impoundments, EPA is proposing that any CCR utilized for the final cover system must be placed above the highest elevation of the surrounding natural ground surface where the CCR unit was constructed.

EPA intends for this requirement to account for the preexisting topography in the area where the incised CCR unit was constructed. The owner or operator would be responsible for determining the preexisting topography of the CCR unit through means of historical documentation or by identifying the highest point of the perimeter of the excavated portion of the unit.

A primary purpose of a final cover system is to encourage free surface drainage in order to limit infiltration from precipitation into the underlying waste. CCR units with incised portions can present an issue with free drainage of liquids because much of the unit is located below the surrounding grade and does not allow for drainage by gravity, *i.e.,* the drainage must occur mechanically, by evapotranspiration, or by infiltration. Placement of CCR below the highest elevation of the surrounding topography would no longer serve the purpose of encouraging drainage, and therefore would not be considered part of constructing the final cover system.

For all other units, including CCR surface impoundments that consist of a diked portion, *e.g.,* diked impoundments, cross-valley impoundments, side-hill impoundments, or some combination thereof, EPA is proposing to require the owner or operator to establish a baseline elevation above which all CCR would need to be placed when constructing the final cover system. EPA is proposing that this baseline elevation be defined as the highest elevation of CCR in the unit, following dewatering and stabilization as required by § 257.102(d)(2).[40] From that point forward, CCR material may only be placed above that elevation for grading and contouring.

These requirements are designed to establish clear and objective geometric boundaries for the permissible placement of CCR. With these two performance standards, EPA is effectively establishing a ''lowest bound'' plane; placement below that elevation would be considered to be disposal, and would still be prohibited. EPA is also proposing to establish an upper bound to ensure that only the amount of CCR necessary for grading and contouring is used. The ''upper bound'' is represented by the maximum final grade of the final cover system of 1:20, *i.e.,* 5 percent (discussed further below). Furthermore, the ''vertical plane'' criteria discussed later in this preamble would also establish ''horizontal bounds'' for placement of CCR material in the cover system. In order to fulfill the ''free drainage'' criteria set forth in § 257.102(d)(1)(ii), the geometry of the waste in the unit must allow for free drainage of all water, sediment, and slurry from any point within the CCR surface impoundment out of the breached portion of the embankment.

Collectively, these criteria are designed to ensure owners and operators place only the amount of CCR necessary to achieve adequate grading and contouring for free drainage.

For example, this proposal would not allow the owner or operator to raise the breached invert elevation and place CCR material above the previously placed ''waste-in-place'' CCR and effectively raise the invert elevation for drainage. EPA intends for the final level of CCR within the CCR unit to essentially be the ultimate height of the surface of the final cover system, with allowance for limited addition of material to ensure effective drainage from the unit. EPA does not intend for this proposal to allow the facility to unnecessarily raise the invert elevation of the breached portion of the embankment, as a means of further disposal of CCR in the interim space between initial invert and adjusted invert elevations.

Within the vertical plane. EPA is proposing that CCR used for construction of the final cover system may not be placed outside the vertical plane. The vertical plane for non-incised units is established as the line which extends from the intersection between the crest of the CCR within the surface impoundment and the berm or dike of the CCR surface impoundment. For incised CCR surface impoundments, the vertical plane is established as the line that extends at the intersection where the cap of the CCR surface impoundment with a slope of no steeper than 5 percent meets the natural topography of the land prior the construction of the CCR unit. Placement beyond this boundary would constitute a lateral expansion as defined in § 257.53.[41] EPA is proposing this requirement in order to prevent the potential release of CCR constituents outside of the waste boundary without the protections EPA deliberately included in the final rule for such lateral expansions.

At no steeper than a 5 percent grade. EPA is proposing that the final cover system using CCR for grading and contouring be constructed with slopes no steeper than 1:20. This ratio of vertical rise to horizontal rise is equal to a 5 percent grade. EPA has identified 5 percent to generally be the maximum necessary grade to promote positive drainage in a vegetated slope runoff, as steeper grades may lead to erosion and deterioration of the final cover system.[42] EPA is proposing a maximum grade for the final cover system to minimize the potential for abuse whereby a facility might unnecessarily grade a cover steeply in order to dispose of additional CCR. EPA intends the grade of the final cover system to allow for free drainage to the invert elevation of the breached portion of the embankment.

However, in rare instances it may be possible that a cover requires a steeper grade. Consequently, EPA is proposing that the Director of a participating state may approve a grade steeper than 5 percent in a permit if such a grade is necessary for the proper function of the cover system. To support a steeper grade, a stability analysis must be performed to evaluate possible erosion potential. A stability analysis looks at the ability of soil to resist sliding on itself on the slope. The analysis, at a minimum, must evaluate: (1) The site geology, (2) characterize soil shear strength, (3) construct a slope stability model, (4) establish groundwater and seepage conditions, if any, (5) select loading conditions, (6) locate critical

[40] As noted, under the existing regulations the owner or operator must first breach and dewater the CCR unit, allowing for free drainage of water, sediment, or slurry out of the CCR surface impoundment via surface runoff, prior to construction of the final cover system. Additionally, if the owner or operator intends to leave waste-in-place, the owner or operator must ''preclude the probability of future impoundment of water, sediment, or slurry,'' per the requirements of § 257.102(d)(1)(ii).

[41] *Lateral expansion* means a horizontal expansion of the waste boundaries of an existing CCR landfill or existing CCR surface impoundment made after October 19, 2015.

[42] USEPA, Solid Waste Disposal Facility Criteria-Technical Manual, EPA Document EPA530–R–93–017.

failure surface, and (7) iterate until minimum factor of safety is achieved.

Finally, EPA recently issued an interpretation that under the current regulations, the prohibition on the placement a unit closing for cause did not preclude the movement of additional wastes (stormwater and associated/accompanying CCR) between the units that operate as part of a multiunit treatment system. The current regulations allow the facility to treat such units as a single unit. See, *e.g.,* § 257.91(d)(1). Based the longstanding interpretation that EPA does not regulate the movement of wastes within a unit, EPA concluded that where the impoundments are being treated as a singular system, the movement of CCR within that system (*i.e.,* from one impoundment to another) would not be considered ''placing CCR'' under the prohibitions of § 257.101. Under this same logic, a facility could conceivably consolidate the CCR from other units in the system into a single unit, even though the unit was deficient. There can be benefits to such a practice; for example, it may facilitate clean closure and allow owners and operators to focus their long term monitoring, care, and cleanup obligations on a single unit rather than many units. And presuming the unit meets all of the performance standards for closure with waste in place, it may be the risks associated with such consolidation are acceptable. However, there are also potentially significant risks associated with the continued placement of large volumes of CCR in a deficient unit. As discussed in the next section, although EPA has preliminarily concluded that the use of CCR in the construction of the cover system will meet the RCRA section 4004(a) standard, there were limitations in the assessment that raise questions about further extrapolation of that assessment to support the placement of large volumes of CCR in these units (*e.g.,* EPA's risk assessment did not model the addition of CCR to partially-filled leaking units). Thus an interpretation that allowed consolidation of CCR into a single unit of a multi-unit system could be seen as inconsistent with the approach outlined in this proposal.

EPA has not determined whether allowing such a practice meets the statutory standard, and is therefore soliciting comment on two potential alternatives. Under one approach EPA would rely on its longstanding interpretation to allow the consolidation of CCR from units operating within a multi-unit system, when the facility treats the system as a single unit for purposes of closure (*i.e.,* all units within the system are closing). Alternatively, EPA would revise the regulations to explicitly clarify that only the use of CCR for purposes of grading and contouring is permitted, even between units within a multi-unit system closing for cause. Note that under either approach, EPA does not intend to revise its interpretation that the movement of stormwater (and associated CCR) between units within a multi-unit system that is closing for cause is permissible. EPA is concerned about the potential risks associated with the continued placement of large volumes of CCR, and similar concerns are not raised by the movement of stormwater and de minimis amounts of CCR between units in the process of clean closing.

Analytic Support of Risk Assessment Results

U.S. EPA (2009) [43] used a response-surface regression method to derive a statistical model for groundwater concentration (as the dependent variable) based on the input parameters from the probabilistic analysis (as independent variables). Concentration, rather than risk, was chosen as the dependent variable for the sensitivity analysis because the additional exposure factors used to calculate human health risk from environmental concentration (*e.g.,* body weight) have well established, peer-reviewed distributions based on EPA policy. The outputs of the sensitivity analysis were goodness-of-fit values used to determine the relative importance of each input parameter. The most sensitive parameters identified are presented in Table 1.

TABLE 1—SENSITIVE PARAMETERS

Pathway:	GW to DW pathway		GW to SW pathway
Constituents:	All constituents	Strongly sorbing	All constituents
Sensitive Parameters	• Infiltration rate • Leachate concentration • Hydraulic gradient • Hydraulic conductivity.	• K_d value • Depth to groundwater • Distance to receptor well	• Infiltration rate. • Leachate concentration. • Water body flow rate.

Note: GW = Groundwater; DW = Drinking Water; SW = Surface Water.

As seen in the table above, the groundwater to drinking water exposure pathway had more input parameters that were highly sensitive (seven) than the groundwater to surface water exposure pathways (three). The most sensitive parameters for the groundwater to drinking water pathways were parameters that impact flux (infiltration rate and leachate concentration) and groundwater flow (hydraulic conductivity and gradient). When modeling strongly sorbing constituents, the K_d values and distance to receptor also become important. The most sensitive parameters for the groundwater to surface water exposure pathways were parameters impacting flux (infiltration rate to groundwater and leachate concentration) and the water body flow rate.

Depth to groundwater was a sensitive parameter for strongly sorbing constituents. However, the sensitivity analysis did not find total waste depth (*i.e.,* total thickness of CCRs disposed in a unit filled to capacity) to be a sensitive parameter for closed landfills and surface impoundments. However, EPA sought to verify this through further analysis of the final risk assessment results (U.S. EPA, 2014).[44]

The risks EPA sought to further evaluate were those from surface impoundments closed for cause with waste in place. In Appendix K of the final risk assessment, EPA modeled dewatered surface impoundments post-closure with waste in place as

[43] U.S. EPA (Environmental Protection Agency). 2009. Sensitivity Analysis for the Coal Combustion Waste Risk Assessment. Draft Technical Report. Prepared by RTI International for U.S. EPA, Office of Solid Waste, Washington, DC.

[44] U.S. EPA. 2014. Human Health and Ecological Risk Assessment of Coal Combustion Residuals. Final. Office of Resource Conservation and Recovery. December. RIN: 2050–AE81.

equivalent to closed landfills. Because the results driving EPA's final rule were those for trivalent arsenic [As(III)] cancer risks, EPA selected As(III) cancer risk results from landfills as the appropriate results on which to conduct this sensitivity analysis.

EPA used the probabilistic model inputs for waste depth to calculate 25th, 50th, and 75th percentile waste depths. These cutoffs were used to filter the model runs into four quartiles. For each quartile EPA calculated a 90th percentile As(III) cancer risk. Below are the As(III) cancer risk results EPA obtained when filtering the landfill risk results for the depth of the waste. As waste depth changed, EPA did not see significant changes in risk for any liner type. This confirms the findings of the sensitivity analysis where depth was not shown to be a sensitive parameter.

TABLE 2—90TH PERCENTILE AS(III) CANCER RISKS ACROSS WASTE DEPTH QUARTILE

	1st Quartile	2nd Quartile	3rd Quartile	4th Quartile
Liner Type:				
Unlined	1.50E–05	1.28E–05	2.66E–05	1.79E–05
Clay Lined	1.28E–05	1.11E–05	1.32E–05	1.93E–05
Composite	1.39E–20	5.34E–29	3.84E–27	<1.00E–30

EPA also notes that the volume of infiltration from precipitation relative to the volume of waste present in a unit is very small. This would lead to a low liquid-to-solid (L/S) ratio for water passing through landfills and dewatered surface impoundments. The low L/S ratio ensures that the leachate is saturated with constituent mass before it exits the bottom of the landfill or surface impoundment. Because the leachate is in equilibrium with the waste, the addition of more mass would not further increase leachate concentrations. Instead, the increased total mass would affect the time necessary for constituent mass to fully deplete from the waste. A majority of the model runs for arsenic already reached a steady state concentration at the well within the modeled timeframe. Therefore, an increase in leaching duration would not substantially alter long-term risks.

The addition of larger volumes of ash for purposes other than expediting closure would result in a greater amount of time without a cap and other appropriate controls in place. This would result in greater opportunity for precipitation to infiltrate into the unit prior to closure. The additional volume of water would increase the hydraulic head within the unit and, ultimately, the rate of infiltration down to the groundwater table. EPA identified infiltration to groundwater as one of the most sensitive variables when modeling risks. Thus, EPA concludes that the addition of ash for purposes other than expediting closure has the potential to increase the transport of constituent mass to groundwater and the associated risks.

Under this proposal, utilities could add ash to construct the cover system for closure of a unit for the purpose of achieving the necessary grade to safely close with waste in place. A review of both the 2009 sensitivity analysis and the final risk assessment found that the comparatively minor addition of CCR mass applied solely for grading purposes would not alter potential risks to receptors. Therefore, EPA finds that the use of ash for grading would remain protective of human health and the environment.

V. The Projected Economic Impacts of This Action

A. Introduction

EPA estimated the costs and benefits of this action in a Regulatory Impact Analysis (RIA) which is available in the docket for this action. The RIA estimates costs and cost savings attributable to the provisions of this action against the baseline costs and cost savings of the 2015 CCR final rule. The RIA estimates that the net annualized impact of these eleven provisions over a 100 year period of analysis will be cost savings of between $32 million and $100 million when discounting at 7 percent and cost savings between $25 million and $76 million when discounting at 3 percent. This action is considered an economically significant action under Executive Order 12866.

B. Affected Universe

The universe of affected entities for this rule consists of the same entities affected by EPA's 2015 CCR final rule. These entities are coal-fired electricity generating plants operated by the electric utility industry. They can be identified by their North American Industry Classification System (NAICS) designation 221112 ''Fossil Fuel Electric Power Generation''. The RIA estimates that there are 414 coal-fired electricity generating plants operating 922 CCR management units (landfills, disposal impoundments, and storage impoundments) that will be affected by this rule.

C. Baseline Costs

The baseline costs for this rule are the costs of compliance with EPA's 2015 CCR final rule, as the provisions of this rule modify the provisions of the 2015 CCR final rule or modify the implementation of the 2015 CCR rule by WIIN Act participating states. The RIA for the 2015 CCR final rule estimated these costs at an annualized $509 million when discounting at 7 percent and an annualized $735 million when discounting at 3 percent.

D. Cost Savings, Other Benefits, and Adjustments to the Baseline

The RIA estimates costs and costs savings for the four proposals associated with the 2015 CCR rule judicial remand as well as the six alternative performance standards that will apply in participating states under the WIIN Act, and the use CCR during certain closure situations. The RIA estimates that the net annualized impact of these eleven provisions over a 100 year period of analysis will be an annualized cost savings of between $32 million and $100 million when discounting at 7 percent, and an annualized cost savings of between $25 million and $76 million when discounting at 3 percent.

The RIA also estimates potential adjustments to the baseline costs of the CCR final rule due to plant closures that occurred after the rule was published but before the effective date of the rule. The RIA accompanying the 2015 CCR final rule assigned compliance costs to these plants, which they are exempt from because they closed before the final rule's effective date. In all, 23 plants closed before the effective date of the final rule that were not accounted for in 2015 final rule RIA. The annualized compliance costs avoided for these plants equals between $22 million and $25 million per year when discounting at 7 percent and between $22 million and $31 million when

discounting at 3 percent. This cost adjustment is detailed in the RIA that accompanies this rulemaking, however it is not factored into the baseline or the benefit estimates for this rule to keep comparisons with the 2015 CCR final rule straight forward.

E. Solicitation of Comments on the Projected Economic Impacts

EPA is soliciting comments on the following aspects of the Regulatory Impact Analysis (RIA), which is available in the docket for this rulemaking. The Agency is soliciting comment primarily on the assumptions and the data sources used in the analysis.

- Do you have information that would refine the RIA assumptions about the number of facilities both in and serving affected NERC regions that would request alternative closure under Additional Provision 1 (the amendment discussed in Unit III.D of this preamble)?
- Do you have information that would refine the RIA assumption that facilities seeking alternative closure requirements under Additional Provision 1 (the amendment discussed in Unit III.D of this preamble) would delay closure by five years (the maximum allowed under the rule)?
- Do you have information that would refine the RIA assumptions about the maximum or minimum number of states that would likely adopt alternative performance standards under the WIIN Act?
- Do you have information that would refine the RIA assumptions about the changes in total corrective action costs for a release due to the Alternative Performance Standard 1 (the amendment discussed in Unit IV.A of this preamble)?
- Do you have information that would refine the RIA assumptions about the total number of CCR units that may avoid corrective action costs due to the Alternative Performance Standard 2 (the amendment discussed in Unit IV.B of this preamble)?
- Do you have information that would refine the RIA assumptions about the number of units that will receive a ''no migration'' waiver under Alternative Performance Standard 3 (the amendment discussed in Unit IV.C of this preamble)?
- Do you have information that would refine the RIA assumption that states adopting Alternative Performance Standard 4 (the amendment discussed in Unit IV.D of this preamble) would on average reduce the post-remedy monitoring from three years to one year?
- Do you have information that would refine the RIA assumption that states adopting Alternative Performance Standard 5 (the amendment discussed in Unit IV.E of this preamble) would on average reduce the period from 30 years to five years?
- Do you have information that would refine the RIA assumptions about the total number of CCR units that would use CCR as allowed under Additional Provision 2 (the amendment discussed in Unit IV.G of this preamble)?
- Do you have information that would refine the RIA assumptions about the average annual number of CCR units closing (RIA page 4–14)?
- Do you have information that would refine the RIA assumptions about the estimated tonnage of CCR that could be used for closure (RIA page 4–14)?
- Do you have information that would refine the RIA description and estimates of impacts related to interactions among CCR Remand Rule provisions (RIA pp. 5–1 through 5–3)?

VI. Statutory and Executive Order (EO) Reviews

A. Executive Order 12866: Regulatory Planning and Review and Executive Order 13563: Improving Regulation and Regulatory Review

This action is a significant regulatory action that was submitted to the Office of Management and Budget (OMB) for review. Any changes made in response to OMB recommendations have been documented in the docket. The EPA prepared an analysis of the potential costs and benefits associated with this action. This Regulatory Impact Analysis (RIA), entitled *Regulatory Impact Analysis; EPA's 2017 RCRA Proposed Rule; Disposal of Coal Combustion Residuals from Electric Utilities; Amendments to the National Minimum Criteria (October 2017),* is summarized in Unit V of this preamble and the RIA is available in the docket for this proposal.

B. Executive Order 13771: Reducing Regulation and Controlling Regulatory Costs

This action is expected to be an Executive Order 13771 deregulatory action. Details on the estimated cost savings of this proposed rule can be found in EPA's analysis of the potential costs and benefits associated with this action.

C. Paperwork Reduction Act (PRA)

The information collection activities in this proposed rule have been submitted for approval to the Office of Management and Budget (OMB) under the PRA. The Information Collection Request (ICR) document that the EPA prepared has been assigned EPA ICR number 1189.27, OMB control number 2050–0053. This is an amendment to the ICR approved by OMB for the Final Rule: Hazardous and Solid Waste Management System; Disposal of Coal Combustion Residuals from Electric Utilities published April 17, 2015 in the **Federal Register** at 80 FR 21302. You can find a copy of the ICR in the docket for this action, and it is briefly summarized here. This rulemaking, specifically the provision clarifying the type and magnitude of non-groundwater releases that would require a facility to comply with some or all of the corrective action procedures set forth in §§ 257.96–257.98, reduces the paperwork burden attributable to provisions of the April 17, 2015 CCR Final Rule.

Respondents/affected entities: Coal-fired electric utility plants that will be affected by the rule.

Respondent's obligation to respond: The recordkeeping, notification, and posting are mandatory as part of the minimum national criteria being promulgated under Sections 1008, 4004, and 4005(a) of RCRA.

Estimated number of respondents: 414.

Frequency of response: The frequency of response varies.

Total estimated burden: EPA estimates the total annual burden to respondents to be *a reduction in burden of* approximately 4,267 hours from the currently approved burden. Burden is defined at 5 CFR 1320.3(b).

Total estimated cost: The total estimated annual cost of this rule is a *cost savings* of approximately $5,713,027. This cost savings is composed of approximately $519,832 in annualized avoided labor costs and $5,193,195 in avoided capital or operation and maintenance costs.

An agency may not conduct or sponsor, and a person is not required to respond to, a collection of information unless it displays a currently valid OMB control number. The OMB control numbers for the EPA's regulations in 40 CFR are listed in 40 CFR part 9.

D. Regulatory Flexibility Act (RFA)

I certify that this action will not have a significant economic impact on a substantial number of small entities under the RFA. In making this determination, the impact of concern is any significant adverse economic impact on small entities. An agency may certify that a rule will not have a significant economic impact on a

substantial number of small entities if the rule relieves regulatory burden, has no net burden or otherwise has a positive economic effect on the small entities subject to the rule. This action is expected to result in net cost savings amounting to approximately $32 million per year to $100 million per year when discounting at 7 percent and annualized over 100 years. It is expected to result in net cost savings of between $25 million and $76 million when discounting at 3 percent and annualized over 100 years. Savings will accrue to all regulated entities, including small entities. Further information on the economic effects of this action can be found in Unit V of this preamble and in the Regulatory Impact Analysis, which is available in the docket for this action. We have therefore concluded that this action will relieve regulatory burden for all directly regulated small entities.

E. Unfunded Mandates Reform Act (UMRA)

This action does not contain any unfunded mandate of $100 million or more as described in UMRA, 2 U.S.C. 1531–1538, and does not significantly or uniquely affect small governments. This action imposes no enforceable duty on any state, local or tribal governments or the private sector. The costs involved in this action are imposed only by participation in a voluntary federal program. UMRA generally excludes from the definition of ''federal intergovernmental mandate'' duties that arise from participation in a voluntary federal program.

F. Executive Order 13132: Federalism

This action does not have federalism implications. It will not have substantial direct effects on the states, on the relationship between the national government and the states, or on the distribution of power and responsibilities among the various levels of government.

G. Executive Order 13175: Consultation and Coordination With Indian Tribal Governments

This action does not have tribal implications as specified in Executive Order 13175. For the ''Final Rule: Hazardous and Solid Waste Management System; Disposal of Coal Combustion Residuals from Electric Utilities'' published April 17, 2015 in the **Federal Register** at 80 FR 21302, EPA identified three of the 414 coal-fired electric utility plants (in operation as of 2012) which are located on tribal lands; however, they are not owned by tribal governments. These are: (1) Navajo Generating Station in Coconino County, Arizona, owned by the Arizona Salt River Project; (2) Bonanza Power Plant in Uintah County, Utah, owned by the Deseret Generation and Transmission Cooperative; and (3) Four Corners Power Plant in San Juan County, New Mexico owned by the Arizona Public Service Company. The Navajo Generating Station and the Four Corners Power Plant are on lands belonging to the Navajo Nation, while the Bonanza Power Plant is located on the Uintah and Ouray Reservation of the Ute Indian Tribe. Moreover, since this action is expected to result in net cost savings to affected entities amounting to approximately $32 million per year to $100 million per year when discounting at 7 percent and annualized over 100 years, or in net cost savings of between $25 million per year and $76 million per year when discounting at 3 percent and annualized over 100 years, it will not have substantial direct effects on one or more Indian tribes. Thus, Executive Order 13175 does not apply to this action.

H. Executive Order 13045: Protection of Children From Environmental Health Risks and Safety Risks

This action is not subject to Executive Order 13045 because the EPA does not believe the environmental health or safety risks addressed by this action present a disproportionate risk to children. This action's health and risk assessments are contained in the document titled ''Human and Ecological Risk Assessment of Coal Combustion Residuals'' which is available in the docket for the final rule as docket item EPA–HQ–RCRA–2009–0640–11993.

As ordered by EO 13045 Section 1–101(a), for the ''Final Rule: Hazardous and Solid Waste Management System; Disposal of Coal Combustion Residuals from Electric Utilities'' published April 17, 2015 in the **Federal Register** at 80 FR 21302, EPA identified and assessed environmental health risks and safety risks that may disproportionately affect children in the revised risk assessment. The results of the screening assessment found that risks fell below the criteria when wetting and run-on/runoff controls required by the rule are considered. Under the full probabilistic analysis, composite liners required by the rule for new waste management units showed the ability to reduce the 90th percentile child cancer and non-cancer risks for the groundwater to drinking water pathway to well below EPA's criteria. Additionally, the groundwater monitoring and corrective action required by the rule reduced risks from current waste management units. This action does adversely affect these requirements and, in fact it enhances the groundwater monitoring requirements by adding boron to the list of constituents in Appendix IV that trigger corrective action. Thus, EPA believes that this rule will be protective of children's health.

I. Executive Order 13211: Actions Concerning Regulations That Significantly Affect Energy Supply, Distribution or Use

This action is not a ''significant energy action'' because it is not likely to have a significant adverse effect on the supply, distribution or use of energy. For the 2015 CCR rule, EPA analyzed the potential impact on electricity prices relative to the ''in excess of one percent'' threshold. Using the Integrated Planning Model (IPM), EPA concluded that the 2015 CCR Rule may increase the weighted average nationwide wholesale price of electricity between 0.18 percent and 0.19 percent in the years 2020 and 2030, respectively. As the proposed rule represents a cost savings rule relative to the 2015 CCR rule, this analysis concludes that any potential impact on wholesale electricity prices will be lower than the potential impact estimated of the 2015 CCR rule; therefore, this proposed rule is not expected to meet the criteria of a ''significant adverse effect'' on the electricity markets as defined by Executive Order 13211.

J. National Technology Transfer and Advancement Act (NTTAA)

This rulemaking does not involve technical standards.

K. Executive Order 12898: Federal Actions To Address Environmental Justice in Minority Populations and Low-Income Populations

The EPA believes that this action does not have disproportionately high and adverse human health or environmental effects on minority populations, low-income populations and/or indigenous peoples, as specified in Executive Order 12898 (59 FR 7629, February 16, 1994).

The documentation for this decision is contained in EPA's Regulatory Impact Analysis (RIA) for the CCR rule which is available in the docket for the 2015 CCR final rule as docket item EPA–HQ–RCRA–2009–0640–12034.

EPA's risk assessment did not separately evaluate either minority or low income populations. However, to evaluate the demographic characteristics of communities that may be affected by the CCR rule, the RIA compares the demographic characteristics of populations surrounding coal-fired electric utility

plants with broader population data for two geographic areas: (1) One-mile radius from CCR management units (*i.e.,* landfills and impoundments) likely to be affected by groundwater releases from both landfills and impoundments; and (2) watershed catchment areas downstream of surface impoundments that receive surface water run-off and releases from CCR impoundments and are at risk of being contaminated from CCR impoundment discharges (*e.g.*, unintentional overflows, structural failures, and intentional periodic discharges).

For the population as a whole 24.8 percent belong to a minority group and 11.3 percent falls below the Federal Poverty Level. For the population living within one mile of plants with surface impoundments 16.1 percent belong to a minority group and 13.2 percent live below the Federal Poverty Level. These minority and low-income populations are not disproportionately high compared to the general population. The percentage of minority residents of the entire population living within the catchment areas downstream of surface impoundments is disproportionately high relative to the general population, *i.e.*, 28.7 percent, versus 24.8 percent for the national population. Also, the percentage of the population within the catchment areas of surface impoundments that is below the Federal Poverty Level is disproportionately high compared with the general population, *i.e.*, 18.6 percent versus 11.3 percent nationally.

Comparing the population percentages of minority and low income residents within one mile of landfills to those percentages in the general population, EPA found that minority and low-income residents make up a smaller percentage of the populations near landfills than they do in the general population, *i.e.*, minorities comprised 16.6 percent of the population near landfills versus 24.8 percent nationwide and low-income residents comprised 8.6 percent of the population near landfills versus 11.3 percent nationwide. In summary, although populations within the catchment areas of plants with surface impoundments appear to have disproportionately high percentages of minority and low-income residents relative to the nationwide average, populations surrounding plants with landfills do not. Because landfills are less likely than impoundments to experience surface water run-off and releases, catchment areas were not considered for landfills.

The CCR rule is risk-reducing with reductions in risk occurring largely within the surface water catchment zones around, and groundwater beneath, coal-fired electric utility plants. Since the CCR rule is risk-reducing and this action does not add to risks, this action will not result in new disproportionate risks to minority or low-income populations.

List of Subjects in 40 CFR Part 257

Environmental protection, Beneficial use, Coal combustion products, Coal combustion residuals, Coal combustion waste, Disposal, Hazardous waste, Landfill, Surface impoundment.

Dated: March 1, 2018.

E. Scott Pruitt,

Administrator.

For the reasons set out in the preamble, title 40, chapter I, of the Code of Federal Regulations is proposed to be amended as follows:

PART 257—CRITERIA FOR CLASSIFICATION OF SOLID WASTE DISPOSAL FACILITIES AND PRACTICES

■ 1. The authority citation for part 257 is revised to read as follows:

Authority: 42 U.S.C. 6907(a)(3), 6912(a)(1), 6944(a), 6945(d); 33 U.S.C. 1345(d) and (e).

■ 2. Section 257.53 is amended by:
■ a. Adding in alphabetical order the definition of ''Contouring'', ''Engineered slope protection measures'', ''Grading'', ''Grassy vegetation'', ''Non-groundwater releases'', ''Participating state'', ''Pertinent surrounding areas'', ''Vegetative height'', and ''Woody vegetation'' in alphabetical order.
■ b. Revising the definition of ''Slope protection'' and ''State director.''

The revisions and additions read as follows:

§ 257.53 Definitions.

* * * * *

Contouring means the placement of material to provide a continuous downward slope on the surface of a drainage area, except for erosion control features (e.g., swales, contour banks).

* * * * *

Engineered slope protection measures means non-vegetative cover systems, which include but are not limited to rock riprap, concrete revetments, vegetated wave berms, concrete facing, gabions, geotextiles, or fascines.

* * * * *

Grading means the placement of CCR only to the extent necessary to create sufficient differences in elevation to support stormwater drainage.

Grassy vegetation means vegetation that meets both of the conditions described in paragraphs (1) and (2) of this definition:

(1) The vegetation develops shallow roots which both do not penetrate the slopes or pertinent surrounding areas of the CCR unit to a substantial depth and do not introduce the potential of internal erosion or risk of uprooting; and

(2) The vegetation creates a continuous dense cover that prevents erosion and deterioration of the surface of the slope or pertinent surrounding areas, thereby preventing deterioration of the surface.

* * * * *

Non-groundwater releases mean releases from the CCR unit other than the releases directly to the groundwater that are detected through the unit's groundwater monitoring system. Examples of non-groundwater releases include seepage through the embankment, minor ponding of seepage at the toe of the embankment of the CCR unit, seepage at the abutments of the CCR unit, seepage from slopes, ponding at the toe of the unit, a release of fugitive dust and releases of a ''catastrophic'' nature such as the release of CCR materials from CCR surface impoundments from the Tennessee Valley Authority's (TVA) Kingston Fossil Plant in Harriman, TN and the Duke Energy Dan River Steam Station in Eden, NC.

* * * * *

Participating state means a state with a state program for control of CCR that has been approved pursuant to Section 4005 of the Resource Conservation and Recovery Act.

Pertinent surrounding areas means all areas of the CCR surface impoundment or immediately surrounding the CCR surface impoundment that have the potential to affect the structural stability and condition of the CCR surface impoundment, including but not limited to the toe of the downstream slope, the crest of the embankment, abutments, and unlined spillways.

* * * * *

Slope protection means measures installed on the slopes or pertinent surrounding areas of the CCR unit that protect the slope against wave action, erosion or adverse effects of rapid drawdown. Slope protection includes grassy vegetation and engineered slope protection measures.

* * * * *

State Director means the chief administrative officer of any State agency operating an approved CCR permit program or the delegated representative of the State Director. If responsibility is divided among two or

more State agencies, State Director means the chief administrative officer of the State agency authorized to perform the particular function or procedure to which reference is made. On Tribal Lands and in non-participating States where Congress has specifically provided appropriations to EPA to administer a CCR permit program, State Director means the EPA Administrator or their designee.

* * * * *

Vegetative height means the linear distance between the ground surface where the vegetation penetrates the ground surface and the outermost growth point of the vegetation.

* * * * *

Woody vegetation means vegetation that develops woody trunks, root balls, or root systems which can penetrate the slopes or pertinent surrounding areas of the CCR unit to a substantial depth and introduce the potential of internal erosion or risk of uprooting.

■ 3. Section 257.73 is amended by:

■ a. Revising paragraphs (a)(4) and (d)(1)(ii); and

■ b. Removing and reserving paragraph (d)(1)(iv).

The revisions read as follows:

§ 257.73 Structural integrity criteria for existing CCR surface impoundments.

(a) * * *

(4) The slopes and pertinent surrounding areas of the CCR unit must be designed, constructed, operated, and maintained with one of the forms of slope protection specified in paragraph (a)(4)(i) of this section that meets all of the performance standards of paragraph (a)(4)(ii) of this section.

(i) Slope protection must consist of one of the following:

(A) A vegetative cover consisting of grassy vegetation;

(B) An engineered cover consisting of a single form or combination of forms of engineered slope protection measures; or

(C) A combination of the forms of cover specified in paragraphs (a)(4)(i)(A) or (a)(4)(i)(B) of this section.

(ii) Any form of cover for slope protection must meet all of the following performance standards:

(A) The cover must be installed and maintained on the slopes and pertinent surrounding areas of the CCR unit;

(B) The cover must provide protection against surface erosion, wave action, and adverse effects of rapid drawdown;

(C) The cover must be maintained to allow for the observation of and access to the slopes and pertinent surrounding areas during routine and emergency events;

(D) Woody vegetation must be removed from the slopes or pertinent surrounding areas. Any removal of woody vegetation with a diameter greater than ½ inch must be directed by a person familiar with the design and operation of the unit and in consideration of the complexities of removal of a tree or a shrubbery, who must ensure the removal does not create a risk of destabilizing the unit or otherwise adversely affect the stability and safety of the CCR unit or personnel undertaking the removal; and

(E) The vegetative height of grassy and woody vegetation must not exceed 12 inches.

* * * * *

(d) * * *

(1) * * *

(ii) Slope protection consistent with the requirements under paragraph (a)(4) of this section.

* * * * *

■ 4. Section 257.74 is amended by:

■ a. Revising paragraphs (a)(4) and (d)(1)(ii); and

■ b. Removing and reserving paragraph (d)(1)(iv).

The revisions read as follows:

§ 257.74 Structural integrity criteria for new CCR surface impoundments and any lateral expansion of a CCR surface impoundment.

(a) * * *

(4) The slopes and pertinent surrounding areas of the CCR unit must be designed, constructed, operated, and maintained with one of the forms of slope protection specified in paragraph (a)(4)(i) of this section that meets all of the performance standards of paragraph (a)(4)(ii) of this section.

(i) Slope protection must consist of one of the following:

(A) A vegetative cover consisting of grassy vegetation;

(B) An engineered cover consisting of a single form or combination of forms of engineered slope protection measures; or

(C) A combination of the forms of cover specified in paragraphs (a)(4)(i)(A) or (a)(4)(i)(B) of this section.

(ii) Any form of cover for slope protection must meet all of the following performance standards:

(A) The cover must be installed and maintained on the slopes and pertinent surrounding areas of the CCR unit;

(B) The cover must provide protection against surface erosion, wave action, and adverse effects of rapid drawdown;

(C) The cover must be maintained to allow for the observation of and access to the slopes and pertinent surrounding areas during routine and emergency events;

(D) Woody vegetation must be removed from the slopes or pertinent surrounding areas. Any removal of woody vegetation with a diameter greater than ½ inch must be directed by a person familiar with the design and operation of the unit and in consideration of the complexities of removal of a tree or a shrubbery, who must ensure the removal does not create a risk of destabilizing the unit or otherwise adversely affect the stability and safety of the CCR unit or personnel undertaking the removal; and

(E) The vegetative height of grassy and woody vegetation must not exceed 12 inches.

* * * * *

(d) * * *

(1) * * *

* * * * *

(ii) Slope protection consistent with the requirements under paragraph (a)(4) of this section.

* * * * *

■ 5. Section 257.83 is amended by revising paragraph (b)(5) to read as follows:

§ 257.83 Inspection requirements for CCR surface impoundments.

* * * * *

(b) * * *

(5) If a deficiency or release is identified during an inspection, the owner or operator must remedy the deficiency or release in accordance with applicable requirements in §§ 257.96 through 257.99.

* * * * *

■ 6. Section 257.84 is amended by revising paragraph (b)(5) to read as follows:

§ 257.84 Inspection requirements for CCR surface landfills.

* * * * *

(b) * * *

(5) If a deficiency or release is identified during an inspection, the owner or operator must remedy the deficiency or release in accordance with applicable requirements in §§ 257.96 through 257.99.

* * * * *

■ 7. Section 257.90 is amended by revising paragraphs (a) and (d) and adding paragraph (g) to read as follows:

§ 257.90 Applicability.

(a) All CCR landfills, CCR surface impoundments, and lateral expansions of CCR units are subject to the groundwater monitoring and corrective action requirements under §§ 257.90 through 257.99, except as provided in paragraph (g) of this section.

* * * * *

(d) The owner or operator of the CCR unit must comply with all applicable

requirements in §§ 257.96, 257.97, and 257.98, or, if eligible, must comply with the requirements in § 257.99.

* * * * *

(g) *Suspension of groundwater monitoring requirements.* (1) Except as provided by paragraph (g)(2) of this section, the State Director of a participating state may suspend for up to ten years the groundwater monitoring requirements under §§ 257.90 through 257.95 for a CCR unit if the owner or operator provides written documentation that there is no potential for migration of the constituents listed in appendices III and IV to this part from that CCR unit to the uppermost aquifer during the active life of the CCR unit and the post-closure care period. This demonstration must be certified by a qualified professional engineer and approved by the State Director, and must be based upon:

(i) Site-specific field collected measurements, sampling, and analysis of physical, chemical, and biological processes affecting contaminant fate and transport; and

(ii) Contaminant fate and transport predictions that maximize contaminant migration and consider impacts on human health and the environment.

(2) The owner or operator of the CCR unit may secure an additional ten years for the suspension of the groundwater monitoring requirements provided the owner or operator provides written documentation that there continues to be no potential for migration of the constituents listed in appendices III and IV to this part. The documentation must be supported by, at a minimum, the information specified in paragraphs (g)(1)(i) and (g)(1)(ii) of this section and must be certified by a qualified professional engineer and approved by the State Director. The owner or operator must submit the documentation of their re-demonstration for the state's review and approval of their extension one year before their groundwater monitoring suspension is due to expire. If the existing groundwater monitoring extension expires, the owner or operator must begin groundwater monitoring according to paragraph (a) of this section within 90 days. The owner or operator may obtain additional ten-year groundwater monitoring suspensions provided the owner or operator continues to make the written demonstration. The owner or operator must place each completed demonstration, if more than one ten-year suspension period is sought, in the facility's operating record.

■ 8. Section 257.95 is amended by revising paragraph (h)(2) and adding paragraph (j) to read as follows:

§ 257.95 Assessment monitoring program.

* * * * *

(h) * * *

(2) For constituents for which an MCL has not been established, the background concentration for the constituent established from wells in accordance with § 257.91, except as provided by paragraph (j) of this section; or

* * * * *

(j) The State Director of a participating state may establish an alternative groundwater protection standard for constituents listed in appendix IV to this part for which MCLs have not been established.

(1) The alternative groundwater protection standards must be appropriate health-based levels that are protective of potential receptors (both human and ecological) and satisfy all of the following criteria:

(i) The alternative groundwater protection standard is at a level derived in a manner consistent with EPA guidelines for assessing the health risks of environmental pollutants, including ''Supplementary Guidance for Conducting Health Risk Assessment of Chemical Mixtures'', ''Guidelines for Developmental Toxicity Risk Assessment'', and ''Reference Dose, (RfD): Description and Use in Health Risk Assessments'' (incorporated by reference);

(ii) The alternative groundwater protection standard is at a level based on scientifically valid studies conducted in accordance with the Toxic Substances Control Act Good Laboratory Practice Standards (40 CFR part 792) or equivalent; and

(iii) For systemic toxicants, the level represents a concentration to which the human population could be exposed to on a daily basis that is likely to be without appreciable risk of deleterious effects during a lifetime; this must be the level that ensures a Hazard Quotient no greater than 1. For purposes of this subpart, systemic toxicants are toxic chemicals that cause effects other than cancer.

(2) In establishing alternative groundwater protection standards under paragraph (j)(1) of this section, the State Director may consider the following:

(i) Multiple contaminants in the groundwater;

(ii) Exposure threats to sensitive environmental receptors; and

(iii) Other site-specific exposure or potential exposure to groundwater.

(3) The owner or operator of the CCR unit must document in the annual groundwater monitoring and corrective action report required by § 257.90(e) or § 257.100(e)(5)(ii) the constituent(s) and level(s) for which an alternative groundwater protection standard has been established by the State Director.

■ 9. Section 257.97 is amended by adding paragraphs (f) and (g) to read as follows:

§ 257.97 Selection of remedy.

* * * * *

(f) The State Director of a participating state may determine that remediation of a release of a constituent listed in appendix IV to this part from a CCR unit is not necessary if the owner or operator demonstrates to the satisfaction of the State Director that:

(1) The groundwater is additionally contaminated by substances that have originated from a source other than a CCR unit and those substances are present in concentrations such that cleanup of the release from the CCR unit would provide no significant reduction in risk to actual or potential receptors; or

(2) The constituent(s) is present in groundwater that:

(i) Is not currently or reasonably expected to be a source of drinking water; and

(ii) Is not hydraulically connected with waters to which the constituent(s) is migrating or are likely to migrate in a concentration(s) that would exceed the groundwater protection standards established under § 257.95(h) or (i); or

(3) Remediation of the release(s) is technically impracticable; or

(4) Remediation results in unacceptable cross-media impacts.

(g) A determination by the Director of approved participating state pursuant to paragraph (f) of this section shall not affect the requirement under § 257.90(d) and § 257.97(b) for the owner or operator to undertake source control measures or other measures (including closure if triggered) that may be necessary to eliminate or minimize further releases to the groundwater, to prevent exposure to the groundwater, or to remediate the groundwater to concentrations that are technically feasible and significantly reduce threats to human health or the environment.

■ 10. Section 257.98 is amended by revising paragraph (c) to read as follows:

§ 257.98 Implementation of the corrective action program.

* * * * *

(c) Remedies selected pursuant to § 257.97 shall be considered complete when:

(1) The owner or operator of the CCR unit demonstrates compliance with the groundwater protection standards established under § 257.95(h) has been achieved at all points within the plume of contamination that lie beyond the groundwater monitoring well system established under § 257.91;

(2) Except as provided by paragraph (c)(4) of this section, compliance with the groundwater protection standards established under § 257.95(h) has been achieved by demonstrating that concentrations of constituents listed in appendix IV to this part have not exceeded the groundwater protection standard(s) for a period of three consecutive years using the statistical procedures and performance standards in § 257.93(f) and (g); and

(3) All actions required to complete the remedy have been satisfied.

(4) The Director of a participating state may specify an alternative length of time to that specified in paragraph (c)(2) of this section during which the owner or operator must demonstrate that concentrations of constituents listed in appendix IV to this part have not exceeded the groundwater protection standard(s) taking into consideration:

(i) Extent and concentration of the release(s);

(ii) Behavior characteristics of the constituents in the groundwater;

(iii) Accuracy of monitoring or modeling techniques, including any seasonal, meteorological, or other environmental variabilities that may affect the accuracy; and

(iv) Characteristics of the groundwater.

* * * * *

■ 11. Add § 257.99 to read as follows:

§ 257.99 Corrective action procedures to remedy eligible non-groundwater releases.

(a) *General.* This section specifies the corrective action requirements that apply to non-groundwater releases from CCR units that can be completely remediated within 180 days from the detection of the release. A release is completely remediated when either a qualified professional engineer or the permitting authority of a participating state completes the certification required in subsection (c)(2) of this section. If the owner or operator determines, at any time, that the release will not be completely remediated within this 180-day timeframe, the owner or operator must comply with all additional procedural requirements specified in §§ 257.96, 257.97, and 257.98.

(b) *Corrective action requirements.* Upon detection of a non-groundwater release from a CCR unit, the owner or operator must comply with all of the following requirements:

(1) Meet the requirement in § 257.90(d) to ''immediately take all necessary measures to control the source(s) of releases so as to reduce or eliminate, to the maximum extent feasible, further releases of contaminants into the environment;''

(2)(i) Determine the corrective measures that will meet the substantive standards in §§ 257.96(a) to prevent further releases, to remediate any releases and to restore the affected area to original conditions; and

(ii) Analyze the effectiveness of potential corrective measures in meeting all of the requirements and objectives of the remedy as described in § 257.96(c);

(3) Select the corrective action that will remedy the non-groundwater release, taking into account, at a minimum, the results of the assessment in paragraph (b)(2)(ii) of this section and the factors specified in § 257.97(c); and

(4) Remediate the non-groundwater release to meet the standards specified in § 257.97(b)(1), (3), (4), and (5).

(5) Complete remedy within 180 days of the date of discovery of the release.

(c) *Required notices and reports.* An owner or operator of a CCR unit that complies with the requirements of this section to remediate a non-groundwater release is responsible for ensuring that the notices and reports specified in paragraphs (c)(1) through (c)(3) of this section are completed in accordance with this section. All required notices and reports must be signed by the owner or operator.

(1) Within 15 days of discovering a non-groundwater release, the owner or operator must prepare a notification of discovery of a non-groundwater release. The owner or operator has completed the notification when it has been placed in the facility's operating record as required by § 257.105(h)(15).

(2) Within 15 days of completing the analysis of the effectiveness of potential corrective measures as required by paragraph (b)(2)(ii) of this section, place the completed analysis in the facility's operating record.

(3) Within 30 days of completion of a corrective action of a non-groundwater release, the owner or operator must prepare a report documenting the completion of the corrective action. The report must, at a minimum, describe the nature and extent of the non-groundwater release, the CCR unit(s) responsible for the non-groundwater release, and how the remedy selected achieves the corrective action requirements specified in paragraph (b) of this section. The notification must include a certification by a qualified professional engineer that the corrective action has been completed in accordance with the requirements of paragraph (b) of this section. The owner or operator has completed the notification when it has been placed in the facility's operating record as required by § 257.105(h)(16).

(d) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in § 257.105(h), the notification requirements specified in § 257.106(h), and the internet requirements specified in § 257.107(h).

■ 12. Section 257.102 is amended by adding paragraph (d)(4) to read as follows:

§ 257.102 Criteria for conducting the closure or retrofit of CCR units.

* * * * *

(d) * * *

(4) *Use of CCR in Design and Construction of Final Cover System.* (i) This paragraph specifies the allowable uses of CCR in the closure of CCR units closing pursuant to § 257.101. Notwithstanding the prohibition on further placement in § 257.101, CCR may be placed in such units but only for the purposes of grading and contouring in the design and construction of the final cover system, based either on:

(A) A determination by the Director of a participating state that the criteria in paragraph (d)(4)(ii) of this section have been met; or

(B) The certification by a qualified professional engineer that the criteria in (d)(4)(ii) of this section have been met, as required in paragraph (d)(4)(iii) of this section.

(ii) *Use of CCR in Design and Construction of Final Cover System Requirements.*

(A) The owner or operator of a CCR unit subject to § 257.101 may continue to place CCR in the unit after initiating closure in order to construct the final cover system required under paragraph (d)(3) of this section but only for the following activities:

(1) Grading; and

(2) Contouring.

(B) The owner or operator of a CCR unit must meet all of the following criteria when placing CCR within a CCR unit for the purposes of grading or contouring:

(1) The CCR placed for construction of the final cover system must have been generated at the facility and be located at the facility at the time closure was initiated;

(2)(i) For incised CCR surface impoundments the CCR must be placed entirely above the highest elevation of

the surrounding natural ground surface where the CCR surface impoundment was constructed;

(ii) For all other CCR units, CCR must be placed entirely above the highest elevation of CCR in the unit, following dewatering and stabilization as required by § 257.102(d)(2);

(3) The CCR must not be placed outside the plane extending vertically from the line formed by the intersection of the crest of the CCR surface impoundment and the upstream slope of the CCR surface impoundment; and

(4) The final cover system must be constructed with either:

(i) A slope not steeper than 5% grade after allowance for settlement; or

(ii) At a steeper grade, if the Director of a participating state determines that the steeper slope is necessary based on conditions at the site, to facilitate run-off and minimize erosion, and that side slopes are evaluated for erosion potential based on a stability analysis to evaluate possible erosion potential. The stability analysis, at a minimum, must evaluate the site geology; characterize soil shear strength; construct a slope stability model; establish groundwater and seepage conditions, if any; select loading conditions; locate critical failure surface; and iterate until minimum factor of safety is achieved.

(iii) If required by paragraph (d)(4)(i)(B) of this section, the owner or operator of the CCR unit must also include in the notification required by § 257.102(h) a certification by a qualified professional that the CCR unit was closed in accordance with the requirements of paragraph (d)(4) of this section.

* * * * *

■ 13. Section 257.103 is amended by:

■ a. Revising § 257.103 introductory text; and

■ b. Redesignating paragraphs (b), (c), and (d) as (c), (e), and (f); and adding new paragraphs (b) and (d).

The revisions and additions read as follows:

§ 257.103 Alternative closure requirements.

The owner or operator of a CCR landfill, CCR surface impoundment, or any lateral expansion of a CCR unit that is subject to closure pursuant to § 257.101(a), (b)(1), or (d) may continue to receive CCR and/or non-CCR wastestreams in the unit provided the owner or operator meets the requirements of either paragraph (a), (b), (c) or (d) of this section.

* * * * *

(b) *No Alternative capacity for non-CCR wastestreams.* (1) Notwithstanding the provisions of § 257.101(a), (b)(1), or (d), a CCR unit may continue to receive non-CCR wastestreams if the owner or operator of the CCR unit certifies that the wastestreams must continue to be managed in that CCR unit due to the absence of alternative capacity both on-site and off-site the facility. For these non-CCR wastestsreams, capacity means the capacity of impoundments, tanks, and other conveyances to manage daily flows currently handled by the unit that is closing pursuant to § 257.101(a) or (b)(1), or (d). To qualify under this paragraph (b)(1), the owner or operator of the CCR unit must document that all of the following conditions have been met for each non-CCR wastestream that will continue to be received by the CCR unit:

(i) No alternative disposal capacity is available. An increase in costs or the inconvenience of existing capacity is not sufficient to support qualification under this section;

(ii) The owner or operator has made, and continues to make, efforts to obtain additional capacity. Qualification under this subsection requires that efforts to obtain additional capacity were made at the earliest date that an owner or operator knew, or had reason to know, that such a unit may become subject to closure under § 257.101(a), (b)(1), or (d). Qualification under this subsection lasts only as long as no alternative capacity is available. Once alternative capacity is identified, the owner or operator must arrange to use such capacity as soon as feasible;

(iii) The owner or operator must certify that the facility generating any wastestream that continues to be placed into a CCR unit pursuant to this section would need to cease generating power and is located in or regularly provides the majority of generated electricity to, one of the following three North American Electric Reliability Corporation regions and sub-regions: the Midcontinent Independent System Operator, the Southeastern Electric Reliability Council-East, and/or the Southeastern Electric Reliability Council-North;

(iv) The owner or operator must remain in compliance with all other requirements of this subpart, including the requirement to conduct any necessary corrective action; and

(v) The owner or operator must prepare an annual progress report documenting the continued lack of alternative capacity and the progress towards the development of alternative capacity for the given wastestream.

(2) Once alternative capacity is available for a given wastestream, the CCR unit must cease receiving that wastestream, and in the case that alternate capacity has been found for all wastestreams, the facility must initiate closure of the CCR unit following the timeframes in § 257.102(e) and (f).

(3) If no alternative capacity is identified within five years after the initial certification as required under (b)(1) of this section, the CCR unit must cease receiving all wastestreams and close in accordance with the timeframes in § 257.102(e) and (f).

* * * * *

(d) *Permanent cessation of a coal-fired boiler(s) by a date certain.* (1) Notwithstanding the provisions of § 257.101(a), (b)(1), and (d), a CCR unit may continue to receive non-CCR wastestreams if the owner or operator certifies that the facility will cease operation of the coal-fired boilers within the timeframes specified in paragraphs (d)(2) and (3) of this section, but in the interim period (prior to closure of the coal-fired boiler), the facility must continue to use the CCR unit due to the absence of alternative capacity. For wastewaters capacity means the capacity of impoundments, tanks, and other units to manage daily flows currently handled by the unit closing pursuant to § 257.101(a) or (b)(1). To qualify under this paragraph (d)(1), the owner or operator of the CCR unit must document that all of the following conditions have been met for each wastestream that will continue to be received by the CCR unit:

(i) No alternative capacity is available. An increase in costs or the inconvenience of existing capacity is not sufficient to support qualification under this section.

(ii) The owner or operator must certify that the facility is located in or regularly provides the majority of generated electricity to one of the following three North American Electric Reliability Corporation regions and sub-regions: The Midcontinent Independent System Operator, the Southeastern Electric Reliability Council-East, and/or the Southeastern Electric Reliability Council-North.

(iii) The owner or operator must remain in compliance with all other requirements of this subpart, including the requirement to conduct any necessary corrective action; and

(iv) The owner or operator must prepare an annual progress report documenting the continued lack of alternative capacity and the progress towards the closure of the coal-fired boiler.

(2) For a CCR surface impoundment that is 40 acres or smaller, the coal-fired boiler must cease operation and the CCR surface impoundment must have

completed closure no later than October 17, 2023.

(3) For a CCR surface impoundment that is larger than 40 acres, the coal-fired boiler must cease operation, and the CCR surface impoundment must complete closure no later than October 17, 2028.

* * * * *

■ 14. Section 257.104 is amended by revising paragraph (c) to read as follows:

§ 257.104 Post-closure care requirements.

* * * * *

(c) *Post-closure care period.* (1) Except as provided by paragraphs (c)(2) and (3) of this section, the owner or operator of the CCR unit must conduct post-closure care for 30 years.

(2) If at the end of the post-closure care period the owner or operator of the CCR unit is operating under assessment monitoring in accordance with § 257.95, the owner or operator must continue to conduct post-closure care until the owner or operator returns to detection monitoring in accordance with § 257.95.

(3)(i) The Director of a participating state may establish an alternate post-closure period upon a determination that the alternate period is sufficient to protect human health and the environment.

(ii) To reduce the post closure care period, the Director must ensure that the post-closure care period is long enough to establish settlement behavior and to detect to wear-in defects in the cover system. At a minimum, the Director must consider the type of cover placed on the unit (*e.g.*, geosynthetic clay liner) and the placement of the groundwater monitoring wells with respect to the waste management units and the groundwater table.

(iii) A determination that a reduced post-closure care period is warranted does not affect the obligation to comply with paragraph (b) of this section.

* * * * *

■ 15. Section 257.105 is amended by adding paragraphs (h)(14) through (h)(16) and paragraph (i)(14) to read as follows:

§ 257.105 Recordkeeping requirements.

* * * * *

(h) * * *

(14) The demonstration, including long-term performance data, supporting the suspension of groundwater monitoring requirements as required by § 257.90(g).

(15) The notification of discovery of a non-groundwater release as required by § 257.99(c)(1).

(16) The report documenting the completion of the corrective action as required by § 257.99(c)(2).

(i) * * *

(14) The demonstration, including long-term performance data supporting the reduced post-closure care period as required by § 257.104(c)(3).

* * * * *

■ 16. Section 257.106 is amended by adding paragraphs (h)(11) through (h)(13) and paragraph (i)(14) to read as follows:

§ 257.106 Notification requirements.

* * * * *

(h) * * *

(11) Provide the demonstration supporting the suspension of groundwater monitoring requirements specified under § 257.105(h)(14).

(12) Provide notification of discovery of a non-groundwater release specified under § 257.105(h)(15).

(13) Provide notification of the availability of the report documenting the completion of the corrective action specified under § 257.105(h)(16).

(i) * * *

(14) Provide the demonstration supporting the reduced post-closure care period specified under § 257.105(i)(14).

* * * * *

■ 17. Section 257.107 is amended by adding paragraphs (h)(11) through (h)(13) and adding paragraph (i)(14) to read as follows:

§ 257.107 Publicly accessible internet site requirements.

* * * * *

(h) * * *

(11) The demonstration supporting the suspension of groundwater monitoring requirements specified under § 257.105(h)(14).

(12) The notification of discovery of a non-groundwater release specified under § 257.105(h)(15).

(13) The report documenting the completion of the corrective action specified under § 257.105(h)(16).

(i) * * *

(14) The demonstration supporting the reduced post-closure care period specified under § 257.105(i)(14).

* * * * *

■ 18. Revise Appendix IV to part 257 to read as follows:

Appendix IV to Part 257—Constituents for Assessment Monitoring

COMMON NAME [1]
Antimony
Arsenic
Barium
Beryllium
Boron
Cadmium
Chromium
Cobalt
Fluoride
Lead
Lithium
Mercury
Molybdenum
Selenium
Thallium
Radium 226 and 228 combined

[1] Common names are those widely used in government regulations, scientific publications, and commerce; synonyms exist for many chemicals.

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Document 27

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A Handbook for Determining the Sources of PCB Contamination in Sediments

Prepared by:
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U.S. Navy SPAWAR Systems Center
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14. ABSTRACT

This handbook provides information on conducting environmental forensic investigations for polychlorinated biphenyls (PCBs) at sediment sites. The document includes a discussion of: 1) the general forensic approach including relevant background information and benefits to Department of Defense (DoD); (2) a general summary of the technical methods that are used in a PCB environmental forensics investigation; and (3) a summary of the application of the described procedures in two demonstration case studies.

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ACRONYMS AND ABBREVIATIONS

2D	two-dimensional
3D	three-dimensional
ACF	advanced chemical fingerprinting
ALS	alternating least square
CD	coefficient of determination
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
COPC	contaminant of potential concern
CSIA	compound specific isotopic analysis
CSM	conceptual site model
CSO	combined sewer overflow
DoD	United States Department of Defense
DQO	data quality objective
ECD	electron capture detection
EDA	exploratory data analysis
ELISA	enzyme-linked immunosorbent assay
EM	end-member
ER	environmental restoration
ESTCP	Environmental Security Technology Certification Program
FA	factor analysis
FCM	fuzzy-c-means
FS	feasibility study
GC	gas chromatography
GIS	geographic information system
GLLA	Great Lakes Legacy Act
GLNPO	Great Lakes National Program Office
GPS	global positioning system
HCA	hierarchical cluster analysis
HOC	hydrophobic organic contaminant
HPS	Hunters Point Shipyard
HRGC	high-resolution gas chromatography
HRMS	high-resolution mass spectrometer
IA	immunoassay
IC	instrument check
ID	identification
IUPAC	International Union of Pure and Applied Chemistry

LCS	laboratory control sample
LRMS-SIM	low resolution mass spectrometry-selected ion monitoring
LRMS	low-resolution mass spectrometer
MCR-ALS	multivariate curve resolution/alternating least square
MDL	method detection limit
ML	minimum level
MS	mass spectrometry
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NRMRL	National Risk Management Research Laboratory
ORD	Office of Research and Development
PAH	polycyclic aromatic hydrocarbon
PB	procedural blank
PBMS	performance based measurement system
PCA	principal component analysis
PCB	polychlorinated biphenyl
PCT	polychlorinated terphenyl
PMF	positive matrix factorization
ppb	parts per billion
ppm	parts per million
PVA	polytopic vector analysis
QA	quality assurance
QC	quality control
RI	remedial investigation
RL	reporting limit
RPD	relative percent difference
RPM	Remedial Project Manager
RSC	rapid sediment characterization
RSD	relative standard deviation
SFPUC	San Francisco Public Utilities Commission
SIS	surrogate internal standard
SRM	standard reference material
TMDL	total maximum daily load
TOC	total organic carbon
UFP-QAPP	Uniform Federal Policy for Quality Assurance Project Plan
U.S. EPA	United States Environmental Protection Agency

WCSD	Watershed Contaminated Source Document
WHO	World Health Organization

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1.0 GENERAL FORENSICS APPROACH

1.1 Introduction

Defining the source of anthropogenic contamination from military facilities into sediments can be a difficult task. This is particularly true in waterways and coastal settings where multiple point sources are present along with persistent non-point sources such as urban background. This situation often results in complex mixtures of contaminants in sediments.

For sediment sites under the Environmental Restoration (ER) Program, Navy Remedial Project Managers (RPMs) are required to implement cleanup programs that include identifying the sources of contaminants at their sites; thus, there is a need for technical guidance on the application of techniques that can be used to determine these sources. Environmental forensics is a methodology to unambiguously identify the contamination and its source or sources.

This handbook provides information on conducting environmental forensic investigations for polychlorinated biphenyls (PCBs) at sediment sites and should give RPMs and their contractor's useful guidance to perform such studies. This document provides an overview of the site-specific information that is needed and the type of technical activities to be conducted. The approach described in this handbook includes the combined use of rapid screening technologies to characterize the distribution of sediment contamination and advanced chemical fingerprinting (ACF) on a subset of samples to more definitively identify sources. This provides a cost-effective, technically advanced, and defensible approach to characterizing the PCB contamination and its sources at a given site.

Handbook Roadmap

This handbook is intended to be a useful guide for determining when a forensics investigation of a PCB contaminated sediment site may be considered and is comprised of the following sections:

- **Section 1:** Summarizes the requirements of Navy policy for source identification at sediment sites and provides background information on PCBs and their analysis. It reviews a step-wise process for implementing environmental forensics as part of a contaminant source study. This section will be of interest to RPMs and contractors wanting to familiarize themselves with the use of environmental forensics for PCBs.

- **Section 2:** Provides more information on PCB chemistry and a summary of the techniques that are used in a PCB environmental forensics investigation. This section covers sample design, sample collection, analysis methods, data analysis, and reporting. While the site-specific information and technical resources required are discussed in detail, this handbook is not intended as a "how to" manual for the actual conduct of a forensics investigation.

- **Section 3:** Summarizes the application of two case study examples to demonstrate the methodology. Discusses both a remedial cleanup and a dredging project case study to provide RPMs with example case studies that may be useful for their sites.

1.1.1 Navy Policy for Source Identification

Determining the original source of contamination is a requirement for cleanup programs within the military. Understanding the source(s) of contaminants to a contaminated sediment site is a prerequisite to implementing any proposed sediment remedial options under cleanup programs [1]. This is because sources must be controlled prior to remedial efforts to ensure that recontamination can be avoided.

It is Navy policy on sediment site investigations and response actions to determine all sources of sediment contamination prior to the start of remediation efforts in order to eliminate ongoing sources that could re-contaminate a closed site and to ensure that government funding is directed towards cleaning up contamination from Navy sources [2]. Under Navy policy, sediment investigations and response actions performed under the ER Program must be directly linked to Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) contaminant releases. The term "directly linked" means that the sediment contamination is scientifically connected to a Navy ER site. Therefore, all potential sources of Navy and non-Navy contamination at a site should be identified. At complex sediment sites, it may be appropriate to apply ACF techniques to support this source determination.

It should also be noted that, consistent with Navy policy, ER Program funding can only be used to perform forensic studies for the purpose of identifying the presence of other sources and/or to verify if the Navy is a contributor. The forensic study can only identify sources as non-Navy or Navy and cannot name a potentially-responsible party. RPMs should consult with the appropriate legal representatives regarding this matter.

1.1.2 PCB Chemistry and Fate Overview

PCBs are not a single compound, but a class of chlorinated organic compounds comprised of a biphenyl backbone with substitutions of from one to 10 chlorine atoms. Although there are 209 possible unique patterns in which these chlorines can be substituted onto the biphenyl rings, in practice there are about 100 to 150 individual compounds (termed congeners) that are present in the PCB formulations that have been in use and found in environmental samples. This is because PCBs are generally released into the environment as a limited set of a few distinct mixtures of congeners, termed Aroclors. It should be noted that while the term "Aroclor" is often thought of as synonymous with "PCB," Monsanto manufactured non-PCB products that also carried their Aroclor trade name. Aroclor 5460 for example was a polychlorinated terphenyl (PCT) product. PCB Aroclors did, however, account for the majority of Monsanto Aroclor production, and the term Aroclor refers to PCB Aroclors throughout this handbook. Less than 10 PCB Aroclor formulations were widely used. They were manufactured for specific industrial uses in the US from the 1930s through the 1970s when production was banned. Old equipment containing PCBs are still in use today, and therefore releases to the environment are still occurring. In addition, contaminated upland sites and runoff from many industrial environments continue to contribute PCBs to aquatic systems. PCBs were also used in caulk, paint, sealants, gasket materials, and numerous other industrial applications, a few of which did not use Aroclor formulations but relied on individual PCB congeners or non-Aroclor mixtures.

Because of their stable and persistent nature, historic PCB contamination can be widely found. In addition, certain PCBs accumulate in fatty biological tissue and the food web. Bioaccumulating contaminants such as PCBs are a concern because past contamination in sediments may represent a continuing source to aquatic food webs, and PCBs are frequently a driver in contaminated sediment management. Human and ecological health risks due to consumption of fish and shellfish are an issue at many Department of Defense (DoD) sites contaminated with PCBs. Because of the wide use of PCBs, many PCB-contaminated sediments near DoD sites may have been contaminated from multiple sources. Delineating the PCB sources is therefore an important concern where the DoD site may represent only one of many potential sources.

Definitions

This section presents a brief overview of PCB chemistry and its fate in the environment. More detailed information on PCB chemistry can be found in Section 2.

- A **PCB congener** is any individual chemical compound in the PCB category. The name of the congener is based on the total number of chlorine substituents and the position of each chlorine. Click here for a complete list of all PCB congeners.
- **PCB homologues** are subcategories of PCB congeners with equal numbers of chlorine substituents. Click here for a list of all PCB homologues.
- **PCB Aroclors** are mixtures of PCB congeners. These PCB mixtures were what was most commonly sold and used for a variety of commercial applications.

1.1.3 PCB Analysis and Environmental Forensics

PCBs can be measured by a number of different techniques depending on the intended use of the data. These techniques range from simple, rapid methods such as immunoassays that can provide total PCB estimates (including near real-time data in the field) to comprehensive PCB congener methods using laboratory gas chromatography (GC) separations with mass spectrometry (MS) detection. In between are laboratory methods that measure total Aroclor, PCB homologues, and limited sets of PCB congeners. Aroclor analysis has been widely used, and the identification of Aroclors is based on using only five to 10 key "representative" congeners selected from an unaltered single Aroclor standard. However, in environmental samples, multiple Aroclor sources with overlapping congeners are often present, and/or the PCB pattern may be altered by a number of natural processes once released into the environment. Aroclor analysis is thus often highly unreliable for identifying the type and amount of PCBs in environmental samples. In order to characterize and more fully understand the PCB contamination, and determine the PCB sources, it may be necessary to generate more detailed PCB data and unravel the alterations that may be "hiding" the original source patterns. Forensic studies may use a combination of sample and data analysis methods to achieve their goals, ranging from identifying sources for initial source control to later use for remedial cost apportionment. Often, forensic investigations are successfully used to eliminate a suspected

source (e.g., a DoD source) as the primary source rather than quantitatively allocate attribution of each source component, which can be much more difficult.

Environmental forensic studies are fairly mature for petroleum contaminated sites [3], but less common for other contaminants. Work on PCB fingerprinting is developing and there is clearly a need for reliable PCB forensics because of the abundance of this contaminant; it is often a decision driver at contaminated sediment sites. PCB forensics is particularly challenging because PCBs do not "weather" (i.e., change in chemical composition) merely in accordance with molecular weight, solubility, or other predictable factors. Some of the diagnostic principles used for polycyclic aromatic hydrocarbon (PAH) fingerprinting can be applied to PCB fingerprinting, but PCB mixtures are vastly different from PAH/petroleum mixtures; many factors need to be considered in addition to the most common weathering factors and interpretation methods need to be modified and new data interpretation and analysis considerations developed [4]. In addition to the mainly physically-based environmental processes (e.g., selective dissolution, adsorption, and volatilization), other environmental transformation and degradation processes (including microbial dechlorination) are also important and must be considered. Emerging PCB fingerprinting techniques have successfully been applied at a few sites in the US [5-9], but there is a need to more fully develop, demonstrate, and validate the utility of fingerprinting PCB contamination. More detailed information on PCB analysis and environmental forensic techniques can be found in Section 2.4.

1.2 General Approach

This section of the handbook presents the general approach (much of which will be discussed in more detail in Section 2.0 and applied to the case study sites in Section 3.0). The case studies provide examples of how to apply the approach described here at a range of sites. The case studies in this document should be viewed as examples and a start in defining the overall usefulness of forensics studies at Navy sediment sites.

Integrated Forensic Approach

This handbook demonstrates an integrated forensic approach to identify sources of sediment PCB contamination that combines sediment screening technologies on a large number of field samples, detailed PCB congener analysis on a subset of samples, followed by environmental forensic data interpretation to identify sources. The sample analysis and contaminant characterization is comprised of two major components:

- **Rapid sediment characterization (RSC)** technologies which provide for wide spatial coverage to delineate sediment contaminant heterogeneity and semi-quantitative characterization in a cost-effective manner; and
- **Advanced chemical fingerprinting (ACF)** on a selected subset of samples to delineate sources. ACF includes both advanced laboratory chemical analysis of samples, along with the application of sophisticated data analysis and interpretation methods.

The objective of combining RSC with ACF is to maximize the benefits of each method and control costs. For example, RSC provides a cost-effective technique for obtaining spatial

concentration information (and perhaps temporal with sediment core age dating), allowing chemical gradients to be determined for initial assessment of the significance of the contamination and preliminary indications of potential sources. However, individual PCB congener data (a component of the ACF) are usually required for actually fingerprinting sources unless the sources are composed of different Aroclor signatures. ACF may require specialty analyses that are beyond the scope of most regulatory requirements and beyond the capabilities of many commercial laboratories. For example, in the case of PCBs, many regulatory programs only require PCB concentrations be determined as total Aroclors, or possibly a limited set of PCB congeners (e.g., the 18 National Oceanic and Atmospheric Administration [NOAA] Status and Trend congeners), while ACF often requires that up to 100 PCB congeners be determined, at a higher cost. Therefore, this integrated approach is a cost-effective and technically defensible methodology to identify PCB sources in sediments at DoD sites.

This combination of relatively inexpensive RSC analyses to map contaminant gradients combined with a subset of ACF analyses with advanced statistical analyses can tease out source compositions. The relative contributions of each source to the impacted sediments can also be estimated depending upon the nature of the co-mingled sources and the degree of weathering. RSC can help cost effectively answer the question of "where" there are sediments with contamination issues, the general distribution of the contamination, and generally where possible sources may be located, while ACF can confirm "what" those potential source fingerprints are, and more definitively link them to physical sources. Contaminant "fingerprinting" using RSC and ACF methods can also have many applications within the regulatory process relative to sediment investigations and response actions. Fingerprinting techniques applied early in the remedial investigation (RI) can be effectively used for source identification to augment the Watershed Contaminated Source Document (WCSD) and/or verification of background locations and concentrations. Fingerprinting methods can also be employed in the later stages of the feasibility study (FS) to evaluate baseline conditions and the potential for natural attenuation in remedy selection and/or setting appropriate cleanup goals. Both source fingerprints, as well as weathering patterns (due to differences in solubility, dechlorination, etc.), can often be discerned using these advanced chemical and statistical analyses [8, 10]. Although it is difficult to isolate all possible changes in PCB congener patterns, the selection of Hunters Point Shipyard (HPS) and Ashtabula River as case studies provides two examples to demonstrate the methodology. Providing both a remedial cleanup (HPS) and a dredging project (Ashtabula River) example will provide the RPMs with example case studies that may be useful for their sites.

1.2.1 Six Step Integrated Forensics Approach

This handbook demonstrates how to apply the techniques used in RSC and ACF to a variety of PCB sites. This handbook follows the approach outlined in Stout et al. [3] for developing a PAH forensics study, but applies this approach to case study sites with PCB contamination. The combined use of RSC and ACF, however, is only one step in the overall integrated forensics approach described in this document. The six steps that are important to follow for conducting a contaminant source study are summarized in Figure 1-1.

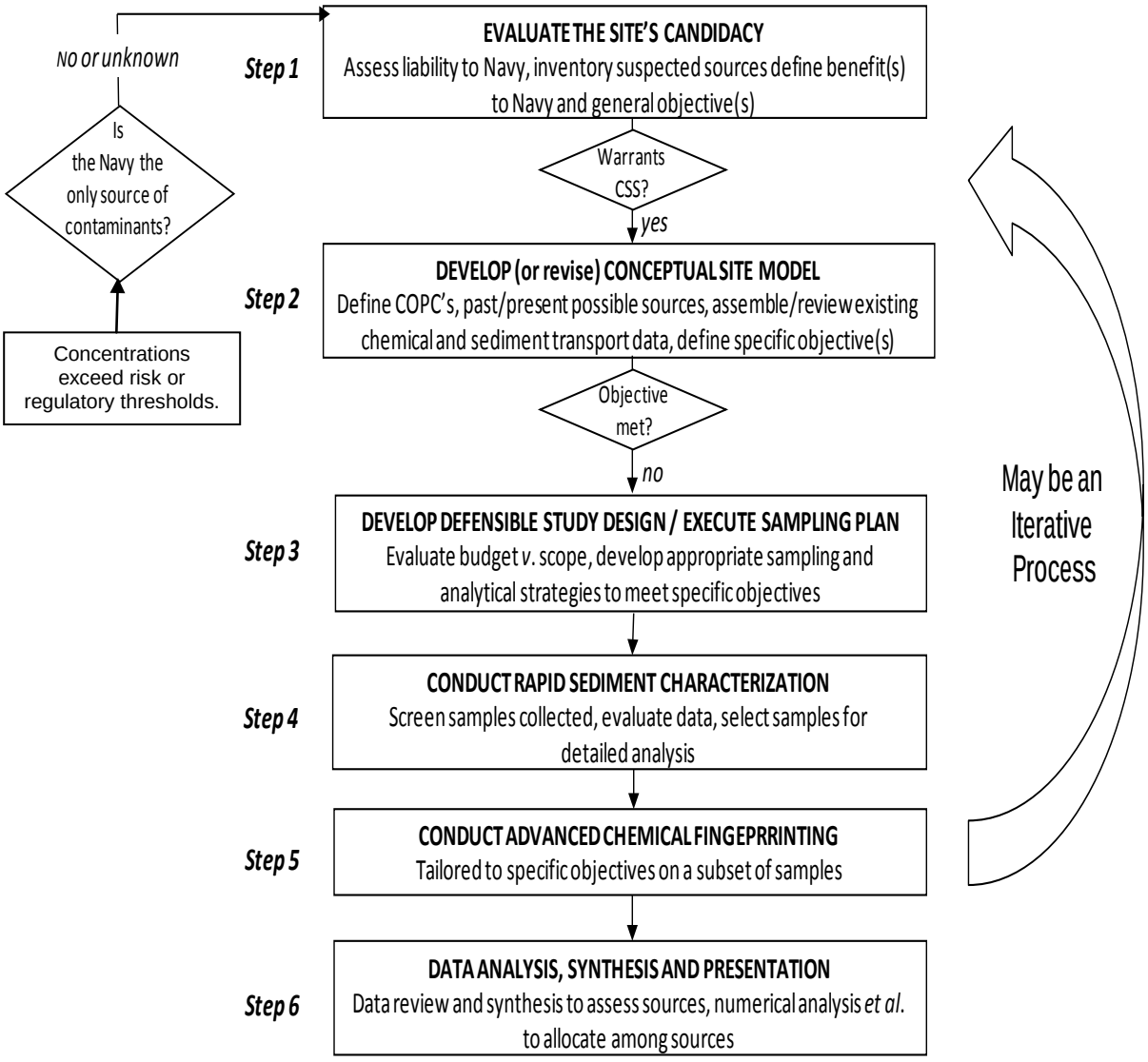


Figure 1-1. Flowchart Showing Considerations, Steps, and Decision Points for Conducting a Contaminant Source Study

1.2.1.1 Step 1: Evaluate Site for Forensic Study

The most obvious and common consideration when evaluating a site's potential for a forensics study is whether or not it is possible that non-site sources may have contributed to the known or suspected contamination at the site. Other questions that may be posed are summarized below. Each question must be considered and weighed in determining if the site will serve as a good candidate to apply forensic techniques.

Step 1: Evaluate Site for Forensic Study

1) Has it been determined that background cannot be established and/or concentrations exceed risk or regulatory thresholds?

2) Is it possible that non-site sources may have contributed to the known or suspected contamination at the site?

3) What known or suspected PCB contaminant sources existed on the site property (now or in the past)?

4) What known or suspected industries and potential sources are (or were) located on nearby properties?

5) What are (or were) the known typical contaminants associated with those industries?

6) What are the general sediment transport dynamics of the area (i.e., could contamination get from "here to there")?

1.2.1.2 Step 2: Develop Conceptual Site Model

The conceptual site model (CSM) is a mental "picture" of the site. It typically includes graphical representations of the contamination (e.g., contaminant contour maps) and fate and transport processes at the site. Once a site's candidacy has been established, a CSM for the ensuing contaminant source study should be developed to help understand how a source, or multiple sources, may have contributed to the contamination. At the completion of a CSM, it should be possible to accomplish the following:

1) Identify (or confirm the identity of) the known or suspected contaminants of potential concern (COPCs) for the site;
2) Identify all of the known or suspected sources or source areas of the COPCs within the study area; and
3) Develop specific objectives (hypotheses or forensic questions) to be evaluated by the study that address the potential PCB sources.

There is obvious overlap with some of the questions in Step 1, but those will be explored in more detail in Step 2. The forensic questions developed under Step 2 will then guide the development

of the sampling design in Step 3 (Sampling and Analysis Plan [SAP]). Specific samples will need to be collected to answer the CSM questions, so this will focus the scope of the forensic study. This does not preclude unforeseen findings, and it is likely that some surprises will occur at most sites. However, this directed development of the forensics study will ensure a cost-effective and well defined study.

An important step in the identification of COPCs is a review of the pre-existing information for the study area, including environmental data. The pre-existing data from past work typically only represent a start in providing defensible interpretations surrounding the source(s) of contamination within the study area. Thoroughly researching existing data, including the history of industries and potential sources in the area, changes over time that could impact contaminant transport (e.g., runoff/drainage, combined sewer outfall/overflow [CSO] activity, site/source cleanup, etc.) are all key components of the records research phase of any forensics investigation. Comprehensive records research is a crucial part of any environmental forensics investigation and is often overlooked or not given the priority it should have.

The case study examples used for this handbook had pre-existing data that were determined to be of sufficient quantity and quality for use in developing the forensics approach in this document, without needing to collect or analyze additional samples. It is rare to be able to conduct a forensics investigation solely using available data, but these case studies were selected, in large part, because of the availability of such data. For instance, all of the PCB data were generated by the same laboratory using consistent procedures, ensuring data comparability and reliable use.

Step 2: Develop a CSM

The CSM is a mental "picture" of the site. It includes graphical representations of the contamination (e.g., contaminant contour maps) and fate and transport processes at the site. CSM development should include the following elements:

- It should provide an understanding of contaminant fate and sediment transport processes at the given site (such as sediment dynamics, identifying areas of net accretion or loss, prop scour, review of dredging records, and more).
- It should include a review of pre-existing information and environmental data to identify COPCs and all of the known or suspected sources or source areas.
- It should support the development of specific objectives (hypotheses or forensic questions) to be evaluated by the study that address the potential PCB sources.

1.2.1.3 Step 3: Develop and Execute a Technically Defensible Sampling Plan

The development of a technically defensible sampling strategy requires a balance between meeting project objectives and data quality objectives (DQOs) within the budget of the project. This often leads to the practical question of how many samples will be used in the study and the type of analyses to be performed. Ultimately, it is the number of samples and analytical costs that will largely determine the cost of the project. By using a tiered study design that allows

RSC data to first characterize the PCB concentrations, the study can be designed to more cost-effectively produce and use the more costly ACF data.

Since forensic investigations are not part of the standard investigation processes, RPMs should contact their Quality Assurance Officer to ensure adherence to Navy policy on the development of SAPs under the Uniform Federal Policy for Quality Assurance Project Plans (UFP-QAPPs). Forensic specialists should also be involved in the DQO and SAP development process as early as possible to ensure proper data collection and analysis.

At some sites, it may be beneficial to include the collection of sediment cores to capture a record of the historic PCB contributions to the sediments. Some of the cores should be age dated to determine sediment chronology (i.e., the rate of sediment deposition and the dates the sediments at different depths were deposited). If only surface sediments are collected, only recent contamination can be assessed and only recent sources can be determined. This may be sufficient if the only objective is to identify and contain current sources prior to a remedial effort to control recontamination, but these are the types of issues that must be considered during the development of a study design. Many of these types of considerations are addressed in outside references (e.g., [11]), to assist with study design.

Step 3: Develop and Execute and Defensible Sampling Plan

- Develop defensible DQOs and SAPs that follow Navy and UFP-QAPP policies.
- Determine how many samples will be used and the type of analyses to be performed.
- Plan for a tiered study approach that implements RSC first to characterize the PCB extent followed by ACF techniques for source determination.

1.2.1.4 Step 4: Conduct Rapid Sediment Characterization

RSC of semi-volatile organics can be conducted using various immunoassay techniques. The techniques for the RSC of PCBs in sediments have been adapted from methods developed for use in soils (U.S. Environmental Protection Agency [U.S. EPA] Method 4020). Total PCB analysis by the standard laboratory Aroclor method (U.S. EPA Method 8082) may not qualify as a *rapid* sediment characterization method, but is a widely available analytical method that provides general PCB concentration information without the information detail of ACF, and such data can be used similarly to RSC data. More detailed information on the use of RSC methods can be found in the *Navy Guide for Using Rapid Sediment Characterization Methods in Ecological Risk Assessments* [12]. Some limitations in the sensitivity and specificity of RSC methods are also discussed in Section 2.4.1.

The PCB concentration data and variations are plotted using geographic contour plots, or other suitable graphical representation of the concentration distribution at the site. RSC data interpretation can benefit from additional physicochemical information for the sediments, such as the grain size distribution and total organic carbon (TOC) content, as PCBs tend to be preferentially associated with fine-grained and higher TOC content sediment. Grain size and

TOC information also may assist in interpretation of sediment transport and sources of the sediment at sample locations. PCBs can be normalized to TOC in order to better visualize the correlation behavior. With additional sediment transport information, the chemical gradients (PCBs sorbed on sediments generally move from high concentration source areas to lower concentration depositional zones) can be used to suggest various PCB sources. The contour maps (both surface and subsurface) thus can, if properly interpreted, display chemical gradients that indicate potential sources, and additional three-dimensional (3D) plumes (i.e., contoured subsurface information) may be defined because a higher number of samples can cost effectively be analyzed. These spatial presentations of the data allow different source areas to be proposed for validation by the more detailed laboratory analysis (ACF). The benefit of using a tiered approach (using RSC to select ACF samples) is a cost-effective study design in a heterogeneous matrix such as sediment. If only higher cost ACF samples are used, fewer locations would be sampled and source areas may be overlooked due to heterogeneity.

Regardless of the approach used in the generation and evaluation of RSC data, it is important to remember that the goal of the RSC analysis is to develop a sufficient set of visual or conceptual displays to aid in the selection of samples for ACF (and not to alone achieve the objectives of the study).

Step 4: Conduct RSC

- RSC of PCBs in sediment is conducted primarily using immunoassay techniques, but total PCB analytical methods may also be employed for site wide screening of PCB levels.
- The benefit of a tiered approach (e.g., using RSC to select ACF sample locations) is a cost-effective study design for a heterogeneous matrix such as sediment.
- The goal of the RSC analysis is ultimately to develop a sufficient set of visual or conceptual displays to aid in the selection of samples for ACF.
- Physicochemical data, such as the grain size distribution and TOC for sediment, may assist in interpretation of sediment transport and provide useful correlations to PCB concentrations.

1.2.1.5 Step 5: Conduct Advanced Chemical Fingerprinting

This section discusses how to select the location of ACF samples and provides an overview of the types of PCB analyses and statistical techniques to be applied to interpret results. More detailed information can be found in Section 2.4.2.

Determining the Number and Location of ACF Samples. The analytical strategy and budget will largely determine the number of samples that will be selected for ACF. It is not possible to define a fixed percent value of RSC samples to be used for ACF because this depends upon the level of detail in the RSC characterization, the heterogeneity of the sediment, and the overall complexity of the site. Therefore, the task of selecting samples for ACF is largely a matter of selecting a reasonable and justified subset from the complete set of RSC samples. Some guiding principles for the selection of samples for ACF are as follows:

1) Select samples that provide ample spatial coverage of the entire study area (try to represent all areas of the study and do not completely ignore any area on the basis of RSC alone),
2) Select a sufficient number of samples from specific location(s) within the study area that address a specific project objective(s) (i.e., select sufficient samples in areas of specific concern or interest [source areas and mixing zones], potentially including accessible upland sites of interest), and
3) Select samples that represent the range of RSC concentrations observed, including those that are (apparently) representative of the ambient/background conditions (i.e., do not exclude all the low concentration samples as they may provide important information on "background" conditions).

The selection of samples for ACF to meet these guidelines is in large part driven by cost. Thus, a degree of professional judgment is needed in the selection of samples for ACF.

Selecting Analytical Method(s) for the ACF Study. The need for an ACF methodology rests with the limitations of standard U.S. EPA methods (SW-846) to meet the objectives of a contaminant source study [3]. The fundamental shortcoming with virtually every conventional U.S. EPA SW-846 method of analysis, when used for measuring contaminants, particularly organic contaminants in sediment and other media, is a lack of detailed measurements of those diagnostic chemicals known to comprise these complex mixtures. Instead, the standard methods are focused on compounds identified as "priority pollutants," which are quite pervasive in contaminant mixtures, and are generally inadequate to distinguish different sources of otherwise similar contaminants [13]. In addition, standard PCB methods are primarily intended to generate bulk PCB concentration information (i.e., total PCB), and not information for identifying compositional and source differences.

Because of these limitations, standard U.S. EPA methods have been modified at some laboratories to yield the data necessary to support detailed contaminant source investigations. With respect to these modified methods, note that U.S. EPA SW-846 guidelines allow flexibility in the deployment of the 'standard' analytical methods, including modification of the list of target compounds. While most commercial laboratories apply unmodified standard methods, some laboratories have the experience and flexibility to optimize methods to meet project goals without violating method guidelines and project DQOs. When properly planned, most data generated by ACF methods can support contaminant source studies, as well as conventional regulatory assessment requirements. In other words, the ACF data can be considered defensible and accepted by regulatory agencies if the DQOs are clearly defined and met. While RSC and most ACF analyses do not require validation or accreditation review/oversight, it is emphasized that any data that will also be used for definitive purposes (e.g., risk assessment or site close out) must be from a laboratory accredited by the DoD-Environmental Laboratory Accreditation Program. RPMs should consult with their Quality Assurance Officer for an evaluation of accreditation requirements.

Aroclor analysis may, in a few rare circumstances, provide sufficient fingerprinting information to indentify sources. However, because many of the Aroclor formulations consist of overlapping congeners and weathering processes further complicate forensic resolution, more advanced ACF

methods are usually needed. The ACF techniques available for the assessment of semi-volatile organic contaminants in sediments (e.g., PCBs) are based on high-resolution GC (HRGC), usually operated in conjunction with compound-specific detectors (e.g., electron capture detection [ECD] or MS). Some laboratories have developed state-of-the-art PCB analytical methods using HRGC with low-resolution MS operating in selected ion monitoring mode (HRGC/LRMS-SIM), which are both highly cost-effective and provide detailed, high-quality data [14, 15]. The method employs components of U.S. EPA Method 680 (HRGC/LRMS PCB homologue and total PCB method) and Method 1668 (HRGC/HRMS PCB congener method). The base methods have been modified to include a large number of non-standard environmentally important and diagnostic PCB congeners that permit data analysis for differentiating potential sources and environmental processes.

Interpreting ACF Results. Once a subset of samples has been selected for ACF, a forensic analysis for PCBs will typically include the characterization of more than 100 discrete PCB congeners (congeners that comprise >98% of the total and possible PCB contamination), which enables scientists to apply a variety of powerful data interpretation methods. In some cases, a smaller set of 50 to 75 congeners may suffice, but the incremental increase in the cost is fairly small relative to the benefit of having the longer analyte list. PCB forensics data reduction and analysis include:

- Various types of statistical and other numerical analyses,
- Forensics graphing/plotting/mapping,
- Cross plotting,
- Cluster and principal component analysis (PCA) for similarity and dissimilarity analysis,
- Analysis for determining the age of the contamination, and
- Determination of degradation and dechlorination activity.

More detailed descriptions of these forensics methods, including specifically for PCBs, have been presented and documented elsewhere [5-10, 14], and some are further described and applied in this document.

PCA is one commonly used multivariate classification data analysis technique for identifying PCB compositional similarities and dissimilarities among samples and source materials. Receptor modeling (e.g., polytopic vector analysis [PVA]) is another often useful chemometric technique that was applied for the HPS and Ashtabula River case studies, in accordance with methodologies outlined by Johnson et al. [9]. For PCA, PVA, and most chemometric data analyses, the data are first carefully reviewed to assess their quality and usefulness, and the potential impact of low concentration samples, non-detects, and the presence of outliers. Data screening is summarized in Section 2 and also outlined by Johnson et al. [9] and may include: (1) data correction; (2) removal of samples from the data set; and (3) removal of congeners/peaks from the data set. After the data are prepared, the resultant data matrix is analyzed using the multivariate receptor modeling method. The first step in this process is the determination of the number of 'fingerprints' in the system. The next step in the receptor modeling process is to resolve the end member compositions (source profiles) and mixing proportions (source contributions) within each sample. The final step in the process is to: (1) compare the resolved end-member congener profiles with known or suspected source patterns (i.e., Aroclors) and

alteration mechanisms (e.g., literature reported dechlorination methods [16]) and (2) map the end-member mixing proportions both temporally and geographically.

PVA can be a useful component of the ACF data analysis because it is a well-established method that has been applied extensively in PCB forensics applications [5, 8, 9, 17]. Other receptor modeling methods (alternating least squares [ALS], positive matrix factorization [PMF], and Unmix [9]) should also be considered for individual studies. Recent receptor modeling method comparisons [9, 18, 19] indicate that results of these various methods are usually comparable, assuming the use of high quality and diligently screened data sets. The more important consideration is experience of the analyst, and their sensitivity to the scientific/chemical context of the problem.

Step 5: Conduct ACF

- The number of ACF samples depends upon the level of detail in the RSC characterization, the heterogeneity of the sediment, and the complexity of the site.
- ACF techniques typically include the characterization of over 100 PCB congeners.
- The PCB analytical methods employ HRGC usually operated in conjunction with compound-specific detectors (e.g., ECD or MS).
- Some laboratories have developed state-of-the-art PCB analytical methods using HRGC with low-resolution MS operating in selected ion monitoring mode (HRGC/LRM-SIM).
- Statistical techniques such as PCA, PVA, and others are then used to determine the number of "fingerprints" in the system, the source profiles, and the mixing proportions within each sample.
- This information is compared to known or suspected source patterns (i.e., Aroclors) and degradation mechanisms.

1.2.1.6 Step 6: Data Analysis, Synthesis, and Presentation of Results

The data analysis, synthesis, and information interpretation is most effective when multiple lines of evidence are used to develop the findings and draw the final conclusions. If multiple lines of evidence support the findings, it provides confidence and lends credibility to the conclusions. If multiple methods to evaluate the data provide confounding or inconsistent results, then that may mean that additional investigations may be warranted, or that there is no strong evidence of discrete and clearly identifiable sources. The multiple approaches to data analysis include:

1) A site history and records research component,
2) Incorporating contaminant/sediment transport and hydrodynamic information,
3) Evaluating the PCB concentrations across a site,
4) Evaluating the PCB composition of samples from across a site and possible sources,
5) Applying one or several available chemometric statistical methods to the PCB data, and
6) Integrated data analysis and interpretation incorporating these multiple approaches to draw conclusions related to potential sources of the contamination.

Section 2.5 provides examples of figures for the synthesis and presentation of ACF data. The manner by which the results and conclusions of a contaminant source study are conveyed needs to consider the audience, particularly whether they are highly technical or non-technical decision-makers and stakeholders. The target audience will dictate the level of technical detail conveyed in a report or presentation. Chemical 'fingerprinting' data in graphical and/or tabular form can be very confusing to all but an experienced chemist. Their interpretation is easier (and thereby useful) when the results of a contaminant source study are reported using different visual displays that either convey the data spatially or by some other easily interpreted visual (e.g., contour maps, bubble plots, histograms, etc.). Such visuals can be readily explained to and interpreted by most audiences. This is important since the value of any contaminant source study will be undermined if the audience cannot understand the results and conclusions.

Step 6: Data Analysis, Synthesis, and Presentation of Results

- Using RSC, it is possible to have the data density to support two-dimensional (2D) and 3D contour mapping, which provides a good visual display of the concentration gradients.
- Other visual displays (such as bubble plots, transect charts, or histograms) can be used with the RSC data. Bubble plots are often used as visual displays of the lower density ACF data when there is not enough data for support contour mapping.
- PCB compositional histograms are useful for illustrating and describing the contaminant composition, relationships among the samples and to potential sources, and link the field samples to source material (e.g., Aroclor formulations or mixtures).
- Single horizon pie chart or multi-horizon core diagram inserts on a map view of sample locations can be used to show the distribution of end members around the site.

The ACF data by themselves only provide information of compositional similarity and dissimilarity in the data set, and must be viewed along with other information (e.g., site history, sediment and contaminant transport, etc.) to determine where sources can be found. In addition, the PCB information and linkages to potential sources must make sense from a chemical reasonableness perspective, and it must be possible for a PCB chemist to understand and justify the observations and source identifications; statistical software packages and graphical representations by themselves are insufficient for explaining sources. The previously mentioned RSC contour maps provide a first impression of where sources are located. By combining this data with other site information (including site contaminant use history, other upland and upstream contaminant studies, sediment transport studies, contaminant deposition history with dated cores, etc.), it may be possible to tell not only what sources are present, but where they are located and when they contaminated the sediments.

2.0 GENERAL SUMMARY OF TECHNICAL METHODS

2.1 Introduction to PCBs and PCB Chemistry

Environmental forensics methodologies are well developed for petroleum-originating contamination, and less so for PCB contamination. PCBs were intentionally produced through chlorination of the biphenyl molecule, unlike petroleum and one of their primary constituent PAHs, which are naturally produced and introduced into the environment both by man and through natural processes. This chemical process that produces PCBs places from one to 10 chlorines on available substitution locations on the six-sided biphenyl molecule (Figure 2-1). Multiple naming conventions have been developed to differentiate the 209 possible congeners (a term given to distinguish different PCB compounds with unique combinations of attached chlorines). Early naming conventions relied on substituted chlorine positions to differentiate congeners. These early methods numbered the six "corners" of each ring in the biphenyl structure, and referred to the individual congener by the numbers where substituted chlorines resided (for example see Figure 2-1 where ortho "corners" are at positions labeled 2,6,2',6'; meta "corners" are at 3,5,3',5'; and para is at 4 and 4'). The International Union of Pure and Applied Chemistry (IUPAC) naming conventions later simplified things by sequentially numbering all congeners by increasing chlorine content, from PCB 1 through PCB 209. PCBs can also be simply divided into homolog groups based on the number of chlorine substitutions on the biphenyl rings (mono-, di-, tri-, tetra-, penta-, hexa-, hepta-, octa-, nona-, or deca-chlorobiphenyl). These naming conventions are all shown in Table 2-1. Information on the 10 homologs, including the number of possible PCB congeners for each level of chlorination (i.e., each homolog), is also summarized in Table 2-2.

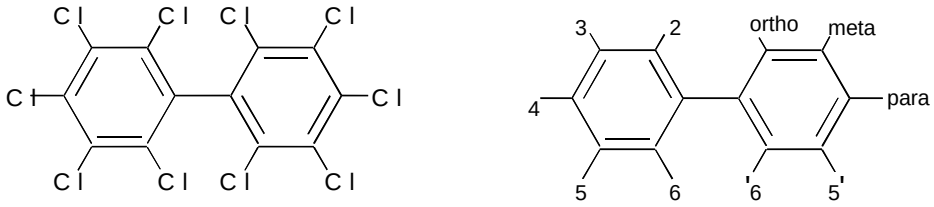


Figure 2-1. PCB Molecule Showing Possible Chlorine Positions

PCBs were produced commercially in the US from 1929 through 1977 by Monsanto Chemical Company. They were produced in specific PCB congener mixtures (termed Aroclors) to obtain chemical properties that were desired for specific industrial applications. PCBs have increasing density, boiling point, and hydrophobicity with increasing levels of chlorination. High molecular weights and boiling points lead to a viscous fluid with low flammability that can tolerate high temperatures without substantial chemical degradation. Most of the PCBs were produced for use in transformers and capacitors, with other uses including hydraulic fluids, carbonless copy paper, printing inks, and other applications [20]. When manufactured in the US by Monsanto, these mixtures were termed Aroclors; those manufactured outside the US by others had trade names such as Clophen (Germany), Prodolec (France), and Phenoclor (Japan). Monsanto reportedly produced from 500,000 to 600,000 metric tons of PCBs (about half the world-wide total) during its almost 50 years of production [21], although most PCBs are no longer being used, some are still held in older equipment and materials (e.g., in landfills) and potentially available for release to the environment.

Table 2-1. The 209 Possible PCB Congeners (IUPAC and Structural Nomenclature)

IUPAC#	Chl Pos	IUPAC#	Chl Pos	IUPAC#	Chl Pos	IUPAC#	Chl Pos
Mono-Chlorobiphenyls		**Tetra-Chlorobiphenyls (cont.)**		**Penta-Chlorobiphenyls (cont.)**		**Hexa-Chlorobiphenyls (cont.)**	
1	2	53	25-2'6'	107	234-3'5'	160	23456-3'
2	3	54	26-2'6'	108	2346-3'	161	2346-3'5'
3	4	55	234-3'	109	235-3'4'	162	235-3'4'5'
Di-Chlorobiphenyls		56	23-3'4'	110	236-3'4'	163	2356-3'4'
4	2-2'	57	235-3'	111	235-3'5'	164	236-3'4'5'
5	23	58	23-3'5'	112	2356-3'	165	2356-3'5'
6	2-3'	59	236-3'	113	236-3'5'	166	23456-4'
7	24	60	234-4'	114	2345-4'	167	245-3'4'5'
8	2-4'	61	2345	115	2346-4'	168	246-3'4'5'
9	25	62	2346	116	23456	169	345-3'4'5'
10	26	63	235-4'	117	2356-4'	**Hepta-chlorobiphenyls**	
11	3-3'	64	236-4'	118	245-3'4'	170	2345-2'3'4'
12	34	65	2356	119	246-3'4'	171	2346-2'3'4'
13	3-4'	66	24-3'4'	120	245-3'5'	172	2345-2'3'5'
14	35	67	245-3'	121	246-3'5'	173	23456-2'3'
15	4-4'	68	24-3'5'	122	345-2'3'	174	2345-2'3'6'
Tri-chlorobiphenyls		69	246-3'	123	345-2'4'	175	2345-2'3'5'
16	23-2'	70	25-34'	124	345-2'5'	176	2346-2'3'6'
17	24-2'	71	26-3'4'	125	345-2'6'	177	2356-2'3'4'
18	25-2'	72	25-3'5'	126	345-3'4'	178	2356-2'3'5'
19	26-2'	73	26-35	127	345-3'5'	179	2356-236
20	23-3'	74	245-4'	**Hexa-chlorobiphenyls**		180	2345-2'4'5'
21	234	75	246-4'	128	234-2'3'4'	181	23456-2'4'
22	23-4'	76	345-2'	129	2345-2'3'	182	2345-2'4'6'
23	235	77	34-3'4'	130	234-2'3'5'	183	2346-2'4'5'
24	236	78	345-3'	131	2346-2'3'	184	2346-2'4'6'
25	24-3'	79	34-3'5'	132	234-2'3'6'	185	23456-2'5'
26	25-3'	80	35-3'5'	133	235-2'3'5'	186	23456-2'6'
27	26-3'	81	345-4'	134	2356-2'3'	187	2356-2'4'5'
28	24-4'	**Penta-chlorobiphenyls**		135	235-2'3'6'	188	2356-2'4'6'
29	245	82	234-2'3'	136	236-2'3'6'	189	2345-3'4'5'
30	246	83	235-2'3'	137	2345-2'4'	190	23456-3'4'
31	25-4'	84	236-2'3'	138	234-2'4'5'	191	2346-3'4'5'
32	26-4'	85	234-2'4'	139	2346-2'4'	192	23456-3'5'
33	34-2	86	2345-2'	140	234-2'4'6'	193	2356-3'4'5'
34	35-2'	87	234-2'5'	141	2345-2'5'	**Octa-chlorobiphenyls**	
35	34-3'	88	2346-2'	142	23456-2'	194	2345-2'3'4'5'
36	35-3'	89	234-2'6'	143	2345-2'6'	195	23456-2'3'4'
37	34-4'	90	235-2'4'	144	2346-2'5'	196	2345-2'3'4'6'
38	345	91	236-2'4'	145	2346-2'6'	197	2346-2'3'4'6'
39	35-4'	92	235-2'5'	146	235-2'4'5'	198	23456-2'3'5'
Tetra-chlorobiphenyls		93	2356-2'	147	2356-2'4'	199	2345-2'3'5'6'
40	23-2'3'	94	235-2'6'	148	235-2'4'6'	200	23456-2'3'6'
41	234-2'	95	236-2'5'	149	236-2'4'5'	201	2346-2'3'5'6'
42	23-2'4'	96	236-2'6'	150	236-2'4'6'	202	2356-2'3'5'6'

Table 2-1. The 209 Possible PCB Congeners (IUPAC and Structural Nomenclature) [Continued]

IUPAC#	Chl Pos	IUPAC#	Chl Pos	IUPAC#	Chl Pos	IUPAC#	Chl Pos
Mono-Chlorobiphenyls		**Tetra-Chlorobiphenyls (cont.)**		**Penta-Chlorobiphenyls (cont.)**		**Hexa-Chlorobiphenyls (cont.)**	
43	235-2'	97	245-2'3'	151	2356-2'5'	203	23456-2'4'5'
44	23-2'5'	98	246-2'3'	152	2356-2'6'	204	23456-2'4'6'
45	236-2'	99	245-2'4'	153	245-2'4'5'	205	23456-3'4'5'
46	23-2'6'	100	246-2'4'	154	245-2'4'6'	**Nona-chlorobiphenyls**	
47	24-2'4'	101	245-2'5'	155	246-2'4'6'	206	23456-2'3'4'5'
48	245-2'	102	245-2'6'	156	2345-3'4'	207	23456-2'3'4'6'
49	24-2'5'	103	246-2'5'	157	234-3'4'5'	208	23456-2'3'5'6'
50	246-2'	104	246-2'6'	158	2346-3'4'	**Deca-chlorobiphenyl**	
51	24-2'6'	105	234-3'4'	159	2345-3'5'	209	23456-2'3'4'5'6'
52	25-2'5'	106	2345-3'				

Table 2-2. PCB Homologs and Number of Congeners within Each Homolog Group

Homolog	Chemical Formula	Number of Chlorines	Number of Congeners in Homolog Group
Mono-chlorobiphenyl	$C_{12}H_9Cl$	1	3
Di-chlorobiphenyl	$C_{12}H_8Cl_2$	2	12
Tri-chlorobiphenyl	$C_{12}H_7Cl_3$	3	24
Tetra-chlorobiphenyl	$C_{12}H_6Cl_4$	4	42
Penta-chlorobiphenyl	$C_{12}H_5Cl_5$	5	46
Hexa-chlorobiphenyl	$C_{12}H_4Cl_6$	6	42
Hepta-chlorobiphenyl	$C_{12}H_3Cl_7$	7	24
Octa-chlorobiphenyl	$C_{12}H_2Cl_8$	8	12
Nona-chlorobiphenyl	$C_{12}H_1Cl_9$	9	3
Deca-chlorobiphenyl	$C_{12}Cl_{10}$	10	1

Only a limited number of Aroclor mixtures were produced in the US, each with a distinct homolog and congener fingerprint. Table 2-3 lists the nine major Aroclors produced in the US, and their PCB homolog composition; Aroclors 1016, 1242, 1254, and 1260 together comprised more than 90% of the PCBs that were produced in the US. A few additional Aroclors were produced, but only in small quantities. Aroclors carried a four digit numbering convention. For many years it was reported/repeated in the literature, and often taken as fact that the first two digits in the Aroclor naming convention represented the number of carbon atoms on the molecule and the last two digits represented the average weight percent chlorine in the formulation. The latter half of that explanation is true: the "60" in Aroclor 1260 indicates that is has a mixture of PCB congeners that result in 60% chlorine by weight. A recent paper by Erickson and Kaley [22] suggest that the 12-carbon part of that common explanation may be incorrect. While PCB congeners do indeed contain 12 carbons, the "12" indicates only that the product is refined PCB.

Hence, nearly all PCB Aroclors follow the naming convention "12xx" (Aroclor 1016 which was produced as a replacement for Aroclor 1242 being the sole exception). Erickson and Kaley [22] point out that if the "12=12 carbon atoms" myth was true, the first two digits of Monsanto's line of PCT products would have been "18," since there are 18 carbon atoms in the terphenyl molecule, assuming the same naming rules were used for PCT as for PCB. But PCT products were named using a 5000 series convention (such as Aroclor 5460 – a PCT product with 60% chlorine).

Table 2-3. PCB Homolog Composition of the Nine Major Aroclors Produced in the US

	Level of Chlorination/Homolog % Composition									
Aroclor	**Mono**	**Di**	**Tri**	**Tetra**	**Penta**	**Hexa**	**Hepta**	**Octa**	**Nona**	**Deca**
A1221	60.1	33.4	4.2	1.2	1.1	0	0	0	0	0
A1232	27.5	26.8	25.5	10.6	9.4	0.2	<0.1	0	0	0
A1016*	0.7	17.5	54.6	22.1	5.1	0	0	0	0	0
A1242*	0.7	15.0	44.9	20.3	18.8	0.3	0	0	0	0
A1248	<0.1	1.1	21.4	32.9	42.9	1.6	<0.1	0	0	0
A1254*	<0.1	0.2	1.3	10.2	59.1	26.8	2.7	<0.1	<0.1	0
A1260*	<0.1	<0.1	0.2	0.4	8.7	43.2	38.4	8.3	0.7	0
A1262	<0.1	0.2	0.4	0.5	3.4	26.4	48.5	19.7	1.6	0
A1268	0	0	<0.1	0.1	0.2	4.4	10.1	45.0	35.0	4.8

From Frame et al., 1996 [23] and Kannan et al., 1997 [24].

*Aroclors 1016, 1242, 1254, and 1260 accounted for >90% of the PCB production.

Each Aroclor mixture was a unique combination of up to approximately 50 individual congeners of significant relative concentration, formulated to provide specific chemical properties. A total of a little more than 100 of the possible 209 PCB congeners were included in the different Aroclor formulations at easily detectable levels, and a few additional congeners may be detected in environmental samples as a result of environmental transformation processes. A set of about 120 PCB congeners can describe more than 99% of the total PCB in all Aroclor formulations and environmental samples, and most of the rest of the possible congeners were never produced or are rarely detected above ultra-trace levels. Information on the PCB congener composition of Aroclors is presented in Appendix A (based on Rushneck et al. [25]), including a series of plots showing the concentrations of a set of 80 major PCB congeners.

Given that only a few distinct Aroclors were produced, and their generally stable chemical characteristic, one might assume fingerprinting the distinct Aroclor sources should be a relatively easy exercise. Figure 2-2 shows the composition of 18 major PCB congeners in fresh Aroclor 1248 and 1260 PCB material, illustrating that one can easily discriminate individual Aroclors even with this relatively small subset of 18 NOAA Status and Trends Program congeners. However, environmental PCB contamination is rarely from a single Aroclor and environmental PCB contamination rarely resembles a fresh Aroclor material; environmental processes and comingling from multiple sources significantly complicate PCB environmental forensics. Furthermore, the changes due to environmental processes (i.e., "weathering" processes) can be difficult to predict (i.e., they are not simply correlated to molecular weight or solubility).

PCB Materials

This section presents an overview of PCB chemistry and its behavior in the environment. PCBs are typically described as:

- **PCB Congeners.** The individual PCB compounds. There are 209 PCB congeners, a subset of which were present in commercial PCB formulations and found in PCB contamination.
- **PCB homologues.** The categories of PCB congeners with equal numbers of chlorine substitutions, or levels of chlorination. There are 10 PCB homologues.
- **PCB Aroclors.** Mixtures of PCB congener mixtures that were most commonly sold and used in the US. A total of nine Aroclors are most commonly described, but a few other rare Aroclors also existed.

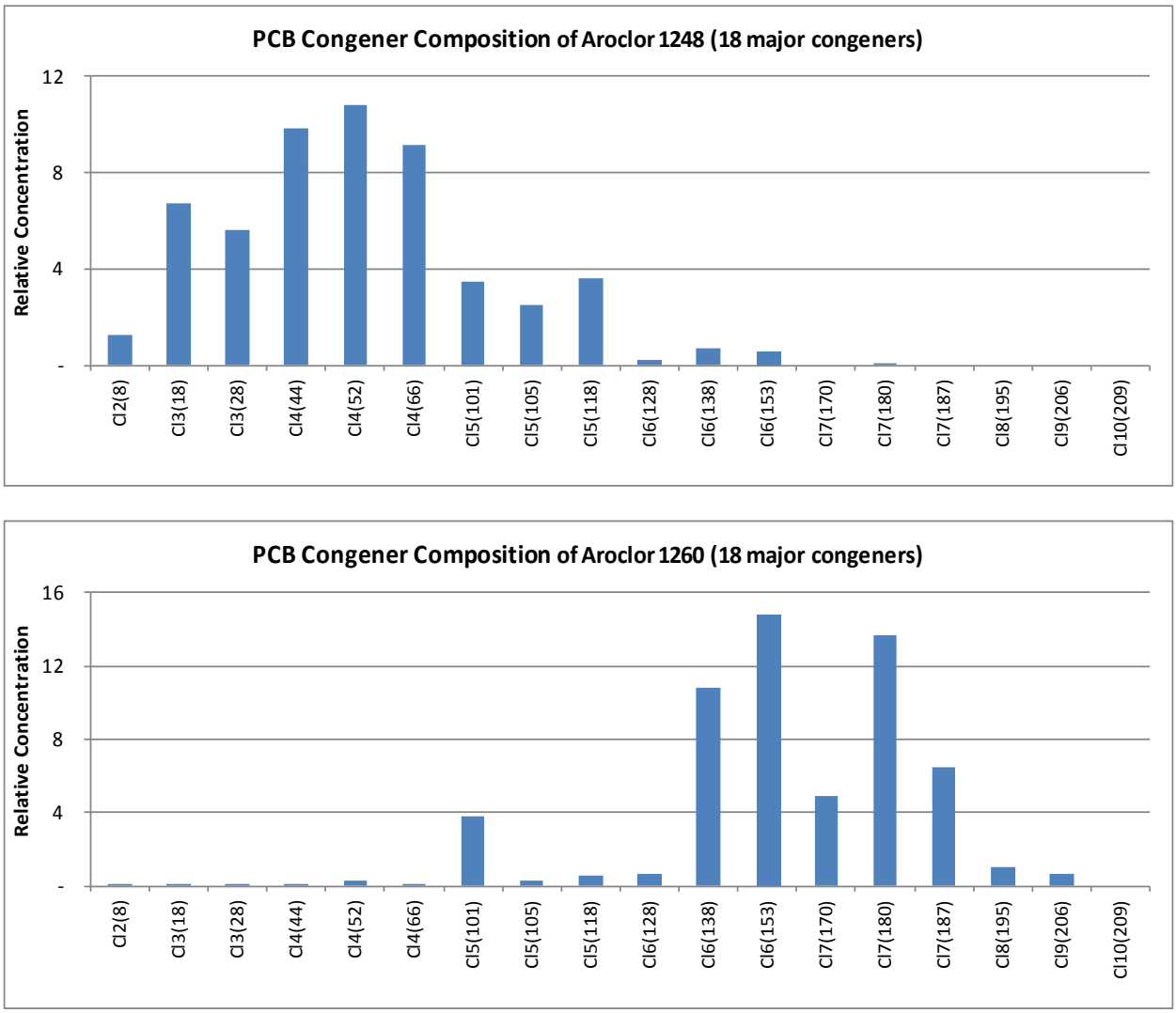


Figure 2-2. PCB Congener Composition of Aroclors 1248 (top) and 1260 (bottom)

The same properties that led to their usefulness for industrial applications also led to PCBs becoming an environmental problem. PCBs resist thermal and other degradation processes; they are stable and thus persist in the environment. The chemical characteristics of PCB also mean that they have low water solubility and adhere to solid soil and sediment particles rather than freely dissolving in water or volatilizing to air; they have high octanol/water partitioning coefficients (k_{ow}) and are therefore lipophilic ("fat loving" rather than hydrophilic or "water loving") and tend to partition into organic phases.

Their hydrophobic nature means that PCBs are usually associated with the organic carbon fractions of soils and sediments (i.e., they concentrate in organic rich sediment, as opposed to sandy sediment); they also accumulate in fatty biological tissue. When organisms consume PCB-containing material (e.g., organic matter or other organisms) some become associated with the lipid fraction of the organism, and some may not be readily metabolized or excreted. This process results in some of the PCBs biomagnifying, or increasing in concentration as PCBs are consumed by higher trophic level organisms, rather than being lost from the organism. Although PCBs may be persistent in the environment because they are recalcitrant, they can still undergo some degradation and alteration in the environment, as well as within the tissue of organism. PCBs as a group are considered very stable and persistent, but they are in fact a diverse mixture of molecules (PCB congeners) with varying chemical properties, including large congener-to-congener differences in the rates of and susceptibility to degradation and alteration. In general, the less chlorinated congeners will be more soluble and volatile. More chlorinated congeners are more hydrophobic and tend to accumulate in organic rich sediments, bioaccumulate up the food chain, and fractionated into the fatty tissues in organisms to a higher degree. Within organisms, different congeners will bioaccumulate and metabolize at different rates, so additional biological fractionation can occur. PCB congeners can also undergo microbial dechlorination, particularly in anaerobic sediments, and the susceptibility to dechlorination is highly dependent on the structure of the PCB molecule (i.e., the degree of chlorination and position of the chlorines on the biphenyl molecule); the environmental PCB composition can thus also be altered by dechlorination processes.

PCB dechlorination can be a particularly confounding PCB transformation process that complicates PCB source identification and PCB analytical chemistry. In anaerobic sediments, certain bacterial groups have been found to be able to dechlorinate PCBs given the right conditions. Long-term studies of contaminated sediments [26, 27] have shown specific bacterial groups have distinctive dechlorination patterns, transforming certain PCB congeners to less chlorinated congeners as chlorines are removed. Specific dechlorination pathways have been documented, and can be predicted [16]. Figure 2-3 illustrates a few examples of potential dechlorination pathways. The dechlorination potential is rather complicated, and depends on factors such as the position of the chlorine subject to dechlorination as well as the number and positions of other chlorines on the molecule, and the overall level of chlorination.

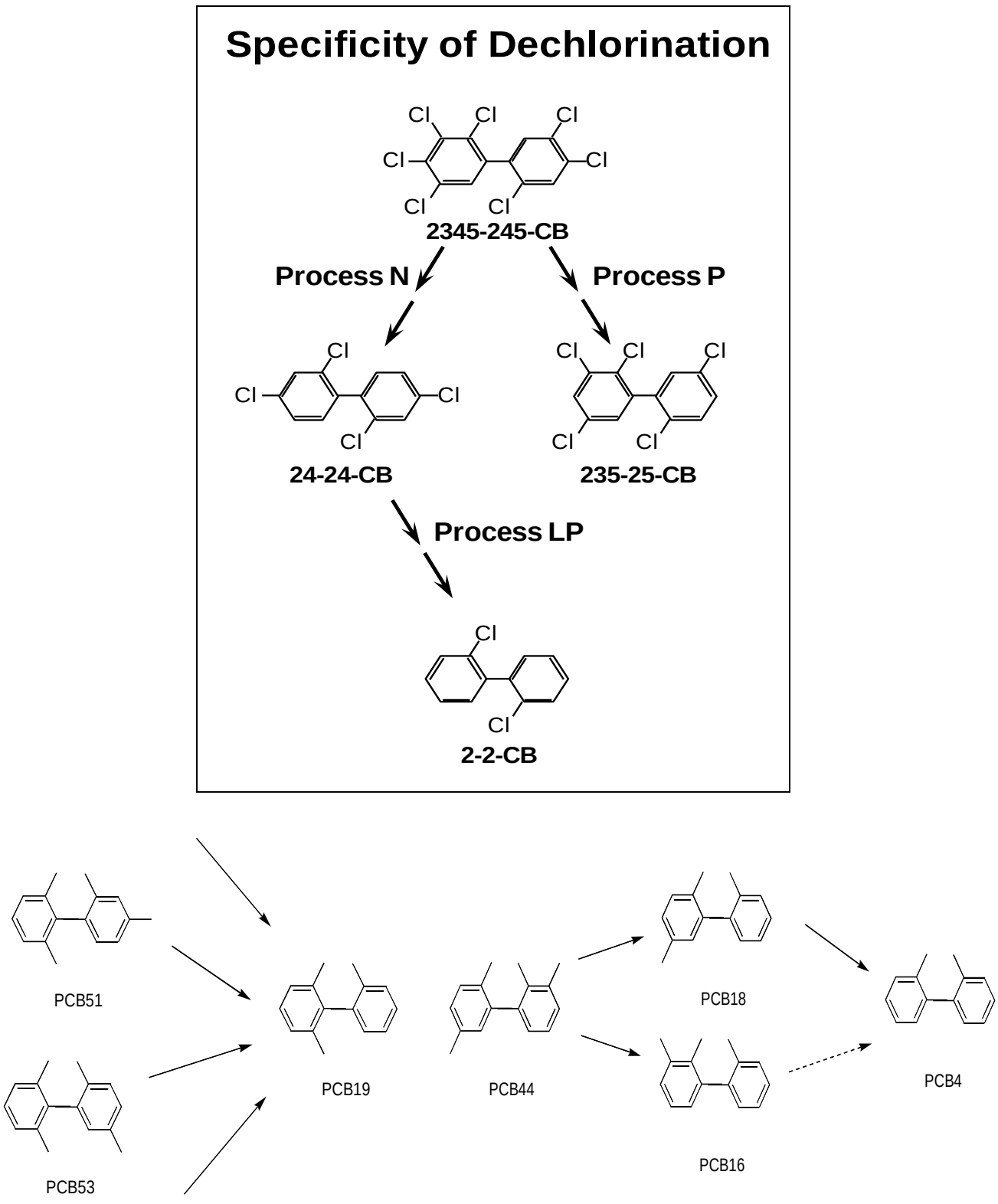


Figure 2-3. Example of Documented PCB Dechlorination Processes and Pathways, Including Pathways Resulting in an Increase in PCB19 and PCB4 Concentrations

Table 2-4. PCB Congeners Susceptible to and Resistant to Dechlorination Mono- to hexa-chlorobiphenyls [28]

Congeners with High *Potential* for Dechlorination (possible dechlorination product congener are listed in parenthesis for major PCB congeners)			**Congeners with High *Resistance* to Dechlorination**
Double Flanked m/p-substitution	Single Flanked m/p-substitution	Unflanked m/p-substitution on di- or tri-substituted ring	All o-substitutions, mono-substituted, or non-para mono-substituted rings
21	5	7	1
38	12	***9*** (1)	2
41 (17)	***16*** (4)	14	3
55	***20*** (6)	***17*** (4)	4
60 (28)	***22*** (8)	***18*** (4)	6
61	23	***25*** (6)	10
62	24	***26*** (6)	11
76	29	***28*** (8)	19
78	***33*** (8, 6)	30	27
81	35	***31*** (8)	32
82 (42)	***37*** (15, 13)	34	54
85 (47)	***40*** (16)	36	
87 (49)	***42*** (17)	39	
88	43	***47*** (17)	
89	***44*** (18)	***49*** (17, 18)	
105 (66)	***45*** (19)	50	
106	***46*** (19)	51	
108	***48*** (17, 18)	***52*** (18)	
109	***56*** (33, 22, 20)	53	
114	57	***66*** (28, 25)	
115	58	69	
116	59	72	
122	63	75	
123	***64*** (32)	80	
124	65	86	
125	67	100	
126	68	103	
127	***70*** (31, 26)	104	
128 (85)	***71*** (32, 27)	121	
129	73	155	
130 (90)	***74*** (28, 31)		
131	77		
132 (91)	79		
137 (99, 90)	***83*** (44, 43)		
138 (99)	***84*** (46, 45)		
139	86		
140	90 (49)		
141 (101, 92)	***91*** (51)		
142	***92*** (52)		
143	93		
144 (103)	94		
145	***95*** (53)		
156 (118, 107)	96		
157	***97*** (48, 42, 44)		
158 (119)	98		

Table 2-4. PCB Congeners Susceptible to and Resistant to Dechlorination. Mono- to hexa-chlorobiphenyls [28] (Continued)

Congeners with High *Potential* for Dechlorination (possible dechlorination product congener are listed in parenthesis for major PCB congeners)			**Congeners with High *Resistance* to Dechlorination**
Double Flanked m/p-substitution	Single Flanked m/p-substitution	Unflanked m/p-substitution on di- or tri-substituted ring	All o-substitutions, mono-substituted, or non-para mono-substituted rings
159	***99*** (47, 49)		
160	***101*** (49, 52)		
161	102 (51)		
162	***107*** (70, 63, 56, 57)		
164 (110, 113)	***110*** (71, 64, 59)		
166	111		
167	112		
168	113		
169	117		
	118 (66, 74, 70)		
	119		
	120		
	133		
	134		
	135 (95, 94)		
	136 (96)		
	146 (101, 90, 92)		
	147 (91)		
	148		
	149 (102, 90, 92)		
	150		
	151 (95)		
	152		
	153 (99, 101)		
	154 (100)		
	163 (117, 110)		
	165		

Bolded and italicized congeners are present at ~0.25% or more in Aroclors 1016/1242, 1248, 1254, and/or 1260.
Only congeners with up to six chlorines are listed; more chlorinated congeners are less susceptible to dechlorination.

In general, meta-substituted chlorines are dechlorinated most readily (process N in Figure 2-3), followed by para-substituted chlorines (process P in Figure 2-3). The presence of adjacent chlorines (i.e., "flanked" meta- and para-substituted chlorine) increases the susceptibility to dechlorination. A double-flanked meta-substituted congener (i.e., with also a chlorine in the adjacent para- and ortho-positions) is particularly susceptible to dechlorination of the chlorine in the meta position [28, 29]. Ortho-substituted chlorines are significantly less likely to be removed through dechlorination and, over time, the primarily ortho-substituted PCB congeners therefore increase in relative concentration if a significant amount of anaerobic dechlorination is occurring in the sediment. The most heavily chlorinated PCB congeners (e.g., hepta-, octa-, nona- and deca-chlorobiphenyls; Table 2-1) tend to be less susceptible to dechlorination than the less chlorinated congeners (e.g., tri-, tetra-, penta-, and hexa-chlorobiphenyls). Table 2-4 presents a summary of congeners (by IUPAC congener number) that are particularly susceptible to dechlorination because of the described chlorine substitution on their molecules, as well as congeners that are relatively resistant to dechlorination. Congeners with high relative concentrations in common Aroclor formulations and much environmental contamination are indicated in bold. PCB dechlorination, in and of itself, does not remove PCBs; it only alters the composition of the PCB congeners. However, dechlorination does transform the PCB into forms that are more amenable to mineralization processes that can occur.

Dechlorination pathways have been used in fingerprinting studies to follow the changes in PCB composition to reconstruct the original source fingerprints [8]. Figure 2-4 (top) illustrates the PCB composition in surface sediment samples from a site in Lake Hartwell, NC, which closely resembles that of the known contamination source (a mixture of Aroclors 1242 and 1254). The bottom portion of Figure 2-4 illustrates the PCB composition in buried sediment which has been significantly dechlorinated and no longer resembles the known source material.

Figure 2-5 illustrates the difference in the PCB congener composition of the deeper and the surface sediment. The dechlorinated sediments have an increase in and very high relative proportion of PCB congeners with primarily ortho substitution (e.g., PCB4 [chlorines in the 2,2' positions], PCB10 [2,6], and PCB19 [2,6,2']), and a decrease in concentration of congeners with meta-substituted chlorines highly susceptible to dechlorination (e.g., PCB22, PCB28, PCB33, PCB44); see Tables 2-1 and 2-4, and Figures 2-1 and 2-3. The deeper, "older", sediments had no PCB compositional resemblance to Aroclors 1242 and 1254, or any other Aroclor, but could be linked to Aroclors 1242 and 1254 as the source material by understanding the chemical processes and through dechlorination pathway and deconvolution analysis [8]. Another important result of significant dechlorination is that PCB-as-Aroclor analysis, which remains the most widely used laboratory PCB analytical method, often results in large errors in the reported PCB concentration of such samples, and may even miss the presence of PCBs altogether. It would not be surprising, for instance, if the sample illustrated in Figure 2-4 (bottom) would be reported as "no PCB detected", even though the sample had very high PCB concentrations, simply because the PCB composition no longer resembles Aroclor material.

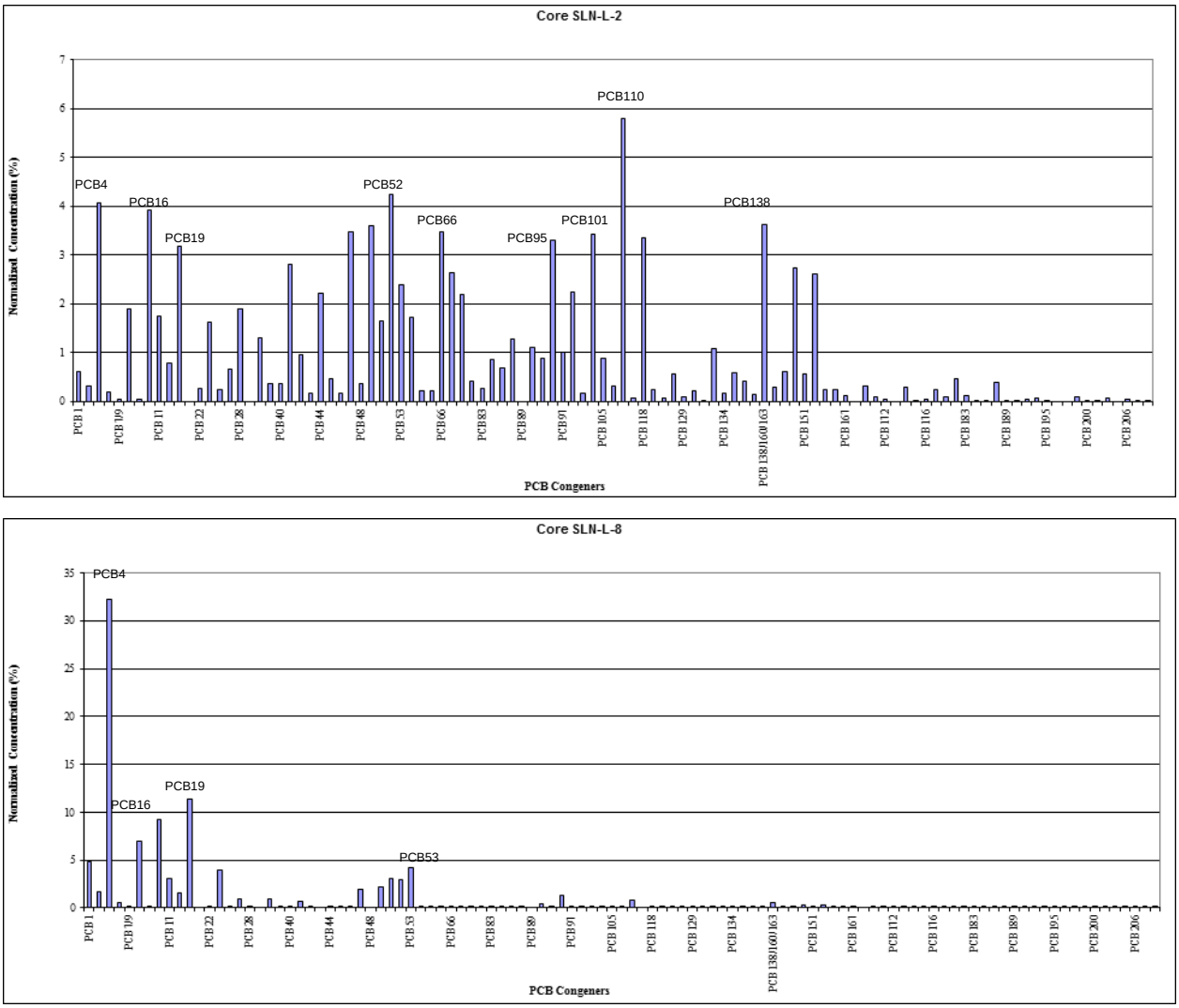


Figure 2-4. PCB Congener Distribution in a Surface (top) and Deep (bottom) Sediment Sample Collected at Location L at Lake Hartwell [6]

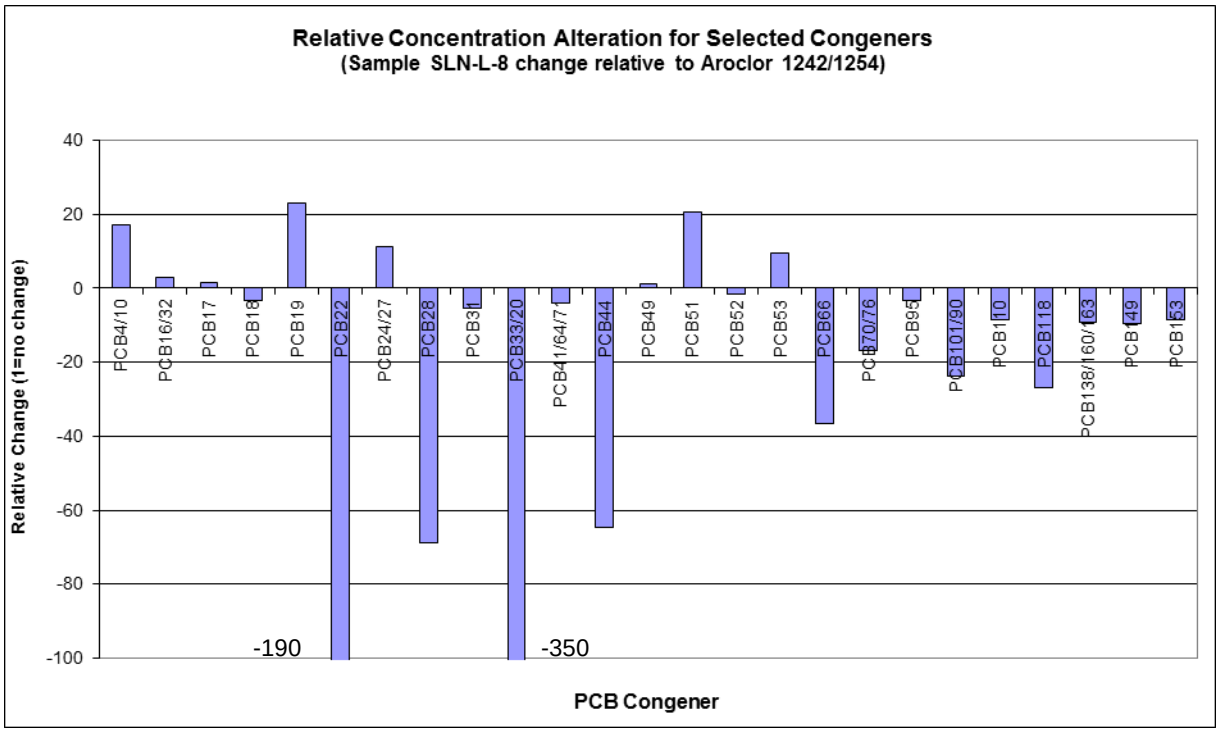


Figure 2-5. Change in Relative PCB Congener Concentrations in a Deep Sediment Sample from Location L at Lake Hartwell Compared to Aroclor 1242/1254

Linking PCB contamination in biological tissue to sources is particularly challenging since one must consider not only the alterations in the environment prior to animal exposure (e.g., selective dissolution, adsorption, and dechlorination processes), but also the biological fractionation in PCB patterns due to differences in uptake and loss of different PCB congeners. The more chlorinated congeners are more lipophilic and have a greater affinity for bioaccumulation, but some congeners also may pass across cell membranes differently from other congeners due to the chlorine substitution pattern on the molecule; different types of biological fractionation occur.

Planar congeners (those with no chlorines in the ortho positions, allowing the molecule to be "flat") are more likely to pass through cell membranes than PCB molecules with ortho-substituted chlorines across from each other (i.e., in the 2,2' and 6,6' positions; Figure 2-1). The World Health Organization (WHO) has identified a set of 13 planar, or mono-ortho substituted, congeners that are of particular concern for human health (Table 2-5). Likewise during metabolism different congeners may show preferential losses, so again biological fractionation can occur. For these and other reasons, it becomes increasingly difficult to trace PCB patterns from tissues back to original sources. But linking PCB tissue data to sediment sources has been done, and some studies [4] have even attempted to fingerprint human blood samples to match ingested fish as likely exposure sources for PCBs in human health studies. This short review demonstrates the need to understand the very complex PCB fate and transport processes in the environment since they impact the observed PCB congener composition in the different environmental matrices, and the ability to associate with sources. If exposure pathways are

going to be traced back to original sources, these types of physical, chemical and biological processes must be better understood (see [4]; and references therein).

Table 2-5. World Health Organization (WHO) List of Toxic PCB Congeners and Their 2,3,7,8-TCDD Toxic Equivalency Factors for Mammals

PCB Congener		Toxic Equivalency Factor (relative to 2,3,7,8-TCDD[a])
Congener Number (IUPAC)	Congener "Type" (chlorine substitution characteristics)	
PCB77	Non-ortho substituted (coplanar)	0.00010
PCB81	Non-ortho substituted (coplanar)	0.00030
PCB105	Mono-ortho substituted	0.00003
PCB114	Mono-ortho substituted	0.00003
PCB118	Mono-ortho substituted	0.00003
PCB123	Mono-ortho substituted	0.00003
PCB126	Non-ortho substituted (coplanar)	0.10000
PCB156	Mono-ortho substituted	0.00003
PCB157	Mono-ortho substituted	0.00003
PCB167	Mono-ortho substituted	0.00003
PCB169	Non-ortho substituted (coplanar)	0.03000
PCB189	Mono-ortho substituted	0.00003

[a] 2,3,7,8-TCDD toxicity is commonly used as a reference for the toxicity of "dioxin like" PCB congeners.

Although PCBs were produced as specific Aroclor mixtures of congeners because of the physical/chemical (solubility, adsorption, volatility, etc.) and biological (bacterial dechlorination, organism metabolism, etc.) processes described, environmental samples are often found with different mixtures and with very different PCB congener composition, and confound the PCB fingerprinting [4, 16, 30]. These various processes alter the congener patterns once the PCB is released into the environment. The impact of weathering and degradation on source patterns is always a concern in environmental forensics; given a situation of multiple sources, and patterns modified by one or more alteration processes, source apportionment can be difficult. For instance, one can easily imagine an onshore spill or source of PCB oil that results in a soil contaminated with PCBs. Subsequent erosion can bring soil particles into surface water bodies where they can deposit out as PCB-contaminated sediments. In aqueous settings, lower weight congeners are more easily dissolved and transported away, and higher molecular weight congeners are more strongly adsorbed to organic matter, so the remaining sediment PCB composition possesses a greater proportion of high molecular weight congeners than that found in the original mixture. If the sediments are anaerobic, microbial dechlorination may occur, and more so for congeners with specific molecular structure. The PCB in the sediments would have a very different composition than the original PCB release due to these environmental processes, and the compositional alteration continues as long as the PCB is exposed to the natural environment.

Taken together, the potential alteration processes demonstrate that the "simple" exercise in fingerprinting environmental samples using a few possible PCB source signatures (i.e., Aroclor patterns, or even a set of PCB congeners) may in fact become a substantially more difficult problem. The compositional analysis and interpretation often require knowledge of the potential

alteration mechanisms to "back out" their effects before identifying the actual original source fingerprints, and associating field samples and sources. In addition, the fact that the PCB congener composition changes in the environment limits the use of Aroclor analyses for identifying contamination sources to only fresh samples (for example, PCB oils or soils with freshly spilled PCB); typical environmental samples require more extensive congener analysis in conjunction with data analysis methods and an understanding of PCB chemistry to be able to determine sources. However, even given the complex PCB compositional alteration scenarios, the data analysis methods discussed in this document are valuable tools to identify sources and estimate both the original source profiles and alteration patterns [8, 31-35].

2.2 Establishing a General Understanding of the Site

It is important to establish an understanding of the site that goes well beyond the PCB contamination characteristics to fully understand the contaminant situation and establish the relationship between the sediment contamination and potential sources. Two key components are: (1) establishing the site history through records and other information research, and (2) establishing the hydrodynamics and sediment transport characteristics of the site.

2.2.1 Site History and Records Research

A crucial aspect of a PCB forensics investigation is determining a relationship between the contamination observed in the sediments and historical activities at or near the site, including recent and historical operations and releases. This requires an understanding of site history, and the history of the area around the site that could have impacted the site. If one cannot identify historical industrial activities, processes, material handling, and possible release and transport scenarios that can explain the sediment contamination, the forensic investigation would be missing an important puzzle piece.

The availability of records can vary widely from project to project, but it is important to devote significant effort to the site history and records research as part of the forensic investigation, and preferably early in the process during the planning phase. In terms of determining potential sources of PCBs in sediments, the types of information that are usually the focus of a records search include:

1. Identifying current and historical production/operations for the properties that could have contaminated the sediments through intentional or unintentional discharge/runoff.
2. Identifying PCB-related activities (e.g., transformer/capacitor use, carbonless copy paper, hydraulic fluid, marine paints) by the potential contributors of sediment contamination, and the timeframe of their use.
3. Identifying historical waste handling and disposal for PCB containing materials/waste.
4. Identifying possible migration pathways to sediment (e.g., waste disposal, landfills, drainage ditches and creeks receiving runoff), and how those have changed over time.
5. Reviewing historical environmental investigation reports and data.
6. Reviewing historical remedial activities, and summarizing their implications on the history of the contamination.

7. Summarizing the activities and site characteristics that may have involved PCBs, the possible history (years) of releases, and possible migration pathways to the sediments.

Conducting a comprehensive site history investigation can be difficult and time consuming, depending on how readily available the information is. The challenges include:

- The nature, volume, and availability of relevant documents vary greatly from project to project.
- Unlike when generating new data, the existence of useful historical information cannot be guaranteed.
- Even information that exists may be forgotten or inaccessible in archived files.
- Identifying the specific information that is relevant to a PCB forensics study, as it may be a small percentage of the available material. Historical document review can become a time-consuming search for a few relevant needles in a very large haystack.
- Obtaining historical information may be particularly challenging if it is perceived that it may implicate them as a PCB source.
- It is often difficult to develop a plan or scope of work for conducting historical records research because the types, locations, and availability of information may be unknown.

However, the potential importance of a thorough historical investigation often far outweighs the challenges, and should be pursued. The following is a summary of possible sources of potentially important historical information, which are described in more detail in Section 2.5.3.

- **Internal Corporate/Facility Documents**. Internal communications and other records of their operations over time, and maybe also study reports of prior site investigations.
- **State and Federal Regulatory Files**. If environmental investigations have been conducted at a site under regulatory authority, then data and reports should be publically available.
- **Publications**. Published literature may provide general information on industrial/commercial use of PCBs, but site-specific studies may also be in the published literature.
- **Interviews**. Interviews with current and past workers and residents can be very useful.
- **Aerial Photographs/Remote Sensing**. Aerial photographs and other remote imaging and sensing information can be purchased, and can be very useful to document the characteristics and changes at a site.

2.2.2 Sediment Transport and Hydrodynamics

It is critical to understand the water and sediment dynamics of a system to be able to understand how contaminants may move from their sources to where they were sampled and measured. This includes drainage, runoff, and discharge from a potential source location, to the movement of waters and sediment in the receiving environment which usually is the primary study site.

Contaminant fate and transport in aquatic systems are influenced by a range of physical, chemical, and biological processes. Physical processes significantly affect the fate and transport of hydrophobic organic contaminants (HOCs), such as PCBs, as well as many inorganic contaminants such as lead and mercury, because they are naturally adsorbed to particles in the sediment bed or suspended in the water column. Often, sediment resuspension, transport, and deposition are the largest components of contaminant transport at a given site. Moreover, the success of many remediation approaches such as in situ capping, dredging, and natural recovery is directly affected by physical sediment transport processes. The effects of physical processes must be evaluated in conjunction with the effects of chemical and biological processes to assess overall fate and transport at a site.

Many Navy sediment sites are located in areas of relatively low hydrodynamic energy such as rivers, bays, and estuaries, where sediments and contaminants tend to accumulate over time. In some cases, the original source(s) of contamination have been eliminated, reduced, or controlled as environmental management practices improved over the past 50 years. At some sites, the deposition of newer, relatively clean sediment on top of more contaminated sediment has resulted in burial of contamination. The most common sediment management questions associated with these sites are as follows:

- Could erosion of the sediment bed lead to the exposure of buried contamination?
- Will sediment transport lead to the redistribution of contamination within the site, or movement of contamination off site?
- Will natural processes lead to the burial and isolation of contamination by relatively clean sediment?
- If a site is actively remediated, could sediment transport lead to the recontamination of the site?

Blake et al. [36] developed a user's guide to address these sediment transport issues. It focuses on the collection and analysis of data needed to address these primary questions. A combination of regional and historical data, site-specific measurements, empirical data evaluation methods, and numerical modeling techniques can be used to characterize sediment transport at a given site. Empirical approaches are particularly useful for characterizing the past and present effects of sediment transport; however, numerical models are more useful for predicting the effects of future events and sediment deposition patterns. The appropriate method(s) and tool(s) should be selected and used on a site-specific basis to qualitatively and/or quantitatively characterize sediment transport, and assess the viability of various remedial options. The approach for a given site will depend upon the size and complexity of the site, the CSM, the specific site objectives, and the available resources.

Information on sediment stability, sediment transport, and other hydrodynamic information (e.g., circulation, currents, tides) are not only important for sediment management considerations, but are essential to help understand the distribution of contamination in a system, and link the contamination to potential sources. An understanding of contaminant transport is essential in any environmental forensic investigation to explain how contamination from a source can be

found where it is ultimately detected in the environment. Sometimes, these locations are not simply immediately downstream from the release.

2.3 Sampling Design and Sample Collection

As noted in the previous section, PCBs tend to be particle bound and selectively associated with such environmental matrices. Even in studies of PCBs in water samples [17], the majority of the PCBs tend to be associated with the suspended solids in the water. By studying suspended material in water samples, recent source information may be determined, possibly identifying active sources that can be targeted in compliance programs such as total maximum daily loads (TMDLs). Surface sediments obtained with surface grab samples similarly provide data on recently deposited sediments and potentially active sources, and often provide similar information as the suspended material in water samples. Deeper, buried sediment samples (ideally with the aid of a sediment age dating technique) may provide a historical record of source contributions to a water body. Depending on the temporal and spatial information needs developed in the study design, a combination of sample matrices and sampling types may be required. Some forensics studies have sampled both sediment and biological tissue (e.g., fish) at the same locations to also follow PCB pathways through the food web. If fish consumption is a risk driver at a site, it may be important to identify the source of the PCBs. Regardless of the management driver (e.g., a sediment or tissue PCB concentration), it is important that the source(s) is identified to ensure it is controlled before considering any remediation.

The sampling design is typically based on some sort of a statistical based sampling (e.g., random, systematic, stratified, cluster, etc.) or professional judgment that can be justified technically, based upon the information assembled in the CSM. Sampling designs are often site-specific and require consideration of many aspects of the study design. These types of considerations are addressed in many references (e.g., [12], and references herein). The extent and density of sampling (i.e., spatial coverage) is usually the issue requiring the greatest consideration in developing a sampling design strategy. It is the number of samples that will largely determine the cost of the project and the confidence in the data analysis. By using a tiered study design that allows RSC data to first characterize the overall PCB concentration (e.g., through geographic information system [GIS]-based concentration contouring), it can be designed to more cost effectively generate the ACF data.

Sediments can be collected with either surface grabs or subsurface coring systems, depending on the objectives of the particular study. Surface grabs (such as Van Veen grabs; Figure 2-6) recover only the surface sediments and therefore are used to recover sediments that represent more recent conditions. Subsurface sediment cores (such as Vibracores or piston cores; Figure 2-7) are used to recover subsurface sediments which cover a longer time period and therefore may provide a historical record of sediment deposition. Sediment cores can also be collected and analyzed for age dating, using lead and cesium isotope (Pb-210 and Cs-137) techniques, to determine the age (approximate year of deposition) of the sediment deposition at different depths, by determining the rate of sediment deposition (usually in cm/yr). Such information on specific years that subsurface sediment was deposited can be extremely useful for associating the contamination at different depths with site and other historical activities, and, generally, helps to better understand the contamination history.

Figure 2-6. Van Veen Sediment Grab Sampler and Sediment from Inside the Grab

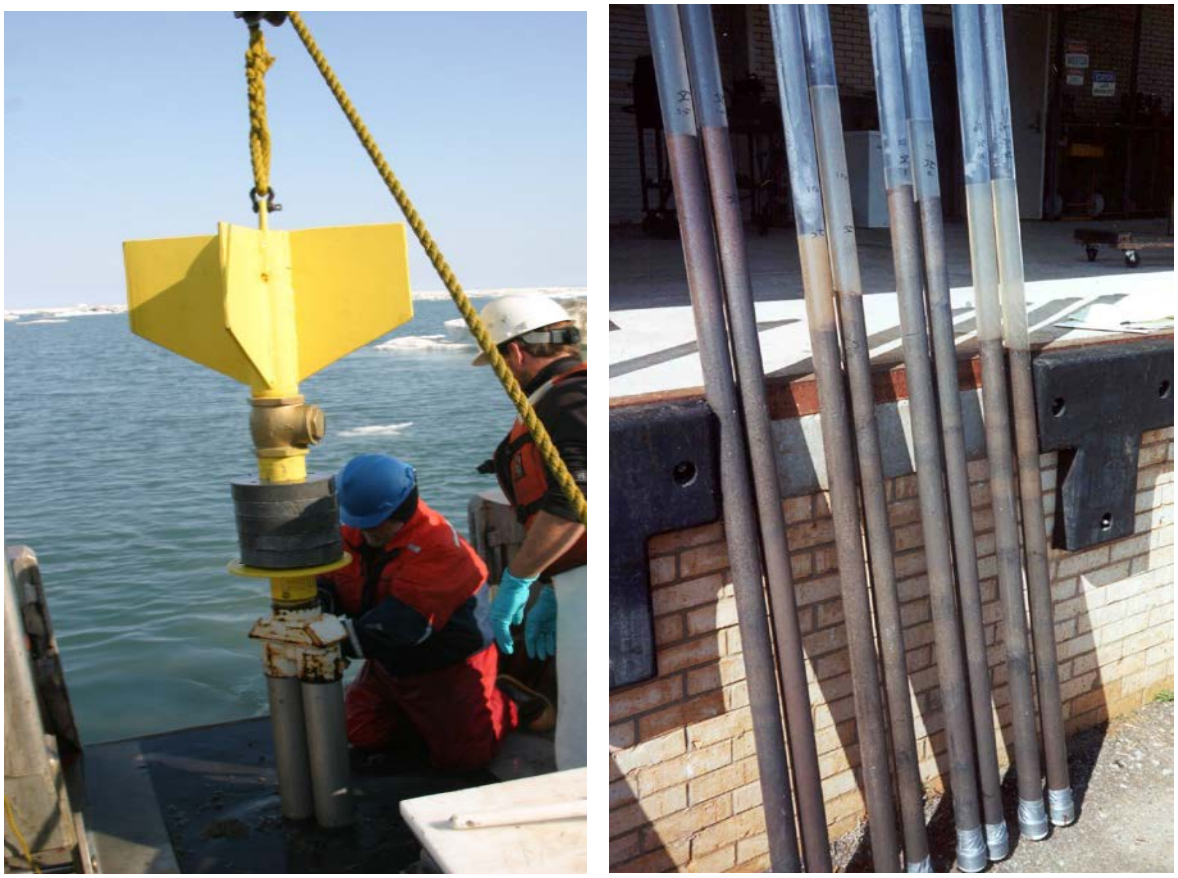


Figure 2-7. Sediment Corer and Collected Sediment Cores in Core Liners

2.4 Sample Analysis

A variety of options are available to determine PCB concentrations in environmental samples. There is also a significant amount of confusion about the benefits and drawbacks of the different methods, and for what purposes one method may be suitable while it is unsuitable for a different purpose. Many of the standard PCB analytical methods that were developed for regulatory programs may not be appropriate for forensic studies, similarly to analysis of samples for petroleum and PAH forensics [3]. For instance, U.S. EPA analytical methods developed for regulatory programs (such as the Superfund Program) require strict adherence to procedures outlined in U.S. EPA's SW-846 Methods [37]. The goal of many of these regulatory programs is to determine the "nature and extent" of the contamination, often of highly contaminated samples, which is not always sufficient to determine the sources of contamination in a forensics study. Forensics studies may require modifications of standard methods, including lower limits of detection and the analysis of additional diagnostic analytical parameters, to obtain the necessary data. U.S. EPA has recognized this for a variety of environmental investigations and is moving towards performance based measurement systems (PBMSs) rather than strict adherence to SW-846 methods. The types of analyses discussed in this document for forensic applications meet the PBMS requirements and, with adequate planning, the data can be used for both forensic and regulatory purposes. There may also be a need to use a combination of analytical methods to most effectively meet the goals of a well-developed forensics study.

Before choosing a PCB analytical method, it must be determined whether all that is needed is a measure of the total PCB concentration, or if more detailed PCB information is needed. For forensic investigations it is often useful to obtain two sets of information, and thus implement the project in a tiered manner – an initial set of Total PCB analysis using RSC or other Total PCB analysis approach, followed by a detailed congener-specific ACF analytical method on a sub-set of the samples to obtain more detailed information for more comprehensive forensic data interpretation.

Total PCB analysis can be conducted using (1) a semi-quantitative enzyme-linked immunosorbent assay (ELISA) screening method, (2) a widely used total PCB as Aroclor laboratory method, (3) a less widely used total PCB as homologs method, or (4) using a method that quantifies individual congeners which are then summed to represent the total PCB, either with or without the application of a Total PCB correction factor.[1] Individual PCB congener analysis can also be performed in a few different ways, the primary differences being the

[1] Total PCB concentrations can be estimated by summing the individual PCB congener concentrations, if those congeners are expected to capture a sufficiently large proportion of the total PCB. The PCB Aroclor compositional information in Appendix A can be useful for estimating the total PCB in a given PCB contamination, recognizing that environmental processes, including dechlorination (Table 2-4), can alter the actual environmental concentrations, as described in this document. A well selected set of a little over 100 PCB congeners, such as the 117 PCB congeners used in the Ashtabula River case study (Appendix B), can capture 97-98% of the total PCB in most environmental samples, and summing the concentrations of those congeners provides a good estimate of the Total PCB. It has been shown that the 18 NOAA National Status and Trends Monitoring Project PCB congeners capture about 50% of the Total PCB in most US coastal sediment environments, and summing the concentrations of those congeners and then multiplying that by 2 has been widely used to estimate the Total PCB concentration in such sediments. Other corrections factors can be developed for other sets of congeners using the information in Appendix A, once the type of contamination is understood.

analytical instrument that is used and the number of PCB congeners that are quantified. These analytical methods are discussed further below.

2.4.1 Total PCB Sample Analysis Techniques (including RSC)

This section describes three analytical methods, based on U.S. EPA Methods 4020, 8082, and 680, that are available for determining the Total PCB concentration in environmental samples. These methods can all be considered for RSC, and the first analytical step in gaining a general understanding of the PCB contamination at a site.

Total PCB Immunoassay Methods

ELISA analysis is a simple and relatively inexpensive immunoassay (IA) option for Total PCB analysis. Recent advances in the environmental field have followed the medical field in the application of ELISA methods for environmental contaminants. The ELISA PCB method is captured with U.S. EPA Method 4020. This is also the method recommended in this handbook for the Tier I, rapid RSC analysis of sediment samples for most situations.

The immunoassay method includes a simple extraction step followed by a reaction step for a competitive reaction between unknown sample PCBs and kit-provided PCB conjugates (PCBs with added color indictors that are activated in later reaction steps). A modification to U.S. EPA Method 4020, which is required for sediment analysis, is the dewatering of the sediment to below about 30% moisture by placing on filter paper to remove excess water. Antibody sites where this competitive reaction occurs have traditionally been on the "frosted" sides of test tubes, but more recent advances have led to antibody sites on free floating particles within the test tube solutions to provide better precision and accuracy. Contaminant concentrations are related to a color change that is either visually observed or quantified using a calibrated spectrometer, and compared to that of PCB calibration solutions with known PCB concentrations. Samples tend to be analyzed in large batches (20 to 50 samples) along with a series of Aroclor calibration standards.

These ELISA methods can be employed in the field as a near real-time method, or in the laboratory with often higher level of control of environmental factors (e.g., temperature) and quality control (QC) (e.g., replicates and calibration standards). ELISA methods are highly specific, and the PCB ELISA method has been developed to be particularly responsive to a limited set of PCB congeners. Although the immunoassay detects individual PCB congeners, individual congener quantities are not determined and total quantities are reported in Aroclor equivalents relative to the standard Aroclor series that was run along with the particular batch. This specificity can provide an advantage in that it is not sensitive to analytical interferences (i.e., it primarily responds to what it was developed to respond to), but this can also be a limitation if the concentrations of the method-specific PCB congeners is low or if the relative composition of those method-specific PCB congeners in the environmental samples and the calibrant differ. For instance, PCB101 is one of the major congeners the PCB ELISA was developed to respond to, and this congener comprises about 10% of the Total PCB in Aroclor 1254, about 4% in Aroclor 1260, and about 1% in Aroclor 1242 (see Appendix A), which impact the response to the PCB ELISA method. The PCB ELISA kit is provided with Aroclor 1254 as the calibrant, even though different Aroclors respond differently in the PCB ELISA method (Table 2-6). The PCB ELISA kit calibrated with Aroclor 1254 as supplied would determine a 10

parts per million (ppm) concentration of Aroclor 1254 to indeed be 10 ppm. However, a 10 ppm concentration of Aroclor 1260 would be reported as 16 ppm Total PCB and a 10 ppm concentration of Aroclor 1242 would be reported as 4 ppm Total PCB. Another way to describe this would be that a Total PCB concentration determined to be 10 ppm could be the result of 52 ppm Aroclor 1232, 24 ppm of Aroclor 1242, 10 ppm of Aroclor 1254, or 6 ppm of Aroclor 1260. Mixtures of Aroclors and environmental transformation would further confound the analysis. However, two simple methods can improve the accuracy of the PCB ELISA IA test results; two techniques that are, unfortunately, not always used or well communicated.

Table 2-6. Sensitivity and Selectivity of PCB ELISA IA Method to Different Aroclors

Compound	PCB Kit Sensitivity	
	Limit of Detection (ppb)	Relative Response
Aroclor	22.6	0.022
Aroclor	2.61	0.19
Aroclor	1.22	0.41
Aroclor	3.56	0.14
Aroclor	0.59	0.85
Aroclor	0.5	1
Aroclor	0.32	1.6
Aroclor	0.66	0.76
Aroclor	3.03	0.17

- Analyze a set of representative site samples using both the PCB ELISA method and a recognized accurate laboratory instrument method, correlate the results, and determine a "correction factor" if the correlation is acceptable. For instance, the ELISA immunoassay results were compared to highly reliable fixed laboratory results for a set of HPS samples (Figure 2-8), and the immunoassay results were determined to be about 1.12 times the laboratory results with a correlation coefficient (r^2 value) of 0.95; the immunoassay results were 12% higher than the "true" concentration. A correction factor could thus be generated; if the immunoassay results were divided by 1.12, the "true" concentration would be obtained. However, this approach is highly site specific and it is important to demonstrate that it applies across the site, or identify subsets of samples that may have different composition and correction factors.
- Analyze a set of representative site samples using a recognized accurate laboratory instrument method, and determine the Aroclor(s) present in the samples, and their relative composition. Prepare a site-specific Aroclor, or mixed Aroclor, calibration solution that represents the Aroclor(s) at the site, rather than simply relying on the Aroclor 1254

standard assumed to be used with the PCB ELISA kit, and measure the field sample concentrations using this site-specific Aroclor standard.

The PCB ELISA method has some analytical limitations, most of which can be avoided as described above. However, it is an excellent semi-quantitative screening method for relatively cost effectively and rapidly obtaining approximate Total PCB concentrations to characterize the PCB distribution within a set of samples and across a site and develop a general understanding of the PCB contamination at a site. A plan for more detailed sampling and analysis can then be developed, as needed.

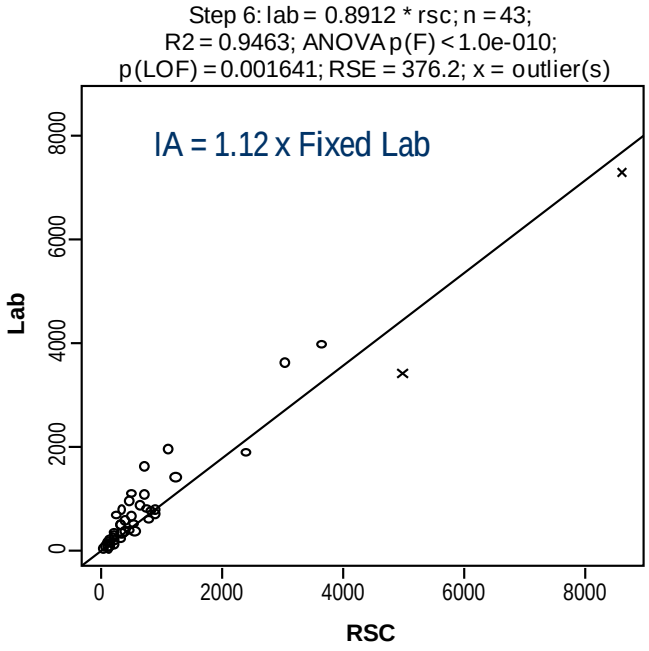


Figure 2-8. Correlation between Laboratory-based and ELISA-based Total PCB Measurements of Hunters Point Shipyard Sediment Samples

Total PCB as Aroclor Methods

U.S. EPA Methods 608 and 8082 have historically been the most widely used analytical methods for providing Total PCB data; Method 608 is for the analysis of water samples and Method 8082 for solid samples (e.g., sediment). The methods are based on identifying and quantifying the predominant Aroclor(s) in the samples. The methods assume a standard extraction technique is used, which is then followed by the method described instrumental analysis which is GC separation and ECD detection. GC columns ensure that the PCB congeners move through the GC column and reach the ECD at different rates generally based on the volatility and molecular weight of the PCB congeners (i.e., the mono- and di-chlorobiphenyls are detected first, and the nona- and deca-chlorobiphenyls last).

The ECD provides a rather unsophisticated detection capability, sensing electro-negative constituents including chlorinated PCBs and chlorinated pesticides. It is considered relatively specific to halogenated organic compounds, but, in fact, can respond to a variety of compounds

and is, thus, quite susceptible to matrix interferences and false positives. GC/ECD instrument output consists of a chromatogram showing a series of peaks, with the PCB congeners spread out by elution time in the x-direction and the peak height/area in the y-direction related to the congener concentration. Identification is made through comparison of the chromatogram to Aroclor standards that are analyzed under the same conditions as the field samples. Quantification is based on the peak area counts of a set of (generally four to eight) representative peaks, or peak clusters, and comparing to the same in the Aroclor standards. Multiple Aroclors may be identified in a sample, and the Total PCBs would be determined by summing the individual Aroclor concentrations. However, multiple Aroclor quantitation is not only complicated by environmental weathering, but mixtures of Aroclors can significantly confound the identification and quantitation of the Aroclors due to the limitations of this method. The relatively non-selective nature of the ECD can result in non-PCB contributions from other sample constituents to the targeted peaks, possibly resulting in erroneous quantitation; this is particularly common with complex environmental matrices, such as sediment or tissue samples. As discussed earlier, the PCB composition undergoes a variety of compositional changes once released to the environment, so it may not closely resemble the Aroclor standards the samples are compared to and quantified against; the Aroclor determination is a "best fit" to the peaks from the Aroclor standards even when they may not be present in the environmental samples, or present at dramatically altered relative composition. This can result in inaccurate quantification or, even worse, identifying a sample as not having any PCBs when there may be significant concentrations of a highly altered PCB. For instance, the PCB composition of the sample illustrated in the bottom of Figure 2-4 does not resemble any Aroclor, and using U.S. EPA Method 608 or 8082 may easily be identified as a "non detect" for PCBs, even though it contained high concentrations of significantly weathered/dechlorinated PCBs.

The standard Total PCB as Aroclor methods (U.S. EPA Methods 608 and 8082) are susceptible to significant identification and quantitation problems due to Aroclor mixing, environmental weathering of PCB, and complex sample matrices, as described above. The method should not be used by itself identifying the type and source of the PCB contamination, unless it is a recent release and there is certainty that the environmental samples have not been subjected to environmental weathering. This may be the case with some soil samples collected near a recent spill, but is otherwise rarely the case. However, assuming the samples have not been weathered to the point where PCB can no longer be identified, the Total PCB as Aroclor methods may be a useful semi-quantitative method for obtaining approximate Total PCB concentrations, and some limited additional compositional information (Figure 2-9) to characterize the PCB distribution within a set of samples and develop a general understanding of the PCB contamination at a site. A plan for more detailed sampling and analysis can then be developed, as needed.

Total PCB Homologue Methods

U.S. EPA Method 680 is available for providing reliable Total PCB data, along with concentration data for each of the 10 levels of chlorination (the Total PCB value is the sum of the 10 levels of chlorination data). The methods are based on identifying and quantifying the concentrations of the 10 levels of chlorination (Tables 2-2 and 2-3) by summing all the "peaks" that represent each level of chlorination separately. The method assumes a standard extraction technique is used, which is then followed by the method described instrumental analysis (GC separation and MS detection).

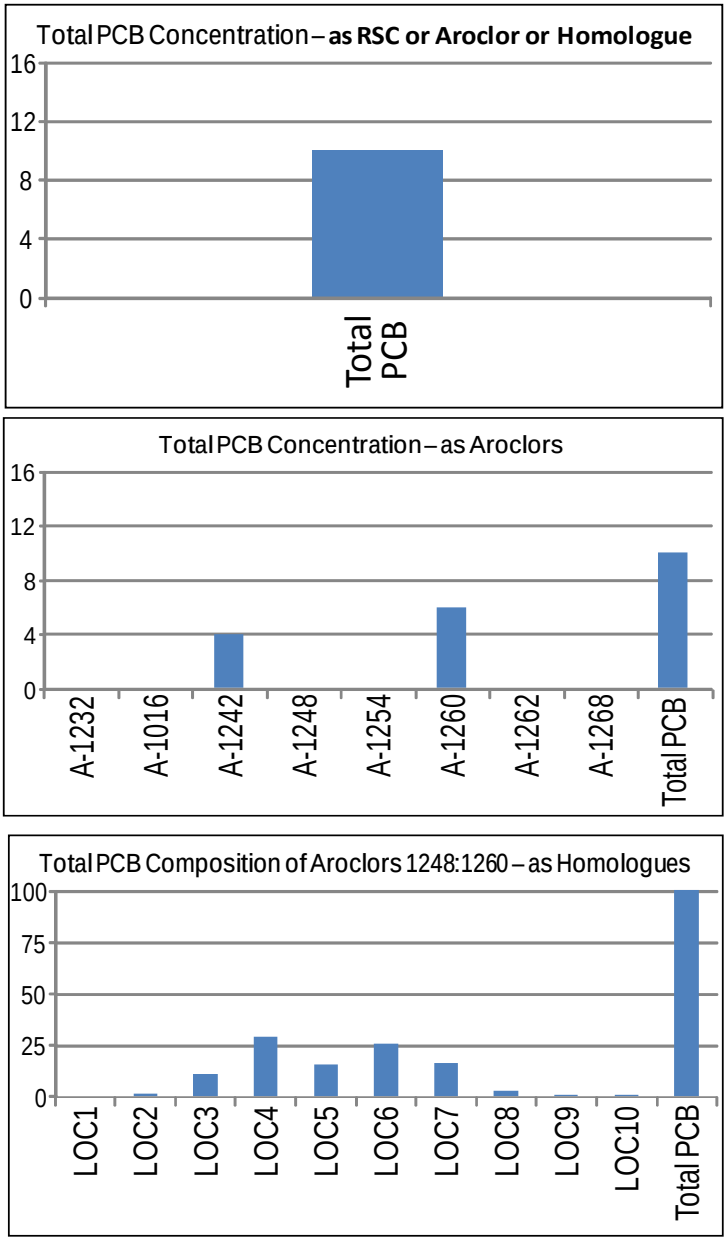


Figure 2-9. The Amount of PCB Information That May Be Available with ELISA (Method 4020), PCB as Aroclor (Method 8082), and PCB as Homologue (Method 680) Total PCB Analytical Methods

The instrument is calibrated by using the first and last eluting PCB congener for each level of chlorination (which has been well established), to obtain information on the chromatographic region for each level of chlorination and the response factor for each level of chlorination (for quantitation; by averaging the response factor for the two congeners). The MS detector provides a significant advantage over the previously described ECD detector. The MS detector is set to within a certain time window in each analysis to detect certain molecule and mass fragments based on their particular mass weight to unit charge, all of which are unique to the originating

molecule. For instance, all tri-chlorobiphenyls will produce two to three unique molecules and mass fragments, the tetra-chlorobiphenyls will produce two to three other molecules and mass fragments, and so on. The MS detector is programmed to detect the molecules and masses that are typical to PCBs. This means that the analysis is highly specific to PCBs and not as prone to interfering compounds and matrix components. Mass spectral detection is not affected by weathering/alteration of the PCB; the PCB composition of an environmental sample may no longer closely resemble an Aroclor, but this is irrelevant in the MS analysis as it reliably quantifies PCBs by level of chlorination regardless of the composition. Another possible advantage with Method 680 is that the MS analysis method can be set up so that PCB congener methods are acquired and stored, for cost-effective reduction of those data at a later time to generate PCB congener results.

The primary drawback of the Total PCB as homologues (level of chlorination) method (U.S. EPA Method 680) is that it is not an analysis that is widely offered by analytical laboratories. The method is an excellent choice for obtaining reliable Total PCB data, regardless of the composition of the PCB (i.e., it is not affected by environmental transformation or Aroclor mixtures), and also provides some level of compositional information by also generating concentration data for each of the 10 levels of chlorination. The method provides accurate Total PCB concentrations, some additional compositional information (Figure 2-9), and can be useful for characterizing the PCB contamination at a site. A plan for more detailed sampling and analysis can then be developed, as needed.

2.4.2 Congener-specific Sample Analysis Techniques (including ACF)

This section summarizes three analytical methods that are available for determining PCB congener concentration in environmental samples; a GC/ECD-based method suitable for approximately 20 PCB congeners (Method 8082), a GC/low-resolution mass spectrometer (LRMS)-based method suitable for 40 to 120 congeners (modified Method 680/1668), and a GC/high-resolution mass spectrometer (HRMS)-based method suitable for more than 100 PCB congeners (Method 1668a).

Congener-specific Methods

U.S. EPA Method 8082, the previously described Total PCB as Aroclor GC/ECD method, can be applied to PCB congener analysis and can provide data for a limited set of congeners (usually about 20 congeners). The NOAA National Status and Trends Project 18-22 PCB congeners are often monitored using this method. However, many of the limitations discussed for GC/ECD and Method 8082 in Section 2.4.1 also apply to its application to PCB congener analysis. The GC/ECD is highly susceptible to interferences from other compounds or sample matrix components, which can, at times, make it difficult to accurately resolve and quantify discrete PCB congeners in the analysis, and can result in inaccurate quantitation (both incorrectly elevated *and* reduced concentrations may be observed, depending on how and to what interferences contribute in the chromatogram). Because of the interference and resolution limitations of conducting PCB congener analysis using a GC/ECD instrument, PCB congener analysis by Method 8082 is generally limited to no more than about 25 PCB congeners.

The previously described method for analyzing PCB homologues using GC/MS and Method 680 can be modified for identifying and quantifying a large set of individual PCB congeners. The

method, as widely used by a number of high-quality analytical laboratories, is generally referred to as a modification and combination of U.S. EPA Methods 680, 8270, and 1668, and can reliably be used to quantify more than 100 PCB congeners (or about 99% of the PCBs in most environmental samples). It is a LRMS method, like Methods 680 and 8270; the "low resolution" refers to the accuracy in the identification of masses that the detector is capable of (to +/- 1 mass unit). The method operated the MS in SIM mode, unlike the base full-scan mode described in Method 8270, but like Method 1668, to obtain a higher degree of specificity and more sensitivity. The method uses individual congener calibration for a very extensive set of PCB congeners, like Method 1668, and many of the QC guidelines from Methods 8270 and 1668. Although this is considered a modified method, it does fall within the general guidelines permitted under Method 8270, adapted for PCB congeners, and is like the widely applied high-quality methods for PAH analysis [3], just adapted to PCB rather than PAH compounds. This PCB analysis method has been available for more than 10 years [6, 14, 15], and is increasingly being used in high quality environmental analytical laboratories.

U.S. EPA Method 1668 is also a GC method but uses a HRMS as the detector, also operating in SIM mode. The "high resolution" refers to the accuracy in the identification of masses that the detector is capable of, which may be to within 0.001 mass units (or better), compared to within 1 mass unit for a LRMS detector. For instance, the molecular mass of trichlorobiphenyl is 255.9613. A HRMS with a 0.001 mass unit resolution would be set to detect this compound with a mass of 255.961 +/- 0.001, while a LRMS would be set to detect it with a mass of 256. This higher mass resolution of the HRMS provides additional compound specificity. However, this additional resolution is rarely needed for most PCB analyses. A benefit to using HRMS is that it can accurately resolve and detect a few of the 12 WHO toxic congeners when other methods may not be able to. Some of the WHO congeners are only present at very low concentrations in PCB contamination (see Appendix A), and the added specificity and sensitivity of HRMS is a benefit for detecting those congeners (e.g., PCB77, PCB81, PCB126). These congeners are often important in human health risk assessment investigations, but are of no significant value for a PCB forensics investigation. Method 1668a can also discretely separate slightly more PCB congeners than a LRMS analysis, but the additional congeners are ultra-trace level congeners that generally do not provide important additional information for PCB forensics.

Recent Analytical Advances in Fingerprinting Techniques

Recent advances in fingerprinting analysis include isotope ratio MS analysis, which allows for the use of isotopic variations between different molecules that are otherwise the same to assist in fingerprinting PCBs and potentially differentiate sources. The use of this technique began in the mid 1990s with carbon isotopic variations in primarily single-compound organic contaminants, such as organic solvents (e.g., trichloroethylene). In recent years isotope ratio MS has been evaluated for use for multi-component contaminants, such as PAHs [3] and PCBs [17]. One of the most important recent advances in the technology has been compound specific isotopic analysis (CSIA) to allow for individual PCB congeners to be analyzed separately, rather than all congeners together producing a bulk isotopic signal. So for carbon isotopic analysis the GC is used to separate the congeners, then each is combusted separately to form carbon dioxide gas which is analyzed by isotope ratio MS. For forensic studies this allows selection of specific PCB congeners that are more resistant to alteration to be used for analysis to avoid changes in source patterns that might be related to environmental alteration rather than differences in original

source signatures. Although the CSIA techniques show great promise, continued work is required to lower detection limits and reduce interference from coeluting components; isotope-ratio mass spectrometry and CSIA are methods that may be considered for a PCB forensics investigation, but are not further discussed in this document.

2.4.3 Selecting Analysis Methods for Forensics Investigations

When selecting the most appropriate analytical method, it is most important to determine what types of data are needed to answer the questions at hand, and then select the method accordingly. Data quality and cost are also important considerations, and it usually becomes a matter of balancing the information needs with the data quality and analytical costs (Figure 2-10).

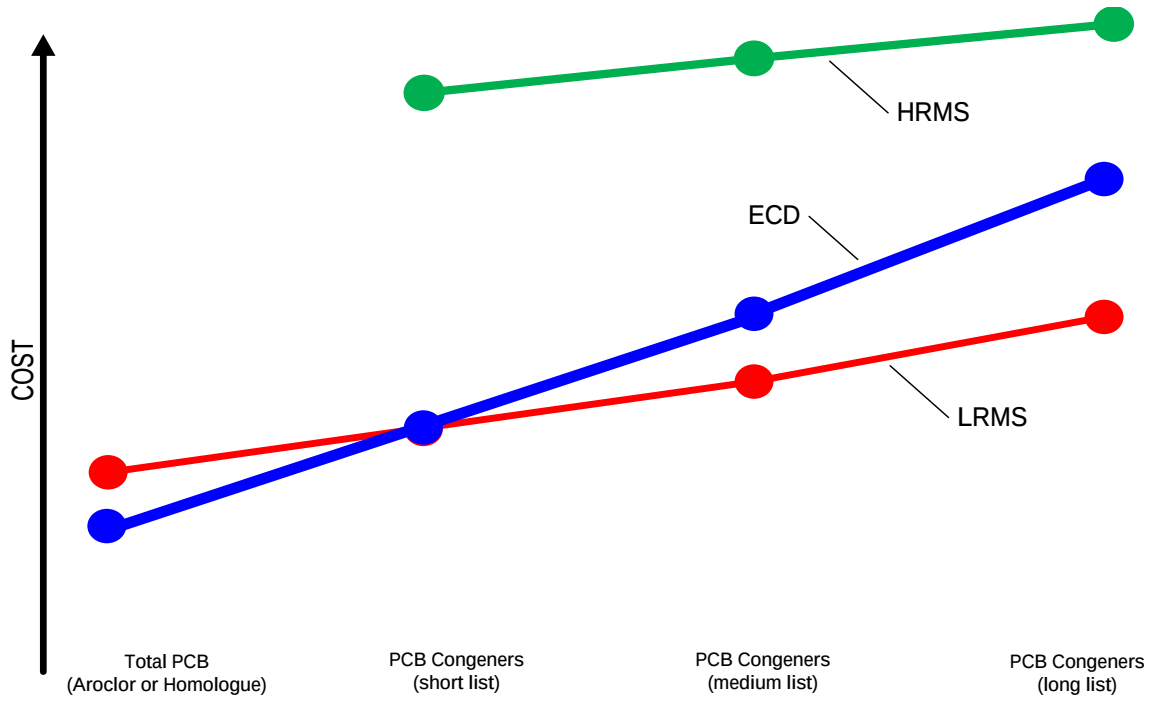


Figure 2-10. General Evaluation of Analytical Costs for Different PCB Analytical Instrument Methods, by the Type (Total PCB or Congeners) and Amount of Data (Number of Congeners) Produced

Total PCB analytical method options (i.e., RSC) were summarized in Section 2.4.1, and some key aspects of the three method options (including relative cost) are also summarized in Table 2-7. As discussed, the ELISA IA technique (Method 4020) is a rapid and cost-effective method for conducting Total PCB analysis, and is usually suitable for RSC (Tier I) analyses. This is also what was used for the two case studies described in this document. The Total PCB as Aroclor (Method 8082) method is an alternative for generating screening-level Total PCB data, as long as the PCB composition has a relatively close resemblance to Aroclors (see discussion in Section 2.4.1). Because Method 8082 is the most widely used Total PCB method, PCB data may have been generated for regulatory or other purposes for the site using this method, and may be available for use in a Tier I assessment. The Total PCB as homologue method (Method 680)

produces the most reliable and highest quality Total PCB data, and additional useful information by producing results for each of the 10 PCB homologues; this is the method of choice, if the slightly higher cost can be justified. However, Method 4020 (ELISA IA analysis) is the most suitable RSC method for most purposes, and can often provide Total PCB analysis for about $100/sample, with sensitivity and data quality that meet most RSC needs. The speed of the ELISA IA analysis is also a significant advantage, with the potential benefit of being able to map out PCB concentration gradients while still in the field and adjust subsequent sampling in a timely manner; the two other Total PCB methods are both laboratory-based and require several days, at best, to obtain the results.

Table 2-7. Comparison of Total PCB Analytical Methods

Method	Approximate Unit Analytical Cost ($)	Approximate Sediment Detection Limit (ppb)	Key Technical Advantages and Disadvantages
ELISA IA Method (Method 4020)	75-150	50	Advantage: Rapid Disadvantage: Potential calibration issues (can be avoided, as discussed)
PCB-as-Aroclor Method (Method 8082)	150-225	10	Advantage: Widely available; slightly more information than IA Disadvantage: Susceptible to interferences and misidentification
PCB-as-Homologue Method (Method 680)	250-325	1	Advantage: Accurate; not impacted by PCB alteration; more information than both IA and PCB-as-Aroclor Disadvantage: Not widely available

PCB congener analytical method options (i.e., ACF) were summarized in Section 2.4.2, and some key aspects of the three method options (including relative cost) are also summarized in Table 2-8. When selecting the detailed PCB congener ACF analytical method (Tier II), balancing the information needs with data quality and cost generally becomes an even more involved consideration than when selecting the RSC method. It is important to select enough PCB congeners and an appropriate set of diagnostic PCB congeners to be able to identify and differentiate potential PCB sources. Using information such as the PCB congener composition of Aroclor formulations (Appendix A and Table 2-3), and possible PCB dechlorination pathways (Table 2-4), it is possible to select a set of congeners that represent common environmental PCB contamination, including possible degradation products that may be of interest. A total of 80 to 120 well-selected PCB congeners are typically sufficient to provide the necessary PCB analytical data. For instance, the 117 PCB congeners reported for the Ashtabula River case study (Appendix B) represent 97 to 98% of the Total PCB in all Aroclor formulations and most environmental samples; the 92 additional possible PCB congeners are either not present in Aroclor formulations or environmental samples, or present at such ultra-trace levels that they would not be detected and/or useful for forensic purposes. Aroclor mixtures are generally the most appropriate PCB source material for assessing potential environmental PCB contamination, but a few non-Aroclor unique PCB source materials are possible. A few individual congeners, including PCB11 and PCB209, have been identified as being used for some industrial applications (e.g., PCB11, as part of some industrial pigment process [38]), and a process

involving the production of titanium tetrachloride has been identified to generate a small set of highly-chlorinated PCB congeners (in the octa- to deca-chlorobiphenyl range [39]). It is usually possible to conduct a high quality PCB forensic investigation with less than 100 PCB congeners. A smaller set of 44 PCB congeners was used in the HPS work (Appendix B), and this did provide solid information for general PCB characterization, but was somewhat limiting for forensic purposes. It can be difficult to predict which congeners will be important for the data analyses, and it is a fairly small increase in analytical cost to analyze 100 to 120 PCB congeners versus, for instance, 60 to 80 PCB congeners.

Table 2-8. Comparison of PCB Congener Analytical Methods

Method	Approximate Unit Analytical Cost ($)	Approximate Sediment Detection Limit (ppb)	Key Technical Advantages and Disadvantages
GC/ECD Congener Method (Method 8082) ~20 PCB congeners	250-400	0.25	Advantage: Widely available Disadvantage: Susceptible to interferences and misidentification
GC/LRMS Congener Method (Modified Method 680/1668) ~40-120 PCB congeners	450-650	0.05	Advantage: Accurate; not significantly impacted by interferences; can determine more congeners than GC/ECD method Disadvantage: Not suitable for a few WHO congeners
GC/HRMS Method (Method1668a) >100 PCB congeners (including WHO congeners)	800-1,200	0.01	Advantage: Accurate and sensitive; not impacted by interferences; can quantify all 12 WHO congeners Disadvantage: Costly

The three different PCB congener analytical instrument options that are available (Section 2.4.2) are suitable for somewhat different sets of information, provide different data quality, and have different costs (Table 2-9 and Figure 2-10). The information in Table 2-9 and Figure 2-10 is quite general, and different scientists may arrive at slightly different conclusions for Table 2-9, for instance. However, they are a general relative assessment, and illustrate a method consideration process that is useful when selecting an analytical method for an investigation.

Table 2-9. General Evaluation of PCB Congener Analytical Method for Method Selection (5="good"; 1="bad")

Performance Measure	ECD	LRMS	HRMS
Data Quality			
Sensitivity/detection limit	3	4	5
Accuracy	2	4	5
Precision/reproducibility	2	4	5
Matrix interference	2	4	5
Lab/field contamination interference	2	5	4
Analyte confirmation	2	4	5
Calibration performance	2	5	5
PCB Information			
Data generation: total PCB	3	5	4
Data generation: PCB homologues	1	5	3
Data generation: PCB congeners (short list)	3	5	5
Data generation: PCB congeners (long list)	2	5	5
Data generation: PCB congeners (WHO list)	1	3	5
Cost			
Cost – initial lab investment	4	3	1
Cost – maintenance/operation	3	4	2
Cost – sample analysis (project price)	3	4	1

As mentioned earlier, Method 8082 is generally considered inadequate for generating PCB congener data for a PCB forensic investigation. The GC/HRMS method (Method 1668a) is widely considered the ultimate PCB congener method for forensics studies, providing the highest quality data; it is, however, a costly analysis (often in excess of $1000 per sample). The GC/LRMS method (modified Method 680/1668) generally provides data of almost equal quality to GC/HRMS, often for about half the analysis cost of GC/HRMS analysis. The number of PCB congeners, sensitivity, and data quality in general that can be obtained with a GC/LRMS is generally adequate for the Tier II ACF analyses. GC/LRMS most often provides the optimum balance between information needs, data quality, and cost for most ACF projects.

A tiered analytical approach is recommended for a PCB forensic investigation, as was also described for PAH forensics [3]. By combining a larger numbers of less expensive RSC immunoassay Total PCB analyses with fewer more costly ACF PCB congener analyses, a high quality, yet cost effective, study design can be developed. The larger number of RSC samples allow for sufficient spatial coverage to map out the contamination and gain a general understanding of the situation, including the possibility of one or more potential sources. The PCB information from the RSC can be used to select a subset of samples for ACF analysis to provide the unique PCB congener diagnostic data needed to match the site samples to potential sources. The initial contour mapping provides an initial understanding of the site to better formulate a conceptual model that makes optimum use of the subsequent ACF analyses. In this manner, the more costly PCB congener analyses are not wasted by analyzing samples with no detectable PCB or generating redundant PCB information. In summary, combining the ELISA IA method (Method 4020) for the RSC Total PCB analysis with the GC/LRMS method (modified Method 680/1668) for the ACF congener-specific analysis generally provides an

effective analytical plan, although the other described methods can also generate useful information, assuming their listed strengths and weaknesses are recognized and accommodated.

Common PCB Analytical Options

This section presents an overview of common available PCB analysis methods, and their advantages and limitations

- **Total PCB Methods.**
  - PCB Immunoassay Method (e.g., RSC)
  - PCB-as-Aroclor Method
  - PCB Homologue Method
- **Individual PCB Congeners Methods**
  - Limited Congener Set Analysis using GC/ECD
  - Extensive Congener Set Analysis using GC/LRMS
  - Extensive Congener Set Analysis using GC/HRMS

2.4.4 Laboratory Data Quality Control

There are several components to a program to ensure that reliable and high quality data are generated, so that such data can be used with confidence, including the analysis of a series of laboratory QC samples and the subsequent evaluation of the resulting data. QC is an integral part of the laboratory activities. It demonstrates the quality of operations and analyses, provides analysts with metrics about method performance, and aids project managers in identifying and correcting systematic and random problems that can plague the laboratory operations.

The laboratory PCB analysis QC measures should allow for an assessment of processing effectiveness, potential laboratory contamination/interference, accuracy, and precision. A routine set of QC samples should accompany every batch of samples processed and analyzed at the laboratory; the following is a description of types of QC samples that are suitable for analysis with each batch of samples; suitable types of performance objectives are summarized in Table 2-10. The exact criteria used should be designated by the PM to ensure the results are suitable for site- and project-specific data needs and decision making. This laboratory QC program is suitable for the ACF analysis, but samples that demonstrate that contamination is controlled and analytical accuracy and precision should also be incorporated with the RSC analyses.

Table 2-10. Example Laboratory Performance Objectives (additional field QC samples may also be included in a project QA Program)

QC Sample Type	Example Performance Objective[a]	Corrective Action
Procedural blank (PB)	< 5× method detection limit (MDL), or field sample concentration >10×blank value	Re-extraction, re-analysis, and/or document and justify per PM; all corrective actions documented
Laboratory control sample (LCS)	40 – 120% recovery	Re-extraction, re-analysis, and/or document and justify per PM; all corrective actions documented
Matrix spike (MS)	40 – 120% recovery Spike levels >5× unspiked field sample concentration for DQO to apply	Re-extraction, re-analysis, and/or document and justify per PM; all corrective actions documented
Matrix spike duplicate precision	Relative percent difference (RPD) < 30% Spike levels >5× unspiked field sample concentration for DQO to apply	Re-extraction, re-analysis, and/or document and justify per PM; all corrective actions documented
Duplicate Precision	RPD < 30% Field sample concentration >5× MDL for DQO to apply	Re-extraction, re-analysis, and/or document and justify per PM; all corrective actions documented
Standard reference material (SRM)	Values to be within 30% of designated certified value on average for all compounds. Target concentration > 5× MDL for DQO to apply	Re-extraction, re-analysis, and/or document and justify per PM; all corrective actions documented
Surrogate internal standard (SIS) recovery	40 – 120% recovery	Re-extraction, re-analysis, and/or document and justify per PM; all corrective actions documented
Initial calibration	< 25% relative standard deviation (RSD) in relative response factors (RRFs), or correlation coefficient $r \geq 0.99$	Re-extraction, re-analysis, and/or document and justify per PM; all corrective actions documented
Continuing calibration	< 25% percent difference (PD) from expected concentration	Re-extraction, re-analysis, and/or document and justify per PM; all corrective actions documented

[a] These are ***example*** performance objectives that may be considered for PCB instrumental analysis. Actual performance objectives or criteria should be set on a project-specific basis to meet project-specific objectives.

- Procedural Blank (PB) - A PB is a combination of solvents, surrogate internal standard (SIS) compounds, and all reagents used during sample processing, processed concurrently with the field samples. It is intended to monitor purity of reagents and potential laboratory contamination and interferences.
- Laboratory Control Sample (LCS) - An LCS is a contaminant-free matrix-specific sample (e.g., Ottawa sand or sodium sulfate). It is spiked with the analytes of interest and processed identically to the field samples to assess analyte recoveries and effectiveness of the method with no influence by the sample matrix.
- Matrix spike - A matrix spike is a field sample spiked with the analytes of interest at approximately 10 × the method detection limit (MDL), processed concurrently with the field samples. It is intended to monitor the recoveries and effectiveness of the method in the presence of the sample matrix.
- Sample duplicate - A duplicate is a second aliquot of a field sample processed and analyzed to monitor precision. The duplicate may be a second matrix spike sample.

- Standard reference material (SRM) – An SRM is prepared like a field sample to assess the accuracy of the analytical procedures. This is natural sediment that has been certified by the National Institute of Standards and Technology (NIST) to contain certified concentrations of the target compounds.
- Instrument Check (IC) – An IC sample is prepared by spiking a small amount of solvent with target compounds obtained from a vendor that is different from that used for the calibration standards, and then analyzing the IC as a sample. The IC sample is used as an independent measure of accuracy in the absence of sample processing.

In addition, a suite of SIS compounds are added to all field and QC ACF samples prior to sample preparation. These compounds are added to determine the efficiency of the sample extraction and analysis procedures, and to aid in the accurate quantification of native concentrations of the target analytes in the field sediment samples. A set of at least three SIS compounds with varying molecular size should be used to represent the range of target analytes (e.g., a trichlorobiphenyl, a pentachlorobiphenyl, and a heptachlorobiphenyl, at a minimum). It is also important that the SIS compounds are representative of the target compounds in the analytical procedure (i.e., have similar behavior). PCB congeners that are not expected to be in environmental samples (i.e., not present in Aroclor formulations and not expected to be generated through environmental processes), and well resolved analytically from PCB congeners that are present, are particularly suitable for use as SIS compounds. Isotopically labeled PCB congeners are also an excellent choice. A PCB chemist should be involved to assist in the selection of these SIS compounds.

Method Detection Limit

The MDL is defined as the minimum concentration that can be measured and reported with 99% confidence that the analyte concentration is greater than zero, and is generally determined by the method outlined in the U.S. Federal Register [37]. However, MDLs are not always the best measure of analytical sensitivity, and are one of several ways to evaluate the sensitivity of an analytical method. Reporting limits (RLs, sometimes referred to as minimum levels [MLs]) are defined by the sample concentration of a compound that is equivalent to the final extract concentration based on the low calibration standard concentration, and is often used to qualify data. However, uncensored data are most useful and should be reported for most environmental forensics studies based on a careful review of the analytical chromatogram by an experienced analytical chemist. Target compounds *confidently* detected below the RL (typically to a concentration with a signal-to-noise ratio criterion of 3:1, and identified with confidence by an experienced PCB analytical chemist) should be reported and qualified appropriately, regardless of how it compares to the calculated MDL. Target compounds detected between the RL and MDL are reported and typically also qualified, with a unique qualifier.

2.5 Data Analysis and Interpretation

Environmental forensics and statistics/data analysis often intersect because forensics projects typically depend on the analysis of large amounts of chemical data that need to be interpreted. PCB environmental forensics investigations often involve the collection of hundreds, if not thousands, of samples. If such data are analyzed by congener-specific methods, each sample will have associated with it 50 to more than 100 chemical measurements. Such large chemical data sets translate to major data management and data analysis challenges. As such, it often makes

sense that multivariate statistical methods are one important tool used to analyze such data. Unfortunately, there are very large sets of different data analysis methods that can be and have been used in environmental forensics investigations. The majority of these have been borrowed from scientific disciplines that predate by decades the current practice of environmental forensics (e.g., diagnostic ratio analysis in petroleum geochemistry, PCA in psychometrics, geology, and countless other disciplines). The methods discussed herein are based on the authors' collective experience. A comprehensive discussion of methods available to PCB forensics investigations goes beyond the scope of this document.

Given the wide range of potentially useful methods, it is best to begin in terms of general data analysis objectives and philosophy. The major objective of a PCB forensics investigation is generally the identification and delineation of multiple sources in an impacted system. Given data from a well-designed sampling plan that spans the desired geographical and temporal range of the study, three things should be determined:

1. The number of chemical patterns contributing to a chemical system. Ideally, different sources produce different chemical patterns, but this is not always the case.
2. The unique chemical composition ("fingerprint") of each chemical pattern.
3. The relative contribution of each fingerprint in each sample.

The systems under study (sites with historical contamination) are not well-designed experiments. Rather, they are the results of inadvertent releases ("accidental experiments") that generally occurred long before any detailed environmental investigations were undertaken. The contamination is often decades old, and records associated with the chemical releases are often sparse or nonexistent. This makes for an extremely complex system with many unknowns: site history, source chemistry, timing of release, and the presence of additional, unsuspected sources. A priori knowledge of all contaminant sources that have impacted a system is rare. A philosophy of exploratory data analysis (EDA) must be adopted, rather than classical hypothesis testing. The objective of EDA is to allow patterns and correlations to be derived directly from the analysis of ambient data, with minimal a priori hypotheses. A number of proven methods are discussed below (e.g., PCA, receptor models, ratio methods, simple graphics), but any number of methods that meet the above listed objectives, and conform to EDA philosophy, are potentially applicable to PCB forensics investigations.

2.5.1 Background and History of Data Analysis

While the term environmental forensics began seeing widespread use in the late 1990s, the data analysis methods most often used (and discussed herein) predate their application to environmental forensic by years, if not decades. The following sections discuss the history of some of the more commonly used methods.

2.5.1.1 Chromatograms and Simple Compositional Analysis

A forensic investigation includes several key steps of information and data analysis, including (1) review of site history and records research, (2) analysis of sediment/contaminant transport and hydrodynamic data, (3) review of the PCB concentrations, (4) initial review of the PCB composition, and (5) comprehensive chemometric analysis of the PCB data. The most basic

assessment of the PCB data and its potential association with sources is to review how the PCB concentration is distributed across a site; attempts to link PCB contamination with potential sources through PCB concentration contours and geographic distribution is the simplest and oldest approach to PCB forensics. Although not statistically rigorous, it has always been a useful first use of the PCB data to develop an image of the source association.

PCB composition (i.e., relative concentrations of PCB homologues and PCB congeners) is generally the next step in the initial PCB characterization of a site to develop ideas of potential sources. This can be done by carefully reviewing analytical chromatograms, or using bar graphs which are, in essence, recreated chromatograms with only the PCB data (e.g., Figure 2-2). Again, although not statistically rigorous, samples that have similar PCB composition may have a contaminant source relationship and understanding which sub-sets of samples have similar PCB compositional characteristics is useful initial information.

Analyzing PCB congener ratios is another type of PCB compositional analysis. Compound ratios have been used to infer sources of contaminants (e.g., [40, 41]) and to identify PCB transformation, including dechlorination [8, 10]. The idea is that if one can identify pairs of source-diagnostic congeners, then ratios between those compounds will retain the initial source signature. Conversely, if one can identify compounds that are susceptible to dechlorination and those that are resistant to dechlorination (Table 2-4), one can monitor the degree of dechlorination, assuming the original type of PCB contamination was a constant. Figure 2-11 illustrates active dechlorination, with the increase in the relative amount of PCB4/10 (dechlorination products) and the simultaneous decrease in PCB118 (a congener susceptible to dechlorination) with depth (time) in the sediment. Active dechlorination was confirmed multiple ways for the Lake Hartwell sediments, including with PCA analysis (Figure 2-12); deeper sediments with “old” PCB contamination exhibited a significant dechlorination, with a unique PCB composition that did not resemble any Aroclor (Figures 2-4 and 2-12). A potential drawback of ratio analysis is that the data analyst must make a decision regarding which chemical pairs are diagnostic of source, and have similar affinities to weathering. This requires a priori knowledge and/or assumption, and generally an uncommon depth of understanding PCB chemistry. As for most (if not all) of the PCB forensics methods discussed herein, diagnostic ratio-based methods were widely used in geochemistry applications prior to being adopted for forensics, most notably in fingerprinting of oil and source rocks in petroleum geochemistry applications [41, 42]. In the HPS demonstration study (Section 3.1), the ratio of PCB28 to PCB153 was used to evaluate the hypothesis of a source of less chlorinated PCB material in Yosemite Creek (a tributary that outfalls near HPS).

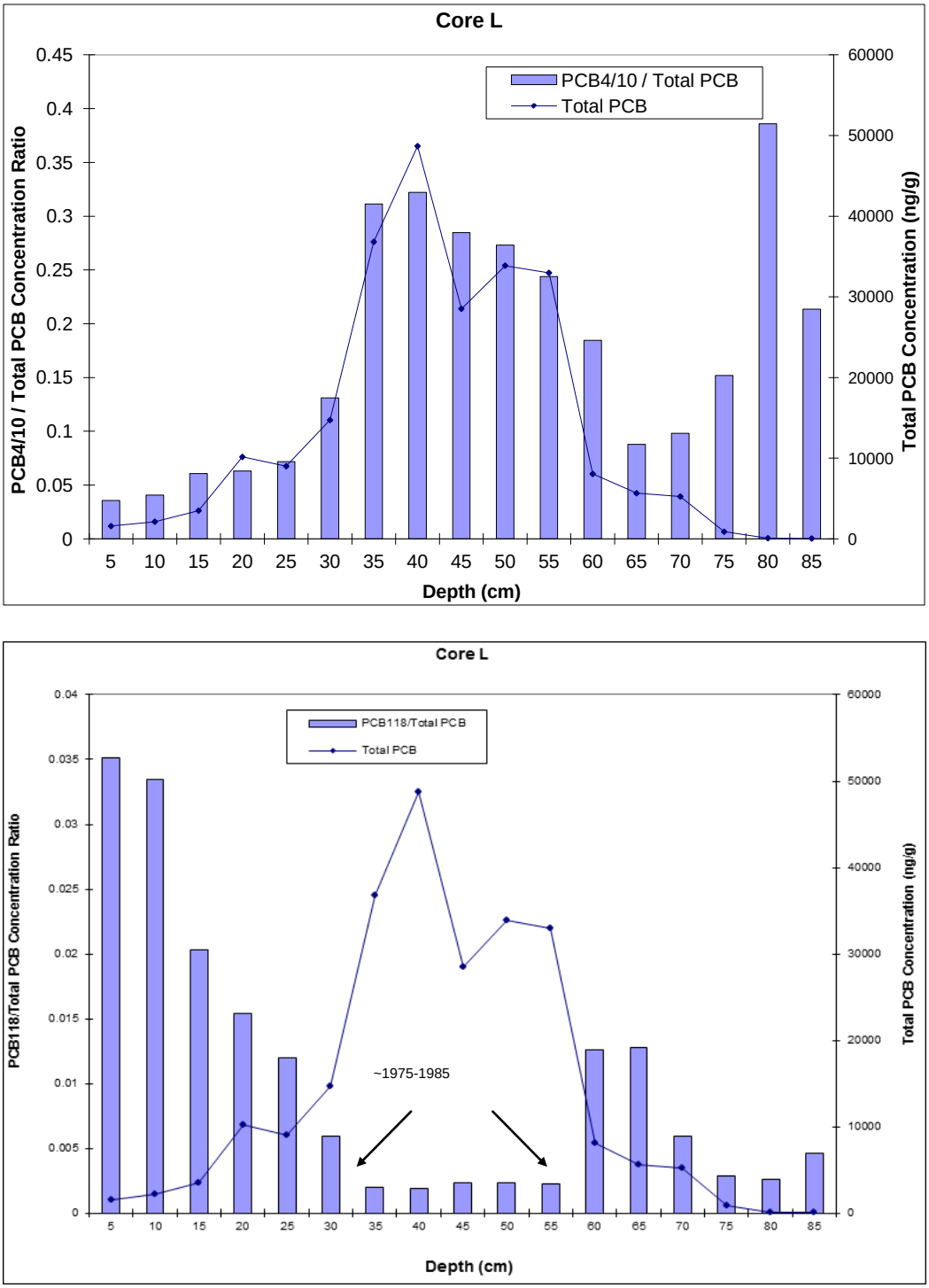


Figure 2-11. PCB4/10 (top) and PCB118 (bottom) to Total PCB Concentration Ratio Bar Graph along with the Total PCB Concentration (line chart) for a Core from Lake Hartwell

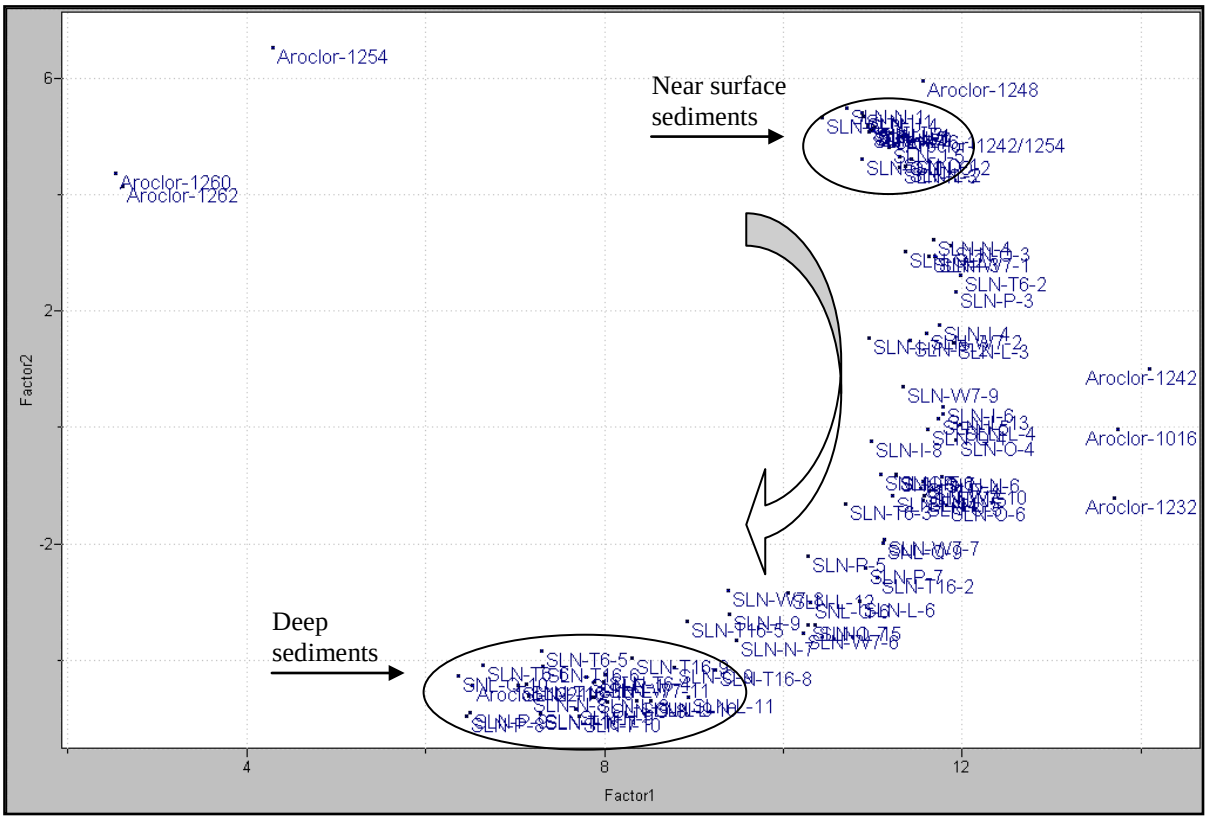


Figure 2-12. Principal Component Analysis Plot Using PCB Congener Data from Lake Hartwell Surface and Subsurface Sediment Samples
(Subsurface samples exhibit dechlorination and have no resemblance to Aroclors.)

2.5.1.2 Multivariate Analysis (Classification Analysis)

Several different classification multivariate analysis methods are available, of which PCA is the most widely used in PCB forensics. PCA is widely used for environmental forensics as a whole and in many scientific disciplines far removed from environmental chemistry. It is used both as an exploratory data analysis method on its own, and as an intermediate step in receptor modeling. PCA was used in many scientific disciplines long before the terms *environmental forensics* or *chemical fingerprinting* were ever coined, and long before the development of quantitative congener-specific PCB analysis. The roots of PCA go back to at least 1904 and psychologist/statistician Charles Spearman [43]. PCA methods began seeing widespread use in the earth sciences in the early 1960s [44]. In those early days, the method was generally referred to by geologists as *factor analysis* (FA) – a term borrowed from the psychologists that followed Spearman. There is considerable confusion on the relationship between PCA and FA. Much of this is due to the fact that there is little agreement on terminology across scientific disciplines (e.g., chemometrics, psychometrics, engineering, mathematical geology, etc.). The confusion still remains. However, *PCA* is generally the term of choice in environmental forensics, and *scores* and *loadings* are generally used for the chemometric definitions.

2.5.1.3 Receptor, Chemical Mass Balance, and Mixing Models

An increasingly common method used in environmental forensic investigations involves the use of receptor models. These methods are designed to resolve three parameters of concern in a multivariate mixed system: (1) the number of components in the mixture, (2) the identity (i.e., chemical composition) of each component, and (3) the relative proportions of each component in each sample.

Receptor methods often (but not always) use PCA as an intermediate step to (1) determine the number of "significant" principal components (i.e., the number of potential sources), and (2) provide a reduced dimensional reference space for resolution of the model. If source compositions are known a priori, then those compositions may be used as a training data set in the receptor model, and source contributions may be found via regression methods such as chemical mass balance [45, 46]. However, in environmental forensics, one typically does not know and/or wishes not to assume knowledge of sources. For such situations, it usually is preferable to use a self-training receptor model method: a class of algorithms designed to resolve the number of sources, and provide feasible estimates of the multivariate source patterns and source contributions, without a priori assumption of sources. Methods in common use in environmental forensics include PVA, multivariate curve resolution/alternating least squares (MCR-ALS), PMF and Unmix.

Based strictly on the environmental forensics literature, it might appear that there was an evolution of methods from less sophisticated PCA applications in the mid to late 1990s to the development and implementation of more sophisticated algorithms in the new millennium. However, once again, all of these methods actually existed long before the term environmental forensics was in widespread use, and certainly well before being applied to PCB congener data. The PVA method used in recent PCB applications (e.g., [8]), and for the HPS and Ashtabula River case studies in this research (Sections 3.1 and 3.2) is essentially the same algorithm published 30 years ago by Full et al. [47, 48]. Similarly, PMF was first published in 1994 [49] and MCR-ALS in 1993 [50]. While not called Unmix at the time, the development of that algorithm can be traced back to the early 1990s [51, 52], and was an extension of self-modeling curve resolution work from the 1970s [53]. These methods have been modified and new options published since they were originally introduced, but the algorithms remain largely unchanged since the early 1990s.

There are a number of likely reasons why it may appear that the receptor model methods came along later than they did. Firstly, there is a big difference in accessibility and user friendliness of receptor model software as compared to more common data analysis techniques such as PCA. In the mid-1980s one needed to use Fortran software running on a main-frame computer to apply PVA. In the 1990s, if one wanted to use PVA, ALS, or PMF one had to contact the academician that had developed it and determine how to apply it. The software was primarily developed for academic research purposes, and as such was neither intuitive nor particularly user friendly. Today, one can download a much improved version of Unmix or PMF from the U.S. EPA Web site (http://www.epa.gov/ttnamti1/unmixmtg.html), and commercial data exploration and analysis software products (e.g., Pirouette from Infometrix) include an ALS module.

The application and comparison of these methods has been presented in the literature [9, 19, 54]. Given high quality chemical data (and data that have undergone rigorous quality assurance [QA]/QC to identify and address any problems with non-detects, interferences, and other analytical issues), each of these methods perform well and resolve similar source patterns and apportionment. However, like PCA, these methods require that the user has a certain level of experience and familiarity with environmental data structures.

2.5.2 Data Review and Preparation

2.5.2.1 Laboratory Data Quality Review

The laboratory QC sample data should be reviewed against the DQO to assess the key QC measures for potential contamination, accuracy, and precision, to ensure that the analytical data represent the PCB concentrations in the samples. The DQOs for the laboratory QC samples included with the ACF analyses from the HPS and Ashtabula River case studies are presented in Table 2-11. A summary of the QC sample results are summarized in Table 2-12. As can be seen, the vast majority of the QC samples prepared and analyzed along with the PCB samples produced QC results that met the DQOs for these sample sets. For instance, 96% of the SIS recoveries and 100% of the LCS recoveries determined with the HPS samples met the DQOs. In general, the QC sample results were of uncommonly high quality for both case studies.

Table 2-11. Comparison of Project Results to Data Quality Objectives – PCB Congener Analysis of Hunters Point Shipyard Sediment Samples

QC Sample or Measurement Type	Data Quality Objective	Total Number of QC Measure Data Points[a]	Number of QC Data Points that Met the DQO	% of QC Data Points that Met the DQO
SIS Recovery	40 to 120% recovery	560	540	96.4
Method/Procedural Blank	No compound to exceed 5 times the RL, unless sample is >10 times blank amount	308	308	100
LCS Recovery	40 to 120% recovery for spiked compounds	308	308	100
Matrix Spike/Duplicate Recovery	40-120% recovery for spiked compounds. Applies to analytes with spiked concentration >5 times the native sample concentration.	616	609	98.6
Matrix Spike/Duplicate Precision	RPD <30%. Applies to analytes with spiked concentration >5 times the native sample concentration.	308	236	76.6
Instrument Check Accuracy/Precision	PD <20%.	308	308	100

[a] Total number of data points of the indicated QC measure. For instance, for surrogate recovery it would be the number of surrogate compounds in each sample multiplied by the total number of samples. For the method blank it would be the numbers of method blank samples analyzed with the sample set, multiplied by the number of target analytes measured.

Table 2-12. Comparison of Project Results to Data Quality Objectives – Ashtabula Sediment Samples (EPA-ORD and GLNPO Project Combined)

QC Sample or Measurement Type	Data Quality Objective	Total # of QC Measure Data Points[a]	# of QC Data Points that Met the DQO	% of QC Data Points that Met the DQO
SIS Recovery	40 to 120% recovery	992	987	99.5
Method/Procedural Blank	No compound to exceed 5 times the MDL, unless sample amount is >10 times blank amount	1,902	1,902	100
LCS Recovery	40 to 120% recovery for spiked compounds	1,902	1,899	99.8
Matrix Spike Recovery	40 to 120% recovery for spiked compounds Applies to analytes with spiked concentration >5 times the native sample concentration.	1,902	1,900	99.9
Sample Duplicate Precision	RPD <30%. Applies to analytes with concentration >5 times the MDL.	1,902	1,899	99.8

[a] Total number of data points of the indicated QC measure. For instance, for surrogate recovery it would be the number of surrogate compounds in each sample multiplied by the total number of samples. For the method blank it would be the numbers of method blank samples analyzed with the sample set, multiplied by the number of target analytes measured.

Some DQO exceedances can be expected with challenging sample matrices and when applying ultra-trace level analytical methods. Analytical results that do not meet the listed DQOs should always be reviewed by a senior analytical chemist for assessment of the potential impact of the results. Affected samples may be reanalyzed if needed to ensure high quality data. QC sample data that are accepted outside the DQOs should be indicated with the appropriate data qualifier, and the rationale for accepting the analysis should be documented, so that subsequent data users can assess if there was any potential impact on the data quality. Overall, the QA program, including the analysis of laboratory QC samples processed and analyzed with the field samples, produced data that demonstrate that the methods were appropriate and that the analyses were under control, generating high quality and reliable data that can be used with confidence.

2.5.2.2 Data Preparation

Typical data assessment and preparation are summarized below, using examples from the Ashtabula River data set for illustration. The laboratory ensures that the data have met the analytical data quality expectations (Section 2.5.2.1), and deliver the data to end users. Additional preparation (Section 2.5.2.2) and quality/usability review and screening (Section 2.5.2.3) are then performed before the final data (and potentially reduced data set) are interpreted for forensic purposes.

Data are typically received in a variety of formats (e.g., spreadsheets, databases, GIS files). Regardless of the format, the first step is to put all data into a format that is readily useable for review and data analysis. A common format is Excel spreadsheets, with samples as rows in the spreadsheet, variables (PCB congeners or homologs) as columns, or vice versa. It is important to compile as much information about the data and samples as possible in the data preparation stage. Additional important sample information to capture in the spreadsheet or data transmission includes:

- **Unambiguous Sample Identification (ID).** Often, the same sample will carry different sample names/numbers, and it is important to be able to cross reference. A common example is a field station ID, field sample ID (the sample name assigned by field personnel) and the lab sample ID (the analytical laboratory's internal tracking number).
- **Laboratory Analytical Batch ID.** It is often valuable to know what analytical batch the sample was analyzed with to be able to associate field samples to laboratory QC sample results (which tend to be analytical batch specific), and should there be a need to discuss the data with the analytical laboratory.
- **Sampling Date.** It is critical to know when the sample was collected to understand what period in time the data represent. This is particularly important if data are available from different time periods for the site, but is important for any sample since putting contamination into a historical perspective is important in any forensic investigation.
- **Sample Sediment Depth.** It is important to know sediment depth interval below surface that the sample represents to understand how samples can be compared with each other, and to link the data to source input history, among other things. The top and bottom depth of the sample (e.g., 5 cm to 10 cm) is important to know. If the sample is a surface sediment sample, it is critical to know to what depth the sample was collected, as surface sediments are collected differently in different projects (it may be just the top 1 cm representing very recent contamination, or as deep as the top 1 ft potentially representing decades of contamination). Samples that represent a wide range of sediment depth (e.g., from the surface to 1 ft deep) are often less useful for a forensics investigation than samples representing smaller depth intervals.
- **Concentration Information.** Having information on the concentration units (e.g., ng/g,), and whether the data are on a dry or wet weight basis, is important to be able to put the contamination into perspective, and to support a variety of data analyses. It is best to avoid the ppm and parts per billion (ppb) nomenclature, and instead use units in a format such as mg/kg and µg/kg. Although some data analysis (e.g., pattern recognition methods) use data normalization and transformations to optimize the analysis, it is important to also maintain a data set with concentration information.
- **Sampling Location.** It is critical to be able to link a sample with a specific sampling location. Manually indicated "dots on a map" showing the approximate locations will not suffice for a forensics investigation; accurate global positioning system (GPS)-based location information (latitude-longitude, northing-easting) are needed. Although some chemometric analysis may be performed with less detailed location information, a high degree of accuracy and location certainty may prove crucial to evaluating the

fingerprinting data, and supporting the results. Location-specific geochronology data (e.g., ^{210}Pb or ^{137}Cs data; Section 2.5.3.2) are extremely valuable, and often critical, for understanding the history of the contamination and support rigorous statistical and other data analysis.

ACF PCB congener analysis requires the application of high QA/QC standards to produce data of sufficiently high quality to support a forensic interpretation. Experienced PCB analysts should be overseeing and conducting the laboratory analyses and reviewing the analytical results. The analyst should have a familiarity with PCB chemistry and sensitivity to common as well as PCB-specific analytical QA/QC issues. The data should be accompanied by information related to the QC sample results and the overall data quality (a QC narrative; Section 2.5.2.1). Data qualifiers should be applied as appropriate to help data users understand potential laboratory data quality limitations, or other important sample or value-specific issues (see below). Additional data quality, reasonableness and usability assessment should be performed separately and independently following the laboratory's delivery of the data, and is discussed in Section 2.5.2.3.

The application of laboratory data qualifiers (sometimes referred to as data "flags") can vary from project to project depending on the project-specific DQOs, but widely applicable DQOs and an example laboratory QC sample program were described in Section 2.4.4. Chemical data reporting conventions and the use of data qualifiers may vary from lab to lab, but such information should accompany the data delivery and QC narrative to be able to understand and use the analytical data.

The "value" reported for non-detects is particularly important to understand for data assessment purposes. Some laboratories will report an empty/blank field if not detected, some laboratories will report a zero, and some laboratories will insert a value based on the laboratory's separately determined detection level (e.g., the MDL, half the MDL, or the RL or ML). Whatever the reporting convention for non-detects, it should be well documented with the data delivery and, ideally, also accompanied by a qualifier in the data set that identifies it as being non-detect. The data qualifier "U" is most commonly used to indicate a non-detect. Additional common laboratory data qualifiers are summarized below, but different qualifying conventions can be used as long as they are appropriately documented.

- **U** – Analyte not detected based on the careful review of the chromatogram by an experienced PCB analyst. A criterion of a signal-to-noise ratio of approximately 3 to 5:1 for the analyte peak in the chromatogram, and acceptable peak shape, is often used, and preferably manually assessed and confirmed.
- **J** – Most laboratories use this qualifier to indicate the identification of an analyte (using the criteria listed for the "U" qualifier), and reporting of a concentration that is below a common reference point; sometimes referred to as an estimated concentration. It is often assigned when a data value is near the detection limit, and below some commonly calculated reference value (e.g., the RL or ML, which is the field sample concentration that produces a final sample extract with a concentration that is equivalent to the low calibration standard). The RL/ML are generally more useful sensitivity and detestability reference values than the MDL, which is a periodically calculated performance measure

that incorporates precision and method performance, but may not be the best measure to represent analytical sensitivity.

- **ME** – This is a common qualifier to use to indicate that there was matrix interference (i.e., not a "clean," well resolved analytical peak in the chromatogram) and that the value should be considered an estimate.
- **N** – This is a common qualifier to use to indicate a value that did not meet the recovery, precision, or accuracy DQO, but is deemed by the laboratory to not impact the overall quality of the field sample results (as discussed in the QC narrative). This qualifier may be used for surrogate compound recoveries of field samples, or recovery, accuracy, and precision results for various QC samples.
- **R** – Rejected. The reported value for this data point was rejected by some laboratory criterion and/or through review by the laboratory, determining that the laboratory could not produce a reliable value or even an estimate. The "reject" assessment may apply to an individual compound, or an entire sample, as indicated, and should be discussed in the QC narrative.
- **D** – Diluted. Sample had to be diluted, usually due to a high concentration of the analyte (i.e., the concentration was above the calibration curve in the initial analysis).
- **C** – Coelution. For PCB congener analysis, some laboratories will report this flag for PCB congeners that coelute with some other congener, usually indicating which congener it coelutes with using the IUPAC number (e.g., C4 for PCB10). Other labs will not report "C" but will identify the analyte as the coeluting set of congeners (e.g., PCB4/PCB10).

If the laboratory qualifying system (i.e., lab-flag scheme) and non-detect reporting method are not clear from the deliverable provided, it is important to contact the laboratory to obtain clarification before proceeding with the data analysis. Such information is extremely useful in deciding which samples/analytes to include in an analysis, determining the proper course of action in handling outliers, and evaluating the validity of a chemometric model's interpretation.

Standard graphics resulting from statistical data analysis (e.g., PCA scores plots) are useful, but are by themselves often insufficient. In any environmental forensics investigation, one must be able to put results in a spatial context, creating maps or other geographical representations. It is often very useful to incorporate the data into a GIS, and producing GIS files of the site; sampling locations are ideally part of the project planning or, at a minimum, an early part of the information analysis. If the primary data interpreter is not proficient in GIS mapping, they should solicit the help of somebody who is. In the case of the Ashtabula data set, GIS information was available in the form of GIS shapefiles, which were used to construct a simple base map, showing key geographic features of the study area (Figure 2-13). The HPS site also had good GIS information available, as will be shown in Section 3. The objective initially is not necessarily to generate report-ready graphics, but to have the ability to quickly put data and analysis results in geographic context.

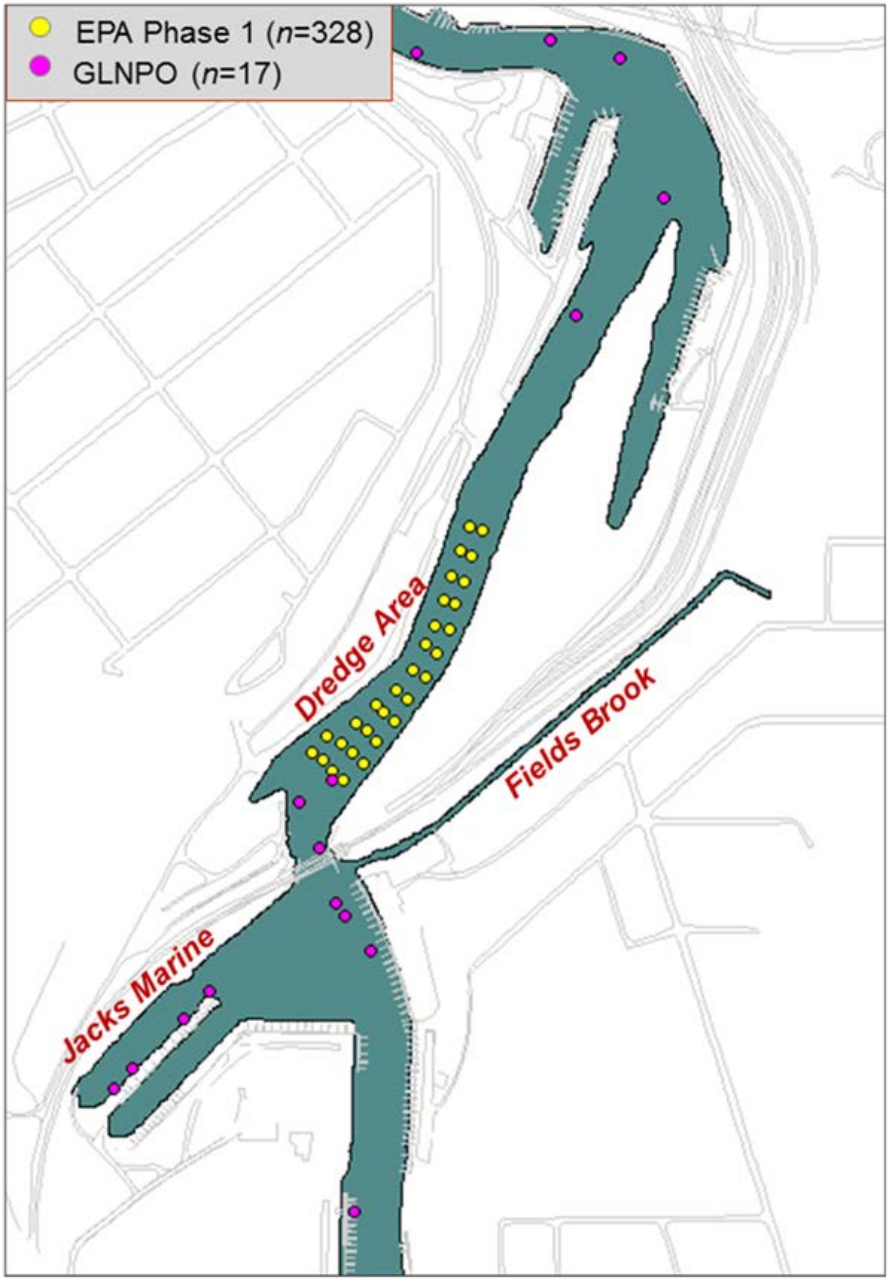


Figure 2-13. Simple Base Map of the Ashtabula River Study Site Showing Sampler/Core Locations

Historical PCB data from a site are commonly available only as hardcopy in old reports. In such cases, a time-consuming first step may be a hand-entry of data into spreadsheets, or the application of a scanning-to-digital information translation software (which, if used, needs to be carefully verified), and digitization of sample locations off of hard-copy maps such that the data can be analyzed in geographic context.

Using PCB congener data from multiple laboratories is another common challenge. Often, when historical PCB data are available for a site, samples may have been analyzed by different laboratories and perhaps using different analytical methods (often with different coelutions characteristics and different PCB congener analyte lists). The ability to perform PCB congener pattern comparisons between samples analyzed by different labs is dependent on (1) determining which reported analytes are most comparable between data sets and (2) reducing both data sets to a PCB congener list that is most comparable.

The solution to such a challenge with merging data from multiple laboratories and/or methods is usually project specific, taking into account the different analytical methods that were used, considering the reported quality of the QC sample results, the age of the data, etc. (for example, PCB153 coelutes with different congeners in different laboratory method systems). On a GC/ECD system using a DB1 column, PCB153 often coelutes with PCB184. In contrast, on a GC/MS system using a DB5 column, PCB153 may coelute with PCBs 168 and 132 [55]. Fortunately, when comparing data from these two analytical systems, it is not unreasonable to compare these two peaks as "PCB153", because PCB153 is more abundant of these potentially coeluting congeners in Aroclors and most environmental compartments. The key to compiling comparable analyte lists is a peak-by-peak comparison between the two data sets, done in context of (1) analytical method comparability considerations, (2) known or suspected sources and potential alteration processes, and (3) the media sampled (e.g., keeping sediment data together, but separate from biota). Most aspects of the data preparation, review, and screening are best performed by a highly experienced PCB environmental chemist.

2.5.2.3 Data Review and Screening

Prior to detailed data analysis and interpretation, the investigator or his/her PCB environmental chemist team member, should conduct a data review focused on assessing data quality and overall usability for forensic purposes, which goes beyond what the laboratory performed when generating the data. This step is an evaluation data quality assessment, but from the data analyst/statistician's perspective rather than that of the laboratory chemist (Section 2.5.2.1).

It is important to point out that in a step-wise framework, as in this handbook, this task has been positioned as a discrete step in a linear process (between data generation, preparation and data analysis). Ideally, data screening should take place before data analysis. However, in practice, that is not always possible. Or it may become an iterative process. Data outliers, for instance, may not be clearly evident during the conduct of the data analysis itself. The outlier issue(s) should then be addressed and the data analysis process repeated. Data quality assessment is an ongoing process, starting with the analytical chemist (long before the end user ever receives the data) and continuing to final analysis and report preparation (as the project team seeks to explain the subtlest bits of variation in the data set). Regardless of specific approach, a key component of this process is outlier detection and sample screening. Johnson et al. [9] discusses statistical and graphical methods for sample screening. A brief overview is provided here.

In environmental forensics investigations, detection and evaluation of outliers is a crucial part of the process. As such, the data analyst should develop a systematic approach for summarizing and reviewing PCB congener data to determine data reliability and usability, with a goal of obtaining a robust data matrix for subsequent chemical fingerprinting. Beyond this general

guidance, the specific approach is often a function of one's training and preferred workflow, and generally an experienced chemist's "chemical reasonableness" assessment that cannot easily be described in a written step-wise fashion.

A common data preprocessing challenge is how one deals with low concentration samples and/or samples with numerous congeners reported at or below the limit of reliable detection. Clearly, such samples will be of limited utility when it comes to congener pattern comparisons, as they either have no concentration reported, tend to have higher uncertainty in the reported value than the rest of the data, and are, simply, of low relative significance in the data set. As such, it is usually advisable to review total PCB concentrations for each sample, as well as a tabulating the number of non-detects in each sample. In the experience of these authors, there are no hard-and-fast rules on what total PCB concentration is acceptable, or what percentage of non-detects is considered too high. These decisions are usually project specific, with logic and analytical accuracy being the key considerations.

Similarly, the analyst should screen the data set for problematic variables (congeners). This typically includes identifying congeners with a high percentage of non-detects, which may have to be omitted from the analysis. One may also want to determine congener concentration as percent of total PCB and the variability in the contribution (as percent relative standard deviation [%RSD]), to identify congeners with significant variability and uncertainty, but ensuring that it cannot be attributed to source or other "real" differences. Any number of approaches can be employed, but the ultimate objective is to determine if variability within a variable is due to "real" composition differences (e.g., different sources or dechlorination) or a function of noise or censored data (i.e., non-detects).

Finally, when outlier samples or congeners are identified, it is important to understand that causes for each may differ, so the appropriate action required to address outliers may vary. For example, if the outlier is the result of data entry error, the appropriate action would be to correct the error and rerun the analysis. If, however, the cause is uncorrectable matrix interference or other analytical issues, the only reasonable course of action might be to delete the sample from the data analysis. Another possible explanation of an apparent outlier may be that the reported concentrations are completely reliable and accurate, but the sample is truly unique. An example of such an outlier might be a single or limited set of samples with significant dechlorination in an otherwise unaltered suite of samples. In this case, the outlier represents a true fingerprint observed in the field, should be possible to identify using PCB chemistry knowledge and sample investigation, and should not be omitted from the analysis solely because it is unique.

Most chemometric studies will include some criterion for handling data points where an analyte was not identified and reported below laboratory detection limits (non-detects). Common reporting and data qualifying of non-detects was discussed in Section 2.5.2.2. If, as part of the data reporting, an artificially inserted value was inserted for the non-detect (e.g., half the MDL), and qualified with a "U", then such values are typically best replaced with a zero in the data screening process, prior to data analysis. Non-detects with an empty value cell often need to be populated with a zero, as many data analysis software cannot handle empty cells. The handling of non-detects is an important project decision, and should be discussed within the project team and the agreed on approach justified and documented.

It is important to conduct a rigorous review and pre-screening of the data before conducting any statistical, chemometric, or other key data presentation and analysis so only the most reliable data are used in subsequent analysis; only data for which there is a high degree of confidence. All samples and all parameters (PCB congeners) are generally not needed to conduct a solid forensics interpretation, and the quality of and confidence in the data analysis is greater if data of low reliability are removed. As discussed, it is difficult to develop strict quantitative screening methods for when to include and when to reject a sample or parameter, and it is important to include an experienced PCB chemist in the data evaluation process to ensure that a solid "chemical reasonable" assessment is part of the data review and screening process. The following are some considerations that may be included in such a data screening process.

***Samples** Inclusion/Removal Assessment*

- Identify the overall PCB concentration below which it is unlikely that reliable results are consistently generated for the sample, and remove those samples from the data set. The following are example guidelines, but project-specific, sample-specific, and analyte-specific decisions are often most appropriate, with accompanying documentation.
  - If >50% of the PCB congeners are non-detect, those samples may be removed.
  - If the sum of the PCB concentrations is low compared to most samples in the data set, and/or low concentrations are contributing to unusually high variability and overall data uncertainty; the congener composition does not appear to be technically reasonable. The PCB concentration is near the limit of detection. This sum of the PCB congener's screening level was in the 80 to 100 ppb range for the Ashtabula River sediment samples; samples with a sum of congener concentrations below that were not used. Most samples had much higher PCB concentrations.
  - If the relative concentration of PCB congeners is unusual for a large number of congeners in the sample (Figure 2-14), and cannot be explained by expected sources or weathering differences, that sample can be removed from the data set (once it has been assured that it cannot be explained by sampling or laboratory error, or the presence of another source).

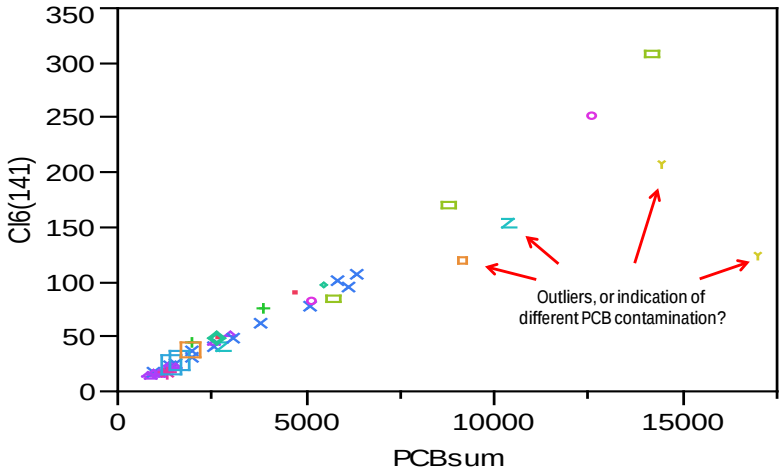


Figure 2-14. PCB Congener Ratio Analysis to Determine Potential Outliers

***PCB Congeners** Inclusion/Removal Assessment*

Considerations for whether to include or exclude specific congeners from a data-set are similar to deciding whether to include or exclude samples (see above), but there are some differences.

- Identify the PCB congeners with inconsistent, unexplainable, or otherwise unreliable results, and remove those congeners from the data set. It is important that the congener is removed altogether from the data set (not only for the samples with low congener data reliability), as it is important that the same set of congeners be used for all samples. The following are example guidelines, but project-specific, sample-specific, and analyte-specific decisions are often most appropriate, with accompanying documentation.
    - If the congener concentration is consistently near the limit of detection in the data set, that PCB congener can be removed from the data set. For the Ashtabula River sediment samples, for example, a congener was removed from the data set if >50% of the samples had a concentration of <1 ppb for that congener.
    - If, after removal of unreliable samples, >50% of the samples have non-detects for a PCB congener, that PCB congener may be removed from the data set.
    - If the relative concentration of a PCB congener is uncommonly low or high for a large proportion of the samples, and cannot be explained by possible source or other weathering differences, that PCB congener can be removed from the data set. For instance, calculating the percent contribution to the total PCB for the congeners in each sample is a useful component of the data assessment. If the percent relative standard deviation (% RSD) in the percent contribution to the total PCB is >100 %RSD, and that high variability cannot be explained by different sources or weathering in the data set, that PCB congener can be removed from the data set. This assessment can also be performed with ratio plots (Figure 2-14).
    - If, using PCB chemical reasonableness evaluation, the results for a congener are frequently anomalous and cannot be reasonably explained by its composition in Aroclor formulations or by degradation or other weathering/transformation processes, that PCB congener can be removed from the data set. For instance, if a PCB congener concentration is relatively constant and does not co-vary with the overall PCB concentration, or if a PCB is detected at high frequency in some analytical batches and not in other analytical batches of samples from the same site, such anomalies can likely be assumed to be due to analytical issues, and the PCB congener should not be used.

The values indicated above are *not* strict criteria, and should only be used as general guidelines (e.g., 50% non-detects for excluding a sample from the data set). The actual assessment cutoff will likely be different from data set to data set, and may also vary from sample to sample and congener to congener, and needs to be determined on a project-specific basis by an experienced PCB chemist. In addition, it is critical that it be determined if any data outliers and apparent anomalies may be the result of different sources, or dechlorination or other weathering processes, before data are removed from the data set; if the variability or anomaly can be explained using an understanding of PCB chemistry, or if there is any doubt about it being a “real” PCB signature, then it may be best to kept such data in the data set. For the Ashtabula River data set, for

instance, there were 345 sediment samples with available data, and 53 of those were removed during the data screening process. In addition, 38 of the 120 PCB congeners were removed, providing a final data set of 292 samples and 82 PCB congeners for the data analysis and interpretation exercises.

2.5.3 Data Analysis and Interpretation

This section describes several common data analysis approaches. This discussion will move from relatively simple graphics through to more sophisticated statistical methods. However, the simpler methods should not be considered less helpful. Often, the most effective method of gaining an intuitive understanding of data is through use of simple graphs or maps.

The primary information analysis components in an environmental forensics investigation are:

- Determine the site history and history of the surrounding area
- Determine the contaminant/sediment transport characteristics and hydrodynamics
- Determine the PCB concentrations across the site, and in relation to potential sources
- Determine the PCB composition across the site, and in relation to potential sources
- Conduct chemometric data analysis, ideally using multiple techniques
- Integrate the data analyses and findings through multiple lines of evidence to identify potential sources, and, if multiple sources, their relative significance.

It is absolutely critical that these components are addressed in an integrated manner. These types of studies are often conducted with the interpretation being limited to basic chemical "fingerprinting" of analytical chromatograms and/or a single statistical analysis method, with other potentially critical information not being used, and conclusions drawn with insufficient knowledge and a low degree of confidence.

Even for more sophisticated data analysis methods, lucid, well-conceived graphics are important. An ideal graphic must, first and foremost, be faithful to the data. But it should also be lucid and simple to understand. These general guidelines provide constraints, but also leave room for considerable creativity.

2.5.3.1 Site History and Record Research

The components of conducting a record research were discussed in Section 2.2.1. This is an important, and often overlooked, component of a forensics investigation, and is conducted to help determine a relationship between the observed contamination and historical activities at or near the site. This requires an understanding of the history of the site and area surrounding the site that could have impacted the site. If one cannot identify historical industrial activities, processes, material handling, and possible release and transport scenarios that can explain the sediment contamination, the forensics investigation would be missing an important puzzle piece.

As discussed in Section 2.2.1, the availability of records can vary widely from project to project, but it is important to devote significant effort to the site history and records research as part of the forensics investigation, and preferably early in the process during the planning phase. In

terms of determining potential sources of PCBs in sediments, the types of information that are usually the focus of records search include:

1. Identifying current and historical production/operations for the properties that through intentional or unintentional discharge/runoff could have contaminated the sediments.
2. Identifying PCB-related activities (e.g., transformer/capacitor use, carbonless copy paper, hydraulic fluid, marine paints) by the potential contributors of sediment contamination, and the timeframe of their use.
3. Identifying historical waste handling and disposal for PCB containing materials/waste.
4. Identifying possible migration pathways to sediment (e.g., waste disposal, landfills, drainage ditches and creeks receiving runoff), and how those have changed over time.
5. Reviewing historical environmental investigation reports and data.
6. Reviewing historical remedial activities, and summarizing their implications on the history of the contamination.
7. Summarizing the activities and site characteristics that may have involved PCBs, the possible history (years) of releases, and possible migration pathways to the sediments.

Obtaining historical information can be challenging because it is rarely readily available and can require creative and atypical research techniques. The elements of a record research investigation were described in Section 2.2.1, and the following summarizes possible sources of potentially important historical information.

- **Internal Corporate/Facility Documents**. Available internal communications and other records that document the operations that may have used PCBs. Documentation of remediation that may have been conducted at the site, as well as past environmental studies and related data and reports. Such information is sometimes publicly available, and at other times may not be made available.
- **State and Federal Regulatory Files**. If environmental investigations have been conducted at a site under regulatory authority, then a case file should exist, and all information should be available in the public domain. Access to such files varies greatly, depending on the regulatory agency. In some instances, many or all case files are available online, and can be searched and downloaded. In other cases, a formal request may be required under the Freedom of Information Act. It may take weeks or months before access is approved, and the agency may require that files be reviewed on their premises. In yet another scenario, regulatory programs may require that a local library or other public facility serve as a document repository, and key documents can then be accessed at that location with no pre-arrangements.
- **Publications**. Published reports and other literature may provide general information on industrial/commercial use of PCBs (e.g., [5, 20, 22, 56]). Such papers are useful, but generally provide information on an industry-wide basis (not a specific facility or site). If one can find specific case study papers or presentations or reports that focus on the specific site, or a similar site, that may provide useful historical information. If such a

document includes citations for such information, it will usually be well worth the effort to track down the original source.

- **Interviews**. Interviews with current and past residents of the area, and workers at the facilities potentially responsible for the contamination or nearby facilities, can often produce a wealth of useful information about past activities. This is a particularly valuable way to obtain information on important activities and site matters that are not well documented.
- **Aerial Photographs/Remote Sensing**. Aerial photographs and other remote imaging and sensing information are publically available from commercial sources and sometimes also from public sources. A wide range of such imagery and information can be purchased if it is not part of the readily available information. Such information can be obtained from many past decades to help reconstruct physical and industrial changes over time to better understand the PCB contamination.

2.5.3.2 Sediment Transport and Hydrodynamics

As discussed in Section 2.2.2, a general approach for a sediment transport evaluation is presented in Blake et al. [36]. Initially, the project team will collect all available data, conduct a site inspection, and develop a site-specific CSM for sediment transport. The team also will formulate the preliminary sediment management questions, define the overall study objectives, and identify the most critical data gaps. After this initial evaluation, the team can conduct a Tier 1 sediment transport evaluation. The goal of the Tier 1 evaluation is to address the most common sediment management questions, using readily available data from the RI and relatively uncomplicated data analysis methods. The Tier 1 evaluation has relatively simple data needs, a lower cost, a shorter timeframe, and a higher level of uncertainty than a Tier 2 evaluation. The Tier 1 results can be used to refine the sediment transport CSM and address the relevant site-specific sediment management questions. Depending on the questions asked at a specific site, this level of analysis may be sufficient.

For large or complex sites, a higher degree of certainty may be needed to characterize sediment transport processes and address sediment management questions. In this case, collection of additional site-specific data may be necessary and more detailed and complex data analysis methods may be warranted, including the possible development and use of predictive models. These activities comprise the Tier 2 evaluation. The scope of data collection and analysis for the Tier 2 evaluation will depend on the complexity of the site, the type of data needed to address the most critical data gaps, and the available project budget. Tier 2 results will be used to refine the CSM until the uncertainty associated with the sediment management decision(s) is reduced to an acceptable level.

The sediment transport and hydrodynamic studies, and associated data generation, conducted as part of a forensics investigation are intended to help determine how contaminants move and deposit at the site. This means understanding runoff and discharge characteristics at potential sources, input characteristics to the study site (e.g., creeks, drainage ditches, discharge pipes, CSOs), and the hydrodynamic and sediment transport conditions that impact how the contaminants are distributed in the aquatic system, and eventually settled to the sediments. It is therefore important to understand and obtain the appropriate data to explain factors including:

- All water and sediment input sources to the study site, including their history and activity
- Water circulation (currents) and their consistency and fluctuation
- Tides and their potential impact on currents and sediment movement
- Suspended sediment transport, suspension, resuspension, transport, and depositional characteristics
- Areas of erosion and deposition
- Sediment deposition rate in areas of demonstrated deposition
- Sediment stability and susceptibility to erosion under different conditions (e.g., storms).

Understanding the hydrodynamic conditions, and particularly the transport and fate of sediments, is crucial to explaining the movement of contaminants, and how the identified sediment contamination may be related to a distant source.

2.5.3.3 PCB Concentrations

One of the first steps in assessing the PCB contamination at a site, and to begin to get an understanding of the contaminant situation in terms of source association, is to review the overall (total) PCB concentration information for the site. Surface sediment data provide information on recent contamination, and subsurface sediment data provide information on historical contamination and needs to incorporate the sediment depth and the rate of sediment deposition. Factors to consider include how high, in general, the PCB concentrations are across the site, how variable the PCB concentrations are across the site, and determining if there are any PCB concentration "hot spots" and spatial gradients that could help understand potential sources. The PCB concentration information is then considered together with the historical site information (Section 2.5.3.1) and hydrology and contaminant transport for the site (Sections 2.5.3.2), to develop a preliminary understanding of the contaminant distribution and how it may relate to potential sources.

In environmental contaminant studies, the highest concentrations of contaminants are, more often than not, found in close proximity to their source. The hydrodynamics of the site and sediment stability and transport (e.g., areas of erosion where sediments do not settle or are resuspended and moved, and areas of deposition where suspended sediment settle) must be considered to support the contaminant distribution interpretation, and to ensure that there are no surprising contaminant transport characteristics that are not being considered. PCB concentration contouring is a widely used, and very useful, technique for understanding the approximate PCB concentration distribution to obtain an initial understanding of the contamination situation, and potential source areas. Thus, a simple map showing concentrations of contaminants in the sediment is a powerful and useful initial analysis, and may be more insightful than some sophisticated statistical technique. Figure 2-15, for instance, illustrates the surface contaminant concentration in a lake with two significant locations where run-off and other input to the lake occur. One of those (the northern one), appears to be associated with contaminating the sediment, while the other does not appear to be, assuming there are no unusual contaminant transport characteristics in the lake. In addition, given that the ultimate audience for

an environmental forensics investigation is not often scientists (an arbitrator, community representatives, a court of law), a map is familiar and easier to explain to a layman. Maps and aerial photos that include data can be simple and powerful tools in environmental forensics. If GIS capabilities are not readily available, then simple histograms can be used to illustrate the concentration changes in sampling stations away from a potential source location (e.g., with stations represented along the x-axis), accompanied by a map or aerial photograph for illustration purposes.

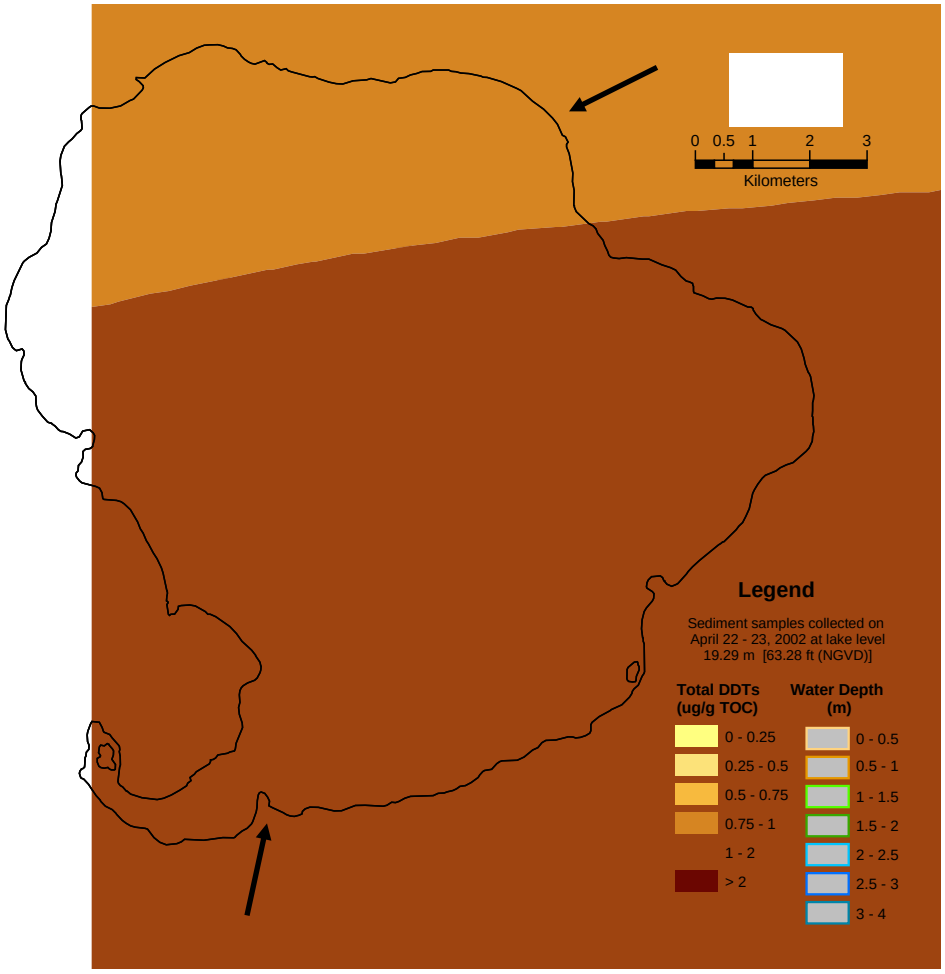


Figure 2-15. Florida Lake with Two Sources of Runoff/Input and Potential Sources of Contamination Indicated
(Contours indicate surface sediment DDT concentrations.)

It is usually important to understand the PCB concentrations both horizontally (i.e., surface sediment concentrations) and vertically (using sediment core data) to understand the history of the contamination. Histograms of sediment core concentrations, ideally linked to a year of contamination by incorporating sedimentation rate information (i.e., sediment dating data), are very useful (Figure 2-16). 3D extrapolations and contouring of sediment core data can further help in developing an understanding of the contamination (Figure 2-17).

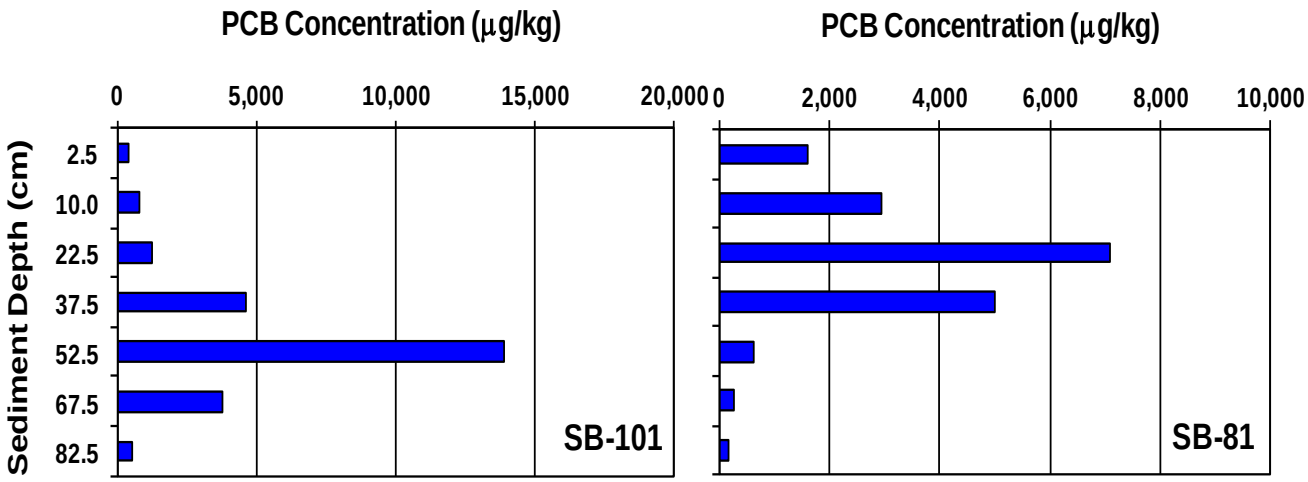


Figure 2-16. Total PCB Concentrations in a Sediment Core Collected on the West (SB-101) and East (SB-81) Side of Hunters Point Shipyard South Basin

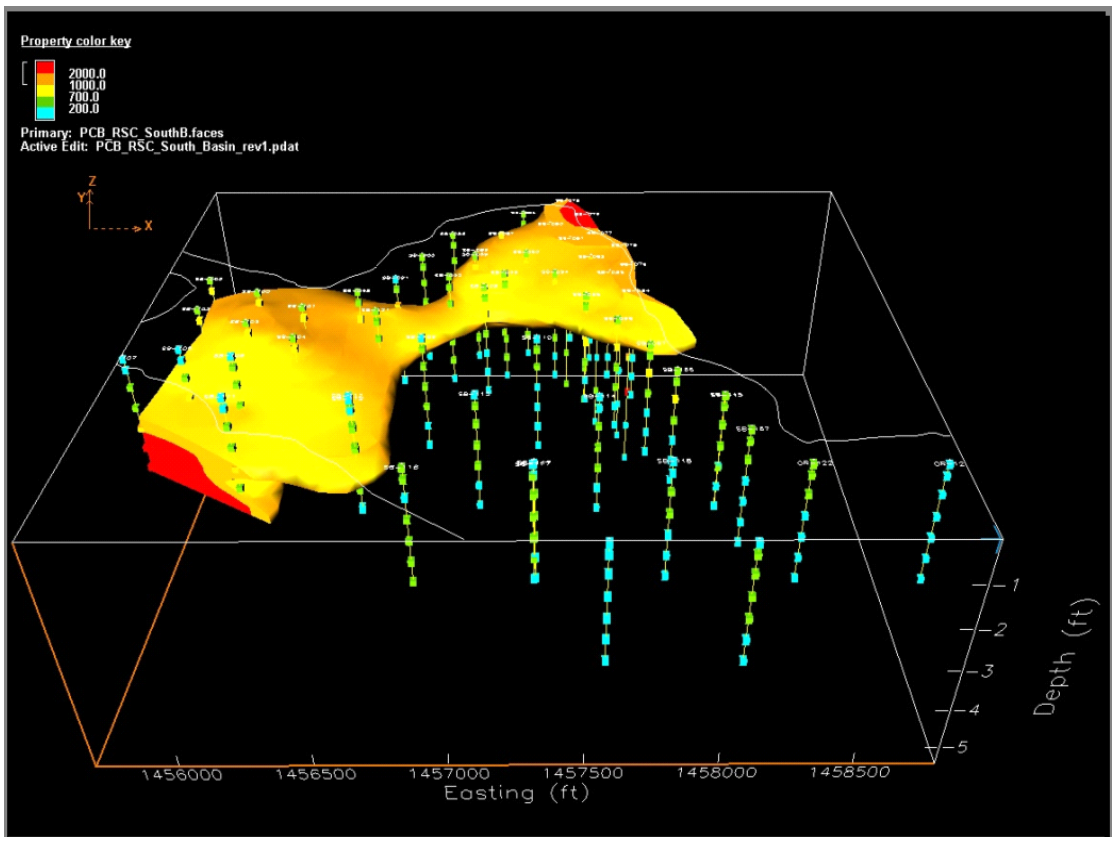


Figure 2-17. Illustration of Subsurface Sediment Total PCB Concentrations and Sediment Coring Locations in the Hunters Point Shipyard Study Area

2.5.3.4 PCB Composition

Once there is a good understanding of the overall PCB concentration distribution and characteristics of a site, the next level of detail in the analysis of the data usually comes with studying the *composition* of the PCB contaminating the sediment – the relative concentrations of the PCB congeners or homologues. One might assume that the PCB composition correlates with concentration gradients and this should then be confirmed as it would provide support to the initial assumptions about sources. If PCB concentrations and PCB composition do not appear to be closely related, then the compositional characteristics need to be more carefully studied and explained.

It is usually important to understand the PCB composition, like the concentrations, both horizontally (i.e., surface sediment concentrations) and vertically (using sediment core data) to understand the history of the contamination. If there is only one source, and that source has been the only source for a long time, the surface PCB composition is likely similar across the site. The subsurface PCB concentrations may be similar to the surface sediment composition if the source has been constant, or it can be altered depending on if dechlorination and other weathering factors have affected the composition. In sandy, aerobic sediment, there may be little alteration of the PCB composition over time (i.e., with sediment depth), although some reduction of congeners with a low level of chlorination has been shown to occur in some environments. However, in some highly organic and anaerobic sediment, with the appropriate microbial conditions, the PCB composition may change significantly over time (Figures 2-4 and 2-5), even if the source and PCB type (e.g., a specific Aroclor) have remained the same.

As with concentrations, it is important to consider what the PCB composition is, in general, across the site, how the PCB composition changes and how variable it is across the site, and determining if there are any PCB composition "hot spots" where the composition is particularly similar to a fresh Aroclor or Aroclor mixture, suggesting proximity to a source and recent contamination. The PCB composition information is then considered together with the PCB concentration information, the historical site information, and hydrology and contaminant transport, to further develop the understanding of the contamination and how it may relate to potential sources.

Compositional information is generally presented using simple bar graphs, and can be done using PCB homologue data presenting the relative concentrations of the 10 levels of chlorination (Figure 2-9), but is most often done using a larger set of PCB congeners (e.g., Figures 2-2 and 2-4). Analytical chromatograms can also be useful for compositional illustrations, but they are often more difficult to compare and decipher than "recreated" chromatograms using simple histogram plots. Comparing the sample compositional information to the composition of Aroclor formulations (see figures in Appendix A), or mixtures of Aroclors, can be useful to help better understand the contamination. Figure 2-18 shows the composition of 18 PCB congeners in sediment samples collected from the west and east sides of HPS South Basin, together with the composition for a mixture of Aroclor 1254/1260 and only Aroclor 1260. The PCB congener composition of the sample from the west side resembles that of the mixed Aroclor, but the sample from the east side resembles that of just Aroclor 1260.

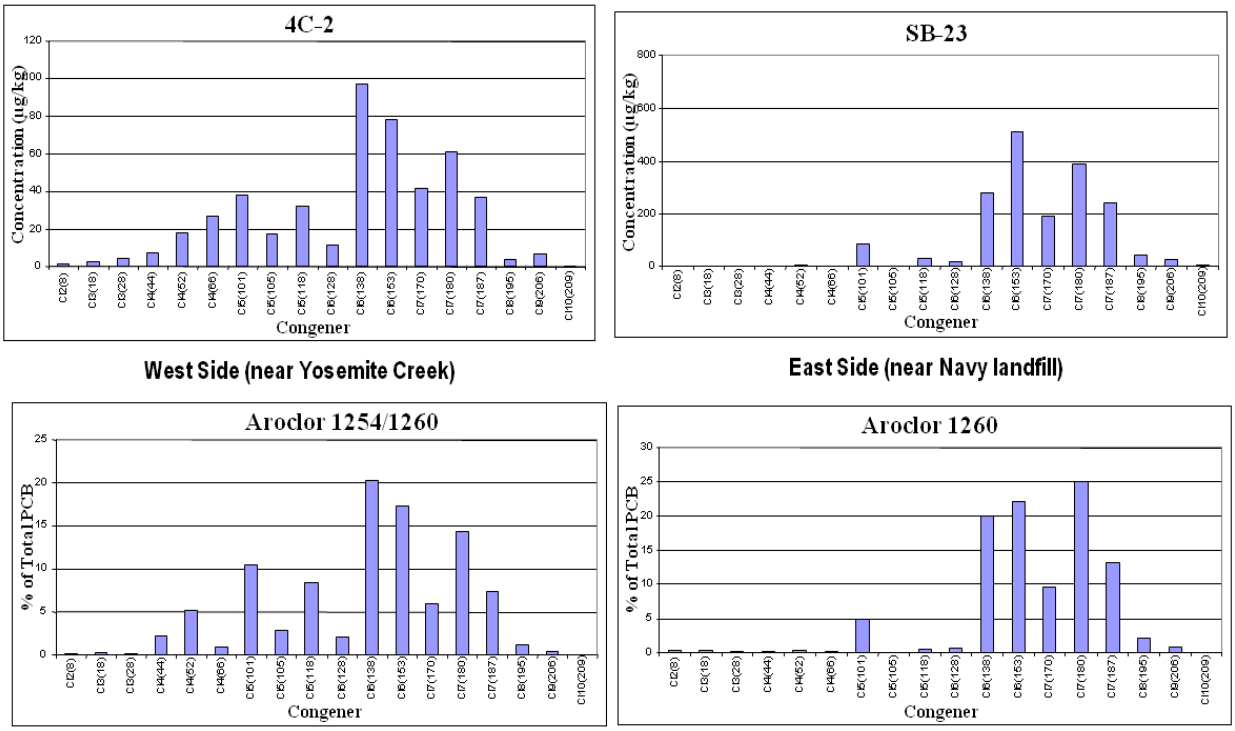


Figure 2-18. PCB Congener Composition in a Sediment Sample Collected on the West (4C-2) and East (SB-23) Side of Hunters Point Shipyard South Basin, and the PCB Composition in a Mixture of Aroclors 1254/1260 and Only Aroclor 1260

Another technique for illustrating compositional characteristics is to plot simple or double ratios of key diagnostic congeners – congeners with a concentration relationship that are resistant to change (i.e., stable congeners; Table 2-4) and unique to a source (e.g., an Aroclor), or that illustrate an active process (e.g., dechlorination/weather) but still can be associated with a source, or a combination of both. Diagnostic ratio analysis requires an in-depth understanding of the PCB chemistry and behavior of different PCB congeners, but when applied correctly can be a powerful technique (Figure 2-19). PCB compositional information can also be integrated with maps to further enhance the power of the information presentation. This can be done using a GIS system and illustrating diagnostic ratios (Figure 2-19) or PCB composition bar graphs for different locations directly on the map, or by presenting the compositional graphics accompanied by maps or aerial photographs.

While direct visual inspection of PCB composition and congener patterns is extremely useful and is often a valuable tool for gaining an intuitive insight into the source of PCBs in samples, it is often also useful to employ some statistical chemometric method, and generate some semi-quantitative similarity metric (Section 2.5.3.5). A similarity metric may assign a value to the degree of similarity between patterns, but no scalar measure will provide information on why or how two patterns differ. Visual pattern analysis allows the user to take qualitative information into account, and explain the observation from a PCB chemistry and environmental processes perspective, which ultimately is critical to the interpretation. Thus, regardless of the numerical methods used for pattern recognition and comparison, the data analyst is well advised to devote

significant effort to direct, visual inspection of congener patterns, and simple graphical presentation analyses. While there may be some comfort in reliance on an objective, quantitative similarity metric, it does not replace qualitative visual pattern analysis and the application of PCB chemical reasonableness considerations.

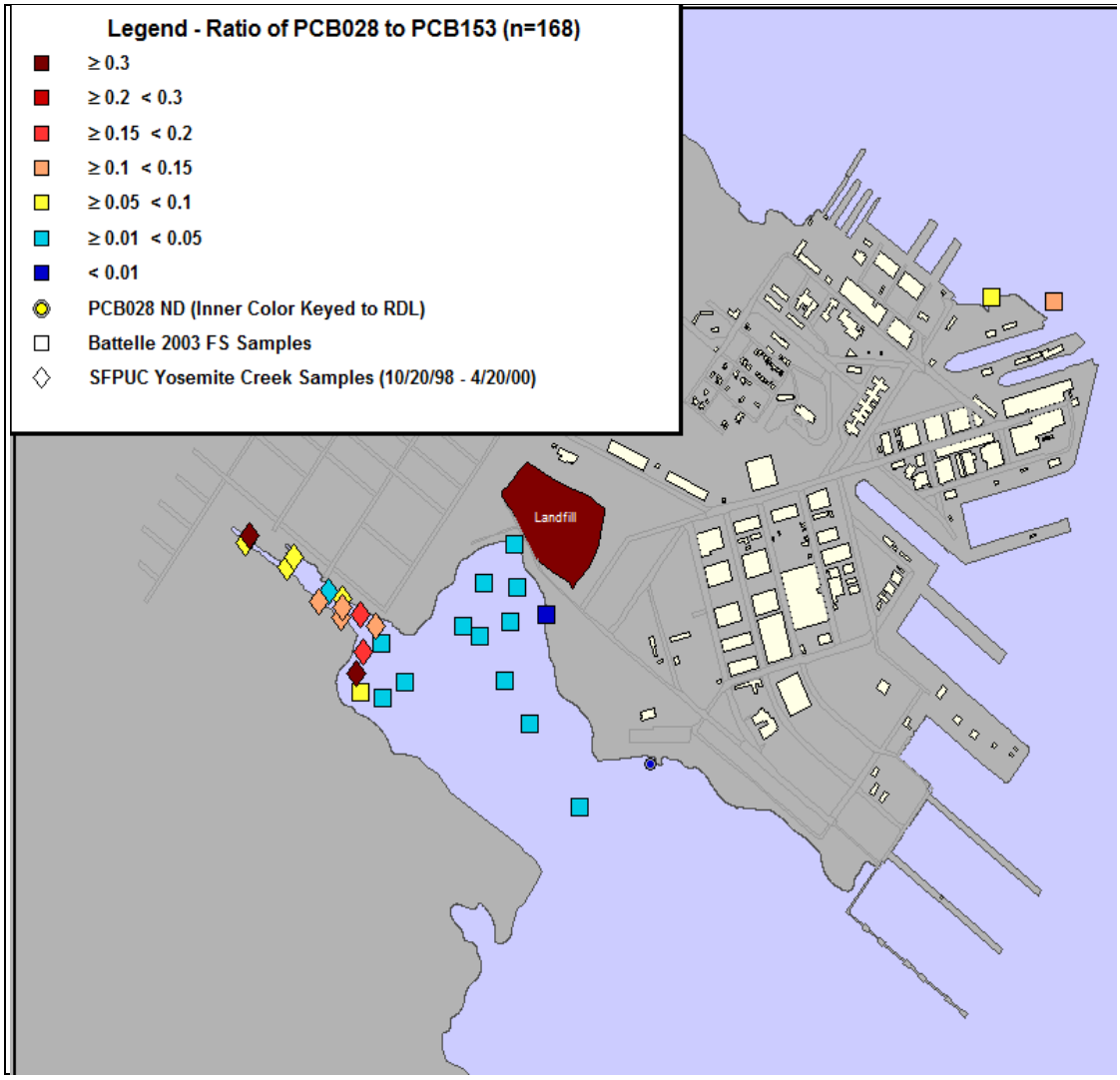


Figure 2-19. Ratio of PCB28 to PCB153 in Sediments near HPS South Basin

2.5.3.5 Chemometric Statistical Methods

Environmental forensics projects typically involve large chemical data sets with many samples and variables. This presents a data management and analysis problem: an inherently multivariate problem. There are numerous multivariate methods in the literature that are potentially applicable, a complete description of which is beyond the scope of this handbook. Three such approaches are presented: (1) cluster analysis, (2) PCA, and (3) mixing model analysis. Cluster analysis and PCA are perhaps the most widespread of these, primarily because of their ease of

use, and the fact that there are cluster analysis and PCA modules available in many different commercial statistical software packages. Mixing models can provide a more detailed insight into a PCB data set, but require more extensive experience, and are often available only as specialty software packages.

Cluster/Classification Analysis

Cluster analysis/classification refers to a general category of algorithms designed to classify samples into discrete groups or clusters. A PCB-related example of a cluster might be all samples in a data set with an Aroclor 1254 congener pattern. Samples that exhibited a different pattern (e.g., Aroclor 1242) would hopefully be grouped in a different cluster.

The most common of these methods is hierarchical cluster analysis (HCA). HCA is an exploratory method that operates on calculation of similarity between samples. Different mathematical criteria are used to group similar samples into clusters. The most common similarity metrics are based on distances calculated in multivariate space. In HCA, distances between individual samples are calculated. When distances between samples are relatively small, this implies that the samples are similar, at least with respect to PCB composition. The most similar samples are linked as a single cluster, and the process is repeated. Numerous linkage criteria/options are usually available in commercial software packages. Dissimilar samples will be separated by larger distances. HCA can be performed on either samples or variables (PCB congeners). The example that follows is HCA conducted in sample space.

The standard graphical method used for visualization of HCA results is the dendrogram. Figure 2-20 shows a dendrogram for HCA of PCB congener data from Lake Hartwell, South Carolina [8, 10]. This data set is composed of 237 samples (211 sediment samples, and 26 pure Aroclor standards), and 54 PCB congeners. HCA was run on samples. While difficult to read, each of the 237 sample names are listed down the left side of the dendrogram. The red lines link samples based on their distance (x-axis) from each other. Samples shown at the bottom of the dendrogram are very different from those at the top.

A hierarchical cluster approach will work well, provided that a data set is “hard-clustered.” In other words, HCA works well if one can safely assume that each sample belongs in one, and only one, cluster. In Lake Hartwell, this was not the case. Most samples were mixtures of two or three Aroclors, and/or were dechlorinated to some degree. As such, numerous samples that were mixtures of Aroclor 1242 and Aroclor 1254 did not cluster with either of the two Aroclor sources that contribute to it. The Lake Hartwell example is not at all unusual. More often than not, PCB forensics studies involve mixing multiple sources and/or weathering. As such, it is recommended to use hard cluster algorithms only in those instances where one can safely preclude mixing and weathering. HCA is readily available in many commercial statistical software packages, including Pirouette, Statistica, and SAS among others. Other classification methods have been described in the literature, which while not considered cluster analysis, are somewhat similar in that they seek to classify samples into discrete groups. One of these methods is SIMCA, which is available as a module in many software packages, primarily those that are focused on general chemometrics applications (e.g., Pirouette and Unscrambler).

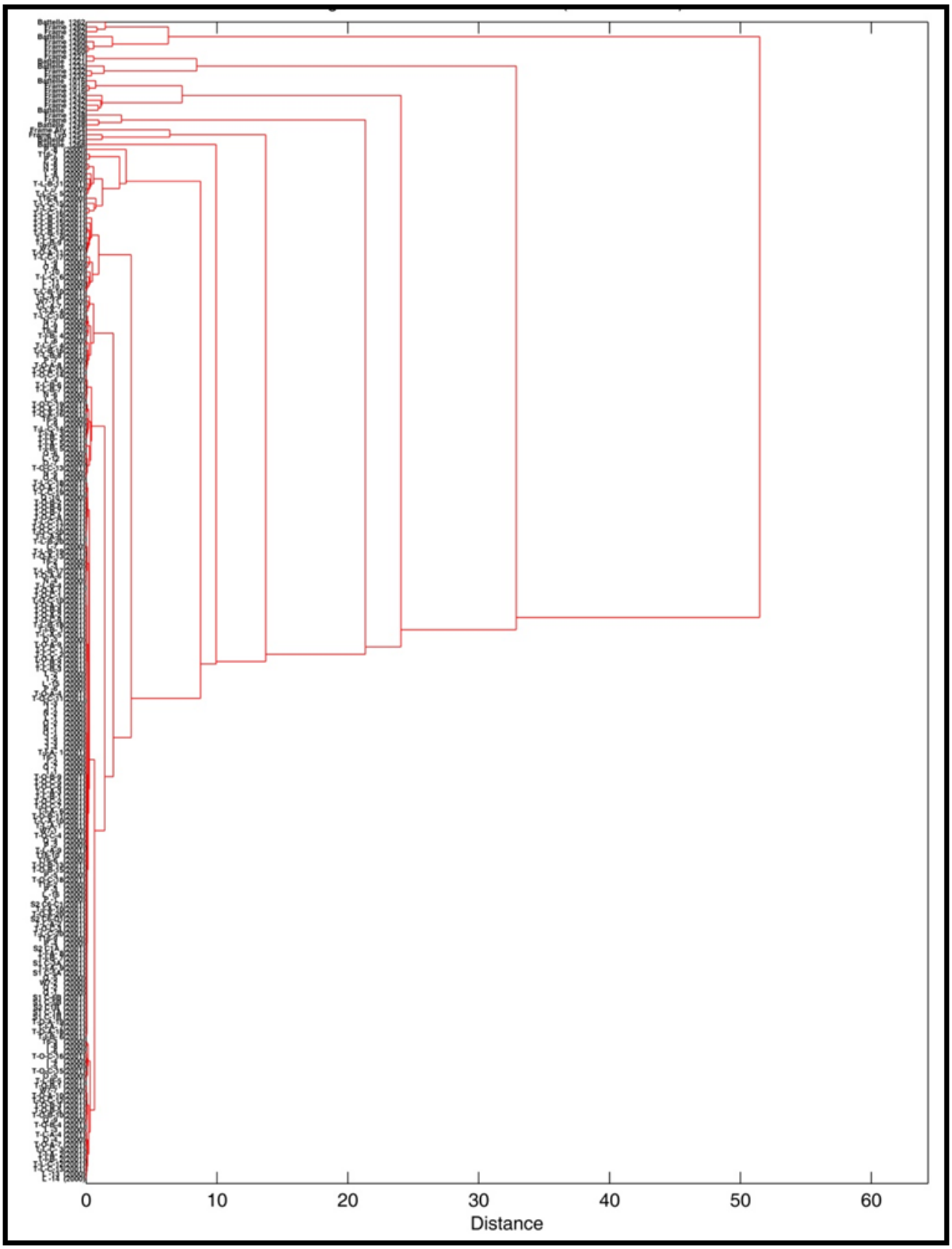


Figure 2-20. HCA Dendrogram of 211 Sediment Samples and 26 Aroclor Standards, Using Ward's Clustering and Euclidean Distance

Another alternative to HCA (especially if one is dealing with gradational data structures such as mixing and dechlorination) is fuzzy-c-means clustering (FCM [57, 58]). FCM is an exploratory data analysis method similar to HCA in that it operates on similarity between samples by calculation of Euclidean distance between samples. It differs in that it allows for a conceptual model of gradations between clusters. Thus, a sample that is a mixture of two Aroclors could be classified as having membership in two different clusters (e.g., a 0.50 membership in the Aroclor 1242 cluster and a 0.50 membership in the Aroclor 1254 cluster). FCM is not as widely used, and therefore is often not included as a module in general purpose statistical software packages. It is, however, available within the fuzzy logic toolbox for use with the software package Matlab.

Principal Component Analysis

PCA is commonly used in environmental forensics as a stand-alone exploratory data analysis method, and as an intermediate step in other chemometric methods (including SIMCA and receptor modeling methods). PCA reduces the dimensionality of a data set so that the similarities and differences between samples can be assessed by direct inspection of 2D or 3D graphs called "score plots" (Figures 2-21 and 2-22). These simple plots carry the advantage of being a single graphic that quickly provides the analyst a genuinely deeper insight into the PCB compositional characteristics of the samples in the system. An advantage of PCA over HCA is that the algorithm does not carry with it the implicit assumption of discrete classes or clusters. Rather, it offers a more objective visualization of the data. If the data are indeed hard clustered, that will be evident on a scores plot (Figure 2-21).

If, however, the data are not hard clustered, but are gradational/mixed, that will also be evident. It will not be hidden on an ambiguous dendrogram or confounded by inherent cluster assumptions. Figure 2-22 shows a scores plot for the same Lake Hartwell data shown on the dendrogram in Figure 2-20. It is now apparent that the vast majority of Lake Hartwell samples are gradational intermediates between pure Aroclor patterns or dechlorination end-products.

There is a natural appeal to being able to reduce such a large multivariate data to a simple 2D plot. However, to the inexperienced practitioner, there are a number of potential pitfalls. Contaminant sources and alteration mechanisms may be inferred from these simple 2D plots, but a more rigorous evaluation of the number of principal components that carry source-relevant information actually show even more. A typical PCA implementation may be limited by graphical limitations of two or three axis score plots. Potential pitfalls for PCA in forensics applications are discussed in detail by Johnson et al. [9]. Like HCA, PCA is readily available in many commercial statistical software packages, including Pirouette, Statistica, SAS, and Matlab.

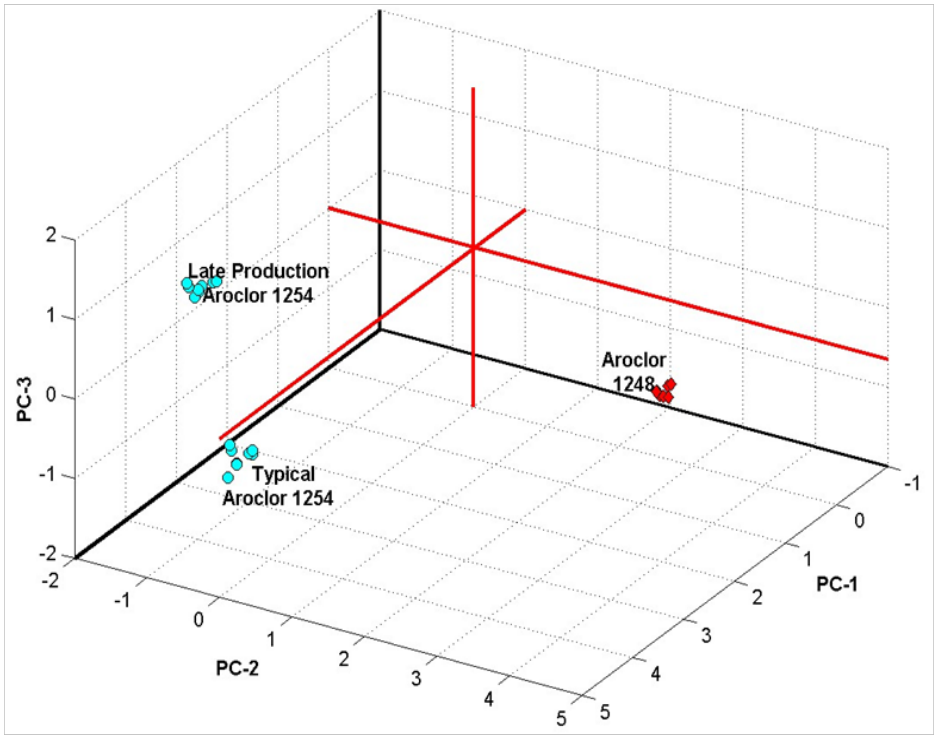


Figure 2-21. A Hard Clustered Three Source Data Set as Observed on a PCA Scores Plot (from Johnson et al., 2007 [9])

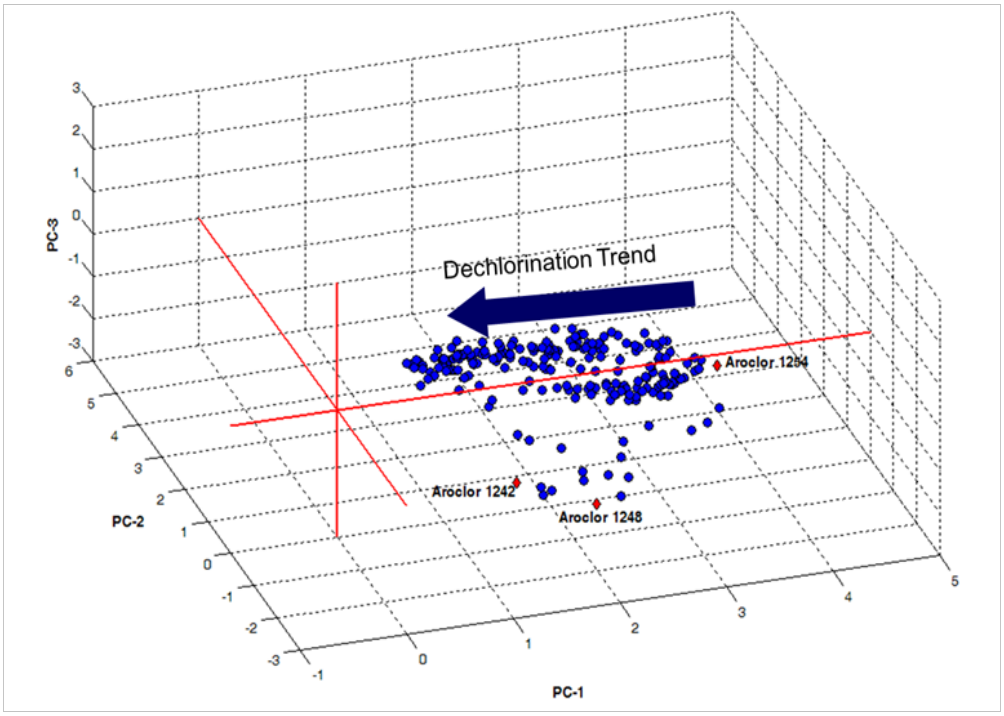


Figure 2-22. Lake Hartwell Data (from Magar, et al., 2005 [8]) Plotted on a Three-dimensional PCA Scores Plot

Receptor/Mixing Model Analysis

An increasingly common method used in environmental forensics investigations involves the use of receptor models. These methods are designed to resolve three parameters of concern in a multivariate mixed system: (1) the number of components in the mixture, (2) the identity (i.e., chemical composition) of each component, and (3) the relative proportions of each component in each sample. Stated mathematically, given a matrix X of m samples and n variables, and the unknown number of components k, one wishes to find a feasible solution to the following equation:

	X	=	A	F
Dimensions	(*m* x *n*)		(*m* x *k*)	(*k* x *n*)

Receptor methods often use PCA as an intermediate step to (1) determine the number of "significant" principal components (i.e., the number of sources), and (2) provide a reduced dimensional reference space for resolution of the model. The number of sources (*k*) essentially reduces the problem of choosing the number of significant principal components.

Within *k* dimensional space, receptor models then resolve the chemical compositions of the sources (F) and the contributions of the sources in each of the samples (**A**). If source compositions are known a priori, then those compositions may be used as the row vectors of **F** or as a training data set. Source contributions can be found via regression methods such as chemical mass balance.

However, in environmental forensics, one typically does not know and/or wishes not to assume such a priori knowledge of sources. For such situations, it is usually preferable to use a self-training receptor model method: a class of algorithms designed to resolve the number of sources, and feasible estimates of the multivariate source patterns and source contributions, without a priori assumption of sources. Receptor model methods in common use in environmental forensics include PVA [48, 49], MCR-ALS [51], PMF [50] and Unmix [59]. Application and comparison of these methods have been presented in the literature [9, 19]. These methods have some differences in the mathematics of their implementation, but all will provide estimates of contributing source fingerprints in a mixed system, without a priori knowledge or assumption of the number or chemical composition of those sources.

In addition to method comparisons cited in the literature above, the DoD Environmental Security Technology Certification Program (ESTCP) research that preceded development of this handbook [19] included a comparison of these four receptor model methods, as part of project performance objectives. That comparison included running these four algorithms on each of three data sets: (1) an artificial data recently published in the peer-reviewed literature [54]; (2) an artificial PCB data set originally published by [9]; and (3) the HPS data set. All four methods have since been analyzed on the second demonstration site data as well (Ashtabula), and reproduced the method comparison of the Henry data set below. The reader is referred to Johnson, et al. [9] for the method comparison applied to the Johnson data. The results of these methods applied to the two demonstration sites (HPS and Ashtabula River) will be included in the case-study discussions (Sections 3.1.7.5 and 3.2.7.5).

The Henry data set offered the advantage that it was created by two researchers that have published extensively on receptor model development and deployment, but who are not involved

in this particular project (the ESTCP research or the development of this handbook). Henry and Christensen [54] proposed a statistical performance criterion to measure the success of the methods that they tested: the standard deviation of the true source composition subtracted from the receptor-model estimated composition ($\sigma_{Est-True}$). This was adopted as one of the performance criterion for the method comparison exercise. Their published results were used for Unmix (the method Henry developed and has used extensively: [51, 56]) and PMF (a method Christensen has published on [34, 35]). For PVA, Dr. Glenn Johnson (co-investigator on this research) ran the Henry data set using Matlab code that he wrote and which he has used in many studies [5, 8, 10]. For ALS [51, 60] Dr. Scott Ramos (Chief Scientist at Infometrix, Inc., Bothell, WA) implemented the ALS. Dr. Ramos is also an experienced ALS practitioner [60]. The Henry data set is an artificial data set with 200 samples and eight chemical compounds, with 1% multiplicative error in the concentrations and three sources. The data set was included in the supporting information on the publishing journal's Web site (http://pubs.acs.org/journal/esthag).

Table 2-13 shows a comparison of true values of source compositions to those estimated by Unmix, three versions of PMF, PVA and ALS. As noted by Henry and Christensen, $\sigma_{Est-True}$ indicates that results from Unmix and the U.S. EPA PMF3 (with fpeak = -0.1) yielded estimated source compositions that were very close to true compositions ($\sigma_{Est-True} < 1$). PMF with other options chosen did not fare as well. The performance evaluation metric ($\sigma_{Est-True}$) was much larger. This observation is confirmed using the two similarity metrics from Johnson et al. [4]: $\cos\theta$ and $\boldsymbol{r}$. Similarity was low for B-PMF and U.S. EPA's PMF without f-peak. The estimated source compositions from PVA and ALS solutions (run by Johnson and Ramos) were added to this table. These methods also performed very well with low $\sigma_{Est-True}$ values, and $\cos\theta$ and $\boldsymbol{r}$ values ≥ 0.99 for all three source compositions.

Before concluding that any of these is the "best" method, note that one could argue that PMF performed among the best (see results for PMF3 with fpeak = -0.01) or that PMF performed the worst (see results for PMF NNLS; Table 2-13. There are many similarities between these methods, and "best performance" is not necessarily a function of the acronym one uses to label their method. Rather, it is often a function of options chosen, the expertise of the analyst, and their sensitivity to the data structure. The results of this method comparison were presented at the Society of Environmental Toxicology and Chemistry North America 31st Annual Meeting in Portland, OR [61].

This receptor model method comparison shows that given good quality chemical data (or data that have undergone rigorous QA/QC to identify and address any issues) these receptor model methods usually perform well and resolve similar source patterns and apportionment estimates. But like PCA, these methods require a certain level of experience and sensitivity to common environmental data structures. When faced with bad data, any or all of these methods can produce spurious results. One of the most crucial steps in the data analysis process is vigilant outlier detection and data cleaning. Even with good data, these methods can be problematic in the hands of an inexperienced user and/or a user without sensitivity to chemistry and environmental science. In the hands of an experienced practitioner, these methods should result in source patterns and contributions that are consistent.

Table 2-13. Comparison of True Source Compositions for Data Set 1 (Henry Data Set) with Values Determined from Unmix, PMF (four versions), PVA, and ALS

	compd #	True value	UNMIX	B-PMF NNLS	B-PMF penalty functions	EPA PMF3	EPA PMF3 fpeak=-0.1	Johnson Matlab PVA	Pirouette MCR-ALS
Source 1	1	11.44	11.31	10.9	10.45	11.07	11.72	11.20	11.40
	2	12.83	13.3	15.24	15.15	15.45	12.67	13.29	12.91
	3	11.9	12.17	12.74	13.26	12.54	11.61	12.25	12.00
	4	15.34	16.01	18.46	18.66	18.57	15.01	16.06	15.50
	5	14.79	15.04	16.18	15.76	16.49	14.9	14.97	14.82
	6	12.27	12.08	10.41	11.51	9.73	11.97	12.20	12.32
	7	11.76	11.29	10.15	9.56	10.3	12.07	11.22	11.59
	8	9.66	8.8	5.91	5.65	5.86	10.04	8.81	9.47
	$\sigma_{Est.-True}$		**0.51**	**2.35**	**2.44**	**2.5**	**0.3**	**0.53**	**0.13**
	Corr Coef (*r*)		**0.992**	**0.947**	**0.941**	**0.939**	**0.989**	**0.990**	**0.999**
	Cos θ		**0.999**	**0.986**	**0.985**	**0.984**	**1.000**	**0.999**	**1.000**
Source 2	1	12.54	12.47	11.13	11.72	12.59	12.6	12.58	12.56
	2	8.85	7.86	6.22	7.16	7.18	9	8.39	8.52
	3	10.46	10.43	11.87	11.24	10.26	10.36	10.36	10.39
	4	10.11	9.08	8.08	8.8	8.24	10.29	9.62	9.77
	5	12.63	11.85	9.58	10.72	11.44	12.82	12.33	12.43
	6	15.29	16.61	21.6	19.12	17.29	14.89	15.74	15.62
	7	14.38	14.71	13.56	14	15.06	14.45	14.63	14.55
	8	15.75	16.99	17.96	17.26	17.95	15.59	16.35	16.17
	$\sigma_{Est.-True}$		**0.93**	**3.16**	**1.95**	**1.56**	**0.21**	**0.41**	**0.29**
	Corr Coef (*r*)		**0.991**	**0.873**	**0.931**	**0.985**	**0.998**	**0.998**	**0.999**
	Cos θ		**0.998**	**0.976**	**0.990**	**0.994**	**1.000**	**1.000**	**1.000**
Source 3	1	13.64	13.7	15.77	15.36	13.87	13.48	13.53	13.49
	2	12.12	12.55	12.24	11.66	11.19	11.76	12.11	12.16
	3	9.43	9.33	6.84	7.36	9.03	9.52	9.47	9.53
	4	13.25	13.61	11.92	11.5	11.94	12.84	13.19	13.26
	5	15.96	16.35	17.76	17.02	15.45	15.58	15.89	15.90
	6	8.77	7.99	3.84	5.57	9.38	9.46	8.93	8.93
	7	14.53	14.57	17.39	17.02	15.3	14.6	14.54	14.49
	8	12.31	11.9	14.18	14.52	13.85	12.76	12.33	12.25
	$\sigma_{Est.-True}$		**0.42**	**2.73**	**2.17**	**0.95**	**0.41**	**0.08**	**0.10**
	Corr Coef (*r*)		**0.994**	**0.956**	**0.941**	**0.926**	**0.990**	**1.000**	**1.000**
	Cos θ		**1.000**	**0.982**	**0.988**	**0.998**	**1.000**	**1.000**	**1.000**

The use of receptor model methods are not as widespread as PCA and HCA, and are therefore not as commonly included in general purpose chemometrics software. Pirouette does, however, include an ALS module. A free Matlab version of ALS is available at the Web site of its developer (Roma Tauler http://www.ub.edu/mcr/ndownload.htm). A free version of PMF is available at http://www.epa.gov/heasd/products/pmf/pmf.html. The developer of PMF (Pentii Paatero offers a commercial version of the software with more features and options than the free version. Unmix is available free at www.epa.gov/heasd/products/unmix/unmix.html. A commercial version of PVA software was available for many years through one of its

developers, Dr. Robert Ehrlich. Current availability of the software is unknown. A Matlab version of PVA can be obtained from the authors of this handbook.

2.5.3.6 Integrated Data Analysis and Interpretation

Integrated data analysis and interpretation is the process of synthesizing information and interpretations from multiple lines of evidence to arrive at scientific interpretations that answer the key questions of a forensics investigation. Various lines of evidence are combined, compared, inconsistencies analyzed, and the "full story" developed. Lines of evidence typically considered include the site history, contaminant transport, PCB concentration distribution, PCB composition considerations, and chemometric statistical analyses, as described in Sections 2.5.3.1 through 2.5.3.5, in addition to conducting the chemical reasonableness assessment and incorporating less easily identifiable pieces and linking the information into one cohesive understanding of the sources of contamination.

Common lines of evidence based on the data that to be integrated and compared include:

- Typically congener patterns will have been analyzed in several different ways, including simple chromatogram inspection (Section 2.5.1.1) and one or more chemometric analysis methods. The inferred congener patterns identified by each of these methods should be compared for consistency across methods. In addition, the geographic distribution of the observed congener patterns should be compared. As an example, if an Aroclor 1242 fingerprint is observed in one specific area of the field by one method, is that in agreement with the geographic distribution for that pattern observed by another method.
- If congener pattern analyses result in inference of a source, determine if that conclusion is supported by concentration gradient mapping. One key tenant of environmental forensics investigations is that the highest concentrations are typically observed near sources or outfalls, but this should be supported by hydrodynamic and sediment transport data.
- Are the locations of sources as inferred through data analysis consistent with known site history? For example, if an Aroclor 1260 congener pattern was observed in high concentrations near a former electrical transformer manufacturing facility, all three independent lines of evidence (concentrations, congener patterns and site history) would support a transformer source interpretation because Aroclor 1260 was often used in transformers.
- If a congener pattern does not match any known Aroclor source patterns, it is often useful to review literature that describes alteration processes. Reference data for common PCB alteration mechanisms such as dechlorination and volatilization may be found in the literature [4, 16].

Ideally, this process leads to an internally consistent and lucid interpretation of contaminant sources and environmental history. However, this is not always the case. Often, there will be one or more ambiguous lines of evidence, and (hopefully) another line of evidence will shed light on that ambiguity confirming that it may not be of value in the overall analysis, and move the final interpretation in the right direction. There may occasionally even be independent lines of evidence that seemingly contradict each other. In such a case, integrated data analysis is

equally important, because in the process of evaluating multiple lines of evidence, an investigator may better decide which lines of evidence deserve more weight and why. The decisions need to be justifiable using sound science, with an understanding of PCB chemistry and reasoning related to the behavior of PCB in the environment often the most critical component. As with other aspects of this workflow, there are no prescribed steps for this task. In fact, the investigator will likely have most success if they are resourceful and creative in finding new lines of evidence that might help shed light on such questions.

Example of a multiple lines of evidence approach to integration of interpretations is provided with the two case studies conducted as part of developing this handbook: HPS (Section 3.1.7.6) and Ashtabula River (Section 3.2.7.6). The summary presented below in this section is from Lake Hartwell, South Carolina. The summary describes aspects of that study integrating multiple lines of evidence to arrive at a conclusion that might not otherwise be apparent. Specifically, aspects of the study where an integrated data analysis approach helped clear up an ambiguous story, or resolve seemingly conflicting lines of evidence are focused on.

A receptor model method (PVA) was used to resolve contributing PCB fingerprints [8]. Dechlorination pathway analyses were performed as part of that study to associate dramatically varying PCB composition across the site to a single source, and the elevated PCB concentrations could be associated with known high historic releases. One of the resolved source patterns in that analysis was consistent with published Aroclor 1248 congener patterns. When this information was compared to historical information, it was learned that the primary suspected source to the lake (a former capacitor manufacture) had not used Aroclor 1248, but had used Aroclor 1242. While these two pieces of evidence apparently conflict, a third line of evidence resulted in a simple, lucid and consistent story. Previously published empirical experimental data [30] had shown that weathering (volatilization) of Aroclor 1242 could result in a residual pattern in sediments that more closely resembles Aroclor 1248 than the original Aroclor 1242. As a result, the apparent Aroclor 1248 fingerprint was entirely consistent with an Aroclor 1242 source. The PCB pattern in buried highly dechlorinated samples, which did not resemble any Aroclor, was also linked to Aroclor 1242 and the primary source through dechlorination pathway analysis.

Data Analysis and Interpretation

This section presents an overview of the data analysis and interpretation, including the inclusion of information other than PCB data, data preparation, and PCB data interpretation.

- **Site History and Records Research**
- **Sediment Transport and Hydrodynamics**
- **Preliminary PCB Concentration Assessment**
- **Preliminary PCB Composition Assessment**
- **Chemometric Statistical Analysis,** such as
    - Cluster analysis
    - Principal component analysis
    - Mixing model analysis
- **Integrated Multiple Lines-of-Evidence Interpretation**

2.6 Presentation and Reporting

The presentation of results of a PCB forensics investigation will vary greatly, depending on the purpose and the venue. For example, given two projects that involve identical technical issues, the context of one might require verbal reporting, where the other might require a detailed technical report. In terms of presentation of results, there are a few guidelines that apply and can be used for most purposes. It is important to find an effective means of data visualization. Standard graphical presentations (e.g., histograms) of concentration and composition information can be useful, and any GIS-based illustration of the contamination and unique signatures are especially useful (e.g., Figures 2-15 and 2-17). Most statistical software packages include standard graphical output for data analysis results (e.g., cross-plots, score plots, loadings plots, etc.) but these graphics may mean little to the non-user and may require simplification; it is important to produce graphics that are intuitive to a non-scientist. The primary objectives of a PCB forensic investigation are identification of contributing chemical patterns (i.e., Aroclor sources and/or alteration patterns) and their geographic and temporal distribution. Summarizing historical industrial practices and local activities that can explain the observations, and using hydrological information to describe how sediments and potential contaminants move around in the system, can also be important to support the PCB chemistry. When describing the findings, it is useful to do so in a step-wise fashion, clearly lining up multiple lines of evidence, showing how they point towards the same findings and support each other.

As discussed in the beginning of this section, the format for presentation of results depend largely on project context and target audience/reader. The following scenarios may involve the exact same technical approach and forensic investigations, but the context of the project dictates different presentation formats.

If the audience does not have extensive technical knowledge (e.g., the public, managers, lawyers), it is likely that they are not intimately familiar with environmental chemistry, statistics, or PCB industrial history. Therefore, a presentation to this audience may require an element of introductory chemistry, statistics, and/or industrial history. In addition, the first communication of results is then often verbal, rather than written. Therefore, the presentation format is less formal than a report (e.g., a conference call, or a face-to-face meeting, perhaps with PowerPoint slides).

A second common context is a presentation to other scientists. This is likely a more formal context than the first example. However, the approach to the presentation will also be different in other ways. In a more technical context (among peers), it is assumed the audience knows much of the prerequisite science. A paper or presentation will then include a great deal of technical short-hand. In this venue, one may summarize important foundational material with no more than a citation at the end of a single sentence summary.

A third, and again, completely different example is a venue where contributions from multiple sources are not widely understood or agreed-on, and is common for forensics investigations. This may include what could be considered expert opinion, and to support that the expert is more likely to produce a report that errs on the side of completeness, even if it means a pedantic narrative and extensive appendices.

3.0 DEMONSTRATION CASE STUDIES

3.1 Site I: Hunters Point Shipyard

3.1.1 Site Description

The HPS site is located in the San Francisco Bay as shown in Figure 3-1. HPS is a former Navy installation located on a peninsula in the southeast corner of San Francisco, CA. The peninsula is bounded on the north, east, and south by San Francisco Bay and on the west by the Bayview Hunters Point district. HPS comprises about 955 acres, with approximately 457 acres of offshore sediment (Parcel F). From 1945 to 1974, the Navy maintained and repaired ships at HPS. The facility was deactivated in 1974 and remained relatively unused until 1976, when it was leased to Triple A Machine Shop, a private ship repair company. In 1986, the Navy resumed occupancy of HPS. The facility was closed in 1991 under the Defense Base Realignment and Closure Act of 1990 and is in the process of conversion to non-military use.

The shipyard is divided into several parcels with the offshore sediments designated as Parcel F. The specific area of interest for a PCB forensics investigation is the Parcel F (offshore) sediments near Parcel E and E-2 in the South Basin (Figure 3-1). This area is shown in more detail in Figure 3-2, where it is labeled Area X. South Basin's current configuration reflects filling activities that took place from the 1940s to the 1970s (Figure 3-3). Previous studies have shown potential PCB source areas associated with the former Navy landfill and multiple CSOs in nearby Yosemite Creek. Of particular concern is whether these different sources have contributed PCBs to sediments in the South Basin area, and to what degree. This site has been under regulatory study and RI/FS has been completed as part of the CERCLA program. The data used in this case study example were collected as part of the RI/FS study, most of it from a comprehensive data gaps investigation [62].

South Basin is a shallow embayment on the south side of HPS, with water depths ranging from 6 ft to less than 2 ft. No streams or rivers enter South Basin except for Yosemite Creek, a shallow, tidally-influenced channel with no permanent flow. Circulation in South Basin is restricted and tidal currents are very weak. The basin is open to the southeast, which is the direction of the maximum winds during winter storms. Although the prevailing winds in the area are westerly, the acute storm waves responsible for sediment resuspension are generated by southeast storm winds. Yosemite Creek enters South Basin at the southwest corner of HPS. Yosemite Creek is listed as a site of concern under the Bay Protection and Toxic Cleanup Program in 1997. Prior to 1965, three CSOs discharged to this area: one at the head of Yosemite Creek (Figure 3-2), one on the north side of the creek near Griffith Street, and one on the south side near Fitch Street. All wet weather overflows were directed to the CSO at the head of Yosemite Creek after 1965. Contaminants identified during investigations of Yosemite Creek by the City and County of San Francisco included PCBs, PAHs, pesticides and metals.

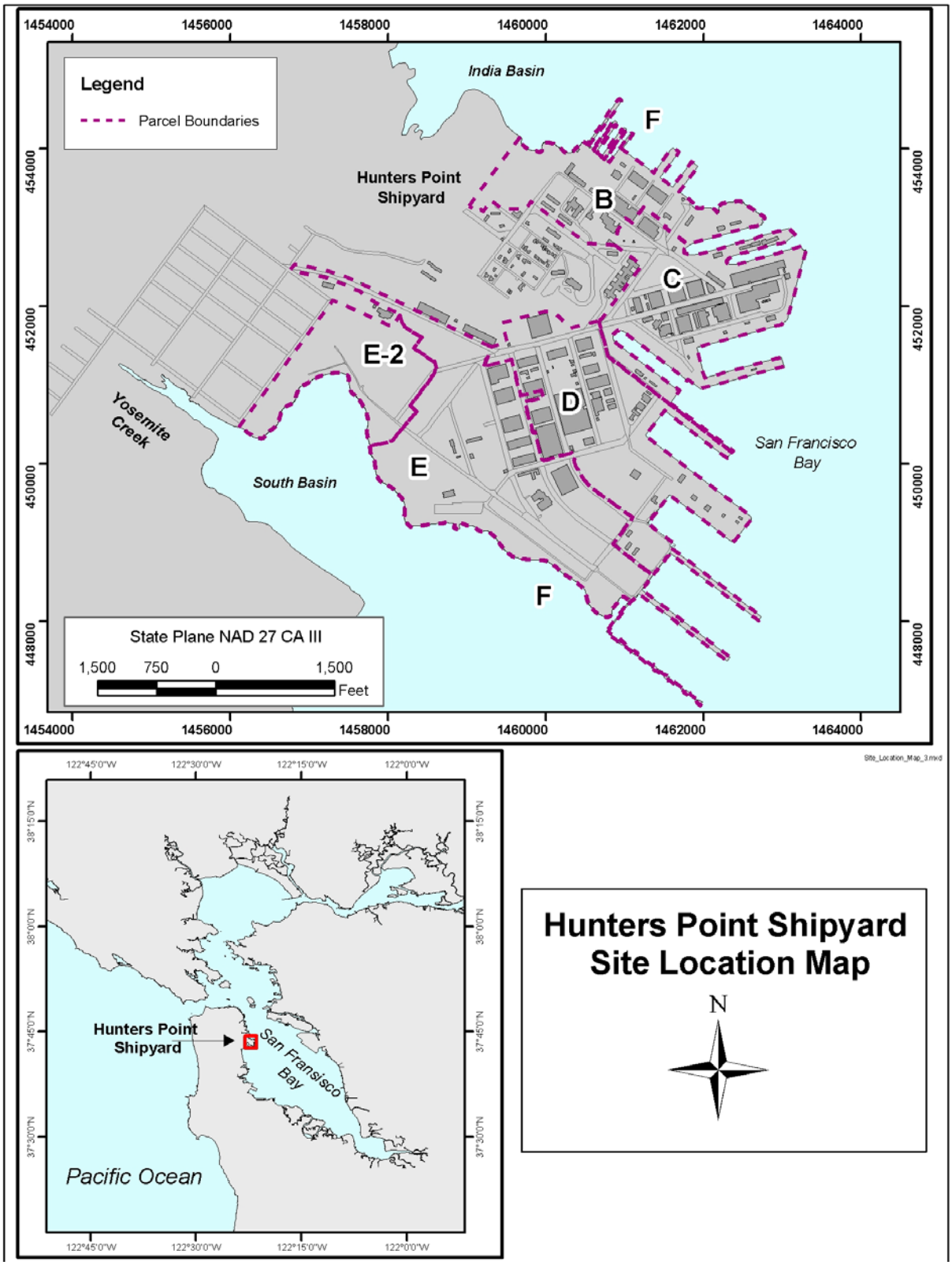


Figure 3-1. Hunters Point Shipyard Location Map Showing South Basin Area

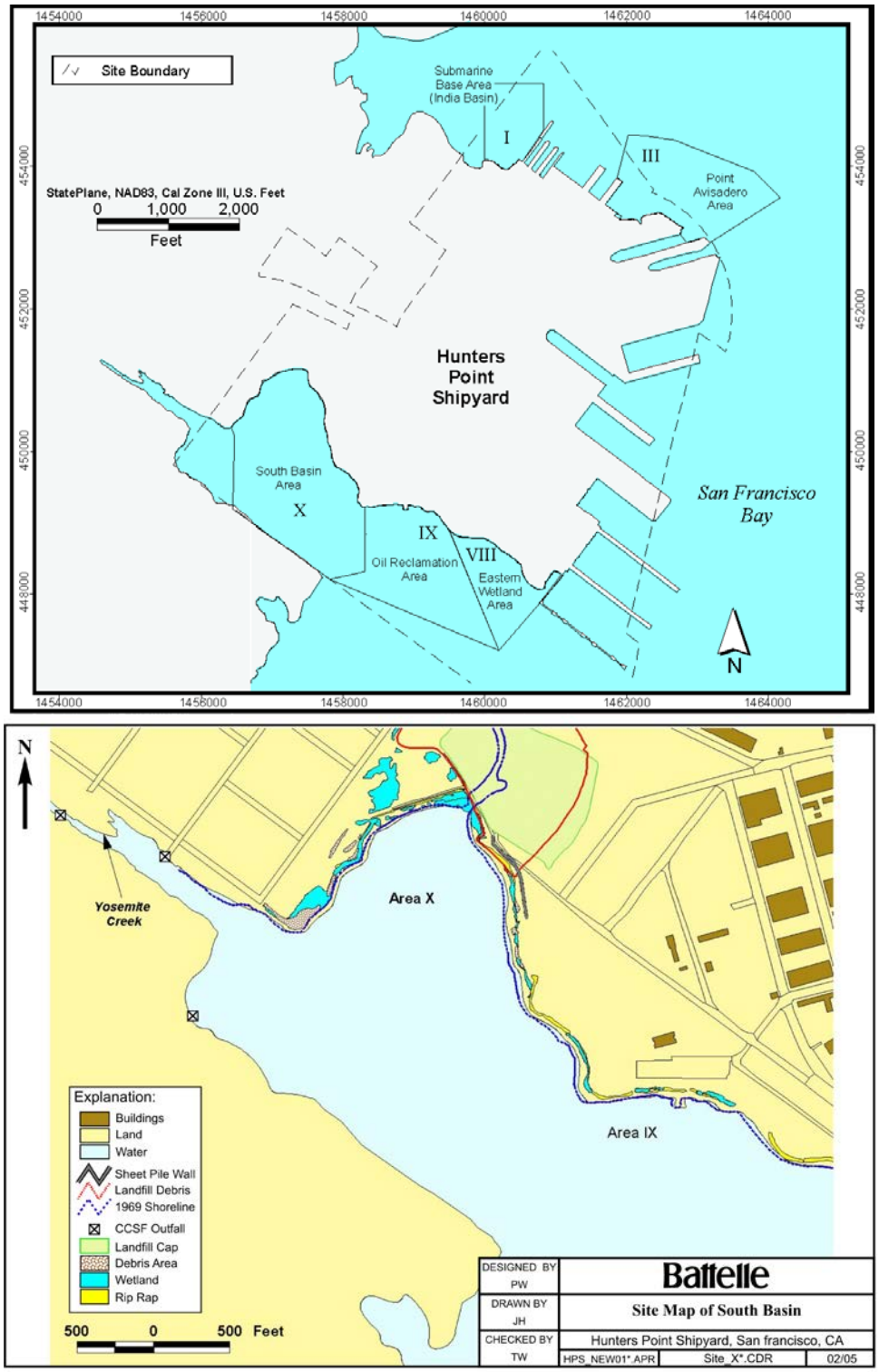


Figure 3-2. Study Areas and Shoreline Features in South Basin (Areas IX-X) of Parcel F Offshore Sediments

(Note Former Landfill to the north and City Outfalls to the west.)

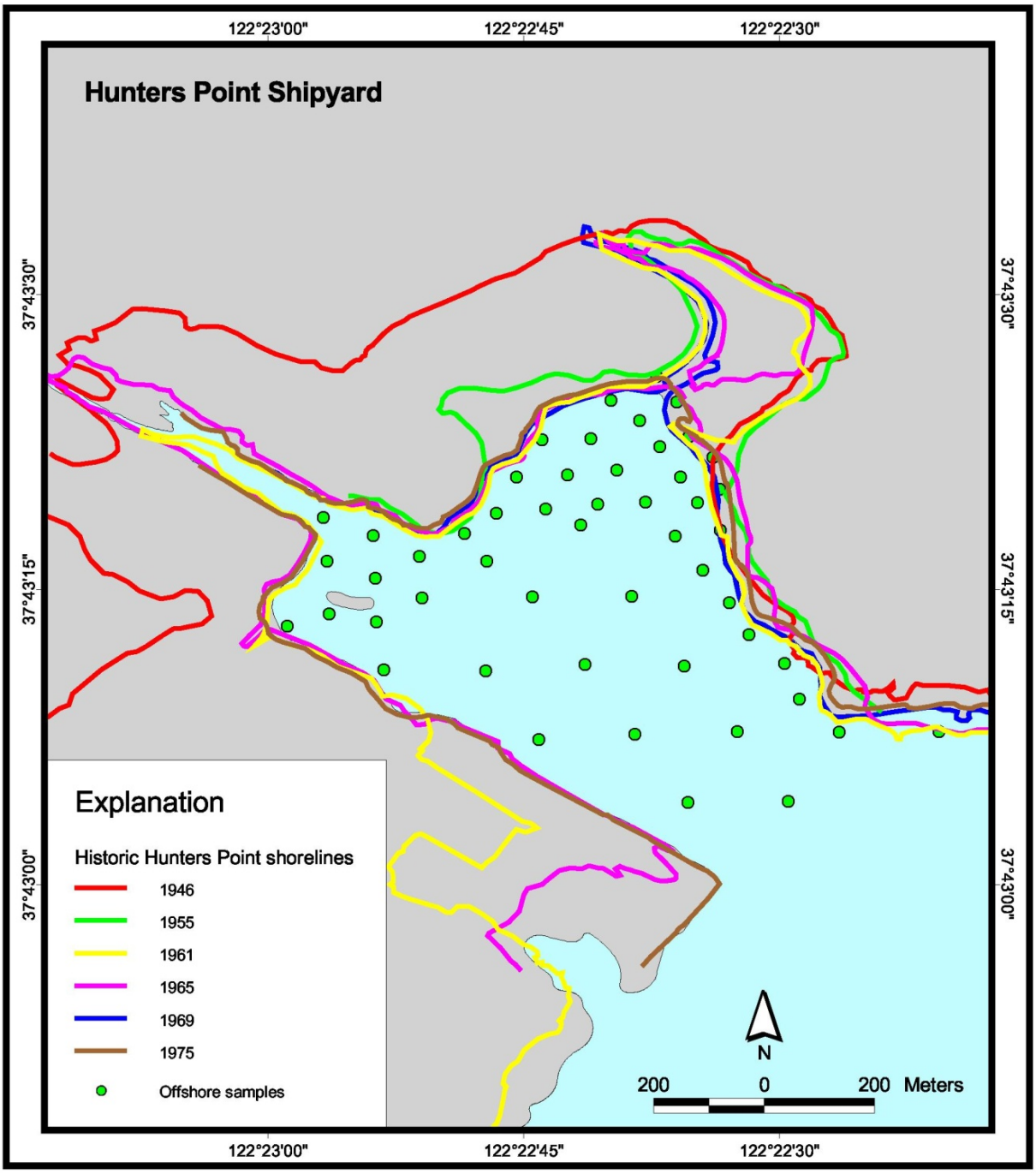


Figure 3-3. Shoreline Evolution in HPS South Basin and 2003 Offshore Sample Locations

3.1.2 Evaluate Site for Forensic Study

To evaluate whether the site is a candidate for a forensic study, the questions posed in Section 1.2.1.1 should be answered. The HPS site has a former landfill in Parcel E-2 (near the northeastern shore of South Basin; Figure 3-2) with records showing wastes (including transformers with PCB oils) deposited at the site from the 1950s through the 1970s. Other records indicate that PCBs with an Aroclor 1260 composition have been detected in some groundwater wells near the shoreline. Related to Questions 2 and 3, there have been known discharges from CSOs in and near Yosemite Creek, and previous studies by the City of San Francisco [63] have shown sediments upstream in Yosemite Creek contain PCBs with both Aroclor 1254 and 1260 contamination. Addressing Question 4, there was a sediment transport study conducted as part of the RI/FS [31, 62] that shows South Basin to be a relatively quiet depositional basin with occasional wind derived local resuspension and local redeposition. This conclusion is further supported by the persistent PCB concentration gradients shown in the sediment contour maps in later sections of this handbook. For Question 5 (i.e., how amenable regulators would be to the use of forensic information), the answer varies depending on when in the process such information would be used. There was a consensus early in the RI/FS process that a forensics study would be useful, and there were plans to incorporate such a study in the RI/FS. Later, there were questions from both the regulators and the Navy about whether they could use such a forensics study at HPS. After the samples for the RI/FS were collected, it was decided not to complete the forensics study as part of the RI/FS. The information from the HPS site was available for use in this handbook to help promote the use of forensics studies at Navy sites, but a dedicated PCB contaminant forensics investigation has not been conducted at HPS. The data generated in the RI/FS, and used in this handbook, support the contention that there appear to be at least two potential sources for PCBs to the offshore sediments in South Basin (one from the former Navy landfill area and one possibly from CSOs in the Yosemite Creek area) and a forensics study could defensibly document this and better understand the relative contributions from the multiple source to the offshore sediments.

3.1.3 Develop Conceptual Site Model

Figure 3-4 shows a contour map of surface PCB concentrations, based on ELISA IA RSC analysis, that assisted in early CSM development at HPS. These data were collected early in the regulatory RI/FS project, and they suggest a potential PCB source in the northeast along the Navy shoreline near the former landfill. An additional source is also suggested at the creek on the west side of the site where PCB concentrations are also elevated. Other data from CSOs in and near this creek have shown PCB levels similar to those along the Navy shoreline. The sampling design for a forensics investigation should therefore be placed strategically to confirm that these two areas represent sources and also in other areas (for example along the south shore of South Basin where construction of Candlestick Park Stadium may have contributed contamination) to ensure that there are no additional unidentified sources to the offshore sediments in the area. Samples should also be placed in all areas of comingling sources and where it is appropriate to determine source contribution and apportioned, for the Navy to share or recover any remedial costs.

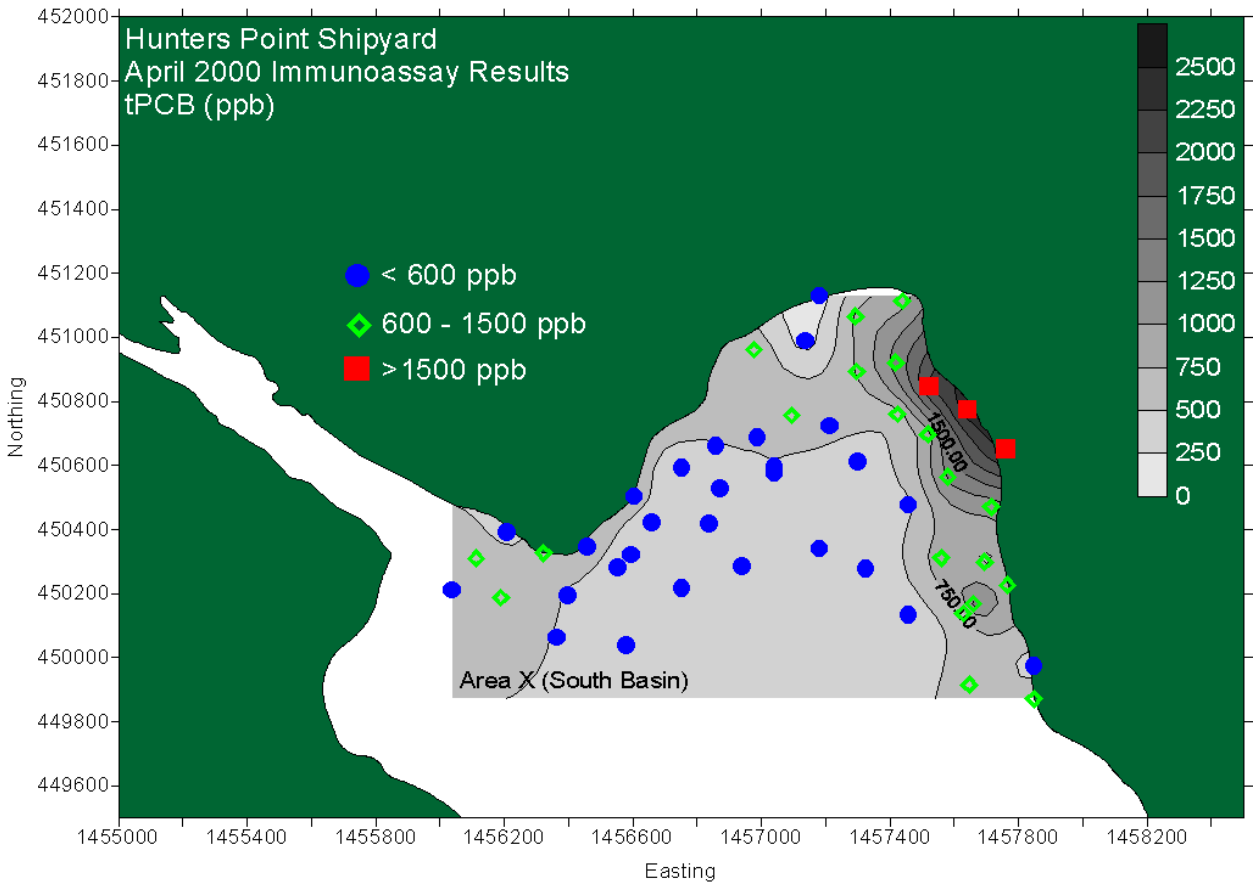


Figure 3-4. Contour Map of PCB Concentrations in Surface Sediments in South Basin at HPS

Since this case study was not a stand-alone project, there were no resources to conduct extensive records research and build a separate CSM. However, a CSM was developed by the regulatory RI/FS program (Figure 3-5) and could be used for some project considerations. The major pathways for PCB contaminant transport to the South Basin sediments are indicated as originating from: (1) historic filling and disposal practices associated with the landfill area, which allowed PCBs to be transported via the historic slough, or channel, out into the South Basin sediments; (2) releases from CSO outfalls in Yosemite Creek area (shown as active red arrows) transports PCBs out into sediments; and (3) erosion of contaminated fill that was used around Yosemite Creek releases PCBs into the sediments. One might consider making the minor active pathway arrow from the "Shoreline Erosion/Runoff" box to the "Sediment" box into a bolder major pathway arrow, indicating the potential for PCB releases from erosion of the fill material along the beach in front of the former landfill. This may be the major continuing active source (although current plans include a removal action to remove this contaminated beach material and stabilize the shoreline) based on the high surface sediment concentrations observed in this area (Figure 3-4). This CSM serves to focus the SAP in the next section, by identifying the locations where samples should be taken to answer the forensic questions raised during development of the CSM.

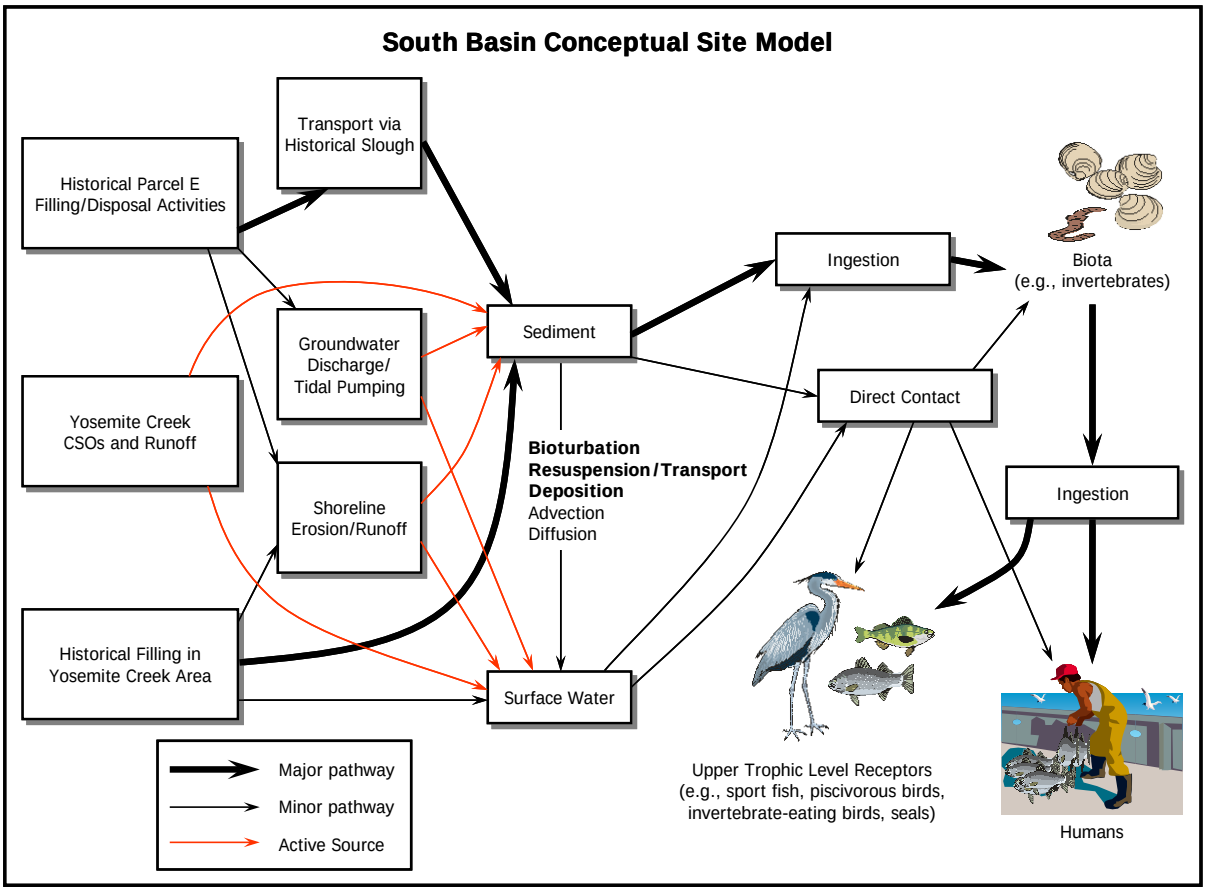


Figure 3-5. HPS South Basin CSM from Regulatory Program RI/FS

3.1.4 Develop and Execute a Technically Defensible Sampling Plan

In the HPS case, the regulatory RI/FS project included a grid design for samples with spacing that would allow for the detection of hotspots larger than a predetermined size. This grid sampling design is shown in Figure 3-6. Higher density sampling is seen in the potential source areas with lower density in the farther offshore sediments. Figure 3-6 also shows the core intervals that would be composited for initial RSC analysis, with only a subset of these samples being later analyzed for ACF. This resulted in about 400 samples being analyzed for RSC and about 100 samples for ACF. Unfortunately, the regulatory project was restricted to sampling primarily on Navy property, so no samples were collected further upstream in Yosemite Creek near several CSOs that were additional potential sources. In addition, additional samples in the zone where the PCB sources are well mixed would have benefitted a forensics investigation.

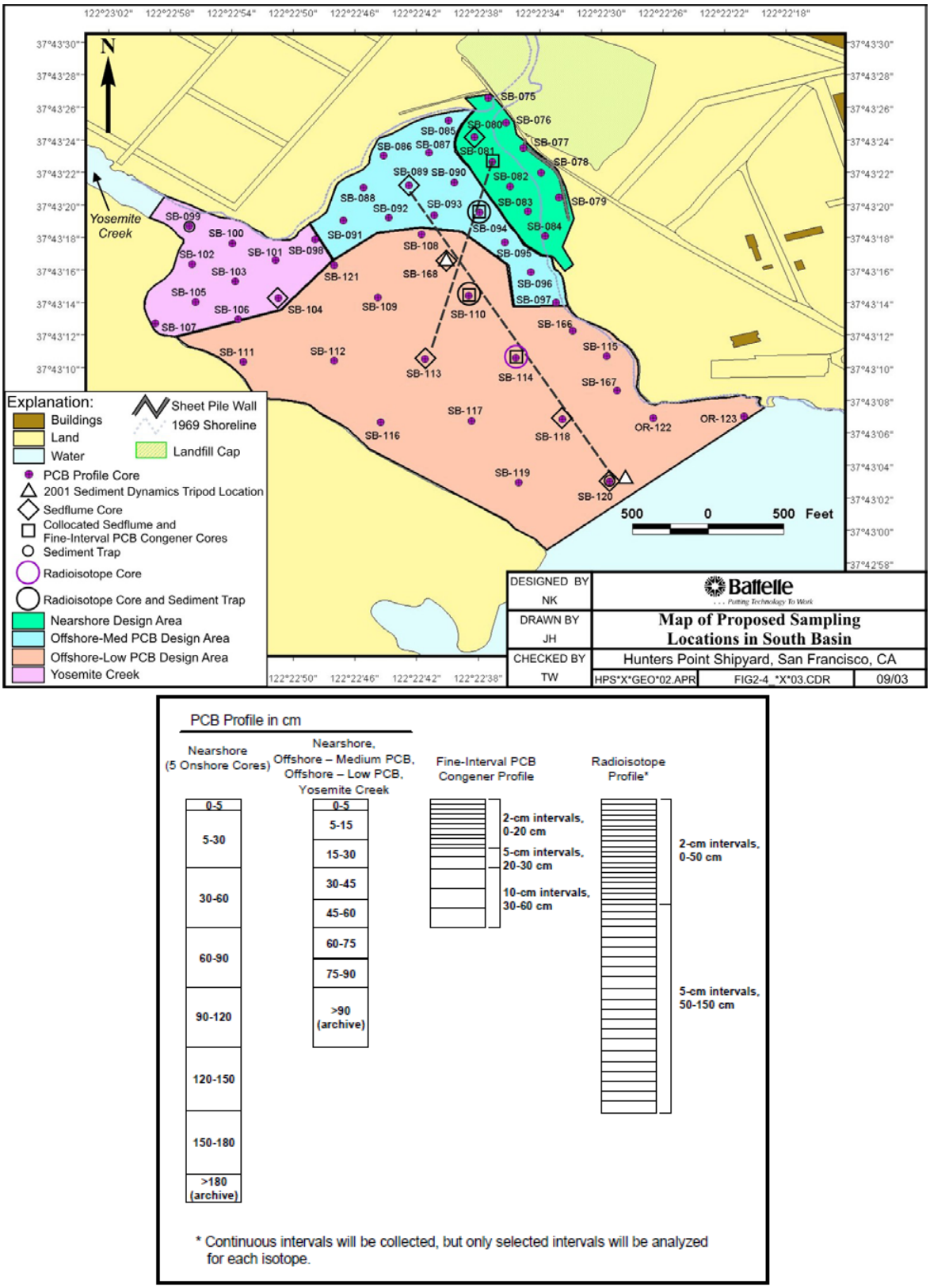


Figure 3-6. Sampling Design Map for the HPS Feasibility Study [62]
(This includes the cores that provided the data used in the forensics demonstration at HPS.)

The HPS case study is based on using existing data from study designs that had not been optimized for a forensics investigation. There are clearly advantages and limitations of designing a forensics study with only pre-existing data. Although using pre-existing data provides a large cost savings, the shortcomings of not being able to design a sampling plan to collect all the samples desired must be accepted. As stated earlier, even in the best designed forensics study, there are likely to be surprises, such as those seen with this case study using only pre-existing data. For example, if additional sources are indicated by some of the study samples (e.g., Yosemite Creek), then there is a need to conduct additional sampling and analysis to identify such sources. That has not been conducted for the HPS site. So although it may be easier to grasp a forensics study that follows a linear process (Figure 1-1), it may be more realistic to assume the process will be iterative with a need to obtain information on additional unknown sources, and fill in additional information gaps.

While it is cost-effective to use pre-existing data (no additional field or analytical costs), the limitations are that the study design may not meet all of the objectives of a well executed forensics study. Fortunately, in the HPS case, the study plans, although not intended to satisfy a forensics study, did include relatively detailed sediment sampling and rather comprehensive PCB congener analysis; significantly more useful information was produced than would be typical in a standard RI. However, detailed sampling and analysis in proximity to a potential second source is missing.

3.1.5 Conduct Rapid Sediment Characterization

For HPS, the ELISA IA technique was used to obtain the RSC data, generating a comprehensive data-set of Total PCB concentrations. The HPS study was tiered, as described earlier, with the 450 RSC analyses followed by a smaller subset of 120 ACF analyses of frozen archived splits. The RSC data were used to generate the contour maps that aided in selecting the ACF samples. The HPS RSC data are summarized in Appendix C. The HPS RSC Total PCB data compared well with Total PCB based on laboratory congener analysis; the laboratory-based Total PCB determination was made by the widely used approach of summing the concentrations of the 18 NOAA National Status and Trend monitoring project congeners, and multiplying that by two [62-63]. On average, the RSC results provided a Total PCB concentration approximately 12% higher than the laboratory congener-based Total PCB analysis (Figure 2-8). This is as can be expected, since the RSC analysis kit "as received" uses Aroclor 1254 as the calibrant, and the HPS samples contained significant amounts of Aroclor 1260 type contamination, which has a greater response than Aroclor 1254 (Table 2-6). This response difference can be corrected for, as discussed in Section 2.4.1, by either calibrating with an Aroclor standard that better represents the Aroclor composition of the field samples or by using a correction factor that represents the response correlation (Figure 2-8). However, these adjustments to the RSC data are not needed as long as the data are mainly to be used to gain a general understanding of the Total PCB concentrations across the site (Figures 2-16 and 2-17).

3.1.6 Conduct Advanced Chemical Fingerprinting

The ACF analysis of the HPS sediment samples consisted of determining the concentrations of 44 PCB congeners using modified Method 680/1668 (a HRGC/LRMS analysis technique), as described in Sections 2.4.2 and 2.4.3. Again, the HPS study was not conducted as a forensics investigation, but the ACF analyses were conducted on a subset of the RSC samples following

review of the full RSC dataset. In addition, the 44 PCB congeners were selected primarily to generate data that were comparable to historical data for San Francisco Bay, and not for forensic purposes. The HPS ACF data are summarized in Appendix B.

During the data review and screening (Section 2.5.2.3) about 14 of the 120 samples were identified as candidates for potentially excluding from the data analysis because of lower data reliability (e.g., low overall PCB concentration [e.g., sum of congeners less than ~50 to 100 ppb] and a high percentage of the 44 PCB congeners with non-detects). Six PCB congeners were also identified as potential candidates for exclusion from the data set prior to detailed data analysis because of possible reliability issues (e.g., high percent non-detect of the congener, low congener concentration, a high %RSD in the percent contribution of the congener to the Total PCB, or other data outlier issues).

3.1.7 Data Analysis, Synthesis, and Presentation of Results

3.1.7.1 Site History and Records Research

The specific area of interest for the PCB forensics investigation was the Parcel F (offshore) sediments near Parcel E and E-2 in the South Basin; the area labeled Area X in Figure 3-2. Previous studies have shown potential PCB source areas associated with the former Navy landfill and multiple CSOs in nearby Yosemite Creek. Historical activities in adjacent upland Parcel E-2 that may have contributed to contamination of sediments in South Basin include filling and disposal activities, residual onshore contamination, and surface runoff. Groundwater discharge was also evaluated as a potential transport pathway of PCBs to South Basin from Parcel E-2, however, the magnitude of PCB release via this pathway is not likely to be significant given the limited extent of PCBs detected in groundwater and their low solubility. A former landfill at Site IR-01/21 in Parcel E-2 (Figures 3-1 and 3-2) was used from 1958 to 1974 for the disposal of materials such as construction and industrial debris and waste, domestic refuse, sandblast waste, paint sludge, solvents, waste oils, transformers and electrical equipment and other potentially contaminating materials. No records that document landfill contents or disposal practices are available. In the mid-1970s, the Navy placed 2 feet of compacted imported fill on top of the landfill and graded the entire site to facilitate storm water drainage. In the 1990s, a sheet pile wall was installed and riprap was placed along the Parcel E-2 shoreline to control the movement of contaminants into South Basin. In 2001, an interim landfill cap was constructed and placed over most of the landfill. The cap consists of a multilayer system of sub-base soil, high density polyethylene membrane, synthetic drainage layer, and topsoil.

South Basin was originally a marshy wetland area. Its current configuration reflects filling activities that took place from the 1940s to the 1970s. Figure 3-3 shows the South Basin shoreline in 1946, 1955, 1961, 1965, 1969, and 1975. The shoreline positions were mapped by digitizing historical aerial photographs. The greatest period of land expansion was between 1946 and 1955, in which the northern, western, and southern portions of the basin were filled, forming the areas now occupied by Parcel E-2, Yosemite Creek, and Candlestick Point, respectively. The second largest period of land expansion occurred between 1965 and 1969, in the northern part of South Basin. This fill event formed a slough, apparent in the 1969 (blue) shoreline contour, through the middle of the waste disposal area now known as the Parcel E-2 landfill. This slough, or channel, drained an unmarked outfall located at the north end of this channel up behind the marked landfill boundary. By 1975 (brown color), this outfall was closed off and the slough had

been filled; today's shoreline is virtually the same as the 1975 contour, and therefore is not shown. Between each recorded shoreline, it is uncertain when each fill event occurred. The sources of material used to fill these areas are not documented. The Navy operated the shipyard during the periods of the major filling events. The property was leased to the Triple A Machine Shop after the current shoreline was established (ca. 1975).

The historical information suggests that there could be sources of PCB from activities at the Navy facility, contributing PCBs to the northeastern side of Area X in South Basin (Figure 3-2), particularly from the landfill near that shoreline and the historical slough that discharged to that area. Historical information also suggests that there could be sources of PCBs associated with runoff to Yosemite Creek, and historical CSOs that discharge into Yosemite Creek and to the west just outside the mouth of Yosemite Creek (Figure 3-2). Review of historical records shows that there were commercial and industrial activities along city streets just north of Yosemite Creek, including a drum recycling facility. The Consent Decree shows that drum recycling activities at the site from 1948 to 1988 likely resulted in releases of PCBs that may have served as a source for PCB contamination to surrounding areas.

3.1.7.2 Sediment Transport and Hydrodynamics

At HPS, a leveraged sediment transport study was conducted as part of the RI/FS, and is reported as a case study in Appendix B of Blake et al. [36]. Sediment stability and transport studies were also conducted as part of the RI/FS data gaps investigation [62]. Blake at al. reported that "PCBs tend to adsorb to fine-grained sediment particles and organic matter, so sediment transport processes (i.e., resuspension, transport, and deposition) are important contaminant transport pathways in South Basin. Because of its restricted circulation, tidal currents in South Basin are very weak. Waves are likely to be the dominant sediment resuspension mechanism because the basin is shallow and open to the southeast, which is the direction of the prevailing winds during winter storms. The primary source of sediment to the basin appears to be suspended sediment from San Francisco Bay; shoreline erosion may contribute some sediment. The basin appears to be a net depositional environment with a net accumulation rate of about 1 cm/yr. The dispersal pattern of PCBs, with higher concentrations near shore and decreasing concentrations offshore, is consistent with wave-influenced and tidally influenced sediment transport. Storm waves breaking along the shoreline suspend fine, low-density sediments in the near shore region. A return flow near the bottom of the water column (balancing the shoreward flow due to waves at the surface of the water column) transports the sediments away from the shoreline and into South Basin. Tidally induced currents may facilitate additional transport across the mudflats and extend the influence of waves further offshore during low tide, potentially carrying material further offshore into South Basin. The deposition of cleaner background sediments transported in from San Francisco Bay and deposited in South Basin results in the dilution and burial of the nearshore and offshore sediments. As new sediments are deposited, mixing processes (physical and biological) act to mix surface and subsurface sediments, resulting in the gradual decrease in surface PCB concentrations over time. The smooth vertical PCB profiles in sediment cores (i.e., gradual increase and then decrease in concentration with increasing depth) indicate that overall, the sediment bed in South Basin appears to be relatively stable and undisturbed."

Sediment stability work conducted in South Basin is also reported in Battelle et al. [62]. The primary purpose of this work was to determine the erosion and deposition characteristics of the South Basin to estimate the fate of the contamination in the sediments, assuming sources were controlled and background level sediments were depositing. The average net deposition was determined to be approximately 1 cm/yr, and the most contaminated zone was expected to, over time, progressively become deeper and deeper in the sediment (Figure 3-7), and surface sediment PCB concentrations would eventually reach background levels (Figure 3-8). The current sediment deposition information in this study was also useful for understanding contaminant transport. The findings indicated that South Basin is a relatively quiet depositional basin with occasional wind derived local resuspension and local redeposition. The information did not indicate any unusual transport characteristics, and suggested that the contamination would be expected to show a gradual decline away from sources. This conclusion is further supported by the PCB concentration gradients shown in the sediment contour maps (Section 3.1.7.3).

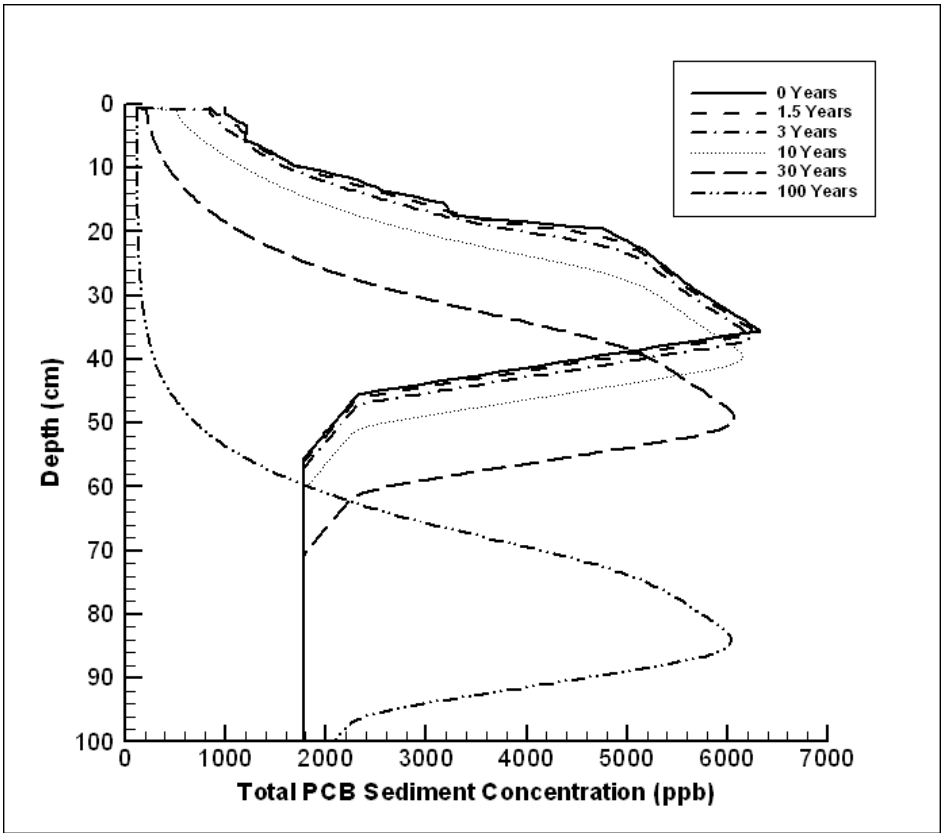


Figure 3-7. Predicted Total PCB Profiles over Time at HPS Station SB-081

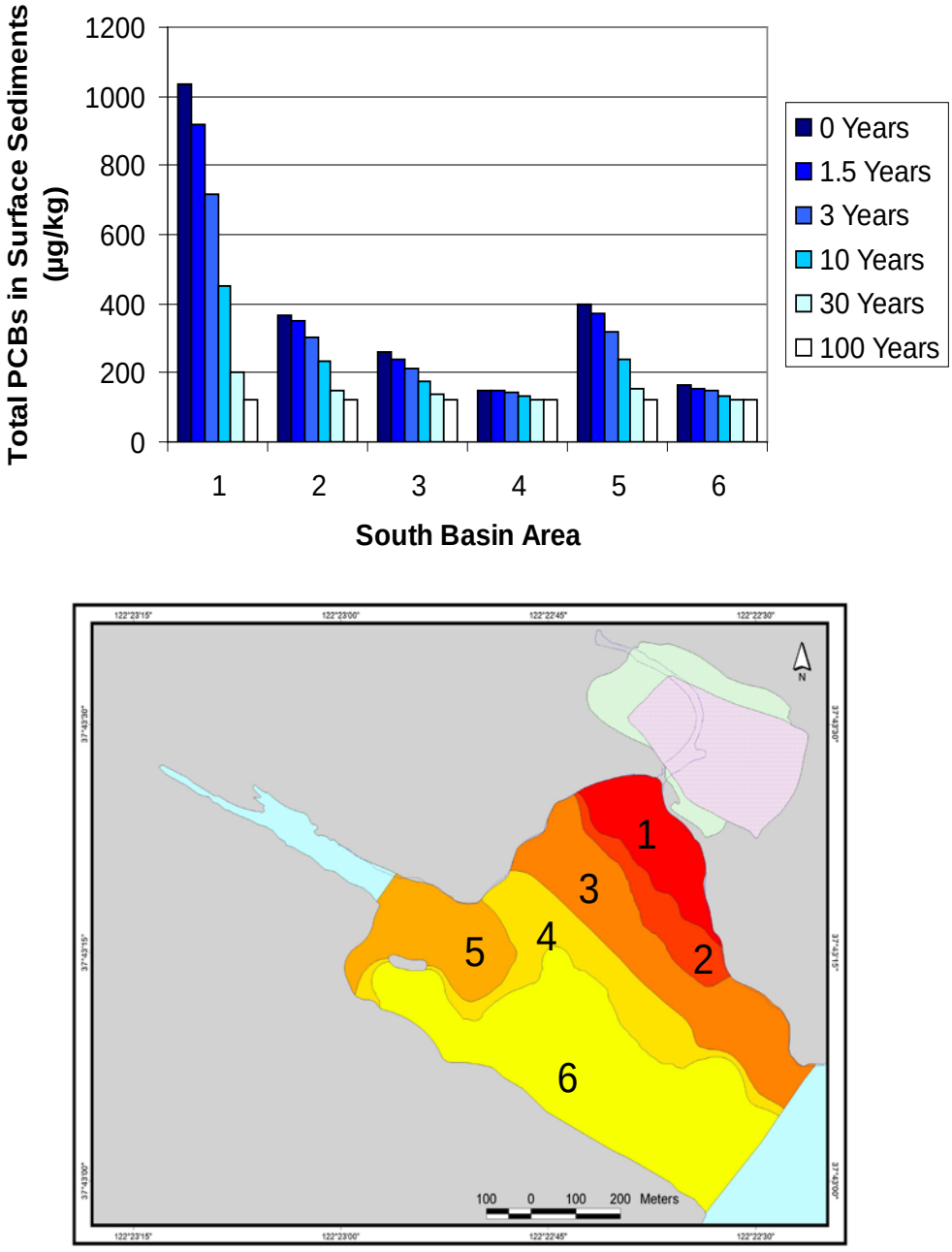


Figure 3-8. Areas Evaluated for PCB flux (top), and Predicted Surface PCB Concentrations over Time (bottom)

3.1.7.3 PCB Concentrations

Elevated PCB concentrations were measured in the northern portions of HPS South Basin; particularly in the northeastern parts near Parcel E-2 and the northwestern parts near the mouth of Yosemite Creek (Figure 3-1). The South Basin sediments with elevated PCB concentrations near Parcel E-2 are also near shoreline locations where high PCB concentrations have been measured (Figure 3-9; [62]).

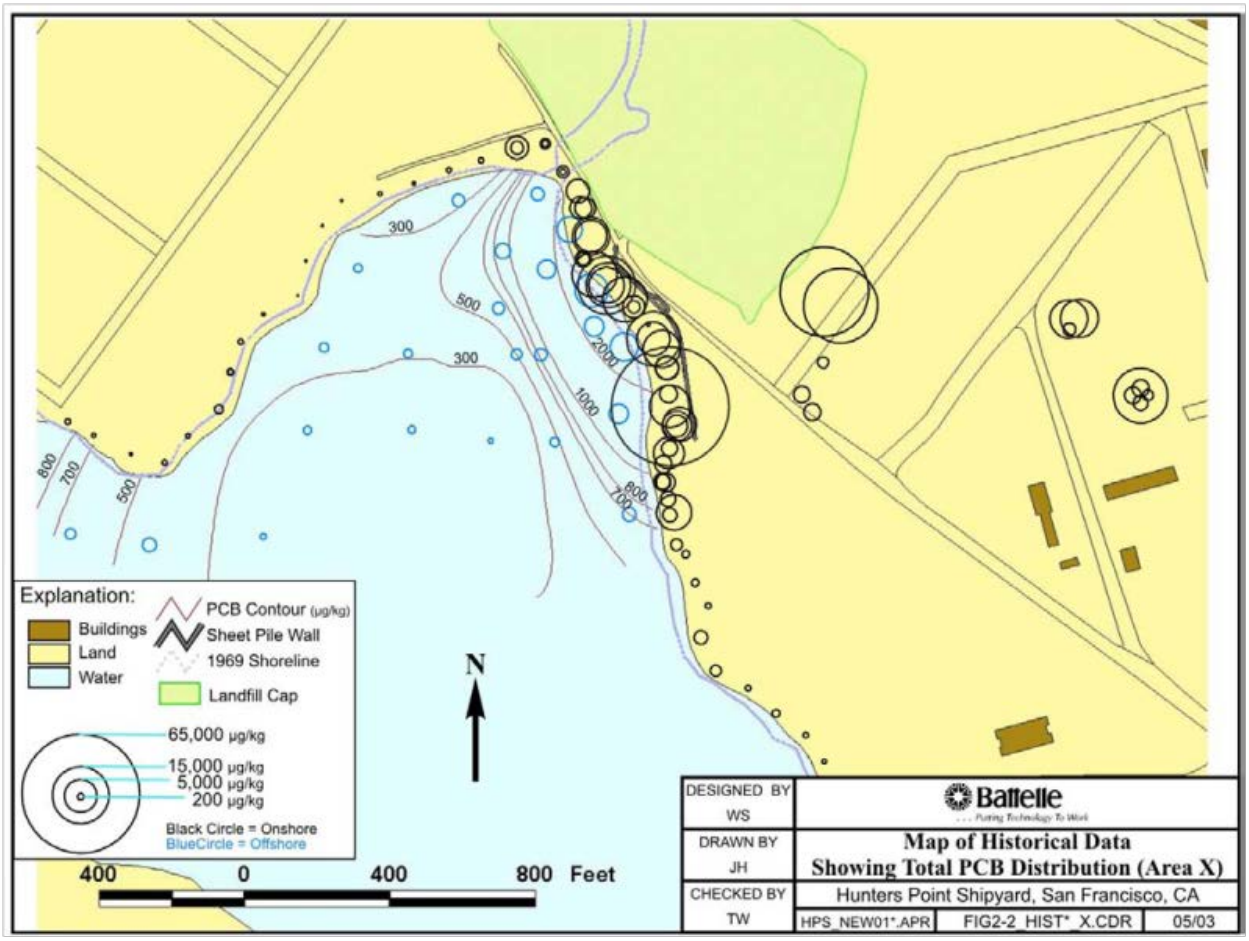


Figure 3-9. Upland Shoreline PCB Concentrations along South Basin

Figures 3-10 and 3-11 show examples of contour maps produced with the HPS RSC data, which can be useful to aid in selection of ACF samples. These contour maps show different PCB concentrations, with the standard red, for instance, representing 2,000 ppb and higher and the deep red representing above 5,000 ppb. It should be noted, and cautioned, that these represent extrapolations using data points spaced well apart, and the actual concentration at a specific location is not known except for where samples were collected (see core and sample locations in top of Figure 3-11). Contouring is, however, a widely used technique for understanding the approximate PCB concentration distribution.

The 3D visualization (Figure 3-11) makes it easy to assess the mass of PCB-contaminated sediment, and its distribution, while the 2D maps (Figure 3-10) are easier to use for directly comparing concentrations at different locations for samples from the same depth. Figure 3-10 features plan view maps of PCB concentrations with increasing depth below the mudline based on the 2003 FS Data Gaps Investigation data [62]. The plan view maps represent horizontal slices at 0.5-ft intervals. Observations based on these maps include the following:

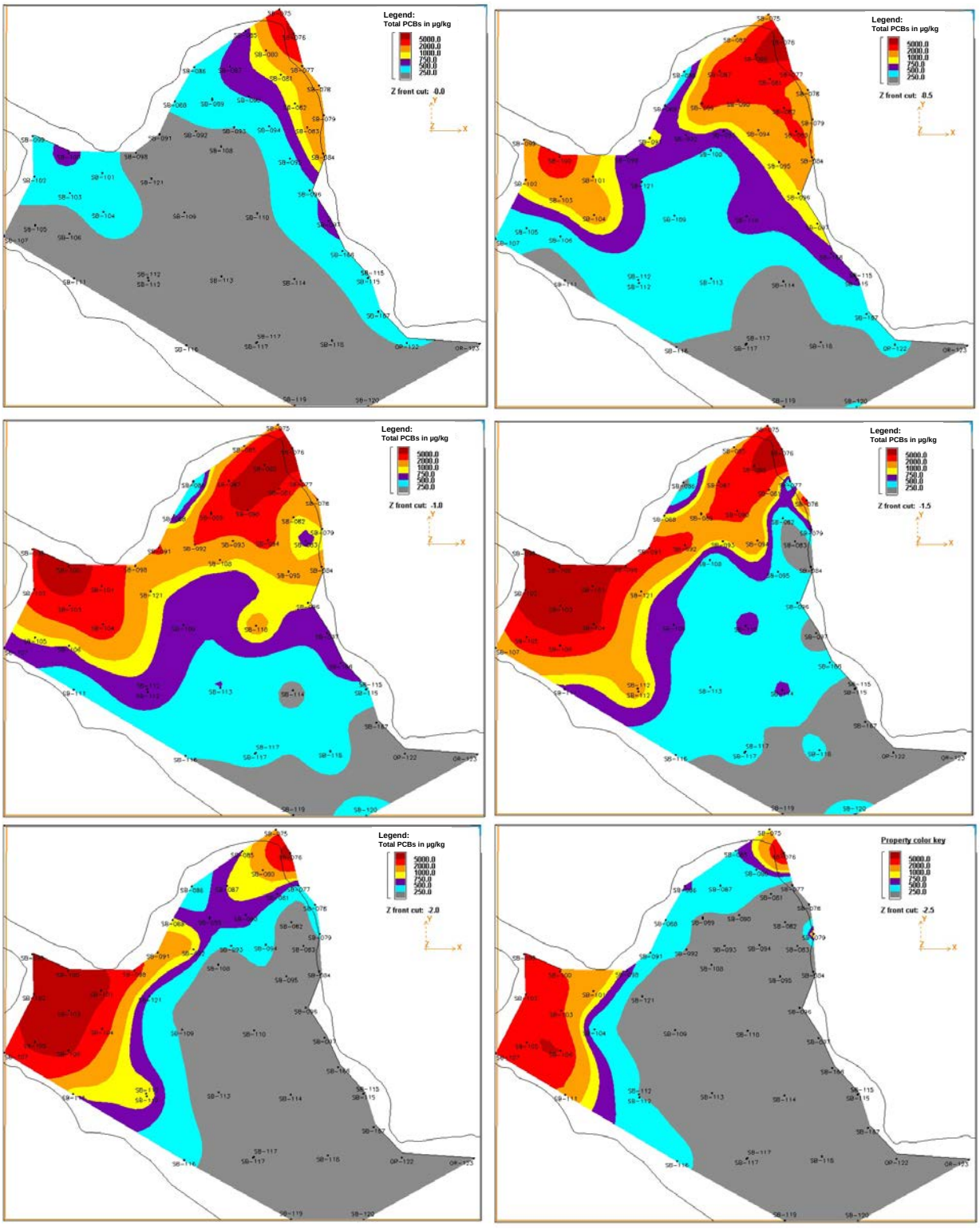


Figure 3-10. HPS Total PCB Concentration in Sediments from Surface, 0.5 ft Depth, 1 ft Depth, 1.5 ft Depth, 2 ft Depth, and 2.5 ft Depth, Respectively, from Top Left to Right

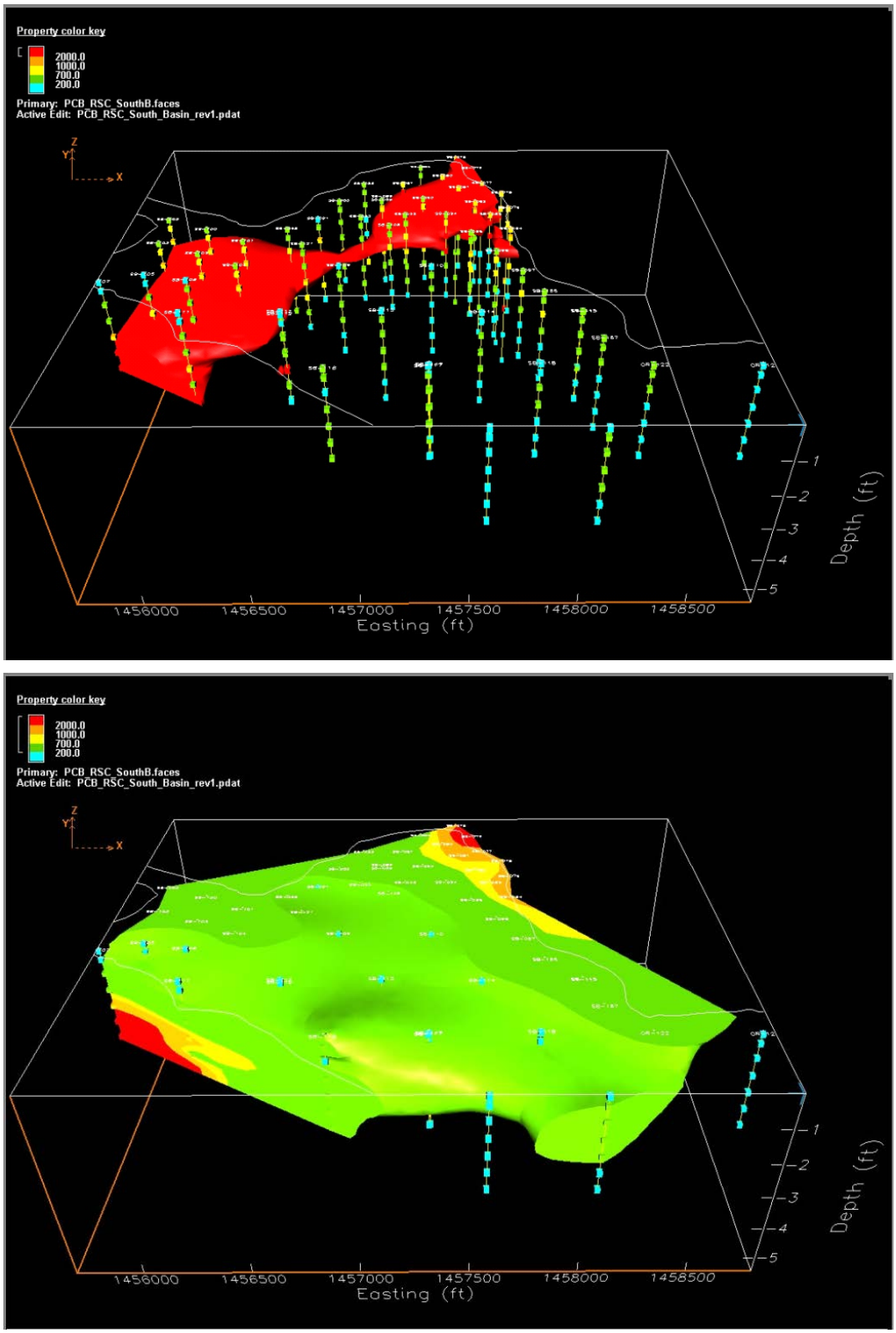


Figure 3-11. 3D Contour Maps from HPS Showing Total PCB Concentrations and Color Coded Core Horizons

(Upper map shows concentrations >2000 ppb in red [62].)

- PCB concentrations in surface sediment are highest (>2,000 µg/kg) at the north end of South Basin, near the area where the former slough connected with South Basin. Surface PCB concentrations decrease with increasing distance from the Parcel E-2 shoreline on the northeast side of South Basin. An area of slightly elevated surface concentrations (i.e., greater than 250 µg/kg) is also apparent near the mouth of Yosemite Creek.
- At a depth of 1-ft below the mudline, the area with PCB concentrations >2,000 µg/kg is more extensive, both at the north end of South Basin and at the mouth of Yosemite Creek. Overall, concentrations are higher 1-ft below the surface than at the surface, and the mass of highly contaminated sediment is greater in the 1 to 2 ft depth zone.
- At 1.5-ft below the mudline, the area of highest PCB concentrations decreases in extent at the north end of South Basin, and increases in extent at the mouth of Yosemite Creek. At 2.5-ft below the mudline, PCB concentrations of >2,000 µg/kg at the north end of South Basin are limited, whereas the affected area at the head of Yosemite Creek has not diminished substantially.

Figure 3-12 shows the surface sediment Total PCB concentrations at each sample station in South Basin and Yosemite Creek, and along the shoreline, based on combined data sets from multiple years (i.e., from 1999-2003). This map uses older historical data for the Yosemite Creek site; Yosemite Creek was not included in the detailed 2003 investigations of HPS. Three regions with the most highly-elevated PCB concentrations can be identified on this map: (1) the Parcel E-2 shoreline south of the Parcel E-2 landfill (shown as blue boxes along the shoreline); (2) the outlet of the former slough at the north end of South Basin; and (3) near the mouth of Yosemite Creek. The highest shoreline PCB concentrations are found to the south of the Parcel E-2 landfill, whereas the highest offshore PCB concentrations are found at the outlet of the former slough and at the mouth of Yosemite Creek.

These PCB data indicate that the South Basin sediment areas with the highest PCB concentrations adjacent to the Parcel E-2 shoreline, and particularly areas in close proximity to the former landfill and slough, and at the mouth of Yosemite Creek, do not appear to be continuous or linked (Figure 3-9), and the elevated PCB near the mouth of Yosemite Creek is at a greater depth than near Parcel E-2. These PCB concentration data suggest that there may be two separate sources of PCBs in South Basin: one associate with Parcel E-2 shoreline and the other with Yosemite Creek. The data also indicate that the contamination near Yosemite Creek is primarily historic and that this source has, for the most part, been controlled, and that the source of most of the contamination near Parcel E-2 is more recent and may still be contributing to the surface sediments (when these samples were collected, in 2003).

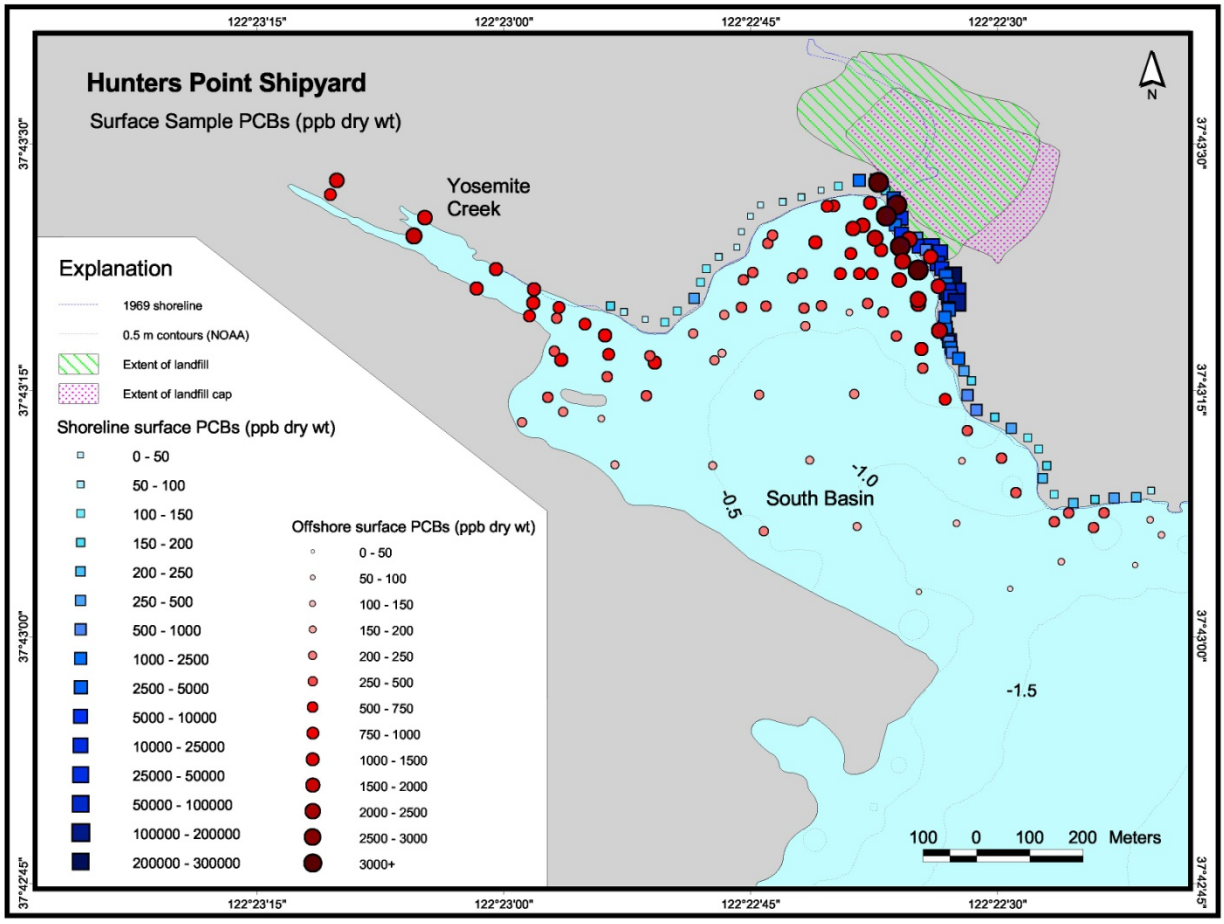


Figure 3-12. Surface Soil and Sediment Total PCB Concentrations
(Sampled 1999-2003)

3.1.7.4 PCB Composition

Comparisons of the PCB patterns of samples and Aroclors are often part of PCB contamination assessments. The similarity of a samples' PCB composition to that of an Aroclor formulation can provide information related to potential source(s) and changes that may have occurred since the contaminant was released to the environment. It is rare that one finds a perfect match in the PCB composition of a sediment field sample and an Aroclor formulation. A close match may be observed for samples that represent a recent release to the environment and are also near the source. However, the PCB composition begins to change as soon as the material enters the environment, and selective PCB congener alterations occur due to different weathering processes, as discussed earlier. Similarities and dissimilarities in the PCB composition were assessed using exploratory data analysis techniques, as described in Section 3.1.7.5.

General PCB composition is usually best studied using simple bar graphs (bar chart "fingerprints"), with the PCB congeners from low to high molecular weight along the x-axis and normalized (percent of Total PCB) concentration along the y-axis. Given the environmental

transformation considerations, it is particularly notable that the PCB compositions of most of the surface sediment field samples were similar to that of one Aroclor formulation – Aroclor 1260.

The PCB composition data suggest that there may also have been partial contributions from Aroclor 1254 source(s), particularly in the Yosemite Creek area and in deeper sediments also on both sides of South Basin, but the majority of the recent PCB clearly appears to be from an Aroclor 1260 source in most of South Basin. The resemblance to Aroclor 1260 was particularly good in surface and near-surface samples collected near the shore of Parcel E-2, in proximity to the historic landfill and slough (Figure 3-13).

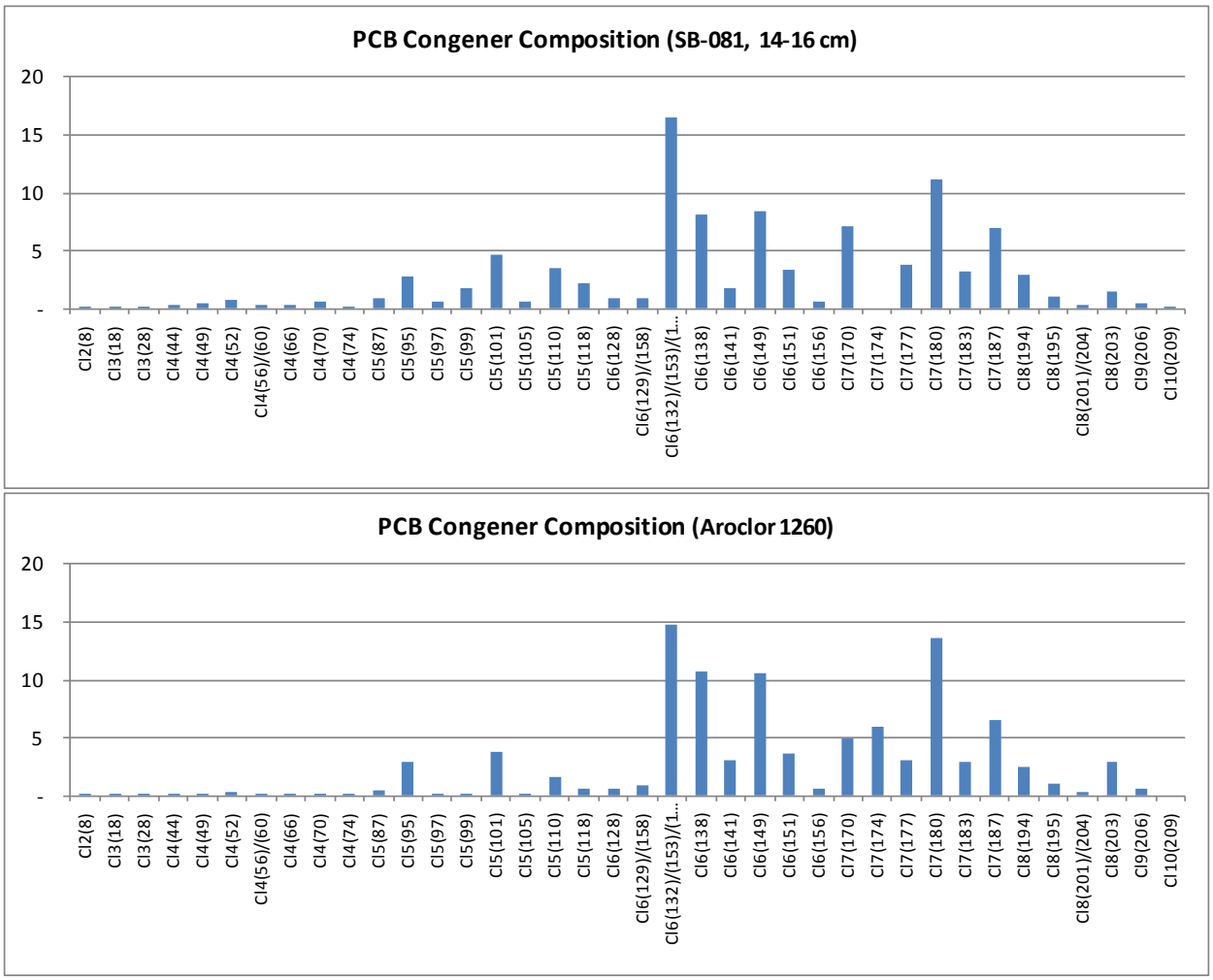


Figure 3-13. PCB Fingerprint of Surface Sediment Samples from the East Side of Hunters Point South Basin Compared to Reference Aroclor 1260

Samples from Yosemite Creek and the westernmost part of the basin, and some of the deeper sediments from the east, showed evidence of PCBs other than Aroclor 1260 contributing to the dominant Aroclor 1260 signature. Lower molecular weight PCB congeners, such as from Aroclor 1254 and possibly also 1242/1248, were evident. This inclusion of lower molecular

weight PCB became increasingly evident in the deeper, more contaminated, sediments from the west side of South Basin (Figure 3-14). The influence of Aroclor 1254 was evident in all samples from and near Yosemite Creek, and the PCB composition was similar throughout the Creek [62]. In contrast, the Aroclor 1260 signature dominated the PCB composition in the surface sediments throughout the basin, including the western parts. There were, proportionately higher concentrations of less chlorinated PCB congeners in the subsurface sediments than in the surface sediments, including in deep sediments from the east side. Slightly higher levels of Aroclor 1254 and/or other less chlorinated Aroclors in historic loadings to the basin may partly explain the subtle difference.

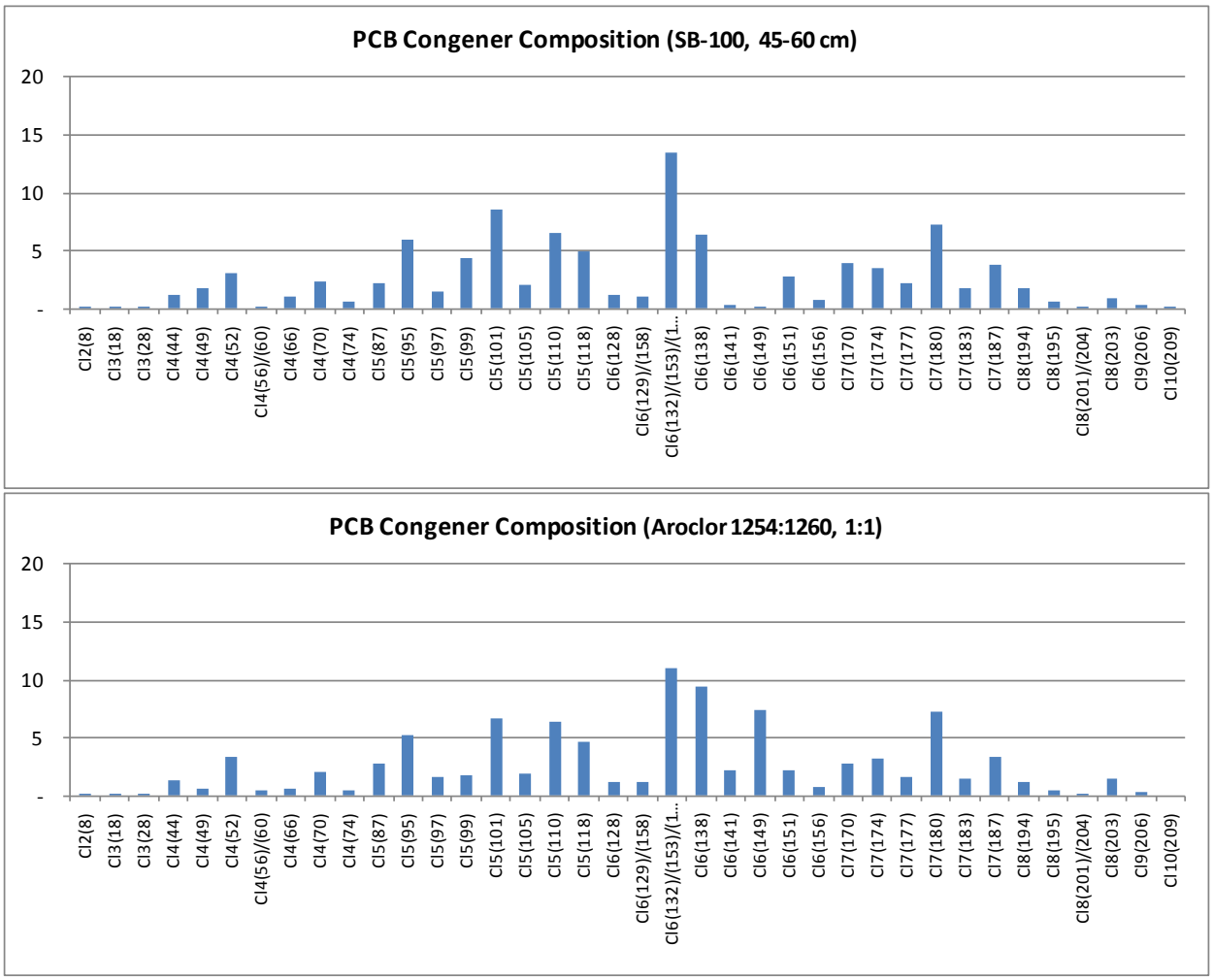


Figure 3-14. PCB Fingerprint of Deeper Sediment Samples from the West Side of Hunters Point South Basin Compared to a Mixture of Reference Aroclors 1254 and 1260 in a 1:1 Proportion

It can sometimes also be useful to examine ratios of key diagnostic PCB congeners (see Tables 2-1 and 2-4) to assess compositional characteristics. For instance, a change in composition (i.e., PCB congener ratios) may represent a change in source composition, and may be linked with

such data for other Aroclors or source material. Changes may also be due to alteration from environmental processes, and the distinction would need to be determined if changes are observed.

After comparing the bar chart fingerprints, one may use techniques such as congener-to-congener cross plots to assess compositional variations in the data. Figure 3-15 shows a cross plot of congeners PCB187 and PCB52 in segments of a core collected at Station SB94, an age-dated core located just offshore from the former landfill. If all depths in the core had similar congener composition, data would fall along a single trend (slope or ratio) which could be interpreted to represent a single source of PCBs over time. However, a change in composition with depth is noted where the ratio of these congeners in the shallow segments (0-20 cm) is about 7.2 and in the deeper/older sediments (30-60 cm) it falls to 1.8. This change may represent a change in source composition (or a change due to compositional alteration, such as dechlorination), so rather than having contamination from one PCB type (e.g., Aroclor 1260) there appears to be two distinct PCB signatures (e.g., Aroclor 1260 as well as another Aroclor), representing different time periods, with intermediate depth samples showing a progression from one ratio to the other. The more recent (shallow) sediments from 0-20 cm show a bar chart fingerprint similar to Figure 3-13 indicating an Aroclor 1260 source. The deeper sediments (30-60 cm) show bar chart fingerprints similar to Figure 3-14, indicating deeper sediments on both sides of the embayment show a mixed Aroclor 1254/1260 pattern. The difference in PCB composition does not necessarily reflect contamination from two different *physical* PCB sources, but indicates that the type of PCB that contaminated the sediments at this location changed over time, which may or may not originate from different locations. This dated core shows the change in composition at about 30 cm (the two highest concentration samples are duplicates of 30-40 cm interval) occurs in sediment deposited around 1965-1970. The timing of this basin-wide compositional shift will be discussed later, but this shows the importance of identifying PCB congener compositional differences to interpret potential source information. It would be tedious to view each possible individual congener cross plots if data for up to 100 different PCB congeners are available, but Aroclor compositional and congener behavioral information (Appendix A and Table 2-4) are available to help focus such an analysis on Aroclor/source-specific diagnostic ratios. Multivariate techniques (Section 3.1.7.5) are more suitable for analyzing comprehensive PCB compositional patterns with large data sets at one time.

In summary, the observed PCB compositional match to Aroclor 1260 in the northeastern part of South Basin suggests that there may be a current (2003) or recent, and possibly also historic, source of PCB in the vicinity of Parcel E-2. It is possible that the type of PCBs entering South Basin from the northeast was slightly different in the past. There is also PCB compositional evidence that there may have been a second source of a slightly different type of PCB (e.g., Aroclors 1254/1260, possibly also with some other Aroclor contribution) in the vicinity of Yosemite Creek, and that this source was more significant historically than recently. This source may have also contributed to the PCB contamination historically throughout South Basin, and not only near Yosemite Creek. The relative contribution of these sources has changed over time, with an apparent decline in the loadings from both sources in the past decades. The combined Aroclor 1254/1260 loadings have declined the most; Aroclor 1260 is dominating the Aroclor composition in the more recently deposited sediments throughout South Basin.

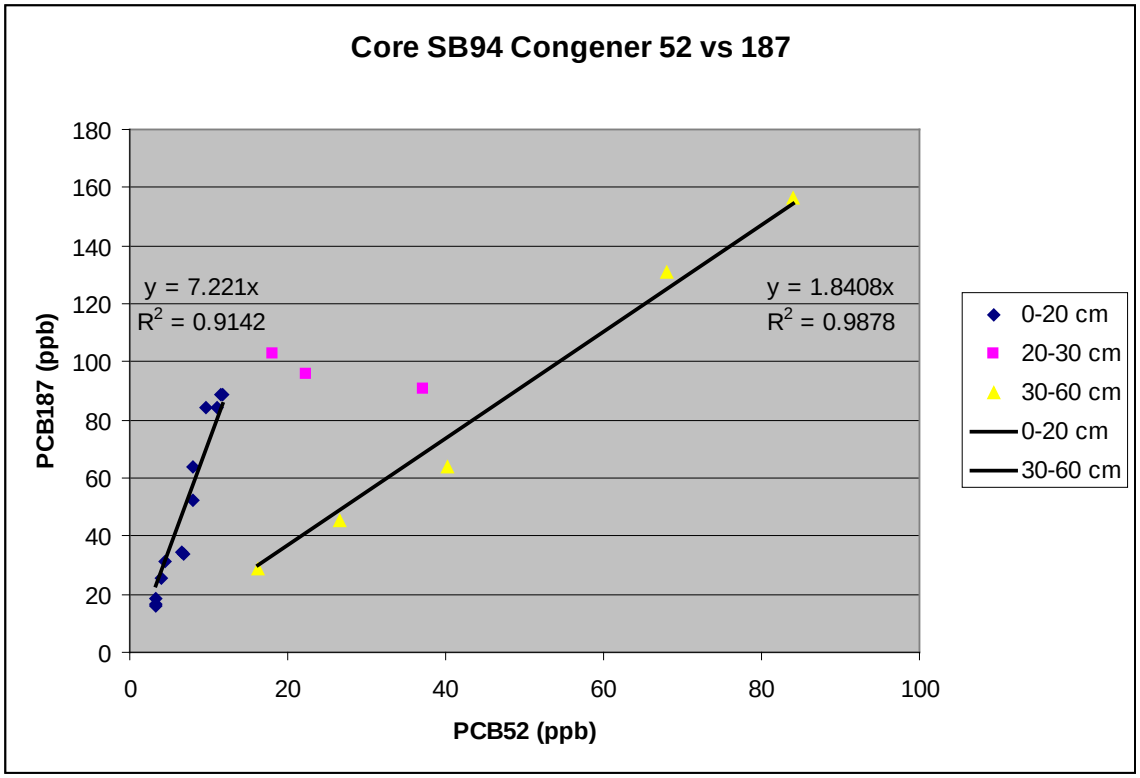


Figure 3-15. HPS Congener Cross Plot Showing Relationship between PCB187 and PCB52

3.1.7.5 Chemometric Statistical Analysis

As per Section 2.5.2.2, the data were reviewed and processed prior to statistical analysis. For the HPS project, PCB congener data had already been compiled and delivered as part of the Hunters Point FS data gaps investigation deliverable [62]. This data spreadsheet contained all of the information listed in Section 2.5.2.2, including: sample ID, sample coordinates, sample depths, analyte identifiers (i.e., congener names), laboratory results, and laboratory qualifiers (e.g., non-detect flags). A digital base map was received in the form of a GIS shapefile, which was used to construct a simple base map (Figure 3-16) showing key geographic features of the study area and sample/core locations. The data set initially considered for statistical analysis was comprised of 120 samples and 44 congeners. As per Sections 2.5.2.2 and 2.5.2.3, the data were assessed and run through an initial multivariate analysis to assess data usability. This process resulted in the removal of 35 samples and eight congeners from the chemometric analysis. For the sake of brevity, every individual decision point that led to these data screening decisions will not be recounted here. However, some of these are discussed below, to provide an idea of the types of considerations in this process. Refer to Johnson et al. [9] for discussions on data screening, outlier identification and general considerations that the data analyst should consider when screening a data set prior to statistical analysis.

Eight samples from two cores (PA-139 and PA-162) were omitted from the analysis because they were not located in or near the South Basin; they were located on the north side of HPS, in the Port Avisadero area (Area III on Figure 3-2). In addition, only those samples with a total

PCB concentration > 100 µg/kg, and samples with fewer than nine non-detects were retained for statistical analysis. It should be noted, and as discussed in Section 2.5.2.2, that these or other thresholds are not solid numbers that can be applied generally to any data set. It is typically an iterative and data set-specific process whereby the user balances a need to keep as much data in the analysis as possible with the desire for a robust data set, where chemical fingerprints are not influenced by less reliable data, such as low concentration samples with multiple non-detects.

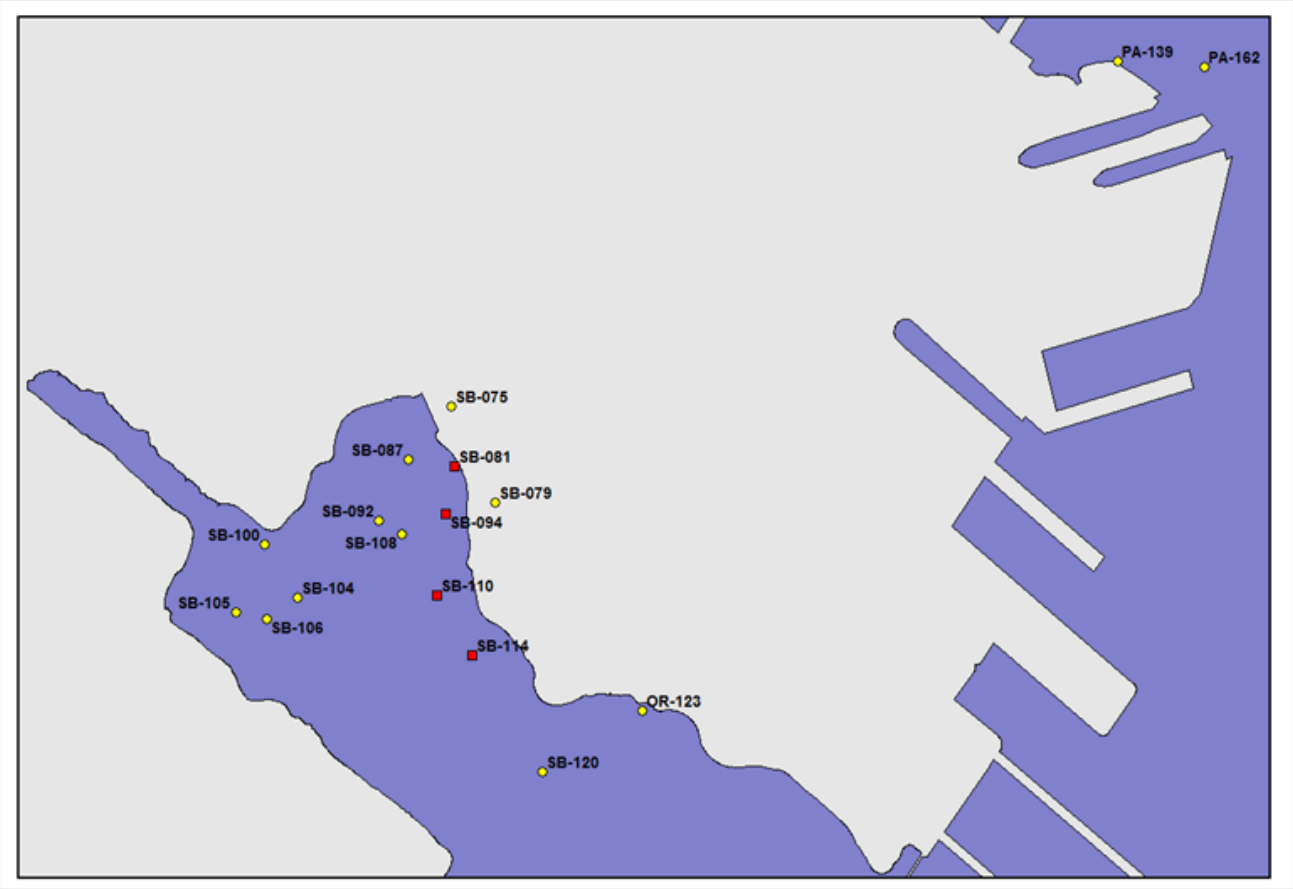


Figure 3-16. Simple Base Map Showing Sample/Core Locations
(Red squares are fine interval cores collected as part of a separate phase of sampling and analysis.)

Criteria used to screen congeners varied. PCB77 and PCB126 were both omitted because they were reported as non-detect in more than 98% of the samples. PCB141 was removed from the analysis for a very different reason. Initial data screening showed a strong bias in the proportion of PB141 as a function of the phase of investigation. Samples from four cores all showed systematically higher concentrations of PCB141, when expressed as percent of total PCBs (Figure 3-17). All other samples from other cores showed systematically lower concentrations.

These cores are not geographically separated from each other. As such, the team concluded that this bias was probably due to an issue such as matrix interference or analytical method bias between investigation phases, rather than a true compositional difference between these two sets

of samples. As such, PCB141 was removed from the analysis. The final data set submitted for analysis using receptor models was 85 samples and 36 congeners.

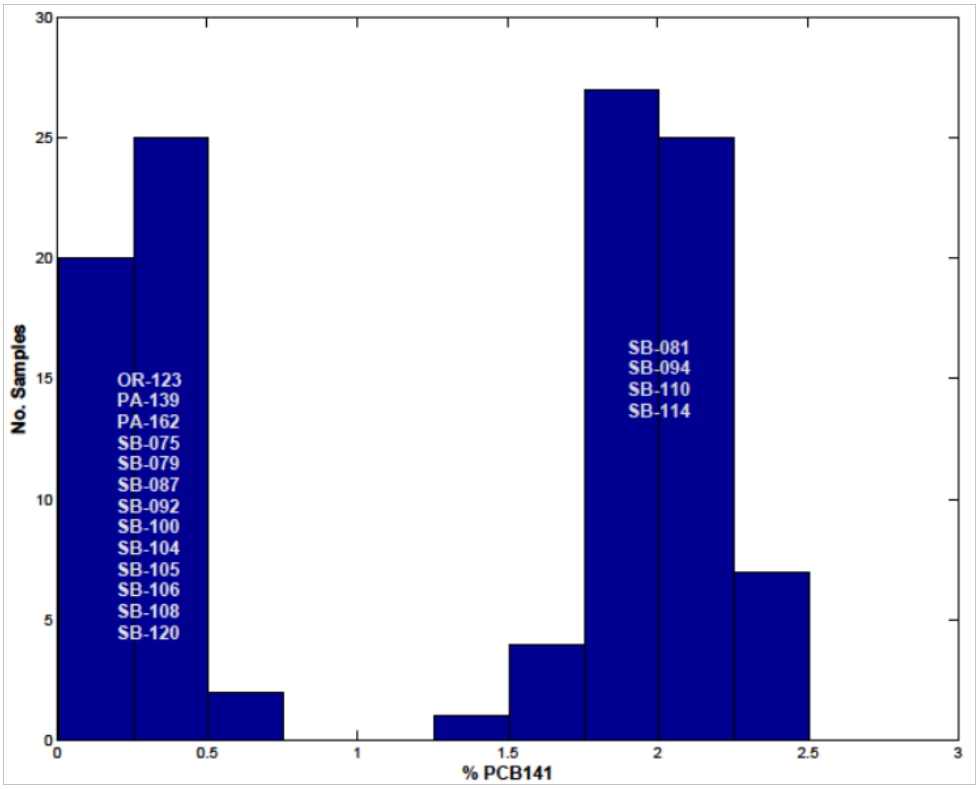


Figure 3-17. Histogram Showing Systematic Bias in PCB141 (as percent of total PCB) between Primary HPS Cores and Subsequent Fine-interval Cores SB-081, SB-094, SB-110 and SB-114

A review/summary of a number of chemometric/statistical analysis methods was presented in Section 2.5.3.5. For analysis of HPS congener data, PCA was applied as an initial exploratory data analysis method, followed by four different receptor model methods (PVA, ALS, Unmix, and PMF). Implementation of four different receptor models is not necessary. Most published applications use one [8-9, 34, 35, 64]. However, as all four have been applied as part of the method comparison, those results will be presented below.

A number of goodness of fit diagnostics were examined to determine the number of end-members (see [9]). One of these methods is shown in Figure 3-18, which is a coefficient of determination (CD) scatter plot array showing the fit of each of the 36 variables for a three end-member model. Each square graph on the array represents a PCB congener (or coeluting peak comprised of two or more congeners). The x-axis of each graph shows the measured amount of that congener/peak. The y-axis shows the amount as back-calculated from a three source model. A perfect fit would show all samples plotting on the 45 degree line that bisects each graph (a 1:1 fit). In PCA based receptor models, the number of principal components retained equals the number end-members. Fit always improves as additional principal components are added, so

one needs to decide at what point the fit is sufficient, without over-fitting and modeling noise. In the case shown on Figure 3-18 (three principal components/end-members), most of the congeners show a fairly good fit between the modeled values on the y-axis and the measured values on the x-axis, indicating that three end-members is a reasonable solution and that no more are needed. Scatter plots and other goodness of fit diagnostics are discussed in more detail by Johnson et al. [9].

Note, however, that some congeners exhibit at best a fair fit (e.g., PCB49 exhibits a wide scatter about the 1:1 fit line [Figure 3-18]). This may suggest the presence of another fingerprint in the system, and/or that this congener is particularly susceptible to environmental alteration or analytical issues (which is, ideally, identified during data screening). The feasibility of a fourth end-member was evaluated and will be discussed later in this section.

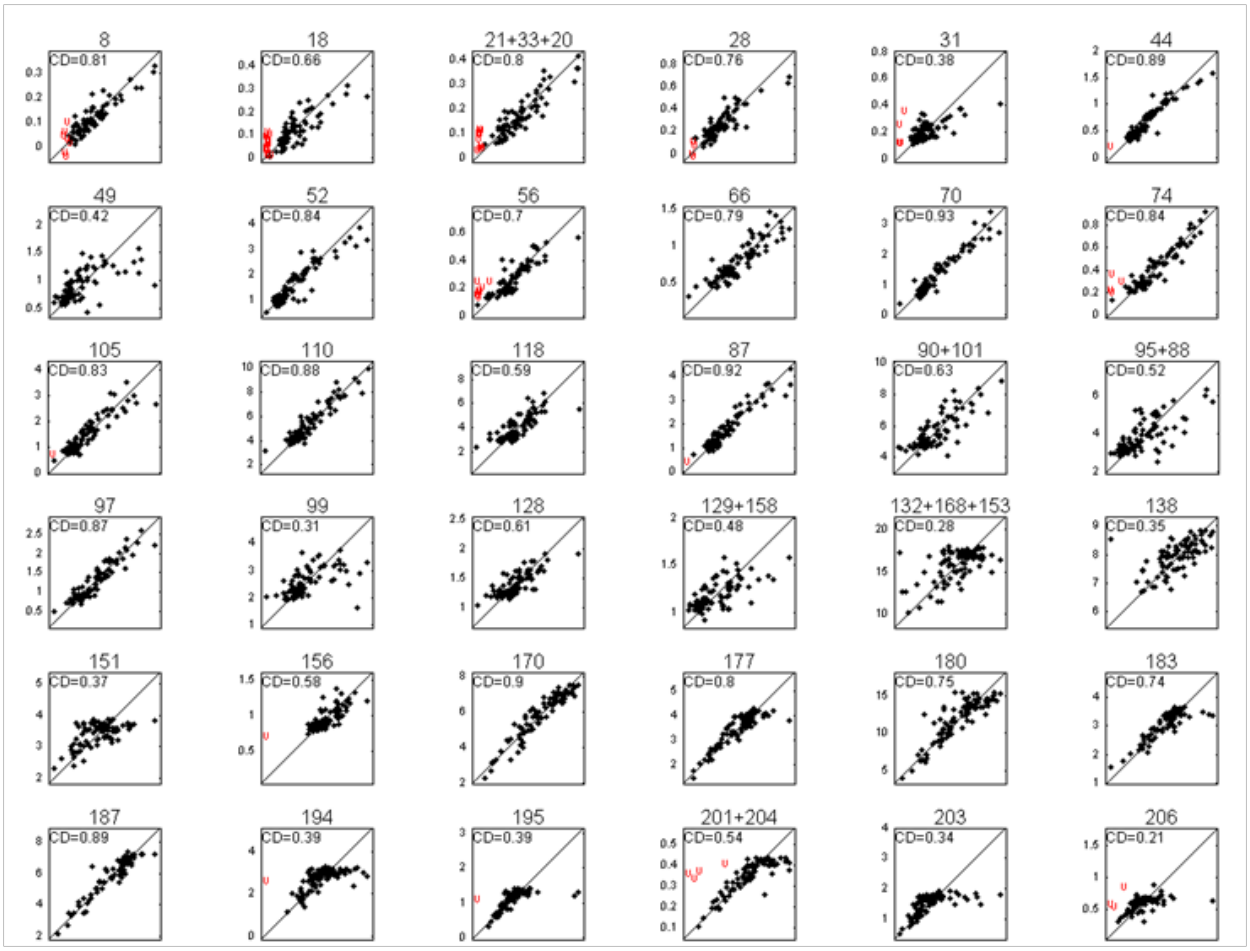


Figure 3-18. CD Scatter-plot Array for 85 Sample, 36 Analyte PCB Data Set from South Basin, Hunters Point Shipyard
(Non-detect samples are indicated as "U".)

This data set was analyzed using the four receptor model methods, each for a three source system. The congener patterns resolved by each of these four methods are shown in Figure 3-19 as blue bar graphs. At the top of each column of bar graphs, the congener pattern of an Aroclor (or a mixture of Aroclors) is shown. Each of the four receptor model methods resolved very similar profiles, and each matched known Aroclor profiles.

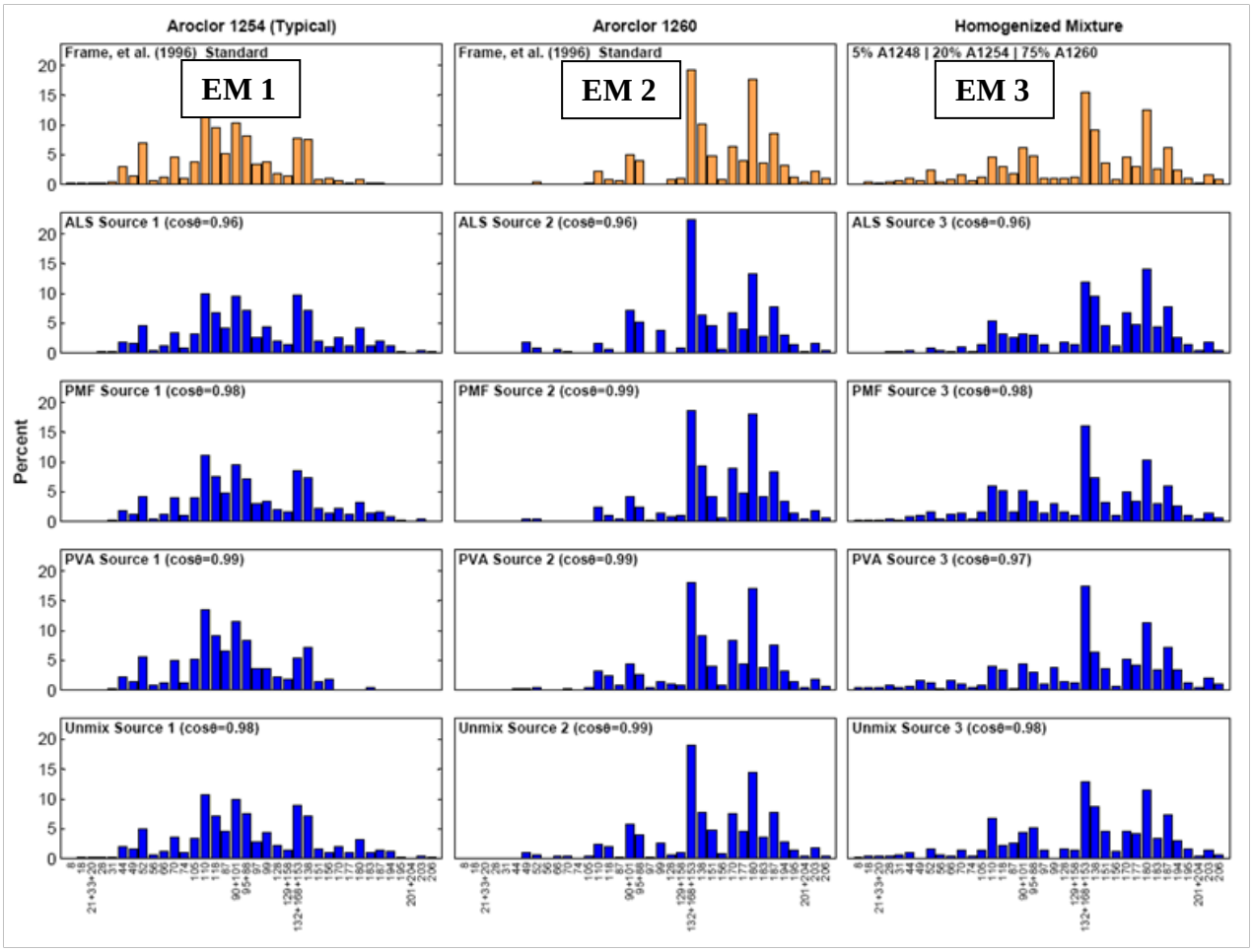


Figure 3-19. Congener Profiles (end-members, source profiles) Derived from Four Receptor Model Methods

Note that the congener patterns of the middle panel (Aroclor 1260) and the right panel (homogenized mixture) are very similar. Both are heavier congener patterns dominated by Aroclor 1260 congeners. The difference is that the "homogenized mixture" also has secondary amounts of congeners in the lighter Aroclors 1248 and 1254 molecular weight range. The discussions that follow evaluate whether these slightly different congener patterns represent real differences in the field.

Figure 3-20 shows the geographic distribution of each source as resolved by each of the four methods. Again, the geographic distribution of the three congener patterns is similar for each of the four receptor model methods. Note also that the slightly lower molecular weight Source 3 pattern is generally higher in proportion to the southwest, near the mouth of Yosemite Creek. This geographic distance suggests that a real PCB compositional pattern difference is being observed in the field.

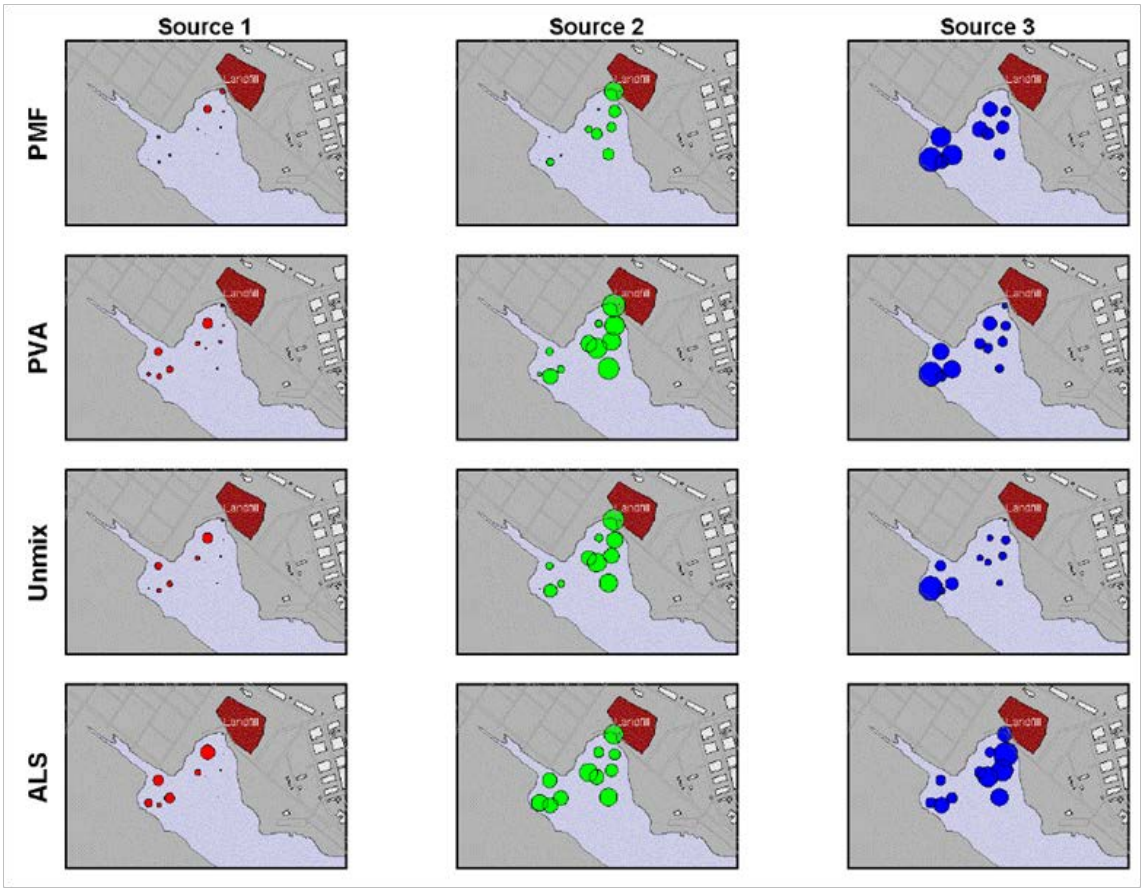


Figure 3-20. Maps of Three Receptor Model Derived End Members (potential sources) in Surface Sediments of the South Basin at Hunters Point Shipyard

Note on Figure 3-20 also that Source 1 (Aroclor 1254) is not present in high proportions in surface sediments. This is because it is much more abundant at depth, as is apparent on the cross section through cores (Figure 3-21). Also note that the terminology "source" in Figure 3-21 may be misleading, as it refers to the differentiation of different PCB compositional characteristics in the sample set (i.e., "end-members", in Figure 3-19), and not necessarily geographically different sources of the PCB. For instance, the three different PCB characteristics identified may be originating with just two different sources.

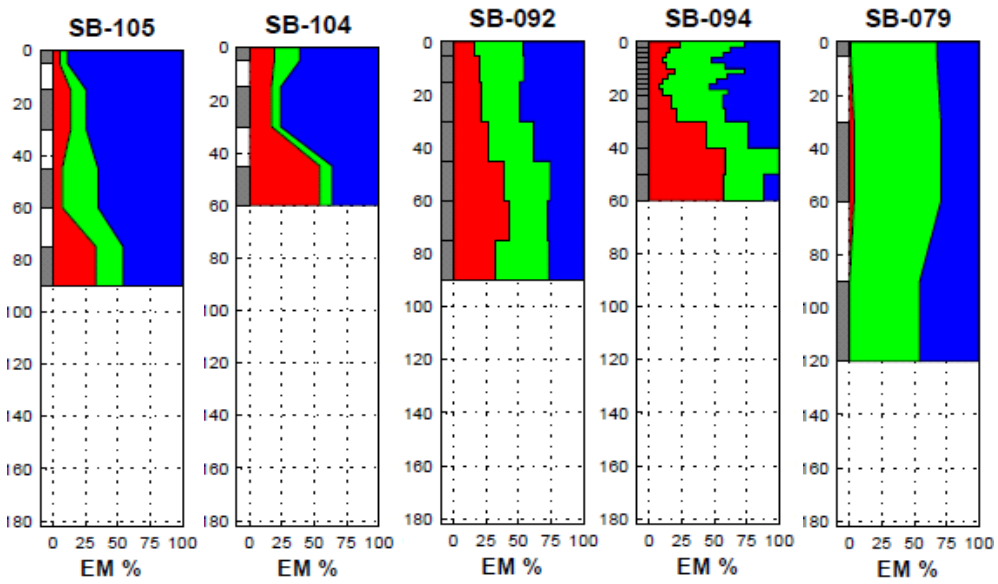


Figure 3-21. HPS EM Compositions in Selected Cores
(Red=EM-1; Green=EM-2; Blue=EM-3)

This three-composition interpretation was confirmed using another chemometric method, PCA (Figure 3-22), which can be used to summarize much of the information in this section. This PCA figure shows the HPS sediment sample PCB data plotted in 3D PCA space. The data cloud exhibits a generally triangular shape (indicative of mixtures, not clusters). This PCA scores plot has also been annotated to show the locations of these three source end-members as vertices of a triangle (i.e., a mixing diagram or, more specifically, a ternary mixing diagram).

Each sample point in the PCA illustration in Figure 3-22 represents the PCB congener data from a separate sample (see Appendix D for sample numbers) that could, for instance, be represented by separate bar chart fingerprints. The closer together samples plot in the PCA graphic the more similarity their bar chart fingerprints would be. A sample point located at the corner of the triangle marked EM1 has a bar chart fingerprint that closely matches Aroclor 1254. A sample point at the corner of the triangle marked EM2 has a fingerprint that matches Aroclor 1260. The third corner of the triangle at EM3 does not appear to match any single Aroclor, and since no evidence of dechlorination was observed, this pattern was intended to match the mixtures of Aroclors. The best fit was obtained with the mixture shown at the bottom of Figure 3-22 (a mixture of 80/15/5 of Aroclors 1260/1254/1248, in this case), which showed a cosine theta (cos θ) value of 0.97 (1.0 represents a perfect match). In summary, the PCA scores plot in Figure 3-22 shows the surface sediments to the east near the former landfill plot (e.g., sample point 5 is the surface sample from core SB79 in front of landfill) closer to the bottom left corner marked EM2 (with a Aroclor 1260 source pattern) and surface samples from near Yosemite Creek (e.g., sample 26 from core SB105) closer to the top corner of the triangle marked EM3 (representing a mixture of Aroclors 1260/1254/1248). Deeper samples from both sides of South Basin plot further to the right near EM1 (e.g., sample point 25 is 45-60 cm in core SB104 and sample point 55 is 30-40 cm in core SB81), which indicates approximately a 50/50 mix of Aroclors 1260 and 1254. One can easily see this change in composition with depth in core SB81, where deeper

samples from 30-60 cm (e.g., sample points 54, 55, 56, 57) all plot close together with the same 50/50 mixture of Aroclors 1260 and 1254. Shallower samples (0-20 cm) plot to the left close to EM2 (e.g., sample points 45 to 51), with a few intermediate depths (e.g., sample points 52 and 53) showing the transition in patterns.

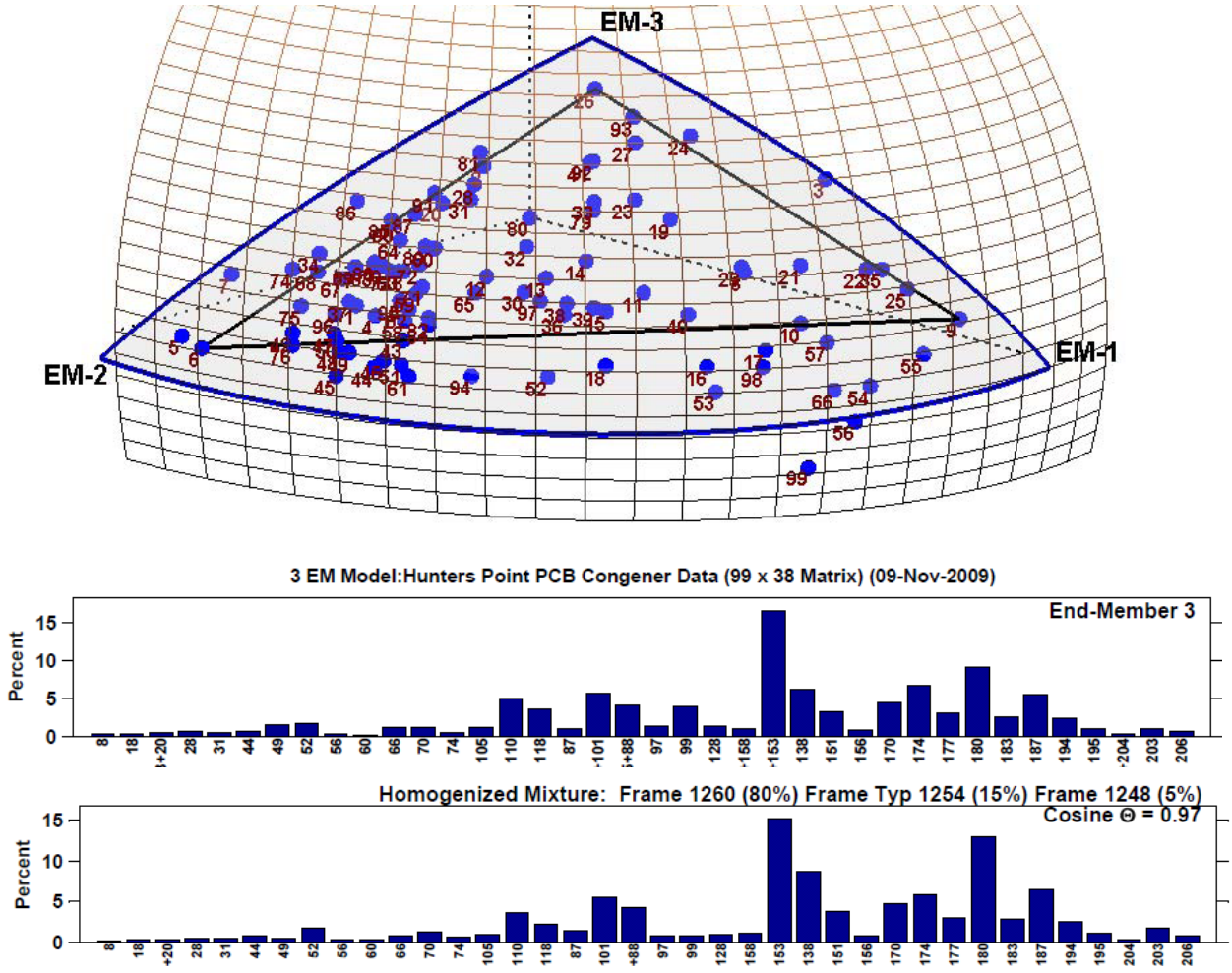


Figure 3-22. Conceptual PCA Model for PVA at HPS
(Each dot represents a sample. Samples plotting close together have similar PCB compositions.)

This is similar to the previous discussions of Figure 3-15 for core SB94, which was a dated core that showed this same transition in PCB composition at depths in the sediment from around 1965 to 1970. There appears to be similar historic PCB composition at depth on both sides of South Basin represented by samples on the right side of the triangle in Figure 3-22, with a composition similar to a 50/50 mix of Aroclors 1260 and 1254. As discussed earlier, the compositional similarities do not necessarily mean they are from one and the same physical source of PCB; this information needs to be combined with other forensic lines of evidence to better understand potential source implications. We might speculate that around 1970 when the CSOs in South Basin were all realigned to the head of Yosemite Creek, some Aroclor 1260 contaminated fill

material was used to close off the former channel that ran through the landfill on the east side (see high concentrations onshore in Figure 3-9). This contaminated fill material along the beach in this area may have become the EM2 source to the east side sediments after about 1970 through continuing erosion along the beach in front of the landfill. On the west side by Yosemite Creek, when the CSOs were realigned and the sewer capacity expanded, overflows were dramatically reduced so PCB loadings (and surface sediment PCB concentrations) were reduced and in recent years appear to have a mixed composition of Aroclor 1260/1254/1248. The remaining questions are whether this third composition pattern (EM3) represents a real and distinctly different pattern, and a different source physically and in time, rather than a mixture of the other two patterns (EM1 and EM2), and whether there is any evidence of an alteration or dechlorination pattern, both of which are addressed in the next few paragraphs.

Confirmation of a Third Source Pattern

All four receptor models resolved a third PCB congener profile that differed subtly from one of the other two. Two PCB congener profiles were consistent with a predominant Aroclor 1260 congener pattern (EM-2 and EM-3; Figure 3-19). End-member 3, however, also included some less chlorinated congeners within the Aroclor 1254 and Aroclor 1248 range (Figure 3-19). These two patterns were somewhat separated geographically (Figure 3-20), although this should be interpreted with care as the relative contribution of the end members can have a fairly substantial amount of uncertainty associated with it. Much of the pure Aroclor 1260 congener pattern appears to be associated with the Navy facility. The PCB composition of Aroclor 1260 together with less chlorinated congeners was observed in higher proportions in the western parts of the study area, near Yosemite Creek. Given the subtle difference in these two congener patterns, it was important to independently confirm the compositional differences to understand if it was possible that there was a different source of Aroclor 1260-like PCB also in Yosemite Creek, based only on the congener pattern information. There was no way to do this purely within the realm of this chemometric analysis so another independent line of evidence was investigated.

Several years before the collection of the congener data used in the chemometric analysis described above (Section 3.1.7.5), the San Francisco Public Utilities Commission (SFPUC) had sampled sediments from Yosemite Creek. Only surface sediment samples had been collected, and the number of congeners reported was much smaller than that available in the South Basin. However, knowing which congeners were important in the distinction between the two PCB patterns discussed above, a simple ratio analysis approach (Section 2.5.1.1) was used to see if the SFPUC data supported the hypothesis of a slightly less chlorinated PCB source up Yosemite Creek. The ratio of two congeners included in both the FS and the SFPUC data sets was calculated: PCB28 and PCB153. PCB28 is a tri-chlorinated congener typical of an Aroclor 1248 source. PCB153 (a hexachlorinated congener) is prominent in both Aroclors 1254 and 1260, but present in low proportions in Aroclors 1242 and 1248. The PCB28/PCB153 ratio was calculated for samples from both data sets and plotted on a map (Figure 3-23); the ratio is approximately 76, 17, 0.03, and 0.003 for Aroclors 1242, 1248, 1254, and 1260, respectively (Appendix A). The combined data set clearly shows a higher ratio (i.e., lower chlorinated pattern) in Yosemite Creek sediments – a ratio that is higher than can be explained by combinations of only Aroclors 1254 and 1260. The augmentation of the main data set with useable data from a completely independent investigation helped confirm (1) the subtle difference in PCB patterns observed in surface sediments in the South Basin (near the landfill and near Yosemite Creek) likely reflects

different sources; and (2) there is/was indeed a lower molecular weight PCB source in Yosemite Creek that contributes some to the PCBs in the South Basin.

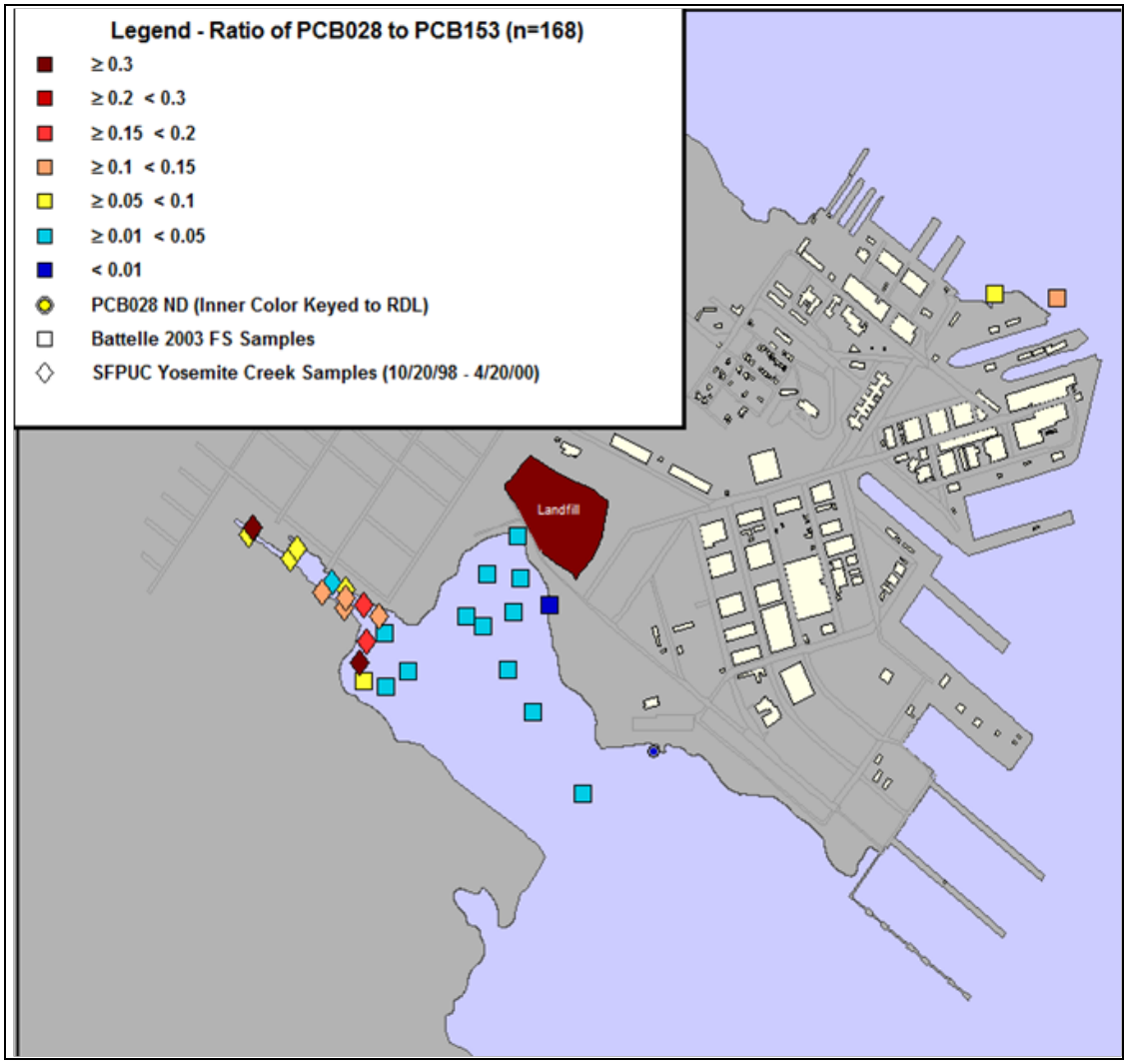


Figure 3-23. Ratio of PCB28 to PCB153 in Sediments Near Hunters Point Shipyard and Yosemite Creek, San Francisco, CA

Consideration of a Possible Fourth Source Pattern

As indicated in Section 3.1.7.5, through the statistical goodness of fit diagnostics, in conjunction with the receptor models (Figure 3-18), a minimum of three PCB compositional patterns were indicated for this data set, likely from at least two different physical sources, but some congeners still exhibited a noisy fit (see for example the PCB49 scatterplot on Figure 3-18). Therefore, the possibility of a fourth end member pattern was evaluated by applying one of the receptor model methods (PVA) to four end-members. The result was a resolution of three end-members very similar to the previous three, plus a fourth that was similar to Aroclor 1254, but with slightly higher proportions of PCB49. PCB49 is a known dechlorination product [65]. A fourth pattern

is plausible but, if present, it is not important to the source apportionment study because (1) it is a slight variant of an Aroclor 1254 weight range pattern; (2) Aroclor 1254 is already represented in the three source model; (3) to the extent that it represents a true congener pattern, there is independent evidence from the literature that suggests that is related to alteration and not a source; and (4) if this pattern does represent dechlorination, it is very subtle.

3.1.7.6 Integrated Data Analysis and Interpretation

As discussed in Section 2.5.3.6, integrated data analysis and interpretation is the process of synthesizing information from multiple lines of evidence to arrive at scientific interpretations that answer the key questions of a forensics investigation (i.e., PCB sources, alteration mechanisms, timing/history of releases). Lines of evidence typically considered include site history, published scientific literature, sediment transport/hydrodynamics, analytical chemistry which is then used to interpret total PCB concentration gradients and inspection of sample chromatograms/compositions, and chemometric analysis.

At HPS, such lines of evidence consistently support the key conclusion – that there appear to be two general physical source areas that have contributed the majority of the PCBs in the South Basin sediments – one of the source areas being the general vicinity of the landfill near the north-east shore of South Basin and the other being Yosemite Creek and, possibly also, old outfalls southwest of the mouth of Yosemite Creek (lower Figure 3-2). The PCB concentrations and compositions from these two source areas have shifted over time. In the past, sediments from deeper than 30 cm, or pre-1970s on both sides of South Basin show a similar 50/50 mix of Aroclors 1254 and 1260, but the concentrations are higher on the west side at greater depth. More recent surface sediments to the west by Yosemite Creek show much lower concentrations (indicating the source has been significantly reduced) and an increase in the relative proportion of Aroclor 1260, with smaller contributions of lower weight Aroclors (1254 and 1248). Surface and more recently deposited subsurface sediments to the east by the former landfill still have elevated concentrations, suggesting a continuing source (as of the 2003 sample collection date), with a composition that is almost entirely Aroclor 1260.

This observation is consistent with and supported by site history (Section 3.1.7.1), which indicates that PCB-contaminated material went into the landfill from 1958 to 1974, and that, in addition to leaching and erosion from the landfill, a former slough/ditch/channel in the area (which was later filled by landfill expansion) could have contributed PCBs to South Basin through runoff from other parts of the Navy property and from the landfill (Figure 3-3). Figures 3-9 through 3-12 show elevated PCB levels along the shoreline in front of the landfill, possibly from contaminated fill used to close off the former slough/channel around 1970 or illegal dumping activities noted by DTSC when HPS operated as a commercial shipyard from 1976 to 1986. The offshore sediment PCB concentration gradients (Figure 3-10) line up with the onshore elevated shoreline PCB levels (Figures 3-9 and 3-12), indicating that erosion of these shoreline materials have represented a source of PCBs to the South Basin.

The presence of numerous commercial/industrial facilities that could contribute PCBs were located up and around Yosemite Creek and could have contributed PCBs through runoff and CSO discharge. For instance, a facility operated as a 55-gallon drum recycling operation from 1948 to 1988 with noted releases of PCBs as well as other contaminants. CSO releases of mixed

stormwater/sewage were more common in the past, but after about 1970 when all CSOs were realigned into Yosemite Creek and the sewer storage capacity was increased, these releases were reduced to about one per year.

The sediment transport and hydrodynamic information for South Basin (Section 3.1.7.2) indicates that contamination entering the Basin would be expected to be relatively predictably deposited and distributed away from sources (i.e., that the geographical distribution of the PCB contamination would radiate and decline away from sources). This implies that the contour maps such as Figure 3-10 can be viewed to show two high concentration areas where PCB sources are likely to have been located. Sedimentation rates derived from the dated cores indicate a constant, steady 1 cm/yr depositional rate, so events that occurred around 1970 should be seen in these cores at about 30 cm depth. The various PCB data analyses further support the initial findings of potential sources, adding additional lines of evidence.

The PCB concentration gradients in the South Basin showed two areas of high concentration: one near the shoreline adjacent to the former landfill and another near the mouth of Yosemite Creek (Section 3.1.7.3 and Figures 3-10, 3-11, and 3-12). The preliminary PCB composition information (Section 3.1.7.4 and Figures 3-13 and 3-14) indicates at least two PCB compositional characteristics of the PCB in the sediments – one closely resembling Aroclor 1260 in the surface and near surface sediments near the former landfill, and another resembling a combination of Aroclors 1254 and 1260 in the deeper sediments near Yosemite Creek. Figures 3-15 and 3-21 show PCB data from core SB94 collected near the landfill, and illustrates a compositional shift in the PCB composition at 30 cm, which was dated at about 1970. This was the time period when the slough/channel was closed off by the landfill, the sewer capacity was increased to reduce CSO events, and the CSOs were realigned within Yosemite Creek. This suggests that the common PCB compositional signature (50/50 mix of Aroclor 1260/1254) seen deeper than 30 cm across South Basin may have been from one source or similar sources, possibly CSO outfalls located both in Yosemite Creek and at the north end of the slough/channel that was being filled by the landfill. Another possibility was that the same contaminated fill was used on both sides of the embayment and this fill served as a common source of PCBs for these deeper sediments. After the slough/channel was filled in the 1970s, the PCB composition in the sediments near the landfill shifted to closely resemble Aroclor 1260, possibly from continued erosion of the contaminated beach in front of the landfill (Figure 3-9). Sediments shallower than 30 cm in the Yosemite Creek area have much lower PCB concentrations because the CSOs (the local source of the PCB) were realigned and the sewer capacity was increased to reduce the overflow events. These PCB composition in the sediments on the west side of South Basin also show a compositional shift from the deeper sediments (Aroclor 1260 [50%]/1254 [50%]) to the shallower sediments (Aroclor 1260 [75%]/1254 [20%]/1248 [5%]).

The various chemometric analyses, which are described in more detail in Section 3.1.7.5, further support the initial findings of potential sources, adding additional lines of evidence. Much of the information from that section can be summarized in the PCA scores plot (Figure 3-22), and accompanying discussion (Section 3.1.7.5). In summary, the PCA scores plot shows the data cloud of sample points that can be enclosed by a geometric shape (triangle) with the corners (vertices) representing end-member (EM) PCB congener compositions that can be linearly mixed to provide the congener composition of all the samples at the site. The surface and near surface

sediments from the east near the former landfill plot closer to the bottom left corner marked EM2 (an Aroclor 1260 source pattern) and the surface sediment samples from Yosemite Creek plot closer to the top corner of the triangle marked EM3 (a mix of Aroclors 1260/1254/1248). Deeper samples from both sides of South Basin, and the most contaminated deep sediments from the west plot near EM1 represent a mix of Aroclors 1260 and 1254. One can easily see the change in composition with depth, where deeper samples from below 30 cm throughout South Basin generally plot close to the same 50/50 mix of Aroclors 1260 and 1254, while shallower samples have a stronger influence of Aroclor 1260.

Another way to visualize these compositional variations in a spatial representation is shown in Figure 3-21. This figure shows an east to west transect of cores to show the vertical and horizontal variations in the end member compositions across the site. On the left of each core are the depth (cm) and darkened sediment horizons that were homogenized and used for ACF congener analysis (undarkened intervals only had RSC total PCB measurements, so there is less data accuracy and the results were interpolated over these horizons). On average, there is more green (EM2) to the east (see core SB079) and more blue (EM3) to the west (see core SB105). The one fine interval dated core in this transect (SB094) shows a sharp transition at 30 cm depth (around 1970) with more red (EM1) at deeper depths. It should be noted that the error bars associated with this type of display in this case study are larger than in typical cases (usually estimated to be about 10 to 20%) because of the similarity in composition between EM2 and EM3. In fact, because Aroclor 1260 is notably present in all samples, the uncertainty in allocation among the end members is greater than in a more desirable candidate site where the different end member compositions are more unique and easy to separate.

Combining multiple lines of evidence, it appears that there are three different PCB contaminant characteristics in the sediments of the South Basin at HPS, which could have originated at two or more general areas at different times. Considering only individual lines of evidence, this might not have been at all apparent. For example, the raw concentration maps show two distinct areas of high concentration (Yosemite Creek and the HPS landfill – Section 3.1.7.3). Analyzed in isolation, this suggests two sources. It is only when one analyzes congener patterns (through direct inspection of sample composition or through chemometric analysis) that it becomes clear that there was a historical shift in congener patterns near the landfill. This suggests a change in source material emanating from the landfill area overt time. An Aroclor 1254 pattern is more dominant at depth, while an Aroclor 1260 pattern is more recent in shallow sediments. Alternatively, it is possible that sources in and around Yosemite Creek also contributed to the PCBs in the deeper, historic, South Basin sediments also closer to the Navy landfill area. However, it should be noted that the amount of PCBs (i.e., the PCB concentrations) are much lower in the deep sediments on the east side of South Basin, and, therefore, accurately identifying the origin of that contamination may be of less importance, from a sediment management perspective.

The HPS case study here has shown that these multiple lines of evidence present a consistent story. Since this case study was done with pre-existing data, it presents both advantages and limitations compared to a typical forensics study planned from the start. The obvious advantage is the cost savings, since the regulatory RI/FS project paid all the planning, sample collection, and sample analytical costs. Ideally, from a technical and defensibility perspective, it would

have been preferable to have additional samples to validate the proposed end member source compositions and sample from physical locations where the sources may have been present. This was possible for EM2, where the composition matched an Aroclor 1260 pattern and samples onshore along the beach on the east side showed the same pattern. The physical source for EM1 and EM2 seen in the deeper sediments (before 1970) is more problematic since these past sources are no longer present and contributing to recent sediments. Additional work upstream in Yosemite Creek might help to find the physical source of EM3, possibly in upstream sewer sumps. However, even without this complete validation of source locations, this case study has shown how forensics studies can be used to identify PCB sources in sediments.

3.2 Site II: Ashtabula River

3.2.1 Site Description

The second case study site is on the Ashtabula River, where the river flows into Lake Erie, east of Cleveland, Ohio (Figure 3-24). A maintenance and contaminated sediment management project was conducted at the site, in conjunction with a U.S. EPA research project of environmental dredging (e.g., investigation of dredging residuals [66]). The detailed study location is highlighted in Figure 3-24 (lower figure).

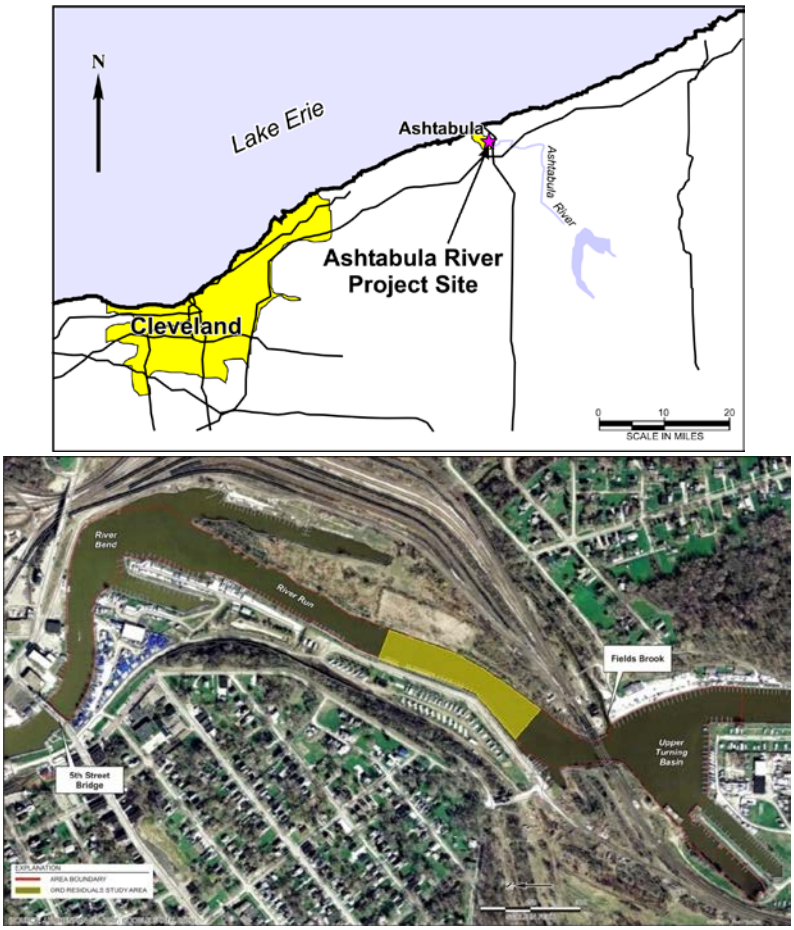


Figure 3-24. Ashtabula River with Dredge Site Study Area Highlighted

A joint partnership project was initiated in 2006 between U.S. EPA's Chicago-based Great Lakes National Program Office (GLNPO) and the U.S. EPA's Office of Research and Development (ORD), National Risk Management Research Laboratory (NRMRL), and the National Exposure Research Laboratory. GLNPO, via its Great Lakes Legacy Act (GLLA) mandate, and ORD, through its research mission, had mutual interests in evaluating the efficacy of environmental dredging. The organizations jointly initiated a monitoring effort on the Ashtabula River Dredging Project. Extensive sampling and analysis were completed before, during, and after dredging operations to measure sediment residuals and the impact of remediation.

The remediation of contamination in rivers and other water bodies often involves dredging bed sediment. Dredging, whether used alone or in conjunction with other treatment technologies like in situ capping or natural recovery, can result in the release of contaminated sediments. These residual sediments ('residuals') can be transported within dredged areas (near-field) and downstream or offsite (far-field). A number of factors can influence residual levels including: dredging equipment; operator technique; debris; dredging to bedrock; over dredging; cut lines, slopes, and depths; sediment characteristics; contaminant characteristics and distribution; and the accuracy and resolution of contaminant characterization. Residuals can be categorized as either undredged or dredge-generated. Undredged residuals are the result of missed areas and incomplete characterization. Dredge-generated residuals are released via resuspension, transport and downstream deposition; dredge mixing and immediate deposition; and sloughing.

The Ashtabula River in extreme northeast Ohio flows into Lake Erie's central basin at the City of Ashtabula (Figure 3-24). Its drainage basin covers an area of 137 square miles, with 8.9 square miles in western Pennsylvania. Major tributaries include Fields Brook, Hubbard Run, and Ashtabula Creek. The City of Ashtabula, with an estimated population of approximately 21,000 (2000 census), is the only significant urban center in the watershed, with the rest of the drainage basin being predominantly rural and agricultural. There is concentrated industrial development around Fields Brook (east of the Ashtabula River) and east of the mouth of the Ashtabula River. Sediments in portions of the Ashtabula River are contaminated with a variety of chemicals, including PCBs, the primary chemical of potential concern for this project.

Approximately 550,000 yd^3 of contaminated sediments were dredged between the Turning Basin at the mouth of Fields Brook and the Fifth Street Bridge. COPCs in this stretch of the river include PCBs, PAHs, hexachlorobenzene, hexachlorobutadiene, metals, and the radionuclides uranium, radium, and thorium. The radionuclides are above background levels but below regulatory criteria. In Phase 1 of the research project, GLNPO conducted a baseline characterization of the river that included these COPCs, while ORD focused only on the PCBs in selected areas of the river. In Phases 2 and 3 of this dredge residuals research project, ORD continued to focus on the PCB inventory in the test reach and selected areas of the river.

Historically, the PCBs are thought to have originated primarily from Fields Brook, a stream that drains into the Ashtabula River in the area of the upper Turning Basin. The Fields Brook source has been controlled and eliminated as a source of contamination (or re-contamination) of the Ashtabula River. A CERCLA cleanup of Fields Brook was completed in 2003. A post-cleanup monitoring program is in place to protect against recontamination of Fields Brook as well as the Ashtabula River.

3.2.2 Evaluate Site for Forensic Study

Potential PCB source areas at the Ashtabula River study site have been associated with upstream locations in Fields Brook (on the east side of river at Transects 185 and 186; Figures 3-25 through 3-27). Subsequent studies suggested a second much smaller source from Strong Brook where it meets the river near Jacks Marine (on the west side of the river across from Transects 187 and 188). The U.S. EPA ORD dredge study focused on identifying techniques to characterize dredge residuals and understand their sources. One technique that was evaluated was using PCB compositional information to characterize dredge residuals (the amount of sediment material that is unintentionally left behind after dredging). To support this part of the research, a large number of sediment core samples were analyzed for a detailed list of more than 100 PCB congeners. These cores were subsectioned based on elevation and sediment characteristics (sand lenses, organic matter layers, etc.). These sections were analyzed for PCB congeners and compared to the dredging information (dredge position, production, sediment slopes, etc.) to evaluate potential mechanisms for contributing to dredge residuals.

For the purposes of a case study for this document, this site resembles a typical Navy dredge site (similar dredge technology, similar deposition of contaminants, similar COPCs, etc.) and the chemical forensics data that were generated can be used to demonstrate the approach used in this document to identify multiple upstream sources of contamination. As was demonstrated in the first case study example in this document, the site history and suspected sources for Ashtabula River justify the need for a forensics study to differentiate potential contributions to the river. There appear to be at least two potential historic and/or current sources of PCBs upstream of the dredge area that may become mixed into the sediments in the downstream dredge area. If this was a Navy dredge project, it would be desirable to develop a technically defensible allocation scheme to apportion dredge costs among the upstream sources. A quantitative forensics analysis to apportion the source contributions from the Navy and other sources would be necessary. A forensics investigation would also be warranted to identify if any potential active sources continue to contaminate the river if it is unclear if all sources have been controlled. Environmental dredging or other sediment management actions should only be implemented once it has been demonstrated that all sources are controlled.

3.2.3 Develop Conceptual Site Model

Figure 3-25 shows a contour map of surface sediment PCB concentrations for the Ashtabula River dredge area to support CSM considerations at this site. Additional historic data show potential source areas up the industrial waterway, Fields Brook. The source area has had significant remediation under Superfund that was completed in the 1990s. These actions include source control to eliminate PCB discharge to Fields Brook and subsequently reduce the contaminant migration off site to Ashtabula River. As a result, the Ashtabula River recently deposited surface sediments no longer show high concentrations of PCB contamination, but the older, deeper sediments in the downstream dredge area still show contamination from these historic Fields Brook sources (Figure 3-26). However, the surface sediment contours suggest increasing concentrations across the river from Fields Brook toward Jacks Marine (and Strong Brook). As a result, additional sediment cores (JAM1-3) were later collected in this area and showed total PCB concentrations well above 1000 ppb. Therefore, this area is considered a second source area for PCBs that has more recently contributed to PCBs transported downstream to the dredge area. A forensics investigation for this area included collecting samples near the

source areas and in the comingled dredge area to compare to the two known source areas. This could be used to allocate relative contribution and apportion costs for the dredge project. Additionally, this forensic analysis provided information to ensure that all sources have been controlled before initiating sediment management activities.

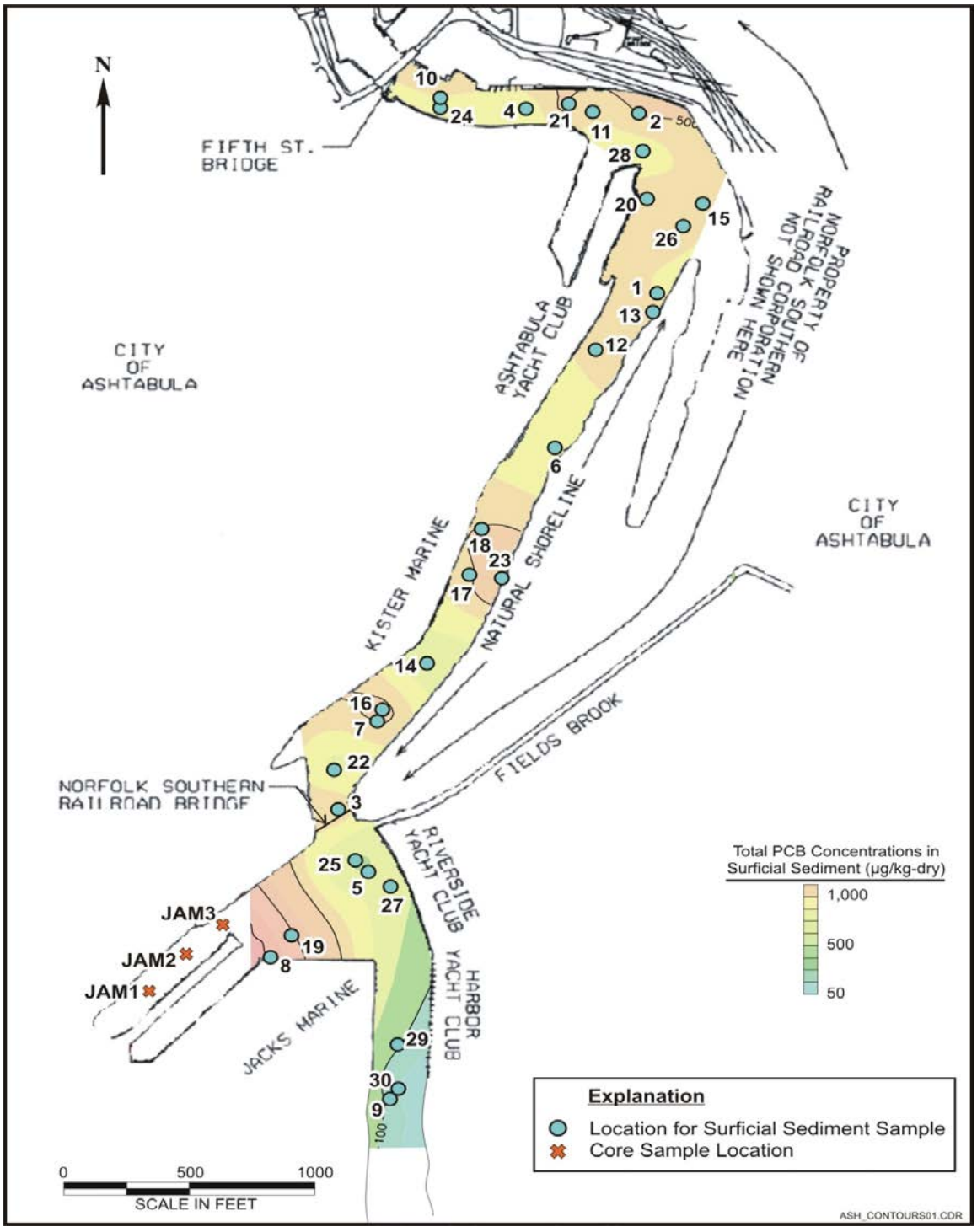


Figure 3-25. Pre-Dredge Contour Map of PCB Concentrations in Surface Sediments in the Ashtabula River Study Area

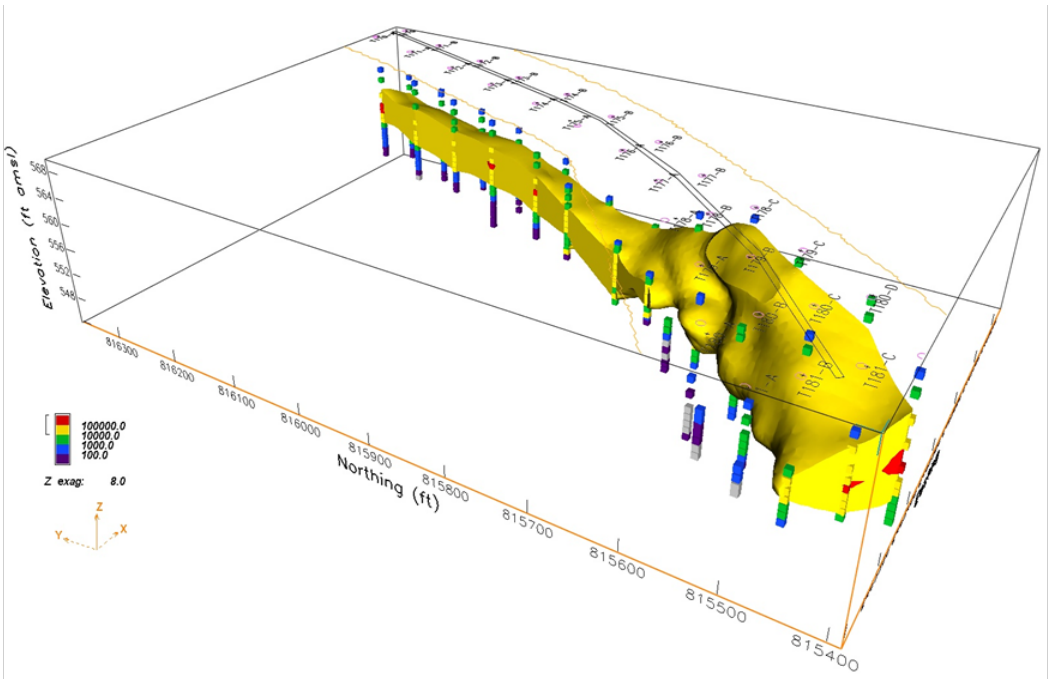


Figure 3-26. Pre-dredge Sub-surface Sediment Concentration Profiles in the Ashtabula River Study Area Indicating Sediment with Total PCB Concentration > 10,000 ppb

3.2.4 Develop and Execute a Technically Defensible Sampling Plan

Though the ORD project on Ashtabula River had significant amounts of data that were used for this case study, there were limitations to the data in terms of use for an environmental forensics investigation. The purpose of the ORD study was not to demonstrate the ACF; however, the study did provide a large portion of the data needs (at a significant cost savings) for the case study for this document. The environmental forensics demonstration made use of available data as best as possible. Figure 3-27 shows a portion of the dredge area where 30 cores were collected and segmented to produce more than 350 subsamples for both RSC and ACF analysis. Additionally, three cores (JAM1-3 in Figure 3-25) were collected in the Jacks Marine area near the confluence of Strong Brook and analyzed to identify another potential source.

To utilize these data as a case study, a data gap analysis was completed. Inconsistent sampling and analysis techniques were used for the two sets of in-river core samples (30 original cores and the JAM cores). One significant problem was the different depths of surface sediment sampling and sediment core segmenting between the two coring events. Secondly, samples were not collected at the mouth of Fields Brook, an historic source. Therefore, older and incomplete information must be relied upon to define this source. In addition, samples were not collected upstream of the confluences of the two brooks discharging to the river to ensure there were no additional sources and to identify the background PCB concentrations and composition of the river sediment. The surface sediments were generally 15 cm or more in depth in the original core samples. This depth may represent many years and even decades, depending on the rate of deposition. For ACF analysis, surface sediment samples should be no more than a few cm deep to obtain information on current or recent sources.

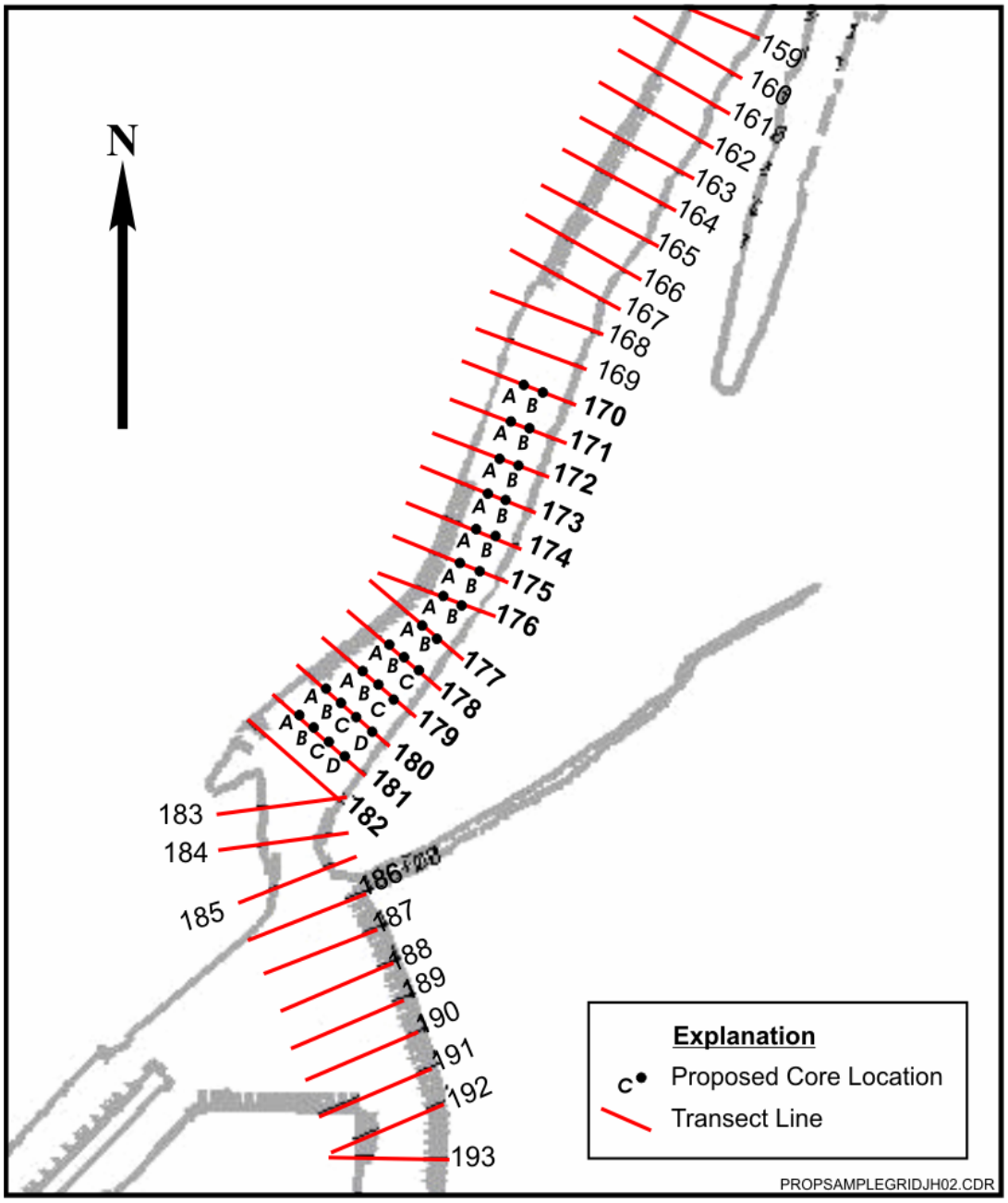


Figure 3-27. Sampling Design Map for ORD Dredge Residuals Study at Ashtabula River Transect Cores
(U.S. EPA, 2010 [67]) (These cores provided the pre-existing data used in this forensics demonstration.)

The Ashtabula River case study, like the HPS study, is based on using existing data from study designs not optimized for a forensics investigation. Clearly, there are advantages and limitations to a forensics study using only pre-existing data. Though pre-existing data provides a large cost savings, the shortcomings of a sampling design to provide information for another purpose must be accepted. As stated earlier, unexpected results are likely to occur even in the best designed forensics study. In the case of the Ashtabula study, this is why the additional JAM1-3 cores

were collected and analyzed. Initial data for this segment of the river showed surprisingly elevated concentrations with a strong Aroclor 1260 signature. This signature was different from the Aroclor 1248-dominated Fields Brook contamination. Originally, Fields Brook had been assumed to be the only source to the Ashtabula River that needed to be managed. The additional sampling in the Jacks Marine/Strong Brook confluence area identified an active source of Aroclor 1260, which subsequently was controlled shortly before dredging began. Although it may be easier to grasp a forensics study that follows a linear process (Figure 1-1), it may be more realistic to assume the process will be iterative with a need to obtain information on additional unknown sources and fill in additional information gaps as the project proceeds.

While it is cost effective and faster to use pre-existing data (no additional field or analytical costs), the limitations are that the study design may not meet all of the objectives of a well-designed forensics study. Fortunately, the study plans in the Ashtabula River case, although not intended to satisfy a forensics study, did include relatively detailed sediment sampling and rather comprehensive PCB congener analysis. Significantly more useful information was produced in the ORD research study than would be typical in a standard RI.

3.2.5 Conduct Rapid Sediment Characterization

The ELISA IA technique was also used to obtain RSC data on Ashtabula River sediment samples and the RSC data are summarized in Appendix C. The Ashtabula River research study was, like the HPS study and as described earlier, not conducted as a forensics investigation. As a result, the analyses were not tiered with the RSC analysis followed by a smaller set of ACF analyses. The PCB congener analyses were also conducted on all RSC samples.

For the Ashtabula River research study, the ELISA RSC data were not used in a tiered approach to select additional analyses. The research question was to compare the RCS to the PCB homologue data. These homologue data were also generated on the samples and provide more reliable and useful Total PCB data (Sections 2.4.1 and 2.4.3). The laboratory-based Total PCB concentrations were determined both using Method 680 to quantify individual homologues and summing those to generate the total PCB (Section 2.4.1) and by summing the 117 PCB congeners quantified during the ACF analysis; the results compared very well. The Total PCB concentrations based on the sum of the 117 PCB congeners are presented along with the individual congener data in Appendix B. As discussed earlier, those 117 congeners represent approximately 97 to 98% of the Total PCB in most environmental samples and are a good representation of the Total PCBs.

3.2.6 Conduct Advanced Chemical Fingerprinting

The ACF analysis of the Ashtabula River sediment samples consisted of determining the concentrations of 123 PCB congeners using modified Method 680/1668 (a HRGC/LRMS technique), as described in Sections 2.4.2 and 2.4.3. As for the HPS study, this work was not conducted as a forensics investigation and the ACF analysis was performed on the majority of the samples, not a subset selected by first reviewing the RSC results. However, the congeners were carefully selected to represent what could reasonably be expected in environmental PCB contamination, considering potential source material (Aroclor formulations) and environmental processes (Section 2.4.3). The Ashtabula River ACF data are summarized in Appendix B.

During the initial data review, the PCB congener set was reduced to 120 PCB congeners, because three of the congeners were consistently not detected (PCB11, PCB30, and PCB50). Those are the 120 PCB congeners reported in Appendix B. During the subsequent more detailed data review and screening (Section 2.5.2.3), about 53 of the 345 sediment samples were identified as candidates for potentially excluding from the data analysis because of lower data reliability (e.g., low overall PCB concentration [e.g., sum of congeners less that ~50 ppb], a high percentage of the PCB congeners with non-detects, or anomalous composition that cannot be explained by PCB chemistry or weathering factors). Thirty-eight of the 120 PCB congeners were also identified as potential candidates for exclusion from the data set prior to detailed data analysis because of possible lower reliability (e.g., high percent non-detect of the congener, low congener concentration, a high %RSD in the percent contribution of the congener to the Total PCB, or other data outlier issues). As discussed earlier, a stronger and more reliable data interpretation can be obtained with a high quality data for a pared down set of 80 PCB congeners than from a larger set that also includes congeners with lower reliability.

3.2.7 Data Analysis, Synthesis, and Presentation of Results

3.2.7.1 Site History and Records Research

Historical source information was lacking for the Ashtabula River case study, posing a limitation that would need to be rectified if a comprehensive forensics investigation was performed. A major tributary to the study area includes Fields Brook, a U.S. EPA Superfund site which had a high concentration of industry around it with significant runoff and drainage to Fields Brook (Figure 3-28). The site had been historically identified as a source of PCBs to the Ashtabula River; this source had been controlled (Section 3.2.1). Other locations of runoff and input to the river but with less information on historical activities include Hubbard Run, Ashtabula Creek, and Strong Brook (which flows into Jacks Marine).

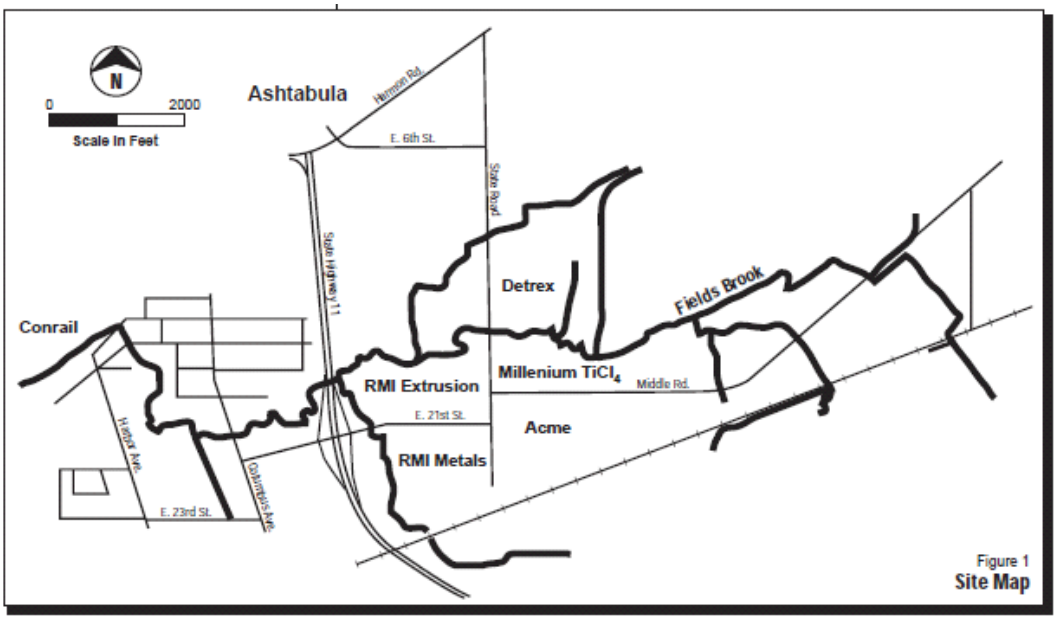


Figure 3-28. Fields Brook Drainage Showing Industrial Activities East of Ashtabula River
(Ashtabula River is located on the left side of this figure.)

3.2.7.2 Sediment Transport and Hydrodynamics

As part of the GLNPO GLLA remediation activities, sediment transport and deposition studies were conducted at Ashtabula River, but the results are not readily available. These studies indicated that an estimated 4 cm of sediment will be deposited annually. These newly deposited sediments are anticipated to be clean materials from upstream of the project area. There were no dedicated studies of hydrology or sediment stability/transport available for this Ashtabula River case study, and this was clearly a limitation that would need to be rectified if a comprehensive forensics investigation was performed. The segment of the river that was studied is upstream of tidal influence, and standard river flow considerations are all the transport information that was available.

3.2.7.3 PCB Concentrations

The PCB concentrations were relatively uniform in the Ashtabula River surface sediments for most of the ORD research study area (Figure 3-25). Figures 3-26 and 3-29 illustrate a 3D model of the sediment PCB concentration profile in the study area. Each color in the 3D figure shows a distinct isoconcentration profile that varies both horizontally and vertically. The surface sediment Total PCB concentration was between 500 and 1,000 ppb in most of the ORD research study area (Figure 3-25 and 3-27). The subsurface sediment PCB concentrations were more variable and were generally much higher than the surface concentrations. The total PCB concentration was above 10,000 ppb in much of the subsurface sediment (Figure 3-26; [66]). The most contaminated sediments were generally found at 5 to 10 ft depth, but highly contaminated sediments were found at less depth at some locations. The sediments at greater depth (below the most contaminated zone) had variable PCB concentrations that were more comparable to the surface sediment PCB concentrations. The subsurface PCB concentrations were somewhat variable within the relatively small ORD study area, but no obvious pattern of increasing or decreasing concentrations geographically was evident with the exception of the highest concentrations being measured at depth close to and immediately downstream of the mouth of Fields Brook (top, Figure 3-29).

On more careful review of the surface sediment data from the Ashtabula River, it appeared that the PCB concentrations might be elevated just outside the ORD research study area (Stations 8 and 19 in Figure 3-25), and near Jacks Marine and the confluence of Strong Brook (Figure 2-13). The PCB composition of downstream surface sediment samples indicated a composition that was slightly different from that of the primary known source (Fields Brook) and these two facts prompted additional sampling near Strong Brook's confluence area to further investigate the elevated concentrations. This was important since the area was to be dredged and it was critical that all known sources of PCBs were controlled to avoid recontamination.

The additional sampling at the confluence of Strong Brook demonstrated that the surface sediment PCB concentrations were significantly elevated (Figure 3-30); surface sediment concentrations in Jacks Marine were around 10,000 ppb (more than 10 times higher than the GLLA project area) and elevated concentrations were also measured in shallow subsurface sediment from this area.

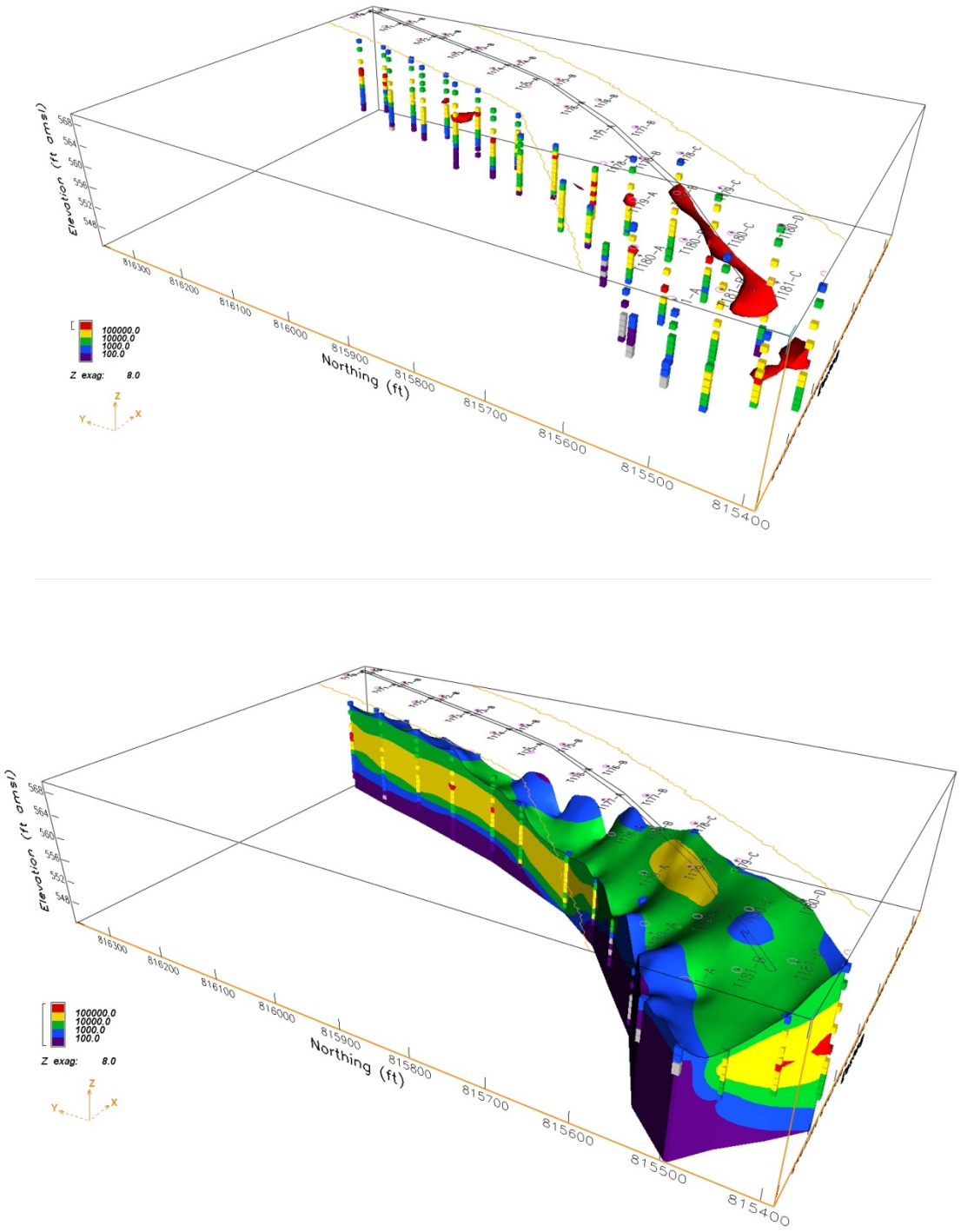


Figure 3-29. Example Ashtabula 3D Contour Maps (µg/kg or ppb total PCB): (a) >100,000 ppb Contoured Volume; (b) all contours including >100, >1000, >10,000, >100,000 ppb
(from U.S. EPA, 2010 [66])

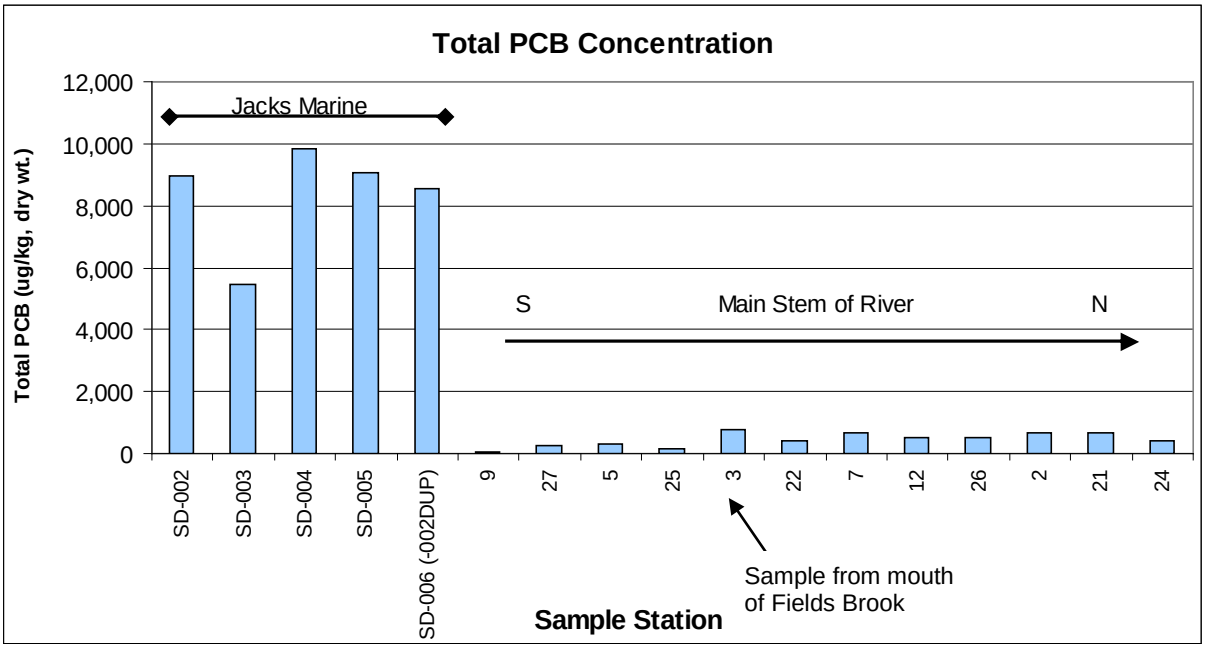
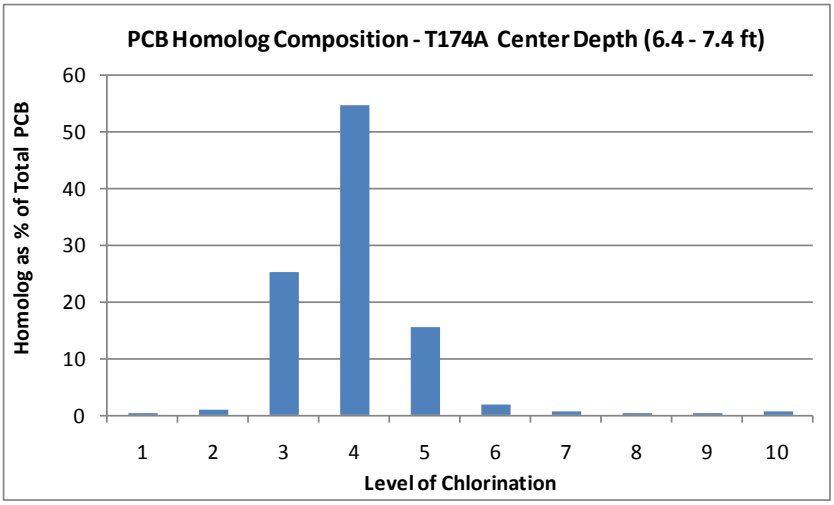


Figure 3-30. Total PCB Concentrations for Selected Ashtabula River Surface Sediment Samples, Including from Jacks Marine and the Main ORD Study Area (µg/kg, dry weight)

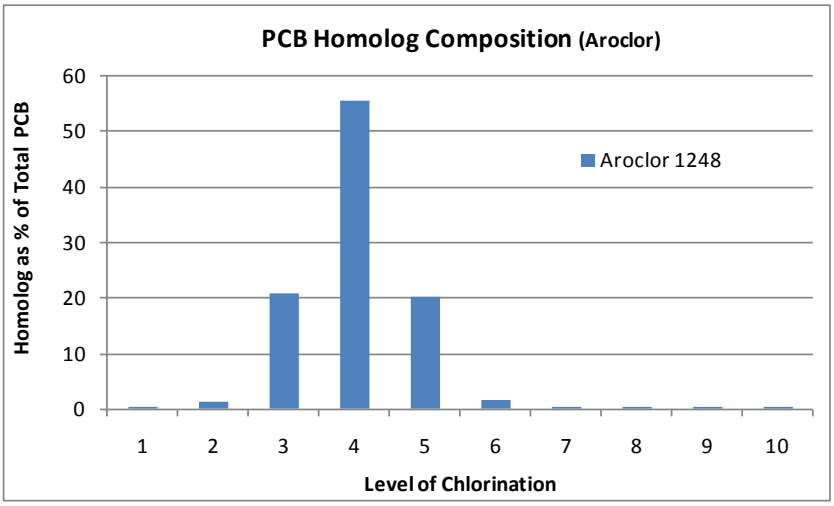
The Ashtabula River PCB concentration data indicate that most of the PCB contamination is historic and originated with the controlled Fields Brook Superfund source. This is apparent by comparing the high subsurface PCB concentrations in the main stem of the river downstream from the mouth of Fields Brook and the substantially lower surface sediment concentrations. The surface sediment PCB concentrations suggest that low levels of PCB may still be discharging from Fields Brook. This is indicated by the slightly higher PCB concentration at Station 3 (at the mouth of Fields Brook) compared to the rest of the study area, but the magnitude of elevation is small. The surface and near-surface data do, however, indicate a recent and active source of PCB to Jacks Marine (i.e., Strong Brook), likely a source of PCBs to the Ashtabula River.

3.2.7.4 PCB Composition

The Ashtabula sediment PCB composition was evaluated using both homolog and congener-specific data. Most samples from the most contaminated zone (at 5 to 10 ft depth) had a PCB composition that closely resembled Aroclor 1248-type contamination consistent with information regarding the historic Fields Brook source. This was demonstrated using both PCB homolog and PCB congener data (Figures 3-31 and 3-32); PCB homologue data can often also be very useful for compositional analysis including for multivariate analysis. This close match with Aroclor 1248 was observed throughout the ORD study area in most sediment below 1 ft in depth and in all of the most contaminated sediment. Sediment samples with a total PCB concentration above 10,000 ppb all showed a very close compositional match with Aroclor 1248.

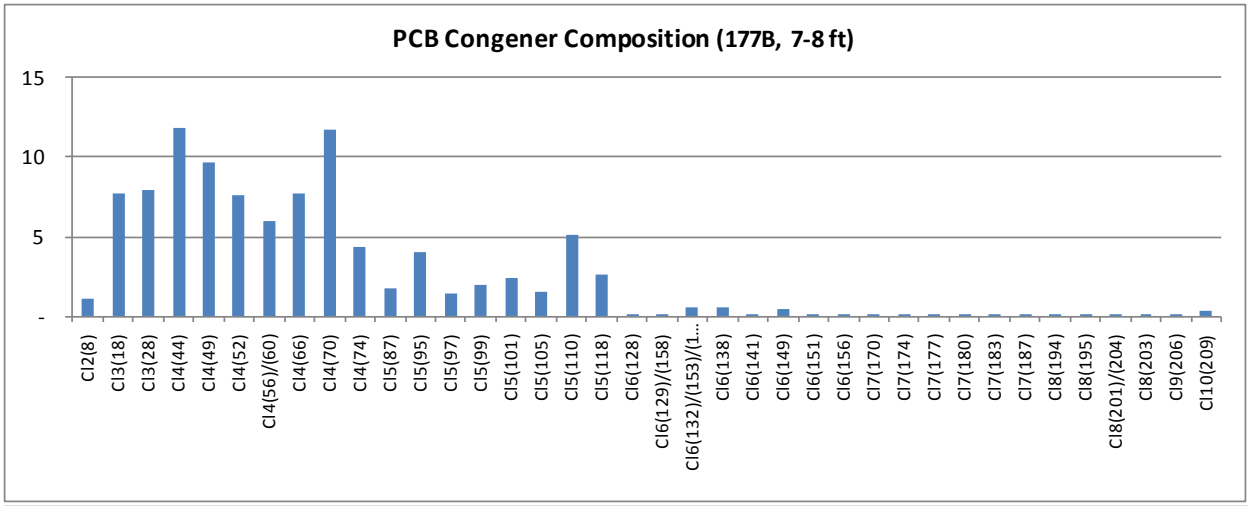


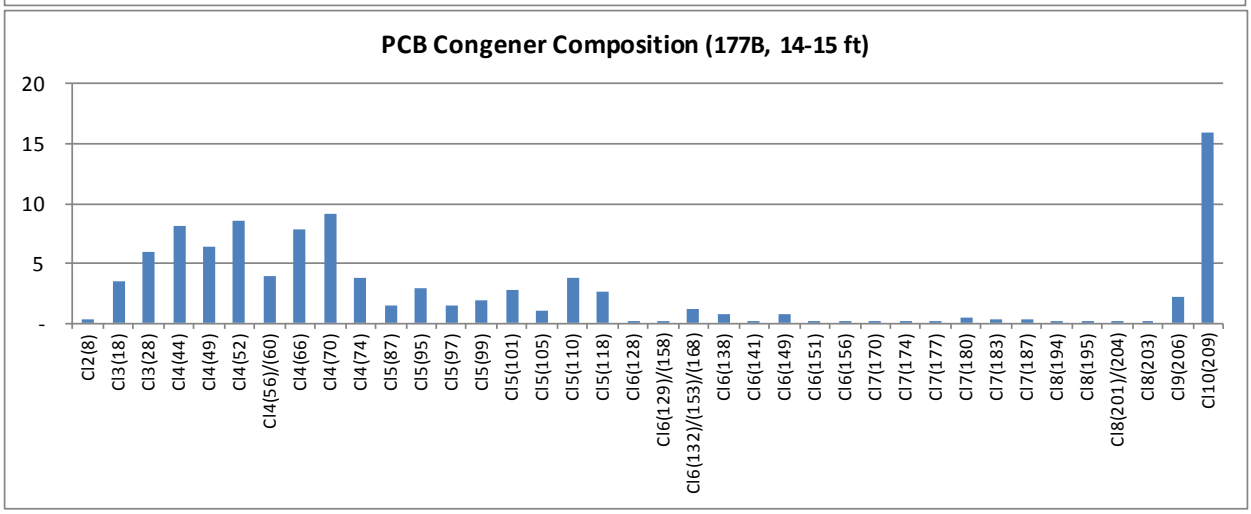
a) Pre-Dredge Core Sample T174A (from 6.4–7.4 ft sediment depth)



b) PCB Aroclor 1248

Figure 3-31. Composition Analysis Showing the Similarity in the PCB Homologue Composition of Ashtabula River: (a) Sediment Core T174A from a Depth of 6.4–7.4 ft; (b) and Aroclor 1248





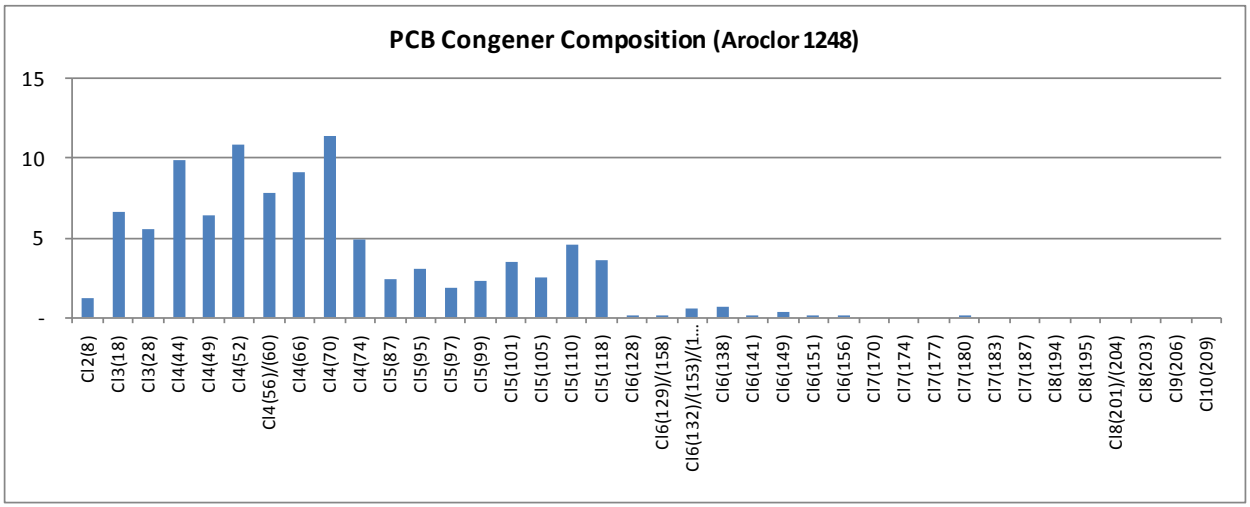


Figure 3-32. PCB Fingerprint of Sediment Samples from 7-8 ft and 14-15 ft Depth in the Center of the Ashtabula Study Area Compared to a Reference Aroclor 1248
(The primary source of the PCB was assumed to be the Fields Brook Aroclor 1248 source.)

The sediments collected from the greatest sediment depth (the lowest elevation) that were below the most contaminated zone exhibited a PCB composition that also was dominated by an Aroclor 1248 signature. However, these deeper sediments (e.g., as illustrated by the 14 to 15 ft segment in Figure 3-32), often also had a contribution by a few chlorinated PCB congeners (e.g., a few octa-, nona-, and deca-chlorobiphenyls) that do not have a clear relationship to any particular Aroclor formulation. The high relative amounts of PCB209 (deca-chlorobiphenyl) compared to the octa- and nona-chlorobiphenyls, for instance, were greater than in the highly-chlorinated Aroclor formulations (e.g., Aroclor 1268, and the rare Aroclors 1269-1271). The distribution cannot be explained by common environmental alteration processes. There are industrial processes (e.g., titanium tetrachloride production) that may selectively produce these highly-chlorinated congeners and this would warrant further investigation in a comprehensive forensics investigation. However, the sediments with this unique composition generally had low PCB concentrations compared to most samples ranging from less than 1,000 to about 3,000 ppb.

The surface and near-surface samples from the Strong Brook and Jacks Marine area did not have an Aroclor 1248-type PCB composition, but instead closely resembled Aroclor 1260 (Figure 3-33) with minor contributions from also a lower molecular weight Aroclor (possibly Aroclor 1248). The downstream surface sediment for the ORD research study area had a PCB composition that indicated contamination from both an Aroclor 1248 and Aroclor 1260 source (Figure 3-32). This was confirmed using data sets with both 38 and 80 PCB congeners (Figures 3-34 and 3-35). The Aroclor 1248 predominance was strongest near Fields Brook even in the surface sediments and the Aroclor 1260 predominance was strongest in the Strong Brook confluence. Figure 3-36 is a PCA analysis of the surface sediment PCB data (homologs and congeners) that demonstrates the association of the sample from the mouth of Fields Brook to Aroclor 1248, the association of the samples from Strong Brook confluence to Aroclor 1260 and the samples from the main study area are influenced by both the Aroclor 1248 and Aroclor 1260 source.

The observed PCB compositional match to Aroclor 1248 near Fields Brook and the sediments that were highly contaminated before the Fields Brook source was controlled. This analysis indicates that this was the source of the majority of the PCB in the ORD research study area and that, for the most part, it has been controlled. The strong Aroclor 1260 signature in the Jacks Marine sediment was evident in the surface sediments, indicating a recent and active source of PCB in this area, most likely Strong Brook which flows into Jacks Marine. The Aroclor 1260 signature and the PCB concentrations declined with depth near the confluence of Strong Brook, indicating that a source may have been active only recently.

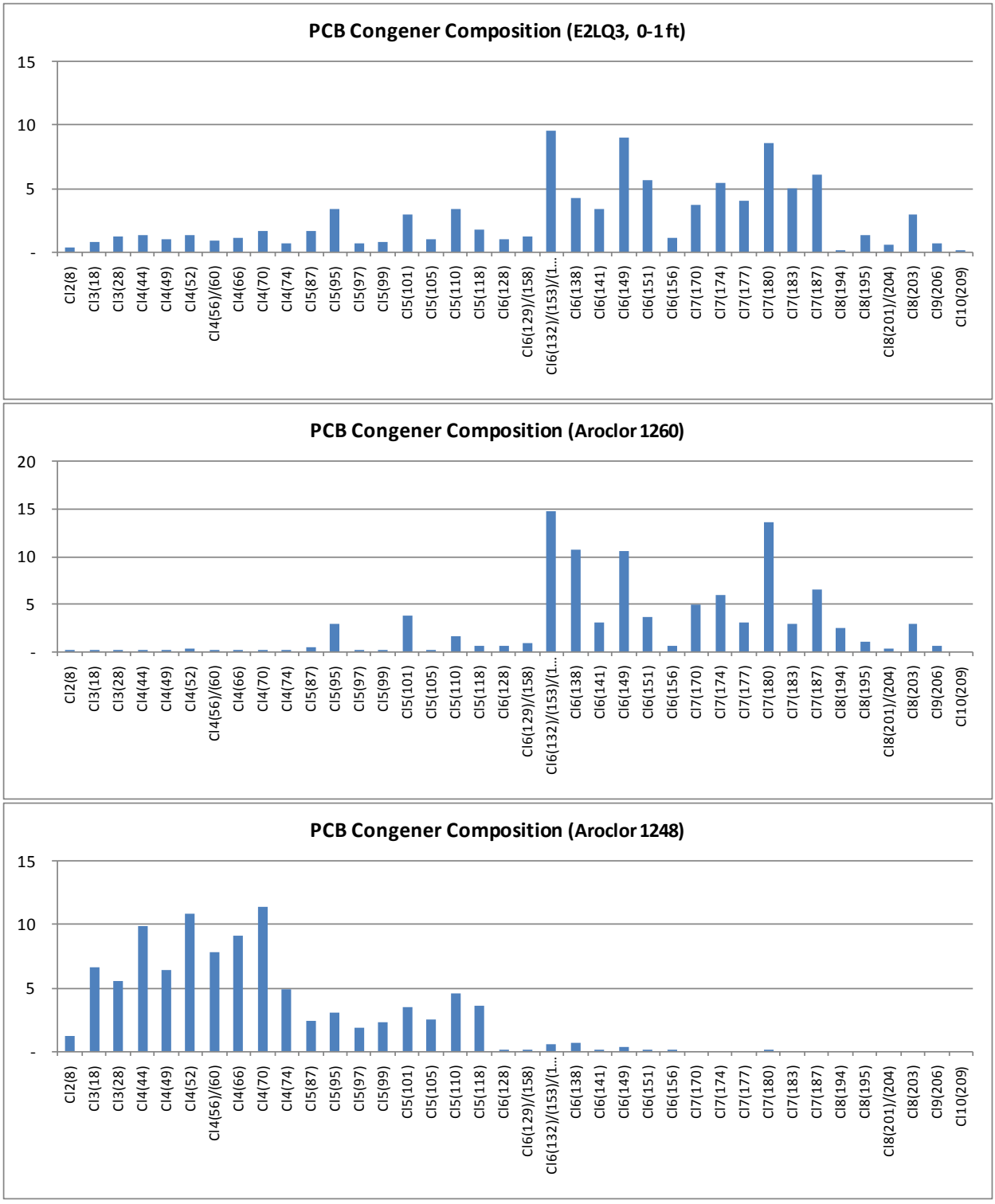


Figure 3-33. PCB Fingerprint of a Sediment Sample from a 0-1 ft Depth in the Jacks Marine Part of the Ashtabula Study Area Compared to a Reference Aroclor 1248 and Aroclor 1260

(Sample is primarily influenced by a local source of Aroclor 1260 as well as smaller proportions of Aroclor 1248.)

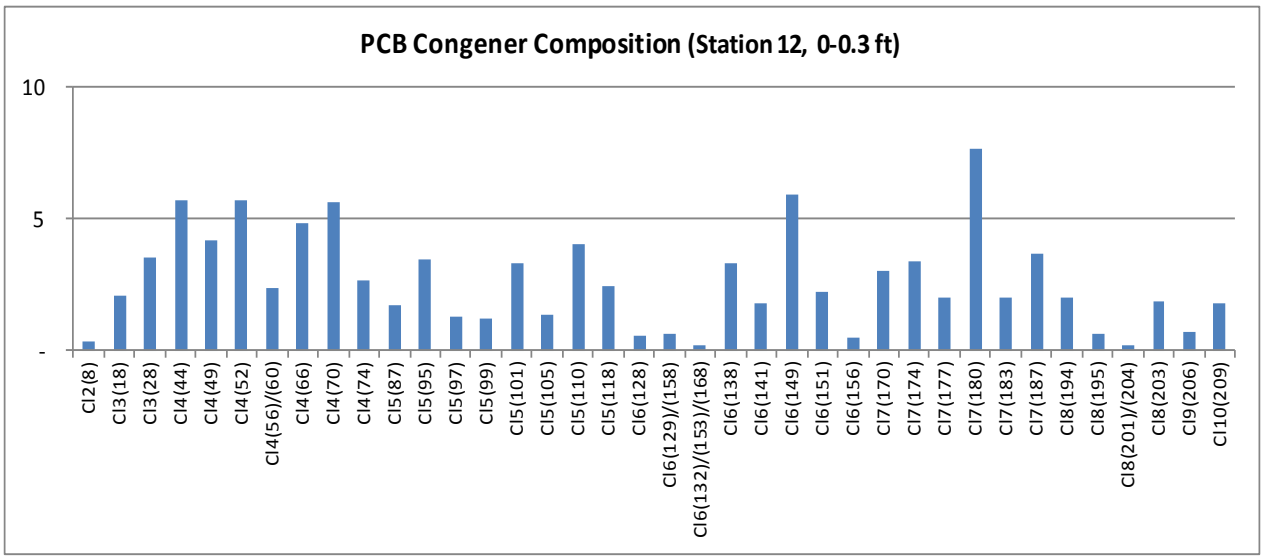


Figure 3-34. PCB Fingerprint of a Surface Sediment Sample from 0-0.3 ft Depth in the Center of the Ashtabula Study Area

(PCB composition indicates contributions from both the Strong Brook Aroclor 1260 source and the Fields Brook Aroclor 1248 Source; see Figure 3-33.)

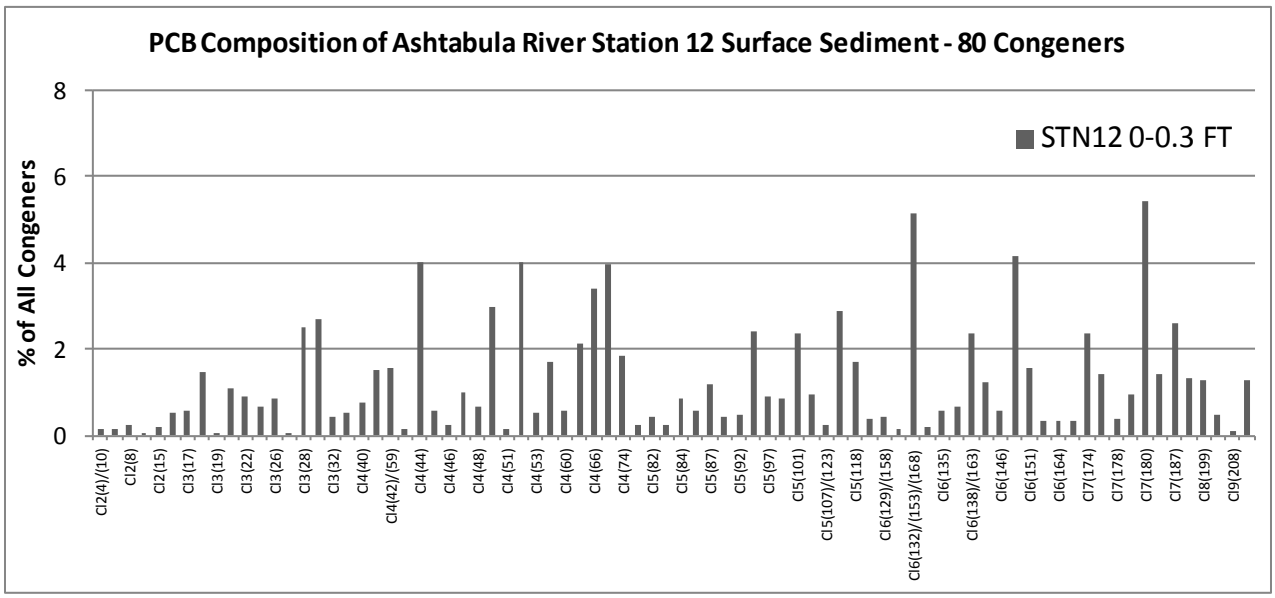


Figure 3-35. PCB Fingerprint of a Surface Sediment Sample from 0-0.3 ft Depth in the Center of the Ashtabula Study Area Using 80 Key Congeners

(A set of 38 congeners are plotted in Figure 3-34.)

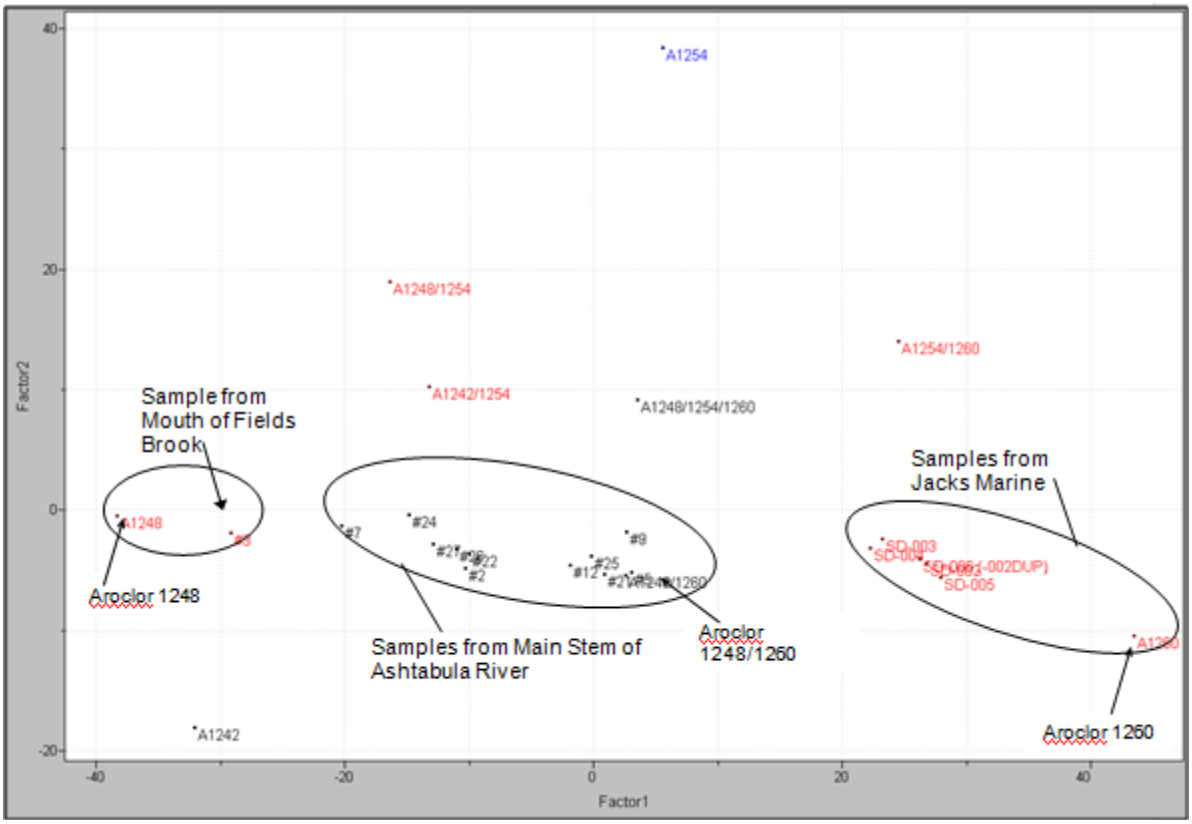


Figure 3-36. Principal Component Analysis Using PCB Data for Selected Ashtabula River Surface Sediment Samples and Aroclor Formulations
(Those illustrated in Figure 3-30; see sample IDs in above figure and x-axis of Figure 3-30.)

3.2.7.5 Chemometric Statistical Analysis

As discussed in Section 2.5.2.3, the data screening process is presented in this handbook as a discrete step between data preparation (2.5.2.2) and data analysis (Section 2.5.3). In reality, it is usually an iterative process with preliminary data interpretations on numerous analyses of the data and finally arriving at data interpretation that are both robust and spatially/temporally representative of a study area. This process is well illustrated with the Ashtabula ORD research data set.

For the Ashtabula project, the PCB congener data were from two separate pre-dredge investigations: (1) the Summer 2006 GLNPO baseline surface sediment sampling (17 samples); and (2) the Fall 2006 EPA ORD Phase 1 core sampling within the proposed dredge area (328 samples). Congener-specific analyses were conducted on both data sets by the same laboratory (Battelle) using the same preparation and analytical methods. Therefore, the data from the two events could be considered comparable and subsequently combined for greater spatial representation.

The combined data were delivered in spreadsheet tables which contained the information listed in Section 2.5.2.2, including: sample ID, sample coordinates, sample depths, analyte identifiers (i.e., congener names), and laboratory results. A digital base map was received in the form of a GIS shapefile, which was used to construct a simple base map (Figure 2-13) showing key geographic features of the study area and sample/core locations.

The data set initially considered for statistical analysis was comprised of 345 samples and 123 congeners. While this represents many more samples and congeners than were available at HPS (Section 3.1), it is clear that this data set still had limitations. The vast majority of samples were a very small area (the ORD research area within the larger GLNPO GLLA project area). GLNPO collected samples across a much wider geographic area but only 17 of surface samples were collected and none at depth. In addition, samples were not collected from Fields Brook (where PCB sources are known to be located). The contribution from Strong Brook was not initially considered and samples were not collected at its confluence. This is understandable given the sampling objectives of the EPA ORD (to establish baseline conditions for evaluating dredge residuals) and EPA GLNPO programs (to evaluate pre-remediation conditions). These two sampling campaigns were designed with a PCB forensics investigation in mind for source identification and allocation.

While not ideal for purposes of source identification and apportionment, the Ashtabula case study makes for a useful and instructive example. If there are limited or no resources available for additional sampling and analysis (as is often the case), existing data may be used to effectively conduct an ACF study. An adaptation of the ideal six-step integrated forensics approach process (Section 1.2.1) that includes development of a detailed sampling plan focused on specific forensic objectives (Section 1.2.1.3) may need to be developed to use existing data with budget or time limitations.

As per Section 2.5.2.1, the Ashtabula ORD research data set underwent laboratory data quality review. Based on that review, the congener data were accompanied by recommendations for exclusion of samples and congeners. These included (1) exclusion of samples with total PCB concentrations less than 100 µg/kg; (2) exclusion of samples with greater than 20% of congeners non-detect and total PCB less than 250 µg/kg; (3) exclusion of congeners with non-detects in more than 25% of samples; and (4) exclusion of congeners that were consistently reported at low concentrations (<0.2% of total sum of all congeners). This data QA review resulted in a recommended reduced data set composed of 293 samples (down from 345) and 83 congeners (down from 123).

As was the case for the HPS case study (Section 3.1.7.5), all individual data screening decision points will not be recounted here. However, one is instructive and provides an idea of the types of considerations typically taken into account in this process. The reduced data set (based on the criteria above) considered a 293 sample/83 congener subset of the full 345 sample/123 congener data set. As per Section 2.5.2.3, these data were processed through initial multivariate analyses to assess data usability for chemometric analysis. As a result of this review, it was found that the initial 100 µg/kg sample cut off resulted in a poor fit for some key congeners, and a receptor model would not converge. As is the iterative nature of this ACF approach, it was necessary to increase the concentration cut off to 500 µg/kg. This new threshold resulted in a 252 sample 83

congener matrix and subsequently, a cleaner, better fit model was developed with more interpretable end-members.

As a means of demonstrating the data evaluation process for ACF, another data screening option is described below. The data set was also evaluated with a higher concentration threshold by increasing the total PCB concentration cut off to 1,000 µg/kg (1 ppm). This resulted in a 222 sample data matrix and an even cleaner model. However, by adopting such an aggressive concentration threshold, many GLNPO surface samples were removed from the analysis (all except those collected near Strong Brook). In addition, many of the lower concentration, deeper, samples were eliminated by the 1,000 µg/kg cut off criterion. Given this, the data set used for chemometric analyses of the Ashtabula ORD and GLNPO data set (Section 3.2.7.5) was based on the 500 µg/kg cut off. This decision was made, not because it was ideal in all respects, but because it was a good compromise between (1) a relatively clean, well fit model and (2) good spatial coverage across the study area. This example is instructive as a lesson for data screening prior to statistical analysis because the best solution is often a compromise that attempts to balance different project objectives.

The 252 sample × 83 congener matrix was analyzed using PCA as an initial exploratory tool, and was then run using all four receptor models. Goodness-of-fit diagnostics were again examined [9]. These indicated the presence of at least four congener patterns contributing to the system. The CD scatter plot array from the PVA analysis is shown in Figure 3-37. Most of the congeners show a fairly good fit, indicating that a four end-member model is a reasonable solution. Those showing a systematic lack of fit (e.g., PCB4/10 and PCB8) may provide evidence for additional source/congener patterns contributing to the system and such possibilities will be discussed in more detail in Section 3.2.7.6.

A PCA was run on these data and the resulting three component scores plot is shown in Figure 3-38. Colored symbols are used to indicate different groups of samples to illustrate the variations in PCB congener composition in the data set. Note that the data are generally not widely distributed, with the majority of the samples (around 200 of the 252) concentrated on the left side of the plot. These mid-depth core samples (green circles) show a range of chemical compositions between two distinct patterns, an Aroclor 1248 (lower left) pattern and a slightly altered Aroclor 1248 (upper left) pattern. A third distinct congener composition is shown in the deeper core samples (red circles) that plot toward the back right of the data cloud.

There is also one small group of five samples on the front right side of the plot (light blue square symbols – the one to the right labeled E2LQ3). These five samples were all collected in Jacks Marine near the confluence of Strong Brook, indicating that samples are very different from the rest of the data set. Direct inspection of chromatograms from these samples (Section 3.2.7.4) indicated that the Strong Brook area sediment samples exhibit a strong Aroclor 1260 pattern. Other surface sediment samples show a progression in congener composition from this Aroclor 1260 pattern back to more of an Aroclor 1248 pattern (bottom left samples in the data cloud). The general shape of the data cloud roughly outlines a tetrahedron in principal component space which has been drawn here using the four most mutually extreme samples as vertices. Each of these four samples are labeled with different symbols and colors on Figure 3-38.

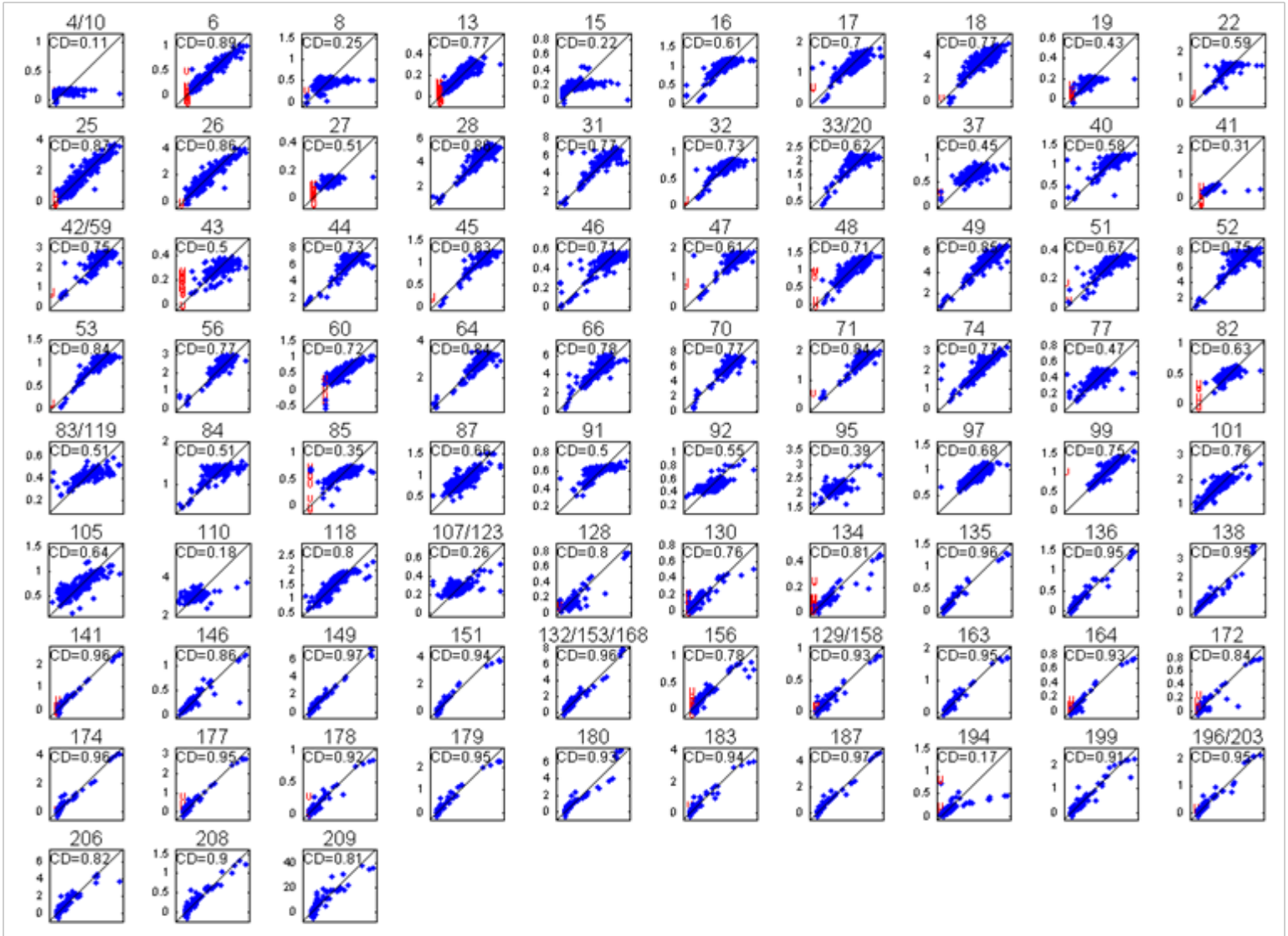


Figure 3-37. CD Scatter-plot Array for a Four Sources System, for 252 Sample 83 Analyte PCB Data Set from Ashtabula River, Ohio

(Non-detect samples are indicated as red "U".)

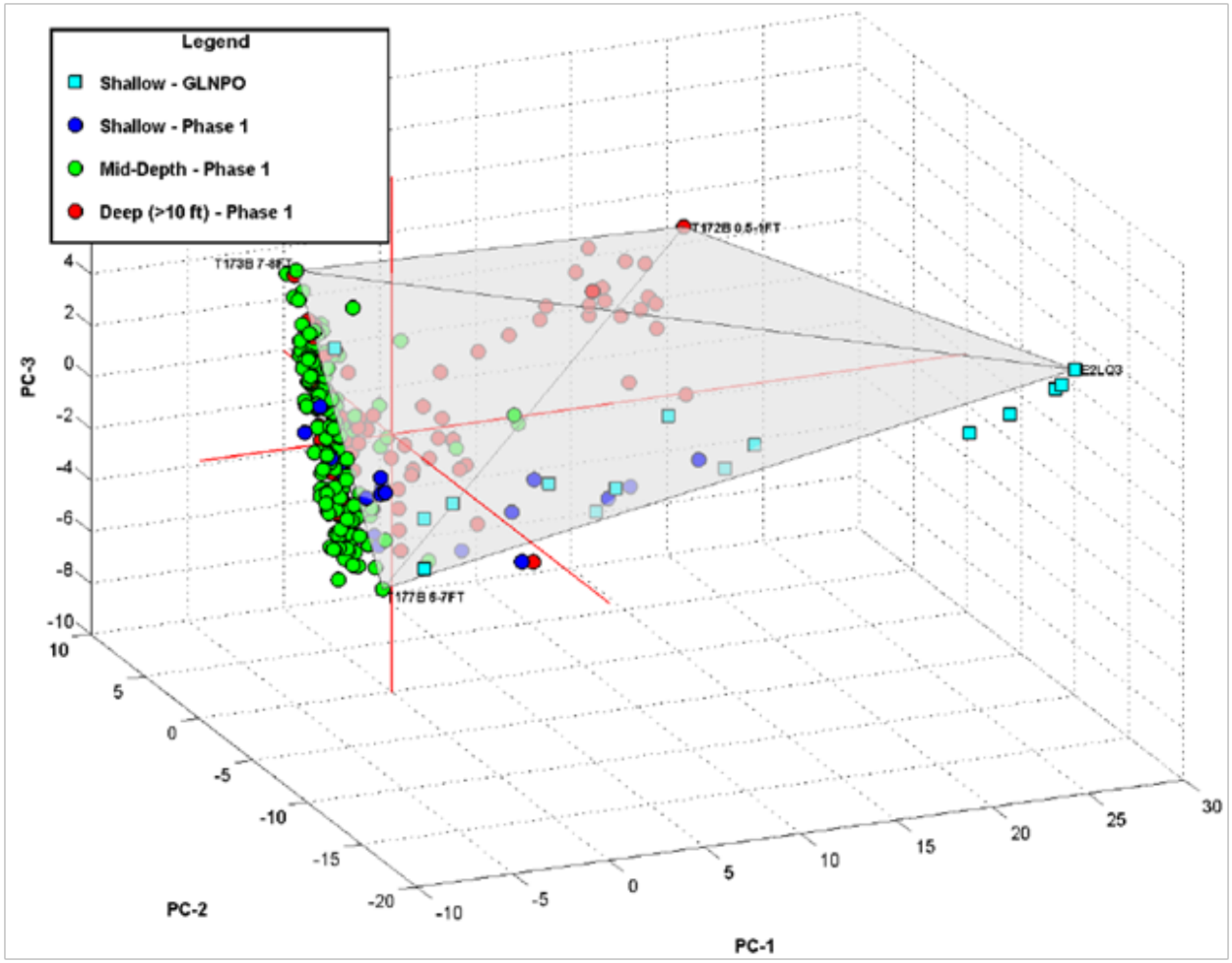


Figure 3-38. PCA Scores Plot for 252 Samples, 83 Analyte PCB Data Set from Ashtabula River

Bar graphs of these four extreme samples are shown on Figure 3-39. The tetrahedron can be thought of as a four end member mixing diagram (as opposed to the three end member triangular mixing diagram from the HPS case study), where each sample congener composition can therefore be represented by a linear mixture of these four distinct end member compositions.

The top pattern of Figure 3-39 (T177B 6-7 feet) is a high concentration sample (∑PCB = 162 ppm) and is a close pattern match to Aroclor 1248 (a source previously identified as the primary Aroclor found in Ashtabula sediments [26]). The second pattern on this figure (T173B 7-8 feet) exhibits a pattern in a similar chlorinated higher range but slightly lighter. This pattern was consistent with a PCB dechlorination pattern reported previously for the Ashtabula River [26].

The third sample (T172B 0.5-1 ft) is a low concentration sample dominated by a single congener; PCB209 (deca-chlorobiphenyl), with additional contributions from a few other highly chlorinated congeners. The bottom sample in Figure 3-39 is E2LQ3, one of the Strong Brook area surface sediment samples. This PCB pattern is primarily composed of highly chlorinated

congeners and is consistent with Aroclor 1260. It would be expected in the receptor modeling that resolved end members (congener source profiles) might be similar to these extreme samples.

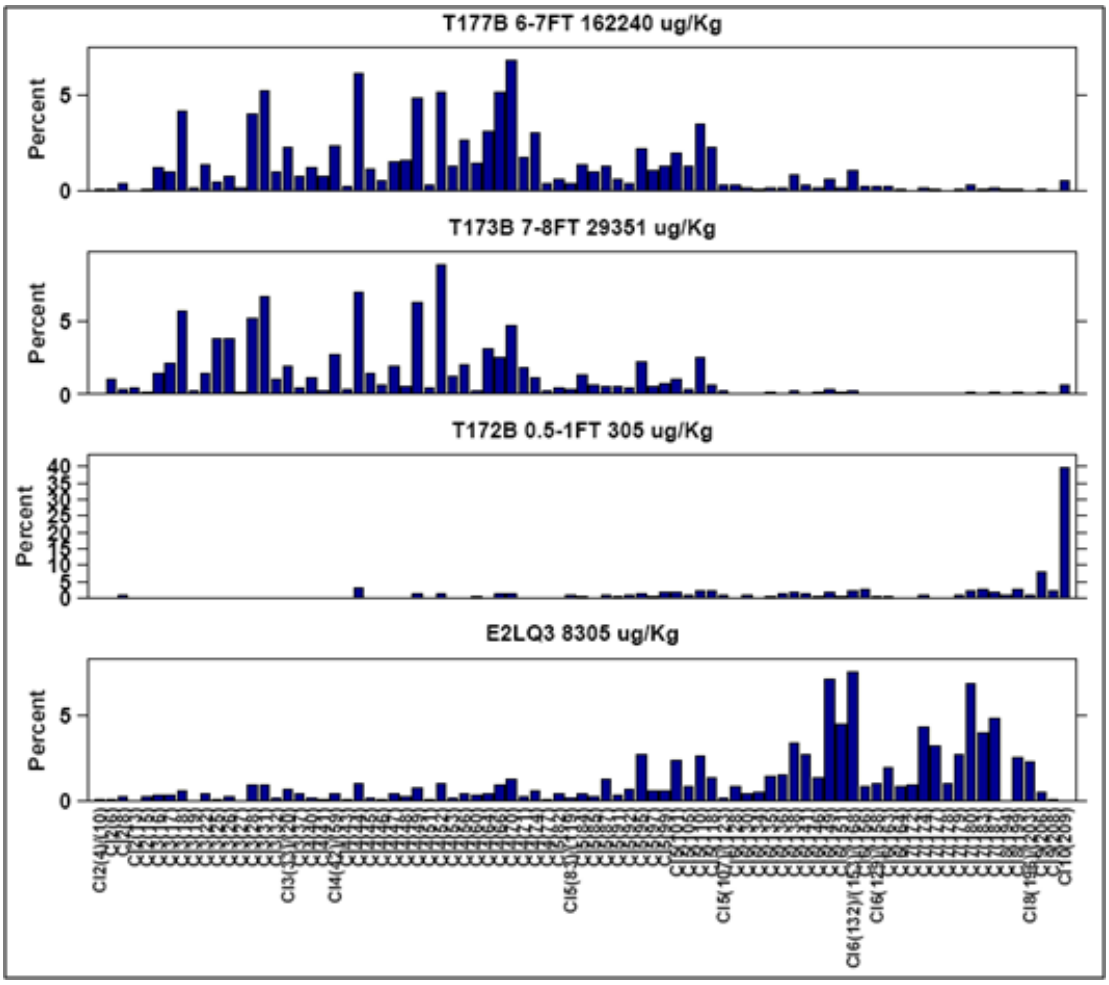


Figure 3-39. Bar Graphs of Four Extreme Samples Labeled on Figure 3-38

This data set was analyzed using the four receptor model methods described in Section 2.5.3.5. Three of the four methods were able to resolve a four compositional solution for this data set. The fourth method (Unmix) was unable to find a feasible solution. The congener profiles resolved by PVA, ALS and PMF are shown in Figure 3-40. All three methods resolved similar congener patterns as "source profiles" and those profiles generally matched those observed in the four extreme samples identified in Figures 3-38 and 3-39. Of these three models, ALS and PVA provided the best estimates. PMF resolved patterns similar to the deca-PCB and Aroclor 1260 patterns, but with notably higher proportions of lower chlorinated congeners not observed in the actual source and/or the most extreme samples in the data set.

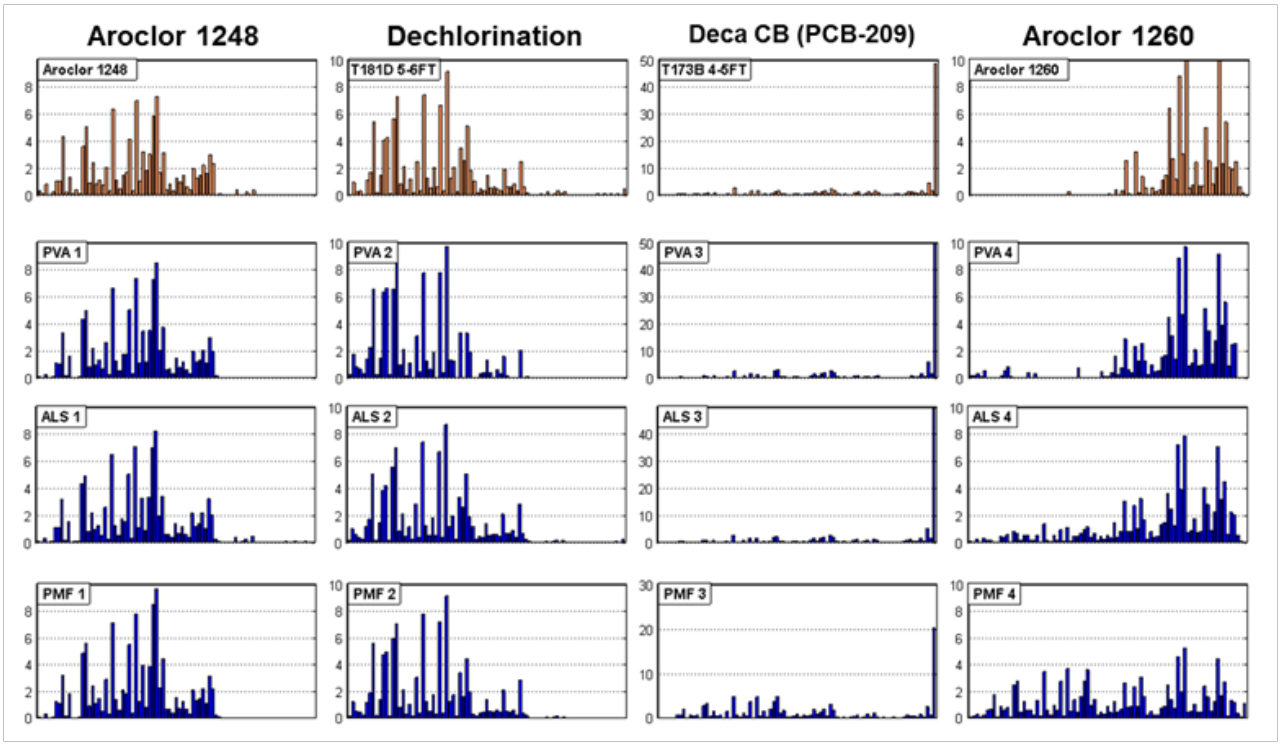


Figure 3-40. Four Congener Profiles (End Members, Source Profiles) Derived from Three Receptor Model Methods (PVA, ALS and PMF), as well as Their Reference Source Composition (e.g., Aroclors 1248 and 1260)

Unmix could not find a feasible solution for this data set. It is suspected that the Unmix method is a mathematical method of finding "edges" in multivariate space. In terms of a four source system, this process involves finding faces of a tetrahedron, which in turn requires a data set with good sample representation along faces of the tetrahedron. As is evident in the PCA scores plot (Figure 3-38), this is not the case for this data set. The data cloud is sparsely populated in the area of the Strong Brook area samples. This is a function of the sampling plan designed for other purposes and not explicitly for ACF (extremely dense sampling in the dredge area; extremely sparse sampling elsewhere) as discussed earlier in this section. Given sampling density inherited for this project, the recommendation is that the data analyst opt for PVA, ALS or PMF as preferred methods over Unmix.

Figure 3-41 shows the spatial distribution of each of the four end members as resolved from the PVA model along a north-south cross section through the dredge area. The predominance of dark and light blue patched areas confirms the observations on the PCA scores plot (Figures 3-38 and 3-39) that the predominant patterns in these cores are the Aroclor 1248 (light blue) and 1248 dechlorination patterns (dark blue). The deca/PCB209 pattern (yellow), when present, is generally observed in deeper samples in the core. Aroclor 1260 (red) is never a predominant pattern within dredge area sediments. However, when it is present, the Aroclor 1260 pattern tends to be in shallower samples. Samples that were omitted as a result of the data screening process are shown as gray patched rectangles and tend to be lower concentration samples (total PCB concentrations [mg/kg] are shown to the right of each sample).

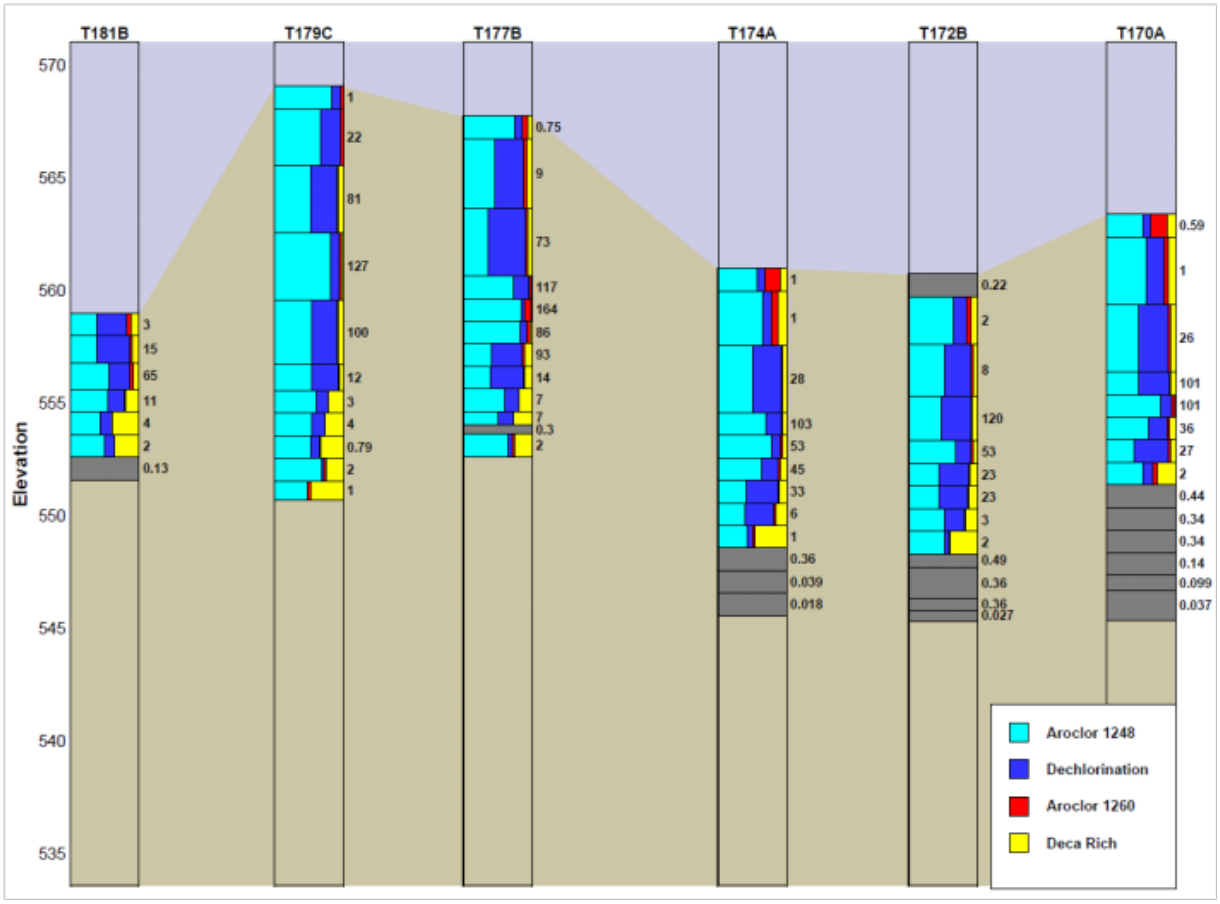


Figure 3-41. South-North Cross Section Showing Percent End-member Compositions and Total PCB Levels (ppm) in Dredge Area Sediments

Aroclor 1260 is not well represented on the sediment/depth profiles (Figure 3-41) because all cores were collected from the dredge area (Figure 2-13). As was evident in the PCA, Aroclor 1260 is predominant in the surface samples collected from the Strong Brook area (south of the dredge area and represented by surface sediment samples only). The absence of an Aroclor 1260 match in the surface sediments is likely because the top 6 inches were sampled in the dredge area, which represents not only relatively recent contamination (e.g., the top 2 cm) but also older deposition. Other work suggests that the Aroclor 1260 source may only have been active in recent years. The spatial distribution of these four patterns in surface sediments is shown on Figure 3-42. As compared to the core profile view (Figure 3-41), this surface sediment map clearly shows that the Aroclor 1260 pattern (right panel – red) is dominant in the Strong Brook area.

As was discussed in relation to HPS, one hopes to find internal consistency across all lines of evidence. However, integrated data analysis often proves most valuable when addressing lingering questions or ambiguities. The remainder of this section provides examples where further chemometric interpretation and separate lines of evidence helped answer such questions.

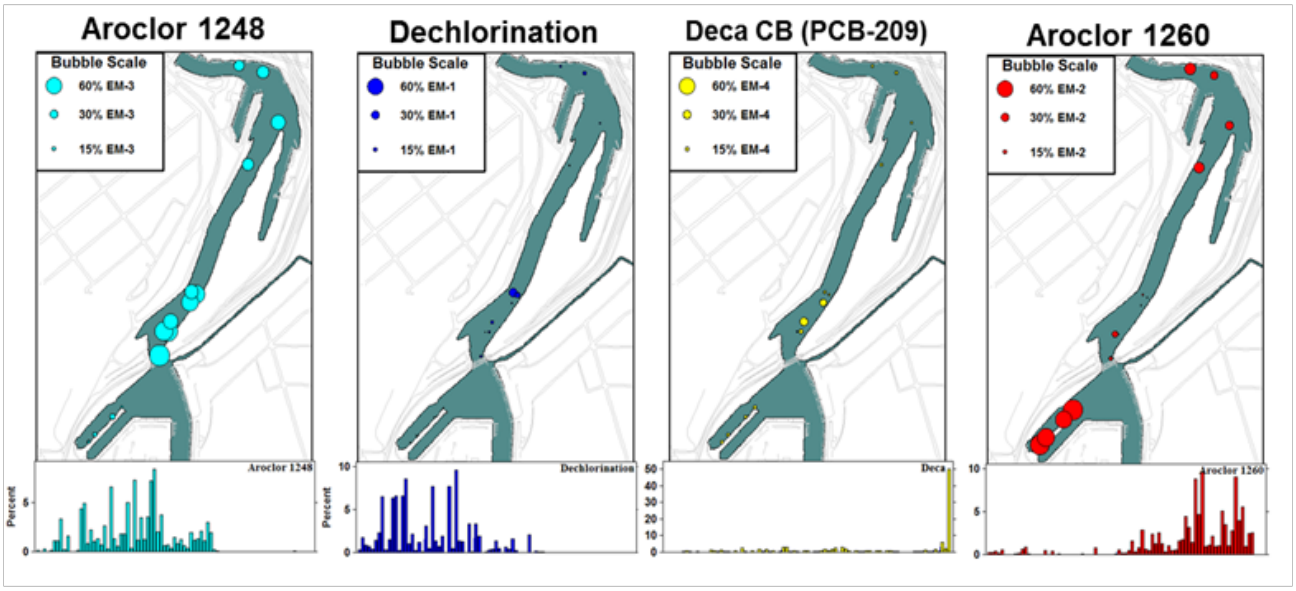


Figure 3-42. Maps of Four PVA Derived Sources in Surface Sediments of Ashtabula River

Source Explanation for Deca Source Pattern

One of the congener patterns resolved in this analysis was dominated by a single congener (deca-chlorobiphenyl; PCB209) which was preferentially observed in deeper (older) sediment taken from cores in the dredge area. This suggests an older historic source, but the specific source, industrial process and/or alteration process, could not be identified. A deca-dominated pattern is not consistent with any known, published Aroclor standard, although it had some resemblance to rarely used PCB products in the Aroclors 1269 to 1271 range. Another possibility could be the production of these highly-chlorinated congeners as part of the titanium tetrachloride manufacturing process [39]. The literature was reviewed, and several publications revealed where a similar, deca-dominated congener had been identified in other study areas [35, 39, 67]. These studies offered some possible interpretations of their version of this pattern, but nothing that could be clearly tied to known sources or alteration processes in Ashtabula. Ultimately, the choice was made to describe and map this congener pattern, but refrain from offering any speculative interpretations. The reason was that when observed in sediments, the deca pattern is usually in older samples (at great depth in sediment cores) and in samples with low relative total PCB concentration (Figure 3-41). Shallower sediment samples often exhibited total PCB concentrations that were two orders of magnitude, or more, higher. In terms of PCB mass that would require remediation, this unusual, highly chlorinated PCB pattern was not a major contributor. Given remediation/dredging concerns as the primary driver in this study, solving the mystery of this fingerprint's origin was not a priority given overall project objectives.

Consideration of a Possible Fifth Source Pattern

As indicated in Section 3.2.7.5, the statistical goodness-of-fit diagnostics performed in conjunction with PVA (Figure 3-37) indicated a minimum of four end members in this system. Some congeners, however, still exhibited a noisy fit (see for example the PCB4/10 and PCB8 scatter plots on Figure 3-37). Therefore, the efficacy of a fifth source pattern was evaluated by

running one PVA for five end members. The result was resolution of four end members very similar to the previous four, and a fifth that was similar to Aroclor 1242 (Figure 3-43).

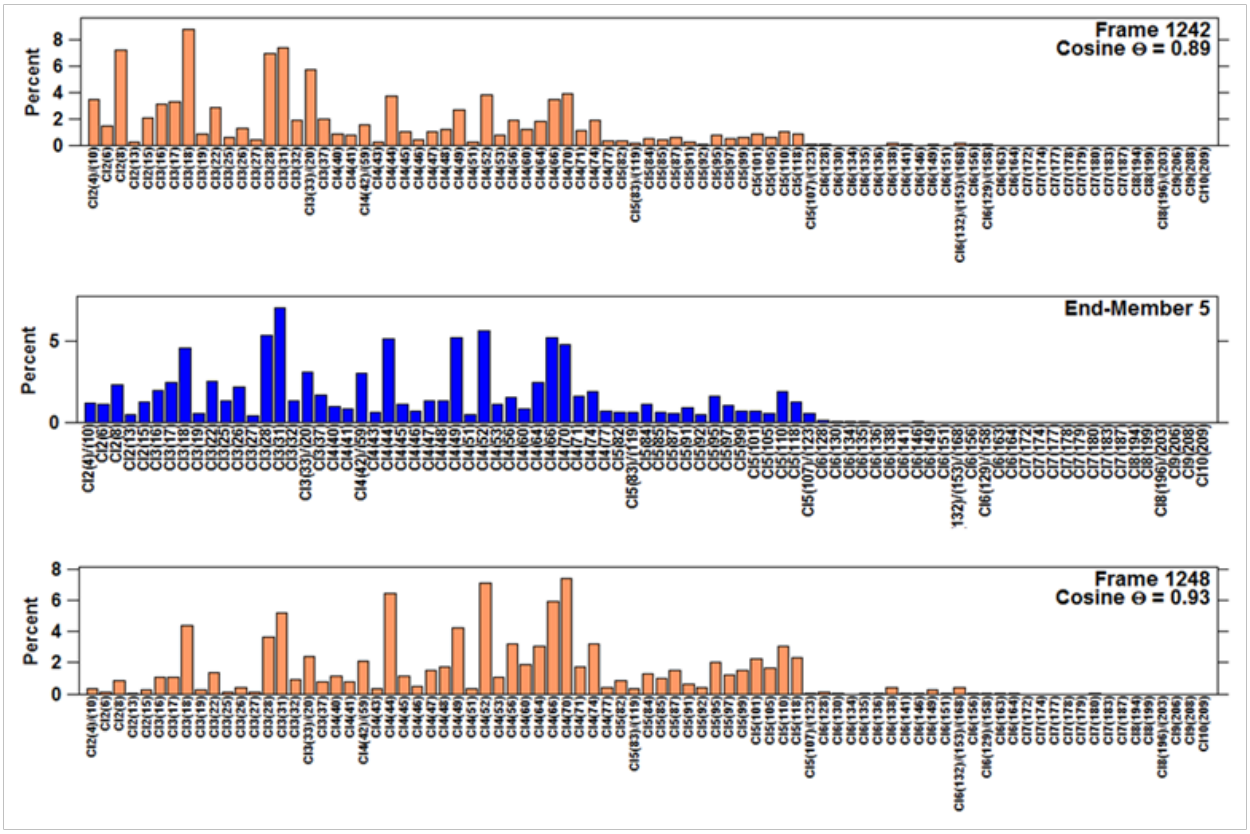


Figure 3-43. Congener Pattern Resolved as a Fifth End Member (blue bar graph) Using PVA Applied to Ashtabula Sediment Data Set
(Two Aroclors with patterns that showed similarity are plotted above and below EM-5.)

The fifth congener pattern is similar (bottom panel of Figure 3-43: cos θ = 0.93) to one of the source patterns already seen in the four end member model (Aroclor 1248). The primary difference is that this new pattern exhibits slightly higher proportions of two congeners that are more characteristic of an Aroclor with very similar chemical pattern: Aroclor 1242 (top panel of Figure 3-43 cos θ = 0.89). The new EM-5 pattern is actually intermediate in composition between Aroclors 1242 and 1248, with more lighter congeners (such as PCB4/10 and PCB8) than is present in Aroclor 1248, but not as much as is observed in Aroclor 1242. The relative contribution of this pattern is shown in Figure 3-44.

The Aroclor 1248 and the new EM-5 (altered Aroclor 1242) are very similar (cos θ = 0.89). This is an issue called "colinearity." When two resolved source patterns have very similar compositions, it increases the uncertainty of reported mixing proportions between these two end members. Ultimately, it seemed best to report the four end member model. By doing this additional exploration of a five end-member model, it is clear that Aroclor 1242 may be a more

important contributor to Ashtabula River than thought. There is clear evidence of an Aroclor 1242 source that has weathered to the point that now looks more like Aroclor 1248. This has been described elsewhere in the literature [4, 8, 30] and was discussed earlier in Section 2.5.2.3.

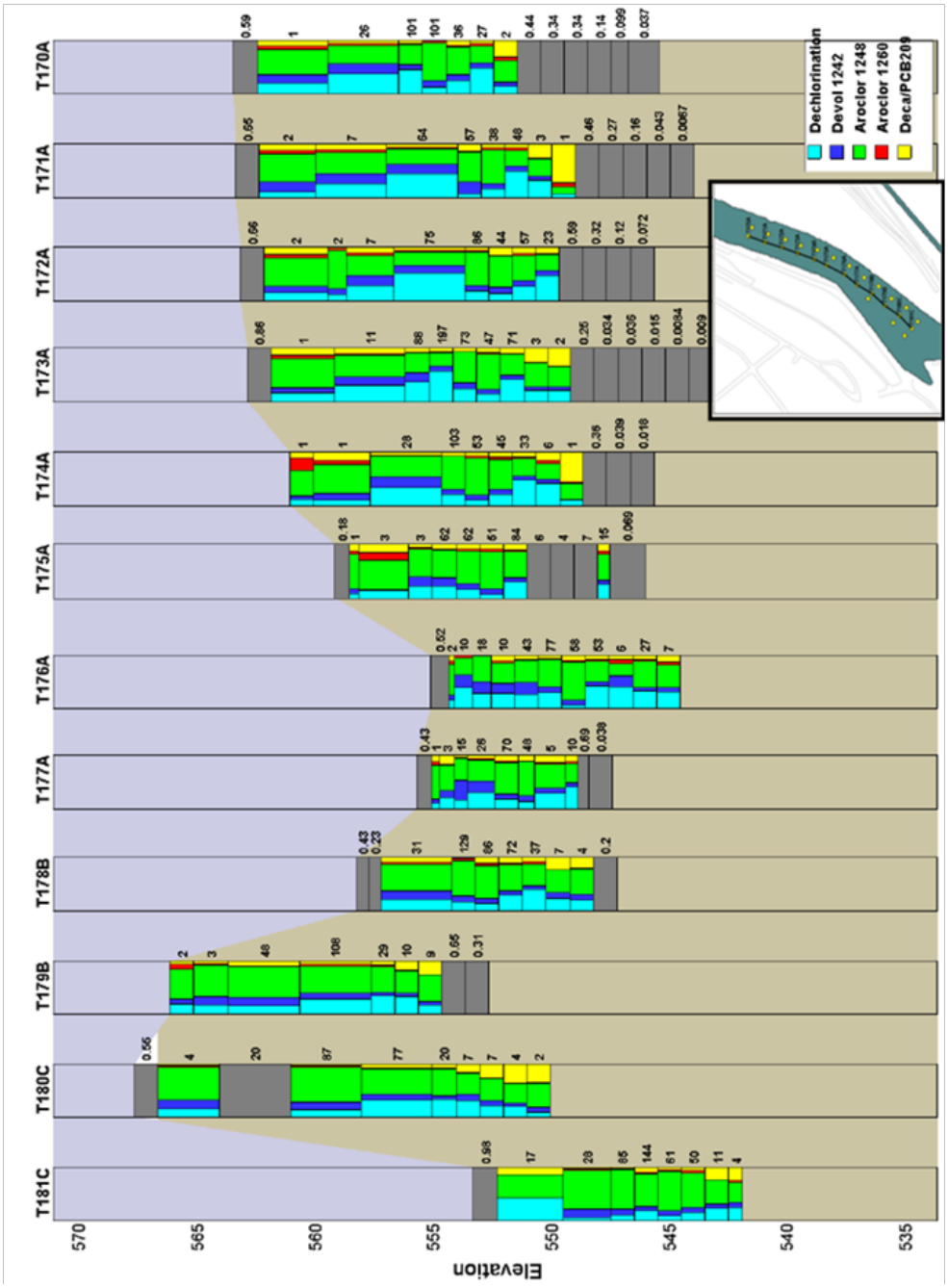


Figure 3-44. Cross-section Showing Percent Contribution of Five Chemical Fingerprints Resolved through PVA of Ashtabula Sediment Data Set

(Each pattern is color-coded. The "new" EM-5 [intermediate between A1242 and A1248] contributions are dark blue. Total PCB concentration [ppm] for each sample is indicated to the right of each sample. Gray shaded samples were omitted from the analysis because they were determined to be outliers [low concentration, or many non-detects].)

3.2.7.6 Integrated Data Analysis and Interpretation

As discussed in Section 2.5.3.6, integrated data analysis and interpretation is the process of synthesizing information from multiple lines of evidence to arrive at scientific interpretations that answer the key questions of a forensics investigation (i.e., PCB sources, alteration mechanisms, timing/history of releases). Lines of evidence typically considered include site history, published scientific literature, sediment transport/hydrodynamics, analytical chemistry which is then used to interpret total PCB concentration gradients and inspection of sample chromatograms/compositions, and chemometric analysis.

At Ashtabula, although we do not have as much data for some lines of evidence as we did for HPS (especially for site history and sediment transport), the lines of evidence consistently support several key conclusions. The analytical chemistry line of evidence may, in fact, be stronger at Ashtabula compared to HPS because of the larger number of congeners (83 versus 38) and samples (252 versus 85) for the chemometric analyses. The primary congener pattern contributing to sediments in the dredge area was consistent with an Aroclor 1248 source, and assumed to be associated with controlled sources within Fields Brook. This was confirmed by direct inspection of PCB compositions (Section 3.2.74) by four separate chemometric analyses (PCA, PVA, ALS and PMF – Section 3.2.7.5). An Aroclor 1260 source in the vicinity of Strong Brook was found to be important to the surface sediments in the study area.

This source observation is consistent with and supported by site history (Section 3.2.7.1). The sediment transport and hydrodynamic information (Section 3.2.7.2) indicates that contamination would be expected to be relatively predictably deposited and distributed away from sources (i.e., that the spatial distribution of the PCB contamination would decline downstream from sources). The PCB concentration distribution showed two general contamination profiles, one associated with historic contamination from Fields Brook and another associated with recent contamination from Strong Brook (Section 3.2.7.3 and Figures 3-25, 3-29, and 3-30). The preliminary PCB composition information (Section 3.2.7.4 and Figures 3-31 through 3-36) indicates two PCB compositional characteristics of the PCB in the sediments: one closely resembling Aroclor 1260 in the sediments near Strong Brook and another resembling Aroclor 1248 in the sediments near Fields Brook, and finally the historic, deeper sediments. The various chemometric analyses further support the initial findings of potential sources adding additional lines of evidence.

There is considerable PCB compositional alteration (e.g., through dechlorination) in some Ashtabula river sediments, suggesting dechlorination of primarily Aroclor 1248; the dechlorination compositional signature was distributed much like the Aroclor 1248 contamination. PCA, receptor models and direction inspection of raw sample compositions all identified a similar dechlorination pattern with key non-Aroclor, less chlorinated, congeners indicating dechlorination. This interpretation was further confirmed by published literature. Dechlorination had previously been reported in Ashtabula sediments [31] by looking at a completely different data set, and using two chemometric methods not used here. The Imamoglu data set [31] had far fewer congeners (24 congeners as opposed to 83). Two congeners that they did have (PCB25 and PCB26) were their primary evidence of dechlorination, and are the same two primary dechlorination indicator congeners in the current data set.

The Aroclor 1260 pattern was confirmed through direct inspection of sample compositions (Section 3.2.7.4) and by four chemometric methods (PCA, PVA, ALS, and PMF). The Aroclor 1260 was associated with sediments in and near Strong Brook, and in combination with Aroclor 1248 in downstream surface sediment. Imamoglu et al. [31] did not report an Aroclor 1260 pattern, but their study included only four cores, none of which were taken near Strong Brook. Another possibility for not observing the Aroclor 1260 pattern could be that their cores were collected in 1998, and this 1260 source appears to be relatively recent and may therefore only be observed in these 2007 cores.

The final congener patterns resolved in this analysis were dominated by a single congener (deca-chlorobiphenyl; PCB209) with lower, secondary contributions from other "heavy" congeners (e.g., PCB199 and PCB206). The deca-chlorinated PCB congener (PCB209) pattern was evident in the data set, whether the data were analyzed by direct inspection of sample congener profiles, or by chemometric analysis. This pattern was observed in deeper sections of cores collected from the dredge area. As with the Aroclor 1260 pattern, Imamoglu et al. [31] did not see the deca pattern in their analysis because PCB209 was not analyzed as part of their study and their cores were much shallower (with a maximum PCB concentration of 10 mg/kg) and never reached the deeper horizons seen in these cores. The high relative amounts of PCB209 were greater than in the highly-chlorinated Aroclor formulations (e.g., Aroclor 1268, and the rare Aroclors 1269 to 1271), and can also not be explained by common environmental alteration processes. There are industrial processes (e.g., titanium tetrachloride production) that may selectively produce these highly chlorinated congeners, and this would warrant further investigation in a comprehensive forensic investigation. This unusual PCB compositional pattern was associated with deep and less contaminated sediment, and was of limited interest from a contaminant source perspective.

Most of this information can be summarized by viewing Figures 3-38, 3-39, and 3-41. The congener compositional information is summarized in Figures 3-38 and 3-39. Most of the samples in Figure 3-38 (around 200 of the 252 samples) are from the middle of the cores and show a congener composition with a mix of Aroclor 1248 (represented at bottom left corner of tetrahedron shape) and slightly dechlorinated Aroclor 1248 (represented at the top left corner of tetrahedron shape). These two congener compositions are shown as the top two bar chart fingerprints in Figure 3-39, and appear similar since they represent the same primary Fields Brook source. The surface samples show more of the Aroclor 1260 pattern (represented at the front right of the tetrahedron) and the deeper samples show a forth compositional pattern characterized by higher levels of congener 209 and other highly chlorinated congeners (represented at the back right of the tetrahedron). The compositions of these two corners of the tetrahedron are shown by the bottom two bar chart fingerprints in Figure 3-39.

The proportion of these four compositional patterns can be better viewed in spatial displays such as the core transect diagram shown in Figure 3-41. These cores were chosen to show the general relationships between end member compositions from south (left) to north (right) in the dredge area, but multiple other transects could be constructed from other cores at the site. Core diagrams are plotted in elevation above sea level on the left, and percent end member composition along the bottom color coded to the legend. The numbers to the right of each core horizon are Total PCB concentrations in parts per million (mg/Kg). The most obvious feature of

these core diagrams is that most of the cores show (>90%) have a source of Aroclor 1248 (although some show dechlorination). Deeper sections of the cores show increasing amounts of the more chlorinated end member composition, but the majority is still Aroclor 1248 and these have lower PCB concentrations. There are only sporadic indications of the very recent additions of Aroclor 1260 in the surface sediments of some cores, ignoring the slight indications of Aroclor 1260 at depth (which is within the margin for error). Error bars on the percent end member contributions are difficult to estimate, but are likely on the order of 10 to 20% in this type of analysis. Compared to the previous HPS case, this allocation of end member compositions at Ashtabula should be more quantitative because of the more unique patterns present in the end member compositions.

In summary, it appears there was a significant source associated with Fields Brook that contributed primarily Aroclor 1248 contamination to the Ashtabula River. The majority of this contamination is several feet down in the Ashtabula River. Deeper sediments also show relatively low amount of a more chlorinated PCB pattern, which may also be from a Fields Brook source. The Fields Brook source(s) appear to have been, for the most part, controlled. It also appears that in recent years, and at the time these samples were collected, there was also a source of primarily Aroclor 1260, in the vicinity of the confluence of Strong Brook. These appear to be the two primary sources of the PCB in the Ashtabula River study area, contributing the four distinct PCB congener compositions that were observed in the Ashtabula River sediment.

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Appendix A: PCB Aroclor Compositional Information

Detailed Congener Composition of Major Aroclor Formulations

PCB CONGENER (IUPAC Number)	PCB Congener Composition as % of Total PCB in Aroclor								
	1221	1232	1016	1242	1248	1254	1260	1262	1268
1	75.47	13.29	0.53	0.48	0.04	0.01	0.02	0.01	0.00
2	4.74	1.54	0.03	0.03	0.00	0.00	0.00	0.00	0.00
3	17.34	9.16	0.21	0.19	0.01	0.00	0.01	0.00	0.00
4	0.55	4.84	3.60	3.02	0.27	0.05	0.04	0.08	0.00
5	0.00	0.60	0.18	0.16	0.01	0.00	0.00	0.00	0.00
6	0.01	2.85	1.59	1.31	0.12	0.02	0.01	0.03	0.00
7	0.01	1.10	0.31	0.26	0.02	0.00	0.00	0.00	0.00
8	0.03	10.05	7.39	6.01	0.66	0.10	0.07	0.16	0.00
9	0.01	1.18	0.53	0.46	0.03	0.01	0.01	0.01	0.00
10	0.06	0.40	0.19	0.15	0.01	0.00	0.00	0.00	0.00
11	0.00	0.07	0.01	0.01	0.00	0.00	0.00	0.00	0.00
12+13	0.00	1.30	0.31	0.27	0.02	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.01	4.29	2.53	2.09	0.25	0.03	0.02	0.06	0.00
16	0.02	1.91	4.01	3.22	1.03	0.06	0.04	0.11	0.00
17	0.02	1.91	4.11	3.34	1.05	0.06	0.04	0.11	0.00
18	0.07	4.70	11.30	7.81	4.06	0.15	0.08	0.22	0.01
19	0.00	0.57	1.15	0.88	0.27	0.02	0.01	0.03	0.00
20	0.01	0.43	1.10	0.72	0.36	0.00	0.00	0.01	0.00
21+33	0.04	2.96	6.08	4.98	2.12	0.08	0.05	0.14	0.00
22	0.02	1.80	3.63	3.05	1.39	0.05	0.03	0.08	0.00
23	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00
24	0.00	0.06	0.18	0.14	0.01	0.00	0.00	0.00	0.00
25	0.00	0.39	0.72	0.57	0.13	0.01	0.01	0.02	0.00
26	0.01	0.74	1.55	1.21	0.41	0.02	0.01	0.03	0.00
27	0.00	0.26	0.58	0.46	0.13	0.01	0.00	0.01	0.00
28	0.07	4.30	7.73	6.13	3.60	0.12	0.03	0.15	0.00
29	0.00	0.05	0.10	0.08	0.01	0.00	0.00	0.00	0.00
30	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
31	0.06	3.95	9.09	7.13	4.61	0.18	0.07	0.18	0.01
32	0.01	1.08	2.19	1.76	0.80	0.03	0.02	0.05	0.00
34	0.00	0.01	0.03	0.02	0.01	0.00	0.00	0.00	0.00
35	0.00	0.06	0.06	0.08	0.01	0.00	0.00	0.00	0.00
36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
37	0.07	1.19	0.99	1.78	0.73	0.03	0.02	0.05	0.00
38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
40	0.02	0.30	0.44	0.54	0.82	0.08	0.01	0.01	0.00
41+71	0.05	1.17	2.32	2.09	3.12	0.20	0.02	0.06	0.01
42	0.02	0.66	1.43	1.18	1.71	0.13	0.01	0.03	0.00
43	0.00	0.11	0.33	0.25	0.30	0.00	0.00	0.01	0.00
44	0.07	2.07	4.75	3.81	6.51	2.44	0.04	0.12	0.01
45	0.01	0.47	1.30	0.94	1.10	0.04	0.01	0.02	0.00
46	0.01	0.19	0.48	0.39	0.46	0.01	0.00	0.01	0.00

PCB CONGENER (IUPAC Number)	PCB Congener Composition as % of Total PCB in Aroclor								
	1221	1232	1016	1242	1248	1254	1260	1262	1268
47	0.02	0.46	1.22	0.84	1.26	0.12	0.01	0.02	0.00
48	0.02	0.61	1.52	1.20	1.57	0.08	0.01	0.03	0.00
49	0.05	1.50	3.60	2.81	4.35	1.20	0.03	0.08	0.01
50	0.00	0.01	0.02	0.02	0.02	0.00	0.00	0.00	0.00
51	0.00	0.13	0.36	0.26	0.30	0.01	0.00	0.01	0.00
52	0.06	1.91	4.29	3.59	6.73	5.36	0.37	0.24	0.01
53	0.01	0.42	1.10	0.79	1.10	0.11	0.01	0.02	0.00
54	0.00	0.01	0.02	0.01	0.02	0.00	0.00	0.00	0.00
55	0.00	0.06	0.01	0.11	0.09	0.00	0.00	0.00	0.00
56	0.02	0.96	0.07	1.64	2.80	0.34	0.02	0.04	0.01
57	0.00	0.01	0.01	0.02	0.02	0.00	0.00	0.00	0.00
58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
59	0.01	0.17	0.49	0.39	0.32	0.01	0.00	0.01	0.00
60	0.01	0.64	0.04	1.15	1.78	0.14	0.01	0.03	0.00
61+74	0.10	1.07	0.37	2.03	3.46	0.71	0.02	0.05	0.00
62+65	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00
63	0.01	0.08	0.04	0.14	0.21	0.03	0.00	0.00	0.00
64	0.05	0.99	1.90	1.84	3.09	0.56	0.02	0.06	0.01
66	0.09	1.71	0.35	3.00	5.13	0.82	0.03	0.08	0.01
67	0.01	0.08	0.05	0.13	0.11	0.00	0.00	0.00	0.00
68	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
70+76	0.22	2.49	0.65	4.64	8.70	3.67	0.05	0.16	0.01
72	0.00	0.01	0.01	0.01	0.02	0.00	0.00	0.00	0.00
73	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
75	0.00	0.05	0.04	0.03	0.14	0.01	0.00	0.01	0.00
77	0.00	0.19	0.00	0.29	0.39	0.02	0.00	0.01	0.00
78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
79	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
81	0.00	0.01	0.00	0.02	0.02	0.00	0.00	0.00	0.00
82	0.00	0.14	0.00	0.24	0.67	0.88	0.01	0.02	0.00
83	0.00	0.04	0.00	0.07	0.18	0.33	0.01	0.01	0.00
84	0.02	0.20	0.05	0.40	1.13	2.43	0.16	0.07	0.01
85+116	0.00	0.12	0.00	0.31	0.75	1.20	0.01	0.03	0.00
86	0.00	0.02	0.00	0.04	0.10	0.00	0.00	0.00	0.00
87+125	0.01	0.20	0.01	0.46	1.20	3.60	0.35	0.10	0.01
88+91	0.01	0.10	0.07	0.24	0.68	1.01	0.01	0.03	0.00
89	0.00	0.02	0.01	0.05	0.13	0.05	0.00	0.00	0.00
90+101	0.03	0.51	0.05	0.94	2.54	10.14	4.01	1.29	0.01
92	0.00	0.07	0.01	0.14	0.38	1.41	0.36	0.09	0.00
93	0.00	0.01	0.01	0.03	0.05	0.09	0.00	0.00	0.00
94	0.00	0.01	0.01	0.01	0.03	0.02	0.00	0.00	0.00
95	0.05	0.41	0.30	0.67	1.95	6.67	2.86	0.98	0.01
96	0.00	0.01	0.03	0.03	0.07	0.04	0.00	0.00	0.00
97	0.01	0.22	0.01	0.41	1.14	2.53	0.09	0.06	0.00

PCB CONGENER (IUPAC Number)	PCB Congener Composition as % of Total PCB in Aroclor								
	1221	1232	1016	1242	1248	1254	1260	1262	1268
98+102	0.00	0.04	0.04	0.08	0.24	0.26	0.00	0.00	0.00
99	0.01	0.26	0.02	0.62	1.68	3.61	0.07	0.11	0.00
100	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00
103	0.00	0.00	0.01	0.01	0.02	0.03	0.00	0.00	0.00
104	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
105	0.01	0.27	0.01	0.53	1.53	2.93	0.04	0.08	0.01
106	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
107+124	0.00	0.02	0.00	0.06	0.15	0.51	0.01	0.01	0.00
108	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
109	0.00	0.03	0.00	0.07	0.17	0.44	0.01	0.01	0.00
110	0.02	0.50	0.01	0.91	2.77	9.10	1.38	0.35	0.02
111	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
112	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
113	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
114	0.00	0.02	0.00	0.05	0.12	0.17	0.00	0.00	0.00
115	0.00	0.05	0.00	0.04	0.11	0.02	0.00	0.00	0.00
117	0.00	0.05	0.00	0.00	0.08	0.00	0.00	0.00	0.00
118	0.01	0.40	0.01	0.77	2.13	6.84	0.54	0.20	0.01
119	0.00	0.01	0.00	0.03	0.06	0.09	0.00	0.00	0.00
120	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
121	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
122	0.00	0.01	0.00	0.02	0.06	0.08	0.00	0.00	0.00
123	0.00	0.01	0.00	0.03	0.07	0.10	0.00	0.00	0.00
126	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
127	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
128	0.00	0.02	0.00	0.04	0.11	1.32	0.50	0.08	0.00
129	0.00	0.01	0.00	0.01	0.04	0.41	0.13	0.02	0.00
130	0.00	0.01	0.00	0.01	0.04	0.43	0.24	0.06	0.00
131	0.00	0.00	0.00	0.00	0.01	0.12	0.05	0.01	0.00
132	0.00	0.04	0.00	0.07	0.19	2.47	2.65	0.99	0.00
133	0.00	0.00	0.00	0.00	0.00	0.06	0.09	0.03	0.00
134+143	0.00	0.01	0.00	0.01	0.03	0.36	0.35	0.13	0.00
135	0.00	0.01	0.00	0.01	0.04	0.59	1.00	0.56	0.00
136	0.00	0.01	0.00	0.02	0.05	0.72	1.51	1.07	0.00
137	0.00	0.01	0.00	0.02	0.04	0.45	0.02	0.01	0.00
138+163	0.02	0.07	0.00	0.14	0.35	5.68	7.93	3.32	0.02
139	0.00	0.00	0.00	0.00	0.01	0.10	0.00	0.00	0.00
140	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00
141	0.00	0.02	0.00	0.03	0.08	1.00	2.65	1.67	0.01
142	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
144	0.00	0.01	0.00	0.01	0.02	0.23	0.63	0.51	0.00
145	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
146	0.00	0.01	0.00	0.02	0.05	0.68	1.14	0.57	0.00
147	0.00	0.00	0.00	0.01	0.04	0.02	0.18	0.00	0.00
148	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
149	0.02	0.08	0.00	0.08	0.23	3.85	9.23	6.90	0.01

PCB CONGENER (IUPAC Number)	PCB Congener Composition as % of Total PCB in Aroclor								
	1221	1232	1016	1242	1248	1254	1260	1262	1268
150	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
151	0.01	0.02	0.00	0.01	0.04	0.69	3.32	3.48	0.01
152	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
153	0.03	0.07	0.00	0.08	0.21	3.81	9.85	7.09	0.04
154	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00
155	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
156	0.00	0.01	0.00	0.03	0.06	0.73	0.46	0.10	0.00
157	0.00	0.00	0.00	0.01	0.02	0.16	0.02	0.01	0.00
158	0.00	0.01	0.00	0.02	0.06	0.75	0.76	0.33	0.01
159	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
160	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00
161	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
162	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00
164	0.00	0.01	0.00	0.01	0.03	0.41	0.62	0.29	0.00
165	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
166	0.00	0.00	0.00	0.00	0.00	0.04	0.04	0.06	0.00
167	0.00	0.00	0.00	0.01	0.02	0.27	0.19	0.03	0.00
168	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
169	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
170	0.01	0.01	0.00	0.01	0.02	0.48	3.97	2.89	0.02
171	0.00	0.01	0.00	0.00	0.01	0.15	1.17	0.86	0.00
172	0.00	0.00	0.00	0.00	0.00	0.07	0.71	0.68	0.00
173	0.00	0.00	0.00	0.00	0.00	0.02	0.09	0.05	0.00
174	0.01	0.02	0.00	0.00	0.02	0.31	4.82	6.65	0.18
175	0.00	0.00	0.00	0.00	0.00	0.02	0.19	0.21	0.00
176	0.00	0.00	0.00	0.00	0.00	0.04	0.60	0.76	0.01
177	0.01	0.01	0.00	0.00	0.01	0.23	2.33	2.65	0.03
178	0.00	0.00	0.00	0.00	0.00	0.05	0.84	1.33	0.07
179	0.01	0.01	0.00	0.00	0.01	0.10	1.92	3.33	0.27
180	0.04	0.04	0.00	0.01	0.04	0.61	9.27	11.38	1.16
181	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.00	0.00
182	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
183	0.01	0.01	0.00	0.00	0.01	0.18	2.67	3.27	0.13
184	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
185	0.00	0.00	0.00	0.00	0.00	0.03	0.59	1.05	0.07
186	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
187	0.02	0.03	0.00	0.00	0.02	0.26	4.92	8.85	2.94
188	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
189	0.00	0.00	0.00	0.00	0.00	0.02	0.12	0.05	0.00
190	0.00	0.00	0.00	0.00	0.00	0.09	0.80	0.74	0.01
191	0.00	0.00	0.00	0.00	0.00	0.02	0.19	0.13	0.00
192	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
193	0.00	0.00	0.00	0.00	0.00	0.02	0.47	0.58	0.01
194	0.01	0.01	0.00	0.00	0.01	0.02	1.93	3.54	3.64
195	0.00	0.00	0.00	0.00	0.00	0.01	0.83	1.42	0.18
196	0.01	0.00	0.00	0.00	0.00	0.01	1.08	2.23	1.42

PCB CONGENER (IUPAC Number)	PCB Congener Composition as % of Total PCB in Aroclor								
	1221	1232	1016	1242	1248	1254	1260	1262	1268
197	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.14	0.04
198	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.22	0.13
199	0.02	0.01	0.00	0.00	0.01	0.02	2.21	5.78	18.42
200	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.71	0.63
201	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.74	1.07
202	0.00	0.00	0.00	0.00	0.00	0.00	0.44	1.25	5.33
203	0.01	0.01	0.00	0.00	0.01	0.01	1.31	3.14	11.60
204	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
205	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.17	0.02
206	0.00	0.01	0.00	0.00	0.01	0.00	0.61	1.25	30.65
207	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.19	2.60
208	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.32	12.58
209	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.03	6.46

Congener characterization of 9 Aroclor formulations using HRGC/HRMS (Method 1668aM) on two different GC columns (DB-octyl and DB-1). Chemosphere 54 (2004) 79-87.

WHO Toxic Congener Concentrations and TEQs in Major Aroclor Formulations

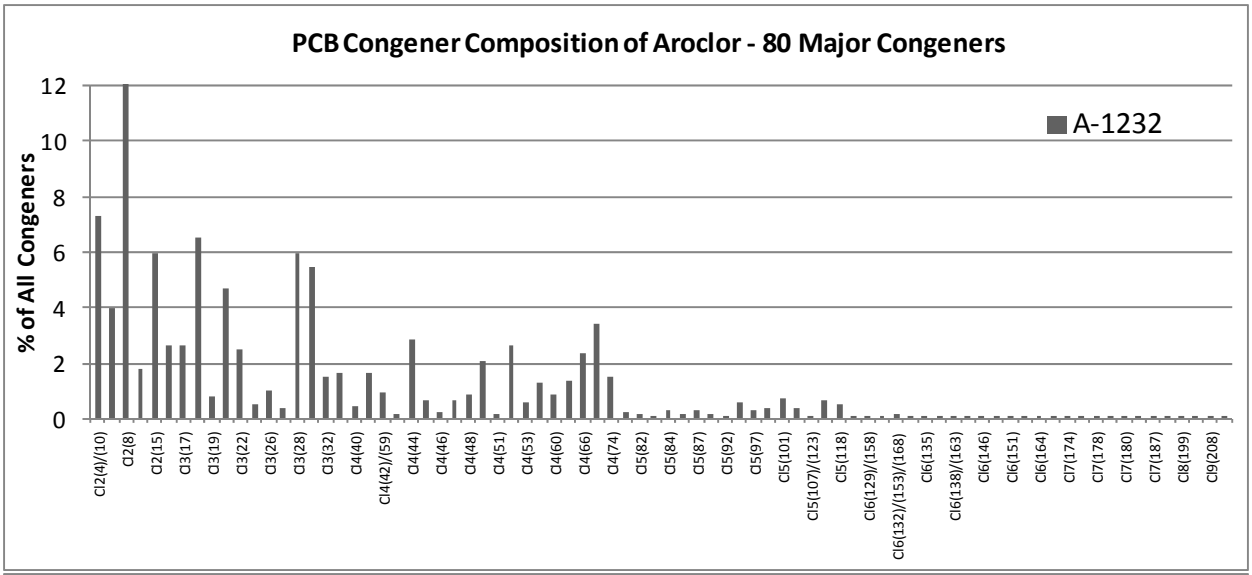
Congener		WHO TEF[a]	WHO Congener Concentrations (ppm) in Aroclor								
Name	IUPAC #		1221	1232	1016	1242	1248	1254	1260	1262	1268
3,3',4,4' -TeCB	77	0.0001	12.6	2,150	40.9	2,590	4,440	174	33.8	84.6	36.1
3,4,4',5 -TeCB	81	0.0001	0.512	111	1.96	156	221	16.4	3.33	4.63	1.35
2,3,3',4,4' -PeCB	105	0.0001	55.9	3,030	69.5	4,840	17,300	33,800	434	764	107
2,3,4,4',5 -PeCB	114	0.0005	4.04	248	6.03	443	1,320	1,930	17.0	46.0	5.86
2,3',4,4',5 -PeCB	118	0.0001	88.1	4,460	110	6,980	24,200	78,900	5,610	1,980	101
2',3,4,4',5 -PeCB	123	0.0001	3.33	164	4.72	277	806	1,150	5.02	27.8	3.24
3,3',4,4',5 -PeCB	126	0.1	0.284	21.0	0.559	33.6	97.8	37.3	2.13	2.28	1.76
2,3,3',4,4',5 -HxCB	156	0.0005	7.49	90.7	3.72	255	654	8,440	4,860	946	17.6
2,3,3',4,4',5' -HxCB	157	0.0005	1.46	22.0	1.03	70.9	171	1,870	252	63.8	7.92
2,3',4,4',5,5' -HxCB	167	0.00001	2.52	32.4	1.10	80.7	207	3,100	1,990	278	4.96
3,3',4,4',5,5' -HxCB	169	0.01	0.08	0.17	0.132	0.106	0.206	0.806	0.82	0.395	0.32
2,3,3',4,4',5,5' -HpCB	189	0.0001	1.17	4.36	0.116	4.53	10.8	246	1290	451	4.40
Sum (ppm)			177	164	4.72	14,687	49,428	127,434	13,802	2,008	11.5
Sum (%)			0.018	0.016	0.00047	1.47	4.94	12.7	1.38	0.201	0.0011
TOTAL TEQ			0.051	3.27	0.085	5.23	15.5	21.3	3.54	1.09	0.21

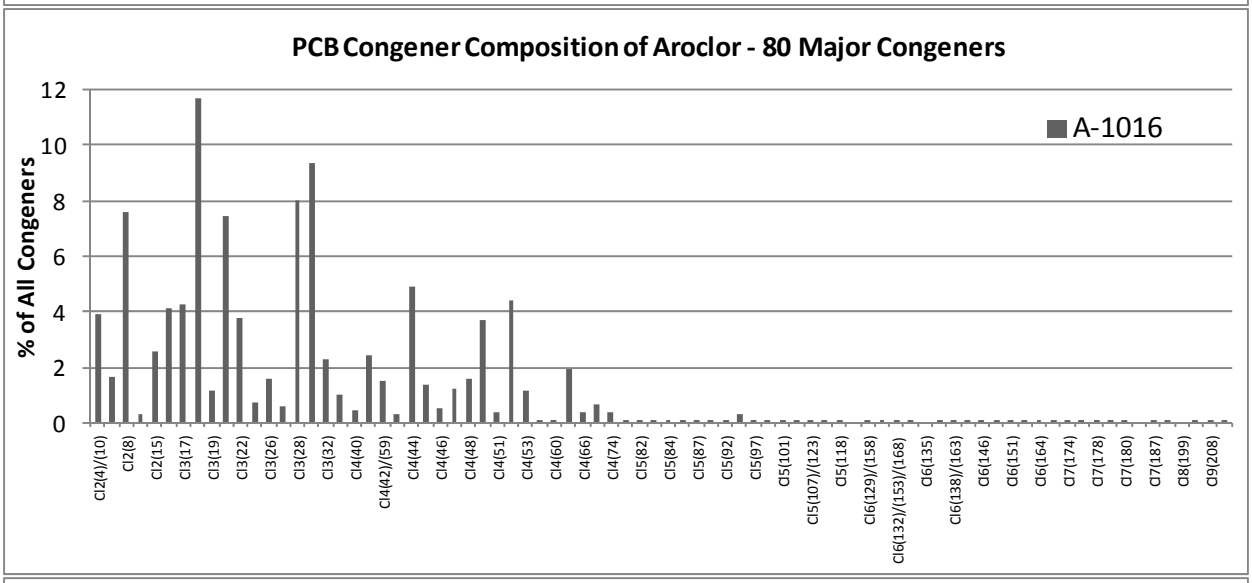
[a] TEF: Toxic equivalency factor.
Chemosphere 54 (2004) 79-87

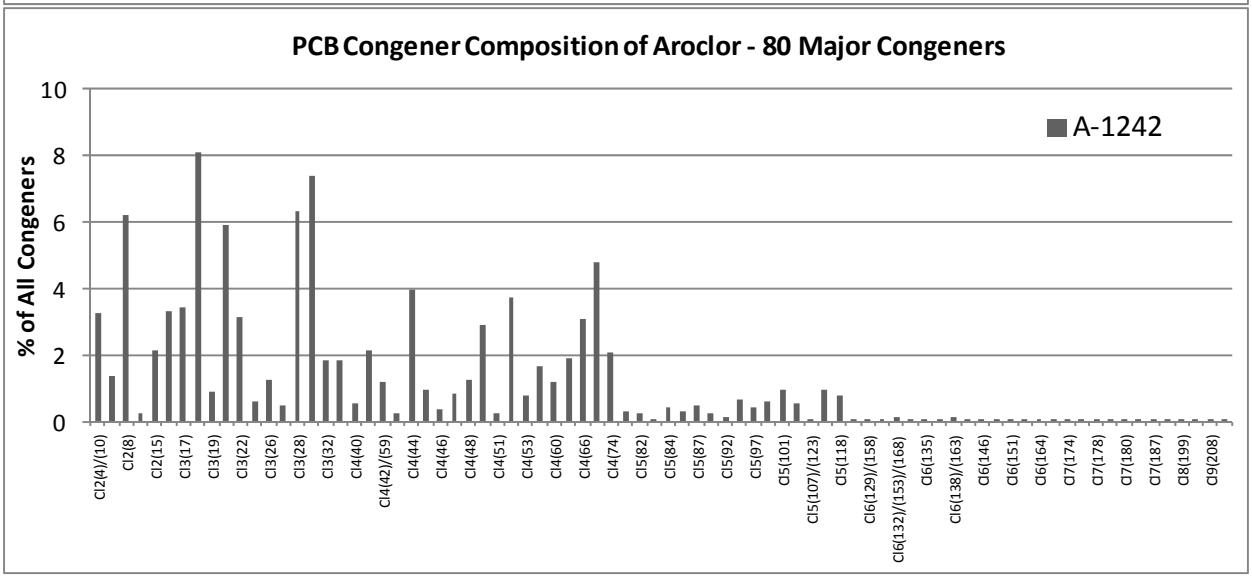
PCB Homolog Composition of Major Aroclor Formulations

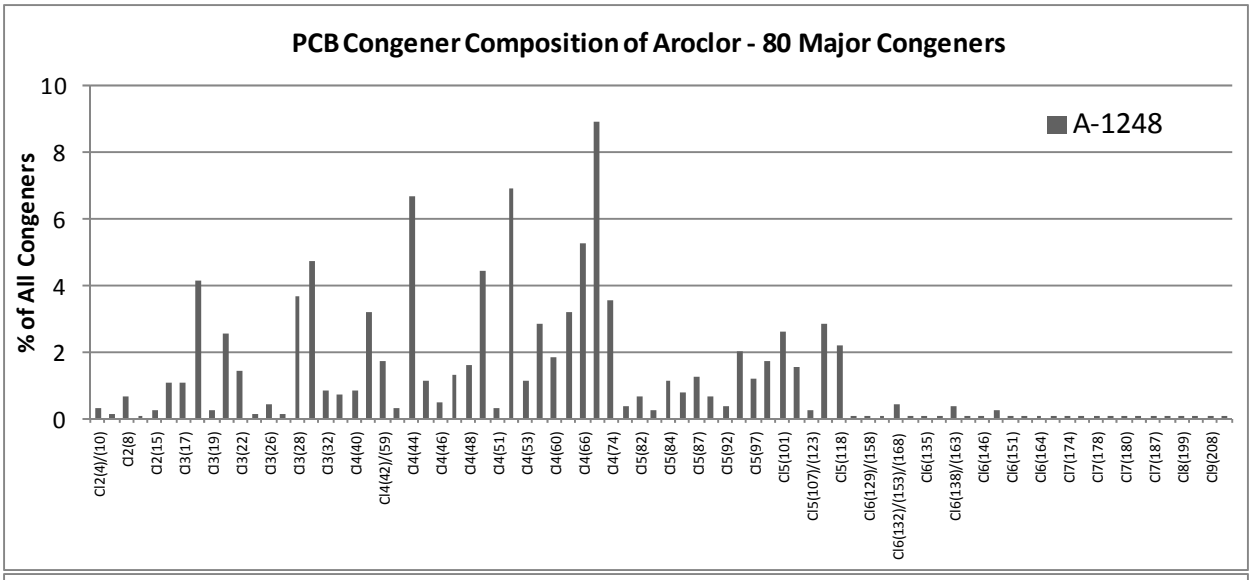
	Homolog Composition as % of Total PCB in Aroclor									
Aroclor	Mon -Cl	Di -Cl	Tri -Cl	Tetra -Cl	Penta -Cl	Hexa -Cl	Hepta -Cl	Octa -Cl	Nona -Cl	Deca -Cl
A1221	60.1	33.4	4.22	1.15	1.23	0.00	0.00	0.00	0.00	0.00
A1232	27.6	26.8	25.6	10.6	9.39	0.21	0.03	0.00	0.00	0.00
A1016	0.70	17.5	54.7	22.1	5.07	0.00	0.00	0.00	0.00	0.00
A1242	0.75	15.0	44.9	20.2	18.8	0.31	0.00	0.00	0.00	0.00
A1248 (A3.5)	0.07	1.55	21.3	32.8	42.9	1.64	0.02	0.00	0.00	0.00
A1248 (G3.5)	0.02	0.36	22.0	31.1	44.1	1.97	0.57	0.00	0.00	0.00
A1254	0.00	0.24	1.26	10.2	59.1	26.8	2.66	0.04	0.04	0.00
A1254 (A4)	0.02	0.09	0.39	4.86	71.4	22.0	1.36	0.00	0.04	0.00
A1260	0.02	0.08	0.21	0.35	8.74	43.4	38.5	8.27	0.70	0.00
A1262	0.02	0.27	0.98	0.5	3.4	26.4	48.5	19.7	1.65	0.00
A1268	0.00	0.00	0.06	0.12	0.19	4.38	10.1	45.0	35.0	4.80

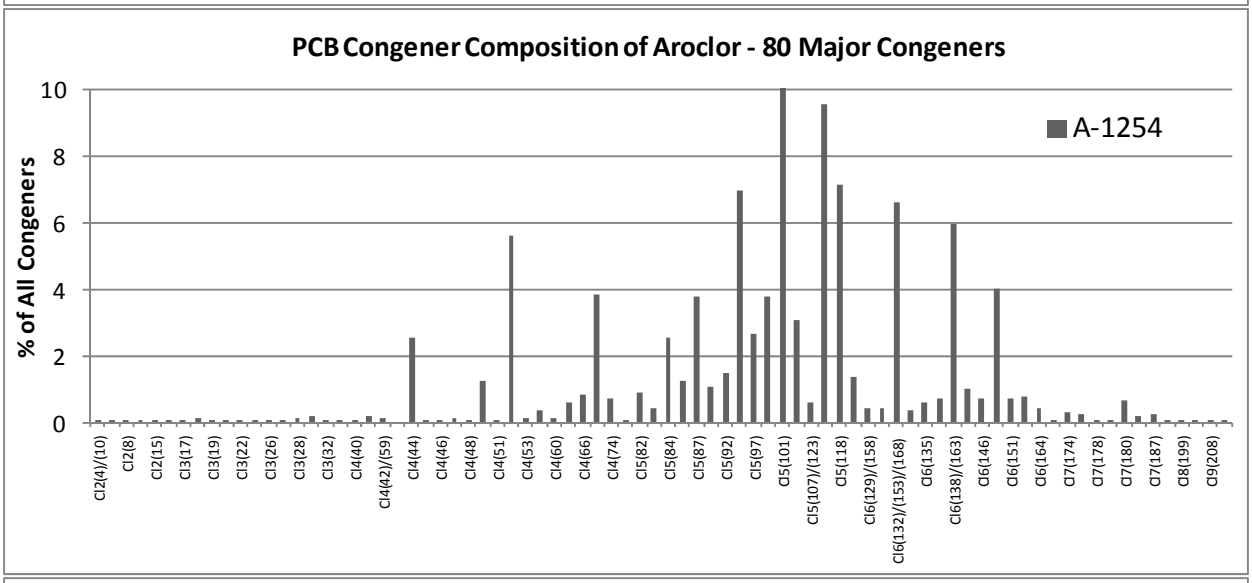
Data for A1221 through A1262 condensed from: Frame, G. M., J.W. Cochran, and S.S Boewadt. J. High Res. Chromatogr., Vol. 19, pp 657-668 (1996). Lot A4 Aroclor 1254 from late production (1974-1977).
Data for A1268 from Kannan, K., K. Maryua, and S.Tanabe. Environ. Sci. Technol. 1997, 31, 1483-1488.

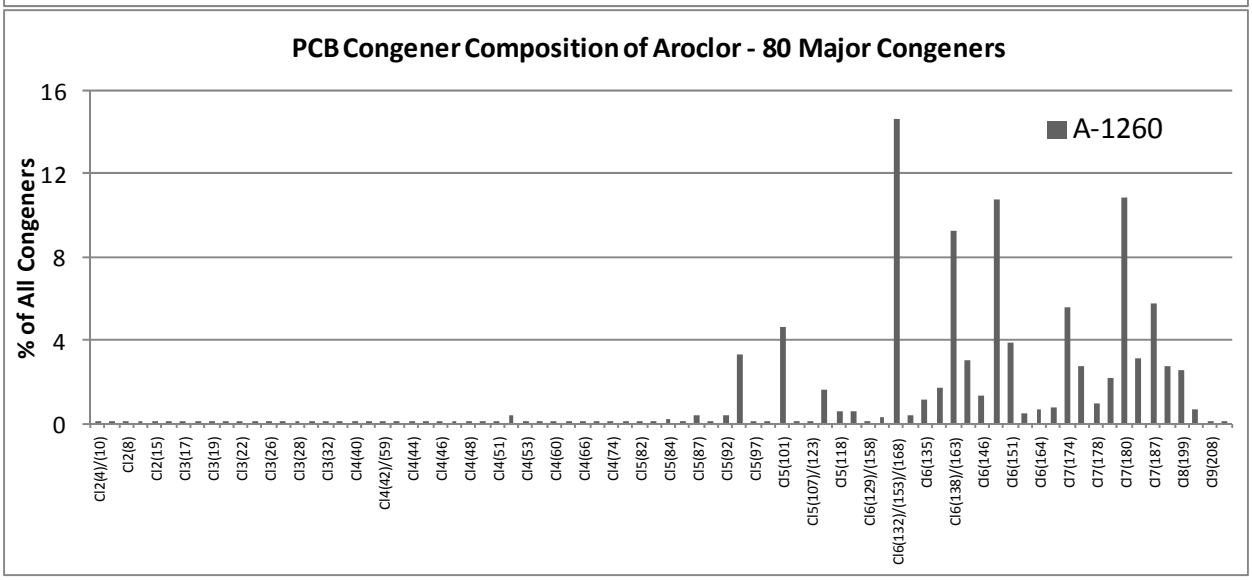

PCB Congener Composition of Aroclor - 80 Major Congeners
% of All Congeners
A-1232
0
2
4
6
8
10
12
Cl2(4)/(10)
Cl2(8)
Cl2(15)
Cl3(17)
Cl3(19)
Cl3(22)
Cl3(26)
Cl3(28)
Cl3(32)
Cl4(40)
Cl4(42)/(59)
Cl4(44)
Cl4(46)
Cl4(48)
Cl4(51)
Cl4(53)
Cl4(60)
Cl4(66)
Cl4(74)
Cl5(82)
Cl5(84)
Cl5(87)
Cl5(92)
Cl5(97)
Cl5(101)
Cl5(107)/(123)
Cl5(118)
Cl6(129)/(158)
Cl6(132)/(153)/(168)
Cl6(135)
Cl6(138)/(163)
Cl6(146)
Cl6(151)
Cl6(164)
Cl7(174)
Cl7(178)
Cl7(180)
Cl7(187)
Cl8(199)
Cl9(208)

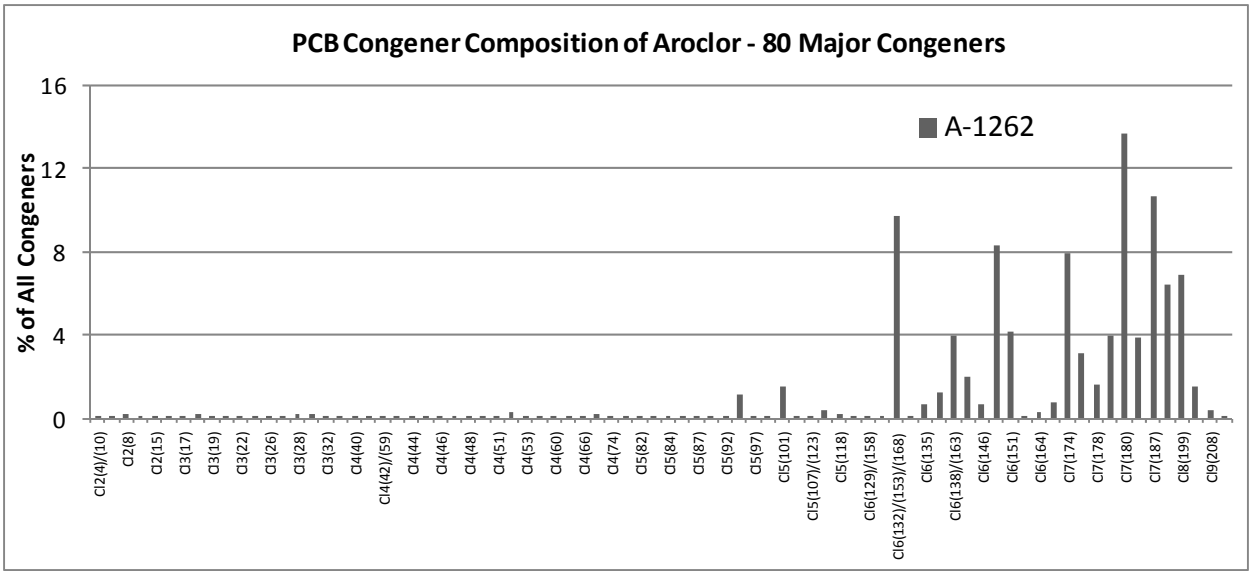

PCB Congener Composition of Aroclor - 80 Major Congeners
% of All Congeners
A-1016
0
2
4
6
8
10
12
Cl2(4)/(10)
Cl2(8)
Cl2(15)
Cl3(17)
Cl3(19)
Cl3(22)
Cl3(26)
Cl3(28)
Cl3(32)
Cl4(40)
Cl4(42)/(59)
Cl4(44)
Cl4(46)
Cl4(48)
Cl4(51)
Cl4(53)
Cl4(60)
Cl4(66)
Cl4(74)
Cl5(82)
Cl5(84)
Cl5(87)
Cl5(92)
Cl5(97)
Cl5(101)
Cl5(107)/(123)
Cl5(118)
Cl6(129)/(158)
Cl6(132)/(153)/(168)
Cl6(135)
Cl6(138)/(163)
Cl6(146)
Cl6(151)
Cl6(164)
Cl7(174)
Cl7(178)
Cl7(180)
Cl7(187)
Cl8(199)
Cl9(208)

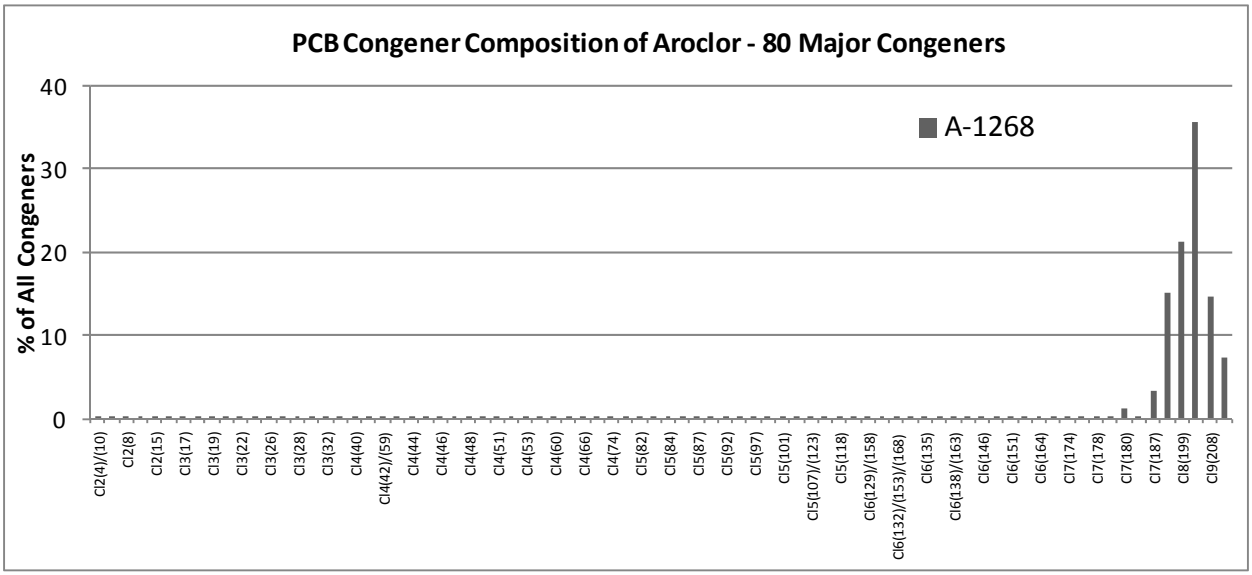

PCB Congener Composition of Aroclor - 80 Major Congeners
% of All Congeners
A-1242
0
2
4
6
8
10
Cl2(4)/(10)
Cl2(8)
Cl2(15)
Cl3(17)
Cl3(19)
Cl3(22)
Cl3(26)
Cl3(28)
Cl3(32)
Cl4(40)
Cl4(42)/(59)
Cl4(44)
Cl4(46)
Cl4(48)
Cl4(51)
Cl4(53)
Cl4(60)
Cl4(66)
Cl4(74)
Cl5(82)
Cl5(84)
Cl5(87)
Cl5(92)
Cl5(97)
Cl5(101)
Cl5(107)/(123)
Cl5(118)
Cl6(129)/(158)
Cl6(132)/(153)/(168)
Cl6(135)
Cl6(138)/(163)
Cl6(146)
Cl6(151)
Cl6(164)
Cl7(174)
Cl7(178)
Cl7(180)
Cl7(187)
Cl8(199)
Cl9(208)


PCB Congener Composition of Aroclor - 80 Major Congeners
% of All Congeners
A-1248
0
2
4
6
8
10
Cl2(4)/(10)
Cl2(8)
Cl2(15)
Cl3(17)
Cl3(19)
Cl3(22)
Cl3(26)
Cl3(28)
Cl3(32)
Cl4(40)
Cl4(42)/(59)
Cl4(44)
Cl4(46)
Cl4(48)
Cl4(51)
Cl4(53)
Cl4(60)
Cl4(66)
Cl4(74)
Cl5(82)
Cl5(84)
Cl5(87)
Cl5(92)
Cl5(97)
Cl5(101)
Cl5(107)/(123)
Cl5(118)
Cl6(129)/(158)
Cl6(132)/(153)/(168)
Cl6(135)
Cl6(138)/(163)
Cl6(146)
Cl6(151)
Cl6(164)
Cl7(174)
Cl7(178)
Cl7(180)
Cl7(187)
Cl8(199)
Cl9(208)


PCB Congener Composition of Aroclor - 80 Major Congeners
% of All Congeners
A-1254
0
2
4
6
8
10
Cl2(4)/(10)
Cl2(8)
Cl2(15)
Cl3(17)
Cl3(19)
Cl3(22)
Cl3(26)
Cl3(28)
Cl3(32)
Cl4(40)
Cl4(42)/(59)
Cl4(44)
Cl4(46)
Cl4(48)
Cl4(51)
Cl4(53)
Cl4(60)
Cl4(66)
Cl4(74)
Cl5(82)
Cl5(84)
Cl5(87)
Cl5(92)
Cl5(97)
Cl5(101)
Cl5(107)/(123)
Cl5(118)
Cl6(129)/(158)
Cl6(132)/(153)/(168)
Cl6(135)
Cl6(138)/(163)
Cl6(146)
Cl6(151)
Cl6(164)
Cl7(174)
Cl7(178)
Cl7(180)
Cl7(187)
Cl8(199)
Cl9(208)


PCB Congener Composition of Aroclor - 80 Major Congeners
% of All Congeners
A-1260
0
4
8
12
16
Cl2(4)/(10)
Cl2(8)
Cl2(15)
Cl3(17)
Cl3(19)
Cl3(22)
Cl3(26)
Cl3(28)
Cl3(32)
Cl4(40)
Cl4(42)/(59)
Cl4(44)
Cl4(46)
Cl4(48)
Cl4(51)
Cl4(53)
Cl4(60)
Cl4(66)
Cl4(74)
Cl5(82)
Cl5(84)
Cl5(87)
Cl5(92)
Cl5(97)
Cl5(101)
Cl5(107)/(123)
Cl5(118)
Cl6(129)/(158)
Cl6(132)/(153)/(168)
Cl6(135)
Cl6(138)/(163)
Cl6(146)
Cl6(151)
Cl6(164)
Cl7(174)
Cl7(178)
Cl7(180)
Cl7(187)
Cl8(199)
Cl9(208)





PCB fingerprints of 80 key PCB congeners in Aroclor formulations

Appendix B: ACF Data

Hunters Point Shipyard: 112 Samples 44 Congeners

Ashtabula River: 345 Samples 117 Congener

HUNTERS POINT SEDIMENT SAMPLES

112 Samples, 44 PCB Congeners

(ng/g, dry weight)

STATION_ID	OR-123	OR-123	SB-075	SB-075	SB-075	SB-075	SB-079	SB-079	SB-079
FIELD SAMPLE_ID	OR-123 0-5	OR-123 15-3(	SB-075 0-5	SB-075 30-6(	SB-075 90-12(	SB-075 150-18	SB-079 0-5	SB-079 30-6(	SB-079 90-12(
SAMPLE DEPTH_TOP	0	15	0	30	90	150	0	30	90
SAMPLE DEPTH_BOT	5	30	5	60	120	180	5	60	120
DEPTH_UNIT	CM	CM	CM	CM	CM	CM	CM	CM	CM
Cl2(08)	0.05	0.00	0.53	1.63	0.48	0.10	0.00	0.00	0.00
Cl3(18)	0.00	0.00	1.76	2.99	1.04	0.40	0.00	0.00	0.59
Cl3(21)/Cl3(33)/Cl3(20)	0.00	0.00	0.87	1.69	1.22	0.00	0.00	0.00	0.00
Cl3(28)	0.00	0.00	1.11	2.51	1.24	0.29	0.00	0.07	0.66
Cl3(31)	0.00	0.00	3.63	4.37	1.38	0.30	0.00	0.00	3.16
Cl4(44)	0.23	0.11	10.82	5.89	3.33	0.77	0.73	0.38	0.00
Cl4(49)	0.45	0.23	30.65	32.51	5.76	2.24	0.68	0.63	26.74
Cl4(52)	0.65	0.24	49.78	33.73	9.56	4.41	2.45	1.98	12.91
Cl4(56)	0.17	0.05	2.79	2.74	1.28	0.26	0.27	0.00	0.69
Cl4(60)	0.17	0.06	0.75	0.37	1.26	0.57	0.00	0.82	0.00
Cl4(66)	0.49	0.15	5.12	5.95	3.53	0.83	0.54	0.16	2.47
Cl4(70)	0.53	0.23	16.98	8.50	8.27	1.91	0.62	0.33	2.14
Cl4(74)	0.14	0.03	3.78	3.07	2.42	0.46	0.23	0.00	0.83
Cl4(77)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(105)	0.81	0.30	22.44	11.46	8.61	1.40	3.14	1.13	5.31
Cl5(110)	3.56	1.32	93.57	54.55	22.68	8.67	20.99	13.51	44.71
Cl5(118)	2.53	0.89	41.79	24.86	15.45	6.33	5.48	5.05	15.52
Cl5(126)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(87)	0.86	0.34	29.30	14.50	8.09	2.19	5.59	4.56	10.76
Cl5(90)/Cl5(101)	4.20	1.55	125.30	101.79	21.71	14.28	36.37	18.50	166.65
Cl5(95)/Cl5(88)	2.95	1.03	113.44	79.10	11.33	9.55	34.45	20.98	122.67
Cl5(97)	0.67	0.35	16.62	10.24	6.16	1.59	1.88	1.80	5.01
Cl5(99)	1.81	0.71	51.40	59.84	11.15	5.52	2.09	2.51	115.33
Cl6(128)	1.13	0.51	23.83	14.80	4.90	2.68	8.32	6.55	19.06
Cl6(129)/Cl6(158)	1.31	0.34	27.18	18.33	3.74	3.25	16.39	9.27	27.79
Cl6(132)/Cl6(168)/Cl6(153)	20.10	6.98	416.91	288.41	39.46	43.99	184.77	99.85	518.52
Cl6(138)	7.32	2.99	188.39	108.51	19.71	18.48	90.30	44.64	223.34
Cl6(141)	0.00	0.00	4.28	0.00	1.31	0.00	0.67	0.00	0.65
Cl6(149)	9.22	4.32	2.47	1.96	23.64	29.68	0.85	75.59	1.50
Cl6(151)	4.04	1.29	95.59	58.56	7.82	8.55	48.09	24.51	109.36
Cl6(156)	0.77	0.30	26.20	12.05	3.37	2.38	9.12	3.77	18.54
Cl7(170)	6.82	2.48	191.23	81.75	9.17	14.99	87.18	37.54	201.12
Cl7(174)	5.30	2.25	175.19	87.57	11.34	14.07	86.21	49.35	193.28
Cl7(177)	4.17	1.64	98.05	51.98	6.96	8.42	51.45	27.90	119.93
Cl7(180)	11.90	5.97	352.03	149.71	21.17	36.18	175.86	98.89	373.43
Cl7(183)	4.00	1.35	76.35	45.56	7.32	11.54	40.12	23.72	87.90
Cl7(187)	8.44	2.89	162.73	83.15	12.68	17.17	84.78	44.46	186.31
Cl8(194)	4.29	1.42	82.35	36.69	6.28	9.00	39.35	19.78	98.75
Cl8(195)	1.28	0.45	35.18	15.10	2.27	2.81	17.07	11.66	34.77
Cl8(201)/Cl8(204)	0.46	0.21	9.59	4.51	0.74	1.10	4.74	2.83	9.29
Cl8(203)	2.40	0.62	47.10	14.25	3.11	4.85	16.90	24.97	36.48
Cl9(206)	2.10	0.29	14.65	7.57	2.24	4.26	6.39	4.77	10.63
Cl10(209)	0.38	0.12	0.80	4.07	1.88	7.58	0.77	1.16	1.13
Sum 44 congeners	116	44	2,653	1,547	335	303	1,085	684	2,808

STATION_ID	SB-087	SB-087	SB-087	SB-087	SB-092	SB-092	SB-092	SB-092	SB-092
FIELD SAMPLE_ID	SB-087 0-5	SB-087 15-30	SB-087 45-60	SB-087 75-90	SB-092 0-5	SB-092 5-15	SB-092 15-30	SB-092 30-45	SB-092 45-60
SAMPLE DEPTH_TOP	0	15	45	75	0	5	15	30	45
SAMPLE DEPTH_BOT	5	30	60	90	5	15	30	45	60
DEPTH_UNIT	CM	CM	CM	CM	CM	CM	CM	CM	CM
Cl2(08)	0.86	2.97	0.89	0.11	0.30	0.58	0.99	1.20	0.50
Cl3(18)	0.74	6.68	2.17	0.76	0.00	0.33	0.68	2.50	1.17
Cl3(21)/Cl3(33)/Cl3(20)	1.52	9.06	2.35	0.00	0.38	0.68	1.63	4.77	1.88
Cl3(28)	2.14	9.62	2.18	0.00	0.52	0.97	1.97	4.40	1.89
Cl3(31)	1.42	12.73	3.26	0.96	0.47	0.72	1.38	4.37	2.29
Cl4(44)	6.19	107.93	14.97	2.34	1.29	2.30	4.59	25.68	16.35
Cl4(49)	7.43	75.05	10.76	3.19	1.45	3.15	7.40	23.44	12.38
Cl4(52)	14.85	237.14	33.99	6.82	2.48	5.10	11.38	50.84	37.13
Cl4(56)	2.67	42.81	4.96	0.88	0.39	1.12	2.33	8.74	5.87
Cl4(60)	2.13	8.66	4.38	0.77	0.41	0.92	2.00	1.64	5.53
Cl4(66)	8.82	54.41	12.23	2.86	1.83	3.91	8.31	22.04	15.81
Cl4(70)	15.29	172.50	28.03	6.31	2.49	5.12	10.61	49.45	31.92
Cl4(74)	4.02	48.69	9.33	2.12	0.93	1.47	3.47	13.80	10.28
Cl4(77)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(105)	16.91	172.60	31.28	6.91	3.17	6.63	12.95	52.01	33.09
Cl5(110)	44.52	573.61	100.19	11.86	9.50	17.52	38.33	195.95	121.93
Cl5(118)	31.30	351.02	71.43	16.87	9.40	12.34	25.23	103.17	86.53
Cl5(126)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(87)	15.33	249.87	38.32	6.24	2.80	6.73	13.88	68.24	46.49
Cl5(90)/Cl5(101)	38.28	552.85	88.95	15.66	9.74	17.51	40.04	217.37	110.56
Cl5(95)/Cl5(88)	25.38	410.80	60.77	10.16	5.75	14.39	25.30	173.91	77.40
Cl5(97)	10.37	138.89	25.46	4.44	1.92	5.32	9.20	40.84	27.50
Cl5(99)	16.39	213.16	28.78	6.89	4.67	11.34	16.45	75.11	34.67
Cl6(128)	11.60	139.66	18.73	3.43	2.81	6.21	12.00	40.72	25.24
Cl6(129)/Cl6(158)	9.11	71.66	18.66	3.13	2.51	4.91	10.04	41.05	22.87
Cl6(132)/Cl6(168)/Cl6(153)	95.42	571.17	182.01	32.29	36.89	55.14	120.63	483.22	274.63
Cl6(138)	48.50	425.44	97.53	14.03	16.88	29.80	55.24	278.62	145.78
Cl6(141)	2.44	34.07	5.59	0.88	0.00	1.09	2.30	9.37	6.31
Cl6(149)	57.71	13.80	116.07	22.10	19.81	34.14	73.22	5.17	168.38
Cl6(151)	17.94	111.24	32.25	8.54	6.05	11.60	23.25	114.81	48.45
Cl6(156)	7.06	61.77	15.16	2.54	2.05	4.09	8.02	33.46	16.35
Cl7(170)	24.97	154.21	60.54	8.23	13.18	21.32	35.79	177.19	87.58
Cl7(174)	24.27	116.13	49.36	13.92	10.66	18.09	36.93	166.94	73.93
Cl7(177)	19.63	94.41	29.59	8.40	7.70	14.51	21.83	100.45	45.02
Cl7(180)	57.69	244.62	120.39	29.66	20.06	47.99	82.28	313.39	188.98
Cl7(183)	15.72	65.72	29.55	10.28	6.64	11.58	23.39	87.68	46.46
Cl7(187)	31.21	136.09	48.07	16.33	13.37	22.10	46.92	166.68	78.23
Cl8(194)	15.40	62.63	26.17	11.85	7.20	12.28	16.85	70.81	29.53
Cl8(195)	5.94	25.01	9.18	3.71	2.50	4.17	8.41	30.61	13.77
Cl8(201)/Cl8(204)	1.75	6.78	2.65	1.29	0.69	1.35	2.71	9.00	3.86
Cl8(203)	9.00	29.07	13.15	5.59	3.47	6.08	11.78	37.02	14.03
Cl9(206)	3.37	12.30	7.79	4.92	1.51	3.14	5.63	12.08	9.21
Cl10(209)	1.23	12.22	7.28	4.14	0.71	0.93	1.59	4.46	4.99
Sum 44 congeners	727	5,839	1,464	311	235	429	837	3,322	1,985

STATION_ID	SB-092	SB-092	SB-100	SB-100	SB-100	SB-100	SB-104	SB-104	SB-104
FIELD SAMPLE_ID	SB-092 60-75	SB-092 75-90	SB-100 0-5	SB-100 15-30	SB-100 45-60	SB-100 75-90	SB-104 0-5	SB-104 15-30	SB-104 45-60
SAMPLE DEPTH_TOP	60	75	0	15	45	75	0	15	45
SAMPLE DEPTH_BOT	75	90	5	30	60	90	5	30	60
DEPTH_UNIT	CM	CM	CM	CM	CM	CM	CM	CM	CM
Cl2(08)	0.22	0.08	1.41	4.48	4.58	0.30	0.94	1.81	4.39
Cl3(18)	0.45	0.00	1.05	11.60	9.55	1.58	0.84	4.65	9.66
Cl3(21)/Cl3(33)/Cl3(20)	0.92	0.00	1.46	12.38	14.35	1.37	1.05	6.25	11.69
Cl3(28)	0.81	0.00	2.42	15.93	14.23	1.13	1.88	7.58	12.79
Cl3(31)	1.03	0.00	2.19	24.39	14.94	2.22	1.60	7.89	15.57
Cl4(44)	5.63	0.80	4.78	53.06	133.38	8.97	3.25	14.03	105.30
Cl4(49)	4.74	1.27	6.86	216.70	210.83	13.07	4.20	21.04	83.62
Cl4(52)	13.22	2.04	12.31	226.13	355.18	26.42	7.87	32.39	286.35
Cl4(56)	2.17	0.42	2.13	22.28	22.35	2.97	1.53	6.10	27.25
Cl4(60)	1.71	0.21	2.01	2.98	4.56	2.03	1.28	2.01	8.29
Cl4(66)	5.38	0.87	6.73	89.93	125.46	9.60	4.30	14.72	61.36
Cl4(70)	13.56	1.99	11.40	109.79	262.05	21.97	6.59	26.49	183.26
Cl4(74)	3.52	0.58	3.61	32.91	70.13	4.68	2.34	8.48	46.17
Cl4(77)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(105)	16.32	2.07	13.83	95.42	232.40	20.17	7.71	23.27	162.80
Cl5(110)	38.89	7.18	33.97	686.98	747.24	50.97	24.10	99.52	596.14
Cl5(118)	27.24	5.96	28.10	385.54	562.98	39.76	14.72	53.73	336.58
Cl5(126)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(87)	14.58	1.83	9.87	107.84	255.83	17.24	8.21	29.24	225.26
Cl5(90)/Cl5(101)	32.48	6.25	34.68	1511.53	972.80	44.95	21.01	118.67	540.97
Cl5(95)/Cl5(88)	24.04	3.91	20.88	1022.42	670.66	32.81	17.28	79.81	484.80
Cl5(97)	8.45	1.73	7.92	107.52	176.84	13.43	6.08	20.58	151.46
Cl5(99)	14.84	3.14	19.26	1509.85	493.11	18.26	12.99	59.71	230.09
Cl6(128)	9.80	1.51	9.65	96.36	135.71	11.17	6.46	18.37	97.68
Cl6(129)/Cl6(158)	9.46	1.02	8.54	188.63	128.77	9.28	5.35	23.97	99.39
Cl6(132)/Cl6(168)/Cl6(153)	77.49	14.77	94.98	3837.05	1522.72	83.13	62.14	257.37	726.15
Cl6(138)	41.12	7.90	44.39	563.93	734.04	45.26	27.23	111.90	481.61
Cl6(141)	1.97	0.00	2.15	53.29	35.58	2.55	1.25	5.00	29.22
Cl6(149)	48.26	9.63	54.75	7.84	13.30	51.05	37.10	2.66	12.11
Cl6(151)	13.89	2.89	16.22	656.34	318.10	17.04	14.73	52.85	166.54
Cl6(156)	6.98	1.08	7.13	110.37	96.29	7.19	4.60	14.75	57.77
Cl7(170)	22.40	5.10	28.80	1071.29	451.83	20.62	19.22	75.47	196.18
Cl7(174)	25.39	4.34	24.48	505.06	403.37	20.58	18.47	66.18	209.93
Cl7(177)	13.86	2.54	18.02	389.83	246.17	13.87	14.61	44.28	107.54
Cl7(180)	52.00	11.81	62.09	2162.58	831.91	49.49	40.47	133.84	366.25
Cl7(183)	13.86	3.28	16.13	446.67	201.99	16.03	13.80	35.90	101.58
Cl7(187)	24.48	6.21	37.65	1255.84	437.29	22.56	23.30	81.54	193.02
Cl8(194)	13.93	3.11	11.19	601.67	195.49	12.21	11.88	36.71	121.76
Cl8(195)	4.52	1.20	5.52	173.86	71.88	4.25	4.01	13.21	33.02
Cl8(201)/Cl8(204)	1.30	0.50	1.84	41.95	19.86	1.34	1.36	4.41	8.99
Cl8(203)	6.79	2.97	8.89	260.96	105.14	7.13	5.87	16.62	37.52
Cl9(206)	4.15	1.52	4.31	70.24	38.14	3.70	2.63	8.83	16.47
Cl10(209)	4.86	1.95	1.03	5.75	15.79	4.23	0.79	2.59	7.35
Sum 44 congeners	627	124	685	18,749	11,357	737	465	1,644	6,654

STATION_ID	SB-104	SB-105	SB-105	SB-105	SB-105	SB-106	SB-106	SB-106	SB-106
FIELD SAMPLE_ID	SB-104 75-90	SB-105 0-5	SB-105 15-30	SB-105 45-60	SB-105 75-90	SB-106 0-5	SB-106 5-15	SB-106 15-30	SB-106 30-45
SAMPLE DEPTH_TOP	75	0	15	45	75	0	5	15	30
SAMPLE DEPTH_BOT	90	5	30	60	90	5	15	30	45
DEPTH_UNIT	CM	CM	CM	CM	CM	CM	CM	CM	CM
Cl2(08)	0.12	0.61	1.37	6.11	1.49	0.00	0.27	0.51	1.28
Cl3(18)	0.00	0.59	1.38	15.60	4.59	0.00	0.37	0.73	1.30
Cl3(21)/Cl3(33)/Cl3(20)	0.00	0.68	2.06	16.70	4.38	0.17	0.37	1.03	2.02
Cl3(28)	0.00	1.43	3.16	22.38	5.25	0.54	0.58	1.31	2.76
Cl3(31)	0.00	1.26	2.39	23.95	6.32	0.46	0.39	0.95	2.51
Cl4(44)	0.68	1.10	4.17	46.02	32.02	0.66	0.86	2.30	5.26
Cl4(49)	1.22	1.53	5.47	47.05	47.30	0.69	1.05	3.06	6.87
Cl4(52)	1.51	2.51	8.03	102.97	75.20	1.55	1.80	5.00	10.26
Cl4(56)	0.00	0.64	2.39	20.58	8.24	0.24	0.38	1.14	2.66
Cl4(60)	0.22	0.53	1.79	5.50	1.53	0.17	0.40	1.15	1.88
Cl4(66)	1.01	2.11	6.83	46.98	30.87	1.01	1.18	3.67	7.49
Cl4(70)	1.32	2.60	8.36	82.90	64.52	1.31	1.64	4.55	10.01
Cl4(74)	0.41	1.06	2.99	27.43	18.22	0.00	0.47	1.44	3.52
Cl4(77)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(105)	1.17	2.81	8.93	70.39	56.14	1.45	1.67	5.29	10.49
Cl5(110)	5.08	7.89	26.08	309.96	179.65	5.51	7.21	23.73	36.51
Cl5(118)	3.65	7.42	17.49	157.36	121.40	4.35	5.84	18.60	26.43
Cl5(126)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(87)	1.04	2.42	8.78	90.14	63.36	1.72	2.09	6.72	12.93
Cl5(90)/Cl5(101)	0.42	7.88	25.56	396.57	236.62	5.40	7.59	23.42	43.89
Cl5(95)/Cl5(88)	0.44	4.65	17.41	339.41	179.57	3.60	4.46	14.80	28.47
Cl5(97)	1.27	1.77	6.96	57.00	45.29	1.38	1.57	5.30	9.26
Cl5(99)	2.52	3.95	14.98	115.54	119.86	2.23	3.17	10.74	18.14
Cl6(128)	1.00	2.39	8.30	67.79	41.78	1.84	2.18	5.27	9.29
Cl6(129)/Cl6(158)	0.95	1.74	6.71	71.55	48.98	1.70	1.44	5.35	7.96
Cl6(132)/Cl6(168)/Cl6(153)	0.90	27.71	80.21	1111.51	437.01	18.94	27.30	59.11	95.51
Cl6(138)	5.24	13.38	39.84	524.68	223.19	8.73	12.54	30.40	45.98
Cl6(141)	0.00	0.45	1.57	17.23	11.69	0.00	0.00	1.45	2.03
Cl6(149)	8.08	15.14	49.32	7.43	6.07	11.78	15.70	44.98	73.25
Cl6(151)	2.43	4.50	14.98	297.92	94.57	4.17	4.69	16.24	19.81
Cl6(156)	0.69	1.61	5.61	64.88	36.85	1.25	1.18	3.79	6.51
Cl7(170)	3.72	9.33	23.29	365.56	120.11	6.40	8.51	22.77	34.68
Cl7(174)	3.55	6.85	22.48	472.05	137.78	6.02	7.66	19.54	27.55
Cl7(177)	2.09	5.84	16.41	269.43	83.25	3.53	5.60	15.75	27.27
Cl7(180)	9.62	13.97	55.26	821.91	253.52	14.96	20.36	46.02	71.53
Cl7(183)	2.64	4.94	14.47	216.47	78.49	3.65	4.77	13.66	22.09
Cl7(187)	4.85	10.76	31.81	479.00	121.09	7.12	10.52	26.29	46.00
Cl8(194)	2.75	5.05	13.69	226.35	67.01	0.00	4.44	12.75	33.32
Cl8(195)	0.78	1.69	5.54	104.94	31.70	0.00	1.53	4.41	6.65
Cl8(201)/Cl8(204)	0.00	0.56	1.87	25.97	8.02	0.00	0.59	1.41	2.26
Cl8(203)	1.37	3.91	7.50	105.14	32.74	3.46	4.06	11.26	8.88
Cl9(206)	1.46	1.29	4.50	35.65	13.49	1.03	1.34	3.06	6.18
Cl10(209)	1.56	0.46	1.18	9.50	8.53	0.70	0.53	0.95	1.96
Sum 44 congeners	76	187	581	7,296	3,158	128	178	480	793

STATION_ID	SB-106	SB-106	SB-106	SB-108	SB-108	SB-108	SB-108	SB-108	SB-120
FIELD SAMPLE_ID	SB-106 45-60	SB-106 60-75	SB-106 75-90	SB-108 0-5	SB-108 5-15	SB-108 15-30	SB-108 30-45	SB-108 45-60	SB-120 0-5
SAMPLE DEPTH_TOP	45	60	75	0	5	15	30	45	0
SAMPLE DEPTH_BOT	60	75	90	5	15	30	45	60	5
DEPTH_UNIT	CM	CM	CM	CM	CM	CM	CM	CM	CM
Cl2(08)	3.32	3.12	1.34	0.20	0.25	0.83	0.52	0.00	0.13
Cl3(18)	9.43	7.12	4.40	0.00	0.27	0.69	0.86	0.00	0.00
Cl3(21)/Cl3(33)/Cl3(20)	9.13	8.08	5.68	0.32	0.39	1.72	1.91	0.00	0.00
Cl3(28)	12.42	9.13	6.14	0.42	0.61	1.63	1.44	0.00	0.30
Cl3(31)	13.96	10.37	5.40	0.30	0.43	0.99	1.75	0.00	0.00
Cl4(44)	30.03	51.52	36.77	0.68	1.50	5.70	8.03	0.19	0.30
Cl4(49)	33.47	39.50	37.87	0.89	1.81	8.10	7.94	0.26	0.44
Cl4(52)	72.74	115.65	92.86	1.75	3.48	13.67	21.51	0.51	0.72
Cl4(56)	13.63	16.09	10.67	0.00	0.47	2.68	2.99	0.10	0.07
Cl4(60)	2.54	4.61	2.35	0.39	0.51	2.33	2.46	0.00	0.00
Cl4(66)	29.21	35.70	27.55	1.16	1.90	8.21	8.67	0.22	0.53
Cl4(70)	55.38	77.76	66.25	1.49	2.72	12.24	17.79	0.37	0.68
Cl4(74)	16.45	24.99	17.98	0.00	0.79	3.37	4.68	0.13	0.17
Cl4(77)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(105)	52.34	73.81	66.58	2.13	3.56	13.30	14.21	0.53	0.95
Cl5(110)	274.97	277.38	294.54	7.07	14.98	49.55	62.29	2.23	2.83
Cl5(118)	132.80	146.62	143.19	6.26	11.11	31.68	42.34	1.05	2.31
Cl5(126)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.00
Cl5(87)	74.20	104.06	93.07	2.11	3.86	17.39	20.02	0.64	0.65
Cl5(90)/Cl5(101)	411.05	253.58	351.80	7.40	14.27	52.58	58.24	2.93	2.44
Cl5(95)/Cl5(88)	360.55	218.45	308.18	3.88	9.63	38.43	33.34	2.40	1.60
Cl5(97)	40.13	62.99	52.99	1.60	2.96	13.90	18.05	0.00	0.70
Cl5(99)	82.05	92.83	99.38	3.08	6.47	21.13	18.59	0.67	1.42
Cl6(128)	67.72	57.58	59.22	2.40	3.95	13.72	14.45	0.54	0.79
Cl6(129)/Cl6(158)	95.56	59.82	66.93	2.34	3.77	12.17	11.52	0.70	0.46
Cl6(132)/Cl6(168)/Cl6(153)	1294.51	282.64	837.66	28.95	18.98	128.43	123.27	9.67	7.91
Cl6(138)	588.79	234.38	433.92	13.92	11.86	72.05	64.54	4.39	4.18
Cl6(141)	15.37	16.34	13.50	0.00	0.00	2.39	3.47	0.28	0.00
Cl6(149)	5.34	7.95	6.09	16.27	15.02	90.20	81.68	0.19	5.15
Cl6(151)	397.70	78.85	193.26	4.75	9.58	30.12	26.67	2.15	1.63
Cl6(156)	67.72	41.61	55.15	1.45	2.62	9.65	10.22	0.54	0.46
Cl7(170)	520.36	102.15	269.68	12.72	11.11	42.67	44.85	3.52	3.46
Cl7(174)	609.82	106.42	289.43	9.76	7.26	42.15	40.29	3.23	2.56
Cl7(177)	371.64	73.37	172.89	7.40	11.68	25.78	30.78	1.99	2.00
Cl7(180)	1050.66	208.48	546.22	25.72	15.36	81.42	84.01	6.84	6.59
Cl7(183)	271.68	65.66	149.39	6.03	9.92	30.57	22.56	1.62	1.68
Cl7(187)	655.38	93.87	254.84	11.94	9.72	54.23	42.79	3.11	3.40
Cl8(194)	171.30	53.08	134.43	7.58	9.84	22.80	37.40	1.65	1.47
Cl8(195)	122.06	22.05	50.13	2.80	3.28	9.45	6.89	0.65	0.00
Cl8(201)/Cl8(204)	34.85	6.75	12.94	0.74	1.17	3.02	2.24	0.20	0.00
Cl8(203)	140.49	27.30	59.86	5.30	4.58	19.94	10.59	1.85	1.39
Cl9(206)	40.92	11.55	19.47	1.92	2.21	4.18	4.32	0.34	0.31
Cl10(209)	5.79	5.47	5.19	0.69	0.87	2.34	3.34	0.43	0.34
Sum 44 congeners	8,257	3,189	5,355	204	235	997	1,014	56	60

STATION_ID	SB-120	SB-081	SB-081	SB-081	SB-081	SB-081	SB-081	SB-081	SB-081
FIELD SAMPLE_ID	SB-120 30-45	SB-081 0-2	SB-081 2-4	SB-081 4-6	SB-081 6-8	SB-081 8-10	SB-081 10-12	SB-081 12-14	SB-081 14-16
SAMPLE DEPTH_TOP	30	0	2	4	6	8	10	12	14
SAMPLE DEPTH_BOT	45	2	4	6	8	10	12	14	16
DEPTH_UNIT	CM	CM	CM	CM	CM	CM	CM	CM	CM
Cl2(08)	0.92	0.56	0.67	0.00	1.03	1.07	1.01	1.01	1.19
Cl3(18)	0.47	1.21	0.00	0.00	0.00	0.95	0.00	0.87	1.78
Cl3(21)/Cl3(33)/Cl3(20)	0.84	0.78	0.90	0.80	0.98	1.06	1.59	1.44	1.92
Cl3(28)	1.22	1.62	1.42	1.69	1.58	2.03	2.52	2.01	3.25
Cl3(31)	0.63	1.28	1.31	1.60	1.87	2.09	2.76	1.88	2.40
Cl4(44)	2.19	3.56	3.98	4.19	4.90	3.85	5.58	6.24	7.09
Cl4(49)	4.57	3.22	4.96	4.55	5.51	6.59	9.37	10.88	13.19
Cl4(52)	4.71	8.21	8.69	8.50	11.96	10.04	14.17	16.58	18.22
Cl4(56)	1.13	1.96	0.98	0.78	2.26	1.17	1.30	3.19	3.60
Cl4(60)	0.82	2.03	1.72	1.46	2.23	2.26	2.56	3.36	3.52
Cl4(66)	4.23	4.36	3.25	4.08	4.65	4.52	7.31	8.55	9.18
Cl4(70)	3.99	5.86	6.83	6.24	9.17	8.19	10.05	12.54	14.39
Cl4(74)	1.30	2.06	2.24	2.00	2.58	2.09	3.47	3.32	4.72
Cl4(77)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(105)	4.24	6.80	6.89	6.79	9.55	8.43	11.31	13.24	14.60
Cl5(110)	17.44	27.50	30.35	30.22	41.57	44.12	59.91	74.66	86.27
Cl5(118)	15.75	19.36	20.39	20.69	29.20	30.47	36.94	45.75	53.16
Cl5(126)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(87)	4.31	9.96	11.01	10.21	12.90	11.27	16.66	20.18	22.12
Cl5(90)/Cl5(101)	14.92	31.68	36.28	36.79	49.12	55.61	75.02	92.55	114.42
Cl5(95)/Cl5(88)	13.33	18.54	22.32	22.15	29.37	32.37	47.22	57.59	66.95
Cl5(97)	4.58	5.30	6.33	4.74	6.74	7.53	10.76	12.86	14.71
Cl5(99)	12.08	13.96	11.19	15.08	18.11	19.92	29.14	32.69	44.26
Cl6(128)	4.84	9.22	9.21	9.58	12.55	13.03	16.18	19.97	22.62
Cl6(129)/Cl6(158)	3.53	6.86	8.69	8.48	9.70	11.19	15.15	18.28	22.74
Cl6(132)/Cl6(168)/Cl6(153)	45.72	99.98	112.98	121.45	159.24	187.14	254.65	333.09	402.59
Cl6(138)	20.08	56.87	67.78	68.09	83.80	96.51	133.62	162.21	197.80
Cl6(141)	0.72	13.29	15.22	15.50	20.04	22.42	29.42	38.19	44.68
Cl6(149)	31.53	60.36	71.18	73.77	96.12	110.83	155.78	200.34	205.75
Cl6(151)	11.08	20.58	24.71	27.41	34.08	40.66	53.29	69.06	83.00
Cl6(156)	2.75	5.85	5.99	6.41	7.74	8.22	11.30	13.58	17.12
Cl7(170)	16.15	51.93	56.62	63.39	71.90	85.82	109.31	135.96	173.17
Cl7(174)	14.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl7(177)	11.58	27.38	30.46	32.55	36.73	45.25	60.27	72.94	93.78
Cl7(180)	32.96	114.92	125.48	142.89	162.46	186.54	249.92	202.67	270.82
Cl7(183)	10.35	23.74	28.47	30.05	34.31	39.20	54.90	66.25	80.18
Cl7(187)	18.51	46.64	55.38	59.42	67.34	80.33	109.79	137.92	168.84
Cl8(194)	7.99	27.25	20.84	29.47	30.35	33.76	44.81	55.40	71.05
Cl8(195)	2.98	10.26	9.77	11.50	13.56	15.23	19.29	20.46	27.54
Cl8(201)/Cl8(204)	1.16	2.86	3.91	3.44	4.22	4.95	6.06	7.96	8.66
Cl8(203)	4.00	26.95	13.56	20.07	16.66	18.19	25.75	30.69	35.42
Cl9(206)	1.60	4.83	7.11	5.98	5.09	6.82	7.74	10.89	11.11
Cl10(209)	1.10	1.71	54.23	2.05	1.06	1.22	2.01	2.21	2.73
Sum 44 congeners	356	781	903	914	1,112	1,263	1,708	2,019	2,441

STATION_ID	SB-081	SB-081	SB-081	SB-081	SB-081	SB-081	SB-081	SB-094	SB-094
FIELD SAMPLE_ID	SB-081 16-18	SB-081 18-20	SB-081 20-25	SB-081 25-30	SB-081 30-40	SB-081 40-50	SB-081 50-60	SB-094 0-2	SB-094 2-4
SAMPLE DEPTH_TOP	16	18	20	25	30	40	50	0	2
SAMPLE DEPTH_BOT	18	20	25	30	40	50	60	2	4
DEPTH_UNIT	CM	CM	CM	CM	CM	CM	CM	CM	CM
Cl2(08)	1.61	3.12	3.15	3.07	0.00	0.00	0.45	0.26	0.23
Cl3(18)	1.73	3.26	4.05	5.51	9.08	0.00	1.43	0.00	0.38
Cl3(21)/Cl3(33)/Cl3(20)	1.51	3.16	3.51	4.00	7.02	0.00	3.43	0.40	0.35
Cl3(28)	3.32	5.39	6.81	8.67	10.21	0.00	2.72	0.98	0.55
Cl3(31)	2.75	5.15	6.70	7.78	11.49	6.38	2.94	0.61	0.55
Cl4(44)	9.41	23.74	40.46	61.26	70.77	25.04	13.23	1.59	1.33
Cl4(49)	17.06	33.07	35.56	42.87	45.46	16.60	8.33	1.58	1.87
Cl4(52)	26.41	62.76	101.68	152.87	181.77	56.76	29.64	3.20	3.37
Cl4(56)	4.10	10.63	14.81	19.49	24.75	9.34	6.53	0.63	0.50
Cl4(60)	4.98	9.53	13.04	16.73	19.41	8.28	5.21	0.66	0.54
Cl4(66)	11.82	23.79	31.38	38.64	34.27	18.18	10.66	1.27	1.29
Cl4(70)	19.79	51.19	82.74	127.73	127.12	46.02	38.51	2.94	2.64
Cl4(74)	5.86	14.51	21.92	32.40	31.09	11.14	9.72	1.20	0.80
Cl4(77)	0.00	0.00	0.00	0.00	0.00	0.00	3.03	0.00	0.00
Cl5(105)	20.54	56.81	90.17	140.40	111.54	38.45	52.82	2.72	2.66
Cl5(110)	112.46	163.58	265.66	320.17	453.11	139.66	93.03	10.30	11.37
Cl5(118)	73.21	175.09	166.81	265.19	306.90	103.18	68.41	8.89	8.94
Cl5(126)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(87)	27.88	78.97	131.18	187.41	175.57	53.65	53.89	3.40	3.14
Cl5(90)/Cl5(101)	148.20	181.93	237.82	288.16	399.59	132.66	79.49	11.70	13.41
Cl5(95)/Cl5(88)	84.98	137.92	180.02	234.48	261.72	81.59	47.73	6.52	7.56
Cl5(97)	17.96	46.68	71.64	119.69	107.69	27.58	24.06	1.73	2.22
Cl5(99)	56.56	95.83	87.63	152.00	150.66	48.51	33.96	5.02	5.18
Cl6(128)	31.67	53.24	70.78	82.59	75.45	27.21	23.31	3.21	3.35
Cl6(129)/Cl6(158)	29.18	48.02	55.53	61.96	46.07	20.98	16.54	2.39	2.95
Cl6(132)/Cl6(168)/Cl6(153)	331.32	445.77	462.27	413.03	504.90	203.79	205.61	36.97	44.10
Cl6(138)	181.88	309.29	321.67	314.39	378.89	138.98	87.04	19.98	23.77
Cl6(141)	58.81	81.54	100.39	84.31	72.74	34.24	24.32	4.22	5.20
Cl6(149)	234.00	334.91	355.09	277.81	335.90	129.25	86.49	20.53	25.31
Cl6(151)	103.17	154.10	147.08	116.71	100.99	45.51	35.51	7.07	8.76
Cl6(156)	21.52	36.19	43.74	49.42	43.78	16.20	19.45	2.03	2.13
Cl7(170)	164.72	213.02	169.03	193.37	142.38	59.31	61.62	15.42	18.35
Cl7(174)	0.00	0.00	0.00	0.00	0.00	0.00	41.77	0.00	0.00
Cl7(177)	111.06	147.18	134.92	99.72	80.23	40.59	29.01	7.99	10.24
Cl7(180)	303.96	399.58	377.67	276.08	299.98	133.04	89.59	37.67	42.02
Cl7(183)	103.47	138.18	131.76	96.37	75.96	38.00	28.03	7.72	9.47
Cl7(187)	166.49	193.67	191.52	176.72	136.40	62.38	46.98	16.26	18.48
Cl8(194)	76.93	106.45	92.45	70.90	43.89	25.31	19.55	7.49	7.20
Cl8(195)	27.93	38.75	30.74	23.63	25.38	0.00	7.96	2.93	3.48
Cl8(201)/Cl8(204)	10.07	13.84	12.36	9.03	0.00	0.00	2.41	1.21	1.45
Cl8(203)	41.51	58.93	53.04	39.23	43.48	25.50	11.17	7.46	5.18
Cl9(206)	12.19	17.85	14.36	13.62	12.54	8.90	5.53	1.92	1.60
Cl10(209)	3.03	6.65	5.99	7.20	7.52	11.26	7.10	0.96	0.80
Sum 44 congeners	2,665	3,983	4,367	4,635	4,966	1,843	1,438	269	303

STATION_ID	SB-094	SB-094	SB-094	SB-094	SB-094	SB-094	SB-094	SB-094	SB-094
FIELD SAMPLE_ID	SB-094 4-6	SB-094 6-8	SB-094 8-10	SB-094 10-12	SB-094 12-14	SB-094 14-16	SB-094 16-18	SB-094 18-20	SB-094 20-25
SAMPLE DEPTH_TOP	4	6	8	10	12	14	16	18	20
SAMPLE DEPTH_BOT	6	8	10	12	14	16	18	20	25
DEPTH_UNIT	CM	CM	CM	CM	CM	CM	CM	CM	CM
Cl2(08)	0.39	0.71	0.00	0.00	0.81	1.15	1.19	1.27	1.44
Cl3(18)	0.00	0.68	0.00	0.00	0.00	0.85	1.16	0.80	1.52
Cl3(21)/Cl3(33)/Cl3(20)	0.75	0.75	0.00	0.00	1.25	2.00	1.93	1.68	1.71
Cl3(28)	1.01	1.21	0.00	0.00	2.18	3.03	3.44	3.51	2.76
Cl3(31)	0.63	1.19	0.00	1.22	0.91	2.13	2.14	1.98	2.97
Cl4(44)	1.71	1.87	3.49	4.47	3.11	5.43	5.11	5.19	7.39
Cl4(49)	2.60	2.85	4.24	5.24	6.70	9.87	9.65	9.95	13.38
Cl4(52)	3.95	4.49	6.82	7.99	8.11	11.88	11.64	11.15	18.18
Cl4(56)	1.00	1.17	0.00	0.00	2.43	3.14	3.50	3.09	3.88
Cl4(60)	0.98	1.08	2.53	2.43	3.14	2.96	0.00	0.00	3.22
Cl4(66)	2.32	2.69	3.43	4.90	5.14	7.87	7.58	8.57	9.94
Cl4(70)	3.75	4.30	4.97	8.58	8.85	10.37	9.80	10.46	15.14
Cl4(74)	1.18	1.54	2.27	2.82	3.25	4.02	4.13	2.84	4.58
Cl4(77)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(105)	4.64	4.60	5.66	11.51	9.70	11.05	11.38	11.80	15.85
Cl5(110)	16.80	20.32	25.07	35.30	42.78	58.76	59.37	58.35	81.87
Cl5(118)	15.25	16.03	19.15	25.66	32.12	41.07	39.71	40.32	53.49
Cl5(126)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(87)	4.51	5.90	8.09	10.47	13.07	14.34	11.99	15.03	19.00
Cl5(90)/Cl5(101)	17.42	22.24	25.79	36.59	47.46	65.19	68.89	68.33	91.59
Cl5(95)/Cl5(88)	10.73	13.69	16.82	24.56	30.67	42.66	42.71	42.10	59.32
Cl5(97)	3.66	4.34	6.88	6.59	9.90	10.37	12.91	12.90	16.66
Cl5(99)	7.92	9.29	10.92	18.63	19.07	27.26	29.56	27.80	36.27
Cl6(128)	5.12	6.06	8.15	9.72	10.09	14.68	15.24	15.95	22.35
Cl6(129)/Cl6(158)	4.11	5.08	6.52	8.04	9.59	12.66	12.73	13.10	16.97
Cl6(132)/Cl6(168)/Cl6(153)	59.79	73.57	75.39	122.42	158.99	218.01	212.48	205.37	252.19
Cl6(138)	32.24	38.96	46.01	64.59	75.83	107.38	105.45	105.03	136.97
Cl6(141)	8.15	9.81	11.60	17.51	19.82	25.76	23.43	23.30	30.69
Cl6(149)	36.52	46.78	52.30	81.55	103.82	145.87	146.53	139.05	176.11
Cl6(151)	11.90	16.32	18.02	27.98	34.11	50.45	49.89	45.83	59.48
Cl6(156)	3.52	3.70	6.02	7.60	6.52	9.90	9.84	9.23	14.13
Cl7(170)	25.69	29.75	37.66	50.63	59.71	84.67	83.73	81.92	93.63
Cl7(174)	21.43	26.04	28.97	43.24	51.66	73.30	69.13	67.24	78.58
Cl7(177)	13.66	17.63	20.45	27.64	35.85	50.63	50.78	46.53	56.38
Cl7(180)	58.05	67.88	67.41	107.86	123.48	177.47	172.69	172.29	199.90
Cl7(183)	12.42	15.14	17.79	27.75	29.71	42.23	41.23	40.89	49.81
Cl7(187)	25.41	31.13	34.12	52.28	63.89	88.93	88.81	84.14	102.63
Cl8(194)	9.70	9.23	18.16	29.24	22.88	33.36	31.60	29.15	36.70
Cl8(195)	5.83	4.66	15.10	11.29	13.32	16.94	11.29	14.55	15.02
Cl8(201)/Cl8(204)	2.10	1.61	0.00	3.72	4.24	4.48	4.73	4.79	4.64
Cl8(203)	5.71	6.22	8.55	12.85	16.47	17.26	20.35	14.31	17.64
Cl9(206)	2.29	2.29	0.00	0.00	5.30	7.25	5.91	7.70	6.81
Cl10(209)	1.13	0.88	0.00	0.00	3.94	3.03	8.47	2.48	3.32
Sum 44 congeners	446	534	618	913	1,100	1,520	1,502	1,460	1,834

STATION_ID	SB-094	SB-094	SB-094	SB-094	SB-094	SB-094	SB-094	SB-094	SB-094
FIELD SAMPLE_ID	SB-094 25-30	SB-094 30-40	SB-094 40-50	SB-094 50-60	SB-094 0-2	SB-094 8-10	SB-094 18-20	SB-094 25-30	SB-094 30-40
SAMPLE DEPTH_TOP	25	30	40	50	0	8	18	25	30
SAMPLE DEPTH_BOT	30	40	50	60	2	10	20	30	40
DEPTH_UNIT	CM	CM	CM	CM	CM	CM	CM	CM	CM
Cl2(08)	1.74	1.63	0.00	0.00	0.27	0.66	1.05	1.61	1.52
Cl3(18)	1.83	5.01	0.00	0.00	0.00	0.00	0.70	1.22	2.82
Cl3(21)/Cl3(33)/Cl3(20)	2.82	3.84	0.00	0.00	0.00	0.70	0.97	2.25	4.71
Cl3(28)	3.57	3.58	0.00	0.00	0.65	1.54	1.75	3.93	3.13
Cl3(31)	3.10	9.86	0.00	1.87	0.00	0.84	1.01	3.17	6.20
Cl4(44)	15.96	36.79	16.85	6.99	1.61	2.80	4.28	9.04	29.52
Cl4(49)	21.26	27.11	11.37	5.77	1.95	4.63	5.99	13.80	23.38
Cl4(52)	37.23	84.00	40.14	16.28	3.41	6.56	9.60	22.40	68.05
Cl4(56)	6.06	16.13	6.44	4.50	0.00	0.00	0.00	4.00	10.86
Cl4(60)	5.83	11.07	6.03	0.00	1.17	0.92	2.03	4.67	10.90
Cl4(66)	17.00	24.01	8.84	6.82	1.94	2.51	6.01	9.83	21.09
Cl4(70)	33.84	83.48	39.09	22.45	3.07	5.53	7.41	18.06	65.80
Cl4(74)	9.69	23.83	11.14	5.66	1.16	1.43	2.60	5.50	18.06
Cl4(77)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(105)	31.83	80.62	39.66	30.12	4.47	7.71	8.22	17.40	78.22
Cl5(110)	138.63	291.12	130.59	84.80	11.58	26.14	44.57	89.26	249.05
Cl5(118)	99.40	211.08	100.87	80.01	10.20	21.26	26.64	60.61	188.20
Cl5(126)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(87)	40.36	114.64	52.37	32.28	3.49	9.08	12.73	25.16	94.05
Cl5(90)/Cl5(101)	128.86	282.12	114.01	69.49	12.59	27.47	55.11	96.58	217.39
Cl5(95)/Cl5(88)	84.79	159.72	73.62	31.05	7.65	17.14	37.98	63.10	134.32
Cl5(97)	30.85	64.89	27.64	19.71	2.94	4.36	8.89	18.42	55.43
Cl5(99)	50.57	88.13	37.07	25.63	5.11	11.48	17.95	35.94	69.49
Cl6(128)	26.54	56.50	25.45	15.50	3.68	7.67	13.24	18.92	48.14
Cl6(129)/Cl6(158)	19.85	42.28	18.86	10.19	3.09	5.78	12.24	17.61	34.44
Cl6(132)/Cl6(168)/Cl6(153)	262.03	392.06	208.77	118.58	33.70	81.14	151.49	215.51	422.82
Cl6(138)	157.87	322.56	135.88	65.32	21.70	44.44	100.42	134.99	272.21
Cl6(141)	34.92	83.24	39.96	22.11	5.06	11.11	26.07	32.41	71.19
Cl6(149)	176.61	340.75	142.10	74.07	23.06	51.74	126.33	170.23	281.97
Cl6(151)	57.10	103.87	42.04	19.36	8.65	18.71	43.05	58.51	84.74
Cl6(156)	16.48	38.97	20.37	10.88	2.51	4.70	10.21	13.76	33.97
Cl7(170)	90.28	164.88	75.69	31.96	17.19	36.87	85.94	86.75	154.52
Cl7(174)	74.91	153.45	63.26	27.06	13.94	29.15	75.35	77.16	121.95
Cl7(177)	51.52	91.14	37.55	16.81	9.41	20.39	47.93	49.48	75.01
Cl7(180)	194.80	346.50	147.92	67.49	35.28	77.49	176.18	193.31	308.77
Cl7(183)	45.50	82.08	36.62	16.07	7.85	17.36	39.40	45.22	68.82
Cl7(187)	90.82	156.49	63.81	28.66	16.54	34.39	84.17	95.56	130.72
Cl8(194)	32.33	47.39	28.65	15.83	9.23	15.49	35.09	32.45	51.72
Cl8(195)	14.60	27.03	15.22	5.19	2.62	9.10	14.46	12.84	26.48
Cl8(201)/Cl8(204)	5.38	8.52	6.98	1.95	1.15	3.25	4.59	5.15	5.75
Cl8(203)	20.24	39.43	15.61	7.26	3.19	9.75	14.93	16.58	20.69
Cl9(206)	6.88	11.67	6.90	5.56	2.19	3.20	6.42	6.14	11.22
Cl10(209)	41.77	7.94	7.85	6.80	0.58	0.00	1.85	3.01	11.76
Sum 44 congeners	2,186	4,139	1,855	1,010	294	634	1,325	1,792	3,589

STATION_ID	SB-094	SB-110	SB-110	SB-110	SB-110	SB-110	SB-110	SB-110	SB-110
FIELD SAMPLE_ID	SB-094 40-50	SB-110 0-2	SB-110 2-4	SB-110 4-6	SB-110 6-8	SB-110 8-10	SB-110 10-12	SB-110 12-14	SB-110 14-16
SAMPLE DEPTH_TOP	40	0	2	4	6	8	10	12	14
SAMPLE DEPTH_BOT	50	2	4	6	8	10	12	14	16
DEPTH_UNIT	CM	CM	CM	CM	CM	CM	CM	CM	CM
Cl2(08)	0.00	0.22	0.16	0.25	0.27	0.33	0.50	0.42	0.70
Cl3(18)	0.00	0.00	0.00	0.17	0.28	0.23	0.36	0.38	0.00
Cl3(21)/Cl3(33)/Cl3(20)	0.00	0.00	0.00	0.24	0.33	0.37	0.53	0.55	0.00
Cl3(28)	0.00	0.52	0.68	0.57	0.86	0.64	1.08	1.15	2.17
Cl3(31)	0.00	0.41	0.50	0.42	0.45	0.48	0.61	0.63	0.00
Cl4(44)	13.10	0.74	0.63	0.83	1.15	1.28	1.60	1.80	1.76
Cl4(49)	8.60	1.00	1.05	1.34	1.82	2.17	2.81	3.13	3.63
Cl4(52)	26.57	2.06	1.75	1.89	2.56	2.85	4.30	4.04	4.54
Cl4(56)	5.12	0.00	0.00	0.49	0.58	0.93	0.84	0.98	0.00
Cl4(60)	6.00	0.00	0.00	0.45	0.66	0.87	1.13	1.21	0.00
Cl4(66)	6.79	0.82	1.02	1.54	1.94	2.41	2.94	3.74	3.64
Cl4(70)	29.13	1.58	1.32	1.69	2.41	2.72	3.56	4.00	3.55
Cl4(74)	7.04	0.57	0.00	0.66	0.78	0.91	1.34	1.27	0.00
Cl4(77)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(105)	28.84	2.01	2.06	2.16	2.99	3.61	4.20	5.61	4.98
Cl5(110)	90.15	7.74	6.46	9.13	12.50	15.06	19.85	24.44	22.32
Cl5(118)	69.59	6.83	6.05	7.65	10.44	12.31	15.33	19.71	15.04
Cl5(126)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(87)	37.18	2.00	1.86	2.25	3.04	3.98	4.55	5.40	5.28
Cl5(90)/Cl5(101)	80.76	5.81	6.47	7.51	11.09	13.59	18.59	19.93	24.14
Cl5(95)/Cl5(88)	51.93	4.74	4.57	5.34	8.05	8.87	12.40	14.35	15.49
Cl5(97)	19.55	1.58	1.57	1.89	2.39	2.94	3.95	4.19	4.65
Cl5(99)	26.16	3.92	3.69	4.71	6.31	7.57	9.27	11.99	10.46
Cl6(128)	17.99	2.22	2.23	2.65	3.81	4.49	4.96	6.27	7.51
Cl6(129)/Cl6(158)	14.48	1.71	1.79	2.12	2.71	3.22	3.97	4.92	6.21
Cl6(132)/Cl6(168)/Cl6(153)	116.07	32.47	30.82	38.45	52.59	59.53	75.96	104.39	91.58
Cl6(138)	97.43	13.12	13.57	16.66	22.93	25.92	33.70	40.66	43.14
Cl6(141)	25.59	4.21	3.95	4.83	6.73	7.29	9.48	13.54	14.02
Cl6(149)	101.13	18.72	18.31	22.12	30.49	34.86	45.57	50.47	60.18
Cl6(151)	30.26	6.18	6.16	7.24	10.12	11.41	15.05	20.25	22.25
Cl6(156)	17.86	1.68	1.34	1.85	2.16	2.67	3.29	3.99	3.59
Cl7(170)	56.10	11.78	12.00	15.65	19.90	20.65	25.73	33.61	40.56
Cl7(174)	45.69	10.05	10.24	13.50	16.33	16.99	22.56	27.65	35.06
Cl7(177)	27.03	6.82	6.80	8.78	11.31	11.79	15.96	18.74	22.18
Cl7(180)	103.53	27.99	27.36	37.10	36.98	44.86	56.70	62.89	77.70
Cl7(183)	26.02	5.47	5.70	7.41	9.85	9.90	12.49	15.77	20.07
Cl7(187)	45.08	10.92	11.95	14.93	19.47	20.66	26.72	32.94	37.20
Cl8(194)	17.25	6.23	6.96	7.10	9.26	9.47	10.63	12.35	20.76
Cl8(195)	0.00	3.21	1.56	2.90	3.25	3.38	4.33	4.80	10.85
Cl8(201)/Cl8(204)	0.00	0.87	0.75	1.02	1.07	1.10	1.58	1.87	3.15
Cl8(203)	12.69	1.95	2.02	3.68	3.67	4.74	5.09	6.51	6.28
Cl9(206)	6.56	1.14	1.13	1.31	1.88	1.76	2.03	2.83	4.87
Cl10(209)	0.00	0.60	0.43	0.38	1.09	0.84	0.71	1.05	0.00
Sum 44 congeners	1,267	210	205	261	337	380	486	594	650

STATION_ID	SB-110	SB-110	SB-110	SB-110	SB-110	SB-110	SB-110	SB-114	SB-114
FIELD SAMPLE_ID	SB-110 16-18	SB-110 18-20	SB-110 20-25	SB-110 25-30	SB-110 30-40	SB-110 40-50	SB-110 50-60	SB-114 0-2	SB-114 2-4
SAMPLE DEPTH_TOP	16	18	20	25	30	40	50	0	2
SAMPLE DEPTH_BOT	18	20	25	30	40	50	60	2	4
DEPTH_UNIT	CM	CM	CM	CM	CM	CM	CM	CM	CM
Cl2(08)	0.00	0.00	0.72	1.05	2.13	1.10	0.23	0.00	0.23
Cl3(18)	0.00	0.00	0.00	0.00	1.92	0.00	0.19	0.00	0.00
Cl3(21)/Cl3(33)/Cl3(20)	0.00	0.00	0.00	0.00	2.70	1.64	0.31	0.00	0.00
Cl3(28)	1.72	2.46	2.01	1.96	3.56	0.00	0.35	0.00	0.60
Cl3(31)	0.00	0.00	1.76	1.98	4.23	2.09	0.00	0.00	0.00
Cl4(44)	1.90	1.91	2.96	3.76	10.36	3.55	0.62	0.43	0.47
Cl4(49)	4.19	4.43	4.33	7.42	14.71	5.83	1.28	1.08	0.76
Cl4(52)	4.35	5.55	6.31	7.28	27.62	9.25	1.69	1.57	1.01
Cl4(56)	0.00	0.00	0.00	0.00	4.63	0.00	0.00	0.00	0.00
Cl4(60)	0.00	2.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl4(66)	3.26	4.09	4.60	6.12	13.30	4.56	0.83	0.91	1.02
Cl4(70)	3.75	4.93	4.89	7.12	20.77	6.78	0.97	1.21	1.46
Cl4(74)	0.00	0.00	1.96	2.29	7.01	0.00	0.40	0.00	0.00
Cl4(77)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(105)	4.45	6.17	5.20	5.50	17.87	7.75	1.17	1.18	1.02
Cl5(110)	21.67	25.38	28.98	36.43	88.60	32.69	5.88	4.40	5.14
Cl5(118)	17.16	21.46	20.76	24.01	62.85	24.31	3.71	4.21	4.41
Cl5(126)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(87)	5.18	7.39	5.97	8.00	24.03	10.23	1.33	0.97	1.45
Cl5(90)/Cl5(101)	24.39	28.62	31.14	39.80	89.12	33.16	6.52	4.23	5.62
Cl5(95)/Cl5(88)	16.00	18.68	19.73	26.98	58.22	22.62	4.10	2.87	3.55
Cl5(97)	4.98	5.45	6.25	8.79	19.68	8.63	1.28	1.32	1.38
Cl5(99)	13.32	14.34	15.46	20.86	37.06	13.53	3.82	2.51	3.00
Cl6(128)	6.06	8.40	8.95	10.45	20.79	7.21	1.23	1.48	1.72
Cl6(129)/Cl6(158)	6.19	7.20	6.10	7.88	13.71	5.46	1.00	1.15	1.37
Cl6(132)/Cl6(168)/Cl6(153)	97.89	126.45	109.91	131.49	223.33	81.52	20.10	15.85	17.67
Cl6(138)	43.98	55.64	51.16	61.62	111.06	41.97	8.30	7.55	9.43
Cl6(141)	12.62	17.36	14.60	15.99	28.91	12.32	2.21	1.78	2.99
Cl6(149)	59.56	75.11	70.32	86.35	142.94	54.52	12.44	9.71	12.57
Cl6(151)	19.67	24.50	23.93	29.47	47.73	19.11	3.93	4.16	4.53
Cl6(156)	4.89	5.15	5.36	7.12	11.59	5.20	0.91	1.51	1.18
Cl7(170)	40.46	53.96	43.92	51.39	74.92	28.37	6.25	6.49	7.52
Cl7(174)	33.95	44.06	38.45	46.36	65.64	25.86	5.35	6.68	7.45
Cl7(177)	23.06	29.64	25.76	30.50	40.88	16.55	3.42	4.05	5.60
Cl7(180)	82.00	106.73	91.40	122.28	174.73	60.66	14.18	13.90	17.39
Cl7(183)	18.79	25.61	21.39	25.17	36.46	16.72	3.16	3.00	3.86
Cl7(187)	37.29	50.98	44.06	51.47	72.29	30.20	6.04	7.26	8.13
Cl8(194)	18.04	28.83	13.56	23.57	33.15	13.46	2.40	1.86	6.26
Cl8(195)	10.48	11.35	8.31	9.99	16.59	7.94	1.30	2.54	3.18
Cl8(201)/Cl8(204)	2.29	2.88	3.48	0.00	4.95	2.43	0.52	0.00	0.00
Cl8(203)	9.56	26.83	10.82	12.31	18.18	6.40	1.36	2.21	3.38
Cl9(206)	3.92	5.32	4.28	5.16	11.81	2.15	0.71	0.00	0.00
Cl10(209)	7.67	4.96	4.56	2.18	4.63	1.87	0.89	0.00	0.00
Sum 44 congeners	665	864	763	940	1,665	628	130	118	145

STATION_ID	SB-114	SB-114	SB-114	SB-114	SB-114	SB-114	SB-114	SB-114	SB-114
FIELD SAMPLE_ID	SB-114 4-6	SB-114 6-8	SB-114 8-10	SB-114 10-12	SB-114 12-14	SB-114 14-16	SB-114 16-18	SB-114 18-20	SB-114 20-25
SAMPLE DEPTH_TOP	4	6	8	10	12	14	16	18	20
SAMPLE DEPTH_BOT	6	8	10	12	14	16	18	20	25
DEPTH_UNIT	CM	CM	CM	CM	CM	CM	CM	CM	CM
Cl2(08)	0.41	0.00	0.26	0.25	0.20	0.20	0.23	0.33	0.09
Cl3(18)	0.50	0.00	0.16	0.25	0.20	0.13	0.16	0.00	0.00
Cl3(21)/Cl3(33)/Cl3(20)	0.31	0.00	0.18	0.27	0.26	0.19	0.23	0.37	0.12
Cl3(28)	0.96	0.00	0.56	0.53	0.57	0.45	0.52	0.68	0.17
Cl3(31)	0.00	0.00	0.27	0.31	0.23	0.38	0.31	0.33	0.00
Cl4(44)	0.98	0.78	0.77	0.59	0.83	0.87	0.90	0.86	0.26
Cl4(49)	1.01	1.30	1.10	0.99	1.09	1.12	1.21	1.44	0.29
Cl4(52)	1.78	1.62	1.82	1.30	1.85	1.54	2.19	1.88	0.38
Cl4(56)	0.00	0.00	0.46	0.40	0.35	0.44	0.42	0.56	0.00
Cl4(60)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl4(66)	1.32	1.34	0.96	0.92	0.94	1.16	1.29	1.31	0.28
Cl4(70)	1.44	1.65	1.45	1.15	1.39	1.60	1.60	1.85	0.37
Cl4(74)	0.00	0.00	0.51	0.49	0.48	0.68	0.57	0.65	0.00
Cl4(77)	0.00	0.00	0.00	0.30	0.00	0.00	0.00	0.00	0.00
Cl5(105)	0.00	1.25	1.47	1.52	1.54	1.99	2.39	1.60	0.36
Cl5(110)	5.47	4.79	6.71	6.30	6.72	8.45	9.55	8.83	1.48
Cl5(118)	3.62	4.77	5.47	5.38	5.69	7.09	8.23	7.06	1.39
Cl5(126)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl5(87)	0.00	0.00	1.60	1.59	1.60	2.12	2.41	2.15	0.41
Cl5(90)/Cl5(101)	5.09	5.50	7.12	7.27	6.94	8.99	8.71	9.06	1.61
Cl5(95)/Cl5(88)	3.94	4.00	4.44	4.16	4.29	5.29	5.46	5.58	1.00
Cl5(97)	1.40	1.47	1.43	1.28	1.46	1.69	2.00	1.94	0.34
Cl5(99)	2.51	3.06	3.54	3.32	3.33	4.08	4.43	5.02	0.92
Cl6(128)	1.94	1.81	2.06	2.05	1.95	2.61	2.59	2.80	0.53
Cl6(129)/Cl6(158)	1.69	2.23	1.39	9.73	1.57	1.91	1.81	2.04	0.37
Cl6(132)/Cl6(168)/Cl6(153)	15.95	18.18	25.07	28.77	26.24	34.21	35.10	36.39	5.57
Cl6(138)	8.62	9.50	11.58	12.42	12.02	15.56	15.41	16.02	2.73
Cl6(141)	2.13	1.99	2.98	3.72	3.44	4.83	4.42	4.14	0.83
Cl6(149)	11.77	12.29	15.30	17.15	15.39	14.92	13.28	21.13	3.42
Cl6(151)	3.74	4.61	5.18	5.89	5.18	6.48	6.53	7.27	1.19
Cl6(156)	0.00	1.52	1.17	1.30	1.23	1.70	1.71	1.50	0.35
Cl7(170)	6.87	7.47	10.50	11.87	10.47	14.48	13.22	12.57	2.60
Cl7(174)	6.16	7.29	9.07	10.32	8.99	11.60	10.75	11.54	2.30
Cl7(177)	5.04	5.25	5.74	6.46	5.60	7.88	7.22	7.57	1.41
Cl7(180)	13.87	17.11	24.18	20.64	19.87	24.08	18.55	29.52	5.39
Cl7(183)	4.04	4.43	4.83	5.34	4.82	6.50	5.87	6.44	1.22
Cl7(187)	7.70	9.15	9.84	10.87	9.67	12.74	12.09	12.95	2.40
Cl8(194)	4.91	5.99	4.25	4.60	4.38	6.15	5.21	6.33	1.15
Cl8(195)	3.36	0.00	2.44	2.57	1.92	2.53	2.67	2.02	0.89
Cl8(201)/Cl8(204)	0.00	0.00	0.72	0.85	0.53	0.91	0.64	0.80	0.00
Cl8(203)	2.45	4.09	2.43	2.83	2.08	2.68	3.17	2.85	0.75
Cl9(206)	0.00	1.09	1.29	1.42	1.04	1.50	1.41	1.34	0.36
Cl10(209)	0.00	0.00	1.17	0.45	0.40	0.61	0.60	0.69	0.23
Sum 44 congeners	131	146	181	198	177	222	215	237	43

STATION_ID	SB-114	SB-114	SB-114	SB-114
FIELD SAMPLE_ID	SB-114 25-30	SB-114 30-40	SB-114 40-50	SB-114 50-60
SAMPLE DEPTH_TOP	25	30	40	50
SAMPLE DEPTH_BOT	30	40	50	60
DEPTH_UNIT	CM	CM	CM	CM
Cl2(08)	0.07	0.76	1.25	1.07
Cl3(18)	0.00	0.57	0.69	0.63
Cl3(21)/Cl3(33)/Cl3(20)	0.00	0.88	1.44	1.01
Cl3(28)	0.22	1.47	1.95	0.98
Cl3(31)	0.13	0.88	0.96	0.61
Cl4(44)	0.21	2.40	3.87	2.51
Cl4(49)	0.33	5.53	10.13	6.28
Cl4(52)	0.39	5.96	10.48	6.81
Cl4(56)	0.00	1.27	1.97	1.16
Cl4(60)	0.00	0.00	0.00	0.00
Cl4(66)	0.31	4.33	7.66	4.63
Cl4(70)	0.45	4.52	7.36	4.65
Cl4(74)	0.00	1.43	2.40	1.57
Cl4(77)	0.00	0.00	0.00	0.00
Cl5(105)	0.39	4.24	7.74	4.57
Cl5(110)	1.75	19.41	32.03	18.95
Cl5(118)	1.49	18.40	22.33	18.50
Cl5(126)	0.00	0.00	0.00	0.00
Cl5(87)	0.40	4.70	7.40	4.79
Cl5(90)/Cl5(101)	1.66	24.38	37.14	19.56
Cl5(95)/Cl5(88)	1.06	17.59	27.45	16.36
Cl5(97)	0.30	5.33	9.19	5.76
Cl5(99)	0.97	16.88	22.33	16.14
Cl6(128)	0.59	6.52	8.97	4.88
Cl6(129)/Cl6(158)	0.37	5.11	6.62	3.50
Cl6(132)/Cl6(168)/Cl6(153)	5.90	70.60	95.57	46.49
Cl6(138)	2.78	35.91	42.73	23.73
Cl6(141)	0.73	11.16	13.51	6.96
Cl6(149)	3.75	47.57	62.12	31.93
Cl6(151)	1.34	20.99	20.17	12.88
Cl6(156)	0.40	3.94	5.76	3.01
Cl7(170)	2.35	30.32	31.66	15.91
Cl7(174)	2.19	27.51	26.63	15.95
Cl7(177)	1.35	21.14	19.50	11.30
Cl7(180)	5.31	59.55	63.28	34.31
Cl7(183)	1.10	17.65	15.70	10.03
Cl7(187)	2.45	31.55	34.42	18.01
Cl8(194)	1.23	12.86	12.73	7.06
Cl8(195)	0.68	4.78	5.44	2.69
Cl8(201)/Cl8(204)	0.27	2.15	2.17	1.14
Cl8(203)	0.73	5.50	7.09	3.71
Cl9(206)	0.30	2.45	3.53	1.72
Cl10(209)	0.13	0.76	2.77	1.22
Sum 44 congeners	44	559	696	393

ASHTABULA PHASE I CORE SEGMENTS and GLNPO SURFACE SEDIMENTS

345 Samples, 117 PCB Congeners

(ng/g, dry weight)

STATION_ID	T170A	T170A	T170A	T170A	T170A	T170A	T170A	T170A	T170A	T170A
FIELD SAMPLE_ID	T170-A-ZY	T170A 1.3-2F	T170A 2-3FT	T170A 3-4FT	T170A 4-5FT	T170A 5-6FT	T170A 6-7FT	T170A 7-8FT	T170A 8-9FT	T170A 9-10FT
SAMPLE DEPTH (from bottom)	0-1.3	1.3-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	0.73	11.85	14.65	19.21	26.18	33.92	31.38	37.17	53.22	114.44
Cl1(1)	0.04	0.06	0.06	0.07	0.07	0.07	0.07	9.43	9.20	26.24
Cl1(3)	0.02	0.03	0.03	0.03	0.03	0.03	0.03	5.94	7.52	18.03
Cl2(4)/(10)	0.08	0.10	0.11	0.12	0.12	0.12	0.12	31.19	47.09	124.56
Cl2(5)	0.07	0.10	0.10	0.11	0.11	0.11	0.11	2.45	0.17	4.49
Cl2(6)	0.06	0.07	0.08	0.08	0.09	0.09	3.67	251.21	172.54	319.84
Cl2(7)	0.04	0.05	0.05	0.06	0.06	0.06	0.06	3.08	4.48	10.36
Cl2(8)	0.07	0.09	0.09	0.10	0.10	0.10	6.12	96.18	125.49	410.87
Cl2(9)	0.05	0.07	0.07	0.08	0.08	0.08	0.08	5.53	6.32	16.56
Cl2(13)	0.05	0.07	0.07	0.08	0.08	0.08	0.08	65.92	53.15	82.11
Cl2(15)	0.09	0.12	0.12	0.13	0.14	0.14	0.14	40.04	46.92	127.31
Cl3(16)	0.51	0.09	0.09	0.10	0.10	2.91	15.22	307.66	375.34	1312.36
Cl3(17)	0.57	0.05	1.13	1.81	1.41	2.55	18.48	354.58	404.08	1373.20
Cl3(18)	1.30	0.07	2.54	4.16	2.21	4.33	39.62	1259.86	1449.35	4126.10
Cl3(19)	0.06	0.08	0.09	0.09	0.09	0.09	1.97	38.02	83.47	207.00
Cl3(22)	0.61	0.07	0.07	0.08	0.08	0.08	19.94	399.02	560.43	1687.55
Cl3(24)	0.04	0.05	0.05	0.06	0.06	0.06	0.06	2.91	5.07	10.14
Cl3(25)	0.76	1.80	2.29	2.93	2.30	3.73	16.97	965.70	680.95	1110.26
Cl3(26)	0.82	1.80	2.94	2.18	1.83	3.57	18.59	999.73	633.92	1281.84
Cl3(27)	0.03	0.04	0.05	0.05	0.05	0.05	1.58	27.88	43.15	123.64
Cl3(28)	1.58	2.49	3.74	3.69	3.96	4.98	55.93	1394.49	1877.92	4202.40
Cl3(31)	2.04	2.68	4.28	5.20	4.49	6.49	62.59	1858.40	2117.27	5481.79
Cl3(32)	0.30	0.04	0.04	0.04	0.04	0.04	9.73	210.81	289.83	935.15
Cl3(33)/(20)	0.90	3.17	3.57	3.95	3.50	4.11	31.83	531.51	814.14	2363.54
Cl3(37)	0.06	0.08	0.09	0.09	0.09	0.09	10.54	145.07	254.82	848.51
Cl4(40)	0.32	0.10	0.10	0.11	0.11	0.11	14.70	332.88	398.67	1397.43
Cl4(41)	0.18	0.05	0.05	0.06	0.06	0.06	28.74	69.16	152.19	681.25
Cl4(42)/(59)	0.80	0.07	2.42	4.20	0.08	4.38	28.17	719.52	952.50	2739.99
Cl4(43)	0.04	0.06	0.06	0.07	0.07	0.07	5.03	96.81	122.78	333.99
Cl4(44)	2.28	6.01	8.40	13.87	14.86	14.32	78.98	1947.69	2446.96	6502.43
Cl4(45)	0.46	0.05	0.05	0.06	0.06	0.06	14.27	274.14	409.96	1367.15
Cl4(46)	0.07	0.09	0.09	0.10	0.10	0.10	6.06	146.39	178.93	592.15
Cl4(47)	0.57	1.07	1.54	3.31	3.72	2.76	23.97	447.16	565.93	1645.43
Cl4(48)	0.36	0.07	0.07	0.08	0.08	0.08	13.83	194.19	342.25	1522.20
Cl4(49)	1.70	3.85	5.17	9.79	8.46	9.11	60.38	1643.91	1873.26	4661.39
Cl4(51)	0.06	0.08	0.09	0.09	0.09	0.09	3.94	87.62	116.70	356.54
Cl4(52)	2.18	3.78	5.89	10.18	8.45	10.64	79.66	2241.04	2716.39	6504.18
Cl4(53)	0.35	0.04	0.63	0.05	0.05	1.70	12.28	313.72	401.85	1281.02
Cl4(54)	0.04	0.05	0.05	0.06	0.06	0.06	0.06	3.75	5.09	17.51
Cl4(56)	0.83	0.09	0.09	0.10	1.65	2.70	33.38	516.66	871.92	2657.44
Cl4(60)	0.26	0.08	0.09	0.09	1.30	1.54	4.35	66.33	181.59	1018.72
Cl4(64)	1.12	1.16	2.19	2.86	2.39	3.90	33.59	857.19	1090.12	3420.96
Cl4(66)	1.46	3.19	3.97	7.27	6.37	7.57	68.56	830.52	1648.44	4462.84
Cl4(70)	1.91	3.63	5.12	8.50	7.75	9.16	79.88	1396.38	2315.71	6012.46
Cl4(71)	0.65	0.76	1.55	1.57	0.08	2.19	24.76	511.78	645.59	2069.39
Cl4(74)	0.83	0.04	1.63	3.01	1.93	3.05	33.26	367.12	803.65	2783.11
Cl4(77)	0.12	0.16	0.16	0.18	0.18	0.18	6.03	64.86	122.26	471.80
Cl4(81)	0.04	0.05	0.05	0.06	0.06	0.06	0.06	1.38	1.99	9.61
Cl5(82)	0.04	0.06	0.06	0.07	0.07	0.07	7.26	118.42	215.07	618.09
Cl5(83)/(119)	0.21	0.08	1.17	2.46	2.18	2.31	6.81	101.41	161.73	364.56
Cl5(84)	0.46	0.92	1.33	2.53	2.35	2.60	17.24	357.73	460.78	1330.57
Cl5(85)	0.21	0.05	0.05	0.89	0.84	0.64	6.48	148.86	250.48	753.38
Cl5(87)	0.37	0.79	1.10	2.12	1.83	2.94	13.21	200.03	433.35	1429.57
Cl5(91)	0.24	0.62	0.81	1.42	1.43	1.23	8.36	183.18	255.21	675.46
Cl5(92)	0.05	0.85	1.27	3.29	3.15	2.46	8.95	138.58	168.39	385.39
Cl5(95)	0.68	1.96	3.11	7.06	5.91	6.80	33.18	593.56	699.69	2149.92
Cl5(97)	0.40	0.83	0.04	2.54	2.70	2.84	14.08	173.70	313.90	1149.24
Cl5(99)	0.35	1.72	2.28	5.35	5.54	6.27	17.35	188.83	363.50	1150.67
Cl5(100)	0.04	0.05	0.05	0.29	0.42	0.06	0.49	4.12	5.39	15.92

STATION_ID	T170A	T170A	T170A	T170A	T170A	T170A	T170A	T170A	T170A	T170A
FIELD SAMPLE_ID	T170-A-ZY	T170A 1.3-2F	T170A 2-3FT	T170A 3-4FT	T170A 4-5FT	T170A 5-6FT	T170A 6-7FT	T170A 7-8FT	T170A 8-9FT	T170A 9-10FT
SAMPLE DEPTH (from bottom)	0-1.3	1.3-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	0.45	1.86	3.29	8.01	7.30	7.43	27.76	327.63	588.35	1616.91
Cl5(105)	0.33	0.08	1.08	1.77	0.98	2.85	8.50	131.41	244.72	1329.28
Cl5(110)	1.14	3.76	5.55	11.90	9.95	11.71	45.74	749.28	989.93	2888.51
Cl5(114)	0.09	0.12	0.12	0.13	0.14	0.14	0.14	3.14	9.65	48.55
Cl5(115)	0.08	0.10	0.11	0.12	0.12	0.12	0.66	4.15	7.68	51.57
Cl5(118)	0.51	2.27	3.04	6.98	6.67	7.90	23.77	209.64	460.02	1510.03
Cl5(107)/(123)	0.08	0.11	0.12	1.37	2.09	2.51	5.35	58.50	89.36	295.64
Cl5(124)	0.05	0.07	0.07	0.08	0.08	0.08	0.08	5.95	15.26	72.91
Cl5(126)	0.07	0.10	0.10	0.11	0.11	0.11	0.11	1.50	3.59	10.24
Cl6(128)	0.07	0.59	0.09	0.10	0.10	0.10	2.40	23.61	41.83	149.02
Cl6(130)	0.07	0.09	0.09	1.62	1.31	1.66	2.39	15.51	23.47	50.85
Cl6(134)	0.06	0.07	0.08	0.08	1.16	1.47	1.47	8.99	14.47	37.86
Cl6(135)	0.06	0.41	0.54	1.34	1.31	1.04	2.32	23.03	30.76	66.93
Cl6(136)	0.08	0.58	0.84	2.64	3.34	4.18	3.10	18.86	42.63	70.99
Cl6(137)	0.09	0.12	0.12	2.36	3.00	4.47	2.28	4.29	10.79	33.40
Cl6(138)	0.07	1.03	1.35	3.43	3.74	5.33	8.90	63.52	96.15	334.33
Cl6(141)	0.04	0.05	0.05	0.06	1.77	1.76	0.06	8.08	19.52	73.03
Cl6(144)	0.08	0.10	0.11	0.12	0.12	0.12	0.60	3.65	7.89	22.12
Cl6(146)	0.02	0.48	0.83	2.12	2.01	1.99	17.54	29.25	40.00	65.68
Cl6(149)	0.13	1.33	1.92	5.30	5.57	5.48	10.91	101.67	127.62	341.18
Cl6(151)	0.07	0.49	0.69	1.62	1.98	1.66	2.78	28.55	42.40	75.51
Cl6(132)/(153)/(168)	0.26	1.64	2.29	6.34	6.28	6.59	12.61	111.92	177.88	449.49
Cl6(156)	0.02	0.02	0.75	1.86	3.65	4.64	2.83	6.57	15.17	56.61
Cl6(157)	0.07	0.09	0.09	0.10	0.10	0.10	0.10	1.98	4.53	16.50
Cl6(129)/(158)	0.06	0.08	0.09	0.98	1.13	1.13	1.33	7.91	15.45	51.73
Cl6(163)	0.06	0.39	0.50	1.28	1.65	1.22	2.15	23.48	28.55	78.56
Cl6(164)	0.04	0.06	0.06	0.07	0.07	0.07	1.28	7.01	12.59	32.78
Cl6(166)	0.07	0.10	0.10	0.11	0.11	0.11	0.11	0.14	0.17	3.76
Cl6(167)	0.04	0.06	0.06	1.15	0.07	5.73	2.98	3.52	8.19	23.12
Cl6(169)	0.09	0.13	0.13	0.14	0.15	0.15	0.14	0.13	0.15	0.24
Cl7(170)	0.05	0.07	0.07	1.53	1.93	2.18	2.10	15.59	24.47	87.77
Cl7(171)	0.04	0.30	0.05	1.24	0.82	0.90	0.85	4.79	8.06	16.56
Cl7(172)	0.05	0.07	1.00	0.08	0.08	0.08	0.08	4.66	6.51	13.99
Cl7(174)	0.03	0.46	0.49	1.31	1.91	1.83	2.29	18.42	29.65	55.62
Cl7(176)	0.04	0.39	0.47	1.59	2.62	4.00	1.90	3.51	4.66	7.98
Cl7(177)	0.05	0.07	0.43	1.63	1.92	2.21	2.08	15.61	22.11	38.18
Cl7(178)	0.04	0.35	0.33	1.40	0.95	1.25	1.30	6.76	8.47	12.03
Cl7(179)	0.07	0.43	0.59	1.52	2.17	2.39	1.92	10.89	16.23	25.44
Cl7(180)	0.05	1.00	0.88	3.16	4.43	5.07	5.99	33.04	62.94	146.51
Cl7(183)	0.05	0.07	0.78	1.82	4.85	6.17	2.37	10.97	18.61	34.38
Cl7(184)	0.03	0.04	0.05	0.25	0.43	0.70	0.41	0.31	0.38	1.21
Cl7(185)	0.05	0.07	0.07	0.08	0.08	0.08	0.08	1.95	3.17	6.66
Cl7(187)	0.04	0.98	0.99	3.04	4.16	4.07	4.30	29.95	39.86	67.12
Cl7(189)	0.07	0.10	0.10	0.99	1.68	1.53	0.11	1.08	1.80	4.89
Cl7(190)	0.06	0.07	0.08	0.08	0.09	0.09	0.08	3.51	6.06	14.94
Cl7(193)	0.03	0.04	0.04	0.04	0.97	1.18	0.04	2.57	3.23	6.68
Cl8(194)	0.04	0.71	0.51	1.27	1.72	1.55	2.43	14.29	20.83	39.16
Cl8(195)	0.04	0.05	0.05	0.06	0.06	0.06	0.06	5.05	6.95	13.84
Cl8(199)	0.07	1.43	2.03	6.38	6.37	6.48	5.46	20.12	28.75	50.10
Cl8(200)	0.08	0.17	0.12	0.13	0.41	0.13	0.48	1.74	2.27	4.29
Cl8(201)	0.08	0.11	0.12	0.97	2.06	2.90	1.23	2.13	3.11	6.91
Cl8(202)	0.06	0.57	0.47	1.64	1.49	1.32	1.21	2.92	4.13	7.61
Cl8(196)/(203)	0.02	0.67	0.89	1.89	2.40	2.31	2.60	13.28	19.08	35.75
Cl8(205)	0.02	0.02	0.02	0.03	0.75	1.25	0.67	1.03	1.56	2.95
Cl9(206)	0.15	3.29	4.36	14.16	13.24	19.35	15.55	23.18	35.62	123.51
Cl9(207)	0.07	0.19	0.14	0.39	0.47	0.87	1.55	2.53	3.77	19.98
Cl9(208)	0.06	1.05	1.33	4.78	4.18	5.48	5.40	6.77	11.25	29.21
Cl10(209)	0.46	12.74	16.52	88.53	75.68	110.15	134.70	145.10	275.57	1350.99
Sum 117 congeners	36	88	130	322	309	404	1,489	26,730	35,593	100,817

STATION_ID	T170A	T170A	T170A	T170A	T170B	T170B	T170B	T170B	T170B	T170B
FIELD SAMPLE_ID	170A 10-11F	T170-A-NML	T170-A-KJI	170A 17-18F	T170B 0-1FT	T170B 1-2FT	170B 2.1-3F	T170B 3-4FT	T170-B-VU	170B 5.5-6F
SAMPLE DEPTH (from bottom)	10-11	11-14	14-17	17-18	0-1	1-2	2.1-3	3-4	4-5.5	5.5-6
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	71.20	52.16	13.11	3.43	1.51	1.17	38.59	29.93	94.36	46.11
Cl1(1)	28.74	13.61	0.08	0.07	0.05	0.05	0.07	0.07	0.07	0.06
Cl1(3)	18.30	10.02	0.04	0.04	0.02	0.03	0.03	0.03	0.04	0.03
Cl2(4)/(10)	124.71	77.08	2.99	0.74	0.09	0.09	0.12	0.12	0.12	0.11
Cl2(5)	10.60	7.08	0.13	0.12	0.08	0.08	0.11	0.11	0.11	0.10
Cl2(6)	981.80	231.69	9.23	1.52	0.52	0.27	0.08	0.09	0.09	0.08
Cl2(7)	20.57	15.27	0.07	0.06	0.04	0.04	0.06	0.06	0.06	0.05
Cl2(8)	395.68	216.72	8.96	1.68	0.26	0.08	2.07	2.28	0.11	0.09
Cl2(9)	30.22	26.31	0.64	0.08	0.06	0.06	0.08	0.08	0.08	0.07
Cl2(13)	205.96	85.87	3.64	0.84	0.06	0.06	0.08	0.08	0.08	0.07
Cl2(15)	126.23	87.09	4.98	1.49	0.10	0.10	3.72	0.14	0.14	0.12
Cl3(16)	1155.42	293.68	16.29	3.53	0.71	0.77	0.10	6.73	12.18	3.56
Cl3(17)	1292.70	435.93	23.03	4.43	0.77	0.58	0.06	9.93	14.34	4.11
Cl3(18)	4756.14	1147.23	43.42	11.27	1.60	1.07	0.08	19.81	30.39	12.08
Cl3(19)	179.48	59.87	2.20	0.64	0.07	0.07	0.09	0.09	0.10	0.08
Cl3(22)	1415.84	385.26	26.06	6.19	0.75	0.61	0.08	10.03	15.63	5.42
Cl3(24)	11.52	9.27	0.07	0.06	0.04	0.04	0.06	0.06	0.06	0.05
Cl3(25)	2782.34	736.17	38.39	7.61	1.07	0.84	1.09	4.38	3.90	5.04
Cl3(26)	3598.84	795.22	31.72	9.05	1.18	0.81	1.24	5.33	5.49	5.75
Cl3(27)	131.11	36.32	2.07	0.56	0.04	0.04	0.05	0.05	0.05	0.05
Cl3(28)	5145.64	1344.84	57.92	19.79	1.88	1.35	1.88	29.61	47.16	15.76
Cl3(31)	6698.67	1581.01	71.53	21.61	2.24	1.54	2.25	33.73	47.75	17.77
Cl3(32)	796.37	229.57	12.31	2.74	0.28	0.24	0.04	4.52	6.40	2.58
Cl3(33)/(20)	1968.70	603.20	37.29	7.81	1.20	0.74	3.75	16.47	26.68	7.76
Cl3(37)	530.64	188.21	14.50	3.80	0.07	0.07	0.09	6.29	9.27	3.07
Cl4(40)	1187.34	295.45	21.91	4.88	0.44	0.08	5.16	8.14	12.00	3.41
Cl4(41)	216.80	69.18	5.28	1.98	0.04	0.04	0.06	0.06	2.83	0.98
Cl4(42)/(59)	2908.11	682.30	33.78	11.79	1.04	0.91	0.08	21.53	31.05	9.79
Cl4(43)	304.27	103.47	5.63	1.12	0.05	0.05	0.07	2.85	3.95	1.01
Cl4(44)	7691.28	1717.62	85.05	28.70	2.30	1.80	11.60	51.34	80.04	24.77
Cl4(45)	1290.20	316.30	18.31	4.24	0.48	0.31	0.06	8.11	12.12	3.67
Cl4(46)	556.20	129.75	7.60	2.00	0.07	0.08	0.10	3.77	5.27	1.71
Cl4(47)	1727.95	471.61	32.52	7.68	0.59	0.45	0.08	15.60	21.19	6.04
Cl4(48)	852.79	204.05	14.82	4.66	0.32	0.06	0.08	6.91	15.11	3.44
Cl4(49)	6770.06	1593.68	73.19	23.14	1.72	1.40	6.23	39.83	52.72	22.37
Cl4(51)	374.08	89.92	5.10	1.28	0.07	0.07	0.09	2.04	3.28	1.01
Cl4(52)	8659.88	2136.99	99.20	30.11	2.26	1.89	6.96	49.70	70.55	31.15
Cl4(53)	1314.21	298.58	16.08	3.53	0.40	0.25	0.05	5.99	9.64	3.01
Cl4(54)	12.62	5.63	0.07	0.26	0.15	0.04	0.06	0.06	0.06	0.05
Cl4(56)	1819.53	516.64	30.10	11.95	0.74	0.57	0.10	20.43	29.30	8.65
Cl4(60)	330.20	93.35	10.36	3.75	0.21	0.07	0.09	1.84	4.49	1.40
Cl4(64)	3316.85	773.82	35.06	14.47	1.01	0.83	1.70	22.62	33.16	10.62
Cl4(66)	3768.64	926.51	58.47	22.69	1.49	1.08	5.43	51.02	75.40	18.85
Cl4(70)	5120.78	1404.41	74.63	28.56	1.86	1.57	7.40	61.55	93.66	29.11
Cl4(71)	1965.05	469.42	33.51	8.02	0.71	0.54	0.08	14.10	20.88	6.14
Cl4(74)	1833.69	466.84	39.66	11.76	0.76	0.50	2.83	18.28	33.69	8.30
Cl4(77)	214.41	84.62	6.91	2.58	0.13	0.13	0.18	3.63	5.66	1.52
Cl4(81)	4.06	2.02	0.07	0.06	0.04	0.04	0.06	0.06	0.06	0.05
Cl5(82)	326.76	120.45	8.57	2.82	0.05	0.05	0.07	3.41	6.56	2.41
Cl5(83)/(119)	327.58	104.45	7.57	2.21	0.07	0.07	2.92	5.10	7.75	3.65
Cl5(84)	1325.85	333.08	23.10	5.41	0.42	0.47	3.02	10.07	14.76	7.10
Cl5(85)	518.12	140.21	10.48	3.18	0.21	0.05	1.78	2.44	6.48	2.88
Cl5(87)	681.44	193.54	15.62	6.25	0.30	0.09	5.02	5.04	15.89	8.85
Cl5(91)	727.97	181.65	11.87	2.71	0.23	0.33	1.91	4.51	8.55	3.48
Cl5(92)	423.37	123.68	9.19	2.90	0.28	0.27	4.35	5.80	9.89	5.81
Cl5(95)	2394.39	552.90	39.87	13.20	0.78	0.63	9.04	19.82	32.69	18.96
Cl5(97)	805.14	232.63	16.25	5.58	0.40	0.31	4.12	8.01	15.40	6.76
Cl5(99)	858.26	253.55	18.13	5.97	0.34	0.32	7.80	11.23	22.01	8.92
Cl5(100)	16.61	6.20	0.35	0.06	0.04	0.04	0.49	0.06	0.77	0.05

STATION_ID	T170A	T170A	T170A	T170A	T170B	T170B	T170B	T170B	T170B	T170B
FIELD SAMPLE_ID	T170A 10-11F	T170-A-NML	T170-A-KJI	T170A 17-18F	T170B 0-1FT	T170B 1-2FT	T170B 2.1-3F	T170B 3-4FT	T170-B-VU	T170B 5.5-6F
SAMPLE DEPTH (from bottom)	10-11	11-14	14-17	17-18	0-1	1-2	2.1-3	3-4	4-5.5	5.5-6
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	1266.93	306.65	25.53	14.05	0.49	0.40	11.14	17.64	31.93	17.76
Cl5(105)	493.23	165.08	13.59	5.64	0.72	0.26	4.40	3.41	9.38	5.45
Cl5(110)	2777.43	781.96	44.16	18.64	1.12	0.90	15.25	28.55	52.42	28.99
Cl5(114)	12.28	5.36	0.16	0.15	0.10	0.10	0.13	0.14	0.14	0.12
Cl5(115)	28.05	8.60	0.56	0.19	0.09	0.09	0.12	0.12	0.98	0.11
Cl5(118)	1037.90	287.33	24.39	9.43	0.51	0.36	11.71	15.25	28.47	14.64
Cl5(107)/(123)	200.06	60.13	4.92	1.84	0.09	0.09	3.22	3.89	7.34	2.53
Cl5(124)	29.46	9.46	0.82	0.42	0.06	0.06	0.08	0.08	0.08	0.63
Cl5(126)	5.71	1.66	0.13	0.12	0.08	0.08	0.11	0.11	0.11	0.89
Cl6(128)	70.61	24.88	2.01	2.04	0.07	0.08	0.10	0.10	0.11	3.00
Cl6(130)	36.44	15.52	1.48	0.93	0.07	0.08	3.49	2.23	3.30	1.37
Cl6(134)	27.57	10.79	0.97	0.87	0.06	0.06	1.99	1.44	2.04	1.10
Cl6(135)	50.54	21.02	1.73	2.14	0.07	0.07	1.54	1.74	3.48	1.98
Cl6(136)	49.72	19.57	1.51	2.32	0.02	0.02	4.63	2.81	5.60	2.21
Cl6(137)	14.38	5.93	0.16	0.41	0.10	0.10	6.69	3.00	6.43	1.21
Cl6(138)	171.51	102.29	6.35	10.55	0.08	0.08	8.33	5.29	11.15	9.90
Cl6(141)	22.36	8.30	1.61	4.18	0.04	0.04	0.06	0.06	0.06	1.92
Cl6(144)	9.29	3.49	0.41	1.06	0.09	0.09	0.44	0.12	0.77	0.51
Cl6(146)	52.29	24.66	2.14	2.29	0.02	0.02	2.13	2.91	4.11	2.15
Cl6(149)	240.16	96.42	8.66	14.48	0.16	0.07	8.35	7.51	12.63	11.92
Cl6(151)	51.44	23.76	2.52	4.98	0.07	0.08	2.20	2.00	0.86	2.60
Cl6(132)/(153)/(168)	259.06	99.97	9.99	18.99	0.16	0.06	9.92	8.19	15.17	13.84
Cl6(156)	17.89	7.77	0.75	1.42	0.02	0.02	4.86	3.05	5.76	1.33
Cl6(157)	6.29	2.66	0.12	0.11	0.07	0.08	0.10	0.10	0.11	0.38
Cl6(129)/(158)	24.00	9.12	1.09	1.41	0.07	0.07	1.94	0.09	2.87	1.52
Cl6(163)	44.00	22.46	1.83	3.13	0.07	0.07	1.67	1.71	2.57	2.40
Cl6(164)	18.64	7.99	0.72	1.12	0.05	0.05	0.07	1.49	0.07	0.87
Cl6(166)	2.70	0.14	0.13	0.12	0.08	0.08	4.79	0.11	0.11	0.10
Cl6(167)	10.77	4.03	0.54	0.70	0.05	0.05	0.07	0.07	7.31	0.62
Cl6(169)	0.22	0.13	0.17	0.12	0.11	0.11	0.14	0.14	0.15	0.13
Cl7(170)	29.26	12.30	1.59	5.79	0.06	0.06	2.66	2.08	3.18	1.60
Cl7(171)	8.67	3.53	0.58	1.40	0.04	0.04	1.25	0.81	0.98	0.42
Cl7(172)	7.24	3.55	0.46	1.13	0.06	0.06	0.08	0.08	3.10	0.52
Cl7(174)	26.65	12.84	1.75	7.21	0.03	0.03	2.38	1.79	3.39	1.59
Cl7(176)	3.88	2.24	0.34	1.01	0.05	0.05	4.69	2.33	4.62	0.49
Cl7(177)	24.11	11.31	1.68	4.34	0.06	0.06	0.08	1.80	3.50	1.34
Cl7(178)	8.64	4.61	0.63	1.27	0.04	0.04	1.00	1.12	1.66	0.48
Cl7(179)	11.90	6.89	0.13	2.80	0.08	0.08	2.65	1.91	3.60	0.93
Cl7(180)	57.88	25.96	4.24	15.68	0.06	0.06	5.78	4.07	9.08	4.00
Cl7(183)	16.92	7.43	1.08	3.64	0.06	0.06	7.71	3.54	7.88	1.36
Cl7(184)	0.35	0.26	0.06	0.06	0.04	0.04	0.80	0.50	0.94	0.05
Cl7(185)	2.63	1.38	0.28	1.00	0.06	0.06	0.08	0.08	0.08	0.07
Cl7(187)	38.48	19.12	2.61	8.05	0.05	0.05	4.87	3.79	6.89	2.34
Cl7(189)	1.95	0.95	0.13	0.12	0.08	0.08	0.11	0.11	0.11	0.10
Cl7(190)	7.57	2.32	0.36	1.26	0.06	0.06	0.08	0.09	0.81	0.40
Cl7(193)	4.26	1.86	3.32	0.77	0.03	0.03	1.10	0.59	1.42	0.19
Cl8(194)	20.62	9.43	1.66	3.54	0.04	0.50	1.78	1.51	3.35	1.37
Cl8(195)	7.78	3.39	0.77	1.47	0.04	0.04	0.06	1.21	0.06	0.41
Cl8(199)	25.22	13.62	1.85	3.50	0.08	0.08	6.91	5.14	9.68	1.66
Cl8(200)	2.41	1.10	0.19	0.53	0.09	0.09	0.13	0.50	0.74	0.18
Cl8(201)	3.11	1.60	0.34	0.57	0.09	0.09	3.79	2.27	3.67	0.26
Cl8(202)	3.85	2.20	0.30	0.68	0.06	0.06	1.54	1.36	2.02	0.35
Cl8(196)/(203)	18.36	8.97	1.29	3.24	0.02	0.03	2.91	1.78	3.80	0.99
Cl8(205)	1.57	0.03	0.03	0.03	0.02	0.02	1.56	0.95	1.87	0.02
Cl9(206)	24.40	14.56	1.43	1.03	0.08	0.08	20.58	11.37	25.88	2.42
Cl9(207)	4.34	2.40	0.23	0.16	0.07	0.08	1.01	2.07	2.85	0.21
Cl9(208)	8.26	6.08	0.51	0.26	0.07	0.07	6.10	5.38	9.04	0.74
Cl10(209)	188.93	250.34	11.27	2.15	0.31	0.46	178.09	217.71	438.15	17.42
Sum 117 congeners	100,641	26,278	1,474	582	40	31	476	1,024	1,745	524

STATION_ID	T170B	T170B	T170B	T170B	T170B	T170B	T170B	T171A	T171A	T171A
FIELD SAMPLE_ID	T170B 6-7FT	T170B 7-8FT	T170B 8-9FT	T170B 9-10FT	T170-B-ONM	T170-B-LKJ	70B 16.1-17.1	T171A 0-1FT	T171A 1-2FT	T171A 2-3FT
SAMPLE DEPTH (from bottom)	6-7	7-8	8-9	9-10	10-13	13-16.1	16.1-17.1	0-1	1-2	2-3
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	59.25	58.53	69.99	77.31	64.95	25.45	4.85	0.15	5.28	18.67
Cl1(1)	0.07	0.12	0.14	38.71	20.15	0.07	0.08	0.05	0.05	0.06
Cl1(3)	0.04	0.06	0.07	26.28	13.89	0.04	0.04	0.02	0.03	0.03
Cl2(4)/(10)	11.24	62.59	58.20	165.89	199.56	10.08	0.13	0.08	0.10	0.11
Cl2(5)	0.12	0.20	0.22	13.02	10.96	0.12	0.12	0.08	0.09	0.10
Cl2(6)	169.85	823.02	120.91	1150.04	354.47	14.62	1.40	0.06	0.07	0.08
Cl2(7)	0.06	6.45	5.78	23.98	21.87	0.06	0.07	0.04	0.05	0.06
Cl2(8)	73.33	468.20	180.13	593.24	327.75	22.37	1.71	0.07	0.08	0.09
Cl2(9)	1.85	10.77	9.13	42.15	36.16	1.47	0.08	0.05	0.06	0.07
Cl2(13)	48.99	358.25	49.25	375.50	140.03	7.10	0.80	0.05	0.06	0.07
Cl2(15)	13.73	191.67	79.85	224.27	209.03	14.73	1.45	0.09	0.11	0.13
Cl3(16)	278.16	1386.98	325.62	1568.19	548.79	30.03	5.67	0.07	0.08	0.09
Cl3(17)	387.45	2232.95	399.57	1976.33	861.41	37.42	6.67	0.04	0.83	0.06
Cl3(18)	1114.47	6214.48	949.21	6219.15	2168.82	105.72	17.41	0.06	1.24	0.08
Cl3(19)	20.23	205.61	73.05	245.54	97.94	6.06	0.96	0.06	0.07	0.09
Cl3(22)	197.56	766.31	730.15	1483.68	663.20	43.14	9.41	0.05	0.75	0.07
Cl3(24)	0.06	5.67	5.10	13.26	12.66	0.06	0.07	0.04	0.05	0.06
Cl3(25)	749.14	4411.30	267.94	4203.86	1265.92	36.29	7.84	0.04	1.02	0.06
Cl3(26)	729.11	4273.99	280.06	5689.15	1472.50	56.39	10.60	0.06	1.28	0.08
Cl3(27)	14.39	153.07	55.71	133.73	85.86	4.68	0.82	0.04	0.04	0.05
Cl3(28)	1336.43	8351.99	1301.60	6711.19	2336.02	122.73	27.05	0.07	1.73	0.09
Cl3(31)	731.58	2497.98	2220.40	5247.92	2868.10	151.75	29.56	0.04	2.03	0.05
Cl3(32)	188.20	1077.48	227.98	1018.79	386.96	29.46	5.21	0.03	0.03	0.04
Cl3(33)/(20)	496.68	3248.48	583.02	2703.09	989.21	55.59	11.35	0.07	0.98	0.09
Cl3(37)	77.93	361.21	423.12	526.01	327.53	30.88	5.52	0.06	0.07	0.09
Cl4(40)	274.66	1827.25	290.18	1398.18	503.76	26.70	8.46	0.08	0.09	0.10
Cl4(41)	25.44	449.94	131.68	275.01	131.13	12.92	3.32	0.04	0.05	0.06
Cl4(42)/(59)	692.22	4494.29	671.14	3731.60	1189.48	69.23	18.56	0.05	1.13	0.07
Cl4(43)	41.30	495.18	138.59	399.68	201.79	10.63	2.04	0.05	0.05	0.06
Cl4(44)	1860.10	11301.82	1646.39	10016.70	3126.31	173.64	44.51	0.06	2.44	0.08
Cl4(45)	294.85	1700.22	250.65	1564.87	503.59	29.35	8.10	0.04	0.05	0.06
Cl4(46)	118.69	714.35	145.63	580.50	236.33	16.79	3.51	0.07	0.08	0.09
Cl4(47)	407.93	2747.98	402.25	2348.65	812.04	7.13	12.64	0.05	0.77	0.07
Cl4(48)	174.90	1214.63	357.90	886.55	353.69	35.37	6.89	0.05	0.06	0.07
Cl4(49)	1482.90	9326.68	1320.43	8503.82	3044.96	152.68	36.07	0.05	1.78	4.98
Cl4(51)	84.93	486.39	99.46	398.27	200.02	10.42	2.20	0.06	0.07	0.09
Cl4(52)	2091.85	12464.80	1813.32	11002.07	3647.76	204.57	49.98	0.04	2.49	4.62
Cl4(53)	269.73	1693.28	292.00	1519.68	520.20	27.18	6.91	0.04	0.36	0.05
Cl4(54)	2.28	8.63	7.38	17.89	8.83	0.06	0.07	0.04	0.05	0.06
Cl4(56)	571.83	4131.40	660.71	2191.02	1004.74	60.25	18.41	0.07	0.83	0.09
Cl4(60)	21.16	461.31	141.90	425.53	148.89	24.37	7.02	0.06	0.07	0.09
Cl4(64)	862.81	5350.53	832.43	4307.74	1468.16	78.05	22.28	0.02	1.09	0.03
Cl4(66)	471.36	1678.11	2237.34	2556.84	1638.24	120.26	35.53	0.05	1.45	3.76
Cl4(70)	1469.56	10539.64	1908.93	5957.57	2372.85	159.06	42.53	0.06	2.02	4.66
Cl4(71)	480.69	3062.96	485.64	2548.23	927.79	47.06	12.60	0.05	0.77	0.07
Cl4(74)	439.14	3149.26	743.86	2047.02	799.19	2.90	18.06	0.04	0.73	0.05
Cl4(77)	53.48	239.60	256.30	306.46	150.95	13.43	3.58	0.12	0.14	0.17
Cl4(81)	0.06	0.11	3.18	4.66	3.26	1.49	0.07	0.04	0.05	0.06
Cl5(82)	61.45	786.78	169.62	494.69	224.03	15.23	4.06	0.05	0.05	0.06
Cl5(83)/(119)	101.99	659.68	198.94	525.39	246.84	11.33	2.90	0.06	0.07	1.50
Cl5(84)	325.54	1963.98	303.65	1624.21	578.68	40.32	12.57	0.09	0.47	1.29
Cl5(85)	135.34	999.45	337.03	579.14	247.98	19.32	5.36	0.04	0.05	0.06
Cl5(87)	187.50	1486.01	338.97	721.50	308.43	29.94	7.48	0.09	0.10	1.20
Cl5(91)	153.72	1011.11	167.99	746.93	384.26	20.75	4.18	0.04	0.04	0.85
Cl5(92)	125.96	811.35	100.98	465.15	225.12	14.99	2.11	0.05	0.06	1.61
Cl5(95)	508.48	3398.88	550.20	2678.31	996.00	55.29	17.40	0.05	0.83	4.34
Cl5(97)	189.89	1351.03	286.78	786.51	402.28	30.57	6.89	0.03	0.03	1.96
Cl5(99)	200.82	1321.34	271.44	737.56	354.85	25.99	8.42	0.05	0.42	3.49
Cl5(100)	2.01	10.84	7.26	20.91	11.18	0.76	0.07	0.04	0.05	0.06

STATION_ID	T170B	T170B	T170B	T170B	T170B	T170B	T170B	T171A	T171A	T171A
FIELD SAMPLE_ID	T170B 6-7FT	T170B 7-8FT	T170B 8-9FT	T170B 9-10FT	T170-B-ONM	T170-B-LKJ	70B 16.1-17.1	T171A 0-1FT	T171A 1-2FT	T171A 2-3FT
SAMPLE DEPTH (from bottom)	6-7	7-8	8-9	9-10	10-13	13-16.1	16.1-17.1	0-1	1-2	2-3
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	268.17	1645.59	368.97	1021.43	570.75	47.33	14.55	0.09	0.55	4.87
Cl5(105)	98.42	859.39	223.49	536.44	267.75	23.45	6.72	0.06	0.07	0.09
Cl5(110)	726.60	4904.90	747.02	3673.19	1378.19	77.96	23.26	0.07	1.29	6.94
Cl5(114)	0.15	6.03	12.64	12.85	7.66	0.14	0.15	0.09	0.11	0.13
Cl5(115)	0.13	0.21	10.68	33.21	23.75	1.09	0.61	0.08	0.10	0.11
Cl5(118)	167.77	693.44	822.98	962.74	540.00	28.50	12.26	0.05	0.58	4.27
Cl5(107)/(123)	32.56	189.92	162.47	254.24	135.36	8.09	1.72	0.09	0.10	1.40
Cl5(124)	2.53	16.33	23.77	34.88	18.72	0.08	0.08	0.05	0.06	0.07
Cl5(126)	0.95	0.20	4.66	6.86	2.19	0.12	0.12	0.08	0.09	0.10
Cl6(128)	11.66	194.29	56.12	108.57	44.70	3.57	1.39	0.07	0.08	0.09
Cl6(130)	8.59	39.56	27.74	48.70	25.22	2.72	0.75	0.07	0.08	0.09
Cl6(134)	4.85	26.76	18.19	37.69	19.04	1.17	0.76	0.06	0.07	0.61
Cl6(135)	13.34	59.44	35.01	63.37	34.69	3.28	1.63	0.06	0.07	0.83
Cl6(136)	10.57	52.00	34.79	103.20	33.59	2.82	2.01	0.02	0.02	1.62
Cl6(137)	2.05	12.17	13.98	18.72	9.87	1.20	0.15	0.09	0.11	1.46
Cl6(138)	35.77	447.51	87.71	219.77	155.74	9.73	7.36	0.08	0.09	2.32
Cl6(141)	2.80	21.59	26.06	33.34	15.73	2.15	2.49	0.04	0.05	0.06
Cl6(144)	2.15	12.12	10.23	13.03	6.12	0.70	0.13	0.08	0.10	0.11
Cl6(146)	18.51	204.99	51.55	61.88	38.72	3.79	1.27	0.02	0.02	1.21
Cl6(149)	99.26	640.78	97.75	331.51	185.08	15.74	10.49	0.06	0.23	3.38
Cl6(151)	16.76	226.99	51.42	69.81	38.90	4.31	3.24	0.07	0.08	0.97
Cl6(132)/(153)/(168)	104.86	707.34	121.41	343.26	204.01	16.19	13.12	0.06	0.23	4.41
Cl6(156)	2.89	15.81	21.55	25.04	13.08	1.81	1.01	0.02	0.02	0.02
Cl6(157)	1.28	6.28	7.19	8.92	3.89	0.11	0.11	0.07	0.08	0.09
Cl6(129)/(158)	2.88	18.66	19.24	31.03	18.25	1.71	0.93	0.06	0.07	0.09
Cl6(163)	12.16	139.25	44.60	70.36	32.54	3.20	2.27	0.06	0.07	0.78
Cl6(164)	3.58	21.39	16.24	24.02	13.82	1.41	0.86	0.05	0.05	0.06
Cl6(166)	0.12	0.20	0.22	3.11	0.17	0.12	0.12	0.08	0.09	0.10
Cl6(167)	2.49	11.60	12.33	15.09	7.50	0.84	0.48	0.05	0.05	0.06
Cl6(169)	0.05	0.45	0.28	0.43	0.97	0.15	0.16	0.10	0.12	0.13
Cl7(170)	8.71	42.86	33.95	47.44	21.56	2.88	3.04	0.05	0.06	0.07
Cl7(171)	2.92	13.75	9.47	14.18	6.14	0.76	1.07	0.04	0.05	0.06
Cl7(172)	2.78	12.69	9.29	12.15	5.37	0.66	0.74	0.05	0.06	0.07
Cl7(174)	12.27	54.27	38.46	40.20	18.91	3.11	4.08	0.03	0.03	0.92
Cl7(176)	2.36	8.72	5.59	6.48	3.03	0.58	0.62	0.05	0.05	0.92
Cl7(177)	10.48	42.07	26.85	36.73	16.59	2.41	2.49	0.05	0.06	1.18
Cl7(178)	4.48	16.52	9.92	12.90	6.18	0.93	0.83	0.04	0.05	0.82
Cl7(179)	6.80	29.71	19.24	18.96	9.41	1.74	1.94	0.08	0.09	0.87
Cl7(180)	20.01	202.52	101.94	120.11	41.97	5.95	9.20	0.05	0.06	1.69
Cl7(183)	7.35	33.48	22.19	27.03	11.84	1.90	2.42	0.05	0.06	0.07
Cl7(184)	0.26	0.49	0.61	0.93	0.33	0.05	0.06	0.04	0.04	0.16
Cl7(185)	0.94	5.58	4.56	4.17	2.00	0.40	0.55	0.05	0.06	0.07
Cl7(187)	19.44	193.34	50.06	57.29	27.88	4.66	4.48	0.05	0.05	1.75
Cl7(189)	0.12	2.37	3.20	3.54	1.46	0.12	0.12	0.08	0.09	0.10
Cl7(190)	2.23	10.00	7.46	12.73	5.33	0.65	0.69	0.06	0.07	0.08
Cl7(193)	1.52	5.97	4.00	5.94	2.95	0.53	0.43	0.03	0.03	0.04
Cl8(194)	9.20	38.66	31.76	34.63	16.67	2.52	2.19	0.04	0.05	1.15
Cl8(195)	2.84	13.08	10.60	12.17	6.21	0.98	1.02	0.04	0.05	0.06
Cl8(199)	14.45	51.12	45.11	39.06	21.39	3.17	2.20	0.08	0.09	3.87
Cl8(200)	1.09	4.36	3.40	3.63	2.03	0.34	0.31	0.09	0.10	0.12
Cl8(201)	1.67	5.27	5.05	6.23	2.47	0.52	0.32	0.09	0.10	0.68
Cl8(202)	2.24	7.68	6.91	5.97	3.67	0.56	0.37	0.06	0.07	1.07
Cl8(196)/(203)	8.34	34.45	29.20	29.91	14.62	2.00	2.01	0.02	0.03	1.29
Cl8(205)	0.73	2.49	2.61	2.82	1.94	0.03	0.03	0.02	0.02	0.02
Cl9(206)	20.04	48.66	123.35	45.20	24.78	2.97	0.89	0.08	0.28	9.13
Cl9(207)	2.41	6.11	10.62	14.73	4.56	0.61	0.13	0.07	0.08	0.31
Cl9(208)	6.78	15.85	23.18	17.89	11.03	0.97	0.22	0.06	0.12	3.04
Cl10(209)	216.72	480.61	900.34	613.83	449.61	29.14	3.31	0.04	0.92	33.10
Sum 117 congeners	22,868	141,006	30,586	122,175	46,978	2,664	735	7	37	137

STATION_ID	T171A	T171A	T171A	T171A	T171A	T171A	T171A	T171A	T171A	T171A
FIELD SAMPLE_ID	T171A 3-4FT	T171A 4-5FT	T171A 5-6FT	T171A 6-7FT	T171A 7-8FT	T171A 8-9FT	T171A 9-10FT	T171-A-PON	T171-A-MLK	T171-A-JIH
SAMPLE DEPTH (from bottom)	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-13	13-16	16-18.4
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	22.61	25.47	40.71	49.52	79.57	49.56	91.61	54.51	44.50	16.62
Cl1(1)	0.07	0.07	0.06	0.07	0.10	0.11	25.38	25.54	7.81	0.07
Cl1(3)	0.03	0.04	0.03	0.03	0.05	0.06	13.83	17.44	6.80	0.03
Cl2(4)/(10)	0.12	0.12	0.11	0.12	52.93	54.62	103.30	140.09	22.23	4.34
Cl2(5)	0.11	0.11	0.10	0.11	0.16	0.18	0.19	12.24	0.12	0.11
Cl2(6)	0.08	0.09	0.08	11.29	456.99	139.93	171.34	651.46	33.34	6.95
Cl2(7)	0.06	0.06	0.06	0.06	3.61	4.54	7.94	28.54	3.01	0.06
Cl2(8)	0.10	0.11	0.10	9.21	188.27	180.23	220.78	391.23	35.75	8.07
Cl2(9)	0.08	0.08	0.07	0.08	7.80	8.19	14.88	46.31	4.01	0.08
Cl2(13)	0.08	0.08	0.07	6.37	130.68	58.01	69.92	215.18	21.44	3.07
Cl2(15)	0.14	0.14	0.13	2.57	45.86	56.59	118.79	168.56	30.47	5.72
Cl3(16)	0.10	0.11	5.99	28.72	563.43	368.87	682.62	739.25	73.12	18.27
Cl3(17)	0.06	0.06	7.53	38.89	739.93	505.27	706.19	1158.43	95.15	26.38
Cl3(18)	0.08	0.09	15.21	97.52	2291.18	1567.43	2156.19	2988.67	232.33	39.57
Cl3(19)	0.09	0.10	0.09	3.92	71.37	87.00	164.26	145.13	12.76	2.53
Cl3(22)	0.08	0.08	7.49	37.72	684.00	507.07	1449.21	916.93	110.70	17.87
Cl3(24)	0.06	0.06	0.06	0.06	4.25	5.02	9.96	16.28	0.07	0.06
Cl3(25)	0.06	0.06	2.64	54.55	1846.20	383.99	490.53	1913.50	155.50	20.55
Cl3(26)	0.08	0.09	3.29	51.13	1825.38	452.75	541.80	2605.53	167.39	26.33
Cl3(27)	0.05	0.05	0.05	3.07	48.90	50.54	105.98	111.63	9.97	2.34
Cl3(28)	0.10	5.80	22.99	117.50	2521.63	1260.11	2261.47	3211.33	315.81	59.96
Cl3(31)	0.05	6.61	24.76	141.98	2609.78	1514.54	4414.55	3991.70	391.72	69.74
Cl3(32)	0.04	0.04	3.34	19.68	383.24	303.50	432.41	544.52	50.25	15.03
Cl3(33)/(20)	0.10	5.90	13.44	51.16	959.48	885.14	1109.69	1362.69	143.09	27.09
Cl3(37)	0.09	0.10	4.90	15.40	232.65	273.03	737.87	377.23	65.72	20.14
Cl4(40)	0.11	0.11	5.74	28.84	550.01	463.38	593.65	725.10	79.99	25.53
Cl4(41)	0.06	0.06	0.06	3.72	137.58	198.78	358.12	133.09	20.09	7.14
Cl4(42)/(59)	0.08	0.08	14.09	71.27	1369.00	1043.91	1366.67	1624.85	200.38	36.38
Cl4(43)	0.07	0.07	0.06	7.94	186.76	122.64	288.39	290.21	27.62	7.16
Cl4(44)	12.63	22.34	37.23	164.10	3347.05	2706.22	3223.47	4373.57	449.38	86.34
Cl4(45)	0.06	0.06	5.54	29.25	573.47	459.47	594.81	746.94	73.78	23.12
Cl4(46)	0.10	0.11	2.62	12.76	257.92	206.33	236.43	347.09	41.14	9.60
Cl4(47)	2.53	4.79	9.36	43.14	816.83	624.53	694.97	1181.23	114.63	23.64
Cl4(48)	0.08	0.08	6.14	20.69	266.59	475.53	680.62	422.35	54.61	19.73
Cl4(49)	8.72	13.78	26.95	129.61	3033.03	1979.27	2463.46	4232.85	372.25	77.96
Cl4(51)	0.09	0.10	1.38	8.47	172.53	116.22	195.66	264.62	24.04	5.88
Cl4(52)	6.70	14.40	36.32	168.17	4146.03	2944.16	3722.39	5242.68	453.57	102.78
Cl4(53)	0.05	0.05	4.27	25.05	566.18	384.66	601.82	732.03	64.16	19.91
Cl4(54)	0.06	0.06	0.06	0.06	7.51	6.64	15.96	11.56	1.85	0.40
Cl4(56)	0.10	0.11	14.35	59.57	977.71	1022.71	1171.35	1184.38	173.17	35.67
Cl4(60)	0.09	0.10	0.09	4.17	126.41	250.85	359.95	167.88	30.91	14.15
Cl4(64)	0.03	2.86	14.36	73.21	1618.33	1307.08	1578.63	2049.03	217.23	41.55
Cl4(66)	5.23	12.05	29.86	107.99	1287.31	2210.37	3727.91	2095.12	312.68	71.66
Cl4(70)	5.37	14.62	48.01	156.25	2691.73	2894.01	3375.01	2939.91	446.79	93.50
Cl4(71)	0.08	1.97	8.94	47.82	961.87	738.34	908.83	1209.54	127.40	25.24
Cl4(74)	0.05	4.33	14.02	46.12	671.57	1118.20	1400.16	999.96	149.95	31.76
Cl4(77)	0.18	0.18	2.30	8.00	143.75	2.97	454.10	165.28	29.39	9.66
Cl4(81)	0.06	0.06	0.06	0.06	1.13	2.79	8.20	3.76	3.00	0.98
Cl5(82)	0.07	0.07	0.06	9.88	195.41	234.74	571.12	337.86	34.31	10.28
Cl5(83)/(119)	2.63	3.23	3.97	12.71	192.12	170.32	348.76	251.44	36.64	9.39
Cl5(84)	1.64	5.11	6.48	30.96	666.77	494.44	575.12	817.53	87.15	28.63
Cl5(85)	0.06	1.96	2.29	9.73	283.25	263.75	312.01	427.43	37.70	12.93
Cl5(87)	1.86	4.02	6.04	17.78	356.88	436.96	564.24	414.26	52.96	20.13
Cl5(91)	1.07	2.11	3.57	14.89	298.11	238.67	279.78	421.78	45.25	13.76
Cl5(92)	2.94	4.37	4.78	12.02	211.66	159.21	237.17	270.40	35.34	11.73
Cl5(95)	6.29	11.39	13.86	51.89	1066.33	865.29	1018.02	1353.09	147.87	29.00
Cl5(97)	2.50	4.71	6.32	21.53	372.55	416.84	519.24	490.02	66.86	21.09
Cl5(99)	5.58	9.16	13.04	25.72	367.22	436.68	459.66	492.66	62.60	23.17
Cl5(100)	0.06	0.06	0.63	0.84	8.30	5.80	15.01	15.14	1.65	0.51

STATION_ID	T171A	T171A	T171A	T171A	T171A	T171A	T171A	T171A	T171A	T171A
FIELD SAMPLE_ID	T171A 3-4FT	T171A 4-5FT	T171A 5-6FT	T171A 6-7FT	T171A 7-8FT	T171A 8-9FT	T171A 9-10FT	T171-A-PON	T171-A-MLK	T171-A-JIH
SAMPLE DEPTH (from bottom)	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-13	13-16	16-18.4
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	6.62	12.81	14.78	34.15	404.50	560.86	644.06	698.05	90.22	22.93
Cl5(105)	0.09	2.52	4.10	9.41	246.71	317.25	389.91	312.69	45.06	16.38
Cl5(110)	10.05	18.28	21.61	77.14	1436.90	1243.78	1253.21	1915.59	214.33	51.33
Cl5(114)	0.14	0.14	0.13	0.13	4.08	13.54	41.40	10.33	0.15	0.14
Cl5(115)	0.12	0.12	0.11	0.12	11.01	16.42	44.09	21.33	2.43	0.66
Cl5(118)	6.29	11.40	17.06	30.83	462.84	643.60	1435.73	781.48	93.99	28.98
Cl5(107)/(123)	2.33	3.37	4.23	7.39	135.51	112.07	287.41	186.23	20.17	6.09
Cl5(124)	0.08	0.08	0.07	0.08	10.04	20.94	57.26	22.41	2.75	0.98
Cl5(126)	0.11	0.11	0.10	0.11	2.71	4.42	9.12	5.92	0.12	0.11
Cl6(128)	0.10	0.11	0.10	4.25	48.65	49.66	130.95	62.35	7.51	2.97
Cl6(130)	1.38	2.58	4.13	2.96	34.28	26.27	48.20	34.40	5.31	1.80
Cl6(134)	0.08	1.66	4.13	1.49	19.63	15.64	34.56	24.57	3.23	1.03
Cl6(135)	1.27	1.71	1.51	2.72	50.02	33.29	60.09	48.62	7.27	2.70
Cl6(136)	2.83	4.10	9.21	3.55	40.35	32.36	62.73	45.19	6.41	2.04
Cl6(137)	1.86	3.18	11.87	0.13	7.96	12.57	32.04	12.14	1.74	0.88
Cl6(138)	2.77	6.30	7.92	8.76	133.79	152.99	314.54	132.92	21.28	8.21
Cl6(141)	0.06	0.06	0.06	0.06	15.58	26.63	56.77	19.64	3.54	1.60
Cl6(144)	0.12	0.12	0.11	0.12	7.62	9.87	20.28	8.00	1.31	0.46
Cl6(146)	2.22	2.81	3.72	4.85	62.64	45.58	75.32	51.53	9.89	3.34
Cl6(149)	4.83	8.42	7.19	12.94	180.87	151.21	174.39	152.96	32.57	11.71
Cl6(151)	1.39	2.37	2.16	3.83	51.83	48.77	71.31	53.33	9.32	3.45
Cl6(132)/(153)/(168)	5.86	10.42	8.17	14.15	218.86	227.78	197.02	204.25	35.47	13.14
Cl6(156)	1.70	3.47	10.02	1.72	12.05	20.58	51.24	17.49	2.78	1.49
Cl6(157)	0.10	0.11	0.10	0.10	4.06	6.14	15.10	6.90	0.95	0.10
Cl6(129)/(158)	0.86	1.15	1.82	1.66	14.15	19.06	46.31	23.47	3.52	1.50
Cl6(163)	1.16	2.03	2.57	2.89	48.70	40.93	86.93	52.92	8.03	2.52
Cl6(164)	0.07	2.26	0.06	1.36	14.69	16.59	33.90	16.56	2.77	1.10
Cl6(166)	0.11	0.11	4.58	0.11	0.16	0.18	2.56	0.19	0.12	0.11
Cl6(167)	0.07	0.07	0.06	1.81	6.95	9.29	22.55	9.79	1.91	0.07
Cl6(169)	0.14	0.15	0.14	0.14	0.75	0.28	0.36	0.31	0.16	0.15
Cl7(170)	1.21	1.83	3.08	2.31	31.52	30.57	82.23	27.07	5.19	2.34
Cl7(171)	0.06	0.58	0.06	0.69	11.54	8.50	16.40	8.02	1.54	0.79
Cl7(172)	0.08	0.08	0.07	1.49	10.58	8.14	13.24	7.20	1.54	0.50
Cl7(174)	1.20	2.08	3.28	2.59	41.96	36.16	55.51	24.13	6.25	2.71
Cl7(176)	1.53	2.47	8.92	1.63	7.56	5.42	8.04	4.01	1.15	0.60
Cl7(177)	0.08	0.08	0.07	2.41	34.59	25.52	38.41	23.37	5.54	2.46
Cl7(178)	0.06	1.49	1.52	1.98	15.60	9.22	12.37	8.05	2.12	0.89
Cl7(179)	1.49	2.11	5.22	2.21	25.30	18.48	24.39	11.62	3.64	1.46
Cl7(180)	3.02	4.78	9.61	5.59	88.27	66.05	159.50	54.81	12.18	5.96
Cl7(183)	0.08	3.85	14.80	3.49	26.50	21.67	32.69	15.33	3.67	1.76
Cl7(184)	0.30	0.45	1.61	0.38	0.46	0.40	0.97	0.47	0.21	0.05
Cl7(185)	0.08	0.08	0.07	0.08	4.48	4.01	5.82	2.31	0.62	0.34
Cl7(187)	2.39	3.72	5.91	5.02	74.45	46.32	70.27	37.55	9.41	4.25
Cl7(189)	0.11	0.11	0.10	0.11	2.26	2.12	4.23	2.00	0.12	0.11
Cl7(190)	0.08	0.09	0.08	0.08	7.41	6.87	13.91	6.79	1.22	0.60
Cl7(193)	0.04	0.60	0.04	0.64	5.37	3.73	5.83	4.02	0.87	0.26
Cl8(194)	1.13	1.80	2.22	3.35	31.71	25.31	40.26	22.15	4.16	1.97
Cl8(195)	0.06	0.06	0.06	1.00	10.25	8.38	13.53	8.09	1.72	0.55
Cl8(199)	5.43	6.67	10.51	11.07	45.22	35.14	48.90	27.42	5.94	2.37
Cl8(200)	0.28	0.45	0.12	0.53	4.02	3.09	4.20	2.70	0.57	0.24
Cl8(201)	0.13	0.13	0.12	1.79	4.98	3.59	6.67	3.43	0.62	0.41
Cl8(202)	1.63	1.69	1.83	1.91	6.90	4.99	7.61	4.35	1.09	0.52
Cl8(196)/(203)	1.64	2.28	3.73	3.38	29.02	22.79	36.86	19.89	3.88	1.94
Cl8(205)	0.79	0.03	0.02	0.03	2.25	1.77	2.25	2.11	0.03	0.03
Cl9(206)	12.13	13.43	67.94	27.12	82.68	43.49	107.87	30.94	6.02	2.12
Cl9(207)	0.31	0.56	1.50	1.12	5.70	4.35	17.85	5.36	0.68	0.33
Cl9(208)	4.28	4.68	8.86	8.00	15.95	13.31	27.26	11.76	2.16	0.69
Cl10(209)	81.55	116.44	236.47	170.15	413.53	420.02	1092.14	399.74	36.64	21.13
Sum 117 congeners	245	433	985	2,605	48,325	38,426	56,578	63,920	6,818	1,570

STATION_ID	T171A	T171B	T171B	T171B	T171B	T171B	T171B	T171B	T171B	T171B
FIELD SAMPLE_ID	71A 18.4-19.4	T171B 0-1FT	T171-B-YX	171B 2.3-3F	T171B 3-4FT	T171B 4-5FT	T171-B-TS	171B 6.3-6.5F	T171-B-QP	T171B 8-9FT
SAMPLE DEPTH (from bottom)	18.4-19.4	0-1	1-2.3	2.3-3	3-4	4-5	5-6.3	6.3-6.5	6.5-8	8-9
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	5.14	0.72	1.19	34.93	54.59	46.35	88.07	29.64	95.53	33.13
Cl1(1)	0.07	0.05	0.04	0.07	0.07	0.07	0.07	0.06	0.08	14.70
Cl1(3)	0.03	0.02	0.02	0.03	0.04	0.03	0.04	0.03	0.04	9.51
Cl2(4)/(10)	1.14	0.09	0.08	0.12	0.12	0.12	0.12	0.10	0.14	69.43
Cl2(5)	0.11	0.08	0.07	0.11	0.11	0.11	0.11	0.09	0.13	0.22
Cl2(6)	1.79	0.06	0.28	0.08	0.09	0.09	0.09	7.92	69.21	372.14
Cl2(7)	0.06	0.04	0.04	0.06	0.06	0.06	0.06	0.05	0.07	5.55
Cl2(8)	2.43	0.07	0.23	0.10	0.11	3.44	0.11	7.73	46.40	212.26
Cl2(9)	0.08	0.06	0.05	0.07	0.08	0.08	0.08	0.06	0.09	11.51
Cl2(13)	0.97	0.06	0.05	0.07	0.08	0.08	0.08	0.06	34.56	121.75
Cl2(15)	1.69	0.10	0.09	0.13	0.14	0.14	0.14	0.12	19.36	98.64
Cl3(16)	4.99	0.53	0.69	0.10	0.11	8.22	10.82	21.99	129.07	612.26
Cl3(17)	5.74	1.02	0.69	0.06	0.06	9.04	12.59	29.44	177.55	849.85
Cl3(18)	14.76	1.71	1.44	0.08	4.03	20.63	25.85	65.74	493.33	1672.91
Cl3(19)	0.90	0.07	0.06	0.09	0.10	0.09	0.10	2.83	24.01	71.68
Cl3(22)	8.76	1.06	0.65	0.07	0.08	11.73	15.68	30.14	159.70	707.51
Cl3(24)	0.06	0.04	0.04	0.06	0.06	0.06	0.06	0.05	0.07	6.48
Cl3(25)	7.54	0.98	0.86	0.06	0.06	4.00	4.04	36.92	218.49	1381.06
Cl3(26)	10.25	1.23	0.96	0.08	0.09	4.21	5.62	36.74	245.31	1445.32
Cl3(27)	0.77	0.04	0.03	0.05	0.05	0.05	0.05	1.97	17.54	76.91
Cl3(28)	26.07	2.56	1.71	0.10	5.36	31.81	37.69	84.36	553.72	2869.95
Cl3(31)	28.80	2.96	2.23	0.05	5.89	34.06	46.41	102.42	660.13	3530.63
Cl3(32)	3.76	0.42	0.32	0.04	0.04	4.48	6.09	15.09	94.26	449.53
Cl3(33)/(20)	11.25	1.30	0.99	0.10	5.87	17.78	24.79	36.37	225.42	1104.62
Cl3(37)	5.06	0.07	0.45	0.09	0.10	6.50	8.18	15.69	68.02	310.39
Cl4(40)	5.93	0.58	0.07	0.11	0.11	6.82	11.71	24.73	142.85	642.32
Cl4(41)	3.15	0.04	0.04	0.06	0.06	0.06	3.72	5.19	27.81	175.01
Cl4(42)/(59)	15.62	1.33	0.96	0.07	0.08	21.28	26.96	54.22	281.86	1637.66
Cl4(43)	1.49	0.05	0.04	0.07	0.07	0.07	4.14	6.52	42.43	177.33
Cl4(44)	36.48	3.31	2.31	12.06	18.12	49.31	63.75	123.58	709.26	4051.65
Cl4(45)	5.60	0.54	0.45	0.06	0.06	7.35	10.75	23.99	129.42	601.21
Cl4(46)	2.58	0.07	0.07	0.10	0.11	0.10	4.50	9.11	64.84	291.27
Cl4(47)	9.43	0.85	0.55	2.00	0.08	14.11	19.89	37.28	198.86	983.80
Cl4(48)	5.98	0.62	0.34	0.07	0.08	7.98	13.91	19.73	114.18	444.07
Cl4(49)	29.12	2.51	1.77	5.63	9.22	40.23	46.49	94.85	661.77	3624.69
Cl4(51)	1.38	0.23	0.06	0.09	0.10	2.20	2.84	5.85	42.59	182.45
Cl4(52)	38.23	3.37	2.39	6.49	11.50	46.08	64.01	126.26	868.61	2888.60
Cl4(53)	4.71	0.49	0.38	0.05	0.05	6.20	8.58	20.63	126.59	630.53
Cl4(54)	0.06	0.04	0.04	0.06	0.06	0.06	0.06	0.05	2.49	9.36
Cl4(56)	15.62	1.43	0.83	0.10	0.11	19.34	27.30	48.33	241.65	1369.75
Cl4(60)	5.87	0.07	0.16	0.09	0.10	0.09	3.58	7.15	26.46	184.90
Cl4(64)	19.16	1.58	1.19	0.03	2.88	19.97	30.43	60.33	322.84	1840.03
Cl4(66)	30.48	2.34	1.58	5.49	8.80	43.47	67.67	94.78	507.15	2368.12
Cl4(70)	38.69	3.04	2.04	6.30	9.99	61.09	86.39	131.85	672.99	3596.17
Cl4(71)	10.59	0.93	0.61	0.07	2.22	13.45	18.61	39.55	198.15	1150.39
Cl4(74)	16.19	1.16	0.78	0.05	3.08	17.59	31.32	44.38	216.76	1060.82
Cl4(77)	3.01	0.13	0.12	0.17	0.18	4.12	5.49	9.25	51.23	190.47
Cl4(81)	0.06	0.04	0.04	0.06	0.06	0.06	0.06	0.05	0.07	1.97
Cl5(82)	3.17	0.05	0.04	0.07	0.07	2.74	6.26	9.82	47.85	317.28
Cl5(83)/(119)	2.14	0.07	0.06	2.50	2.44	4.32	6.78	9.66	54.21	297.84
Cl5(84)	7.15	0.59	0.50	2.47	3.22	9.85	14.90	24.78	147.36	860.13
Cl5(85)	4.04	0.04	0.04	0.06	0.06	2.73	5.24	11.62	82.87	389.03
Cl5(87)	7.27	0.59	0.24	2.78	4.20	5.30	13.95	18.24	95.00	478.16
Cl5(91)	3.06	0.34	0.29	1.21	1.78	4.54	7.95	13.08	70.22	314.47
Cl5(92)	2.35	0.06	0.28	2.71	3.57	6.02	8.83	9.80	40.66	300.53
Cl5(95)	13.35	1.12	0.87	6.13	8.50	18.94	30.15	41.38	218.41	1253.45
Cl5(97)	6.10	0.73	0.39	2.37	3.49	7.52	13.50	19.93	99.56	436.55
Cl5(99)	6.78	0.52	0.43	6.73	8.95	12.20	20.19	22.40	115.02	567.27
Cl5(100)	0.06	0.04	0.04	0.06	0.06	0.06	0.64	0.05	2.82	11.21

STATION_ID	T171A	T171B	T171B	T171B	T171B	T171B	T171B	T171B	T171B	T171B
FIELD SAMPLE_ID	71A 18.4-19.4	T171B 0-1FT	T171-B-YX	171B 2.3-3F	T171B 3-4FT	T171B 4-5FT	T171-B-TS	171B 6.3-6.5F	T171-B-QP	T171B 8-9FT
SAMPLE DEPTH (from bottom)	18.4-19.4	0-1	1-2.3	2.3-3	3-4	4-5	5-6.3	6.3-6.5	6.5-8	8-9
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	11.53	0.81	0.48	7.96	10.24	18.39	30.68	33.78	161.13	863.84
Cl5(105)	6.26	0.40	0.32	0.09	3.63	3.80	9.26	12.25	61.07	292.22
Cl5(110)	20.35	1.70	1.16	11.11	13.66	28.29	44.74	64.50	306.71	1743.71
Cl5(114)	0.14	0.10	0.09	0.13	0.14	0.14	0.14	0.12	0.15	0.27
Cl5(115)	0.33	0.09	0.08	0.12	0.12	0.12	1.27	0.89	2.69	10.23
Cl5(118)	10.49	0.73	0.63	7.76	10.21	16.08	27.20	28.96	162.05	698.62
Cl5(107)/(123)	1.93	0.09	0.08	3.02	3.18	5.20	4.55	4.60	24.99	141.72
Cl5(124)	0.08	0.06	0.05	0.07	0.08	0.08	0.08	0.06	3.16	17.67
Cl5(126)	0.11	0.08	0.07	0.11	0.11	0.11	0.11	0.09	0.13	4.09
Cl6(128)	1.40	0.07	0.07	0.10	0.11	0.10	0.11	2.66	13.81	77.28
Cl6(130)	0.65	0.07	0.07	2.65	3.26	3.69	3.54	2.17	10.51	50.65
Cl6(134)	0.55	0.06	0.06	0.08	0.09	1.46	2.12	1.16	5.20	27.68
Cl6(135)	1.40	0.07	0.06	1.50	1.75	2.01	2.41	2.11	12.82	63.20
Cl6(136)	1.71	0.02	0.12	5.02	4.85	3.66	5.55	2.20	11.26	56.64
Cl6(137)	0.14	0.10	0.09	5.20	0.14	3.60	6.31	0.12	3.16	13.80
Cl6(138)	7.45	0.18	0.07	5.45	8.01	6.31	9.89	7.09	38.39	172.49
Cl6(141)	2.77	0.04	0.04	2.13	0.06	0.06	0.06	0.05	4.31	22.17
Cl6(144)	0.66	0.09	0.08	0.12	0.12	0.12	0.80	0.49	2.50	13.49
Cl6(146)	1.65	0.02	0.02	2.56	1.89	3.16	4.28	2.77	19.99	91.66
Cl6(149)	10.02	0.20	0.24	6.23	8.16	8.12	12.43	9.56	46.14	225.70
Cl6(151)	3.39	0.07	0.07	1.90	2.33	2.66	3.66	2.54	17.11	86.99
Cl6(132)/(153)/(168)	12.66	0.21	0.24	7.13	9.25	10.14	14.63	10.45	58.88	241.92
Cl6(156)	1.00	0.02	0.02	4.84	5.88	2.99	6.06	0.70	4.46	19.03
Cl6(157)	0.10	0.07	0.07	0.10	2.72	0.10	0.11	0.09	1.14	8.48
Cl6(129)/(158)	1.11	0.07	0.06	0.09	1.58	0.09	2.02	0.88	4.34	18.88
Cl6(163)	2.10	0.07	0.11	1.45	1.70	2.18	2.71	2.12	13.05	60.96
Cl6(164)	0.91	0.05	0.04	0.07	0.07	0.07	0.07	0.87	4.90	23.96
Cl6(166)	0.11	0.08	0.07	0.11	0.11	0.11	0.11	0.09	0.13	0.22
Cl6(167)	0.44	0.05	0.04	0.07	0.07	4.80	8.38	0.06	3.55	14.16
Cl6(169)	0.15	0.10	0.09	0.14	0.15	0.15	0.15	0.12	1.15	0.26
Cl7(170)	3.49	0.06	0.05	2.10	3.16	2.32	3.13	1.62	9.83	51.65
Cl7(171)	1.22	0.04	0.04	0.06	1.33	0.06	1.76	0.52	3.02	16.20
Cl7(172)	0.68	0.06	0.05	0.07	0.08	0.08	0.08	0.74	3.97	15.85
Cl7(174)	4.76	0.03	0.03	1.95	2.37	2.15	2.99	1.67	12.39	63.58
Cl7(176)	0.69	0.05	0.04	4.34	4.72	2.95	4.87	0.75	2.52	10.09
Cl7(177)	2.63	0.06	0.05	0.07	0.08	0.08	3.45	1.67	10.48	48.48
Cl7(178)	0.97	0.04	0.04	0.06	0.06	1.25	1.38	1.19	5.14	18.33
Cl7(179)	2.05	0.08	0.07	2.69	3.09	2.51	3.64	1.21	7.05	32.73
Cl7(180)	10.36	0.06	0.05	5.34	6.84	5.98	8.52	3.53	22.31	83.78
Cl7(183)	2.64	0.06	0.05	7.18	8.93	0.08	9.35	1.55	8.47	39.82
Cl7(184)	0.05	0.04	0.03	0.74	0.79	0.75	0.88	0.18	0.54	0.55
Cl7(185)	0.51	0.06	0.05	0.07	0.08	0.08	0.08	0.06	1.40	6.50
Cl7(187)	5.36	0.05	0.04	4.51	4.67	4.56	6.57	2.93	19.16	90.44
Cl7(189)	0.11	0.08	0.07	0.11	0.11	0.11	0.11	0.09	0.93	2.47
Cl7(190)	0.85	0.06	0.06	0.08	0.09	0.09	0.09	0.07	2.51	11.75
Cl7(193)	0.29	0.03	0.03	0.04	1.31	0.04	1.55	0.32	1.60	7.87
Cl8(194)	2.11	0.04	0.04	1.67	1.79	2.62	3.35	1.65	10.27	49.44
Cl8(195)	0.89	0.04	0.04	0.06	0.06	1.50	0.23	0.05	3.38	14.68
Cl8(199)	2.44	0.08	0.07	6.66	7.17	8.09	9.40	5.57	26.17	62.47
Cl8(200)	0.35	0.09	0.08	0.12	0.13	0.83	0.13	0.21	1.32	5.39
Cl8(201)	0.40	0.09	0.08	3.84	0.13	3.12	4.34	0.51	2.17	6.73
Cl8(202)	0.41	0.06	0.06	1.56	1.37	2.00	1.87	0.93	3.55	8.86
Cl8(196)/(203)	2.01	0.02	0.02	2.89	3.47	2.84	3.93	1.58	9.66	41.66
Cl8(205)	0.03	0.02	0.02	1.30	1.84	1.54	1.80	0.02	0.03	3.00
Cl9(206)	0.67	0.08	0.38	19.82	22.05	18.90	26.80	14.06	91.51	70.33
Cl9(207)	0.10	0.07	0.07	1.01	1.47	3.93	2.99	0.67	2.39	7.70
Cl9(208)	0.20	0.07	0.13	5.91	6.52	9.00	9.26	4.08	15.11	19.91
Cl10(209)	2.13	0.53	2.63	139.49	233.23	310.12	400.11	97.60	363.11	550.26
Sum 117 congeners	642	51	41	359	537	1,128	1,596	2,003	11,500	55,736

STATION_ID	T171B	T171B	T171B	T171B	T171B	T171B	T172A	T172A	T172A	T172A
FIELD SAMPLE_ID	T171B 9-10FT	T171B 10-11F	T171-B-LKJ	T171-B-IHG	71B 17.2-17.6	71B 17.6-18.2	T172A 0-1FT	T172A 1-2FT	T172A 2-3FT	T172A 3-4FT
SAMPLE DEPTH (from bottom)	9-10	10-11	11-14	14-17.2	17.2-17.6	17.6-18.2	0-1	1-2	2-3	3-4
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	31.10	96.61	62.81	22.68	3.43	2.01	2.36	15.34	17.12	15.33
Cl1(1)	14.09	31.28	18.93	0.07	0.05	0.05	0.05	0.06	0.07	0.07
Cl1(3)	9.42	20.83	13.56	0.03	0.03	0.03	0.03	0.03	0.04	0.03
Cl2(4)/(10)	60.60	116.66	114.03	3.43	0.95	0.09	0.09	0.11	0.13	0.12
Cl2(5)	0.23	6.36	10.28	0.11	0.09	0.09	0.09	0.10	0.12	0.11
Cl2(6)	99.02	22.09	256.68	12.01	1.37	0.71	0.50	0.08	0.09	0.09
Cl2(7)	5.59	13.92	20.34	0.06	0.05	0.05	0.05	0.05	0.06	0.06
Cl2(8)	150.16	19.87	311.31	13.72	2.35	0.88	0.26	0.09	0.11	2.26
Cl2(9)	8.44	21.86	32.56	1.05	0.06	0.06	0.06	0.07	0.08	0.08
Cl2(13)	51.50	5.33	94.89	5.15	0.06	0.06	0.06	0.07	0.08	0.08
Cl2(15)	90.55	131.04	158.21	11.54	1.54	0.59	0.11	0.12	0.14	0.14
Cl3(16)	466.26	56.16	514.94	34.78	6.33	2.41	0.74	0.09	0.11	0.10
Cl3(17)	521.77	69.94	726.11	35.92	7.48	2.78	1.02	1.11	2.85	4.57
Cl3(18)	1419.91	229.22	1851.87	96.94	20.02	7.17	2.34	2.15	4.19	9.84
Cl3(19)	75.36	12.34	90.27	4.09	0.92	0.49	0.07	0.08	0.10	0.10
Cl3(22)	520.53	66.83	656.10	32.71	11.18	3.34	1.26	0.07	0.08	6.61
Cl3(24)	8.16	9.57	11.58	0.06	0.05	0.05	0.44	0.05	0.06	0.06
Cl3(25)	335.71	64.78	865.28	39.66	7.28	2.39	1.67	2.40	0.06	8.58
Cl3(26)	372.11	87.14	1003.39	47.02	10.19	3.81	1.99	2.93	0.09	6.72
Cl3(27)	57.31	5.99	53.50	4.04	0.91	0.35	0.04	0.05	0.05	0.05
Cl3(28)	1847.59	222.14	2221.12	125.19	33.23	9.41	3.23	2.90	4.77	12.26
Cl3(31)	1972.43	277.40	2486.70	141.88	38.61	11.18	4.03	3.21	5.26	14.56
Cl3(32)	294.56	40.60	364.47	24.89	5.17	1.60	0.59	0.04	0.05	2.26
Cl3(33)/(20)	878.64	102.13	1019.68	61.35	13.51	4.35	1.80	2.55	4.06	7.33
Cl3(37)	330.27	24.66	313.84	27.62	6.74	1.73	0.69	0.08	0.10	0.10
Cl4(40)	447.08	56.14	489.16	26.12	9.24	2.67	0.93	0.10	0.12	0.11
Cl4(41)	240.94	18.52	117.73	12.27	4.33	1.28	0.30	0.05	0.06	0.06
Cl4(42)/(59)	997.61	117.51	1194.53	74.64	21.19	5.46	1.79	0.07	0.08	9.08
Cl4(43)	141.76	14.89	161.34	9.04	2.21	0.59	0.05	0.06	0.07	0.07
Cl4(44)	2527.03	333.64	3009.22	177.21	39.20	15.44	4.53	8.20	17.55	25.92
Cl4(45)	452.53	68.92	470.15	30.26	7.91	2.26	0.69	0.05	0.06	3.34
Cl4(46)	199.78	28.59	207.83	15.31	3.50	1.05	0.08	0.09	0.11	0.10
Cl4(47)	626.63	78.03	798.49	44.34	13.11	3.46	1.11	0.07	3.53	5.55
Cl4(48)	473.51	51.63	389.82	25.74	8.71	2.59	0.51	0.07	0.08	2.58
Cl4(49)	1983.98	268.35	2632.14	150.58	38.79	11.25	3.66	5.31	9.45	18.84
Cl4(51)	127.50	14.30	167.97	9.10	2.22	0.74	0.30	0.08	0.10	0.10
Cl4(52)	3047.40	388.00	3546.22	206.47	44.12	16.18	4.64	5.58	8.83	21.13
Cl4(53)	417.15	55.29	483.08	28.12	7.11	2.27	0.72	0.05	0.05	2.42
Cl4(54)	7.48	14.59	7.70	0.72	0.05	0.05	0.05	0.05	0.06	0.06
Cl4(56)	1097.06	121.48	995.38	61.11	21.75	5.64	1.58	1.48	0.11	6.88
Cl4(60)	199.73	25.96	172.11	22.77	8.21	1.87	0.40	0.08	0.10	0.10
Cl4(64)	1208.66	150.53	1360.75	76.66	25.75	7.47	2.11	2.08	3.13	7.79
Cl4(66)	2141.60	207.47	1990.71	126.54	40.92	10.64	2.84	3.41	7.52	14.32
Cl4(70)	2804.10	298.78	2639.36	160.88	40.15	13.86	3.60	4.42	9.08	18.40
Cl4(71)	681.03	85.06	825.16	53.54	14.88	4.17	1.23	1.21	0.08	4.93
Cl4(74)	1086.07	109.46	950.25	54.86	22.82	5.32	1.30	1.02	3.25	5.52
Cl4(77)	172.15	12.62	154.81	13.55	3.63	0.94	0.14	0.16	0.19	0.18
Cl4(81)	2.51	6.34	2.59	0.06	0.05	0.05	0.05	0.05	0.06	0.06
Cl5(82)	208.07	22.31	208.66	17.11	4.29	1.08	0.05	0.06	0.07	0.07
Cl5(83)/(119)	204.59	17.11	172.34	18.63	2.48	0.76	0.33	0.08	2.18	3.27
Cl5(84)	437.48	78.05	543.58	30.80	8.76	2.47	0.85	1.01	2.78	3.86
Cl5(85)	317.63	584.14	264.01	18.39	4.52	1.31	0.40	0.05	0.06	0.06
Cl5(87)	474.25	41.29	322.10	23.11	8.63	2.49	0.70	1.04	2.28	3.66
Cl5(91)	229.90	29.64	281.72	20.70	4.39	1.22	0.37	0.55	1.40	2.45
Cl5(92)	215.60	13.17	212.18	25.69	3.21	1.06	0.42	0.79	2.65	4.57
Cl5(95)	754.91	95.31	1001.80	60.15	16.14	5.11	1.43	2.33	5.64	9.65
Cl5(97)	440.01	38.40	402.23	25.82	7.57	2.07	0.68	1.18	2.38	4.16
Cl5(99)	532.22	46.89	407.04	34.18	8.47	2.28	0.60	1.76	4.69	6.94
Cl5(100)	7.12	15.03	10.10	0.55	0.05	0.05	0.05	0.05	0.06	0.41

STATION_ID	T171B	T171B	T171B	T171B	T171B	T171B	T172A	T172A	T172A	T172A
FIELD SAMPLE_ID	T171B 9-10FT	T171B 10-11F	T171-B-LKJ	T171-B-IHG	71B 17.2-17.6	71B 17.6-18.2	T172A 0-1FT	T172A 1-2FT	T172A 2-3FT	T172A 3-4FT
SAMPLE DEPTH (from bottom)	9-10	10-11	11-14	14-17.2	17.2-17.6	17.6-18.2	0-1	1-2	2-3	3-4
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	660.23	69.06	626.55	63.03	12.88	3.53	0.85	2.43	6.32	9.38
Cl5(105)	290.18	32.35	275.71	24.82	7.33	2.07	0.52	0.08	0.10	2.53
Cl5(110)	1267.29	121.53	1269.90	86.26	23.02	6.43	2.27	4.00	10.47	15.12
Cl5(114)	11.98	23.41	9.31	0.57	0.11	0.72	0.67	0.12	0.14	0.14
Cl5(115)	15.96	29.88	11.57	0.87	0.59	0.16	0.09	0.11	0.13	0.12
Cl5(118)	687.84	53.59	569.62	37.43	11.61	2.88	0.90	2.09	6.09	8.12
Cl5(107)/(123)	162.71	10.46	119.48	10.23	1.98	0.37	0.10	0.11	0.14	2.80
Cl5(124)	25.02	48.60	19.01	1.54	0.53	0.06	0.06	0.07	0.08	0.08
Cl5(126)	3.75	8.80	3.42	0.11	0.09	0.09	0.09	0.10	0.12	0.11
Cl6(128)	67.75	111.50	42.42	6.35	1.01	0.39	0.08	0.09	0.11	0.10
Cl6(130)	34.89	45.65	21.35	5.92	0.49	0.08	0.08	0.09	0.11	2.01
Cl6(134)	21.94	31.96	16.59	4.23	0.07	0.07	0.07	0.08	0.09	0.09
Cl6(135)	40.42	60.12	30.57	17.65	0.68	0.36	0.07	0.35	1.12	2.63
Cl6(136)	40.67	59.74	29.50	13.31	0.61	0.41	0.13	0.65	2.25	3.27
Cl6(137)	15.98	25.59	9.97	1.30	0.38	0.11	0.11	0.12	2.44	3.10
Cl6(138)	134.43	14.07	148.32	40.15	2.62	1.47	0.09	0.10	3.63	5.07
Cl6(141)	29.01	49.11	16.43	14.30	0.78	0.67	0.05	0.05	0.06	0.06
Cl6(144)	12.72	17.18	5.82	2.56	0.09	0.09	0.09	0.11	0.13	0.12
Cl6(146)	59.29	71.97	35.34	23.33	0.59	0.36	0.02	0.61	1.90	3.49
Cl6(149)	156.75	12.63	115.60	75.58	3.38	2.25	0.31	1.19	4.51	10.50
Cl6(151)	59.93	74.71	34.05	27.45	0.89	0.82	0.08	0.33	1.68	4.11
Cl6(132)/(153)/(168)	168.45	17.44	150.60	78.18	3.98	2.64	0.20	1.53	5.02	10.79
Cl6(156)	23.74	40.23	14.40	4.56	0.49	0.20	0.02	0.02	2.21	3.66
Cl6(157)	8.57	11.89	5.21	0.10	0.08	0.08	0.08	0.09	0.11	0.10
Cl6(129)/(158)	20.24	39.83	15.74	5.12	0.55	0.07	0.07	0.08	0.10	0.10
Cl6(163)	43.12	62.29	32.35	23.44	0.63	0.47	0.07	0.08	0.99	2.25
Cl6(164)	20.41	30.61	12.13	5.71	0.44	0.05	0.05	0.06	0.07	0.07
Cl6(166)	0.23	4.10	0.18	0.11	0.09	0.09	0.09	0.10	0.12	0.11
Cl6(167)	15.71	19.62	8.24	3.09	0.05	0.05	0.05	0.06	0.07	0.07
Cl6(169)	0.50	0.44	0.29	0.18	0.11	0.11	0.11	0.13	0.15	0.15
Cl7(170)	43.14	69.52	18.93	32.97	0.90	0.49	0.06	0.07	1.46	4.20
Cl7(171)	12.61	17.35	5.27	9.54	0.26	0.23	0.05	0.05	0.06	1.64
Cl7(172)	11.95	14.96	5.49	7.04	0.30	0.18	0.06	0.07	1.40	2.33
Cl7(174)	50.14	56.16	18.24	41.35	0.70	0.75	0.03	0.04	2.12	6.46
Cl7(176)	7.10	6.97	2.72	6.67	0.18	0.11	0.05	0.30	1.16	2.32
Cl7(177)	32.98	40.19	15.74	29.42	0.66	0.45	0.06	0.07	1.14	4.49
Cl7(178)	12.81	12.78	5.68	10.40	0.27	0.21	0.05	0.27	1.08	2.97
Cl7(179)	25.87	21.36	8.79	22.75	0.38	0.32	0.09	0.27	1.80	4.73
Cl7(180)	80.27	160.53	40.06	79.05	1.68	1.51	0.06	0.70	4.74	14.64
Cl7(183)	29.89	32.63	10.77	24.08	0.46	0.41	0.06	0.07	2.18	5.62
Cl7(184)	0.75	1.25	0.42	0.05	0.04	0.04	0.04	0.05	0.28	0.31
Cl7(185)	6.42	6.00	1.87	5.40	0.16	0.17	0.06	0.07	0.08	1.03
Cl7(187)	66.41	63.87	24.72	44.82	1.00	0.99	0.05	0.50	3.81	11.77
Cl7(189)	3.72	5.84	1.95	1.45	0.09	0.09	0.09	0.10	0.12	1.59
Cl7(190)	10.42	16.76	4.89	7.73	0.07	0.19	0.07	0.08	0.09	0.93
Cl7(193)	5.51	8.07	2.60	4.91	0.03	0.03	0.03	0.04	0.05	0.78
Cl8(194)	43.63	50.22	15.75	22.85	0.65	0.35	0.05	0.05	2.52	5.90
Cl8(195)	12.79	15.73	5.19	8.48	0.05	0.05	0.05	0.05	0.06	2.68
Cl8(199)	60.38	51.54	19.83	19.65	0.73	0.48	0.09	1.31	6.69	13.38
Cl8(200)	5.25	4.55	1.86	3.11	0.10	0.10	0.10	0.11	0.53	0.93
Cl8(201)	6.98	7.41	2.78	3.19	0.10	0.10	0.10	0.11	1.31	2.54
Cl8(202)	9.21	6.98	3.49	3.81	0.07	0.07	0.07	0.45	1.82	2.52
Cl8(196)/(203)	39.83	39.19	14.20	22.50	0.03	0.32	0.03	0.03	2.93	7.00
Cl8(205)	3.13	3.53	0.04	1.39	0.02	0.02	0.02	0.02	0.03	0.84
Cl9(206)	124.49	68.53	23.93	6.60	0.55	0.22	0.12	3.77	15.22	23.99
Cl9(207)	11.97	19.52	5.17	1.21	0.08	0.08	0.08	0.09	0.53	0.71
Cl9(208)	30.14	26.45	10.42	1.71	0.13	0.07	0.07	1.20	4.58	6.54
Cl10(209)	824.15	875.59	423.03	38.18	2.19	0.69	0.53	14.68	83.49	86.76
Sum 117 congeners	40,167	8,067	44,145	3,416	705	225	69	101	302	573

STATION_ID	T172A	T172A	T172A	T172A	T172A	T172A	T172A	T172A	T172A	T172B
FIELD SAMPLE_ID	T172A 4-5FT	T172A 5-6FT	T172A 6-7FT	T172A 7-8FT	T172-A-RQP	T172-A-ON	I72A 13-13.8I	T172-A-LKJI	72A 16.5-17.5	172B 0-0.5F
SAMPLE DEPTH (from bottom)	4-5	5-6	6-7	7-8	8-11	11-13	13-13.8	13.8-16.5	16.5-17.5	0-0.5
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	47.06	69.24	28.57	88.22	68.26	43.46	5.74	19.73	3.88	1.00
Cl1(1)	0.09	14.77	14.27	21.78	33.19	0.07	0.06	0.08	0.07	0.05
Cl1(3)	0.04	10.61	8.79	12.41	21.43	0.04	0.03	0.04	0.04	0.02
Cl2(4)/(10)	24.89	77.86	62.49	91.04	207.76	19.58	3.82	0.13	0.13	0.08
Cl2(5)	0.14	0.18	0.21	2.51	19.06	0.12	0.09	0.12	0.12	0.08
Cl2(6)	211.59	316.61	125.68	386.61	783.20	34.80	4.80	5.74	1.12	0.06
Cl2(7)	2.02	7.11	5.23	6.64	35.41	3.74	0.53	0.07	0.06	0.04
Cl2(8)	77.26	230.32	229.57	312.40	461.66	37.80	10.43	7.11	1.48	0.07
Cl2(9)	4.20	14.09	10.00	12.06	42.49	5.54	0.86	0.09	0.08	0.05
Cl2(13)	62.41	110.66	54.95	83.01	225.11	25.15	2.10	2.62	0.08	0.05
Cl2(15)	29.34	80.38	68.12	95.91	172.61	34.35	5.16	4.83	1.28	0.10
Cl3(16)	261.47	700.91	519.01	1163.26	766.51	74.85	22.92	17.38	4.33	0.07
Cl3(17)	408.11	863.06	594.09	1344.57	1229.75	112.28	25.66	24.62	4.92	0.46
Cl3(18)	861.89	1901.58	1442.12	2836.14	3383.36	254.34	97.73	49.39	12.44	0.63
Cl3(19)	46.48	78.02	80.11	144.58	153.43	16.41	3.40	2.47	0.77	0.07
Cl3(22)	315.88	802.70	586.88	1213.69	1077.85	103.25	34.13	31.08	8.27	0.05
Cl3(24)	0.08	8.37	7.82	7.41	20.16	0.06	0.05	0.07	0.06	0.54
Cl3(25)	832.78	1234.87	369.39	923.71	2761.02	153.25	20.00	35.09	5.90	0.81
Cl3(26)	826.66	1160.02	454.24	1127.72	3282.51	157.84	28.60	31.61	7.51	0.72
Cl3(27)	33.57	57.18	62.11	93.38	91.71	11.89	2.54	2.09	0.78	0.04
Cl3(28)	1223.32	2840.49	2103.99	4214.54	3961.13	350.30	102.94	73.45	25.15	1.03
Cl3(31)	1566.53	3427.14	2378.58	5201.23	5094.50	391.68	129.07	85.43	25.70	1.41
Cl3(32)	200.42	560.15	367.66	808.37	586.06	57.01	16.55	14.26	3.22	0.03
Cl3(33)/(20)	441.25	1136.23	990.12	1956.33	1642.53	145.65	48.60	30.15	9.25	0.57
Cl3(37)	95.79	357.61	283.33	532.88	362.38	46.16	21.24	20.34	5.19	0.07
Cl4(40)	278.51	741.33	580.36	957.63	909.86	73.37	27.40	25.66	6.12	0.08
Cl4(41)	62.10	223.87	214.00	413.10	118.72	21.59	14.49	6.72	2.64	0.04
Cl4(42)/(59)	691.29	1577.32	1094.04	2213.95	2182.11	196.20	68.04	48.89	15.54	0.61
Cl4(43)	89.00	191.25	143.59	275.53	234.65	30.62	7.21	6.79	1.63	0.05
Cl4(44)	1739.90	4070.38	2920.75	6488.63	5277.23	458.36	169.58	113.28	38.54	1.55
Cl4(45)	286.58	645.71	504.25	963.45	829.76	74.57	26.33	22.25	5.64	0.31
Cl4(46)	123.62	275.03	250.29	579.11	374.72	31.05	10.85	9.58	2.37	0.07
Cl4(47)	445.07	984.20	780.73	1456.96	1383.95	123.35	40.01	31.42	10.14	0.40
Cl4(48)	138.86	567.48	632.83	1131.43	440.45	54.61	31.29	18.84	5.53	0.22
Cl4(49)	1476.97	3565.63	2288.79	4776.43	5020.19	409.45	144.27	96.38	29.55	1.14
Cl4(51)	85.55	212.99	128.72	288.08	256.84	27.04	6.74	6.20	1.45	0.07
Cl4(52)	1405.62	3307.89	2598.90	4328.87	6325.37	508.19	202.61	121.60	39.58	1.35
Cl4(53)	282.04	627.08	514.00	1230.10	864.78	74.78	21.91	19.28	4.49	0.04
Cl4(54)	4.18	9.76	6.97	13.58	14.15	2.79	0.05	0.07	0.38	0.04
Cl4(56)	519.05	1452.87	1231.72	2470.08	1302.66	158.12	69.56	40.77	17.21	0.52
Cl4(60)	45.07	226.57	273.76	711.92	185.76	32.66	26.27	13.43	5.92	0.07
Cl4(64)	763.77	1861.16	1423.54	2930.66	2584.42	202.39	84.54	50.61	20.06	0.60
Cl4(66)	802.34	2461.81	2391.72	4333.04	2282.25	327.38	141.22	91.17	34.34	0.80
Cl4(70)	1334.86	3811.95	3139.06	5969.01	3467.62	454.99	187.00	115.56	42.79	1.24
Cl4(71)	436.77	1018.52	815.24	1639.36	1448.99	126.46	46.48	30.06	10.83	0.49
Cl4(74)	315.45	1263.36	1123.40	2337.96	998.52	137.85	67.49	36.84	17.39	0.33
Cl4(77)	62.92	228.51	181.22	326.42	173.22	32.16	10.91	10.51	3.47	0.13
Cl4(81)	0.08	3.09	3.79	7.23	2.72	0.06	0.05	0.07	0.06	0.04
Cl5(82)	99.00	301.10	254.65	496.50	291.20	37.35	13.96	10.63	3.65	0.05
Cl5(83)/(119)	100.71	243.03	199.29	287.93	287.33	32.38	8.48	10.10	2.51	0.07
Cl5(84)	379.33	837.39	397.27	1207.60	953.16	88.29	27.41	28.51	6.67	0.09
Cl5(85)	110.31	381.84	350.51	612.99	382.29	39.98	16.55	12.91	4.42	0.04
Cl5(87)	153.54	559.34	477.80	948.02	410.13	46.85	28.97	20.43	7.73	0.09
Cl5(91)	132.55	341.56	265.57	531.20	465.16	47.55	13.51	14.16	3.57	0.21
Cl5(92)	75.97	256.15	281.79	365.95	427.87	40.91	9.77	11.61	4.00	0.05
Cl5(95)	471.64	1182.51	845.45	1975.50	1641.24	150.62	52.96	40.52	14.72	0.52
Cl5(97)	154.43	459.38	484.96	713.47	524.64	66.15	25.63	21.75	7.02	0.03
Cl5(99)	172.41	696.82	551.74	1041.70	443.51	52.26	26.20	23.18	7.90	0.37
Cl5(100)	4.69	10.37	7.56	12.44	18.08	2.22	0.46	0.49	0.06	0.04

STATION_ID	T172A	T172A	T172A	T172A	T172A	T172A	T172A	T172A	T172A	T172B
FIELD SAMPLE_ID	T172A 4-5FT	T172A 5-6FT	T172A 6-7FT	T172A 7-8FT	T172-A-RQP	T172-A-ON	172A 13-13.8F	T172-A-LKJI	72A 16.5-17.5	T172B 0-0.5F
SAMPLE DEPTH (from bottom)	4-5	5-6	6-7	7-8	8-11	11-13	13-13.8	13.8-16.5	16.5-17.5	0-0.5
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	265.16	911.25	879.76	1438.99	667.98	88.85	39.34	33.86	12.97	0.38
Cl5(105)	75.47	376.19	274.19	686.58	277.19	38.25	23.15	17.56	7.59	0.07
Cl5(110)	718.04	1779.68	1246.37	2420.19	2267.60	217.51	79.91	53.75	22.78	0.88
Cl5(114)	0.17	12.03	16.78	33.99	9.34	0.14	1.72	0.15	0.15	0.10
Cl5(115)	0.15	20.48	16.67	35.52	26.16	2.83	1.51	1.22	0.13	0.08
Cl5(118)	234.89	770.02	678.01	1159.29	667.21	88.75	33.33	30.88	12.47	0.37
Cl5(107)/(123)	53.20	199.23	170.94	211.90	160.00	24.35	6.19	6.47	2.21	0.55
Cl5(124)	5.23	24.38	26.63	48.90	22.24	2.66	1.27	0.09	0.08	0.05
Cl5(126)	0.14	4.10	4.72	9.10	3.24	0.12	0.09	0.12	0.12	0.08
Cl6(128)	24.94	76.29	59.59	101.54	117.12	10.12	2.45	2.91	1.52	0.07
Cl6(130)	17.80	45.40	31.76	48.58	37.30	6.01	1.05	1.77	0.77	0.07
Cl6(134)	9.59	28.27	20.29	29.46	29.86	3.99	0.81	0.90	0.09	0.06
Cl6(135)	25.35	62.99	38.92	55.35	41.87	8.87	1.45	2.57	1.52	0.07
Cl6(136)	21.30	58.50	38.57	54.99	69.78	7.73	1.56	1.96	1.66	0.17
Cl6(137)	3.99	16.99	15.57	26.66	11.35	2.43	0.86	0.79	0.15	0.10
Cl6(138)	70.92	206.85	158.71	242.25	151.02	25.32	6.47	8.06	7.04	0.16
Cl6(141)	6.65	43.81	30.14	50.35	19.40	3.55	1.32	1.65	2.83	0.04
Cl6(144)	4.21	15.80	12.31	17.95	8.21	1.44	0.45	0.56	0.77	0.08
Cl6(146)	36.43	78.87	55.05	67.47	45.97	12.50	1.71	3.14	1.58	0.02
Cl6(149)	73.45	233.68	160.79	263.05	183.97	34.30	7.23	12.03	9.74	0.28
Cl6(151)	31.95	92.16	56.95	72.95	49.34	10.71	1.80	3.21	3.28	0.07
Cl6(132)/(153)/(168)	102.20	284.79	199.95	295.12	200.00	40.19	8.45	12.73	12.85	0.06
Cl6(156)	5.53	22.88	22.25	44.79	17.66	3.00	1.25	1.25	0.95	0.02
Cl6(157)	2.52	7.05	7.07	12.72	5.62	1.19	0.35	0.11	0.11	0.07
Cl6(129)/(158)	6.15	26.62	22.71	42.73	24.59	3.75	0.94	1.28	1.24	0.07
Cl6(163)	22.59	66.05	43.40	67.22	54.77	8.02	1.18	2.45	2.09	0.10
Cl6(164)	9.06	25.86	18.13	28.18	19.07	3.28	0.79	0.96	1.15	0.05
Cl6(166)	0.14	0.18	0.21	0.19	0.17	0.12	0.09	0.12	0.12	0.08
Cl6(167)	4.01	14.38	12.10	18.91	9.61	2.11	0.52	0.08	0.07	0.05
Cl6(169)	0.31	0.40	0.30	0.53	1.00	1.02	0.12	0.93	0.16	0.10
Cl7(170)	16.34	50.33	35.15	64.76	26.92	5.56	1.14	2.24	3.75	0.05
Cl7(171)	5.68	16.31	10.26	15.90	8.90	2.02	0.38	0.86	1.05	0.04
Cl7(172)	5.90	14.82	9.29	14.24	7.87	1.75	0.35	0.60	0.63	0.05
Cl7(174)	21.88	61.83	40.76	55.37	25.98	7.95	1.27	2.66	4.65	0.03
Cl7(176)	4.40	9.92	5.79	6.91	4.57	1.46	0.22	0.51	0.67	0.05
Cl7(177)	18.70	45.56	27.67	38.55	25.74	6.90	0.92	2.28	2.78	0.05
Cl7(178)	7.73	17.12	10.17	12.22	9.13	2.66	0.38	0.83	0.95	0.04
Cl7(179)	13.13	33.29	20.79	22.02	13.39	4.40	0.64	1.49	1.92	0.08
Cl7(180)	39.13	113.91	77.79	138.27	64.00	14.52	2.90	5.82	10.14	0.05
Cl7(183)	14.41	39.17	24.92	32.55	16.53	5.19	0.76	1.60	2.71	0.05
Cl7(184)	0.43	0.69	0.66	0.88	0.56	0.05	0.04	0.06	0.05	0.04
Cl7(185)	2.34	6.96	4.96	5.99	2.57	0.86	0.25	0.25	0.60	0.05
Cl7(187)	35.58	72.29	51.75	60.63	39.57	12.01	1.58	3.87	5.36	0.05
Cl7(189)	1.68	2.54	2.88	4.58	1.98	0.12	0.09	0.12	0.12	0.08
Cl7(190)	3.83	11.81	7.70	14.87	7.30	1.72	0.32	0.64	1.00	0.06
Cl7(193)	2.44	6.82	3.65	7.36	4.44	1.15	0.19	0.29	0.45	0.03
Cl8(194)	18.13	42.77	28.51	43.11	21.64	4.47	1.04	1.67	2.16	0.04
Cl8(195)	6.36	14.30	8.98	13.75	8.01	1.95	0.37	0.64	0.91	0.04
Cl8(199)	27.52	61.86	43.35	47.01	28.03	7.56	1.06	2.09	2.44	0.08
Cl8(200)	1.92	5.10	3.63	3.77	2.51	0.77	0.15	0.32	0.23	0.09
Cl8(201)	2.96	6.19	4.50	5.88	3.67	1.30	0.22	0.38	0.24	0.09
Cl8(202)	3.76	8.49	6.34	6.60	4.61	1.45	0.21	0.46	0.42	0.06
Cl8(196)/(203)	15.93	38.52	26.47	35.91	19.65	4.81	0.81	1.72	2.19	0.02
Cl8(205)	1.18	3.49	2.31	2.71	2.27	0.50	0.02	0.03	0.03	0.02
Cl9(206)	38.24	72.73	60.81	61.38	28.61	6.45	1.05	2.15	1.07	0.42
Cl9(207)	3.99	6.14	8.23	14.05	6.26	0.86	0.14	0.34	0.13	0.07
Cl9(208)	11.70	19.36	20.47	22.76	12.46	2.21	0.34	0.64	0.31	0.10
Cl10(209)	282.92	502.95	748.14	734.99	457.95	69.28	8.30	19.43	2.28	1.11
Sum 117 congeners	23,210	57,379	43,792	85,700	74,992	7,022	2,462	1,806	653	26

STATION_ID	T172B	T172B	T172B	T172B	T172B	T172B	T172B	T172B	T172B	T172B
FIELD SAMPLE_ID	T172B 0.5-1F	T172-B-XW	T172B 2.4-3F	T172B 3-4FT	T172B 4-5FT	T172B 5-6FT	T172B 6-7FT	T172B 7-8FT	T172-B-PO	T172-B-NML
SAMPLE DEPTH (from bottom)	0.5-1	1-2.4	2.4-3	3-4	4-5	5-6	6-7	7-8	8-10	10-12.3
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	28.64	40.16	29.33	101.31	39.65	52.21	63.58	76.20	73.01	28.50
Cl1(1)	0.06	0.07	0.06	0.07	0.07	0.09	0.08	18.65	47.52	7.72
Cl1(3)	0.03	0.03	0.03	0.03	0.03	0.04	0.04	9.64	29.41	3.67
Cl2(4)/(10)	0.11	0.12	0.10	0.12	0.12	24.44	21.33	70.76	194.13	42.10
Cl2(5)	0.10	0.11	0.09	0.11	0.11	0.14	0.13	0.22	21.70	2.62
Cl2(6)	0.08	0.08	0.07	0.09	16.36	162.95	190.55	189.38	910.80	54.25
Cl2(7)	0.05	0.06	0.05	0.06	0.06	0.08	0.07	6.86	41.83	5.25
Cl2(8)	2.24	0.10	2.21	3.44	14.98	62.66	80.00	182.96	663.55	95.21
Cl2(9)	0.07	0.07	0.06	0.08	0.08	3.47	4.07	10.44	46.78	7.06
Cl2(13)	0.07	0.07	0.06	0.08	6.77	63.37	41.22	75.19	319.22	20.69
Cl2(15)	0.13	0.13	0.12	0.14	5.27	27.81	26.75	62.59	260.81	36.39
Cl3(16)	0.09	0.10	3.94	11.53	38.61	278.36	259.30	584.30	1225.69	141.99
Cl3(17)	0.05	0.06	4.48	14.04	47.61	346.80	373.23	705.87	1968.51	171.57
Cl3(18)	0.08	0.08	10.43	30.53	125.13	1103.85	1100.75	2173.51	5431.29	427.26
Cl3(19)	0.09	0.09	0.74	0.09	5.13	41.64	39.22	101.86	268.09	24.40
Cl3(22)	0.07	0.07	5.41	15.95	41.59	318.48	276.79	771.64	1751.19	143.28
Cl3(24)	0.05	0.06	0.05	0.06	0.06	0.08	0.07	7.02	24.81	3.10
Cl3(25)	0.05	0.06	1.44	4.40	53.47	630.90	576.71	700.37	3191.07	144.64
Cl3(26)	0.08	0.08	2.62	7.03	60.64	649.44	635.13	757.87	3782.38	159.21
Cl3(27)	0.05	0.05	0.04	0.05	3.76	28.19	27.39	71.86	122.20	14.82
Cl3(28)	0.09	3.58	16.16	46.04	141.39	1152.38	1147.12	2480.63	6037.82	426.69
Cl3(31)	0.05	3.17	15.68	49.25	171.87	1353.49	1420.17	2783.16	7534.80	491.75
Cl3(32)	0.04	0.04	2.39	6.56	27.69	198.97	170.33	411.17	916.91	81.70
Cl3(33)/(20)	0.09	3.30	8.96	25.25	64.90	428.97	445.77	1146.18	2637.96	204.56
Cl3(37)	0.09	0.09	3.19	7.89	24.09	106.86	95.82	368.87	741.47	55.29
Cl4(40)	0.10	0.11	3.34	11.95	43.10	279.93	274.19	554.19	1329.16	87.77
Cl4(41)	0.05	0.06	1.13	2.74	7.96	59.61	39.62	230.05	367.99	30.00
Cl4(42)/(59)	0.07	0.07	7.97	28.33	79.20	587.65	572.13	1362.30	3387.20	204.76
Cl4(43)	0.06	0.07	0.06	3.34	11.82	69.26	81.04	167.58	440.01	25.39
Cl4(44)	8.77	10.40	21.79	68.56	211.91	1571.83	1610.18	3533.41	8276.48	486.15
Cl4(45)	0.05	0.06	3.03	11.46	41.57	305.42	255.46	582.22	1570.73	89.96
Cl4(46)	0.09	0.10	1.62	4.69	18.20	121.12	146.63	328.06	636.26	41.31
Cl4(47)	0.07	1.71	5.13	19.65	57.75	393.55	425.23	872.24	2156.79	125.32
Cl4(48)	0.07	1.30	4.41	14.00	31.91	159.16	169.74	586.21	1171.57	77.84
Cl4(49)	4.17	6.53	15.99	51.54	180.46	1311.34	1392.88	2730.01	7292.79	397.33
Cl4(51)	0.09	0.09	1.13	3.16	10.63	83.96	85.79	163.35	426.82	23.92
Cl4(52)	3.96	7.05	23.30	65.75	249.12	1886.92	1915.59	4101.86	9907.03	537.65
Cl4(53)	0.05	0.05	2.84	9.68	34.27	257.96	247.71	550.77	1453.85	80.52
Cl4(54)	0.05	0.06	0.05	0.06	0.06	3.69	3.92	9.53	21.18	2.37
Cl4(56)	0.09	1.77	8.29	27.69	78.90	512.09	520.93	1460.40	2295.88	176.54
Cl4(60)	1.36	0.09	1.34	3.59	9.73	44.48	43.83	308.42	370.14	36.70
Cl4(64)	0.03	1.81	9.39	32.84	102.50	696.03	697.22	1689.64	4058.90	238.25
Cl4(66)	4.03	6.25	19.15	67.81	145.04	862.56	862.25	2681.79	4517.89	328.27
Cl4(70)	4.36	6.92	24.77	83.87	199.68	1328.06	1250.98	3666.53	6840.08	438.71
Cl4(71)	0.07	1.04	5.52	19.24	58.66	395.42	402.71	948.54	2314.00	128.12
Cl4(74)	0.05	2.50	9.27	31.42	59.10	373.71	369.75	1318.81	2153.31	149.77
Cl4(77)	0.16	0.17	1.59	5.49	13.36	82.91	72.87	186.57	275.78	31.87
Cl4(81)	0.05	0.06	0.05	0.06	0.06	0.08	0.07	4.09	6.41	0.08
Cl5(82)	0.06	0.07	1.91	5.88	15.21	111.15	90.71	252.90	516.45	35.84
Cl5(83)/(119)	1.90	1.76	1.93	6.82	16.44	111.94	84.84	188.62	457.05	34.67
Cl5(84)	1.44	1.95	5.07	14.71	45.13	361.99	325.54	699.39	1540.74	92.69
Cl5(85)	0.05	0.06	1.97	5.63	17.19	135.08	131.46	329.86	687.15	32.74
Cl5(87)	1.92	2.53	6.15	13.28	28.21	182.70	152.38	494.51	883.57	57.33
Cl5(91)	0.87	1.12	2.14	6.97	22.26	108.67	107.54	269.38	912.23	58.81
Cl5(92)	2.45	2.87	3.42	7.50	17.50	108.21	102.86	203.33	633.76	37.64
Cl5(95)	4.12	5.08	12.22	29.25	69.74	476.97	445.51	1071.37	2644.40	154.08
Cl5(97)	1.53	2.42	5.48	14.53	31.18	180.02	171.23	463.04	911.24	62.70
Cl5(99)	4.80	5.89	6.79	19.04	35.20	185.57	196.47	563.96	1083.07	61.43
Cl5(100)	0.60	0.06	0.05	0.06	0.86	3.90	3.96	8.27	26.25	1.45

STATION_ID	T172B	T172B	T172B	T172B	T172B	T172B	T172B	T172B	T172B	T172B
FIELD SAMPLE_ID	T172B 0.5-1F	T172-B-XW	T172B 2.4-3F	T172B 3-4FT	T172B 4-5FT	T172B 5-6FT	T172B 6-7FT	T172B 7-8FT	T172-B-PO	T172-B-NML
SAMPLE DEPTH (from bottom)	0.5-1	1-2.4	2.4-3	3-4	4-5	5-6	6-7	7-8	8-10	10-12.3
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	5.57	6.73	12.20	28.54	53.00	291.76	301.22	831.67	1445.38	103.98
Cl5(105)	1.87	1.69	4.50	8.66	17.63	86.22	68.70	390.52	531.75	43.05
Cl5(110)	6.94	9.14	18.14	42.40	95.53	604.20	621.52	1470.93	3381.99	219.42
Cl5(114)	0.13	0.13	0.12	0.14	0.14	0.17	0.16	13.19	20.83	2.79
Cl5(115)	0.11	0.12	0.10	0.12	1.01	4.16	4.19	19.11	32.82	3.71
Cl5(118)	6.25	6.37	10.79	25.95	42.71	235.93	235.55	730.44	1140.48	83.74
Cl5(107)/(123)	2.44	2.46	1.61	5.27	9.46	55.65	51.99	107.29	309.90	19.95
Cl5(124)	0.07	0.07	0.06	0.08	0.08	4.97	2.50	25.18	49.63	2.94
Cl5(126)	0.10	0.11	0.09	0.11	0.11	0.14	0.13	6.68	9.38	0.14
Cl6(128)	0.09	0.10	1.78	0.10	4.56	22.42	22.27	60.71	110.40	7.34
Cl6(130)	2.77	1.80	1.10	3.29	2.38	14.91	14.06	31.04	54.59	4.55
Cl6(134)	0.08	1.46	0.62	0.09	1.78	8.50	8.02	21.27	42.01	2.63
Cl6(135)	1.23	0.98	1.17	2.04	3.61	19.95	19.21	39.96	62.76	5.40
Cl6(136)	4.41	3.96	1.29	4.34	3.52	18.53	17.83	37.99	64.89	10.85
Cl6(137)	6.87	4.20	0.86	5.09	0.14	3.76	4.67	14.86	25.37	1.93
Cl6(138)	4.71	3.83	5.68	9.57	11.16	68.52	53.80	150.49	263.75	18.06
Cl6(141)	3.23	0.06	0.93	0.06	0.06	6.39	6.65	26.13	43.19	3.20
Cl6(144)	0.11	0.12	0.32	0.12	0.86	4.03	3.91	11.16	15.28	0.91
Cl6(146)	1.79	1.72	1.55	3.62	5.26	29.89	30.11	54.15	67.68	9.23
Cl6(149)	4.84	5.11	5.54	10.56	15.98	72.24	86.19	158.41	386.65	26.02
Cl6(151)	1.57	0.51	1.47	3.24	4.46	28.04	26.08	53.14	64.44	5.78
Cl6(132)/(153)/(168)	6.02	5.39	7.48	13.81	17.88	105.69	100.94	230.34	470.45	29.53
Cl6(156)	7.18	3.87	1.13	4.48	0.98	5.42	4.74	23.99	33.04	3.02
Cl6(157)	0.09	0.10	0.09	0.10	0.10	2.28	1.68	6.90	10.48	1.07
Cl6(129)/(158)	1.16	1.14	0.92	2.11	1.89	5.74	6.00	23.24	41.89	3.73
Cl6(163)	1.36	1.48	1.14	2.39	3.82	18.53	18.80	41.47	83.63	5.74
Cl6(164)	0.06	1.49	0.71	0.07	1.25	7.77	7.17	19.03	30.49	2.41
Cl6(166)	0.10	0.11	0.09	0.11	0.11	0.14	0.13	0.22	2.95	0.14
Cl6(167)	0.06	0.07	0.06	5.50	1.21	4.08	4.65	10.41	18.09	2.02
Cl6(169)	0.13	0.14	0.12	0.14	0.15	1.22	0.66	0.20	0.60	0.49
Cl7(170)	2.48	1.64	1.01	3.38	2.23	14.20	15.16	34.01	48.37	3.89
Cl7(171)	0.05	0.06	0.05	1.19	0.72	5.10	5.14	10.05	12.80	1.23
Cl7(172)	0.07	0.07	0.06	0.08	1.07	5.01	4.69	10.15	11.63	2.11
Cl7(174)	2.41	1.66	0.97	3.18	2.76	20.09	19.55	35.25	41.54	3.97
Cl7(176)	4.83	3.78	0.38	3.34	0.93	3.50	3.37	5.13	6.19	0.66
Cl7(177)	0.07	0.07	0.72	3.13	2.38	15.52	15.33	26.85	34.88	3.62
Cl7(178)	0.05	1.16	0.34	1.33	1.83	6.95	6.59	9.12	12.30	1.35
Cl7(179)	2.98	2.21	0.65	2.56	1.70	11.29	10.94	19.19	18.71	1.74
Cl7(180)	6.83	4.35	2.19	6.94	6.28	35.64	33.08	72.95	120.75	9.86
Cl7(183)	8.22	6.81	0.95	6.49	2.41	13.05	12.80	21.37	25.36	3.66
Cl7(184)	0.77	0.53	0.17	0.70	0.34	0.47	0.40	0.85	0.67	0.27
Cl7(185)	0.07	0.07	0.06	0.08	0.42	2.07	1.87	3.79	4.86	0.52
Cl7(187)	5.40	4.10	1.47	5.05	4.38	30.56	28.85	46.46	55.68	6.07
Cl7(189)	0.10	0.11	0.09	1.70	0.11	0.14	1.33	2.99	3.22	0.65
Cl7(190)	0.08	0.08	0.07	0.09	0.89	3.76	3.60	8.12	11.85	2.17
Cl7(193)	1.95	0.85	0.04	0.76	0.04	2.49	1.95	4.46	5.87	0.66
Cl8(194)	2.08	1.96	1.00	3.27	3.20	15.50	14.87	28.05	32.51	3.67
Cl8(195)	1.41	0.06	0.05	1.37	1.32	4.88	4.36	9.19	12.30	1.47
Cl8(199)	8.25	6.07	2.21	8.22	8.57	29.20	27.00	43.61	39.20	4.89
Cl8(200)	0.12	0.12	0.11	0.65	0.38	1.94	1.74	3.82	3.35	0.70
Cl8(201)	3.82	3.19	0.56	3.55	0.96	2.41	2.26	5.84	5.23	0.99
Cl8(202)	1.51	1.51	0.42	1.54	1.39	3.99	3.62	7.14	6.16	0.90
Cl8(196)/(203)	3.09	2.13	0.96	3.38	3.33	14.14	13.42	26.95	30.17	4.73
Cl8(205)	1.48	1.35	0.02	0.03	0.03	1.61	1.44	2.53	2.08	3.95
Cl9(206)	24.46	16.51	5.01	24.21	23.45	55.10	48.75	75.30	40.08	6.42
Cl9(207)	1.02	0.76	0.34	1.91	1.08	3.04	3.14	14.71	8.79	1.90
Cl9(208)	6.34	4.75	1.54	7.61	7.09	14.59	13.63	27.33	16.06	3.08
Cl10(209)	120.71	110.13	56.76	279.34	178.58	332.67	339.48	1076.56	575.78	158.36
Sum 117 congeners	333	324	457	1,471	3,352	22,717	22,547	52,514	119,737	7,990

STATION_ID	T172B	T172B	T173A	T173A	T173A	T173A	T173A	T173A	T173A	T173A
FIELD SAMPLE_ID	T172-B-KJI	72B 14.4-15.4	T173A 0-1FT	T173A 1-2FT	T173A 2-3FT	T173A 3-4FT	T173A 4-5FT	T173A 5-6FT	T173A 6-7FT	T173A 7-8FT
SAMPLE DEPTH (from bottom)	12.3-14.4	14.4-15.4	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	22.41	6.64	0.29	0.29	1.93	7.44	11.87	20.01	48.95	45.09
Cl1(1)	0.07	0.06	0.05	0.05	0.05	0.06	0.06	0.06	0.07	0.07
Cl1(3)	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04
Cl2(4)/(10)	0.12	0.10	0.09	0.09	0.09	0.10	1.76	0.11	0.12	0.13
Cl2(5)	0.11	0.10	0.08	0.08	0.09	0.09	0.10	0.10	0.11	0.12
Cl2(6)	5.68	1.03	0.06	0.06	0.07	0.07	0.08	0.08	4.87	6.23
Cl2(7)	0.06	0.05	0.04	0.04	0.05	0.05	0.05	0.05	0.06	0.06
Cl2(8)	5.67	0.94	0.08	0.08	0.08	0.08	0.09	1.48	6.70	9.08
Cl2(9)	0.08	0.07	0.06	0.06	0.06	0.06	0.07	0.07	0.07	0.08
Cl2(13)	3.10	0.45	0.06	0.06	0.06	0.06	0.07	0.07	0.07	0.08
Cl2(15)	5.19	0.59	0.10	0.10	0.11	0.11	0.12	0.12	0.13	0.15
Cl3(16)	16.70	1.85	0.08	0.08	0.08	0.08	0.09	0.09	18.31	30.36
Cl3(17)	23.24	2.35	0.04	0.04	0.33	0.05	0.05	1.57	26.51	43.00
Cl3(18)	49.90	6.21	0.06	0.06	0.42	0.69	0.69	2.52	48.49	99.42
Cl3(19)	2.35	0.51	0.07	0.07	0.07	0.08	0.08	0.09	2.22	4.00
Cl3(22)	23.13	3.09	0.06	0.06	0.06	0.06	0.07	0.07	25.04	43.07
Cl3(24)	0.06	0.05	0.04	0.04	0.05	0.05	0.05	0.05	0.06	0.06
Cl3(25)	26.05	3.29	0.04	0.04	0.05	0.69	0.05	2.45	23.26	31.55
Cl3(26)	34.13	4.25	0.06	0.06	0.07	0.07	0.08	2.16	23.71	34.20
Cl3(27)	2.17	0.04	0.04	0.04	0.04	0.04	0.05	0.05	1.99	2.89
Cl3(28)	75.60	9.39	0.08	0.08	0.41	0.89	0.78	2.98	64.33	129.25
Cl3(31)	89.73	11.07	0.04	0.04	0.55	1.17	1.29	4.01	73.99	150.50
Cl3(32)	13.73	1.51	0.03	0.03	0.03	0.03	0.04	0.04	11.61	20.64
Cl3(33)/(20)	30.37	3.99	0.08	0.08	0.36	1.34	1.63	2.84	38.92	59.79
Cl3(37)	17.69	1.81	0.07	0.07	0.07	0.08	0.08	0.09	11.81	20.90
Cl4(40)	25.16	2.39	0.64	0.59	0.50	0.09	0.10	1.73	16.66	33.56
Cl4(41)	6.89	1.03	0.04	0.04	0.05	0.05	0.05	0.05	2.88	3.99
Cl4(42)/(59)	50.08	5.29	0.32	0.06	0.06	0.87	0.07	2.87	44.87	77.53
Cl4(43)	6.54	0.59	0.05	0.05	0.05	0.06	0.06	0.06	4.62	9.52
Cl4(44)	113.75	14.53	0.36	0.24	0.68	2.01	2.69	9.88	88.07	185.40
Cl4(45)	21.77	2.18	0.04	0.04	0.05	0.55	0.05	0.05	18.14	31.39
Cl4(46)	9.05	1.05	0.08	0.08	0.08	0.08	0.09	0.09	7.63	13.08
Cl4(47)	29.35	3.31	0.06	0.06	0.06	0.60	0.07	2.51	29.90	48.67
Cl4(48)	18.55	2.16	0.06	0.06	0.06	0.06	0.07	0.07	15.72	28.16
Cl4(49)	98.48	10.33	0.05	0.05	0.36	1.11	0.06	6.90	72.34	140.13
Cl4(51)	5.73	0.63	0.07	0.07	0.07	0.08	0.08	0.09	4.88	8.04
Cl4(52)	127.72	14.06	0.20	0.04	0.39	1.26	0.76	6.64	90.15	180.22
Cl4(53)	18.87	1.95	0.04	0.04	0.04	0.04	0.05	0.05	15.13	26.90
Cl4(54)	0.45	0.16	0.04	0.04	0.14	0.05	0.22	0.24	0.06	0.06
Cl4(56)	45.47	5.30	0.08	0.08	0.24	0.80	0.09	1.55	36.73	73.76
Cl4(60)	14.78	1.68	0.07	0.07	0.07	0.08	0.08	1.37	3.00	5.23
Cl4(64)	58.00	6.70	0.03	0.03	0.22	0.71	0.03	2.40	41.38	85.77
Cl4(66)	95.27	10.43	0.27	0.06	0.37	1.56	1.11	5.03	74.60	151.15
Cl4(70)	117.10	13.81	0.20	0.17	0.42	1.49	0.81	6.16	99.16	202.65
Cl4(71)	33.05	3.77	0.06	0.06	0.12	0.44	0.07	1.36	28.94	52.32
Cl4(74)	38.07	5.21	0.04	0.04	0.26	0.83	0.05	2.39	33.47	62.35
Cl4(77)	8.74	1.20	0.13	0.13	0.14	0.15	0.16	0.16	5.90	12.73
Cl4(81)	0.90	0.05	0.04	0.04	0.05	0.05	0.05	0.05	0.06	0.06
Cl5(82)	9.91	1.09	0.05	0.05	0.05	0.06	0.06	0.06	6.14	11.02
Cl5(83)/(119)	8.71	0.85	0.07	0.07	0.07	0.08	0.08	1.34	7.53	13.69
Cl5(84)	25.43	2.54	0.09	0.10	0.10	0.54	0.11	1.79	18.21	33.50
Cl5(85)	12.02	1.35	0.04	0.13	0.05	0.05	0.05	0.05	6.21	12.40
Cl5(87)	19.70	2.40	0.09	0.10	0.22	0.62	0.70	1.06	12.07	22.69
Cl5(91)	13.78	1.22	0.04	0.04	0.04	0.27	0.05	0.92	8.96	16.04
Cl5(92)	12.01	1.05	0.06	0.06	0.06	0.06	0.07	2.16	9.04	14.97
Cl5(95)	41.87	4.32	0.05	0.05	0.20	0.42	0.31	4.28	34.66	56.88
Cl5(97)	19.81	2.22	0.03	0.03	0.03	0.49	0.04	1.69	14.04	24.41
Cl5(99)	21.35	1.94	0.05	0.05	0.14	0.43	0.06	3.62	18.56	29.62
Cl5(100)	0.48	0.05	0.04	0.04	0.05	0.05	0.05	0.05	0.75	0.77

STATION_ID	T172B	T172B	T173A	T173A	T173A	T173A	T173A	T173A	T173A	T173A
FIELD SAMPLE_ID	T172-B-KJI	72B 14.4-15.4	T173A 0-1FT	T173A 1-2FT	T173A 2-3FT	T173A 3-4FT	T173A 4-5FT	T173A 5-6FT	T173A 6-7FT	T173A 7-8FT
SAMPLE DEPTH (from bottom)	12.3-14.4	14.4-15.4	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	29.69	3.18	0.10	0.10	0.25	0.46	0.29	4.64	27.58	45.54
Cl5(105)	16.54	2.01	0.07	0.07	0.07	0.50	0.08	1.15	6.77	14.25
Cl5(110)	58.47	6.85	0.08	0.15	0.23	0.71	0.78	7.79	46.95	88.78
Cl5(114)	0.96	0.68	0.10	0.10	0.11	0.11	0.12	0.12	0.13	0.15
Cl5(115)	0.82	0.10	0.09	0.09	0.09	0.10	0.11	0.11	0.12	0.73
Cl5(118)	27.60	3.07	0.06	0.06	0.15	0.49	0.07	4.35	22.88	37.78
Cl5(107)/(123)	5.79	0.11	0.09	0.10	0.23	0.10	0.11	1.53	3.40	5.07
Cl5(124)	1.03	0.07	0.06	0.06	0.06	0.06	0.07	0.07	0.07	0.08
Cl5(126)	0.11	0.10	0.08	0.08	0.09	0.09	0.10	0.10	0.11	0.12
Cl6(128)	2.57	0.59	0.08	0.08	0.08	0.08	0.09	0.09	2.48	3.97
Cl6(130)	1.66	0.09	0.08	0.08	0.08	0.08	0.09	0.09	2.23	3.19
Cl6(134)	0.94	0.07	0.06	0.06	0.07	0.07	0.08	0.08	1.18	1.60
Cl6(135)	2.28	0.30	0.07	0.07	0.07	0.08	0.08	0.68	1.99	3.21
Cl6(136)	1.81	0.35	0.02	0.02	0.02	0.02	0.02	1.59	2.99	3.02
Cl6(137)	0.64	0.12	0.10	0.10	0.11	0.11	0.12	1.74	0.13	0.15
Cl6(138)	6.97	1.14	0.08	0.08	0.09	0.09	0.10	2.01	7.19	10.84
Cl6(141)	1.62	0.48	0.04	0.04	0.05	0.05	0.05	0.05	0.06	1.14
Cl6(144)	0.47	0.10	0.09	0.09	0.09	0.10	0.11	0.11	0.44	0.52
Cl6(146)	2.69	0.36	0.02	0.02	0.02	0.02	0.02	1.16	3.67	5.12
Cl6(149)	9.79	1.37	0.07	0.07	0.07	0.08	0.08	3.04	9.96	13.95
Cl6(151)	2.79	0.43	0.08	0.08	0.08	0.08	0.09	0.98	2.57	3.69
Cl6(132)/(153)/(168)	11.04	1.82	0.06	0.06	0.07	0.07	0.08	3.93	11.34	15.62
Cl6(156)	1.42	0.02	0.02	0.02	0.02	0.02	0.02	1.57	1.95	1.16
Cl6(157)	0.45	0.09	0.08	0.08	0.08	0.08	0.09	0.09	0.10	0.11
Cl6(129)/(158)	1.37	0.08	0.07	0.07	0.07	0.08	0.08	0.09	1.37	1.54
Cl6(163)	1.91	0.21	0.07	0.07	0.07	0.08	0.08	0.80	1.90	2.86
Cl6(164)	0.95	0.06	0.05	0.05	0.05	0.06	0.06	0.06	0.79	0.91
Cl6(166)	0.11	0.10	0.08	0.08	0.09	0.09	0.10	0.10	0.11	0.12
Cl6(167)	0.67	0.06	0.05	0.05	0.05	0.06	0.06	0.06	0.07	1.33
Cl6(169)	0.15	0.13	0.11	0.11	0.11	0.12	0.13	0.13	2.17	0.15
Cl7(170)	1.83	0.57	0.06	0.06	0.06	0.06	0.07	0.91	1.80	2.10
Cl7(171)	0.69	0.05	0.04	0.04	0.05	0.05	0.05	0.05	0.63	0.81
Cl7(172)	0.47	0.07	0.06	0.06	0.06	0.06	0.07	0.07	1.45	1.39
Cl7(174)	2.11	0.48	0.03	0.03	0.03	0.03	0.04	0.72	2.16	2.30
Cl7(176)	0.36	0.06	0.05	0.05	0.05	0.06	0.06	1.10	1.57	0.96
Cl7(177)	1.82	0.44	0.06	0.06	0.06	0.06	0.07	1.08	1.97	2.42
Cl7(178)	0.77	0.05	0.04	0.04	0.05	0.05	0.05	0.80	1.30	2.00
Cl7(179)	1.12	0.23	0.08	0.08	0.09	0.09	0.10	0.85	1.43	1.97
Cl7(180)	4.77	0.96	0.06	0.06	0.06	0.06	0.07	1.79	4.16	6.34
Cl7(183)	1.37	0.25	0.06	0.06	0.06	0.06	0.07	1.45	3.02	2.07
Cl7(184)	0.05	0.04	0.04	0.04	0.04	0.04	0.05	0.18	0.46	0.35
Cl7(185)	0.18	0.07	0.06	0.06	0.06	0.06	0.07	0.07	0.07	0.45
Cl7(187)	3.37	0.52	0.05	0.05	0.05	0.06	0.06	1.74	3.70	4.57
Cl7(189)	0.11	0.10	0.08	0.08	0.09	0.09	0.10	0.10	0.11	0.12
Cl7(190)	0.63	0.14	0.06	0.06	0.07	0.07	0.08	0.08	0.08	0.69
Cl7(193)	0.37	0.04	0.03	0.03	0.03	0.03	0.04	0.44	0.04	0.43
Cl8(194)	1.74	0.34	0.04	0.04	0.05	0.05	0.05	1.16	2.31	3.44
Cl8(195)	0.77	0.05	0.04	0.04	0.05	0.05	0.05	0.55	0.75	1.07
Cl8(199)	2.20	0.57	0.08	0.08	0.09	0.09	0.10	4.24	7.52	9.88
Cl8(200)	0.21	0.11	0.09	0.10	0.10	0.10	0.11	0.12	0.43	0.33
Cl8(201)	0.33	0.11	0.09	0.10	0.10	0.10	0.11	0.82	1.53	0.92
Cl8(202)	0.40	0.07	0.06	0.06	0.07	0.07	0.08	1.48	1.28	1.51
Cl8(196)/(203)	1.63	0.36	0.03	0.03	0.03	0.03	0.03	1.04	2.54	3.40
Cl8(205)	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.56	0.86	0.57
Cl9(206)	2.04	0.30	0.08	0.08	0.09	0.09	0.17	11.88	18.03	27.21
Cl9(207)	0.31	0.09	0.08	0.08	0.08	0.08	0.09	0.24	1.22	0.99
Cl9(208)	0.71	0.10	0.07	0.07	0.07	0.08	0.09	3.58	6.44	7.81
Cl10(209)	20.56	0.82	0.04	0.04	0.05	0.21	0.42	64.41	196.00	186.83
Sum 117 congeners	1,798	211	9	8	13	28	22	230	1,679	2,894

STATION_ID	T173A	T173A	T173A	T173A	T173A	T173A	T173A	T173A	T173B	T173B
FIELD SAMPLE_ID	T173A 8-9FT	T173A 9-10FT	173A 10-11F	173A 11-12F	173A 12-13F	T173-A-MLK	T173-A-JIH	73A 18.7-19.7	T173-B-ZY	T173-B-XW
SAMPLE DEPTH (from bottom)	8-9	9-10	10-11	11-12	12-13	13-16	16-18.7	18.7-19.7	0-1.8	1.8-3
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	87.34	34.35	108.88	52.25	73.41	38.68	13.14	10.59	1.94	16.03
Cl1(1)	17.79	12.44	33.01	52.42	28.73	0.07	0.08	0.08	0.05	0.06
Cl1(3)	10.99	8.66	17.19	31.99	21.31	0.04	0.04	0.04	0.02	0.03
Cl2(4)/(10)	92.13	51.45	93.11	174.20	287.19	28.89	0.13	1.27	0.09	0.10
Cl2(5)	3.90	0.22	3.75	20.54	22.21	0.12	0.12	0.13	0.08	0.09
Cl2(6)	513.45	107.58	322.93	2347.90	678.29	62.93	2.94	1.67	0.06	0.07
Cl2(7)	6.54	5.04	7.44	40.95	43.92	5.03	0.07	0.07	0.04	0.05
Cl2(8)	226.94	159.61	274.90	1087.46	807.54	64.95	3.52	2.26	0.07	0.08
Cl2(9)	12.35	8.18	13.99	66.57	77.91	7.70	0.08	0.09	0.06	0.06
Cl2(13)	185.18	54.75	91.46	558.11	221.93	26.12	1.49	0.84	0.06	0.06
Cl2(15)	67.11	80.56	96.59	298.50	296.54	34.57	2.69	1.54	0.10	0.11
Cl3(16)	684.14	452.01	881.26	2473.36	1039.90	119.64	9.84	6.82	0.07	0.08
Cl3(17)	971.27	559.43	1061.22	3628.28	1535.62	156.78	14.00	7.88	0.99	0.05
Cl3(18)	3070.76	1623.41	3492.51	10204.59	3892.21	385.32	32.09	20.37	1.20	0.99
Cl3(19)	109.41	69.43	190.45	178.55	178.39	21.01	1.60	0.89	0.07	0.08
Cl3(22)	931.80	592.67	1044.26	2409.19	1283.00	159.21	17.92	10.70	0.06	0.06
Cl3(24)	7.17	6.54	9.17	22.18	26.59	3.07	0.07	0.07	1.64	0.05
Cl3(25)	2094.28	380.68	938.90	6708.04	2153.98	262.80	18.39	10.61	1.20	0.95
Cl3(26)	2107.39	483.54	995.27	8963.20	2381.53	288.52	25.24	13.43	1.15	0.07
Cl3(27)	75.88	56.91	103.66	125.07	131.59	17.66	1.42	0.92	0.04	0.04
Cl3(28)	3598.74	2133.00	3513.82	9716.08	4664.36	533.76	46.66	36.83	1.96	1.37
Cl3(31)	4422.30	2328.66	4085.61	13020.23	5268.65	654.57	56.51	40.42	2.42	1.32
Cl3(32)	521.07	336.12	652.91	1740.50	727.95	76.00	8.24	4.56	0.03	0.03
Cl3(33)/(20)	1272.64	974.34	1527.47	3818.35	2013.26	240.48	24.11	15.00	1.37	0.80
Cl3(37)	338.83	307.11	456.40	657.49	583.68	83.19	10.81	7.82	0.07	0.08
Cl4(40)	816.04	598.31	859.92	2476.13	1036.60	117.55	14.13	9.88	0.08	0.09
Cl4(41)	179.08	251.48	315.15	222.35	152.99	37.40	4.35	2.99	0.04	0.05
Cl4(42)/(59)	1934.94	1210.17	1861.65	5441.21	2328.89	311.32	31.87	22.82	0.94	0.06
Cl4(43)	229.67	183.77	201.93	678.63	250.02	29.99	4.29	2.01	0.05	0.06
Cl4(44)	4925.49	3039.12	5005.03	14995.38	6263.01	740.41	76.46	54.79	2.20	2.76
Cl4(45)	862.31	584.14	903.09	2658.76	1012.68	111.79	12.63	9.44	0.43	0.05
Cl4(46)	370.41	267.81	393.97	1205.54	447.26	49.38	5.52	3.82	0.07	0.09
Cl4(47)	1274.54	746.33	1176.59	3743.27	1610.77	188.57	23.15	15.19	0.68	0.06
Cl4(48)	425.70	549.35	890.67	1332.73	760.71	87.43	12.39	7.68	0.06	0.06
Cl4(49)	4295.25	2382.93	3876.88	13547.36	5470.66	671.01	62.90	45.70	1.77	1.69
Cl4(51)	204.86	132.50	261.40	688.89	309.40	34.92	3.58	1.92	0.07	0.08
Cl4(52)	5877.76	3522.17	5637.56	18323.76	7079.89	813.36	79.84	60.15	2.21	1.68
Cl4(53)	778.27	506.02	883.07	2656.18	909.30	108.98	11.28	7.10	0.39	0.04
Cl4(54)	10.81	7.43	11.89	24.27	12.16	3.32	0.07	0.07	0.04	0.14
Cl4(56)	1738.71	1369.58	1938.37	3214.70	2173.84	241.32	28.35	24.62	0.82	0.08
Cl4(60)	182.29	291.68	335.14	415.67	271.09	48.56	8.46	7.96	0.31	0.08
Cl4(64)	2374.32	1514.78	2386.42	6900.38	2782.49	331.91	34.10	26.69	1.04	0.67
Cl4(66)	2664.08	2601.48	3494.35	5748.35	3329.37	469.45	62.69	47.91	1.35	1.32
Cl4(70)	4187.35	3374.60	5028.60	8590.39	5148.55	664.56	75.22	57.56	1.87	1.20
Cl4(71)	1349.50	775.62	1281.21	3653.39	1544.20	185.08	23.50	14.86	0.69	0.06
Cl4(74)	1220.73	1393.52	1674.86	2720.61	1622.36	201.28	31.48	22.65	0.69	0.04
Cl4(77)	214.57	187.02	253.63	324.01	251.56	40.18	5.86	4.23	0.13	0.15
Cl4(81)	1.78	2.68	4.30	4.23	2.47	0.06	0.07	0.07	0.04	0.05
Cl5(82)	298.06	266.49	306.55	520.43	381.83	47.03	6.02	5.16	0.05	0.06
Cl5(83)/(119)	314.59	181.67	279.63	838.10	372.93	47.64	5.68	3.53	0.07	0.08
Cl5(84)	1147.41	671.98	1123.05	3014.81	1380.80	136.12	16.50	11.43	0.42	0.49
Cl5(85)	469.84	334.57	506.23	957.98	465.59	64.63	6.86	0.07	0.29	0.05
Cl5(87)	550.64	536.42	631.07	857.60	470.01	82.14	12.40	8.52	0.46	0.10
Cl5(91)	408.06	267.54	453.18	1202.96	553.36	71.88	8.13	5.45	0.25	0.27
Cl5(92)	276.91	146.03	176.41	878.19	291.18	61.91	6.91	4.14	0.18	0.35
Cl5(95)	1457.76	962.92	1439.74	4459.91	1854.79	246.23	28.47	18.98	0.74	0.72
Cl5(97)	503.07	456.71	630.92	1136.55	637.04	92.53	12.74	8.96	0.03	0.03
Cl5(99)	562.68	616.15	730.46	1433.01	768.95	90.38	14.02	11.21	0.31	0.53
Cl5(100)	12.79	6.98	10.96	30.69	16.55	2.36	0.38	0.07	0.04	0.05

STATION_ID	T173A	T173A	T173A	T173A	T173A	T173A	T173A	T173A	T173B	T173B
FIELD SAMPLE_ID	T173A 8-9FT	T173A 9-10FT	173A 10-11F	173A 11-12F	173A 12-13F	T173-A-MLK	T173-A-JIH	73A 18.7-19.7	T173-B-ZY	T173-B-XW
SAMPLE DEPTH (from bottom)	8-9	9-10	10-11	11-12	12-13	13-16	16-18.7	18.7-19.7	0-1.8	1.8-3
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	963.61	837.81	1073.50	2123.59	1135.06	148.30	20.47	17.77	0.44	0.66
Cl5(105)	323.28	351.64	507.21	606.79	345.66	63.65	10.51	9.84	0.42	0.08
Cl5(110)	2249.20	1470.53	1955.70	5679.48	2629.55	324.57	36.99	30.68	1.04	1.27
Cl5(114)	4.30	17.86	20.25	11.92	12.77	2.56	0.15	0.16	0.10	0.11
Cl5(115)	10.62	24.72	24.23	20.79	15.72	4.44	0.87	4.83	0.09	0.10
Cl5(118)	815.18	757.79	911.18	1514.79	984.45	134.53	18.37	16.06	0.56	0.74
Cl5(107)/(123)	138.17	112.92	135.45	276.88	184.94	30.16	3.46	2.65	0.09	0.10
Cl5(124)	17.55	26.85	34.38	38.88	29.84	3.73	0.67	0.09	0.06	0.06
Cl5(126)	6.33	6.33	7.99	8.60	6.32	0.12	0.12	0.13	0.08	0.09
Cl6(128)	72.73	63.63	79.77	121.94	63.18	11.00	1.63	1.29	0.07	0.08
Cl6(130)	49.36	32.56	42.52	57.60	33.71	6.58	0.94	0.12	0.07	0.08
Cl6(134)	28.98	20.95	27.88	46.48	26.93	4.40	0.68	0.10	0.06	0.07
Cl6(135)	68.47	39.79	51.64	86.51	48.52	9.79	1.58	0.97	0.07	0.08
Cl6(136)	61.93	40.15	50.55	85.34	47.84	8.74	1.30	0.94	0.02	0.23
Cl6(137)	13.26	18.17	19.55	20.68	16.54	2.56	0.15	0.16	0.10	0.11
Cl6(138)	180.34	204.90	245.60	249.56	191.62	31.37	5.51	4.97	0.08	0.09
Cl6(141)	21.82	33.33	36.13	31.65	22.87	4.62	1.34	1.07	0.04	0.05
Cl6(144)	13.55	12.86	14.71	13.27	8.13	1.79	0.41	0.38	0.09	0.10
Cl6(146)	79.96	54.91	71.35	79.42	55.27	13.29	1.90	1.36	0.02	0.02
Cl6(149)	260.43	204.47	257.23	323.71	214.98	46.20	7.47	5.33	0.18	0.33
Cl6(151)	62.61	60.16	67.13	69.54	54.63	12.67	2.26	0.12	0.10	0.08
Cl6(132)/(153)/(168)	289.33	226.62	369.37	522.43	221.98	43.73	8.25	7.20	0.22	0.45
Cl6(156)	16.21	25.35	32.43	23.56	21.41	3.77	0.81	0.03	0.02	0.02
Cl6(157)	5.98	7.13	9.27	9.84	7.39	1.79	0.11	0.12	0.07	0.08
Cl6(129)/(158)	19.25	24.46	31.22	35.26	23.14	5.28	1.11	0.99	0.07	0.08
Cl6(163)	82.16	43.40	52.92	89.96	46.40	10.13	1.51	1.07	0.07	0.08
Cl6(164)	24.67	20.62	24.77	28.80	20.29	4.07	0.95	0.57	0.05	0.06
Cl6(166)	0.19	0.22	0.23	0.20	0.20	0.12	0.12	0.13	0.08	0.09
Cl6(167)	12.50	12.42	17.35	16.91	12.93	2.47	0.52	0.08	0.05	0.06
Cl6(169)	0.24	2.56	0.38	0.36	0.63	0.41	0.16	0.17	0.10	0.12
Cl7(170)	49.56	42.04	62.93	49.23	31.21	6.88	1.58	1.86	0.06	0.06
Cl7(171)	16.71	11.18	16.72	15.12	8.31	2.21	0.53	0.53	0.04	0.05
Cl7(172)	15.32	9.82	13.46	12.89	8.51	2.05	0.39	0.09	0.06	0.06
Cl7(174)	64.47	46.26	54.75	41.56	27.41	8.27	2.04	1.69	0.03	0.03
Cl7(176)	11.52	6.42	7.15	6.59	4.35	1.48	0.30	0.21	0.05	0.06
Cl7(177)	49.35	31.20	38.87	42.32	23.61	6.58	1.55	1.27	0.06	0.06
Cl7(178)	19.30	10.98	12.91	14.66	8.00	2.68	0.61	0.52	0.04	0.05
Cl7(179)	36.22	22.98	21.72	19.01	11.89	4.38	1.02	0.82	0.08	0.13
Cl7(180)	98.64	66.89	158.18	122.10	60.71	16.07	3.87	4.00	0.06	0.06
Cl7(183)	39.44	27.07	32.31	26.71	15.80	5.28	1.08	1.27	0.06	0.06
Cl7(184)	0.54	0.55	0.82	0.78	0.65	0.18	0.06	0.06	0.04	0.04
Cl7(185)	6.57	5.65	6.20	4.32	2.73	0.91	0.23	0.09	0.06	0.06
Cl7(187)	83.59	56.20	63.67	63.44	38.53	12.13	2.84	1.98	0.08	0.16
Cl7(189)	2.54	3.89	4.13	4.16	1.78	0.64	0.12	0.13	0.08	0.09
Cl7(190)	11.15	8.92	14.86	12.45	8.11	1.66	0.46	0.58	0.06	0.07
Cl7(193)	8.22	5.53	7.10	7.63	4.40	0.96	0.22	0.05	0.03	0.03
Cl8(194)	49.37	36.52	44.47	36.00	24.94	5.21	1.20	0.99	0.04	0.14
Cl8(195)	15.21	11.04	15.28	14.03	9.20	1.79	0.46	0.07	0.04	0.05
Cl8(199)	62.87	45.78	50.82	42.26	31.43	7.92	1.62	1.87	0.08	0.51
Cl8(200)	5.55	3.66	3.78	3.79	2.79	0.79	0.19	0.15	0.09	0.10
Cl8(201)	6.98	4.76	6.55	5.01	4.66	1.08	0.23	0.15	0.09	0.10
Cl8(202)	9.08	6.10	7.32	6.33	5.99	1.49	0.34	0.10	0.06	0.14
Cl8(196)/(203)	42.68	30.09	35.76	31.70	22.87	5.61	1.09	1.46	0.02	0.17
Cl8(205)	0.04	3.11	3.31	3.73	2.06	0.03	0.03	0.03	0.02	0.02
Cl9(206)	65.29	65.71	62.75	45.22	43.25	7.50	1.50	0.98	0.08	1.05
Cl9(207)	7.93	7.08	11.90	9.53	9.97	0.88	0.25	0.12	0.07	0.08
Cl9(208)	18.33	18.87	24.67	15.45	21.93	2.75	0.57	0.31	0.07	0.32
Cl10(209)	508.00	692.76	794.29	468.11	976.65	101.37	22.35	8.16	0.45	3.63
Sum 117 congeners	70,659	46,768	72,620	196,559	88,224	10,809	1,185	851	38	33

STATION_ID	T173B	T173B	T173B	T173B	T173B	T173B	T173B	T173B	T173B	T173B
FIELD SAMPLE_ID	T173B 3-4FT	T173B 4-5FT	T173B 5-6FT	T173B 6-7FT	T173B 7-8FT	T173B 8-9FT	T173B 9-10FT	T173B 10-11F	T173B 11-12F	T173-B-MLK
SAMPLE DEPTH (from bottom)	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-15.3
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	32.09	46.94	35.63	56.89	76.15	41.96	36.66	28.80	15.34	20.17
Cl1(1)	0.07	0.07	0.07	0.08	0.08	10.39	13.86	38.45	33.01	4.40
Cl1(3)	0.03	0.04	0.03	0.04	0.04	6.87	9.73	25.83	20.72	3.20
Cl2(4)/(10)	0.12	0.13	0.12	0.14	23.75	51.05	58.77	142.40	241.55	27.15
Cl2(5)	0.11	0.12	0.11	0.13	0.14	0.39	0.26	12.50	14.61	2.36
Cl2(6)	0.08	0.09	1.03	50.81	306.62	309.75	147.23	778.69	679.94	34.26
Cl2(7)	0.06	0.06	0.06	0.07	0.07	5.51	6.25	23.44	31.31	4.22
Cl2(8)	0.10	0.11	3.84	26.19	95.31	188.44	193.76	554.92	550.94	68.06
Cl2(9)	0.08	0.08	0.08	0.09	4.11	10.45	10.61	38.98	51.23	6.87
Cl2(13)	0.08	0.08	0.08	33.62	121.37	131.70	47.49	214.40	175.53	16.34
Cl2(15)	0.13	0.15	0.14	10.44	33.85	75.44	97.17	152.12	216.03	38.09
Cl3(16)	0.10	2.71	9.71	85.81	428.27	578.97	541.89	1243.22	1102.72	94.07
Cl3(17)	0.06	3.12	15.18	114.77	624.07	672.58	591.80	1665.28	1554.27	108.55
Cl3(18)	0.08	3.76	31.55	326.71	1669.91	2131.67	1838.47	5503.77	4620.53	269.55
Cl3(19)	0.09	0.10	1.45	15.04	55.84	76.39	82.18	160.55	302.03	15.43
Cl3(22)	0.08	0.08	15.19	122.33	422.59	558.72	666.59	1345.30	1231.65	130.23
Cl3(24)	0.06	0.06	0.06	0.07	3.17	4.67	6.29	16.66	18.45	2.96
Cl3(25)	0.06	3.19	7.58	285.35	1114.22	1242.96	430.85	2503.97	2166.53	106.66
Cl3(26)	0.08	2.31	8.24	267.48	1116.47	1110.45	453.53	3732.42	2757.01	121.78
Cl3(27)	0.05	0.06	0.05	11.34	38.76	59.34	64.44	254.78	138.90	11.40
Cl3(28)	1.72	4.07	36.54	412.91	1535.31	2311.93	2120.62	5320.17	4724.50	338.92
Cl3(31)	1.82	5.15	38.05	566.90	1963.07	2712.11	2257.19	6692.38	6060.55	403.75
Cl3(32)	0.04	0.05	6.70	56.73	289.91	414.29	344.86	905.20	789.81	56.47
Cl3(33)/(20)	2.63	5.01	26.02	160.25	563.70	942.93	1081.89	2301.39	1920.16	176.05
Cl3(37)	0.09	0.10	9.10	50.73	116.69	309.19	293.03	564.98	567.58	70.71
Cl4(40)	3.43	0.12	11.44	98.96	326.64	531.14	573.11	1304.02	1041.82	75.88
Cl4(41)	0.06	0.06	0.06	21.01	59.46	155.62	263.87	622.85	232.49	24.44
Cl4(42)/(59)	0.08	4.01	33.77	245.54	794.78	1170.79	1262.20	2901.03	2662.75	196.47
Cl4(43)	0.07	0.07	4.88	32.75	88.60	149.49	180.67	523.23	328.29	23.20
Cl4(44)	10.80	15.90	63.36	641.92	2058.82	3275.96	2948.99	8598.00	7215.73	434.42
Cl4(45)	0.06	0.06	11.89	92.35	407.47	581.47	559.97	1472.08	1273.96	75.40
Cl4(46)	0.10	0.11	4.12	56.94	199.90	280.99	332.99	698.82	563.38	35.14
Cl4(47)	1.27	3.16	23.02	149.17	572.34	893.22	776.02	2060.20	1735.34	116.13
Cl4(48)	0.08	0.08	13.90	57.14	164.12	383.55	762.66	848.26	945.67	74.32
Cl4(49)	6.01	8.26	47.18	504.45	1844.08	2793.35	2427.32	7108.36	6116.81	348.26
Cl4(51)	0.09	0.10	3.58	33.60	130.69	176.92	188.72	533.99	322.26	21.32
Cl4(52)	5.47	10.20	57.65	667.47	2625.46	4006.24	3298.23	9743.70	8385.80	441.01
Cl4(53)	0.05	0.06	10.34	88.53	365.13	508.98	512.20	1382.41	1146.56	64.20
Cl4(54)	0.06	0.06	0.06	2.05	5.23	8.32	10.23	19.64	16.28	1.20
Cl4(56)	0.10	2.50	32.12	198.83	598.65	1227.13	1341.56	2354.43	2254.52	179.59
Cl4(60)	0.09	0.10	0.09	32.58	59.28	192.50	328.09	654.93	393.93	36.98
Cl4(64)	1.08	2.80	35.50	288.38	904.68	1569.51	1699.48	3762.39	3403.32	216.31
Cl4(66)	4.68	8.17	58.05	286.66	745.41	1885.02	2721.30	4000.94	3751.54	347.01
Cl4(70)	5.62	9.28	66.16	518.21	1396.38	3141.15	3568.20	6178.50	5709.78	461.74
Cl4(71)	1.18	2.37	21.48	168.50	540.59	928.79	858.69	2172.61	1942.57	133.59
Cl4(74)	1.73	2.74	29.70	138.35	328.76	949.38	1309.83	1928.83	1800.23	170.06
Cl4(77)	0.18	0.19	6.18	25.70	57.08	158.79	247.62	286.32	293.83	35.69
Cl4(81)	0.06	0.06	0.06	0.07	0.07	2.81	4.37	7.80	5.92	0.54
Cl5(82)	0.07	0.07	4.30	52.16	123.90	245.40	221.22	608.84	400.90	33.09
Cl5(83)/(119)	2.45	2.99	6.55	49.58	104.22	213.33	189.02	497.24	427.93	33.87
Cl5(84)	2.66	2.34	12.95	114.50	398.85	883.58	722.42	2054.68	1447.73	82.28
Cl5(85)	0.06	0.06	3.77	51.96	173.88	319.88	377.24	788.08	663.15	41.95
Cl5(87)	2.10	3.75	8.37	75.49	168.87	441.44	573.82	860.66	714.36	64.06
Cl5(91)	1.15	2.34	7.12	54.28	153.23	333.69	281.15	661.02	580.46	42.25
Cl5(92)	2.01	3.53	8.72	49.93	140.46	186.37	181.35	355.38	482.11	38.19
Cl5(95)	5.30	8.11	27.57	188.21	647.40	1150.04	1048.78	2421.04	2146.90	146.69
Cl5(97)	2.50	3.37	12.26	70.56	165.06	400.58	577.51	840.93	780.53	71.90
Cl5(99)	5.83	7.65	16.73	70.16	205.36	482.51	624.70	1022.69	958.73	67.10
Cl5(100)	0.59	0.06	0.46	1.96	4.76	8.99	8.65	22.10	21.87	1.41

STATION_ID	T173B	T173B	T173B	T173B	T173B	T173B	T173B	T173B	T173B	T173B
FIELD SAMPLE_ID	T173B 3-4FT	T173B 4-5FT	T173B 5-6FT	T173B 6-7FT	T173B 7-8FT	T173B 8-9FT	T173B 9-10FT	T173B 10-11F	T173B 11-12F	T173-B-MLK
SAMPLE DEPTH (from bottom)	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-15.3
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	6.47	9.34	25.82	84.02	295.02	640.53	858.11	1552.98	1278.48	93.51
Cl5(105)	1.93	3.13	4.85	51.32	98.68	257.98	384.78	803.54	664.94	52.12
Cl5(110)	9.43	12.55	40.83	276.27	740.24	1519.49	1389.32	3358.05	2718.20	209.12
Cl5(114)	0.13	0.15	0.14	0.15	0.80	7.97	23.98	31.94	22.38	2.35
Cl5(115)	0.12	0.13	0.40	3.35	3.34	8.99	21.59	50.94	34.31	2.63
Cl5(118)	7.09	9.39	21.89	89.22	183.51	527.47	719.34	1264.48	1023.87	107.66
Cl5(107)/(123)	2.32	3.19	5.29	23.61	73.65	157.69	122.77	370.52	212.95	18.60
Cl5(124)	0.08	0.08	0.08	2.09	3.68	18.64	33.67	57.68	49.05	2.95
Cl5(126)	0.11	0.12	0.11	0.13	2.48	5.64	7.69	11.26	8.99	0.10
Cl6(128)	0.10	0.11	0.10	9.90	23.85	66.78	69.77	116.07	92.85	6.41
Cl6(130)	3.01	2.69	2.88	8.67	18.26	37.14	34.99	59.02	47.39	3.73
Cl6(134)	1.93	1.94	2.19	3.81	9.94	21.47	20.58	43.60	36.44	2.45
Cl6(135)	0.93	1.45	2.00	9.76	25.81	51.89	42.58	78.16	63.75	4.85
Cl6(136)	4.37	4.64	3.10	8.29	20.59	66.10	42.65	79.56	65.50	4.31
Cl6(137)	5.50	5.54	0.14	2.51	3.46	12.78	20.46	32.44	25.33	1.78
Cl6(138)	4.86	6.25	5.82	29.02	63.50	185.72	204.76	444.04	220.11	17.74
Cl6(141)	2.19	0.06	0.06	3.55	6.14	23.99	38.26	56.31	43.37	3.08
Cl6(144)	0.12	0.13	0.12	1.84	4.13	10.31	13.03	19.43	14.19	1.04
Cl6(146)	1.88	2.52	3.44	14.03	35.87	72.93	56.91	82.32	65.64	6.37
Cl6(149)	5.05	7.11	8.90	42.19	109.68	230.06	211.86	439.38	273.34	23.40
Cl6(151)	1.43	2.44	2.58	12.16	32.67	68.21	62.76	93.52	73.50	5.73
Cl6(132)/(153)/(168)	5.62	8.49	9.87	42.78	83.06	225.29	251.33	368.50	272.08	24.27
Cl6(156)	5.90	5.63	2.85	2.79	4.67	19.63	27.92	45.49	36.34	1.99
Cl6(157)	0.10	0.11	0.10	0.81	1.46	8.81	8.95	13.51	11.03	0.94
Cl6(129)/(158)	0.09	0.10	0.09	4.83	5.63	23.48	27.14	54.67	42.68	2.83
Cl6(163)	1.44	1.54	1.89	8.66	20.79	57.77	48.31	87.15	65.98	5.33
Cl6(164)	0.07	0.07	1.06	3.58	7.16	22.53	20.90	34.51	26.69	1.94
Cl6(166)	0.11	0.12	0.11	0.13	0.14	0.39	0.26	0.26	3.12	0.10
Cl6(167)	0.07	7.90	4.25	2.72	3.53	10.71	15.25	23.21	17.90	1.49
Cl6(169)	0.14	0.16	0.14	0.37	1.17	2.28	0.72	0.90	0.20	0.07
Cl7(170)	2.52	3.48	2.12	7.08	15.47	41.54	43.26	65.94	44.95	3.61
Cl7(171)	1.10	0.06	0.76	2.17	5.79	12.48	12.18	18.17	11.35	0.92
Cl7(172)	0.08	0.08	0.08	3.44	5.79	10.81	10.65	15.45	10.04	0.94
Cl7(174)	1.99	2.71	2.26	9.78	21.44	49.02	46.25	53.28	36.74	3.84
Cl7(176)	4.59	4.40	2.32	2.08	4.42	0.24	6.60	7.86	5.20	0.58
Cl7(177)	0.08	2.72	2.08	7.60	18.55	39.26	30.35	44.83	29.33	3.17
Cl7(178)	0.06	1.39	1.37	4.15	7.90	14.01	12.67	14.38	9.97	1.18
Cl7(179)	2.61	3.03	2.08	5.62	13.01	25.33	25.60	23.61	15.20	1.87
Cl7(180)	5.93	6.66	5.38	19.72	35.64	91.04	99.71	114.38	87.47	8.01
Cl7(183)	0.08	8.14	3.27	6.88	13.57	29.45	28.06	33.55	21.31	2.01
Cl7(184)	0.77	0.90	0.45	0.51	0.36	0.18	1.03	1.42	0.53	0.12
Cl7(185)	0.08	0.08	0.08	1.04	2.18	5.05	6.08	6.77	3.85	0.58
Cl7(187)	4.08	4.66	4.66	16.21	36.39	69.30	59.59	66.41	46.83	5.50
Cl7(189)	2.53	0.12	0.11	0.13	1.16	2.77	3.67	4.86	3.83	0.10
Cl7(190)	0.08	0.09	0.09	2.27	3.60	9.15	10.46	16.95	11.05	0.90
Cl7(193)	1.66	0.99	0.60	1.36	3.17	5.93	4.69	7.55	4.85	0.51
Cl8(194)	1.97	2.36	2.28	10.91	18.75	37.98	38.71	47.61	33.55	3.42
Cl8(195)	1.21	1.94	1.28	3.20	6.83	12.27	12.11	18.48	10.29	1.44
Cl8(199)	8.02	8.64	6.74	21.74	25.43	45.35	54.21	49.75	34.37	4.27
Cl8(200)	0.13	0.98	0.51	1.35	2.14	4.42	4.27	4.65	3.20	0.49
Cl8(201)	3.20	5.07	2.20	2.06	2.50	5.48	6.32	8.39	4.60	0.70
Cl8(202)	1.92	2.02	1.58	2.84	3.32	6.40	7.80	7.60	5.26	0.75
Cl8(196)/(203)	2.87	3.85	2.68	9.64	16.04	32.27	34.58	40.10	26.72	2.97
Cl8(205)	1.64	2.16	1.18	1.12	1.02	3.42	3.08	6.48	1.99	0.02
Cl9(206)	25.15	26.21	15.94	48.96	27.28	46.42	91.82	64.22	41.79	6.62
Cl9(207)	1.09	3.84	2.62	2.65	2.60	5.60	12.65	20.32	8.64	1.47
Cl9(208)	6.37	8.89	6.43	12.76	7.56	13.49	27.85	26.43	14.23	3.00
Cl10(209)	143.97	277.94	210.90	225.81	175.90	366.93	919.04	724.84	395.62	192.70
Sum 117 congeners	373	616	1,288	8,902	29,448	48,901	48,735	114,676	98,570	7,108

STATION_ID	T173B	T174A	T174A	T174A	T174A	T174A	T174A	T174A	T174A	T174A
FIELD SAMPLE_ID	73B 15.3-16.3	T174A 0-1FT	T174A 1-2FT	T174A 2-3FT	T174A 3-4FT	T174A 4-5FT	T174A 5-6FT	T174A 6-7FT	T174A 7-8FT	T174A 8-9FT
SAMPLE DEPTH (from bottom)	15.3-16.3	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	3.46	5.61	10.00	38.06	38.65	48.61	70.28	35.14	41.41	113.12
Cl1(1)	0.06	0.05	0.06	0.06	0.07	0.07	0.10	13.67	16.30	29.86
Cl1(3)	0.03	0.03	0.03	0.03	0.03	0.03	0.05	10.50	10.00	18.20
Cl2(4)/(10)	0.10	0.09	0.10	8.76	0.12	0.12	25.81	52.14	54.40	103.16
Cl2(5)	0.09	0.08	0.09	0.10	0.11	0.11	0.16	0.24	0.30	0.28
Cl2(6)	1.85	0.06	0.07	0.08	1.28	41.49	229.15	168.47	138.50	358.67
Cl2(7)	0.05	0.04	0.05	0.06	0.06	0.06	0.09	5.42	4.26	9.34
Cl2(8)	1.44	0.08	0.09	0.10	3.19	19.85	91.23	155.69	156.69	346.26
Cl2(9)	0.06	0.06	0.07	0.07	0.08	0.08	4.01	8.83	9.14	14.50
Cl2(13)	0.60	0.06	0.07	0.07	0.08	20.40	93.33	57.36	49.80	85.68
Cl2(15)	0.97	0.10	0.12	0.13	0.14	7.94	42.48	83.78	89.12	107.64
Cl3(16)	4.46	0.08	0.09	0.10	8.29	60.00	370.42	443.07	592.01	1136.63
Cl3(17)	5.32	0.38	0.05	1.77	10.55	67.62	535.02	551.54	642.54	1409.81
Cl3(18)	15.10	0.41	0.07	2.80	22.39	220.35	1617.76	1767.48	1833.32	4614.53
Cl3(19)	0.63	0.07	0.08	0.09	0.09	8.81	61.75	80.21	80.79	239.09
Cl3(22)	5.81	0.06	0.07	2.03	12.53	63.36	410.59	575.51	642.01	1488.86
Cl3(24)	0.05	0.45	0.05	0.06	0.06	0.06	0.09	6.88	0.16	11.46
Cl3(25)	4.97	0.04	0.05	1.98	6.87	178.14	1030.67	641.78	441.86	1014.69
Cl3(26)	7.17	0.06	0.07	2.62	7.00	163.96	1020.03	746.64	458.85	1373.58
Cl3(27)	0.60	0.04	0.04	0.05	0.05	6.58	45.97	62.78	64.33	106.14
Cl3(28)	17.32	0.42	0.73	3.72	39.54	244.92	1690.31	2131.63	2384.18	4871.29
Cl3(31)	21.62	0.62	0.97	5.07	41.08	326.13	2117.18	2304.88	2585.11	5832.65
Cl3(32)	3.36	0.03	0.04	0.04	4.60	39.41	282.63	348.20	407.56	862.73
Cl3(33)/(20)	8.15	0.49	0.85	3.83	19.96	98.04	605.18	921.60	1067.07	2276.60
Cl3(37)	2.95	0.07	0.08	0.09	7.27	34.36	125.82	281.57	386.39	640.35
Cl4(40)	4.61	0.08	0.09	0.10	9.15	68.79	424.63	484.77	628.33	1331.56
Cl4(41)	1.93	0.04	0.05	0.06	0.06	10.02	77.43	180.62	311.02	477.79
Cl4(42)/(59)	10.37	0.06	0.59	5.07	23.85	129.70	919.79	1231.44	1192.92	2808.33
Cl4(43)	1.30	0.05	0.06	0.06	0.07	22.73	91.52	115.79	140.34	291.99
Cl4(44)	26.61	0.63	1.70	11.76	54.22	351.42	2325.93	3074.00	3334.57	7252.90
Cl4(45)	4.56	0.04	0.05	1.94	8.32	71.59	397.76	573.25	680.26	1329.48
Cl4(46)	2.12	0.08	0.09	0.10	3.88	34.09	192.49	265.21	258.34	535.77
Cl4(47)	6.31	0.06	0.07	1.69	18.27	104.40	595.79	719.39	839.18	1698.02
Cl4(48)	4.60	0.06	0.07	0.07	9.67	42.63	198.09	419.88	799.12	1378.67
Cl4(49)	18.87	0.46	1.12	6.91	36.93	335.60	2064.95	2481.21	2595.13	5694.81
Cl4(51)	1.35	0.07	0.08	0.09	2.41	19.80	106.77	153.83	217.93	356.98
Cl4(52)	27.32	0.59	1.34	7.35	47.47	435.82	2793.60	3344.27	4017.86	8239.00
Cl4(53)	4.30	0.04	0.04	0.91	7.32	56.87	378.51	507.13	580.07	1235.88
Cl4(54)	0.05	0.16	0.05	0.06	0.06	1.47	5.35	8.55	10.60	15.79
Cl4(56)	8.75	0.08	0.09	2.42	24.47	118.86	701.29	1203.90	1582.42	2715.40
Cl4(60)	2.77	0.07	0.08	1.34	2.58	11.76	68.69	191.59	435.75	562.26
Cl4(64)	12.47	0.27	0.58	2.78	26.10	168.53	1118.47	1413.86	1766.82	3501.76
Cl4(66)	16.41	0.41	0.95	5.40	48.94	156.98	1094.58	2265.07	2867.79	4984.50
Cl4(70)	23.79	0.42	1.17	6.71	50.48	286.49	1840.73	2936.54	3873.15	7180.71
Cl4(71)	7.47	0.06	0.07	1.87	16.16	100.71	618.71	824.10	940.79	1916.09
Cl4(74)	9.31	0.04	0.04	2.20	23.81	77.52	475.34	1136.74	1620.29	2421.60
Cl4(77)	1.35	0.13	0.15	0.17	4.52	17.22	75.14	154.02	218.28	367.30
Cl4(81)	0.05	0.04	0.05	0.06	0.06	0.06	0.09	3.51	5.36	8.49
Cl5(82)	1.85	0.05	0.06	0.06	4.83	37.33	156.63	236.66	323.65	517.67
Cl5(83)/(119)	1.09	0.07	0.08	1.57	5.60	34.08	140.25	149.34	185.68	360.42
Cl5(84)	4.05	0.10	0.11	2.26	10.64	96.83	501.77	615.88	804.78	1542.57
Cl5(85)	1.90	0.04	0.05	0.06	3.97	39.91	197.80	353.30	447.85	703.20
Cl5(87)	3.64	0.10	0.11	2.20	8.59	45.56	227.85	521.35	623.57	999.96
Cl5(91)	2.11	0.04	0.04	0.84	5.68	30.38	191.49	249.53	309.40	563.56
Cl5(92)	1.13	0.06	0.07	1.66	7.39	39.69	128.65	246.11	215.61	288.81
Cl5(95)	7.20	0.05	0.61	4.69	22.09	117.56	635.80	1042.12	1014.08	2089.40
Cl5(97)	3.26	0.03	0.04	2.29	10.18	43.37	236.69	431.55	465.19	861.26
Cl5(99)	3.16	0.05	0.39	3.67	14.06	43.90	264.60	489.18	645.58	1180.34
Cl5(100)	0.05	0.04	0.05	0.06	0.06	1.45	6.05	8.30	9.65	16.20

STATION_ID	T173B	T174A	T174A	T174A	T174A	T174A	T174A	T174A	T174A	T174A
FIELD SAMPLE_ID	73B 15.3-16.3	T174A 0-1FT	T174A 1-2FT	T174A 2-3FT	T174A 3-4FT	T174A 4-5FT	T174A 5-6FT	T174A 6-7FT	T174A 7-8FT	T174A 8-9FT
SAMPLE DEPTH (from bottom)	15.3-16.3	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	5.06	0.10	0.53	5.48	21.43	68.55	337.36	815.34	1046.96	1735.90
Cl5(105)	3.17	0.07	0.08	0.09	5.15	28.26	116.47	330.70	512.16	761.10
Cl5(110)	10.03	0.32	0.88	8.07	33.19	164.73	948.89	1307.42	1627.21	2799.68
Cl5(114)	0.11	0.10	0.12	0.13	0.14	0.13	0.20	15.52	35.88	36.84
Cl5(115)	0.10	0.09	0.10	0.11	0.12	1.33	4.97	11.60	30.30	39.65
Cl5(118)	4.36	0.06	0.73	5.35	18.82	51.38	277.58	668.24	835.12	1295.17
Cl5(107)/(123)	0.86	0.10	0.11	1.84	4.41	17.17	79.12	110.04	172.62	206.66
Cl5(124)	0.06	0.06	0.07	0.07	0.08	1.44	7.03	27.79	39.34	57.76
Cl5(126)	0.09	0.08	1.23	0.10	0.11	0.11	0.16	7.13	9.50	10.81
Cl6(128)	0.42	0.08	0.09	0.10	0.10	7.92	33.08	69.86	80.22	111.43
Cl6(130)	0.09	0.08	0.09	2.13	3.11	5.88	22.92	38.90	36.50	60.04
Cl6(134)	0.07	0.06	0.07	0.08	1.84	3.11	12.03	23.19	25.56	35.88
Cl6(135)	0.44	0.07	0.08	0.84	1.73	6.64	32.04	45.31	46.84	68.53
Cl6(136)	0.35	0.02	0.28	2.21	3.52	5.90	26.49	47.15	49.97	70.22
Cl6(137)	0.11	0.10	0.12	2.73	3.01	1.83	5.54	16.32	23.89	29.79
Cl6(138)	1.32	0.08	0.09	3.17	7.43	20.76	79.61	141.42	232.92	311.32
Cl6(141)	0.50	0.04	0.05	0.06	0.06	2.67	9.88	33.82	49.96	64.29
Cl6(144)	0.10	0.09	0.10	0.11	0.12	1.27	5.98	13.85	17.43	20.15
Cl6(146)	0.31	0.02	0.02	1.37	3.11	9.90	45.31	65.27	63.06	91.75
Cl6(149)	2.05	0.07	0.36	3.79	8.29	31.23	116.88	220.91	212.89	343.34
Cl6(151)	0.73	0.08	0.09	1.24	2.43	8.71	43.25	68.07	73.45	90.62
Cl6(132)/(153)/(168)	2.34	0.06	0.36	4.66	10.22	31.13	128.41	245.79	321.18	407.07
Cl6(156)	0.27	0.02	0.02	3.01	4.50	2.49	7.24	25.09	37.51	51.09
Cl6(157)	0.09	0.08	0.09	0.10	0.10	1.01	2.46	7.35	13.42	14.37
Cl6(129)/(158)	0.20	0.07	0.08	1.10	2.03	2.49	7.39	26.59	36.55	50.67
Cl6(163)	0.31	0.07	0.08	0.96	1.94	7.58	34.32	53.82	51.75	83.08
Cl6(164)	0.06	0.05	0.06	1.46	0.07	2.51	9.35	21.22	25.71	35.68
Cl6(166)	0.09	0.08	0.09	0.10	0.11	0.11	0.16	0.24	0.30	0.28
Cl6(167)	0.06	0.05	0.06	0.06	5.58	2.08	5.45	17.06	16.16	23.97
Cl6(169)	0.12	0.11	0.12	0.14	0.14	0.41	0.08	0.79	0.73	0.98
Cl7(170)	0.65	0.06	0.07	1.44	2.85	5.19	24.91	45.36	57.75	95.62
Cl7(171)	0.05	0.04	0.05	0.06	0.06	1.54	8.33	14.42	14.72	23.34
Cl7(172)	0.06	0.06	0.07	0.07	0.08	2.52	8.28	11.42	13.55	20.61
Cl7(174)	0.57	0.03	0.04	1.36	2.40	6.41	32.66	54.68	58.17	76.07
Cl7(176)	0.06	0.05	0.24	1.82	3.04	1.67	5.49	8.35	8.03	9.43
Cl7(177)	0.45	0.06	0.07	0.07	2.70	5.91	25.92	38.05	37.84	55.18
Cl7(178)	0.05	0.04	0.05	0.75	1.44	2.47	10.43	13.01	13.32	16.12
Cl7(179)	0.35	0.08	0.20	1.40	2.34	3.66	18.52	26.73	26.64	28.62
Cl7(180)	1.11	0.06	0.07	3.20	6.82	13.36	55.24	89.26	122.83	125.53
Cl7(183)	0.35	0.06	0.07	3.35	6.14	5.12	20.23	32.56	34.34	46.41
Cl7(184)	0.04	0.04	0.04	0.38	0.81	0.40	0.34	0.53	1.13	1.03
Cl7(185)	0.06	0.06	0.07	0.07	0.08	0.90	3.40	6.63	6.88	8.66
Cl7(187)	0.65	0.05	0.06	2.93	5.26	10.03	48.91	67.97	67.52	85.21
Cl7(189)	0.09	0.08	0.09	1.52	0.11	0.11	1.99	2.90	4.44	6.10
Cl7(190)	0.07	0.06	0.07	0.08	0.08	1.56	5.40	10.20	13.33	23.77
Cl7(193)	0.04	0.03	0.04	0.43	0.86	1.32	4.13	5.81	7.16	11.01
Cl8(194)	0.53	0.04	0.05	1.57	2.49	7.68	27.09	37.71	45.62	62.55
Cl8(195)	0.05	0.04	0.05	1.03	1.99	2.33	8.73	12.74	14.83	20.06
Cl8(199)	0.42	0.08	0.34	4.14	7.10	12.48	34.15	49.58	54.51	63.96
Cl8(200)	0.11	0.10	0.11	0.54	0.88	0.75	2.98	4.34	4.70	5.69
Cl8(201)	0.11	0.10	0.11	1.86	3.78	1.62	3.30	5.24	7.04	7.82
Cl8(202)	0.07	0.06	0.15	1.08	2.08	1.61	4.71	7.10	8.12	9.53
Cl8(196)/(203)	0.35	0.03	0.40	1.81	3.50	5.99	23.39	33.93	39.14	53.33
Cl8(205)	0.02	0.02	0.02	0.94	1.88	0.94	1.87	2.92	3.77	3.89
Cl9(206)	0.19	0.08	1.18	11.41	21.96	25.55	34.02	56.33	77.71	67.36
Cl9(207)	0.09	0.08	0.09	2.36	6.02	1.66	4.08	5.94	11.86	17.49
Cl9(208)	0.08	0.07	0.33	4.91	10.27	7.38	9.90	17.01	26.32	28.73
Cl10(209)	0.51	0.04	4.05	107.22	246.28	131.63	226.27	327.90	795.48	714.91
Sum 117 congeners	370	12	29	321	1,184	5,506	32,707	44,916	53,378	102,977

STATION_ID	T174A	T174A	T174A	T174B	T174B	T174B	T174B	T174B	T174B	T174B
FIELD SAMPLE_ID	T174-A-QPO	T174-A-NML	74A 14.4-15.4	T174B 0-1FT	T174B 1-2FT	T174B 2-3FT	T174B 3-4FT	T174B 4-5FT	T174B 5-6FT	T174B 6-7FT
SAMPLE DEPTH (from bottom)	9-12	12-14.4	14.4-15.4	0-1	1-2	2-3	3-4	4-5	5-6	6-7
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	47.13	12.79	4.31	1.16	41.16	43.00	68.28	45.70	42.83	55.04
Cl1(1)	13.32	0.07	0.07	0.05	0.07	0.07	0.08	0.08	11.74	22.46
Cl1(3)	9.38	0.04	0.03	0.02	0.03	0.03	0.04	0.04	8.02	13.75
Cl2(4)/(10)	101.67	2.49	1.05	0.09	0.12	0.12	0.13	19.59	60.48	76.10
Cl2(5)	6.76	0.12	0.11	0.08	0.11	0.11	0.12	0.13	0.26	4.81
Cl2(6)	203.63	3.10	2.11	0.06	0.09	0.08	11.95	84.50	54.58	128.35
Cl2(7)	13.56	0.06	0.06	0.04	0.06	0.06	0.07	2.56	5.69	6.89
Cl2(8)	236.19	3.38	2.94	0.07	0.10	2.29	18.24	35.91	175.73	221.78
Cl2(9)	23.26	0.08	0.08	0.06	0.08	0.07	0.09	2.18	9.88	11.41
Cl2(13)	65.27	1.44	1.16	0.06	0.08	0.07	0.09	35.03	121.86	47.73
Cl2(15)	94.87	3.01	2.54	0.10	0.14	0.13	5.55	12.60	71.83	92.14
Cl3(16)	348.31	10.48	7.00	0.81	0.10	6.86	65.31	116.32	69.46	73.69
Cl3(17)	460.41	13.51	8.62	0.98	0.06	8.93	89.60	143.99	92.08	76.62
Cl3(18)	1271.06	23.02	20.92	2.24	0.09	19.18	178.10	417.69	294.74	269.76
Cl3(19)	61.60	1.60	1.13	0.07	0.10	1.12	10.90	19.88	83.47	105.25
Cl3(22)	450.43	18.21	13.23	1.06	0.08	8.91	81.33	135.92	98.99	103.38
Cl3(24)	8.62	0.06	0.06	0.04	0.06	0.06	0.07	0.07	7.05	7.58
Cl3(25)	640.26	18.11	11.97	1.73	0.06	3.49	52.40	326.38	180.16	52.09
Cl3(26)	754.27	23.25	15.00	1.55	0.09	4.49	51.18	337.30	177.57	63.13
Cl3(27)	34.70	1.35	0.91	0.04	0.05	0.05	7.42	14.43	61.30	77.99
Cl3(28)	1436.89	38.25	39.71	3.42	0.10	28.30	241.73	508.73	343.59	323.75
Cl3(31)	1786.47	47.05	44.73	4.02	0.05	28.64	256.01	661.09	411.54	360.89
Cl3(32)	236.78	7.95	5.57	0.52	0.04	4.02	48.31	88.82	52.51	56.32
Cl3(33)/(20)	667.26	23.22	16.19	1.77	0.10	14.36	119.28	200.09	136.26	162.02
Cl3(37)	208.25	12.29	8.02	0.74	0.10	5.01	42.76	54.87	38.85	57.73
Cl4(40)	267.06	14.54	10.11	0.08	0.11	7.78	78.63	105.03	69.80	74.76
Cl4(41)	92.05	4.60	3.47	0.04	0.06	0.06	7.21	18.39	189.07	40.36
Cl4(42)/(59)	765.42	26.66	24.67	1.89	0.08	18.40	121.22	256.77	166.70	172.39
Cl4(43)	93.59	3.97	2.62	0.05	0.07	2.76	22.29	41.08	168.26	202.19
Cl4(44)	1962.86	64.09	58.53	4.56	13.07	41.13	283.83	652.08	414.54	424.65
Cl4(45)	329.61	12.95	8.63	0.82	0.06	7.71	69.78	103.74	71.87	73.00
Cl4(46)	133.10	5.81	3.71	0.07	0.10	4.12	32.81	67.78	33.76	33.77
Cl4(47)	440.35	24.29	15.62	1.26	2.07	13.97	112.33	179.62	107.26	109.69
Cl4(48)	267.10	12.83	8.13	0.56	0.08	8.01	66.90	71.16	49.70	97.05
Cl4(49)	1675.39	49.42	46.49	3.56	6.35	37.41	256.59	607.01	360.58	332.21
Cl4(51)	96.40	3.95	2.50	0.07	0.10	2.28	21.04	42.72	175.39	197.78
Cl4(52)	2156.16	64.31	63.84	4.70	7.03	47.68	337.46	792.90	501.57	478.72
Cl4(53)	304.12	11.53	7.41	0.80	0.05	6.46	68.20	132.79	70.47	69.99
Cl4(54)	4.40	0.06	0.06	0.04	0.06	0.06	1.70	2.75	10.08	13.19
Cl4(56)	558.10	26.29	24.94	1.92	0.10	19.59	136.74	216.84	164.50	211.07
Cl4(60)	114.70	10.08	7.52	0.07	0.10	2.52	10.95	19.92	209.88	58.37
Cl4(64)	887.16	30.61	30.06	2.17	1.56	19.20	148.67	298.04	52.60	211.25
Cl4(66)	1135.15	56.77	48.54	3.14	6.45	43.34	279.29	317.62	257.63	382.49
Cl4(70)	1513.63	66.41	63.86	4.55	6.85	49.57	349.22	506.39	385.40	483.82
Cl4(71)	474.63	25.00	16.98	1.34	0.08	11.94	111.13	176.22	119.25	130.49
Cl4(74)	547.55	24.51	24.04	1.35	0.05	17.79	106.47	122.93	121.16	212.86
Cl4(77)	81.24	6.44	4.29	0.13	0.18	4.34	30.94	32.28	176.97	248.63
Cl4(81)	1.44	0.06	0.06	0.04	0.06	0.06	0.07	0.07	3.07	6.62
Cl5(82)	115.87	6.57	5.34	0.37	0.07	3.65	26.54	53.31	36.87	38.29
Cl5(83)/(119)	96.11	5.94	3.74	0.34	2.12	4.58	31.64	54.72	237.18	238.26
Cl5(84)	392.71	16.48	12.26	0.87	2.88	10.88	66.54	100.80	88.93	85.02
Cl5(85)	148.10	8.74	6.27	0.42	0.06	2.87	24.66	62.51	44.45	56.19
Cl5(87)	197.13	14.49	11.80	0.68	3.70	6.13	41.42	69.22	52.38	77.14
Cl5(91)	172.32	8.01	5.56	0.58	1.31	3.81	38.25	77.23	36.21	39.22
Cl5(92)	116.50	8.14	5.53	0.48	3.61	5.48	33.85	47.45	26.15	257.93
Cl5(95)	595.43	24.22	26.82	1.46	7.43	18.89	121.63	184.42	147.79	149.03
Cl5(97)	201.47	13.65	9.70	0.80	3.27	7.87	56.99	81.97	52.83	72.98
Cl5(99)	215.87	15.72	10.94	0.82	7.21	11.38	68.89	87.06	57.26	87.94
Cl5(100)	5.04	0.37	0.06	0.04	0.06	0.06	1.43	2.47	8.76	9.87

STATION_ID	T174A	T174A	T174A	T174B	T174B	T174B	T174B	T174B	T174B	T174B
FIELD SAMPLE_ID	T174-A-QPO	T174-A-NML	74A 14.4-15.4	T174B 0-1FT	T174B 1-2FT	T174B 2-3FT	T174B 3-4FT	T174B 4-5FT	T174B 5-6FT	T174B 6-7FT
SAMPLE DEPTH (from bottom)	9-12	12-14.4	14.4-15.4	0-1	1-2	2-3	3-4	4-5	5-6	6-7
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	345.42	22.25	22.90	1.17	8.96	19.45	104.71	128.80	97.41	142.50
Cl5(105)	162.01	12.33	10.19	0.49	3.47	4.24	18.00	35.93	37.22	68.53
Cl5(110)	762.63	34.65	34.92	2.30	11.91	27.77	154.43	301.43	198.40	217.54
Cl5(114)	6.12	0.77	0.14	0.10	0.14	0.13	0.15	0.17	7.90	26.91
Cl5(115)	10.58	0.67	0.42	0.09	0.12	0.12	0.13	0.15	0.28	17.83
Cl5(118)	307.39	19.98	16.76	0.96	9.17	16.84	93.37	106.53	85.53	120.67
Cl5(107)/(123)	77.11	4.75	2.68	0.09	3.35	3.45	15.81	27.06	138.98	162.14
Cl5(124)	10.86	0.79	0.68	0.06	0.08	0.07	0.09	0.09	16.98	39.26
Cl5(126)	2.99	0.12	0.11	0.08	0.11	0.11	0.12	0.13	4.90	6.56
Cl6(128)	23.49	2.29	3.24	0.07	0.10	1.77	8.18	12.08	71.53	85.21
Cl6(130)	12.04	1.39	1.07	0.07	2.78	2.19	7.10	9.60	40.69	38.74
Cl6(134)	9.31	0.89	1.54	0.06	0.09	1.63	3.70	5.90	28.02	28.39
Cl6(135)	16.62	1.94	4.22	0.07	1.19	1.79	6.98	14.01	59.89	49.09
Cl6(136)	15.81	1.55	4.82	0.19	5.00	3.09	7.28	11.78	54.73	55.90
Cl6(137)	6.23	0.15	0.70	0.10	6.67	2.68	0.15	2.09	12.66	24.19
Cl6(138)	56.53	6.61	18.00	0.27	5.86	5.91	23.82	34.72	204.74	253.06
Cl6(141)	9.73	1.65	8.34	0.04	0.06	0.06	1.62	3.01	23.18	40.92
Cl6(144)	3.27	0.53	2.17	0.09	0.12	0.12	1.38	2.32	14.46	17.38
Cl6(146)	16.96	2.66	4.22	0.02	1.92	2.77	13.02	18.73	81.80	66.04
Cl6(149)	75.74	9.73	29.47	0.42	6.96	7.65	31.11	51.60	234.89	230.59
Cl6(151)	18.30	2.66	10.55	0.16	1.92	2.03	9.31	16.00	78.25	70.84
Cl6(132)/(153)/(168)	83.83	11.04	35.43	0.45	7.83	9.57	40.89	54.57	31.15	33.27
Cl6(156)	7.77	1.02	2.18	0.02	5.80	3.29	2.32	2.66	18.62	35.44
Cl6(157)	2.46	0.11	0.25	0.07	2.11	0.10	0.11	1.60	8.38	10.66
Cl6(129)/(158)	9.19	1.60	2.49	0.07	0.10	1.05	3.43	3.44	18.59	31.05
Cl6(163)	16.74	2.26	5.62	0.07	1.94	1.95	9.60	13.83	67.04	65.03
Cl6(164)	6.36	0.94	2.11	0.05	0.07	1.21	3.51	4.54	22.59	27.28
Cl6(166)	0.14	0.12	0.42	0.08	0.11	0.11	0.12	0.13	0.26	0.27
Cl6(167)	4.06	0.56	0.85	0.05	0.07	0.07	1.61	1.77	12.81	18.34
Cl6(169)	0.51	0.16	0.15	0.11	0.15	0.14	0.11	0.28	0.38	0.50
Cl7(170)	10.11	2.41	10.79	0.06	3.18	2.32	4.38	7.35	43.79	50.14
Cl7(171)	2.87	0.49	3.08	0.04	0.06	0.83	1.76	3.07	14.69	15.03
Cl7(172)	2.59	0.51	2.07	0.06	0.08	5.35	0.09	3.43	15.53	12.84
Cl7(174)	9.04	2.48	14.21	0.17	2.38	1.97	7.26	10.05	55.31	50.64
Cl7(176)	1.52	0.46	1.88	0.09	4.28	2.10	1.65	2.13	8.85	7.31
Cl7(177)	8.50	2.28	8.34	0.14	0.08	1.95	5.12	8.31	41.04	32.27
Cl7(178)	2.98	0.72	2.51	0.04	1.46	1.27	3.78	5.05	17.19	12.41
Cl7(179)	4.42	1.43	6.22	0.11	3.00	1.84	4.47	6.73	30.19	26.21
Cl7(180)	21.89	5.62	28.60	0.20	6.42	4.87	12.66	16.82	90.43	100.16
Cl7(183)	5.77	1.71	8.37	0.20	10.24	2.20	5.29	6.98	32.20	29.39
Cl7(184)	0.22	0.05	0.05	0.04	0.95	0.45	0.72	0.49	0.66	1.40
Cl7(185)	1.13	0.30	1.75	0.06	0.08	0.07	0.75	1.11	5.91	5.72
Cl7(187)	12.87	3.72	15.41	0.15	4.52	3.52	11.19	18.19	77.56	62.69
Cl7(189)	0.93	0.12	0.51	0.08	0.11	2.17	0.12	1.54	2.46	3.45
Cl7(190)	2.97	0.70	2.29	0.06	0.09	0.60	0.89	2.01	10.95	10.54
Cl7(193)	1.22	0.43	1.20	0.03	1.60	0.71	1.00	1.94	7.53	5.09
Cl8(194)	7.59	1.73	6.21	0.04	1.88	2.71	9.35	11.48	44.31	41.42
Cl8(195)	3.86	0.49	2.24	0.04	1.42	1.65	0.07	4.17	16.84	15.10
Cl8(199)	10.37	2.03	6.50	0.08	7.35	5.87	27.69	22.94	62.95	57.54
Cl8(200)	1.13	0.17	0.82	0.09	0.13	0.47	0.99	1.31	5.31	5.26
Cl8(201)	1.69	0.33	0.81	0.09	4.22	1.86	2.43	1.63	6.96	7.86
Cl8(202)	2.08	0.42	1.02	0.06	1.74	1.66	3.17	2.93	8.30	9.14
Cl8(196)/(203)	7.54	1.54	6.03	0.02	2.57	3.04	8.19	10.73	40.38	42.23
Cl8(205)	0.03	0.03	0.55	0.02	1.77	1.49	0.03	1.04	2.57	3.76
Cl9(206)	16.09	2.00	1.86	0.65	22.83	18.79	66.41	49.55	77.29	95.16
Cl9(207)	3.83	0.23	0.30	0.09	1.35	2.76	2.36	2.29	8.10	18.99
Cl9(208)	6.68	0.59	0.39	0.23	6.75	6.00	17.78	12.49	19.01	31.52
Cl10(209)	414.96	29.48	5.16	3.19	159.65	125.84	187.10	138.10	40.42	106.23
Sum 117 congeners	27,936	1,128	1,143	74	417	904	5,395	10,022	9,695	10,636

STATION_ID	T174B	T174B	T174B	T174B	T175A	T175A	T175A	T175A	T175A	T175A
FIELD SAMPLE_ID	T174B 7-8FT	T174B 8-9FT	T174-B-QPO	74B 11.7-12.7	T175-A-ZY	「175A 1.5-2F	T175A 2-3FT	T175A 3-4FT	T175A 4-5FT	T175A 5-6FT
SAMPLE DEPTH (from bottom)	7-8	8-9	9-11.7	11.7-12.7	0-1.5	1.5-2	2-3	3-4	4-5	5-6
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	42.90	14.53	13.11	3.82	14.14	114.37	123.62	49.79	63.71	49.59
Cl1(1)	39.81	17.45	0.07	0.06	0.05	0.10	0.13	0.07	0.10	0.16
Cl1(3)	19.58	9.68	0.03	0.03	0.03	0.05	0.06	0.03	0.05	0.08
Cl2(4)/(10)	151.66	86.57	15.46	1.14	0.09	16.25	24.49	27.65	57.77	77.99
Cl2(5)	8.48	6.28	1.15	0.09	0.09	0.16	0.21	0.11	0.16	0.26
Cl2(6)	424.11	431.23	34.91	1.11	0.07	67.07	152.91	13.93	28.13	491.31
Cl2(7)	16.45	12.89	2.33	0.05	0.05	0.09	2.59	0.06	0.08	6.99
Cl2(8)	454.45	295.38	38.81	1.21	0.02	31.17	63.14	45.60	103.16	216.99
Cl2(9)	27.77	20.21	3.85	0.06	0.06	1.96	3.21	2.57	3.74	10.43
Cl2(13)	121.79	125.17	16.36	0.47	0.06	33.76	73.73	55.45	89.59	188.08
Cl2(15)	143.30	103.68	15.90	1.86	0.10	13.87	29.78	17.43	42.10	102.61
Cl3(16)	1124.68	514.73	66.48	2.34	0.72	128.57	40.34	18.70	42.29	764.32
Cl3(17)	1219.75	784.87	72.53	2.91	0.76	163.12	50.98	27.48	54.67	1078.55
Cl3(18)	4307.52	2510.90	177.50	7.40	1.85	518.69	172.23	86.16	183.44	3326.34
Cl3(19)	164.19	80.15	9.47	0.44	0.07	19.43	46.20	29.00	61.14	123.96
Cl3(22)	1307.24	790.96	76.07	3.71	0.88	200.11	61.68	26.56	60.70	1155.16
Cl3(24)	12.42	7.98	1.54	0.05	0.05	0.09	0.11	0.06	0.08	0.14
Cl3(25)	1205.45	1636.48	110.53	3.26	1.19	335.49	102.08	71.63	103.22	2056.03
Cl3(26)	1561.43	1871.70	125.23	4.51	1.03	325.83	97.61	67.52	109.33	2114.45
Cl3(27)	114.52	60.16	7.60	0.04	0.04	19.01	36.25	20.47	46.28	94.93
Cl3(28)	4305.02	2737.73	236.28	10.98	2.43	675.53	214.52	98.99	190.13	4214.77
Cl3(31)	5353.14	3504.33	274.03	11.22	2.84	844.98	267.93	126.60	250.49	5032.87
Cl3(32)	801.79	411.97	37.19	1.97	0.42	100.05	34.22	14.81	33.56	632.09
Cl3(33)/(20)	2098.81	1196.64	100.73	4.54	1.03	279.80	90.00	39.23	85.06	1710.33
Cl3(37)	575.56	304.45	36.59	2.63	0.31	80.70	167.87	65.04	22.21	440.48
Cl4(40)	1072.55	605.32	36.03	2.70	0.61	154.15	54.42	22.29	46.69	909.07
Cl4(41)	395.94	125.94	13.98	1.28	0.05	53.39	153.07	52.68	16.13	281.20
Cl4(42)/(59)	2306.90	1519.51	129.56	5.84	1.45	348.21	115.94	48.07	105.29	2171.27
Cl4(43)	294.38	167.11	17.18	0.61	0.05	54.46	116.63	58.67	116.17	271.70
Cl4(44)	6017.93	3719.83	309.30	14.42	3.59	915.53	281.26	127.18	256.82	5353.99
Cl4(45)	1081.18	629.42	47.15	2.51	0.66	144.98	51.13	19.77	47.27	890.60
Cl4(46)	488.80	256.59	24.25	1.35	0.35	79.44	179.22	92.16	23.05	445.90
Cl4(47)	1386.36	1015.16	78.83	3.96	0.90	247.70	73.55	33.23	72.05	1409.20
Cl4(48)	1153.23	407.73	41.49	2.22	0.47	119.92	39.69	92.35	37.23	713.52
Cl4(49)	4764.57	3367.20	265.74	11.87	2.64	790.52	239.62	109.31	217.73	4607.86
Cl4(51)	270.46	160.12	15.80	0.66	0.23	53.42	115.46	59.33	120.08	270.91
Cl4(52)	6865.11	4375.71	327.18	16.19	3.47	1098.31	340.93	153.49	306.01	6478.22
Cl4(53)	1021.04	586.96	49.90	2.42	0.46	152.54	46.53	18.40	42.49	917.10
Cl4(54)	18.06	9.16	1.07	0.30	0.15	3.24	6.64	3.17	7.01	14.92
Cl4(56)	2496.51	1282.72	97.89	5.80	1.39	404.00	129.61	46.23	101.51	2221.24
Cl4(60)	792.81	187.29	23.43	2.01	0.26	91.93	25.72	49.31	30.71	301.94
Cl4(64)	2943.24	1860.76	144.90	6.51	1.54	453.72	26.79	61.15	130.84	2627.41
Cl4(66)	4359.73	2056.57	200.42	11.22	2.15	615.24	198.76	53.37	156.42	3775.01
Cl4(70)	6144.16	3126.48	260.64	13.65	3.18	950.23	294.80	103.66	241.31	5090.04
Cl4(71)	1635.79	1027.07	86.87	4.00	0.92	273.92	83.90	35.25	76.13	1602.87
Cl4(74)	2395.34	951.54	94.24	5.34	1.05	307.16	102.45	22.16	84.37	1856.03
Cl4(77)	386.31	178.72	20.85	0.93	0.39	60.74	127.67	33.08	102.07	325.72
Cl4(81)	10.53	3.09	2.13	0.05	0.05	0.09	2.20	0.06	2.19	3.76
Cl5(82)	531.31	259.05	23.49	1.31	0.30	95.61	24.19	88.55	19.40	494.58
Cl5(83)/(119)	312.17	219.00	23.60	0.88	0.29	71.18	140.06	69.62	128.64	366.65
Cl5(84)	1236.00	760.44	54.40	3.49	0.57	189.41	44.28	21.54	55.33	1233.21
Cl5(85)	724.34	411.13	29.76	1.39	0.30	115.21	37.36	105.59	30.40	704.06
Cl5(87)	911.19	331.17	33.08	2.31	0.54	134.06	45.39	13.44	34.08	753.34
Cl5(91)	547.08	356.64	36.93	1.37	0.35	101.42	26.82	101.56	23.24	488.31
Cl5(92)	386.55	279.68	22.14	0.89	0.29	67.95	191.13	84.50	16.19	343.42
Cl5(95)	1962.06	1205.67	100.55	4.89	1.03	302.84	91.04	35.62	85.00	1704.20
Cl5(97)	974.78	450.96	47.38	2.07	0.47	133.14	42.67	114.82	31.60	728.63
Cl5(99)	1053.84	484.70	36.51	2.73	0.54	148.49	45.36	107.04	36.89	881.00
Cl5(100)	15.98	11.10	1.17	0.05	0.05	3.04	5.63	2.87	5.57	16.34

STATION_ID	T174B	T174B	T174B	T174B	T175A	T175A	T175A	T175A	T175A	T175A
FIELD SAMPLE_ID	T174B 7-8FT	T174B 8-9FT	T174-B-QPO	74B 11.7-12.7	T175-A-ZY	「175A 1.5-2F	T175A 2-3FT	T175A 3-4FT	T175A 4-5FT	T175A 5-6FT
SAMPLE DEPTH (from bottom)	7-8	8-9	9-11.7	11.7-12.7	0-1.5	1.5-2	2-3	3-4	4-5	5-6
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	1562.94	815.70	64.31	3.99	0.72	264.38	80.64	20.10	62.34	1422.67
Cl5(105)	845.72	334.13	25.01	1.95	0.32	124.64	40.56	67.93	31.31	526.24
Cl5(110)	2698.80	1756.37	134.43	7.05	1.54	457.85	145.10	56.79	124.57	2776.63
Cl5(114)	50.91	8.15	1.22	0.11	0.10	0.20	0.25	0.14	7.81	12.19
Cl5(115)	49.95	20.18	1.71	0.10	0.09	6.01	10.10	3.63	16.18	19.05
Cl5(118)	1336.65	677.48	55.71	3.31	0.65	223.24	68.08	105.43	50.75	1303.82
Cl5(107)/(123)	219.16	123.53	13.70	0.62	0.44	42.98	89.46	35.96	81.30	206.97
Cl5(124)	64.05	22.15	2.08	0.06	0.06	7.16	15.44	2.20	17.22	34.28
Cl5(126)	10.83	5.10	0.11	0.09	0.09	0.16	5.16	0.11	3.81	6.88
Cl6(128)	99.11	50.73	4.83	0.51	0.08	22.13	39.17	15.32	34.85	100.16
Cl6(130)	45.39	26.00	3.30	0.08	0.08	12.90	23.06	11.81	20.99	61.21
Cl6(134)	37.50	21.11	2.01	0.26	0.07	7.31	15.19	6.60	12.72	41.00
Cl6(135)	60.16	37.88	3.89	0.31	0.07	17.35	30.39	16.16	29.11	92.12
Cl6(136)	65.02	38.22	3.45	0.51	0.10	15.85	29.59	13.61	28.38	88.93
Cl6(137)	30.47	11.58	1.40	0.11	0.10	4.97	10.00	2.42	8.45	22.14
Cl6(138)	254.41	125.81	13.35	1.50	0.18	66.11	133.50	45.47	104.79	329.79
Cl6(141)	0.16	19.33	2.19	0.67	0.05	11.92	19.02	4.66	18.96	45.01
Cl6(144)	20.12	7.42	0.78	0.10	0.09	4.69	9.24	2.97	7.72	23.57
Cl6(146)	68.60	36.46	5.24	0.37	0.02	25.58	41.21	21.87	34.51	123.04
Cl6(149)	223.97	131.30	19.24	1.83	0.28	76.10	132.34	58.89	120.18	371.00
Cl6(151)	70.54	39.30	5.01	0.69	0.08	25.61	42.06	18.80	40.09	129.67
Cl6(132)/(153)/(168)	327.74	146.65	20.52	2.34	0.30	99.35	170.63	61.72	142.72	487.17
Cl6(156)	48.35	16.42	1.78	0.02	0.02	3.69	8.56	3.02	9.68	27.56
Cl6(157)	14.82	6.10	0.57	0.08	0.08	3.03	5.73	1.52	4.07	11.15
Cl6(129)/(158)	45.45	20.28	2.05	0.26	0.07	12.62	19.12	4.66	16.24	34.00
Cl6(163)	75.54	42.68	3.97	0.48	0.07	22.01	37.41	16.53	33.76	110.09
Cl6(164)	30.71	14.95	1.79	0.06	0.05	7.67	12.37	4.90	10.60	36.11
Cl6(166)	0.30	0.15	0.11	0.09	0.09	0.16	0.21	0.11	0.16	0.26
Cl6(167)	21.94	8.03	0.96	0.06	0.05	5.54	8.77	2.28	6.68	17.53
Cl6(169)	0.76	0.19	0.30	0.12	0.11	0.20	0.33	0.14	0.28	0.39
Cl7(170)	63.61	22.58	2.95	0.64	0.06	18.09	31.56	9.59	25.40	91.87
Cl7(171)	15.85	6.38	0.96	0.21	0.05	6.34	10.40	3.98	8.59	32.33
Cl7(172)	13.30	6.68	0.87	0.06	0.06	7.01	10.96	4.76	7.91	24.84
Cl7(174)	49.84	17.86	3.23	0.70	0.03	26.80	37.66	12.99	31.70	110.72
Cl7(176)	6.84	2.90	0.48	0.11	0.05	4.04	6.06	2.36	5.27	17.88
Cl7(177)	34.18	15.83	2.84	0.44	0.06	16.42	24.30	10.20	22.01	79.13
Cl7(178)	11.40	5.87	1.10	0.05	0.05	9.06	12.24	5.74	10.05	30.18
Cl7(179)	19.35	8.17	1.75	0.34	0.09	15.37	20.19	7.90	16.85	57.36
Cl7(180)	114.96	41.32	7.29	1.51	0.06	53.81	78.87	23.49	63.14	190.07
Cl7(183)	27.87	11.43	1.95	0.37	0.06	17.09	23.07	9.12	18.29	66.02
Cl7(184)	1.03	0.38	0.09	0.04	0.04	1.07	1.09	0.38	0.30	0.70
Cl7(185)	6.47	2.09	0.40	0.06	0.06	3.95	4.49	1.37	4.01	13.74
Cl7(187)	55.41	25.58	4.96	1.00	0.05	39.65	52.56	21.93	44.92	149.70
Cl7(189)	4.95	2.10	0.11	0.09	0.09	2.04	2.93	0.76	1.67	4.22
Cl7(190)	14.83	5.43	0.76	0.07	0.07	4.19	7.54	2.62	5.15	20.25
Cl7(193)	6.04	2.54	0.49	0.12	0.03	3.42	4.65	1.89	3.99	12.40
Cl8(194)	43.17	18.41	2.63	0.68	0.05	29.72	43.30	15.68	29.93	87.62
Cl8(195)	17.16	7.60	0.87	0.05	0.05	9.49	14.47	5.46	9.68	32.60
Cl8(199)	47.53	20.83	3.36	0.65	0.09	52.37	57.13	23.02	38.68	105.05
Cl8(200)	4.71	1.66	0.36	0.10	0.10	3.13	4.07	1.58	2.87	9.59
Cl8(201)	7.45	2.33	0.38	0.14	0.10	5.08	5.97	2.24	3.70	10.98
Cl8(202)	7.29	2.92	0.64	0.09	0.07	6.35	7.54	2.91	5.07	13.30
Cl8(196)/(203)	39.62	16.30	2.11	0.66	0.03	28.29	39.13	13.88	27.66	80.56
Cl8(205)	4.00	1.58	0.02	0.02	0.02	2.55	4.31	1.64	2.10	5.59
Cl9(206)	61.16	23.53	3.41	0.20	0.45	81.53	83.63	36.62	35.39	72.54
Cl9(207)	16.38	4.20	0.49	0.08	0.08	7.81	9.84	2.28	3.81	10.52
Cl9(208)	21.19	7.19	1.16	0.08	0.14	20.67	20.25	8.55	9.34	18.10
Cl10(209)	475.42	179.86	55.21	0.78	2.01	316.75	44.51	16.80	22.82	441.87
Sum 117 congeners	92,086	54,938	4,654	236	55	14,955	7,138	3,750	5,914	84,343

STATION_ID	T175A	T175A	T175A	T175A	T175A	T175A	T175A	T175B	T175B	T175B
FIELD SAMPLE_ID	T175A 6-7FT	T175A 7-8FT	T175A 8-9FT	T175A 9-10FT	T175-A-ON	75A 12.1-12.5	75A 12.5-13.1	T175B 0-1FT	T175B 1-2FT	T175B 2-3FT
SAMPLE DEPTH (from bottom)	6-7	7-8	8-9	9-10	10-12.1	12.1-12.5	12.5-13.1	0-1	1-2	2-3
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	42.58	60.86	41.22	13.10	17.30	6.98	4.40	8.62	47.56	224.80
Cl1(1)	14.75	22.63	26.03	0.06	0.08	0.08	0.05	0.05	0.07	0.10
Cl1(3)	9.07	14.25	14.66	0.03	0.04	0.04	0.03	0.03	0.03	0.05
Cl2(4)/(10)	62.03	88.22	138.58	8.82	0.13	1.62	0.72	1.38	0.12	0.18
Cl2(5)	0.26	0.26	8.59	0.09	0.12	0.12	0.08	0.09	0.11	0.17
Cl2(6)	125.26	203.87	313.50	16.86	5.00	2.14	0.55	0.25	8.60	176.33
Cl2(7)	5.40	6.39	18.34	1.28	0.07	0.07	0.04	0.05	0.06	0.09
Cl2(8)	174.98	219.28	382.34	20.46	4.46	2.49	0.63	0.08	7.32	68.82
Cl2(9)	9.49	11.82	30.29	1.86	0.09	0.08	0.06	0.06	0.08	0.12
Cl2(13)	58.24	79.39	105.09	7.47	2.49	1.21	0.06	0.06	4.61	77.34
Cl2(15)	79.06	89.74	155.97	14.08	3.47	2.42	0.38	0.11	0.14	27.29
Cl3(16)	615.34	769.26	698.73	41.74	14.02	8.94	1.88	0.08	25.71	270.08
Cl3(17)	557.79	805.59	915.65	51.81	20.24	11.60	2.24	0.73	33.15	371.65
Cl3(18)	1729.16	2620.22	2814.25	131.04	54.73	27.39	6.32	1.10	69.56	1117.24
Cl3(19)	78.91	117.98	121.69	7.23	2.11	1.10	0.38	0.08	2.83	37.02
Cl3(22)	720.70	922.67	937.78	54.93	25.61	15.09	2.50	0.06	35.87	415.11
Cl3(24)	8.05	6.58	12.29	0.05	0.07	0.07	0.25	0.05	0.06	0.09
Cl3(25)	466.11	787.57	982.20	63.75	72.66	12.89	1.54	0.05	44.15	695.49
Cl3(26)	551.73	795.07	1101.61	76.35	90.48	15.82	2.37	0.07	43.10	705.83
Cl3(27)	58.96	85.71	87.72	5.13	1.77	1.12	0.34	0.04	2.22	32.13
Cl3(28)	2303.35	3019.79	3003.38	151.31	93.72	37.26	6.89	0.92	91.06	1352.04
Cl3(31)	2649.66	3484.24	3577.93	190.79	119.47	39.93	7.81	1.03	104.65	1795.94
Cl3(32)	361.69	499.51	516.23	31.52	12.16	7.11	1.64	0.03	17.35	210.33
Cl3(33)/(20)	1194.72	1363.47	1443.80	77.11	46.14	17.53	2.99	0.62	52.28	571.04
Cl3(37)	444.68	446.60	473.28	30.16	16.37	9.76	1.44	0.08	15.92	138.52
Cl4(40)	562.65	676.36	664.20	52.06	28.90	14.51	1.77	0.09	29.52	362.97
Cl4(41)	260.29	337.69	206.55	16.07	7.66	4.17	0.92	0.05	5.24	116.30
Cl4(42)/(59)	1223.76	1496.78	1575.83	93.60	78.12	31.46	4.69	0.06	57.22	800.92
Cl4(43)	150.30	211.00	220.23	12.04	7.77	3.29	0.53	0.05	8.03	86.61
Cl4(44)	2922.42	3770.15	3928.11	203.46	166.20	53.08	11.83	2.14	132.91	2059.99
Cl4(45)	506.96	679.12	694.86	45.71	20.38	12.04	2.06	0.05	26.61	339.41
Cl4(46)	238.25	347.16	338.90	21.25	9.20	5.28	1.08	0.08	11.07	139.53
Cl4(47)	744.23	954.99	1054.43	64.33	48.84	21.03	2.69	0.48	45.27	470.75
Cl4(48)	658.43	709.89	613.26	38.14	19.28	10.71	2.16	0.06	24.24	278.77
Cl4(49)	2509.41	3156.25	3273.13	173.60	147.48	45.51	8.77	1.17	108.44	1574.43
Cl4(51)	154.39	210.49	210.70	13.00	6.02	3.19	0.58	0.08	6.79	89.35
Cl4(52)	3535.87	4550.75	4609.24	244.10	170.38	58.10	12.73	1.33	142.40	2280.69
Cl4(53)	531.44	599.25	628.51	43.27	17.53	10.59	1.73	0.29	23.62	300.74
Cl4(54)	10.41	11.82	12.38	1.12	0.07	0.07	0.17	0.19	0.06	4.63
Cl4(56)	1432.74	1715.05	1599.78	82.15	65.60	31.76	4.41	0.08	52.05	750.58
Cl4(60)	438.09	343.46	317.83	28.60	18.14	10.02	1.73	0.08	4.70	174.92
Cl4(64)	1548.70	1930.37	2024.94	102.69	84.27	34.69	5.67	0.34	62.98	958.16
Cl4(66)	2921.26	3117.70	3003.30	144.29	123.35	48.41	8.25	1.20	101.66	1229.02
Cl4(70)	3562.31	4122.37	3988.89	198.81	163.73	57.17	10.83	1.06	145.71	1968.70
Cl4(71)	974.57	1053.84	1135.30	68.62	50.11	20.99	3.09	0.42	45.22	575.67
Cl4(74)	1547.55	1628.11	1491.70	78.12	61.89	30.93	4.05	0.38	44.58	647.88
Cl4(77)	219.81	295.10	211.68	15.01	10.65	6.05	0.74	0.14	9.93	98.41
Cl4(81)	4.60	4.75	4.98	0.40	0.07	0.07	0.04	0.05	0.06	0.09
Cl5(82)	302.22	336.97	312.25	18.02	22.58	6.14	0.88	0.05	11.81	164.44
Cl5(83)/(119)	198.83	249.02	238.82	14.84	18.75	4.63	0.56	0.54	13.09	115.91
Cl5(84)	750.14	762.51	774.27	45.08	50.98	18.07	2.04	0.45	32.97	346.12
Cl5(85)	429.98	519.51	398.49	24.04	33.44	8.71	1.20	0.05	11.42	194.89
Cl5(87)	577.40	622.59	476.25	29.52	49.85	12.15	1.72	0.10	25.32	341.52
Cl5(91)	328.20	346.14	386.57	23.85	24.13	7.43	0.98	0.04	15.07	170.33
Cl5(92)	238.92	234.79	264.16	15.95	24.44	5.46	0.92	0.34	14.41	147.05
Cl5(95)	1046.63	1209.82	1242.02	74.40	79.30	25.65	3.95	0.74	51.13	625.13
Cl5(97)	578.98	636.85	562.12	31.94	43.76	11.29	1.41	0.47	26.41	287.45
Cl5(99)	703.17	661.55	615.90	35.36	44.61	14.53	1.68	1.07	30.74	284.18
Cl5(100)	8.45	10.08	11.42	0.81	0.66	0.07	0.04	0.05	0.93	4.59

STATION_ID	T175A	T175A	T175A	T175A	T175A	T175A	T175A	T175B	T175B	T175B
FIELD SAMPLE_ID	T175A 6-7FT	T175A 7-8FT	T175A 8-9FT	T175A 9-10FT	T175-A-ON	75A 12.1-12.5	75A 12.5-13.1	T175B 0-1FT	T175B 1-2FT	T175B 2-3FT
SAMPLE DEPTH (from bottom)	6-7	7-8	8-9	9-10	10-12.1	12.1-12.5	12.5-13.1	0-1	1-2	2-3
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	1087.19	1225.39	1067.38	50.81	60.69	22.29	3.08	1.19	47.50	402.60
Cl5(105)	539.70	505.88	442.93	26.11	43.80	11.15	1.38	0.08	13.83	261.32
Cl5(110)	1655.36	1737.77	1915.07	93.18	148.86	28.43	4.72	1.41	82.84	916.71
Cl5(114)	30.36	17.90	16.29	1.67	2.28	0.15	0.10	0.11	0.14	0.21
Cl5(115)	22.73	20.83	23.34	1.56	2.25	0.56	0.09	0.10	0.89	9.61
Cl5(118)	959.04	1004.94	972.19	44.28	68.06	21.51	2.49	1.22	39.83	393.67
Cl5(107)/(123)	140.20	161.94	149.43	8.53	10.80	3.17	0.40	0.10	8.58	75.15
Cl5(124)	35.19	33.43	31.78	1.71	2.19	0.96	0.06	0.06	0.08	12.69
Cl5(126)	6.78	8.04	6.35	0.09	0.12	0.12	0.08	0.09	0.11	3.30
Cl6(128)	78.93	89.33	67.93	4.23	6.62	1.74	0.44	0.08	5.95	31.71
Cl6(130)	34.51	42.05	32.70	2.58	3.26	1.08	0.08	0.08	4.12	18.43
Cl6(134)	25.56	28.51	24.84	1.83	2.27	0.70	0.06	0.07	2.19	10.08
Cl6(135)	46.87	51.60	42.92	3.34	5.66	1.65	0.40	0.15	3.33	22.99
Cl6(136)	50.07	53.63	46.28	3.28	4.32	1.29	0.40	0.74	4.77	21.22
Cl6(137)	22.17	19.75	17.85	1.23	1.69	0.15	0.10	1.06	3.07	6.80
Cl6(138)	233.92	258.67	186.83	12.14	20.24	6.06	1.04	0.58	16.25	91.24
Cl6(141)	44.82	38.28	31.16	2.35	4.63	1.27	0.44	0.05	2.95	16.51
Cl6(144)	16.39	17.56	11.03	0.75	1.39	0.49	0.09	0.10	0.80	6.22
Cl6(146)	59.31	75.36	52.82	4.34	6.61	1.83	0.26	0.02	5.33	31.94
Cl6(149)	217.43	231.88	187.05	15.63	28.45	6.63	1.85	0.71	17.93	120.37
Cl6(151)	66.55	66.04	49.52	3.68	7.74	2.02	0.58	0.22	4.62	35.01
Cl6(132)/(153)/(168)	290.66	300.70	234.61	17.50	32.37	9.23	2.34	0.73	21.90	138.21
Cl6(156)	39.43	33.96	25.18	1.74	3.39	0.78	0.25	0.62	3.48	7.05
Cl6(157)	12.78	9.85	9.10	0.67	0.85	0.11	0.08	0.46	0.10	2.85
Cl6(129)/(158)	33.35	33.96	26.79	2.15	2.92	0.71	0.12	0.08	2.34	16.00
Cl6(163)	67.29	73.30	51.40	4.32	6.55	1.92	0.50	0.19	3.75	23.21
Cl6(164)	24.45	26.75	20.06	1.17	2.35	1.08	0.17	0.05	2.42	9.81
Cl6(166)	0.26	0.26	0.22	0.09	0.12	0.12	0.08	0.09	0.11	0.17
Cl6(167)	15.69	18.27	13.06	0.85	0.97	0.66	0.21	0.05	4.20	7.08
Cl6(169)	0.62	0.36	0.37	0.08	0.11	0.16	0.11	0.12	0.14	0.16
Cl7(170)	48.94	63.25	41.98	3.57	7.76	1.65	0.46	0.06	3.53	24.76
Cl7(171)	14.45	17.50	11.77	1.14	1.86	0.54	0.20	0.05	1.10	7.07
Cl7(172)	13.31	16.70	10.49	0.90	1.56	0.44	0.09	0.06	2.28	8.46
Cl7(174)	54.01	57.84	34.22	2.94	8.05	1.71	0.56	0.03	3.39	31.26
Cl7(176)	7.58	7.46	4.48	0.45	1.20	0.33	0.12	0.59	2.40	4.79
Cl7(177)	32.05	38.78	23.14	2.44	6.10	1.31	0.36	0.06	3.21	20.92
Cl7(178)	12.83	14.31	8.73	1.00	1.98	0.48	0.15	0.27	1.75	9.59
Cl7(179)	28.37	25.94	13.94	1.53	3.83	0.78	0.29	0.41	2.58	16.87
Cl7(180)	106.86	121.09	77.70	6.59	18.79	4.01	1.19	0.71	8.48	67.59
Cl7(183)	31.42	33.10	19.34	1.79	4.72	1.07	0.32	0.36	3.84	21.47
Cl7(184)	0.88	1.36	0.68	0.12	0.06	0.06	0.04	0.14	0.58	0.82
Cl7(185)	6.59	6.80	4.18	0.41	0.85	0.08	0.06	0.06	0.08	4.47
Cl7(187)	64.17	71.32	39.99	4.29	11.04	2.44	0.68	0.51	5.64	44.73
Cl7(189)	4.70	5.95	3.40	0.36	0.48	0.12	0.08	0.09	0.11	2.21
Cl7(190)	10.89	15.91	9.55	0.86	1.66	0.56	0.15	0.07	0.08	6.40
Cl7(193)	5.77	7.04	4.11	0.70	0.92	0.05	0.09	0.03	1.26	3.43
Cl8(194)	43.03	51.75	28.65	3.03	7.41	1.83	0.20	0.53	3.61	30.86
Cl8(195)	14.45	19.13	11.29	1.70	2.61	0.68	0.28	0.05	1.56	9.31
Cl8(199)	58.48	72.37	35.02	3.12	7.37	1.55	0.32	0.97	10.90	47.07
Cl8(200)	4.77	5.68	2.83	0.35	0.63	0.20	0.10	0.10	0.67	2.99
Cl8(201)	6.18	7.96	4.16	0.41	0.85	0.28	0.10	0.10	1.98	4.80
Cl8(202)	8.12	10.56	5.37	0.43	0.96	0.42	0.06	0.23	1.61	6.05
Cl8(196)/(203)	39.94	50.61	26.99	2.97	5.88	1.07	0.39	0.60	3.87	27.73
Cl8(205)	2.56	4.28	2.62	0.02	0.63	0.03	0.02	0.02	1.30	2.83
Cl9(206)	82.92	92.07	44.19	2.93	4.55	1.55	0.08	3.66	29.95	77.00
Cl9(207)	9.06	16.96	10.77	0.34	0.47	0.16	0.08	0.18	1.49	6.84
Cl9(208)	23.43	32.21	16.17	0.74	1.08	0.33	0.07	0.86	8.46	20.38
Cl10(209)	631.60	594.04	507.58	17.31	67.58	20.78	0.37	16.05	226.23	420.21
Sum 117 congeners	51,326	61,621	61,731	3,413	2,936	1,016	176	58	2,516	29,676

STATION_ID	T175B	T175B	T175B	T175B	T175B	T175B	T175B	T175B	T175B	T175B
FIELD SAMPLE_ID	T175B 3-4FT	T175B 4-5FT	T175B 5-6FT	T175B 6-7FT	T175B 7-8FT	T175B 8-9FT	175B 9-9.85F	75B 9.85-10.7	75B 10.7-11.3	75B 11.3-11.7
SAMPLE DEPTH (from bottom)	3-4	4-5	5-6	6-7	7-8	8-9	9-9.85	9.85-10.7	10.7-11.3	11.3-11.7
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	107.33	61.41	31.77	39.59	32.02	12.42	11.00	24.23	8.33	1.83
Cl1(1)	0.11	0.18	13.27	12.46	25.57	20.63	22.89	7.18	0.07	0.06
Cl1(3)	0.05	0.09	8.31	9.12	16.45	14.89	16.82	4.92	0.03	0.03
Cl2(4)/(10)	0.19	33.80	86.78	58.34	122.84	151.47	174.20	67.33	1.68	0.38
Cl2(5)	0.17	0.29	0.26	0.28	5.56	7.58	15.11	4.63	0.11	0.09
Cl2(6)	127.16	206.57	536.10	132.30	352.76	327.18	769.44	118.19	2.75	0.62
Cl2(7)	0.09	0.16	6.46	6.12	14.56	13.75	29.91	8.91	0.06	0.05
Cl2(8)	56.79	70.43	297.91	225.02	405.30	401.92	542.57	163.52	3.32	0.75
Cl2(9)	0.12	0.20	12.24	8.82	21.27	23.41	50.82	15.03	0.08	0.06
Cl2(13)	55.08	79.83	174.86	49.92	113.67	110.61	245.50	39.60	1.64	0.06
Cl2(15)	21.93	21.88	98.75	93.97	127.95	159.42	221.40	70.15	2.70	0.49
Cl3(16)	237.68	268.52	963.48	590.98	1036.50	888.48	927.78	165.60	8.86	1.71
Cl3(17)	320.13	392.06	1385.50	683.09	1202.84	1128.51	1444.82	212.34	12.05	1.87
Cl3(18)	982.10	1132.55	3999.88	1957.19	3833.04	3429.31	3885.72	512.46	29.80	5.07
Cl3(19)	30.25	41.85	144.21	81.27	158.46	139.13	136.26	28.05	1.24	0.08
Cl3(22)	325.50	369.36	1379.46	850.80	1308.70	1186.06	1350.92	201.36	17.50	2.36
Cl3(24)	0.09	0.16	7.87	7.37	11.06	10.03	19.14	4.83	0.06	0.05
Cl3(25)	594.32	922.10	2438.73	399.97	959.91	1064.09	3484.04	205.13	18.33	2.16
Cl3(26)	563.14	984.28	2513.50	567.01	1277.27	1298.85	3955.02	266.62	23.94	2.90
Cl3(27)	21.89	25.61	106.24	63.77	111.68	83.66	98.44	21.23	1.15	0.04
Cl3(28)	1145.62	1386.57	5117.86	2665.37	4080.15	3759.51	5120.15	599.00	45.63	6.60
Cl3(31)	1477.08	1866.28	6407.01	2962.86	5237.77	4983.57	7005.77	689.37	54.62	7.93
Cl3(32)	186.17	198.60	708.03	422.05	731.51	638.45	663.94	102.66	7.30	1.07
Cl3(33)/(20)	454.00	510.24	1976.74	1341.57	2031.99	1801.60	2027.96	281.48	22.85	2.88
Cl3(37)	113.42	101.15	543.50	471.78	575.98	500.82	491.51	96.91	10.86	1.26
Cl4(40)	267.31	308.23	1157.24	662.59	1091.51	1003.76	1175.63	116.20	14.80	1.72
Cl4(41)	82.64	57.33	259.22	295.63	469.80	351.48	179.11	32.05	3.97	0.77
Cl4(42)/(59)	631.55	731.21	2704.30	1489.33	2436.12	2317.97	2833.13	300.93	35.68	3.93
Cl4(43)	73.01	85.43	293.07	151.19	262.90	258.12	291.15	33.27	3.40	0.46
Cl4(44)	1582.49	1914.79	7019.14	3784.38	6380.80	6050.99	7429.27	663.76	71.22	10.09
Cl4(45)	273.38	308.16	1128.81	625.76	1105.76	1036.09	1110.64	121.54	11.74	1.48
Cl4(46)	124.26	131.00	485.90	262.61	469.54	440.92	458.93	54.19	5.18	0.74
Cl4(47)	374.63	452.49	1646.96	872.15	1384.60	1378.14	1733.50	168.88	22.86	2.51
Cl4(48)	210.05	149.11	815.22	824.89	1241.10	1097.39	625.20	105.29	10.58	1.33
Cl4(49)	1246.13	1556.73	5559.76	2685.75	4719.98	4682.80	6451.85	561.43	59.09	7.90
Cl4(51)	68.38	78.62	286.77	153.22	291.57	239.82	272.16	31.27	3.12	0.42
Cl4(52)	1764.96	2293.63	8127.89	3988.65	7062.96	6772.50	9389.47	709.26	75.69	10.10
Cl4(53)	245.47	274.84	1018.61	551.03	1039.03	972.36	1008.68	99.30	10.10	1.41
Cl4(54)	3.32	7.32	12.88	9.74	14.97	10.45	13.44	1.66	0.06	0.05
Cl4(56)	557.64	573.90	2396.99	1617.94	2329.19	2156.97	2117.56	226.40	33.81	3.94
Cl4(60)	79.38	49.16	244.22	362.95	721.52	576.16	253.52	52.01	9.68	1.21
Cl4(64)	749.25	881.65	3193.51	1848.41	3043.88	2873.83	3376.60	323.96	41.66	4.69
Cl4(66)	893.65	810.61	4170.26	3347.46	4670.76	4309.07	3157.91	475.50	62.79	7.23
Cl4(70)	1475.24	1414.89	6330.25	4274.74	6577.04	6174.02	5477.84	640.29	77.70	9.61
Cl4(71)	448.23	505.74	1870.71	1058.44	1705.52	1592.93	1861.58	187.05	23.23	2.92
Cl4(74)	436.18	384.91	1981.63	1817.43	2567.86	2235.55	1521.67	225.69	33.27	3.49
Cl4(77)	64.78	61.79	321.03	271.02	337.94	292.03	242.46	43.10	6.29	0.58
Cl4(81)	0.09	0.16	2.38	3.50	9.24	5.73	2.92	0.78	0.06	0.05
Cl5(82)	117.82	128.84	505.81	337.71	528.46	439.73	423.71	42.29	5.78	0.57
Cl5(83)/(119)	96.61	108.71	413.48	238.21	319.27	304.14	429.35	42.92	5.15	0.64
Cl5(84)	261.62	327.82	1170.73	737.84	1121.16	1134.73	1371.91	116.83	15.41	1.64
Cl5(85)	127.04	145.04	553.99	393.45	605.36	495.52	550.29	55.88	7.70	0.89
Cl5(87)	231.56	208.71	921.32	751.79	1109.55	904.10	659.41	68.23	12.87	1.64
Cl5(91)	136.11	155.74	593.55	328.90	554.40	541.85	663.95	57.58	8.06	0.94
Cl5(92)	106.70	124.71	432.46	238.36	428.45	335.51	458.76	42.14	7.03	0.63
Cl5(95)	462.54	546.28	2114.19	1239.84	2001.98	1885.36	2265.45	199.52	27.69	3.15
Cl5(97)	200.56	192.47	885.96	659.42	965.57	868.94	763.59	88.06	12.16	1.48
Cl5(99)	199.99	194.27	885.43	716.90	1006.82	916.90	739.14	90.02	14.29	1.57
Cl5(100)	3.42	3.78	16.72	8.04	14.24	12.85	22.20	2.03	0.30	0.05

STATION_ID	T175B	T175B	T175B	T175B	T175B	T175B	T175B	T175B	T175B	T175B
FIELD SAMPLE_ID	T175B 3-4FT	T175B 4-5FT	T175B 5-6FT	T175B 6-7FT	T175B 7-8FT	T175B 8-9FT	175B 9-9.85F	75B 9.85-10.7	75B 10.7-11.3	75B 11.3-11.7
SAMPLE DEPTH (from bottom)	3-4	4-5	5-6	6-7	7-8	8-9	9-9.85	9.85-10.7	10.7-11.3	11.3-11.7
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	280.23	269.70	1285.34	1026.99	1407.43	1325.70	1033.20	131.70	19.78	2.38
Cl5(105)	143.37	118.35	499.10	519.72	913.66	747.13	513.40	57.14	11.88	1.55
Cl5(110)	664.95	809.86	3089.59	1810.60	2806.63	2623.71	3291.28	302.76	41.83	4.79
Cl5(114)	0.21	0.35	5.90	24.52	45.55	29.39	10.06	3.05	0.14	0.86
Cl5(115)	5.63	4.14	0.28	21.42	44.62	41.25	19.81	2.51	0.63	0.10
Cl5(118)	243.87	251.66	1240.76	1071.94	1430.38	1298.67	904.38	131.08	19.70	2.12
Cl5(107)/(123)	54.90	62.95	247.53	169.26	228.14	206.14	239.77	25.00	3.91	0.48
Cl5(124)	6.43	5.09	25.87	32.69	59.80	40.69	25.32	4.41	0.08	0.06
Cl5(126)	0.17	0.29	8.10	5.66	9.67	6.05	6.31	1.43	0.11	0.09
Cl6(128)	20.40	27.28	99.73	72.90	96.24	59.53	80.62	7.98	1.61	0.44
Cl6(130)	12.17	18.48	64.76	34.55	41.24	25.75	46.07	3.82	1.17	0.08
Cl6(134)	6.55	10.65	38.76	22.77	30.54	21.40	35.20	3.15	0.86	0.07
Cl6(135)	15.91	24.28	86.73	41.74	52.75	37.21	65.16	6.55	1.57	0.23
Cl6(136)	14.75	19.35	78.10	43.77	55.00	39.88	62.24	6.05	1.28	0.22
Cl6(137)	4.58	4.12	18.06	20.40	30.07	18.74	16.11	2.10	0.68	0.11
Cl6(138)	59.54	66.87	293.57	232.41	288.68	184.09	195.04	22.03	5.16	0.96
Cl6(141)	8.55	6.76	29.72	39.72	59.40	34.16	25.08	3.56	1.09	0.41
Cl6(144)	3.67	4.48	18.13	13.94	18.51	10.41	10.94	1.08	0.33	0.10
Cl6(146)	22.48	31.57	132.70	63.88	60.45	37.47	65.88	7.76	2.23	0.29
Cl6(149)	84.21	108.92	421.84	248.33	298.54	214.51	291.93	31.86	7.48	1.28
Cl6(151)	22.48	30.21	117.22	65.48	70.33	42.32	69.45	7.41	2.28	0.46
Cl6(132)/(153)/(168)	88.32	103.76	462.75	323.32	369.36	269.97	278.77	34.90	8.60	1.62
Cl6(156)	5.56	8.58	24.22	31.58	48.09	25.52	23.18	3.55	0.87	0.18
Cl6(157)	1.81	2.42	9.87	8.22	14.39	7.16	7.81	1.13	0.10	0.08
Cl6(129)/(158)	8.54	6.77	26.33	27.47	43.87	26.52	33.02	3.27	0.75	0.21
Cl6(163)	13.36	26.32	86.67	47.47	67.83	39.16	71.94	6.37	1.55	0.33
Cl6(164)	5.84	9.25	32.25	24.35	30.57	17.36	24.69	2.51	0.73	0.06
Cl6(166)	0.17	0.29	0.26	0.28	4.71	2.02	1.89	0.14	0.11	0.09
Cl6(167)	4.83	5.02	16.98	15.79	20.50	10.99	11.97	1.82	0.80	0.06
Cl6(169)	0.29	0.63	0.36	1.28	0.37	0.17	0.19	0.18	0.15	0.12
Cl7(170)	16.29	22.87	69.32	48.17	61.65	28.72	37.12	3.39	2.08	0.29
Cl7(171)	4.16	6.72	22.52	13.61	14.42	6.74	10.30	1.32	0.46	0.21
Cl7(172)	5.27	7.51	22.22	12.01	12.47	5.92	10.23	0.93	0.48	0.06
Cl7(174)	18.09	26.85	85.59	55.42	51.94	23.13	31.34	4.09	2.18	0.42
Cl7(176)	2.75	4.61	13.15	7.90	6.52	3.00	4.99	0.66	0.35	0.06
Cl7(177)	14.09	24.14	66.59	35.67	34.54	17.39	29.61	3.45	1.66	0.39
Cl7(178)	5.94	8.85	25.11	12.40	11.03	5.23	10.45	1.46	0.57	0.14
Cl7(179)	10.04	14.75	45.87	27.98	21.83	8.45	15.61	2.14	1.04	0.19
Cl7(180)	40.06	49.62	164.12	108.54	120.98	56.70	68.90	9.32	4.66	0.98
Cl7(183)	12.80	16.13	53.10	32.60	29.53	13.21	19.90	2.38	1.26	0.25
Cl7(184)	0.34	0.13	0.52	0.70	1.17	0.37	0.60	0.15	0.05	0.04
Cl7(185)	2.23	3.07	8.84	5.56	5.83	2.77	3.57	0.67	0.08	0.06
Cl7(187)	27.17	42.80	136.24	68.02	55.01	26.78	46.72	6.31	3.03	0.49
Cl7(189)	1.41	2.82	3.39	3.22	4.47	2.82	2.78	0.14	0.11	0.09
Cl7(190)	4.12	4.88	16.84	12.75	14.03	7.31	8.55	1.45	0.61	0.07
Cl7(193)	3.00	4.71	12.18	6.00	6.02	3.33	5.12	0.62	0.04	0.04
Cl8(194)	20.74	39.45	67.91	44.24	41.05	18.03	26.30	3.19	1.61	0.05
Cl8(195)	5.47	13.28	21.73	12.54	14.19	7.36	9.73	1.40	0.66	0.05
Cl8(199)	27.92	40.08	88.42	61.53	46.43	20.54	36.21	4.53	1.83	0.09
Cl8(200)	1.80	5.81	6.44	4.37	4.23	1.98	3.38	0.53	0.20	0.11
Cl8(201)	2.25	2.86	8.54	6.32	7.72	2.94	4.20	0.97	0.33	0.11
Cl8(202)	3.43	4.91	11.96	8.49	6.89	3.12	6.27	1.08	0.37	0.07
Cl8(196)/(203)	17.42	25.61	59.87	40.26	34.66	17.92	24.34	3.30	1.23	0.03
Cl8(205)	1.50	2.06	4.75	3.32	2.66	1.45	2.18	0.03	0.03	0.02
Cl9(206)	46.96	46.92	101.14	100.29	68.60	25.40	38.55	8.74	1.90	0.17
Cl9(207)	2.91	3.54	11.40	11.51	20.57	6.17	7.31	2.78	0.27	0.08
Cl9(208)	10.84	9.42	28.89	28.94	27.54	7.88	15.68	4.74	0.56	0.08
Cl10(209)	275.36	209.41	708.49	1001.25	990.68	244.16	410.63	343.35	31.08	0.87
Sum 117 congeners	22,697	26,463	98,774	58,107	92,716	84,824	100,383	11,095	1,195	154

STATION_ID	T176A	T176A	T176A	T176A	T176A	T176A	T176A	T176A	T176A	T176A
FIELD SAMPLE_ID	T176A 0-1FT	T176A 1-2FT	T176A 2-3FT	T176A 3-4FT	T176A 4.5FT	T176A 5-6FT	T176A 6-7FT	T176A 7-8FT	176A 8-8.77F	76A 8.77-9.55
SAMPLE DEPTH (from bottom)	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-8.77	8.77-9.55
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	67.86	216.83	149.44	282.10	42.65	127.49	37.24	19.79	21.73	44.31
Cl1(1)	0.07	0.09	0.09	0.12	20.50	40.58	27.08	0.08	12.29	7.44
Cl1(3)	0.03	0.05	0.04	0.06	12.02	17.25	15.26	0.04	4.93	4.25
Cl2(4)/(10)	0.12	15.60	16.46	36.37	57.25	114.29	150.09	26.81	87.67	34.45
Cl2(5)	0.11	0.15	0.14	0.20	0.33	0.20	13.48	1.96	5.16	2.94
Cl2(6)	36.83	180.57	48.49	413.30	116.33	377.50	290.10	54.07	107.01	95.23
Cl2(7)	0.06	0.08	0.07	0.11	6.02	7.68	26.97	4.53	9.69	5.43
Cl2(8)	17.73	65.18	16.92	149.79	204.19	329.35	408.11	55.60	169.93	92.69
Cl2(9)	0.08	0.10	0.10	5.26	9.57	11.15	46.32	6.77	16.50	9.51
Cl2(13)	24.79	57.63	16.23	145.05	46.29	92.95	87.49	37.69	41.89	35.79
Cl2(15)	7.69	29.15	20.38	57.12	89.21	82.14	172.05	49.43	57.20	36.82
Cl3(16)	59.21	270.25	59.15	545.93	568.55	959.62	543.18	101.00	258.36	138.79
Cl3(17)	84.92	357.53	88.50	755.28	659.02	1197.81	685.78	140.37	273.92	149.32
Cl3(18)	239.22	1092.40	257.39	2271.32	1921.42	3682.78	1789.72	353.71	905.90	481.00
Cl3(19)	10.30	41.54	35.26	84.46	83.01	168.91	89.49	20.87	49.68	24.16
Cl3(22)	86.51	403.93	80.78	769.20	824.23	1203.39	692.66	147.39	253.69	147.18
Cl3(24)	0.06	0.08	0.07	0.11	0.18	7.38	16.67	3.83	6.13	3.13
Cl3(25)	174.69	640.85	193.28	1677.04	342.21	1423.30	891.02	231.94	349.25	239.05
Cl3(26)	175.75	703.83	192.78	1754.07	498.73	1566.64	1024.38	257.47	403.75	343.51
Cl3(27)	9.17	31.87	24.08	62.97	66.06	99.36	79.12	16.87	32.55	18.20
Cl3(28)	295.71	1266.23	274.01	2613.84	2520.44	3811.05	2184.81	483.97	871.32	519.03
Cl3(31)	386.41	1644.59	378.35	3520.51	2898.00	4948.15	2621.97	591.85	1123.63	637.27
Cl3(32)	44.95	200.74	45.39	406.29	418.05	702.36	350.08	70.98	166.77	82.60
Cl3(33)/(20)	113.94	546.80	110.02	1065.86	1390.18	1827.94	1088.62	216.81	402.54	233.76
Cl3(37)	42.70	131.03	21.41	208.49	438.18	466.96	354.21	72.36	114.79	68.94
Cl4(40)	80.91	328.48	68.50	662.79	661.35	939.86	503.42	117.47	233.88	105.46
Cl4(41)	26.34	104.27	53.74	160.79	328.08	302.85	132.31	39.47	84.12	31.35
Cl4(42)/(59)	182.84	730.96	149.26	1453.42	1483.31	2085.25	1167.24	281.10	486.39	229.20
Cl4(43)	27.60	74.19	16.15	163.89	150.16	252.09	132.58	45.21	50.08	36.51
Cl4(44)	450.67	1888.58	365.85	3735.16	3728.90	5312.37	2736.87	670.58	1257.16	652.01
Cl4(45)	70.96	312.74	63.69	608.87	622.05	972.43	460.52	108.84	233.36	115.27
Cl4(46)	43.98	131.80	28.53	262.79	264.53	403.40	195.18	42.70	98.05	54.13
Cl4(47)	105.54	432.45	91.29	890.73	845.76	1241.07	665.48	167.75	299.93	160.06
Cl4(48)	48.29	239.22	29.10	377.05	843.99	822.23	389.27	78.71	190.32	80.48
Cl4(49)	354.09	1439.68	309.37	2983.75	2599.31	4225.58	2237.01	563.76	1068.75	589.12
Cl4(51)	26.21	79.56	16.35	159.75	158.57	239.14	113.02	38.99	65.27	35.77
Cl4(52)	495.09	2076.50	416.97	4322.11	3932.79	6031.73	3033.77	732.35	1443.60	764.15
Cl4(53)	63.56	289.24	59.23	554.29	558.14	881.08	398.02	88.54	212.76	96.06
Cl4(54)	2.04	3.91	3.44	8.31	9.94	11.32	7.62	2.91	4.88	2.28
Cl4(56)	165.71	659.84	114.63	1155.69	1577.94	1835.46	1005.63	248.91	420.75	198.15
Cl4(60)	42.32	123.01	39.79	177.05	466.10	418.01	202.88	41.40	149.97	53.67
Cl4(64)	218.56	885.12	168.96	1743.52	1805.33	2527.53	1323.10	318.97	587.58	283.54
Cl4(66)	255.49	1117.05	156.23	1771.00	3349.66	3271.36	1849.85	443.50	709.43	339.30
Cl4(70)	429.95	1713.36	290.26	3050.45	4339.07	4972.01	2678.26	661.20	1112.02	489.71
Cl4(71)	126.44	526.06	100.61	1013.11	1054.53	1421.35	752.40	179.53	326.01	153.24
Cl4(74)	128.79	576.51	65.77	903.81	1840.62	1726.45	918.61	203.63	353.99	152.05
Cl4(77)	24.79	94.59	39.96	135.56	252.49	234.22	152.54	44.18	56.61	32.90
Cl4(81)	0.06	1.61	0.07	1.96	5.79	4.73	2.94	0.07	1.77	0.75
Cl5(82)	43.94	154.24	22.08	278.07	375.13	370.55	199.23	49.93	83.74	42.98
Cl5(83)/(119)	32.09	99.45	20.05	213.69	219.88	276.17	174.19	59.06	60.77	36.02
Cl5(84)	83.92	324.45	60.13	664.44	722.19	928.34	521.75	130.35	281.27	128.54
Cl5(85)	41.07	160.59	24.02	304.45	374.33	397.32	231.79	60.59	131.00	55.01
Cl5(87)	72.45	289.36	35.60	510.21	804.61	746.84	361.17	83.42	150.61	68.90
Cl5(91)	39.95	155.79	29.87	316.60	346.38	422.97	252.25	62.97	92.29	43.98
Cl5(92)	41.96	130.28	23.97	239.41	274.24	289.41	178.00	50.51	54.25	46.27
Cl5(95)	144.82	567.36	101.70	1128.35	1230.34	1567.07	864.51	216.75	329.32	195.74
Cl5(97)	64.43	238.06	35.68	452.12	683.96	678.79	395.13	91.23	137.08	57.01
Cl5(99)	64.36	249.37	32.31	444.34	725.99	660.13	379.02	93.69	153.91	72.96
Cl5(100)	1.67	4.11	3.19	8.20	9.46	11.63	8.42	2.38	3.17	1.85

STATION_ID	T176A	T176A	T176A	T176A	T176A	T176A	T176A	T176A	T176A	T176A
FIELD SAMPLE_ID	T176A 0-1FT	T176A 1-2FT	T176A 2-3FT	T176A 3-4FT	T176A 4.5FT	T176A 5-6FT	T176A 6-7FT	T176A 7-8FT	176A 8-8.77F	76A 8.77-9.55
SAMPLE DEPTH (from bottom)	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-8.77	8.77-9.55
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	91.29	345.53	46.64	633.94	1063.69	974.62	544.56	131.28	204.29	104.60
Cl5(105)	61.40	216.29	16.58	335.75	635.71	573.93	283.09	73.25	132.63	62.70
Cl5(110)	228.13	839.76	148.00	1667.24	1842.83	2164.56	1339.03	345.72	489.18	256.44
Cl5(114)	0.14	0.18	0.17	8.92	41.43	21.94	12.39	2.76	8.24	3.62
Cl5(115)	2.91	9.02	1.60	16.73	27.89	20.03	13.87	3.16	6.99	3.17
Cl5(118)	91.72	362.36	36.63	593.00	1107.17	888.38	535.71	134.02	174.67	88.52
Cl5(107)/(123)	20.49	66.68	41.00	131.27	167.18	171.44	119.38	31.94	37.68	20.59
Cl5(124)	2.59	11.17	2.12	17.62	40.19	28.29	17.07	4.17	8.34	3.70
Cl5(126)	0.11	3.02	0.14	4.63	9.65	6.70	5.19	0.12	0.13	0.10
Cl6(128)	9.09	25.76	13.78	50.05	77.80	72.51	39.40	11.57	15.18	9.07
Cl6(130)	6.38	13.27	10.32	27.85	35.58	38.58	20.74	7.36	7.23	4.91
Cl6(134)	3.75	8.81	5.69	18.02	24.26	25.81	15.26	4.58	6.18	3.79
Cl6(135)	7.03	20.19	15.76	40.83	45.84	50.27	29.24	9.49	11.42	7.71
Cl6(136)	7.55	18.46	11.87	37.85	48.12	46.85	25.99	8.63	11.88	7.30
Cl6(137)	2.73	5.92	1.96	11.36	24.47	17.16	8.85	2.64	4.15	2.35
Cl6(138)	24.64	81.83	36.53	145.36	245.49	198.18	102.87	29.17	42.24	25.28
Cl6(141)	4.99	12.99	3.41	25.07	57.62	34.66	16.08	4.66	7.59	4.55
Cl6(144)	1.94	5.31	2.07	10.27	17.54	12.71	5.52	1.76	0.14	0.11
Cl6(146)	9.42	25.87	22.40	52.28	55.06	63.21	34.56	11.35	11.54	7.73
Cl6(149)	34.89	100.60	17.03	206.65	262.97	254.36	139.74	44.16	51.37	31.29
Cl6(151)	9.89	28.46	19.23	56.45	72.52	62.38	33.15	10.77	12.34	8.32
Cl6(132)/(153)/(168)	37.35	116.04	58.49	211.96	343.05	301.28	152.27	46.83	57.43	36.26
Cl6(156)	3.52	6.54	2.05	16.54	38.67	31.20	13.62	3.63	6.14	3.57
Cl6(157)	1.19	2.45	1.04	5.11	10.32	8.95	3.78	0.74	1.74	1.14
Cl6(129)/(158)	5.13	10.23	2.95	16.95	33.69	29.83	14.02	4.78	6.21	3.69
Cl6(163)	7.63	20.69	13.27	46.00	59.82	61.19	30.03	9.25	12.37	7.98
Cl6(164)	3.02	7.05	4.27	17.23	26.19	21.74	11.92	3.41	4.06	2.97
Cl6(166)	0.11	0.15	0.14	0.20	0.33	0.20	0.21	0.12	0.13	0.10
Cl6(167)	3.71	5.25	2.04	7.91	17.01	13.95	6.86	2.88	2.74	1.76
Cl6(169)	0.15	0.31	0.12	0.29	0.29	0.29	0.28	0.12	0.17	0.12
Cl7(170)	6.64	18.85	9.52	40.01	55.42	47.64	17.84	5.54	7.33	5.32
Cl7(171)	2.71	5.76	3.31	10.99	15.52	12.81	5.11	1.66	2.22	1.53
Cl7(172)	3.54	6.34	3.64	11.99	13.43	11.79	5.25	1.69	1.78	1.23
Cl7(174)	7.74	24.84	11.97	45.41	62.72	44.33	18.87	6.47	7.12	4.85
Cl7(176)	2.94	4.13	2.26	7.25	8.99	6.53	2.96	1.16	1.11	0.85
Cl7(177)	7.64	17.54	11.33	34.46	36.48	34.96	16.07	5.34	5.58	3.90
Cl7(178)	3.25	7.42	5.44	13.21	11.81	11.72	6.33	2.36	2.63	1.72
Cl7(179)	5.61	12.99	7.33	23.82	31.46	20.01	9.60	4.18	3.53	2.53
Cl7(180)	19.37	52.98	21.27	118.77	130.60	110.44	39.97	13.72	17.29	11.58
Cl7(183)	7.91	15.44	7.54	27.72	36.60	27.73	11.42	4.21	3.60	2.95
Cl7(184)	0.65	0.59	0.21	0.55	0.82	0.76	0.50	0.22	0.17	0.10
Cl7(185)	0.97	3.00	1.16	5.39	8.01	4.85	1.79	0.92	0.85	0.35
Cl7(187)	13.77	35.49	21.71	65.12	72.19	57.99	26.72	10.23	9.90	7.73
Cl7(189)	0.11	1.46	0.69	3.16	4.47	4.14	4.65	0.12	0.13	0.10
Cl7(190)	2.07	5.16	2.38	10.75	13.80	12.31	4.85	1.39	1.80	1.25
Cl7(193)	1.70	2.91	1.92	6.09	6.63	6.44	2.91	1.10	1.13	0.81
Cl8(194)	9.48	25.72	12.55	49.41	46.91	39.57	14.68	4.88	7.16	5.10
Cl8(195)	3.68	7.84	3.83	13.83	13.86	12.01	5.34	1.98	2.82	1.84
Cl8(199)	15.44	32.20	17.38	57.50	60.41	46.07	23.56	7.79	7.50	5.76
Cl8(200)	1.12	2.48	1.29	4.61	4.93	3.57	1.91	0.66	0.74	0.57
Cl8(201)	3.58	3.62	1.71	5.02	6.16	5.57	3.28	1.05	0.86	0.71
Cl8(202)	2.57	4.08	2.47	6.97	7.72	6.69	3.91	1.31	1.22	0.98
Cl8(196)/(203)	7.82	21.86	10.67	38.61	40.85	32.80	14.71	5.01	6.25	4.71
Cl8(205)	1.30	2.00	0.95	3.47	4.30	3.03	1.02	0.03	0.03	0.02
Cl9(206)	33.27	46.82	20.82	71.81	95.50	61.00	37.85	9.30	8.69	6.17
Cl9(207)	4.07	5.78	1.48	4.95	10.69	13.20	7.94	0.95	0.84	0.87
Cl9(208)	10.17	11.63	5.13	16.51	26.96	23.50	17.22	2.89	2.08	1.62
Cl10(209)	297.87	259.00	113.93	381.50	1003.04	717.32	981.36	83.98	47.36	31.51
Sum 117 congeners	6,972	26,890	5,757	52,891	58,098	77,193	43,135	10,092	18,135	9,635

STATION_ID	T176A	T176A	T176B	T176B	T176B	T176B	T176B	T176B	T176B	T176B
FIELD SAMPLE_ID	76A 9.55-9.8	76A 9.8-10.55	T176B 0-1FT	T176B 1-2FT	T176B 2-3FT	T176B 3-4FT	T176B 4-5FT	T176B 5-6FT	T176B 6-7FT	T176B 7-8FT
SAMPLE DEPTH (from bottom)	9.55-9.8	9.8-10.55	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	8.30	24.58	477.49	136.49	83.66	135.67	45.70	150.44	16.99	13.01
Cl1(1)	0.07	0.05	0.11	0.09	0.08	20.95	14.72	30.51	13.14	36.57
Cl1(3)	0.03	0.03	0.06	0.05	0.04	13.62	11.39	22.56	7.54	22.60
Cl2(4)/(10)	2.07	2.46	0.20	0.16	0.14	97.37	83.05	120.75	55.15	385.52
Cl2(5)	0.11	0.09	0.18	0.15	0.13	0.23	0.25	4.44	2.92	14.14
Cl2(6)	4.44	3.82	163.73	117.95	105.19	655.04	124.20	130.95	143.94	1008.34
Cl2(7)	0.06	0.28	0.10	0.08	0.07	8.33	7.69	9.51	5.34	25.71
Cl2(8)	4.55	5.18	80.04	53.96	55.51	292.39	219.71	394.74	180.58	731.44
Cl2(9)	0.08	0.44	0.13	0.10	0.09	13.24	12.52	16.01	8.90	42.91
Cl2(13)	2.14	1.03	69.67	44.33	45.45	236.96	52.91	46.46	50.16	228.92
Cl2(15)	3.75	1.85	39.11	21.13	20.01	103.06	97.67	129.31	66.08	259.62
Cl3(16)	11.21	7.41	389.99	211.18	185.87	1048.95	625.57	1420.85	573.29	1569.07
Cl3(17)	15.32	7.98	490.54	298.34	229.68	1409.47	733.19	1339.62	611.12	2252.71
Cl3(18)	37.96	22.56	1610.60	982.60	759.73	4604.51	2090.42	5154.23	2032.32	6858.24
Cl3(19)	1.65	1.27	56.54	32.18	32.77	153.13	103.63	265.72	65.58	305.44
Cl3(22)	19.61	9.25	523.76	287.14	235.14	1347.52	839.92	1690.28	678.43	1892.00
Cl3(24)	0.06	0.05	0.10	0.08	0.07	9.31	9.26	10.25	5.03	16.88
Cl3(25)	25.34	8.14	672.99	454.09	401.65	2756.72	430.82	373.21	592.09	3209.10
Cl3(26)	30.42	10.82	791.67	447.48	402.16	2865.22	577.94	748.10	741.61	3959.37
Cl3(27)	1.52	0.78	45.19	22.47	22.09	108.31	76.47	137.90	49.07	209.06
Cl3(28)	61.39	25.47	1734.73	988.17	844.21	5338.26	2543.29	5016.74	2142.20	6736.64
Cl3(31)	71.92	28.66	2243.64	1229.59	1026.80	6466.04	2923.42	6399.39	2776.26	8722.82
Cl3(32)	9.93	5.45	301.94	186.44	138.51	780.90	463.37	1050.98	405.86	1228.80
Cl3(33)/(20)	26.03	11.90	746.08	394.41	336.44	1957.18	1368.57	2719.38	1131.58	2881.01
Cl3(37)	12.49	3.69	232.06	92.18	87.82	549.52	466.31	922.47	349.80	723.15
Cl4(40)	19.10	5.63	481.81	239.16	185.61	1250.45	702.78	1406.86	665.73	1835.43
Cl4(41)	6.09	2.06	176.77	94.09	68.00	304.89	321.13	852.89	305.19	658.25
Cl4(42)/(59)	41.58	13.56	1016.27	550.66	457.19	2768.65	1422.28	3236.75	1482.60	3881.45
Cl4(43)	4.57	1.28	118.88	60.02	59.12	330.64	132.81	351.21	152.56	399.51
Cl4(44)	93.94	30.63	3025.40	1434.68	1180.12	7263.97	3746.75	8480.02	3995.63	10436.74
Cl4(45)	15.55	6.25	458.30	257.45	208.17	1245.67	656.00	1704.53	638.92	1748.78
Cl4(46)	7.42	2.80	193.44	115.45	99.58	578.97	312.07	706.70	310.15	836.16
Cl4(47)	28.51	9.09	636.69	347.61	316.90	1957.36	916.80	2057.27	836.61	2551.76
Cl4(48)	14.10	4.75	442.31	166.57	151.95	793.80	803.13	2009.56	720.13	1413.45
Cl4(49)	82.21	25.78	2286.36	1146.29	1015.16	6392.13	2913.89	6236.58	3052.42	9236.92
Cl4(51)	4.60	1.68	152.83	75.37	62.29	345.19	152.81	425.12	177.91	478.66
Cl4(52)	106.65	35.46	3275.11	1666.04	1391.48	8786.49	4238.14	9692.06	4257.29	13271.13
Cl4(53)	13.42	5.37	424.02	244.29	189.97	1154.29	570.95	1392.15	687.46	1855.18
Cl4(54)	0.06	0.05	7.65	3.54	3.52	16.64	12.92	29.74	9.77	21.19
Cl4(56)	41.53	11.70	1245.85	503.31	441.16	2707.58	1784.41	3784.68	1494.59	3499.09
Cl4(60)	13.38	3.74	385.88	98.62	97.32	370.63	580.48	1740.68	527.06	1061.07
Cl4(64)	47.35	15.37	1393.41	688.84	598.67	3483.44	1896.10	4272.69	1736.90	5029.29
Cl4(66)	82.82	21.60	2098.75	820.68	705.71	4130.75	3353.75	7352.02	2710.86	5907.41
Cl4(70)	102.75	27.03	2969.00	1295.86	1125.86	6544.88	4245.08	9713.78	3719.91	8752.16
Cl4(71)	28.44	8.78	798.37	396.00	343.90	1915.65	1081.81	2289.35	969.47	2740.10
Cl4(74)	38.97	10.62	1052.89	416.13	353.45	1931.48	1774.91	4391.25	1416.73	3009.87
Cl4(77)	7.79	1.70	182.83	63.75	55.41	250.15	295.50	489.18	188.85	388.64
Cl4(81)	0.06	0.05	2.95	0.08	1.04	3.61	7.17	17.27	5.62	9.62
Cl5(82)	8.53	2.24	281.15	113.58	78.57	556.80	318.08	772.60	295.67	675.89
Cl5(83)/(119)	6.79	1.68	206.69	91.72	58.84	372.86	205.32	418.36	192.10	549.72
Cl5(84)	21.95	7.55	628.40	255.76	279.84	1519.20	868.70	2095.42	831.41	2312.30
Cl5(85)	11.68	2.83	340.00	127.46	114.33	665.72	481.22	924.01	405.76	996.10
Cl5(87)	14.75	3.97	455.91	182.15	156.68	922.42	698.78	1642.12	531.09	1302.13
Cl5(91)	10.10	2.67	237.69	111.41	89.08	656.13	328.49	700.46	339.67	941.17
Cl5(92)	7.32	1.46	171.05	90.19	43.85	453.99	192.71	301.20	219.58	557.52
Cl5(95)	33.69	9.85	877.39	397.06	323.17	2258.54	1177.46	2709.00	1188.76	3098.18
Cl5(97)	14.85	3.73	384.48	161.85	118.84	768.71	591.19	1288.00	512.96	1087.61
Cl5(99)	17.65	4.34	462.66	180.17	163.32	987.62	766.61	1657.22	589.63	1391.14
Cl5(100)	0.40	0.05	5.76	2.77	2.72	16.12	9.56	17.37	7.63	21.65

STATION_ID	T176A	T176A	T176B	T176B	T176B	T176B	T176B	T176B	T176B	T176B
FIELD SAMPLE_ID	76A 9.55-9.8	76A 9.8-10.55	T176B 0-1FT	T176B 1-2FT	T176B 2-3FT	T176B 3-4FT	T176B 4-5FT	T176B 5-6FT	T176B 6-7FT	T176B 7-8FT
SAMPLE DEPTH (from bottom)	9.55-9.8	9.8-10.55	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	26.38	6.73	645.81	299.88	244.96	1541.24	1101.81	2552.92	861.97	2098.83
Cl5(105)	14.98	2.91	427.24	122.71	125.94	587.04	611.52	1461.32	502.71	1055.48
Cl5(110)	49.33	12.84	1308.57	526.74	506.82	3078.77	1839.26	3639.54	1554.35	4208.45
Cl5(114)	0.14	0.11	6.20	0.18	3.13	14.92	35.72	99.88	30.84	48.79
Cl5(115)	0.70	0.28	17.58	5.15	6.42	23.80	30.60	95.03	25.33	61.22
Cl5(118)	25.79	5.27	686.47	217.76	212.80	1244.79	1027.97	2122.19	725.01	1710.17
Cl5(107)/(123)	4.08	0.99	117.69	41.95	40.91	223.39	136.65	245.28	124.32	312.92
Cl5(124)	0.08	0.06	22.73	6.86	6.84	30.81	41.42	97.68	32.49	62.44
Cl5(126)	0.11	0.09	0.18	0.15	0.13	7.63	8.45	12.61	5.41	10.01
Cl6(128)	2.09	0.71	44.73	18.38	19.05	97.94	82.81	143.98	52.71	101.67
Cl6(130)	1.33	0.08	21.24	10.21	10.78	66.87	35.80	62.08	23.76	50.20
Cl6(134)	1.01	0.07	14.88	6.34	6.64	40.23	28.05	47.49	18.75	40.04
Cl6(135)	1.85	0.48	31.49	14.23	15.17	101.92	47.62	75.36	33.45	68.01
Cl6(136)	1.63	0.54	32.56	14.37	15.91	90.87	53.43	86.61	35.85	75.33
Cl6(137)	0.14	0.11	12.41	4.01	4.39	20.61	23.97	51.89	15.19	29.94
Cl6(138)	6.88	1.81	126.15	55.64	56.93	251.04	187.62	397.25	151.38	203.58
Cl6(141)	1.59	0.46	29.04	8.42	9.25	44.84	51.33	103.82	33.00	52.38
Cl6(144)	0.12	0.10	0.20	0.16	0.14	0.25	0.27	0.26	0.15	0.22
Cl6(146)	2.12	0.54	36.45	18.75	20.16	112.57	58.67	78.63	35.18	63.98
Cl6(149)	8.27	2.47	169.90	70.55	64.48	384.97	247.83	348.49	167.47	283.91
Cl6(151)	2.08	0.73	45.04	19.08	20.35	176.75	71.21	100.73	41.12	73.75
Cl6(132)/(153)/(168)	10.24	2.91	210.39	74.69	66.10	487.29	295.36	499.82	213.35	466.03
Cl6(156)	1.25	0.02	13.54	5.64	5.31	28.33	39.55	88.53	24.68	40.91
Cl6(157)	0.10	0.08	8.24	2.51	2.52	11.03	13.72	24.19	8.29	14.22
Cl6(129)/(158)	1.20	0.34	24.67	7.36	8.86	34.02	40.71	70.78	25.98	45.47
Cl6(163)	2.39	0.50	39.32	16.00	16.84	107.03	63.35	100.48	35.81	70.05
Cl6(164)	0.72	0.05	12.92	5.65	6.14	35.00	25.85	42.22	14.99	28.67
Cl6(166)	0.11	0.09	0.18	0.15	0.13	0.23	0.25	5.66	0.14	0.20
Cl6(167)	0.91	0.05	10.30	2.93	4.08	18.10	17.59	32.25	10.37	18.07
Cl6(169)	0.15	0.12	0.14	0.14	0.15	0.29	0.32	0.32	0.48	0.29
Cl7(170)	2.12	0.50	35.35	12.54	13.95	79.36	48.15	93.45	30.98	47.07
Cl7(171)	0.59	0.17	11.02	4.27	4.60	29.37	14.93	22.75	8.35	13.04
Cl7(172)	0.82	0.06	11.00	4.15	5.04	25.35	12.61	18.26	7.71	11.34
Cl7(174)	1.86	0.66	43.82	15.79	17.75	101.62	53.43	0.09	28.88	37.54
Cl7(176)	0.31	0.10	6.90	2.39	2.86	17.43	7.51	9.22	4.17	5.26
Cl7(177)	1.53	0.46	26.14	10.37	12.60	78.77	31.75	45.68	18.76	28.06
Cl7(178)	0.60	0.25	11.93	4.67	5.63	33.74	12.95	15.11	7.71	10.00
Cl7(179)	1.01	0.35	23.43	8.79	9.63	58.62	28.20	30.03	13.81	15.02
Cl7(180)	4.50	1.36	113.49	33.07	35.23	196.37	104.82	141.12	61.37	85.04
Cl7(183)	1.19	0.34	27.31	9.94	10.92	62.54	29.88	41.39	16.74	20.94
Cl7(184)	0.05	0.04	1.13	0.40	0.33	0.64	1.09	1.89	0.50	0.71
Cl7(185)	0.08	0.06	6.24	1.78	2.03	11.37	7.06	8.47	3.39	4.61
Cl7(187)	2.54	0.91	58.69	22.86	25.43	170.86	63.93	76.70	35.02	45.15
Cl7(189)	0.11	0.09	3.47	1.22	1.44	3.58	3.80	7.33	3.42	4.05
Cl7(190)	0.57	0.07	9.50	3.14	3.15	18.63	12.68	21.49	7.17	12.44
Cl7(193)	0.30	0.09	5.27	2.33	2.50	13.96	6.27	9.38	3.75	5.29
Cl8(194)	2.37	0.35	48.67	19.64	19.76	83.23	45.67	60.86	28.19	34.07
Cl8(195)	0.90	0.05	16.94	5.49	6.57	30.58	13.63	21.95	10.03	14.08
Cl8(199)	2.04	0.49	68.99	25.19	28.69	116.44	62.69	71.25	30.28	34.41
Cl8(200)	0.13	0.13	4.75	1.56	1.83	9.65	4.88	5.62	2.61	3.32
Cl8(201)	0.31	0.10	6.82	2.24	2.64	11.12	6.53	10.43	3.66	4.64
Cl8(202)	0.45	0.07	8.55	2.98	3.64	15.82	9.01	9.92	4.26	5.12
Cl8(196)/(203)	1.73	0.45	44.33	15.86	17.06	77.18	41.58	54.89	24.36	30.17
Cl8(205)	0.03	0.02	3.97	1.56	1.59	5.74	3.60	5.33	2.99	3.51
Cl9(206)	2.09	0.52	124.96	42.18	48.30	93.44	95.47	101.54	29.69	37.91
Cl9(207)	0.24	0.08	10.55	2.70	2.68	10.91	11.99	33.95	4.84	8.60
Cl9(208)	0.55	0.14	24.02	9.27	11.12	23.67	27.39	37.38	8.01	10.54
Cl10(209)	16.62	2.14	600.64	247.02	190.80	650.95	935.46	1443.89	175.86	278.57
Sum 117 congeners	1,504	496	42,544	20,353	17,460	105,435	59,352	128,399	53,246	147,381

STATION_ID	T176B	T176B	T176B	T177A	T177A	T177A	T177A	T177A	T177A	T177A
FIELD SAMPLE_ID	176B 8-8.95F	76B 8.95-9.9	76B 9.9-10.9	T177A 0-1FT	177A 1-1.45F	177A 1.45-2F	T177-A-WV	177A 3.3-4F	T177A 4-5FT	177A 5-6.15F
SAMPLE DEPTH (from bottom)	8-8.77	8.77-9.55	9.55-9.8	0-1	1-1.45	1.45-2	2-3.3	3.3-4	4-5	5-6.15
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	15.15	25.76	27.55	0.62	8.20	52.01	31.93	44.73	39.17	18.76
Cl1(1)	17.14	11.73	0.08	0.05	0.05	0.09	0.07	14.61	19.24	14.90
Cl1(3)	10.65	6.83	0.04	0.02	0.03	0.04	0.04	11.03	9.08	6.89
Cl2(4)/(10)	120.41	84.08	18.67	0.09	0.09	15.58	0.13	70.64	72.11	76.80
Cl2(5)	7.91	7.02	0.12	0.08	0.08	0.14	0.12	0.44	0.31	5.65
Cl2(6)	449.76	186.11	59.50	0.26	4.78	60.65	27.26	144.86	269.34	210.90
Cl2(7)	16.40	13.48	2.78	0.04	0.04	0.08	0.06	8.41	7.79	11.16
Cl2(8)	363.02	225.23	45.61	0.07	2.34	24.29	20.45	203.77	231.36	239.89
Cl2(9)	27.49	23.12	4.26	0.06	0.06	0.10	0.08	13.82	12.03	19.26
Cl2(13)	152.77	78.14	26.67	0.06	1.69	28.21	10.87	53.07	93.79	64.33
Cl2(15)	151.95	115.34	43.71	0.10	0.83	8.47	6.09	92.81	91.12	96.88
Cl3(16)	641.61	328.63	81.54	0.07	7.53	104.20	63.57	523.78	672.60	344.05
Cl3(17)	897.74	476.20	122.04	0.79	10.76	151.74	77.54	606.77	798.99	443.42
Cl3(18)	2599.79	1175.26	324.95	1.70	28.42	439.27	215.74	1760.84	2596.63	1080.96
Cl3(19)	77.21	51.76	13.99	0.07	1.56	15.39	7.89	77.86	100.78	48.06
Cl3(22)	785.95	398.31	118.29	1.02	9.99	136.99	68.53	652.02	978.93	399.16
Cl3(24)	10.28	9.16	0.07	0.04	0.04	0.08	0.06	8.68	5.67	7.06
Cl3(25)	1697.96	662.18	229.35	0.88	18.23	307.18	119.22	421.66	974.05	593.29
Cl3(26)	1920.69	682.21	256.93	0.91	17.01	300.82	101.91	557.97	1039.42	673.52
Cl3(27)	59.74	40.65	10.95	0.04	0.91	10.61	6.47	57.12	75.70	36.54
Cl3(28)	2849.58	1485.67	404.34	1.54	31.30	489.89	243.05	2179.84	3531.34	1355.47
Cl3(31)	3452.49	1709.83	490.13	2.11	37.12	625.75	287.46	2350.50	4075.63	1586.35
Cl3(32)	435.31	198.09	60.18	0.42	5.78	71.48	37.04	378.25	509.44	218.05
Cl3(33)/(20)	1157.12	642.67	164.10	0.76	15.00	175.84	109.27	1027.74	1490.28	575.12
Cl3(37)	287.03	191.93	59.56	0.07	4.07	46.94	33.26	365.07	513.01	209.56
Cl4(40)	701.89	316.15	100.23	0.41	9.46	121.72	57.97	630.14	730.77	281.05
Cl4(41)	150.25	72.64	22.86	0.04	1.94	24.76	19.19	211.80	262.51	633.42
Cl4(42)/(59)	1556.66	794.16	234.39	0.87	18.60	264.71	127.95	1185.56	1652.60	686.97
Cl4(43)	162.46	88.32	28.54	0.05	1.89	34.41	17.30	157.62	200.19	80.72
Cl4(44)	3772.81	1762.64	572.91	2.28	43.56	682.47	335.59	3202.68	4785.85	1561.30
Cl4(45)	692.38	322.42	92.29	0.52	8.46	127.41	60.26	590.44	729.53	264.15
Cl4(46)	251.53	129.51	45.07	0.07	4.25	55.96	26.77	249.28	353.11	127.41
Cl4(47)	1047.19	550.19	160.55	0.61	12.36	181.18	83.25	807.42	1110.84	422.64
Cl4(48)	413.57	244.18	61.90	0.06	5.43	66.52	53.01	609.19	765.19	177.52
Cl4(49)	3773.14	1713.23	539.16	1.95	36.66	596.27	273.90	2490.01	3964.79	1457.44
Cl4(51)	172.09	85.46	27.92	0.07	2.28	35.18	15.39	153.54	199.89	75.20
Cl4(52)	4891.33	2144.01	675.75	2.68	50.46	847.31	371.47	3566.02	5336.92	1928.30
Cl4(53)	656.25	270.57	86.85	0.45	7.96	102.01	51.20	490.59	670.34	241.12
Cl4(54)	8.19	5.02	2.34	0.04	0.04	1.94	1.00	9.15	11.29	3.86
Cl4(56)	1311.95	723.50	209.86	0.97	17.21	248.19	117.20	1398.75	1889.03	596.92
Cl4(60)	178.60	106.35	39.85	0.07	2.48	32.39	22.44	320.86	439.84	84.34
Cl4(64)	1722.70	896.16	281.29	1.19	21.79	336.49	158.74	1495.36	2069.41	747.33
Cl4(66)	2005.94	1211.39	367.84	1.42	24.67	340.17	216.57	2685.82	3482.08	1069.73
Cl4(70)	3223.75	1853.27	521.20	2.14	38.40	602.26	309.74	3339.17	4654.23	1540.41
Cl4(71)	1007.73	490.00	155.46	0.63	12.94	187.83	90.92	899.66	1260.17	404.89
Cl4(74)	882.86	559.69	153.23	0.65	12.32	145.22	102.55	1320.26	1892.86	486.29
Cl4(77)	119.60	91.48	31.47	0.13	2.38	26.11	19.01	217.22	299.15	87.48
Cl4(81)	1.79	2.25	0.07	0.04	0.04	0.08	0.06	5.73	4.28	0.08
Cl5(82)	244.75	115.63	37.55	0.05	3.47	53.04	27.53	294.42	400.14	105.63
Cl5(83)/(119)	221.32	117.79	40.03	0.07	2.90	43.77	23.59	188.39	283.49	102.76
Cl5(84)	1044.69	451.12	133.52	0.09	9.71	149.80	63.96	761.08	943.19	330.34
Cl5(85)	372.07	152.45	53.86	0.04	4.03	64.02	30.69	348.17	567.02	169.76
Cl5(87)	332.21	169.75	55.07	0.44	5.41	79.16	52.15	477.94	712.05	138.35
Cl5(91)	369.64	174.80	60.03	0.04	4.00	62.33	32.63	253.01	391.61	181.68
Cl5(92)	192.14	96.71	49.24	0.06	2.99	48.11	28.63	217.73	296.14	114.34
Cl5(95)	1232.61	588.77	178.54	0.78	13.76	201.39	101.65	969.37	1418.89	524.76
Cl5(97)	408.78	228.10	72.29	0.47	5.74	77.96	49.15	429.46	663.07	218.29
Cl5(99)	439.86	257.47	77.83	0.43	6.15	80.33	47.58	607.18	789.40	205.62
Cl5(100)	10.87	6.31	2.10	0.04	0.04	1.89	0.85	7.89	9.51	4.89

STATION_ID	T176B	T176B	T176B	T177A	T177A	T177A	T177A	T177A	T177A	T177A
FIELD SAMPLE_ID	176B 8-8.95F	76B 8.95-9.9	76B 9.9-10.9	T177A 0-1FT	177A 1-1.45F	177A 1.45-2F	T177-A-WV	177A 3.3-4F	T177A 4-5FT	177A 5-6.15F
SAMPLE DEPTH (from bottom)	8-8.77	8.77-9.55	9.55-9.8	0-1	1-1.45	1.45-2	2-3.3	3.3-4	4-5	5-6.15
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	618.35	392.46	111.41	0.50	8.94	109.16	79.01	922.44	1317.89	356.91
Cl5(105)	223.49	177.67	49.27	0.07	3.29	50.93	28.36	414.02	518.01	135.14
Cl5(110)	1728.45	839.30	290.20	1.10	19.64	298.35	148.55	1418.36	2164.80	745.88
Cl5(114)	7.58	6.24	1.88	0.10	0.10	0.17	0.14	13.44	26.34	4.36
Cl5(115)	14.99	9.19	2.51	0.09	0.09	3.06	1.87	21.66	0.33	0.16
Cl5(118)	545.65	308.20	102.73	0.50	7.44	90.54	58.61	833.05	1181.55	312.00
Cl5(107)/(123)	130.38	63.29	20.68	0.09	1.52	23.24	14.32	126.75	162.58	58.32
Cl5(124)	15.50	9.38	3.30	0.06	0.06	2.38	1.74	32.52	32.46	8.48
Cl5(126)	2.49	0.16	0.12	0.08	0.08	0.14	0.12	0.44	7.04	0.15
Cl6(128)	44.54	25.84	9.25	0.07	1.09	10.11	6.65	57.66	85.84	22.87
Cl6(130)	25.53	14.50	5.49	0.07	0.08	7.89	3.75	27.25	43.79	11.62
Cl6(134)	18.81	11.05	3.92	0.06	0.06	4.52	2.03	20.74	30.07	9.65
Cl6(135)	35.08	21.45	8.27	0.07	0.64	9.73	5.01	35.16	55.91	17.32
Cl6(136)	35.25	20.40	7.58	0.02	0.88	9.28	4.23	38.42	60.09	17.85
Cl6(137)	8.67	5.13	2.30	0.10	0.10	0.17	1.43	17.03	20.12	4.53
Cl6(138)	114.72	69.91	25.21	0.08	2.10	28.86	17.69	176.64	279.15	61.23
Cl6(141)	12.39	8.87	3.48	0.04	0.04	3.62	2.91	30.09	40.60	7.91
Cl6(144)	0.17	0.17	0.13	0.09	0.09	0.15	1.04	0.47	16.62	3.24
Cl6(146)	38.30	24.80	9.03	0.02	0.95	14.61	7.00	43.88	79.14	21.38
Cl6(149)	136.02	87.21	33.93	0.07	2.70	40.90	22.78	168.53	253.64	75.22
Cl6(151)	36.15	22.42	8.94	0.07	0.77	11.96	6.11	44.87	78.18	19.35
Cl6(132)/(153)/(168)	163.24	99.55	36.94	0.06	3.24	45.71	26.21	227.49	392.20	93.39
Cl6(156)	12.79	7.33	4.09	0.02	0.02	3.62	2.15	24.40	31.55	6.52
Cl6(157)	4.58	3.16	0.11	0.07	0.08	2.88	0.69	7.64	10.55	2.17
Cl6(129)/(158)	15.03	9.84	4.42	0.07	0.41	5.53	2.82	28.64	29.32	8.34
Cl6(163)	36.50	21.91	8.62	0.07	0.73	11.93	4.98	41.83	65.91	21.32
Cl6(164)	12.33	7.58	3.17	0.05	0.05	3.98	1.91	17.55	26.41	7.00
Cl6(166)	0.16	0.16	0.12	0.08	0.08	0.14	0.12	0.44	0.31	0.15
Cl6(167)	6.67	5.36	1.83	0.05	0.05	2.63	1.37	14.13	14.54	4.19
Cl6(169)	0.20	0.17	0.16	0.10	0.11	0.20	0.35	0.57	0.34	0.18
Cl7(170)	17.37	11.39	4.94	0.06	0.58	8.19	3.90	33.87	55.11	11.92
Cl7(171)	6.02	3.96	1.52	0.04	0.04	2.91	1.14	11.42	17.47	3.83
Cl7(172)	4.76	3.38	1.58	0.06	0.06	3.29	1.17	8.68	13.39	3.70
Cl7(174)	17.03	12.08	5.13	0.03	0.70	8.90	4.88	35.00	60.72	11.75
Cl7(176)	2.61	2.10	0.89	0.05	0.32	1.95	0.83	4.36	8.75	1.79
Cl7(177)	14.62	10.08	4.44	0.06	0.56	6.48	3.60	19.89	38.36	9.19
Cl7(178)	6.23	4.50	2.27	0.04	0.41	3.98	1.60	8.63	15.82	3.77
Cl7(179)	8.89	6.78	2.90	0.08	0.47	6.02	2.60	15.98	31.86	6.03
Cl7(180)	34.41	25.02	10.69	0.06	1.06	19.40	10.08	72.24	112.49	23.90
Cl7(183)	9.97	7.42	3.10	0.06	0.64	6.59	3.08	18.97	35.09	6.95
Cl7(184)	0.43	0.42	0.06	0.04	0.04	0.63	0.21	1.24	0.44	0.19
Cl7(185)	2.06	1.16	0.65	0.06	0.06	1.16	0.58	4.95	6.62	1.15
Cl7(187)	25.50	18.96	8.26	0.05	1.09	15.54	7.20	39.02	79.06	15.71
Cl7(189)	1.48	0.16	0.12	0.08	0.08	0.14	0.12	3.88	3.99	1.48
Cl7(190)	4.35	2.71	1.45	0.06	0.06	2.61	0.98	8.61	11.47	3.07
Cl7(193)	2.91	1.70	0.93	0.03	0.03	1.67	0.66	4.17	7.06	1.47
Cl8(194)	16.27	12.40	4.81	0.04	1.01	12.94	5.11	30.63	51.27	10.06
Cl8(195)	6.43	4.54	1.74	0.04	0.04	3.77	1.69	10.81	18.90	3.49
Cl8(199)	20.88	17.84	6.61	0.08	1.59	28.33	9.42	43.36	76.73	15.43
Cl8(200)	1.80	1.44	0.56	0.09	0.09	1.25	0.50	4.30	6.03	1.26
Cl8(201)	2.94	2.03	0.78	0.09	0.28	2.36	0.88	5.87	8.25	1.85
Cl8(202)	3.45	3.11	1.13	0.06	0.27	3.48	1.17	6.54	9.68	2.78
Cl8(196)/(203)	15.42	12.24	4.73	0.02	1.09	11.33	4.40	31.44	26.61	5.44
Cl8(205)	1.74	1.44	0.03	0.02	0.02	1.40	0.69	4.10	3.93	0.84
Cl9(206)	24.74	25.94	8.61	0.21	3.75	62.73	22.41	82.08	107.78	23.69
Cl9(207)	4.29	3.66	0.88	0.07	0.26	2.44	1.21	13.00	13.66	4.02
Cl9(208)	8.33	9.17	2.10	0.07	0.95	15.33	5.58	23.23	30.40	8.72
Cl10(209)	248.49	314.06	61.34	0.56	16.22	206.57	120.74	526.72	870.27	247.72
Sum 117 congeners	56,321	28,388	8,610	37	679	10,174	5,096	48,052	70,155	25,840

STATION_ID	T177A	T177A	T177A	T177A	T177B	T177B	T177B	T177B	T177B	T177B
FIELD SAMPLE_ID	T177-A-RQ	177A 6.7-7.3F	77A 7.3-7.65	77A 7.65-8.3	T177B 0-1FT	177B 1-1.4FT	177B 1.4-2F	T177B 2-3FT	T177B 3-4FT	T177B 4-5FT
SAMPLE DEPTH (from bottom)	6.15-6.7	6.7-7.3	7.3-7.65	7.65-8.3	0-1	1-1.4	1.4-2	2-3	3-4	4-5
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	14.95	15.49	9.13	2.85	147.24	38.74	266.70	139.77	40.38	34.83
Cl1(1)	9.77	0.08	0.07	0.05	0.06	0.06	0.09	0.08	0.07	0.12
Cl1(3)	6.67	0.04	0.04	0.03	0.03	0.03	0.04	0.04	0.03	0.06
Cl2(4)/(10)	101.40	6.94	1.60	0.80	0.11	0.10	0.15	0.13	0.12	84.05
Cl2(5)	6.18	0.13	0.11	0.09	0.10	0.10	0.14	0.12	0.11	0.19
Cl2(6)	115.59	7.88	2.90	1.14	0.30	0.40	14.03	17.88	124.08	733.71
Cl2(7)	12.98	0.07	0.06	0.05	0.06	0.05	0.08	0.07	0.06	7.02
Cl2(8)	235.15	8.68	3.07	2.05	4.47	0.21	16.85	18.29	35.88	317.25
Cl2(9)	19.79	0.09	0.08	0.06	0.07	0.07	0.10	0.09	0.08	11.66
Cl2(13)	42.06	5.14	1.72	0.47	0.07	0.07	5.76	9.24	43.86	268.14
Cl2(15)	110.50	9.71	3.11	0.99	0.13	0.12	4.58	6.44	13.15	91.13
Cl3(16)	263.49	21.84	10.89	5.29	16.60	1.93	76.50	66.02	187.21	1013.65
Cl3(17)	331.50	33.77	14.06	5.40	20.88	2.79	103.58	88.63	215.31	1480.09
Cl3(18)	737.93	72.35	34.03	16.64	48.08	6.49	260.26	246.67	657.76	4564.20
Cl3(19)	52.76	4.60	1.52	0.95	2.35	0.08	12.48	10.35	22.49	127.88
Cl3(22)	290.13	33.67	18.19	6.08	22.09	2.21	88.72	81.05	214.18	1392.91
Cl3(24)	7.26	0.07	0.06	0.05	0.06	0.05	0.08	0.07	0.06	7.27
Cl3(25)	165.22	32.46	14.99	4.25	4.35	2.47	58.28	68.81	519.02	3248.93
Cl3(26)	221.38	42.41	19.56	6.29	9.03	2.95	59.03	70.77	550.01	3480.44
Cl3(27)	28.22	2.58	1.19	0.46	1.11	0.04	7.39	6.87	15.78	94.89
Cl3(28)	872.74	118.49	56.28	17.62	80.63	7.48	316.46	315.49	777.14	5037.98
Cl3(31)	885.58	135.47	57.89	21.24	63.62	8.62	365.22	342.48	1052.91	6580.91
Cl3(32)	155.71	17.98	9.25	3.78	12.20	1.07	53.15	48.42	139.56	744.88
Cl3(33)/(20)	418.49	41.62	22.45	8.94	33.89	3.82	145.85	141.13	316.78	1912.54
Cl3(37)	142.72	21.01	11.88	3.21	11.90	0.08	43.14	40.44	52.73	504.26
Cl4(40)	147.17	30.32	14.65	3.84	19.98	2.02	86.06	81.13	174.43	1131.58
Cl4(41)	58.99	3.79	5.91	1.62	7.78	0.05	0.08	15.37	37.05	236.41
Cl4(42)/(59)	376.38	69.39	37.49	10.68	41.81	4.83	164.30	153.70	396.59	2407.78
Cl4(43)	46.33	6.98	3.10	0.05	4.92	0.06	21.58	21.04	47.58	337.39
Cl4(44)	929.05	156.46	81.79	25.02	110.25	14.82	416.62	393.60	1038.79	6546.27
Cl4(45)	175.69	27.58	14.52	5.17	20.02	2.25	79.83	69.54	173.05	1185.71
Cl4(46)	84.43	12.71	6.47	2.07	8.57	0.65	39.11	32.77	75.09	566.65
Cl4(47)	219.83	49.06	24.96	6.79	28.77	3.87	131.35	110.01	267.65	1728.90
Cl4(48)	204.59	22.49	13.97	4.81	24.36	1.38	57.50	73.60	93.15	558.81
Cl4(49)	803.49	151.33	70.21	21.20	87.28	15.46	387.97	326.30	920.35	5946.85
Cl4(51)	45.61	8.05	4.09	1.38	5.45	0.31	24.09	21.93	48.52	255.95
Cl4(52)	956.81	179.67	91.49	28.78	117.80	22.00	476.61	451.99	936.81	5217.33
Cl4(53)	171.11	25.68	13.05	4.49	17.70	2.08	77.01	68.07	174.11	955.36
Cl4(54)	2.40	0.93	0.06	0.14	0.06	0.05	1.66	0.77	2.88	15.07
Cl4(56)	338.21	64.06	40.76	10.83	45.36	4.74	180.28	185.61	327.57	2180.12
Cl4(60)	49.88	10.11	12.88	4.14	9.44	0.41	0.12	19.31	40.60	303.42
Cl4(64)	446.70	73.66	43.44	12.51	47.83	5.89	193.87	196.75	479.74	3112.35
Cl4(66)	733.75	133.30	77.12	20.53	107.74	10.97	390.84	348.71	425.87	3015.49
Cl4(70)	890.00	156.86	89.57	25.88	124.28	16.26	452.68	432.03	781.75	5118.19
Cl4(71)	258.50	46.86	25.64	7.02	30.99	3.19	116.69	120.43	268.05	1746.94
Cl4(74)	351.28	58.11	37.74	10.15	52.18	4.40	129.38	165.44	213.07	1398.44
Cl4(77)	49.26	11.77	7.32	2.34	8.30	0.84	30.10	28.23	31.18	293.16
Cl4(81)	0.70	0.07	0.06	0.05	0.06	0.05	0.08	0.07	0.06	2.34
Cl5(82)	79.58	9.02	7.97	2.69	8.71	0.67	23.95	31.89	66.07	377.57
Cl5(83)/(119)	51.59	11.19	6.08	1.80	7.81	1.87	34.40	26.54	54.95	409.14
Cl5(84)	193.13	35.40	21.19	5.62	22.92	4.15	74.82	63.19	186.86	1352.25
Cl5(85)	88.72	13.03	11.40	3.94	9.89	1.12	18.42	34.58	78.64	553.15
Cl5(87)	114.51	15.35	14.66	5.34	20.10	2.04	32.73	52.78	102.78	586.41
Cl5(91)	90.90	16.60	9.50	2.50	11.27	1.66	43.03	36.74	84.35	546.75
Cl5(92)	64.02	11.48	7.38	1.76	8.72	1.72	37.14	29.54	81.81	501.35
Cl5(95)	274.68	54.66	31.00	9.04	39.28	8.99	138.80	123.84	307.29	2008.56
Cl5(97)	144.28	23.16	14.82	4.61	20.29	2.32	53.67	59.52	100.10	625.01
Cl5(99)	153.70	30.68	17.85	6.07	26.84	3.55	69.37	68.30	107.93	734.32
Cl5(100)	2.37	0.57	0.06	0.05	0.06	0.05	0.08	1.08	2.07	14.84

STATION_ID	T177A	T177A	T177A	T177A	T177B	T177B	T177B	T177B	T177B	T177B
FIELD SAMPLE_ID	T177-A-RQ	177A 6.7-7.3F	77A 7.3-7.65	77A 7.65-8.3	T177B 0-1FT	177B 1-1.4FT	177B 1.4-2F	T177B 2-3FT	T177B 3-4FT	T177B 4-5FT
SAMPLE DEPTH (from bottom)	6.15-6.7	6.7-7.3	7.3-7.65	7.65-8.3	0-1	1-1.4	1.4-2	2-3	3-4	4-5
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	236.27	42.57	26.50	8.22	39.07	6.89	128.98	125.10	174.44	1091.67
Cl5(105)	81.49	15.40	13.51	6.13	14.76	1.63	16.84	34.78	58.56	455.86
Cl5(110)	344.39	75.68	45.60	14.29	52.34	11.15	198.84	196.62	391.58	3001.21
Cl5(114)	3.85	0.16	0.14	0.48	0.13	0.12	0.17	0.15	0.14	14.66
Cl5(115)	2.87	0.14	0.12	0.09	0.11	0.10	0.15	0.13	0.12	0.20
Cl5(118)	195.05	38.09	24.80	9.42	35.67	4.63	96.08	114.50	135.06	992.98
Cl5(107)/(123)	39.63	6.45	4.21	1.39	5.74	1.05	17.41	14.61	28.66	226.98
Cl5(124)	6.00	1.03	0.08	0.06	0.99	0.07	0.10	2.06	3.43	20.19
Cl5(126)	1.50	0.13	0.11	0.09	0.10	0.10	0.14	0.12	0.11	4.66
Cl6(128)	11.68	3.09	1.87	0.82	2.47	0.61	7.84	6.99	11.95	85.81
Cl6(130)	5.81	1.09	1.13	0.29	3.00	0.35	5.47	4.09	8.45	60.06
Cl6(134)	4.45	1.31	0.96	0.07	1.46	0.07	3.61	2.63	4.83	38.70
Cl6(135)	7.59	2.78	1.69	0.43	1.99	0.64	8.12	5.36	12.47	89.40
Cl6(136)	7.41	2.64	1.54	0.51	4.77	1.06	8.53	6.16	10.84	80.04
Cl6(137)	2.83	0.92	0.14	0.25	2.25	0.12	0.17	1.37	2.05	14.87
Cl6(138)	31.80	8.45	6.30	2.49	11.11	1.67	21.54	22.24	34.54	308.40
Cl6(141)	4.33	1.30	1.48	0.68	0.06	0.05	0.08	3.01	4.70	34.17
Cl6(144)	1.76	0.35	0.35	0.10	0.55	0.19	0.15	1.31	2.13	16.46
Cl6(146)	10.21	3.36	1.92	0.50	2.96	0.75	13.39	9.35	14.61	105.89
Cl6(149)	54.61	11.98	8.17	2.45	11.64	3.13	32.68	25.66	48.01	345.85
Cl6(151)	9.46	3.24	2.35	0.40	3.61	0.51	9.22	7.98	14.98	111.58
Cl6(132)/(153)/(168)	49.55	14.95	10.38	3.58	15.99	3.28	42.08	35.76	51.54	438.20
Cl6(156)	4.36	1.27	0.93	0.83	3.39	0.02	0.03	2.17	2.76	23.39
Cl6(157)	1.20	0.12	0.11	0.36	2.23	0.09	0.13	0.77	1.04	8.34
Cl6(129)/(158)	4.52	1.40	1.03	0.56	1.68	0.33	3.06	3.03	4.16	29.35
Cl6(163)	7.92	3.35	2.09	0.68	2.68	1.24	10.26	6.11	12.97	98.20
Cl6(164)	3.55	1.04	0.65	0.29	1.96	0.22	2.62	2.35	3.64	27.66
Cl6(166)	0.13	0.13	0.11	0.09	0.10	0.10	0.14	0.12	0.11	0.19
Cl6(167)	2.00	0.56	0.69	0.45	2.36	0.06	0.09	1.67	1.69	10.88
Cl6(169)	0.19	0.17	0.15	0.11	0.14	0.12	0.18	0.16	0.15	0.21
Cl7(170)	4.97	1.84	2.13	0.91	2.91	0.37	4.36	5.47	7.95	56.52
Cl7(171)	1.39	0.53	0.39	0.29	0.64	0.05	1.77	1.58	2.90	20.61
Cl7(172)	1.24	0.46	0.32	0.26	2.64	0.22	2.04	2.39	3.17	17.67
Cl7(174)	5.23	2.33	1.90	0.72	2.91	0.49	6.02	6.16	10.31	71.21
Cl7(176)	0.83	0.50	0.32	0.14	2.80	0.24	1.79	1.31	1.94	13.92
Cl7(177)	4.21	1.84	1.36	0.62	1.66	0.18	4.98	4.04	8.05	60.14
Cl7(178)	1.43	0.95	0.60	0.23	1.17	0.27	5.43	2.73	3.89	26.86
Cl7(179)	2.38	1.45	1.27	0.40	2.86	0.39	4.13	3.98	6.33	44.91
Cl7(180)	10.68	4.59	4.77	2.17	6.40	0.75	10.65	13.49	21.00	116.23
Cl7(183)	3.25	1.27	1.13	0.53	4.79	0.30	3.85	4.51	6.32	44.99
Cl7(184)	0.06	0.06	0.05	0.04	0.57	0.04	0.82	0.50	0.28	0.09
Cl7(185)	0.71	0.09	0.18	0.11	0.07	0.07	0.59	0.09	1.24	7.89
Cl7(187)	6.64	3.53	2.91	1.05	4.46	0.83	11.21	9.52	16.58	113.77
Cl7(189)	0.81	0.13	0.11	0.26	0.10	0.10	0.14	0.12	0.11	2.29
Cl7(190)	1.42	0.42	0.42	0.22	0.77	0.07	0.75	1.63	2.10	12.82
Cl7(193)	0.60	0.45	0.12	0.03	0.97	0.04	1.09	0.88	1.29	9.04
Cl8(194)	4.18	1.81	1.80	0.98	3.47	0.64	8.59	9.37	12.60	57.06
Cl8(195)	1.76	0.30	0.06	0.45	0.74	0.05	2.17	1.51	3.80	20.78
Cl8(199)	5.66	2.71	2.03	0.84	9.17	1.51	34.59	26.64	18.15	80.67
Cl8(200)	0.56	0.40	0.13	0.10	0.56	0.11	0.70	0.90	1.33	6.68
Cl8(201)	0.82	0.49	0.20	0.10	1.62	0.11	1.64	1.49	1.52	7.97
Cl8(202)	1.43	0.69	0.45	0.16	1.55	0.35	4.37	2.75	2.20	11.10
Cl8(196)/(203)	3.99	1.00	1.05	1.00	2.51	0.19	4.22	4.41	5.26	27.16
Cl8(205)	0.89	0.03	0.03	0.23	1.23	0.02	0.99	0.94	0.91	3.89
Cl9(206)	8.96	4.07	2.52	0.79	29.55	3.79	73.22	72.72	30.65	66.28
Cl9(207)	2.15	0.79	0.23	0.11	2.03	0.17	2.28	1.70	1.65	7.46
Cl9(208)	6.06	1.57	0.64	0.21	7.62	1.13	22.17	17.19	6.95	17.10
Cl10(209)	333.72	77.21	34.90	2.76	216.65	24.80	327.62	273.82	93.11	396.92
Sum 117 congeners	15,383	2,492	1,364	431	1,967	264	6,786	6,532	14,376	92,732

STATION_ID	T177B	T177B	T177B	T177B	T177B	T177B	T178A	T178A	T178A	T178A
FIELD SAMPLE_ID	T177B 5-6FT	T177B 6-7FT	T177B 7-8FT	T177-B-QPO	T177-B-NML	77B 14.1-15.1	T178A 0-1FT	T178A 1-2FT	T178A 2-3FT	T178A 3-4FT
SAMPLE DEPTH (from bottom)	5-6	6-7	7-8	8-11	11-14.1	14.1-15.1	0-1	1-2	2-3	3-4
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	41.45	22.52	17.99	18.74	38.25	7.84	0.51	0.14	0.41	1.26
Cl1(1)	21.28	29.82	43.68	30.49	2.99	0.07	0.05	0.05	0.05	0.06
Cl1(3)	8.97	16.91	22.19	19.42	2.77	0.04	0.03	0.03	0.03	0.03
Cl2(4)/(10)	92.40	115.23	265.31	166.90	17.77	0.13	0.09	0.09	0.09	0.10
Cl2(5)	3.57	5.14	13.70	18.88	1.45	0.12	0.08	0.08	0.09	0.09
Cl2(6)	142.28	120.00	518.38	823.06	53.06	1.37	0.06	0.06	0.07	0.07
Cl2(7)	8.74	8.64	23.26	35.15	2.91	0.06	0.04	0.05	0.05	0.05
Cl2(8)	422.78	568.93	790.04	663.90	47.13	1.81	0.08	0.08	0.08	0.09
Cl2(9)	13.01	15.36	39.40	41.51	4.62	0.08	0.06	0.06	0.06	0.06
Cl2(13)	53.70	43.44	120.66	298.90	31.87	0.63	0.06	0.06	0.06	0.06
Cl2(15)	117.20	120.70	199.69	269.16	41.65	1.58	0.10	0.10	0.10	0.11
Cl3(16)	1024.65	1958.40	1538.89	883.78	87.31	5.50	0.08	0.08	0.08	0.09
Cl3(17)	1025.29	1621.33	1626.48	1264.75	127.18	6.93	0.04	0.05	0.05	0.05
Cl3(18)	3748.52	6794.61	5392.77	3428.34	306.60	17.34	0.06	0.06	0.07	0.07
Cl3(19)	120.78	284.53	364.68	119.31	14.59	0.89	0.07	0.07	0.07	0.08
Cl3(22)	1289.18	2204.58	1659.92	1098.69	123.62	9.72	0.06	0.06	0.06	0.06
Cl3(24)	10.30	9.72	14.51	20.13	1.53	0.06	0.04	0.05	0.05	0.05
Cl3(25)	625.69	751.72	1504.17	2811.43	243.53	7.83	0.04	0.05	0.05	0.05
Cl3(26)	848.90	1208.83	2115.04	3054.20	286.92	10.84	0.14	0.06	0.07	0.07
Cl3(27)	86.72	208.31	125.60	82.17	11.84	0.72	0.04	0.04	0.04	0.04
Cl3(28)	3944.59	6565.83	5527.51	3681.86	392.31	28.96	0.08	0.08	0.08	0.09
Cl3(31)	4577.20	8516.20	7305.62	4843.56	530.49	30.75	0.04	0.04	0.04	0.04
Cl3(32)	724.80	1535.81	1052.96	628.18	59.62	4.98	0.03	0.03	0.03	0.04
Cl3(33)/(20)	2210.21	3717.20	2742.30	1547.80	184.71	11.41	0.08	0.08	0.08	0.09
Cl3(37)	747.20	1175.85	791.92	399.34	55.60	5.45	0.07	0.07	0.07	0.08
Cl4(40)	984.50	2003.41	1289.02	765.00	79.19	8.05	0.08	0.13	0.09	0.09
Cl4(41)	530.88	1240.27	801.48	155.04	29.24	3.69	0.04	0.05	0.05	0.05
Cl4(42)/(59)	2080.56	3781.78	3107.73	2164.76	230.00	20.04	0.06	0.13	0.06	0.06
Cl4(43)	221.76	404.45	329.12	292.51	30.82	2.10	0.05	0.05	0.05	0.06
Cl4(44)	5038.19	9989.57	8189.29	5070.03	592.68	47.28	0.06	0.25	0.07	0.20
Cl4(45)	1038.47	1830.91	1632.24	851.27	86.13	7.69	0.04	0.05	0.05	0.05
Cl4(46)	448.24	865.97	662.01	401.41	41.27	3.58	0.08	0.08	0.08	0.09
Cl4(47)	1240.55	2400.56	1930.70	1193.78	147.27	13.53	0.06	0.10	0.06	0.06
Cl4(48)	1143.76	2519.89	1747.70	553.05	61.05	8.04	0.06	0.06	0.06	0.06
Cl4(49)	4062.91	7915.27	6676.09	4577.24	530.22	38.35	0.05	0.09	0.05	0.13
Cl4(51)	239.68	521.66	528.15	293.93	30.99	2.27	0.07	0.07	0.07	0.08
Cl4(52)	6035.07	8363.27	5247.72	5798.93	662.98	52.24	0.20	0.28	0.04	0.22
Cl4(53)	842.94	2042.55	1448.85	878.44	92.34	7.34	0.04	0.04	0.04	0.04
Cl4(54)	11.87	26.30	22.33	11.81	1.81	0.32	0.04	0.05	0.05	0.05
Cl4(56)	2457.86	4295.22	2961.88	1337.50	173.75	21.87	0.08	0.16	0.08	0.12
Cl4(60)	919.92	2331.50	1176.32	210.25	40.52	7.85	0.07	0.07	0.07	0.08
Cl4(64)	2669.38	4990.17	3783.40	2218.92	270.50	24.01	0.03	0.18	0.03	0.07
Cl4(66)	4584.47	8321.33	5388.21	2117.71	322.01	41.54	0.06	0.30	0.06	0.07
Cl4(70)	6116.27	11036.24	8142.73	3159.21	488.61	46.83	0.06	0.28	0.07	0.07
Cl4(71)	1547.04	2760.68	2040.47	1220.53	156.77	13.96	0.06	0.06	0.06	0.06
Cl4(74)	2569.10	4918.90	2998.60	1004.50	144.52	20.52	0.04	0.04	0.04	0.04
Cl4(77)	426.98	608.36	364.48	194.17	29.06	3.92	0.13	0.14	0.14	0.15
Cl4(81)	7.79	17.11	11.24	2.75	0.06	0.06	0.04	0.05	0.05	0.05
Cl5(82)	510.57	977.80	687.28	293.14	45.63	4.35	0.05	0.05	0.05	0.06
Cl5(83)/(119)	318.87	595.75	378.35	359.16	36.63	3.04	0.07	0.07	0.07	0.08
Cl5(84)	1126.35	2243.95	1547.90	1108.89	111.42	12.29	0.09	0.10	0.10	0.11
Cl5(85)	690.43	1534.23	1068.74	503.60	57.57	5.62	0.04	0.05	0.05	0.05
Cl5(87)	981.76	2081.65	1215.88	500.58	61.06	8.95	0.09	0.10	0.10	0.11
Cl5(91)	470.07	996.52	853.66	531.43	57.21	4.89	0.04	0.04	0.04	0.04
Cl5(92)	340.48	665.03	503.23	249.91	56.66	2.79	0.06	0.06	0.06	0.06
Cl5(95)	1727.64	3573.09	2785.42	1691.86	206.70	16.96	0.05	0.05	0.05	0.06
Cl5(97)	927.58	1679.64	1025.15	487.96	62.25	7.38	0.03	0.03	0.03	0.04
Cl5(99)	1060.06	2090.27	1373.86	516.01	73.38	9.75	0.05	0.05	0.05	0.06
Cl5(100)	10.70	19.63	20.99	15.26	1.94	0.06	0.04	0.05	0.05	0.05

STATION_ID	T177B	T177B	T177B	T177B	T177B	T177B	T178A	T178A	T178A	T178A
FIELD SAMPLE_ID	T177B 5-6FT	T177B 6-7FT	T177B 7-8FT	T177-B-QPO	T177-B-NML	77B 14.1-15.1	T178A 0-1FT	T178A 1-2FT	T178A 2-3FT	T178A 3-4FT
SAMPLE DEPTH (from bottom)	5-6	6-7	7-8	8-11	11-14.1	14.1-15.1	0-1	1-2	2-3	3-4
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	1770.74	3186.08	1661.38	730.42	101.36	14.93	0.10	0.10	0.10	0.11
Cl5(105)	971.01	2138.60	1112.27	366.26	52.13	7.92	0.07	0.07	0.07	0.08
Cl5(110)	2777.77	5617.93	3559.54	2038.96	275.28	24.54	0.08	0.08	0.08	0.09
Cl5(114)	44.38	114.82	59.16	10.77	2.40	0.61	0.10	0.10	0.10	0.11
Cl5(115)	0.25	85.85	52.46	21.63	3.07	0.13	0.09	0.09	0.09	0.10
Cl5(118)	1558.34	3671.60	1863.86	708.04	100.27	12.78	0.06	0.06	0.06	0.06
Cl5(107)/(123)	172.91	491.55	343.37	179.97	24.09	1.99	0.09	0.10	0.10	0.11
Cl5(124)	49.57	125.41	74.02	18.54	2.71	0.82	0.06	0.06	0.06	0.06
Cl5(126)	8.31	14.62	12.14	2.84	0.12	0.37	0.08	0.08	0.09	0.09
Cl6(128)	94.91	539.67	106.37	56.95	8.35	1.10	0.08	0.08	0.08	0.09
Cl6(130)	43.95	234.67	51.48	31.31	5.53	0.37	0.08	0.08	0.08	0.09
Cl6(134)	30.12	102.02	37.78	24.05	3.78	0.54	0.06	0.06	0.07	0.07
Cl6(135)	57.01	230.11	62.23	44.42	9.48	1.10	0.07	0.07	0.07	0.08
Cl6(136)	62.21	245.00	71.71	115.51	7.56	1.05	0.02	0.02	0.02	0.02
Cl6(137)	27.62	125.11	35.60	10.13	1.93	0.39	0.10	0.10	0.10	0.11
Cl6(138)	349.93	1400.09	413.15	115.00	23.82	4.68	0.08	0.08	0.09	0.09
Cl6(141)	58.47	428.10	63.48	16.04	4.24	1.53	0.04	0.05	0.05	0.05
Cl6(144)	20.34	69.37	21.22	7.12	1.24	0.13	0.09	0.09	0.09	0.10
Cl6(146)	67.59	290.57	68.18	48.66	9.72	1.38	0.02	0.02	0.02	0.02
Cl6(149)	293.31	986.25	326.99	196.86	35.47	6.09	0.07	0.07	0.07	0.08
Cl6(151)	80.26	217.68	75.36	42.70	10.48	1.86	0.08	0.08	0.08	0.09
Cl6(132)/(153)/(168)	411.90	1658.23	406.26	191.99	33.26	7.40	0.06	0.06	0.07	0.07
Cl6(156)	46.77	353.81	56.85	16.34	2.90	0.63	0.02	0.02	0.02	0.02
Cl6(157)	13.89	70.03	18.64	5.37	1.30	0.09	0.08	0.08	0.08	0.09
Cl6(129)/(158)	47.35	319.15	63.34	17.79	3.64	0.50	0.07	0.07	0.07	0.08
Cl6(163)	65.19	350.09	80.59	45.87	8.28	1.39	0.07	0.07	0.07	0.08
Cl6(164)	28.51	119.13	28.97	15.38	2.85	0.35	0.05	0.05	0.05	0.06
Cl6(166)	0.23	12.19	3.60	0.15	0.12	0.13	0.08	0.08	0.09	0.09
Cl6(167)	19.15	93.50	24.89	7.60	1.47	0.33	0.05	0.05	0.05	0.06
Cl6(169)	0.32	0.85	0.50	0.38	0.31	0.16	0.11	0.11	0.11	0.12
Cl7(170)	58.73	244.57	57.95	23.84	5.72	1.69	0.06	0.06	0.06	0.06
Cl7(171)	16.42	61.72	15.52	7.52	1.73	0.34	0.04	0.05	0.05	0.05
Cl7(172)	15.41	42.12	12.69	6.32	1.41	0.49	0.06	0.06	0.06	0.06
Cl7(174)	58.99	194.53	42.41	21.53	6.41	1.99	0.03	0.03	0.03	0.04
Cl7(176)	8.72	24.16	5.89	3.72	1.25	0.28	0.05	0.05	0.05	0.06
Cl7(177)	35.37	109.82	29.58	21.90	6.00	1.39	0.06	0.06	0.06	0.06
Cl7(178)	14.08	33.27	10.79	8.54	2.38	0.51	0.04	0.05	0.05	0.05
Cl7(179)	32.98	61.03	18.11	11.88	3.79	0.94	0.08	0.08	0.09	0.09
Cl7(180)	119.24	453.55	99.53	57.12	13.16	4.54	0.06	0.06	0.06	0.06
Cl7(183)	34.84	100.61	27.39	13.62	3.70	1.22	0.06	0.06	0.06	0.06
Cl7(184)	1.32	1.39	1.04	0.40	0.06	0.06	0.04	0.04	0.04	0.04
Cl7(185)	7.41	20.79	5.05	2.17	0.82	0.36	0.06	0.06	0.06	0.06
Cl7(187)	71.30	250.98	49.79	36.00	10.66	2.48	0.05	0.05	0.05	0.06
Cl7(189)	4.05	15.80	9.62	2.02	0.72	0.24	0.08	0.08	0.09	0.09
Cl7(190)	13.53	52.46	15.84	6.51	1.23	0.33	0.06	0.06	0.07	0.07
Cl7(193)	7.01	17.53	5.88	3.47	1.02	0.16	0.03	0.03	0.03	0.04
Cl8(194)	52.49	114.22	39.94	19.99	4.72	1.71	0.04	0.05	0.05	0.05
Cl8(195)	17.85	42.65	14.39	7.50	1.68	0.64	0.04	0.05	0.05	0.05
Cl8(199)	75.42	123.12	42.61	25.01	6.34	1.29	0.08	0.08	0.09	0.09
Cl8(200)	5.48	11.04	3.79	2.06	0.63	0.44	0.09	0.10	0.10	0.11
Cl8(201)	7.95	13.44	5.02	3.33	0.87	0.36	0.09	0.10	0.10	0.11
Cl8(202)	10.67	14.62	5.51	4.36	1.07	0.26	0.06	0.06	0.07	0.07
Cl8(196)/(203)	25.33	54.48	36.50	17.71	4.38	1.15	0.03	0.03	0.03	0.03
Cl8(205)	3.78	8.72	3.24	1.79	0.03	0.21	0.02	0.02	0.02	0.02
Cl9(206)	121.40	90.10	43.46	29.58	5.71	0.80	0.08	0.08	0.09	0.09
Cl9(207)	16.66	23.60	9.30	5.03	0.58	0.09	0.08	0.08	0.08	0.09
Cl9(208)	33.81	27.30	11.55	11.73	1.63	0.27	0.07	0.07	0.07	0.08
Cl10(209)	928.38	913.61	263.76	435.94	62.83	2.85	0.04	0.08	0.05	0.07
Sum 117 congeners	86,222	163,653	117,380	72,839	8,532	741	7	9	7	8

STATION_ID	T178A	T178A	T178A	T178A	T178B	T178B	T178B	T178B	T178B	T178B
FIELD SAMPLE_ID	T178A 4-5FT	178A 5-6.05F	78A 6.05-7.1	178A 7.1-8.1F	T178B 0-1FT	T178B 1-2FT	T178B 2-3FT	T178B 3-4FT	T178B 4-5FT	T178B 5-6FT
SAMPLE DEPTH (from bottom)	4-5	5-6.05	6.05-7.1	7.1-8.1	0-1	1-2	2-3	3-4	4-5	5-6
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	5.87	9.86	11.67	10.71	2.13	60.22	177.65	380.17	126.29	49.18
Cl1(1)	0.05	0.06	0.06	0.08	0.05	0.07	0.08	0.10	0.13	0.23
Cl1(3)	0.03	0.03	0.03	0.04	0.02	0.03	0.04	0.05	0.06	0.11
Cl2(4)/(10)	0.09	1.79	5.67	9.30	0.52	9.79	15.16	14.13	28.62	125.02
Cl2(5)	0.09	0.10	0.10	0.13	0.08	0.11	0.13	0.16	0.21	0.37
Cl2(6)	0.07	1.06	18.08	11.95	0.91	13.25	25.99	254.53	373.37	301.09
Cl2(7)	0.05	0.05	0.05	0.07	0.04	0.06	0.07	0.09	5.33	10.22
Cl2(8)	0.08	0.99	12.42	16.61	0.64	12.93	23.35	81.99	223.96	287.01
Cl2(9)	0.06	0.07	0.07	1.32	0.06	0.08	0.09	0.11	11.04	17.90
Cl2(13)	0.06	0.07	7.18	5.61	0.24	6.65	10.08	107.51	128.01	136.18
Cl2(15)	0.11	0.12	5.53	10.17	0.10	4.14	5.10	37.60	96.39	151.53
Cl3(16)	0.08	2.33	29.19	36.52	1.66	52.67	79.57	369.30	715.54	862.13
Cl3(17)	0.05	2.65	40.30	54.74	2.74	61.86	83.04	522.13	1039.82	1003.39
Cl3(18)	0.07	6.97	102.40	97.43	7.30	159.82	236.79	1531.82	2953.06	2902.43
Cl3(19)	0.07	0.08	4.19	5.49	0.33	7.39	11.95	65.25	117.79	164.29
Cl3(22)	0.06	2.89	35.32	53.68	2.72	55.35	92.08	519.12	1041.91	1121.08
Cl3(24)	0.05	0.05	0.05	0.07	0.04	0.06	0.07	2.05	6.56	10.40
Cl3(25)	0.05	6.54	70.96	49.35	3.86	59.15	105.50	1158.86	1527.68	1104.60
Cl3(26)	0.07	6.26	69.94	53.15	3.88	61.64	100.80	1198.89	1540.58	1215.25
Cl3(27)	0.04	0.04	3.26	3.51	0.04	5.30	8.20	49.51	106.76	126.51
Cl3(28)	0.08	9.56	135.20	163.27	9.34	196.88	309.22	1861.55	3767.27	3878.77
Cl3(31)	0.04	13.00	169.10	178.09	11.53	240.46	353.96	2452.54	4314.01	4513.00
Cl3(32)	0.03	1.38	23.24	27.00	1.53	41.42	55.44	281.70	567.68	624.29
Cl3(33)/(20)	0.08	4.24	50.61	63.61	4.34	94.46	138.07	682.53	1466.76	1846.56
Cl3(37)	0.07	1.58	22.04	34.33	1.07	31.40	47.17	172.44	359.17	671.71
Cl4(40)	0.09	1.79	40.33	46.47	2.06	47.22	73.14	506.07	1010.31	1032.08
Cl4(41)	0.05	0.05	4.34	8.31	0.72	12.61	10.53	97.15	254.41	431.75
Cl4(42)/(59)	0.06	4.66	72.58	76.30	3.64	103.05	176.68	896.36	1705.02	2130.07
Cl4(43)	0.05	0.06	10.52	12.43	0.47	15.24	23.79	111.92	238.08	229.25
Cl4(44)	0.07	14.53	175.43	204.32	13.05	259.99	421.82	2430.99	4655.85	4836.13
Cl4(45)	0.05	2.63	35.59	40.48	2.35	46.24	65.24	418.57	846.44	924.14
Cl4(46)	0.08	0.09	16.43	18.95	1.04	25.62	38.63	194.37	377.96	383.40
Cl4(47)	0.06	3.64	53.98	56.48	2.98	73.39	113.48	617.43	1168.12	1357.66
Cl4(48)	0.06	1.53	21.23	27.92	1.52	43.34	57.51	242.63	675.36	944.35
Cl4(49)	0.05	12.11	163.98	191.87	10.46	230.15	360.77	2154.01	4083.15	4467.02
Cl4(51)	0.07	0.08	9.41	11.20	0.64	15.21	23.79	106.03	216.39	212.72
Cl4(52)	0.04	14.26	215.90	236.18	14.76	316.71	468.80	2969.80	5588.97	6298.23
Cl4(53)	0.04	2.02	33.41	37.80	2.01	41.36	69.03	405.26	808.89	849.27
Cl4(54)	0.05	0.05	0.05	0.07	0.04	0.06	0.07	5.49	14.48	15.80
Cl4(56)	0.08	4.53	59.00	79.29	4.99	107.75	167.72	813.14	1716.82	2576.18
Cl4(60)	0.07	0.08	8.24	19.17	0.78	12.90	12.47	167.14	272.26	557.02
Cl4(64)	0.03	5.62	78.23	98.17	6.32	124.81	197.41	1187.90	2253.07	2600.22
Cl4(66)	0.06	8.05	115.47	161.02	9.03	214.85	340.13	1146.92	3138.96	4534.11
Cl4(70)	0.07	11.10	165.54	227.22	12.93	278.20	440.33	2119.47	4364.09	5503.69
Cl4(71)	0.06	3.76	45.96	51.59	3.13	74.74	114.35	682.35	1260.03	1585.23
Cl4(74)	0.04	2.61	43.16	65.12	4.48	85.96	136.45	631.06	1474.12	2373.84
Cl4(77)	0.14	0.16	10.18	16.46	0.75	20.69	30.26	111.12	286.08	427.65
Cl4(81)	0.05	0.05	0.05	0.07	0.04	0.06	0.07	0.09	2.69	6.76
Cl5(82)	0.05	0.06	11.00	16.49	1.04	22.63	29.80	208.53	421.10	541.72
Cl5(83)/(119)	0.07	0.08	15.09	17.88	0.55	20.23	32.15	156.15	296.86	344.59
Cl5(84)	0.10	2.47	52.89	39.06	2.88	78.24	69.98	637.96	1214.44	1201.79
Cl5(85)	0.05	0.05	18.76	24.54	1.52	27.98	33.67	315.70	538.27	755.12
Cl5(87)	0.10	0.98	16.68	25.56	1.67	41.93	56.70	332.28	705.39	943.13
Cl5(91)	0.04	1.28	20.61	25.69	1.17	28.40	43.86	216.27	434.91	536.07
Cl5(92)	0.06	1.05	16.01	21.38	0.77	21.54	31.08	218.49	417.28	539.78
Cl5(95)	0.05	3.89	58.86	68.16	4.06	76.03	128.70	722.94	1331.95	1839.00
Cl5(97)	0.03	1.23	26.57	36.00	1.68	45.00	55.90	310.95	698.72	905.89
Cl5(99)	0.05	1.77	30.15	42.47	2.24	42.21	62.76	315.87	805.19	1096.80
Cl5(100)	0.05	0.05	0.61	0.85	0.04	0.92	1.16	5.73	11.74	14.41

STATION_ID	T178A	T178A	T178A	T178A	T178B	T178B	T178B	T178B	T178B	T178B
FIELD SAMPLE_ID	T178A 4-5FT	178A 5-6.05F	78A 6.05-7.1	178A 7.1-8.1F	T178B 0-1FT	T178B 1-2FT	T178B 2-3FT	T178B 3-4FT	T178B 4-5FT	T178B 5-6FT
SAMPLE DEPTH (from bottom)	4-5	5-6.05	6.05-7.1	7.1-8.1	0-1	1-2	2-3	3-4	4-5	5-6
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	0.11	2.81	42.18	50.57	3.64	80.86	118.21	491.83	1215.18	1746.03
Cl5(105)	0.07	1.81	14.21	25.37	1.21	25.93	28.03	263.36	481.80	762.64
Cl5(110)	0.08	6.84	89.67	111.31	6.19	134.29	203.94	1051.54	2008.45	2823.77
Cl5(114)	0.11	0.12	0.12	0.16	0.10	0.14	0.16	0.19	6.27	27.85
Cl5(115)	0.09	0.10	0.67	1.05	0.09	1.18	1.07	12.02	22.61	22.55
Cl5(118)	0.06	2.49	36.32	53.29	3.04	70.61	99.32	418.84	965.65	1619.91
Cl5(107)/(123)	0.10	0.56	5.86	7.23	0.90	8.40	12.21	64.09	136.57	179.12
Cl5(124)	0.06	0.07	0.07	1.79	0.06	0.08	0.09	10.46	27.11	50.58
Cl5(126)	0.09	0.10	0.10	0.13	0.08	0.11	0.13	0.16	0.21	0.37
Cl6(128)	0.08	0.09	3.03	4.83	0.29	6.09	8.88	34.04	77.88	130.51
Cl6(130)	0.08	0.09	2.15	2.68	0.07	3.34	6.37	22.84	45.94	65.22
Cl6(134)	0.07	0.07	1.39	1.52	0.06	2.27	2.71	12.49	27.92	40.79
Cl6(135)	0.07	0.08	2.28	4.41	0.23	3.87	7.22	35.12	67.20	81.45
Cl6(136)	0.02	0.21	2.38	3.09	0.26	4.84	6.67	30.94	72.79	91.55
Cl6(137)	0.11	0.12	0.12	0.16	0.10	0.14	0.16	6.02	16.92	28.92
Cl6(138)	0.09	0.90	8.60	13.30	0.73	14.96	23.45	116.96	252.21	396.40
Cl6(141)	0.05	0.05	0.58	2.07	0.04	0.06	2.17	15.98	31.90	67.11
Cl6(144)	0.09	0.10	0.11	0.78	0.09	0.88	0.90	7.63	17.34	26.57
Cl6(146)	0.02	0.02	3.46	5.25	0.39	6.77	11.67	43.52	90.81	113.36
Cl6(149)	0.07	0.89	11.30	17.20	0.68	18.83	29.03	133.53	276.54	338.76
Cl6(151)	0.08	0.27	3.02	4.94	0.18	5.57	8.24	44.29	95.24	117.95
Cl6(132)/(153)/(168)	0.07	0.89	14.03	21.04	0.98	23.77	38.35	162.23	352.54	535.45
Cl6(156)	0.02	0.02	1.49	3.21	0.02	0.03	0.03	7.36	17.51	39.88
Cl6(157)	0.08	0.09	0.09	0.12	0.07	0.10	0.12	6.90	8.81	17.02
Cl6(129)/(158)	0.07	0.08	1.92	3.25	0.07	2.38	3.25	19.12	25.62	40.46
Cl6(163)	0.07	0.45	3.36	4.87	0.19	5.72	7.65	35.19	84.24	95.35
Cl6(164)	0.05	0.06	0.06	1.18	0.05	1.87	3.01	10.52	24.39	39.69
Cl6(166)	0.09	0.10	0.10	0.13	0.08	0.11	0.13	0.16	3.44	0.37
Cl6(167)	0.05	0.06	0.06	0.08	0.05	1.72	0.08	5.36	13.24	22.31
Cl6(169)	0.11	0.13	0.13	0.17	0.10	0.15	0.17	0.21	0.27	2.98
Cl7(170)	0.06	0.07	1.90	2.63	0.06	2.54	5.01	25.98	57.05	84.45
Cl7(171)	0.05	0.05	0.83	0.91	0.04	1.05	1.73	9.65	21.57	27.71
Cl7(172)	0.06	0.07	0.69	1.03	0.14	1.37	2.34	10.11	17.95	20.95
Cl7(174)	0.03	0.04	1.63	2.63	0.27	4.15	5.80	35.03	77.20	97.93
Cl7(176)	0.05	0.06	0.32	0.64	0.05	1.41	1.66	6.09	11.34	14.35
Cl7(177)	0.06	0.07	1.64	2.57	0.06	3.41	5.00	27.61	53.84	61.62
Cl7(178)	0.05	0.05	0.83	0.99	0.04	1.87	3.81	13.38	20.21	23.24
Cl7(179)	0.09	0.10	1.02	1.82	0.22	2.77	4.36	21.99	41.21	50.10
Cl7(180)	0.06	0.07	3.74	6.59	0.66	8.82	11.65	69.53	116.10	209.22
Cl7(183)	0.06	0.07	1.04	1.87	0.18	3.69	5.60	24.21	45.29	60.98
Cl7(184)	0.04	0.04	0.05	0.06	0.04	0.56	0.69	0.99	0.10	0.84
Cl7(185)	0.06	0.07	0.32	0.28	0.06	0.08	0.09	3.70	9.06	11.03
Cl7(187)	0.05	0.31	3.01	5.14	0.38	6.89	11.16	58.67	105.10	126.42
Cl7(189)	0.09	0.10	0.10	0.13	0.08	0.11	0.13	2.34	3.17	5.71
Cl7(190)	0.07	0.07	0.08	0.92	0.06	0.94	1.51	6.89	13.49	17.67
Cl7(193)	0.03	0.04	0.36	0.05	0.03	0.98	0.05	5.35	8.76	9.67
Cl8(194)	0.05	0.05	1.85	3.09	0.04	5.74	7.19	36.71	52.03	70.24
Cl8(195)	0.05	0.05	0.73	0.73	0.04	1.65	2.48	12.02	21.42	26.45
Cl8(199)	0.09	0.47	2.49	3.29	0.47	13.24	23.33	52.90	65.98	93.83
Cl8(200)	0.10	0.11	0.36	0.15	0.09	0.62	0.84	4.44	7.03	8.20
Cl8(201)	0.10	0.11	0.55	0.15	0.23	1.27	2.11	5.48	7.37	9.67
Cl8(202)	0.07	0.07	0.71	0.92	0.06	2.21	2.97	8.15	10.63	12.91
Cl8(196)/(203)	0.03	0.03	2.00	1.90	0.02	1.83	4.34	17.98	28.64	36.77
Cl8(205)	0.02	0.02	0.02	0.03	0.02	0.03	0.77	2.41	2.81	6.16
Cl9(206)	0.09	1.01	4.23	5.59	0.91	41.59	74.90	105.96	60.98	125.02
Cl9(207)	0.08	0.09	0.51	0.73	0.07	1.22	2.21	6.46	10.19	14.99
Cl9(208)	0.07	0.46	1.24	1.19	0.21	11.69	16.07	21.35	19.39	36.33
Cl10(209)	0.05	2.55	28.99	45.66	5.28	191.76	290.21	392.73	505.16	919.00
Sum 117 congeners	8	194	2,761	3,317	199	4,409	6,702	36,871	71,539	85,775

STATION_ID	T178B	T178B	T178B	T178B	T178C	T178C	T178C	T178C	T178C	T178C
FIELD SAMPLE_ID	T178B 6-7FT	T178-B-SRQ	T178B 10-10.5F	T178B 10.5-11F	T178C 0.5-1F	T178C 1-2FT	T178C 2-3FT	T178C 3-4FT	T178C 4-5FT	T178C 5-6FT
SAMPLE DEPTH (from bottom)	6-7	7-10	10-10.5	10.5-11	0.5-1	1-2	2-3	3-4	4-5	5-6
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	27.54	57.58	2.62	2.55	75.66	278.28	323.96	83.76	53.02	185.72
Cl1(1)	61.86	18.15	0.06	0.08	0.07	0.07	0.07	0.06	0.07	0.07
Cl1(3)	24.94	11.41	0.03	0.04	0.03	0.03	0.03	0.03	0.04	0.04
Cl2(4)/(10)	215.88	74.44	0.11	1.86	0.12	0.12	0.12	0.11	0.13	0.13
Cl2(5)	15.58	5.74	0.10	0.14	0.11	0.11	0.11	0.10	0.12	0.12
Cl2(6)	537.25	147.54	0.95	1.43	0.09	0.08	0.09	5.56	53.36	0.09
Cl2(7)	32.40	10.41	0.05	0.07	0.06	0.06	0.06	0.05	0.06	0.07
Cl2(8)	611.49	226.14	0.92	2.69	0.10	6.13	8.87	10.26	37.35	102.18
Cl2(9)	52.12	16.39	0.07	0.09	0.08	0.08	0.08	0.07	0.08	0.08
Cl2(13)	160.37	39.66	0.07	0.09	0.08	0.08	0.08	0.07	32.89	78.33
Cl2(15)	178.04	83.05	0.12	0.17	0.14	0.13	0.14	0.12	13.04	37.76
Cl3(16)	1337.92	354.92	2.74	4.47	10.24	25.98	34.41	34.39	123.77	397.10
Cl3(17)	1533.55	447.67	2.63	4.10	10.86	30.82	46.58	35.15	180.15	542.30
Cl3(18)	5460.35	1281.26	7.33	11.12	26.72	61.48	90.42	86.14	560.23	1604.27
Cl3(19)	214.16	61.67	0.08	0.12	0.09	0.09	5.10	5.30	24.64	56.05
Cl3(22)	1786.34	442.96	3.16	4.75	14.00	30.30	43.12	38.86	178.18	524.33
Cl3(24)	18.43	6.24	0.05	0.07	0.06	0.06	0.06	0.05	0.06	0.07
Cl3(25)	1858.89	383.69	3.32	4.00	0.06	0.06	10.94	24.71	273.76	788.44
Cl3(26)	2078.46	473.40	4.05	4.99	0.09	9.53	19.02	27.11	290.55	759.29
Cl3(27)	130.60	35.76	0.55	0.06	0.05	0.05	0.05	3.88	18.70	57.20
Cl3(28)	5287.62	1459.81	9.78	14.26	39.73	89.25	122.36	111.21	658.69	1954.65
Cl3(31)	7542.18	1744.06	11.79	16.20	37.63	78.81	136.87	120.90	759.56	2332.32
Cl3(32)	998.07	258.89	1.84	2.58	5.95	17.55	24.09	24.57	98.39	305.56
Cl3(33)/(20)	2806.91	665.53	4.74	7.19	21.00	44.51	60.18	48.62	237.01	792.55
Cl3(37)	848.09	207.04	1.78	2.72	10.28	18.45	23.91	21.19	68.72	209.92
Cl4(40)	1521.07	329.76	3.05	3.66	9.58	28.34	33.95	37.31	160.04	463.62
Cl4(41)	700.09	117.67	0.88	2.15	0.06	11.47	12.64	0.05	44.48	124.40
Cl4(42)/(59)	3184.34	851.19	5.95	8.53	27.97	45.74	68.04	48.48	296.56	935.42
Cl4(43)	386.16	108.95	0.06	0.08	0.07	0.07	10.57	10.04	51.76	110.07
Cl4(44)	8760.91	2017.24	14.41	22.23	70.28	128.80	165.01	141.18	800.46	2424.06
Cl4(45)	1536.50	370.28	2.49	4.19	10.22	27.03	37.73	34.98	141.61	442.30
Cl4(46)	661.18	188.64	1.14	1.76	0.10	12.07	16.72	16.28	65.61	209.00
Cl4(47)	2066.96	513.63	3.53	5.86	19.39	40.80	55.15	40.91	243.96	657.19
Cl4(48)	1429.21	423.97	2.48	3.99	14.62	37.29	45.06	25.74	114.31	405.90
Cl4(49)	7096.53	1702.65	11.77	18.15	46.94	99.18	144.65	130.65	724.73	2051.41
Cl4(51)	351.52	91.64	0.08	0.12	0.09	6.24	9.42	9.22	53.47	109.24
Cl4(52)	10530.13	2307.22	15.89	24.82	58.43	138.27	207.28	158.46	1014.86	2987.99
Cl4(53)	1404.04	354.10	2.07	3.42	8.90	22.44	33.64	30.71	136.88	396.16
Cl4(54)	26.92	6.12	0.05	0.07	0.06	0.06	0.06	0.05	0.06	0.07
Cl4(56)	3223.53	734.65	5.83	9.08	26.60	58.34	77.71	59.16	309.61	956.81
Cl4(60)	1432.09	170.09	1.85	2.93	0.09	16.06	12.38	6.47	46.86	186.83
Cl4(64)	4106.10	1024.97	7.08	11.03	26.66	61.83	82.54	68.48	394.69	1253.56
Cl4(66)	5493.66	1609.86	11.07	17.07	60.02	126.48	172.50	128.83	499.06	1517.54
Cl4(70)	8438.70	2057.63	14.24	20.86	69.45	144.93	196.92	163.85	749.56	2345.48
Cl4(71)	2346.04	560.74	3.67	5.93	15.60	39.34	46.51	37.31	249.48	681.00
Cl4(74)	3271.26	28.11	5.06	9.02	27.79	61.23	74.67	48.23	244.42	822.56
Cl4(77)	518.72	97.86	0.99	1.62	5.93	10.38	15.41	11.22	42.29	123.97
Cl4(81)	10.82	2.37	0.05	0.07	0.06	0.06	0.06	0.05	0.06	0.07
Cl5(82)	801.59	195.82	1.03	2.90	0.07	11.82	13.76	9.54	62.44	193.89
Cl5(83)/(119)	459.45	174.03	0.08	0.12	6.72	10.07	14.85	13.04	54.73	130.51
Cl5(84)	1808.67	482.16	2.99	4.63	17.19	33.04	42.24	42.17	174.07	440.42
Cl5(85)	1189.14	196.18	0.78	3.08	6.65	13.40	15.88	9.61	84.70	258.52
Cl5(87)	1504.79	321.32	2.28	4.47	12.13	23.35	27.39	14.76	106.60	320.97
Cl5(91)	807.85	226.85	1.67	2.71	7.24	13.88	18.03	17.61	73.45	204.73
Cl5(92)	759.06	121.69	1.22	2.51	8.69	14.67	16.96	13.93	61.96	131.19
Cl5(95)	2862.64	741.69	5.23	11.77	30.34	48.37	63.32	45.75	245.06	689.51
Cl5(97)	1306.34	334.92	2.20	3.75	14.13	26.11	32.17	21.97	105.55	332.87
Cl5(99)	1539.01	348.05	2.28	4.87	20.90	37.63	43.42	29.57	124.59	364.81
Cl5(100)	22.18	6.27	0.05	0.07	0.06	0.06	0.06	0.05	2.13	5.76

STATION_ID	T178B	T178B	T178B	T178B	T178C	T178C	T178C	T178C	T178C	T178C
FIELD SAMPLE_ID	T178B 6-7FT	T178-B-SRQ	T178B 10-10.5F	T178B 10.5-11F	T178C 0.5-1F	T178C 1-2FT	T178C 2-3FT	T178C 3-4FT	T178C 4-5FT	T178C 5-6FT
SAMPLE DEPTH (from bottom)	6-7	7-10	10-10.5	10.5-11	0.5-1	1-2	2-3	3-4	4-5	5-6
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	2189.62	557.58	4.93	11.26	32.88	58.17	73.47	48.17	189.85	595.50
Cl5(105)	1523.01	222.69	2.23	3.75	9.52	20.64	18.91	9.16	74.51	247.36
Cl5(110)	3738.12	878.25	7.68	13.77	44.31	71.42	103.91	75.54	356.31	1067.96
Cl5(114)	77.99	12.13	0.12	0.17	0.14	0.13	0.14	0.12	0.15	6.63
Cl5(115)	95.56	16.25	0.11	0.15	0.12	0.12	0.12	0.11	0.13	0.13
Cl5(118)	2012.22	468.00	3.85	7.64	29.68	54.01	63.36	39.09	165.11	456.74
Cl5(107)/(123)	221.22	112.85	0.11	0.16	0.13	5.59	6.83	4.93	22.89	55.30
Cl5(124)	81.65	20.48	0.07	0.09	0.08	0.08	0.08	0.07	5.12	13.27
Cl5(126)	9.86	4.97	0.10	0.14	0.11	0.11	0.11	0.10	0.12	0.12
Cl6(128)	134.68	68.00	0.09	0.13	0.10	0.10	0.10	0.09	10.91	28.20
Cl6(130)	62.35	17.87	0.09	0.13	0.10	0.10	0.10	0.09	9.35	17.62
Cl6(134)	41.33	12.26	0.08	0.10	0.09	3.16	0.09	0.08	4.21	10.10
Cl6(135)	81.84	21.17	0.08	1.69	2.44	3.37	4.36	3.18	10.39	24.33
Cl6(136)	89.14	22.43	0.47	2.04	6.24	5.95	5.32	4.05	10.45	26.31
Cl6(137)	42.34	13.12	0.12	0.17	0.14	0.13	0.14	0.12	0.15	6.75
Cl6(138)	394.33	118.51	1.46	7.51	11.78	16.14	17.74	10.70	36.12	101.06
Cl6(141)	75.26	21.16	0.53	2.68	0.06	0.06	0.06	0.05	5.12	16.95
Cl6(144)	27.01	6.24	0.11	0.91	0.12	0.12	0.12	0.11	2.33	7.24
Cl6(146)	83.06	27.68	0.37	1.20	5.18	4.64	6.54	4.83	15.71	31.66
Cl6(149)	328.75	99.46	1.92	9.89	12.32	14.40	17.54	14.00	47.56	110.77
Cl6(151)	95.05	25.36	0.68	3.62	3.32	4.67	5.71	3.58	13.34	33.61
Cl6(132)/(153)/(168)	455.76	137.19	2.34	12.77	17.13	20.24	24.23	17.78	57.67	142.33
Cl6(156)	64.36	25.83	0.02	0.03	0.03	0.03	0.03	0.02	2.89	8.58
Cl6(157)	20.85	9.87	0.09	0.13	0.10	0.10	0.10	0.09	0.11	0.11
Cl6(129)/(158)	67.81	23.87	0.08	1.07	0.09	0.09	0.09	0.08	4.24	14.96
Cl6(163)	86.49	22.68	0.49	2.70	4.31	4.87	5.11	4.55	11.68	33.31
Cl6(164)	39.09	11.20	0.06	0.08	0.07	0.07	0.07	0.06	4.02	9.66
Cl6(166)	3.38	0.14	0.10	0.14	0.11	0.11	0.11	0.10	0.12	0.12
Cl6(167)	22.53	14.50	0.06	0.08	0.07	0.07	0.07	0.06	0.07	6.82
Cl6(169)	0.24	1.68	0.13	0.18	0.15	0.14	0.15	0.13	2.48	0.16
Cl7(170)	70.49	18.75	0.07	3.59	4.25	4.17	0.08	0.07	7.08	23.46
Cl7(171)	20.59	5.22	0.05	1.24	0.06	0.06	0.06	0.05	2.80	7.01
Cl7(172)	13.62	5.40	0.07	0.81	0.08	0.08	0.08	0.07	2.43	6.80
Cl7(174)	59.85	14.25	0.65	4.08	3.40	3.52	3.47	2.28	10.43	28.18
Cl7(176)	8.69	2.17	0.06	0.90	4.97	3.67	2.41	1.24	1.91	4.54
Cl7(177)	43.29	11.44	0.54	2.46	4.23	3.24	2.68	2.45	8.60	18.52
Cl7(178)	13.10	3.91	0.05	0.84	2.49	1.95	2.27	2.24	4.10	8.39
Cl7(179)	28.68	6.10	0.39	2.42	4.14	3.97	3.21	1.71	6.51	15.68
Cl7(180)	159.05	53.41	1.38	9.91	8.76	10.20	7.98	5.59	20.87	55.91
Cl7(183)	37.81	10.42	0.07	3.11	9.97	7.13	3.98	2.34	6.86	17.20
Cl7(184)	0.70	0.43	0.05	0.06	1.17	0.85	0.05	0.45	0.05	0.55
Cl7(185)	7.02	1.76	0.07	0.09	0.08	0.08	0.08	0.07	0.08	3.62
Cl7(187)	69.78	17.89	0.79	5.09	6.82	6.81	6.24	5.11	16.54	42.08
Cl7(189)	4.94	3.92	0.10	0.14	0.11	0.11	0.11	0.10	0.12	0.12
Cl7(190)	15.61	4.98	0.08	0.68	0.09	1.04	0.09	0.08	2.06	5.60
Cl7(193)	7.58	1.92	0.04	0.05	1.51	0.04	0.04	0.04	1.65	3.23
Cl8(194)	50.52	11.21	0.05	2.13	3.64	3.58	4.59	2.81	11.78	26.84
Cl8(195)	21.86	3.92	0.05	0.07	0.06	0.06	0.06	0.05	4.06	9.54
Cl8(199)	53.97	12.77	0.10	2.04	9.39	10.62	13.93	10.94	20.58	46.20
Cl8(200)	4.86	1.27	0.11	0.16	0.13	0.13	0.13	0.11	1.64	2.90
Cl8(201)	7.69	1.98	0.11	0.16	0.13	0.13	0.13	0.11	1.77	3.80
Cl8(202)	8.22	1.98	0.08	0.10	2.25	2.65	2.36	1.89	2.52	5.41
Cl8(196)/(203)	18.35	10.57	0.03	0.04	4.75	4.73	4.03	2.99	5.34	13.71
Cl8(205)	6.89	1.91	0.02	0.03	0.03	0.03	0.03	0.02	0.03	0.03
Cl9(206)	70.90	14.16	0.10	0.97	30.18	30.71	38.98	25.19	35.90	83.68
Cl9(207)	14.11	3.14	0.09	0.13	3.64	2.39	1.49	1.23	1.96	3.31
Cl9(208)	20.65	4.50	0.08	0.12	9.20	9.27	11.48	7.93	8.88	16.65
Cl10(209)	582.16	186.17	1.41	2.92	304.01	342.24	333.19	156.44	111.35	261.67
Sum 117 congeners	128,935	30,683	225	430	1,401	2,505	3,231	2,499	12,451	36,609

STATION_ID	T178C	T178C	T178C	T178C	T178C	T179A	T179A	T179A	T179A	T179A
FIELD SAMPLE_ID	T178C 6-7FT	T178-C-SRQ	T178-C-PON	T178-C-MLKJ	78C 16.6-17.6	T179A 0-1FT	T179A 1-2FT	T179A 2-3FT	T179A 3-4FT	T179A 4-5FT
SAMPLE DEPTH (from bottom)	6-7	7-10	10-13	13-16.16	16.6-17.6	0-1	1-2	2-3	3-4	4-5
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	107.18	216.27	205.49	15.13	8.24	0.16	0.22	0.21	0.23	0.21
Cl1(1)	0.08	0.10	51.02	21.88	0.08	0.05	0.05	0.05	0.06	0.05
Cl1(3)	0.04	0.05	39.70	14.92	0.04	0.03	0.03	0.03	0.03	0.03
Cl2(4)/(10)	0.15	83.36	255.45	98.29	0.14	0.09	0.09	0.09	0.10	0.09
Cl2(5)	0.14	0.17	18.27	11.21	0.13	0.08	0.09	0.09	0.09	0.09
Cl2(6)	129.83	812.11	269.32	638.56	2.19	0.06	0.07	0.07	0.07	0.07
Cl2(7)	0.07	8.54	34.74	20.94	0.07	0.05	0.05	0.05	0.05	0.05
Cl2(8)	56.35	383.14	959.08	501.45	2.35	0.08	0.08	0.08	0.08	0.08
Cl2(9)	0.09	13.77	41.32	36.56	0.09	0.06	0.06	0.06	0.06	0.06
Cl2(13)	56.95	351.24	74.64	283.89	0.09	0.06	0.06	0.06	0.06	0.06
Cl2(15)	19.77	91.84	278.36	125.62	2.28	0.10	0.10	0.11	0.11	0.11
Cl3(16)	217.44	1127.48	2054.06	1043.13	7.06	0.08	0.08	0.08	0.08	0.08
Cl3(17)	312.84	1276.75	2175.70	1290.21	8.73	0.05	0.05	0.05	0.05	0.05
Cl3(18)	956.54	4332.47	8310.82	3340.88	22.92	0.06	0.07	0.07	0.07	0.07
Cl3(19)	37.02	263.49	431.78	142.98	1.42	0.07	0.07	0.07	0.08	0.07
Cl3(22)	310.53	1323.68	2782.74	1101.06	11.80	0.06	0.06	0.06	0.06	0.06
Cl3(24)	0.07	6.87	24.69	12.75	0.07	0.05	0.05	0.05	0.05	0.05
Cl3(25)	742.28	2561.48	883.80	2026.33	10.13	0.05	0.05	0.05	0.05	0.05
Cl3(26)	732.30	2682.98	1528.80	2444.61	13.62	0.06	0.07	0.07	0.07	0.07
Cl3(27)	27.74	127.22	289.95	110.71	0.06	0.04	0.04	0.04	0.04	0.04
Cl3(28)	1116.72	4552.15	8133.75	3982.20	34.95	0.08	0.08	0.08	0.08	0.08
Cl3(31)	1552.00	5860.00	10082.35	4821.62	38.12	0.04	0.04	0.04	0.04	0.04
Cl3(32)	169.99	696.52	1605.52	676.90	6.25	0.03	0.03	0.03	0.03	0.03
Cl3(33)/(20)	424.76	1815.59	4245.47	1751.64	14.37	0.08	0.08	0.08	0.08	0.08
Cl3(37)	99.86	468.58	1439.94	541.24	7.46	0.07	0.07	0.07	0.08	0.07
Cl4(40)	270.91	1033.53	2249.79	837.69	10.47	0.08	0.09	0.09	0.09	0.09
Cl4(41)	68.33	282.14	1423.59	250.10	5.47	0.05	0.05	0.05	0.05	0.05
Cl4(42)/(59)	602.54	2411.97	4940.72	2126.26	23.86	0.06	0.06	0.06	0.06	0.06
Cl4(43)	77.95	264.33	526.41	196.20	0.08	0.05	0.05	0.05	0.06	0.05
Cl4(44)	1458.70	6269.08	13427.37	5609.01	57.53	0.06	0.07	0.07	0.07	0.07
Cl4(45)	254.69	1005.16	2463.76	1105.67	9.16	0.05	0.05	0.05	0.05	0.05
Cl4(46)	110.75	477.07	895.78	399.88	4.75	0.08	0.08	0.08	0.08	0.08
Cl4(47)	394.65	1444.38	2835.39	1352.58	15.26	0.06	0.06	0.06	0.06	0.06
Cl4(48)	131.60	768.54	3310.29	680.75	10.15	0.06	0.06	0.06	0.06	0.06
Cl4(49)	1345.91	4912.27	9572.71	4770.13	46.38	0.05	0.05	0.05	0.06	0.05
Cl4(51)	66.38	285.05	556.91	330.71	2.24	0.07	0.07	0.07	0.08	0.07
Cl4(52)	1793.91	6945.67	14497.48	6289.81	65.19	0.04	0.04	0.04	0.04	0.04
Cl4(53)	233.06	1042.14	2334.56	970.89	8.06	0.04	0.04	0.04	0.04	0.04
Cl4(54)	4.66	13.95	42.97	11.46	0.07	0.05	0.05	0.05	0.05	0.05
Cl4(56)	547.69	1677.02	4682.09	1647.90	24.95	0.08	0.08	0.08	0.08	0.08
Cl4(60)	73.72	314.85	2094.36	290.07	9.80	0.07	0.07	0.07	0.08	0.07
Cl4(64)	743.10	2909.37	6664.50	2546.69	28.74	0.03	0.03	0.03	0.03	0.03
Cl4(66)	731.18	3057.44	10268.13	3041.08	45.89	0.06	0.06	0.06	0.06	0.06
Cl4(70)	1211.67	4578.38	13680.87	4110.84	55.56	0.06	0.07	0.07	0.07	0.07
Cl4(71)	426.69	1682.47	3633.33	1453.48	16.47	0.06	0.06	0.06	0.06	0.06
Cl4(74)	325.08	1379.04	6057.19	1485.51	23.98	0.04	0.04	0.04	0.04	0.04
Cl4(77)	56.93	190.07	636.07	251.81	4.31	0.14	0.14	0.14	0.15	0.14
Cl4(81)	0.07	19.60	22.34	3.41	0.07	0.05	0.05	0.05	0.05	0.05
Cl5(82)	116.05	403.95	1066.92	293.99	5.30	0.05	0.05	0.05	0.06	0.05
Cl5(83)/(119)	88.99	359.23	630.01	255.28	4.60	0.07	0.07	0.07	0.08	0.07
Cl5(84)	271.72	1179.24	2520.01	957.21	12.22	0.10	0.10	0.10	0.10	0.10
Cl5(85)	167.77	370.69	1345.98	437.70	7.66	0.05	0.05	0.05	0.05	0.05
Cl5(87)	172.23	742.97	2331.18	602.93	10.02	0.10	0.10	0.10	0.10	0.10
Cl5(91)	129.45	564.99	1246.67	462.41	6.25	0.04	0.04	0.04	0.04	0.04
Cl5(92)	147.15	390.57	664.29	405.01	5.92	0.06	0.06	0.06	0.06	0.06
Cl5(95)	473.24	1886.08	4309.95	1785.77	22.36	0.05	0.05	0.05	0.06	0.05
Cl5(97)	175.13	558.53	2018.61	764.07	9.62	0.03	0.03	0.03	0.03	0.03
Cl5(99)	169.33	671.64	2259.69	574.16	11.81	0.05	0.05	0.05	0.06	0.05
Cl5(100)	3.50	29.84	28.91	30.59	0.07	0.05	0.05	0.05	0.05	0.05

STATION_ID	T178C	T178C	T178C	T178C	T178C	T179A	T179A	T179A	T179A	T179A
FIELD SAMPLE_ID	T178C 6-7FT	T178-C-SRQ	T178-C-PON	T178-C-MLKJ	78C 16.6-17.6	T179A 0-1FT	T179A 1-2FT	T179A 2-3FT	T179A 3-4FT	T179A 4-5FT
SAMPLE DEPTH (from bottom)	6-7	7-10	10-13	13-16.16	16.6-17.6	0-1	1-2	2-3	3-4	4-5
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	273.74	1079.14	3537.25	931.23	20.08	0.10	0.10	0.11	0.11	0.11
Cl5(105)	132.27	381.05	1936.32	351.60	9.56	0.07	0.07	0.07	0.08	0.07
Cl5(110)	613.93	2267.49	4816.65	2073.44	30.27	0.08	0.08	0.08	0.08	0.08
Cl5(114)	0.17	10.10	149.70	15.36	0.17	0.10	0.10	0.11	0.11	0.11
Cl5(115)	0.15	13.80	119.76	24.02	0.14	0.09	0.09	0.09	0.10	0.09
Cl5(118)	210.28	681.66	2686.42	801.75	15.48	0.06	0.06	0.06	0.06	0.06
Cl5(107)/(123)	38.02	219.81	567.68	169.48	1.37	0.10	0.10	0.10	0.10	0.10
Cl5(124)	0.09	23.46	159.25	26.29	0.09	0.06	0.06	0.06	0.06	0.06
Cl5(126)	0.14	2.92	18.05	5.32	0.13	0.08	0.09	0.09	0.09	0.09
Cl6(128)	24.11	92.60	220.18	67.70	0.12	0.08	0.08	0.08	0.08	0.08
Cl6(130)	15.32	61.77	92.41	34.72	0.12	0.08	0.08	0.08	0.08	0.08
Cl6(134)	7.78	31.09	56.83	23.81	0.10	0.06	0.07	0.07	0.07	0.07
Cl6(135)	21.26	77.39	91.39	46.69	1.81	0.07	0.07	0.07	0.08	0.07
Cl6(136)	16.84	67.07	108.18	44.75	1.59	0.02	0.02	0.02	0.02	0.02
Cl6(137)	4.17	14.57	75.60	12.63	0.17	0.10	0.10	0.11	0.11	0.11
Cl6(138)	62.99	235.47	585.32	149.59	6.89	0.08	0.09	0.09	0.09	0.09
Cl6(141)	9.65	31.79	164.17	21.33	2.20	0.05	0.05	0.05	0.05	0.05
Cl6(144)	5.06	15.03	39.75	8.91	0.14	0.09	0.09	0.09	0.10	0.09
Cl6(146)	25.87	107.78	99.33	43.27	1.65	0.02	0.02	0.02	0.02	0.02
Cl6(149)	71.31	374.32	386.11	183.70	7.66	0.07	0.07	0.07	0.08	0.07
Cl6(151)	23.39	97.78	120.64	40.01	2.89	0.08	0.08	0.08	0.08	0.08
Cl6(132)/(153)/(168)	87.28	439.61	726.93	223.96	10.52	0.06	0.07	0.07	0.07	0.07
Cl6(156)	0.03	21.77	130.80	19.36	0.03	0.02	0.02	0.02	0.02	0.02
Cl6(157)	0.12	6.95	26.52	5.94	0.12	0.08	0.08	0.08	0.08	0.08
Cl6(129)/(158)	10.17	24.64	109.10	23.22	1.69	0.07	0.07	0.07	0.08	0.07
Cl6(163)	23.58	83.87	133.48	47.47	2.26	0.07	0.07	0.07	0.08	0.07
Cl6(164)	6.84	26.45	54.37	17.41	0.08	0.05	0.05	0.05	0.06	0.05
Cl6(166)	0.14	0.17	5.45	1.75	0.13	0.08	0.09	0.09	0.09	0.09
Cl6(167)	0.08	13.58	37.92	9.59	0.08	0.05	0.05	0.05	0.06	0.05
Cl6(169)	5.46	1.38	1.73	0.19	0.18	0.11	0.11	0.11	0.12	0.11
Cl7(170)	15.32	81.81	145.62	26.09	2.31	0.06	0.06	0.06	0.06	0.06
Cl7(171)	5.59	20.62	25.12	7.82	0.69	0.05	0.05	0.05	0.05	0.05
Cl7(172)	6.35	18.35	20.75	6.68	0.09	0.06	0.06	0.06	0.06	0.06
Cl7(174)	17.47	93.66	99.46	24.50	2.51	0.03	0.03	0.03	0.03	0.03
Cl7(176)	3.37	14.42	11.85	3.77	0.39	0.05	0.05	0.05	0.06	0.05
Cl7(177)	13.57	79.49	57.23	22.37	2.15	0.06	0.06	0.06	0.06	0.06
Cl7(178)	6.83	25.82	18.14	8.14	0.53	0.05	0.05	0.05	0.05	0.05
Cl7(179)	11.21	47.05	39.00	11.90	1.32	0.08	0.09	0.09	0.09	0.09
Cl7(180)	39.41	193.78	291.33	70.68	6.55	0.06	0.06	0.06	0.06	0.06
Cl7(183)	13.26	53.51	52.93	15.57	1.77	0.06	0.06	0.06	0.06	0.06
Cl7(184)	0.06	0.59	1.40	0.40	0.06	0.04	0.04	0.04	0.04	0.04
Cl7(185)	2.23	7.78	11.12	2.50	0.09	0.06	0.06	0.06	0.06	0.06
Cl7(187)	31.39	139.37	114.85	35.78	3.34	0.05	0.05	0.05	0.06	0.05
Cl7(189)	0.14	3.47	7.20	2.58	0.13	0.08	0.09	0.09	0.09	0.09
Cl7(190)	3.70	14.18	23.34	6.55	0.10	0.06	0.07	0.07	0.07	0.07
Cl7(193)	2.83	10.36	10.21	3.66	0.05	0.03	0.03	0.03	0.03	0.03
Cl8(194)	21.09	101.47	124.52	21.79	0.07	0.05	0.05	0.05	0.05	0.05
Cl8(195)	7.38	20.56	23.54	7.74	0.07	0.05	0.05	0.05	0.05	0.05
Cl8(199)	34.09	103.24	109.43	28.61	0.13	0.08	0.09	0.09	0.09	0.09
Cl8(200)	2.34	7.12	7.14	2.32	0.16	0.10	0.10	0.10	0.10	0.10
Cl8(201)	2.79	8.63	9.23	3.08	0.16	0.10	0.10	0.10	0.10	0.10
Cl8(202)	5.08	10.86	10.53	4.62	0.10	0.06	0.07	0.07	0.07	0.07
Cl8(196)/(203)	9.86	79.24	82.11	18.40	0.04	0.03	0.03	0.03	0.03	0.03
Cl8(205)	0.03	3.65	5.26	1.98	0.03	0.02	0.02	0.02	0.02	0.02
Cl9(206)	53.57	110.24	157.20	28.24	0.13	0.08	0.09	0.09	0.09	0.09
Cl9(207)	3.28	7.34	18.73	4.52	0.12	0.08	0.08	0.08	0.08	0.08
Cl9(208)	13.56	18.54	31.16	10.33	0.11	0.07	0.07	0.07	0.08	0.07
Cl10(209)	207.88	565.03	1289.99	334.69	2.65	0.28	0.05	0.05	0.05	0.05
Sum 117 congeners	22,032	87,306	191,306	77,510	892	8	7	8	8	8

STATION_ID	T179A	T179A	T179B	T179B	T179B	T179B	T179B	T179B	T179B	T179B
FIELD SAMPLE_ID	T179-A-UTSF	179A 8.4-9.4F	T179B 0-1FT	T179B 1-2FT	T179B 2-3FT	T179B 3-4FT	T179B 4-5FT	T179-B-UTS	T179-B-RQP	T179-B-ON
SAMPLE DEPTH (from bottom)	5-8.4	8.4-9.4	0-1	1-2	2-3	3-4	4-5	5-8	8-11	11-12.5
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	6.34	11.87	10.04	27.57	173.46	125.01	261.27	149.33	87.01	18.20
Cl1(1)	0.06	0.06	0.06	0.06	0.08	0.07	0.09	51.29	31.43	0.07
Cl1(3)	0.03	0.03	0.03	0.03	0.04	0.04	0.04	26.21	18.11	0.03
Cl2(4)/(10)	0.10	1.23	0.10	0.11	0.14	0.13	0.16	143.95	108.77	5.22
Cl2(5)	0.09	0.10	0.10	0.10	0.13	0.12	0.14	10.18	13.51	0.11
Cl2(6)	0.07	0.08	1.48	0.08	16.10	49.08	174.43	643.68	193.51	8.44
Cl2(7)	0.05	0.05	0.05	0.05	0.07	0.06	0.08	22.79	24.81	0.61
Cl2(8)	0.08	0.51	1.65	2.22	28.96	27.03	65.41	448.45	331.19	14.15
Cl2(9)	0.06	0.07	0.07	0.07	0.09	0.08	0.10	37.13	40.24	0.85
Cl2(13)	0.06	0.07	0.07	0.07	0.09	18.99	61.63	165.64	87.26	3.36
Cl2(15)	0.11	0.12	0.12	0.12	6.55	5.30	27.37	163.15	148.07	8.76
Cl3(16)	0.08	1.54	2.47	5.30	87.73	86.27	287.71	1302.28	500.59	26.74
Cl3(17)	0.46	2.42	3.77	7.31	113.68	133.77	366.68	1361.34	675.20	33.31
Cl3(18)	0.63	5.78	11.96	16.87	302.73	386.83	1243.74	4689.06	1682.83	73.70
Cl3(19)	0.08	0.08	0.08	1.16	17.04	16.24	48.13	167.57	100.27	4.00
Cl3(22)	0.06	2.00	4.96	6.57	122.08	130.91	386.64	1658.70	688.50	42.69
Cl3(24)	0.05	0.05	0.05	0.05	0.07	0.06	0.08	16.79	14.65	0.06
Cl3(25)	0.05	0.05	5.87	0.05	53.75	206.17	712.40	2118.00	559.83	38.24
Cl3(26)	0.07	1.21	7.08	3.50	72.93	202.10	742.51	2542.43	703.98	50.58
Cl3(27)	0.04	0.05	0.04	0.05	9.71	10.82	33.38	113.51	73.57	3.44
Cl3(28)	0.84	7.47	14.75	22.41	433.63	469.33	1508.96	5417.23	2104.48	110.79
Cl3(31)	1.04	8.64	18.75	23.41	451.82	574.79	1925.38	6359.65	2372.16	129.78
Cl3(32)	0.04	1.56	2.01	3.30	62.68	77.79	214.62	814.21	353.44	22.09
Cl3(33)/(20)	0.74	3.36	6.19	10.59	166.98	184.09	561.07	2267.12	1104.44	60.60
Cl3(37)	0.08	2.74	1.94	4.18	53.39	44.15	142.71	679.81	375.21	23.96
Cl4(40)	0.09	0.10	0.10	1.70	86.39	96.40	304.46	1231.26	496.38	36.65
Cl4(41)	0.05	0.05	1.00	0.05	10.16	28.10	96.64	457.51	158.72	15.05
Cl4(42)/(59)	0.06	4.44	7.28	13.37	188.37	228.89	541.13	2725.99	1164.80	72.79
Cl4(43)	0.06	0.06	0.06	0.06	27.36	33.22	82.11	346.47	138.79	9.21
Cl4(44)	1.33	11.08	21.11	36.62	516.30	593.84	1993.39	7499.37	3539.84	178.35
Cl4(45)	0.05	1.38	3.89	5.81	88.98	94.69	305.82	1310.65	550.57	33.71
Cl4(46)	0.08	0.09	2.41	3.42	47.43	52.23	137.84	572.63	216.33	15.47
Cl4(47)	0.06	3.98	5.18	9.40	143.58	163.85	478.16	1638.88	781.16	49.62
Cl4(48)	0.06	0.07	1.82	4.79	88.73	81.97	186.64	1166.94	556.84	32.64
Cl4(49)	0.84	10.70	16.76	29.34	452.96	517.68	1727.85	6104.41	2463.10	133.44
Cl4(51)	0.08	0.08	0.08	1.40	32.83	32.35	74.45	349.69	136.10	10.06
Cl4(52)	1.39	12.73	22.43	39.90	602.78	708.30	2527.42	8265.59	3796.17	189.14
Cl4(53)	0.04	1.59	3.32	4.43	72.19	82.10	296.86	1259.50	458.24	30.68
Cl4(54)	0.05	0.05	0.05	0.05	0.07	0.06	4.38	22.10	9.85	0.74
Cl4(56)	0.58	4.87	8.22	13.64	243.33	240.63	732.27	2397.16	1219.91	70.93
Cl4(60)	0.08	0.08	1.57	0.08	4.82	31.62	167.21	516.37	304.56	25.37
Cl4(64)	0.41	4.81	9.67	15.79	242.96	284.55	910.83	3442.96	1447.81	81.77
Cl4(66)	1.33	11.89	15.83	32.96	544.74	413.64	1077.27	4735.85	2471.63	124.17
Cl4(70)	1.63	13.55	19.88	38.25	661.62	596.09	1851.62	6447.70	3623.89	159.13
Cl4(71)	0.06	3.21	5.81	9.19	145.43	165.59	530.87	2117.89	862.38	52.55
Cl4(74)	0.04	3.82	7.26	12.84	223.91	175.81	578.89	2353.45	1294.33	67.64
Cl4(77)	0.15	0.16	1.65	3.13	45.78	32.56	96.59	358.15	203.56	9.79
Cl4(81)	0.05	0.05	0.05	0.05	0.07	0.06	0.08	6.37	3.91	0.06
Cl5(82)	0.06	0.06	0.06	0.06	41.37	49.20	158.71	578.44	274.44	13.32
Cl5(83)/(119)	0.08	0.96	0.08	4.36	43.24	39.50	104.63	335.56	204.37	10.76
Cl5(84)	0.11	2.66	3.77	9.21	114.12	101.41	327.76	1318.12	584.84	39.94
Cl5(85)	0.05	0.05	0.05	0.05	43.85	54.99	219.33	670.43	365.19	17.72
Cl5(87)	0.11	1.41	2.56	4.13	52.26	67.45	251.99	1025.14	447.37	25.73
Cl5(91)	0.04	0.45	0.88	3.28	51.87	47.49	145.94	672.32	329.51	16.92
Cl5(92)	0.06	0.97	1.62	3.53	49.47	36.00	160.84	429.69	208.03	11.21
Cl5(95)	0.41	4.09	5.92	16.60	173.50	175.57	588.06	2219.18	975.77	56.97
Cl5(97)	0.04	2.06	3.14	5.90	80.27	80.41	235.87	1123.73	498.81	24.59
Cl5(99)	0.42	2.67	3.17	9.05	92.12	87.55	261.94	972.17	590.81	27.34
Cl5(100)	0.05	0.05	0.05	0.05	0.98	0.06	2.26	19.53	9.88	0.52

STATION_ID	T179A	T179A	T179B	T179B	T179B	T179B	T179B	T179B	T179B	T179B
FIELD SAMPLE_ID	T179-A-UTSF	179A 8.4-9.4F	T179B 0-1FT	T179B 1-2FT	T179B 2-3FT	T179B 3-4FT	T179B 4-5FT	T179-B-UTS	T179-B-RQP	T179-B-ON
SAMPLE DEPTH (from bottom)	5-8.4	8.4-9.4	0-1	1-2	2-3	3-4	4-5	5-8	8-11	11-12.5
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	0.44	4.92	6.01	18.42	182.49	150.14	456.31	1672.52	802.74	40.58
Cl5(105)	0.08	1.35	2.21	3.16	35.67	53.01	219.24	725.26	399.27	20.44
Cl5(110)	0.64	6.52	9.99	24.44	266.74	284.32	856.93	2931.00	1508.73	66.33
Cl5(114)	0.11	0.12	0.12	0.12	0.15	0.14	0.18	26.71	16.49	1.11
Cl5(115)	0.10	0.11	0.10	0.11	0.14	0.13	0.16	31.00	24.04	1.30
Cl5(118)	0.06	3.66	4.48	12.96	158.16	117.10	394.36	1513.52	788.11	34.27
Cl5(107)/(123)	0.11	0.11	0.88	1.18	15.09	13.96	46.36	339.12	158.97	5.87
Cl5(124)	0.06	0.07	0.07	0.07	0.09	0.08	10.51	48.36	25.89	1.36
Cl5(126)	0.09	0.10	0.10	0.10	0.13	0.12	0.14	7.29	3.58	0.11
Cl6(128)	0.08	0.09	0.09	1.62	10.33	9.24	31.95	102.25	40.06	2.36
Cl6(130)	0.08	0.09	0.09	0.09	7.08	4.82	15.56	52.09	20.57	1.45
Cl6(134)	0.07	0.08	0.07	0.08	3.05	3.61	7.66	39.64	16.30	1.13
Cl6(135)	0.08	0.08	0.08	0.99	8.06	8.10	24.26	81.27	29.56	2.26
Cl6(136)	0.02	0.50	0.22	1.82	7.95	8.57	22.83	81.90	30.98	2.26
Cl6(137)	0.11	0.12	0.12	0.12	0.15	0.14	5.84	25.95	11.70	0.86
Cl6(138)	0.09	1.27	0.81	5.60	28.29	28.74	87.50	354.60	126.96	7.60
Cl6(141)	0.05	0.05	0.05	0.05	2.56	5.11	13.58	48.97	21.40	1.77
Cl6(144)	0.10	0.11	0.10	0.23	1.11	2.10	4.66	22.95	8.29	0.59
Cl6(146)	0.02	0.02	0.02	1.80	15.17	13.65	30.65	100.04	33.35	2.68
Cl6(149)	0.08	1.48	1.42	6.24	34.22	36.51	89.85	411.36	153.26	10.73
Cl6(151)	0.08	0.09	0.09	1.51	10.60	10.98	31.85	142.03	34.76	3.09
Cl6(132)/(153)/(168)	0.07	1.83	1.39	7.77	51.18	48.58	123.83	431.98	172.18	12.38
Cl6(156)	0.02	0.02	0.02	0.02	0.03	2.97	7.48	31.77	13.94	0.98
Cl6(157)	0.08	0.09	0.09	0.09	0.12	0.11	6.37	10.05	4.69	0.23
Cl6(129)/(158)	0.08	0.08	0.08	0.08	3.50	6.34	14.57	37.23	19.23	1.19
Cl6(163)	0.08	0.08	0.44	1.83	10.90	10.02	25.81	81.16	27.91	2.46
Cl6(164)	0.06	0.06	0.06	0.06	3.31	2.69	8.46	33.15	13.25	0.96
Cl6(166)	0.09	0.10	0.10	0.10	0.13	0.12	0.14	0.25	0.17	0.11
Cl6(167)	0.06	0.06	0.06	0.06	3.04	0.07	6.62	17.35	6.79	0.50
Cl6(169)	0.12	0.13	0.13	0.13	0.16	0.15	14.36	1.30	0.40	0.29
Cl7(170)	0.06	0.07	0.07	0.67	7.81	8.39	23.27	55.94	17.94	1.86
Cl7(171)	0.05	0.05	0.05	0.05	1.85	1.82	6.83	20.16	5.37	0.62
Cl7(172)	0.06	0.07	0.07	0.07	3.44	4.03	6.60	16.37	4.85	0.49
Cl7(174)	0.04	0.34	0.24	1.15	6.95	8.92	28.13	72.96	18.11	2.26
Cl7(176)	0.06	0.14	0.12	0.49	1.95	1.98	4.75	11.96	2.96	0.43
Cl7(177)	0.06	0.07	0.07	0.75	5.98	5.06	19.01	50.78	13.52	1.68
Cl7(178)	0.05	0.20	0.05	0.87	3.17	4.20	9.78	19.78	5.21	0.74
Cl7(179)	0.09	0.36	0.21	0.84	4.92	5.73	16.57	41.70	9.62	1.30
Cl7(180)	0.06	0.67	0.77	2.38	12.71	19.49	56.78	221.48	38.97	4.58
Cl7(183)	0.06	0.24	0.07	1.07	5.44	6.73	18.33	43.58	11.22	1.41
Cl7(184)	0.04	0.05	0.04	0.05	0.52	0.71	0.79	0.99	0.46	0.05
Cl7(185)	0.06	0.07	0.07	0.07	0.77	1.16	3.93	8.43	2.10	2.19
Cl7(187)	0.06	0.55	0.47	2.00	12.63	15.32	41.72	100.47	24.92	3.41
Cl7(189)	0.09	0.10	0.10	0.10	0.13	0.12	0.14	3.25	1.41	0.11
Cl7(190)	0.07	0.08	0.07	0.08	1.09	1.64	5.86	13.53	4.39	0.51
Cl7(193)	0.04	0.04	0.04	0.04	0.05	0.04	49.65	7.58	2.63	0.30
Cl8(194)	0.05	0.57	0.05	1.34	7.63	11.46	27.96	45.84	12.52	1.40
Cl8(195)	0.05	0.05	0.05	0.05	2.41	3.23	10.32	17.22	5.10	0.68
Cl8(199)	0.09	1.89	0.65	3.93	24.44	30.62	37.83	67.69	18.16	1.96
Cl8(200)	0.11	0.11	0.11	0.11	0.91	1.56	2.77	6.43	1.70	0.21
Cl8(201)	0.11	0.11	0.11	0.11	1.49	1.62	3.98	8.69	3.00	0.30
Cl8(202)	0.07	0.27	0.07	0.36	3.46	3.78	5.41	11.04	3.70	0.35
Cl8(196)/(203)	0.03	0.03	0.03	0.90	3.85	5.95	12.94	48.05	11.58	1.57
Cl8(205)	0.02	0.02	0.02	0.02	0.03	0.03	0.03	2.69	1.18	0.03
Cl9(206)	0.43	6.04	1.28	12.90	50.15	96.06	61.25	70.69	21.03	1.57
Cl9(207)	0.08	0.09	0.09	0.36	1.86	2.43	5.02	10.91	5.33	0.24
Cl9(208)	0.15	1.37	0.37	3.69	16.16	21.35	15.64	23.82	9.11	0.48
Cl10(209)	1.81	24.59	8.52	56.43	294.92	278.65	294.41	1177.59	475.07	15.57
Sum 117 congeners	22	205	304	622	8,551	9,382	28,991	107,493	47,939	2,579

STATION_ID	T179B	T179C	T179C	T179C	T179C	T179C	T179C	T179C	T179C	T179C
FIELD SAMPLE_ID	79B 12.5-13.5	179C 1.15-2F	T179C 2-3FT	T179C 3-4FT	T179C 4-5FT	T179C 5-6FT	T179-C-UT	T179-C-SRQ	T179-C-PON	T179-C-MLK
SAMPLE DEPTH (from bottom)	12.5-13.5	1.15-2	2-3	3-4	4-5	5-6	6-7.15	7.15-10	10-13	13-16
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	9.36	119.65	251.19	60.44	111.55	42.51	59.59	148.59	122.75	60.29
Cl1(1)	0.07	0.07	0.08	0.07	0.07	0.07	0.06	0.11	38.30	24.79
Cl1(3)	0.03	0.03	0.04	0.03	0.04	0.03	0.03	0.06	22.63	14.27
Cl2(4)/(10)	1.96	0.12	0.13	0.12	0.13	0.12	0.11	93.94	161.06	131.75
Cl2(5)	0.11	0.11	0.12	0.11	0.12	0.11	0.10	0.18	10.96	14.20
Cl2(6)	4.43	0.09	0.09	0.09	6.27	3.43	65.15	582.51	246.18	501.82
Cl2(7)	0.06	0.06	0.07	0.06	0.06	0.06	0.05	8.34	21.54	25.77
Cl2(8)	5.07	0.10	5.38	2.43	11.59	9.08	36.09	283.04	565.88	499.82
Cl2(9)	0.08	0.08	0.08	0.08	0.08	0.08	0.07	16.45	34.62	41.56
Cl2(13)	2.13	0.08	0.08	0.08	0.08	0.08	29.65	200.70	76.37	175.28
Cl2(15)	3.79	0.14	0.15	0.14	0.14	0.13	11.54	107.29	198.64	219.25
Cl3(16)	15.21	7.07	20.50	7.10	46.50	33.93	137.76	906.88	1382.89	827.42
Cl3(17)	20.49	8.59	28.13	10.24	54.46	43.03	183.56	1313.96	1491.99	1131.10
Cl3(18)	48.16	17.24	74.57	25.20	131.21	106.22	554.63	4697.01	5407.92	3599.29
Cl3(19)	2.35	0.09	0.10	0.10	6.25	5.72	21.68	138.86	229.88	109.30
Cl3(22)	26.27	8.09	27.27	8.71	50.09	36.68	182.79	1355.49	1649.99	1107.40
Cl3(24)	0.06	0.06	0.07	0.06	0.06	0.06	0.05	9.06	16.75	14.74
Cl3(25)	26.99	0.06	0.07	4.61	36.04	19.09	286.63	2284.32	694.57	1978.43
Cl3(26)	36.66	4.16	9.19	5.74	36.77	22.85	290.14	2471.46	1053.57	2362.51
Cl3(27)	1.44	0.05	0.06	0.05	3.47	0.05	14.84	104.39	136.33	82.44
Cl3(28)	76.77	25.81	72.91	31.18	190.67	132.76	605.24	5431.74	5775.24	4313.88
Cl3(31)	96.92	28.39	79.66	34.25	212.35	141.45	783.11	7097.54	7444.42	5694.43
Cl3(32)	13.21	3.46	15.58	5.48	32.60	22.82	100.29	726.83	996.88	611.03
Cl3(33)/(20)	35.47	15.72	44.06	15.02	80.54	61.29	249.03	1936.65	2824.26	1771.22
Cl3(37)	15.23	3.34	12.43	4.31	29.22	19.53	58.24	515.44	850.13	504.09
Cl4(40)	0.11	5.05	13.64	6.60	50.65	28.99	134.37	1039.11	1343.69	859.36
Cl4(41)	7.94	0.06	0.07	0.06	0.06	7.41	41.64	308.24	732.83	247.71
Cl4(42)/(59)	43.23	11.83	49.42	9.90	74.84	52.83	303.29	2417.17	2942.41	2085.08
Cl4(43)	4.16	0.07	2.04	0.07	7.90	7.79	37.08	280.89	320.23	234.30
Cl4(44)	110.75	44.90	105.88	45.45	239.33	157.20	846.99	7785.35	9470.36	6138.35
Cl4(45)	19.72	7.96	21.97	8.79	45.22	31.00	146.02	1070.94	1428.86	842.87
Cl4(46)	9.09	0.10	7.99	1.65	21.92	13.00	59.47	474.45	641.91	360.67
Cl4(47)	33.83	13.69	36.15	13.69	66.61	50.76	188.42	1534.53	1826.02	1280.27
Cl4(48)	17.10	9.06	31.50	0.08	36.56	32.36	109.91	896.81	1883.19	731.29
Cl4(49)	106.57	35.30	84.52	38.50	223.60	132.19	638.19	6286.55	6685.00	5158.79
Cl4(51)	5.15	1.14	6.16	1.24	11.85	8.43	38.36	277.88	378.73	239.04
Cl4(52)	131.11	44.51	124.52	53.11	282.53	175.76	921.50	8723.48	10101.92	6838.10
Cl4(53)	18.15	6.01	19.49	6.65	43.53	29.70	136.63	1002.25	1352.45	829.38
Cl4(54)	0.06	0.06	0.07	0.06	0.06	0.06	2.58	17.22	27.09	12.22
Cl4(56)	47.85	21.43	55.56	18.54	105.57	68.10	261.24	2197.14	3057.76	1779.00
Cl4(60)	16.96	0.09	11.22	0.10	4.60	5.97	49.29	466.14	1231.98	358.44
Cl4(64)	56.77	18.47	55.69	18.74	105.06	78.82	375.99	2873.06	3712.97	2477.14
Cl4(66)	91.79	43.71	106.22	37.28	219.94	144.33	442.67	4193.03	7385.40	3221.37
Cl4(70)	110.74	48.83	124.21	48.61	283.30	181.57	692.90	6497.90	10011.05	4882.42
Cl4(71)	35.60	11.57	33.85	10.27	58.94	47.90	226.23	1774.42	2237.16	1461.94
Cl4(74)	45.08	18.92	58.82	14.64	89.09	61.93	222.06	1844.70	3663.08	1604.06
Cl4(77)	8.88	5.23	8.96	3.09	18.88	12.91	30.02	267.39	501.18	229.18
Cl4(81)	0.06	0.06	0.07	0.06	0.06	0.06	0.05	3.59	12.07	3.00
Cl5(82)	9.97	0.07	8.05	2.39	15.87	10.44	54.95	445.65	746.04	385.56
Cl5(83)/(119)	8.76	1.21	9.38	4.44	20.74	10.27	40.41	359.03	414.51	341.73
Cl5(84)	31.69	10.62	30.35	12.62	44.04	30.94	137.68	1093.52	1451.18	1009.44
Cl5(85)	12.41	5.12	10.81	3.21	12.91	0.06	70.02	665.81	910.58	551.21
Cl5(87)	18.45	9.83	20.16	6.92	23.84	21.11	100.14	921.81	1499.08	624.73
Cl5(91)	13.60	3.76	12.28	4.25	24.89	14.77	62.28	519.50	790.86	524.55
Cl5(92)	9.28	6.36	12.19	4.01	24.40	13.21	42.18	389.00	449.42	381.76
Cl5(95)	46.26	21.89	55.92	21.15	76.79	52.86	226.03	1889.76	2554.38	1690.30
Cl5(97)	18.15	10.12	24.61	7.50	33.33	23.96	85.90	834.19	1297.56	709.13
Cl5(99)	0.07	15.59	33.05	9.51	44.98	31.05	94.26	867.32	1577.86	743.46
Cl5(100)	0.06	0.06	0.07	0.06	0.06	0.06	1.65	15.63	18.78	13.56

STATION_ID	T179B	T179C	T179C	T179C	T179C	T179C	T179C	T179C	T179C	T179C
FIELD SAMPLE_ID	79B 12.5-13.5	179C 1.15-2F	T179C 2-3FT	T179C 3-4FT	T179C 4-5FT	T179C 5-6FT	T179-C-UT	T179-C-SRQ	T179-C-PON	T179-C-MLK
SAMPLE DEPTH (from bottom)	12.5-13.5	1.15-2	2-3	3-4	4-5	5-6	6-7.15	7.15-10	10-13	13-16
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	35.35	25.11	55.05	21.28	73.77	46.00	149.91	1244.52	2189.66	982.08
Cl5(105)	17.79	8.32	17.23	5.26	10.71	11.61	64.28	669.59	1258.69	503.11
Cl5(110)	60.04	34.04	65.54	30.89	129.59	75.53	290.19	2758.96	3386.64	2353.08
Cl5(114)	0.14	0.14	0.15	0.14	0.14	0.13	1.26	12.13	64.32	14.01
Cl5(115)	0.12	0.12	0.13	0.12	0.13	0.12	2.79	26.54	68.86	24.99
Cl5(118)	28.49	22.21	46.13	14.98	65.19	38.58	118.17	1141.16	2078.80	903.94
Cl5(107)/(123)	3.65	2.80	0.14	1.61	7.40	4.17	22.12	229.18	350.68	158.52
Cl5(124)	0.08	0.08	0.08	0.08	0.08	0.08	3.21	29.60	81.33	23.11
Cl5(126)	0.11	0.11	0.12	0.11	0.12	0.11	0.10	4.83	9.26	3.36
Cl6(128)	2.23	0.10	4.33	2.54	5.65	2.52	7.98	80.56	112.85	52.10
Cl6(130)	1.76	0.10	0.11	0.10	4.22	0.10	5.01	53.56	51.78	28.61
Cl6(134)	0.80	1.25	0.95	0.09	2.29	0.08	3.42	34.52	41.14	22.11
Cl6(135)	3.46	1.71	2.75	1.56	5.34	2.55	7.66	86.94	72.39	42.66
Cl6(136)	2.66	4.72	4.92	2.15	5.74	2.44	7.61	75.70	78.36	41.31
Cl6(137)	0.72	1.79	0.15	0.14	0.14	0.13	1.82	17.00	35.99	11.20
Cl6(138)	10.61	8.93	19.25	6.33	17.32	8.83	26.18	301.67	392.88	141.44
Cl6(141)	3.07	0.06	0.07	0.06	0.06	0.06	4.41	39.60	74.75	19.06
Cl6(144)	1.08	0.12	0.47	0.12	0.13	0.12	0.11	19.24	26.10	8.52
Cl6(146)	3.57	2.14	3.69	1.79	9.10	4.06	9.95	105.10	83.21	45.52
Cl6(149)	15.77	9.07	18.51	6.39	20.15	10.37	36.22	395.37	375.74	238.43
Cl6(151)	5.23	1.72	4.16	1.92	6.34	3.50	10.66	110.91	94.87	45.34
Cl6(132)/(153)/(168)	18.42	12.51	26.35	8.96	29.12	14.46	42.11	426.64	483.91	241.22
Cl6(156)	1.17	4.37	4.17	0.03	0.03	0.03	2.22	20.70	49.34	14.37
Cl6(157)	0.10	0.10	0.11	0.10	0.11	0.10	0.83	7.25	14.16	5.09
Cl6(129)/(158)	1.24	0.09	2.04	0.10	0.10	0.09	3.73	34.54	57.55	22.26
Cl6(163)	5.64	2.56	4.89	1.73	5.30	2.98	7.70	78.93	73.86	38.67
Cl6(164)	1.22	0.07	0.08	0.07	0.07	0.07	2.78	26.87	35.01	16.29
Cl6(166)	0.11	0.11	0.12	0.11	0.12	0.11	0.10	0.18	2.90	1.16
Cl6(167)	0.07	0.07	0.08	0.07	0.07	0.07	1.36	12.68	19.66	7.94
Cl6(169)	1.34	0.15	0.16	0.15	0.15	0.14	0.09	0.62	0.16	0.19
Cl7(170)	3.59	2.61	2.86	0.08	2.66	2.11	5.32	53.92	57.58	20.56
Cl7(171)	1.22	0.06	0.07	0.06	0.72	0.82	1.99	21.86	17.48	7.20
Cl7(172)	0.98	0.08	0.08	0.08	1.72	0.90	1.94	18.07	13.49	5.92
Cl7(174)	5.25	2.31	2.87	0.82	3.21	2.73	7.69	78.59	62.36	21.95
Cl7(176)	0.88	3.83	1.93	0.40	1.12	0.54	1.32	14.70	9.45	3.79
Cl7(177)	3.75	0.08	1.88	0.52	2.77	1.96	5.32	24.23	41.44	18.69
Cl7(178)	1.20	1.20	1.25	0.63	2.33	1.03	2.57	26.34	14.99	7.64
Cl7(179)	2.96	2.79	2.70	0.87	2.54	1.58	4.57	49.83	33.09	11.71
Cl7(180)	11.12	6.76	8.20	2.67	6.63	4.92	15.00	143.38	134.55	44.03
Cl7(183)	3.31	4.86	3.06	0.80	2.66	1.60	4.77	50.57	36.77	13.75
Cl7(184)	0.05	0.86	0.32	0.05	0.46	0.05	0.21	0.85	1.00	0.46
Cl7(185)	0.12	0.08	0.08	0.08	0.08	0.08	0.87	9.11	7.25	2.34
Cl7(187)	7.61	4.34	5.32	1.98	7.06	3.79	11.55	123.03	77.56	32.85
Cl7(189)	0.11	0.11	0.12	0.11	0.12	0.11	0.36	2.92	3.83	1.29
Cl7(190)	0.78	0.09	0.09	0.09	0.77	0.08	1.36	13.51	13.35	5.16
Cl7(193)	0.62	0.04	0.84	0.04	0.76	0.04	0.97	8.65	5.98	3.55
Cl8(194)	2.53	2.53	2.91	0.06	3.62	3.28	7.15	54.21	41.58	15.81
Cl8(195)	1.43	0.06	0.07	0.06	1.15	0.06	2.35	19.45	14.93	6.20
Cl8(199)	3.25	7.85	7.53	3.40	13.98	7.87	11.96	76.10	56.40	22.99
Cl8(200)	0.88	0.13	0.14	0.13	0.13	0.52	0.82	7.16	4.94	2.04
Cl8(201)	0.69	2.42	1.45	0.13	1.07	0.13	1.06	9.02	7.12	3.09
Cl8(202)	0.63	1.38	1.40	0.46	2.23	1.35	1.58	11.98	8.69	4.12
Cl8(196)/(203)	1.70	1.82	1.50	0.03	1.80	1.91	6.50	53.15	40.71	16.58
Cl8(205)	0.03	1.26	0.03	0.03	0.03	0.03	0.50	3.61	2.85	1.47
Cl9(206)	2.92	26.11	15.76	7.86	34.76	24.21	18.03	64.20	65.24	22.84
Cl9(207)	0.10	2.32	1.07	0.10	1.28	0.10	0.95	8.10	10.95	3.95
Cl9(208)	0.92	7.74	5.51	1.99	10.35	6.35	4.99	18.75	21.04	8.46
Cl10(209)	10.09	226.92	156.26	30.11	202.37	77.02	54.71	598.57	834.95	323.25
Sum 117 congeners	1,817	1,011	2,073	731	3,948	2,571	11,442	100,125	127,293	81,247

STATION_ID	T179C	T179C	T180A	T180A	T180A	T180A	T180A	T180A	T180A	T180B
FIELD SAMPLE_ID	T179-C-JIH	79C 18.5-19.5	T180A 0-1FT	T180A 1-2FT	T180A 2-3FT	T180A 3-4FT	T180A 4-4.8F	T180A 4.8-5.6F	T180A 5.6-6.6F	T180B 0-1FT
SAMPLE DEPTH (from bottom)	16-18.5	18.5-19.5	0-1	1-2	2-3	3-4	4-4.8	4.8-5.6	5.6-6.6	0-1
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	42.57	7.15	4.86	5.16	13.96	14.04	19.96	15.60	14.04	2.02
Cl1(1)	7.29	0.08	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.05
Cl1(3)	3.39	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02
Cl2(4)/(10)	72.11	0.89	0.10	0.11	3.14	2.95	4.54	9.06	7.29	0.61
Cl2(5)	2.71	0.13	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.08
Cl2(6)	123.01	2.50	0.07	0.08	0.07	0.08	0.08	0.08	0.07	0.06
Cl2(7)	5.02	0.07	0.05	0.05	0.05	0.06	0.05	0.06	0.05	0.04
Cl2(8)	169.16	2.62	0.09	0.09	0.09	0.10	0.09	0.10	0.09	0.07
Cl2(9)	8.58	0.09	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.05
Cl2(13)	28.56	1.17	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.05
Cl2(15)	60.75	2.32	0.12	0.12	0.12	0.13	0.12	0.13	0.12	0.09
Cl3(16)	322.35	11.03	0.09	0.09	0.09	0.10	0.09	0.10	0.09	0.07
Cl3(17)	302.20	12.14	0.05	0.05	0.05	0.06	0.05	2.23	0.05	1.06
Cl3(18)	1052.92	37.88	0.07	0.08	0.07	0.08	0.08	3.69	1.18	2.41
Cl3(19)	60.56	1.38	0.08	0.08	0.08	0.09	0.08	0.09	0.08	0.06
Cl3(22)	372.08	19.02	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.78
Cl3(24)	3.43	0.07	0.05	0.05	0.05	0.06	0.05	0.06	0.05	0.04
Cl3(25)	358.09	13.16	0.05	0.05	0.05	0.06	0.05	0.06	0.05	1.34
Cl3(26)	426.39	18.68	0.07	0.08	0.07	0.08	0.08	0.08	0.07	2.05
Cl3(27)	23.76	0.91	0.04	0.05	0.04	0.05	0.05	0.05	0.04	0.04
Cl3(28)	1038.78	51.85	0.09	0.09	0.09	0.10	0.09	3.94	2.35	3.37
Cl3(31)	1340.40	60.92	0.04	0.05	0.04	0.05	0.05	5.58	2.29	3.64
Cl3(32)	199.58	9.09	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.66
Cl3(33)/(20)	512.75	25.30	0.09	0.09	0.09	0.10	0.09	3.32	0.09	1.71
Cl3(37)	152.59	11.07	0.08	0.08	0.08	0.09	0.08	0.09	0.08	0.06
Cl4(40)	239.12	19.43	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.08
Cl4(41)	118.36	9.37	0.05	0.05	0.05	0.06	0.05	0.06	0.05	0.04
Cl4(42)/(59)	615.73	30.30	0.07	0.07	0.07	0.07	0.07	0.07	2.72	1.75
Cl4(43)	63.87	3.74	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.05
Cl4(44)	1550.02	84.71	0.07	0.08	0.07	0.08	0.08	16.70	8.39	4.51
Cl4(45)	258.73	16.20	0.05	0.05	0.05	0.06	0.05	0.06	0.05	0.81
Cl4(46)	113.94	6.99	0.09	0.09	0.09	0.10	0.09	0.10	0.09	0.07
Cl4(47)	338.22	24.88	0.07	0.07	0.07	0.07	0.07	3.27	2.01	1.23
Cl4(48)	281.65	18.04	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.05
Cl4(49)	1167.98	70.52	0.06	0.06	0.06	0.06	0.06	8.31	5.38	3.62
Cl4(51)	85.30	4.11	0.08	0.08	0.08	0.09	0.08	0.09	0.08	0.06
Cl4(52)	1665.16	106.66	0.04	0.05	0.04	0.05	0.05	9.79	6.05	4.74
Cl4(53)	284.80	14.86	0.04	0.05	0.04	0.05	0.05	0.05	0.04	0.72
Cl4(54)	4.92	0.07	0.05	0.05	0.05	0.06	0.05	0.06	0.05	0.04
Cl4(56)	494.01	37.78	0.09	0.09	0.09	0.10	0.09	2.89	0.09	1.73
Cl4(60)	188.36	17.78	0.08	0.08	0.08	0.09	0.08	2.17	1.38	0.06
Cl4(64)	663.63	45.21	0.03	0.03	0.03	0.03	0.03	2.26	2.14	2.38
Cl4(66)	979.12	67.68	0.07	0.07	0.07	0.07	0.07	8.53	4.86	2.93
Cl4(70)	1331.20	77.34	0.07	0.08	0.07	0.08	0.08	8.19	4.62	3.39
Cl4(71)	382.15	27.96	0.07	0.07	0.07	0.07	0.07	1.98	0.07	1.19
Cl4(74)	529.05	37.74	0.04	0.05	0.04	0.05	0.05	0.05	0.04	1.04
Cl4(77)	60.85	5.42	0.15	0.16	0.16	0.17	0.16	0.17	0.16	0.12
Cl4(81)	1.72	0.07	0.05	0.05	0.05	0.06	0.05	0.06	0.05	0.04
Cl5(82)	110.40	6.49	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.05
Cl5(83)/(119)	71.75	3.05	0.08	0.08	0.08	0.09	0.08	1.58	0.08	0.06
Cl5(84)	279.34	15.84	0.11	0.11	0.11	0.12	0.11	2.60	1.43	0.72
Cl5(85)	127.11	0.07	0.05	0.05	0.05	0.06	0.05	0.06	0.05	0.04
Cl5(87)	247.00	13.04	0.11	0.11	0.11	0.12	0.11	1.99	2.05	0.79
Cl5(91)	140.68	7.21	0.04	0.05	0.04	0.05	0.05	1.15	1.12	0.04
Cl5(92)	78.59	6.85	0.07	0.07	0.07	0.07	0.07	2.05	1.48	0.47
Cl5(95)	456.45	28.95	0.06	0.06	0.06	0.06	0.06	5.05	3.79	1.38
Cl5(97)	180.27	11.71	0.04	0.04	0.04	0.04	0.04	2.60	2.18	0.80
Cl5(99)	223.30	13.95	0.06	0.06	0.06	0.06	0.06	3.80	3.27	0.73
Cl5(100)	3.13	0.07	0.05	0.05	0.05	0.06	0.05	0.06	0.05	0.04

STATION_ID	T179C	T179C	T180A	T180A	T180A	T180A	T180A	T180A	T180A	T180B
FIELD SAMPLE_ID	T179-C-JIH	79C 18.5-19.5	T180A 0-1FT	T180A 1-2FT	T180A 2-3FT	T180A 3-4FT	T180A 4-4.8F	T180A 4.8-5.6F	T180A 5.6-6.6F	T180B 0-1FT
SAMPLE DEPTH (from bottom)	16-18.5	18.5-19.5	0-1	1-2	2-3	3-4	4-4.8	4.8-5.6	5.6-6.6	0-1
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	310.27	23.22	0.12	0.12	0.12	0.13	0.12	6.81	5.43	1.11
Cl5(105)	195.29	11.99	0.08	0.08	0.08	0.09	0.08	2.87	2.21	0.44
Cl5(110)	529.48	37.77	0.09	0.09	0.09	0.10	0.09	9.45	7.46	1.72
Cl5(114)	12.20	0.16	0.12	0.12	0.12	0.13	0.12	0.13	0.12	0.09
Cl5(115)	12.66	0.14	0.10	0.11	0.10	0.11	0.11	0.11	0.10	0.08
Cl5(118)	262.88	18.37	0.07	0.07	0.07	0.07	0.07	6.43	4.92	1.03
Cl5(107)/(123)	37.49	1.84	0.11	0.11	0.11	0.12	0.11	0.12	0.11	0.09
Cl5(124)	10.60	0.70	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.05
Cl5(126)	1.74	0.13	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.08
Cl6(128)	15.56	1.47	0.09	0.09	0.09	0.10	0.09	1.42	2.58	0.07
Cl6(130)	7.93	0.12	0.09	0.09	0.09	0.10	0.09	0.10	0.09	0.07
Cl6(134)	4.37	0.10	0.07	0.08	0.07	0.08	0.08	0.08	0.07	0.06
Cl6(135)	10.34	1.22	0.08	0.08	0.08	0.09	0.08	0.09	0.64	0.06
Cl6(136)	10.18	1.09	0.02	0.02	0.02	0.02	0.02	1.42	1.04	0.02
Cl6(137)	5.54	0.16	0.12	0.12	0.12	0.13	0.12	0.13	0.12	0.09
Cl6(138)	48.33	4.31	0.10	0.10	0.10	0.10	0.10	3.09	2.98	0.08
Cl6(141)	9.63	1.11	0.05	0.05	0.05	0.06	0.05	0.06	1.11	0.04
Cl6(144)	3.20	0.14	0.10	0.11	0.10	0.11	0.11	0.11	0.10	0.08
Cl6(146)	11.94	0.69	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Cl6(149)	63.08	4.36	0.08	0.08	0.08	0.09	0.08	3.28	3.47	0.36
Cl6(151)	12.38	1.40	0.09	0.09	0.09	0.10	0.09	0.10	0.86	0.07
Cl6(132)/(153)/(168)	61.58	6.37	0.07	0.08	0.07	0.08	0.08	4.21	4.69	0.40
Cl6(156)	8.36	0.79	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Cl6(157)	2.94	0.12	0.09	0.09	0.09	0.10	0.09	0.10	0.09	0.07
Cl6(129)/(158)	9.27	0.11	0.08	0.08	0.08	0.09	0.08	0.09	0.08	0.06
Cl6(163)	11.43	1.46	0.08	0.08	0.08	0.09	0.08	1.27	1.04	0.06
Cl6(164)	4.48	0.08	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.05
Cl6(166)	0.12	0.13	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.08
Cl6(167)	4.32	0.08	0.06	0.06	0.06	0.06	0.06	0.06	1.23	0.05
Cl6(169)	0.01	0.17	0.13	0.13	0.13	0.14	0.13	0.14	0.13	0.10
Cl7(170)	8.48	1.11	0.07	0.07	0.07	0.07	0.07	0.07	0.68	0.05
Cl7(171)	2.58	0.07	0.05	0.05	0.05	0.06	0.05	0.06	0.05	0.04
Cl7(172)	2.36	0.09	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.05
Cl7(174)	7.65	1.22	0.04	0.04	0.04	0.04	0.04	0.70	1.10	0.03
Cl7(176)	1.35	0.08	0.06	0.06	0.06	0.06	0.06	0.85	0.49	0.05
Cl7(177)	5.86	0.82	0.07	0.07	0.07	0.07	0.07	0.07	0.61	0.05
Cl7(178)	2.25	0.29	0.05	0.05	0.05	0.06	0.05	0.61	0.53	0.04
Cl7(179)	3.48	0.63	0.10	0.10	0.10	0.10	0.10	0.67	0.89	0.08
Cl7(180)	18.72	2.88	0.07	0.07	0.07	0.07	0.07	0.92	2.20	0.05
Cl7(183)	6.04	0.73	0.07	0.07	0.07	0.07	0.07	0.07	0.86	0.05
Cl7(184)	0.39	0.06	0.04	0.05	0.04	0.05	0.05	0.26	0.04	0.04
Cl7(185)	0.96	0.09	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.05
Cl7(187)	10.37	1.73	0.06	0.06	0.06	0.06	0.06	0.95	1.53	0.05
Cl7(189)	1.25	0.13	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.08
Cl7(190)	2.32	0.10	0.07	0.08	0.07	0.08	0.08	0.08	0.07	0.06
Cl7(193)	1.19	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03
Cl8(194)	6.19	0.07	0.05	0.05	0.05	0.06	0.05	0.06	0.81	0.04
Cl8(195)	2.36	0.07	0.05	0.05	0.05	0.06	0.05	0.06	0.05	0.04
Cl8(199)	6.88	0.13	0.10	0.10	0.10	0.10	0.10	3.11	2.03	0.08
Cl8(200)	0.76	0.15	0.11	0.11	0.11	0.12	0.11	0.12	0.11	0.09
Cl8(201)	1.13	0.15	0.11	0.11	0.11	0.12	0.11	0.12	0.35	0.09
Cl8(202)	1.07	0.10	0.07	0.08	0.07	0.08	0.08	1.35	0.79	0.06
Cl8(196)/(203)	6.38	0.77	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02
Cl8(205)	0.47	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Cl9(206)	6.59	0.78	0.10	0.10	0.10	0.10	1.03	10.89	6.80	0.18
Cl9(207)	0.99	0.12	0.09	0.09	0.09	0.10	0.09	0.10	0.20	0.07
Cl9(208)	1.80	0.24	0.08	0.08	0.08	0.09	0.08	3.44	2.20	0.06
Cl10(209)	26.75	2.86	0.05	0.05	0.46	1.15	3.37	50.79	31.85	0.60
Sum 117 congeners	21,797	1,252	8	8	12	13	17	233	164	63

STATION_ID	T180B	T180B	T180B	T180B	T180B	T180B	T180C	T180C	T180C	T180C
FIELD SAMPLE_ID	T180B 1-2FT	T180B 2-3FT	T180B 3-4FT	T180B 4-5FT	T180-B-UTS	T180-B-RQ	T180C 0-1FT	T180C 1-2FT	T180C 2-3FT	T180C 3-4FT
SAMPLE DEPTH (from bottom)	1-2	2-3	3-4	4-5	5-8.2	8.2-9.2	0-1	1-2	2-3	3-4
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	14.29	19.99	1191.36	23.47	28.82	2.11	69.60	166.22	124.37	83.80
Cl1(1)	0.06	0.08	0.08	0.07	0.08	0.06	0.06	0.07	0.07	0.06
Cl1(3)	0.03	0.04	0.04	0.04	0.04	0.03	0.03	0.04	0.04	0.03
Cl2(4)/(10)	2.40	5.27	12.79	11.06	13.09	0.10	6.94	9.92	18.34	14.53
Cl2(5)	0.10	0.12	0.13	0.12	0.72	0.09	0.10	0.12	0.12	0.10
Cl2(6)	2.07	10.75	43.82	43.31	19.88	0.71	1.78	7.28	14.52	38.78
Cl2(7)	0.05	0.07	0.07	0.06	1.38	0.05	0.05	0.06	0.06	0.05
Cl2(8)	2.26	14.58	34.71	28.60	29.14	1.03	3.79	9.62	19.87	24.96
Cl2(9)	0.07	0.08	0.09	0.08	2.63	0.06	0.07	0.08	0.08	0.07
Cl2(13)	1.08	3.72	13.91	14.98	7.45	0.06	0.07	0.08	5.66	14.42
Cl2(15)	0.99	6.96	20.92	16.72	17.84	0.55	0.12	0.15	4.69	6.27
Cl3(16)	6.42	30.79	61.74	66.96	50.79	2.05	13.35	38.37	68.80	81.52
Cl3(17)	9.33	42.80	90.80	86.20	61.72	2.32	16.79	53.18	108.55	104.37
Cl3(18)	24.15	93.33	237.50	260.65	164.97	6.20	42.88	145.47	263.46	293.94
Cl3(19)	1.14	4.55	10.57	9.58	9.92	0.32	1.93	6.02	10.91	13.74
Cl3(22)	9.65	45.59	81.50	90.95	69.51	2.78	16.96	45.86	84.19	89.48
Cl3(24)	0.05	0.07	0.07	0.06	1.23	0.05	0.05	0.06	0.06	0.05
Cl3(25)	10.84	47.37	123.90	153.74	65.29	2.28	10.01	33.51	66.07	143.81
Cl3(26)	13.14	60.10	161.90	188.88	83.48	3.01	10.89	33.39	65.23	141.79
Cl3(27)	1.11	3.29	8.54	7.29	6.90	0.26	0.04	0.05	7.48	9.35
Cl3(28)	29.94	118.13	293.38	325.89	211.32	7.63	54.80	165.58	293.25	322.50
Cl3(31)	35.39	144.30	359.23	404.23	252.57	8.91	58.44	172.65	327.81	381.23
Cl3(32)	4.24	23.69	51.90	53.59	34.61	1.48	8.66	28.48	52.18	55.29
Cl3(33)/(20)	14.76	64.39	121.30	136.65	95.50	4.01	27.02	69.28	122.46	139.14
Cl3(37)	3.92	22.71	51.13	54.08	29.03	1.55	9.18	25.32	42.89	43.27
Cl4(40)	6.45	36.89	67.38	78.24	52.19	1.86	13.63	43.76	66.62	79.73
Cl4(41)	0.05	11.96	17.18	23.22	18.16	0.87	4.10	0.06	8.89	20.80
Cl4(42)/(59)	17.53	71.66	163.80	185.73	122.59	4.52	31.08	99.05	166.51	187.05
Cl4(43)	0.06	8.98	19.95	24.37	14.49	0.48	3.56	11.02	20.20	24.91
Cl4(44)	43.45	184.62	410.39	495.49	290.51	10.93	81.28	243.04	412.96	434.32
Cl4(45)	8.26	35.14	69.31	72.17	46.23	2.04	13.65	40.88	74.84	83.13
Cl4(46)	2.69	15.96	33.30	38.04	25.19	0.88	5.47	18.85	36.94	43.74
Cl4(47)	12.68	61.87	115.61	130.86	72.51	2.72	23.14	78.27	121.14	117.73
Cl4(48)	6.69	30.20	47.80	56.36	39.90	1.92	15.77	32.13	58.55	54.30
Cl4(49)	37.62	153.21	383.42	438.30	253.99	8.61	64.56	210.73	367.03	398.81
Cl4(51)	1.80	9.31	20.47	21.87	15.64	0.53	3.10	10.37	20.42	25.41
Cl4(52)	48.16	203.37	478.78	580.87	325.47	12.66	89.03	266.82	469.17	538.07
Cl4(53)	6.75	31.81	62.06	71.50	42.57	1.79	12.12	38.55	65.59	73.88
Cl4(54)	0.05	0.07	0.07	0.06	1.46	0.14	0.05	0.06	0.06	0.05
Cl4(56)	16.28	70.73	143.56	175.43	101.37	4.18	33.14	99.51	169.58	167.80
Cl4(60)	2.93	20.15	29.21	40.83	30.33	1.56	4.85	7.03	11.27	21.39
Cl4(64)	20.04	88.23	194.45	225.28	137.85	5.47	35.19	109.60	189.39	208.14
Cl4(66)	33.17	134.71	287.38	322.94	214.28	7.94	71.89	211.40	353.34	288.60
Cl4(70)	42.06	180.14	369.33	439.12	269.91	10.36	88.95	265.37	447.83	419.91
Cl4(71)	11.27	58.17	108.20	131.04	81.63	3.17	21.45	58.56	108.35	126.50
Cl4(74)	12.81	69.51	108.08	131.55	84.29	4.08	33.63	77.00	141.12	136.79
Cl4(77)	2.84	12.56	25.87	28.24	16.61	0.57	5.71	16.17	27.54	25.56
Cl4(81)	0.05	0.07	0.07	0.06	0.07	0.05	0.05	0.06	0.06	0.05
Cl5(82)	3.18	14.26	27.81	34.19	19.82	1.04	5.58	11.90	26.11	35.71
Cl5(83)/(119)	3.33	11.56	28.31	32.91	19.82	0.80	6.37	20.45	33.08	31.82
Cl5(84)	9.61	44.12	97.63	89.82	57.06	2.15	15.44	60.13	98.31	90.65
Cl5(85)	3.73	18.74	38.01	47.96	26.90	1.16	7.05	14.26	28.52	39.44
Cl5(87)	4.25	22.72	43.78	60.94	35.90	2.45	10.39	19.63	42.77	51.65
Cl5(91)	4.17	19.26	42.89	47.26	30.27	1.06	7.51	22.01	38.83	46.03
Cl5(92)	3.68	15.98	34.99	38.21	24.67	1.23	8.21	22.06	34.26	33.40
Cl5(95)	15.49	70.76	112.19	146.32	91.01	6.36	28.40	85.05	128.35	129.36
Cl5(97)	5.99	26.00	57.22	57.72	35.68	2.02	12.99	29.95	57.07	53.48
Cl5(99)	7.27	31.25	64.61	58.41	38.11	2.01	18.73	40.73	72.08	65.92
Cl5(100)	0.05	0.63	1.26	1.56	0.97	0.05	0.05	0.78	1.72	1.35

STATION_ID	T180B	T180B	T180B	T180B	T180B	T180B	T180C	T180C	T180C	T180C
FIELD SAMPLE_ID	T180B 1-2FT	T180B 2-3FT	T180B 3-4FT	T180B 4-5FT	T180-B-UTS	T180-B-RQ	T180C 0-1FT	T180C 1-2FT	T180C 2-3FT	T180C 3-4FT
SAMPLE DEPTH (from bottom)	1-2	2-3	3-4	4-5	5-8.2	8.2-9.2	0-1	1-2	2-3	3-4
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	13.66	49.87	77.62	94.67	61.54	6.06	28.80	70.45	113.23	92.17
Cl5(105)	3.96	21.81	37.33	48.03	29.72	1.88	8.04	11.25	19.46	34.41
Cl5(110)	22.57	88.37	187.69	223.98	133.13	6.82	41.28	127.74	202.00	192.08
Cl5(114)	0.12	0.15	0.16	0.15	1.86	0.11	0.12	0.15	0.14	0.12
Cl5(115)	0.26	1.16	1.45	2.56	1.63	0.13	0.58	0.79	1.99	1.76
Cl5(118)	10.26	40.78	65.57	82.84	52.93	3.45	25.03	54.02	99.50	77.08
Cl5(107)/(123)	1.33	7.44	15.94	19.91	10.92	0.57	5.75	11.59	12.05	18.20
Cl5(124)	0.07	1.06	1.74	3.39	1.89	0.14	0.07	0.08	0.08	1.72
Cl5(126)	0.10	1.87	0.13	0.12	0.13	0.09	0.10	0.12	0.12	0.10
Cl6(128)	0.09	3.44	4.33	7.53	4.53	0.96	2.60	5.18	8.45	8.18
Cl6(130)	0.09	2.40	3.04	4.73	2.87	0.45	0.09	5.98	5.66	4.71
Cl6(134)	0.08	1.27	2.31	2.94	1.93	0.53	1.45	2.71	2.88	2.66
Cl6(135)	1.04	2.93	5.70	7.57	5.01	1.54	1.45	5.39	7.59	6.59
Cl6(136)	0.93	2.74	5.52	6.69	4.24	1.85	3.33	5.79	7.68	6.49
Cl6(137)	0.12	0.81	1.97	1.29	1.04	0.19	2.27	0.15	0.14	0.12
Cl6(138)	3.16	10.33	21.25	25.65	13.86	7.26	7.80	15.90	23.51	23.48
Cl6(141)	0.05	2.25	2.74	3.94	3.12	3.23	0.05	3.11	0.06	3.82
Cl6(144)	0.11	0.13	1.35	1.25	1.11	0.82	0.10	0.13	0.13	2.02
Cl6(146)	0.89	3.26	7.45	8.71	5.89	1.46	2.43	8.52	11.79	9.13
Cl6(149)	3.28	12.89	26.12	31.38	22.53	11.03	7.88	20.74	30.93	30.42
Cl6(151)	0.95	3.11	7.27	9.33	6.44	4.16	2.26	5.58	8.34	8.89
Cl6(132)/(153)/(168)	4.22	15.88	30.65	38.18	24.31	14.37	10.76	27.09	38.27	35.83
Cl6(156)	0.02	1.28	2.36	2.46	1.86	0.79	2.11	1.84	2.14	1.25
Cl6(157)	0.09	0.11	0.12	0.11	0.55	0.08	5.09	0.11	0.11	0.09
Cl6(129)/(158)	0.84	1.16	2.69	3.15	2.42	1.04	0.08	0.10	0.10	3.60
Cl6(163)	0.97	2.63	6.71	7.21	5.52	2.44	2.39	5.35	9.01	7.26
Cl6(164)	0.06	0.08	1.90	2.58	1.74	0.79	0.06	0.07	2.77	2.26
Cl6(166)	0.10	0.12	0.13	0.12	0.13	0.09	0.10	0.12	0.12	0.10
Cl6(167)	0.06	1.41	1.29	1.96	0.96	0.30	2.76	1.80	0.07	1.25
Cl6(169)	0.13	0.16	0.17	0.16	0.16	0.02	0.13	0.16	0.15	0.13
Cl7(170)	0.07	2.47	4.16	5.77	4.11	4.50	1.69	2.82	5.67	4.91
Cl7(171)	0.05	0.83	1.17	2.05	1.34	1.39	1.17	0.72	1.41	1.76
Cl7(172)	0.07	0.97	1.47	1.62	1.11	0.96	2.02	1.81	2.05	2.13
Cl7(174)	0.63	2.52	4.94	5.65	5.27	5.99	1.82	3.15	5.97	6.55
Cl7(176)	0.39	0.65	0.87	1.05	0.91	0.80	2.33	1.69	2.01	1.49
Cl7(177)	0.66	2.06	4.19	4.71	4.06	3.48	1.44	3.18	3.82	5.27
Cl7(178)	0.43	1.22	2.04	2.31	1.74	1.07	0.57	4.15	3.24	2.71
Cl7(179)	0.56	1.41	2.84	3.29	2.81	2.51	2.38	3.12	4.10	4.72
Cl7(180)	1.63	5.62	9.41	13.04	10.35	12.73	4.99	7.34	10.12	13.34
Cl7(183)	0.58	2.00	2.87	3.74	3.15	3.54	4.18	3.52	5.67	4.59
Cl7(184)	0.05	0.19	0.06	0.27	0.05	0.04	0.41	0.81	0.77	0.24
Cl7(185)	0.07	0.28	0.38	0.77	0.61	0.77	0.07	0.08	0.85	0.72
Cl7(187)	1.38	3.98	7.37	9.36	7.78	6.56	3.72	8.33	11.05	11.51
Cl7(189)	0.10	0.12	0.13	0.12	0.13	0.20	0.10	0.12	0.12	0.10
Cl7(190)	0.08	0.80	1.36	1.52	1.05	1.17	0.07	0.09	1.06	1.22
Cl7(193)	0.04	0.05	1.07	1.20	0.59	0.55	0.67	0.64	1.13	1.28
Cl8(194)	0.96	1.55	4.16	4.60	3.67	2.57	2.05	4.06	5.95	6.76
Cl8(195)	0.05	0.07	1.09	2.53	1.28	1.15	1.38	0.90	2.34	2.19
Cl8(199)	2.40	3.74	5.06	6.12	4.41	2.77	5.22	19.33	21.18	17.34
Cl8(200)	0.12	0.14	0.15	0.67	0.49	0.47	0.11	0.14	0.95	0.69
Cl8(201)	0.12	0.42	0.73	1.11	0.62	0.43	1.85	1.34	1.47	1.43
Cl8(202)	0.30	0.55	0.89	1.39	0.76	0.46	1.46	3.33	2.99	2.08
Cl8(196)/(203)	0.72	1.82	2.85	4.34	3.61	2.85	1.17	2.56	3.36	3.31
Cl8(205)	0.02	0.03	0.03	0.03	0.03	0.18	1.30	0.69	0.03	0.02
Cl9(206)	4.75	7.85	5.35	7.52	4.66	0.63	21.45	41.60	47.38	41.97
Cl9(207)	0.09	0.56	0.57	0.94	0.63	0.10	2.14	1.85	2.07	1.16
Cl9(208)	1.39	2.22	1.65	2.45	1.38	0.12	6.00	14.16	15.67	11.12
Cl10(209)	26.87	48.67	51.50	82.11	37.29	0.73	177.64	353.20	322.45	151.10
Sum 117 congeners	682	2,881	6,125	7,094	4,374	285	1,474	3,987	6,569	6,852

STATION_ID	T180C	T180C	T180C	T180C	T180C	T180C	T180D	T180D	T180D	T180D
FIELD SAMPLE_ID	T180C 4-5FT	T180-C-UTS	T180-C-RQP	T180-C-ONM	T180-C-KJI	80C 16.6-17.6	T180D 0-1FT	T180D 1-2FT	T180D 2-3FT	T180D 3-4FT
SAMPLE DEPTH (from bottom)	4-5	5-8	8-11	11-14	14-16.6	16.6-17.6	0-1	1-2	2-3	3-4
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	279.07	188.25	66.23	70.52	20.66	5.25	1.03	8.44	37.04	122.53
Cl1(1)	0.08	0.13	36.65	67.93	2.44	0.07	0.05	0.06	0.06	0.07
Cl1(3)	0.04	0.07	19.92	8.27	1.02	0.03	0.02	0.03	0.03	0.04
Cl2(4)/(10)	19.93	0.23	208.62	250.93	11.12	0.46	0.08	1.06	9.65	12.49
Cl2(5)	0.12	0.22	11.60	7.04	0.53	0.11	0.08	0.09	0.10	0.12
Cl2(6)	102.43	468.71	301.80	112.56	11.83	1.34	0.06	0.07	1.88	17.95
Cl2(7)	0.07	0.12	20.59	10.48	0.81	0.06	0.04	0.05	0.05	0.06
Cl2(8)	59.30	323.82	465.65	302.85	22.08	1.37	0.07	0.08	2.69	21.17
Cl2(9)	0.09	0.15	34.11	17.38	1.34	0.08	0.05	0.06	0.07	0.08
Cl2(13)	43.49	143.63	68.32	19.47	4.65	0.51	0.05	0.06	0.07	6.54
Cl2(15)	16.69	79.38	193.55	51.72	11.65	1.08	0.09	0.11	0.12	5.01
Cl3(16)	211.04	867.85	1095.35	488.51	46.28	4.52	0.74	0.08	8.70	74.28
Cl3(17)	278.95	1120.70	1114.84	419.34	43.71	4.71	0.82	0.05	15.06	101.96
Cl3(18)	885.10	3494.08	3524.93	1454.13	132.40	15.15	2.03	0.07	36.43	272.33
Cl3(19)	33.61	173.36	184.10	92.08	7.08	1.05	0.06	0.08	0.08	11.94
Cl3(22)	262.09	1256.47	1242.37	350.91	63.15	7.11	0.89	0.06	12.48	88.54
Cl3(24)	0.07	0.12	13.92	4.50	0.50	0.06	0.39	0.05	0.05	0.06
Cl3(25)	430.19	1746.14	769.64	223.25	46.21	5.75	0.97	0.05	10.85	74.03
Cl3(26)	432.70	1776.42	1044.70	319.32	71.09	8.18	0.96	0.07	9.27	69.12
Cl3(27)	23.33	123.35	110.67	31.40	4.95	0.75	0.04	0.04	1.28	8.10
Cl3(28)	941.67	3915.89	3871.21	975.62	187.62	21.87	2.17	0.08	38.42	324.10
Cl3(31)	1158.86	4823.71	4797.96	1191.13	220.63	24.55	3.00	0.04	42.52	354.29
Cl3(32)	154.13	658.18	640.07	246.43	33.84	3.56	0.30	0.03	7.80	61.04
Cl3(33)/(20)	403.85	1643.97	1999.55	499.19	77.16	8.83	1.05	0.08	19.16	137.22
Cl3(37)	89.75	429.77	660.86	119.15	32.31	4.35	0.06	0.08	5.86	47.57
Cl4(40)	237.32	874.40	1000.82	233.82	44.60	6.65	0.08	0.09	7.21	73.59
Cl4(41)	58.42	330.52	477.93	122.58	20.73	2.44	0.04	0.05	0.05	5.91
Cl4(42)/(59)	524.74	2089.55	2311.25	486.66	100.59	13.11	1.10	0.06	23.01	173.02
Cl4(43)	66.05	264.96	301.89	64.34	10.58	0.99	0.05	0.06	0.06	23.69
Cl4(44)	1335.09	5198.71	6030.46	1276.21	249.17	34.39	3.36	0.07	57.95	437.53
Cl4(45)	262.70	931.58	1013.15	269.48	42.55	5.49	0.84	0.05	9.86	81.05
Cl4(46)	105.24	435.31	469.05	114.77	18.87	2.15	0.07	0.08	4.53	38.65
Cl4(47)	352.18	1280.89	1367.01	279.11	59.79	8.60	0.80	0.06	17.82	136.80
Cl4(48)	198.53	837.61	1355.75	257.86	39.23	5.27	0.55	0.06	7.05	61.04
Cl4(49)	1078.73	4315.29	4460.70	949.58	208.90	27.89	2.89	0.06	45.87	382.23
Cl4(51)	59.96	238.80	290.74	67.99	11.52	1.50	0.06	0.08	2.86	23.85
Cl4(52)	1584.87	6030.92	6423.99	1440.38	269.84	36.95	3.90	0.04	55.65	497.24
Cl4(53)	218.93	895.60	1032.93	264.99	37.49	4.87	0.56	0.04	9.44	71.63
Cl4(54)	0.07	13.26	16.89	8.13	0.90	0.06	0.04	0.05	0.05	0.06
Cl4(56)	528.29	1814.08	2134.03	372.07	92.22	14.37	1.50	0.08	21.67	193.38
Cl4(60)	100.24	329.67	792.13	121.88	39.79	5.10	0.42	0.08	0.08	10.95
Cl4(64)	625.80	2369.74	2818.11	579.15	120.11	17.18	1.69	0.03	22.86	208.64
Cl4(66)	818.12	3238.12	4710.81	758.29	203.12	27.81	2.29	0.06	44.68	374.98
Cl4(70)	1272.08	4585.24	5966.05	1003.13	244.55	33.01	3.29	0.07	54.44	476.59
Cl4(71)	376.39	1453.72	1605.80	306.06	68.31	9.33	0.98	0.06	13.67	113.17
Cl4(74)	432.59	1646.19	2484.27	379.23	95.97	13.30	1.15	0.04	17.73	145.44
Cl4(77)	58.69	235.68	315.93	45.40	16.05	2.27	0.12	0.15	4.43	29.99
Cl4(81)	0.07	3.49	9.61	0.91	0.06	0.06	0.04	0.05	0.05	0.06
Cl5(82)	102.40	368.55	400.48	85.62	19.59	2.85	0.53	0.06	3.49	26.63
Cl5(83)/(119)	55.88	294.54	300.94	66.87	15.03	1.79	0.06	0.08	4.15	34.81
Cl5(84)	242.15	987.29	1194.54	177.85	46.33	7.14	0.65	0.10	11.24	95.91
Cl5(85)	122.31	441.76	519.61	96.47	24.42	4.59	0.04	0.05	3.19	26.13
Cl5(87)	164.49	716.20	997.49	150.22	37.58	5.59	0.42	0.10	5.38	42.71
Cl5(91)	110.74	466.82	609.14	99.28	23.22	3.12	0.04	0.04	4.84	42.15
Cl5(92)	74.46	314.81	377.10	74.74	16.98	2.01	0.24	0.06	5.01	35.49
Cl5(95)	385.23	1627.76	1935.57	319.23	72.31	13.00	1.10	0.06	19.58	139.13
Cl5(97)	154.30	647.12	895.61	136.41	35.73	5.46	0.65	0.03	7.63	62.53
Cl5(99)	179.93	666.44	1008.05	141.23	39.19	5.70	0.67	0.06	9.31	69.34
Cl5(100)	3.23	12.96	15.67	2.61	0.64	0.06	0.04	0.05	0.05	1.77

STATION_ID	T180C	T180C	T180C	T180C	T180C	T180C	T180D	T180D	T180D	T180D
FIELD SAMPLE_ID	T180C 4-5FT	T180-C-UTS	T180-C-RQP	T180-C-ONM	T180-C-KJI	80C 16.6-17.6	T180D 0-1FT	T180D 1-2FT	T180D 2-3FT	T180D 3-4FT
SAMPLE DEPTH (from bottom)	4-5	5-8	8-11	11-14	14-16.6	16.6-17.6	0-1	1-2	2-3	3-4
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	258.91	1068.04	1475.03	251.61	54.05	12.40	0.94	0.11	18.42	110.76
Cl5(105)	118.40	436.23	744.76	117.86	34.32	4.82	0.61	0.08	3.00	19.89
Cl5(110)	544.90	1972.79	2259.19	380.48	97.29	18.20	1.60	0.08	27.36	216.45
Cl5(114)	3.27	8.73	51.88	6.89	2.24	0.14	0.09	0.11	0.12	0.15
Cl5(115)	7.62	21.98	55.39	7.51	2.41	0.12	0.08	0.10	0.81	1.53
Cl5(118)	215.87	879.30	1171.33	199.09	48.14	8.62	0.82	0.06	14.00	101.61
Cl5(107)/(123)	29.53	144.98	134.69	48.01	9.19	1.61	0.65	0.10	1.44	21.26
Cl5(124)	7.32	27.62	62.48	7.47	2.10	0.50	0.05	0.06	0.07	0.08
Cl5(126)	2.58	5.10	7.05	1.92	0.11	0.11	0.08	0.09	0.10	0.12
Cl6(128)	16.67	64.77	121.14	15.21	4.00	0.64	0.07	0.08	2.26	8.48
Cl6(130)	11.57	39.11	38.08	7.78	2.15	0.36	0.07	0.08	2.14	6.60
Cl6(134)	5.62	27.11	30.77	4.75	1.43	0.09	0.06	0.07	0.70	3.13
Cl6(135)	14.98	59.98	54.32	9.11	3.30	1.32	0.06	0.08	1.17	7.83
Cl6(136)	14.68	57.77	59.21	8.69	2.81	1.29	0.02	0.02	1.93	7.88
Cl6(137)	3.65	14.50	29.70	5.90	1.07	0.14	0.09	0.11	0.92	2.24
Cl6(138)	52.14	232.87	224.44	40.89	11.65	4.36	0.22	0.09	4.88	25.74
Cl6(141)	11.96	33.04	58.60	8.50	2.78	1.48	0.04	0.05	0.05	1.89
Cl6(144)	4.80	16.24	19.68	2.76	0.86	0.48	0.08	0.10	0.11	1.48
Cl6(146)	19.72	75.52	58.18	11.95	3.49	0.88	0.02	0.02	1.63	13.34
Cl6(149)	56.35	316.49	252.44	71.39	15.38	5.69	0.28	0.08	5.64	32.89
Cl6(151)	22.98	87.94	70.15	10.86	4.25	2.05	0.07	0.08	1.28	9.15
Cl6(132)/(153)/(168)	86.75	331.04	343.72	62.62	17.86	7.69	0.45	0.07	7.81	43.20
Cl6(156)	5.31	15.93	38.37	10.78	2.01	0.54	0.02	0.02	0.02	0.03
Cl6(157)	3.40	6.47	12.06	4.85	0.60	0.10	0.07	0.08	0.09	0.11
Cl6(129)/(158)	9.80	26.79	39.72	12.14	2.07	0.55	0.06	0.08	1.47	0.10
Cl6(163)	17.99	55.71	55.86	8.68	3.52	0.85	0.06	0.08	1.82	9.87
Cl6(164)	6.46	21.93	27.36	4.32	1.32	0.35	0.05	0.06	0.06	2.74
Cl6(166)	0.12	0.22	2.34	0.36	0.11	0.11	0.08	0.09	0.10	0.12
Cl6(167)	5.16	11.79	16.43	6.58	0.86	0.07	0.05	0.06	0.06	0.07
Cl6(169)	0.16	0.38	1.07	0.10	0.08	0.15	0.10	0.12	0.13	0.16
Cl7(170)	13.87	44.24	45.53	8.28	3.17	1.84	0.05	0.06	0.07	4.39
Cl7(171)	5.01	15.72	12.75	2.66	0.97	0.35	0.04	0.05	0.05	1.16
Cl7(172)	5.85	14.29	11.22	2.57	0.81	0.41	0.05	0.06	0.07	2.21
Cl7(174)	21.29	62.98	46.54	6.92	3.52	2.07	0.03	0.03	0.86	5.78
Cl7(176)	3.90	10.87	6.81	1.13	0.57	0.42	0.05	0.06	0.96	1.92
Cl7(177)	13.44	44.32	30.39	5.45	2.78	1.32	0.05	0.06	0.86	4.84
Cl7(178)	6.64	17.50	10.11	2.03	1.26	0.42	0.04	0.05	0.43	3.85
Cl7(179)	12.63	35.12	21.57	3.43	1.78	1.00	0.08	0.09	1.08	4.44
Cl7(180)	44.81	174.99	114.76	17.70	8.11	4.93	0.17	0.06	2.48	10.84
Cl7(183)	14.74	38.13	27.28	5.97	2.21	1.25	0.05	0.06	1.16	5.28
Cl7(184)	0.51	0.56	0.88	0.33	0.05	0.05	0.04	0.04	0.18	0.85
Cl7(185)	3.11	7.34	5.69	0.78	0.46	0.32	0.05	0.06	0.07	0.71
Cl7(187)	32.04	89.49	52.55	9.15	5.05	2.48	0.17	0.06	1.91	11.73
Cl7(189)	0.12	2.75	3.42	2.63	0.11	0.11	0.08	0.09	0.10	0.12
Cl7(190)	4.39	10.56	11.11	2.44	0.91	0.46	0.06	0.07	0.08	1.10
Cl7(193)	3.20	8.39	4.73	1.17	0.53	0.24	0.03	0.03	0.04	1.20
Cl8(194)	20.22	48.80	33.81	5.83	3.13	1.47	0.04	0.05	0.05	6.68
Cl8(195)	7.13	17.11	11.56	2.08	1.14	1.01	0.04	0.05	0.05	1.78
Cl8(199)	32.53	59.55	40.47	6.02	3.07	1.23	0.08	0.09	3.54	22.16
Cl8(200)	2.12	5.65	4.23	0.65	0.37	0.13	0.09	0.10	0.11	0.84
Cl8(201)	3.23	7.43	6.02	0.97	0.39	0.33	0.09	0.10	0.11	1.26
Cl8(202)	4.64	9.59	6.78	0.99	0.47	0.09	0.06	0.07	0.71	3.31
Cl8(196)/(203)	8.98	43.89	31.67	5.89	2.82	1.12	0.02	0.03	1.32	3.34
Cl8(205)	1.50	3.16	2.71	0.77	0.31	0.03	0.02	0.02	0.02	0.03
Cl9(206)	53.18	61.68	51.80	7.43	3.21	0.61	0.08	0.33	10.51	48.51
Cl9(207)	3.50	7.95	10.18	1.33	0.32	0.21	0.07	0.08	0.38	1.92
Cl9(208)	14.53	18.36	17.64	2.00	0.74	0.20	0.06	0.08	2.74	16.11
Cl10(209)	280.56	786.23	759.57	92.13	14.52	1.43	0.63	0.50	39.69	292.53
Sum 117 congeners	19,614	76,711	86,972	19,544	3,755	541	54	9	887	6,932

STATION_ID	T180D	T180D	T180D	T180D	T180D	T180D	T180D	T181A	T181A	T181A
FIELD SAMPLE_ID	T180D 4-5FT	T180-D-UTS	T180-D-RQP	T180-D-ONM	T180-D-LKJ	T180-D-IHG	80D 20.3-21.3	T181A 0.5-1F	T181A 1-2FT	T181A 2-3.2F
SAMPLE DEPTH (from bottom)	4-5	5-8	8-11	11-14	14-17	17-20.3	20.3-21.3	0.5-1	1-2	2-3.3
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	90.23	122.56	127.87	56.99	58.59	39.04	14.26	7.37	9.75	13.26
Cl1(1)	0.08	0.08	25.26	32.15	18.06	5.48	0.07	0.06	0.06	0.06
Cl1(3)	0.04	0.04	15.07	17.63	8.63	2.42	0.04	0.03	0.03	0.03
Cl2(4)/(10)	0.13	0.13	88.26	106.09	112.70	16.92	1.89	0.10	0.11	0.11
Cl2(5)	0.12	0.12	4.63	9.93	10.47	0.79	0.12	0.10	0.10	0.10
Cl2(6)	16.08	128.97	418.31	331.84	194.92	25.73	2.98	0.07	0.08	0.08
Cl2(7)	0.07	0.07	10.79	17.82	19.11	1.62	0.07	0.05	0.05	0.05
Cl2(8)	20.90	83.92	293.43	440.93	270.30	46.25	4.67	0.09	0.09	0.52
Cl2(9)	0.08	0.08	19.99	29.27	33.35	2.47	0.08	0.07	0.07	0.07
Cl2(13)	0.08	62.88	142.94	89.66	63.51	8.50	1.45	0.07	0.07	0.07
Cl2(15)	0.15	26.24	111.25	199.79	127.32	15.58	2.81	0.12	0.12	0.13
Cl3(16)	60.99	305.14	952.88	982.86	346.11	72.93	23.03	0.09	0.09	1.41
Cl3(17)	82.04	345.29	1206.22	1102.44	396.21	79.40	22.26	0.05	0.05	2.07
Cl3(18)	218.43	1131.51	5402.12	3778.24	1268.66	242.31	99.07	0.07	0.08	4.89
Cl3(19)	13.46	48.58	165.87	212.39	62.77	10.28	3.25	0.08	0.08	0.09
Cl3(22)	69.64	372.68	1351.09	1222.72	399.06	93.21	33.22	0.07	0.07	2.96
Cl3(24)	0.07	0.07	12.22	10.94	11.34	1.03	0.07	0.05	0.05	0.05
Cl3(25)	46.42	557.93	1778.79	1329.34	604.23	97.91	16.14	0.05	0.05	2.81
Cl3(26)	50.32	544.47	2028.61	1498.41	730.28	134.22	23.42	0.07	0.08	3.05
Cl3(27)	7.61	31.26	96.84	70.54	52.63	7.12	2.45	0.04	0.05	0.05
Cl3(28)	275.03	1224.87	6386.14	3867.74	1383.76	283.84	125.61	0.09	0.09	7.52
Cl3(31)	299.43	1536.78	8007.25	5095.89	1713.47	345.54	177.62	0.04	0.05	8.32
Cl3(32)	42.33	208.59	732.63	667.11	237.71	51.16	17.69	0.04	0.04	1.28
Cl3(33)/(20)	108.98	520.15	2138.99	1845.68	616.63	139.58	47.29	0.09	0.09	4.31
Cl3(37)	42.36	116.94	674.37	578.25	198.92	37.93	18.55	0.08	0.08	1.23
Cl4(40)	51.54	280.17	1142.22	1009.01	263.05	56.96	35.96	0.10	0.10	0.10
Cl4(41)	10.35	95.13	451.25	464.38	83.47	22.48	20.11	0.05	0.05	0.05
Cl4(42)/(59)	123.68	662.23	2631.20	2380.35	635.01	131.40	20.24	0.07	0.07	4.11
Cl4(43)	21.88	92.34	286.57	277.70	79.64	15.24	0.07	0.06	0.06	0.06
Cl4(44)	357.67	1755.76	9078.42	6285.20	1740.45	333.58	270.20	0.07	0.08	10.66
Cl4(45)	51.17	301.50	1051.33	1052.80	277.77	51.81	32.00	0.05	0.05	2.07
Cl4(46)	34.71	136.18	457.43	464.22	119.17	25.61	14.08	0.09	0.09	0.09
Cl4(47)	104.52	400.99	1575.00	1412.22	409.91	88.32	43.02	0.07	0.07	3.19
Cl4(48)	51.52	296.76	1092.85	1091.59	203.53	47.87	39.95	0.07	0.07	0.07
Cl4(49)	327.48	1357.09	7029.66	4868.38	1503.20	286.65	197.47	0.06	0.06	8.74
Cl4(51)	22.60	94.64	277.58	299.88	80.40	15.47	8.45	0.08	0.08	0.58
Cl4(52)	426.69	2119.30	10100.39	6964.98	1921.58	366.37	284.66	0.04	0.05	13.48
Cl4(53)	53.20	290.77	1085.26	994.38	250.57	49.70	29.12	0.04	0.05	1.45
Cl4(54)	0.07	4.46	22.87	14.79	6.11	3.04	0.53	0.05	0.05	0.05
Cl4(56)	143.52	574.76	2644.56	2021.26	533.35	107.88	114.26	0.09	0.09	4.48
Cl4(60)	11.87	119.69	783.55	711.11	125.48	40.35	34.84	0.08	0.08	1.45
Cl4(64)	166.13	802.73	4131.67	2924.44	739.35	154.13	122.28	0.03	0.03	5.53
Cl4(66)	337.54	1025.70	5633.95	3997.26	884.16	228.81	220.75	0.07	0.07	9.29
Cl4(70)	407.52	1544.69	7812.03	5704.43	1288.37	288.20	286.65	0.07	0.08	11.97
Cl4(71)	102.40	472.92	1875.17	1531.00	420.87	92.52	50.39	0.07	0.07	2.71
Cl4(74)	122.03	556.67	2631.83	2048.14	473.15	99.33	102.32	0.04	0.05	4.04
Cl4(77)	29.12	73.92	468.14	228.02	88.62	16.90	11.03	0.16	0.16	1.10
Cl4(81)	0.07	1.00	7.75	7.03	1.40	0.33	0.07	0.05	0.05	0.05
Cl5(82)	26.86	121.24	654.97	408.12	106.37	22.24	16.05	0.06	0.06	0.06
Cl5(83)/(119)	32.11	89.14	406.22	320.18	95.77	20.89	8.54	0.08	0.08	0.09
Cl5(84)	96.19	303.77	1284.64	1111.31	284.00	63.66	32.54	0.11	0.12	2.16
Cl5(85)	29.82	117.48	841.34	569.78	151.76	29.94	19.35	0.05	0.05	0.05
Cl5(87)	44.92	239.23	1211.55	933.65	186.66	41.44	30.57	0.11	0.12	1.78
Cl5(91)	40.23	152.54	599.88	585.44	134.08	30.45	16.39	0.04	0.05	1.03
Cl5(92)	34.71	112.58	422.44	362.26	104.53	23.68	3.84	0.07	0.07	1.01
Cl5(95)	105.20	509.05	2242.13	2008.70	481.73	98.30	52.51	0.06	0.06	3.48
Cl5(97)	50.33	208.49	1066.99	804.61	195.32	40.35	26.12	0.04	0.04	1.59
Cl5(99)	58.81	205.46	1138.23	862.77	192.29	43.98	31.23	0.06	0.06	1.89
Cl5(100)	0.07	4.55	21.18	15.44	5.26	0.95	0.07	0.05	0.05	0.05

STATION_ID	T180D	T180D	T180D	T180D	T180D	T180D	T180D	T181A	T181A	T181A
FIELD SAMPLE_ID	T180D 4-5FT	T180-D-UTS	T180-D-RQP	T180-D-ONM	T180-D-LKJ	T180-D-IHG	80D 20.3-21.3	T181A 0.5-1F	T181A 1-2FT	T181A 2-3.2F
SAMPLE DEPTH (from bottom)	4-5	5-8	8-11	11-14	14-17	17-20.3	20.3-21.3	0.5-1	1-2	2-3.3
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	127.31	377.81	1668.40	1329.43	275.79	60.58	46.65	0.12	0.12	3.13
Cl5(105)	23.95	141.61	1031.06	711.79	159.81	35.65	27.27	0.08	0.08	1.42
Cl5(110)	179.67	659.38	3457.15	2371.32	685.71	133.23	117.08	0.09	0.09	5.82
Cl5(114)	0.15	3.79	33.41	38.08	7.68	2.10	1.57	0.12	0.12	0.13
Cl5(115)	0.13	10.27	46.17	45.24	9.73	2.03	0.13	0.10	0.11	0.11
Cl5(118)	99.16	284.68	1642.78	1092.50	252.00	53.40	40.83	0.07	0.07	2.93
Cl5(107)/(123)	16.24	69.03	265.56	209.64	53.11	11.29	5.80	0.11	0.12	0.44
Cl5(124)	0.08	9.21	55.71	48.15	8.86	1.75	0.08	0.07	0.07	0.07
Cl5(126)	0.12	2.27	7.33	5.53	1.43	1.56	0.12	0.10	0.10	0.10
Cl6(128)	8.40	19.97	155.90	70.03	18.58	4.67	2.44	0.09	0.09	0.09
Cl6(130)	5.68	12.76	71.57	37.63	10.92	2.59	0.91	0.09	0.09	0.09
Cl6(134)	2.92	8.34	49.24	27.58	8.79	1.78	1.20	0.07	0.08	0.08
Cl6(135)	6.58	19.02	131.57	49.91	17.71	4.45	1.95	0.08	0.08	0.25
Cl6(136)	7.15	18.30	101.27	51.37	16.37	3.49	2.07	0.02	0.02	0.23
Cl6(137)	0.15	4.66	29.21	22.65	4.72	1.32	0.78	0.12	0.12	0.13
Cl6(138)	23.81	51.50	482.37	179.15	46.77	12.56	8.44	0.10	0.10	0.82
Cl6(141)	0.07	11.68	77.07	42.73	8.16	2.40	1.86	0.05	0.05	0.05
Cl6(144)	0.13	5.09	32.15	14.96	3.24	0.83	0.38	0.10	0.11	0.11
Cl6(146)	12.57	24.40	165.63	52.34	18.49	4.36	1.52	0.02	0.02	0.02
Cl6(149)	30.96	82.01	540.55	238.12	66.99	18.08	9.88	0.08	0.08	0.92
Cl6(151)	8.50	26.31	154.58	58.52	19.34	4.83	2.12	0.09	0.09	0.33
Cl6(132)/(153)/(168)	40.75	99.24	623.02	291.32	65.92	19.52	13.23	0.07	0.08	1.21
Cl6(156)	0.03	5.05	39.97	30.55	6.27	2.82	1.49	0.02	0.02	0.02
Cl6(157)	0.11	2.26	12.64	9.30	2.02	1.24	0.11	0.09	0.09	0.09
Cl6(129)/(158)	2.61	9.65	55.99	33.88	7.88	3.22	1.30	0.08	0.08	0.09
Cl6(163)	8.41	19.79	151.26	51.06	16.45	4.10	2.28	0.08	0.08	0.30
Cl6(164)	1.77	7.20	43.42	21.47	6.16	1.58	0.79	0.06	0.06	0.06
Cl6(166)	0.12	0.12	2.54	1.85	0.12	0.12	0.12	0.10	0.10	0.10
Cl6(167)	0.08	3.88	21.53	12.48	3.19	1.44	0.07	0.06	0.06	0.06
Cl6(169)	0.16	0.10	2.14	0.03	0.15	0.06	0.16	0.13	0.13	0.13
Cl7(170)	5.85	14.82	183.06	36.05	8.51	3.02	2.23	0.07	0.07	0.07
Cl7(171)	1.91	4.98	35.97	10.93	2.98	0.97	0.51	0.05	0.05	0.05
Cl7(172)	2.86	4.92	27.75	9.01	2.51	1.04	0.08	0.07	0.07	0.07
Cl7(174)	6.36	21.25	196.79	34.27	9.29	3.00	2.53	0.04	0.04	0.23
Cl7(176)	1.37	3.70	25.50	5.32	1.73	0.62	0.42	0.06	0.06	0.06
Cl7(177)	4.61	14.51	117.30	26.52	8.30	2.78	1.48	0.07	0.07	0.07
Cl7(178)	3.05	6.52	40.69	9.18	3.74	1.19	0.55	0.05	0.05	0.05
Cl7(179)	3.94	12.28	83.90	15.64	5.60	1.76	1.09	0.10	0.10	0.19
Cl7(180)	11.79	38.74	320.80	72.32	18.09	7.20	5.44	0.07	0.07	0.40
Cl7(183)	4.26	13.54	83.58	20.43	5.56	2.30	1.42	0.07	0.07	0.14
Cl7(184)	0.28	0.43	0.88	0.46	0.20	0.12	0.06	0.04	0.05	0.05
Cl7(185)	0.08	2.68	16.77	3.99	0.90	0.44	0.30	0.07	0.07	0.07
Cl7(187)	10.45	30.44	211.85	42.44	14.70	4.90	2.69	0.06	0.06	0.32
Cl7(189)	0.12	0.88	4.89	2.69	0.64	1.00	0.12	0.10	0.10	0.10
Cl7(190)	2.01	3.59	23.11	9.23	2.18	0.94	0.37	0.07	0.08	0.08
Cl7(193)	1.04	2.66	17.45	4.83	1.33	0.52	0.05	0.04	0.04	0.04
Cl8(194)	8.85	19.58	80.17	26.33	6.60	2.69	1.53	0.05	0.05	0.05
Cl8(195)	2.42	6.02	31.01	9.43	2.38	0.93	0.07	0.05	0.05	0.05
Cl8(199)	26.38	26.33	183.45	28.66	9.31	2.97	1.57	0.10	0.10	0.10
Cl8(200)	0.99	2.16	12.32	2.84	1.07	0.37	0.14	0.11	0.12	0.12
Cl8(201)	1.45	2.99	14.54	3.95	1.58	0.56	0.14	0.11	0.12	0.12
Cl8(202)	2.69	4.30	18.60	4.92	2.03	0.61	0.09	0.07	0.08	0.08
Cl8(196)/(203)	5.03	17.14	77.52	24.02	7.20	2.50	0.67	0.03	0.03	0.03
Cl8(205)	0.03	1.22	5.23	2.32	0.68	0.52	0.03	0.02	0.02	0.02
Cl9(206)	71.54	37.04	73.11	27.34	9.98	3.29	0.91	0.10	0.10	0.28
Cl9(207)	1.72	2.59	11.04	5.24	1.92	0.55	0.11	0.09	0.09	0.09
Cl9(208)	16.09	10.65	22.93	9.44	4.46	1.03	0.11	0.08	0.08	0.09
Cl10(209)	234.11	276.49	734.87	363.35	156.48	20.90	3.92	0.05	0.05	1.19
Sum 117 congeners	5,870	24,942	118,030	86,232	25,039	5,127	3,121	8	9	163

STATION_ID	T181A	T181B	T181B	T181B	T181B	T181B	T181B	T181B	T181C	T181C
FIELD SAMPLE_ID	181A 3.2-4.2F	T181B 0-1FT	T181B 1-2FT	T181B 2-3FT	T181B 3-4FT	181B 4-5.2F	181B 5.2-6.4F	181B 6.4-7.4F	181C 0.4-1F	T181C 1-2FT
SAMPLE DEPTH (from bottom)	3.2-4.2	0-1	1-2	2-3	3-4	4-5.2	5.2-6.4	6.4-7.4	0.4-1	1-2
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	7.85	18.57	68.44	177.02	188.25	124.60	27.98	15.69	123.17	258.91
Cl1(1)	0.07	0.06	0.07	0.08	0.08	26.21	0.09	0.07	0.06	0.08
Cl1(3)	0.04	0.03	0.04	0.04	0.04	14.85	0.04	0.04	0.03	0.04
Cl2(4)/(10)	0.49	1.98	6.11	0.14	0.15	82.40	34.35	10.33	0.11	0.14
Cl2(5)	0.12	0.10	0.11	0.13	0.14	0.31	0.14	0.12	0.10	0.13
Cl2(6)	1.22	0.07	0.09	6.80	45.93	501.24	169.51	28.33	26.56	35.07
Cl2(7)	0.06	0.05	0.06	0.07	0.07	0.17	2.30	0.06	0.06	0.07
Cl2(8)	1.85	0.09	5.31	9.66	31.35	252.83	79.72	33.28	15.26	39.46
Cl2(9)	0.08	0.07	0.08	0.09	0.09	14.67	6.55	0.08	0.07	0.09
Cl2(13)	0.08	0.07	0.08	0.09	16.84	143.18	53.66	17.61	8.18	18.34
Cl2(15)	1.30	0.12	0.14	0.16	0.17	84.49	55.86	19.23	0.13	8.81
Cl3(16)	3.89	0.09	19.99	39.34	97.55	627.37	155.69	29.20	39.25	105.59
Cl3(17)	5.02	1.14	28.73	46.28	154.20	909.54	207.91	43.74	41.59	131.32
Cl3(18)	13.30	4.43	49.11	112.30	418.37	2608.33	665.15	111.82	128.29	391.58
Cl3(19)	0.44	0.08	3.43	5.56	22.67	102.64	34.11	6.53	7.77	20.77
Cl3(22)	6.75	1.58	24.75	48.40	145.91	1027.99	223.42	40.96	40.14	135.57
Cl3(24)	0.06	0.05	0.06	0.07	0.07	0.17	0.08	0.06	0.06	0.07
Cl3(25)	6.73	1.22	8.02	31.95	164.28	1722.38	486.14	86.62	65.39	166.29
Cl3(26)	7.85	1.37	11.91	32.03	188.05	1827.79	632.95	121.67	60.06	147.43
Cl3(27)	0.05	0.04	0.05	0.06	13.67	68.06	26.46	4.88	4.40	15.82
Cl3(28)	22.29	4.38	73.68	150.08	541.21	3184.19	758.38	154.27	164.89	505.29
Cl3(31)	23.31	5.42	84.02	167.03	611.45	3733.03	963.38	191.56	185.63	563.17
Cl3(32)	3.33	0.04	14.31	27.32	76.66	517.20	116.91	33.62	38.77	78.34
Cl3(33)/(20)	8.07	0.09	40.12	66.31	214.73	1424.36	297.64	51.06	58.62	213.21
Cl3(37)	5.02	0.08	13.52	25.70	62.23	387.79	77.96	30.57	27.23	63.14
Cl4(40)	5.10	0.10	22.24	48.30	107.15	755.39	177.95	0.12	42.06	104.34
Cl4(41)	0.06	0.05	0.06	0.07	23.58	180.73	51.86	8.47	0.06	26.10
Cl4(42)/(59)	9.42	0.07	41.98	63.49	289.47	1312.39	437.06	82.05	69.58	269.04
Cl4(43)	0.07	0.06	0.07	0.08	37.48	191.56	49.28	5.90	13.05	39.78
Cl4(44)	32.24	6.99	89.03	214.38	704.11	3836.10	984.50	200.11	204.27	658.77
Cl4(45)	4.54	1.42	22.23	41.07	117.56	782.48	171.17	34.00	38.15	108.54
Cl4(46)	1.89	0.09	9.54	19.55	39.74	331.38	74.83	18.33	23.92	22.04
Cl4(47)	9.51	2.52	36.29	67.38	184.72	1117.76	285.82	51.93	55.95	185.72
Cl4(48)	4.19	0.07	0.08	0.09	92.30	525.25	65.29	20.24	35.42	98.07
Cl4(49)	27.17	5.98	86.07	204.47	583.36	3540.36	935.29	200.88	183.52	553.73
Cl4(51)	0.65	0.08	5.75	11.82	39.91	181.41	42.38	11.25	13.73	44.41
Cl4(52)	35.37	7.77	107.87	243.53	792.32	4868.90	1168.24	234.65	276.06	694.19
Cl4(53)	4.26	0.04	19.72	37.90	110.95	701.48	160.79	42.09	34.95	106.86
Cl4(54)	0.06	0.05	0.06	0.07	0.07	12.62	3.33	0.06	0.06	0.07
Cl4(56)	14.49	2.79	44.74	95.31	289.46	1740.77	264.44	62.92	74.65	295.31
Cl4(60)	4.98	0.08	2.40	0.11	28.38	330.28	64.23	16.84	8.49	35.01
Cl4(64)	15.79	3.08	45.06	92.15	330.61	2143.75	506.77	86.57	93.93	311.91
Cl4(66)	28.75	6.21	95.49	208.54	588.50	2288.49	401.64	105.82	158.52	489.76
Cl4(70)	33.88	7.68	118.17	249.75	721.01	3540.51	639.73	143.43	227.99	705.23
Cl4(71)	9.12	2.08	34.42	53.45	213.37	1285.43	295.00	53.65	57.20	187.99
Cl4(74)	12.31	2.55	40.15	79.61	257.25	1334.44	247.47	45.52	62.88	258.39
Cl4(77)	2.78	0.15	8.46	17.94	47.19	270.46	54.73	14.87	15.42	47.33
Cl4(81)	0.06	0.05	0.06	0.07	0.07	0.17	0.08	0.06	0.06	0.07
Cl5(82)	2.92	0.06	7.01	0.08	39.18	388.89	72.11	14.64	19.02	46.51
Cl5(83)/(119)	0.86	0.08	9.95	15.83	48.32	263.09	65.85	17.26	21.74	50.32
Cl5(84)	8.10	1.29	27.02	46.00	149.81	1063.64	225.30	42.84	58.10	135.43
Cl5(85)	3.91	0.05	8.00	13.50	61.36	545.51	0.08	0.06	0.06	0.07
Cl5(87)	4.58	0.11	13.85	19.90	83.70	646.03	102.20	23.49	36.46	76.44
Cl5(91)	2.78	0.42	11.31	22.55	57.85	407.12	104.64	26.76	27.25	64.08
Cl5(92)	2.03	0.45	8.81	19.04	56.86	312.84	73.96	21.69	26.23	45.87
Cl5(95)	13.52	2.56	41.54	73.92	221.86	1566.36	368.86	60.63	73.48	217.12
Cl5(97)	4.88	0.04	17.06	30.40	97.46	634.42	115.64	29.10	39.18	104.38
Cl5(99)	6.63	1.55	23.51	41.33	113.46	674.73	142.35	34.46	41.65	121.22
Cl5(100)	0.06	0.05	0.06	0.07	0.07	11.35	4.14	0.06	0.06	0.07

STATION_ID	T181A	T181B	T181B	T181B	T181B	T181B	T181B	T181B	T181C	T181C
FIELD SAMPLE_ID	181A 3.2-4.2F	T181B 0-1FT	T181B 1-2FT	T181B 2-3FT	T181B 3-4FT	181B 4-5.2F	181B 5.2-6.4F	181B 6.4-7.4F	181C 0.4-1F	T181C 1-2FT
SAMPLE DEPTH (from bottom)	3.2-4.2	0-1	1-2	2-3	3-4	4-5.2	5.2-6.4	6.4-7.4	0.4-1	1-2
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	12.85	2.52	39.93	73.83	219.41	1172.14	235.78	37.58	76.57	200.12
Cl5(105)	5.98	0.08	8.65	13.22	63.01	524.03	95.30	19.85	21.71	58.52
Cl5(110)	19.03	4.07	62.19	117.51	364.25	2000.96	479.14	100.85	121.26	334.86
Cl5(114)	0.14	0.12	0.14	0.16	0.17	12.91	0.18	0.15	0.13	0.16
Cl5(115)	0.13	0.10	1.00	0.14	0.15	0.33	0.16	16.36	13.80	44.54
Cl5(118)	10.21	2.25	34.63	66.22	175.46	1056.71	200.85	42.03	59.50	168.70
Cl5(107)/(123)	1.55	0.11	4.93	11.30	25.19	133.58	29.38	6.06	6.76	20.66
Cl5(124)	0.08	0.07	0.08	0.09	0.09	26.27	4.69	0.08	0.07	0.09
Cl5(126)	0.12	0.10	0.11	0.13	0.14	0.31	0.14	0.12	0.10	0.13
Cl6(128)	1.27	0.09	2.59	4.66	12.25	87.89	16.21	5.90	6.98	12.77
Cl6(130)	0.11	0.09	2.13	4.44	8.67	48.71	6.79	2.92	3.86	8.51
Cl6(134)	0.09	0.07	1.39	2.53	4.06	27.04	0.11	1.58	2.22	4.21
Cl6(135)	1.50	0.08	2.22	5.50	10.33	66.55	13.59	3.98	5.36	9.40
Cl6(136)	1.81	0.39	3.05	6.12	10.47	68.32	12.63	3.29	6.54	8.73
Cl6(137)	0.14	0.12	0.14	0.16	0.17	18.67	4.91	0.15	0.13	0.16
Cl6(138)	9.09	0.10	9.20	16.28	39.44	279.53	46.37	11.98	23.51	35.90
Cl6(141)	3.55	0.05	0.06	0.07	4.49	39.02	8.18	0.06	0.06	0.07
Cl6(144)	0.77	0.10	0.12	0.14	0.15	14.11	1.44	0.13	0.11	0.14
Cl6(146)	1.88	0.02	4.27	9.85	16.66	89.28	15.15	4.61	6.89	15.92
Cl6(149)	11.70	0.83	10.69	21.55	44.82	265.08	48.94	16.74	23.90	41.62
Cl6(151)	3.95	0.09	2.81	5.48	13.61	90.55	15.74	4.52	6.59	13.15
Cl6(132)/(153)/(168)	16.77	1.05	15.48	29.62	52.16	381.32	59.43	19.62	33.39	51.98
Cl6(156)	0.97	0.02	0.03	0.03	4.79	27.96	6.86	0.03	0.02	0.03
Cl6(157)	0.11	0.09	0.11	0.12	0.13	12.04	0.13	0.11	0.10	0.12
Cl6(129)/(158)	1.28	0.08	1.30	2.07	5.67	30.91	6.24	2.06	2.77	0.11
Cl6(163)	2.73	0.08	3.16	8.38	12.09	84.73	13.58	5.16	5.77	10.84
Cl6(164)	0.82	0.06	1.33	0.08	4.49	28.74	4.17	1.45	0.06	3.63
Cl6(166)	0.12	0.10	0.11	0.13	0.14	0.31	0.14	0.12	0.10	0.13
Cl6(167)	0.07	0.06	0.07	0.08	0.08	16.76	0.09	0.07	0.06	0.08
Cl6(169)	0.15	0.12	0.15	0.17	0.18	25.73	0.19	0.16	0.14	0.17
Cl7(170)	4.89	0.07	1.76	3.93	9.21	55.11	6.35	3.10	3.05	6.64
Cl7(171)	1.47	0.05	0.06	1.36	2.94	18.13	2.41	0.71	0.06	2.37
Cl7(172)	0.75	0.07	0.08	1.91	4.06	12.95	2.25	0.08	0.87	3.20
Cl7(174)	6.13	0.04	1.94	3.73	10.19	62.33	7.71	3.16	4.70	7.80
Cl7(176)	0.66	0.18	0.86	1.63	2.05	11.15	1.69	0.93	1.75	1.95
Cl7(177)	3.06	0.07	1.77	3.76	7.17	44.34	6.34	2.72	2.80	6.59
Cl7(178)	1.00	0.05	1.48	4.34	4.49	18.04	2.48	1.07	1.53	3.71
Cl7(179)	2.39	0.22	1.83	3.18	6.31	36.44	4.59	2.05	2.99	6.69
Cl7(180)	12.95	0.46	4.10	8.54	20.86	143.53	19.37	7.09	8.79	18.32
Cl7(183)	2.93	0.07	1.61	3.89	7.45	38.24	5.92	1.85	4.01	7.12
Cl7(184)	0.05	0.04	0.39	0.89	0.73	1.04	0.07	0.06	0.05	0.67
Cl7(185)	0.98	0.07	0.08	0.09	0.83	7.12	1.34	0.08	0.07	0.09
Cl7(187)	6.23	0.06	3.56	8.79	15.86	92.87	12.99	4.84	7.09	14.79
Cl7(189)	0.12	0.10	0.11	0.13	0.14	0.31	0.14	0.12	0.10	0.13
Cl7(190)	0.93	0.07	0.09	0.75	2.20	13.92	2.15	0.09	0.08	0.95
Cl7(193)	0.48	0.04	0.42	0.05	1.85	7.36	1.50	0.05	0.04	1.13
Cl8(194)	2.93	0.05	3.62	7.41	13.95	46.90	6.12	2.30	3.80	8.03
Cl8(195)	1.32	0.05	0.73	1.24	3.71	16.27	3.25	0.06	0.06	2.53
Cl8(199)	3.30	1.04	13.86	38.68	40.09	57.87	7.40	3.25	10.79	25.84
Cl8(200)	0.55	0.11	0.35	0.62	1.51	5.21	0.17	0.14	0.12	1.40
Cl8(201)	0.51	0.11	0.66	0.63	1.75	6.02	1.51	0.14	1.01	1.31
Cl8(202)	0.40	0.07	1.73	4.42	3.98	10.70	1.45	0.70	1.74	3.49
Cl8(196)/(203)	1.72	0.03	1.56	3.56	6.70	24.97	2.49	2.51	1.95	4.94
Cl8(205)	0.03	0.02	0.03	0.03	1.11	0.07	0.03	0.03	0.02	0.03
Cl9(206)	1.14	2.36	42.67	98.21	127.20	73.78	11.84	3.95	27.22	110.88
Cl9(207)	0.11	0.09	1.33	2.71	2.75	10.08	2.15	0.67	1.01	2.04
Cl9(208)	0.22	0.60	10.76	25.87	24.14	20.69	3.61	1.30	7.97	16.08
Cl10(209)	3.08	13.88	231.94	440.15	466.70	743.13	118.50	57.35	198.81	372.30
Sum 117 congeners	588	112	1,923	3,872	11,217	65,256	14,968	3,135	3,667	10,420

STATION_ID	T181C	T181C	T181C	T181C	T181C	T181C	T181C	T181D	T181D	T181D
FIELD SAMPLE_ID	T181C 2-3FT	T181C 3-4FT	T181C 4-5FT	T181C 5-6FT	T181-C-TS	T181-C-RQP	81C 10.8-11.8	T181D 0-1FT	T181D 1-2FT	T181D 2-3FT
SAMPLE DEPTH (from bottom)	2-3	3-4	4-5	5-6	6-8	8-10.8	10.8-11.8	0-1	1-2	2-3
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	658.83	135.60	246.84	202.10	67.81	45.82	157.22	604.97	314.35	417.23
Cl1(1)	36.17	0.11	56.50	19.01	13.79	2.13	0.05	0.07	0.08	0.08
Cl1(3)	19.26	0.06	22.36	10.87	8.21	1.63	0.02	0.04	0.04	0.04
Cl2(4)/(10)	34.11	71.55	156.88	109.41	69.81	7.89	2.45	13.40	10.23	12.68
Cl2(5)	0.18	0.18	0.31	3.56	4.74	0.11	0.08	0.12	0.13	0.12
Cl2(6)	231.25	137.90	696.55	224.95	55.50	17.12	3.50	0.09	7.59	12.26
Cl2(7)	0.10	0.10	13.45	9.52	8.69	0.73	0.04	0.06	0.07	0.07
Cl2(8)	121.07	150.19	522.13	405.11	140.35	20.36	5.91	8.86	12.17	22.02
Cl2(9)	0.13	0.13	28.62	14.85	13.21	1.00	0.06	0.08	0.09	0.09
Cl2(13)	78.94	44.10	201.59	79.41	22.35	7.38	1.14	0.08	0.09	3.99
Cl2(15)	59.00	50.05	148.94	145.36	73.13	12.18	2.79	0.15	0.17	5.81
Cl3(16)	514.74	649.36	1620.27	1090.30	332.17	203.89	13.89	31.82	45.09	82.58
Cl3(17)	470.31	714.82	1979.60	0.17	296.29	50.39	14.52	38.56	74.72	121.10
Cl3(18)	1796.15	2590.93	5777.55	3601.32	1109.31	681.02	40.45	107.97	165.21	313.69
Cl3(19)	69.87	84.20	237.72	165.92	63.88	5.68	1.85	4.68	6.96	11.37
Cl3(22)	676.93	862.25	2202.45	1211.28	389.15	303.72	16.97	38.16	58.81	99.21
Cl3(24)	0.10	0.10	13.32	12.98	5.54	0.06	0.04	0.06	0.07	0.07
Cl3(25)	779.48	580.86	2201.26	646.56	113.38	404.07	10.03	7.36	33.64	52.75
Cl3(26)	742.61	709.60	2598.53	849.01	200.04	516.35	14.88	13.74	36.39	59.46
Cl3(27)	70.73	58.58	150.08	97.68	42.25	4.61	1.33	3.52	4.58	7.64
Cl3(28)	2122.77	2684.27	6638.12	3956.94	1139.27	944.62	40.52	121.40	212.83	361.18
Cl3(31)	2609.00	3415.74	8097.34	4564.17	1393.77	1261.95	47.69	135.42	225.21	394.42
Cl3(32)	400.19	493.92	1213.78	708.86	227.71	31.70	10.27	22.81	34.06	58.52
Cl3(33)/(20)	992.12	1438.87	2602.42	2035.10	628.13	408.77	22.78	67.22	89.18	166.93
Cl3(37)	344.92	439.88	1020.76	664.82	211.18	144.70	7.03	20.15	30.43	45.43
Cl4(40)	607.79	742.82	1860.57	921.20	331.37	206.86	10.50	32.91	49.78	82.19
Cl4(41)	274.81	395.08	729.64	533.09	194.49	13.68	5.30	13.67	5.44	11.66
Cl4(42)/(59)	1145.14	1330.49	3259.65	2080.40	736.83	570.34	22.99	74.77	123.61	206.11
Cl4(43)	144.11	144.67	335.77	247.36	77.69	13.37	2.36	8.61	12.55	20.92
Cl4(44)	2984.72	3884.45	8954.32	5550.16	1909.30	1495.59	56.24	192.45	294.14	496.13
Cl4(45)	601.09	684.78	1773.51	1003.93	322.93	215.46	11.66	35.08	49.34	95.93
Cl4(46)	258.16	272.93	815.29	489.72	161.73	19.46	5.33	14.67	23.21	38.45
Cl4(47)	726.14	972.59	2547.58	1285.09	430.73	371.84	13.98	54.42	93.70	152.36
Cl4(48)	581.35	856.73	1761.97	1196.57	511.51	35.75	11.42	45.98	45.90	80.88
Cl4(49)	2548.69	3279.12	7719.69	4196.34	1423.20	1178.90	42.10	147.04	242.66	434.24
Cl4(51)	154.45	178.70	455.06	306.19	96.71	12.56	2.26	8.54	12.47	21.80
Cl4(52)	3581.32	4681.20	10063.57	6327.30	2289.46	1562.78	67.30	217.40	336.95	552.84
Cl4(53)	564.91	653.96	1634.25	866.20	303.91	193.52	11.02	30.39	46.69	81.41
Cl4(54)	9.80	12.61	27.84	0.17	7.05	0.86	0.04	0.06	0.07	0.07
Cl4(56)	1370.49	1622.03	3362.21	2470.07	713.44	470.37	19.28	85.93	130.47	220.46
Cl4(60)	487.49	802.72	1182.23	791.97	288.03	25.60	7.80	26.58	8.88	14.83
Cl4(64)	1507.10	1825.50	4406.98	2630.94	881.15	634.98	26.71	91.85	134.24	245.37
Cl4(66)	2294.28	2976.55	6734.07	4587.97	1510.62	946.40	35.74	181.07	272.49	452.04
Cl4(70)	3302.31	4144.69	9436.00	6133.71	1954.56	1251.56	47.82	221.88	330.09	556.28
Cl4(71)	800.45	1150.66	2540.89	1492.64	502.66	357.14	16.03	54.61	80.66	136.88
Cl4(74)	1202.48	1695.03	3573.19	2535.97	814.28	3.37	18.92	96.08	111.52	187.93
Cl4(77)	253.17	297.38	644.51	372.23	99.06	17.57	2.63	12.75	20.18	31.10
Cl4(81)	0.10	10.85	12.95	8.18	3.31	0.06	0.04	0.06	0.07	0.07
Cl5(82)	361.00	414.14	868.38	400.03	181.36	18.92	3.21	13.16	17.22	26.53
Cl5(83)/(119)	197.62	212.64	541.70	269.16	122.26	18.73	1.79	11.05	19.34	28.67
Cl5(84)	602.62	855.97	2241.29	1270.93	348.56	248.28	8.44	39.40	64.08	113.51
Cl5(85)	0.10	0.10	0.17	645.28	220.26	23.11	4.47	18.15	16.53	30.66
Cl5(87)	503.48	730.66	1733.37	958.36	349.42	34.26	5.88	29.16	31.66	45.68
Cl5(91)	325.04	344.28	891.80	450.62	195.15	28.69	3.52	15.68	25.30	38.27
Cl5(92)	212.72	250.00	651.58	263.12	121.24	26.78	3.14	12.93	24.43	32.01
Cl5(95)	975.54	1230.29	2817.24	1649.08	584.03	428.92	15.32	64.65	105.06	153.31
Cl5(97)	589.30	691.15	1650.31	866.83	298.28	37.39	6.21	31.58	42.24	60.81
Cl5(99)	551.18	771.43	1885.73	963.07	329.07	167.41	6.66	41.64	55.49	81.55
Cl5(100)	1.97	4.30	25.80	9.37	5.35	0.97	0.04	0.82	0.80	1.34

STATION_ID	T181C	T181C	T181C	T181C	T181C	T181C	T181C	T181D	T181D	T181D
FIELD SAMPLE_ID	T181C 2-3FT	T181C 3-4FT	T181C 4-5FT	T181C 5-6FT	T181-C-TS	T181-C-RQP	81C 10.8-11.8	T181D 0-1FT	T181D 1-2FT	T181D 2-3FT
SAMPLE DEPTH (from bottom)	2-3	3-4	4-5	5-6	6-8	8-10.8	10.8-11.8	0-1	1-2	2-3
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	991.31	1207.26	2846.72	1479.18	524.48	273.45	12.16	61.52	97.86	137.06
Cl5(105)	605.60	783.73	1550.51	707.86	281.57	28.53	4.66	25.61	19.00	27.78
Cl5(110)	1562.60	1755.01	4278.01	2444.47	728.55	609.72	17.46	93.59	167.00	228.35
Cl5(114)	10.63	16.74	47.28	44.00	21.90	1.35	0.10	0.15	0.17	0.15
Cl5(115)	310.39	340.00	0.33	46.96	21.51	1.27	0.38	2.17	0.15	0.13
Cl5(118)	851.23	1137.62	2680.74	1413.11	473.22	223.84	8.39	58.39	88.50	117.05
Cl5(107)/(123)	106.62	121.07	274.84	187.34	77.55	11.06	0.81	5.43	14.33	11.33
Cl5(124)	28.64	49.29	84.55	49.92	25.80	1.49	0.06	1.86	0.09	1.71
Cl5(126)	0.18	4.53	10.45	0.31	2.52	0.11	0.08	0.12	0.13	0.12
Cl6(128)	50.10	68.73	161.53	100.06	30.05	4.36	1.08	4.31	7.93	7.76
Cl6(130)	24.70	31.66	76.48	42.17	13.75	2.78	0.07	1.91	5.32	4.70
Cl6(134)	16.42	21.54	53.37	27.53	11.07	1.66	0.06	1.56	2.45	2.78
Cl6(135)	37.86	50.30	115.15	53.13	19.42	4.80	0.56	3.18	4.72	6.60
Cl6(136)	40.36	54.87	133.56	60.88	20.33	3.42	0.42	4.90	5.32	6.64
Cl6(137)	11.31	19.25	40.79	27.16	10.81	1.31	0.10	2.15	1.71	0.15
Cl6(138)	213.56	215.99	645.81	322.91	93.52	11.45	1.98	13.79	21.11	21.06
Cl6(141)	35.27	55.94	102.37	61.67	22.18	2.21	0.71	0.06	2.51	0.07
Cl6(144)	11.36	17.08	42.74	19.89	0.17	0.66	0.09	0.13	1.44	1.69
Cl6(146)	42.91	49.59	123.92	66.14	20.40	5.39	0.43	3.54	8.52	10.27
Cl6(149)	201.88	181.16	540.26	276.16	81.04	20.12	2.11	13.53	24.28	28.35
Cl6(151)	58.96	69.39	174.19	76.10	25.55	5.10	0.61	4.12	6.46	8.00
Cl6(132)/(153)/(168)	284.78	275.12	813.01	425.14	115.75	18.98	2.74	18.95	35.28	37.27
Cl6(156)	15.75	31.52	60.84	48.22	14.78	1.99	0.02	2.92	2.96	0.03
Cl6(157)	7.85	8.27	22.83	13.89	4.14	0.89	0.07	0.11	0.12	0.11
Cl6(129)/(158)	30.67	38.64	79.49	44.85	16.32	2.06	0.07	1.42	2.69	2.94
Cl6(163)	43.80	52.15	526.65	71.63	20.76	4.67	0.69	3.01	6.98	8.04
Cl6(164)	18.58	20.98	58.27	27.28	9.64	1.51	0.05	0.07	2.52	2.99
Cl6(166)	0.18	0.18	0.31	0.31	0.16	0.11	0.08	0.12	0.13	0.12
Cl6(167)	9.80	12.18	32.19	20.43	6.53	0.85	0.05	2.43	0.08	0.08
Cl6(169)	0.24	22.25	44.21	1.27	0.31	0.14	0.11	0.16	0.18	0.16
Cl7(170)	36.43	53.40	155.32	60.64	16.52	3.08	0.40	3.50	3.02	3.36
Cl7(171)	12.40	16.53	37.48	16.25	4.73	1.03	0.04	0.87	1.59	1.74
Cl7(172)	11.59	11.83	26.94	14.13	4.54	1.08	0.06	5.69	2.00	2.07
Cl7(174)	53.05	63.58	144.66	63.96	17.05	3.53	0.53	3.44	3.79	5.30
Cl7(176)	8.91	9.38	21.30	9.91	2.61	0.75	0.13	2.80	0.99	1.60
Cl7(177)	31.33	37.35	92.21	37.37	11.15	3.62	0.26	2.56	2.93	3.91
Cl7(178)	13.11	14.52	32.25	15.14	4.12	1.76	0.04	1.31	1.88	2.80
Cl7(179)	29.19	33.01	72.93	36.33	8.38	2.15	0.38	3.24	2.22	3.72
Cl7(180)	151.53	147.45	334.85	139.80	36.22	7.64	1.40	7.49	8.25	9.57
Cl7(183)	31.86	35.04	81.47	40.30	10.63	2.32	0.38	5.25	3.67	4.10
Cl7(184)	0.44	0.08	0.14	0.14	0.52	0.10	0.04	0.41	0.41	0.39
Cl7(185)	7.72	7.99	16.44	8.02	2.29	0.44	0.18	0.08	0.47	0.09
Cl7(187)	71.93	68.07	177.28	78.46	20.83	6.30	0.58	5.10	7.16	9.15
Cl7(189)	4.11	3.67	6.16	5.15	1.60	0.11	0.08	0.12	0.13	0.12
Cl7(190)	10.40	14.16	27.81	12.64	4.22	0.68	0.06	0.09	0.95	1.20
Cl7(193)	5.84	8.35	18.23	7.19	2.24	0.53	0.03	0.87	0.97	1.07
Cl8(194)	40.68	48.41	81.03	45.88	10.96	2.95	0.38	3.20	3.12	4.88
Cl8(195)	13.13	17.75	33.53	18.34	5.10	1.16	0.04	1.16	1.27	1.58
Cl8(199)	58.14	52.52	104.56	62.39	15.72	3.80	0.44	8.88	10.26	17.61
Cl8(200)	6.07	5.09	10.18	5.10	1.70	0.48	0.09	0.14	0.60	0.93
Cl8(201)	5.91	5.55	11.83	8.12	2.92	0.48	0.09	1.45	1.25	1.04
Cl8(202)	8.50	6.99	15.66	9.73	2.94	0.76	0.06	1.62	1.64	2.67
Cl8(196)/(203)	24.89	21.76	42.76	44.80	13.18	2.96	0.47	3.36	3.44	5.51
Cl8(205)	1.81	2.60	5.22	3.58	0.04	0.03	0.02	0.59	0.03	0.03
Cl9(206)	160.72	42.98	83.34	108.76	22.64	3.74	0.51	24.97	24.20	38.84
Cl9(207)	6.69	5.30	16.42	11.85	5.93	0.63	0.24	1.24	1.16	1.41
Cl9(208)	21.96	11.08	28.08	30.52	8.24	1.33	0.38	7.13	7.99	12.49
Cl10(209)	584.46	456.64	1141.16	1133.10	398.93	65.67	3.68	352.88	180.11	276.41
Sum 117 congeners	48,927	61,211	143,780	84,588	28,211	17,028	822	3,341	4,681	7,651

STATION_ID	T181D	T181D	T181D	T181D	T181D	T181D	T181D	T181D	9	24
FIELD SAMPLE_ID	T181D 3-4FT	T181D 4-5FT	T181D 5-6FT	T181-D-TSR	T181-D-QPO	T181-D-NML	T181-D-KJIH	81D 18.5-19.5	FAD-001	FAD-003
SAMPLE DEPTH (from bottom)	3-4	4-5	5-6	6-9	9-12	12-15	15-18.5	18.5-19.5	0-0.3	0-0.3
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	114.28	639.94	702.21	175.27	67.23	90.67	24.34	3.63	6.66	6.92
Cl1(1)	0.08	18.24	0.10	29.61	33.35	11.40	2.07	0.07	0.05	0.04
Cl1(3)	0.04	8.29	0.05	19.34	19.44	4.63	1.45	0.03	0.02	0.02
Cl2(4)/(10)	6.64	25.01	41.86	109.77	187.40	48.77	5.91	0.92	0.09	0.56
Cl2(5)	0.13	0.15	0.17	4.99	14.92	3.47	0.11	0.11	0.08	0.06
Cl2(6)	20.83	258.83	603.41	378.53	252.95	54.38	15.07	1.66	0.06	0.66
Cl2(7)	0.07	0.08	0.09	12.11	26.91	6.12	0.56	0.06	0.04	0.03
Cl2(8)	20.33	102.39	171.60	368.17	507.73	110.92	13.60	1.95	0.16	0.85
Cl2(9)	0.09	0.10	5.16	18.64	44.45	10.05	0.81	0.07	0.06	0.04
Cl2(13)	8.80	96.33	184.93	125.50	53.01	18.33	5.77	0.70	0.06	0.33
Cl2(15)	6.04	36.85	43.71	129.15	269.34	65.59	8.44	1.25	0.10	0.78
Cl3(16)	100.62	492.65	705.31	1436.48	1152.91	225.25	32.32	6.59	0.07	1.92
Cl3(17)	129.40	641.74	1085.17	1249.90	891.15	173.32	50.65	6.75	0.34	2.43
Cl3(18)	365.22	2052.67	3478.87	5084.56	3927.51	737.63	143.90	23.33	0.64	5.99
Cl3(19)	11.92	63.09	118.14	272.02	216.82	45.19	4.76	1.03	0.07	0.31
Cl3(22)	111.50	629.90	946.39	1829.84	1403.28	254.58	55.74	9.42	0.60	3.71
Cl3(24)	0.07	0.08	4.16	12.22	15.56	3.80	0.06	0.06	0.04	0.03
Cl3(25)	97.87	1088.90	2615.63	1347.64	520.46	150.13	87.44	8.44	0.04	3.58
Cl3(26)	111.57	1206.73	2725.66	1559.69	839.19	240.24	113.22	10.91	0.29	4.88
Cl3(27)	8.14	44.88	73.45	111.56	94.27	23.47	3.54	0.81	0.04	0.25
Cl3(28)	413.63	2246.31	3612.03	5919.82	4028.88	766.67	178.99	28.59	1.03	9.38
Cl3(31)	448.67	2832.00	4657.10	6865.54	5132.20	932.17	223.41	41.45	1.21	11.92
Cl3(32)	66.93	373.18	516.25	1011.71	798.80	160.04	24.79	5.05	0.22	1.56
Cl3(33)/(20)	169.97	913.80	1352.55	2946.62	2266.17	413.20	78.19	13.52	0.76	4.22
Cl3(37)	48.04	202.53	273.18	864.14	726.55	124.92	25.78	5.06	0.39	2.82
Cl4(40)	97.75	573.50	762.61	1473.74	1216.79	211.06	42.52	8.20	0.08	3.82
Cl4(41)	23.48	191.13	126.21	717.96	690.55	100.37	12.29	4.06	0.04	1.32
Cl4(42)/(59)	217.03	1213.80	1580.50	3186.65	2314.48	455.06	104.74	18.54	0.47	8.83
Cl4(43)	22.47	148.65	197.87	396.64	248.88	58.71	10.74	1.50	0.05	0.76
Cl4(44)	541.28	3314.74	4740.10	8499.39	6621.40	1081.50	264.29	60.62	1.60	19.66
Cl4(45)	105.93	577.62	826.27	1371.73	1180.33	200.64	41.65	7.34	0.28	2.80
Cl4(46)	40.38	278.74	365.44	591.20	514.38	99.74	16.46	3.07	0.07	1.24
Cl4(47)	154.68	803.91	1295.21	1891.60	1415.97	242.75	65.37	11.52	0.37	5.38
Cl4(48)	105.74	439.99	386.86	1731.75	1583.54	249.04	28.29	7.70	0.27	2.82
Cl4(49)	448.64	2669.49	4270.03	6393.23	5002.22	858.01	234.44	45.51	0.87	15.28
Cl4(51)	23.19	161.48	209.45	419.37	368.73	52.97	9.50	1.84	0.07	0.72
Cl4(52)	659.15	3828.56	5847.75	9224.10	6885.52	1192.90	303.31	65.43	1.38	19.82
Cl4(53)	101.43	551.65	812.48	1458.30	1030.08	181.60	33.27	7.13	0.22	2.41
Cl4(54)	0.07	0.08	8.43	21.71	14.68	4.74	0.82	0.06	0.04	0.08
Cl4(56)	232.49	1255.09	1323.49	3037.31	2276.78	394.42	79.46	19.97	0.54	7.92
Cl4(60)	25.11	386.23	168.54	925.10	1094.78	159.15	21.43	7.78	0.34	2.44
Cl4(64)	268.98	1563.65	2215.13	4014.32	3046.98	524.18	127.12	23.21	0.69	10.67
Cl4(66)	432.60	2021.88	1646.81	6752.63	5110.12	818.91	164.89	39.23	1.28	15.97
Cl4(70)	592.61	3010.03	3266.97	9123.83	6547.83	1108.12	223.76	56.79	1.64	18.99
Cl4(71)	162.13	928.85	1173.18	2444.92	1753.81	294.67	73.96	12.84	0.40	6.04
Cl4(74)	207.50	1012.46	675.18	3638.66	2887.64	419.94	67.21	18.78	0.74	9.51
Cl4(77)	29.81	144.95	115.44	495.10	398.79	63.64	12.68	3.13	0.13	1.78
Cl4(81)	0.07	2.10	0.09	9.90	10.00	1.63	0.06	0.06	0.04	0.03
Cl5(82)	42.16	237.13	302.55	663.37	554.23	86.89	16.36	3.99	0.05	2.32
Cl5(83)/(119)	28.95	190.41	206.30	442.83	288.64	51.04	15.08	2.20	0.07	1.35
Cl5(84)	124.90	736.66	941.91	1554.67	1311.40	229.95	51.22	8.53	0.27	4.84
Cl5(85)	50.22	339.27	329.31	857.07	631.22	109.48	20.44	5.81	0.23	2.59
Cl5(87)	74.36	421.87	379.18	1435.52	1161.38	195.42	29.54	7.29	0.68	5.22
Cl5(91)	44.85	252.85	286.36	859.87	603.10	105.19	23.00	4.22	0.22	2.63
Cl5(92)	26.21	160.50	194.08	550.97	434.82	49.89	19.40	3.85	0.06	2.19
Cl5(95)	172.35	944.07	1220.39	2771.61	2040.26	370.16	86.74	15.23	1.11	10.69
Cl5(97)	80.62	377.23	377.56	1282.38	966.41	147.52	29.07	6.71	0.42	4.63
Cl5(99)	88.12	454.65	375.45	1335.05	1016.66	166.57	29.97	8.14	0.44	4.39
Cl5(100)	1.16	4.97	8.13	18.07	13.13	2.71	0.72	0.06	0.04	0.03

STATION_ID	T181D	T181D	T181D	T181D	T181D	T181D	T181D	T181D	9	24
FIELD SAMPLE_ID	T181D 3-4FT	T181D 4-5FT	T181D 5-6FT	T181-D-TSR	T181-D-QPO	T181-D-NML	T181-D-KJIH	81D 18.5-19.5	FAD-001	FAD-003
SAMPLE DEPTH (from bottom)	3-4	4-5	5-6	6-9	9-12	12-15	15-18.5	18.5-19.5	0-0.3	0-0.3
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	144.45	688.06	545.91	2234.29	1640.17	264.43	47.97	13.53	1.20	8.92
Cl5(105)	51.27	372.43	202.16	1010.33	913.76	156.47	23.25	7.34	0.69	4.24
Cl5(110)	257.78	1332.18	1579.74	3391.40	2530.67	423.29	112.02	21.95	1.54	14.49
Cl5(114)	0.16	6.18	0.21	44.07	478.42	11.32	1.20	0.37	0.49	0.64
Cl5(115)	2.01	19.08	0.18	56.99	43.12	9.16	1.25	0.39	0.09	0.36
Cl5(118)	120.76	582.42	390.27	1989.44	1463.91	234.62	39.39	12.15	1.11	7.93
Cl5(107)/(123)	13.85	58.69	91.86	359.13	247.73	43.93	8.42	1.20	0.09	1.26
Cl5(124)	2.56	16.82	7.77	71.39	79.10	10.37	1.30	0.49	0.06	0.33
Cl5(126)	0.13	3.83	2.69	10.48	9.47	2.13	0.92	0.11	0.08	0.06
Cl6(128)	7.80	34.83	41.99	153.72	93.52	16.12	3.00	0.62	0.45	1.22
Cl6(130)	4.17	19.76	28.84	58.88	32.18	6.76	1.86	0.10	0.07	0.56
Cl6(134)	2.26	11.85	15.93	41.66	26.81	5.56	1.32	0.08	0.06	0.59
Cl6(135)	5.57	29.70	47.44	87.79	42.52	9.98	3.16	0.48	0.33	1.50
Cl6(136)	6.16	28.31	38.10	90.25	48.70	10.49	2.52	0.74	0.31	1.68
Cl6(137)	1.34	7.24	6.00	35.07	30.63	5.14	0.89	0.13	0.10	0.24
Cl6(138)	23.57	111.92	139.95	351.77	233.41	53.40	8.63	2.83	1.27	6.60
Cl6(141)	3.51	20.87	12.11	82.31	68.94	11.07	1.97	0.76	0.62	3.16
Cl6(144)	1.24	7.29	7.39	29.79	16.94	3.07	0.59	0.27	0.18	0.76
Cl6(146)	8.74	35.45	55.84	103.96	44.87	10.65	3.05	0.62	0.32	1.50
Cl6(149)	28.76	157.30	223.85	492.57	249.46	46.16	14.15	2.93	2.04	10.55
Cl6(151)	8.71	38.67	52.28	148.82	49.11	12.92	3.69	0.87	0.71	3.73
Cl6(132)/(153)/(168)	37.38	175.86	178.79	576.34	309.09	58.69	13.47	4.20	2.38	12.59
Cl6(156)	2.54	10.15	8.28	49.18	42.40	7.80	1.40	0.35	0.02	1.04
Cl6(157)	1.03	4.63	3.63	14.44	11.35	2.06	0.49	0.10	0.07	0.06
Cl6(129)/(158)	3.28	21.33	14.82	55.37	39.29	7.57	1.59	0.42	0.28	1.08
Cl6(163)	6.04	29.15	42.40	89.86	42.40	10.51	2.85	0.84	0.43	1.84
Cl6(164)	2.50	10.33	11.80	37.72	22.88	4.67	1.08	0.07	0.05	0.85
Cl6(166)	0.13	0.15	1.51	0.22	3.46	0.10	0.11	0.11	0.08	0.06
Cl6(167)	1.50	6.21	5.61	25.38	16.43	3.48	0.66	0.24	0.05	0.39
Cl6(169)	3.01	0.20	0.22	0.48	1.26	0.16	0.14	0.14	0.10	0.08
Cl7(170)	5.60	26.71	29.82	86.84	46.24	8.31	2.14	0.73	0.86	5.06
Cl7(171)	1.23	8.13	10.94	26.17	10.98	2.02	0.66	0.20	0.26	1.19
Cl7(172)	1.88	8.42	10.83	21.71	9.88	1.89	0.66	0.07	0.18	0.90
Cl7(174)	6.83	32.40	34.72	126.70	38.42	7.59	2.30	0.74	1.03	5.60
Cl7(176)	1.48	5.72	7.12	16.92	5.09	1.29	0.42	0.11	0.13	0.63
Cl7(177)	4.27	23.28	32.55	68.87	25.32	6.25	2.45	0.54	0.59	3.28
Cl7(178)	2.10	10.65	15.31	23.57	7.21	2.31	1.05	0.11	0.19	0.86
Cl7(179)	3.79	20.18	23.57	57.31	14.79	3.63	1.49	0.53	0.44	2.11
Cl7(180)	15.72	97.11	71.85	316.84	121.63	17.66	4.97	1.91	2.40	12.93
Cl7(183)	4.72	23.04	24.13	65.40	22.15	4.87	1.52	0.54	0.60	3.22
Cl7(184)	0.33	0.88	0.38	0.85	0.57	0.19	0.05	0.05	0.04	0.03
Cl7(185)	0.74	4.49	4.06	12.82	4.67	0.93	0.35	0.09	0.13	0.71
Cl7(187)	9.92	52.39	72.69	130.02	40.25	9.61	4.42	1.14	1.14	6.16
Cl7(189)	0.13	2.36	0.17	4.83	3.90	0.64	0.11	0.11	0.08	0.23
Cl7(190)	1.28	7.21	7.82	21.83	10.77	1.88	0.50	0.30	0.15	1.07
Cl7(193)	1.29	3.90	5.75	10.17	4.50	0.96	0.32	0.18	0.12	0.51
Cl8(194)	7.89	30.24	38.59	80.55	33.52	5.75	1.89	0.51	0.61	3.11
Cl8(195)	2.62	11.98	14.29	25.28	10.37	1.91	0.83	0.26	0.04	0.91
Cl8(199)	16.76	43.91	50.20	90.61	34.09	6.83	2.23	0.51	0.63	2.98
Cl8(200)	0.73	3.41	3.71	8.73	3.22	0.56	0.23	0.12	0.09	0.37
Cl8(201)	1.26	4.77	5.16	9.81	4.66	0.76	0.45	0.12	0.09	0.33
Cl8(202)	2.16	6.80	6.68	13.02	4.85	1.11	0.43	0.20	0.15	0.45
Cl8(196)/(203)	6.55	29.30	32.82	68.44	27.97	5.01	1.93	0.50	0.64	3.01
Cl8(205)	0.03	2.00	2.58	4.81	2.79	0.72	0.02	0.02	0.02	0.01
Cl9(206)	41.67	60.94	55.40	87.03	47.81	7.86	2.27	0.53	0.25	0.86
Cl9(207)	1.00	6.07	4.41	11.55	9.71	0.94	0.27	0.10	0.03	0.12
Cl9(208)	10.33	16.16	12.55	25.62	15.82	2.41	0.72	0.10	0.08	0.17
Cl10(209)	195.29	367.74	318.35	1185.26	661.24	68.84	15.87	1.69	0.39	1.15
Sum 117 congeners	8,473	47,284	64,504	125,593	94,713	16,488	3,689	745	48	402

STATION_ID	21	2	26	12	7	22	3	25	5	27
FIELD SAMPLE_ID	FAD-005	FAD-008	FAD-012	FAD-015	FAD-021	FAD-022	FAD-023	FAD-024	FAD-025	FAD-026
SAMPLE DEPTH (from bottom)	0-0.3	0-0.3	0-0.3	0-0.3	0-0.3	0-0.3	0-0.3	0-0.3	0-0.3	0-0.3
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Biphenyl	10.12	8.34	7.21	7.29	9.83	3.63	8.93	6.42	4.70	3.78
Cl1(1)	0.05	0.04	0.04	0.04	0.06	0.03	0.03	0.05	0.04	0.04
Cl1(3)	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02
Cl2(4)/(10)	1.03	0.97	0.70	0.76	0.71	0.83	1.42	0.33	0.46	0.37
Cl2(5)	0.08	0.07	0.07	0.06	0.10	0.05	0.05	0.07	0.07	0.06
Cl2(6)	1.29	1.39	0.91	0.70	1.14	0.86	1.62	0.26	0.45	0.35
Cl2(7)	0.04	0.04	0.04	0.05	0.05	0.03	0.12	0.04	0.04	0.03
Cl2(8)	1.52	1.69	1.25	1.22	1.54	1.06	3.39	0.39	0.60	0.50
Cl2(9)	0.05	0.05	0.05	0.09	0.07	0.04	0.20	0.05	0.05	0.04
Cl2(13)	0.55	0.74	0.45	0.34	0.54	0.35	0.70	0.05	0.23	0.20
Cl2(15)	1.40	1.50	1.25	1.08	1.50	0.92	2.14	0.42	0.59	0.52
Cl3(16)	3.02	3.49	2.70	2.75	3.75	2.21	7.83	0.87	1.09	1.31
Cl3(17)	3.65	4.58	3.22	3.00	3.90	2.55	7.31	0.99	1.39	1.54
Cl3(18)	9.11	11.49	7.65	7.21	10.16	6.66	21.03	1.85	3.10	3.92
Cl3(19)	0.57	0.54	0.50	0.42	0.59	0.39	1.24	0.17	0.22	0.17
Cl3(22)	5.51	6.96	5.26	4.44	8.21	4.22	12.00	1.68	2.36	2.72
Cl3(24)	0.04	0.04	0.04	0.03	0.05	0.03	0.03	0.04	0.04	0.03
Cl3(25)	4.70	6.90	4.08	3.40	4.75	3.10	5.82	0.91	1.80	1.72
Cl3(26)	6.21	8.40	5.21	4.34	6.61	4.09	9.01	1.25	2.44	2.41
Cl3(27)	0.41	0.50	0.42	0.37	0.53	0.29	0.93	0.14	0.15	0.19
Cl3(28)	14.53	19.63	14.44	12.46	21.40	11.13	29.20	3.80	5.97	7.34
Cl3(31)	16.12	22.30	15.31	13.30	22.30	12.04	34.15	3.82	6.22	8.18
Cl3(32)	2.48	3.00	2.43	2.15	3.29	2.01	5.80	0.77	0.89	1.13
Cl3(33)/(20)	6.20	8.30	5.86	5.35	8.66	5.04	14.12	1.92	2.70	3.13
Cl3(37)	3.35	3.97	3.26	2.67	4.73	2.45	6.73	0.85	1.53	1.42
Cl4(40)	4.49	5.48	4.47	3.88	6.55	3.46	9.90	1.12	1.92	2.31
Cl4(41)	2.06	2.06	2.17	1.70	3.47	1.82	5.55	0.71	0.87	1.23
Cl4(42)/(59)	8.71	11.60	10.78	7.72	12.22	6.86	18.10	2.41	3.64	4.19
Cl4(43)	0.90	1.15	0.97	0.70	1.27	0.66	1.91	0.05	0.32	0.43
Cl4(44)	23.83	30.40	24.24	20.00	35.36	18.43	47.90	6.42	10.03	12.10
Cl4(45)	3.69	4.45	3.76	2.99	5.45	2.97	9.01	0.95	1.41	1.75
Cl4(46)	1.59	1.95	1.49	1.36	2.44	1.24	3.82	0.40	0.61	0.73
Cl4(47)	6.10	7.94	6.22	5.10	9.11	4.61	12.22	1.59	2.43	3.03
Cl4(48)	3.63	4.16	3.94	3.30	6.25	3.22	10.41	1.10	1.53	2.04
Cl4(49)	17.62	22.73	17.26	14.68	25.26	13.12	32.74	4.51	7.16	8.78
Cl4(51)	0.93	1.14	0.92	0.75	1.38	0.71	2.11	0.25	0.32	0.39
Cl4(52)	23.50	29.70	23.19	19.97	34.95	18.00	45.03	6.40	9.99	11.93
Cl4(53)	3.01	3.94	3.13	2.64	4.64	2.53	7.49	0.87	1.18	1.48
Cl4(54)	0.04	0.17	0.13	0.03	0.19	0.09	0.03	0.04	0.08	0.03
Cl4(56)	9.53	11.99	9.83	8.45	15.63	7.33	19.92	2.65	4.03	5.22
Cl4(60)	3.17	3.34	3.71	2.98	6.30	2.73	8.96	1.16	1.50	1.80
Cl4(64)	12.39	15.75	12.78	10.60	19.47	9.59	26.24	3.15	5.06	6.23
Cl4(66)	18.92	22.61	19.90	16.92	31.19	14.55	36.17	5.71	8.59	10.89
Cl4(70)	22.61	28.21	22.30	19.64	34.50	16.79	43.39	6.31	9.74	13.18
Cl4(71)	6.88	9.03	7.27	5.84	10.71	5.48	15.31	1.76	2.77	3.48
Cl4(74)	10.37	12.02	10.82	9.27	17.69	8.35	22.63	3.06	4.56	5.73
Cl4(77)	1.36	1.72	1.62	1.27	2.65	0.77	3.38	0.02	0.40	0.65
Cl4(81)	0.04	0.04	0.04	0.03	0.05	0.03	0.07	0.04	0.04	0.03
Cl5(82)	2.46	2.78	2.61	2.12	3.86	1.77	4.91	0.72	1.17	1.41
Cl5(83)/(119)	1.69	2.17	1.49	1.37	2.18	1.07	2.77	0.41	0.59	0.76
Cl5(84)	5.10	6.59	4.90	4.27	7.15	3.74	9.51	1.21	2.02	2.48
Cl5(85)	3.23	3.38	3.00	2.81	4.92	2.29	5.95	0.86	1.32	1.56
Cl5(87)	7.00	4.64	6.35	5.96	9.41	4.93	11.67	2.06	3.09	3.29
Cl5(91)	2.60	3.37	2.52	2.25	3.73	1.82	4.85	0.69	1.15	1.23
Cl5(92)	3.13	3.28	2.54	2.50	3.39	1.90	3.65	0.72	1.36	1.27
Cl5(95)	15.17	15.48	11.86	12.05	15.53	9.48	17.96	4.10	6.76	5.96
Cl5(97)	5.10	5.81	4.95	4.49	7.41	3.90	9.19	1.54	2.20	2.51
Cl5(99)	5.05	5.76	4.90	4.31	7.35	3.76	8.92	1.50	2.26	2.46
Cl5(100)	0.04	0.09	0.09	0.03	0.12	0.06	0.03	0.04	0.04	0.03

STATION_ID	21	2	26	12	7	22	3	25	5	27
FIELD SAMPLE_ID	FAD-005	FAD-008	FAD-012	FAD-015	FAD-021	FAD-022	FAD-023	FAD-024	FAD-025	FAD-026
SAMPLE DEPTH (from bottom)	0-0.3	0-0.3	0-0.3	0-0.3	0-0.3	0-0.3	0-0.3	0-0.3	0-0.3	0-0.3
DEPTH_UNIT	FT	FT	FT	FT	FT	FT	FT	FT	FT	FT
Cl5(101)	13.93	12.83	10.81	11.65	13.68	8.72	14.87	4.09	6.52	5.34
Cl5(105)	5.89	5.95	5.70	4.77	8.74	4.28	9.91	1.71	2.57	2.83
Cl5(110)	17.51	19.21	15.06	14.27	20.03	11.09	22.86	5.06	7.81	7.64
Cl5(114)	0.58	0.09	0.73	0.50	1.09	0.07	0.85	0.42	0.38	0.50
Cl5(115)	0.45	0.55	0.44	0.42	0.41	0.31	4.23	0.11	0.14	0.20
Cl5(118)	9.99	10.04	9.01	8.54	12.62	6.67	13.33	3.04	4.76	4.55
Cl5(107)/(123)	1.63	1.72	1.49	1.37	2.19	1.13	2.33	0.49	0.68	0.87
Cl5(124)	0.45	0.41	0.36	0.36	0.57	0.34	0.67	0.05	0.27	0.19
Cl5(126)	0.08	0.07	0.07	0.06	0.10	0.05	0.05	0.07	0.07	0.06
Cl6(128)	2.60	2.08	1.50	1.92	1.74	1.20	1.29	0.73	1.15	0.85
Cl6(130)	1.05	0.97	0.70	0.77	0.73	0.57	0.61	0.32	0.48	0.36
Cl6(134)	1.32	0.99	0.75	0.95	0.71	0.53	0.59	0.45	0.54	0.36
Cl6(135)	3.63	2.75	2.20	2.96	1.77	1.77	1.37	0.98	1.78	0.90
Cl6(136)	4.21	3.16	2.48	3.28	2.10	2.05	1.54	1.10	1.91	1.12
Cl6(137)	0.52	0.31	0.30	0.31	0.43	0.21	0.35	0.09	0.18	0.08
Cl6(138)	16.70	12.44	9.91	11.70	8.28	7.73	5.93	4.17	7.48	4.51
Cl6(141)	8.56	6.16	4.77	6.20	4.09	4.13	2.87	2.26	3.96	2.15
Cl6(144)	2.01	1.37	1.20	1.68	1.07	1.05	0.71	0.58	1.03	0.48
Cl6(146)	3.93	2.82	2.29	2.99	1.91	1.74	1.40	1.10	1.77	0.96
Cl6(149)	26.65	19.62	15.58	20.66	13.64	12.81	9.40	7.54	12.72	7.03
Cl6(151)	10.14	7.40	5.74	7.89	4.99	4.79	3.43	2.73	4.98	2.50
Cl6(132)/(153)/(168)	34.23	24.59	19.02	25.45	16.67	15.73	11.34	8.49	15.31	8.77
Cl6(156)	2.09	1.67	1.37	1.73	1.30	1.07	0.89	0.64	1.01	0.64
Cl6(157)	0.07	0.06	0.06	0.27	0.29	0.05	0.21	0.07	0.07	0.06
Cl6(129)/(158)	2.61	2.20	1.54	2.16	1.40	1.26	0.96	0.67	1.28	0.75
Cl6(163)	5.94	3.92	2.63	4.39	2.76	2.36	1.94	1.40	2.48	1.37
Cl6(164)	2.18	1.75	1.37	1.66	1.17	0.91	0.78	0.62	1.00	0.57
Cl6(166)	0.39	0.29	0.20	0.32	0.25	0.05	0.14	0.07	0.07	0.06
Cl6(167)	0.91	0.74	0.56	0.71	0.56	0.37	0.38	0.32	0.54	0.30
Cl6(169)	0.10	0.09	0.09	0.08	0.13	0.07	0.07	0.10	0.09	0.08
Cl7(170)	14.31	10.02	7.52	10.63	6.31	6.09	3.79	3.34	6.79	3.53
Cl7(171)	3.69	2.59	1.98	2.61	1.49	1.48	0.94	0.83	1.61	0.93
Cl7(172)	2.56	1.88	1.43	1.82	1.16	1.06	0.77	0.68	1.23	0.74
Cl7(174)	16.12	11.31	8.75	11.80	7.21	6.73	4.21	4.02	7.47	3.91
Cl7(176)	1.98	1.42	1.09	1.40	0.88	0.83	0.55	0.53	0.90	0.49
Cl7(177)	10.03	6.90	5.27	7.06	4.25	4.15	2.70	2.39	4.56	2.47
Cl7(178)	2.69	1.89	1.34	1.91	1.13	1.07	0.74	0.65	1.31	0.65
Cl7(179)	6.49	4.49	3.42	4.66	2.96	2.68	1.66	1.51	2.81	1.60
Cl7(180)	35.63	25.58	19.60	26.90	16.96	15.59	10.17	9.54	17.42	9.32
Cl7(183)	9.76	6.80	5.05	7.08	4.16	4.11	2.62	2.34	4.43	2.28
Cl7(184)	0.04	0.03	0.03	0.03	0.04	0.02	0.02	0.03	0.03	0.03
Cl7(185)	2.17	1.47	1.10	1.59	0.92	0.92	0.59	0.51	1.03	0.60
Cl7(187)	17.63	12.40	9.76	12.91	7.98	7.69	4.79	4.27	8.20	4.43
Cl7(189)	0.62	0.49	0.34	0.44	0.25	0.36	0.18	0.07	0.28	0.06
Cl7(190)	3.31	2.16	1.79	2.35	1.56	1.43	0.90	0.84	1.54	0.77
Cl7(193)	1.55	1.04	0.88	1.05	0.66	0.65	0.39	0.34	0.79	0.43
Cl8(194)	9.11	6.53	5.33	7.04	4.10	4.07	2.49	2.39	4.54	2.39
Cl8(195)	2.78	2.00	1.52	2.16	1.37	1.08	0.78	0.69	1.32	0.77
Cl8(199)	8.09	6.02	4.59	6.36	3.94	3.53	2.50	2.31	3.78	2.43
Cl8(200)	1.10	0.68	0.53	0.75	0.52	0.44	0.31	0.27	0.52	0.29
Cl8(201)	1.11	0.70	0.54	0.75	0.43	0.41	0.28	0.24	0.50	0.31
Cl8(202)	1.24	0.89	0.73	0.90	0.61	0.48	0.34	0.36	0.61	0.33
Cl8(196)/(203)	8.60	5.99	4.56	6.65	3.57	3.47	2.50	2.09	4.01	2.18
Cl8(205)	0.49	0.32	0.02	0.30	0.02	0.01	0.01	0.02	0.02	0.01
Cl9(206)	2.36	2.10	1.58	2.38	1.65	1.13	1.06	0.69	1.20	0.80
Cl9(207)	0.32	0.20	0.17	0.27	0.15	0.13	0.11	0.08	0.14	0.09
Cl9(208)	0.46	0.43	0.30	0.48	0.33	0.20	0.21	0.15	0.25	0.23
Cl10(209)	3.02	5.51	3.73	6.35	3.48	2.74	2.58	0.85	1.08	1.67
Sum 117 congeners	665	660	522	537	660	404	790	177	294	258

STATION_ID	SD-002	SD-003	SD-004	SD-005	)06 (SD-002D
FIELD SAMPLE_ID	E2LQ0	E2LQ1	E2LQ2	E2LQ3	E2LQ4
SAMPLE DEPTH (from bottom)	0-0.3	0-0.3	0-0.3	0-0.3	0-0.3
DEPTH_UNIT	FT	FT	FT	FT	FT
Biphenyl	20.36	32.78	50.92	15.26	18.34
Cl1(1)	0.07	0.05	0.12	0.06	0.06
Cl1(3)	0.03	0.02	0.06	0.03	0.03
Cl2(4)/(10)	10.02	9.72	18.99	9.16	10.08
Cl2(5)	0.11	0.08	0.20	0.10	0.10
Cl2(6)	5.52	5.27	9.04	5.76	5.47
Cl2(7)	1.08	0.99	1.70	1.09	1.01
Cl2(8)	25.31	22.63	41.07	24.95	25.43
Cl2(9)	1.85	1.69	3.08	1.70	1.68
Cl2(13)	2.91	2.60	4.73	2.61	3.21
Cl2(15)	22.40	17.46	28.91	21.07	22.06
Cl3(16)	32.61	23.20	42.27	28.88	31.51
Cl3(17)	28.86	22.86	41.06	26.43	30.43
Cl3(18)	58.89	46.04	85.85	54.08	59.63
Cl3(19)	5.72	4.94	9.70	4.72	5.27
Cl3(22)	41.15	29.22	56.46	38.93	42.55
Cl3(24)	0.06	0.04	0.11	0.06	0.05
Cl3(25)	9.84	5.89	12.05	8.49	10.18
Cl3(26)	19.64	13.87	25.28	19.75	19.84
Cl3(27)	4.18	3.54	6.17	3.83	4.15
Cl3(28)	83.84	58.01	107.32	78.15	80.64
Cl3(31)	82.14	57.68	105.34	79.07	81.48
Cl3(32)	20.23	15.46	27.12	18.51	19.43
Cl3(33)/(20)	59.87	41.44	79.44	58.53	59.04
Cl3(37)	42.72	31.94	55.25	38.89	42.51
Cl4(40)	16.27	12.09	22.10	14.32	13.28
Cl4(41)	13.75	8.81	16.09	11.77	14.00
Cl4(42)/(59)	36.55	24.82	58.02	34.19	36.36
Cl4(43)	6.83	5.88	16.68	5.77	8.16
Cl4(44)	94.41	71.34	140.27	86.24	96.39
Cl4(45)	16.65	11.84	24.02	14.50	16.79
Cl4(46)	8.41	6.71	15.05	7.19	8.46
Cl4(47)	36.00	30.21	58.74	39.58	35.24
Cl4(48)	21.38	16.24	31.58	20.85	20.80
Cl4(49)	66.27	54.18	99.80	65.13	67.08
Cl4(51)	9.97	7.86	16.23	11.07	9.58
Cl4(52)	94.36	71.43	136.87	86.89	93.82
Cl4(53)	16.58	13.90	26.56	16.75	17.07
Cl4(54)	0.06	0.04	0.11	0.06	0.05
Cl4(56)	36.72	24.92	44.88	35.84	34.63
Cl4(60)	29.30	17.36	31.95	27.25	28.68
Cl4(64)	41.22	27.97	51.00	39.22	40.91
Cl4(66)	79.47	55.32	104.46	75.17	76.13
Cl4(70)	111.72	77.24	145.55	106.64	108.83
Cl4(71)	25.13	18.97	32.64	24.21	24.93
Cl4(74)	48.65	31.85	63.89	47.81	47.83
Cl4(77)	8.93	7.41	17.65	11.29	12.40
Cl4(81)	0.06	2.46	0.11	0.06	0.05
Cl5(82)	36.94	23.43	42.54	36.44	38.09
Cl5(83)/(119)	15.54	12.83	25.16	15.23	14.67
Cl5(84)	38.98	30.80	58.60	38.78	37.28
Cl5(85)	22.72	16.76	31.60	21.07	21.44
Cl5(87)	117.70	78.38	139.48	106.68	113.39
Cl5(91)	25.23	22.71	42.80	26.66	25.40
Cl5(92)	68.78	38.79	69.81	59.21	71.00
Cl5(95)	241.63	160.03	292.79	224.93	234.49
Cl5(97)	53.60	41.30	75.35	48.38	52.20
Cl5(99)	56.48	44.25	81.51	53.73	54.51
Cl5(100)	2.80	2.46	5.14	4.07	2.82

STATION_ID	SD-002	SD-003	SD-004	SD-005	)06 (SD-002D
FIELD SAMPLE_ID	E2LQ0	E2LQ1	E2LQ2	E2LQ3	E2LQ4
SAMPLE DEPTH (from bottom)	0-0.3	0-0.3	0-0.3	0-0.3	0-0.3
DEPTH_UNIT	FT	FT	FT	FT	FT
Cl5(101)	205.27	133.20	249.65	196.99	195.49
Cl5(105)	69.13	45.12	77.41	69.37	68.72
Cl5(110)	234.91	164.98	301.97	221.29	226.42
Cl5(114)	0.14	0.10	0.24	0.13	0.12
Cl5(115)	1.71	2.36	2.44	1.41	0.67
Cl5(118)	119.87	79.56	146.90	115.83	111.81
Cl5(107)/(123)	14.73	10.63	19.05	14.65	15.51
Cl5(124)	7.23	4.27	7.09	6.22	6.84
Cl5(126)	0.11	0.08	0.20	0.10	0.10
Cl6(128)	71.67	43.34	71.95	70.05	66.11
Cl6(130)	33.63	20.55	30.49	35.85	33.32
Cl6(134)	43.11	25.60	40.62	42.95	41.56
Cl6(135)	120.57	68.71	111.20	119.11	115.99
Cl6(136)	131.15	76.17	130.00	127.40	126.70
Cl6(137)	11.05	7.31	14.14	11.14	9.43
Cl6(138)	275.95	168.48	291.31	277.95	254.56
Cl6(141)	221.99	127.31	209.35	223.38	208.48
Cl6(144)	68.90	37.78	60.55	69.19	65.87
Cl6(146)	109.01	61.02	104.54	110.73	102.23
Cl6(149)	597.49	354.48	625.25	590.44	564.07
Cl6(151)	372.23	203.62	316.82	373.02	362.18
Cl6(132)/(153)/(168)	621.46	368.52	633.23	624.74	582.04
Cl6(156)	69.59	36.77	60.56	73.19	65.46
Cl6(157)	6.29	3.90	6.13	6.53	4.78
Cl6(129)/(158)	81.82	46.82	73.41	82.91	74.63
Cl6(163)	144.44	91.63	132.21	164.05	155.57
Cl6(164)	70.63	39.50	62.58	72.87	68.02
Cl6(166)	10.82	5.66	12.41	10.26	9.99
Cl6(167)	28.53	15.39	23.00	29.89	25.09
Cl6(169)	0.14	0.10	0.26	0.14	0.13
Cl7(170)	0.08	0.05	458.57	0.07	0.07
Cl7(171)	102.26	56.48	87.84	109.25	95.29
Cl7(172)	73.73	39.81	62.35	77.65	66.79
Cl7(174)	345.24	195.56	323.73	360.32	320.58
Cl7(176)	72.86	37.83	55.08	77.55	70.68
Cl7(177)	252.17	139.41	218.22	265.28	234.79
Cl7(178)	78.19	43.21	64.86	82.75	73.73
Cl7(179)	216.56	117.31	173.43	224.69	208.96
Cl7(180)	533.03	304.17	543.76	563.94	487.19
Cl7(183)	307.60	163.76	244.25	331.77	292.29
Cl7(184)	0.05	0.04	0.09	0.09	0.04
Cl7(185)	70.12	37.29	55.72	74.53	66.35
Cl7(187)	379.72	214.82	352.26	397.51	354.10
Cl7(189)	14.72	8.27	9.16	17.85	14.01
Cl7(190)	81.78	43.69	70.33	91.41	74.87
Cl7(193)	40.15	24.24	32.24	42.17	36.72
Cl8(194)	0.06	0.04	0.11	0.06	0.05
Cl8(195)	72.82	36.81	53.88	85.09	66.88
Cl8(199)	193.53	103.13	158.57	214.38	174.92
Cl8(200)	31.84	16.22	24.75	35.07	29.72
Cl8(201)	32.19	16.38	23.13	35.93	30.33
Cl8(202)	36.24	19.06	27.78	40.41	34.60
Cl8(196)/(203)	172.75	94.51	150.22	192.97	158.96
Cl8(205)	8.28	4.05	6.21	10.13	7.62
Cl9(206)	33.81	16.37	24.35	42.98	30.32
Cl9(207)	5.15	2.65	3.79	6.47	4.59
Cl9(208)	6.86	3.65	5.03	8.07	6.54
Cl10(209)	0.90	0.63	1.42	1.44	0.86
Sum 117 congeners	8,964	5,468	9,826	9,073	8,536

Appendix C: RSC Data

Hunters Point Shipyard Immunoassay
Ashtabula River Immunoassay

Appendix C. Hunters Point RSC Data (ng/g)

Field ID	Sample Label	tPCB (ng/g) 1		2	3	Mean	Stdev	%RSD
SB75	CAD-461	1,587				1,587		
	CAD-462	635				635		
	CAD-463	2,409				2,409		
	CAD-464	780				780		
	CAD-465	556				556		
	CAD-466	354				354		
	CAD-467	406				406		
SB76	CAD-468	6,645				6,645		
	CAD-469	12,709				12,709		
	CAD-470	53,304		52,990		53,147	222	0.42%
	CAD-471	9,763		9,157		9,460	428	4.52%
	CAD-472	714		885		800	120	15.06%
	CAD-473	415				415		
	CAD-474	366				366		
SB77	CAD-475	1,732				1,732		
	CAD-476	2,332				2,332		
	CAD-477	131				131		
	CAD-478	102		132		117	22	18.39%
	CAD-479	151		178		164	20	11.98%
	CAD-480	227				227		
	CAD-481	96				96		
SB78	CAD-482	1,224				1,224		
	CAD-483	1,338		1,604		1,471	188	12.78%
	CAD-484	3,701	E	5,337		4,519	1,156	25.59%
	CAD-485	0.1				0.1		
	CAD-486	12		13		13		
	CAD-487	4				4		
	CAD-488	5				5		
SB79	CAD-489	1,233				1,233		
	CAD-490	970				970		
	CAD-491	826				826		
	CAD-492	1,882				1,882		
	CAD-493	4,518		7,334		5,926	1,991	33.59%
	CAD-494	12				12		
	CAD-495	1				1		

Appendix C. Hunters Point RSC Data (ng/g)

Field ID	Sample Label	tPCB (ng/g) 1	2	3	Mean	Stdev	%RSD
SB80	CAD-496	1,169			1,169		
	CAD-497	3,113			3,113		
	CAD-498	8,256	8,555		8,405	212	2.52%
	CAD-499	8,737			8,737		
	CAD-500	2,922			2,922		
	CAD-501	358			358		
	CAD-502	362			362		
SB81 R1	CAD-503	1,464			1,464		
	CAD-504	2,660			2,660		
	CAD-505	6,425			6,425		
	CAD-506	4,522	2,972		3,747	1,096	29.24%
	CAD-507	568			568		
	CAD-508	242			242		
	CAD-509	161			161		
SB82	CAD-510	1,007			1,007		
	CAD-511	1,957			1,957		
	CAD-512	2,179	1,999		2,089	128	6.12%
	CAD-513	407	261		334	104	31.01%
	CAD-514	150			150		
	CAD-515	104			104		
	CAD-516	106			106		
SB83	CAD-517	1,200			1,200		
	CAD-518	2,175			2,175		
	CAD-519	2,119	2,112		2,116	5	0.26%
	CAD-520	154	117		135	26	19.24%
	CAD-521	21			21		
	CAD-522	2			2		
	CAD-523	1			1		
SB84	CAD-524	1,386			1,386		
	CAD-525	1,263			1,263		
	CAD-526	3,006			3,006		
	CAD-527	948			948		
	CAD-528	15			15		
	CAD-529	5			5		
	CAD-530	7			7		
SB85	CAD-531	539			539		
	CAD-532	671			671		
	CAD-533	1,314			1,314		
	CAD-534	1,501			1,501		
	CAD-535	1,001			1,001		
	CAD-536	472			472		
	CAD-537	414			414		

Appendix C. Hunters Point RSC Data (ng/g)

Field ID	Sample Label	tPCB (ng/g) 1	2	3	Mean	Stdev	%RSD
SB86	CAD-538	280			280		
	CAD-539	328			328		
	CAD-540	245			245		
	CAD-541	88	45		67		
	CAD-542	164			164		
	CAD-543	383			383		
	CAD-544	714			714		
SB87	CAD-545	763			763		
	CAD-546	2,059			2,059		
	CAD-547	5,177	E 7,989		6,583	1,988	30.20%
	CAD-548	3,201			3,201		
	CAD-549	719			719		
	CAD-550	403			403		
	CAD-551	237			237		
SB88	CAD-552	317			317		
	CAD-553	446			446		
	CAD-554	307			307		
	CAD-555	305			305		
	CAD-556	1,029			1,029		
	CAD-557	572			572		
	CAD-558	180			180		
SB89	CAD-559	400			400		
	CAD-560	1,144			1,144		
	CAD-561	5,145			5,145		
	CAD-562	3,616			3,616		
	CAD-563	983			983		
	CAD-564	237			237		
	CAD-565	156			156		
SB90	CAD-566	590			590		
	CAD-567	909			909		
	CAD-568	4,045			4,045		
	CAD-569	4,533			4,533		
	CAD-570	1,054			1,054		
	CAD-571	272			272		
	CAD-572	184			184		
SB91	CAD-573	186			186		
	CAD-574	614			614		
	CAD-575	1,056			1,056		
	CAD-576	3,667			3,667		
	CAD-577	2,145			2,145		
	CAD-578	765			765		
	CAD-579	112	105		108	5	4.63%

Appendix C. Hunters Point RSC Data (ng/g)

Field ID	Sample Label	tPCB (ng/g) 1		2	3	Mean	Stdev	%RSD
SB92	CAD-580	219				219		
	CAD-581	333				333		
	CAD-582	766	E	467	492	575	166	28.78%
	CAD-583	1,598				1,598		
	CAD-584	639				639		
	CAD-585	261				261		
	CAD-586	129				129		
SB93	CAD-587	262				262		
	CAD-588	386				386		
	CAD-589	855				855		
	CAD-590	1,556				1,556		
	CAD-591	431				431		
	CAD-592	219				219		
	CAD-593	105				105		
SB94	CAD-594	527				527		
	CAD-595	953				953		
	CAD-596	2,044		1,800		1,922	173	8.99%
	CAD-597	2,240				2,240		
	CAD-598	349				349		
	CAD-599	164				164		
	CAD-600	27				27		
SB95	CAD-601	414				414		
	CAD-602	570				570		
	CAD-603	1,481				1,481		
	CAD-604	712				712		
	CAD-605	224				224		
	CAD-606	126				126		
	CAD-607	76				76		
SB96	CAD-608	397				397		
	CAD-609	846		662		754	130	17.20%
	CAD-610	851				851		
	CAD-611	550		436		493	81	16.36%
	CAD-612	204				204		
	CAD-613	119				119		
	CAD-614	94				94		
SB97	CAD-615	615				615		
	CAD-616	670				670		
	CAD-617	982				982		
	CAD-618	288				288		
	CAD-619	83				83		
	CAD-620	89				89		
	CAD-621	110				110		

Appendix C: Hunters Point RSC Data (ng/g)

Field ID	Sample Label	tPCB (ng/g) 1		2	3	Mean	Stdev	%RSD
SB98	CAD-622	210				210		
	CAD-623	461				461		
	CAD-624	707				707		
	CAD-625	2,413				2,413		
	CAD-626	7,304				7,304		
	CAD-627	1,221				1,221		
	CAD-628	377				377		
SB99	CAD-629	362				362		
	CAD-630	847				847		
	CAD-631	1,142		917		1,029	159	15.47%
	CAD-632	8,766				8,766		
	CAD-633	11,608	E	15,696		13,652	2,891	21.17%
	CAD-634	4,331				4,331		
	CAD-635	1,353				1,353		
SB100	CAD-636	349				349		
	CAD-637	934				934		
	CAD-638	1,313				1,313		
	CAD-639	9,034				9,034		
	CAD-640	14,662				14,662		
	CAD-641	5,460				5,460		
	CAD-642	902				902		
SB101	CAD-643	307				307		
	CAD-644	676				676		
	CAD-645	1,095				1,095		
	CAD-646	4,024				4,024		
	CAD-647	5,960	E	11,653		8,806	4,026	45.71%
	CAD-648	3,250				3,250		
	CAD-649	464				464		
SB102	CAD-650	368				368		
	CAD-651	771				771		
	CAD-652	1,124				1,124		
	CAD-653	5,799				5,799		
	CAD-654	7,836	E	14,438		11,137	4,668	41.91%
	CAD-655	11,531		14,880		13,206	2,368	17.93%
	CAD-656	1,807				1,807		
SB103	CAD-657	379				379		
	CAD-658	885				885		
	CAD-659	1,370				1,370		
	CAD-660	5,656				5,656		
	CAD-661	6,665	E	11,550		9,107	3,454	37.93%
	CAD-662	6,016				6,016		
	CAD-663	756				756		

Appendix C: Hunters Point RSC Data (ng/g)

Field ID	Sample Label	tPCB (ng/g) 1		2	3	Mean	Stdev	%RSD
SB104 R2	CAD-664	308				308		
	CAD-665	871				871		
	CAD-666	1,066				1,066		
	CAD-667	5,206				5,206		
	CAD-668	5,460	E	8,220		6,840	1,952	28.54%
	CAD-669	1,350				1,350		
	CAD-670	139				139		
SB105	CAD-671	138				138		
	CAD-672	160				160		
	CAD-673	482				482		
	CAD-674	755				755		
	CAD-675	4,495	E	6,558		5,527	1,459	26.40%
	CAD-676	4,698				4,698		
	CAD-677	3,056				3,056		
SB106	CAD-678	146				146		
	CAD-679	229				229		
	CAD-680	517				517		
	CAD-681	622				622		
	CAD-682	5,225	E	7,669		6,447	1,728	26.80%
	CAD-683	4,863				4,863		
	CAD-684	4,131		5,167		4,649	732	15.75%
SB107	CAD-685	189				189		
	CAD-686	195				195		
	CAD-687	339				339		
	CAD-688	605				605		
	CAD-689	1,834		1,622		1,728	150	8.66%
	CAD-690	1,647				1,647		
	CAD-691	3,106		2,634		2,870	334	11.63%
SB108	CAD-692	203				203		
	CAD-693	342				342		
	CAD-694	727				727		
	CAD-695	508				508		
	CAD-696	64				64		
	CAD-697	24				24		
	CAD-698	9				9		
SB109	CAD-699	193				193		
	CAD-700	439				439		
	CAD-701	276				276		
	CAD-702	605				605		
	CAD-703	575				575		
	CAD-704	89				89		
	CAD-705	6				6		

Appendix C: Hunters Point RSC Data (ng/g)

Field ID	Sample Label	tPCB (g/ng) 1		2	3	Mean	Stdev	%RSD
SB110 R3	CAD-706	179		186		182	5	2.82%
	CAD-707	377		291		334	61	18.33%
	CAD-708	443		491		467	34	7.25%
	CAD-709	27		16		22		
	CAD-710	8		12		10		
	CAD-711	5		9		7		
	CAD-712	5		12		8		
SB111	CAD-713	148				148		
	CAD-714	152				152		
	CAD-715	210				210		
	CAD-716	249				249		
	CAD-717	1,089	E	1,403		1,246	222	17.82%
	CAD-718	350				350		
	CAD-719	1,541				1,541		
SB112	CAD-720	142				142		
	CAD-721	315				315		
	CAD-722	446				446		
	CAD-723	636				636		
	CAD-724	1,423	E	2,103		1,763	480	27.25%
	CAD-725	508				508		
	CAD-726	111				111		
SB113	CAD-727	175				175		
	CAD-728	200				200		
	CAD-729	368				368		
	CAD-730	597		619		608	16	2.57%
	CAD-731	236				236		
	CAD-732	17				17		
	CAD-733	12				12		
SB114 R1	CAD-734	193				193		
	CAD-735	166				166		
	CAD-736	299				299		
	CAD-737	394				394		
	CAD-738	626				626		
	CAD-739	111		122		117	8	6.73%
	CAD-740	32				32		
SB115	CAD-741	320				320		
	CAD-742	484				484		
	CAD-743	561				561		
	CAD-744	350				350		
	CAD-745	113				113		
	CAD-746	37				37		
	CAD-747	19				19		

Appendix C: Hunters Point RSC Data (ng/g)

Field ID	Sample Label	tPCB (ng/) 1	2	3	Mean	Stdev	%RSD
SB116	CAD-748	205			205		
	CAD-749	238			238		
	CAD-750	183			183		
	CAD-751	279			279		
	CAD-752	233			233		
	CAD-753	297			297		
	CAD-754	391			391		
SB117	CAD-755	176			176		
	CAD-756	266			266		
	CAD-757	366			366		
	CAD-758	313			313		
	CAD-759	342			342		
	CAD-760	363			363		
	CAD-761	21			21		
SB118	CAD-762	100			100		
	CAD-763	162			162		
	CAD-764	352			352		
	CAD-765	420			420		
	CAD-766	196			196		
	CAD-767	33			33		
	CAD-768	11			11		
SB119	CAD-769	81			81		
	CAD-770	78			78		
	CAD-771	110			110		
	CAD-772	78			78		
	CAD-773	99			99		
	CAD-774	148			148		
	CAD-775	101			101		
SB120	CAD-776	128	135	93	119	5	4.15%
	CAD-777	201			201		
	CAD-778	331			331		
	CAD-779	473			473		
	CAD-780	495	484		489	8	1.64%
	CAD-781	1			1		
	CAD-782	4			4		
SB121	CAD-783	216			216		
	CAD-784	359			359		
	CAD-785	526			526		
	CAD-786	1,119	1,634		1,376	364	26.42%
	CAD-787	836			836		
	CAD-788	204			204		
	CAD-789	66			66		

Appendix C: Hunters Point RSC Data (ng/g)

Field ID	Sample Label	tPCB (ng/g) 1		2	3	Mean	Stdev	%RSD
OR122	CAD-790	250		252		251	2	0.62%
	CAD-791	328				328		
	CAD-792	315				315		
	CAD-793	94		126		110	23	20.70%
	CAD-794							
	CAD-795							
	CAD-796							
OR123	CAD-797	124		159		141	25	17.59%
	CAD-798	128				128		
	CAD-799	33		67		50		
	CAD-800							
	CAD-801							
	CAD-802							
	CAD-803							
SB166	CAD-804	411				411		
	CAD-805	574				574		
	CAD-806	751				751		
	CAD-807	457				457		
	CAD-808	165				165		
	CAD-809	98				98		
	CAD-810	58				58		
SB167	CAD-811	344				344		
	CAD-812	220				220		
	CAD-813	334				334		
	CAD-814	37				37		
	CAD-815	77				77		
	CAD-816	88				88		
	CAD-817	24				24		
SB103DUP	CAD-818	379				379		
	CAD-819	1,140				1,140		
	CAD-820	1,225				1,225		
	CAD-821	6,590				6,590		
	CAD-822	7,083	E	11,580		9,331	3,180	34.08%
	CAD-823	3,447				3,447		
	CAD-824	305				305		
SB89DUP	CAD-825	371				371		
	CAD-826	738				738		
	CAD-827	3,285				3,285		
	CAD-828	4,472	E	5,661		5,066	840	16.59%
	CAD-829	1,062				1,062		
	CAD-830	302				302		
	CAD-831	141				141		

Appendix C: Hunters Point RSC Data (ng/g)

Field ID	Sample Label	tPCB (ng/g) 1		2	3	Mean	Stdev	%RSD
SB115DUP	CAD-832	452				452		
	CAD-833	504				504		
	CAD-834	585				585		
	CAD-835	402				402		
	CAD-836	235				235		
	CAD-837	92				92		
	CAD-838	13				13		
SB112DUP	CAD-839	129				129		
	CAD-840	180				180		
	CAD-841	288				288		
	CAD-842	437				437		
	CAD-843	3,217	E	2,359		2,788	606	21.75%
	CAD-844	325				325		
	CAD-845	59				59		
SB117DUP	CAD-846	145				145		
	CAD-847	185				185		
	CAD-848	286				286		
	CAD-849	281				281		
	CAD-850	344				344		
	CAD-851	36				36		
	CAD-852	23				23		

Definitions:

Mean: Arithmethic Mean

Stdev: Standard Deviation from replicate assay analyses (n=2 or 3)

% RSD: Percent Relative Standard Deviation [{stdev/mean} * 100]

Label: **SB =** South Basin, **DUP** = Field Duplicate,
R = Field Resample, **E** = Laboratory Extraction Duplicate

Appendix C. Ashtabula RSC Data (ng/g, dry weight)

STATION_ID	SAMPLE_ID	RESULT
T170A	T170-A-KJI	702
T170A	T170-A-NML	9,357
T170A	T170-A-ZY	40.0
T170B	T170-B-LKJ	1,050
T170B	T170-B-ONM	18,734
T170B	T170-B-VU	445
T170A	T170A 1.3-2FT	96.4
T170A	T170A 10-11FT	11,893
T170A	T170A 17-18FT	332
T170A	T170A 2-3FT	61.7
T170A	T170A 3-4FT	186
T170A	T170A 4-5FT	200
T170A	T170A 5-6FT	261
T170A	T170A 6-7FT	310
T170A	T170A 7-8FT	17,108
T170A	T170A 8-9FT	6,938
T170A	T170A 9-10FT	15,718
T170B	T170B 0-1FT	29.3
T170B	T170B 1-2FT	11.6
T170B	T170B 16.1-17.1FT	695
T170B	T170B 2.1-3FT	253
T170B	T170B 3-4FT	352
T170B	T170B 5.5-6FT	339
T170B	T170B 6-7FT	11,031
T170B	T170B 7-8FT	22,642
T170B	T170B 8-9FT	16,834
T170B	T170B 9-10FT	36,545
T171A	T171-A-JIH	742
T171A	T171-A-MLK	2,177
T171A	T171-A-PON	25,275
T171B	T171-B-IHG	1,039
T171B	T171-B-LKJ	52,240
T171B	T171-B-QP	2,488
T171B	T171-B-TS	616
T171B	T171-B-YX	23.7
T171A	T171A 0-1FT	200
T171A	T171A 1-2FT	8.0
T171A	T171A 18.4-19.4FT	317
T171A	T171A 2-3FT	191
T171A	T171A 3-4FT	178
T171A	T171A 4-5FT	277

STATION_ID	SAMPLE_ID	RESULT
T176A	T176A 4.5FT	9,167
T176A	T176A 5-6FT	6,890
T176A	T176A 6-7FT	6,766
T176A	T176A 7-8FT	3,904
T176A	T176A 8-8.77FT	2,846
T176A	T176A 8.77-9.55FT	4,136
T176A	T176A 9.55-9.8FT	184
T176A	T176A 9.8-10.55FT	537
T176B	T176B 0-1FT	7,598
T176B	T176B 1-2FT	4,444
T176B	T176B 2-3FT	5,107
T176B	T176B 3-4FT	8,843
T176B	T176B 4-5FT	7,150
T176B	T176B 5-6FT	11,615
T176B	T176B 6-7FT	7,209
T176B	T176B 7-8FT	9,541
T176B	T176B 8-8.95FT	7,761
T176B	T176B 8.95-9.9FT	5,108
T176B	T176B 9.9-10.9FT	3,072
T177A	T177-A-RQ	10,856
T177A	T177-A-WV	2,750
T177B	T177-B-NML	8,381
T177B	T177-B-QPO	42,008
T177A	T177A 0-1FT	19.1
T177A	T177A 1-1.45FT	488
T177A	T177A 1.45-2FT	2,798
T177A	T177A 3.3-4FT	7,617
T177A	T177A 4-5FT	11,068
T177A	T177A 5-6.15FT	2,593
T177A	T177A 6.7-7.3FT	957
T177A	T177A 7.3-7.65FT	572
T177A	T177A 7.65-8.3FT	213
T177B	T177B 0-1FT	765
T177B	T177B 1-1.4FT	160
T177B	T177B 1.4-2FT	1,668
T177B	T177B 14.1-15.1FT	461
T177B	T177B 2-3FT	1,564
T177B	T177B 3-4FT	2,540
T177B	T177B 4-5FT	5,481
T177B	T177B 5-6FT	6,042
T177B	T177B 6-7FT	7,476

Appendix C. Ashtabula RSC Data (ng/g, dry weight)

STATION_ID	SAMPLE_ID	RESULT
T171A	T171A 5-6FT	660
T171A	T171A 6-7FT	963
T171A	T171A 7-8FT	16,733
T171A	T171A 8-9FT	11,635
T171A	T171A 9-10FT	10,617
T171B	T171B 0-1FT	15.9
T171B	T171B 10-11FT	51,437
T171B	T171B 17.2-17.6FT	749
T171B	T171B 17.6-18.2FT	1,617
T171B	T171B 2.3-3FT	338
T171B	T171B 3-4FT	466
T171B	T171B 4-5FT	499
T171B	T171B 8-9FT	7,636
T171B	T171B 9-10FT	24,120
T171B	T171B6.3-6.5FT	1,508
T172A	T172-A-LKJI	931
T172A	T172-A-ON	3,856
T172A	T172-A-RQP	40,824
T172B	T172-B-KJI	1,221
T172B	T172-B-NML	4,092
T172B	T172-B-PO	40,667
T172B	T172-B-XW	198
T172A	T172A 0-1FT	147
T172A	T172A 1-2FT	175
T172A	T172A 13-13.8FT	1,754
T172A	T172A 16.5-17.5FT	692
T172A	T172A 2-3FT	413
T172A	T172A 3-4FT	258
T172A	T172A 4-5FT	20,753
T172A	T172A 5-6FT	6,343
T172A	T172A 6-7FT	31,370
T172A	T172A 7-8FT	470,031
T172B	T172B 0-0.5FT	115
T172B	T172B 0.5-1FT	453
T172B	T172B 14.4-15.4FT	170
T172B	T172B 2.4-3FT	253
T172B	T172B 3-4FT	531
T172B	T172B 4-5FT	1,465
T172B	T172B 5-6FT	2,302
T172B	T172B 6-7FT	37,674
T172B	T172B 7-8FT	13,479

STATION_ID	SAMPLE_ID	RESULT
T177B	T177B 7-8FT	5,298
T178B	T178-B-SRQ	19,550
T178C	T178-C-MLKJ	43,523
T178C	T178-C-PON	64,191
T178C	T178-C-SRQ	43,085
T178A	T178A 0-1FT	15.1
T178A	T178A 1-2FT	11.5
T178A	T178A 2-3FT	36
T178A	T178A 3-4FT	50.7
T178A	T178A 4-5FT	47.2
T178A	T178A 5-6.05FT	135
T178A	T178A 6.05-7.1FT	1,246
T178A	T178A 7.1-8.1FT	1,353
T178B	T178B 0-1FT	143
T178B	T178B 1-2FT	1,873
T178B	T178B 10-10.5FT	116
T178B	T178B 10.5-11FT	191
T178B	T178B 2-3FT	2,118
T178B	T178B 3-4FT	4,790
T178B	T178B 4-5FT	7,446
T178B	T178B 5-6FT	8,216
T178B	T178B 6-7FT	8,175
T178C	T178C 0.5-1FT	701
T178C	T178C 1-2FT	1,252
T178C	T178C 16.6-17.6FT	451
T178C	T178C 2-3FT	1,279
T178C	T178C 3-4FT	1,309
T178C	T178C 4-5FT	3,251
T178C	T178C 5-6FT	5,124
T178C	T178C 6-7FT	4,629
T179A	T179-A-UTSR	0
T179B	T179-B-ON	2,010
T179B	T179-B-RQP	18,102
T179B	T179-B-UTS	44,667
T179C	T179-C-JIH	3,197
T179C	T179-C-MLK	4,028
T179C	T179-C-PON	56,393
T179C	T179-C-SRQ	23,881
T179C	T179-C-UT	1,200
T179A	T179A 0-1FT	55.1
T179A	T179A 1-2FT	23.6

Appendix C. Ashtabula RSC Data (ng/g, dry weight)

STATION_ID	SAMPLE_ID	RESULT
T173A	T173-A-JIH	907
T173A	T173-A-MLK	4,150
T173B	T173-B-MLK	3,200
T173B	T173-B-XW	53.7
T173B	T173-B-ZY	200
T173A	T173A 0-1FT	0
T173A	T173A 1-2FT	200
T173A	T173A 10-11FT	58,960
T173A	T173A 11-12FT	52,264
T173A	T173A 12-13FT	35,708
T173A	T173A 18.7-19.7FT	1,012
T173A	T173A 2-3FT	3.99
T173A	T173A 3-4FT	0
T173A	T173A 4-5FT	200
T173A	T173A 5-6FT	66.0
T173A	T173A 6-7FT	573
T173A	T173A 7-8FT	1,957
T173A	T173A 8-9FT	12,453
T173A	T173A 9-10FT	25,437
T173B	T173B 10-11FT	45,788
T173B	T173B 11-12FT	51,419
T173B	T173B 15.3-16.3FT	165
T173B	T173B 3-4FT	254
T173B	T173B 4-5FT	2,899
T173B	T173B 5-6FT	1,163
T173B	T173B 6-7FT	761
T173B	T173B 7-8FT	3,000
T173B	T173B 8-9FT	22,012
T173B	T173B 9-10FT	27,269
T174A	T174-A-NML	767
T174A	T174-A-QPO	7,345
T174B	T174-B-QPO	2,268
T174A	T174A 0-1FT	200
T174A	T174A 1-2FT	7.7
T174A	T174A 14.4-15.4FT	563
T174A	T174A 2-3FT	135
T174A	T174A 3-4FT	393
T174A	T174A 4-5FT	1,080
T174A	T174A 5-6FT	38,538
T174A	T174A 6-7FT	22,746
T174A	T174A 7-8FT	20,457

STATION_ID	SAMPLE_ID	RESULT
T179A	T179A 2-3FT	49.5
T179A	T179A 3-4FT	62.3
T179A	T179A 4-5FT	15.2
T179A	T179A 8.4-9.4FT	176
T179B	T179B 0-1FT	262
T179B	T179B 1-2FT	506
T179B	T179B 12.5-13.5FT	1,201
T179B	T179B 2-3FT	2,511
T179B	T179B 3-4FT	3,680
T179B	T179B 4-5FT	5,325
T179C	T179C 1.15-2FT	814
T179C	T179C 18.5-19.5FT	766
T179C	T179C 2-3FT	947
T179C	T179C 3-4FT	1,008
T179C	T179C 4-5FT	2,200
T179C	T179C 5-6FT	1,476
T180B	T180-B-RQ	214
T180B	T180-B-UTS	1,741
T180C	T180-C-KJI	1,600
T180C	T180-C-ONML	6,256
T180C	T180-C-RQP	73,313
T180C	T180-C-UTS	35,857
T180D	T180-D-IHG	2,006
T180D	T180-D-LKJ	14,676
T180D	T180-D-ONM	55,068
T180D	T180-D-RQP	28,168
T180D	T180-D-UTS	39,960
T180A	T180A 0-1FT	64.3
T180A	T180A 1-2FT	73.4
T180A	T180A 2-3FT	101
T180A	T180A 3-4FT	46.4
T180A	T180A 4-4.8FT	54.3
T180A	T180A 4.8-5.6FT	111
T180A	T180A 5.6-6.6FT	191
T180B	T180B 0-1FT	211
T180B	T180B 1-2FT	345
T180B	T180B 2-3FT	1,213
T180B	T180B 3-4FT	2,458
T180B	T180B 4-5FT	2,776
T180C	T180C 0-1FT	774
T180C	T180C 1-2FT	2,300

Appendix C. Ashtabula RSC Data (ng/g, dry weight)

STATION_ID	SAMPLE_ID	RESULT
T174A	T174A 8-9FT	38,576
T174B	T174B 0-1FT	71.1
T174B	T174B 1-2FT	311
T174B	T174B 11.7-12.7FT	197
T174B	T174B 2-3FT	698
T174B	T174B 3-4FT	2,839
T174B	T174B 4-5FT	3,746
T174B	T174B 5-6FT	52,523
T174B	T174B 6-7FT	44,446
T174B	T174B 7-8FT	62,308
T174B	T174B 8-9FT	47,431
T175A	T175-A-ON	1,160
T175A	T175-A-ZY	73.4
T175A	T175A 1.5-2FT	9,917
T175A	T175A 12.1-12.5FT	476
T175A	T175A 12.5-13.1FT	270
T175A	T175A 2-3FT	24,096
T175A	T175A 3-4FT	12,302
T175A	T175A 4-5FT	26,056
T175A	T175A 5-6FT	54,799
T175A	T175A 6-7FT	36,434
T175A	T175A 7-8FT	63,356
T175A	T175A 8-9FT	48,132
T175A	T175A 9-10FT	1,751
T175B	T175B 0-1FT	110
T175B	T175B 1-2FT	1,403
T175B	T175B 10.7-11.3FT	699
T175B	T175B 11.3-11.7FT	81.0
T175B	T175B 2-3FT	5,785
T175B	T175B 3-4FT	5,084
T175B	T175B 4-5FT	3,569
T175B	T175B 5-6FT	9,904
T175B	T175B 6-7FT	8,631
T175B	T175B 7-8FT	6,688
T175B	T175B 8-9FT	9,236
T175B	T175B 9-9.85FT	8,828
T175B	T175B 9.85-10.7FT	3,470
T176A	T176A 0-1FT	3,526
T176A	T176A 1-2FT	5,592
T176A	T176A 2-3FT	4,547
T176A	T176A 3-4FT	6,034

STATION_ID	SAMPLE_ID	RESULT
T180C	T180C 16.6-17.6FT	596
T180C	T180C 2-3FT	2,324
T180C	T180C 3-4FT	3,525
T180C	T180C 4-5FT	5,073
T180D	T180D 0-1FT	40.0
T180D	T180D 1-2FT	102
T180D	T180D 2-3FT	632
T180D	T180D 20.3-21.3FT	507
T180D	T180D 3-4FT	2,472
T180D	T180D 4-5FT	1,425
T181C	T181-C-RQP	11,949
T181C	T181-C-TS	13,586
T181D	T181-D-KJIH	0
T181D	T181-D-NML	801
T181D	T181-D-QPO	7,881,167
T181D	T181-D-TSR	10,143,844
T181A	T181A 0.5-1FT	38.7
T181A	T181A 1-2FT	200
T181A	T181A 2-3.2FT	91.4
T181A	T181A 3.2-4.2FT	190
T181B	T181B 0-1FT	60.7
T181B	T181B 1-2FT	239
T181B	T181B 2-3FT	360
T181B	T181B 3-4FT	2,717
T181B	T181B 4-5.2FT	4,556
T181B	T181B 5.2-6.4FT	3,858
T181B	T181B 6.4-7.4FT	1,057
T181C	T181C 0.4-1FT	1,616
T181C	T181C 1-2FT	2,845
T181C	T181C 10.8-11.8FT	541
T181C	T181C 2-3FT	6,982
T181C	T181C 3-4FT	7,722
T181C	T181C 4-5FT	9,245
T181C	T181C 5-6FT	21,407
T181D	T181D 0-1FT	2,503
T181D	T181D 1-2FT	7,193
T181D	T181D 18.5-19.5FT	1,574
T181D	T181D 2-3FT	6,234
T181D	T181D 3-4FT	7,911
T181D	T181D 4-5FT	15,995
T181D	T181D 5-6FT	30,067

Appendix D: Polytopic Vector Analysis (PVA) Solutions

Hunters Point Shipyard (3 EM Sources; Based on 38 Congeners; 99 Samples)

Ashtabula River (4 EM Sources; Based on 83 Congeners; 252 Samples)

Appendix D. PVA Three End Member (EM) Solution for Hunters Point Data

		EM Compositions		
	Congener	EM1	EM2	EM3
1	8	0	0	0.2787
2	18	0.1555	0	0.2693
3	21+33+20	0.1803	0	0.3768
4	28	0.0161	0	0.5351
5	31	0.286	0	0.4009
6	44	2.2544	0	0.6297
7	49	1.4674	0	1.4853
8	52	5.3081	0	1.6579
9	56	0.805	0	0.3182
10	60	0.5718	0.1504	0.023
11	66	1.4347	0	1.1951
12	70	4.7614	0	1.1941
13	74	1.2394	0	0.456
14	105	4.86	0	1.1886
15	110	12.798	0.6674	4.887
16	118	9.2403	0.6261	3.5744
17	87	5.9064	0	1.027
18	90+101	10.4574	1.9346	5.5804
19	95+88	7.1518	0.995	4.0506
20	97	3.3952	0	1.2485
21	99	3.4746	0	3.8554
22	128	2.3331	0.7353	1.2731
23	129+158	1.712	0.8808	1.0283
24	132+168+153	5.9089	17.5526	16.5542
25	138	7.5091	8.8523	6.15
26	151	1.412	4.192	3.2801
27	156	1.6034	0.6002	0.8108
28	170	0.4605	9.735	4.4371
29	174	0	3.8637	6.6987
30	177	0.401	5.1885	3.1028
31	180	0.5367	20.3379	9.1304
32	183	1.0449	4.4577	2.5425
33	187	0.2352	8.9771	5.4999
34	194	0.428	4.2253	2.3388
35	195	0	1.8832	1.0214
36	201+204	0	0.5481	0.339
37	203	0.3429	2.8069	0.9746
38	206	0.3087	0.79	0.5866

Appendix D. Cont.

	PVA 3 EM Solution	Mixing Proportions		
	Sample (core horizon)	EM1	EM2	EM3
1	SB-075 (0-5 cm)	11%	50%	41%
2	SB-075 (30-60 cm)	6%	25%	70%
3	SB-075 (90-120 cm)	33%	1%	66%
4	SB-075 (150-180 cm)	13%	50%	39%
5	SB-079 (0-5 cm)	1%	68%	33%
6	SB-079 (30-60 cm)	4%	69%	30%
7	SB-079 (90-120 cm)	-2%	56%	47%
8	SB-087 (0-5 cm)	34%	22%	45%
9	SB-087 (15-30 cm)	68%	9%	25%
10	SB-087 (45-60 cm)	44%	25%	33%
11	SB-087 (75-90 cm)	29%	31%	41%
12	SB-092 (0-5 cm)	16%	38%	47%
13	SB-092 (5-15 cm)	20%	35%	46%
14	SB-092 (15-30 cm)	21%	30%	49%
15	SB-092 (30-45 cm)	27%	35%	39%
16	SB-092 (45-60 cm)	39%	36%	26%
17	SB-092 (60-75 cm)	43%	30%	28%
18	SB-092 (75-90 cm)	33%	42%	27%
19	SB-100 (0-5 cm)	23%	20%	57%
20	SB-100 (15-30 cm)	6%	33%	63%
21	SB-100 (45-60 cm)	40%	16%	45%
22	SB-100 (75-90 cm)	46%	11%	43%
23	SB-104 (0-5 cm)	19%	20%	62%
24	SB-104 (15-30 cm)	17%	7%	76%
25	SB-104 (45-60 cm)	55%	10%	36%
26	SB-105 (0-5 cm)	5%	6%	89%
27	SB-105 (15-30 cm)	14%	12%	75%
28	SB-105 (45-60 cm)	7%	28%	66%
29	SB-105 (75-90 cm)	34%	21%	46%
30	SB-106 (0-5 cm)	21%	38%	42%
31	SB-106 (5-15 cm)	8%	30%	63%
32	SB-106 (15-30 cm)	16%	32%	53%
33	SB-106 (30-45 cm)	17%	23%	61%

Appendix D. Cont.

		Mixing Proportions		
	Sample (core horizon)	EM1	EM2	EM3
34	SB-106 (45-60 cm)	3%	46%	52%
35	SB-106 (60-75 cm)	49%	10%	42%
36	SB-106 (75-90 cm)	25%	38%	38%
37	SB-108 (0-5 cm)	10%	50%	42%
38	SB-108 (5-15 cm)	25%	37%	39%
39	SB-108 (15-30 cm)	26%	35%	40%
40	SB-108 (30-45 cm)	33%	31%	37%
41	SB-120 (30-45 cm)	13%	18%	70%
42	OR-123 (0-5 cm)	9%	58%	35%
43	SB-081 (0-2 cm)	17%	51%	34%
44	SB-081 (2-4 cm)	17%	55%	29%
45	SB-081 (4-6 cm)	16%	59%	27%
46	SB-081 (6-8 cm)	17%	54%	30%
47	SB-081 (8-10 cm)	12%	54%	36%
48	SB-081 (10-12 cm)	14%	56%	32%
49	SB-081 (12-14 cm)	15%	55%	32%
50	SB-081 (14-16 cm)	13%	55%	34%
51	SB-081 (16-18 cm)	19%	54%	29%
52	SB-081 (18-20 cm)	29%	46%	26%
53	SB-081 (20-25 cm)	43%	39%	20%
54	SB-081 (25-30 cm)	59%	28%	14%
55	SB-081 (30-40 cm)	65%	19%	18%
56	SB-081 (40-50 cm)	62%	35%	5%
57	SB-081 (50-60 cm)	50%	25%	26%
58	SB-094 (2-4 cm)	15%	48%	38%
59	SB-094 (4-6 cm)	14%	44%	44%
60	SB-094 (6-8 cm)	11%	38%	53%
61	SB-094 (10-12 cm)	20%	54%	27%
62	SB-094 (12-14 cm)	14%	46%	41%
63	SB-094 (14-16 cm)	11%	42%	48%
64	SB-094 (16-18 cm)	8%	39%	55%
65	SB-094 (20-25 cm)	17%	40%	44%
66	SB-094 (50-60 cm)	58%	32%	12%

Appendix D. Cont.

		Mixing Proportions		
	Sample (core horizon)	EM1	EM2	EM3
67	SB-110 (0-2 cm)	7%	47%	47%
68	SB-110 (2-4 cm)	5%	48%	48%
69	SB-110 (4-6 cm)	7%	45%	49%
70	SB-110 (6-8 cm)	9%	43%	50%
71	SB-110 (8-10 cm)	13%	43%	45%
72	SB-110 (10-12 cm)	11%	41%	49%
73	SB-110 (12-14 cm)	10%	43%	48%
74	SB-110 (14-16 cm)	3%	49%	49%
75	SB-110 (16-18 cm)	7%	53%	41%
76	SB-110 (18-20 cm)	10%	59%	33%
77	SB-110 (20-25 cm)	7%	45%	49%
78	SB-110 (25-30 cm)	11%	43%	48%
79	SB-110 (30-40 cm)	17%	24%	60%
80	SB-110 (40-50 cm)	14%	29%	58%
81	SB-110 (50-60 cm)	5%	24%	73%
82	SB-114 (0-2 cm)	17%	47%	38%
83	SB-114 (2-4 cm)	8%	44%	49%
84	SB-114 (6-8 cm)	17%	48%	36%
85	SB-114 (8-10 cm)	5%	37%	59%
86	SB-114 (10-12 cm)	1%	37%	63%
87	SB-114 (12-14 cm)	6%	35%	60%
88	SB-114 (14-16 cm)	8%	43%	50%
89	SB-114 (16-18 cm)	10%	38%	53%
90	SB-114 (18-20 cm)	6%	37%	58%
91	SB-114 (30-40 cm)	6%	31%	64%
92	SB-114 (40-50 cm)	13%	18%	70%
93	SB-114 (50-60 cm)	11%	9%	81%
94	SB-094 (0-2 cm)	24%	50%	27%
95	SB-094 (8-10 cm)	13%	46%	42%
96	SB-094 (18-20 cm)	10%	51%	40%
97	SB-094 (25-30 cm)	22%	38%	42%
98	SB-094 (30-40 cm)	45%	33%	24%
99	SB-094 (40-50 cm)	62%	44%	-4%

Appendix D. PVA Four End Member (EM) Solution for Ashtabula River

		EM Compositions			
	Congener	EM1	EM2	EM3	EM4
1	Cl2(4)/(10)	0.1051	0.2705	0.1830	0.0000
2	Cl2(6)	0.0000	1.7578	0.1763	0.0000
3	Cl2(8)	0.2735	0.8239	0.3420	0.0000
4	Cl2(13)	0.0000	0.6463	0.1262	0.0000
5	Cl2(15)	0.0848	0.3347	0.5353	0.0000
6	Cl3(16)	1.1011	1.3716	0.0000	0.2059
7	Cl3(17)	1.0524	2.2432	0.0000	0.5920
8	Cl3(18)	3.2936	6.5409	0.0000	0.1515
9	Cl3(19)	0.1560	0.2847	0.0403	0.0000
10	Cl3(22)	1.5768	1.4406	0.1578	0.1963
11	Cl3(25)	0.0000	6.3426	0.5676	0.0000
12	Cl3(26)	0.0000	6.6332	0.8426	0.0000
13	Cl3(27)	0.0949	0.2183	0.0748	0.0000
14	Cl3(28)	4.3458	6.5693	0.0000	0.9436
15	Cl3(31)	4.9613	8.6024	0.0000	0.4278
16	Cl3(32)	0.8193	0.9778	0.0000	0.0010
17	Cl3(33)/(20)	2.2097	2.0871	0.0000	0.9975
18	Cl3(37)	0.9840	0.1682	0.4078	0.0630
19	Cl4(40)	1.3231	1.1412	0.0000	0.1580
20	Cl4(41)	0.6597	0.0415	0.3296	0.0000
21	Cl4(42)/(59)	2.6204	3.0971	0.0000	0.6264
22	Cl4(43)	0.2732	0.4779	0.0411	0.0000
23	Cl4(44)	6.6089	7.7315	0.0000	2.5115
24	Cl4(45)	1.2787	1.2802	0.0000	0.1730
25	Cl4(46)	0.5525	0.6431	0.0000	0.0000
26	Cl4(47)	1.7678	1.8579	0.0000	0.8269
27	Cl4(48)	1.7663	0.0000	0.0000	0.0000
28	Cl4(49)	5.0132	7.7570	0.0000	1.6390
29	Cl4(51)	0.3163	0.4262	0.0032	0.0104
30	Cl4(52)	7.3176	9.6723	0.0000	1.3925
31	Cl4(53)	1.1281	1.3248	0.0000	0.0506
32	Cl4(56)	3.4339	1.2568	0.0000	0.6550
33	Cl4(60)	1.1931	0.0000	0.7302	0.0000
34	Cl4(64)	3.5054	3.3264	0.0000	0.2990
35	Cl4(66)	7.2635	0.0612	0.0000	2.7088
36	Cl4(70)	8.4708	3.3041	0.0000	2.9786

Appendix D. Cont.

		EM Compositions			
	Congener	EM1	EM2	EM3	EM4
37	Cl4(71)	2.0109	1.9183	0.0000	0.3864
38	Cl4(74)	3.7253	0.0000	0.0000	0.5225
39	Cl4(77)	0.6037	0.0074	0.0068	0.1924
40	Cl5(82)	0.6469	0.3197	0.4826	0.0000
41	Cl5(83)/(119)	0.3352	0.3998	0.0944	0.6515
42	Cl5(84)	1.4452	1.3317	0.1369	0.5767
43	Cl5(85)	0.7894	0.4073	0.4134	0.0000
44	Cl5(87)	1.2046	0.0000	1.5903	0.2597
45	Cl5(91)	0.6043	0.5972	0.2701	0.3351
46	Cl5(92)	0.3048	0.3438	0.7546	0.8113
47	Cl5(95)	1.9435	1.5931	2.8751	1.4614
48	Cl5(97)	1.1868	0.1856	0.6142	0.6505
49	Cl5(99)	1.3258	0.0000	0.3997	1.6539
50	Cl5(101)	2.0435	0.0000	2.3551	2.1381
51	Cl5(105)	1.1150	0.0000	1.2772	0.0000
52	Cl5(110)	2.9533	2.0332	2.5410	2.8373
53	Cl5(118)	1.9581	0.0000	1.2551	2.0752
54	Cl5(107)/(123)	0.1762	0.1361	0.2592	0.5562
55	Cl6(128)	0.0570	0.0126	0.9596	0.0000
56	Cl6(130)	0.0000	0.0021	0.4349	0.5127
57	Cl6(134)	0.0000	0.0000	0.5326	0.2114
58	Cl6(135)	0.0000	0.0000	1.5637	0.1681
59	Cl6(136)	0.0000	0.0000	1.6908	0.7388
60	Cl6(138)	0.0000	0.0000	4.4381	0.8236
61	Cl6(141)	0.0000	0.0000	3.1247	0.0000
62	Cl6(146)	0.0000	0.0000	1.4138	0.4377
63	Cl6(149)	0.0000	0.0000	8.8152	0.5251
64	Cl6(151)	0.0000	0.0000	4.6665	0.0000
65	Cl6(132)/(153)/(168)	0.0000	0.0000	9.6592	0.6840
66	Cl6(156)	0.0000	0.0000	0.9158	0.8502
67	Cl6(129)/(158)	0.0000	0.0000	1.0905	0.0302
68	Cl6(163)	0.0000	0.0000	2.0790	0.1396
69	Cl6(164)	0.0000	0.0000	0.9278	0.0000
70	Cl7(172)	0.0000	0.0000	0.9674	0.0000
71	Cl7(174)	0.0000	0.0000	5.1116	0.0000
72	Cl7(177)	0.0000	0.0000	3.4587	0.0000

Appendix D. Cont.

		EM Compositions			
	Congener	EM1	EM2	EM3	EM4
73	**Cl7(178)**	0.0000	0.0000	1.0122	0.1500
74	**Cl7(179)**	0.0000	0.0000	2.7407	0.3017
75	**Cl7(180)**	0.0000	0.0000	9.1027	0.1858
76	**Cl7(183)**	0.0000	0.0000	3.9190	0.9773
77	**Cl7(187)**	0.0000	0.0000	5.5796	0.3944
78	**Cl8(194)**	0.0197	0.0000	0.9019	0.3848
79	**Cl8(199)**	0.0000	0.0000	2.4561	1.5905
80	**Cl8(196)/(203)**	0.0000	0.0000	2.5545	0.4072
81	**Cl9(206)**	0.0000	0.0000	0.0000	5.9601
82	**Cl9(208)**	0.0000	0.0000	0.0000	1.7228
83	**Cl10(209)**	0.0000	0.0000	0.0000	50.0875

Appendix D. Cont.

	Sample (core horizon)	Mixing Proportions			
		EM1	EM2	EM3	EM4
1	T170A 6-7FT	52.5%	15.1%	6.2%	26.2%
2	T170A 7-8FT	40.6%	48.6%	2.9%	7.9%
3	T170A 8-9FT	61.5%	26.9%	3.3%	8.3%
4	T170A 9-10FT	79.2%	15.7%	5.0%	0.1%
5	T170A 10-11FT	46.8%	45.0%	1.2%	7.1%
6	T170-A-NML	46.3%	42.8%	3.6%	7.4%
7	T170-A-KJI	57.5%	25.7%	6.5%	10.3%
8	T170A 17-18FT	53.0%	11.6%	24.0%	11.3%
9	T170B 2.1-3FT	5.7%	-2.1%	17.8%	78.6%
10	T170B 3-4FT	45.0%	10.9%	1.2%	42.9%
11	T170-B-VU	48.5%	4.0%	4.0%	43.4%
12	T170B 5.5-6FT	48.3%	3.2%	15.3%	33.2%
13	T170B 6-7FT	42.9%	43.2%	-0.4%	14.4%
14	T170B 7-8FT	49.5%	39.8%	2.6%	8.1%
15	T170B 8-9FT	67.6%	15.3%	4.4%	12.8%
16	T170B 9-10FT	38.2%	53.2%	1.4%	7.2%
17	T170-B-ONM	44.4%	43.2%	3.3%	9.1%
18	T170-B-LKJ	62.0%	29.6%	8.4%	0.1%
19	T170B 16.1-17.1FT	68.8%	13.1%	12.4%	5.7%
20	T171A 5-6FT	21.8%	6.1%	5.3%	66.8%
21	T171A 6-7FT	43.8%	31.8%	1.4%	23.0%
22	T171A 7-8FT	38.9%	48.7%	2.8%	9.6%
23	T171A 8-9FT	70.1%	18.6%	3.6%	7.7%
24	T171A 9-10FT	69.2%	16.7%	4.7%	9.4%
25	T171-A-PON	40.7%	49.3%	3.1%	6.9%
26	T171-A-MLK	54.3%	31.8%	4.2%	9.8%
27	T171-A-JIH	64.0%	18.1%	7.6%	10.3%
28	T171A 18.4-19.4FT	66.2%	13.3%	15.8%	4.7%
29	T171B 3-4FT	2.9%	-2.3%	11.3%	88.1%
30	T171B 4-5FT	37.1%	8.4%	0.2%	54.3%
31	T171-B-TS	48.7%	3.5%	4.0%	43.9%
32	T171B 6.3-6.5FT	57.6%	21.8%	1.7%	18.9%
33	T171-B-QP	50.8%	33.2%	2.3%	13.7%
34	T171B 8-9FT	49.9%	33.7%	3.0%	13.4%
35	T171B 9-10FT	66.3%	16.2%	3.3%	14.2%
36	T171-B-LKJ	55.0%	33.9%	2.5%	8.6%

Appendix D. Cont.

		Mixing Proportions			
	Sample (core horizon)	EM1	EM2	EM3	EM4
37	T171-B-IHG	44.7%	21.1%	19.5%	14.7%
38	T171B 17.2-17.6FT	80.9%	11.1%	5.8%	2.3%
39	T172A 3-4FT	9.2%	13.1%	14.3%	63.4%
40	T172A 4-5FT	38.8%	47.9%	1.8%	11.5%
41	T172A 5-6FT	56.2%	28.8%	3.0%	12.1%
42	T172A 6-7FT	67.9%	16.9%	2.8%	12.4%
43	T172A 7-8FT	72.1%	20.9%	2.7%	4.4%
44	T172-A-RQP	35.2%	54.1%	2.4%	8.2%
45	T172-A-ON	50.8%	35.0%	4.7%	9.6%
46	T172A 13-13.8FT	81.1%	13.9%	3.7%	1.4%
47	T172-A-LKJI	63.2%	18.5%	6.0%	12.3%
48	T172A 16.5-17.5FT	70.0%	5.6%	14.9%	9.5%
49	T172B 3-4FT	52.4%	5.5%	2.7%	39.4%
50	T172B 4-5FT	52.0%	28.2%	2.0%	17.8%
51	T172B 5-6FT	44.8%	40.9%	1.4%	12.8%
52	T172B 6-7FT	44.8%	42.2%	0.8%	12.1%
53	T172B 7-8FT	67.8%	23.2%	2.0%	7.0%
54	T172-B-PO	47.4%	42.3%	1.7%	8.7%
55	T172-B-NML	51.3%	38.7%	2.9%	7.1%
56	T172-B-KJI	64.8%	19.3%	5.7%	10.2%
57	T173A 6-7FT	49.7%	21.4%	1.4%	27.6%
58	T173A 7-8FT	57.0%	20.3%	0.0%	22.7%
59	T173A 8-9FT	46.5%	40.9%	1.9%	10.7%
60	T173A 9-10FT	73.5%	15.8%	3.0%	7.8%
61	T173A 10-11FT	66.0%	26.6%	1.4%	6.0%
62	T173A 11-12FT	34.0%	56.5%	-0.2%	9.7%
63	T173A 12-13FT	48.5%	42.0%	0.8%	8.8%
64	T173-A-MLK	51.6%	35.0%	3.5%	10.0%
65	T173-A-JIH	64.8%	18.0%	5.5%	11.7%
66	T173A 18.7-19.7FT	71.5%	11.3%	5.8%	11.4%
67	T173B 4-5FT	-4.3%	4.1%	9.7%	90.6%
68	T173B 5-6FT	47.7%	11.3%	1.2%	39.9%
69	T173B 6-7FT	42.7%	40.5%	3.8%	13.1%
70	T173B 7-8FT	33.1%	56.9%	1.8%	8.2%
71	T173B 8-9FT	51.6%	35.1%	3.3%	10.0%
72	T173B 9-10FT	74.3%	15.5%	3.4%	6.8%

Appendix D. Cont.

		Mixing Proportions			
	Sample (core horizon)	EM1	EM2	EM3	EM4
73	T173B 10-11FT	52.4%	39.7%	2.9%	5.0%
74	T173B 11-12FT	52.6%	38.0%	1.9%	7.5%
75	T173-B-MLK	61.7%	26.9%	3.4%	8.0%
76	T174A 3-4FT	42.5%	8.2%	2.8%	46.6%
77	T174A 4-5FT	39.8%	41.0%	4.3%	15.0%
78	T174A 5-6FT	41.9%	46.1%	1.5%	10.6%
79	T174A 6-7FT	64.5%	22.7%	4.3%	8.6%
80	T174A 7-8FT	77.5%	13.0%	4.3%	5.3%
81	T174A 8-9FT	70.1%	22.7%	1.4%	5.9%
82	T174-A-QPO	51.8%	40.4%	2.3%	5.6%
83	T174-A-NML	64.7%	14.2%	8.5%	12.7%
84	T174A 14.4-15.4FT	56.9%	11.9%	23.0%	8.3%
85	T174B 2-3FT	46.4%	8.5%	6.2%	38.9%
86	T174B 3-4FT	55.0%	18.8%	1.1%	25.1%
87	T174B 4-5FT	37.7%	44.9%	3.3%	14.1%
88	T174B 7-8FT	71.5%	21.9%	3.4%	3.2%
89	T174B 8-9FT	48.1%	40.2%	2.2%	9.6%
90	T174-B-QPO	50.3%	37.4%	4.0%	8.4%
91	T175A 1.5-2FT	56.7%	26.4%	5.7%	11.3%
92	T175A 5-6FT	55.5%	30.5%	3.7%	10.4%
93	T175A 6-7FT	76.4%	11.1%	4.8%	7.8%
94	T175A 7-8FT	69.1%	19.7%	3.5%	7.7%
95	T175A 8-9FT	62.3%	27.5%	2.5%	7.7%
96	T175A 9-10FT	62.4%	28.8%	5.1%	3.7%
97	T175-A-ON	59.5%	10.8%	11.4%	18.3%
98	T175A 12.1-12.5FT	72.2%	10.9%	7.7%	9.3%
99	T175B 1-2FT	47.7%	21.0%	4.2%	27.1%
100	T175B 2-3FT	58.7%	29.3%	4.2%	7.8%
101	T175B 3-4FT	53.0%	35.0%	2.1%	9.9%
102	T175B 4-5FT	39.1%	47.1%	2.6%	11.2%
103	T175B 5-6FT	52.4%	33.8%	1.9%	11.9%
104	T175B 6-7FT	76.3%	10.9%	3.3%	9.5%
105	T175B 7-8FT	73.7%	18.8%	3.4%	4.1%
106	T175B 8-9FT	71.1%	21.6%	1.8%	5.4%
107	T175B 9-9.85FT	41.4%	46.9%	1.8%	10.0%
108	T175B 9.85-10.7FT	50.3%	42.8%	3.4%	3.5%

Appendix D. Cont.

		Mixing Proportions			
	Sample (core horizon)	EM1	EM2	EM3	EM4
109	T175B 10.7-11.3FT	67.0%	15.2%	6.2%	11.6%
110	T176A 0-1FT	52.2%	31.4%	5.9%	10.5%
111	T176A 1-2FT	56.8%	31.9%	3.4%	7.9%
112	T176A 2-3FT	36.1%	47.3%	8.6%	8.0%
113	T176A 3-4FT	46.6%	41.2%	3.2%	9.0%
114	T176A 4.5FT	79.8%	8.2%	4.6%	7.4%
115	T176A 5-6FT	61.9%	31.1%	1.8%	5.3%
116	T176A 6-7FT	56.0%	34.2%	3.0%	6.9%
117	T176A 7-8FT	51.7%	34.0%	4.1%	10.3%
118	T176A 8-8.77FT	62.2%	37.0%	3.3%	-2.5%
119	T176A 8.77-9.55FT	46.6%	48.0%	4.5%	0.9%
120	T176A 9.55-9.8FT	68.3%	16.9%	6.1%	8.6%
121	T176A 9.8-10.55FT	59.9%	35.9%	4.6%	-0.5%
122	T176B 0-1FT	69.1%	19.9%	4.0%	6.9%
123	T176B 1-2FT	55.3%	34.4%	1.8%	8.5%
124	T176B 2-3FT	57.2%	34.4%	2.9%	5.6%
125	T176B 3-4FT	51.8%	36.8%	2.6%	8.8%
126	T176B 4-5FT	81.3%	10.5%	4.1%	4.1%
127	T176B 5-6FT	92.0%	6.2%	3.8%	-2.0%
128	T176B 6-7FT	76.4%	18.2%	2.9%	2.6%
129	T176B 7-8FT	59.3%	35.5%	2.0%	3.3%
130	T176B 8-8.95FT	44.9%	45.7%	1.2%	8.2%
131	T176B 8.95-9.9FT	52.2%	37.4%	2.0%	8.5%
132	T176B 9.9-10.9FT	48.7%	38.0%	3.7%	9.6%
133	T177A 1-1.45FT	49.7%	36.8%	2.4%	11.1%
134	T177A 1.45-2FT	44.1%	41.1%	2.6%	12.3%
135	T177-A-WV	53.9%	30.4%	3.0%	12.8%
136	T177A 3.3-4FT	72.6%	16.3%	2.7%	8.4%
137	T177A 4-5FT	68.0%	19.9%	3.1%	8.9%
138	T177A 5-6.15FT	52.1%	39.2%	3.2%	5.5%
139	T177-A-RQ	58.7%	34.7%	3.0%	3.6%
140	T177A 6.7-7.3FT	58.9%	23.9%	2.4%	14.8%
141	T177A 7.3-7.65FT	72.3%	11.3%	6.0%	10.5%
142	T177B 0-1FT	65.1%	5.7%	3.3%	25.9%
143	T177B 1.4-2FT	50.9%	23.5%	-1.6%	27.2%
144	T177B 2-3FT	60.9%	19.6%	0.7%	18.8%

Appendix D. Cont.

		Mixing Proportions			
	Sample (core horizon)	EM1	EM2	EM3	EM4
145	T177B 3-4FT	39.6%	48.1%	1.9%	10.3%
146	T177B 4-5FT	41.3%	45.2%	2.3%	11.2%
147	T177B 5-6FT	82.7%	10.1%	3.9%	3.3%
148	T177B 6-7FT	84.4%	5.2%	8.9%	1.5%
149	T177B 7-8FT	73.0%	22.5%	4.0%	0.5%
150	T177-B-QPO	36.4%	54.0%	3.4%	6.2%
151	T177-B-NML	46.5%	40.7%	5.0%	7.9%
152	T177B 14.1-15.1FT	75.4%	10.3%	8.3%	6.1%
153	T178A 6.05-7.1FT	47.8%	35.3%	2.0%	14.9%
154	T178A 7.1-8.1FT	59.6%	23.4%	4.0%	13.0%
155	T178B 1-2FT	58.5%	23.0%	1.7%	16.8%
156	T178B 2-3FT	54.0%	26.0%	1.2%	18.8%
157	T178B 3-4FT	48.7%	39.5%	3.9%	7.9%
158	T178B 4-5FT	57.6%	29.5%	2.8%	10.1%
159	T178B 5-6FT	69.9%	15.9%	4.9%	9.3%
160	T178B 6-7FT	74.7%	19.4%	5.1%	0.8%
161	T178-B-SRQ	59.5%	26.3%	3.5%	10.7%
162	T178C 0.5-1FT	52.7%	-1.8%	3.2%	45.9%
163	T178C 1-2FT	69.6%	1.1%	2.3%	27.0%
164	T178C 2-3FT	65.4%	9.0%	0.0%	25.6%
165	T178C 3-4FT	56.8%	21.3%	-1.0%	22.9%
166	T178C 4-5FT	54.0%	33.3%	2.2%	10.6%
167	T178C 5-6FT	63.9%	27.7%	1.5%	6.9%
168	T178C 6-7FT	45.3%	42.1%	3.3%	9.3%
169	T178-C-SRQ	42.8%	46.7%	3.2%	7.3%
170	T178-C-PON	84.9%	11.4%	3.7%	0.1%
171	T178-C-MLKJ	48.9%	42.7%	1.9%	6.5%
172	T178C 16.6-17.6FT	75.7%	8.7%	8.1%	7.6%
173	T179B 1-2FT	49.8%	7.9%	0.9%	41.5%
174	T179B 2-3FT	61.8%	16.6%	-0.7%	22.4%
175	T179B 3-4FT	52.3%	31.9%	1.7%	14.1%
176	T179B 4-5FT	55.8%	33.3%	3.6%	7.3%
177	T179-B-UTS	60.4%	30.1%	2.9%	6.6%
178	T179-B-RQP	68.3%	20.4%	2.6%	8.7%
179	T179-B-ON	70.9%	22.4%	4.2%	2.4%
180	T179B 12.5-13.5FT	68.1%	19.4%	8.9%	3.6%

Appendix D. Cont.

		Mixing Proportions			
	Sample (core horizon)	EM1	EM2	EM3	EM4
181	T179C 1.15-2FT	50.2%	-3.1%	4.1%	48.8%
182	T179C 2-3FT	69.6%	2.6%	3.8%	24.1%
183	T179C 3-4FT	53.5%	11.4%	2.6%	32.5%
184	T179C 4-5FT	55.5%	18.7%	-1.3%	27.1%
185	T179C 5-6FT	62.5%	18.1%	-2.0%	21.5%
186	T179-C-UT	54.0%	38.5%	1.5%	6.0%
187	T179-C-SRQ	55.2%	35.4%	2.3%	7.1%
188	T179-C-PON	81.9%	12.3%	2.7%	3.0%
189	T179-C-MLK	53.2%	37.6%	1.7%	7.4%
190	T179-C-JIH	68.8%	29.2%	3.5%	-1.5%
191	T179C 18.5-19.5FT	83.0%	13.7%	3.9%	-0.6%
192	T180B 1-2FT	55.4%	23.2%	1.7%	19.7%
193	T180B 2-3FT	62.7%	23.8%	3.5%	10.1%
194	T180B 3-4FT	52.3%	34.5%	2.9%	10.4%
195	T180B 4-5FT	54.8%	32.6%	3.8%	8.9%
196	T180-B-UTS	59.1%	29.7%	4.4%	6.8%
197	T180C 0-1FT	56.6%	11.6%	1.7%	30.1%
198	T180C 1-2FT	50.8%	19.8%	-1.1%	30.5%
199	T180C 2-3FT	54.9%	22.8%	-0.6%	22.9%
200	T180C 3-4FT	50.8%	33.7%	1.8%	13.7%
201	T180C 4-5FT	58.8%	33.4%	2.2%	5.6%
202	T180-C-UTS	56.8%	34.6%	2.3%	6.4%
203	T180-C-RQP	76.7%	18.2%	3.3%	1.7%
204	T180-C-KJI	71.9%	21.6%	4.8%	1.7%
205	T180C 16.6-17.6FT	71.8%	12.9%	10.4%	4.9%
206	T180D 2-3FT	50.2%	21.1%	1.2%	27.4%
207	T180D 3-4FT	54.0%	23.8%	-0.7%	23.0%
208	T180D 4-5FT	56.0%	19.3%	0.4%	24.4%
209	T180-D-UTS	56.7%	33.8%	2.1%	7.4%
210	T180-D-RQP	66.8%	23.7%	4.3%	5.3%
211	T180-D-ONM	69.0%	25.1%	3.0%	3.0%
212	T180-D-LKJ	51.0%	43.5%	3.7%	1.8%
213	T180-D-IHG	58.3%	34.8%	3.2%	3.7%
214	T180D 20.3-21.3FT	94.1%	6.1%	1.2%	-1.3%
215	T181A 3.2-4.2FT	67.2%	7.3%	19.1%	6.4%
216	T181B 1-2FT	50.7%	13.8%	-0.4%	35.9%

Appendix D. Cont.

		Mixing Proportions			
	Sample (core horizon)	EM1	EM2	EM3	EM4
217	T181B 2-3FT	44.8%	17.1%	-1.7%	39.8%
218	T181B 3-4FT	54.7%	24.1%	0.8%	20.5%
219	T181B 4-5.2FT	55.6%	31.3%	5.1%	8.0%
220	T181B 5.2-6.4FT	38.8%	47.4%	4.2%	9.6%
221	T181B 6.4-7.4FT	38.8%	43.6%	6.5%	11.1%
222	T181C 0.4-1FT	48.1%	26.6%	3.3%	22.1%
223	T181C 1-2FT	55.8%	23.4%	0.4%	20.4%
224	T181C 2-3FT	72.0%	17.4%	4.8%	5.9%
225	T181C 3-4FT	81.2%	10.9%	4.2%	3.7%
226	T181C 4-5FT	68.1%	19.3%	4.2%	8.5%
227	T181C 5-6FT	82.5%	13.4%	3.5%	0.6%
228	T181-C-TS	81.9%	11.8%	4.2%	2.2%
229	T181-C-RQP	51.8%	37.9%	-6.0%	16.4%
230	T181C 10.8-11.8FT	71.3%	31.6%	2.1%	-5.0%
231	T181D 0-1FT	76.1%	6.7%	2.1%	15.1%
232	T181D 1-2FT	59.4%	16.2%	0.1%	24.3%
233	T181D 2-3FT	62.6%	20.4%	-2.1%	19.0%
234	T181D 3-4FT	65.6%	21.9%	0.1%	12.4%
235	T181D 4-5FT	62.2%	31.9%	2.4%	3.5%
236	T181D 5-6FT	36.3%	58.0%	0.8%	4.9%
237	T181-D-TSR	74.1%	17.2%	3.0%	5.8%
238	T181-D-QPO	84.5%	13.2%	3.8%	-1.5%
239	T181-D-NML	77.6%	20.9%	4.6%	-3.0%
240	T181-D-KJIH	55.1%	33.7%	2.6%	8.6%
241	T181D 18.5-19.5FT	78.2%	15.0%	4.5%	2.3%
242	FAD-005	39.3%	7.4%	43.1%	10.1%
243	FAD-008	45.8%	12.5%	29.7%	12.0%
244	FAD-012	55.1%	6.0%	30.7%	8.2%
245	FAD-015	44.3%	5.2%	39.6%	10.9%
246	FAD-021	69.6%	2.7%	22.1%	5.6%
247	FAD-023	77.7%	8.2%	13.8%	0.3%
248	E2LQ0	11.1%	2.4%	73.7%	12.8%
249	E2LQ1	17.0%	3.1%	67.2%	12.7%
250	E2LQ2	21.2%	3.0%	63.1%	12.7%
251	E2LQ3	8.5%	2.9%	75.3%	13.4%
252	E2LQ4	11.9%	2.7%	72.5%	12.9%

Document 28

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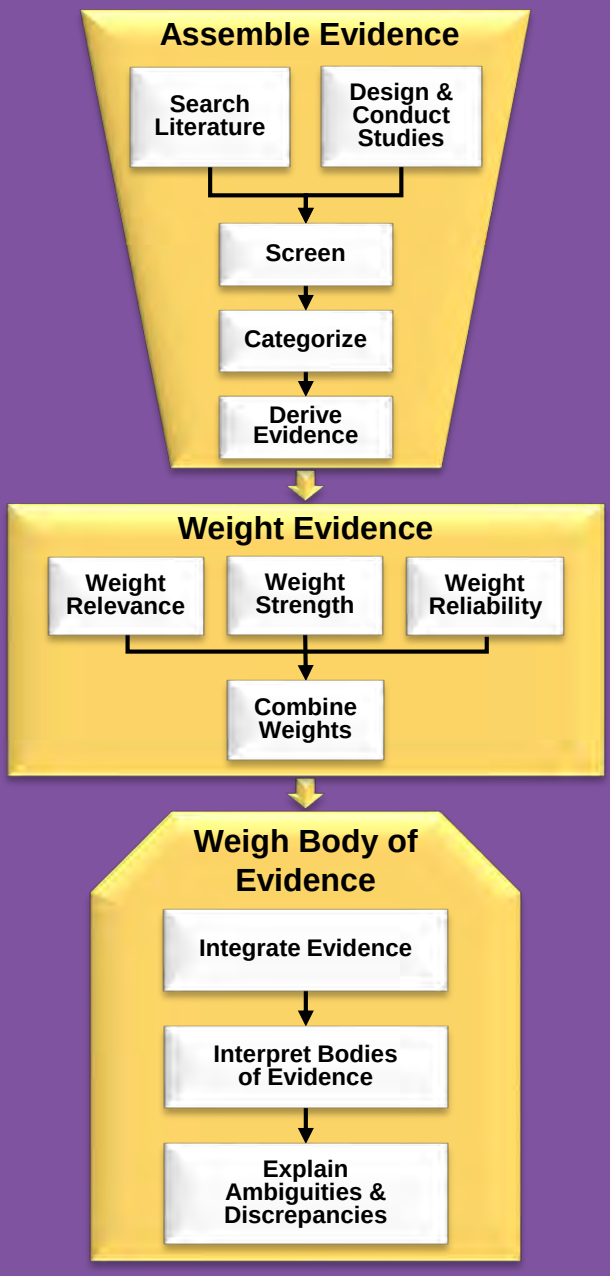

Office of the Science Advisor
Risk Assessment Forum

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WEIGHT OF EVIDENCE IN ECOLOGICAL ASSESSMENT

Risk Assessment Forum
U.S. Environmental Protection Agency
Washington, DC 20460

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PREFACE

The impetus for this document includes U.S. Environmental Protection Agency (EPA) policy, outside advice, and the expressed needs of EPA ecological assessors. Ensuring and maximizing the quality, objectivity, utility and integrity of information disseminated by the EPA "involves a 'weight-of-evidence' (WoE) approach that considers all relevant information and its quality, consistent with the level of effort and complexity of detail appropriate to a particular risk assessment" (U.S. EPA, 2002b). The EPA Science Advisory Board recommended that the Risk Assessment Forum's Ecological Oversight Committee consider the development of guidance for using the WoE approach a high priority (SAB, 2012). This document was prepared for EPA ecological assessors who expressed a desire for assistance in determining which WoE approaches are potentially appropriate for their assessments (U.S. EPA, 2010b).

This document has three goals. The first is to assist ecological assessors who plan to weigh multiple pieces of scientific evidence. We provide a standard framework consisting of three steps: assemble evidence, weight evidence, and weigh the body of evidence. We also present a broadly applicable system for assigning weights by evaluating and scoring the evidence and for combining the weighted evidence to determine the best-supported hypothesis. Additional material addresses how to deal with bodies of evidence that are discrepant or anomalous and how to express confidence in inferences based on the weight of evidence. Finally, we briefly address the weighing of evidence to derive quantities used in or generated by assessments.

The second goal is to make the weighing of evidence in ecological assessments more formal and defensible. Weighing evidence is best performed using pre-existing and well-described methods. The standard framework and default approach to weighing evidence presented in this document are expected to improve the practice and acceptance of weighing evidence.

The third goal is to make the logic of weighing evidence clearer and more consistent. For example, many of the EPA's weight-of-evidence analyses are based on Hill's considerations, a 50-year-old list that mixes characteristics of causal relationships, types of evidence, and properties of evidence. This document addresses those aspects of evidence separately and uses them systematically.

This document provides methods for weighing ecological evidence. Use of the methods will improve the consistency and reliability of WoE-based assessments and the defensibility of scientific input to decision making. This guidance is not meant to be prescriptive, nor does it dictate methods for specific programs and applications.

Tables, figures, and text boxes throughout the document provide examples of WoE practices. The specific methods in the examples were designed for particular statutory contexts and might need to be adapted before they are used in other contexts.

This document was prepared under the auspices of EPA's Risk Assessment Forum. The Risk Assessment Forum was established to promote scientific consensus on risk assessment issues and to incorporate this consensus into appropriate risk assessment guidance. To accomplish this purpose, the Forum assembles experts from throughout EPA in a formal process to study and report on these issues from an Agency-wide perspective.

ACRONYMS AND ABBREVIATIONS

BBN	Bayesian belief network
EPA	U.S. Environmental Protection Agency
FIFRA	Federal Insecticide, Fungicide, and Rodenticide Act
IRIS	Integrated Risk Information System
ISA	Integrated Science Assessment
LC_{50}	median lethal concentration
LOAEL	lowest-observed-adverse-effect level
MCDA	multi-criteria decision analysis
NE	No Evidence
NOAEL	no-observed-adverse-effect level
OECD	Organization for Economic Cooperation and Development
PRG	preliminary remedial goal
QA	quality assurance
QAPP	Quality Assurance Project Plan
r	correlation coefficient
RQ	risk quotient
SMAV	species mean acute value
SSD	species sensitivity distribution
TMDL	total maximum daily load
WoE	weight of evidence

EXECUTIVE SUMMARY

This document presents an approach for using weight of evidence (WoE) in ecological assessments. WoE integrates multiple pieces of evidence to infer a quality such as causality, teratogenicity, impairment, protection, or recovery. WoE can also be used to derive quantities such as a benchmark value, a magnitude of effect or a bioaccumulation factor when multiple estimates are available. WoE is essential for ecological risk assessment, because diverse laboratory and field information must be assembled, evaluated and integrated. The EPA has often employed WoE in ecological assessments, but, in the absence of guidelines, the methods are inconsistent and often informal. Advisory bodies, professional societies and the assessment science literature all encourage more and better WoE. The proper use of an explicit WoE methodology can mean the difference between an ecological risk characterization with a murky rationale and one that is persuasive and consistent with best practices. The system presented here to improve the practice and acceptance of weighing evidence is broadly applicable for evaluating and scoring evidence and combining the weighted evidence to determine the best supported risk characterization. By helping to make the logic of weighing evidence clearer and more consistent, WoE will help make ecological assessments more informative and defensible.

Ecological assessments that employ WoE have made numerous important contributions to environmental protection. The following five examples of high profile ecological assessments demonstrate the value added through incorporating a WoE methodology. 1)The Bristol Bay, Alaska watershed assessment to protect the world's best remaining wild salmon populations, and the people and wildlife that depend on them, used formal WoE analyses to integrate evidence from laboratory tests, field studies, and effects of similar mines to estimate risks to salmon of various mining activities. 2) The restoration of thousands of biologically impaired waters uses a WoE method to determine the cause of impairment (https://www3.epa.gov/caddis). 3) The assessment to support the definition of waters of the United States used WoE to show how different types of aquatic systems are connected. 4) The protection of ambient water quality depends on the ecological assessments that derive aquatic life criteria. The recent benchmark and proposed criteria method for major ions measured as conductivity are based on effects observed in the field. They depend on WoE to determine that the relationships in the field are not confounded and that the same value applies to different areas. 5) The high profile assessment of risks to pollinators from the neonicotinoid pesticide imidicloprid relies on weighing evidence from laboratory tests, semi-field tests, crop applications, and reports from bee keepers. WoE has been increasingly important to ecological assessment and Agency decisions because of the use of eco-epidemiological approaches.

Although WoE has been used in various types of assessments for programs across the U.S. Environmental Protection Agency (EPA), approaches have varied. Many of the EPA's WoE applications use a narrative approach with some guidance provided by lists of considerations, but that approach has been deemed inadequate by the National Research Council (NRC, 2014). The approach in this document is more formal. It provides a framework, a set of properties of evidence, a scoring system, tables for presenting results of weighting, and weighing evidence, a system for organizing evidence in terms of types and the characteristics they address and a means of dealing with ambiguous or discrepant results.

The framework and methods in this document also provide an integrated approach to both infer a quality of interest and estimate an associated quantitative value. For example, WoE can be used to weigh the evidence that a chemical causes malformations in fish in ambient exposures (qualitative) and to derive the best estimate of a benchmark concentration for the chemical (quantitative). Unlike qualitative WoE, quantitative WoE is not an established practice in the EPA. Therefore, quantitative methods are only briefly discussed.

The frameworks for qualitative and quantitative WoE are presented in Figure S-1 and Figure S-2. Although the qualitative processes might appear complex, the basic framework is simple: assemble the evidence, weight the evidence, and weigh the body of evidence. The document explains how to perform each step (Sections 4−6) and explains when and how the process can be adapted or abbreviated (Section 7). Figure S-2 previews Section 8, which presents the process for using WoE to estimate quantities.

The sections preceding the explanation of the process include an introduction that defines and explains WoE (Section 1), a description of the uses of WoE in the EPA's ecological assessments (Section 2), and an explanation of how to perform planning and problem formulation for assessments that includes WoE (Section 3). Sections following the process sections describe the complementary relationship between WoE and uncertainty (Section 9) and the path forward for implementing WoE in the EPA (Section 10). Section 11 presents the literature cited in support of the document.

Appendix A presents a glossary of terms, as used in this document, related to WoE. Additional appendices briefly review WoE methods for estimating quantities (Appendix B), selecting models (Appendix C), and inferring qualities (Appendix D). They provide context for the methods in this document. Appendix E explains that qualities such as causation have characteristics such as co-occurrence that can be used to organize bodies of evidence and to provide a basis for determining the completeness of the body of evidence. Characteristics of causation are established, but characteristics of other inferred qualities such as protective or impaired are new and have not been tested.

The result of the qualitative WoE process (Figure S-1) is a qualitative conclusion (e.g., the metal mixture is the most likely cause) and an overall weight that expresses confidence in the conclusion (e.g., weight of evidence for the conclusion is moderate) or multiple weights (e.g., relevance of the evidence is low, but strength and reliability are both high).

The result of the quantitative WoE process (Figure S-2) is a weighted quantitative value. In a WoE analysis, those results could consist of the value and its units (the proposed remedial goal is 2 mg/kg dry sediment), one or more expressions of weight (the overall weight of evidence is high) and the estimated statistical scatter of the value (the 95% confidence interval [CI] = ± 0.5 mg/kg dry sediment).

This document provides methods for weighing ecological evidence. Use of the methods will improve the consistency and reliability of WoE-based assessments and the defensibility of scientific input to decision making. This guidance is not meant to be prescriptive, nor does it dictate methods for specific programs and applications.

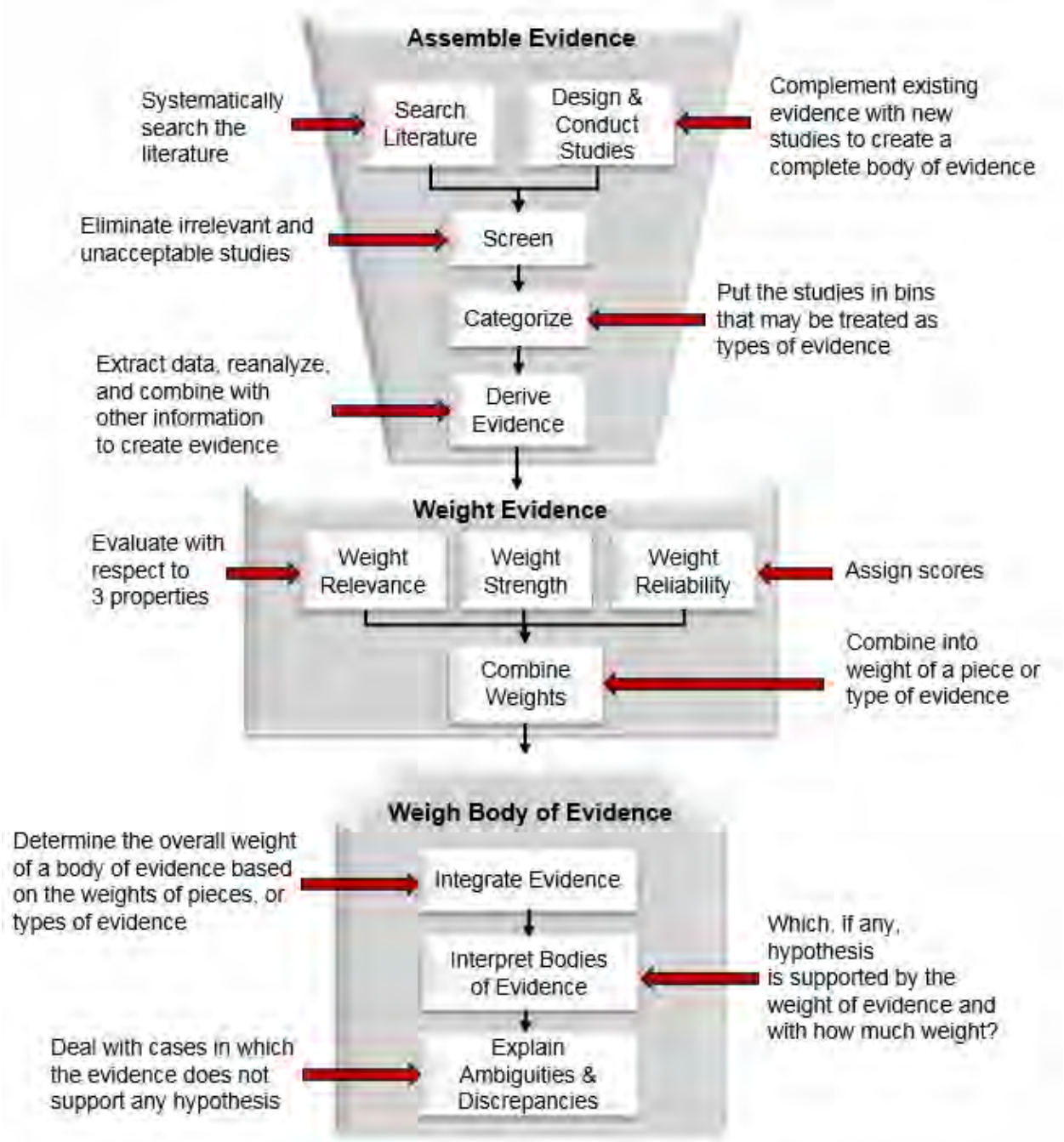

Figure S-1. An annotated diagram of the process for WoE to infer qualities by assembling evidence, weighting it, and weighing the resulting body of evidence, explained in Sections 4–7.

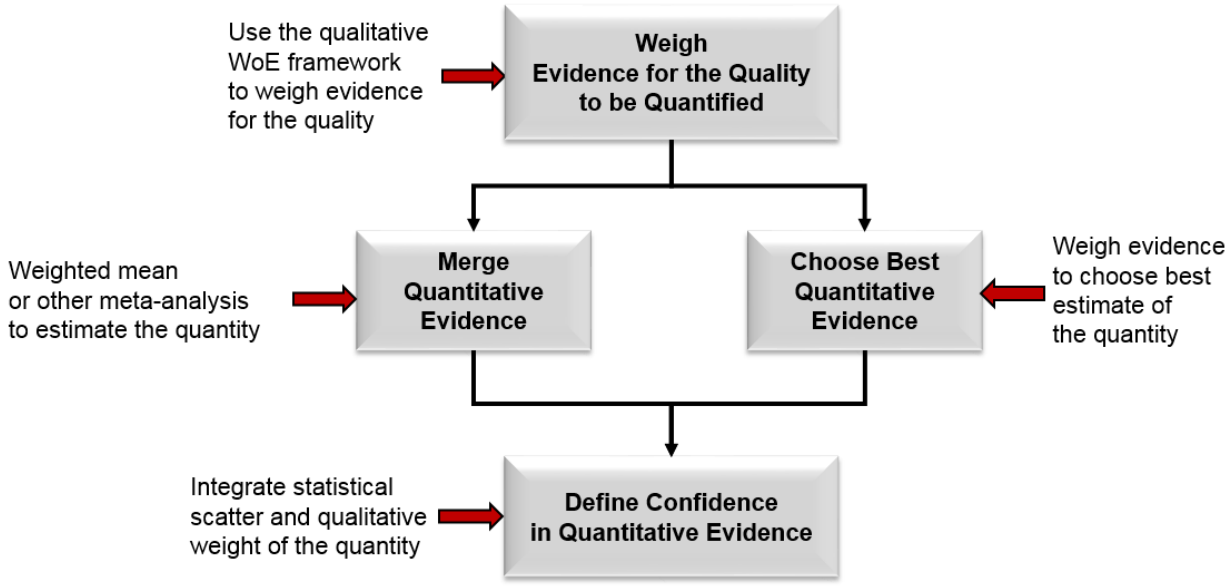

Figure S-2. An annotated diagram of the process for using WoE to estimate quantities, explained in Section 8. It begins by weighing evidence to determine the quality of interest (a qualitative WoE as depicted in Figure S-1), then uses one of two alternative methods to obtain results from multiple quantitative estimates, and finally defines the confidence in the result.

1. INTRODUCTION

The process of weighing multiple pieces of evidence is useful for judging the truth of hypotheses, identifying the best explanation of phenomena, or deriving best models or best estimates. The weight-of-evidence (WoE) process involves (1) assembling evidence, (2) weighting evidence with respect to properties, and (3) weighing the integrated body of evidence. This WoE process is embedded in larger assessment processes, which include planning, problem formulation, analysis, synthesis, and communicating results.

Scientific investigations of a topic often generate multiple pieces of evidence of various types. For that reason, WoE is inherent in medicine, engineering, and other applied sciences, including environmental assessment. Because weighing evidence is so common, the importance of the process is often overlooked and as a result, it is generally performed informally and presented as a narrative. WoE, like other scientific activities, depends on transparency for its credibility. This document encourages more explicit WoE methods, but it also encourages fitting the WoE process to the assessment to avoid processes that complicate the assessment without enhancing the results.

The *Guidelines for Ecological Risk Assessment* did not include WoE (U.S. EPA, 1998). Instead, guidance was provided for a lines-of-evidence process that is equivalent to a narrative WoE guided by considerations (see Appendix D.2). Assessment practices now have advanced sufficiently to recommend WoE for ecological assessments.

1.1. Definitions

WoE is a metaphor adapted from jurisprudence, in which multiple pieces of evidence are metaphorically placed in the pans of the scales of justice and the side with the greatest weight prevails. The metaphor is appropriate for any situation in which multiple and diverse evidence are evaluated to reach a conclusion.

In this document, WoE is defined as an inferential process that assembles, evaluates, and integrates evidence to perform a technical inference in an assessment. WoE methods have been derived to estimate a quantity (Appendix B), inform model selection (Appendix C), or reach qualitative conclusions in an assessment (Appendix D).

As part of that inferential process, WoE characterizes properties of pieces of evidence and of bodies of evidence. First, WoE determines the degree of support for a hypothesis that a piece or type of evidence provides (i.e., the weight of a piece of evidence dropped into a pan of the scales). Hence, weights indicate which pieces and types of evidence make the greatest contribution to the inference. Second, WoE determines the degree of support for a hypothesis, relative to alternatives, that the available body of evidence provides (i.e., the accumulated weight in one pan relative to the other). These cumulative weights not only inform inferences, they also indicate how much confidence assessors have in the conclusion (Section 9).

For example, “WoE was used to determine the likely cause of a bird kill” (the process). “The occurrence of carbofuran granules in the crops of dead birds is convincing evidence of exposure” (a property of a piece of evidence). “The body of evidence consistently supports carbofuran as the cause” (a property of the body of evidence). Further discussion of these terms is presented in Box 1-1. Other terms are defined in the glossary in Appendix A.

1.2. After 50 Years, Advancing Beyond Hill's Considerations

The touchstone of WoE in health and environmental assessments is Hill's considerations (Hill, 1965). Hill recognized that causal inference requires qualitative WoE because no amount of quantitative analysis of associations can suffice (i.e., correlation is not causation). He listed nine considerations to guide the process. Hill's considerations include, but do not distinguish, characteristics of causal relationships (e.g., temporality), types of evidence (e.g., experiment), properties of evidence (e.g., strength), and properties of bodies of evidence [e.g., consistency; (Cormier et al., 2010)]. EPA has adopted Hill's considerations for hazard identification in Integrated Risk Information System (IRIS) assessments and Integrated Science Assessments (ISAs).[1] Hill's considerations were designed for determining the causes of observed epidemiological effects, however, and not for applications in which effects have not been observed. In particular, Hill presumed that co-occurrence of the putative causal agent and the effect of interest (smoking and lung cancer, in his case) was clearly documented, and his goal was to demonstrate that the relationship is causal. We, however, must also address cases for which a clear real-world association has not been demonstrated.

Box 1-1. Weight versus Weigh, Weighting versus Weighing

The terms weight, weigh, weighting, and weighing, which are used throughout this document, can be confusing. This ambiguity results in part from the fact that weight is both a noun and a verb.

To *weight* a piece of evidence is to assign importance to it (a process designated by a verb). As a result of that action, the evidence has weight (a result designated by a noun). The *weighting* process formalizes the evaluation of evidence, by assigning a descriptor or score.

To *weigh* a body of evidence is to combine the weights assigned to each of the pieces (a process designated by a verb). As a result of *weighing*, the body of evidence has weight (a result designated by a noun). The weighing process formalizes the integration of evidence by determining the weight of the body of evidence.

The WoE system presented here treats explanatory implication of evidence, types of evidence, properties of evidence, and properties of bodies of evidence as separate aspects of WoE (Box 1-2). Because each serves a different function in the WoE process, they are not treated as equivalent considerations. Distinguishing them makes clear that Hill's list lacks essential characteristics, types, and properties of evidence. These aspects are the basis for weighting and weighing evidence for causation and other qualities as presented in Sections 5–7.

[1] IRIS is a program that evaluates information on health effects of environmental contaminants to determine what hazards they pose to humans and to develop benchmark values (http://www.epa.gov/iris/). ISAs assess the scientific evidence for health and welfare effects of criteria air pollutants (http://www.epa.gov/ncea/isa/).

Box 1-2. Aspects of Evidence

This approach to weighing evidence distinguishes aspects of evidence in the WoE process that may not be clearly distinguished in prior approaches. They are introduced here and explained in more detail as they appear in the WoE process.

Piece of evidence: A piece is the evidence derived from a particular experiment or observational study. A piece of evidence is the minimum unit that might be weighted.

Type of evidence: A type is a category of evidence based on the nature of the study from which the evidence is derived. Examples include single-species, laboratory toxicity tests; microcosms; mesocosms; biomarker surveys; and community surveys. Types are used to organize and combine pieces of evidence to simplify weighting and weighing.

Explanatory implication of evidence: An explanation expresses the logical relationships between evidence and inference. For example, laboratory toxicity tests may provide evidence of the sufficiency of an exposure to cause the effect, and community surveys may provide evidence of co-occurrence of the effect and putative cause.

Body of evidence: A body of evidence is all of the evidence that applies to a particular hypothesis.

Property of evidence: Properties are the aspects of evidence that determine how much weight (influence) it should have. This approach uses three general properties: relevance, strength, and reliability.

Property of bodies of evidence: Bodies of evidence are weighted with respect to collective properties including number, coherence, diversity, and absence of bias.

1.3. SCOPE

This document is intended to inform ecological assessments. Human health assessments are mentioned and cited only as background and for purposes of comparison. Weighing multiple types of evidence has been performed more widely in ecological assessments than in human health assessments (Krimsky, 2005; Suter, 1993). Although ecological and human health assessments can be performed similarly, the types of ecological assessments that have driven the development of WoE tend to differ in important respects from human health assessments. In particular, types of ecological studies that contribute evidence to Superfund and Clean Water Act assessments include effluent and ambient media toxicity tests, toxicity identification evaluation, in situ tests, biotic community surveys, and demographic models. In addition, ecological assessments must weigh evidence related to multiple endpoint species and levels of organization, which increases the need for formal WoE methods.

This document presents a framework for application of WoE in various assessment contexts. WoE is an assessment tool, just as modeling and statistical analysis are assessment tools. Therefore, the framework for WoE is not a substitute for assessment frameworks (see Section 3).

WoE can be carried through the entire assessment process or be applied to an inference that is only a component of the assessment. WoE can be limited to hazard identification (e.g., Does ozone reduce plant growth at ambient levels?), the determination of an assumption (e.g., Should a bioaccumulation factor be used?), or the estimation of a parameter (e.g., weighing field and laboratory estimates of a chemical's half-life in water). In contrast, a WoE process can carry through an entire condition or causal assessment.

This document cites literature that is directly relevant to explaining this approach to WoE but does not attempt to cover the history of WoE in environmental assessments. Reviews of WoE approaches are available elsewhere (Rhomberg et al., 2013; Linkov et al., 2009; Pope et al., 2007; Krimsky, 2005; Weed, 2005).

This document focuses on WoE for qualities such as causality and impairment (Box 1-3). WoE methods to derive quantities and to choose models are discussed in Appendix B and Appendix C, and the use of qualitative WoE to enhance the derivation of quantitative results is discussed in Section 8. Qualitative WoE is emphasized because it is more common in ecological assessments than is quantitative WoE (Appendix D).

Box 1-3. Qualities and Qualitative Weight of Evidence

Qualitative WoE: A qualitative WoE is an assessment for which the endpoint is a quality such as a condition, mode of action, source, or type of effect. It typically includes both quantitative and qualitative evidence, but the result is not a numerical quantity.

Quality of Interest: The quality for which evidence is weighed is most often causality, but it can be any quality of interest. Examples of qualities that can be or have been inferred by WoE include:

- Coxie Creek is impaired.
- Acid mine drainage causes the impairment.
- Polychlorinated biphenyls are bioaccumulative.
- Selenium is teratogenic in fish.

Quality of Evidence: This document does not recommend weighting the quality of evidence. Instead, specific properties and sub-properties of evidence are weighted. This is because the term quality has been found to be too broad to be useful in the weighing of evidence (Higgins and Green, 2011). However, quality is used in a broad sense that is consistent with U.S. government data quality policy (U.S. EPA, 2002b).

1.4. Benefits and Challenges of Weight of Evidence

Although this document recommends the use of WoE, it recognizes that WoE can have limitations in practice. We assume that assessors will consider the potential benefits and challenges of WoE (Box 1-4) relative to the requirements of their assessment before proceeding to implement the approach recommended here.

WoE techniques inevitably involve subjective expert judgments. Such judgments can cause WoE to be criticized for being biased or arbitrary. However, the objections to subjectivity can be diminished by some good practices.

1. Prior to the assessment, specify the WoE method in as much detail as is practical to minimize the need for improvised judgments about methods or assumptions during the assessment.

2. Use the standard judgments of a program expressed as standard criteria for assigning or integrating weights. For example, tests performed using an Organization for Economic Cooperation and Development (OECD) protocol with good laboratory practices might be given a standard score of +++ for reliability.

3. Be objective, in the sense of being unbiased, by self-auditing (Box 1-5).

4. Work in groups and attempt to achieve consensus concerning judgments.

5. When making judgments, try to represent the opinions that knowledgeable and unbiased members of the scientific community would have, given the evidence and the inference to be made.

6. Find assessors with sufficient relevant knowledge and experience to qualify as experts.

Box 1-4 Potential Benefits and Challenges

Inference by weighing multiple pieces of evidence has advocates who recognize its potential benefits, but challenging aspects of its application have led some assessors to oppose its use.

Potential Benefits of WoE

The primary potential benefit of WoE is the greater confidence in results obtained by considering all relevant and reliable evidence. For example, it is not uncommon for causal assessments to consider only statistical evidence of co-occurrence of an effect and its potential causes. This approach provides much less confidence than one that also considers evidence of temporal sequence, interaction, and other characteristics of causal relationships. In many cases, no single type of evidence is sufficient to reach a conclusion. Ecological assessments of polluted ecosystems commonly benefit from considering evidence from laboratory toxicity tests of chemicals, tests of effluents, or ambient media and biological surveys. This benefit of WoE occurs because the body of relevant and scientifically credible evidence provides a more complete picture than does any piece of evidence alone.

A second potential benefit is an increase in the defensibility of an assessment. An explicit WoE method demonstrates that all relevant evidence has been considered and no credible evidence, either in support of or contrary to a hypothesis, has been arbitrarily dismissed. Without an explicit process planned in advance, reviewers might criticize or even dismiss an assessment for excluding data or evidence that they believe should have been given more consideration.

Defensibility of assessments also might be increased by the transparency of the processes it uses for inference. A formal WoE method enables reviewers and readers to understand and critique the processes of assembling, weighting, and weighing the evidence.

Potential Challenges to WoE

A formal WoE process can require considerable time and effort, which could lead to performance of fewer assessments or delayed decisions. Completing and documenting a formal systematic literature review or implementing an evidence scoring system might not be resource effective if the same conclusion can be obtained with a less resource-intensive assessment. The solution to this challenge is to tailor the WoE method to the assessment.

Box 1-5. Subjectivity and Objectivity

WoE-based assessments rely on subjective professional judgments because there is no other means of weighing a diverse body of evidence from models, laboratory tests, field tests, field surveys, and other information sources to identify the best-supported hypothesis. Although inevitable, subjectivity often is considered undesirable in assessments as in other scientific contexts.

Objective properties, such as the number of fish species in a stream, are properties external to the investigator that can be confirmed by any other investigator. Subjective properties such as the reliability of biological survey results are opinions of the investigator evaluating the survey, not inherent properties. The extent to which assessors agree in their judgment of reliability is due to shared preferences, not a measurable attribute of the surveyed community.

Subjective inferences can be objective in another sense, which is defined in federal policy (U.S. EPA, 2002b): Any inference can be considered objective if it is performed in a disinterested—and therefore impartial—manner. The guidance in this document aims to create circumstances for which an inference is minimally influenced by any personal or institutional biases and in which any systematic bias can be detected.

Performing laboratory or field studies to generate data for multiple types of evidence (e.g., chemistry, toxicity, and biology) for a WoE analysis—as opposed to simply summarizing data from available literature—is more resource intensive than generating a single type of evidence (e.g., only chemistry). The value of new information to the assessment should be considered during the planning stage to obtain sufficient, but not surplus, evidence (Keilser et al., 2014).

Complex WoE methods can obscure rather than clarify the derivation of results, particularly if the method is not clearly presented. A reader is likely to dismiss the results if the assessment is incomprehensible. Clear and consistent methods can reduce this problem.

Finally, a fundamental objection to WoE is that it might mix scientifically less robust evidence with highly reliable evidence. In some cases, the body of at least minimally relevant and reliable evidence might not contribute information beyond that supplied by a single best piece of evidence. This issue is addressed by including explicit steps for screening and weighting evidence rather than treating all evidence as equal.

These objections can be minimized by careful planning and by clearly presenting the WoE process. The WoE methods should be appropriate to the assessment. The amount of detail in evaluating and scoring evidence should be appropriate to the amount and diversity of the evidence, the time and resources available, and the degree to which decision makers and stakeholders wish to engage in a WoE process. The amount of detail can also be based on the degree to which the results of an assessment are potentially contentious. If, for example, an informal review of the evidence clearly shows a site is highly toxic and the obvious decision will be to remediate, a more detailed WoE process might waste resources, prolong the contamination, and confuse the issue. In situations for which the decision is obvious and could be urgent, a protracted WoE process is counterproductive.

2. APPLICATIONS OF WEIGHT OF EVIDENCE

The uses of WoE in ecological assessments are diverse, in part because ecological assessments are conducted in diverse regulatory contexts that require different assessment methods. In addition to asking assessors for predictions of potential adverse outcomes of proposed actions (i.e., to perform risk assessments), decision makers ask assessors to determine conditions (i.e., to perform condition assessments), determine the likely causes of adverse conditions (i.e., to perform causal assessments), and determine the actual outcomes of actions [i.e., to perform outcome assessments (U.S. EPA, 2010b; Cormier and Suter, 2008)]. Each type of assessment has its own logic and methods, and therefore, weighs evidence somewhat differently. Figure 2-1 illustrates a way to organize such assessments. Assessments can be initiated by the results of a prior assessment, and WoE results from prior assessments can inform subsequent assessments. For example, if a condition assessment identifies a biological impairment, a causal assessment should follow to identify the cause and source of the causal agent, a predictive risk assessment should follow to determine the remedy, and an outcome assessment should determine whether the remedy has sufficiently improved conditions. Assessments also can be initiated by external demands. For example, a predictive risk assessment might be prompted by an application to market a new pesticide.

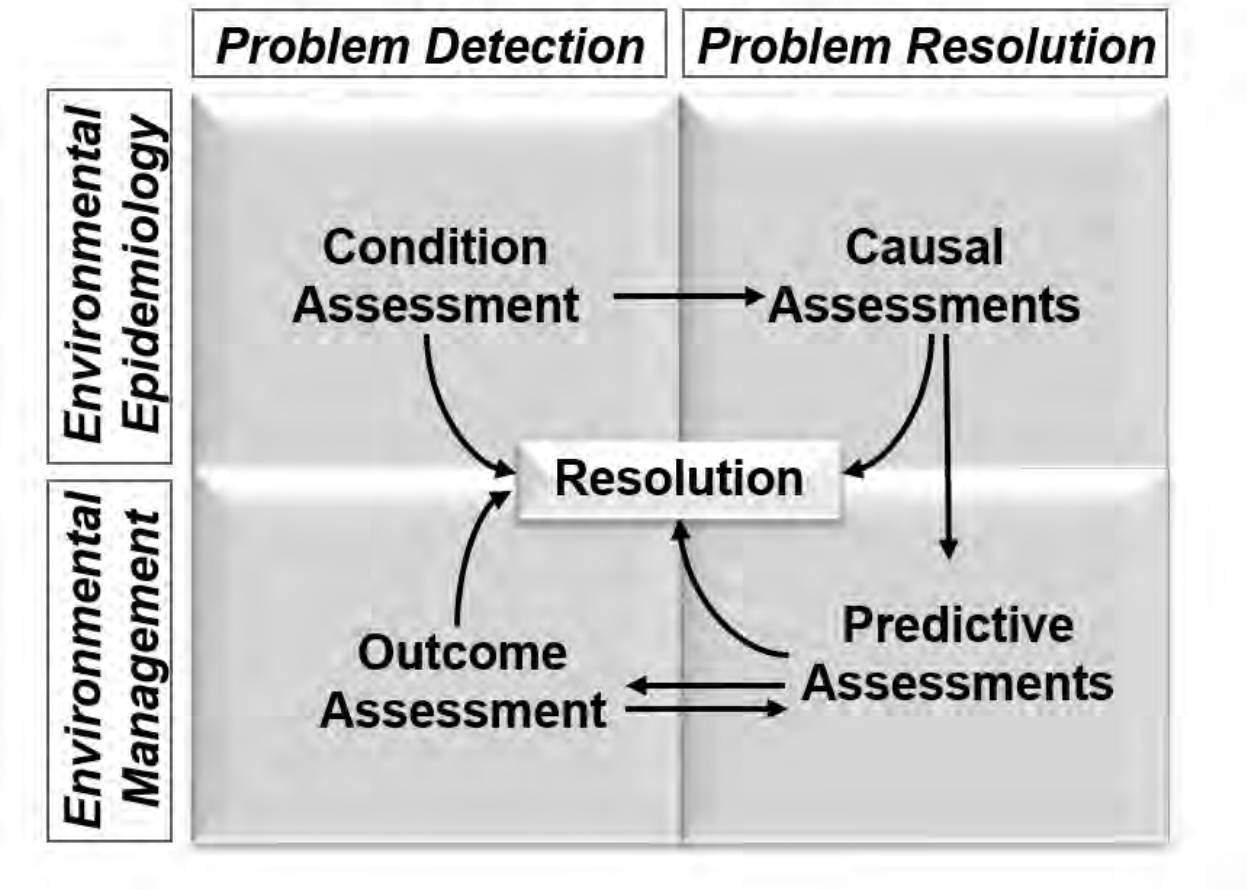

Figure 2-1. A framework depicting the relationships among types of environmental assessments. Modified from U.S. EPA (2010b); Cormier and Suter (2008).

All types of ecological assessments can weigh evidence quantitatively to combine multiple numerical values or to choose a model (see Appendix B and 11.Appendix C). This document, however, emphasizes using WoE for integrating evidence to derive a qualitative conclusion that supports a decision. Examples of qualitative conclusions are the biotic community of a stream is impaired, selenium causes cranial deformities, low pH caused the impairment, or coal ash is the source of the arsenic. To determine what qualities might require WoE, it can be helpful to consider what qualitative questions are answered by the various types of environmental assessments (Box 2-1).

Environmental problem solving often requires sequences of inferences to derive qualitative results and then quantitative results. For example, an ISA, that qualitatively weighs evidence to determine whether relevant concentrations of the pollutant cause particular effects, precedes the development of National Ambient Air Quality Standards. A qualitative weighing of evidence to determine whether the contaminated medium is causing significant adverse impacts precedes development of quantitative cleanup goals for a contaminated site. A qualitative weighing of evidence to determine whether a water pollutant is causing biological impairment might precede the development of quantitative total maximum daily load (TMDL) for the pollutant. These qualitative assessments could be treated as a separate product from the quantitative assessment (e.g., a qualitative ISA before a quantitative Welfare, Risk and Exposure Assessment). Alternatively, the qualitative assessment might be nested within the quantitative assessment as part of the problem formulation (e.g., as a hazard identification).

This section describes the various types of assessments, their application by EPA and the current and potential roles of WoE in performing the assessments.

2.1. Contaminated Sites

Contaminated sites provide a wide scope for applying WoE because the contaminated and potentially biologically impaired conditions allow for the generation of diverse evidence from observation, sampling, analysis, and testing. As a result, most of the relevant methods and literature on ecological WoE address contaminated sediments, soils, and waters (Appendix D). In the EPA, the primary venue for contaminated site assessments is Superfund sites.

The goal of contaminated site assessments is to determine whether contaminants pose an unacceptable ecological risk and, if so, what should be done to reduce it. When assessing a site, specific impaired areas can be identified without WoE by comparing contaminant concentrations to screening benchmarks. Those benchmark concentrations also could serve in some cases as the remedial goals, allowing for completion of the assessment without weighing evidence. For Superfund sites, however, multiple types of site-specific evidence are typically collected, including results of toxicity tests of contaminated media, biological surveys, or analysis of biological samples for biomarkers or body burdens of contaminants (Luftig, 1999). Such bodies of evidence can be weighed in a merged condition and causal assessment to answer the question: Is an unacceptable risk associated with the site contaminants? Such a qualitative assessment is the topic of the approaches for the sediment quality triad and the Massachusetts and Oak Ridge National Laboratory WoE methods described in Appendices D.3, 11.D.5, and D.7. Such assessments can also be performed using the approach presented in the following sections.

Box 2-1. Qualitative Questions for Which Evidence is Weighed in Different Types of Assessments

Causal Assessment

Causal assessments identify causes of observed effects and they take one of two general forms.

What causes general effect y? This is the general causal question. Examples: What causes colony collapse disorder in honeybees? What causes coral bleaching?

What causes specific effect y? This is the specific causal question. Examples: What caused low invertebrate species richness in the Coal River? What caused the 1980s decline in San Joaquin kit foxes in Elk Hills?

Risk (Predictive) Assessment

Most EPA predictive assessments are risk assessments. They begin with a problem formulation that includes a causal question regarding what hazard is associated with an agent and could be assessed.

Does agent x cause general effect y? This is a general hazard identification question for assessments like setting benchmarks or permitting use of a chemical. Examples: Does smoking cause lung cancer? Does atrazine cause deformities in frogs?

Might agent x cause effect y? This is a hazard identification question asked in risk assessments for specific actions. Examples: Might a tailings spill at the proposed mine cause a loss of salmon spawning? Might permitting a new use of atrazine result in an increase in frequency of frog deformities?

Is agent x causing effect y? This is a hazard identification question asked in risk assessments for an agent under existing conditions. Examples: Are the sediment contaminants reducing invertebrate species richness or abundance? Is acid deposition reducing forest production?

These causal questions can be answered by a separate causal assessment prior to the risk assessment or in the problem formulation for the risk assessment. Without hazard identification, defining the endpoint entity and attribute has no basis beyond using default endpoints such as fish mortality.

Other qualitative questions that might involve WoE also are answered in risk assessments. For example:

- Should dietary exposure be considered?
- Will the endangered species occur on the site in the future?
- Is the site large enough to support an assessment population of the species of concern?
- Is long-range transport a significant source?
- What are the contaminants of concern?
- Is the chemical a persistent organic pollutant?

Condition Assessment

Qualitative questions concerning conditions, such as the following, are relatively straightforward to assess when standard definitions of conditions are provided.

- Is the ecosystem impaired?
- Is the species endangered?
- Is the water contaminated?

However, framing the question could be conceptually difficult, particularly with respect to the standard of comparison: natural conditions, reference conditions, historical conditions, or defined standards.

Outcome Assessment

Qualitative questions of concerning outcome are like condition questions but include issues regarding the efficacy of remedial or regulatory actions.

- Is bioremediation sufficiently reducing exposure of endpoint species?
- Is the liner leaking?
- Is the site acceptable for recreational fishing?

Many Superfund assessments treat pieces of evidence as independent lines of evidence without weighing them (Integral Consulting Inc., 2013). Causal assessments performed by WoE for contaminated sites are illustrated by the Elk Hills and California Gulch cases (U.S. EPA, 2011c, 2009a). Such WoE assessments can be sufficient to complete the investigation, provided the decision logic is as follows: If the sediment or soil presents unacceptable risk due to waste contamination, remediate it (e.g., cap, remove, or biotreat it). For Superfund sites, however, a separate step defines chemical-specific preliminary remedial goals (PRGs). Either site-specific values or standard benchmark values might be used as PRGs for the areas identified as impaired by WoE. Site-specific PRGs can be derived from tests of site media or field exposure-response relationships used in the qualitative WoE to identify waste-impaired areas. However they are derived, PRGs represent acceptable risks, and are typically used in selecting a final remedy.

2.2. Environmental Condition

Although the condition of all ecosystems is of concern, the Clean Water Act is unique among U.S. antipollution laws in requiring that all sites (i.e., all state waters) be assessed to determine if they are impaired. The result is each state's 303(d) lists of impaired waters. Most listings are for exceedance of water quality standards, including concentrations of chemicals, levels of biological pollutants (e.g., fecal coliform counts), and physical properties (e.g., temperature). In addition, ecological properties can serve to identify impaired waters based on biological or narrative criteria. Commonly, multiple types of biological data, termed metrics, are combined into an index (Blocksom and Johnson, 2009; U.S. EPA, 1996). The regulations indicate that states should evaluate "all existing and readily available information" in developing their 303(d) lists (40 CFR §130.7(b)(5)), which suggests a WoE approach or other approaches (such as independent applicability) that consider all information (Appendix D, Box D-1).

If a water body is declared impaired based on biological effects, the cause should be identified. Guidance for using WoE to determine the cause of biological impairment was developed for the Office of Water (U.S. EPA, 2000), and a web-based support system was developed to aid in its application (http://www.epa.gov/caddis/). This system is the principal model for the WoE approach presented in this document.

Once the cause of water body impairment has been determined, the sources can be identified so that TMDLs can be developed (Clean Water Act §§ 130.2(f)-(i) and 130.7(c)). This is similar to the practice of determining sources at contaminated sites is known as environmental forensics because it often involves establishing legal liability (Murphy and Morrison, 2002). Its methods include environmental fingerprinting, isotope analyses, tracer studies, and transport modeling, and it often uses WoE. TMDLs are developed and implemented to eliminate the impairment by apportioning pollutant loading among the sources. This step typically does not involve WoE. The TMDL process often includes evaluation of the results, which can lead to removal of the stream reach from the 303(d) list. This outcome assessment can rely on biological endpoints and could involve WoE.

2.3. Existing Pesticides and Industrial Chemicals

The reregistration of pesticides provides an opportunity to collect multiple pieces and types of evidence related to pesticide use, as well as conventional laboratory data, that is generated from the registrant's data package and literature reviews by EPA. This body of evidence, which is weighed in a WoE narrative, can include results from laboratory studies of chemistry and toxicity, mesocosms, field experiments, surveys, and incident reports; pesticide monitoring and use data; and transport, fate, and exposure modeling.

Risks to animals and plants from pesticides are assessed using a tiered approach. In general, most assessments are focused on Tier 1, intended to estimate conservative environmental exposures. The risks associated with those exposures are assessed using risk quotients (RQs), which are predicted exposure levels divided by effect benchmark levels. RQs are based on the most sensitive endpoints available for survival, growth, or reproduction. When RQs exceed levels of concern, risks are characterized using a narrative WoE analysis. Although the process for deriving RQs is well established, the WoE analysis depends on the nature of the available data and the assessed chemical and its use patterns. Examples of evidence analyzed to evaluate risk conclusions include comparing estimates of exposure from models or monitoring data to available toxicity endpoints, evaluating whether laboratory fate studies are consistent with field dissipation studies, and using species sensitivity distributions to evaluate impacts of conservative assumptions on risk conclusions.

Assessments of existing chemicals under the Toxic Substances Control Act (TSCA) can weigh diverse bodies of evidence to determine whether a chemical substance presents or could present unreasonable risk of injury to health or the environment. WoE is used when conducting risk evaluations under TSCA Section 6(b) and making risk management decisions for existing chemical substances. Existing chemical assessments typically rely on a combination of predictive modeling and other computational approaches, empirical laboratory or field data specific for the chemical being assessed and empirical laboratory or field data from analogous chemicals. For example, the body of evidence can include empirical or modeled data on use and release and on transport and fate, physical/chemical properties of the chemical in question, exposure data that include field monitoring and modeled data and hazard data from laboratory toxicity tests or modeling. This information is used to assess risk and, much like the registration of pesticides, RQs are developed and the analysis depends on the available data. The assessments rely on a set of seven study quality and selection considerations (U.S. EPA, 2015b). Implementation of the new (signed June 22, 2016) Frank R. Lautenberg Chemical Safety for the 21st Century Act may change these practices. The act expressly uses the term "the weight of the scientific evidence."

2.4. New Pesticides and Industrial Chemicals

Registration of new pesticides is based on a large and diverse body of evidence (relative to other new chemicals) pursuant to the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) pesticide registration data requirements (http://www2.epa.gov/pesticide-registration/data-requirements). Similar to risk assessments for existing chemicals, a tiered approach is used. The major difference between risk assessments for new versus existing pesticides is generally the amount and types of available data. For new chemicals, the data required under FIFRA generally are available. Incident reports, monitoring data, and toxicity data for nonstandard test species, however, are rarely available for new chemicals.

The available evidence is also weighed when reviewing, assessing, and regulating new industrial chemicals under TSCA before they enter commerce. Assessments of new chemicals rely on a combination of predictive modeling and other computational approaches and empirical data from analogous substances and chemical categories and from empirical data the manufacturer submits. As with existing chemicals, the implementation of the Lautenberg act is likely to increase the importance of WoE for new chemicals.

Review of chemicals for potential endocrine-disruptive mechanisms of action is required for all pesticide active ingredients, all food-use pesticide inert ingredients, and some industrial chemicals. A WoE approach based on a set of considerations has been used for that purpose (U.S. EPA, 2012b).

2.5. Benchmark Derivation

The derivation of numerical criteria, standards, remedial goals, screening levels, and other benchmark concentrations or doses involves performing a type of risk assessment. Qualitative WoE can be applied during problem formulation to determine what hazards should be considered in the assessment. For example, ISAs—which identify hazards that may be assessed in Welfare Risk and Exposure Assessments for National Ambient Air Quality Standards—use WoE to determine what effects on welfare occur in the relevant range of air pollutant levels (U.S. EPA, 2014b, 2013). If different methods or data sets are used to derive benchmarks for different exposure routes or modes of action, WoE can be used to determine which approach to apply, as in the development of IRIS values (human health benchmarks) for carcinogens versus noncarcinogens (U.S. EPA, 2005b). Finally, if a benchmark is derived using field data, WoE can be used to determine whether the evidence suggests the relationship is causal or confounded (U.S. EPA, 2011b).

2.6. Proposed Discharges

WoE is seldom an option when assessing risks from proposed new discharges because evidence is limited to predicted release rates of constituent chemicals used in transport models, and the resulting estimated concentrations are related to benchmark concentrations. Tests of synthetic effluents or analogies to existing effluents that are expected to be similar to the proposed discharge, however, could create bodies of evidence that could be weighed.

2.7. Special Purpose Assessments

Some assessments are performed for particular nonroutine decisions. For example, the EPA performed a watershed risk assessment to inform potential decisions concerning the mining of metals in the Bristol Bay, Alaska, watershed (U.S. EPA, 2014a). The evidence used was diverse and included analogies to prior metal mines and pipelines. The evidence was therefore weighted and weighed using a method like the one in this document. Similarly, EPA borrowed from the WoE method developed for causal assessment of impaired waters to assess the connectivity of streams and wetlands to support the definition of waters of the United States (U.S. EPA, 2015a). These examples show how one-of-a-kind assessments can adapt the general approach presented in this document.

3. PROCESSES FOR WEIGHING EVIDENCE

3.1. An Introduction to the Weight of Evidence Process

The weighing of evidence is a tool that can be used for any type of assessment, at any point in an assessment process or throughout the entire assessment (Section 2; Figure 3-1). In a risk assessment, WoE is used in the problem formulation phase to identify the hazardous properties of the agent being assessed and the appropriate assessment endpoints. In particular, evidence can be weighed to determine whether it supports the hypothesis that a chemical causes some particular effect, such as failure to hatch, effects on a particular taxon, or effects by a particular route of exposure or mode of action (Meek et al., 2014). In the analysis phase, WoE can be used to select assumptions, estimate parameters, and develop models (Section 8, Appendix B, and Appendix C). In the synthesis phase, the models and parameter estimates are used to characterize risks, determine most likely causes, or determine whether an ecosystem is impaired. When multiple exposure-response relationships, spatial/temporal associations, or other relationships have been developed, WoE is used to combine them or to determine which relationship is the best (weightiest). Other types of assessments use WoE at different points in their frameworks (Section 2). In a causal assessment, WoE is carried through all analysis and synthesis phases (Norton et al., 2014).

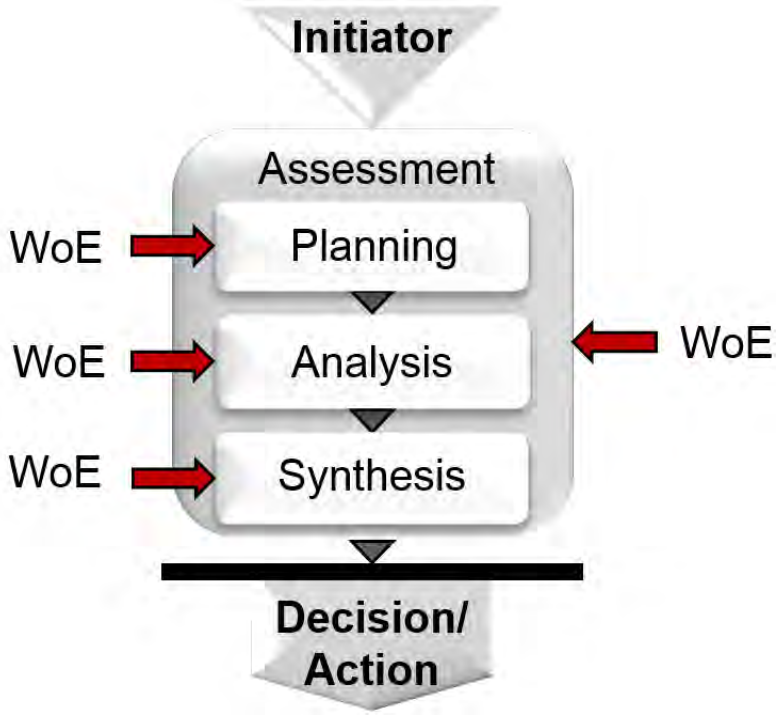

Figure 3-1. A basic framework for all types of environmental assessments (U.S. EPA, 2010b; Cormier and Suter, 2008). Weight of evidence can contribute to one or more individual steps (WoE on the left) or can be the basis for the entire assessment (WoE on the right).

However used, a formal WoE involves the same basic process (Figure 3-2). First, the evidence is assembled. This step involves finding published studies or performing new studies, determining whether their results are acceptably relevant and reliable, and extracting and analyzing data to generate useful evidence. Second, the pieces of evidence are weighted (i.e., evaluated and scored) to determine their influence on the results. Third, the body of evidence is weighed (i.e., weights are integrated and the body of evidence is interpreted) to arrive at a result.

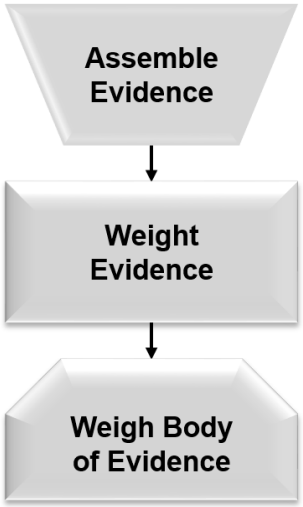

Figure 3-2. The basic WoE process (Suter and Cormier, 2011). The steps are elaborated in Sections 4–6, respectively, in this document.

WoE processes vary among applications, but these three steps are fundamental. First, you must have evidence. The final step, combining and interpreting (i.e., weighing) the evidence, is necessary to make the body of evidence inform the inference. The middle step, weighting, is also essential in that different pieces and types of evidence seldom have the same influence in an inference. However, the explicit assignment of weights is often skipped. This should be done only if the evidence is found to all be equally relevant and reliable (Section 7).

In many cases, multiple pieces of evidence are not explicitly weighed. Instead, evidence is informally weighed in a narrative (Box 3-1).

WoE can be applied to derive qualitative or quantitative results. It might be used to assess qualities such as causality, impairment, recovery, or occurrence of a specific effect or used to estimate quantitative results such as a benchmark value, a model parameter value, or the magnitude of effects. Inferences to quantities begin with quantitative evidence and apply quantitative methods (Section 8 and Appendix B). Inferences to qualities, however, use all relevant evidence (qualitative and quantitative) but apply qualitative inferential methods (Sections 5–7 and Appendix D). Even in WoE methods such as the Massachusetts system that use numerical scores, those scores are used to document qualitative judgments to reach a qualitative result (Menzie et al., 1996). The same qualitative methods can be used to make qualitative judgments about quantitative results (Section 8). For example, they might be used to judge the reliability of a quantitative effect estimate (e.g., 26 km of stream would be impaired and that result is highly reliable).

The general approach introduced in this section is intended to be flexible and broadly applicable. It is intended to provide more rigor and transparency than narrative WoE but less complexity and more flexibility than numerical systems and indices (Appendix D). The approach also is intended to merge inferences to qualitative and quantitative results in a useful manner. It can be applied to all types of environmental assessments and to both data-rich and data-poor cases.

Box 3-1. Best Practices for Narrative Weight of Evidence

Although this document explains how to use a formal method for WoE with explicit weighting and weighing, we recognize not everyone will follow this approach. Some assessors will continue to use a traditional narrative approach. In such cases, WoE narratives can benefit from some good practices.

1. When using evidence from the literature, design and carry out a literature search that will find the information needed in an unbiased manner (Section 4). Define not only the search terms but also the criteria for screening the results to obtain relevant and reliable evidence.
2. Even in a narrative approach, provide a table summarizing the selected evidence and indicate what was excluded and why.
3. Avoid narrative reviews that describes one piece of evidence after another and then present a conclusion. Instead, logically structure the narrative. At a minimum, present the evidence for a hypothesis and the evidence against it, and explain why one side has greater weight.
4. Make the narrative organization clear. Use lists and subsection headings to help the reader understand the logical structure.
5. Present the results clearly. Which hypothesis is best supported by the WoE, and how much confidence can be placed in the conclusion?
6. Express the degree of confidence in the conclusion.

3.2. Planning the Assessment to Use Weight of Evidence

All environmental assessments begin with a planning phase that defines how the assessment will be conducted. In risk assessments, this phase includes two steps termed planning and problem formulation (U.S. EPA, 1998). Assessment plans identify the evidence needs, methods that will be used to generate the evidence and methods for weighting and weighing multiple pieces and types of evidence. Specifying the WoE method in advance enhances transparency and defensibility. In particular, a previously defined system for evaluating evidence and assigning scores prevents the adjustment of weights to achieve a desired result. To the extent feasible and helpful, standard frameworks and methods should be used (Box 3-2).

In practice, there are levels of standardization. Sections 4–7 present a general WoE approach for EPA, which could reduce the burden of planning an assessment. Additional standardization can be achieved at the program level or in individual regions. The greatest specificity, however, occurs in the planning of individual assessments. Not specifying in advance how evidence will be

Box 3-2. Standardization of Weight of Evidence

Standardization of assessment practices is desirable in general. Standardization can increase efficiency by reducing the number of decisions to be made, improve assessments by setting standards of practice, and reduce bias by reducing the opportunities for assessors to make personal judgments. If the standard practices are too rigid and prescriptive given the variability in assessment problems and conditions, they can reduce efficiency, force less than optimal assessment practices, and create frustration. This conundrum is compounded when WoE approaches are used. Decisions are made concerning, among others, which inferences should be based on WoE, what evidence should be included, what properties of the evidence should be considered, and how the weights should be expressed. These decisions should be made on a program-specific basis.

weighed delays the decisions until the data are in hand and the evidence is being generated, weighted and weighed. At that point, the consequences of decisions might be apparent to the assessor. For example, if sediment toxicity tests for an area result in an average 33-percent mortality and no standard for scoring has been set, an assessor can score the evidence as 0, + or ++ (ambiguous, weak, or strong). That judgment could be biased if the assessor knows that the choice can tip the balance for or against dredging the sediment. Removing the temptation to choose a weight that gives a preferred answer by standardizing weights whenever appropriate is the better option.

Exceptions do exist. A detailed plan, on occasion, can result in nonsensical results when implemented, due to peculiarities of the case (Johnston et al., 2002). Therefore, allowing for deviations, and documenting the rationale, as Johnston et al. (2002) did, is essential.

Finally, when a decision is made to use WoE but the method was not prescribed in an analysis plan, assessors should document how they weighed the evidence and why they made their choices. Expert judgment, although essential, should be transparent.

Assessment planning should be adapted to include WoE considerations. Stakeholders and decision makers can be consulted for assurance that the weighing process is acceptable. WoE methods that are compatible with the potentially available data and evidence should be chosen. Alternatively, data needs should be specified with WoE in mind. In particular, literature reviews and new studies should be coordinated to generate complementary evidence. If a field survey will sample benthic invertebrates, literature reviews should seek toxicity studies of benthic invertebrates. Any new laboratory tests should address benthic invertebrates and preferably taxa that are sensitive or important at the site. Field sampling for different pieces of evidence (e.g., chemical concentrations, habitat characteristics, and occurrence of biological taxa) should be collocated in space and time so that the results can be used to derive relevant relationships or make comparisons.

When possible, the assessment problem to be addressed by WoE should be formulated in terms of alternative hypotheses. Identifying the hypothesis best supported by the WoE is conceptually simpler and more convincing than determining whether a single hypothesis has sufficient WoE. One hypothesis, considered alone, may appear to have sufficient evidence, but another hypothesis may have more and weightier evidence. Alternatively, a hypothesis may appear weak, but its status will be unclear until a stronger alternative is identified. For example, a study of a declining San Joaquin kit fox population began as an attempt to determine whether toxic chemicals were the cause. Its conclusion that they were not the cause became more convincing when a strongly supported alternative cause, predation, was identified (U.S. EPA, 2009a).

Because of the complexity of ecological systems and their responses to interventions, the development of conceptual models is essential to planning an ecological assessment (U.S. EPA, 1998). Conceptual models convey the processes and entities that link sources with effects on endpoints. The links can be used to guide the development of evidence for the WoE process. In risk assessments and other predictive assessments, questions can be asked such as, what sequence of events must occur following the proposed action before the endpoint effect can occur? For example, when assessing the risks from input of phosphorus to a lake, if an endpoint is fish kills due to low dissolved oxygen, the WoE should consider evidence for the occurrence of algal blooms, respiration and decomposition, and evidence against the occurrence of mixing because they all can influence dissolved oxygen (Figure 3-3). Similarly, when assessing the cause of an observed fish kill, if low dissolved oxygen is a hypothesized proximate cause, evidence of phosphorus input, algal production, decomposition, and the absence of mixing are supporting evidence that could be generated and evaluated. An approach for applying WoE to conceptual models is provided by the OECD (2013) guidance on adverse outcome pathways (Box 3-3).

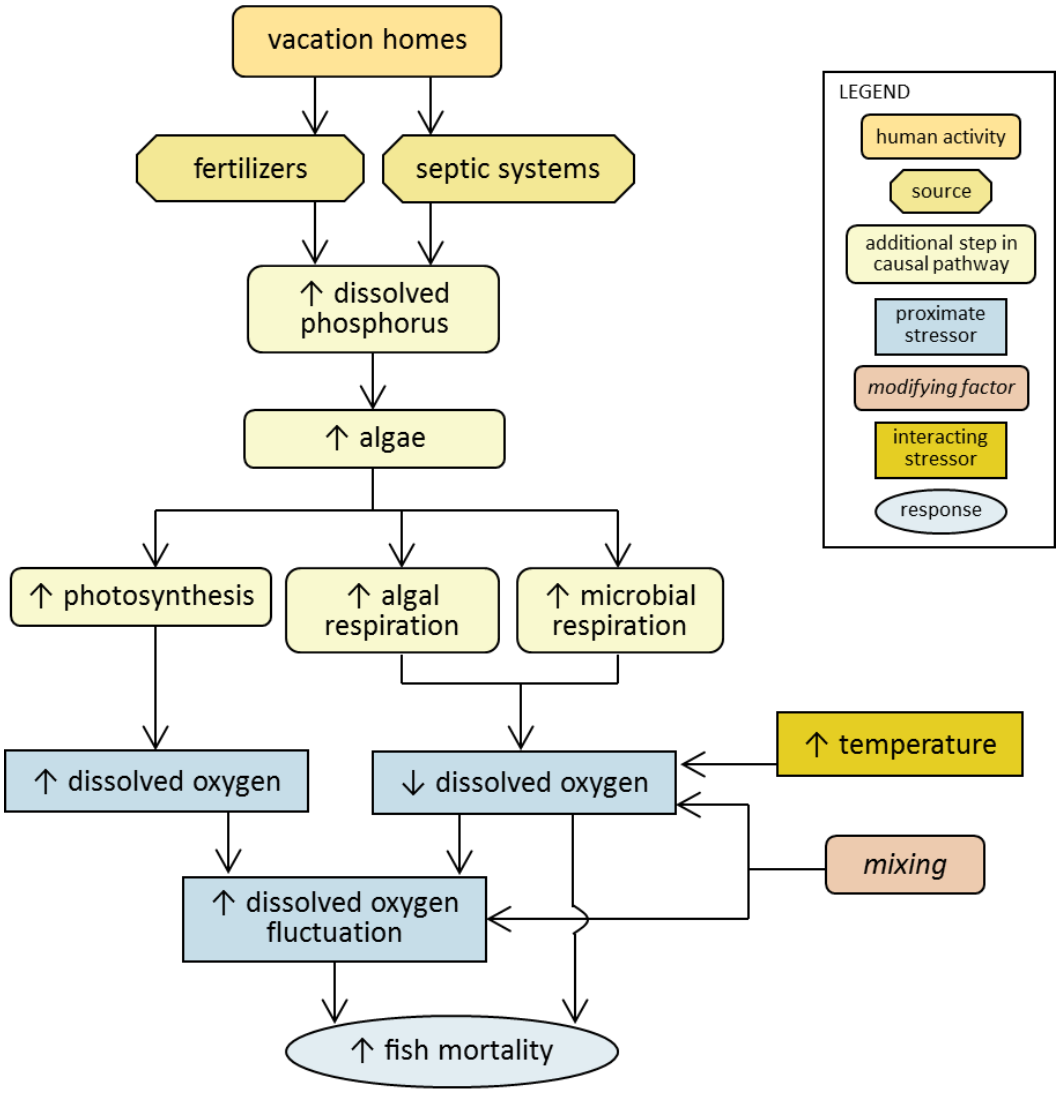

Figure 3-3. Conceptual model for a hypothetical ecological risk assessment of the relationship of phosphorous releases from a vacation home development to the risk of fish kills in a lake (graphic by Kate Schofield, using the conventions in CADDIS, at http://www3.epa.gov/caddis/).

Box 3-3. Weighing Evidence for Adverse Outcome Pathways

Adverse outcome pathways (AOPs) are representations of linkages between molecular initiating events and adverse outcomes measured at levels of biological organization considered relevant to risk assessments (Ankley et al., 2010). Although a goal of AOP development is to quantitatively implement them and predict relevant effects, currently they are primarily a form of hazard identification represented as conceptual models. For example, an AOP might link the binding of a chemical with a receptor in larval fish through a series of steps to failure of swim bladder inflation and then to reduced survival and perhaps to reduced population production (Villeneuve et al., 2014). As with other hazard identification exercises, WoE can be applied to determine the most likely hazards posed by a chemical and also to reveal gaps and weaknesses in the evidence. The OECD (2013) has recommended using Hill's considerations, tailored for AOPs, to evaluate key events, key event relationships, and overall AOPs. The tailored considerations are biological plausibility, essentiality, and empirical evidence. For each consideration, definitions of high, moderate and low confidence are provided. For example, moderate confidence in biological plausibility is defined as "the key event relationship is plausible based on analogy to accepted biological relationships but scientific understanding is not completely established." These OECD standard weights and definitions are equivalent to the standard findings and scores in Table 5-2, but types of evidence are not separately evaluated. Example cases of WoE are provided in the OECD (2013) guidance and derivative publications (Becker et al., 2015; Villeneuve et al., 2014). Subsequently, another WoE approach for AOPs was developed and demonstrated using numerical scores that were aggregated in a linear additive fashion into an overall WoE, a procedure analogous to multi-criteria decision analysis (Collier et al., 2016).

The planning of an assessment should include consideration of uncertainty. However, in the context of WoE analyses, uncertainty is one component of a set of complex issues related to confidence in the results (Section 9). As the OECD found when applying WoE to adverse outcome pathways, analysis of qualitative uncertainty is redundant with WoE (Becker et al., 2015). Conventional statistical measures such as distribution functions, standard deviations and confidence intervals are used to express the variability and uncertainty that appear as scatter in the data or scatter in modeling results. Many sources of uncertainty are unquantified or unquantifiable, however, and conventionally are simply listed. WoE can address this wider range of qualitative issues that determine confidence in the results—not just how closely the curve fits the points, but does the curve represent a causal relationship, and how relevant is the relationship to the case? A formal WoE method is a means to engage with these issues more clearly and consistently. Ideally, each quantitative result would have a conventional statistical estimate of uncertainty or variability and associated qualitative weights.

All assessments require professional judgments by assessors, but WoE makes the judgments more transparent. Clearly indicating where the assessors' judgments end and those of the decision maker begin is critical. It is clear that the decision maker, after conferring with assessors and potentially with stakeholders during the planning phase, specifies the topic and scope of the assessment and the decision to be made (U.S. EPA, 1998). It is also clear that, in the end, the decision maker determines what action will be taken. Judgments regarding the scientific evidence made between these management decisions are generally considered to be in the purview of science and are made by assessment scientists to avoid any potential political biases of decision makers (NRC, 1983). A point of potential ambiguity arrives at the conclusion of the assessment. A decision maker might request only a compilation and summary of the evidence and then decide, for example, whether the stream is impaired, which cause is the most likely or what concentration is the best benchmark value? The boundary between assessment and management, therefore, should be made clear in the planning phase because it determines the ultimate product of the assessment.

Because professional judgments play such a prominent role when weighing evidence, avoiding making the judgments in isolation is essential, particularly for less experienced assessors and for unconventional assessments. Support in professional judgment can be provided during the assessment by collaboration within the assessment team or afterwards by internal and external peer reviewers.

In the EPA, the planning of assessments includes the development and approval of a Quality Assurance Project Plan (QAPP). Although quality assurance (QA) and weighing evidence are not the same, WoE includes the screening of studies and the evaluation of evidence to weight it with respect to relevance and reliability, which encompasses evaluating the quality of input data. To avoid duplication of effort, an explicit WoE process can be used to meet the requirement for a QAPP (Box 3-4 and Section 9).

Box 3-4. Data Quality Assurance and Weight of Evidence

Quality assurance (QA) and WoE both consider the quality of scientific information and thus are related. The QA process determines whether the quality of environmental data and information supporting EPA decisions are appropriate for their intended uses (U.S. EPA, 2008). It includes documenting the process for ensuring information quality, including data generation, data analysis, and assessment methods. Thus, the development of a QAPP should encompass all aspects of the assessment planning process, including methods for WoE (U.S. EPA, 2002a). WoE contributes to QA because QA for assessments "involves a 'weight-of-evidence' approach that considers all relevant information and its quality" (U.S. EPA, 2002b). Therefore, during planning, QA should determine what WoE method is acceptable, and during the assessment, weighting determines whether the quality of information is acceptable. A formal WoE process should provide the rigor and transparency needed to meet QA requirements. Assessors should read the QA guidance and check with their organization's QA official to ensure that they properly merge QA and WoE.

3.3. Results and Transition

In this section we have dealt with determining the role of WoE in the assessment by integrating WoE considerations into the planning and problem formulation process. That is, we have identified one or more assessment problems with multiple pieces of evidence to be weighed, we have identified the WoE approach to be used, and we have determined how it relates to other aspects of the assessment. We are ready for the first step in the WoE framework, assembling the evidence.

4. ASSEMBLING EVIDENCE

4.1. The Process for Assembling Evidence

The success of WoE depends on identifying or generating useful evidence (Figure 4-1). Evidence is information that can be used to make an inference. For risk assessments and causal assessments, useful evidence principally includes information about causality (i.e., a relationship between the exposure and response and either an estimated exposure level or a response level). Exposure levels are used to solve the exposure-response relationship to estimate a future response to the potential exposure (e.g., to estimate the frequency of mortality in a conventional risk assessment) or plausible effects of the exposure (e.g., to determine whether the level of exposure was sufficient to cause the observed effect in a causal assessments; Figure 4-2). Response levels considered thresholds for unacceptability (e.g., 10-percent mortality) are used to solve the exposure-response relationship to estimate the exposure level that will protect against that unacceptable response (criteria assessments) or the exposure level that would be required to cause an observed effect (causal assessments; Figure 4-2). Exposure and response information can occur separately in a condition assessment. For example, evidence that the abundance of an endangered species is declining is sufficient for a condition assessment to prompt a causal assessment. Similarly, accumulation of a chemical in fish can be sufficient evidence of condition to prompt a risk assessment. In addition to information about exposure, response and the relationship between them, information about environmental conditions such as habitat structure or water chemistry also might be required to complete the information that constitutes a piece of evidence.

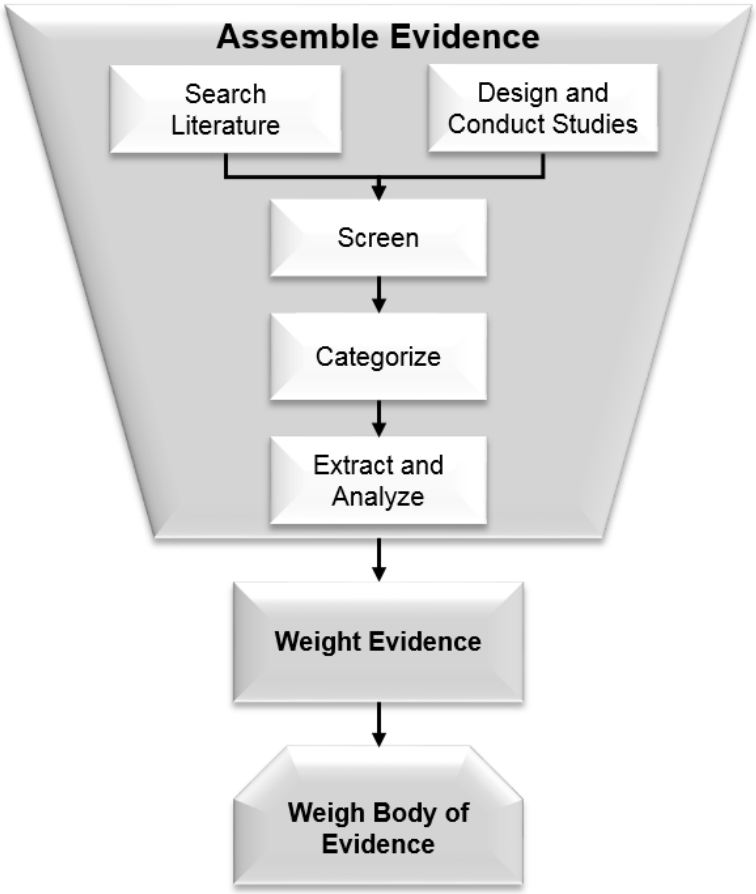

Figure 4-1. An elaboration of the process for assembling evidence, the first step in WoE.

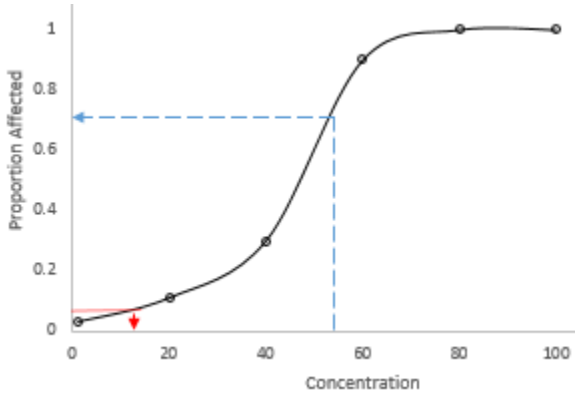

Figure 4-2. An exposure-response relationship (black curve) alone is evidence that the measured chemical can cause the effect. With a concentration, it can provide evidence of the level of effect that is expected (blue dashed arrow). With a level of effect, it can provide evidence of the concentration that would cause that level of effect or, in benchmark derivation, a concentration that would prevent greater effects (red dotted arrow).

Data alone are not evidence because evidence should indicate a hypothesized spatial, temporal, or causal relationship or the absence of a relationship. For example, contaminant concentrations are related to a particular place that has been, or potentially will be, exposed to some source and to reference concentrations from sites that are not exposed to the source. Concentrations without those relationships do not constitute evidence.

In sum, evidence usually requires more than one type of information. Recognizing this, Hope and Clarkson (2014) developed the term "evidence group" to describe the combination of an exposure-response relationship, information concerning environmental conditions that influence the relationship and either an exposure estimate or a response level. Thus, as this document discusses evidence, note that the discussion typically refers to a set of related bits of information that together constitute evidence.

4.2. Searching Literature and Assembling Evidence

A systematic literature review can provide more complete information than an informal review and can reduce the perception of bias in data selection (NRC, 2014). Recognition of the importance of performing reviews systematically has prompted development of several formal methods for systematic reviews (Box 4-1). Recent peer reviews of high-profile EPA assessments such as the stream and wetland connectivity report have called for better documented and systematic literature reviews (SAB, 2014). The method for literature review should be described in the analysis plan (U.S. EPA, 1998).

The EPA has developed the Health and Environmental Research Online (http://hero.epa.gov) database to document the literature searches and screening processes for ISAs and IRIS assessments. It provides transparency in literature searching, screening, and sorting processes and makes the results available to the public.

Box 4-1. Systematic Review

Systematic review is an approach for reviewing published scientific evidence based on a formal search protocol that provides a reasonably complete set of relevant studies that has been screened and reviewed in a consistent and replicable manner (Bilotta et al., 2014). The goal of systematic review methods is to ensure that the review is complete, unbiased, and transparent.

Systematic review was developed as a tool for integrating results of clinical trials in evidence-based medicine. The most prominent example is the Cochrane Collaboration, an organization that reviews evidence of the efficacy of medical treatments (Higgins and Green, 2011). The Campbell Collaboration (http://www.campbellcollaboration.org) extends systematic reviews to education, crime and justice, social welfare, and other issues. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) provides "an evidence-based minimum set of items for reporting in systematic reviews and meta-analyses" (http://www.prisma-statement.org/). More recently, systematic review has been adapted to mammalian toxicology, epidemiology, and human health risk assessment. Examples include the industry-funded Evidence-Based Toxicology Collaboration (http://www.ebtox.com), the foundation-funded *Navigation Guide* (Woodruff and Sutton, 2014), and the U.S. National Toxicology Program's Office of Health Assessment and Translation method (Rooney et al., 2014). Another systematic review system has been developed for environmental management (CEE, 2013). None of the specific existing methods for systematic review are directly applicable to weighing evidence in the EPA's ecological assessments. In particular, systematic review does not integrate heterogeneous evidence, which is typically necessary in ecological assessments. However, they provide methods for the assembly of information from the literature.

4.2.1. Search the literature

The two major components of a literature search are defining the topic and designing the search. The first step identifies the topic with sufficient specificity to enable assessors or information specialists to design a search strategy. Examples include the chronic toxicity of arsenic to marine teleost fish and the biodegradation rate of benzene in fresh surface waters. If the assessments performed by an organization are sufficiently consistent, developing a standard format and content for defining the search topic might be desirable. The variants of Population, Exposure, Comparator, Outcomes, and Study Design (PECOS) systems, developed for reviews of epidemiological or clinical studies, could serve as models for defining ecological search topics (Woodruff and Sutton, 2014; CRD, 2009).

Comparisons of systematic reviews to conventional literature reviews have revealed that the latter are often incomplete or biased (Egger et al., 2003). One reason is the lack of professional assistance with searches. Some useful strategies such as the use of wild cards and truncation to obtain all forms of a search term as well as procedures for using different databases and search engines might not be familiar. Although guidance on literature searching is available (Gough et al., 2012; Higgins and Green, 2011; CRD, 2009), it is not specific to ecological assessment and could soon become outdated due to advances in information science such as text mining techniques.

Multiple search strategies and tools can be employed. Some examples include:

- Electronic databases such as ECOTOX;
- Literature search engines such as PUBMED, Web of Science, or Google Scholar;
- General search engines such as Google or Bing;

- Hand searches of key journals and books;
- Citation tracking of literature cited in key papers, books, or reports;
- Citation searching for publications citing key papers, books, or reports;
- Contacts with key authors and experts;
- Solicitation of information from stakeholders; and
- Internal databases (if they are not business confidential).

One should maintain a search log of sources searched, date, terms, and syntax (i.e., the combinations of the Boolean operators: and, or, not) used. Doing so can make the search explicit, transparent, and potentially replicable. Downloading search results to reference management software such as Endnote or Reference Manager, with a distinct name for the results of each search, also can be helpful.

The inclusion of difficult-to-locate studies (i.e., not published in a journal, not in English, or not indexed in MEDLINE) influenced the results of medical meta-analyses, but the influence varied among fields (Egger et al., 2003). Such studies tended to be less comprehensive and to have lower methodological quality. Identifying relevant studies in an unbiased fashion, however, is important. Issues of study relevance and reliability should be addressed during screening or weighting of the evidence rather than during the literature search.

4.2.2. Screen the studies

Screening the search results and studies performed for the assessment identifies irrelevant or clearly unreliable studies for elimination. Elimination criteria should be defined in advance, to the extent practicable, to avoid perceived or actual bias. Defining irrelevance is relatively straightforward. If the topic is chronic toxicity of arsenic to marine teleost fish, a freshwater invertebrate study would be eliminated. Some issues of relevance might not be apparent in advance. For example, assessors might realize during the screening process that not all arsenic species are relevant, so they should also screen out studies of irrelevant arsenic species. Screening for reliability is generally more difficult than screening for relevance and might not be performed at all. That is, assessors might choose to include all relevant studies and leave differences in reliability for the evidence-weighting phase. Eliminating studies with some obviously unacceptable attribute, such as lack of replication or lack of controls in a test, however, could be efficient. If the weighting phase is skipped (Section 7), performing a more thorough screening and considering the elimination of marginally reliable studies is important.

Some criteria commonly used to screen studies are not so clearly related to relevance or reliability. They include language (English only, unless translation services are available); peer review; and use of a standard protocol or good laboratory practices. Standard protocols ensure consistent and interpretable results, and good laboratory practices improve methodological reliability. Nonstandard studies, however, could provide relevant results and might also have good QA. Entire categories of sources could be eliminated, particularly secondary sources (if possible, primary literature should be used as sources of information), unpublished reports, or abstracts.

Some EPA programs have specific data-screening criteria. For example, the Office of Pesticide Programs screens open literature publications using 14 criteria (U.S. EPA, 2011a), and the ecological soil screening levels for plants and soil invertebrates have 11 acceptance criteria (U.S. EPA, 2005a). Other screening criteria are assessment specific, such as the assessment of connectivity of U.S. waters, which used a logic diagram for screening literature (U.S. EPA, 2015a).

When very large numbers of studies are screened, a tiered process can be used. For example, in the ISAs for criteria air pollutants, publications are screened based on their titles, then on abstracts, and finally on a full reading of the text (U.S. EPA, 2013). Duplicate screeners can minimize errors by identifying and resolving differences.

The EPA has published guidance on determining whether information quality is adequate (see Box 3-3). This procedure is conceptually equivalent to the screening process described here, but it is not followed by evidence weighting and weighing. The screening and weighting processes together should be sufficient to fulfill the EPA's mandate for information quality review.

4.2.3. Categorize the studies

Sorting studies is generally desirable so that distinct categories of evidence can be weighed before they are integrated to reach a conclusion (see Section 6.2). The categorization depends on the type of assessment, amount and diversity of evidence, circumstances of the assessment, and preferences of the assessors.

The most common approach to categorization is to assign evidence to types based on the sorts of studies from which the evidence is derived. For example, the Oak Ridge National Laboratory scheme for ecological assessment of contaminated sites divided evidence into single-chemical toxicity tests, body burdens, ambient media toxicity tests, biomarkers and pathologies, and biological surveys (Suter et al., 2000; Suter, 1996). Other types of assessments would use different types of evidence. In general, field studies are separated from laboratory studies, mechanistic studies are separated from studies of overt effects, and studies of effects at different levels of organization are separated. When only toxicity benchmark values are used as measures of effects, evidence might be categorized by mode of exposure [e.g., whole sediment, pore water, or tissue concentrations (Integral Consulting Inc., 2013)]. An assessment of a specific site might separate evidence from the site from evidence derived from other locations.

Evidence could also be categorized by the characteristic it illustrates. For example, evidence in causal assessments can be organized by characteristics of causal relationships such as interaction and co-occurrence (see Appendix E). Classification in terms of characteristics serves to explain the implication of the evidence for the inference.

4.2.4. Derive evidence from data and general knowledge

Data are raw materials for generating evidence. Data are generated by observation or experimentation and must be obtained from the investigators or extracted from the published studies that pass screening. Data can include:

- Numerical data such as the median lethal concentration (LC_{50}) values or raw exposure-response data;
- Categorical data such as whether benchmark levels are exceeded; or
- Narrative data such as the appearance of a water body, the behavior of animals, or a researcher's interpretations.

In addition to data, generally accepted knowledge such as physical laws and biological principles (e.g., receptor binding of certain chemicals or the role of species competition in structuring communities) contributes to evidence generation. Such knowledge can determine the information sought for generating evidence and the way to structure that evidence. Knowledge also might be the evidence itself. For

example, evidence that a biotic community was exposed to a release from an upstream source is provided by the general knowledge that flow would carry a persistent and soluble chemical downstream. General knowledge might appear as facts (water flows downhill) or as a mathematical model (e.g., a transport and fate model for streams).

If possible, numerical data sets should be obtained from the journal's supplementary material files or directly from the investigator. Transcribing numbers from data tables is prone to error.

If the data to be extracted are sufficiently consistent (e.g., all are from laboratory toxicity tests), development of a data form can facilitate extraction and increase completeness and consistency of the extracted data. Particularly if quantitative analysis is planned, an electronic form can efficiently combine data extraction and data entry. Any form should be piloted with a subset of the studies.

Ensuring data quality by checking the entered data for consistency with the source is desirable. One way to accomplish this is to have two individuals separately extract the data and then compare their results. Discrepancies can be due to errors or to ambiguities in the source that might be variously interpreted.

Some processing of the extracted data could be required before they can be used. In the simplest cases, a summary statistic such as an annual average is calculated. If evidence will be weighed, additional processing often is required. Evidence (as opposed to data) generally involves some sort of relationship such as the impaired stream reach was channelized, but the reference reach was not. Evidence of a condition could involve simple observation. For example, the absence of a taxon (e.g., no fish) is evidence of impairment. In addition, pieces of evidence that will be numerically combined must be converted into the same form and units (e.g., LC_{50}s converted to mg/L).

Processing data to obtain evidence also might require adjusting for the conditions to which the evidence will be applied. For example, laboratory test data might not be comparable to field data until they have been adjusted for water properties such as pH, hardness, or dissolved organic matter levels. Adjusting for the occurrence of mixtures involves applying an additivity model or other combined effects model to the individual chemical test data. Adjusting for biology might require considering seasonal occurrence of sensitive life stages.

Derivation of evidence involves the consideration of variance. Different data sets might appear to be inconsistent, until it is recognized that their distributions overlap.

4.3. Design and Conduct Studies and Assemble the Evidence

In some cases, studies can be performed to provide evidence for an assessment. In such cases, the inferential process should determine the evidence needs and drive the research planning. A simple example is provided by the sediment quality triad [(Chapman, 1996); see Appendix D, Table D-1]. That WoE method includes standard inference rules that require reliable data for the sediment's chemical composition, toxicity, and biological community composition. If any of these types of evidence are missing or unreliable, the inferential method fails. Some EPA offices and programs specify data to be generated for assessments. A prime example is the Office of Pesticide Programs' FIFRA data requirements. For other purposes, such as Superfund remedial investigations, the data needs are determined for individual cases. The Data Quality Objectives Process was developed for that purpose (Bilyard et al., 1997; U.S. EPA, 1994).

Like data from the literature, data produced for the assessment should be screened for acceptability. The Office of Solid Waste and Emergency Response provided detailed guidance to determine if contaminant data are useable (U.S. EPA, 1992a, b). If data quality objectives are developed, they should specify

standards for data acceptability. The description of data to be generated is a conventional component of the analysis plan (U.S. EPA, 1998).

As with data from literature reviews, data generated for the assessment must be input to the assessment's data management system and analyzed to derive the evidence. Unlike data from the literature, the raw data from studies performed for the assessment always should be available for analysis. Results of those studies should be categorized into the same types of evidence as the results of literature reviews.

4.4. Summary

The process of assembling evidence is more complex than the simple phrase implies. When weighing evidence, ensuring the process begins with a complete search of the literature is essential. QA procedures should be applied to the processes of obtaining or extracting data or other information from the literature. Information should be screened for relevance and reliability. Finally, information should be analyzed and organized in a way that facilitates its use as evidence.

4.5. Results and Transition

The results of assembling evidence are pieces of evidence that are at least minimally relevant and reliable, and are organized and presented in a useful form. The next step in WoE is to assign weights to the evidence that have been assembled.

5. WEIGHTING EVIDENCE

5.1. The Process of Weighting Evidence

In most assessments, some pieces of evidence will be more influential than others. The evaluation of the evidence can be implicit, as in a narrative WoE. When a formal WoE method is used, however, weighting the evidence determines the appropriate degree of influence (Figure 5-1). By not only evaluating the evidence but also expressing the weights explicitly as scores, assessors transparently determine the influence that particular pieces of evidence will have when the entire body of evidence is weighed (see Section 6). Weights are usually assigned to pieces of evidence. However, if the pieces of evidence in a category (Section 4.2.3) are similar, the category may be assigned a weight (see Section 6.2).

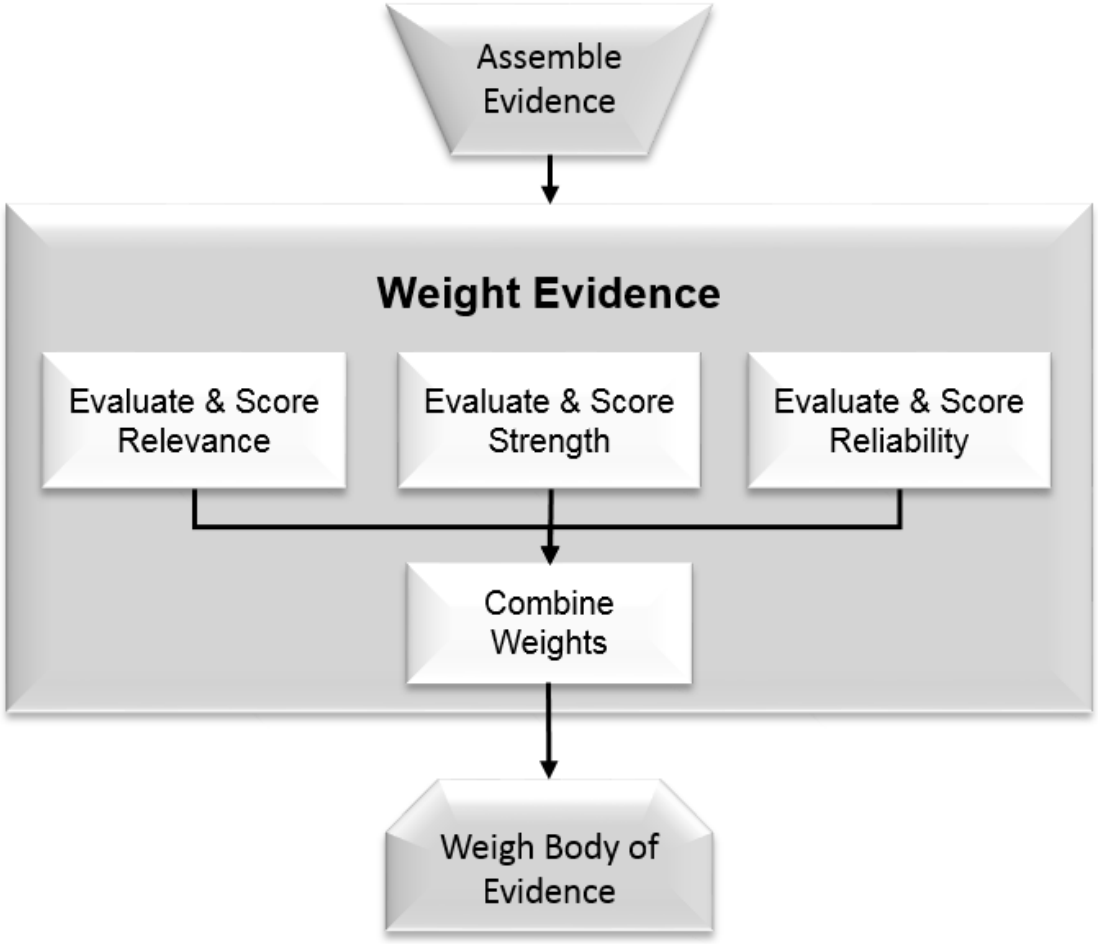

Figure 5-1. An elaboration of the process for weighting evidence, the second step in WoE.

The concept of weighting is familiar in statistics. For example, a weighted mean is the mean of study or sample values multiplied by weights, which are usually the numbers of observations. If one stream invertebrate survey of 10 sites reported a mean of 20 species and another survey of 40 sites reported a mean of 30 species, the true mean species richness across studies is found by multiplying each mean by the number of sites, adding the resulting products and dividing by 50. By weighting, the mean is shown

to be 28, not 25. Statistical weighting is an important tool of WoE for deriving quantities (see Section 8 and Appendix B) but is not considered further in this section.

The qualitative weighting of evidence has two components: evaluation and scoring. Evaluation of evidence determines the weight—how influential a piece of evidence should be, preferably based on defined properties. Scoring uses symbols to formalize the results of the evaluation. The weight is conceptual and the scores are symbolic. For example, a piece of evidence may be evaluated as moderately relevant, so the score for relevance is ++.

Many uses of WoE have not involved scoring. In these cases, either no results of evaluation are expressed or the results are expressed by descriptions. When assessors score the evidence, they are compelled to clarify the evaluation for the reader and themselves. In addition, scoring helps assessors provide clearly weighted evidence for the next step, the integration of evidence (see Section 6).

The approach presented here for qualitatively weighting evidence has been used in assessments of specific causation in the *Stressor Identification Guidance* (U.S. EPA, 2000) and in the Causal Analysis/Diagnosis Decision Information System (CADDIS, http://www3.epa.gov/caddis) and its applications. It has been used in an assessment of general causation for major ions as a cause of the impairment in stream communities (U.S. EPA, 2011b) and has been adapted to integrate evidence in a watershed risk assessment (U.S. EPA, 2014a). Below, the scoring system is presented first and then used to illustrate the evaluation of evidence.

5.2. Scoring Systems

A generally useful qualitative scoring system uses the symbols, +, − and 0, to represent evidence that, respectively, supports, weakens, or has no effect on the credibility of a hypothesis. More symbols represent greater weight. For example, the *Stressor Identification Guidance* and the CADDIS system for ecological causal assessment use the following scores.

+ + +, − − −	Convincingly supports or weakens
+ +, − −	Strongly supports or weakens
+, −	Somewhat supports or weakens
0	No effect (neutral or ambiguous)
NE	No evidence

The interpretation of plus or minus symbols is reasonably intuitive, and they have been used in other WoE systems (Rooney et al., 2014; Higgins and Green, 2011; Fox, 1991; Susser, 1986). These scoring symbols are quite general. They can be applied to a simple quantifiable property like strength of association or to a complex qualitative property like study design. Their regular use could result in clear and consist expression of WoE results. Nevertheless, other scoring systems might be more useful in particular applications.

Most other scoring systems used in environmental assessments only distinguish different degrees of support for a hypothesis. Some evidence, however, is clearly contrary to a hypothesis or has no effect. When a scoring system does not include those possibilities, a separate step must follow scoring to distinguish the logical implications of evidence [e.g., the evidence for the hypothesis is ++ for reliability and +++ for strength but it is contrary to the hypothesis (Johnston et al., 2002)]. The use of 0 and − symbols as well as + makes the logical implication of the evidence part of the weighting process rather than an afterthought.

Symbols are preferable to numerical scores because their use implies that they cannot be numerically combined. Two strongly supporting laboratory tests (++ and ++) are not equal to four somewhat supporting field tests (+, +, +, +). For a test result, a − score for study design and a + score for replication of the test do not sum to 0, because they are not commensurable. They simply signify different results for the different qualitative properties. Adding numerical scores generates a number with no units that signifies no quantity in particular.

These symbols also facilitate interpretation of bodies of evidence. When scanning a WoE table (see Section 6.2), seeing patterns in the frequencies of +, − and 0 symbols that indicate which hypotheses are supported by the weight of evidence is easier than if words or numbers are used to score evidence.

The system described above with three types of weight (positive, negative, and none) and three levels of weight (low, medium and high) has been found useful in environmental assessments, but more or less discrimination might be useful in some assessments. Binary (+/−) scores such as accept/reject and consistent/inconsistent have been recommended because more complex systems could be confusing or overwhelming (Hope and Clarkson, 2014). Alternatively, studies of survey responses have shown that people can distinguish five to seven possible response levels as in the Likert scale [e.g., very low, low, medium, high, very high (Dawes, 2008)]. Hence, the complexity of the scoring system can be adapted to the assessment and the desired degree of discrimination.

5.3. Properties to Be Weighted

Various properties of a piece or type of evidence can contribute to the degree of influence that it should exert. The specific properties fall within three general properties: relevance, strength, and reliability (defined in Box 5-1, Box 5-2, and Box 5-3).

Relevance (Box 5-1) includes biological, physical/chemical, and environmental aspects. It is at least minimally ensured when the assembled evidence is screened. Screening might be sufficient, and no further weighting of individual pieces of evidence for relevance may be necessary. For example, when assessing risk to black bears, if the only available mammalian toxicity tests are for laboratory rats and mice, the relevance of the tests cannot be distinguished because the relationships of rat and mouse sensitivities to bear sensitivity is unknown. In many cases, however, differences in study relevance are important to consider.

A strong signal is better differentiated from noise than is a weak signal, so a strong signal should be given more weight. Strong evidence shows (1) a large magnitude of difference between a treatment and control in an experiment or between exposed and reference conditions in an observational study, (2) a high degree of

Box 5-1. Relevance of a Piece or Type of Evidence

The relevance of a piece or type of evidence is the degree of correspondence between the evidence and the assessment endpoint to which it is applied.

Biological relevance—correspondence among the taxa, life stages, and processes measured or observed and the assessment endpoint (e.g., a *Daphnia* acute lethality test does not correspond well to insect life-cycle survival and fecundity, so relevance may be low).

Physical/chemical relevance—correspondence between the chemical or physical agent tested or measured at the studied site and the chemical or physical agent constituting the stressor of concern (e.g., pyrene may be used to represent a polycyclic aromatic hydrocarbon mixture, but relevance may be low).

Environmental relevance—correspondence between test conditions and conditions at the assessed site or the environmental conditions in a studied system and conditions in the region of concern (e.g., a pond mesocosm does not correspond well to a stream for many environmental parameters, so relevance may be low).

association between a putative cause and effect, or (3) a large number of elements in a set of evidence (see Box 5-2). Strength is a property of the study results, not the type of evidence or study method. The metrics for strength of evidence are familiar. Magnitude is typically represented by absolute and relative differences (e.g., body burdens were 20 times higher than at reference sites). Association is typically represented by correlation coefficients (e.g., Pearson's *r* for the correlation of emission rate and ambient concentrations was 0.8) or slopes (e.g., the regression of species richness on dissolved oxygen had a slope of 7). Number is commonly represented by the number of elements or frequency of occurrences (e.g., a fish kill has occurred at snowmelt every year for the past 6 years). Although strength occurs less frequently in WoE systems than relevance and reliability, some weight only strength (Chapman, 2007).

Box 5-2. Strength of a Piece or Type of Evidence

The strength of a piece or type of evidence is the degree of differentiation from control, reference, or randomness [modified from Norton et al. (2014)].

Magnitude—degree of difference between the amount of response at affected sites and at reference sites or in treatments and controls, between degrees of exposure or other relevant differences in the evidence, most commonly expressed as a difference between means or a ratio of means.

Association—degree to which variation in a variable representing a cause explains variation in a variable representing an effect, most commonly expressed as a correlation coefficient.

Number—the number of elements of a set of evidence (e.g., of symptoms or overt effects in a response or of steps in a causal pathway) that are reported to be observed or the number of occurrences.

Strength metrics lend themselves to standardization. For example, correlation coefficients were calculated for several associations in regional field data to determine the WoE for major ions as a cause of the extirpation of invertebrate genera and for potential confounding by other variables (U.S. EPA, 2011b). Standard scores were developed for the strength of correlations based on the authors' experience with correlations of parameters in surveys of physical, chemical, and biological properties of streams (Table 5-1). In this example, a correlation coefficient (r) between 0.25 and 0.75 is supportive but is not assigned an extra plus for strength. Because $r > 0.75$ is considered relatively strong for a correlation between a water quality measure and a biological response from a regional data set, it is given a second plus. No field correlations are believed to be convincing evidence, so none receive three + or − signs. Consistency and reasonableness of the scores are more important than the precise values chosen for the cutoffs, when they are used to compare alternative hypotheses. Documenting scoring criteria in advance also reduces the opportunities to bias the scoring relative to scoring performed without previously defined cutoff values.

Standard scores based on strength and logical implication are provided for evidence in causal assessments in the CADDIS system. The examples in Table 5-2 are based on standard alternative possible outcomes (findings) for each of 16 types of evidence and the interpretations of those outcomes in terms of the degree to which they support a potential cause. These scores show that different types of evidence have different outcomes with different implications for a hypothesis. The CADDIS table was developed for causal assessment in aquatic ecosystems. This approach to standard scoring is useful if the types of evidence and their findings are conventional. Other applications of this approach could have different types of evidence, possible outcomes, and interpretations.

Table 5-1. Weighting the strength of correlations (absolute value of *r*) and noting the logical **implication—an** example for evidence from stream biological surveys (Cormier and Suter, 2013; U.S. EPA, 2011b)

Assessment	Logical Implication and Strength	Score
The sign of the correlation coefficient depends on the relationship. For toxic relationships such as the correlation between conductivity and number of Ephemeroptera, the sign should be negative. Weak or positive correlations weaken the case for that candidate cause.	$\lvert r \rvert > 0.75$	+ +
	$0.75 \geq \lvert r \rvert \geq 0.25$	+
	$0.1 < \lvert r \rvert < 0.25$	0
	$\lvert r \rvert \leq 0.1$	−
	r has the wrong sign	− −

Table 5-2. Table of standard scores for 3 example types of evidence out of 15 types in CADDIS (http://www.epa.gov/caddis/si_step_scores.html). Each type of evidence is explained in its own CADDIS page.

Type of Evidence	Finding	Interpretation	Score
Spatial/temporal co-occurrence in site surveys	The effect occurs where or when the candidate cause occurs, OR the effect does not occur where or when the candidate cause does not occur.	This finding *somewhat supports* the case for the candidate cause, but is not strongly supportive because the association could be coincidental.	+
	Whether the candidate cause and the effect co-occur is uncertain.	This finding *neither supports nor weakens* the case for the candidate cause because the evidence is ambiguous.	0
	The effect does not occur where or when the candidate cause occurs, OR the effect occurs where or when the candidate cause does not occur.	This finding *convincingly weakens* the case for the candidate cause because causes must co-occur with their effects.	− − −
	The effect does not occur where and when the candidate cause occurs, OR the effect occurs where or when the candidate cause does not occur, and the evidence is indisputable.	This finding *refutes* the case for the candidate cause because causes must co-occur with their effects. Because the evidence is indisputable, other evidence need not be assessed.	R
Laboratory tests of site media	Laboratory tests with site media show clear biological effects that are closely related to the observed impairment.	This finding *convincingly supports* the case for the candidate cause.	+ + +
	Laboratory tests with site media show ambiguous effects, OR show clear effects that are not closely related to the observed impairment.	This finding *somewhat supports* the case for the candidate cause.	+
	Laboratory tests with site media show uncertain effects.	This finding *neither supports nor weakens* the case for the candidate cause.	0
	Laboratory tests with site media show no toxic effects that can be related to the observed impairment.	This finding *somewhat weakens* the case for the candidate cause but is not strongly weakening because test species, responses, or conditions might be inappropriate relative to field conditions.	−
Symptoms	Symptoms or species occurrences observed at the site are diagnostic of the candidate cause.	This finding is sufficient to *diagnose* the candidate cause as the cause of the impairment, even without the support of other types of evidence.	D
	Symptoms or species occurrences observed at the site include some but not all of a diagnostic set, OR symptoms or species occurrences observed at the site characterize the candidate cause and a few others.	This finding *somewhat supports* the case for the candidate cause, but is not strongly supportive because symptoms or species are indicative of multiple possible causes.	+

Type of Evidence	Finding	Interpretation	Score
	Symptoms or species occurrences observed at the site are ambiguous or occur with many causes.	This finding *neither supports nor weakens* the case for the candidate cause.	0
	Symptoms or species occurrences observed at the site are contrary to the candidate cause.	This finding *convincingly weakens* the case for the candidate cause.	−−−
	Symptoms or species occurrences observed at the site are indisputably contrary to the candidate cause.	This finding *refutes* the case for the candidate cause.	R

Properties of evidence that suggest the evidence is more reliable and should be given greater weight are listed in Box 5-3. Additional properties may be applicable in particular cases. Although scoring numerous properties for every piece of evidence could be burdensome, doing so would provide completeness and transparency for the weighting process. An alternative is to choose one or a few properties to be weighted that are judged most important or most likely to discriminate the various pieces of evidence. For example, if all evidence is consistent with prior knowledge (as is usually the case), consilience need not be scored. This approach—scoring the most important component properties of reliability—is generally useful. The least burdensome, but also least transparent, approach is to integrate the component properties of reliability implicitly for each piece of evidence and assign an overall reliability score.

Of these 11 component properties of reliability, the most attention has been devoted to study design. Developing a checklist of design features for each commonly used type of evidence is advisable. For example, Batley et al. (2002) developed a checklist of considerations for laboratory and field studies of sediment chemistry, toxicology, and community structure.

Box 5-3. Reliability of Evidence

Reliability consists of inherent properties that make evidence convincing [modified from Norton et al. (2014)].

Design and execution—evidence generated with a good study design that is well performed is more reliable.

Abundance—evidence from more numerous data is more reliable because it reflects greater replication or resolution.

Minimized confounding—evidence is more reliable when the sampling design or analysis controls extraneous correlates.

Specificity—evidence (e.g., a symptom or set of symptoms) specific to one cause or a few related causes is more reliable.

Potential for bias—evidence from a study that is not funded by an interested party, is not produced for advocacy, and is not produced by an investigator with conflicts of interest is more reliable.

Standardization—a standard method decreases the likelihood that the evidence is biased or analyses are inaccurate.

Corroboration—using models, indicators, or symptoms that have been verified by many studies and are accepted technical practice can greatly increase reliability.

Transparency—complete description of methods and inferential logic and availability of data for reanalysis provide the means to check the results and are presumed to increase reliability by reducing the likelihood of hidden faults.

Peer review—an independent peer review increases reliability of a source of information.

Consistency—the degree to which evidence does not vary in repeated instances within a study (e.g., across years, locations, sampling teams, or methods) is an indicator of reliability of a piece of evidence; when weighting types of evidence, consistency among studies of the same type is an indicator of reliability of the type.

Consilience—evidence shown to be consistent with scientific knowledge and theory, particularly with respect to underlying mechanisms, is more reliable.

Reliability is less if a study or a body of work appears biased. The potential for bias in scientific publications, although controversial, is well documented (Suter and Cormier, 2014; McGarity and Wagner, 2008). One clearly important source is publication bias, the disinclination of authors to submit and editors to accept studies with negative results (i.e., no effect is found). This bias can be detected by statistical analysis if the number of studies is sufficiently large (Ferguson and Brannick, 2012; Hunter and Schmidt, 2004). Other sources of bias can be detected only by comparing the results of studies from different sources. In particular, numerous reviews have identified different results from industry-funded studies and studies funded by neutral sources (Suter and Cormier, 2014; McGarity and Wagner, 2008). The most conspicuous example in ecological risk assessment is the difference between industry-funded and other studies and reviews concerning the teratogenicity of atrazine (Ralof, 2010). Such patterns of biases are not used to exclude data, but potential sources of bias should be identified, if possible, as they help interpret the body of evidence (NRC, 2014). For example, if results of industry-funded studies differ from government- or foundation-funded studies, they all must be carefully reviewed. If the cause of the difference cannot be determined, the reliability of the whole body of evidence may be down-weighted.

Biases may also result from personal ideologies, from a desire for publicity, or other reasons. These more personal sources are more difficult to detect but may show up in non-scientific writings.

In general, secondary sources should be screened out (Section 4.2.2), but if information from secondary sources is used, it cannot be considered highly reliable. The creation of secondary sources is an opportunity to introduce errors and biases in the extraction, analysis, and interpretation of data. Bad citing practices have been reported in the ecological literature, resulting in unsubstantiated conclusions (Sanz-Martin et al., 2016; Tood et al., 2010; Todd et al., 2007). Hence, if primary sources are unavailable, information may be taken from secondary sources but should be considered to have weak reliability. Cases in which a secondary source identifies and corrects an error in a primary source may be exceptions.

In addition to relevance, strength, and reliability, the type of evidence has sometimes been a weighting consideration. In particular, some assessors give more weight to field biological survey results than to other evidence (Chapman and Anderson, 2005). However, some field surveys have low relevance because they do not address the endpoint, do not address the sensitive taxa or other sensitive entities, or measure an irrelevant or insensitive response. In addition, field surveys might be so poorly designed or executed that the results are unreliable. For example, field data were given priority in a contaminated sediment study even though the field survey had "many limitations," including no appropriate reference sites (McPherson et al., 2008). Weighting the properties of the evidence is preferable to assuming that one type is always weightier.

Statistical analysis also has been a consideration in WoE. For example, a criterion for study evaluation in ISAs is "Are the statistical analyses appropriate, properly performed, and properly interpreted?" (U.S. EPA, 2013). However, the appropriateness of the analyses reported in a publication is immaterial if assessors perform their own analyses. Published studies should include original data or the authors should make data available for reanalysis. At least for influential evidence, assessors should consider reanalyzing the data so that results are relevant to the assessment, properly interpreted, and free of statistical errors or biases in assumptions. In such cases, evaluating the statistics the authors used is not pertinent. If original data are not available, the evidence could be given a negative score for transparency. To the extent possible, improper interpretations should be corrected (e.g., $p > 0.05$ does ***not*** mean no effect occurred), and assessors should consider down-weighting evidence that has inappropriate statistics if reanalysis is not feasible (e.g., time and resources are not available).

5.4. Tables of Weights

The primary inferential tool in weighting evidence is tabulations of pieces or categories of evidence and the weights assigned to them with respect to their properties. Because the assigned weights are expressed as scores, they are called scoring tables. Scoring tables may be aggregated to the extent that the weighting process is aggregated. Table 5-3 is a basic, generic scoring table in which both the evidence and properties are aggregated. The rows could have been individual pieces of evidence, but in this table, they are conventional types of evidence. Each of the three general properties is assigned a score based on the evaluation of the evidence each type provides. In the example, when assessing a contaminant as a potential cause of effects in the field, the results of laboratory tests of the contaminant can be positive but have low relevance to the field (+), the responses in the tests can be moderately strong (++), and the reliability of the tests can be high due to standard test designs, good laboratory practices, and regular audits (+++). In this example, the combined score (overall weight) might be + (weak supporting evidence) because the low relevance of the tests could make the strength of the results and the reliability of the method irrelevant to the inference. In other cases, a highly relevant test of the species of concern may not be sufficient to overcome very low reliability (e.g., due to absence of controls). In general, a property with very low weight will have greater influence than a moderate- or high-weight property. In

other words, a bad property of a piece of evidence tends to contaminate the whole thing. These examples illustrate why qualitative WoE is not arithmetic—you can't just add up the scores. It also illustrates why weights should be explained.

Table 5-3. Generic scoring table based on conventional types of evidence, with first line hypothetically completed. The overall weight is positive but low because the test relevance is low.

Types of Evidence	Relevance	Strength	Reliability	Overall Weight
Laboratory toxicity tests of a defined agent	+	++	+++	+
Effluent toxicity tests				
Ambient media toxicity tests				
Field biological surveys				
Field biomarkers and organ or whole-body concentrations				
Field symptoms				

Table 5-4 presents an example from a general causal assessment to determine whether dissolved major ions, measured as conductivity, cause extirpation of stream invertebrate genera. This scoring table presents three types of evidence for one characteristic of causation: the sufficiency of the observed conductivity levels to cause extirpation. Equivalent tables were presented for evidence related to each characteristic of causation. The properties of evidence were treated as binary (e.g., either the evidence is corroborated or not), so no more than one symbol was applied to a property. In this case, evidence is screened for sufficient relevance, and each relevant type of evidence is given one score designating its logical implication. Strength is scored using quantitative criteria as in Table 5-1. Corroboration is scored as the most important component of reliability in this case. Inclusion of a description of the evidence aids reader understanding.

After having assigned weights to each property of evidence (relevance, strength, and reliability), and possibly to multiple component properties of relevance, strength, or reliability, combining them into an overall weight for each piece or type of evidence might be desirable. If evidence is abundant, providing a single summary weight score can facilitate the integration step. Developing a system for combining the property weights can be relatively straightforward. The system used for the casual assessment, from which Table 5-4 was taken, is designed to provide a maximum cumulative score of three + or – units, for each of the three properties. However, as with other processes in WoE, the weights could be combined by expert judgment without defined procedures or criteria to maintain flexibility.

If evidence is scored for multiple component properties, the components should be combined before the three properties are combined. Seldom are multiple component properties of relevance or strength separately scored for a piece of evidence. Reliability has at least 11 component properties that are conceptually distinct, however, and more than one can be applied to a piece of evidence (Box 5-3). In Table 5-3, only corroboration is evaluated, but if multiple component properties of reliability were judged sufficiently important to be evaluated and scored, a separate reliability scoring table would be needed.

In any case, making the weighting convincing and transparent by explaining the reasons for the scores is desirable. This explanation could be presented in the text, but a simple statement, as in the last line of Table 5-4, might be sufficient.

Table 5-4. Example scoring table: scoring types of evidence for sufficiency (U.S. EPA, 2011b). The table is a direct copy and calls out a figure that does not appear in this document.

Type of Evidence	Description of Evidence	Log[a]	Str[b]	Cor[c]
Laboratory tests of ambient waters	A test showed acute lethality to an apparently resistant species, *Isonychia bicolor*, at conductivity levels similar to its XC_{95}.	+		
Field exposure-response relationships of biological metrics	Ephemeroptera were negatively correlated with conductivity in two data sets $r = -0.61$ and -0.72 (Figs. 2b and 4b) and $r = -0.90$ in Pond et al. (2008). This highly relevant evidence was obtained independently in two separate data sets, with moderate-to-strong correlations. Exposures were in the field with native species. Removal of sites with high levels of potential confounders had little effect on the correlation.	+		+
Field exposure-response relationships of composite indices	The field observations showed that, as conductivity increases, indices of stream condition (WVSCI and GLIMPSS) decrease [Fig. 5 and Pond et al. (2008)]. Correlations were strong [$r = -0.80$; $r = -0.90$ in Pond et al. (2008)]. Results were further corroborated by U.S. EPA (2010a). Exposures were in the field with native species.	+	+	+
Field exposure-response relationships of susceptible genera	At 500 µS/cm, the capture probabilities of more than 65% of genera began to decline. Similar results were obtained with West Virginia and Kentucky data sets.	+	+	+
Summary of sufficiency: Exposure to saline waters in Appalachia is sufficient to cause the declines of genera (+) with the salts found in the region's streams. The increases in effects of conductivity are strong even when other stressors are present (+). Different analytical approaches demonstrate that ionic strength is associated with different effect endpoints in different data sets in two states (+). The evidence is consistent. The total score is + + +.				

[a] Log = logical implication of relevant evidence, [b] Str = strength, [c] Cor = corroborated evidence.
GLIMPSS = Genus-Level Index of Most Probable Stream Status, WVSCI = West Virginia Stream Condition Index.

5.5. Not Combining Weights for Properties of Evidence

Assigning scores to each property of each piece or type of evidence might complete the weighting step. That is, separate scores for the properties, rather than a single combined weight, could be carried forward to the integration step. The advantage is that the weights assigned to each property are available to assessors while they are integrating across evidence within a hypothesis as shown in Table 6-2. In such cases, the WoE table shows which pieces of evidence are relevant, which are strong, and which are reliable. One might even score biological, physical/chemical, and environmental relevance separately if relevance is a particularly important issue in the case. The obvious disadvantage is that the integration becomes more complex because the assessor must consider weights for multiple properties while integrating multiple pieces of evidence. In addition, the relative influence of the properties might be evaluated less consistently and transparently if it is not determined in a separate step.

5.6. Summary

Once the evidence has been assembled, the WoE analysis begins in earnest with the assignment of weights to the evidence. Weights are represented by a generally useful scoring system that represents both the implication of the evidence (+, −, and 0) and the weightiness of the evidence (the number of

symbols). Three properties are scored: relevance, strength, and reliability. The evidence and associated weights are summarized in a scoring table. Weights for the three properties may be combined into an overall weight for each piece of evidence or all three may be carried forward into the next step, weighing the body of evidence.

5.7. Results and Transition

The result of the weighting step is a set of pieces or categories of evidence for each hypothesis, each of which has been assigned weights indicating how relevant, strong, and reliable it is. It is recommended that the weights be expressed as qualitative scores and organized in scoring tables. A narrative should also be provided describing the evidence and explaining the weights. This weighted set of pieces or categories of evidence are integrated and interpreted in the weighing step, which follows.

6. WEIGHING BODIES OF EVIDENCE

6.1. The Weighing Process

After weights have been assigned to pieces or categories of evidence, each resulting body of evidence is weighed to determine which, if any, hypothesis is supported. First, weighted evidence for each hypothesis is integrated to form weighed bodies of evidence for the hypotheses (Figure 6-1). Second, the bodies of evidence are interpreted to determine which hypothesis the evidence best supports. Finally, if the bodies of evidence are ambiguous or discrepant, the case should be reconsidered and additional evidence may be required.

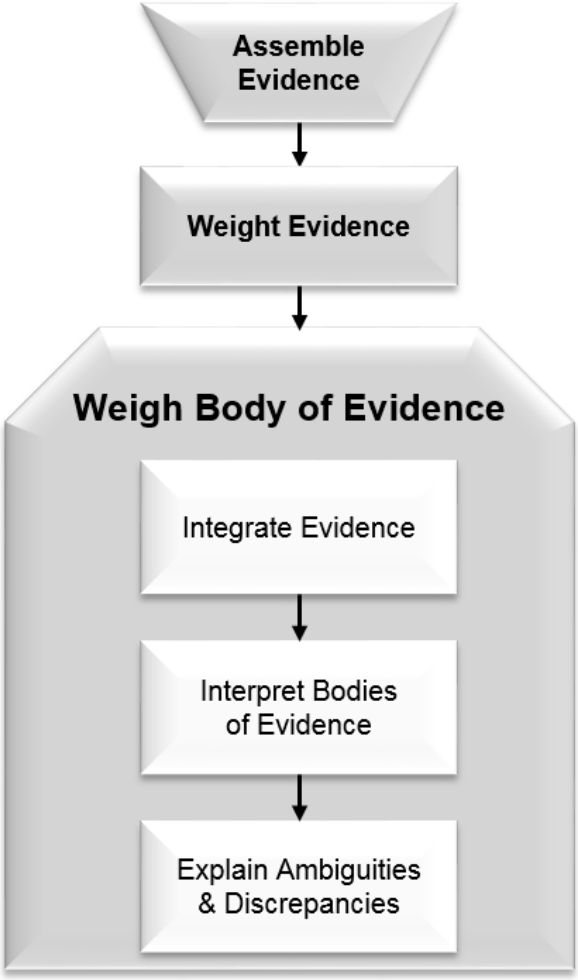

Figure 6-1. An elaboration of the process for weighing the body of evidence, the third step in weight of evidence.

6.2. Integrating Evidence

The input to the integration step is weighted pieces or categories of evidence, and the output is the weighed body of evidence for each hypothesis. The essential purpose of integration is to aggregate the evidence and associated weights into an overall weight. A secondary purpose of integration is to explain the role that the evidence serves in the inference.

1. Integration can aggregate numerous weighted pieces or categories of evidence (depending on the output of the weighting step) into a body of evidence. This purpose is typically served by deriving a combined weight for each type of evidence: evidence derived from laboratory acute tests, biomarkers, biological surveys, etc. Then, the weights are integrated across categories to weigh the body of evidence for each hypothesis.

2. Explanation can answer the question, what does the evidence do to support or weaken a hypothesis? For example, evidence from field surveys can support a hypothesized cause by showing that the cause and effect co-occur. Because WoE is often used to infer causation, the most broadly useful explanation is to associate the evidence with the characteristics of causation such as time order and interaction [Table 6-1, Table 6-4, and Table E-1 (Norton et al., 2014; Cormier et al., 2010)]. Characteristics, however, can be defined for any quality inferred by WoE such as impairment or remediation (see Appendix E). Even without defined characteristics, explanation can be performed by determining how each category of evidence relates to the hypotheses. For example, when weighing evidence for dietary bioaccumulation of a chemical in fish, concentrations in algae are evidence that the chemical occurs in the food web of the fish. If the evidence has been associated with characteristics, the sets of evidence for the characteristics can be used as categories of evidence in place of the conventional types of evidence (e.g., Table 6-4).

Evidence can be integrated in one or more steps, depending on the amount and its diversity and the circumstances of the assessment (Figure 6-2). The categories into which evidence is integrated can be types of evidence or characteristics of the quality of interest. If the pieces of evidence are few or all of one type, the body of evidence can simply be integrated after each piece of evidence is weighted (Figure 6-2a). If the differences among pieces of evidence within a category are small, weighting the pieces can be skipped and the category of evidence weighted as a whole (Figure 6-2b). When evidence is both abundant and diverse, the pieces of evidence can be weighted in each category, the categories weighed based on the weights of the pieces and the collective properties of the category (Box 6-1) and finally, the body of evidence weighed (Figure 6-2c). At the extreme, weighing a very large and diverse body of evidence can be very methodical and use multiple tiers of categories (Figure 6-2d). For example, evidence for fish acute toxicity, fish chronic toxicity, invertebrate acute toxicity, and invertebrate chronic toxicity might be separately weighted and the weights combined to weigh the evidence from all laboratory toxicity tests. Evidence from a laboratory toxicity test then could be weighed along with field tests, field surveys, and any other type of evidence to determine whether the weight of the body of evidence is sufficient to indicate that a chemical exposure is a cause of aquatic community impairment.

The degree to which the weighing of evidence is elaborated depends primarily on a tradeoff between rigor and disclosure on one hand and efficiency and simplicity on the other. The potential to confuse or overwhelm the reader with an elaborate weighing process, however, could also be a consideration. To address this problem, detailed weighting tables and text could be presented in an appendix for peer reviewers and others who need a deep understanding and a summary provided for decision makers and stakeholders.

As in the weighting step, the fundamental tool of evidence integration is a table, but this one is called a WoE table. A WoE table presents the evidence, organized in categories (types or characteristics), and the WoE scores for each evidence category and alternative hypothesis (Table 6-1). These scores come from the scoring tables created by weighting the evidence (Section 5). The same symbols are used in the weighing step as in weighting, because they express the same conceptual weights. In addition, collective properties of the body of evidence such as coherence are scored (Box 6-1). Finally, the overall weight for each hypothesis is presented. This generic table form is broadly useful, but the form of the table in any application depends on the amount of evidence, number of hypotheses, detail of the weighting, degree of

involvement of the decision maker, and other considerations. Examples of WoE tables for integrated evidence from actual assessments are presented in Table 6-2 through Table 6-4.

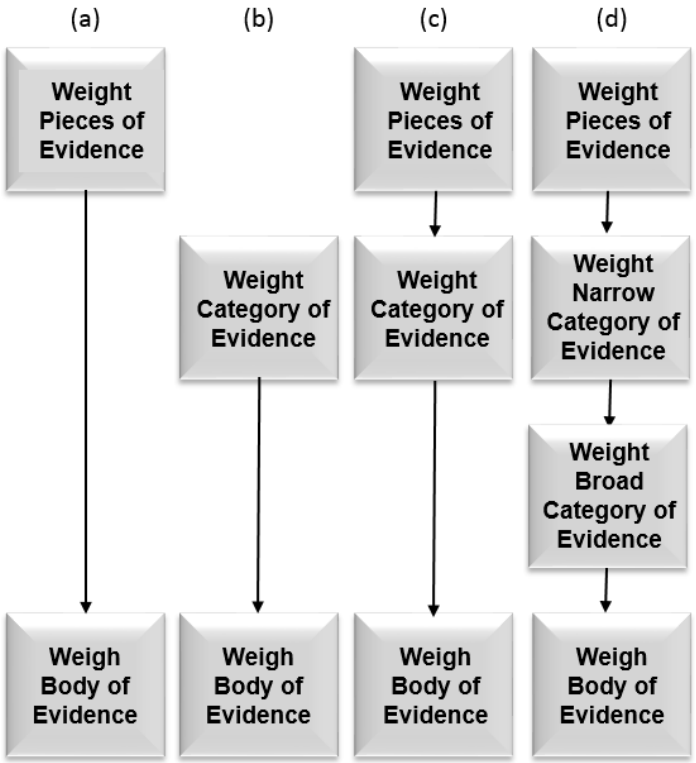

Figure 6-2. **Some alternative approaches (a–d) to weighting and weighing evidence based on different approaches to aggregating evidence.** Categories could be types of evidence or evidence for characteristics of the quality of interest. The choice depends on the amount and diversity of evidence, the circumstances of the assessment, and the judgments of the assessors. From Norton et al. (2014).

Box 6-1. Collective Properties of Bodies of Evidence. Modified from Norton et al. (2014).

The following collective properties of the body of evidence can be considered in addition to considering the relevance, strength, and reliability of the pieces or types of evidence. As with the properties of pieces or types of evidence, any of these could be used, depending on their relevance and utility for distinguishing among the hypotheses.

Number—more pieces or categories of evidence within a body of evidence increase the reliability, if they are consistent and are generated independently.

Coherence—logical consistency among types of evidence increases the reliability of a body of evidence, particularly when empirical and mechanistic evidence and evidence from a case and from elsewhere are coherent.

Absence of bias—consistent results from different funders and types of investigators (e.g., academic, industry, nongovernmental organization, government) are more reliable.

Diversity—evidence from more responses, taxa, life stages, or communities under more conditions is more likely to detect important exposures, responses, and relationships reliably.

Table 6-1. A generic weight-of-evidence table for *n* alternative causal hypotheses (H_1, H_2, ... H_n), based on causal characteristics and collective properties of the bodies of evidence

	Combined Weight		
	H_1	H_2	H_n
Characteristics of Causation			
Co-occurrence			
Sufficiency			
Time order			
Interaction			
Specific alteration			
Antecedents			
Body of Evidence, Collective Properties			
Number			
Coherence			
Absence of bias			
Diversity			
Integrated WoE			
WoE for the hypothesis			

Table 6-2 presents, for illustrative purposes, a subset of the types of evidence and causal hypotheses from a WoE table for determining the cause of a precipitous decline in the abundance of San Joaquin kit foxes on the Elk Hills Naval Petroleum Reserve, California (U.S. EPA, 2009a). The full table occupies multiple pages. The evidence was scored using the types and standard scores in CADDIS, which eliminates the need to weight the evidence for relevance, strength, and reliability. However, it requires accepting the relevance of the standard weights and scores. One collective property of the body of evidence (coherence) is the primary basis for weighing the body of evidence. The conclusion was that predation by coyotes was the dominant cause of the decline and the evidence was convincing. The

coyotes appear to have increased on the site (co-occurrence), the cause of death of radio-collared foxes was known (evidence of exposure or mechanism), population modeling showed that predation was sufficient alone to account for the decline (stressor-response relationship), and coyote control coincided with an end to the decline (manipulation of exposure). Toxic chemicals were present and exposure occurred and was documented by analysis, but far too few foxes were significantly exposed to account for the decline. Accidents contributed but the contribution was relatively small. Note that the + for coherence of disease indicates that the evidence consistently fails to support that hypothesis, so that cause can be eliminated.

Table 6-2. Partial WoE table for alternative possible causes of the decline of San Joaquin kit foxes. Only 4 of 6 potential causes and 7 of 16 types of evidence are included. Adapted from U.S. EPA (2009a).

Types of Evidence	Predation	Toxics	Accidents	Disease
Spatial/temporal co-occurrence	+	+	+	−
Temporal sequence	0	0	NE	NE
Evidence of exposure or biological mechanism	++	++	++	−−
Causal pathway	+	+	+	0
Manipulation of exposure	+	NE	NE	NE
Stressor-response relationships from simulation models	+++	−	+	−−
Coherence	+++	−	+	+

Table 6-3 provides an example of a WoE table from a risk assessment. One hazard in the Bristol Bay watershed assessment was the potential failure of a diesel fuel pipeline at a stream or river crossing, so evidence was weighed for the hypothesis that a spill at a crossing would reduce salmon production (U.S. EPA, 2014a). Unlike the generic types of evidence, Table 6-2 shows types of evidence that are specific to the hypothesis. Evidence concerning the exposure-response relationship was available from laboratory tests of dissolved or dispersed diesel fuel and from eight studies of diesel spills into streams. Exposure was estimated by modeling hypothetical spills to estimate dissolved concentrations, diesel/water ratios, and total volume spilled. The results of combining the weights across properties for each type are presented as brief narratives rather than as combined scores, but the scores for each property are combined across types of evidence. This WoE table shows the consistency of results (all are supportive). It also illustrates where the weakness in the evidence lies—studies of oil spills in streams have not characterized exposure well, as indicated by ambiguous reliability.

Table 6-4 presents a table with combined scores for assessing whether major ions in streams cause extirpation of benthic invertebrates (U.S. EPA, 2011b). The evidence is categorized in terms of characteristics of causation and is derived from the results of scoring tables for each characteristic like Table 5-4. That is, the summary score from weighting evidence for sufficiency in Table 5-4 (+++) is the sufficiency score in Table 6-4 (also +++).

Table 6-4 illustrates how explanation of the pieces or types of evidence in terms of characteristics of causation elucidates the meaning of the evidence for a hypothesis. For example, elevated concentrations of a chemical in numerous streams with impaired communities mean that the chemical and community *co-occur*, and therefore, exposure is likely. If the concentration is greater than concentrations that cause relevant toxic effects, that means that the exposure believed to be *sufficient* to cause the effect. Although such explanations of the evidence might appear self-evident to assessors, it can be an important part of the inference. Although organizing evidence in terms of characteristics serves primarily to help explain the

implications of the evidence, it can also show that a study can provide evidence of multiple characteristics. For example, a laboratory toxicity test can provide evidence of sufficiency (the level of exposure required to cause effects) and of alteration (symptomatic effects of the exposure that may be observed in the field).

Table 6-3. Summary of evidence concerning risks to fish from a diesel spill (U.S. EPA, 2014a). The risk characterization is based on weighing four pieces of evidence for different routes of exposure. All evidence is qualitatively weighted on three properties: logical implication, strength, and reliability of methods. Here, all pieces of evidence have the same logical implication: all suggest a diesel spill would have adverse effects.

Route of Exposure Source of Evidence (Exposure/E-R)	Logical Implication[a]	Strength	Reliability		Result
			Exposure	E-R[b]	
Dissolved hydrocarbons: Model/laboratory acute tests	+	+	0	+	Modeled dissolved diesel concentrations are clearly lethal to invertebrates and approximately lethal to trout.
Dissolved hydrocarbons: Model/laboratory-based standard	+	++	0	++	Modeled dissolved diesel concentrations greatly exceed the state standard.
Dispersed hydrocarbons: Diesel oil:water ratio/laboratory acute tests	+	++	0	+	Diesel oil:water ratios in the spills and in tests suggest lethality to invertebrates and trout.
All routes in actual spills: Amount spilled/observed effects	+	++	+	+	Diesel spills in other streams cause acute biological effects.
Integrated weight of evidence	+	++	0	+	The effects by four types of evidence are consistent, and the observed effects are strong. The greatest uncertainty is the relation of laboratory to field exposures.

Notes:
[a] Logical implication indicates relevance and a particular direction of the evidence (supports or weakens)
[b] E-R = exposure-response relationship

Table 6-4. Example of weighing evidence for a potential cause, major ions measured as conductivity, of the loss of macroinvertebrate genera (U.S. EPA, 2011b). The evidence is organized in terms of characteristics of causation.

Characteristic	Body of Evidence	Scores
Co–occurrence	Loss of genera occurs when conductivity is high but is rare when conductivity is low.	+++
Antecedence	Sources of the ionic mixture are present and are shown to increase stream conductivity in the region.	+++
Interaction	Aquatic organisms are directly exposed to dissolved ions. Based on first principles of physics, ionic gradients in high-conductivity streams would not favor the exchange of ions across gill epithelia. Physiological studies over the past 100 years have documented the many ways that physiological functions of organisms are affected by the relative amounts and concentrations of ions (i.e., combinations of ions that some genera do not have mechanisms or the capacity to regulate).	++
Alteration	Some genera and other response metrics and assemblages are affected at sites with higher conductivity, whereas others are not. These differences are characteristic of relative sensitivity to high conductivity.	+++
Sufficiency	Laboratory analyses report results of effects for a tolerant species, but test durations and most ionic compositions are not representative of exposure in streams. Based on field observations, however, regular increases in effects on invertebrates with increased ionic exposure indicate that exposures are sufficient.	+++
Time order	Conductivity is high and extirpation has occurred after mining permits are issued, but conductivity and biological data before and after mining began are not available.	NE
Summary of body of evidence	Five characteristics are supported and none weaken the body of evidence that increases in conductivity causes extirpation of freshwater benthic invertebrates.	Very likely

6.3. Interpreting Bodies of Evidence

Interpretation is the step in which the bodies of evidence for each hypothesis are used to determine which, if any, hypothesis is supported, and therefore, is likely to be true. Depending on the case, the interpretation of evidence could be performed by comparing alternative hypotheses or by judging whether the evidence sufficiently supports a particular hypothesis. Comparison of alternatives typically occurs in specific causal assessments (e.g., What is causing the low species richness in Jones Creek?). The hypothesis with the greatest weight of evidence is the most likely of the assessed possible causes. This is not just a matter of counting the scores. In particular, the coherence of each body of evidence with respect to the associated hypothesis is considered.

Multiple hypotheses might be likely or at least well supported. For example, both a water treatment plant effluent and stream channelization might be sufficient causes of low species richness in a stream, so both hypotheses could be accepted.

Judging a single hypothesis can be conceptualized as comparing the hypothesis against its negation (e.g., WoE for teratogen versus WoE for not a teratogen) or as a comparison of the weight of evidence for the hypothesis with a standard of sufficient evidence (e.g., a sufficient WoE for teratogenicity versus insufficient evidence). One particular hypothesis can be judged in some particular types of assessments:

(1) a general causal assessment (e.g., Does selenium cause terata in frogs?), (2) specific causal assessments for which only one potential cause is considered (e.g., Does the effluent cause the observed biological impairment?), (3) a condition assessment (e.g., Is the stream impaired?), or (4) an outcome assessment (e.g., Has the wetland recovered?).

These approaches to weighing evidence are consistent with that for the conventional standard of proof in civil legal proceedings and public policy, the "preponderance of the evidence." To meet a preponderance-of-evidence standard, a hypothesis must be shown to be more likely than its negation or than the alternative hypotheses. This standard is met by comparing the weights of the bodies of evidence for a hypothesis and its alternatives.

Hume (1748), Laplace (1812), and Sagan (1980) all made the point that extraordinary claims require extraordinary evidence. This inferential rule should be kept in mind when interpreting bodies of evidence. A hypothesis is extraordinary if there is no prior evidence for it (e.g., the agent has not previously been shown to cause the effect or has been shown to be effective only at much higher levels), or it is simply not plausible. Extraordinary evidence is very weighty evidence: highly relevant, strong, and reliable.

Interpreting the evidence for hypotheses usually involves applying a three-value logic (e.g., yes, no, maybe; true, false, uncertain; or high, low, intermediate). If the interpretation is comparative, as in determining which alternative cause is best supported by the evidence, examining a summary table of the scored evidence and identifying the likely causal hypothesis are possible. Even if the best hypothesis is not clear, proposed hypotheses that clearly are not supported and can be eliminated can nearly always be identified. For example, an assessment of the cause of a precipitous decline in smallmouth bass in the Susquehanna and Juniata Rivers, Pennsylvania, using the CADDIS WoE method and existing information was inconclusive (Shull and Pulket, 2015). It did, however, classify the 18 candidate causes into three bins: 2 likely, 8 unlikely, and 8 uncertain. These results are being used to prioritize and design subsequent research and monitoring. Similarly, when judging a single hypothesis (e.g., spilled tailings would pose a substantial risk to salmon production), the hope is for a body of evidence that clearly either supports or counters the hypothesis, but the evidence might be ambiguous (U.S. EPA, 2014a).

Some WoE systems have standard categorical outcomes defined in terms of properties of the body of evidence (U.S. EPA, 2013, 2005b). A description of the potential weights of evidence used for causal determinations (i.e., categorical outcomes for general causal assessments) of criteria air pollutants is shown in Table 6-5. In such cases, interpreting the evidence involves matching the properties of the body of evidence to one of the categories. The definitions of categories, however, could be based on the scored properties rather than narratives as in this example.

Ultimately, the interpretation of evidence is a matter of logic applied to evidence and background knowledge, preferably by multiple individuals with a range of expertise. It is not simply a matter of adding or counting scores. In particular, some pieces of evidence are conclusive alone. For example, if the effect precedes a potential cause or if an aqueous effect occurs upstream of the putative source, the cause can be eliminated even if other evidence is positive. More commonly, one piece or type of evidence will influence the interpretation of other evidence. Even WoE systems that use standard scoring criteria and arithmetic integration of numerical scores rely on logic to identify and correct results that are contrary to knowledge of the system (COA Sediment Task Group, 2008; Johnston et al., 2002). As a result, applying expert judgment in any WoE is necessary to achieve an adequate, explanatory account.

At this stage, it is desirable to limit the interpretation to the hypotheses and evidence that were defined in advance. Otherwise, "ad hoc machinations" to achieve an acceptable answer can occur (Douglas, 2012). If interpreting the evidence does not identify a clear preponderance of evidence for a hypothesis, techniques that go beyond the simple weighing of evidence can be applied, as explained in the following

section. However, it should be remembered that they violate the admonition against improvised reasoning so they are less convincing than results of weighing bodies of evidence and hypotheses defined in advance.

Table 6-5. Weight of evidence for causal determinations in the 2013 lead ISA (U.S. EPA, 2013).

Causal Determination	Evidence for Ecological and Welfare Effects
Causal relationship	Evidence is sufficient to conclude a causal relationship with relevant pollutant exposures (i.e., doses or exposures generally within one to two orders of magnitude of current levels). That is, the pollutant has been shown to result in effects in studies in which chance, bias, and confounding could be ruled out with reasonable confidence. Controlled exposure studies (laboratory or small- to medium-scale field studies) provide the strongest evidence for causality, but the scope of inference could be limited. Generally, determination is based on multiple studies conducted by multiple research groups, and evidence that is considered sufficient to infer a causal relationship is usually obtained from the joint consideration of many lines of evidence that reinforce each other.
Likely to be a causal relationship	Evidence is sufficient to conclude a likely causal association with relevant pollutant exposures. That is, an association has been observed between the pollutant and the outcome in studies in which chance, bias, and confounding are minimized, but uncertainties remain. For example, field studies show a relationship, but suspected interacting factors cannot be controlled, and other lines of evidence are limited or inconsistent. Generally, determination is based on multiple studies in multiple research groups.
Suggestive of a causal relationship	Evidence is suggestive of a causal relationship with relevant pollutant exposures, but chance, bias, and confounding cannot be ruled out. For example, at least one high-quality study shows an effect, but the results of other studies are inconsistent.
Inadequate to infer a causal relationship	The available studies are of insufficient quality, consistency, or statistical power to permit a conclusion regarding the presence or absence of an effect.
Not likely to be a causal relationship	Several adequate studies, examining relationships with relevant exposures, are consistent in failing to show an effect at any level of exposure.

6.4. Explaining Ambiguities and Discrepancies

The results of weighing bodies of evidence can be ambiguous and discrepancies among pieces or types of evidence can occur. Examples include WoE results for which:

1. The bodies of evidence for all assessed hypotheses are incoherent.

2. One hypothesis has sufficient, consistently positive evidence to support acceptance, but some other hypotheses also have some relevant and reliable positive evidence.

3. No hypothesis has predominantly positive evidence.

In ambiguous, discrepant, or nonsensical cases, one can stop the assessment process and call for more data or proceed to perform follow-on analyses to resolve problems with the existing evidence. The latter course could allow successful completion of the assessment by reconsidering the evidence or by reformulating the hypotheses. Having completed the WoE analysis, some hypotheses could have been

eliminated, but the grounds for elimination might need re-examination. Also, assessors should have become deeply familiar with the evidence. That familiarity and the assessors' background knowledge could make it possible to reinterpret the data or revise the hypotheses to explain and resolve the ambiguities. Reinterpretations, however, provide opportunities to fabricate false explanations of apparent patterns in the evidence. Formulating hypotheses to accommodate the evidence is discouraged in scientific inference because it can lead to bias or self-deception. It has come to be known as HARKing (hypothesizing after results are known). As in other judgments during the assessment process, clearly articulating arguments, avoiding over interpretation, involving multiple assessors with different perspectives, and using a clear and consistent method to build the case are essential. A generally useful approach is to (1) list the discrepancies, (2) ask whether each discrepancy could be explained by a misinterpretation of the evidence or by a misspecification of the hypothesis, (3) determine whether all discrepancies can be resolved by some combination of reinterpreting evidence and respecifying hypotheses, and (4) evaluate additional evidence relevant to the explanations.

Reinterpreting the evidence is facilitated by considering ambiguities in the data and the methods used to generate them. As presented in Appendix E, Table E-3, toxicity tests might not include sensitive species, life stages, or responses; the bioavailability or form of a toxicant might be inappropriate; the exposure durations might be too long or too short, etc. Biological surveys could be conducted in the wrong season, compared to an inappropriate reference, to measured responses or taxa that are insensitive to the causal agent, etc. Measures of exposure might miss episodic events, be taken under atypical conditions, not include the causal agents, be disjunct from the biological samples, etc. Any of the evidence could be derived from studies that are biased, poorly designed, or poorly conducted in ways that were not reported or not recognized in the weighting. Inventing explanations is not difficult—the difficulty is determining which are likely to be true.

In addition to reinterpreting the evidence, assessors might explain discrepancies by changing the hypotheses or adding hypotheses in light of the evidence. At least four strategies can be applied.

Redefine the endpoint effect. Causal relationships are often unclear because the effect is unclear. For example, determining the cause of decline in peregrine falcons depended on redefining the effect as reproductive failure associated with thin eggshells. That more specific definition steered assessors away from potential causes such as habitat loss, shooting, and egg collecting and toward toxic effects. In some cases, discrepancies might be explained by defining the spatial or temporal scope of the effect more specifically. For example, defining the effect as the occurrence of fish kills in a stream as a whole will lead to discrepancies in the evidence if kills occur only in a reach below an outfall and the dead fish drift downstream.

Reconsider sources and agents. Discrepancies in evidence could be due to sources, components of emissions, or actions that were not considered, because they were overlooked or of no concern to the decision maker or stakeholders.

Integrate causal agents or networks. Rather than being alternatives, the proposed causes of an effect could be acting jointly. Also, a proposed proximate cause might actually be an indirect cause that contributes to the true proximate cause. For example, habitat disturbance did not cause the decline in San Joaquin kit foxes on the Elk Hills Petroleum Reserve, but it apparently made the foxes more susceptible to the major cause, predation (U.S. EPA, 2009a). Such possibilities can be represented in practice by rearranging the components of a conceptual model or by combining alternative conceptual models. The conceptual model can be revised by removing the box-and-arrow combinations that are not supported by evidence and examining how the remaining boxes and arrows might link within the model or among models for different causes.

Look for patterns in the evidence. Looking for properties that the pieces or categories of evidence supporting a hypothesis share, which the contrary evidence does not share, might be helpful. This examination could be facilitated by creating a matrix of evidence versus relevant attributes of the evidence. Different results might be observed, for example, in field versus laboratory studies, lotic versus lentic studies, industry-funded versus foundation-funded studies, insect versus crustacean studies, etc.

Reinterpreted evidence or revised hypotheses could explain discrepancies in a manner that seems convincing to the assessors who developed them, but explanations improvised after the analysis to account for discrepancies might not convince others without independent evidence. Independent evidence might have been available but unused in prior weighing of evidence, because it had not been relevant. For example, if the proposed resolution of a discrepancy was low bioavailability of metals, measurements of dissolved organic matter might be used to confirm that explanation. Similarly, if low dissolved oxygen is a proposed cause of a fish kill, the survival of air-breathing organisms such as frogs and turtles is supportive (Cormier et al., 2010). Ideally, confirmatory evidence would be generated by identifying a previously unmeasured or unobserved property of the system that should occur under the revised hypothesis and then taking the measurements or observations that would establish its occurrence. If the amount of evidence and the number of possible explanations of the evidence are substantial, a formal reweighing of the evidence to address the revised hypotheses might be appropriate.

6.5. Presenting Results

The results of a qualitative WoE have two parts: the conclusion and the justification. The conclusion, in the best case, is a statement of the hypothesis that is clearly supported by the WoE (e.g., the cause is the thermal effluent, the stream is biologically impaired, or the population has recovered). Ambiguous results require more explanation (e.g., hypothetical causes 1, 3, and 5 can be eliminated, but 2 and 4 are somewhat supported). Graphical presentations can be useful, such as a revised conceptual model of the identified causal relationship or a map of the areas biologically impaired by the waste. When the assessments are sufficiently standardized, a standard reporting format could be implemented as in the International Uniform Chemical Information Database (IUCLID) dossier for assessing the toxic properties of chemicals in the European Union (ECHA, 2010).

The justification of a conclusion is a summary of the evidence and logic that support the conclusion. The justification, which will vary among assessments, typically includes:

1. Statements of overall weight of evidence for the conclusion (e.g., the evidence convincingly supports, strongly supports, or somewhat supports the cause) relative to the weights for alternatives or relative to a standard of evidence.

2. Statements of consistency or coherence (e.g., all the evidence was either convincingly or strongly supportive of the cause, except for laboratory acute tests, which had low relevance).

3. Statements of the extent to which characteristics of causation or other relevant characteristics are satisfied by the evidence (e.g., evidence was available to support all characteristics of causation except time order). Alternatively, state the extent to which standard types of evidence were available (e.g., all three components of the sediment quality triad were available). In any case, state how the body of evidence provides an explanation of the credibility of the accepted hypothesis.

4. Statements explaining why the conclusion is justified despite a low weight of the body of evidence, if necessary (e.g., even if other causes could be substantially contributing, collection and treatment of the effluent is likely to improve conditions and is mandated by regulations).

6.6. Summary

Having assigned weights to the pieces of evidence, the process of weighing evidence integrates and interprets the body of evidence to determine which, if any hypothesis has sufficient weight to be accepted. Depending on the amount and types of evidence, this may include a process of aggregating the evidence into categories and integrating the weights within categories. Once the weights have been integrated, the bodies of evidence for all hypotheses should be compared and the results interpreted. Interpretation may be obvious (e.g., only one hypothesis has positive evidence) but often it requires careful logic and judgment informed by the knowledge and experience of multiple assessors. If interpretation does not provide a conclusion, an analysis of the ambiguities and discrepancies that confounded the interpretation can suggest what additional evidence or alternative hypotheses should be considered. Finally, the results should be presented in a way that make clear the results and the process that generated them.

7. SPECIAL CASES AND ABBREVIATED PROCESSES

In some circumstances, the full three-step WoE process is not necessary or practical, but a two-step process is useful. The systematic assembly of evidence is always appropriate, but weighting might be unnecessary if all evidence is equivalent (Figure 7-1a), and weighing a body of evidence is unnecessary if only one piece of evidence is available (Figure 7-1b).

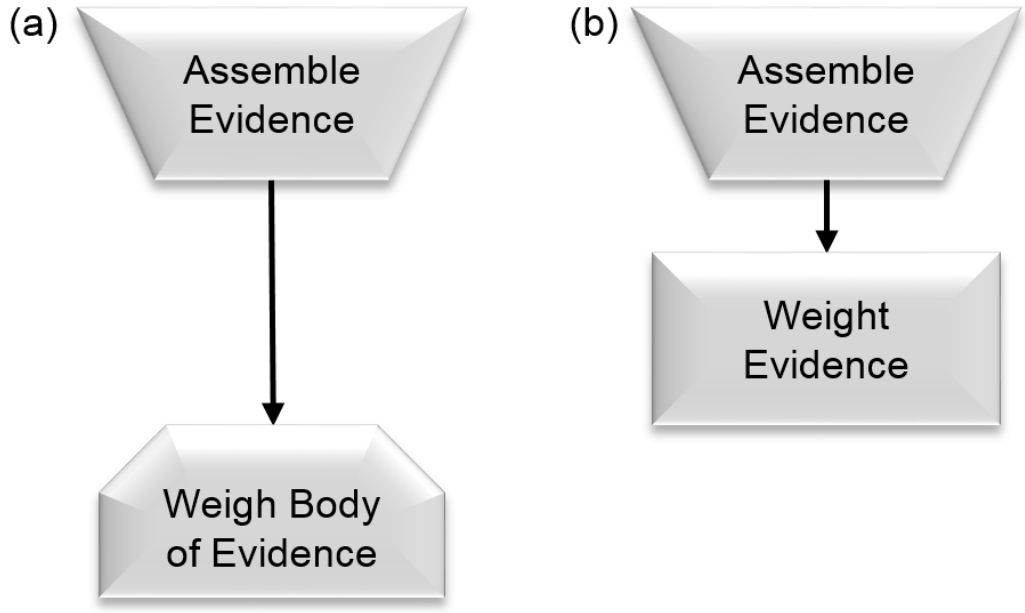

Figure 7-1. Steps in abbreviated weight-of-evidence processes: (a) skipping the weighting step when all evidence is equivalent or (b) weighting a single piece of evidence when multiple pieces are not available.

7.1. Weighing Without Weighting

Some WoE methods presume that all evidence is equal or at least that the differences are uninformative, so the weighting step (Section 5) can be skipped. For example, if all evidence is reliable and of the same type (e.g., multiple acute lethality tests performed by standard protocols), each piece of evidence will have equal influence in most cases. In practice, weighting is often skipped without determining that the relevance, strength, and reliability of the evidence are similar across pieces of evidence. Instead, if the pieces of evidence pass the screening step (see Section 3), the differences are assumed unimportant. An example of weighing evidence without weighting is the causal determination in an ISA regarding exposure to a specific air pollutant and specific effects (U.S. EPA, 2013).

A case for which distinguishing weights was unnecessary is provided by the studies used to determine that ingesting lead from lead mining and smelting caused the tundra swan kills in the Coeur d'Alene basin, Idaho (Table 7-1). The data used in the evidence were generated for the case, so they were all highly relevant; the studies were conducted by competent and reputable investigators following prescribed quality standards, so they were highly reliable; and the relationships were all strong. Because of that ideal situation, the presentation of evidence in WoE Table 7-1 is sufficient. Table 7-1 organizes the evidence in terms of characteristics of causation, rather than listing pieces or types, and briefly summarizes the evidence for each.

Table 7-1. Summary of evidence for lead as a cause of mass mortality of tundra swans in the **Coeur d'Alene** River Watershed (Norton et al., 2014). Based on evidence from URS Greiner Inc. and CH2M Hill (2011).

Causal Characteristic	Evidence
Co-occurrence	Swan kills occurred in Pb-contaminated lakes and wetlands and not elsewhere in the region.
Sufficiency	Mortality occurred in laboratory tests at Pb doses and body burdens observed in dead or moribund swans in the field. Consistent mortality in the field at blood Pb levels >0.5 µg/g.
Time order	No evidence—no pre-mining information on swan mortality.
Interaction	Dead and moribund swans had high blood and liver Pb levels. Pb-contaminated sediments were found in swan guts and excreta.
Specific alteration	Swans had pathologies characteristic of Pb toxicity, particularly, enlarged gall bladders containing viscous dark green bile.
Antecedents	Spills of Pb mine tailings and atmospheric deposition from smelters account for the high sediment Pb levels.

7.2. Weighting a Single Piece of Evidence

The concept of WoE was developed to combine multiple pieces of evidence in a way that gives each piece proper influence on the conclusion. When only one piece of evidence is available for an inference, the integration function of WoE does not apply. WoE, however, also leads assessors to consider the importance that should be assigned to a body of evidence and reveals the assessors' judgments to decision makers and stakeholders. This purpose of evaluating and interpreting a body of evidence can apply to a single piece. That is, explicitly evaluating the relevance, strength and reliability of a single piece of evidence can be informative.

Weighting a single piece of evidence also might provide consistent communication of the assessment process. That is, if many pieces of evidence are evaluated and scored for some hypotheses, the reader will expect to see scores for all hypotheses. If a hypothesis has only a single, stand-alone piece of evidence, scoring that one piece provides the expected consistency in weighing the evidence for all hypotheses.

In addition, weighting a single piece of evidence might reveal its inadequacy and lead to obtaining and weighing more evidence. For example, for the Patrick Bayou Superfund site, assessors intended to use modeling of toxicity to an amphipod as their primary approach to assessing risks to benthic invertebrates (Anchor, 2013). However, they found that the data were unreliable due to lack of reference data, confounding, poor correspondence to tests of other species, and unreliable polychlorinated biphenyl analyses. As a result, they adopted a WoE approach using the conventional triad of sediment quality evidence.

8. WEIGHT OF EVIDENCE FOR QUANTITATIVE RESULTS

Quantitative results of ecological assessments, such as benchmark concentrations, areas of habitat lost or rate constants, might be derived from multiple pieces of quantitative evidence. Commonly, these quantitative analyses follow the qualitative analyses that establish the hazard or other qualities to be quantified (Figure 8-1). Methods for deriving quantities by weighing evidence are discussed in Appendix B. They fall into two basic approaches: combine the quantitative evidence or choose the best quantitative evidence. Finally, weights can be assigned to the quantitative results to indicate how influential they should be.

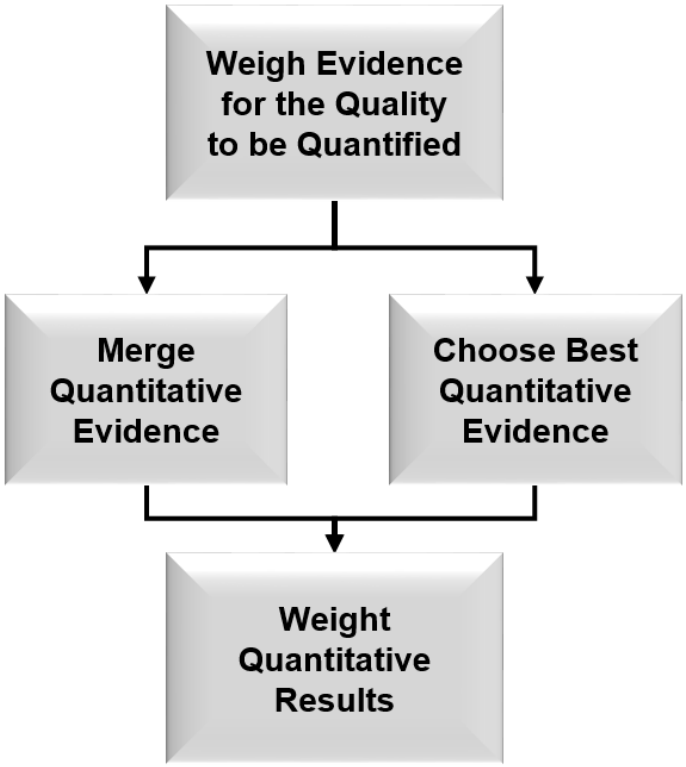

Figure 8-1. Potential steps in a process for using WoE to derive a quantitative result. Note that the top box of this process diagram encompasses the qualitative WoE process (Figure 3-2).

8.1. Weight of Evidence for the Quality to Be Quantified

Before deriving a quantity, determining what quality is to be quantified (Table 8-1) is necessary. This determination could require weighing evidence. For example, conventional risk assessments quantify, if possible, the magnitude and likelihood of a defined hazard. Environmental hazards are potential effects on an attribute of a biological entity (the assessment endpoint) resulting from exposure to an agent in particular conditions (described by the conceptual model). Similarly, criterion assessments quantify a threshold level of exposure corresponding to an unacceptable level of effect, and the effect itself is a quality that might be identified by WoE. Qualitative assessment could even precede the derivation of a model parameter. For example, a narrative WoE was used to determine whether a bioavailability adjustment factor should be used at a dioxin-contaminated site, and then the factor's value was chosen based on a prior quantitative WoE in a published review (Integral Consulting Inc., 2013). Quantitative condition assessments might determine the magnitude and spatial extent of impairment after a site has

been determined impaired by qualitative WoE applied to multiple metrics. In sum, this qualitative WoE determines whether the property to be quantified is real and significant in the context of the assessment.

Table 8-1. Qualities that could be identified by qualitative WoE and the associated quantities that could be derived by the quantitative WoE process (see Figure 3-2)

Example Quality	Example Corresponding Quantity
General cause: teratogen	Sufficient maternal body burden
General cause: carcinogen	Slope factor
Specific cause: chloride in effluent as cause of fish kills	Allowable maximum concentration
Specific cause: ammonia in stream as cause of biological impairment	Total maximum daily load
Bioaccumulative	Bioaccumulation factor
Exposure	Bioavailable concentration at point of contact
Susceptibility	Probability of responding
Alteration	Area of wetland

In some cases, assessments weigh evidence to derive a quantitative result without a prior WoE for a quality. For example, the derivation of ambient water quality criteria for aquatic life is nearly always based on a generic endpoint—protection of aquatic life from effects of direct aqueous exposures on survival, growth, or reproduction. However, for some criteria the generic endpoint is found to not be protective because an important specific effect or route of exposure is not adequately addressed. An example is the water quality criterion for selenium, which addressed a nonstandard effect (skeletal deformities in vertebrates) and route of exposure (exposure in ovo to selenium accumulated from a food web by the female parent). Such examples suggest that it may be desirable to weigh evidence for nonstandard qualities. Even if default qualities are assumed, the first step of WoE, the systematic assembly of evidence, should be performed to obtain all potentially useful quantitative estimates as well as associated information.

The place of these qualitative WoE processes in an overall assessment process depends on the type of assessment. For a conventional risk assessment, a WoE to choose the endpoints (i.e., What effects does the chemical or other agent cause in which potentially exposed organisms?) would be part of the problem formulation. The quantitative analysis and characterization phases follow to quantify the risks. In other cases, separate qualitative and quantitative assessments are performed. For example, a qualitative causal assessment to determine the cause of an observed effect may be followed by a quantitative risk assessment to derive a total maximum daily load, cleanup goal or other quantitative benchmark. In cases like the bioavailability adjustment factor example presented earlier, the qualitative and quantitative WoE processes might both be embedded in the analytical phase of an assessment.

8.2. Weight of Evidence for Deriving the Quantity

If more than one source of data with acceptable relevance and reliability is available to derive a quantitative result, the data sets should be weighed. Conventionally, the data sets would be integrated by combining the quantitative evidence or by choosing the best (i.e., weightiest) evidence. Another approach, the Rule of Five, has been useful in weighing evidence to determine a contaminated site cleanup goal (Box B-2).

8.2.1. Combining quantitative evidence

If the quantitative value can be derived from multiple data sets that are of sufficiently high relevance and reliability, the data sets can be numerically combined (Appendix B). In past EPA practices, this combining has involved taking the arithmetic or geometric mean. For example, multiple acceptable LC_{50} values are available for a species-chemical combination, their geometric mean is used when deriving national ambient water quality criteria (U.S. EPA, 1985). Geometric means of toxicity values are also used to derive soil screening levels (U.S. EPA, 2005a). Rather than treating all evidence equally, the values might be weighted before they are combined. Quantitative weighting could use a quantitative property of the study that influences its reliability such as the inverse variance.

Alternatively, quantities might be weighted based on some qualitative property. In this case, the qualitative weights are converted to numerical equivalents. For example, high, moderate, and low reliability of the study design might be converted to weights of 1, 0.7, and 0.5 or some other values, depending on how much influence study design should have and how great the variance in the study design might be.

Rather than using numerical weights to express the properties of the individual estimates, qualitative weights can be applied to the combined estimate. That is, after a combined value is derived, it might be assigned scores to express one or more qualitative aspects of its relevance or reliability. The weighted mean or other quantity derived from multiple sources should provide greater confidence than a quantity derived from any single source. Otherwise, the evidence should not have been combined.

8.2.2. Choosing the best quantitative evidence

If the range of relevance or reliability of alternative numerical values is large, choosing the best value rather than combining them is advisable. That is, the numerical values should be weighted for relevance and reliability, and the weightiest one used. (Note that in some contexts, established policy might require using the most protective acceptable value to ensure the degree of protection required by law.) Choosing the best value is particularly advisable when values can be derived from multiple types of evidence. For example, if a benchmark value of a contaminant could be derived from laboratory toxicity tests, a mesocosm test or a regional field survey, the results are likely to represent qualitatively different effects and might not be averaged, with or without weighting.

Using WoE to choose the best estimate is illustrated by Table 8-2. This table format presents the magnitude or probability of effects versus integrated weights of evidence for types or groups of evidence as recommended by Hope and Clarkson (2014). The table shows risk assessment results (probability of achieving the effect endpoint) estimated by analysis of each of four evidence groups (numbered circles) with integrated weights derived as in Section 6. In this hypothetical example, Evidence Group 3 might be chosen because it has the highest weight and is not an outlier in terms of the quantitative result (probability of effect). The result might be, Group 3 (evidence derived from stream mesocosm tests) is convincing and gives an estimate of 15% probability of reduced species richness.

Using WoE to choose the best value is not an established practice, but it is recommended for choosing among alternative test data for the same species, endpoint, duration, life stage, and testing conditions by the European Chemical Agency (ECHA, 2008). Although the European Chemical Agency does not specify a method of weighing, it indicates that various studies can provide supporting information to add weight to a particular test.

Table 8-2. WoE matrix to summarize quantitative risk estimates for four evidence types or groups (numbered circles) and their weights. Adapted from Hope and Clarkson (2014).

		Evidence Weight			
		0	+	++	+++
Probability of Achieving Effect Endpoint	>75%				
	51–75%				
	25–50%			①	
	5–24%			②	③
	<5%		④		

8.3. Weighting a Quantitative Result

Quantitative results are often accompanied by statistical expressions of variability or uncertainty, but determining how much weight the result should be given might also be useful. Weighting a quantitative result could inform decision makers and stakeholders about the result's relevance and reliability, irrespective of data scatter (Section 9). For example, an estimate of biological effects might have a small confidence interval, but it could have been generated from laboratory test data with low relevance to the case or might have been generated with poor controls or otherwise unreliable methods. As in weighting qualitative evidence, the specific properties of relevance and reliability listed in Box 5-1 and Box 5-3 and the collective properties listed in Box 6-1 could be included in the weighting of quantitative evidence if they are important.

Strength is generally not a relevant property for weighting quantitative results. For example, an exposure-response model with a high slope is strong, and therefore, lends weight to a causal hypothesis (i.e., a qualitative WoE). However, the result of a quantitative analysis to derive a benchmark exposure has whatever strength it has. An estimate of a benchmark value derived from an exposure-response relationship with a high slope is not given more weight than one derived from a relationship with a low slope.

Weighting might be used to determine the applicability of a number to particular uses. For example, at contaminated sites, weights might be used to distinguish soil benchmark values that are suitable only for screening values from those that might be suitable for cleanup goals. In any case, weights can be used along with statistical uncertainty measures to communicate confidence in results.

9. WEIGHT OF EVIDENCE AND UNCERTAINTY

The process of weighing evidence can be considered a means not only of deriving a conclusion, but also of documenting the assessors' confidence in the conclusion. That is, the weights assigned to pieces and categories of evidence are expressions of how confident the assessors are that the evidence should influence the conclusion in one direction or another. Additionally, the overall weight of the body of evidence is an expression of how much confidence the assessors have in that conclusion. If both laboratory tests and field surveys indicate that a chemical causes spinal deformities in fish, and both categories of evidence are evaluated and scored as highly relevant, strong, and reliable, we are confident that the chemical is a cause of deformities. Even if the WoE analysis is limited to a narrative, the narrative should describe the degree of confidence in the conclusion. For example, the categories of results in the ISAs and IRIS hazard assessments are explicit expressions of confidence in WoE narratives (e.g., "likely to be a causal relationship"—see Table 6-3). Such qualitative expressions of confidence are appropriate for a qualitative conclusion such as the observed relationship is likely causal, the chemical is likely a carcinogen, or the chemical is a contaminant of concern. If the standard scoring system was used to weight evidence, the resulting expression of overall confidence might be that the evidence is convincingly supportive, strongly supportive, or somewhat supportive of the conclusion. The appropriate expression of weight/confidence depends on the assessment and the decision to be supported.

The confidence concerning numerical values should include qualitative weights as well as conventional measures of scatter such as range or confidence limits[Figure 9-1 (Spiegelhalter and Riesch, 2011)].[2] For example, one would have low confidence in a benchmark value that is based on irrelevant evidence, even if it is statistically precise. Hence, presentations of quantitative results might have four parts:

1. The quality expressed—threshold for reproductive effects
2. The numerical result and units—*x* mg/L.
3. Scatter—95% CI of ±0.2*x* mg/L.
4. Weight—the body of evidence is highly relevant and moderately reliable, diverse, and coherent.

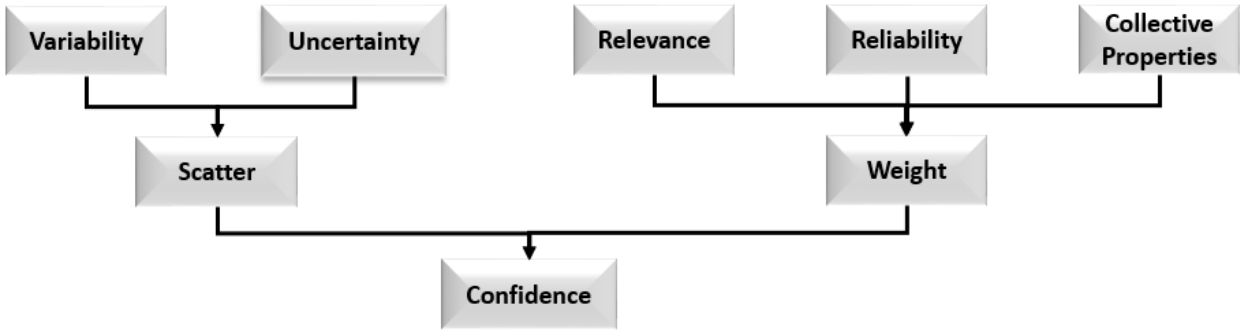

Figure 9-1. A diagram of the combination of statistical scatter and qualitative weight to define the confidence that should be afforded an assessment result.

[2] This discussion assumes an objectivist view that conceives uncertainty and variability as probabilities based on frequencies, which are distinct from qualitative judgments of weight. A subjectivist would consider all components of Figure 9-1 to be encompassed by degree of belief, and all components could be expressed as subjective probabilities.

The pieces and types of evidence that are not used to derive the numerical result could still provide information concerning the result. For example, another piece of evidence might place a limit on the possible range of effects and that information can be used to truncate the confidence limit on the estimated effect. Other evidence might inform the scope of a result. For example, a field-based benchmark value for a contaminant in streams might be based on benthic invertebrates because they provide the best data. Fish survey data that are not sufficient to derive a benchmark, however, might be sufficient to conclude that the invertebrate-based benchmark is likely also protective of the fish assemblage.

Conceivably, assessors could address the uncertainty concerning the confidence expressed by the WoE. No methods have been found for estimating or describing such meta-uncertainties. An estimate of WoE uncertainty, however, can be obtained by replicating the assessment. That is, multiple assessment teams could be engaged to assemble, weight, and weigh the evidence so that the variance among WoE results might be estimated. That implies an extraordinary effort for a routine assessment, but replication of a WoE for a condition assessment has been done experimentally (Bay et al., 2007). Six experts were provided conventional sediment quality triad data for 25 embayment sites in California. They were asked to rank the sites from best to worst and to categorize them into one of six standard categories. No instructions were provided, so the participants apparently used whatever WoE method they used in their professional practice. The rankings were highly correlated (mean Spearman rank correlation = 0.92). Differences in categorization of a site were common but mostly small and were primarily due to differences in relative weighting of the three types of evidence, so common weighting guidelines might have reduced discrepancies.

A sensitivity analysis would be more practical than replicating the assessment as a means of determining the variability in the weighting process. That is, assessors could determine the influence of changing the weights on WoE results. If the choice between alternative hypotheses could change when, for example, the reliability of a piece of evidence was scored as + rather than ++, that sensitivity would be noted. Such cases would tend to occur when few pieces of evidence are considered, when the overall weight for a body of evidence is marginal, or the bodies of evidence for alternative hypotheses have similar weights.

10. WEIGHT-OF-EVIDENCE SUMMARY AND THE PATH FORWARD

The basic framework of assembling evidence, weighting it, and weighing the body of evidence is fundamental to making inferences based on WoE (Figure 10-1). Even if a WoE is not explicitly performed using these steps, assessors should at least consider each of these processes. Adhering to an explicit framework can improve the WoE results, enhance transparency, and increase the confidence of reviewers, stakeholders, and decision makers.

The steps to implement the framework for qualitative WoE, with section numbers, include:

- Finding information (4.2.1),
- Design and conduct studies to fill information gaps (4.3)
- Screening studies (4.2.2),
- Categorizing studies (4.2.3),
- Deriving evidence from the data (4.2.4),
- Evaluating the evidence with respect to properties (5.3),
- Assigning weight scores based on the evaluation (5.3),
- Creating a scoring table to summarize the results of evidence weighting (5.4),
- Integrating the weighted evidence into bodies of evidence for each hypothesis (6.2),
- Creating a WoE table to summarize the results of evidence integration (6.2),
- Interpreting the bodies of evidence (6.3),
- Explaining ambiguities and discrepancies (6.4),
- Reiterating the process if necessary (6.4), and
- Presenting results (6.5).

In addition to the approach for applying WoE to qualities such as causality and impairment, this document briefly addresses WoE for quantities and how WoE for qualities and quantities are related (Section 8). Although WoE for quantities such as benchmark or parameter values is uncommon now, it seems likely that the use of meta-analysis and other techniques for weighting and combining quantities will gain increasing use. A combined approach to WoE for qualities and quantities is likely advantageous.

Similarly, this document briefly discusses the relationship between uncertainty and WoE (Section 9). By combining the somewhat narrow concept of uncertainty (i.e., measures of the scatter of data or of estimates) with the broader concept that some evidence and conclusions deserve more weight, it should be possible to improve the communication of confidence in assessment results.

The WoE approach in this document is based on experience in the EPA, particularly with determining the causes of impairment in ecosystems (http://www3.epa.gov/caddis/). Its application in practice will vary among programs due to differences in issues, policies, prior practices, and the amount and variety of evidence potentially available for weighing. As implementation of this approach progresses, context-specific guidance is expected to be developed in the form of exemplary applications of WoE or program-specific WoE guidance documents.

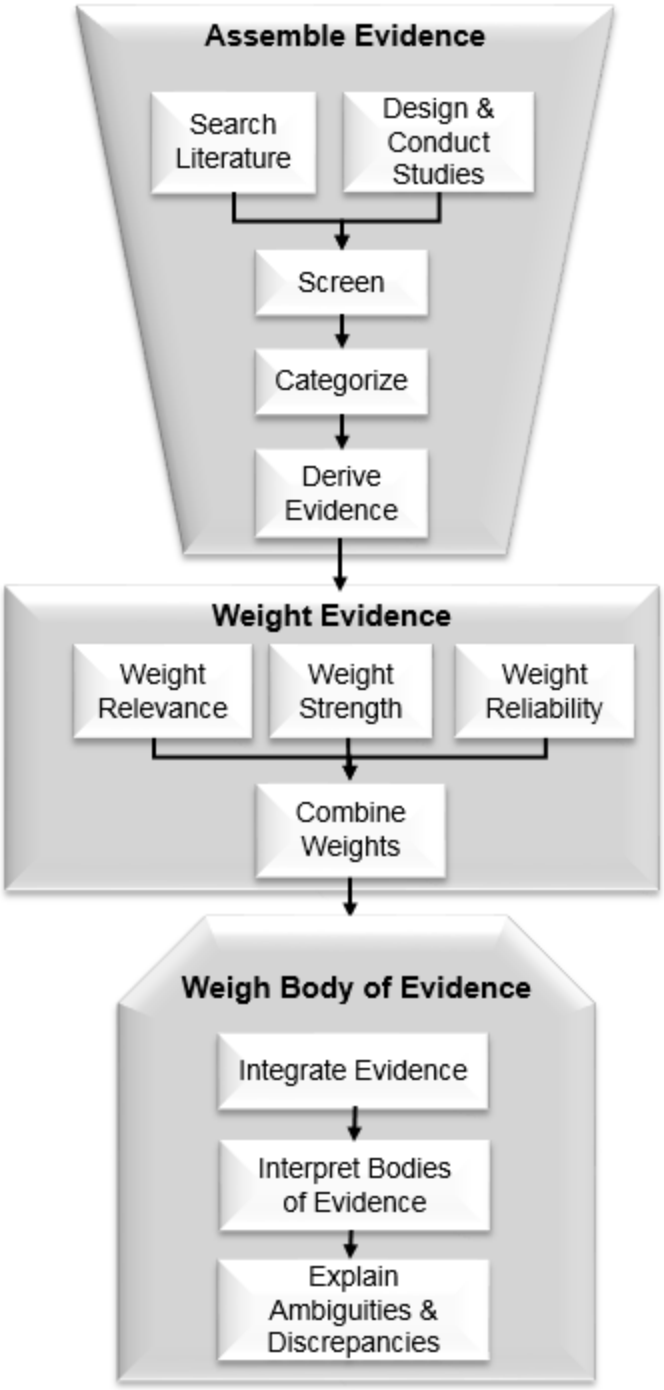

Figure 10-1. The detailed framework for qualitative WoE.

In summary, this document is intended to help ecological assessors improve the practice of WoE without imposing burdensome prescriptions. If read and applied in that spirit, this document should help advance the cause of well-informed environmental protection.

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APPENDIX A. GLOSSARY OF WEIGHT-OF-EVIDENCE TERMS

The following terms are defined as used in this document. The U.S. Environmental Protection Agency (EPA) might use these terms differently in other contexts.

Alteration: (1) A characteristic of causal relationships; it specifies that the affected entity is changed by physical, chemical, or other mechanisms leading to the defined effect. (2) A change in an entity that is consistent with interaction with a cause.

Ambiguous: Evidence that has no clear meaning or more than one possible meaning. Evidence may be ambiguous because it is weak (e.g., shows no clear relationships) or unreliable (e.g., reference sites may have important extraneous differences from exposed sites).

Antecedence: A characteristic of causal relationships; it specifies that the causal interaction is itself connected to processes that precede it, potentially leading back to a source.

Assessment, environmental: (1) A process of generating and presenting scientific information to inform an environmental regulatory or management decision. (2) The product of an environmental assessment process.

Benchmark: A criterion, standard, screening value, effect threshold, or other value used to differentiate potential exposure levels that are of concern from levels that are not of concern.

Case: (1) The situation that is the subject of an environmental assessment; for example, the case may be a water body experiencing an algal bloom, a hazardous waste site or a proposed pesticide use. (2) The weighted body of evidence for an assessment hypothesis; for example, "the lack of co-occurrence weakens the case for fine sediments as the cause."

Characteristics: Properties that define a quality of interest and that could be supported by evidence. For example, when weighing evidence for causation, evidence is sought to support six characteristics of causal relationships (Table E-1).

Coherence: The property of a body of evidence that its constituent pieces are logically linked together, thus, forming a reasonable explanation.

Confidence: The credence given a conclusion. For quantitative results, confidence is determined by the scatter of estimates as well as the weight of the evidence.

Considerations: Sets of heterogeneous aspects of causation or other qualitative hypotheses that are used to structure narrative weight of evidence (WoE). They are derived from or analogous to Hill's considerations (Hill, 1965).

Co-occurrence: (1) A characteristic of causal relationships; it specifies that the cause and effect are collocated in space and time at a scale appropriate to the cause and effect. (2) An instance of collocation in space and time.

Correspondence: The similarity of a piece or type of evidence to the entity or conditions to which the evidence will be applied. Evidence is relevant if it corresponds well to all aspects of the case (biological, physical/chemical, and environmental conditions).

Corroboration: Supporting evidence for an assessment proposition from one or more independent studies providing similar results.

Data: Unanalyzed results of measurements, counts, or observations used as a basis for reasoning or calculation.

Discrepant: Evidence that is inconsistent or contrary to established facts or theory.

Endpoint, assessment: An explicit expression of the environmental values to be protected, operationally defined as an ecological entity and its attributes.

Evaluation: The determination of how much influence a piece or category of evidence should be assigned. Evaluation plus the scoring of its results constitutes the weighting of evidence.

Evidence: Information that informs inferences regarding a condition, cause, prediction, or outcome.

Evidence, body of: All the applicable evidence used to make inferences concerning a proposition.

Evidence, category of: A grouping of evidence for consistency and to facilitate weighting. In WoE for environmental assessments, evidence is categorized in terms of conventional *types of evidence*, or in terms of characteristics that the evidence supports.

Evidence, line of: (1) A complex piece of evidence including multiple causal or logical steps that establishes a line of reasoning. (2) A general term used to refer to a piece or type of evidence—this use is discouraged to reduce ambiguous terminology.

Evidence, piece of: The basic unit of evidence; examples include the results of a toxicity test or a stream survey.

Evidence, type of: A category of evidence that is based on a distinct form of study. Conventional types include biological surveys, biomarkers, ambient media toxicity tests, single-substance toxicity tests, population and ecosystem models, and quantitative structure-activity relationships.

Explanation: The process of translating pieces or types of evidence into a characteristic of causation or some other attribute that is relevant to a hypothesis. It is part of evidence integration in the weighing of the body of evidence step.

Hazard: The potentially adverse properties of an agent that, with potential exposure of a receptor, imparts a risk. Hazards are identified by a general causal assessment, such as an Integrated Science Assessment, that typically employs a qualitative WoE.

Hypothesis: A proposition proposed to be a potential explanation of a phenomenon (the fish kill may be caused by high temperatures) or a potential outcome of a phenomenon (building more rooftops and parking areas will interfere with groundwater recharge).

Inference: (1) The act of reasoning from evidence. (2) A result of such reasoning.

Information: Data or other facts used to derive evidence.

Integration: The first step in the weighing of the body of evidence in which the pieces or categories of evidence are combined to characterize the body of evidence.

Interaction: (1) A characteristic of causal relationships; it specifies that a causal agent impinges upon, enters, binds to, or initiates a response in a susceptible entity in a way that can lead to the effect of concern. (2) An instance of interaction of a causal agent on a susceptible entity that can lead to an effect.

Interpretation: The second step in the weighing of the body of evidence in which the body of evidence for each hypothesis is compared to other hypotheses or judged against a standard to determine what conclusion is best supported by the weight of evidence.

Property: A feature of evidence that determines how much weight it should be assigned. In this document, the major properties are relevance, strength, and reliability.

Property, collective: A feature of bodies of evidence that, along with the properties of the constituent pieces of evidence, determines how much weight a body of evidence should be assigned. In this document, the collective properties are number, coherence, diversity, and absence of bias.

Proposition: A condition, cause, prediction, or outcome hypothesized as a possible outcome of an assessment.

Qualitative WoE: Weight of evidence to infer a quality such as causation or impairment.

Quality of interest: A distinctive attribute of an entity, relationship, or system that should be determined to exist or not for a hypothesis in an assessment.

Quantitative WoE: Weight of evidence to estimate a quantity such as a benchmark value or a biodegredation rate.

Reasonable explanation: (1) A statement or account that coherently explains a body of evidence. (2) Informed reasons for apparent inconsistencies in a body of evidence that provide coherence.

Refutation: The logical process of demonstrating the impossibility of a condition, cause, predicted effect, or outcome.

Relevance: A property of a piece or type of evidence that expresses the degree of correspondence between the evidence and the assessment endpoint to which it is applied.

Reliability: A property of evidence determined by the degree to which it has quality or other attributes that inspire confidence**.**

Risk: The likelihood of adverse effects associated with exposure to a stressor.

Scatter: The distribution of measured or estimated values due to uncertainty, variability, or both.

Scoring: The process of formalizing the evaluation of evidence by assigning a numeral, term, or symbol. Evaluation plus scoring constitutes weighting of evidence.

Strength: A property of evidence determined by the degree of differentiation from randomness or from control, background, or reference conditions.

Sufficiency: (1) A characteristic of a causal relationship; it specifies that the causal agent or event must be adequate to induce the effect in susceptible entities. (2) An occurrence of enough of an agent or process to affect a susceptible entity.

Table, scoring: A table created in the weighting step that presents the pieces or categories of evidence and their scores with respect to relevant properties.

Table, weight of evidence: A table created in the weighing step that summarizes the bodies of evidence and their weights for one or more hypotheses.

Time order: (1) A characteristic of a causal relationship; it specifies that the cause precedes the effect. (2) The sequence, in time, of the occurrence of a candidate cause and the effect of concern. It is sometimes called temporality or temporal sequence.

Uncertainty: Lack of knowledge concerning the state of an organism or system or concerning the true value of a quantity. Uncertainty is a property of the investigator and, unlike variability, may be reduced by measurement or observation.

Variability: Heterogeneity over time, space or members of a population. Variability is a property of nature and may not be reduced by measurement or observation.

Weigh: Consider the relevance, strength, and reliability of the body of evidence to assess the likelihood of a hypothesis.

Weight: (noun) The importance to an inference of a piece or category of evidence. (verb) To assign an importance descriptor or score to a piece or category of evidence.

Weight of evidence: (1) A process of making inferences from multiple pieces of evidence, adapted from the legal metaphor of the scales of justice. (2) The relative degree of support for a conclusion provided by evidence. The result of weighing the body of evidence.

APPENDIX B. WEIGHT-OF-EVIDENCE METHODS FOR QUANTITATIVE RESULTS

Assessors are often confronted with multiple estimates of a quantitative value such as the median lethal concentration (LC_{50}) for a fish species, the half-life of a chemical in surface water, or the pH at which species richness is reduced in streams. A single estimate might be derived from multiple estimates, by weighing evidence to identify the best estimate or by using statistical techniques from meta-analysis to combine estimates (Borenstein et al., 2009; Hunter and Schmidt, 2004).

A simple method for combining values is selection of the single best (i.e., weightiest) estimate. This approach is commonly used because often one quantitative estimate is clearly superior to all others, so averaging would diminish accuracy. This approach also might be necessitated by statistical considerations, if the values cannot be combined because they do not represent independent samples from a common population of estimates (Borenstein et al., 2009). When this approach is used, a good practice is to identify in advance the properties of good estimates. Various procedures and criteria can be applied to various study properties when weighting to identify the best value (see Section 5). For example, LC_{50} values might be screened using reliability properties such as use of good laboratory practices and then the most relevant value could be chosen (e.g., the test performed in water most similar to water at the assessment site).

A common method in meta-analysis is averaging of multiple estimates. The geometric mean is often used because many environmental data sets are asymmetrical. Although weighting studies before averaging them is not common in environmental assessments, weighted averages are conventional in meta-analysis. The most common statistical model for weighting is the fixed-effects model, which weights by the inverse of the error variance (Borenstein et al., 2009). The term fixed effects is used because it implies that the estimates are all based on sampling a common variable from a common population with a set effects level (i.e., the only significant source of differences among the estimates being combined is sampling error). It has the advantage of giving more weight to larger studies and of normalizing the variance. If this assumption does not hold, a random effects model or the IVhet model can be employed (Borenstein et al., 2009).

Weighting also might be based on properties of the individual members of a higher-level entity that is being assessed. For example, in an assessment of ozone effects on forest production, estimates of reduction in timber production of individual tree species were weighted by the proportional basal trunk area before they were averaged to estimate loss of forest production (U.S. EPA, 2014b). Because of weighting, the average represented the loss of forest production and not just the averages of production losses for individuals of each species.

Although weighting in meta-analysis is usually based on statistical properties, weights based on qualitative properties also can be used (Turner et al., 2009). This approach is appropriate when studies vary significantly in terms of relevance or reliability relative to sampling variance or variance among the studied systems. For example, chronic toxicity test endpoints, even for the same species, often differ in the endpoint response, so statistical weighting would not capture the most critical differences among chronic test data. A statistical model has been developed that incorporates data quality or any other qualitative scale (Doi and Thalib, 2008). Statistical weighting models depend on variance estimates, which are not available for many environmental values such as conventional toxicity test endpoints. In those cases, weights can be assigned using improvised methods. Weighting for study quality has been common in meta-analysis, but it may introduce bias if not done appropriately (Turner et al., 2009; Greenland and O'Rourke, 2001).

Multiple quantitative estimates also can be used in regression analyses such as derivation of exposure-response relationships from multiple tests. As in averaging, the values are commonly weighted by the inverse of their error variance.

Quantitative results also can be combined into distributions. A common use is derivation of a value in environmental assessments from species sensitivity distributions (SSDs). SSDs are statistical distribution functions that, conventionally, are fit to the results of chemical toxicity tests and are generally interpreted as representing the distribution of sensitivity of species in communities. They are used to derive an exposure level that would be protective of a defined proportion of species or genera in communities or to estimate the proportion of species or genera that a defined exposure level would affect. The derivation of SSDs illustrates the issues involved in quantitative weighting of evidence (Box B-1).

Finally, rather than combining estimates, data sets from multiple studies have been combined to perform a statistical test or analysis. Some investigators combine data sets from multiple small studies with statistically insignificant results to obtain a data set large enough for the differences among treatments to be statistically significant. This practice is *not* recommended because it violates the premise of hypothesis testing that the likelihood of a data set given a null hypothesis is being determined. It is a form of *P*-hacking, which is the selection of data sets, tests, or hypotheses to achieve statistical significance. Alternatively, data sets can be combined to obtain a potentially better estimate of a mean and confidence interval than simply taking the mean of means. Also, multiple sets of exposure-response data might be combined to obtain a more accurate regression model of the relationship. As with averaging estimates, analyzing combined data sets requires attention to the statistical properties of the data.

Choosing the best estimate poses fewer technical issues than combining estimates. Combining estimates or data sets to generate an estimate introduces complications in computation and interpretation due to heterogeneity. In contrast, in a well-designed individual study, what the data and the summary statistics derived from the data represent is known. Different data sets representing the same relationship but generated at different times in different places or at different scales also might be so different due to ecological complexity and variability that they cannot or should not be combined. Further, if the studies to be combined have greatly different sample sizes and variance structures, statistically combining them might give counterintuitive results. At worst, studies that all indicate one relationship (e.g., declining species richness with increasing exposure) might give the opposite result when combined (i.e., increasing species richness with increasing exposure), a phenomenon known as Simpson's paradox (Blyth, 1972). Finally, the set of studies may be biased, particularly by the bias against publishing studies that show no effects. Thus, care should be taken when combining multiple estimates or data sets.

Despite these warnings, the benefits of combining estimates or data sets can be substantial. The combined estimate might be more accurate, particularly when sampling error is important. Inconsistencies among studies can be quantified and their sources can be analyzed. The influence on results of methodological or environmental differences among studies can be quantified. Further, some cases of combining estimates, such as averaging multiple toxicity test results for the same species following a standard protocol with moderate water chemistries, are unlikely to go astray.

Qualitative WoE may be used to derive quantitative results without combining or choosing among estimates. An example is the Rule of Five (Box B-2).

Box B-1. Combining and Weighting Data in Species Sensitivity Distributions

The combining and weighting of data in SSDs has two components. First, to derive the points in the distribution, the results of multiple tests of a species or of closely related species are combined. When deriving the species mean acute value (SMAV) for national ambient water quality criteria, multiple LC_{50}s are combined by taking the geometric mean and assigning that mean value to the species (U.S. EPA, 1985).

$$SMAV = \exp [(\sum \log LC_{50})/n]$$

The genus geometric mean value (i.e., the genus mean acute value or GMAV) is used when multiple congeneric species have been tested.

$$GMAV = \exp [(\sum \log SMAV)/n]$$

Weighting is not part of the currently accepted method for combining test results into either the species or genus means and its implications have not been investigated. However, one might weight the test results (e.g., LC_{50}s) before averaging, based on the variance, number of organisms tested, number of concentrations with partial response or some other property.

$$SMAV = \exp [(\sum(w_t \log LC_{50}))/\sum w_t]$$

Also, one might weight the species mean values before calculating the genus means based on the number of tests of each species or some other property.

$$GMAV = \exp [(\sum w_s \log SMAV)/\sum w_s]$$

(Note: Subscripts *t* and *s* indicate weights [w] for tests and species, respectively.)

Second, weighting might be involved in deriving the SSD from the species or genus mean values. If the SSD is intended to represent aquatic communities, a problem can occur with over- or under-representing particular taxa or functional groups, which might be resolved by weighting the data to achieve proportional representation (Duboudin et al., 2004; Forbes and Calow, 2002; Suter et al., 2002). This situation would require some difficult decisions. Should the weighting be based on the number of species in a higher taxon, a trophic group, or other grouping; on the relative abundance or biomass or on some measure of importance? Invertebrates would be weighted more than vertebrates for species richness, abundance, or biomass and perhaps much less for importance (depending on the measure of importance). Also, the assumption that the weighting should be based on particular categories [e.g., algae, invertebrates, and fish (Duboudin et al., 2004; Forbes and Calow, 2002)] presupposes low variance in sensitivities within those categories relative to between categories. That assumption is questionable given the large taxonomic differences within categories (e.g., cyanobacterial versus eukaryotic algae and arthropods versus mollusks, rotifers, and other invertebrates), which result in large differences in sensitivity. The communities represented by an SSD also would influence the weights. For example, stream invertebrates are predominantly benthic insects, but planktonic crustaceans and rotifers are important in lakes. Clearly, research would be required before introducing a weighting scheme for SSDs.

The derivation of weighted SSDs has been demonstrated by Semenzin et al. (2015); OECD (2013); U.S. EPA (2013). They weighted species and derived the SSD by weighted bootstrapping.

Box B-2. Cleanup Goals by Weight of Evidence Using the Rule of Five

Superfund cleanup goals for ecological risks are concentrations of contaminants that are higher than the no--observed-adverse-effect level (NOAEL) and lower than the lowest-observed-adverse-effect level (LOAEL). Because the interval between these values could be large (i.e., greater than a factor of 10) and because the measures of effect that define the bounds are not consistent, the common practice of interpolating by taking the geometric mean is often inadequate. Instead, a technique called the Rule of Five is used (Greenberg and Charters, 2007; Charters and Greenberg, 2004). The NOAEL-LOAEL interval is divided into six geometrically scaled intervals delimited by seven nodes. The node chosen as the cleanup goal depends on characteristics of the NOAEL and LOAEL, including their relevance to the assessment endpoint and their severity (e.g., Is the LOAEL defined by acute lethality or chronic reproductive effects?). The choice of node also can be influenced by measures of effects other than the LOAEL and NOAEL and by qualitative evidence concerning ecological exposure and effects on the site. The weighing of evidence to choose a node can be, at least in part, rule based. For example, a LOAEL based on mortality would move the choice one node below the middle node. The WoE also uses expert judgment. An example of applying the Rule of Five is in the Baseline Ecological Risk Assessment for the Estuary at the LCP Chemical Site in Brunswick, Georgia.

Another example of using qualitative methods to weigh evidence for quantities is the selection of surrogate values. When there are no data for a property of a chemical, the best estimate of the property may be derived from the best surrogate chemical for which the property is known. This approach, termed "read across," can be based on weighing multiple attributes of the chemicals including structure, physical/chemical properties (e.g., melting point, octanol/water partitioning coefficient) or biological properties [e.g., enzymes induced (ECHA, 2015; Wang et al., 2012)].

APPENDIX C. WEIGHT-OF-EVIDENCE METHODS FOR DERIVING A MODEL

Weight of evidence (WoE) can play three roles in the derivation of mathematical models. First, the selection of a model from a set of alternatives can be based on WoE, where WoE refers to the relative weight provided to a model by the evidence (i.e., the available data). Good (1950) defined the WoE for members of a set of alternative models as their relative likelihoods, given a data set. Models can be compared using the sum of squares or other simple goodness-of-fit statistic, Bayes's factor or Akaike's information criterion (Anderson, 2008; Hilborn and Mangel, 1997). If the models represent alternative causal hypotheses, choice of the model that best explains the data can be said to have chosen the best causal explanation of the modeled effect (Newman and Clements, 2008). This use of the term WoE is distinct from the others in this document. Rather than weighting and weighing multiple pieces or types of evidence, Good's followers weigh the alternative models against each other with respect to a common data set. That approach is included here for completeness because it has appeared in the ecological assessment literature (Linkov et al., 2009; Smith et al., 2002). Rhomberg (2015) described using relative likelihoods for selecting among human toxicological hazards. He admits, however, that it is difficult to calculate likelihoods of models of toxicological hazards, and in practice, he uses qualitative WoE.

Bayesian model averaging extends this concept to provide a more recognizable example of weighing evidence to derive a model (U.S. EPA, 2009b). That is, rather than choosing a single best model, one might combine suitable models after weighting them based on their weights in Good's sense (i.e., their consistency with the data).

A more conventional use of the concept of WoE is the weighing of evidence concerning model assumptions. For example, to determine whether certain phenomena should be included in a model, one might assemble, weight, and weigh evidence concerning their occurrence. Such phenomena might include compensatory processes in a fish population, dietary toxicity in aquatic invertebrates exposed to an aqueous contaminant, nonlinearities in exposure-response relationships, or avoidance behavior at subtoxic exposures. The methods for weighing evidence for these model assumptions would be the same as for other qualitative conclusions. For example, Hertzberg and Teuschler (2002) developed a numerical index to weigh three properties of evidence for alternative models of mixtures toxicity.

Finally, model selection can be based on weighing a mixture of statistical and biological considerations. The benchmark dose guidance recommends choosing a dose-response model based on both biological plausibility and Akaike's information criterion (U.S. EPA, 2012a). A Science Advisory Board panel has recommended broadening the statistical and nonstatistical considerations to be weighed during model selection and using a more formal and transparent weighing process (SAB, 2015). For example, for dose-response modeling, they recommended prioritizing regression models that directly use exposure data for individuals.

Because any causal hypothesis, in theory, can be represented by a mathematical model, uses of WoE for model selection could be equivalent to the approaches for deriving qualitative conclusions presented in Sections 3−7.

APPENDIX D. WEIGHT-OF-EVIDENCE APPROACHES FOR QUALITATIVE CONCLUSIONS

This appendix summarizes the diversity of weight-of-evidence (WoE) approaches that have been used in assessments to answer questions concerning environmental qualities. Each approach has been useful in some cases, and they were carefully considered during the development of the approach presented in this document.

D.1. Narrative Weight of Evidence

Traditional narrative literature reviews and the assessments that adopt their approach describe a body of evidence and reach a conclusion by methods and criteria that are not explicit. The expertise of the reviewer is assumed sufficient to ensure a correct conclusion. The WoE is the conclusion that the author reaches through reading the literature and presents to the reader by logically structuring the review's narrative. This is a common approach for weighing evidence in environmental assessments. Narrative WoE is highly flexible, but the method by which results are obtained is not as transparent or reproducible as for other methods.

D.2. Consideration-Guided Narrative Weight of Evidence

WoE narratives can be given greater structure and logical consistency by organizing the narrative in terms of a set of considerations. For example, the U.S. Environmental Protection Agency's (EPA's) Integrated Risk Information System and Integrated Science Assessment documents use modifications of Hill's considerations when weighing evidence of general causation. Also, the WoE method for Tier 1 screening of potentially endocrine-disrupting chemicals provides five considerations (U.S. EPA, 2012b), and the chemical risk assessments conducted pursuant to the Toxic Substances Control Act use seven considerations (U.S. EPA, 2015b). However, these WoE methods depend on narratives and have not explicitly weighted or tabulated the evidence for the considerations. Also, the considerations are mixtures of various types of issues to consider, not consistent sets of criteria, properties, types of evidence, or characteristics. This method is an advance over unstructured narratives and is generally accepted.

D.3. Evidence Summary and Scoring Tables

Methodological rigor and transparency can be increased by creating summary tables for the evidence concerning an inference and assigning scores. For example, a set of summary and scoring tables was developed at ORNL for contaminated site assessments (Suter et al., 2000). The authors included tables for summarizing the methods and results for each type of evidence: biological surveys, bioindicators, ambient toxicity tests, tissue analyses, and single-chemical toxicity. Another table combined the results of the types of evidence (a score and associated explanation) and presented a score for the body of evidence for an endpoint.

D.4. Criteria-Guided Scoring

Criteria for weighting evidence have been combined with evidence scoring tables in the *Stressor Identification Guidance Document* and Causal Analysis/Diagnosis Decision Information System (CADDIS) to determine the causes of specific environmental impairments (http://www3.epa.gov/caddis/). Several examples of the application of this approach can be found in the CADDIS case studies. Pieces or types of evidence were scored based on Susser's method (U.S. EPA, 2000; Susser, 1986), but scoring types of evidence has been supplemented by scoring characteristics of causation to explain the relationship of the evidence to the hypotheses (Norton et al., 2014; Cormier et al., 2010). This approach

also has been applied to a risk assessment. The Bristol Bay watershed assessment used tables of evidence and scores to clarify the WoE for risks to salmon from spills of tailings, product concentrate and diesel fuel (U.S. EPA, 2014a). Pieces of evidence were described and scored for logical implication (relevance), strength, and quality (reliability), and summary scores were derived for the bodies of evidence. A version of criteria-guided scoring is presented in this document that generalizes the approach beyond causal assessment.

D.5. Standardized Scoring and Weighting

Consistency can be increased by specifying the evidence and criteria to be considered and the scores and weights to be assigned to the possible outcomes for each type of evidence. An example is provided by the Massachusetts weight-of-evidence method for assessing ecological risks at contaminated sites (Menzie et al., 1996). The method numerically scores evidence (termed measurement endpoints) on a scale of 1 to 5 for 10 properties, weights the scores by scaling values based on the importance of the properties, normalizes the scaled scores, and sums the result to give a "measurement endpoint weight." The body of evidence is then qualitatively weighed based on concurrence of the numerical weights. The standardization of scores and weights requires consistency of the cases to which the method is applied and is facilitated by consensus of all parties.

D.6. Indices

Standardized numerical scoring and weighting of evidence has been extended to the calculation of rather complex risk indices (Benedetti et al., 2012; Dagnino et al., 2008; Semenzin et al., 2008; Bombardier and Blaise, 2000). These indices are not quantitative risk estimates, but they often contain component calculations that are part of quantitative risk assessments such as sums of toxic units, so that the index values provide estimates "of relative hazard for the sites being investigated" (Bombardier and Bermingham, 1999). Because the indices often combine evidence across pieces, types, and endpoints, many of them are computationally complex and require support systems for data entry and computations (Semenzin et al., 2009).

Indices are also used to combine multiple metrics from biological survey data into a value that can be said to represent biological integrity (Karr et al., 1986) or deviation from reference condition (Hawkins, 2006). These indices are arithmetic combinations of metrics believed to discriminate impaired and unimpaired waters. Their derivation is not normally considered to constitute a weight-of-evidence process, but they do combine multiple pieces of evidence to determine a quality—the impairment of a biotic community.

Indices are specialized and their results are difficult to relate to the input data. For example, an index of biotic integrity serves its purpose of identifying impaired waters by numerically aggregating numerous incommensurable biological metrics. To assess the cause of the impairment or risks from remedial actions, however, the individual metrics should be extracted, weighted, and weighed appropriately, as described in Sections 4–6.

D.7. Rule Based

If the potential evidence results are few and all the results are reliable, specifying an interpretation of each potential body of evidence can be possible. The decision matrix for the sediment quality triad is a commonly used example of this approach to weighing evidence [Table D-1 (Chapman, 1990)]. The triad is used to determine whether toxic contaminants are impairing a sediment community. Its elements are chemical analyses of sediments that are compared to toxicological benchmark values, toxicity tests of the sediment and surveys of the sediment biotic community. If the scores for the triad elements are, for example, −, +, +, "unmeasured toxic chemicals are causing degradation," but if it is −, −, +, "alteration is

not due to toxic chemicals." The logic of Chapman's decision matrix is correct if the evidence is reliable, but the evidence might not be sufficiently reliable to support it for many reasons (Table D-2). As a result, weighting and interpreting the evidence often is required. Thus, the standard decision matrix is an idealization that serves primarily to clarify the potential relationships among types of evidence. More recently, ambiguities in results have been recognized and new decision matrices have been developed for sediment assessments that specify a decision for only a few of the possible outcomes; for the other outcomes that include conflicting results, they direct assessors to perform additional analyses (COA Sediment Task Group, 2008; Grapentine et al., 2002). Those additional analyses could use any of the other qualitative WoE methods.

Table D-1. Inference based on the sediment quality triad (Chapman, 1990)

Situation	Chemicals Present	Toxicity	Community Alteration	Possible Conclusions
1	+	+	+	Strong evidence for pollution-induced degradation
2	−	−	−	Strong evidence for no pollution-induced degradation
3	+	−	−	Contaminants are not bioavailable, or are present at nontoxic levels.
4	−	+	−	Unmeasured chemicals or conditions exist with the potential to cause degradation.
5	−	−	+	Alteration is not due to toxic chemicals.
6	+	+	−	Toxic chemicals are stressing the system but are not sufficient to significantly modify the community.
7	−	+	+	Unmeasured toxic chemicals are causing degradation.
8	+	−	+	Chemicals are not bioavailable or alteration is not due to toxic chemicals.

Responses are shown as either positive (+) or negative (−) indicating whether measurable and potentially significant differences from control/reference conditions are determined.

Table D-2. Some ways in which the triad decision table might fail (not including errors or poor technique)

Type of Evidence	False Positive (Exaggerated Effect)	False Negative (Minimized Effect)
Single-chemical analyses/ toxicity tests	Higher bioavailability in the laboratory Site background is high Overly sensitive test organisms (sensitive test species or life stages not present at the site)	Short duration Insensitive test species or life stages Critical response not included Multiple chemicals interact Incomplete routes of exposure
Whole-medium samples/ toxicity tests	Bioavailability increased by handling Sampling below bioactive zone Overly sensitive test organisms Inappropriate reference sites	Chemical lost or altered by handling Insensitive test organisms Inappropriate reference sites Insensitive test organisms Ambient conditions (e.g., UV light) are important to effects Critical response not included Contaminated locations or times missed
Sampling locations/ biological surveys	Confounding Inappropriate reference sites	Organisms too rare Response too infrequent Sensitive organisms not sampled Critical response not included Large sample scale Contaminated locations missed Inappropriate reference sites

Another rule for weighing evidence is independent applicability. The Office of Water classifies a water body as impaired if an adequate piece of evidence demonstrates an impairment, even if other evidence did not detect the impairment. This policy takes into consideration the possibility of false negatives and that different types of evidence detect different types of impairment (Box D-1).

A two-stage rule was developed by the European Center for Ecotoxicology and Toxicology of Chemicals for weighing human and animal data in chemical risk assessments (ECETOC, 2009). The category of evidence with the highest quality for a chemical is used, but if the quality of animal and human evidence is similar, an effect is assumed to be caused by the chemical if either category of evidence shows the effect. This logic could be applied to more than two categories of evidence if equivalent quality scales could be developed for all categories.

D.8. Quantitative Alternatives

Some authors have suggested that quantitative methods are inherently superior for making qualitative inferences from multiple pieces of evidence (Linkov et al., 2009). In particular, multi-criteria decision analysis (MCDA) and Bayesian belief networks (BBNs) have been suggested to be alternatives to conventional WoE (Linkov et al., 2015; Fenton and Neil, 2013).

Box D-1. Independent Applicability and Weight of Evidence

Independent applicability of evidence of impairment has been a policy of the EPA Office of Water. That is, if a water body fails to meet water quality criteria, is toxic, or is biologically impaired, it is an impaired water body. Independent applicability can result from two possible logics.

1. All types of evidence are fallible, so any evidence can generate false negative results. Rather than weigh evidence of impairment against evidence that failed to detect impairment, the evidence of impairment is accepted. Therefore, if any type of reliable evidence detects impairment, the water body is considered impaired. This logic is defensible if the consequences of not detecting an impaired ecosystem are more serious than the consequences of failing to detect. This justification is policy based. In addition, the logic can be defended by recognizing that poor methods or poor implementation are inherently more likely to fail to detect an effect than to detect a false effect. This justification is based on the fact that poor practices introduce extraneous variance are not spatially comprehensive and otherwise tend to obscure effects. Further, it is unlikely that a type of evidence will test or measure the most sensitive conditions, taxa, life stages, responses and interactions between species and stressors. Therefore, even good studies are likely to miss real effects. This does not imply that false positives never occur (see Table D-1), but rather, poor evidence is more likely to result in false negatives and unprotective decisions.

2. Each type of evidence addresses a distinct aspect of impairment. If any one aspect is found in a water body, the water body is impaired in that way. This assumption involves no synthesis. Each type of evidence is independently evaluated with respect to its aspect of impairment. This is explicitly the case with the European Union's Water Framework Directive that distinguishes good chemical status from good ecological and good hydrological statuses (van der Ohe et al., 2014; EC, 2013). European waters should achieve all three. Equivalently, the policy of independent applicability can be interpreted as a requirement to protect three types of integrity: chemical, toxicological, and ecological. This approach is supported by the inherent differences in the types of evidence. For example, a biocriterion based on the index of biotic integrity discriminates sites on a human disturbance gradient (Blocksom and Johnson, 2009). The index responds to the multiple stressors that occur commonly on such gradients and is most responsive to those stressors that are common components of human disturbance. Many of those stressors, such as flashy flow, have no numeric criteria. On the other hand, water quality criteria are based on responses to particular chemicals or other stressors and not necessarily to common human disturbances of aquatic systems. Water quality criteria and biocriteria are criteria for different impairments.

Note that this discussion applies to integrating evidence across types. When applying independent applicability, one might weigh evidence within types. For example, multiple toxicity tests of an ambient water could be combined to determine whether the water has unacceptable toxicity. Also, once a water body is declared impaired, WoE approaches can be applied when assessing the risks associated with alternative remedial or regulatory actions.

Although WoE integrates evidence concerning some environmental quality of interest, MCDA is intended to go farther and identify the best decision, given the problem framing, decision criteria, and preferences [e.g., Which is the best option for dredge spoil disposal given costs, risks, and stakeholder preferences? (Stahl et al., 2002)]. MCDA conventionally requires that probabilities be estimated for the outcomes of a decision and that a decision maker assign utilities to attributes of the outcomes (i.e., the decision criteria) to allow calculation of the expected utility of a decision (Linkov and Moberg, 2012). Weighting is involved in conventional MCDA when combining the multiple decision criteria (cost, aquatic toxicity, public acceptance, etc.). The computational methods of MCDA, however, have been adapted for a variety of uses beyond decision making, including combining numerically weighted evidence (Linkov and Moberg, 2012). One example is weighing the evidence for adverse outcome pathways [Box 3-3, (Collier et al., 2016)]. Linkov et al. (2015) described MCDA as a suitable proxy for Bayesian analysis.

BBNs are graphical models of the uncertainties and dependencies used to calculate the probability of an outcome in a causal network (Fenton and Neil, 2013). BBNs adapted for decision analysis are termed influence diagrams (Carriger and Barron, 2011). BBNs are computationally complex and not familiar to most environmental assessors and stakeholders, but available software makes their application relatively easy. When BBNs are involved in environmental inferences, they may not have data-derived probabilities; instead expert judgment is commonly used. These networks are WoE in the sense that the probability of a variable's state can be considered as its weight and branches of the network can considered chains of evidence (Small, 2008). For example, the probabilities of fishery closure could be one weighted piece of evidence and probabilities of levels of ecological impacts might be another; these can be combined by calculating the conditional probabilities to derive levels of offshore ecosystem services impacts (Carriger and Barron, 2011). Carriger and Barron (2016) have adapted BBNs to explicitly weigh multiple types of ecological evidence. They treated the three types of evidence in the sediment quality triad as branches of a BBN, calculated probabilities that each type was indicative of effects, weighted each in terms of its importance, and then calculated an overall probability of impairment. Because this method does not use a causal network, it is no longer a BBN in the conventional sense. However, it does provide a means of computationally combining evidence rather than using qualitative logic.

Although these methods have not been used for conventional qualitative WoE tasks such as identifying causes or hazards, nothing in this document precludes using them where appropriate. An example of a relevant potential regulatory application is the use of BBNs to optimize choices of toxicity tests in European chemical regulation in place of judgment-based WoE (Jaworska et al., 2010). This case is ideal for these quantitative methods because it is a relatively simple and consistent problem with a clear decision structure. Objectively estimating constituent probabilities of, for example, a positive rat carcinogenicity test given a positive Ames assay is possible. One simply needs a sufficient database of test results.

D.9. Summarize Only

Some assessors have argued that the weighing of evidence should not determine what conclusion is best supported by the evidence (Gray, 1994). Instead, they argue that assessors should assemble, clearly summarize, and simply present the evidence to the decision maker with enough background information for them to make a decision. Although this approach takes subjective judgments concerning the integration of evidence away from assessment scientists, it confers responsibility on decision makers to interpret scientific information, which they might not be trained to do, and requires time for inferential work that they might not have.

D.10. Conclusions

This summary of WoE approaches is intended to show the range of techniques that might be used for qualitative WoE. Methods proposed or used, however, do not necessarily fit into these categories. For example, McDonald et al. (2007) translated qualitative weights to numbers that are combined algebraically and then translated into a final qualitative conclusion. This method is typical of the WoE literature, which is replete with methods developed for the individual application. The inclination to develop a new WoE method for each application might be diminished by the availability in this document of a generic WoE approach that is flexible but provides some consistency across a variety of applications.

APPENDIX E. CHARACTERISTICS OF INFERRED QUALITIES

Qualitative weight of evidence (WoE) addresses qualities, each of which is characterized by certain characteristics. For example, if the quality of interest is causation, the hypothesized relationship should have the characteristics of causation such as, the causal agent and the affected entity interact. Association of evidence with characteristics of causation, or characteristics of any other quality being addressed, can serve two purposes. First, characteristics explain what the evidence does for the hypothesis (Section 6.2). For example, aqueous concentrations of a chemical in streams can demonstrate co-occurrence but not interaction. Second, categorizing the evidence in terms of the characteristics can help to perform and justify the inference. For example, a WoE table organized in terms of causal characteristics may show that there is abundant evidence for co-occurrence but none for interaction, which would raise questions about bioavailability. Only characteristics of causation are established, but considering appropriate characteristics of other inferred qualities such as impairment or protectiveness also might be useful. Potential characteristics for five qualities are presented here.

E.1. Characteristics of Causation

In environmental assessments, WoE has been used primarily to assess causality. In fact, WoE has been equated with determining the degree of credence due a causal hypothesis (Rhomberg et al., 2013; Krimsky, 2005). WoE is particularly associated with causation because causality is a fundamental concept, and no one piece or type of evidence can prove causation (Norton et al., 2014). Rather, the relationships of evidence to characteristics of causal relationships should be considered. Six characteristics of causation, developed for ecological causal assessments, have proven useful for that purpose (Table E-1). By analogy to Hill's considerations, they have been called Cormier's causal characteristics (CCC).

Few bodies of evidence for causal assessments include evidence for all of these characteristics. Even in very well-studied cases, evidence of conditions prior to induction of the effect is seldom available to consider time order (Table 7-1). Even an incomplete WoE table based on characteristics, however, provides more insight into what is known about causation in a case than a table based only on types of evidence.

Although these characteristics were developed for causation in specific cases, they also can be relevant to general causation (i.e., Does agent *x* cause effect *y*?), if actual cases are available. The characteristics can be used to demonstrate that, at least in those actual cases, the agent could cause the effect. They can be particularly useful when the general question is framed in terms of real-world conditions. An example is the use of the characteristics to determine that, where aqueous conductivity is elevated due to major mineral ions in West Virginia and Kentucky, the ion mixture causes the extirpation of invertebrate genera (Cormier et al., 2013; Cormier and Suter, 2013; U.S. EPA, 2011b).

Although the characteristics apply to, and can be observed in actual cases, they are not observable in the same way when the general causal question is hypothetical. That is, hypothetically, can *x* cause *y* rather than, in fact, did *x* cause *y* or is *x* causing *y*? In particular, when the only evidence of effects is from toxicity tests, the co-occurrence and its antecedents are simply the design and setup of the test, and the time order is inevitable. Sufficiency in hypothetical causal assessments is not of interest because no particular effect level is identified, so no particular exposure is sufficient. Instead, we use the test data to establish an exposure-response relationship that can be applied generally. The real causal concerns are with the relevance of the co-occurrence, interaction, and alteration in the test to those in the field. Are the conditions, durations, species, and life stages in the tests relevant to the co-occurrence of interest in the

field? Are the interactions of the stressor and test organisms and the resulting alterations plausible in the field? Are others likely to be more sensitive or important?

Table E-1. Characteristics of causal relationships[a]

Causal Characteristics	Description	What Evidence of a Characteristic Shows
Time order	The cause precedes the effect.	Change in the entity after exposure to the cause and not before
Antecedence	The causal relationship is a result of a larger web of antecedent cause-and-effect relationships. Evidence includes sources and routes of transport.	Earlier events that led to the particular causal event. It demonstrates that a potential causal event is part of a network of prior causal events, which increases confidence that the potential causal event actually occurred (e.g., that it was not a result of a measurement error or hoax).
Co-occurrence	The cause co-occurs with the susceptible entity in space and time. Evidence includes contaminant concentrations in ambient media and habitat alterations.	The presence of both a causal agent and the affected entity in circumstances that create the potential for exposure
Interaction	The cause interacts with the entity in a way that can lead to the effect. Evidence includes injuries, body burdens, and biomarkers.	Signs that the entity has been exposed to the agent in such a way that changes can be initiated
Sufficiency	The intensity, frequency and duration of the cause are adequate, and the entity is sufficiently susceptible to produce the type and magnitude of the effect.	Enough of the cause and a sufficiently susceptible entity that can result in the level of the observed effect
Alteration	The entity is changed by physical, chemical, or other mechanisms leading to the defined effect. Evidence includes symptoms and related attributes of the affected entities.	Changes in the entity attributable to or at least appropriate to the cause, which can indicate that the mechanism is acting

[a] Modified from Norton et al. (2014); Cormier et al. (2010).

The characteristics of causation can be arranged in a logical sequence: *antecedent* causes lead to *co-occurrence* of the proximate cause with susceptible or affected organisms, which leads to *interaction* with the affected organisms and, if the interaction is *sufficient*, leads to *alteration* of the organisms. The characteristics also serve to prompt assessors to make full use of the evidence with respect to all characteristics of causation. For example, it is obvious that laboratory test data provide evidence concerning sufficiency, but the data also might provide evidence of alterations characteristic of organisms affected by the tested agent that might be observed in the field.

E.2. Characteristics of Protection

Criteria, standards, screening levels and other benchmarks are intended to define a limit on exposure that would be adequately protective. Protection, like causation, is a difficult concept with multiple characteristics (Table E-2). Benchmarks are usually derived using one piece or one type of evidence. WoE might be used, however, to assess the confidence provided by diverse evidence that a benchmark or a procedure for deriving benchmarks is appropriately protective. Although the U.S. Environmental Protection Agency has not explicitly used this potential application of WoE, characteristics like those Table E-2 might be useful.

Table E-2. Potential characteristics of a protective benchmark

Characteristics of Protective Benchmarks	Description
Causal relationship	The exposure-response relationship used in the derivation is likely to be causal.
Predictive model of the relationship	The model of the relationship predicts the effects of specified exposures.
Represent sensitive endpoints	Known sensitive endpoint species or other entities and responses can be represented by the relationship.
Exposure metric is relevant	The exposure metric represents the relevant exposure of the sensitive entities.
Set at an appropriately protective level	Independent data demonstrate, with sufficient confidence, a lack of effects of concern on the aquatic community and constituent taxa.
Discriminatory power	The benchmark discriminates between impaired and unimpaired communities with sufficient confidence.

E.3. Characteristics of Contaminants of Concern

Risk assessments of contaminated sites typically develop lists of contaminants of concern based on chemical analyses of site media. The contaminants of concern are then the subjects of the risk assessment. Concern may be determined by comparison to ecological benchmarks, but more often multiple characteristics of a contaminant are weighed to determine which make the list. The characteristics in Table E-3 are based on a text and a recent Superfund ecological risk assessment (Black & Veatch Special Projects Corps, 2011; Suter et al., 2000). The list may not be exhaustive.

Table E-3. Characteristics of a contaminant of concern at a contaminated site

Characteristics of Contaminants of Concern	Description
Associated with the waste or source	Chemicals that are not associated with the waste or effluent of interest could be from an extraneous local source, regional contamination, or natural background.
Frequently detected	Chemicals that are infrequently detected at the site are of lesser concern and might be artifacts.
Greater than local background	Chemicals at background levels are not of concern, unless the anthropogenic form is more bioavailable or toxic.
At potentially toxic levels	Concentrations above relevant ecotoxicological benchmarks are of concern.
Detection limits are inadequate	Chemicals that could not be detected at toxic levels are of concern, particularly if they are associated with the waste or source.
Belongs to the same class as an identified contaminant of concern	A chemical that is not of concern alone might belong to a class, such as polycyclic aromatic hydrocarbons, that could be assessed jointly.

E.4. Characteristics of Biological Impairment

Impairment of biotic populations or communities is determined under the Clean Water Act's Section 303(d) and in various other contexts. Although a population or community need be impaired in only one way to be categorized as impaired (Box D-1), multiple characteristics of impairment could increase confidence in the designation and increase support for a regulatory or remedial action. A few of

the possible characteristics of impairment include low taxonomic richness, proportion of dominant taxa, toxicity, contamination, poor physical habitat, and poor aesthetics, among others. These characteristics are familiar to ecological assessors and require no descriptions here.

E.5. Characteristics of Remediation

Assessments of the success of remedial actions are common and important examples of outcome assessments. Remediation is judged in terms of performance and effectiveness of the intervention (Table E-4). Obtaining sufficient evidence to determine whether ecological goals are attained because of the remedial action and not just natural recovery is valuable.

Table E-4. Potential characteristics of remediation

Characteristic of Remediation	Description
Performance of the Intervention	
Functions	The remedial technology functions as intended.
Reduces the agent	The technology substantially reduces the level and extent of the contaminant or other agent that causes the risk.
Achieves the physical/chemical goal	The levels of the causal agent are reduced sufficiently to achieve the goal.
Effectiveness of the Intervention	
Endpoint less exposed	The exposure of the environmental endpoint entity to the agent and their interaction are reduced as predicted.
Endpoint improved	The abundance, diversity, function, or other attributes of the endpoint entity improve within the expected time following the remediation.
Endpoint goal achieved	Reference conditions or other ecological endpoint goal are achieved in response to remediation.

E.6. Summary

Qualitative WoE is performed to support inferences concerning some qualitative property such as causality, protection, concern, or impairment. Causality has been the principal quality inferred by WoE in environmental assessments and is the only quality for which characteristics have been available. Tentative lists of characteristics are presented here as examples to demonstrate the potential use of characteristics as an organizing principle for WoE. Other qualitative properties such as recovery also might be addressed by weighing the evidence for defined characteristics. As in causal inference, weighing evidence for characteristics of these other properties could provide a better explanatory structure to WoE than simply weighing pieces or types of evidence.

Document 29

U.S. EPA, Test Methods for Evaluating Solid Waste, Physical/Chemical Methods (SW-846), Abstract, https://www.epa.gov/hw-sw846SW-846/abstract-test-methods-evaluating-solid-waste-physicalchemical-methods-compendium-sw-846.

ABSTRACT

Test Methods for Evaluating Solid Waste, Physical/Chemical Methods (SW-846) provides test procedures and guidance which are recommended for use in conducting the evaluations and measurements needed to comply with the Resource Conservation and Recovery Act (RCRA), Public Law 94-580, as amended. These methods are approved by the U.S. Environmental Protection Agency for obtaining data to satisfy the requirements of 40 Code of Federal Regulations (CFR) Parts 122 through 270 promulgated under RCRA, as amended. This manual presents the state-of-the-art in routine analytical testing adapted for the RCRA program. It contains procedures for field and laboratory quality control, sampling, determining hazardous constituents in wastes, determining the hazardous characteristics of wastes (toxicity, ignitability, reactivity, and corrosivity), and for determining physical properties of wastes. It also contains guidance on how to select appropriate methods.

Several of the hazardous waste regulations under Subtitle C of RCRA require that specific testing methods described in SW-846 be employed for certain applications. Refer to 40 CFR Parts 260 through 270, for those specific requirements. Any reliable analytical method may be used to meet other requirements under Subtitle C of RCRA.

Document 30

U.S. Geological Survey, Derivation of Equations Describing Solute Transport in Ground Water, Water-Resources Investigations 77-19, 1977.

STEINKAMP

DERIVATION OF EQUATIONS DESCRIBING SOLUTE TRANSPORT IN GROUND WATER

$$+ \frac{\varepsilon}{V_0} \sum_{j=1}^{S} \frac{\partial m_j}{\partial t} + W^* P^*$$

$$q_i = \frac{-k_{ij}}{\mu} \left(\frac{\partial P}{\partial x_j} + \rho g \frac{\partial z^*}{\partial x_j} \right)$$

$$\frac{\partial}{\partial x_j} \left(T_{ij} \frac{\partial h}{\partial x_j} \right) = S \frac{\partial h}{\partial t} + W$$

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i} \left(D_{ij} \frac{\partial C}{\partial x_j} \right) - \frac{\partial}{\partial x_i} \left(C V_i \right) - \frac{C' W}{\varepsilon b}$$

$$D_{ij} = a_{ijmn} \frac{V_m V_n}{|V|}$$

$$|V| = \sqrt{V_1^2 + V_2^2 + V_3^2}$$

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DERIVATION OF EQUATIONS DESCRIBING SOLUTE TRANSPORT IN GROUND WATER

By Leonard F. Konikow and David B. Grove

ABSTRACT

A general equation describing the three-dimensional transport and dispersion of a reacting solute in flowing ground water is derived from the principle of conservation of mass. The derivation presented in this report is more detailed but less rigorous than derivations published previously. The general solute-transport equation relates concentration changes to hydrodynamic dispersion, convective transport, fluid sources and sinks, and chemical reactions. Because both dispersion and convective transport depend on the velocity of ground-water flow, the solute-transport equation must be solved in conjunction with the ground-water flow equation.

INTRODUCTION

In recent years there has been an increased awareness of problems of ground-water contamination. Reliable predictions of contaminant movement can only be made if we understand and can quantitatively describe the physical and chemical processes that control solute transport in flowing ground water. Several reports have been published recently that develop and present solute-transport equations to compute the concentration of a dissolved chemical species in ground water as a function of space and time. Examples of these reports include Reddell and Sunada (1970), Bear (1972), and Bredehoeft and Pinder (1973). The three main processes affecting solute transport, and consequently chemical concentrations, are convective transport, hydrodynamic dispersion (including diffusion and mechanical dispersion), and chemical reactions. Because convective transport and hydrodynamic dispersion depend on the velocity of ground-water flow, the solute-transport equation must be considered in conjunction with the ground-water flow equation.

Aquifers generally have heterogeneous properties and complex boundary conditions. Therefore, the solution of the partial differential equations that describe the solute-transport processes generally require the use of a deterministic, distributed parameter, digital simulation model. Among the reports that describe or present numerical models to solve the solute-transport equations are Reddell and Sunada (1970), Bredehoeft and Pinder (1973), Pinder (1973), Ahlstrom and Baca (1974), Gupta and others (1975), Grove (1976), and Lantz and others (1976). Furthermore, several documented case histories show that where adequate hydrogeologic data are available, solute-transport models can be used to compute the rates and directions of spreading of contaminants from known or projected sources. Examples of model applications to field problems include Konikow and Bredehoeft (1974), Robertson (1974), Robson (1974), Konikow (1976), and Segol and Pinder (1976).

These models use either finite-difference methods, finite-element methods, or the method of characteristics. The selection of the "best" numerical method depends largely on the nature of the specific field problem, but also depends to some extent on the mathematical background of the analyst. Although solute-transport models are best utilized when the analyst is thoroughly familiar both with the equations and with the numerical algorithm, the increasing availability of documented and published programs affords the opportunity for the use of a model by persons with only minimal familiarity with both.

The basic purpose of this report is to derive a general form of the solute-transport equation from general principles in a more detailed, step-by-step, but less rigorous manner than has been done in previously published literature. The report is intended to serve as an introduction to quantitative modeling of solute-transport processes in ground water. It will also show how the general solute-transport equation can be modified or simplified for application to a variety of different types of field problems. Because of the interrelation between the flow equation and the solute-transport equation, the former will also be presented in some

detail although not specifically derived. It is assumed that the mathematical background of the reader includes at least a familiarity with partial differential equations.

GROUND-WATER FLOW

General flow equation

A quantitative description of ground-water flow is a prerequisite to accurately representing solute transport in aquifers. A general form of the equation describing the transient flow of a compressible fluid in a nonhomogeneous anisotropic aquifer may be derived by combining Darcy's Law with the continuity equation. By following the developments of Cooper (1966) and of Bredehoeft and Pinder (1973), the general flow equation may be written in cartesian tensor notation as:

$$\frac{\partial}{\partial x_i}\left[\frac{\rho k_{ij}}{\mu}\left(\frac{\partial P}{\partial x_j} + \rho g \frac{\partial z^*}{\partial x_j}\right)\right] = \rho\alpha \frac{\partial P}{\partial t} + \rho_o \varepsilon\beta \frac{\partial P}{\partial t}$$

$$+ \frac{\varepsilon}{v_o} \sum_{i=1}^{s} \frac{\partial m_i}{\partial t} + W^*\rho^* \qquad (1)$$

where k_{ij} is the intrinsic permeability (a second-order tensor), L^2;

ρ is the fluid density, ML^{-3};

μ is the dynamic viscosity, $ML^{-1}T^{-1}$;

P is the fluid pressure, $ML^{-1}T^{-2}$;

g is the gravitational acceleration constant, LT^{-2};

z^* is the elevation of the reference point above a standard datum, L;

W^* = $W^*(x,y,z,t)$ is the volume flux per unit volume (positive sign for outflow and negative for inflow), T^{-1};

ρ^* is the density of the source/sink fluid, ML^{-3};

α is the vertical compressibility coefficient of the medium, $LM^{-1}T^2$;

ρ_o is the fluid density at a reference pressure, temperature, and and concentration, ML^{-3};

ε is the effective porosity (dimensionless);

β is the compressibility coefficient of the fluid, $LM^{-1}T^2$;

v_o is the reference volume of the fluid, L^3;

m_i is the mass of species i in the reference volume v_o, M;

s is the number of species, (dimensionless);

x_i are the cartesian coordinates, L; and

t is time, T.

The summation convention of Cartesian tensor analysis is implied in equation 1. That is, each term is summed over the range of its subscripts. Bredehoeft and Pinder (1973) note that the derivation of equation 1 is based on the following assumptions:

1. The porous medium may only deform vertically.
2. Isothermal conditions prevail.
3. The volume of individual grains remains constant during deformation of the medium.
4. Fluid density is a linear function of pressure and concentration, as indicated by the following relationship:

$$\rho = \rho_o + \rho_o\beta\ (P-P_o) + \frac{1}{v_o} \sum_{i=1}^{s} (m_i-m_{io}) \qquad (2)$$

where P_o is the reference fluid pressure, $ML^{-1}T^{-2}$; and

m_{io} is the mass of species i in the reference volume v_o at the reference pressure, M.

5. The permeability is independent of pressure, temperature, and concentration.
6. There is no change in volume caused by mixing fluids of different ionic concentrations.
7. The proportionality constants α and β are independent of pressure and concentration.
8. Hydraulic head gradients are the only significant driving mechanism.
9. The vertical velocity of grains is negligible.

Equations of state

The density and viscosity of ground water are both related to its temperature, pressure, and chemical content. Because isothermal conditions have been assumed, temperature changes need not be considered.

Equation 2 expresses the dependence of density on both the pressure and the mass concentrations of all species. Equation 2 may be rewritten

in terms of the concentration of a single chemical species of interest as:

$$\rho = \rho_o + \rho_o\beta(P-P_o) + \gamma(C-C_o) \tag{3}$$

where C is the mass concentration per unit volume of solution for the solute species of interest, ML^{-3};
C_o is the concentration of the solute at the reference pressure and temperature, ML^{-3}; and
γ is the constant of proportionality between concentration and fluid density (dimensionless).

If the relationship indicated by equation 3 is substituted for equation 2, then equation 1 may be rewritten as:

$$\frac{\partial}{\partial x_i}\left[\frac{\rho k_{ij}}{\mu}\left(\frac{\partial P}{\partial x_j} + \rho g \frac{\partial z^*}{\partial x_j}\right)\right] = \rho\alpha \frac{\partial P}{\partial t} + \rho_o\varepsilon\beta \frac{\partial P}{\partial t} + \varepsilon\gamma \frac{\partial C}{\partial t} + W^*\rho^* \tag{4}$$

Viscosity may be similarly expressed as a linear function of concentration by the following:

$$\mu = \mu_o + \lambda(C - C_o) \tag{5}$$

where μ_o is the dynamic viscosity of the fluid at the reference pressure, temperature, and concentration, $ML^{-1}T^{-1}$; and
λ is the constant of proportionality between concentration and viscosity, L^2T^{-1}.

Flow velocity

The seepage velocity, or average interstitial velocity, of groundwater flow may be computed as:

$$V_i = \frac{q_i}{\varepsilon} \tag{6}$$

where V_i is the seepage velocity in the direction of x_i, LT^{-1}; and
q_i is the specific discharge, or specific flux, in the direction of x_i, LT^{-1}.

The specific discharge may be computed directly from Darcy's Law, which is written as:

$$q_i = \frac{-k_{ij}}{\mu}\left(\frac{\partial P}{\partial x_j} + \rho g \frac{\partial z^*}{\partial x_j}\right) \tag{7}$$

Simplifying assumptions

The general flow equation written as equation 4 can be simplified considerably if certain conditions can be satisfied. Several of these are described next.

Homogeneous fluid properties

When changes in concentrations of dissolved chemical species are relatively small, the fluid density and viscosity remain essentially constant. This assumption of homogeneous fluid properties both simplifies the flow equation and allows it to be solved independently from the solute-transport equation. If density is independent of concentration, then the third term on the right side of equation 4 can be eliminated from the flow equation.

We may aim next to express equation 4 in terms of hydraulic head rather than pressure. Following the development of Hubbert (1940), we may define the hydraulic head as:

$$h = z^* + \int_{P_a}^{P} \frac{dP}{\rho g} \tag{8}$$

where h is the hydraulic head, L; and

P_a is atmospheric pressure, $ML^{-1}T^{-2}$.

If we differentiate equation 8 with respect to x_i, for constant density we obtain:

$$\frac{\partial h}{\partial x_i} = \frac{\partial z^*}{\partial x_i} + \frac{1}{\rho g}\frac{\partial P}{\partial x_i} \tag{9}$$

Solving equation 9 for $\frac{\partial P}{\partial x_i}$ yields:

$$\frac{\partial P}{\partial x_i} = \rho g\left(\frac{\partial h}{\partial x_i} - \frac{\partial z^*}{\partial x_i}\right) \tag{10}$$

We may similarly differentiate equation 8 with respect to time to obtain:

$$\frac{\partial h}{\partial t} = \frac{\partial z^*}{\partial t} + \frac{1}{\rho g}\frac{\partial P}{\partial t} \tag{11}$$

Because $\frac{\partial z^*}{\partial t} = 0$, we can express equation 11 as:

$$\frac{\partial P}{\partial t} = \rho g \frac{\partial h}{\partial t} \tag{12}$$

If we next substitute the relations indicated by equations 10 and 12 into equation 4, and then divide both sides of the equation by the constant density, we obtain:

$$\frac{\partial}{\partial x_i}\left(\frac{\rho g}{\mu} k_{ij} \frac{\partial h}{\partial x_j}\right) = g(\rho\alpha + \rho_o \varepsilon\beta)\frac{\partial h}{\partial t} + W^* \tag{13}$$

Equation 13 may be further reduced if we consider that

$$K_{ij} = \frac{\rho g}{\mu} k_{ij} \tag{14}$$

where K_{ij} is the hydraulic conductivity tensor, LT^{-1}, and that

$$S_s = g(\rho\alpha + \rho_o \varepsilon\beta) \tag{15}$$

where S_s is the specific storage, L^{-1}.

By substituting equations 14 and 15 into equation 13, we obtain:

$$\frac{\partial}{\partial x_i}\left(K_{ij}\frac{\partial h}{\partial x_j}\right) = S_s \frac{\partial h}{\partial t} + W^* \tag{16}$$

Two-dimensional areal flow

In many ground-water studies it can be reasonably assumed that ground-water flow is areally two-dimensional. This allows the three-dimensional flow equation to be reduced to the case of two-dimensional areal flow, for which several additional simplifications are possible. The advantages of reducing the dimensionality of the equations include less stringent data requirements, smaller computer storage requirements, and shorter computer execution times to achieve a numerical solution.

An expression similar to equation 16 may be derived for the two-dimensional areal flow of a homogeneous fluid and written as:

$$\frac{\partial}{\partial x_i}\left(K_{ij} b \frac{\partial h}{\partial x_j}\right) = S_s b \frac{\partial h}{\partial t} + W^* b \tag{17}$$

where b is the saturated thickness of the aquifer, L, and it is assumed that the hydraulic conductivity, specific storage, and hydraulic head represent vertically integrated mean values (Cooley, 1974).

The transmissivity of the aquifer may be defined as:

$$T_{ij} = K_{ij} b \tag{18}$$

where T_{ij} is the transmissivity, L^2T^{-1}.

Similarly, the storage coefficient of the aquifer may be defined as:

$$S = S_s b \tag{19}$$

where S is the storage coefficient (dimensionless).

After substituting the relationships indicated by equations 18 and 19 into equation 17, we obtain:

$$\frac{\partial}{\partial x_i}\left(T_{ij} \frac{\partial h}{\partial x_j}\right) = S \frac{\partial h}{\partial t} + W \tag{20}$$

where $W = W(x,y,t) = W^*b$ is the volume flux per unit area, LT^{-1}.

Although fluid sources and sinks may vary in space and time, they have been lumped into one term (W) in the previous development. There are several possible ways to compute W. If we consider only sources and sinks such as (1) direct withdrawal or recharge, such as pumpage from a well, well injection, or evapotranspiration, and (2) steady-state leakage into or out of the aquifer through a confining layer, streambed, or lake bed, then for the case of two-dimensional horizontal flow, the source/sink terms may be specifically expressed as:

$$W(x,y,t) = Q(x,y,t) - \frac{K_z}{m}(H_s - h) \tag{21}$$

where Q is the rate of withdrawal (positive sign) or recharge (negative sign), LT^{-1};

K_z is the vertical hydraulic conductivity of the confining layer, streambed, or lake bed, LT^{-1};

m is the thickness of the confining layer, streambed, or lake bed, L; and

H_s is the hydraulic head in the source bed, stream, or lake, L.

Alignment of coordinate axes

The cross-product terms of the permeability tensor drop out when the coordinate axes are aligned with the principal axes of the tensor (Bredehoeft, 1969); that is, $k_{ij} = 0$ when $i \neq j$. Therefore, the only permeability terms with possible nonzero values are k_{xx}, k_{yy}, and k_{zz}. This assumption simplifies the general flow equation, which can now be rewritten to include all permeability terms as:

$$\frac{\partial}{\partial x}\left[\frac{\rho k_{xx}}{\mu}\left(\frac{\partial P}{\partial x} + \rho g \frac{\partial z^*}{\partial x}\right)\right] + \frac{\partial}{\partial y}\left[\frac{\rho k_{yy}}{\mu}\left(\frac{\partial P}{\partial y} + \rho g \frac{\partial z^*}{\partial y}\right)\right]$$

$$+ \frac{\partial}{\partial z}\left[\frac{\rho k_{zz}}{\mu}\left(\frac{\partial P}{\partial z} + \rho g \frac{\partial z^*}{\partial z}\right)\right] = \rho\alpha \frac{\partial P}{\partial t} + \rho_o \varepsilon\beta \frac{\partial P}{\partial t} + \varepsilon\gamma \frac{\partial C}{\partial t} + W^*\rho^* \qquad (22)$$

Darcy's Law may be written similarly for the three flow directions as:

$$q_x = -\frac{k_{xx}}{\mu}\left(\frac{\partial P}{\partial x} + \rho g \frac{\partial z^*}{\partial x}\right) \qquad (23a)$$

$$q_y = -\frac{k_{yy}}{\mu}\left(\frac{\partial P}{\partial y} + \rho g \frac{\partial z^*}{\partial y}\right) \qquad (23b)$$

$$q_z = -\frac{k_{zz}}{\mu}\left(\frac{\partial P}{\partial z} + \rho g \frac{\partial z^*}{\partial z}\right) \qquad (23c)$$

For the case of two-dimensional areal flow, if the coordinate axes are aligned with the principal directions of the transmissivity tensor, equation 20 may be written as:

$$\frac{\partial}{\partial x}\left(T_{xx} \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_{yy} \frac{\partial h}{\partial y}\right) = S \frac{\partial h}{\partial t} + W \qquad (24)$$

SOLUTE-TRANSPORT EQUATION

Derivation of general transport equation

An equation describing the three-dimensional transport and dispersion of a reacting dissolved chemical in flowing ground water will be derived from the principle of conservation of mass (continuity condition). The derivation presented here is based on the developments of Reddell and Sunada (1970), Bear (1972), and Bredehoeft and Pinder (1973).

The principle of conservation of mass requires that the net mass of solute entering or leaving a specified volume of aquifer during a given time interval must equal the accumulation or loss of mass stored in that volume during the interval. This may be expressed in a verbal equation as:

(Rate of Solute Accumulation)

= (Rate of Solute Inflow) - (Rate of Solute Outflow)

+ (Rate of Chemical Production by Reactions) (25)

This relationship may then be expressed mathematically by considering all fluxes into and out of a representative elementary volume (REV), as described by Bear (1972, p. 19). The REV shown in figure 1 is centered at coordinates (x, y, z) and has dimensions (Δx, Δy, Δz).

First we will determine fluxes in the x-direction. We know that at the center of the REV the mass flux of solute in the x-direction across the y-z plane (face IJKL) is equal to ($CV_x^* \varepsilon \Delta y \Delta z$), where C is the concentration of the solute (ML^{-3}), V_x^* is the instantaneous mass velocity of the solute (LT^{-1}), and Δy and Δz are the dimensions (L) of face IJKL. Note that the term ($\varepsilon \Delta y \Delta z$) simply represents the total effective cross-sectional area through which flow is occurring.

We need expressions for the fluxes across the outer faces ABCD and EFGH. The difference between the mass flux of solute across face ABCD and face IJKL equals the rate of change of mass flux in the x-direction times the distance between these two faces. The rate of change of the mass flux of solute in the x-direction equals $\frac{\partial}{\partial x}(CV_x^* \varepsilon \Delta y \Delta z)$, and the distance from the center to face ABCD is $(-\Delta x/2)$. Thus, the mass flux through face ABCD equals

$$CV_x^* \varepsilon \Delta y \Delta z - \frac{\partial}{\partial x}(CV_x^* \varepsilon \Delta y \Delta z)\frac{\Delta x}{2}$$

Similarly, the distance from the center to face EFGH is $(+\Delta x/2)$ and the mass flux through face EFGH is given by

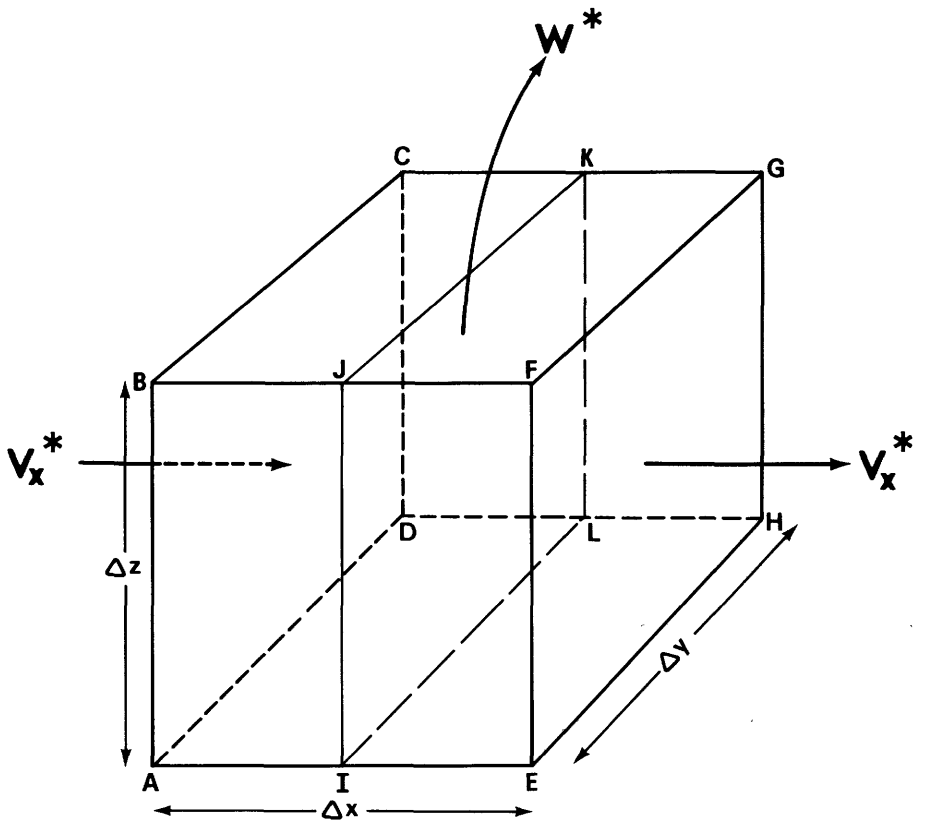

Figure 1.--Representative elementary volume (REV) of aquifer.

$$CV_x^* \varepsilon \Delta y \Delta z + \frac{\partial}{\partial x} (CV_x^* \varepsilon \Delta y \Delta z) \frac{\Delta x}{2}$$

The net mass flux of the solute entering or leaving the REV in the x-direction equals the difference (input-output) between the two previous terms:

$$(\text{Net Mass Flux})_x = \left[CV_x^* \varepsilon \Delta y \Delta z - \frac{\partial}{\partial x} (CV_x^* \varepsilon \Delta y \Delta z) \frac{\Delta x}{2} \right]$$

$$- \left[CV_x^* \varepsilon \Delta y \Delta z + \frac{\partial}{\partial x} (CV_x^* \varepsilon \Delta y \Delta z) \frac{\Delta x}{2} \right]$$

$$= - \frac{\partial}{\partial x} (CV_x^* \varepsilon \Delta y \Delta z) \Delta x \qquad (26)$$

This equation can also be derived by writing a Taylor series for the mass flux term about the point (x, y, z) (Reddell and Sunada, 1970, p. 39). Note that if the value of the derivative in the x-direction (equation 26) is negative, then the mass flux of solute entering through face ABCD is greater than the mass leaving through face EFGH. If all other fluxes balance, there will then be a positive accumulation of solute mass in the REV. Conversely, if the derivative is positive, there will be a decrease over time of solute mass stored in the REV.

It can similarly be shown that for the y-direction:

$$(\text{Net Mass Flux})_y = - \frac{\partial}{\partial y} (CV_y^* \varepsilon \Delta x \Delta z) \Delta y \qquad (27a)$$

and for the z-direction:

$$(\text{Net Mass Flux})_z = - \frac{\partial}{\partial z} (CV_z^* \varepsilon \Delta x \Delta y) \Delta z \qquad (27b)$$

Solute may also enter or leave the REV as a flux through a source or sink (W). This may be expressed mathematically as:

$$(\text{Source/Sink Mass Flux})_{REV} = C'W^* \Delta x \Delta y \Delta z \qquad (28)$$

where C' is the concentration of the solute in the source or sink fluid, ML^{-3}.

If a sink (withdrawal) is considered positive in sign and a source (recharge or injection) is considered negative in sign, then when all other fluxes balance, a positive W must be balanced by a decrease over time of solute mass stored in the REV (negative $\frac{\partial C}{\partial t}$), and vice versa. Note that for a sink C' is equivalent to the concentration in the aquifer at the location of the sink.

A particular solute may also be added to or removed from solution within the REV by the effects of chemical reactions. Examples of such reactions include radioactive decay, ion exchange, and adsorption. The amount of solute that is produced (that is, added to or removed from solution) within the REV is equal to the rate of production of the solute times the volume of solution and may be expressed as:

$$(\text{Solute Mass Produced})_{REV} = \varepsilon \Delta x \Delta y \Delta z \sum_{k=1}^{s} R_k \tag{29}$$

where R_k is the rate of production of the solute in reaction k of s different reactions (positive for addition of solute and negative for removal), $ML^{-3}T^{-1}$.

The conservation of mass for a given solute may be expressed in a continuity equation by combining the terms in equations 26, 27a, 27b, 28, and 29, resulting in:

$$\begin{aligned} \frac{\partial}{\partial t}(C\varepsilon\Delta x\Delta y\Delta z) = &- \frac{\partial}{\partial x}(CV_x^* \varepsilon\Delta y\Delta z)\Delta x \\ &- \frac{\partial}{\partial y}(CV_y^* \varepsilon\Delta x\Delta z)\Delta y - \frac{\partial}{\partial z}(CV_z^* \varepsilon\Delta x\Delta y)\Delta z \\ &- C'W^*\Delta x\Delta y\Delta z + \varepsilon\Delta x\Delta y\Delta z \sum_{k=1}^{s} R_k \end{aligned} \tag{30}$$

If we assume that changes over time in porosity of the aquifer are not significant and Δx, Δy, and Δz are constants, then their derivatives equal zero. Using an indicial notation to represent directions in which x_1, x_2, and x_3 correspond to the x-, y-, and z-directions respectively, equation 30 can be rewritten as:

$$\begin{aligned} \varepsilon\Delta x_1\Delta x_2\Delta x_3 \frac{\partial C}{\partial t} = &- \Delta x_1\Delta x_2\Delta x_3 \frac{\partial}{\partial x_i}(CV_i^* \varepsilon) - C'W^*\Delta x_1\Delta x_2\Delta x_3 \\ &+ \varepsilon\Delta x_1\Delta x_2\Delta x_3 \sum_{k=1}^{s} R_k \end{aligned} \tag{31}$$

Dividing both sides of equation 31 by $(\Delta x_1 \Delta x_2 \Delta x_3)$ to remove the common factors results in:

$$\varepsilon \frac{\partial C}{\partial t} = - \frac{\partial}{\partial x_i} (CV_i^* \varepsilon) - C'W^* + \varepsilon \sum_{k=1}^{s} R_k \qquad (32)$$

The instantaneous mass flux of the solute is given as CV_i^*. As shown by Bear (1972, p. 101), this flux can be separated into two parts:

$$CV_i^* = CV_i + \overset{\circ}{CV}_i \qquad (33)$$

where $\overset{\circ}{V}_i$ is the deviation of the mass average velocity of the solute from the average insterstitial velocity of the fluid $(\overset{\circ}{V}_i = V_i^* - V_i)$, LT^{-1}.

The term CV_i represents the convective flux of solute carried by the average fluid motion through the REV. Neglecting diffusion, the term $\overset{\circ}{CV}_i$ represents the dispersive flux resulting from velocity fluctuations.

Bear (1972, p. 101) also shows that the dispersive flux can be approximated by:

$$\overset{\circ}{CV}_i = - D_{ij} \frac{\partial C}{\partial x_j} \qquad (34)$$

where D_{ij} is the coefficient of mechanical dispersion (a second-order tensor), L^2T^{-1}.

Equation 34 indicates that the dispersive flux is directly proportional to the concentration gradient and occurs in a direction from higher concentrations towards lower concentrations. The form of equation 34 is analogous to Fick's Law describing diffusive flux, as described by Bear (1972, p. 78). In considering flowing ground water, diffusive fluxes are assumed to be negligible in comparison to dispersive fluxes. If diffusion is negligible, the coefficient of mechanical dispersion is equivalent to the coefficient of hydrodynamic dispersion described by Bear (1972, p. 606).

Coupling between forces of one type and fluxes of another type are discussed by Bear (1972, p. 85-90). By following the development of Bredehoeft and Pinder (1973), and by assuming that the only significant driving mechanism is the gradient of hydraulic head and that Darcy's Law is fully valid, we eliminate the necessity of considering coupled processes.

As a result of substituting equation 34 into equation 33, the instantaneous mass flux may be expressed in terms of the dispersion coefficient as:

$$CV_i^* = CV_i - D_{ij} \frac{\partial C}{\partial x_j} \tag{35}$$

Equation 35 can next be substituted into equation 32 to yield:

$$\varepsilon \frac{\partial C}{\partial t} = - \frac{\partial}{\partial x_i} \left[\varepsilon \left(CV_i - D_{ij} \frac{\partial C}{\partial x_j} \right) \right] - C'W^* + \varepsilon \sum_{k=1}^{s} R_k \tag{36}$$

which is equivalent to:

$$\varepsilon \frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i} \left(\varepsilon D_{ij} \frac{\partial C}{\partial x_j} \right) - \frac{\partial}{\partial x_i} (\varepsilon CV_i)$$

$$- C'W^* + \varepsilon \sum_{k=1}^{s} R_k \tag{37}$$

If spatial changes in porosity are negligible, both sides of equation 37 can be divided by ε to produce:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i} \left(D_{ij} \frac{\partial C}{\partial x_j} \right) - \frac{\partial}{\partial x_i} (CV_i) - \frac{C'W^*}{\varepsilon} + \sum_{k=1}^{s} R_k \tag{38}$$

which is a general equation for computing the concentration of a single dissolved chemical species in flowing ground water.

For the general case of three-dimensional transport of a single dissolved chemical species in flowing ground water, equations 4 and 38 must be solved simultaneously. This requires the use of the auxiliary equations 3, 5, 6, and 7.

At this point it is of value to consider in more detail the second term on the right side of equation 38, which describes convective transport. This term may be expanded as follows:

$$- \frac{\partial}{\partial x_i} (CV_i) = - C \frac{\partial V_i}{\partial x_i} - V_i \frac{\partial C}{\partial x_i} \tag{39}$$

It is often assumed in cases of steady-state flow that the divergence of velocity ($\partial V_i / \partial x_i$) equals zero and the first term on the right side of equation 39 can be eliminated. However, as shown by the following

development, this would be an erroneous assumption if any fluid sources are present or if fluid density varies in space.

By using the definition of V_i indicated by equation 6, we may rewrite the first term on the right side of equation 39 as:

$$-C \frac{\partial V_i}{\partial x_i} = - \frac{C}{\varepsilon} \frac{\partial q_i}{\partial x_i} \tag{40}$$

Next, substitution of the definition of q_i from equation 7 into equation 40 gives:

$$-C \frac{\partial V_i}{\partial x_i} = - \frac{C}{\varepsilon} \frac{\partial}{\partial x_i} \left[\frac{-k_{ij}}{\mu} \left(\frac{\partial P}{\partial x_j} + \rho g \frac{\partial z^*}{\partial x_j} \right) \right] \tag{41}$$

If we multiply the expression within the brackets by ρ/ρ and substitute the relationships shown in equations 4 and 7, we obtain:

$$-C \frac{\partial V_i}{\partial x_i} = \frac{C\alpha}{\varepsilon} \frac{\partial P}{\partial t} + \frac{C\rho_o \beta}{\rho} \frac{\partial P}{\partial t} + \frac{C\gamma}{\rho} \frac{\partial C}{\partial t} + \frac{CW^*\rho^*}{\varepsilon\rho} + \rho q_i \frac{\partial (1/\rho)}{\partial x_i} \tag{42}$$

If steady-state flow existed, $\frac{\partial P}{\partial t} = 0$ and the first two terms on the right side are eliminated. Although the third term may be insignificant, the fourth term, which describes sources and sinks, would have to be included in the analysis, as would the fifth term, which is related to the spatial variability of fluid density.

Two-dimensional areal solute transport

A solute-transport equation for problems involving two-dimensional areal flow may be derived in a manner analogous to the previous derivation of a general three-dimensional equation by assuming that vertical variations in head and concentration are negligible. Consider the total volume of aquifer under a representative square area, as shown in figure 2. Note that the vertical dimension is represented by the saturated thickness, b, and that b may vary within the representative area. In this case the mass flux through face ABCD is approximately equal to

$$CV_x^* \varepsilon \Delta y b - \frac{\partial}{\partial x} \left(CV_x^* \varepsilon \Delta y b \right) \frac{\Delta x}{2}$$

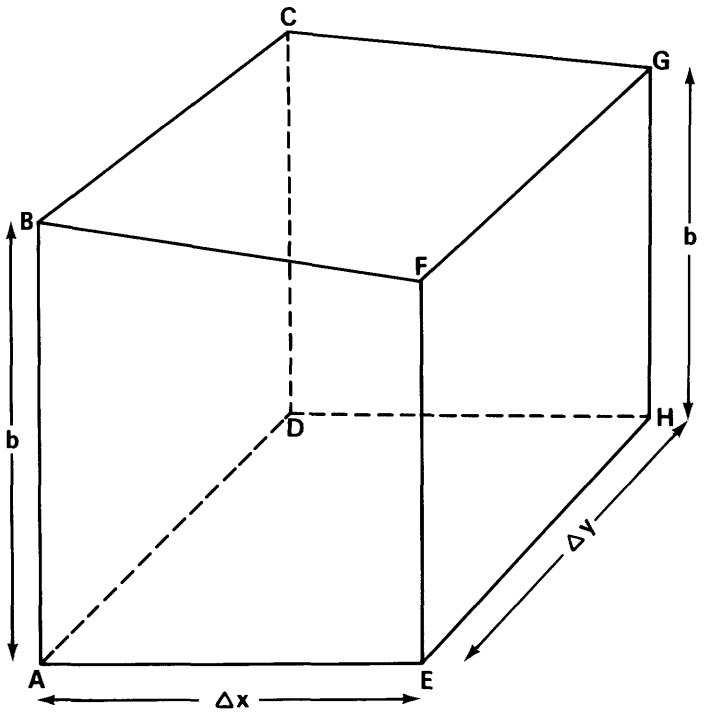

Figure 2.--Representative volume of aquifer having variable saturated thickness.

Similarly, the mass flux through face EFGH may be given by

$$CV_x^* \varepsilon \Delta yb + \frac{\partial}{\partial x}\left(CV_x^* \varepsilon \Delta yb\right)\frac{\Delta x}{2}$$

The net mass flux of the solute entering or leaving the representative volume thus equals the difference between the two previous terms:

$$(\text{Net Mass Flux})_x = -\frac{\partial}{\partial x}\left(CV_x^* \varepsilon \Delta yb\right)\Delta x \tag{43}$$

It can also be shown in the same manner that for the y-direction:

$$(\text{Net Mass Flux})_y = -\frac{\partial}{\partial y}\left(CV_y^* \varepsilon \Delta xb\right)\Delta y \tag{44}$$

In the case of two-dimensional areal flow, it is assumed that any flux across the upper or lower faces of the representative volume is included in the source/sink term. Solute entering or leaving the representative volume through a source or sink may be expressed mathematically as:

$$(\text{Source/Sink Mass Flux}) = C'W\Delta x\Delta y \tag{45}$$

Solute added to or removed from solution within the representative volume by the effects of chemical reactions may be expressed as:

$$(\text{Solute Mass Produced}) = \varepsilon \Delta x \Delta yb \sum_{k=1}^{s} R_k \tag{46}$$

The conservation of mass for a given solute may be expressed in a continuity equation by combining the terms in equations 43, 44, 45, and 46, resulting in:

$$\frac{\partial}{\partial t}\left(C\varepsilon \Delta x \Delta yb\right) = -\frac{\partial}{\partial x}\left(CV_x^* \varepsilon \Delta yb\right)\Delta x$$

$$-\frac{\partial}{\partial y}\left(CV_y^* \varepsilon \Delta xb\right)\Delta y$$

$$-C'W\Delta x\Delta y + \varepsilon \Delta x \Delta yb \sum_{k=1}^{s} R_k \tag{47}$$

If ε, Δx, and Δy are constants, equation 47 may be rewritten as:

$$\varepsilon\Delta x\Delta y \frac{\partial(Cb)}{\partial t} = - \varepsilon\Delta x\Delta y \frac{\partial}{\partial x}\left(CV_x{}^* b\right) - \varepsilon\Delta x\Delta y \frac{\partial}{\partial y}\left(CV_y{}^* b\right) - C'W\Delta x\Delta y + \varepsilon\Delta x\Delta y b \sum_{k=1}^{s} R_k \tag{48}$$

Dividing both sides of equation 48 by ($\varepsilon\Delta x\Delta y$) results in:

$$\frac{\partial(Cb)}{\partial t} = - \frac{\partial}{\partial x}\left(CV_x{}^* b\right) - \frac{\partial}{\partial y}\left(CV_y{}^* b\right) - \frac{C'W}{\varepsilon} + b \sum_{k=1}^{s} R_k \tag{49}$$

By expressing equation 49 in tensor notation and substituting equation 35, written for two dimensions, into equation 49, we obtain:

$$\frac{\partial(Cb)}{\partial t} = - \frac{\partial}{\partial x_i}\left[b\left(CV_i - D_{ij}\frac{\partial C}{\partial x_j}\right)\right] - \frac{C'W}{\varepsilon} + b \sum_{k=1}^{s} R_k \tag{50}$$

which is equivalent to:

$$\frac{\partial(Cb)}{\partial t} = \frac{\partial}{\partial x_i}\left(bD_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}\left(bCV_i\right) - \frac{C'W}{\varepsilon} + b \sum_{k=1}^{s} R_k \tag{51}$$

The left side of equation 49 may be expanded as:

$$\frac{\partial(Cb)}{\partial t} = C\frac{\partial b}{\partial t} + b\frac{\partial C}{\partial t} \tag{52}$$

Substituting equation 52 into equation 51 and solving for $\partial C/\partial t$ results in:

$$\frac{\partial C}{\partial t} = \frac{1}{b}\frac{\partial}{\partial x_i}\left(bD_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{1}{b}\frac{\partial}{\partial x_i}\left(bCV_i\right)$$

$$- \frac{C}{b}\frac{\partial b}{\partial t} - \frac{C'W}{\varepsilon b} + \sum_{k=1}^{s} R_k \tag{53}$$

If the saturated thickness is constant in space, the spatial derivatives of b are equal to zero. Under these conditions, equation 53 can be further simplified to:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}\left(CV_i\right)$$

$$- \frac{C'W}{\varepsilon b} - \frac{C}{b}\frac{\partial b}{\partial t} + \sum_{k=1}^{s} R_k \tag{54}$$

The two-dimensional solute-transport equation can be reduced further if changes in saturated thickness over time are negligible and if the solute is not affected by chemical reactions. Under these conditions equation 54 may be simplified to:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}\left(CV_i\right) - \frac{C'W}{\varepsilon b} \tag{55}$$

The difference between equation 53 and equation 54 can be presented more explicitly by expanding the first two terms on the right side of equation 53. After combining terms, equation 53 may then be rewritten as:

$$\frac{\partial C}{\partial t} = \frac{1}{b}\left[D_{ij}\frac{\partial C}{\partial x_j} - CV_i\right]\frac{\partial b}{\partial x_i} + \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right)$$

$$- \frac{\partial (CV_i)}{\partial x_i} - \frac{C'W}{\varepsilon b} - \frac{C}{b}\frac{\partial b}{\partial t} + \sum_{k=1}^{s} R_k \qquad (56)$$

Thus, the difference between equations 53 and 54 is equal to:

$$\frac{1}{b}\left[D_{ij}\frac{\partial C}{\partial x_j} - CV_i\right]\frac{\partial b}{\partial x_i}$$

In other words, the error in computed concentrations caused by assuming that the saturated thickness is uniform, when it actually varies in space, is inversely proportional to the saturated thickness and directly proportional to the divergence of the saturated thickness. If the rate of change in saturated thickness is small compared to the total saturated thickness, the simpler equation 54 can be used as a reasonable approximation to equation 53.

We may also rewrite equation 53 by expanding the convective transport term, as was done by equation 39 to obtain:

$$\frac{\partial C}{\partial t} = \frac{1}{b}\frac{\partial}{\partial x_i}\left(bD_{ij}\frac{\partial C}{\partial x_j}\right) - V_i\frac{\partial C}{\partial x_i} - \frac{C}{b}\frac{\partial (V_i b)}{\partial x_i}$$

$$- \frac{C}{b}\frac{\partial b}{\partial t} - \frac{C'W}{\varepsilon b} + \sum_{k=1}^{s} R_k \qquad (57)$$

The third, fourth, and fifth terms on the right side of equation 57 may be combined into one term as follows:

$$- \frac{C}{b} \frac{\partial (V_i b)}{\partial x_i} - \frac{C}{b} \frac{\partial b}{\partial t} - \frac{C'W}{\varepsilon b}$$

$$= \frac{C\left[- \frac{\partial (\varepsilon V_i b)}{\partial x_i} - \varepsilon \frac{\partial b}{\partial t} \right] - C'W}{\varepsilon b} \tag{58}$$

It can be shown from equations 6, 7, 9, 14, and 18 that:

$$\varepsilon V_i b = - T_{ij} \frac{\partial h}{\partial x_j} \tag{59}$$

Thus, from equation 20 we can state that:

$$- \frac{\partial}{\partial x_i} \left(\varepsilon V_i b \right) = S \frac{\partial h}{\partial t} + W \tag{60}$$

By substituting equation 60 into equation 58 we can rewrite equation 57 as:

$$\frac{\partial C}{\partial t} = \frac{1}{b} \frac{\partial}{\partial x_i} \left(b D_{ij} \frac{\partial C}{\partial x_j} \right) - V_i \frac{\partial C}{\partial x_i}$$

$$+ \frac{C \left[S \frac{\partial h}{\partial t} + W - \varepsilon \frac{\partial b}{\partial t} \right] - C'W}{\varepsilon b}$$

$$+ \sum_{k=1}^{s} R_k \tag{61}$$

For the case of a water-table aquifer we may assume:

$$S = S_y \tag{62}$$

where S_y is the specific yield of the aquifer (dimensionless). We may also assume that in the case of a water-table aquifer, the Dupuit-Forchheimer assumptions hold (Bear, 1972, p. 361-366), so that:

$$\frac{\partial b}{\partial t} = \frac{\partial h}{\partial t} \tag{63}$$

For the case of an artesian aquifer we can normally assume that:

$$\frac{\partial b}{\partial t} = 0 \tag{64}$$

If changes in saturated thickness over time and space are both negligible, equation 49 may be simplified to:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right) - V_i\frac{\partial C}{\partial x_i} + \frac{C\left(S\frac{\partial h}{\partial t} + W\right) - C'W}{\varepsilon b} + \sum_{k=1}^{s} R_k \tag{65}$$

In the case of steady-state flow, the third term on the right side of equation 65 may be simplified to:

$$\frac{C\left(S\frac{\partial h}{\partial t} + W\right) - C'W}{\varepsilon b} = \frac{W(C-C')}{\varepsilon b} \tag{66}$$

It is interesting to note that when W represents withdrawal only, then C' = C and the right side of equation 66 becomes equal to zero. Therefore, withdrawals from the aquifer produce concentration changes only indirectly through the effects of the withdrawals on the velocity field, rather than by any direct effect on the mass or concentration of solutes.

If vertical variations of head or concentration are significant, then the two-dimensional equations previously derived would not precisely describe areal solute transport. Cooley (written commun., 1976) shows that when a two-dimensional solute-transport equation is derived with a more rigorous vertical integration of the three-dimensional equation, the third dimension is not actually eliminated in converting to areal coordinates but instead is transformed to boundary conditions.

Dispersion coefficient

The solution of the solute-transport equation requires consideration of the dispersion coefficient. Because of its tensorial properties, its consideration may not appear to be straightforward. Hence, we will next consider this coefficient in more detail.

Bear (1972, p. 580-581) states that hydrodynamic dispersion is the macroscopic outcome of the actual movements of individual tracer particles through the pores and that it includes two processes. One process is mechanical dispersion, which depends upon both the flow of the fluid and the nature of the pore system through which the flow takes place. The second process is molecular and ionic diffusion, which because it depends on time, is more significant at low flow velocities. Bear (1972) further states that the separation between the two processes is artificial. In developing our model we assume for flowing ground-water systems that the definable contribution of molecular and ionic diffusion to hydrodynamic dispersion is negligible.

The relationship between the dispersion coefficient, the fluid flow, and the nature of the pore system is given in tensor notation by Scheidegger (1961, p. 3275) as:

$$D_{ij} = a_{ijmn} \frac{V_m V_n}{|V|} \tag{67}$$

where a_{ijmn} is the dispersivity of the porous medium (a fourth-order tensor), L;

V_m and V_n are the components of the flow velocity of the fluid in the m and n directions, respectively, LT^{-1}; and

$|V|$ is the magnitude of the velocity vector, LT^{-1}.

Scheidegger (1961, p. 3275) states that the dispersivity tensor possesses 81 components, but that even in the case of an anisotropic medium, symmetry properties reduce the number of components to 36. Both Scheidegger (1961) and Bear (1972) show that the dispersivity of an isotropic porous medium can be defined by two constants. These are the longitudinal dispersivity of the medium, a_L, and the transverse dispersivity of the medium a_T. For an isotropic porous medium the components of the dispersivity tensor in three dimensions ($i,j = 1,2,3$) are:

$$a_{iiii} = a_L \tag{68a}$$

$$a_{iijj} = a_T \tag{68b}$$

$$a_{iiij} = a_{iiji} = a_{ijii} = a_{ijjj} = 0 \tag{68c}$$

$$a_{ijij} = a_{ijji} = \frac{1}{2}(a_L - a_T) \tag{68d}$$

The components of the dispersion coefficient for three-dimensional flow may be stated explicitly by expanding equation 67 for a range of three on i and j. After eliminating terms with coefficients that equal zero (shown by equation 68c), we obtain:

$$D_{11} = a_{1111}\frac{V_1V_1}{|V|} + a_{1122}\frac{V_2V_2}{|V|} + a_{1133}\frac{V_3V_3}{|V|} \tag{69a}$$

$$D_{22} = a_{2211}\frac{V_1V_1}{|V|} + a_{2222}\frac{V_2V_2}{|V|} + a_{2233}\frac{V_3V_3}{|V|} \tag{69b}$$

$$D_{33} = a_{3311}\frac{V_1V_1}{|V|} + a_{3322}\frac{V_2V_2}{|V|} + a_{3333}\frac{V_3V_3}{|V|} \tag{69c}$$

$$D_{12} = D_{21} = a_{1212}\frac{V_1V_2}{|V|} + a_{1221}\frac{V_2V_1}{|V|} \tag{69d}$$

$$D_{13} = D_{31} = a_{1313}\frac{V_1V_3}{|V|} + a_{1331}\frac{V_3V_1}{|V|} \tag{69e}$$

$$D_{23} = D_{32} = a_{2323}\frac{V_2V_3}{|V|} + a_{2332}\frac{V_3V_2}{|V|} \tag{69f}$$

If we substitute the identities presented in equations 68a and b into equations 69a, b, and c, we obtain directly:

$$D_{11} = a_L\frac{V_1V_1}{|V|} + a_T\frac{V_2V_2}{|V|} + a_T\frac{V_3V_3}{|V|} \tag{70a}$$

$$D_{22} = \alpha_T \frac{V_1 V_1}{|V|} + \alpha_L \frac{V_2 V_2}{|V|} + \alpha_T \frac{V_3 V_3}{|V|} \tag{70b}$$

$$D_{33} = \alpha_T \frac{V_1 V_1}{|V|} + \alpha_T \frac{V_2 V_2}{|V|} + \alpha_L \frac{V_3 V_3}{|V|} \tag{70c}$$

Next, by substituting the identities given by equation 68d into equations 69d, e, and f, we see that:

$$D_{12} = D_{21} = (\alpha_L - \alpha_T) \frac{V_1 V_2}{|V|} \tag{71a}$$

$$D_{13} = D_{31} = (\alpha_L - \alpha_T) \frac{V_1 V_3}{|V|} \tag{71b}$$

$$D_{23} = D_{32} = (\alpha_L - \alpha_T) \frac{V_2 V_3}{|V|} \tag{71c}$$

Scheidegger (1961) and Bachmat and Bear (1964) also show that for a Cartesian coordinate system x_i in which one of the axes, say x_1, coincides with the direction of the average velocity, then $V_1 = |V|$ and $V_2 = 0$. Substituting these relations into equations 70 and 71 we obtain:

$$D_{11} = \alpha_L |V| = D_L \tag{72a}$$

$$D_{22} = D_{33} = \alpha_T |V| = D_T \tag{72b}$$

$$D_{12} = D_{21} = D_{13} = D_{31} = D_{23} = D_{32} = 0 \tag{72c}$$

where D_L and D_T are respectively the longitudinal and transverse dispersion coefficients, L^2T^{-1}

Solving equations 72a and b for α_L and α_T results in:

$$\alpha_L = \frac{D_L}{|V|} \tag{73a}$$

$$\alpha_T = \frac{D_T}{|V|} \tag{73b}$$

Introducing equations 73a and b into equations 70 and 71 produces:

$$D_{11} = D_L \frac{(V_1)^2}{|V|^2} + D_T \frac{(V_2)^2}{|V|^2} + D_T \frac{(V_3)^2}{|V|^2} \tag{74a}$$

$$D_{22} = D_T \frac{(V_1)^2}{|V|^2} + D_L \frac{(V_2)^2}{|V|^2} + D_T \frac{(V_3)^2}{|V|^2} \tag{74b}$$

$$D_{33} = D_T \frac{(V_1)^2}{|V|^2} + D_T \frac{(V_2)^2}{|V|^2} + D_L \frac{(V_3)^2}{|V|^2} \tag{74c}$$

$$D_{12} = D_{21} = (D_L - D_T) \frac{V_1 V_2}{|V|^2} \tag{74d}$$

$$D_{13} = D_{31} = (D_L - D_T) \frac{V_1 V_3}{|V|^2} \tag{74e}$$

$$D_{23} = D_{32} = (D_L - D_T) \frac{V_2 V_3}{|V|^2} \tag{74f}$$

Equation 74 defines the local transformation of D_{ij} from orthogonal axes, in which x_1 is parallel to V_1, to global cartesian axes. Note that while D_{11}, D_{22}, and D_{33} must have positive values, it is possible for the cross-product terms (equations 74d, e, and f) to have negative values.

For the case of two-dimensional flow, all components and terms in equation 74 that have a subscript 3 are eliminated.

The magnitude of the velocity, $|V|$, is defined as:

$$|V| = \sqrt{V_1^2 + V_2^2 + V_3^2} \tag{75}$$

In summary, the components of the dispersion tensor that must be evaluated for three-dimensional flow in an isotropic porous medium are:

$$D_{ij} = \begin{vmatrix} D_{11} & D_{12} & D_{13} \\ D_{21} & D_{22} & D_{23} \\ D_{31} & D_{32} & D_{33} \end{vmatrix} = \begin{vmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{vmatrix} \tag{76}$$

SUMMARY

A general equation describing the three-dimensional transport and dispersion of a reacting dissolved chemical in flowing ground water was derived nonrigorously from the principle of conservation of mass. The general equation relates concentration changes to hydrodynamic dispersion, convective transport, fluid sources and sinks, and chemical reactions.

Concentration changes caused by dispersion are assumed to be a function of both the dispersion coefficient and the concentration gradient. The dispersion coefficient is a second-order tensor and is related to the dispersivity of the porous medium and to the flow velocity of the ground water. If solute concentrations are affected by chemical reactions, specific mathematical expressions describing the rates of reactions must be incorporated into the general solute-transport equation.

Because both the dispersion coefficient and convective transport depend on the flow velocity, the solution of the solute-transport equation requires the definition of the velocity field, which in the general case requires that the flow and solute-transport equations be solved simultaneously. However, the solution of these equations can be considerably simplified if conditions of homogeneous fluid properties and (or) two-dimensional flow can be validly assumed.

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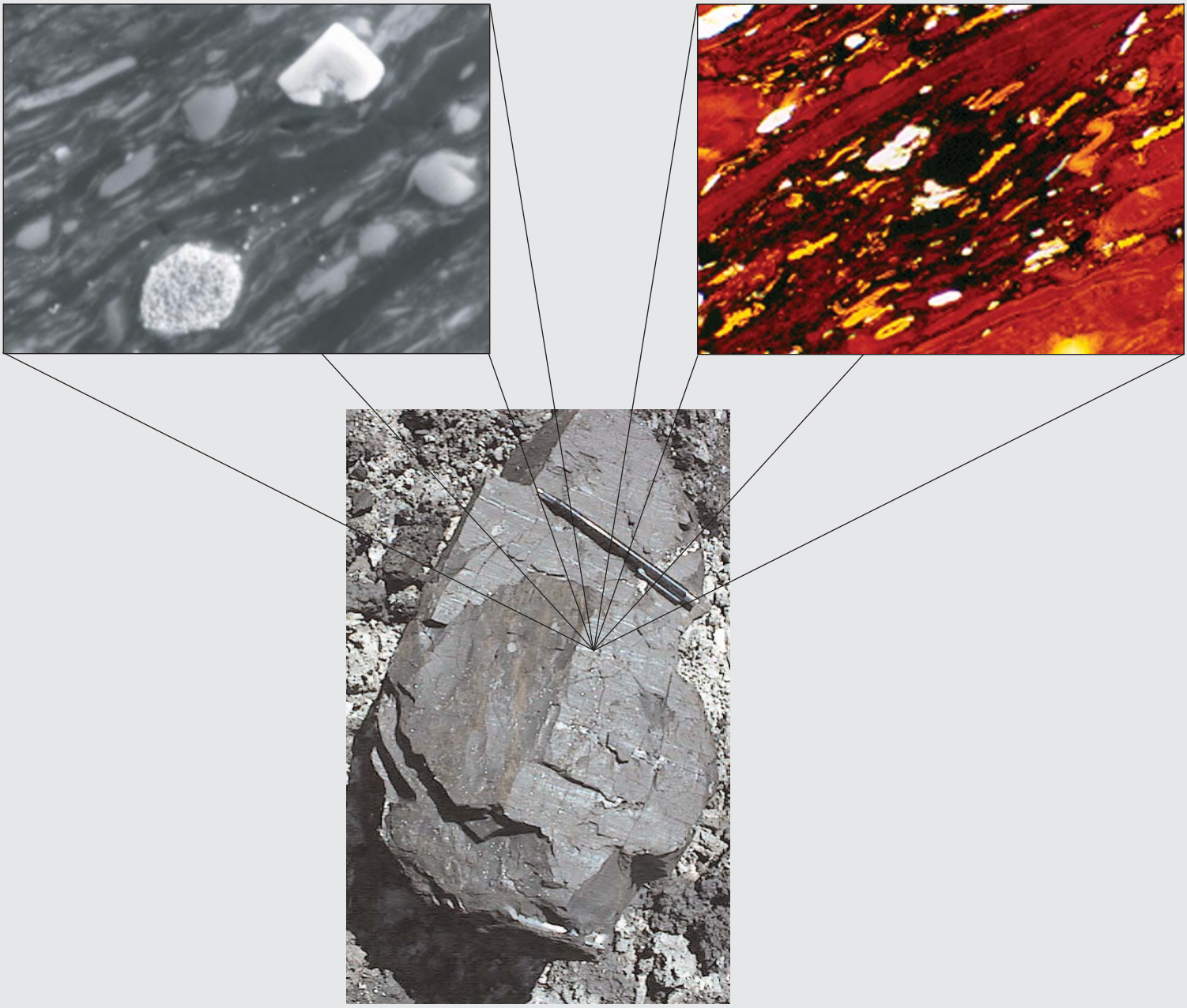
Coal—A Complex Natural Resource

An overview of factors affecting coal quality and use in the United States
With a contribution on coal quality and public health



U.S. GEOLOGICAL SURVEY CIRCULAR 1143

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science for a changing world

Cover: Chunk of Texas subbituminous coal in the field. Pen for scale. Note the very thin, light-colored laminations that indicate bedding. Top-left enlargement is an example of a scanning photomicrograph showing minerals in coal. The bright-white, oval-shaped fragment is a pyrite framboid; the bright-white triangular fragment is zircon; each fragment is about 10 microns wide. The light-colored, equant blebs are quartz grains. They are set in a light-gray matrix consisting of coal macerals and a variety of clay minerals. Top-right enlargement is an example of a transmitted-light photomicrograph showing various coal macerals (organic components) such as vitrinite (dark reddish orange); liptinite (yellow and light orange); and fusinite, inertinite, and minerals (black). View is about 200 micrometers wide.

U.S. Department of the Interior
U.S. Geological Survey

Coal—A Complex Natural Resource

An overview of factors affecting coal quality and use in the United States

By Stanley P. Schweinfurth
With a contribution on coal quality and public health by Robert B. Finkelman

U.S. GEOLOGICAL SURVEY CIRCULAR 1143

A primer on the origins and quality of coal with a brief examination of how quality affects coal use, and a separate section on coal and public health

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
CHARLES G. GROAT, Director

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FOREWORD

During the 20th century, dramatic shifts took place in the types and sources of energy consumed in the United States. The future energy mix and the technologies used in fuel combustion will be critical in determining the economic and environmental health of the Nation as we move ahead in the 21st century. Coal was a major primary energy source within the United States for all of the last century, and, currently, coal is used to generate more than 50 percent of the Nation's electric energy. Coal supplies are adequate within the United States for this century and coal is the least expensive of the fossil fuels, making it a reliable and economical source of energy. Recent studies, however, suggest that an increased use of coal may contribute to the degradation of the environment and to global warming. A thorough understanding of coal quality will lead to the development of methods to better control the harmful effects of coal use on the environment and human health.

The U.S. Geological Survey (USGS) is actively involved in research on the quality and abundance of coal, as well as on the complex geological and geochemical factors that govern coal quality. In addition, the U.S. Geological Survey gathers information on the location, size, and nature of coal deposits, which also contributes to a basic understanding of the Nation's energy resources. This research is pertinent to discussions of future energy resources, global warming, and the dependence of the Nation on imported fossil fuels—all of which are concerns that are being faced daily at local, State, and National levels. Understanding the nature of coal quality is important for two critical issues facing our Nation—the economy and the environment.

The wise use of our Nation's resources and the careful stewardship of our public lands depend on the dissemination of accurate and timely earth science information. The U.S. Geological Survey is proud to present this report on one of the major issues to be addressed in the future use of coal.

Charles G. Groat
Director

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Coal—A Complex Natural Resource

An overview of of factors affecting coal quality and use in the United States

By Stanley P. Schweinfurth

INTRODUCTION

Coal is abundant in the U.S., is relatively inexpensive, and is an excellent source of energy and byproduct raw materials. Because of these factors, domestic coal is the primary source of fuel for electric power plants in the U.S., and will continue to be well into the 21st century. In addition, other U.S. industries continue to use coal for fuel and coke production and there is a large overseas market for high-quality American coal.

Because humans have used coal for centuries, much is known about it. The usefulness of coal as a heat source and the myriad of byproducts that can be produced from coal are well understood. The continued and increasingly large-scale use of coal in the United States and in many other industrialized and developing nations has resulted in known and anticipated hazards to environmental quality and human health. As a result, there is still much to be learned about the harmful attributes of coal and how they may be removed, modified, or avoided to make coal use less harmful to humans and nature. These issues of coal quality have not been examined carefully until recently.

Some of the problems that accompany the mining and use of coal are well known. Acid mine drainage results when coal beds and surrounding strata containing medium to high amounts of sulfur, in the form of compounds known as sulfides, are disrupted by mining, thereby exposing the sulfides to air and water. Atmospheric sulfur oxides (SO_x) and subsequent acid deposition (such as acid rain) result from the burning of medium- to high-sulfur coal. The quality of surface and ground water may be affected adversely by the disposal of the ash and sludge that result from the burning of coal and cleaning of flue gases. These are some of the serious problems requiring either improved or new remedies. Other environmental problems are associated with emissions of carbon dioxide (CO_2) and nitrogen oxides (NO_x), two of the so-called "greenhouse gases." These emissions are often attributed to coal use only; however, they also result from the burning of any fossil or biomass fuel, such as wood, natural gas, gasoline, and heating oil. The greenhouse gas problem requires a broader solution than just reducing the use of coal. Research currently is being conducted in the U.S. and several other countries into the reduction and disposal of CO_2 from coal combustion. An excellent review of the results of this research and the prospects for coal can be found in a publication of IEA Coal Research (1999).

Fluidized-bed combustion (FBC) of coal, which is a new method for controlling sulfur emissions, is gaining wide acceptance. In this system, finely ground coal is mixed with finely ground limestone. Both are fed together into a furnace in a constant stream onto a horizontally moving grate. Air is forced up through the grate and the entire mass is ignited at relatively low temperatures. The forced air causes the ground coal and limestone to be mixed with the hot gases of combustion, which in turn promotes the conversion of any SO_x to gypsum as the burning mass moves along on the grate. According to the U.S. Department of Energy (2000), high-sulfur coal may be burned in this way while simultaneously capturing up to 95 percent of the SO_x and most of the NO_x emitted.

Reduction and disposal of CO_2 emissions is the subject of current research in the U.S. and several other countries.

The Clean Air Act Amendments of 1990 (Public Law 101-549) required the U.S. Environmental Protection Agency (EPA) to conduct studies of 15 trace elements released by the burning of coal to determine if they present health hazards. These 15 elements (antimony, arsenic, beryllium, cadmium, chlorine, chromium, cobalt, lead, manganese, mercury, nickel, potassium, selenium, thorium, and uranium), along with many other potentially hazardous substances released into the air by other industries, are termed "hazardous air pollutants" (HAPs).

On the basis of epidemiological studies, the EPA concluded that, with the possible exception of mercury, there is no compelling evidence to indicate that trace-element emissions from coal-burning power plants cause human health problems (U.S. Environmental Protection Agency, 1996). In December 2000, after extensive study, the EPA announced a

finding that regulation of mercury emissions from coal-fired power plants is necessary and appropriate because coal-fired power plants are the largest unregulated source of manmade emissions of mercury in the U.S. (U.S. Environmental Protection Agency, 2000).

EPA will propose regulations to limit mercury emissions in 2003 and will issue final emissions rules by 2004. Meanwhile, arsenic is still under study, not as an emissions problem from coal combustion, but for its potential role as a hazard in ground water if it is leached from coal-mining waste or from fly ash in disposal sites. Additional coal-quality research on both mercury and arsenic is being conducted at the U.S. Geological Survey (USGS) and elsewhere in order to (1) help identify their sources in coal, and (2) help resolve any remaining potential hazards issues with regard to these two elements.

In 1996, the EPA said that, of the potential HAPs from coal combustion, only mercury and arsenic needed additional study. In 2000, EPA determined that mercury emissions require regulation.

Other problems that may arise from the use of coal are not necessarily harmful to the environment or human health, but affect the use and efficiency of coal-burning equipment. For example, certain constituents in coal may cause severe erosion and corrosion of, or the buildup of mineral deposits on, furnace and boiler parts. These effects greatly reduce the efficiency and life expectancy of furnaces or boilers; as a result, costly repairs are often required.

Thus far, coal has been discussed as if it were a single homogeneous material, but this is done only for convenience in this report. In fact, a wide variety of coal types exists, depending on differing proportions and combinations of organic and inorganic (mineral) components, sulfur, and ash. For example, sulfur content may range from low (less than 1 percent), through medium (1 to 3 percent), to high (greater than 3 percent), and ash yields may range from a low of about 3 percent to a high of 49 percent (if ash yields are 50 percent or greater, the substance is no longer called coal). Coal may produce high or low amounts of energy, or contain high or low amounts of the substances that produce organic chemicals and synthetic fuels, or contain higher or lower amounts of the elements that are considered to be hazardous air pollutants (HAPs). This range in properties results from coal's diverse origins, including the long and complex geologic histories of coal deposits.

The purpose of this report is to acquaint students, non-coal scientists, and the general public with some basic information on (1) the subject of coal quality and the reasons why it is so complex, (2) methods for determining coal quality, and (3) the need for continuing studies of this complex subject. A discussion on the origins of coal is included in order to provide a framework for understanding coal's complex nature. See the section on "Further Reading" for a bibliography on coal quality and other topics (such as coal mining, uses for coal, or health effects of coal use).

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Grateful acknowledgment is extended to the following scientists and technicians without whose contributions and careful reviews this report would not have been possible: Philip J. Aruscavage, Linda J. Bragg, M. Devereux Carter, William A. DiMichele, Frank T. Dulong, Robert B. Finkelman, Romeo M. Flores, Harold J. Gluskoter, Joseph R. Hatch, Robert G. Johnson, Rustu S. Kalyoncu, Elizabeth D. Koozmin, Ronald J. Litwin, Paul C. Lyons, Peter J. McCabe, Eric A. Morrissey, Charles L. Oman, William H. Orem, Curtis A. Palmer, Tom A. Phillips, Eleanora I. Robbins, Leslie F. Ruppert, Ronald W. Stanton, Frank G. Walthall, Peter D. Warwick, William D. Watson, Jason C. Willett, Christopher Wnuk, and Chris J. Zygarlicke.

SPECIAL ACKNOWLEDGMENT

A special acknowledgment is included in remembrance of the late Ronald W. Stanton, a U.S. Geological Survey geologist and coal scientist. Ron's belief in the value of a report that would make the mysteries of coal quality more accessible to the public, and his encouragement and physical support during its preparation, were essential to the completion of this circular.

COAL IN THE UNITED STATES

A discussion of coal use in the U.S. and of the beneficial things that come from coal is necessary in order to provide the reader with a better understanding of the importance of coal quality and the need for continuing research on coal quality.

COAL PRODUCTION AND CONSUMPTION

Coal use in the U.S. began around two thousand years ago. Early inhabitants of this continent probably gathered coal from outcroppings, beaches, and streambeds. Coal

mining by European-Americans began in the Richmond basin of Virginia between 1720 and 1750. The Richmond area is known to have furnished coal during the American Revolution. Between 1750 and 1800, coal was discovered in many parts of the northern and southern Appalachian basin. As the population moved westward after the American Revolution, coal deposits were discovered, progressively, in the midcontinent (including Texas), the Rocky Mountains region, the Colorado Plateau, and the northern Great Plains. The first coal in the West was found along the Missouri River in 1804 by the explorers Meriwether Lewis and George Rogers Clark (Collier's Encyclopedia, 1960).

In the U.S., coal is used to produce approximately 56 percent of the annual electricity requirement; 90 percent of the coal produced is used for this purpose.

After 1830, with the beginning of the railroads, the real growth of the coal industry began. The railroads not only used coal, they also provided the means to transport coal, which encouraged the growth of energy-intensive industries. The growth of the railroads also encouraged the expansion of the iron and steel industry, which, by the 1860s, had abandoned charcoal in favor of coke for the reduction of iron ore to pig iron. In the 1880s, after the invention of electric turbines, coal soon became the principle energy source for steam-generated electricity. For a much more detailed account of the early days of coal discovery and use in the U.S., see Eavenson (1942).

By 1918, industry in the U.S. depended almost entirely on coal. During World War II, demand for coal drove coal production to record highs, but shortly thereafter, petroleum replaced coal as our chief source of energy. For about a decade following World War II, most of the decline in coal use was due to the replacement of coal-burning railroad engines with diesel engines. In the 1960s, coal production and consumption began to rise due to an increasing demand for electricity, and has risen ever since. In 1961, the U.S. produced 420.4 million tons (1 ton=2000 pounds) and used 390.4 million tons for domestic purposes; in 1998, production was 1,118.7 million tons and domestic use in 1999 was 1,045.2 million tons (figs. 1, 2) (Energy Information Administration, 2000).

The difference between the amounts of coal produced and used in the U.S. is accounted for mainly by exports. Revenue from coal exports helps reduce the deficit in the balance of payments the U.S. makes to its foreign suppliers of consumer goods. In 1998, coal exports of 78 million tons earned approximately $2.9 billion (Energy Information Administration, 1999b).

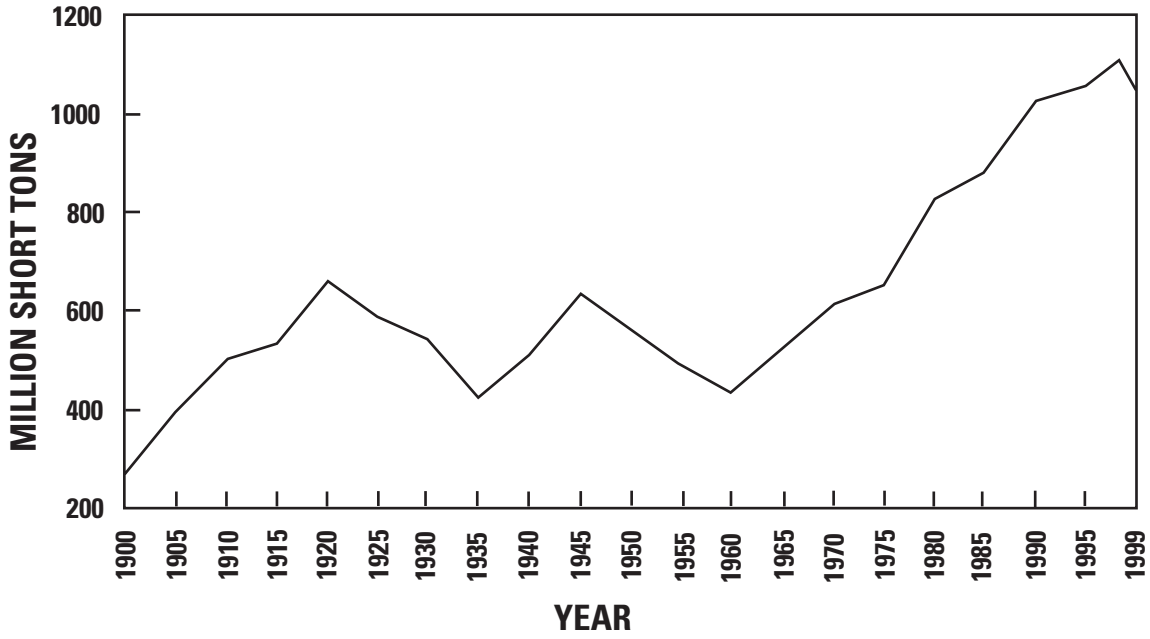


Figure 1. Graph showing trends in U.S. coal production from 1900 to 1999. The rapid growth in production after 1960 is attributed to (1) abundant reserves, (2) high productivity resulting in favorable prices for coal, and (3) the large increase in demand for electricity. Data from Energy Information Administration (2000).

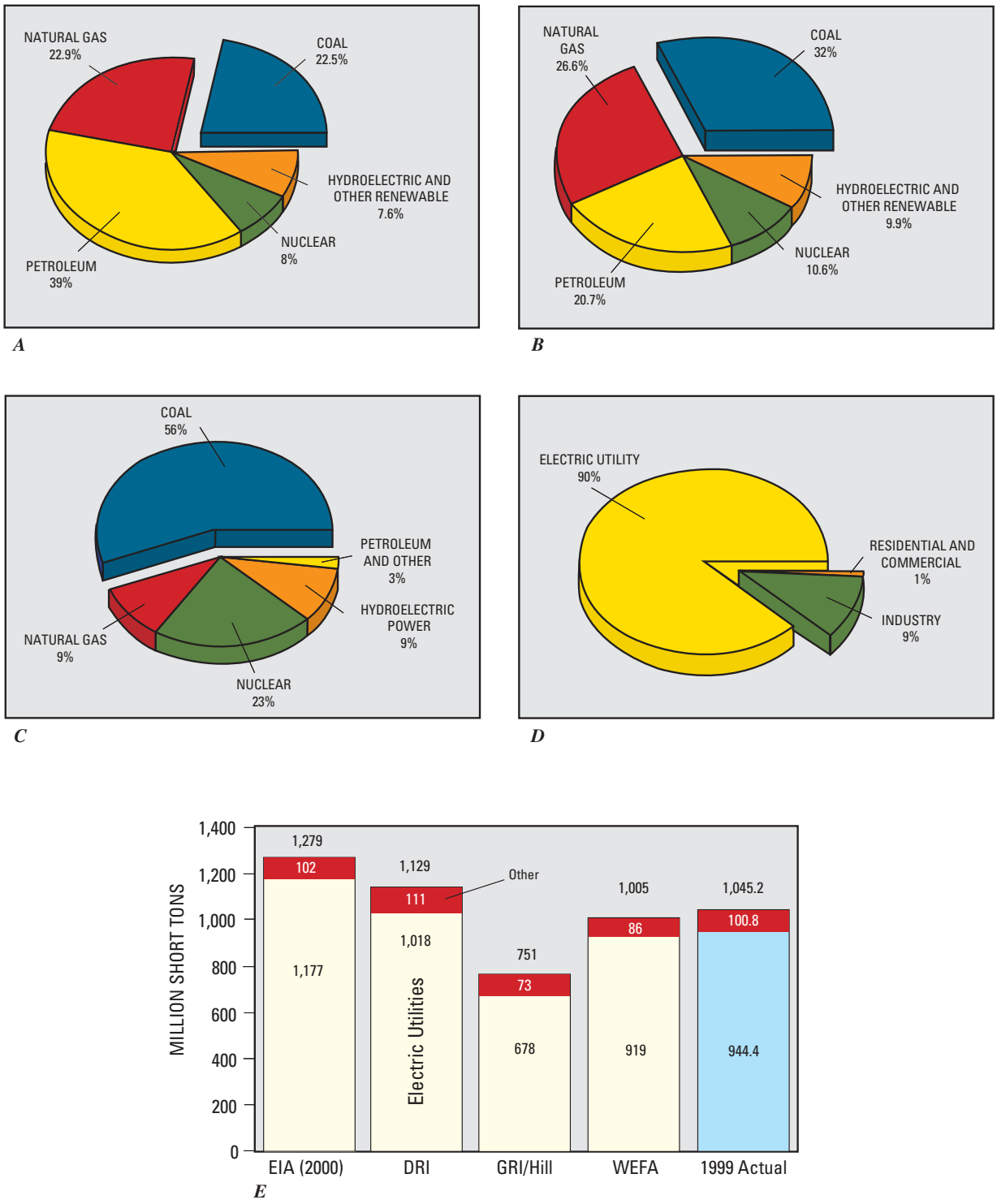


Figure 2. Diagrams showing energy consumption and production in the U.S. ***A***, Energy consumption in 1999. Of the various commodities consumed, approximately 54 percent of the oil and 16 percent of the natural gas are imported; the coal and other commodities are almost entirely domestic. ***B***, Energy production in 1999. ***C***, Electricity generated in 1999, by all commodities. ***D***, Coal consumption in 1999 by the economic sectors shown. ***E***, Forecasted coal consumption for 2020 by electric utilities (yellow) and other uses (red). The basis for comparison of commodities in diagrams *A*, *B*, and *C* is quadrillion Btu, or "quads." Total quads produced and consumed in 1999, were, respectively, 72.5 and 96.6. The basis for diagrams *D* and *E* is million short tons. EIA, Energy Information Administration; DRI, Standard & Poor's Data Resources Inc.; GRI/Hill, Gas Research Institute; WEFA, The WEFA Group. Data from Energy Information Administration (1999a, 2000).

Figure 3. Photograph of the Navajo power plant, which is a coal-fired, electric-power-generation plant near Page, Ariz. Photograph by J.C. Willett (U.S. Geological Survey).

According to the Energy Information Administration (2000), approximately 1,099.1 million tons of coal were produced in 1999 (slightly less than in 1998) and 1,045.2 million tons were used domestically (slightly more than in 1998). The differences in production and consumption between 1998 and 1999 were due to a reduction in exports of 20 million tons in 1999. Of the total coal used domestically in 1999, 90 percent (944.4 million tons) was used to fuel electric power plants (fig. 3), which produced 56 percent of the electricity in the U.S. The other 10 percent was used in industrial (coke and heating), residential, and commercial applications (fig. 2).

COAL PRICES

Steady improvements in the efficiency of coal mining in the U.S. have kept coal prices low. In 1998, the average price of a ton of coal at the mine was $17.67; the average price of a ton of coal delivered to electric utilities was $25.64 (Energy Information Administration, 2000). Prices in 1986 of $23.99 and $33.30 per ton, respectively, demonstrate this trend. Furthermore, over the last decade, coal has been the least expensive of the three main fuel sources—coal, natural gas, and petroleum—in the U.S. On the basis of a common unit of heat (million Btu) over the ten-year period, coal prices averaged about $0.91 at the mine; natural gas averaged $1.72 at the wellhead; and crude oil averaged $2.70 at the domestic first point of purchase (Energy Information Administration, 2000). Lower prices probably encourage continued high and (probably) increasing levels of coal use in the U.S.

In 1999, the Energy Information Administration (EIA) forecasted that, by the year 2020, average coal prices would decrease further to approximately $20.01 per ton delivered to electric power plants (in 1998 dollars). Coal production is forecast by the EIA (fig. 2) to grow to approximately 1,300 million tons by 2020, of which domestic use will account for 1,279 million tons; of that amount, 1,177 million tons will be used by electric power plants. These figures indicate a rate of growth of approximately one percent per year for both coal production and power plant use. Other domestic uses of coal are forecast by the EIA to remain about the same by 2020 (Energy Information Administration, 2000).

COAL SUPPLY

Although coal deposits are widely distributed throughout the U.S., the bulk of coal mining and consumption remained, until recently, in the eastern part of the country, mostly in the Appalachian basin. This was due to the concentration of population and industry in the East. Coal production recently has been moving to the Western States because the bulk of the remaining resources of low-sulfur coal are located in the Rocky Mountains and northern Great Plains regions. The demand for low-sulfur coal is based on the Clean Air Act Amendments of 1990, which began implementation in 2000. The new regulations limit SO_x emissions from coal-fired power plants to 1.2 lbs per million Btu. Power-plant managers are finding that converting their coal supplies from medium- and high-sulfur coal to low-sulfur coal, rather than installing flue-gas desulfurization (FGD) systems, generally is the least expensive option for achieving the required level of SO_x emissions (U.S. Geological Survey, 2000). There are reserves of low-sulfur coal remaining in the Appalachian basin, but most of the remaining reserves occur at depths requiring costlier underground mining methods to recover them.

Whether or not substantially more coal is used in the future than presently, coal is abundant enough in the U.S. to supply anticipated requirements for much of the 21st century. In 1999, the National Mining Association (NMA) reported that 30 of the largest coal companies in the U.S. have

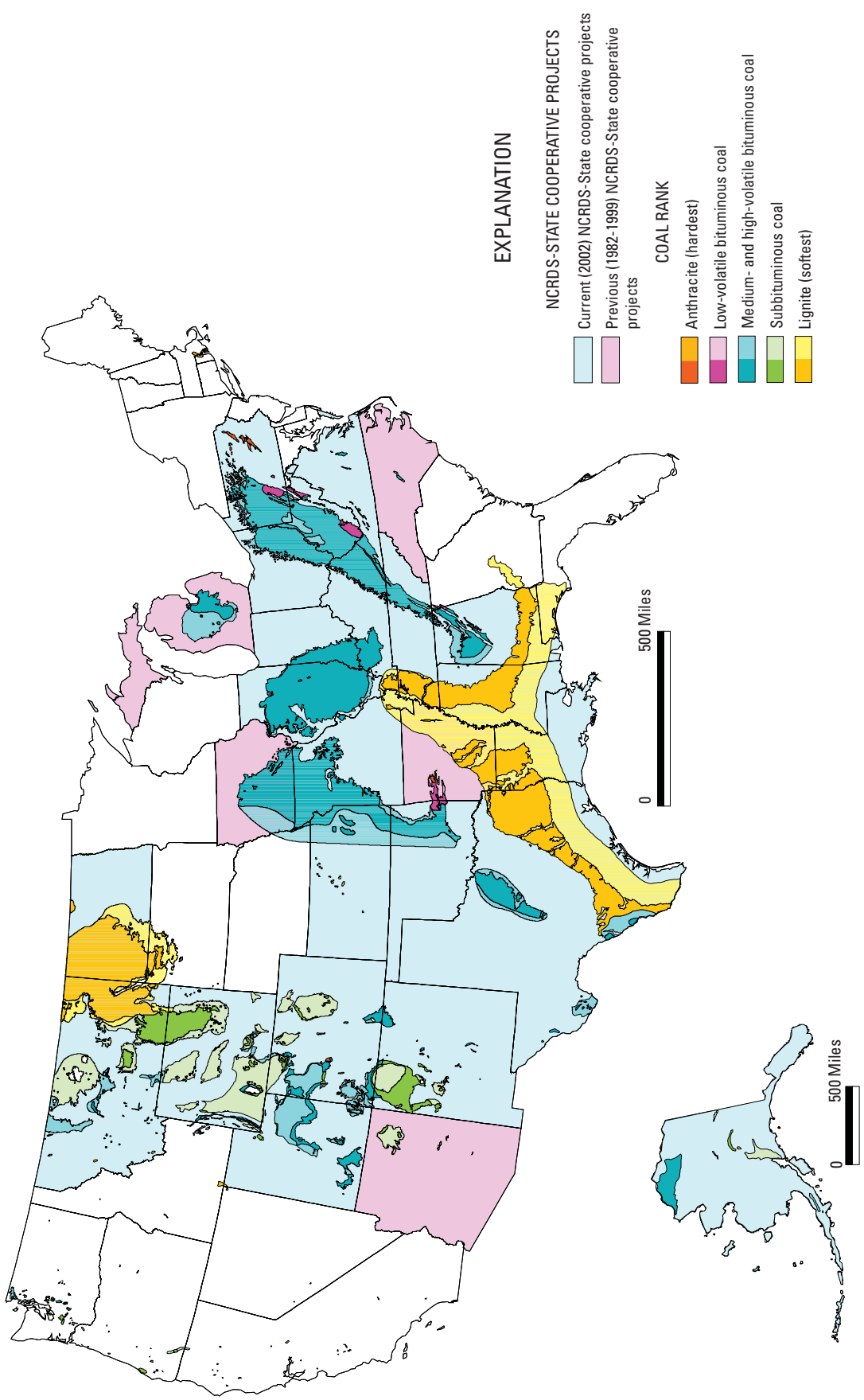


Figure 4. Map showing coal fields of the U.S. classified by coal rank and areas of cooperative study of coal resources and quality. For each category of coal rank, darker color indicates area of coal outcroppings and lighter color indicates area of subsurface coal. Also shown are States with long-term, current (light blue) or previous (light pink) cooperative relationships with the U.S. Geological Survey in the National Coal Resources Data System (NCRDS) for the long-term study of coal resources and quality. Modified from Tully (1996) and M.D. Carter (U.S. Geological Survey, written commun., 2002). (Some States contain coal fields that are too small to show rank colors.)

approximately 68 billion tons of coal in reserve (National Mining Association, 1999). In addition, numerous small coal-mining companies have reserves that are not included in the NMA's report, and there are additional coal deposits that could be mined, when and if needed.

In order to estimate the abundance of coal in beds and zones that will provide the largest percentage of the Nation's domestic energy production for the next 50 years, the USGS, in cooperation with the geological surveys of the major coal-producing States (Arizona, Colorado, Illinois, Indiana, Kentucky, Maryland, Missouri, Montana, New Mexico, North Dakota, Ohio, Pennsylvania, Tennessee, Texas, Utah, Virginia, West Virginia, and Wyoming) is in the midst of a basinwide reassessment of the coal resources of the U.S. (U.S. Geological Survey, 1996, 2000). Figure 4 shows the general distribution of coal deposits in the U.S. Results of the assessment for the Northern Rocky Mountains and Great Plains region, which includes selected coal beds of the Greater Green River, Hanna-Carbon, Powder River, and Williston basins; the Colorado Plateau; and the northern and central Appalachian Basin coal regions are available in CD-ROM format (Fort Union Coal Assessment Team, 1999; Kirschbaum and others, 2000; Northern and Central Appalachian Basin Coal Regions Assessment Team, 2001).

The USGS also is leading a cooperative program with some of the same States to assess the actual availability and recoverability of coal in areas smaller than basins. This study takes into account the many restrictions on mining imposed by environmental and land-use regulations and by the physical constraints based on geology and mining practices (Eggleston and others, 1990). For additional information on coal resources, please see the "Coal Resources" subsection of the "Further Reading" section.

COAL BYPRODUCTS

Coal—that black, dusty rock that evokes punishment of bad children at holiday times—is actually a very remarkable and rewarding material. In addition to providing heat to generate electricity (which is currently the primary use of coal), a myriad of other beneficial substances are derived from coal. Perhaps the best known of these substances is coke, which is used in the steel industry to separate iron from its ore. Coal is used in the production of other, perhaps unexpected products such as pharmaceuticals, textile dyes, food and wood preservatives, and other simple or highly complex chemicals (see centerfold). These chemicals typically are produced during the production of coke by a process called destructive distillation. In this process, coal is packed into a closed, oxygen-restricted container (retort, or coke oven) and then heated to a high temperature. This process drives off the volatile matter in the coal. The volatile matter contains the parent compounds that are used to produce the products shown in the centerfold. The lack of oxygen in the retort prevents the chemicals from completely burning.

In the past, large quantities of an impure gas containing methane and carbon monoxide (called town gas or water gas) were derived from coal in the U.S. and elsewhere. Water gas was used for heating and cooking, but has been replaced largely by natural gas in the U.S. since the 1940s. In other parts of the world, notably in Germany during World War II and in South Africa today, gasoline and heating oil have been derived from coal. Currently, research is being conducted in the U.S. to improve the techniques and economics of producing both gas and oil (called "synfuels") from coal. This work is sponsored by the U.S. Department of Energy and involves numerous private, industrial, and academic organizations (U.S. Department of Energy, 2000).

Coal is more than just a fuel source; it contains complex tars, oils, and gases that can be broken down into many useful products such as dyes,

Coal combustion products (CCPs), consisting of fly ash, bottom ash, boiler slag, and flue-gas-desulfurization (FGD) material, also have become important in the economy. As coal burns, it emits sulfur in the form of sulfur oxide. FGD is the process by which a chemical, such as calcium carbonate ($CaCO_3$), is injected into the flue-gas stream to trap the sulfur by combining with it to produce gypsum ($CaSO_4$). Gypsum is heavy and falls to the bottom of the FGD unit as sludge in a wet process, or as a powder in a dry process.

According to the USGS (Kalyoncu, 1999), approximately 57.2 million tons of fly ash, 15.2 million tons of bottom ash, 2.7 million tons of boiler slag, and 22.7 million tons of FGD material were produced in 1998. The amounts of each CCP that were used in 1998 were (in percent) 33.6, 31.3, 80.1, and 10, respectively; the rest was disposed of in landfills, settling ponds, or by other means. Coal fly ash is used mainly as an additive in concrete; fly ash may also be used as structural fill, as road base material, in waste stabilization, or in mining applications. Bottom ash is used mainly as road base and structural fill material as well as in concrete and as grit for snow and ice control. Boiler slag is used mostly in blasting grit and roofing granules. FGD gypsum is used mainly in wallboard, with small amounts being used in concrete and agricultural applications. Figure 5 shows photographs of examples of some uses for fly ash and FGD gypsum.

There are other, perhaps less well known products that can be derived from coal. For example, sulfur oxides can be captured from flue gas and used to make sulfuric acid,

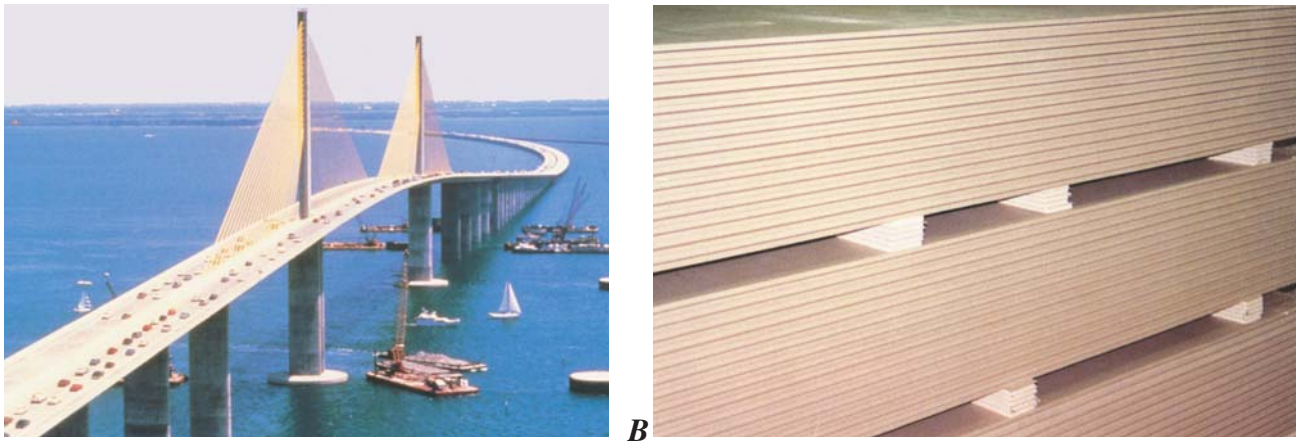


Figure 5. Photographs showing examples of the uses for coal combustion byproducts. ***A***, Fly-ash concrete was used in the decking and piers of the Sunshine Skyway bridge over Tampa Bay in Florida. ***B***, The gypsum produced by wet scrubbers was used in the manufacture of high-quality wallboard. Photographs from American Coal Ash Association (1998), used with permission.

Figure 6. Photograph of the Okefenokee Swamp, Ga., which is a modern peat-forming swamp. Modern swamps are studied as possible analogs of ancient environments in which coal beds formed. The tall trees are mostly bald cypress with some bay and black gum, the foreground is mostly sedge and reed-like plants, and the open-water areas contain water lilies. Common characteristics that modern swamps share with ancient swamps include low topography, fresh water, and varying climate. Photograph by W.H. Orem (U.S. Geological Survey).

which is an important industrial raw material. Other valuable elements, such as mercury and chlorine, also can be recovered from flue gas (Finkelman and Brown, 1991).

WHAT IS COAL?

ORIGINS

Coal begins as peat, which consists of loosely consolidated layers of various mixtures of plant and mineral matter. Peat accumulates in wetlands called "peat swamps," "bogs," or "mires." In this report, the term "peat swamp" is used to indicate a peat-forming wetland. Figure 6 is a photograph of the Okefenokee Swamp, which is a modern swamp where peat is forming. Peat swamps are wetlands that have the appropriate conditions for peat accumulation, such as abundant moisture, a stable to slowly sinking land surface, and protection from rapidly eroding forces such as rivers and ocean waves.

Over millions of years, burial, compression by overlying inorganic sediments, and the effects of heat (from depth in the earth or proximity to volcanic sources) cause peat to change to coal (fig. 7). The resultant coal is an extremely complex, mostly organic, generally well bedded sedimenta-

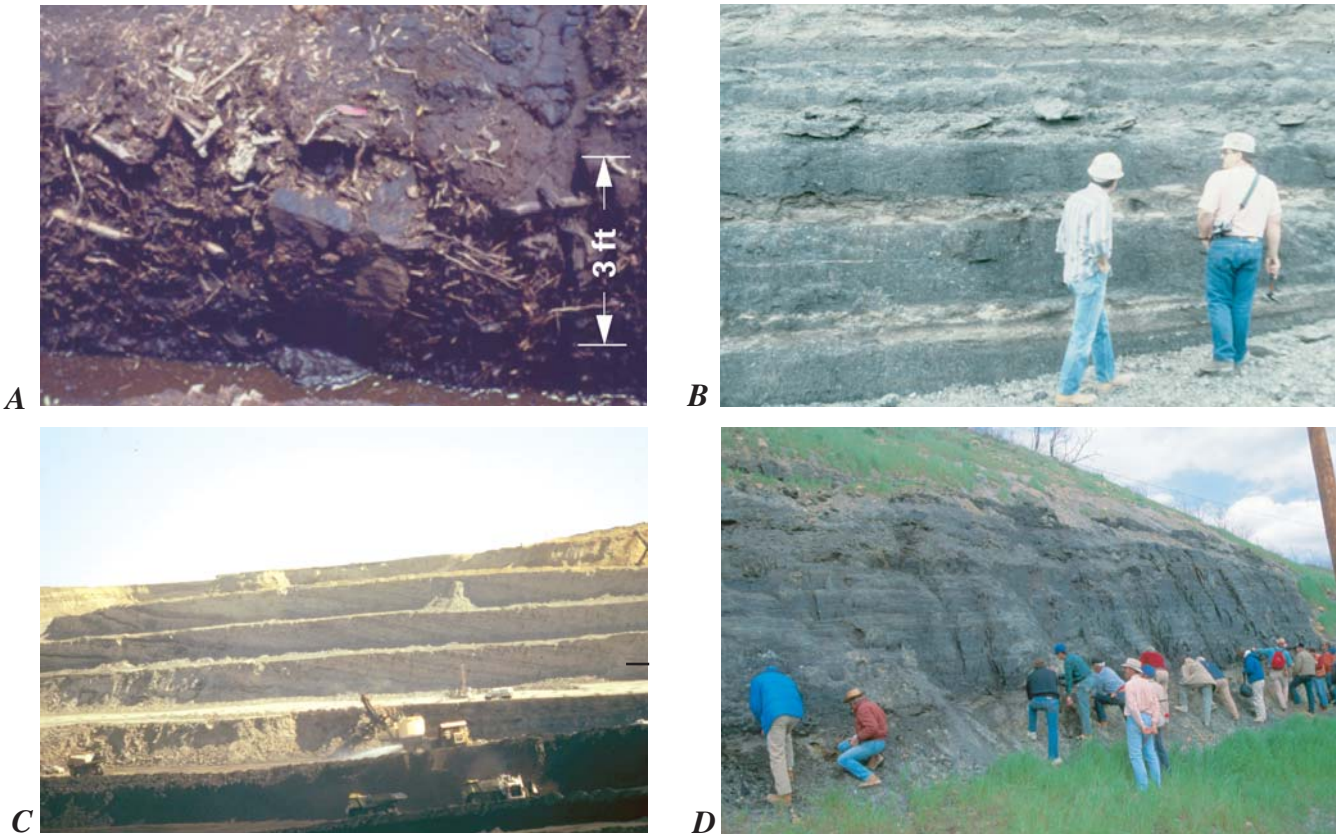


Figure 7. Photographs showing examples of peat and coal beds. ***A***, Peat bed in Indonesia. The face is approximately 3 ft high. Note heterogeneous plant material in a finer groundmass of peat. At this location, the peat bed is approximately 20 ft thick and 5,000 yrs old at the base. Photograph by S.G. Neuzil (U.S. Geological Survey). ***B***, San Miguel lignite beds of Eocene age in a coal strip mine in Texas. The individual beds of lignite (dark) are interspersed with beds of volcanic ash (lighter). The original peat has been compressed into a relatively homogeneous, evenly bedded material, but it still has a dull luster. Photograph by P.D. Warwick (U.S. Geological Survey). ***C***, Subbituminous coal strip mine in the Paleocene Anderson-Wyodak coal zone, Powder River basin, Wyoming. This bed is approximately 100 ft thick at this location, and is divided into two 50-ft-thick sections by the light-colored sedimentary rock parting above the power shovel. Photograph by P.D. Warwick (U.S. Geological Survey). ***D***, Roadcut exposing the bituminous Pennsylvanian Pittsburgh coal bed, near Morgantown, W. Va. The normal lustrous, black appearance of this coal has been dulled by exposure to the weather. Photograph by C.B. Cecil (U.S. Geological Survey).

ry rock. To be classified as coal, the rock must contain less than 50 percent ash-forming mineral matter. If it contains between 30 and 50 percent mineral matter, it is classified as impure coal.

In the U.S., individual coal beds may be as thin as a few inches or (rarely) as thick as 200 ft and may cover areas as small as a few square yards or as large as several counties or even States; for example, the Pittsburgh coal bed extends over all or parts of 25 counties in the area where Ohio, Pennsylvania, and West Virginia join (see fig. 4). Figure 8 shows two examples from the Powder River basin in Wyoming of peat deposits in relation to laterally and vertically bounding sediments deposited by rivers. The deposits were subsequently buried and coverted to lignite and coal.

COMPOSITION

Coal is composed of complex mixtures of organic and inorganic compounds. The organic compounds, inherited from the plants that live and die in the swamps, number in the millions. The approximately more than 120 inorganic compounds in coal either were introduced into the swamp from waterborne or windborne sediment, or were derived from elements in the original vegetation; for instance, inorganic compounds containing such elements as iron and zinc are needed by plants for healthy growth. After the plants decompose, the inorganic compounds remain in the resulting peat. Some of those elements combine to form discrete

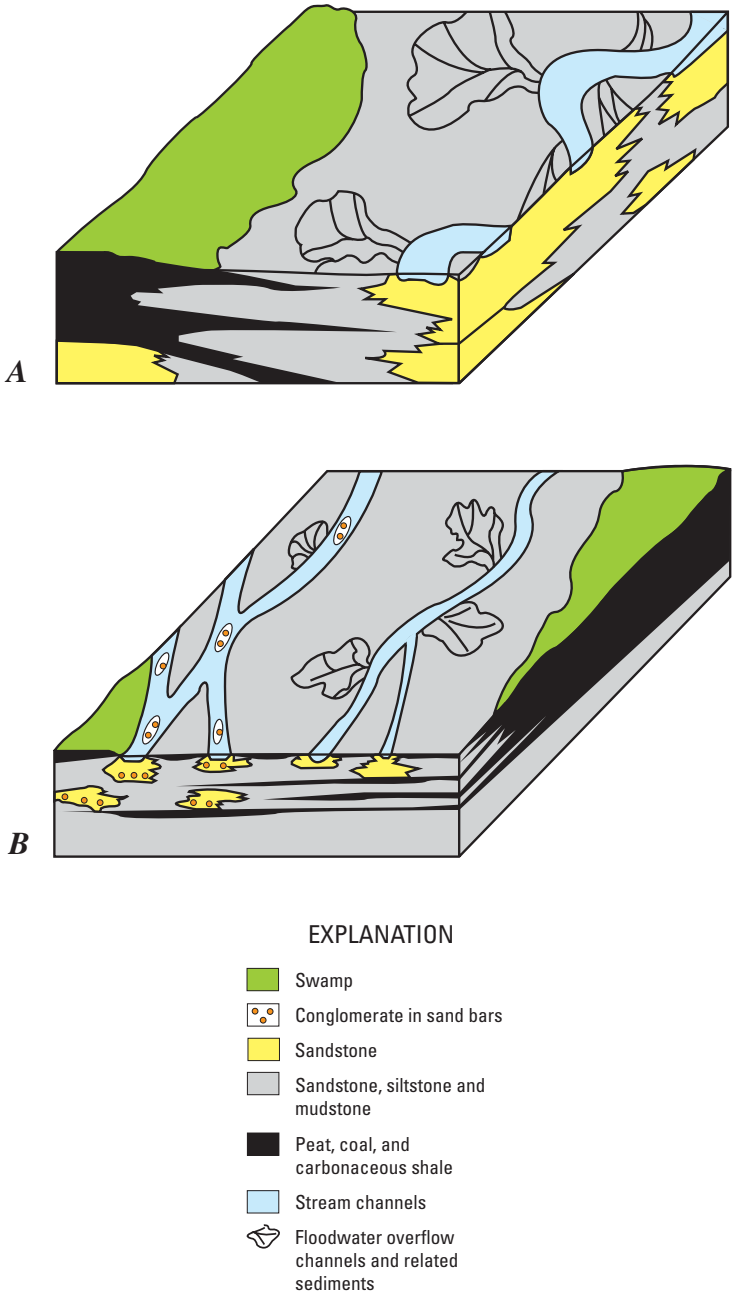


Figure 8. Block-diagram models illustrating some of the peat-sediment-climate relationships possible in the process of peat development and burial. These models explain the environments of deposition for two large coal deposits of Paleocene age in the Powder River basin of Wyoming. No specific scale implied, but the blocks represent general areas of approximately 9 to 25 mi^2, and depths of approximately 50 to 100 ft. ***A***, Decker-Tongue River area. This peat deposit developed continuously in the same place because low areas, formed by faulting or compaction of underlying sediments, may have restricted the location of a meandering stream to the edge of the peat deposit. Also, the river system may have had a somewhat restricted sediment supply, or the river system may not have been vigorous enough to invade the peat swamp except at the margin. The climate probably was wet most of the year because the peat surface in the model is shown to be higher than the surface of the stream valley. A wet climate promotes vigorous plant growth on top of the peat, which holds water like a sponge, allowing the peat to pile up above the surrounding area. The result is a large, thick, clean, coal deposit. ***B***, Kaycee-Linch area. In this case, the river system apparently had a coarser and more abundant sediment supply and was more vigorous than in part *A*, as shown by the conglomerate bars in some of the stream channels, which are a sign of stronger current flow. This river system was able to move back and forth across the peat swamps, limiting the resulting deposits, in part, to thin, discontinuous beds. This environment appears also to have been wet, but a better supply of sediment and stronger stream flows limited peat preservation. Modified from Flores and others (1989), used with permission of the American Geophysical Union.

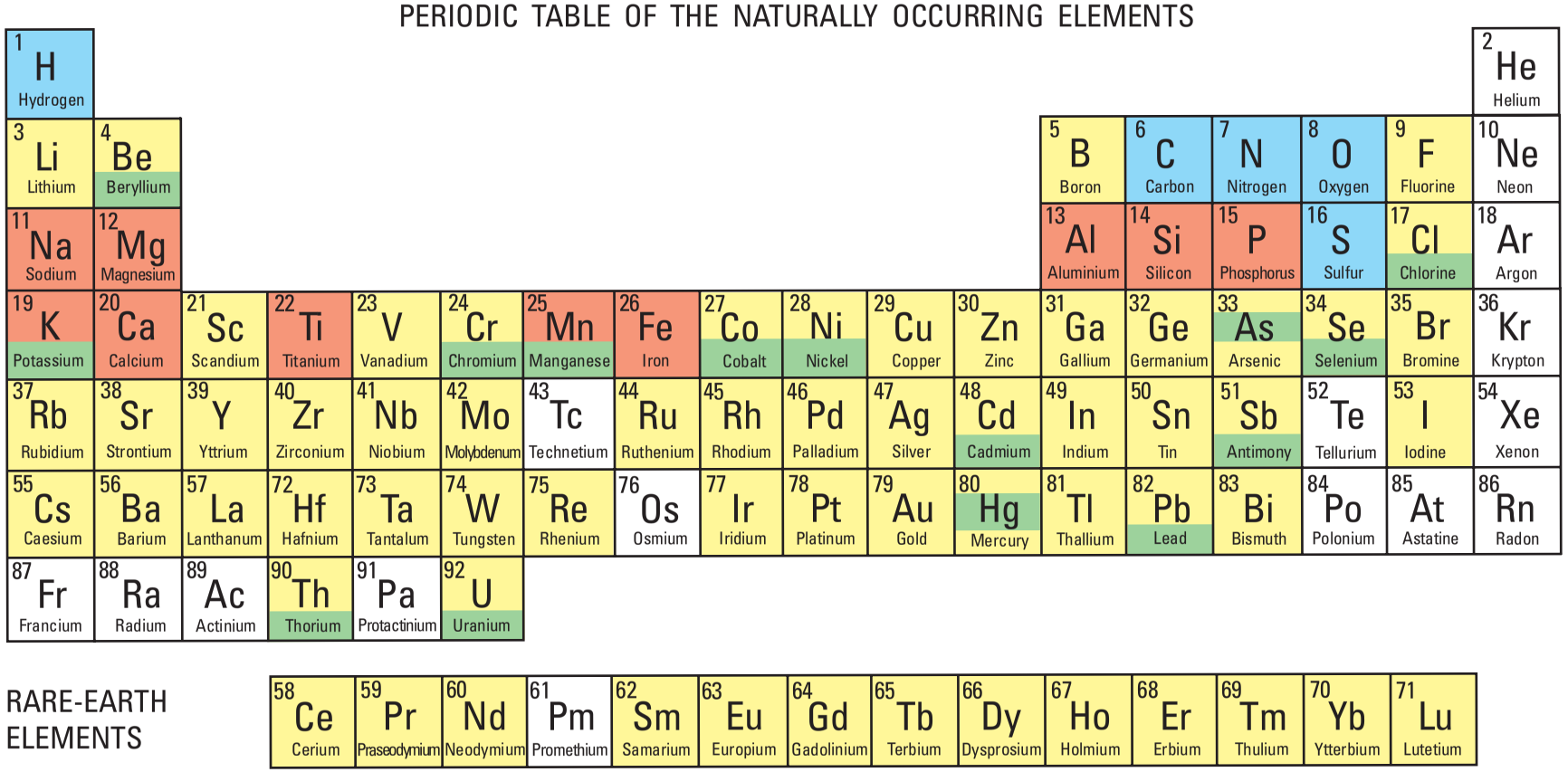


Figure 9. Periodic table of the elements. The 76 elements found in coal are highlighted by colors with regard to their general abundance in coal, as follows: blue, major elements (generally greater than 1.0 percent in abundance); red, minor elements (generally greater than or equal to 0.01 percent); and yellow, trace elements (generally less than 0.001 percent). Pursuant to the Clean Air Act Amendments of 1990 (Public Law 101-549), the U.S. Environmental Protection Agency (EPA) studied fifteen of these elements as potentially hazardous air pollutants (HAPs); green bars in their boxes indicate those fifteen elements. Thirteen of the original were cleared when the EPA found that there was no compelling evidence that they cause human health problems; a green bar across the bottom of the box indicates those elements. Two elements from the original fifteen, mercury (Hg) and arsenic (As), indicated by a green bar across the centers of their boxes, are still under study—mercury as a HAP and arsenic as a potential pollutant in ground water that flows through fly-ash and coal-mine spoil piles. Subsequently, in December 2000, EPA found that mercury emissions from coal-fired power plants require regulation; EPA will propose regulations in 2003 and issue final rules in 2004. Modified from Periodic Table of the Elements (Sargent-Welch Scientific Company, 1979), used with permission.

Table 1. Common minerals found in coal and their elemental compositions.

[Although more then 120 different minerals have been identified in coal samples, only about 33 of these occur in most coal samples; of these, only about 8 generally are abundant enough to be considered as major constituents. Data from R.B. Finkelman (U.S. Geological Survey, written commun., 2000).]

Mineral name	Chemical composition	Remarks
	Major Mineral Constituents (In general order of abundance)	
Quartz	SiO_2	
Clay Minerals:		
Kaolinite	$Al_2Si_2O_5(OH)_4$	
Illite	$KAl_4(AlSi_7O_{20})(OH)_4$	
Montmorillonite	$(\frac{1}{2}Ca,Na)_{0.7}(Al,Mg,Fe)_4[(Si,Al)_4O_{10}]_2(OH)_4 \cdot nH_2O$	
Chlorite	$(Mg,Al,Fe)_{12}[(Si,Al)_8O_{20}](OH)_{16}$	May have Mn. (Clays may also contain Be, Cr, Ni, and other trace elements.)
Pyrite	FeS_2	May contain As, Cd, Co, Hg, Ni, Sb, and Se.
Calcite	$CaCO_3$	
Siderite	$FeCO_3$	May contain Mn.
	Minor Mineral Constituents	
Analcime	$NaAlSi_2O_6 \cdot H_2O$	
Apatite	$Ca_5(PO_4)_3(OH,F,Cl)$	
Barite	$BaSO_4$	
Chalcopyrite	$CuFeS_2$	
Clausthalite	PbSe	
Crandallite Group		
Crandallite	$CaAl_3(PO_4)_2(OH)_5 \cdot H_2O$	
Florencite	$CeAl_3(PO_4)_2(OH)_6$	
Gorceixite	$BaAl_3(PO_4)_2(OH)_5 \cdot H_2O$	
Goyazite	$SrAl_3(PO_4)_2(OH)_5 \cdot H_2O$	
Dolomite	$CaMg(CO_3)_2$	
Feldspars	$(Ca,K,Na)AlSi_3O_8$	
Galena	PbS	
Marcasite	FeS_2	May contain same elements as pyrite.
Monazite	$(Ce,La,Y,Th,Nd)PO_4$	
Rutile/Anatase	TiO_2	
Sphalerite	ZnS	May contain Cd.
Xenotime	YPO_4	
Zircon	$Zr[SiO_4]$	
	Trace Mineral Constituents	
Chromite	$FeCr_2O_4$	
Gibbsite	$Al(OH)_3$	
Gold	Au	
Gypsum	$CaSO_4 \cdot 2H_2O$	
Halite	NaCl	
Magnetite	Fe_3O_4	
Muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$	

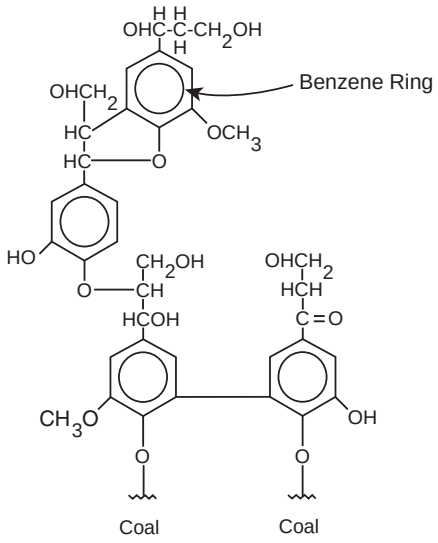


Figure 10. Diagram showing hypothetical structure of a lignin-derived organic molecule in a brown coal (lignite). This structure is based on studies using carbon-13 nuclear-magnetic-resonance (^{13}C NMR) spectroscopy and other organic-geochemical methods such as those described in table 2. Lignin is one of the constituents of woody tissue found in all vascular plants, such as trees and shrubs (W.H. Orem, U.S. Geological Survey, written commun., 1997). Studying organic matter helps provide information about the plant sources of coal and, subsequently, coal quality. See figure 9 for chemical elements.

minerals, such as pyrite. Other sources of inorganic compounds used by the plants may be either the mud that coats the bottom of the swamp, sediments introduced by drainage runoff, dissolved elements in the swamp water, windborne sand, ash, or dust.

Coals may contain as many as 76 of the 92 naturally occurring elements of the periodic table (fig. 9); however, most of those elements usually are present in only trace amounts on the order of parts per million. Occasionally, some trace elements may be concentrated in a specific coal bed, which may make that bed a valuable resource for those elements (such as silver, zinc, or germanium) (Finkelman and Brown, 1991). Some elements, however, have the potential to be hazardous (for example, cadmium or selenium), particularly if they are concentrated in more than trace amounts. Although as many as 120 different minerals have been identified in coal, only about 33 of them commonly are found in coal, and of these, only about 8 (quartz, kaolinite, illite, montmorillonite, chlorite, pyrite, calcite, and siderite) are abundant enough to be considered major constituents (table 1).

The organic compounds in coal are composed of the elements carbon, hydrogen, oxygen, nitrogen, sulfur, and trace amounts of a variety of other elements. Although only a few elements compose the organic compounds found in coal, these compounds are extremely complex and, as a result, they are not well understood; for example, an attempt to define the structure of just one organic compound in a brown coal (lignite) is shown in figure 10, but even this relatively simple structure is based on scientific conjecture. The organic compounds in coal produce heat when coal is burned; they also may be converted to synthetic fuels, or may be used to produce the organic chemicals shown in the centerfold illustration.

The affinities of trace elements for either the organic compounds or the minerals in coal affect the quality of the coal. If trace elements are organically bound, then it is difficult to remove them from the coal by cleaning processes, such as crushing and washing, which remove mineral matter from coal before it is burned. Organically bound trace elements may be released only by burning, or by deep chemical leaching, which is both very difficult and uneconomical. In contrast, trace elements associated with clays or pyrite may be largely removed from the coal by cleaning processes. The trace elements then may be disposed of in an environmentally safe manner or recovered and put to some other use. To date, however, the recovered mineral matter from coal has not been used for very many purposes, with a few major exceptions such as gypsum, the various forms of ash, and a small amount of germanium (used in semiconductors).

Coal may contain as many as 76 of the 92 naturally occurring elements of the periodic table.

MINERALS IN COAL

The most common minerals in coal (for example, illite clay, pyrite, quartz, and calcite) are made up of these most common elements (in rough order of decreasing abundance): oxygen, aluminum, silicon, iron, sulfur, and calcium. These minerals and other less common minerals usually contain the bulk of the trace elements present in coal (table 1). Minerals in coal commonly occur as single crystals or clusters of crystals that are intermixed with organic matter or that fill void spaces in the coal; sizes of mineral grains range from submicroscopic to a few inches. Some clusters of mineral grains, however, such as fracture fillings (fig. 11) or coal balls (fig. 12), may reach sizes that range from fractions of an inch up to several feet across. Coal balls result when mineral matter (such as calcite, pyrite, or siderite) infuses peat before it is compressed. Mineral grains in coal also often occur as discrete particles, such as the blebs of pyrite (framboids), which may be identified in the photomicrographs of coal in figure 13. The more finely divided the mineral grains, the higher the magnification needed to identify them (figs. 13, 14).

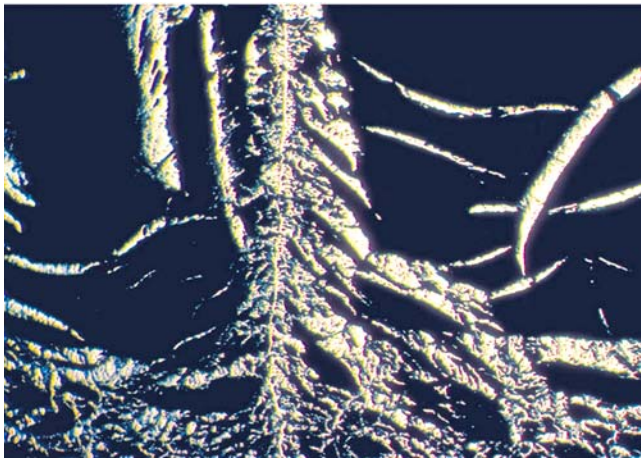


Figure 11. Photomicrograph of pyrite (yellow) filling fractures in the Upper Freeport coal bed in Pennsylvania. Magnification approximately ×4000. From Atlas of Coal Geology, American Association of Petroleum Geologists (AAPG) Studies in Geology No. 45 (Papp and others, 1998); AAPG copyright 1998, reprinted by permission of the AAPG, whose permission is required for further use.

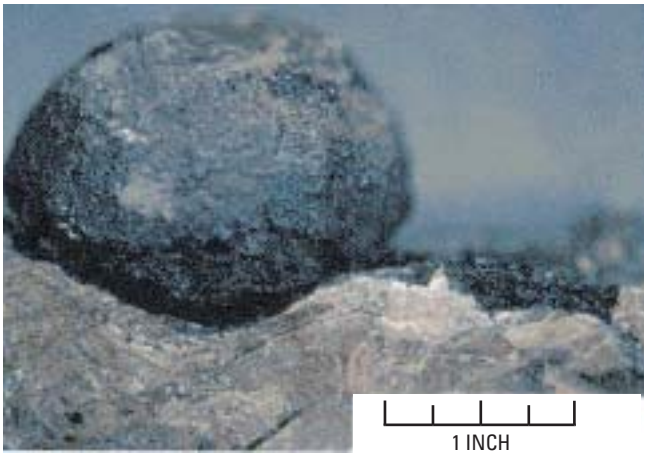


Figure 12. Photograph of small coal ball specimen from the Carbondale Formation, Illinois basin. Coal balls are concretions that occur within coal beds and are composed largely of carbonate minerals and occasionally of pyrite. Modified from a photograph by James Humphrey (Curragh Queensland Mining Ltd., Australia) in Atlas of Coal Geology, American Association of Petroleum Geologists (AAPG) Studies in Geology No. 45 (Papp and others, 1998); AAPG copyright 1998, reprinted by permission of the AAPG, whose permission is required for further use.

Although much is known about the minerals in coal, much remains to be learned about their occurrence, abundance, origin, and composition. For example, the type of clay mineral in a coal, whether montmorillonite or illite, determines how a coal will react when burned. Montmorillonite (table 1) may or may not break down (dissociate) into its constituent parts when coal is burned; if it does dissociate, then, upon cooling, it may recombine with other elements or minerals to form mineral deposits on the inside surfaces of furnaces and boilers (fig. 15). This process (called "slagging" or "fouling") produces barriers to heat exchange in the affected equipment, which can substantially reduce its efficiency and require costly repairs. Illite (table 1), however, with its simpler composition, does not cause such problems under normal furnace operating conditions. Where these two clay minerals and others occur, their relative abundances, relationships to other minerals, and exact compositions are subjects for continued research in coal quality.

The mineral content of coal determines what kind of ash will be produced, which in turn determines the design of a furnace or boiler.

When coal is burned, most of the mineral matter and trace elements generally form ash; however, some minerals break down into gaseous compounds which go out the furnace's flue. Pyrite, for example, breaks down into the individual elements iron and sulfur. Each element then combines with oxygen to become, respectively, iron oxide and SO_x. Iron oxide, a heavy solid, becomes part of the ash and SO_x, a gas, is emitted as part of the flue gas. Some trace elements also dissociate from their organic or mineral hosts when coal is burned and follow separate paths. Most become part of the ash, but a few of the more volatile elements, such as mercury and selenium, may be emitted in the flue gas.

The mineral content of coal determines what kind of ash will be produced when it is burned. The fusion temperature (melting point) of the ash dictates the design of furnaces and boilers. In general, if the fusion temperature is relatively low, then the molten ash is collected at the bottom of the furnace as bottom ash, requiring one design; however, if the fusion temperature is relatively high, then the part of the ash that doesn't melt easily, called "fly ash," is blown through the furnace or boiler with the flue gas and is collected in giant filter bags, or electrostatic precipitators, at the bottom of the flue stack, requiring a different design. Coals that are relatively rich in iron-bearing minerals (such as pyrite or siderite) have low fusion temperatures while coals relatively rich in aluminum-bearing minerals (such as kaolinite or illite) tend to have high fusion temperatures. If an electric generating or heating plant is designed to burn one type of coal, then it must continue to be supplied with a similar coal or undergo an extensive and costly redesign in order to adapt to a different type of coal. Similarly, furnaces designed to use coal that produces high amounts of heat will suffer severe losses in efficiency if they must accept coal that burns with substantially less heat.

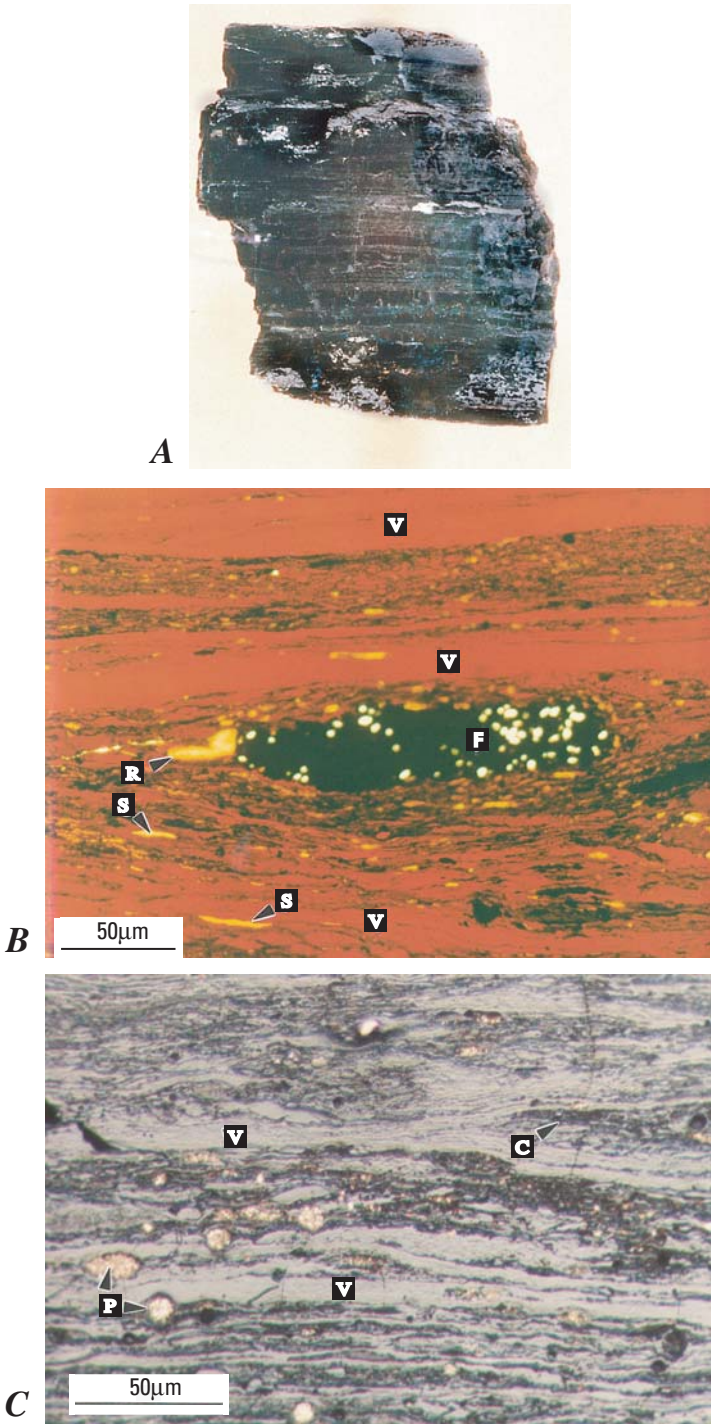


Figure 13. Photograph and photomicrographs of Pennsylvanian bituminous coal. ***A***, Photograph of a lump of bituminous coal from Pennsylvania showing typical banding caused by layering of a variety of preserved plant types as they accumulated in an ancestral peat swamp. Magnification ×0.55. ***B***, Photomicrograph of a thin section of a small piece of bituminous coal from Illinois photographed in transmitted light. Magnification approximately ×330. ***C***, Photomicrograph of a polished surface of a small piece of bituminous coal from Pennsylvania photographed in reflected light. Magnification approximately ×250. Parts *B* and *C* show some typical constituents—macerals (plant remains) and minerals—found in bituminous coals. Macerals are abbreviated as follows: V, vitrinite; F, fusinite; S, sporinite; and R, resinite. Minerals are abbreviated as follows: P, pyrite; and C, clay-sized minerals. The scale bar on parts *B* and *C* is 50 micrometers, which is equivalent to about 0.002 inch. The lump of bituminous coal is included to provide a comparison between what can be seen in a lump of coal and the wealth of detail in coal that can be seen with high magnification. The lump of coal is approximately 260 times larger than the chips of coal represented by either of the photomicrographs. Photographs and photomicrographs by R.W. Stanton (U.S. Geological Survey).

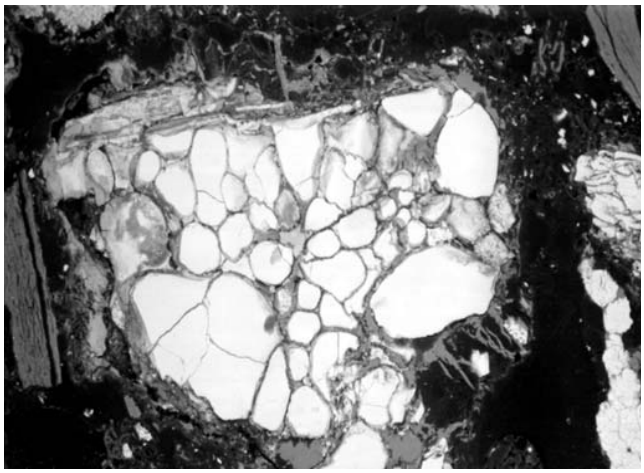
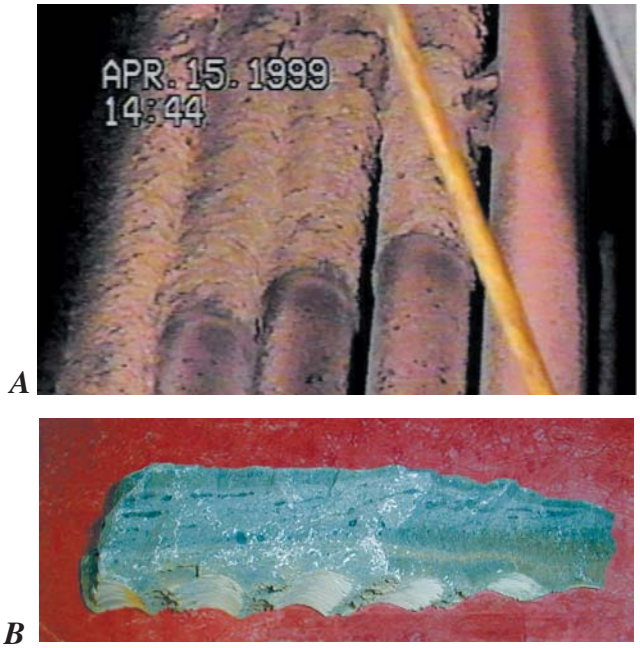


Figure 14. Scanning-electron microscope photomicrograph of a fragment of pyrite infilling plant cells in coal. Bright areas are pyrite, gray areas are organic cell walls, and black area is epoxy mounting media. Sample is from a bituminous coal from Pennsylvania. Magnification approximately ×1000. Modified from a photomicrograph by L.F. Ruppert (U.S. Geological Survey).



A

B

Figure 15. Photographs of mineral deposits ("slagging and fouling") on boiler pipes. ***A***, Slag deposits forming on tubes in platen area of a coal-fired boiler at Alliant Energy WP&L, Columbia Energy Center Unit 1, Portage, Wisc. Tubes are about 1.75 inches in diameter. ***B***, Ash deposit removed from steam tubes in a coal-fired boiler at an AmerenUE plant using subbituminous coal from the Powder River Basin, Wyoming. The plant was originally designed to use bituminous coal. Ash fragment is approximately 12 inches long by 5 inches wide by 3 inches tall at its tallest point. This deposit was removed by explosive cleaning. Photographs by C.J. Zygarlicke (University of North Dakota Energy and Environmental Research Center, Grand Forks, N.D.); used with permission of Alliant Energy, Portage, Wisc. (*A*), and AmerenUE, St. Louis, Mo. (*B*).

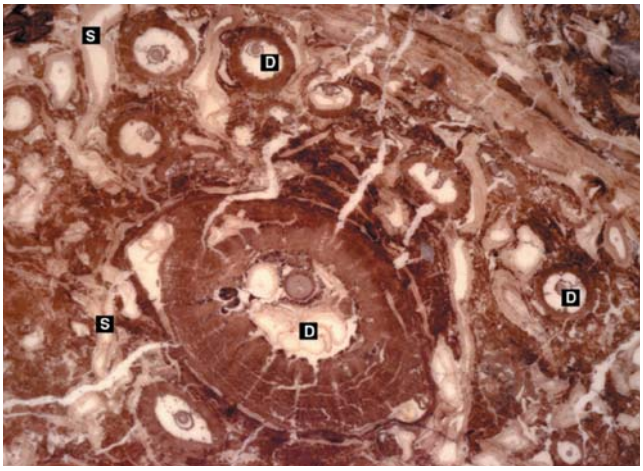


Figure 16. Photograph of a cross section of a calcareous coal ball from the Middle Pennsylvanian Murphysboro coal bed equivalent, Indiana. The coal ball contains permineralized plant material that enables scientists to identify the individual plants and the plant communities (flora) that contributed to the peat, which later became a coal bed. The coal ball contains some identifiable remains of branches and twigs of lycopsid trees (*Diaphorodendron vasculare*), labeled D on the photograph. The structures, labeled S, are sections of lycopsid rootlets, called stigmaria. Compare these structures with the shapes of the macerals in the photomicrographs of coal (fig. 13). Modified from a photograph by W.A. DiMichele (National Museum of Natural History, Smithsonian Institution, Washington, D.C.).

MACERALS

The particles of organic matter in coal, inherited from the remains of plant parts, are called "macerals." Many different types of macerals occur in coal; a few of the more common macerals are identified in the photomicrographs of a bituminous coal from Illinois (fig. 13) The identification of the original plant and its parts (such as bark, roots, spores, or seeds) that produced an individual coal maceral is helpful in determining coal quality. These connections usually are difficult to make because the original plant material has been compressed or altered beyond recognition. Coal balls (fig. 12) result when mineral matter (such as calcite, pyrite, or siderite) infuses peat before it is compressed. Coal balls often contain permineralized plant materials that have maintained their original structures because the mineral matter has prevented compression and degradation of the plants (fig. 16). Coal balls, therefore, can be used as an aid in connecting the degraded, compressed plant matter of a coal bed to the original plants.

Macerals are grouped into three main types: (1) vitrinite, (2) liptinite, and (3) inertinite. Liptinite and inertinite each contain additional maceral subtypes (American Association of Petroleum Geologists, 1998); however, in

this report, just the principal maceral types will be discussed with brief referral to some of the subtypes for illustrative purposes. Vitrinite, which is the most common maceral, results from the coalification of amorphous humic plant material (structureless plant remains). Vitrinite, sometimes called pure coal, is sensitive to heat and becomes denser, tougher, and more vitreous as it is subjected to higher heat levels, either with depth in the earth, or by proximity to an external heat source, such as a volcano. An index of vitrinite reflectance is used by coal scientists to determine the level of heat, or maturity, to which coals and other organic matter, such as petroleum, have been subjected.

Liptinite develops from waxy or oily plant parts such as spores, algae, and resin; the liptinite group contains several subgroups based on these original plant parts—sporinite, alginite, and resinite, respectively. Liptinite macerals are more enriched in hydrogen than either vitrinite or fusinite; liptinite-rich coals produce larger amounts and higher grades of liquid fuel when subjected to destructive distillation than either vitrinite- or fusinite-rich coals. Some coals, called "bog-head" or "cannel" coals consist almost entirely of oil-rich algal and plant spore material. These coals tend to yield large amounts of coal oil (kerosene) when subjected to destructive distillation because the macerals are rich in oily material. However, both cannel and bog-head coals are relatively rare.

Inertinite incorporates a group of common macerals that forms from partially oxidized or burned plant cell walls. Fusinite, or mineral charcoal, is a prominent representative of this group. Mineral charcoal is produced when, occasionally and sometimes seasonally, the surface layers of a peat swamp dry out and some surface peat either slowly oxidizes or catches fire, or some growing plants are partially charred. (The common and naturally occurring fires of the Florida Everglades are modern examples of this process.)

Coals can range in maceral composition from mostly vitrinite to mostly fusinite, depending on the original plant matter and the degree of preservation. Vitrinite-rich coals are shiny black, clean, fractured conchoidally, and often exhibit iridescence (called "peacock coal") on fresh surfaces. Fusinite-rich coals, in contrast, are similar to charcoal and are dull, black, friable, and dusty. For more information on macerals and vitrinite reflectance see the subsection on "Coal Quality" in the "Further Readings" section.

COAL RANK

A major factor in determining coal quality is coal rank. Rank refers to steps in a slow, natural process called "coalification," during which buried plant matter changes into an ever denser, drier, more carbon rich, and harder material. The major coal ranks, from lowest to highest, are lignite (also called "brown coal" in some parts of the world),

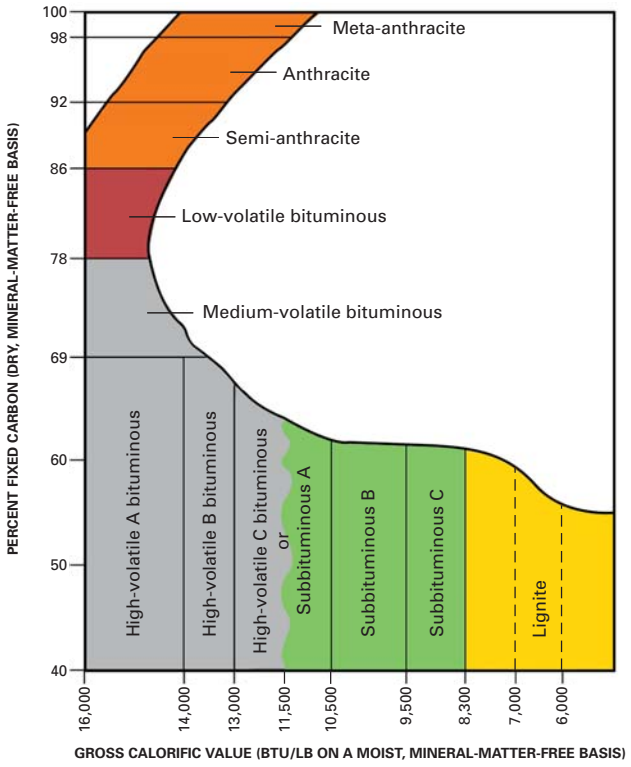


Figure 17. Diagram showing classification of coals by rank in the U.S. Rank is a measure of the progressive alteration in the series from lignite to anthracite. Higher rank coals are generally harder, contain less moisture and volatile matter, and have higher calorific values. Modified from Trumbull (1960). For a more detailed explanation of coal rank determination, see ASTM International (2002).

subbituminous coal, bituminous coal, and anthracite. Each rank may be further subdivided, as shown in figure 17. The rank of coal is determined by the percentage of fixed carbon, moisture (water), volatile matter, and calorific value in British thermal units (Btu) after the sulfur and mineral-matter content have been subtracted. Fixed carbon is solid, combustible matter left in coal after the lighter, volatile, hydrogen-rich compounds are driven off during coalification. Volatile matter is slowly removed from coal during coalification, but may be rapidly removed during destructive distillation. Volatile matter contains the raw materials from which the organic chemicals are obtained. In the U.S., the tests to determine the amounts of the above-mentioned substances and the rank of the coal are performed using standards published by ASTM International (2002).

In general, the higher the rank of a coal, the more deeply it was buried, and, therefore, the higher the temperature it was subjected to during and after burial. Older coals tend to be of higher rank because they are more likely to have been buried more deeply for longer periods of time than younger coals. To give a sense of the effects of increasing rank, the following comparison may be used: lignite is

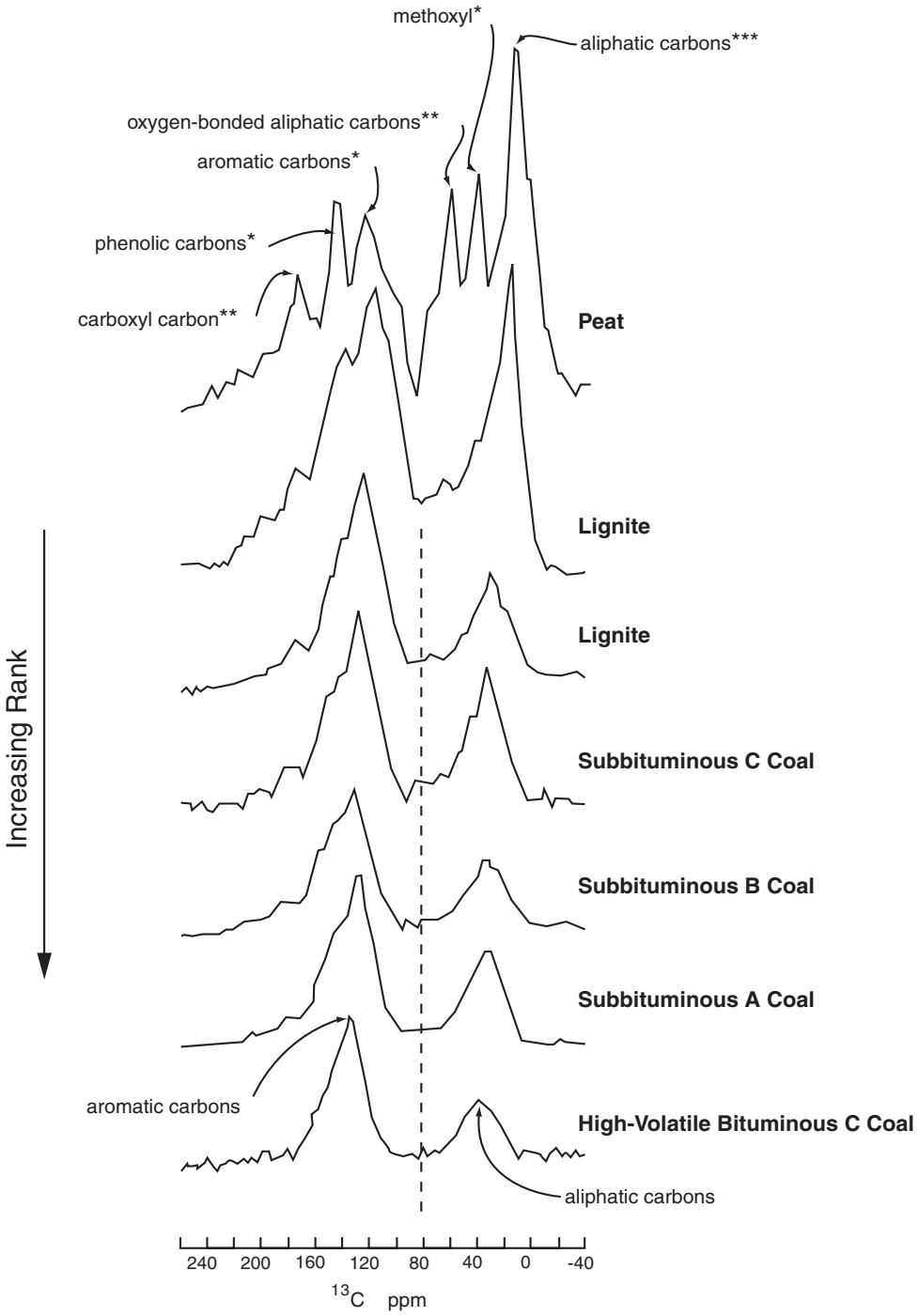


Figure 18. Carbon-13 nuclear-magnetic-resonance (^{13}C NMR) spectra of coals of increasing rank (see figure 17); ^{13}C is a stable isotope of carbon. Diagram shows changes in certain organic compounds brought about by increased coalification. The peaks represent varieties of organic compounds. As rank increases, the variety of compounds decreases and the remaining compounds become structurally tighter and denser. The compounds lost are those that are high in hydrogen and oxygen. Peaks marked with a single asterisk are lignin (woody tissue) indicators; those marked with a double asterisk represent carbohydrates (sugars); and those marked with a triple asterisk represent aliphatic substances (such as waxes and resins). The diagram shows that the carbohydrates are eliminated early in the coalification process, whereas the lignins, waxes, and resins persist to become the principal constituents of higher ranked coals. The scale at the bottom of the figure is a standard ^{13}C NMR scale in ppm (parts per million) representing distance, in frequency units, from a standard, which is assigned a position of zero on the scale. The position of peaks is used to interpret the chemical structure of the substance being analyzed, in this case coal. Data from W.H. Orem (U.S. Geological Survey).

Centerfold. Coal byproducts in tree form showing basic chemicals as branches and derivative substances as twigs and leaves. The basic chemicals may be obtained from coal through heating in a closed container (destructive distillation); the derivatives require additional processing of those basic materials. One ton of bituminous coal roasted in an airtight oven (destructive distillation) produces approximately 1,300 to 1,500 pounds of coke, 8 to 10 gallons of coal tar, 3 gallons of light oil, 5 to 6 pounds of ammonia, and 9,500 to 11,000 cubic feet of gas. Modified from an undated public domain illustration provided by the Virginia Surface Mining and Reclamation Association, Inc. Norton, Va.

COAL
GAS
FUEL GAS
CITY GAS
ILLUMINATING GAS
Steel Furnaces
Refractory Burning
Cement Burning
Gas Engines
Steam Raising
Industrial Use
Glass Manufacture
House Heating
Blend With Other Gas
Bakeries
City Gas
Street Lighting
House Lighting
Factory Lighting
Reddish Brown Dye
Industrial Lighting
Paint Solvent
Motor Fuel
CHEMICALS
AMMONIA
Refrigeration
Artificial Silk
Paint Pigments
Cooking
Mordants
Dyes
Silver Recovery
Cotton Finishing
Wallpaper Color
Rubber Vulcanizing
Photography
Resins
SULFO CYANIDES
Vulcanized Rubber
PRUSSIAN BLUE
ALKALI CYANIDE
FERRICYANIDE
Blueprinting
Photography
Gold Recovery
Gold Plating
Silver Plating
Insecticide
Alcohol Denaturant
Disinfectant
Plastics
Rubber Cement
Insecticide
Paper Manufacture
Solvents
Chemical Agent
Dyes
CYANOGEN
NEUTRAL BLUE
Pigment
Refrigeration
Chemical
Wool Scouring
Baking Powder
Rubber Goods
Smelling Salts
Fertilizers
Laughing Gas
Dyes
Explosives
Fertilizer
AMMONIUM CARBONATE
AMMONIUM NITRATE
NITROUS OXIDE
ANHYDROUS
PYRIDINE
AQUA AMMONIA
AMMONIUM CHLORIDE
AMMONIUM PHOSPHATE
Pharmacy
Dry Batteries
Galvanizing
Radio Parts
Photo Developer
Amber Substitute
Phonograph Records
Dyes
Buttons
Stains
Lysol
Fertilizers
Photo Developer
Bleaching
Oxidizing Agent
Photography
Explosives
Dyes
AMMONIUM PERSULFATE
AMMONIUM SULFATE
Firepoofing
ALUMS
Dyes
Explosives
Plastics
Insecticide
Moth Balls
Dyes
Carbolic Acid
Antiseptic
Photographic Dyes
Disinfectant
Food Preservatives
Oil of Wintergreen
Jewlery
Gears
Perfumes
Medicines
Insulation
Electric Plugs
Explosives
Medicine
Chemicals
Dyes
BAKELITE
SALICYLIC ACID
PICRIC ACID
NITRO PHENOL
AMINO PHENOLS
BAKELITE
Beads
CRESOLS
PHENOLS
Explosives
Perfumes
Medicines
Dyes
Pipe Stems
Auto Parts
Billiard Balls
Iron Heating
Fuel
Core Compounds
Electrodes
Heating
Laxatives
Dyes
Paint Thinner
Rosin Soap
Shingle Stain
Resins
Alizarin
Embalming Fluid
Fungicide
Wood Preservative
Lamp Black
Motor Fuel
Lubricant
NEUTRAL OILS
PHENANTHRENE
ANTHRA QUINONE
ANTHRACENE
Wood Preservative
Dyes
Flotation Oil
CARBAZOL
CARBOLINEUM
HARD PITCH
SOFT PITCH
HEAVY OILS
TAR ACIDS
TAR BASES
HEAVY BASES
PURIDINE
Insecticide
Disinfectant
Alcohol Denaturant
Insecticide
Sulfuric Acid
Insecticide
Fungicide
Chemical Industry
Dyes
Fertilizer
Explosives
SULFUR
NITRIC ACID
Agriculture
LIGHT OIL
BENZOL
BENZALDEHYDE
SOLVENT NAPHTHA AND XYLOL
XYLENES
TOLUOL
RESINS
XYLIDINES
Dyes
Varnish
Rubber Composition
Radio Parts
Electrical Insulation
Roofing
TRINITROTOLUOL
TNT Explosive
Paint
Flotation Oils
Organic Solvent
Stains
Sizing for Paper
TOLUIDINES
Cotton Dyes
Blue Sulfur Dyes
NITRO TOLUENE
Linoleum
SACCHARIN
Sugar Substitute
Stilbene Dyes
Dyes for Silk
SULFO ACID
Antiseptic
Tobacco Seasoning
Food Preservatives
Dental Preparation
SODIUM BENZOATE
Perfume
Food Preservative
Blue Dyes
Almond Flavor
BENZOIC ACID
Red, Orange, and Yellow Dyes
Malachite Green
DYE STUFFS
Mauve, Yellow
Methylene Blue
Patent Blue
Perfume
Indelible Pencils
Medicine
Airplane Dope
ANILINE
Aniline Salt
Perfume
Jasmine Oil
Rubber Stamp Ink
Acetanilide
Aniline Black
Methyl Orange
DIPHENYLAMINE
NITRO BENZENE
HYDRO QUINONE
DINITRO BENZENE
Anti-Flash
Dye
Bismark Brown
Photo Developers
Dye Stuffs
Water Soluble Dyes
Maleic Acid
Cotton Yellow
Tanning
Plastics
PHENO SULFO ACIDS
Solvent
Airplane Fuel
Solvent For Rubber
CARBON DISULFIDE
Synthetic Rubber
Congo Red
AZO BENZENE
Motor Fuel
Acetylene
Azo Dyes
Gas Enrichment
Artifical Silk
Insecticide
Acetic Acid
Briquets
Gas Producers
Boiler Fuel
Washing Soda
Cyanimid
CALCIUM CARBIDE
COKE
Baking Powder
Carborundum
Graphite
RETORT CARBON
Electrodes
Carbons
FOUNDRY COKE
METALLURGICAL COKE
COKE AND COKE BREEZE
Cupola
Soda Water
CARBON DIOXIDE
GAS MANUFACTURE
Lead-Zinc Melting
Brass Melting
Electrodes
Carbide
Pulverizing Combustion
ELECTRIC POWER
Iron Blast Furnace
Lead Smelting
Copper Smelting
Blue Gas
Water Gas
Producer Gas
Combined Cycle Gasification
Fluidized Bed Combustion
TAR
REFINED TAR
Flotation Oils
Paints
Insulation
Varnish
Disinfectant
Sidewalk Composition
Paving
Concrete Water Proofing
Pipe Covering
Roofing
MIDDLE OILS
NAPHTHALENE
LYEOSOTE
PHTHALIC ANHYDRIDE
Tanning
Halo Wax
Pitch Thinner
Wood Preservative
Lamp Black
Disinfectant
Antiseptics
Dyes
Photography
Alcohol Denaturant
Dyes
Indigo
Phenolphthalein
Targets
Briquetting
Electrodes
Storage Batteries
Roofing
Water-proofing
Insulation
Paving
Kippax Paint
HARD PITCH
GAS
COKE

Schweinfurth, S.P., 2003 , Coal—A complex natural resource; an overview of factors affecting coal quality and use in the United States: U.S. Geological Survey Circular 1143, 43 p.

Eon	Era	Period	Epoch	Millions of Years Ago
Phanerozoic	Cenozoic	Quaternary	Holocene Pleistocene	1.6
		Tertiary	Pliocene Miocene Oligocene Eocene Paleocene	66
	Mesozoic	Cretaceous	Late Early	138
		Jurassic	Late Middle Early	205
		Triassic	Late Middle Early	240
	Paleozoic	Permian	Late Early	290
		Pennsylvanian	Late Middle Early	330
		Mississippian	Late Early	360
		Devonian	Late Middle Early	410
		Silurian	Late Middle Early	435
		Ordovician	Late Middle Early	500
		Cambrian	Late Middle Early	570
Proterozoic	Late Proterozoic Middle Proterozoic Early Proterozoic			2,500
Archean	Late Archean Middle Archean Early Archean			3,800?
pre-Archean				

Figure 19. Chart showing divisions of geologic time (ages are approximate). Since the Mississippian Period, major coal deposits have formed some place in the world except during the most recent period (Quaternary); how ever, major peat deposits formed (and are still forming) during the Quaternary and it is possible that there may be Quaternary lignite deposits as well. Periods of major coal deposits in the U.S. are shaded.

Figure 20. Photograph of an in-situ fossilized tree base and root system in the roof of an underground coal mine. The coal bed being mined is in the Cretaceous Blackhawk Formation, Wasatch Plateau coal field near Huntington, Utah. Note the radiating root network. Photograph by Alex Papp (ARCO Coal Company, Denver, Colo.) in Atlas of Coal Geology, American Association of Petroleum Geologists (AAPG) Studies in Geology No. 45 (Papp and others, 1998); AAPG copyright 1998, reprinted by permission of the AAPG, whose permission is required for further use.

soft, dusty, and can ignite spontaneously under the appropriate conditions, whereas anthracite is quite hard, clean to the touch, and must reach a temperature of about 925° F before it will ignite. Furthermore, anthracite contains about twice the calorific value of lignite (about 15,000 Btu/lb and 7,000 Btu/lb, respectively) because lignite contains more moisture and oxygen and less fixed carbon than anthracite. Subbituminous and high-volatile bituminous C coals have oxygen and moisture content and calorific values that range between those of lignite and anthracite. Bituminous coals of higher rank have calorific values that may exceed those of anthracite (fig. 17). Figure 18 shows nuclear-magnetic-resonance (^{13}C NMR) spectra of coals of increasing rank, illustrating the changes in the organic structures as coal progresses through stages of increasing rank.

WHY IS COAL SO COMPLEX?

Coal is complex because of the wide variety of factors that determine the quality of coal. These factors include the following: (1) the plants, plant remains, and other organisms (such as bacteria) in the peat swamp; (2) biological and chemical processes, and the degree of preservation of the plant matter; (3) the geometry and location of the swamp; (4) the mineral matter that accumulated with the plant material, or was introduced at some later stage; and (5) coalification. Geologic age and history will be a recurring theme throughout this discussion. Figure 19 shows the times in geologic history when coal beds formed.

THE PLANTS

Coal begins as peat, which forms in swamps having favorable conditions as explained in a previous section entitled “Origins.” These swamps, which are generally filled with standing or slowly moving water, are ideal places for prolific plant growth. When plants fall into the swamp, water covers them and slows or prevents rapid decomposition. Slow decomposition and a quiet environment allow plant matter to accumulate and form peat. The organic matter composing the peat may accumulate in place or, less commonly, may be carried by flowing water to accumulate elsewhere, but generally nearby. Most coal beds were formed from plant material that accumulated in place (fig. 20).

Coal is a complex material formed by a mix of substances and processes. The substances are plant remains and mineral matter. The processes aren’t completely understood, but involve chemical and biological reactions, heat, burial, and time.

Plant communities (flora) in peat swamps may consist of many plant types, or of only a few. Swamp flora have changed substantially through geologic time because of evolution. For instance, lycopsids and tree ferns (fig. 21) are found in older coal beds; more modern forms, such as rushes, water lilies, mangrove, and bald cypress trees (shown in figure 6) may be found in younger coal beds. Flora of the Cretaceous Period (fig. 22) included abundant species that contained relatively more resinous substances than those of the much earlier Pennsylvanian Period. Tertiary plants generally were woodier than those of either the Pennsylvanian or the Cretaceous Periods. In addition, floral communities varied from location to location even within the same time period. These changes in plant species resulted in small changes in nutrient requirements. The result is that geologically younger coals may have different mineral matter compositions than older coals.

BIOLOGICAL AND CHEMICAL PROCESSES

Once plant debris has been deposited in a peat swamp, it is subjected to degradation and decomposition by micro-

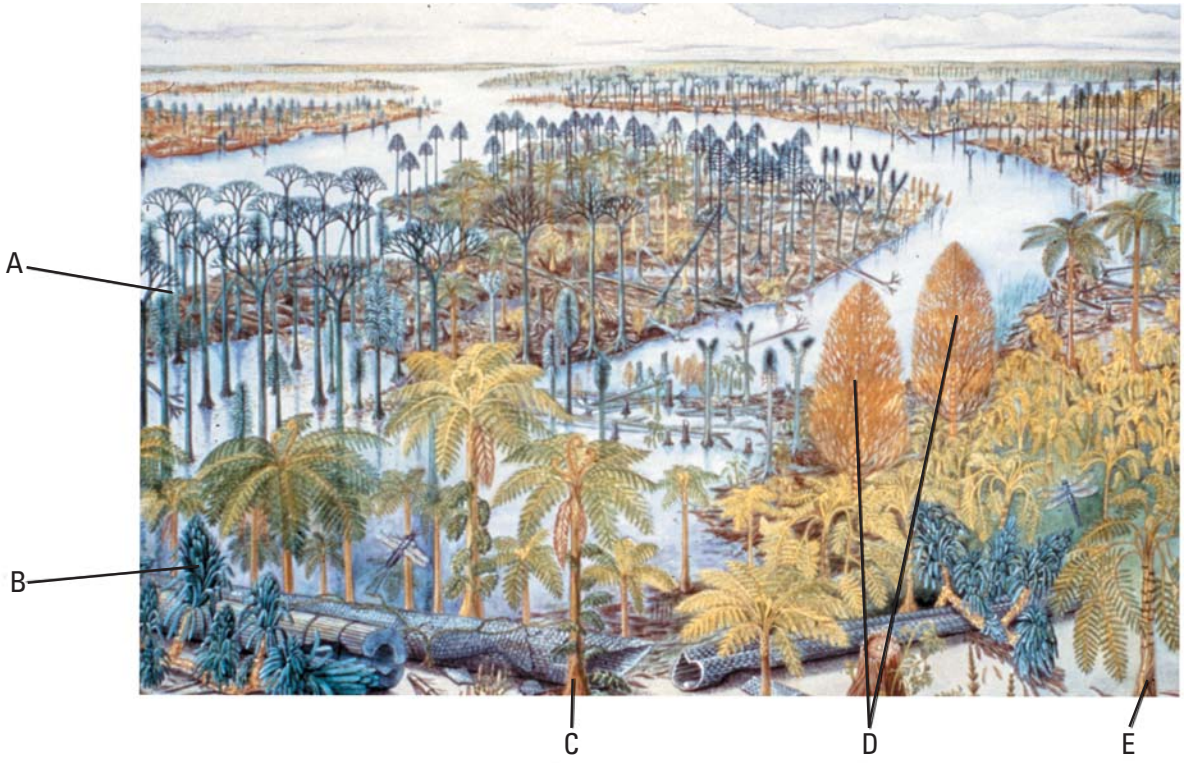


Figure 21. Reconstruction of a tropical peat swamp of Middle Pennsylvanian age (about 300 million years ago). The taller plants (A) were tree lycopsids (Lepidophloios), some of which grew to heights of 80 to 100 ft. Today, the lycopsids are represented by lowly club mosses. Other plants include cordaites (B), which were seed plants with strap-shaped leaves that are now extinct; tree ferns (C), which still live in warm, damp areas; calamites (D), which is a tree-size scouring rush; and pteridosperms (E), which were seed plants with fernlike leaves that are now extinct. The tree-like scouring rushes, which reached heights of 30 to 50 ft, are represented today by plants that grow in damp, but not necessarily warm, areas usually to only a few feet in height. From an illustration by Alice Pricket in GSA Today (Gastaldo and others, 1996, fig. 1); Geological Society of America (GSA), copyright 1996, reproduced with permission of the GSA (Boulder, Colo.), whose permission is required for further use.

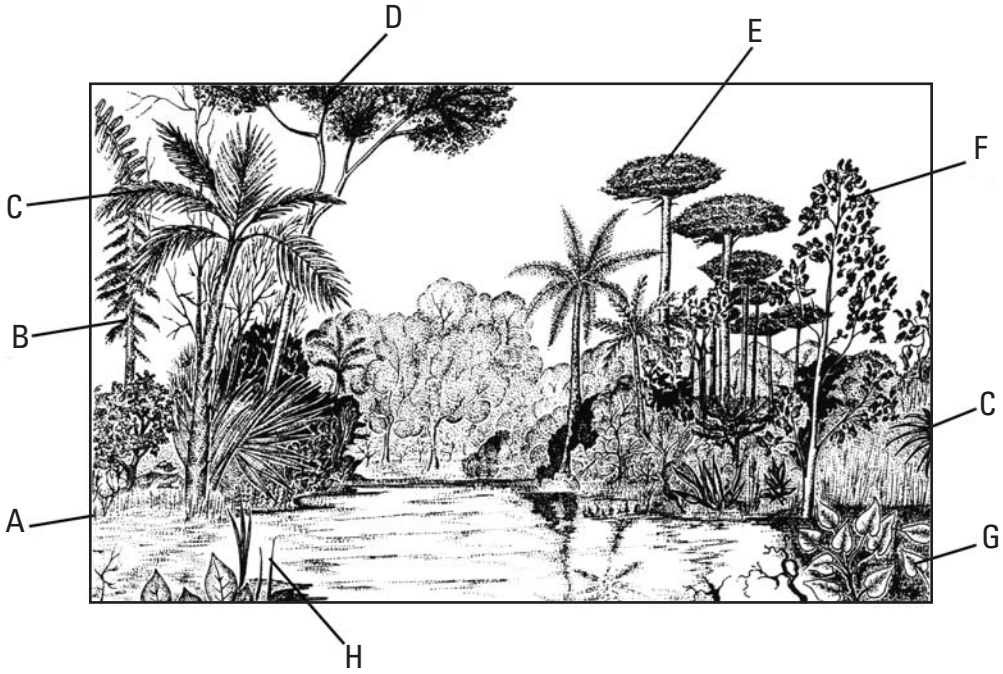


Figure 22. Reconstruction of a peat-forming, fluvial coal swamp and peripheral, bottom-land vegetation of Late Cretaceous age (about 70 million years ago) in what is now eastern Utah. Representative plants are as follows: A, horse-tail rush; B, sequoia; C, palm; D, *Rhamnites*, now extinct; E, *Araucaria*, now extinct; F, sycamore; G, fig; and H, cattail. Plants were growing on the banks of the swamp. Modified from Tidwell (1998, figure 37), used with permission of the author.

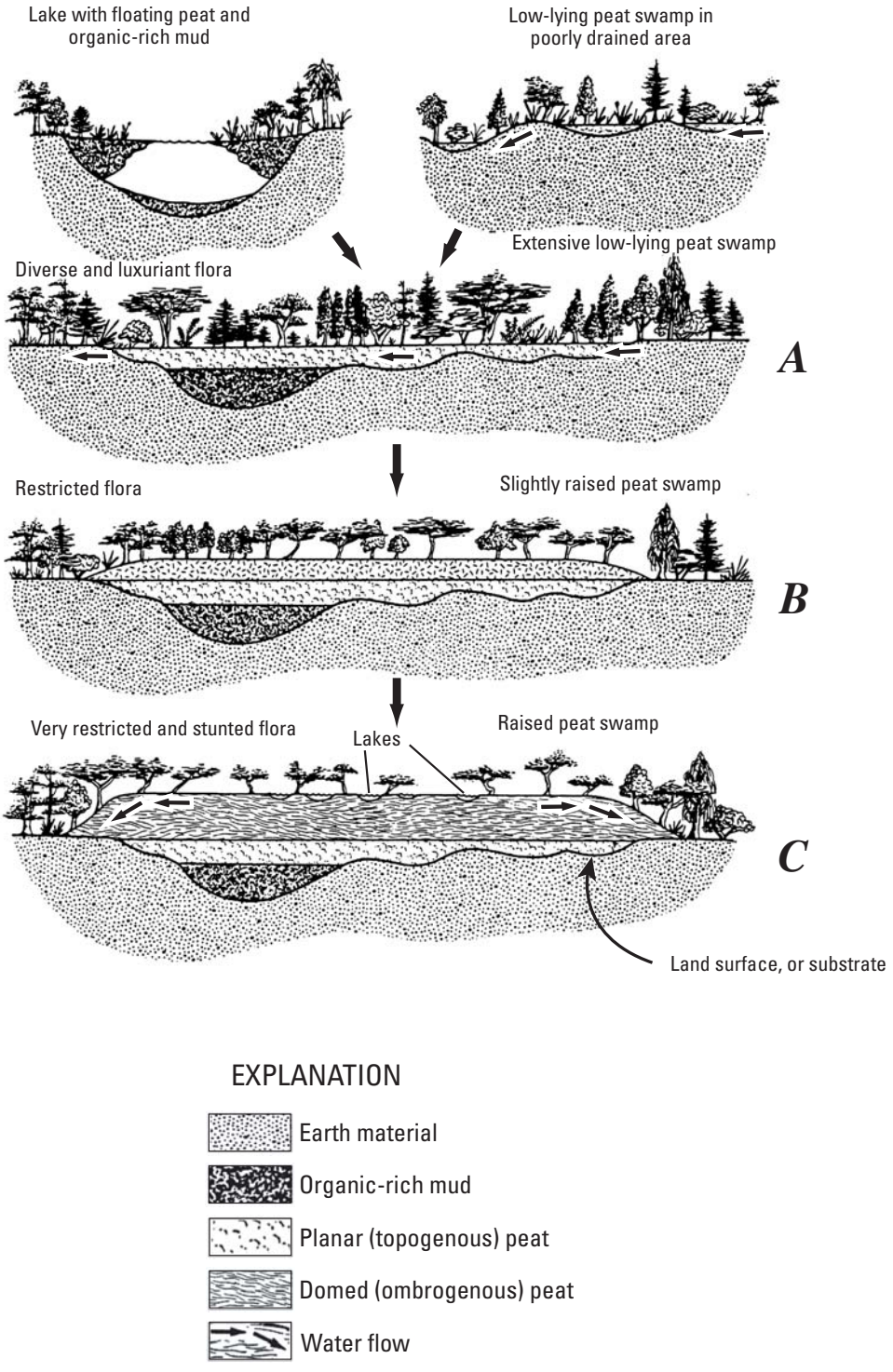


Figure 23. Sketches illustrating a possible evolution from a planar (topogenous) peat deposit to a domed (ombrogenous) peat deposit. ***A***, planar; ***B***, transitional, slightly domed; and ***C***, domed. A planar deposit may evolve into a transitional or domed deposit if climatic conditions change; the two types of peat deposits also may occur independently. No scale implied, but the horizontal dimension could be many miles and the vertical dimension could be 500 to 1,000 ft. Individual plant types were not identified in the source for this figure, but a typical flora might include cypress, magnolia, and willow trees; sassafras, sumac, and witch hazel shrubs; and ferns, reeds, and lilies as low-growing and water plants. Modified from McCabe (1987), used with permission of The Geological Society (London).

bial action, oxidation, and biogeochemical processes. These processes are pervasive and, to a large extent, determine the character of any resultant coal. The processes, which operate on microbiological and microchemical levels, are constantly changing and, therefore, are difficult to characterize. What is known is that (1) the degradation processes are carried out by oxygen from the atmosphere and various microorganisms, such as bacteria and fungi; and (2) the processes are moderated by the acidity or alkalinity of the available water. When the oxygen in the peat has been depleted, anaerobic bacteria (such as those responsible for fermentation) continue the process of degradation. Although pervasive, the process of plant decomposition is also selective in that different plant parts degrade at different rates. The most resistant parts, such as bark, cuticle, spores, lignin-rich wood, and charcoal (fusinized peat), are the parts most often retained in coal as macerals.

When standing water covers fallen plant matter, atmospheric oxidation is halted; soon thereafter, biochemical change slows to a virtual halt. Once plant matter is converted to peat and is buried, further substantial changes depend more on increases in temperature and pressure than on oxidation and biochemical processes. The acidity or alkalinity of peat swamp water may also control the rate and amount of change that takes place. Usually, the more acidic the water, the more plant matter is preserved because bacterial activity is reduced. If their work is carried to completion, bacteria and fungi produce CO_2, water, and ash; in effect, it is a slow-burning process.

SWAMP GEOMETRY, LOCATION, AND CLIMATE

From the late Paleozoic to the present, two principal types of peat swamps have existed: planar (topogenous) and domed (ombrogenous) (fig. 23). Each has unique floral characteristics that affect the quality of the resulting coal.

The planar peat swamp generally develops in areas of seasonal rainfall, mainly in low-lying areas, and depends on a high ground-water table for its continued existence. The resulting peat deposit often has an undulating bottom and a flat top. Because it forms in low-lying areas, the planar swamp is subject to periodic flooding, which results in the introduction of extraneous mineral matter such as clay, silt, and sand. This sediment brings in nutrients, but may also add impurities to any resulting coal; in extreme cases, the sediment may bury the swamp, which results in the termination of peat formation.

The domed peat swamp develops in areas that receive substantial rainfall during most of the year. In this environment, new plants grow above fallen plants, which decay very slowly because the swamp, like a sponge, remains saturated with water. This process gradually allows the top of the swamp to rise above the surrounding topography. The result is a peat deposit that has a raised, or domed, surface.

Figure 24. Photograph of a coal strip-mine highwall exposure of a thick lens-shaped parting, possibly a floodwater overflow (see fig. 9) in the Upper Freeport coal bed, central Appalachian basin. Photograph by Mark Scanlon (Canyon Fuel Co., LLC, Price, Utah) in Atlas of Coal Geology, American Association of Petroleum Geologists (AAPG) Studies in Geology No. 45 (Papp and others, 1998); AAPG copyright 1998, reprinted by permission of the AAPG, whose permission is required for further use.

The dome prevents or limits the extent of flooding of the swamp and thereby prevents the introduction of mud, silt, and sand, except around the fringes. New plants depend on dead ones for their nutrients, thus depleting the earlier deposited peat of mineral matter. The flora become stunted and restricted to plants that can survive in a mineral-poor, acidic soil. As a result, domed peat tends to contain much less mineral matter than planar peat and the resulting coals are purer.

A peat deposit may have originated as either the planar or the domed type and then, due to a change in the climate or topography or both, may transform into the other type and even back again (fig. 23). The resulting coal beds may be composites of the two types. These conditions make determining the quality of the composite coal beds difficult.

The geographic location and climate of the precursor peat swamp also affect coal quality. At present, swamps are located in tropical, temperate, and cool climates, near coastlines and inland, beside rivers and within river deltas, and in upland areas. This wide variety of geographic locations and climates in which swamps develop was most likely the case at least as far back as the Devonian Period (fig. 19).

Peat swamps located close to rivers or within river deltas suffer the possibility of periodic flooding and the introduction of large amounts of mineral matter. Swamps along coastlines, while not as easily subjected to river flooding, may be affected by offshore or coastal storms that wash sediment over offshore bars and beaches into the swamps behind them. The added mineral matter may be disseminated in the peat, may occur as layers in the peat, or may cause peat formation to stop. Discrete layers of mineral matter in coal beds are called “partings” (fig. 24).

Climate, which to some extent depends on geography, affects the growing season and the amount of rainfall that a swamp receives and, therefore, helps determine the kind of peat that will eventually form. Thick, extensive coal beds generally are thought to have originated as large peat swamps in warm, humid, and tropical to subtropical regions (Cecil, 1990). For example, extensive, thick (some up to 50 ft) peat deposits have been accumulating on the coastal areas of the islands of Indonesia (principally Sumatra; fig. 7A) and Borneo, as well as others (Neuzil and others, 1993). Those areas are in warm, ever-wet, climatic zones.

Extensive peat deposits currently are forming in the Florida Everglades, but the climate there is much more variable than that of Borneo. Southern Florida has periodic rainfall and extended dry periods that allow the surface peat to dry out and oxidize, or even burn off, resulting in a relatively thin deposit.

Other modern peat deposits form in a wide variety of climatic conditions; two additional examples are provided. The Vasjugankojev swamp in Siberian Russia, which is a notoriously cold region, is described by Cameron and others (1989) as, at an area of approximately 21,000 mi^2, the largest "peatland" in the world; however, even though the region is cold, the location of the swamp is low, flat, and wet, and part of the year is conducive to adequate plant growth while the coldness of the rest of the year serves to protect much of the plant matter from decay. No thickness of peat in this swamp was reported.

A swamp on Great Cranberry Island, Maine, also described by Cameron and others (1989), is another example of a swamp located in a cool temperate climate. This swamp formed during the recent past as sea level rose and built up a beach ridge approximately 11 to 12 ft high. A lake, which was formed behind the rising beach ridge, slowly filled with peat as the beach rose. The resultant peat deposit is relatively small (less than 250 acres) but it reaches thicknesses of as much as 27 ft. Whether either of these modern peat deposits will ever become a coal bed cannot now be determined; however, research on modern peat deposits, wherever they are located and under whatever climatic conditions they are deposited, may help in finding additional high-quality coal deposits in older rocks.

MINERAL MATTER

The living plants in a peat swamp absorb mineral matter from (1) the soil they grow in, (2) dissolved mineral matter in the water of the swamp, and (3) introduced mineral matter, such as waterborne or windborne sediment, or volcanic ash. Some of the dust and ash may be dissolved in the swamp water and serve to support plant growth, as described in the discussion of domed peat deposits, or they may occur as disseminated grains in the peat or as discrete layers called partings (fig. 24). Partings may be paper thin or they may be several feet thick. In the case of the planar swamp, dust or ash will further dilute the organic matter composing the peat, thus raising the mineral-matter content or creating partings. In the case of the domed swamp, however, these sediments may add enough new nutrients to the swamp to prolong its life and produce a thicker peat and ultimately a thicker coal bed. Volcanic ash and some types of dust are rich in the nutrients required for vigorous plant growth.

Throughout geologic time, the peat swamps that were not destroyed by erosion or oxidation were buried by sediments, which, depending on their source, affected the mineral-matter content of the resultant coal in different ways. In general, riverborne sediments tend to be richer in some elements, such as iron, whereas oceanborne sediments tend to be richer in other elements, such as sulfur.

In many coals, some of the mineral matter was introduced by epigenetic (low temperature) mineralization after the bed was formed (fig. 11). In this process, the minerals were introduced into fractures (called "cleat;" see below under "Coalification") and along bedding planes in the coal bed as ions in moving water and were deposited when the water lost its ability to maintain the mineral-forming ions in solution. This could occur when the ion-bearing water entered a different temperature and (or) chemical environment.

Epigenetic minerals commonly include pyrite, calcite, siderite, and kaolinite, and in rare cases, sphalerite and galena (see table 1 for compositions of these minerals). Epigenetic mineralization, estimated to have been introduced during the Permian Period into coal beds of older Pennsylvanian age (see fig. 19), is particularly notable in coals of the midcontinent region of the U.S. (Cobb, 1979; Brannon and others, 1997).

COALIFICATION

From the time the peat is buried, it goes through a series of chemical and physical changes called "coalification," which is the process that produces coals of increasing rank (fig. 17). Coalification is a continuing process involving increases in both temperature and pressure resulting from burial in the earth. Burial is a process that may happen very slowly or relatively rapidly depending on the speed and magnitude of the geologic forces operating on the region. Increasing temperature is considered more important than increasing pressure in promoting coalification. Higher temperatures eliminate moisture and volatile elements and, therefore, help produce coals of higher rank and higher heat (calorific) value. Higher temperatures are generally associated with deeper burial in the earth, although proximity to an unusual source of heat, such as a volcano, could produce similar effects.

Figure 25. Photograph of part of an exposed coal bed showing well-developed face cleat and poorly developed butt cleat. The coal bed is in the Cretaceous Fruitland Formation in the San Juan basin, near Durango, Colo. The compass is 2.75 in. wide. Photograph by Walter Ayers (S.A. Holditch Assoc., Inc., College Station, Tex.) in Atlas of Coal Geology, American Association of Petroleum Geologists (AAPG) Studies in Geology No 45 (Papp and others, 1998); AAPG copyright 1998, reprinted by permission of the AAPG, whose permission is required for further use.

When increases in depth of burial or temperature no longer occur, coalification slows and then ceases (unless another source of higher heat affects the coal). Thereafter, the coal will remain at the same rank even if it is raised up again (either by tectonic uplift or erosion of overlying sediments, or both) into a region of much lower temperature or pressure. Once the coal is exposed to weathering (oxidation), however, it is slowly reduced to ash.

> *Coalification is a baking process in the earth, under pressure. As it proceeds, it produces coal of increasing hardness and calorific value and results in a reduction of tar, oil and gas.*

Coalification affects not only the organic matter in coal, but the mineral matter as well. As coalification proceeds, organic matter, which is relatively rich in water, oxygen, and hydrogen, gradually loses those constituents and becomes relatively enriched in fixed carbon. Some of the hydrogen and carbon are converted to methane gas (CH_4) in the process. Changes that occur to the mineral matter during coalification are less well understood. During coalification, clay minerals may become more refractory (that is, less affected by heat and chemicals), and the elements in other minerals may become rearranged, making them more crystalline. Although deeper burial, and therefore higher temperatures, implies greater age, coals of approximately the same geologic age may exhibit a wide range in rank depending on their geologic histories. For example, Pennsylvanian coals in the eastern U.S. (figs. 4, 19) range in rank from anthracite in easternmost Pennsylvania to high-volatile C bituminous coal in western Illinois and Iowa. Coals beds in what is now eastern Pennsylvania were subjected to strong mountain-building forces during the late Paleozoic, when the Appalachian Mountains were formed. During this time, the beds were forced deep into the earth into zones of high heat, and then were compressed into tight folds. In contrast, the coals to the west, in what are now the States including western Pennsylvania, Ohio, Indiana, Illinois and Iowa, were subjected to lesser depths of burial and little or no mountain-building forces.

During the process of coalification, sets of roughly parallel, closely spaced fractures (cleat) form in the coal. Cleat tend to form in two sets at right angles to one another; one set, the face cleat, is dominant, while the other set, the butt cleat, may be only poorly developed (fig. 25). Cleat are generally well developed in bituminous coals; lignites and subbituminous coals, both less well coalified, generally exhibit only incipient cleat. Anthracite in eastern Pennsylvania generally does not exhibit cleat because strong mountain-building forces welded the coal back together into solid massive beds. (For a thorough discussion, see Damberger, 1991.)

DETERMINING THE QUALITY OF COAL

By now, it should be clear why coal is such a complex and heterogeneous material. The interplay of the many factors that affect the peat and the resulting coal affects its composition, but the composition is never quite static because it is subject to continuing change. In the past, coal was simply dug up and burned or turned into coke with little concern for its quality as long as it made a hot fire, did not have too much ash or sulfur, and would ship long distances without turning to dust. Now we know that a complete understanding of coal quality is important in order to address environmental or industrial concerns such as (1) SO_x and hazardous air pollutants (elements such as mercury and selenium in hot flue gases); (2) boiler slagging and fouling; (3) the high costs of flue-gas desulfurization; (4) the disposal of scrubber sludge, ash, and CO_2; (5) the development of clean-coal technologies; and (6) the promotion of coal as a source for synthetic oil and gas.

Many techniques currently exist for studying coal quality. Some analytical techniques (such as the ones used to determine coal rank, moisture, ash yield, sulfur content, and

Table 2. Procedures and purposes of American Society for Testing and Materials (ASTM) methods for testing coal.

Procedure	Purpose
Classification of coal by rank	Classify coal into categories indicating ranges of physical and chemical characteristics that are useful in making broad estimates of the behavior of coal in mining, preparation, and use.
Coal ash	Determine amount of ash at a given temperature.
Equilibrium moisture	Determine moisture-holding capacity of coal.
Forms of sulfur	Determine whether sulfur is in pyrite, organically bound, or in sulfates.
Free-swelling index	Determine how well a coal will form coke.
Fusibility of ash	Predict whether the coal ash will perform properly in the process for which it was chosen.
Gross calorific value	Determine potential for energy production, in kilocalories per kilogram.[1]
Hardgrove grindability	Determine resistance to grinding.
Major and minor elements	Identify major and minor elements.
Proximate analysis	Determine amount of ash, fixed carbon, moisture, and volatile matter.
Reflectance of organic matter	Determine rank and how well a coal will form coke.
Total moisture	Determine inherent water and any other water present.
Trace elements	Identify trace elements.
Ultimate analysis	Determine amount of ash, carbon, hydrogen, nitrogen, oxygen, and sulfur.
Volatile matter	Identify products given off as gases or vapors.
Maceral analysis	Determine kinds and amounts of macerals in coal.

[1] One kilocalorie per kilogram = 1.798 British thermal units (Btu) per pound.

volatile matter) are highly standardized. Coal mines, electric utilities, the coke industry, and commercial analytical labs commonly employ these tests. Many of the standards for these techniques, as well as the standards for precision in their use, are published by ASTM International (2002) and are widely followed by the coal industry in the U.S. Research scientists studying coal quality use not only the results of ASTM-based analyses in their work, but also other generally accepted techniques that have not been standardized by the ASTM; however, once research shows that a new technique is useful and accepted by the coal industry, standards may be developed for its application.

Research is currently underway to improve the existing techniques used by coal scientists for analyzing coal, to adapt some techniques used in the analysis of other materials, and to develop new analytical techniques. Procedures approved by the ASTM and their purposes are given in table 2. A list of analytical techniques currently used in coal-quality research at the USGS and their purposes is given in table 3. The two suites of analyses serve different purposes. The results of the ASTM suite of analyses allow coal-using industries to directly compare coals of differing qualities, which enables them to select a coal that is best suited to their needs. These results also allow coal research scientists to study the geologic history of a coal bed through levels of rank, and ash, sulfur, and moisture contents. The suite of analyses used by the USGS was developed to (1) aide in the search for valuable mineral byproducts, (2) develop methods to aide in determining the origins and correlations of individual coal beds, and (3) analyze for the locations, amounts, and affinities of elements that are known to, or might, pose a hazard to health. The results of both sets of analyses performed on a sample of bituminous coal from Alabama are provided in table 4 (the results of ASTM analyses are given first; the results of USGS analyses follow). The ASTM analyses were performed by the U.S. Department of Energy at the Pittsburgh, Pa., laboratory; the USGS analyses were performed at USGS laboratories at Reston, Va., and Denver, Colo.

The USGS has developed a large file of data on coal quality including the results of both ASTM and USGS procedures (Bragg and others, 1997). These data result from analyses performed on coal samples collected by USGS scientists or by cooperating agencies, such as

Table 3. Analytical methods and individual techniques used in research on coal quality and their purposes.

Method	Purpose
1. Analytical chemistry.	Determine inorganic elements and compounds.
Wet chemistry.	
Inductively coupled plasma mass spectroscopy (ICP-MS).	
Inductively coupled plasma atomic emission spectroscopy (ICP-AES).	
Neutron activation (NA).	
Atomic absorption spectroscopy (AAS).	
Molecular absorption spectroscopy (MAS).	
Optical emission spectroscopy (OES).	
Stable-isotope mass spectrometry (SINS).	
2. X-ray fluorescence.	Determine elemental composition.
3. X-ray diffraction.	Determine mineral structure.
4. Optical microscopy.	Determine distribution of coal particles and minerals and content of macerals, pollen, and spores.
5. Accelerated particle.	
Scanning-electron microscope (SEM) with energy dispersive X-ray analyzer (EDAX).	Determine shapes, sizes, and distribution of mineral grains at very high magnification and semiquantitative determination of some elements.
Transmission-electron microscope (TEM).	Similar to SEM. Also used for mineral identification.
Electron microprobe (EMP).	Determine structure and elemental composition of individual mineral and maceral grains.
Proton induced X-ray excitation (PIXE)	Similar to EMP, but more sensitive.
Laser microprobe-mass analyzer (LAMMA).	Determine trace-element presence in coal macerals.
Ion microprobe (IM).	Determine trace element presence in coal macerals.
6. Nuclear magnetic resonance (NMR).	Determine structures and structural changes of organic compounds.
7. Gas chromatography/mass spectrometry (GC/MS).	Determine organic compounds.
8. Thermoluminescence (TD) and cathodoluminescence (CD) detectors.	Infer the origin of specific minerals, whether from an igneous or sedimentary source.
9. Fourier transform infrared analysis (FTIR).	Quantitatively determine clay mineralogy and organic compounds.

Table 4. Results of standard ASTM International (ASTM) analyses and U.S. Geological Survey (USGS) research analyses of a sample (USGS 212277) of Pennsylvanian bituminous C coal from the Mary Lee coal bed, Walker County, Ala.

[Data from Bragg and others (1988). Btu, British thermal units; na, not available]

ASTM Standard Analyses	
Proximate (in percent)	
Moisture	2.6
Volatile matter	32.2
Free carbon	50.1
Ash	15.1[1]
Ultimate (in percent, unless otherwise noted)	
Hydrogen	5.0
Carbon	67.6
Nitrogen	1.5
Oxygen	9.6
Sulfur	1.2
Calorific value (Btu/lb)	12,060
Air-dried loss	0.3
Forms of sulfur	
Sulfate	0.01
Pyritic	0.66
Organic	0.55
Free swelling index	2.5
Ash fusion temperature (in °F)	
Initial	2,300
Softening	2,430
Fluid	2,520
Hardgrove grindability index	na
Equilibrium moisture (in percent)	na
USGS Research Analyses	
USGS Ash (in percent)	16.0[1]
Oxides (in weight percent of ash)	
SiO_2	50.0
Al_2O_3	26.0
CaO	3.4
MgO	0.28
MnO	0.02
Na_2O	0.38
K_2O	2.5
Fe_2O_3	7.0
TiO_2	1.2
P_2O_5	1.3
SO_3	2.3
Minor elements (whole-coal basis, in parts per million (ppm))	
Si	37,000
Al	22,000
Ca	38,000
Mg	270
Na	450
K	3,400
Fe	7,800
Ti	1,100
S	1,500
Trace elements (whole-coal basis, in parts per million (ppm))	
Ag	0.011
As	7.6
Au	1.1
B	66.0
Ba	150.0
Be	0.99
Bi	1.1
Br	11.0
Cd	0.058
Ce	24.0
Cl	540.0
Co	3.9
Cr	22.0
Cs	2.3
Cu	12.0
Dy	2.5
Er	1.1
Eu	0.47
F	140.0
Ga	5.3
Gd	1.7
Ge	0.98
Hf	1.0
Hg	0.22
Ho	0.76
In	0.76
Ir	1.7
La	13.0
Li	40.0
Lu	0.15
Mn	35.0
Mo	0.19
Nb	2.1
Nd	8.5
Ni	9.4
Os	2.5
P	900.0
Pb	4.8
Pd	0.11
Pr	7.6
Pt	0.52
Rb	32.0
Re	1.1
Rh	0.25
Ru	0.25
Sb	0.7
Sc	5.1
Se	1.5
Sm	1.9
Sn	0.34
Sr	340.0
Ta	0.36
Tb	0.33
Th	3.9
Tl	0.52
Tm	0.52
U	1.0
V	24.0
W	0.6
Y	5.9
Yb	1.1
Zn	11.0
Zr	24.0

[1]USGS ash slightly different from ASTM ash because of different temperatures used in ashing furnaces.

State geological surveys and universities. ASTM analyses were performed by the former U.S. Bureau of Mines (USBM) and by independent testing laboratories; analyses for oxides and trace elements were performed at USGS laboratories based on USGS-developed standards.

SAMPLING TECHNIQUES

Most analyses of coal, for both standard and research purposes, are conducted on carefully collected samples of whole coal. Coal samples are taken from a variety of places—individual coal beds in place, coal-mine conveyor systems, trucks, train cars, or stockpiles—depending on the needs of the sampling and analytical programs. The goal of this process is to collect a sample that will be as representative as possible of the coal bed or other source from which it is taken. In order to produce reliable results from testing programs, sampling must be done very carefully. Samples must be taken without contamination from extraneous material, and location and orientation must be documented.

There are also a few techniques for analyzing coal beds in place. Geophysical logging is conducted in drill holes during exploration and mine planning programs. This technique measures electrical resistivity, transmissivity of sound, inherent electrical properties (such as self-potential), and the reaction of coal to bombardment by atomic particles (such as neutrons) (Wood and others, 1983). These methods accurately identify coal beds and their boundaries, and help determine whether a coal bed merits additional exploration and mining; however, they are only good for an approximate analysis of coal quality.

Channel and drill-holecore samples are two of the most common types of samples used for characterizing a coal bed. A channel sample is taken from a freshly exposed coal bed (usually in an underground or surface coal mine) by cutting a 2- to 4-in channel into the bed from top to bottom and collecting all the coal from the channel (fig. 26). Drill-hole core samples (fig. 27) are taken from subsurface coal beds where the coring bit does the cutting. If the coal bed is divided horizontally into benches (individual beds of coal separated by mineral partings), or if the bed is layered by distinct types of coal, then the benches or beds may be sampled separately, which allows for a more detailed characterization of the individual parts. The ASTM recently has published standards for the collection of channel and core coal samples (ASTM International, 2002).

The number of channel or core samples taken depends on how well the coal bed needs to be characterized. If any two samples of the same bed show considerable variation in quality between them, then more samples may be taken from the area between the two initial samples; however, cost may be a factor in the decision to collect more samples.

Figure 26. Photograph of a coal bed "face" in an underground coal mine showing personnel collecting a channel sample of fresh coal. The collecting team is standing on a floor that has been excavated below the base of the coal bed to facilitate mining. The white color in the background is limestone dust sprayed on the coal face to control coal dust. The coal sample is collected on a clean plastic sheet to minimize contamination from the floor of the mine. This sample is from the Lower Freeport coal bed, Indiana County, Pa., where the bed is about 56 in thick. Photograph by R.W. Stanton (U.S. Geological Survey).

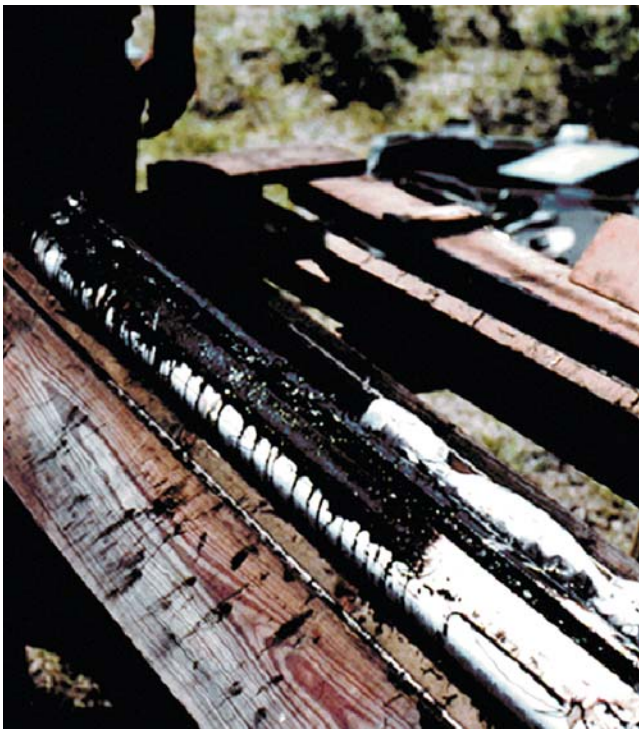
The purpose of the analysis often determines the type of sample that is collected. If the purpose is to characterize a stock of already mined coal, then gross samples may be taken at regularly or randomly spaced intervals from the stockpile, coal car, or conveyor belt. If the purpose is to examine some specific property of a coal bed, then a sample of only a small part of the bed may be taken. If the purpose of the sample is to study some directionally controlled characteristic, such as the orientation of mineral grains, the sample must be labeled to show top and bottom and, in some cases, compass directions. For some types of analyses (for example, by either petrographic or scanning-electron microscope, figs. 11, 13B, 13C, 14), small blocks of coal are cut out of larger samples and one side is polished and examined. This technique is used when it is necessary to see the microscopic details of the types, distributions, and arrangements of the macerals and minerals in a coal sample.

When a coal sample arrives at the lab, it is crushed (unless it is to be examined in block form) and its particles are thoroughly mixed to ensure that the sample is homogeneous. The crushed sample then is divided into appropriately sized subsamples for each analytical technique to be used.

ANALYSIS

The primary reason for analyzing coal is to determine whether it will meet the needs of a specific application, or to characterize the general quality of the coal for future ref-

A



B

Figure 27. Photographs of a core-drilling rig and a collected core. ***A***, A truck-mounted, mobile, core-drilling rig on location in the process of collecting core of the Upper Freeport coal bed in western Pennsylvania. Photograph by R.W. Stanton (U.S. Geological Survey). ***B***, Coal core, 3 inches in diameter, from a coal bed in the Powder River basin, Wyoming. The white material beneath the core is plastic tubing used to collect the core and prevent it from falling apart. The upper half of the tubing has been removed to provide access to the coal. Photograph by P.D. Warwick (U.S. Geological Survey).

erence. For instance, coal may be analyzed to determine how much sulfur (or other element) is present, its form, and how it is distributed. If the sulfur is present in discrete pyrite grains, then much of it may be cleaned out of the coal; but, if it is organically bound, then the sulfur may be released only by burning, by using a solvent, or by employing a bacteriologic technique (although the latter two techniques are still largely experimental). If the coal has a high organic sulfur content, then it may have to be mixed or blended with a coal of lower sulfur content in order to meet sulfur emissions standards, or the sulfur may have to be cleaned out of the flue gas by flue-gas desulfurization (FGD), which is an expensive procedure. Similarly, analysis may determine whether a trace element, such as arsenic, may be eliminated from a coal by washing or whether it must be trapped in the flue gas. Finally, in extreme cases, analysis may determine that the coal cannot be used.

In general, the coal-mining and coal-consuming industries determine coal quality for immediate or near-term use, whereas Federal and State governments analyze coal to (1) characterize large areas of unmined coal (resources) for future reference, (2) to support policy decisions related to future coal use, and (3) to supply Federal and State regulatory agencies with information about the quality or special characteristics of future coal supplies, such as the presence, amounts, and modes of occurrence of sulfur and potentially toxic trace elements. Figure 28 shows a coal scientist at work identifying coal macerals and coal rank in a polished sample of coal using a high-powered, reflected-light microscope.

Coal samples may be received at the laboratory in a variety of conditions. Accordingly, analytical results may be reported in a variety of ways, depending on the condition of the samples when received and the use of the analysis. Some samples arrive in a fresh condition, not long after sampling; these may be analyzed without further processing, except grinding and mixing. The analytical results for these samples are reported on an “as-received” basis. Some samples arrive dried out due to long storage, transportation over long distances, or mishandling. The results of analyses on dried-out samples are reported on a “dry” basis. The opposite conditions may also occur if the sample arrives

wet because of excess moisture in the sample that may or may not be present in the coal bed; in this case the analyses may be reported on a "moist" basis.

Analyses also may be reported on a "mineral-matter-free" or "dry, mineral-matter-free" basis for use in calculating coal rank because rank is a function only of the maturity of the organic matter. "Mineral-matter-free" means that the amount of mineral matter in the sample has been subtracted from the total analytical results to provide only the amount that is organic. "Dry, mineral-matter-free" means that the sample was received in a dry or nearly dry state, or was dried out before an analysis was made.

An analysis on a mineral-matter-free basis also may be used for comparison with the results of an as-received analysis of "run-of-mine" coal (as it comes from the mine) if there is to be further processing, such as coal cleaning. Run-of-mine coal frequently contains (1) large amounts of mineral matter from partings in the coal bed, (2) rocks from above and below the coal bed that are mined along with the coal, (3) minerals that fill veins in the coal bed, and (4) mineral matter dispersed in the coal (such as pyrite grains). Mineral matter in run-of-mine coal may cause the coal to exceed the ash and sulfur limits set by contract requirements and environmental regulations. A mineral-matter-free analysis may indicate whether or not it will be worthwhile to clean the coal; however, the need for cleaning depends on the intended use of the coal and normal cleaning practices may not bring a coal to a completely mineral-free condition.

Most chemical analyses require the destruction of the coal sample in order to determine calorific value, volatile matter, and mineral-matter content. Destruction is achieved by burning the coal sample in a high-temperature furnace. Although that procedure is fine for determining the calorific value of coal, it is not suitable for retention of some of its volatile inorganic elements, such as mercury. Subjecting the sample to a process called "low temperature ashing," in which the sample is exposed to high-frequency radiation in a high-oxygen atmosphere, permits the organic matter to be driven off while preserving most of the mineral matter. Nevertheless, some of the very volatile inorganic elements (such as chlorine, mercury, or selenium) may be lost in this process and are best measured in whole-coal samples by X-ray fluorescence or other techniques. Most microscopic and microprobe techniques require whole-coal samples because the objective is to determine the interrelations between the constituent parts of the coal.

ORGANIC GEOCHEMISTRY

Because coal is principally an organic substance, organic geochemistry is an important factor in the study of the origin, structure, quality, and utilization of coal.

Figure 28. Photograph of a coal scientist at work identifying coal macerals and rank in a polished sample of coal using a high-powered, reflected-light microscope. Photograph by R.W. Stanton (U.S. Geological Survey).

Determining the organic matter in coal is necessary for studying (1) the organic structure and the organic sulfur compounds in coal, (2) modern peat-forming swamps as analogues of ancient peat-forming swamps, (3) the potential for coal gasification and liquefaction, and (4) the effects of coal mining and coal use on surface water, ground water, and air quality.

Recent advances in analytical instrumentation have greatly aided organic geochemical studies of coal. Most coals consist of a mechanical mixture of two principal organic components: (1) resin-like (aliphatic) organic matter of uncertain origin (that is, the specific plant structures have been destroyed during the coalification process), and (2) benzene-like (aromatic) organic matter derived from wood tissues (lignin). Using solid-state, ^{13}C nuclear-magnetic-resonance (NMR) spectroscopy, coals now are routinely classified based on their aromatic content.

Organic geochemical studies of modern peat attempt to relate processes occurring in modern environments to those that occurred in ancient peat swamps.

Other commonly used analytical techniques such as gas chromatography/mass spectrometry, the electron microscope, and the scanning electron microscope are used to study the organic sulfur concentration and distribution in coals. So far, these studies seem to indicate that most of the sulfur in organic compounds in coal is present at the edges of the organic molecules. This finding may aid the development of effective desulfurization procedures for coal containing large amounts of organically bound sulfur.

The energy produced and the reactivity of coal during burning is determined by its chemical and physical struc-

ture. Through computer-assisted molecular design, scientists can now construct two- and three-dimensional models of organic compounds in coal and determine the arrangements of the elements in various model structures.

Organic geochemical studies of modern peat deposits attempt to relate processes occurring in modern environments to those that occurred in ancient peat swamps. Such studies serve as a mechanism for a better understanding of and an ability to predict coal quality by providing insight into the early stages of coal formation; for example, a geochemical analysis of an ombrogenous peat, which is easy to sample, greatly enables the ability to predict the quality of other coal deposits that originated as ombrogenous peat deposits but that are much more difficult and costly to sample.

MINERAL-MATTER CHEMISTRY

Studies of mineral matter in coal are performed by a variety of analytical techniques. The principal techniques are analytical chemistry, X-ray spectroscopy, scanning-electron microscopy, petrography, and mineralogical studies (table 2). Two newer techniques, (1) inductively coupled plasma, atomic-emission spectrometry (ICP-AES); and (2) inductively coupled plasma, mass spectrometry (ICP-MS), have been applied to coal analysis with excellent results and are worth a brief description. Using these techniques, a sample of coal ash is first decomposed with various acids and put into solution. The solution is then aspirated into a flame (plasma), which energizes the atoms of the different elements present in the solution to generate characteristic wavelengths of radiation. The spectrum produced by the radiation is then measured in a spectrometer. The data from the spectrometer are fed into a computer where the results are compared to standard samples and the concentration of each element in the sample is calculated. The two ICP techniques simultaneously and quantitatively analyze about 50 different inorganic elements, which is a large increase in the efficiency of coal analysis. The ASTM recently has adopted ICP-AES and ICP-MS techniques as industry standard methods for analyzing coals for inorganic elements (ASTM International, 2002).

Microscopic studies of coal petrography are used to identify the constituents in coal and how they are arranged and to provide knowledge of the maceral composition and distribution. Coal petrographers may assess the rank of a coal by measuring the intensity of light reflected from the vitrinite macerals in a polished surface of a coal sample; the higher the reflectivity, the higher the rank. In some instances, however, petrographic study is not adequate to characterize all of the coal constituents. For example, if mineral matter, such as pyrite, exists as extremely small discrete grains, or if it is located inside plant cells (which are also extremely small), then identification becomes difficult with an optical microscope. In these cases, a scanning-electron microscope is used to study minute particles of mineral material. Figure 14 is a photomicrograph taken with a scanning-electron microscope of plant cells in coal containing minute grains of pyrite. In this case, chemical and mineralogic analyses had already determined the presence of pyrite, but the photomicrograph allows the pyrite to be studied in greater detail. This information could be used to determine whether the coal must be ground into a powder that is fine enough to liberate such fine-grained pyrite (an expensive process).

CONCLUSIONS

Although much is known about coal quality, much also remains to be learned. To this end, research on coal quality is being conducted in both the public and private sectors. Current studies encompass all aspects of the origin, burial history, and composition of coal in order to understand the various factors involved in determining coal quality, such as how and where to find the right coal for a specific use and how to clean coal to make its use more environmentally and industrially acceptable.

In the past, the only consideration given to coal quality was whether coal lumps held together during shipping burned easily to produce a hot fire and didn't produce too much ash. Today, however, concerns about human health, the environment, energy demands, and the supply of certain raw materials have broadened our concept of coal quality and our need to know much more about the origins, nature, and effects of coal quality. An extensive evaluation of coal quality must be central to coal use. Whatever coal is used for, whether for the direct production of energy, chemicals, synthetic fuels, or the recovery of useful minerals, and whatever problems and solutions accompany that use depend on the quality of the coal. Additional, sophisticated, multidisciplinary research on coal quality is required for the future. The results will help make it possible for society to continue to benefit from the good qualities of coal and to make progress in avoiding the undesirable affects of coal use.

In the near term, the most immediate advancements related to coal-quality research appear to be improvements in the efficiency of coal use (including more efficient production of synthetic fuels) and the development of methods to best understand, and thus control, the less desirable components in coal that have the potential to contribute to environmental degradation and adverse health effects. In the longer term, the recovery of useful substances from coal (such as iron, silver, sulfur, and zinc, as well as organic chemicals, gypsum, and ash) should be an exciting area for research related to coal quality.

COAL QUALITY AND PUBLIC HEALTH

By Robert B. Finkelman

Prior to the widespread adoption of selective mining procedures and pollution-control technology, human health had been affected by sulfur and particulates emitted from coal combustion. This section describes several examples of how organic compounds and trace elements are still affecting the health of people in Europe, Asia, and America.

The inorganic (and in some cases, organic) constituents in coal may have profound effects on the health of those people burning coal in their homes or living near coal deposits, coal mines, or coal-burning power plants. Trace elements, such as arsenic (As), emitted from coal-burning power plants in Europe and Asia have been shown to cause severe health problems. Water leaching of organic compounds from lignites may be the cause of a kidney disease that has taken the lives of more than 100,000 people in the Balkans. Widespread health problems may be caused by domestic coal combustion in developing countries. Millions of people suffer from fluorosis, thousands from arsenism. In the southwestern U.S., many members of the Navajo Nation are dependent on coal as their primary source of energy. Many Navajo suffer from chronic respiratory problems that are attributed to emissions from the burning of coal in their hogans.

A better knowledge of coal-quality parameters may help to minimize some of these health problems. Information on the concentrations and distributions of potentially toxic elements in coal may help us to avoid those parts of a coal deposit having undesirably high concentrations of these elements.

Information on the modes of occurrence of these elements and the textural relations of the minerals and macerals in which they occur may help us to anticipate the behavior of the potentially toxic components during coal cleaning, combustion, weathering, and leaching. Coal quality characterization, therefore, offers coal scientists opportunities to contribute to important societal needs such as improved public health.

POLYCYCLIC AROMATIC HYDROCARBONS (PAHS)

BALKAN ENDEMIC NEPHROPATHY

Balkan endemic nephropathy (BEN) is a potentially fatal degenerative kidney disease common in parts of former Yugoslavia, Bulgaria, and Romania. An article in a popular science magazine attributed more than 100,000 deaths to BEN since it was recognized as a distinct disease in 1956 (Zimmerman, 1983). Intensive medical research had failed to identify the cause of BEN or to explain why it occurs in clusters of villages along river valleys.

In the early 1990s, U.S. Geological Survey (USGS) researchers identified a link between the occurrence of BEN and the distribution of Pliocene lignites, which are the youngest, most chemically reactive coals in the Balkans region (Feder and others, 1991). They suggested that BEN is attributable to ingestion of organic compounds from well water that had been in contact with Pliocene lignites. Ground water in the endemic villages was found to be highly concentrated in organic chemicals such as PAHs. They also suggested that the hydrocarbons, some of which were known carcinogens, were the cause of BEN. Further evidence was found from laboratory experiments. Using distilled water to leach samples of Pliocene lignites from Yugoslavia, USGS researchers extracted a suite of PAHs similar to that found in the well water of the endemic villages (Orem and others, 1999).

BEN also may exist in Turkey and other countries. Turkey has extensive near-surface deposits of Pliocene lignites and many Turkish villagers rely solely on well water for their drinking needs. If these wells are drilled into the Pliocene lignite aquifers or into aquifers in contact with the lignites, BEN could result from drinking the water.

Information on the concentrations and distributions of potentially toxic elements in coal may help us to avoid those parts of a coal deposit that have undesirably high concentrations of those elements.

LUNG CANCER

PAHs released during unvented coal combustion in homes in Xuan Wei County, China, have been cited as the primary cause for the highly elevated incidence of lung cancer there. The PAH levels in the homes burning "smokey" coal are at industrial levels resulting in a lung cancer mortality rate five times the national average of China (Mumford and others, 1987).

TRACE ELEMENTS

Concerns have been expressed in the United States and elsewhere over the release of As, Be, Cd, Cl, Co, Cr, F, Hg, Mn, Ni, Pb, Sb, Se, and U during the burning of coal. Recent data from the U.S. Environmental Protection Agency (EPA) (1996) indicate that trace-element emissions

from coal-burning power plants that use coal with relatively low to moderate trace-element concentrations, or that have efficient pollution control devices may not present a significant health risk. Their data indicate that the risk of cancer from trace elements inhaled by humans who live or work near power plants is less than 1 in 1 million.

Elsewhere in the world, trace elements emitted from coal-burning power plants have been shown to cause severe health problems. In Czechoslovakia, children living in the vicinity of a power plant that burned high-arsenic lignite (about 1,000 parts per million (ppm) on a dry basis) suffered significant hearing loss that was attributed to arsenic poisoning from the power-plant emissions (Bencko and Symon, 1977). Perhaps the most widespread health problems are caused by domestic coal combustion in developing countries. Millions of people suffer from fluorosis and thousands suffer from arsenosis caused by coal combustion in China. Selenium and mercury poisoning also have been attributed to domestic coal combustion in China. Adsorption of fluorine by corn dried over high-fluorine (>200 ppm) coal fires is the probable cause of extensive dental and skeletal fluorosis in southwest China. The problem is compounded by the use of clay as a binder for making briquettes; that clay typically is a high-fluorine (about 900 ppm) residue from the intense leaching of the limestone substrate.

In Guizhou Province, China, the practice of drying chili peppers over high-arsenic coal fires has led to thousands of cases of arsenic poisoning (Finkelman and others, 1999). The contaminated chili peppers commonly are used for cooking and thus become the principal source of arsenic poisoning. One coal sample from this region analyzed at the U.S. Geological Survey laboratory contained 35,000 ppm arsenic on an as-received basis! Chili peppers dried over the high-arsenic coal fires contain more than 500 ppm arsenic (fresh chili peppers contain less than 1 ppm arsenic). Arsenosis, which results from ingestion of the chili peppers tainted with arsenic from the mineralized coal, also has led to severe skin cancers in the affected population (Finkelman and others, 1999).

Nearly 500 cases of human selenosis in southwest China have been attributed to the use of selenium-rich, carbonaceous shales known locally as "stone coal" (Zheng, 1992). The stone coals contain as much as 8,390 ppm selenium. The selenosis is attributed to the practice of using the combustion ash as a soil amendment. This introduces large amounts of selenium to the soil and results in selenium uptake by the crops.

Coal combustion is considered to be the largest man-made source of mercury in the environment. Although there are no confirmed reports that mercury from emissions directly impacts human health, mercury may contribute to health problems through bioaccumulation in the food chain. Mercury, a portion of which is derived from coal combustion, is deposited in lakes and rivers and can be converted to toxic methylmercury, which then accumulates and becomes enriched in fish and birds. Cases of mercury poisoning have been documented in people who eat contaminated fish for prolonged periods, both in the United States and abroad. Pregnant women and subsistence fishermen are particularly vulnerable.

A rare occurrence of chronic thallium poisoning was reported from Guizhou Province, China (Zhou and Liu, 1985). The source of the thallium poisoning appears to be from vegetables grown in soil developed over a mercury-thallium-rich mining slag. Most symptoms, such as hair loss, are typical of thallium poisoning; however, loss of vision in several patients was considered to be unique. Mineralogical analysis of coal used in the homes of the patients with visual impairment revealed abundant mercury minerals. Chemical analysis of a sample of coal being used in Guizhou Province, China, indicated the mercury concentration to be 55 ppm (Finkelman, 1999), about 200 times the average mercury concentration found in U.S. coals.

SUMMARY

Coal scientists and technologists are ideally positioned to help minimize health problems due to coal combustion by providing information on coal quality. Information on the concentrations and distributions of potentially toxic elements in coal may assist people dependent on local coal sources to avoid those areas of a coal deposit having undesirably high concentrations of toxic compounds. Information on the modes of occurrence of potentially toxic elements and the textural relations of the minerals and macerals in which they occur may help us to anticipate the behavior of the potentially toxic components during coal cleaning, combustion, weathering, and leaching.

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APPENDIX 1

FEDERAL AGENCIES WITH REGULATORY OR RESEARCH RESPONSIBILITIES FOR COAL AND COAL QUALITY

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Prepared in cooperation with Servicio Geológico Colombiano, Bogotá, Colombia

Topics in Coal Geochemistry—Short Course

Open-File Report 2018–1145

U.S. Department of the Interior
U.S. Geological Survey

Topics in Coal Geochemistry—Short Course

By Allan Kolker

Prepared in cooperation with Servicio Geológico Colombiano, Bogotá, Colombia

Open-File Report 2018–1145

U.S. Department of the Interior
U.S. Geological Survey

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Preface

This short course consists of material presented by Allan Kolker at Servicio Geológico Colombiano (SGC), the Geological Survey of Colombia, in Bogotá, Colombia, November 28–30, 2016, and November 27–30, 2017. The material is organized into five sessions, prepared at the invitation of the SGC as a training module for its research staff. The material presented is primarily based on studies conducted by the author and his collaborators during previous USGS investigations.

Colombia is a major coal producer, primarily of export coal, and the module provides information needed by SGC on coal quality and environmental issues related to coal production and use. Some examples given are specific to Colombian coal, but the overall principles discussed are relevant to the topic of coal geochemistry and should be useful for general application. Slide headings in English and Spanish are included in presentation slides (appendix 2).

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Abbreviations

Al	aluminum
AMD	acid mine drainage
APCD	air pollution control device
As	arsenic
ASTM	American Society for Testing and Materials (now ASTM International)
atm	atmosphere
Au	gold
Be	beryllium
Boiling PTS	boiling points
Br	bromine
BSE	backscattered electron (image)
Btu	British thermal unit
Btu/lb	British thermal unit per pound
CCP	coal combustion product
Cd	cadmium
cESP	cold side electrostatic precipitator
Cl	chlorine
CLR/clr	centered log-ratio transformation
Co	cobalt
CO_2	carbon dioxide
COALQUAL	U.S. Geological Survey coal quality database
CPP	Clean Power Plan
Cr	chromium
Cu	copper
CVAA	cold vapor atomic absorption
CVAFS	cold vapor atomic fluorescence
°C	degrees Celsius
DMA	direct mercury analysis/analyzer
D,mmf	Dry, mineral matter free
DOE	U.S. Department of Energy
EDX	energy dispersive X-ray spectroscopy/analyzer
EERSC	USGS Eastern Energy Resources Science Center
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency

EPMA	electron probe microanalysis
Eskom	South Africa national electric utility
ESP	electrostatic precipitator
eV	electronvolts
FA	fly ash
Fe	iron
FeS_2	pyrite, marcasite, or iron disulfide
FF	fabric filter
FGD	flue-gas desulfurization
°F	degrees Fahrenheit
GWh	gigawatt hours
HCl	hydrochloric acid
hESP	hot side electrostatic precipitator
HF	hydrofluoric acid
Hg	mercury
Hg°	elemental mercury
Hg_p	particulate mercury
HNO_3	nitric acid
HR	high resolution
HREE	heavy rare earth elements
ICP-MS	inductively coupled plasma-mass spectrometry
ICR	Information Collection Request
IEA	International Energy Agency
ILR/ilr	isometric log-ratio transformation
INAA	instrumental neutron activation analysis
IUPAC	International Union of Pure and Applied Chemistry
km	kilometer
kt	thousand tonnes
LA-ICP-MS	laser ablation-inductively coupled plasma-mass spectrometry
LNLS	Laboratório Nacional de Luz Síncrotron, Brazilian National Synchrotron Laboratory
LOI	loss on ignition
LREE	light rare earth elements
MATS	Mercury and Air Toxics Standards
mg/kg	milligram per kilogram
mg/L	milligram per liter

mi	mile
MJ/kg	Megajoules per kilogram
m,mmf	Moisture containing, mineral matter free
Mn	manganese
MREE	middle rare earth elements
Mt	million tonnes
$\mu g/m^3$	microgram per cubic meter
µm	micrometer
n	number
na	not applicable
NASC	North American shale composite
Ni	nickel
NIST	National Institute of Standards and Technology
Norm.	normalized
NO_x	nitrogen oxides
O_3	ozone
Pb	lead
PbS	galena
PbSe	lead selenide
PC	pulverized coal
PCD	particulate control device
PIXE	proton induced X-ray emission
$PM_{2.5}$	fine particulate matter $\leq$ 2.5 micrometers
ppb	parts per billion
ppm	parts per million
PTS	points
Rb	rubidium
REE	rare earth elements
Ref	EIA Annual Energy Outlook 2016 Reference with Clean Power Plan (CPP)
RGM	reactive gaseous mercury
Sb	antimony
SCR	selective catalytic reduction
SDA	spray dry absorber
Se	selenium
SEM	scanning electron microscope/microscopy

SGC	Servicio Geológico Colombiano
SO_2	sulfur dioxide
SOP	standard operating procedure
SRM	standard reference material
SXRF	synchrotron X-ray fluorescence
TCLP	Toxicity Characteristic Leaching Procedure
TEM	transmission electron microscope/microscopy
Ti	titanium
UNEP	United Nations Environment Programme
USGS	U.S. Geological Survey
V	vanadium
wt. %	weight percent
XAFS	X-ray absorption fine structure
XANES	X-ray absorption near-edge structure
XRD	X-ray diffraction
Y	yttrium
Zn	zinc
Zr	zirconium

Topics in Coal Geochemistry—Short Course

By Allan Kolker

Introduction

This short course was prepared at the request of Servicio Geológico Colombiano (SGC) as a module for staff training. Prior to the short course, the SGC expressed interest in receiving training in (1) geochemistry and quality of coal; (2) geochemistry of trace elements in coal; (3) mercury and halogens in coal; (4) characterization and cycling of atmospheric mercury; (5) mercury, trace elements, and organic constituents in atmospheric fine particulate matter; (6) mercury in coal and the effect of coal quality on mercury emissions from combustion systems; (7) environmental and health effects related to coal use; and (8) related topics in coal combustion processes. A five-session short course was prepared that addressed all but the engineering aspects of coal use. In the sections that follow, topic overviews are given for the material that was presented. Brief descriptions of each slide are given in appendix 1, and the actual short course material, presented as a series of PowerPoint slides, is included in Portable Document Format (PDF) as appendix 2.

Session 1

The goal of this session is to present the larger context of coal geochemistry, before discussing specific details. World coal production is examined as well as dependence on coal for power generation. Columbia has extensive hydroelectric resources and, as a result, exports most of its coal production. Also in this session, basic parameters applicable to coal characterization are reviewed. Emerging limits for mercury and carbon dioxide (CO_2) emissions from coal-burning utility power stations are discussed from global and U.S. perspectives, updated to their status as of November 2017.

1.1 Global Coal Production and Use

In this section, available information about global coal production is discussed from Colombian and U.S. perspectives based on the most recent International Energy Agency (IEA) and U.S. Energy Information Administration (EIA) data. Colombia is highlighted as the 11th largest coal producer and the 4th largest coal exporter in the world. The United States is 1st in terms of coal reserves, and Colombia is 12th (World Energy Council, 2013). Because of its abundant hydroelectric resources, Colombia is among the lowest in the world in its dependency on coal for electric power generation (only about 10 percent). By contrast, the United States is slightly below the world average in terms of dependence on coal for power generation, but this dependence has been steadily decreasing due to the abundance of shale gas (World Bank, 2013; EIA, 2016). International Energy Agency data on coal production show increasing production of Colombian coal for nearly three decades with almost all of that produced for export (IEA, 2016; appendix 2, slide 1.1-5). The La Guajira and Cesar Departments of Colombia are the largest producers of coal relative to other parts of the country (World Coal, 2011), but smaller coal mines are present over a large part of both the eastern and western basins (Tewalt and others, 2006; appendix 2, slide 1.1-6).

In a series of slides, the U.S. energy mix for power generation is compared to that of Colombia. Coal production in the United States increased steadily for three decades up until about 2010, when it began to decline (EIA, 2016). This decline was most pronounced in the two largest U.S. coal-producing regions: the Appalachian Basin and the Powder River Basin. At the same time, coal production in the Illinois Basin was increasing, due in large part to the increased use of flue-gas desulfurization (FGD) scrubbers in the United States, because high-sulfur coal is needed to operate the scrubbers efficiently. As a result, sulfur emissions were no longer an impediment to the use of high-sulfur coal (EIA, 2016; appendix 2, slide 1.1-10). The larger trends of increasing gas-fired power generation and decreasing coal-fired power generation in the United States mirror the increase in U.S. shale gas production (EIA, 2016; appendix 2, slides 1.1-11, 1.1-14). In the current (2015) U.S. energy mix, coal and gas each account for 33 percent of net electric generation. Trends projected by the EIA show an increase in renewables and a continued increase in gas in the United States, with a corresponding decrease in the proportion of coal used for power generation. The extent of reduction in coal use depends on whether the proposed U.S. Environmental Protection Agency (EPA) Clean Power Plan (CPP; EPA, 2015) is adopted (EIA, 2016; section 1.3).

To conclude this section, U.S. Geological Survey (USGS) studies about shale gas production and its effects and about CO_2 storage capacity in U.S. saline reservoirs are discussed (USGS, 2013). Shale gas topics include studies of pore structure in shales to understand gas distribution, sampling of water produced together with gas (produced water) and testing of produced water for additives used in hydraulic fracturing. The USGS assessment of CO_2 storage capacity shows the largest capacity in the Gulf Coast, Rocky Mountains, northern Great Plains, and Alaska. The assessment of CO_2 storage capacity shows that the largest storage capacity for CO_2 is not near the greatest concentration of U.S. coal-fired power stations in the Midwestern States, requiring substantial addition of pipeline infrastructure to take advantage of this storage capacity (USGS, 2013; appendix 2, slide 1.1-16).

1.2 Review of Basic Coal Data

In this section, basic approaches to coal characterization are reviewed, and more detailed information specific to trace elements in coal and coal ash is presented later in the short course. To begin this section, basic concepts such as coal rank, heating value, moisture, and mineral matter (ash) are reviewed. Important American Society for Testing and Materials (ASTM) approaches for coal characterization are described, including how to collect coal samples and prepare them for analysis, and what is included in essential ASTM determinations such as Proximate Analysis (ASTM D3172), Ultimate Analysis (ASTM D3176), Forms of Sulfur (ASTM D2492), and Rank Classification (ASTM D388). An example of ASTM D388 Rank Classification is given in appendix 2, slide 1.2-6, for four Colombian coal samples based on proximate analyses reported by Tewalt and others (2006). Three examples of sulfur forms determinations are provided, including a freshly collected low-sulfur South African coal and a freshly collected U.S. Illinois Basin high-sulfur coal, each having different total and pyritic sulfur contents. The third example is a weathered, moderate-sulfur Ukrainian coal sample collected from an outcrop, showing characteristic sulfate formation (appendix 2, slide 1.2-10). Useful publications are highlighted, including USGS Circular 1143 (Schweinfurth, 2003), which provides an introduction to coal science and coal quality, and USGS Open-File Report 2012–1205 (East, 2013), which shows the distribution of U.S. coal basins and illustrates the ASTM D388 Rank Classification for coal.

1.3 Toward Global Emissions Standards

In this section, implications of coal use for the global environment are considered in a status report on the state of efforts to limit carbon and mercury emissions, both globally and in the United States. For carbon emissions, the global effort is the Paris Agreement on Climate Change adopted on December 12, 2015 (United Nations, 2017). In the Paris Agreement, each participating country is expected to have a plan to reduce carbon emissions. At the time of the first short course in November 2016, ratification status of the agreement had been reached. Since then, in June 2017, the United States has sought to withdraw from the agreement. Current status of the Paris Agreement on Climate Change is given at http://unfccc.int/paris_agreement/items/9485.php. The U.S. plan to limit powerplant carbon emissions is the EPA Clean Power Plan (CPP), introduced in 2015 (EPA, 2015). The CPP has a goal of a 32-percent carbon reduction relative to 2005 emissions by 2030 (appendix 2, slide 1.3-3). However, at the time of the first short course, implementation of the CPP was on hold by the U.S. Supreme Court, and more recently, the EPA has proposed to repeal it.

The Minamata Convention on Mercury (United Nations Environment Programme [UNEP], 2016) is a global effort to control the release of mercury and limit its use. The convention includes controls on air emissions of mercury as well as a ban on new mercury mines, phase-out of existing ones, and regulation of mercury used in small-scale gold mining. At the time of the first short course in November 2016, more than 100 countries had signed the convention, but it had not reached the 50 ratifications required for it to go into effect. Since then, the minimum needed for ratification has been reached, and in August 2017, the Minamata Convention entered into force. The current status of the Minamata Convention is given at http://mercuryconvention.org/.

In the United States, the EPA Mercury and Air Toxics Standards (MATS) were introduced to limit emissions of mercury [Hg], other harmful trace elements (Beryllium [Be], Chromium [Cr], Manganese [Mn], Cobalt [Co], Nickel [Ni], Arsenic [As], Selenium [Se], Antimony [Sb], and Lead [Pb]), listed in order of increasing atomic number, and acid gases (hydrofluoric acid [HF], and hydrochloric acid [HCl]; EPA, 2011a). These standards apply to all coal- and oil-fired power generating units greater than 25 megawatts, which is essentially all power generation at the utility scale. Rationale for MATS is given in a series of slides showing that (1) powerplants are the largest source of U.S. mercury emissions; (2) other toxic metals from powerplants such as arsenic, chromium, and nickel can cause cancer; (3) fish consumption advisories for mercury are in effect in every State; (4) substantial health benefits, including avoidance of premature deaths and hospitalizations for respiratory and cardiovascular diseases, are projected to result from MATS (EPA, 2011b); and (5) compared to other industrial sectors that have become regulated, the unregulated utility sector has shown minimal reduction in mercury emissions (appendix 2, slide 1.3-6, 1.3-7). Finalization of MATS in April 2016 preceded the first short course. The current status of the MATS program is given at https://www.epa.gov/mats.

Session 2

In this session, detailed information on the distribution and controls of trace elements in coal is presented. Emphasis is given to iron disulfides pyrite and marcasite (both FeS_2) because these minerals host many of the elements of environmental interest, such as As, Se, Sb, Hg, and Pb in coal. Results are presented on the basis of published determinations by the author using microanalysis and by other results from the literature. The goal of this session is to provide a better understanding of the occurrence and effect of trace elements in coal as a foundation for a later session on the behavior of trace elements in coal combustion (Session 4).

2.1 Trace Elements in Coal

This section begins by providing the rationale for understanding trace element distribution in coal. Reasons include effects on power station operation, prediction of emissions, prediction of element behavior in coal preparation, control of metals release from coal and coal combustion products to groundwater, and minimizing health consequences. This discussion is followed by an introduction to the mode of occurrence concept, which is the form that a chemical element takes within coal. The mode of occurrence of an element determines its behavior during coal combustion and its environmental impact. Mode of occurrence is a function of geologic setting and can also provide information on the geologic history of a sample. In a broad sense, elements in coal may have primary organic and inorganic associations. Among inorganic associations, minor and trace elements may substitute for major constituents, such as chromium in illite-smectite, or occur as discrete trace phases, such as lead selenide (PbSe; Finkelman, 1981; Kolker and Finkelman, 1998). Summaries of mineral matter in coal, trace phases, and modes of occurrence of potentially toxic metals in coal are given in a series of slides (appendix 2, slides 2.1-6 to 2.1-8). An overview of analytical approaches for investigating trace elements is given in this session but is expanded in Session 5. In both Session 2 and Session 5, the importance of moisture determination in accurately expressing the concentration of elements in coal is discussed.

The topic of arsenic in coal is introduced in this section by USGS Fact Sheet 2005–3152, “Arsenic in Coal” (Kolker and others, 2006a; appendix 2, slide 2.1-11). Past USGS studies used a selective chemical leaching approach to infer the mode of occurrence of elements, such as arsenic, in coal (Palmer and others, 1998; Finkelman and others, 2018). On the basis of the removal of arsenic in the nitric acid leaching step of the multi-stage leaching procedure, arsenic shows a predominant pyritic association in bituminous coals. Leaching studies also indicated a less pronounced pyritic association for arsenic in lower rank coals. The occurrence of arsenic as an abundant minor constituent in coal pyrite was confirmed by direct determinations, using electron microprobe analysis (Kolker and others, 2000; Kolker, 2012).

Using a spectroscopic approach, Huffman and others (1994) recognized that a portion of the arsenic associated with coal pyrite is converted spontaneously to arsenate, an oxidized arsenic form, over time. Huggins and others (2002) compared this spectroscopic approach to USGS selective leaching results to monitor progressive arsenic oxidation in the same coal samples. Both methods give similar proportions of arsenate if the HF and HCl leaching fractions combined are assumed to represent the arsenate fraction in coal. In a series of experiments over 18 months, Kolker and Huggins (2007) investigated the extent of arsenic substitution in pyrite on the rate of formation of arsenate in coal. Results showed similar rates of progressive arsenic oxidation under dry conditions regardless of the initial amount of pyritic arsenic. As an analogue for development of acid mine drainage in samples that were wetted, arsenic oxidation is much more rapid, leading to nearly 100 percent arsenate, a highly mobile arsenic form, by the end of the experiment (appendix 2, slide 2.1-15; Kolker and Huggins, 2007).

2.2 Trace Elements in Iron Disulfides

Iron disulfides are common components of coal and are known to contain harmful elements such as arsenic, selenium, and mercury. Studying the distribution of these constituents is especially helpful in understanding dispersion of air and water pollutants and in optimizing approaches for their reduction by coal preparation. In this section, the extents and modes of substitution of minor constituents into iron disulfides is reviewed together with the growth history of iron disulfides in coal. Divalent cations such as Co^{2+}, Ni^{2+}, Cu^{2+}, and Zn^{2+} generally substitute for Fe^{2+}, whereas monovalent anions such as As^{-}, Se^{-}, and Sb^{-} generally substitute for S^{-} (Deditius and others, 2008). Coupled substitution has been recognized most notably as a mechanism for hosting gold in pyrite as As^{3+} plus Au^{+}. Substitution of minor constituents in iron disulfides is compiled from the literature, with emphasis on the occurrence of arsenic and mercury in pyrite (appendix 2, slide 2.2-3; Kolker, 2012).

Backscattered electron (BSE) imaging and wavelength-dispersive elemental mapping reveal similar growth histories and patterns of element enrichment in iron disulfides occurring in widely dispersed coals. Framboidal pyrite is always the earliest iron disulfide generation and is almost always arsenic poor. Single framboids or composite framboid masses are commonly overgrown by a later pyrite generation that is distinguished by a subhedral texture. Overgrowths on framboids may also be

distinct compositionally, often showing enrichment in arsenic or other constituents relative to the earlier framboid as shown in appendix 2, slides 2.2-7 to 2.2-9, and in Kolker (2012). In some cases, framboids were found to have preferential nickel enrichment at or near their centers, which may indicate nickel availability in earliest diagenesis when its precursor existed in a monosulfide form (slide 2.2-10; discussed in Kolker, 2012). At the other extreme of the coal-forming sequence, cleat or vein-filling pyrite is always the last iron disulfide generation, based on crosscutting relations and, in some cases, by contrasting trace element contents.

2.3 Introduction to Mercury in Coal

In this section, common forms of mercury occurrence in coal are reviewed as an introduction to Session 3, which goes into this topic in greater detail. A brief discussion is provided about how we know that certain minerals, such as pyrite, are common hosts for mercury in bituminous coals. This section also compares available results for mercury in U.S. coals published in a USGS database (Bragg and others, 1997; updated by Palmer and others, 2015) and by the EPA, following extensive surveys of U.S. coal used in power generation conducted in 1999 (EPA, 2003) and again in 2010 (EPA, 2011c). Mean mercury contents (0.17 parts per million [ppm]) are higher in the USGS database than in the EPA databases (0.11 and 0.12 ppm, respectively) primarily because the USGS data represent coals as mined whereas the EPA databases represent delivered coals that may have undergone some degree of preparation prior to delivery (appendix 2, slide 2.3-3). This difference also reflects a greater proportion of low-mercury western coals included in the EPA databases. Mercury and arsenic in coals exported to the Netherlands are shown in appendix 2, slide 2.3-4, from the compilation by Meij and te Winkel (2009). The plots show a large range in values for each element in coal from different international sources and that coal exported from Colombia is below average for both mercury and arsenic.

Also in this section, approaches are reviewed that show how the occurrence of mercury in iron disulfides in coal is known (slide 2.3-5). In most cases, the mercury content of iron disulfides is below the detection limit of electron-beam instruments, such as an electron microprobe, but can be determined by using more sensitive instruments, such as laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). In addition, the occurrence of mercury in pyrite is inferred in selective leaching studies of coal and in bulk elemental analysis by correlation of mercury with iron disulfide proxies such as total iron contents. Different pyrite populations can have different mercury contents, as shown in slide 2.3-6. Coals with similar pyritic sulfur contents from the U.S. Illinois Basin are compared to coals from Donets Basin of eastern Ukraine, a known mercury-enriched province. A plot showing bulk mercury content versus pyritic sulfur for coals from these locations shows strongly diverging trends despite similar pyrite contents. The trend for the Ukraine samples reflects greater substitution of mercury in pyrite compared to the Illinois Basin samples.

Session 3

This session focuses on the distribution of mercury and halogens in coal and their behavior in determining mercury emissions and promoting mercury capture in coal-fired boilers. The session also emphasizes inexpensive approaches for improving mercury capture from utility boilers on the basis of past EPA and USGS field studies and recommendations of UNEP. Past USGS studies, measuring ambient mercury contents and speciation, and using trace elements in fine particulate matter for source apportionment, are also discussed in Session 3.

3.1 Mercury and Halogens in Coal

This section begins with a review of the introductory material on mercury in coal presented in section 2.3 of the previous session. To introduce the effect of halogens in combustion systems, slide 3.1-3 shows that halogens can have positive effects by helping to improve mercury capture but can also have negative effects on boiler operation if the concentration of halogens, especially chlorine, is too high. Kolker and others (2012) reviewed the effect of halogens on mercury capture and showed how mercury, halogens, and particulates interact in the boiler. On a mass basis, bromine is more effective than chlorine in oxidizing elemental mercury in power station flue gas, thereby promoting mercury capture. On a mass basis, bromine is typically 1–4 percent of the chlorine content of U.S. coals (Vosteen and others, 2010; Kolker and others, 2012). Halogen contents of U.S. coals vary with rank and are lowest in low-rank coals and anthracite (Kolker and Quick, 2015; appendix 2, slide 3.1-6). The mode of occurrence of halogens in coal was investigated by Huggins and Huffman (1995), using spectroscopic approaches, which showed that halogens in coal are associated with the organic fraction, indicating a predominant association where halogens present in coal moisture are loosely bound to maceral surfaces or retained in pore spaces. In addition to rank variation,

halogen contents are controlled by geologic factors, including depth of burial, chemistry of associated formation waters, and proximity to geologic structures, such as fault zones, that may provide pathways for halogen-bearing fluids to interact with coal. Examples of the variation of chlorine content of U.S. coals with depth are presented for the U.S. Illinois Basin (from Gluskoter and Rees, 1964; appendix 2, slides 3.1-9, 3.1-10) and for the central Appalachian Basin (Bragg and others, 1991; appendix 2, slides 3.1-11, 3.1-12).

In the remainder of this section, a series of slides is presented from a USGS collaborative study of coals used for power generation in South Africa (Kolker and others, 2014). In this study, funded by UNEP and conducted in cooperation with Eskom, the national electric utility of South Africa, the USGS was provided with 42 samples of composite feed coals, representing all 13 operating coal-fired power stations in South Africa. A separate group of eight density separates of South African Highveld #4 coal was provided to study mercury and trace element partitioning expected during coal preparation. The mean mercury content of the South African feed coals, determined in USGS laboratories, is more than twice that of U.S. feed coals and approximately four times that of South African coal produced for export (appendix 2, slide 3.1-14). Investigation of the Highveld #4 density separates shows a strong correspondence of pyrite contents with ash and mercury. Results show that the lowest ash and mercury contents are in the lowest density separates that approximate the values of South African export coals (Kolker and others, 2017b). In situ determination of arsenic and mercury in pyrite by LA-ICP-MS confirms enrichment of these elements in pyrite relative to whole coal values and shows considerable grain-scale variation (Kolker and others, 2017b). On the basis of values for the bulk separates of the Highveld #4 coal used in South Africa, mercury contents would be expected to vary by a factor of about eight between exported coal and its discarded stone (Kolker and others, 2017b; appendix 2, slide 3.1-19).

3.2 Improving Mercury Capture

Mercury capture in coal-fired utility power stations is a function of coal quality, including rank, mercury content, and coal halogen content, as well as plant operations, including type and positioning of air pollution control devices (APCDs), the amount of unburned carbon in the particulate fraction, and whether there are specific controls for nitrogen oxides (NO_x) and (or) mercury (UNEP, 2011; Senior, 2015). For power stations with conventional APCDs, a minimum of about 300 ppm chlorine is optimal to promote mercury capture, whereas concentrations of significantly more than 1,000 ppm have a diminishing benefit and may result in corrosion of the boiler (Quick and others, 2005; Kolker and others, 2006b; appendix 2, slide 3.2-3). In the boiler, gas-phase and gas-particle reactions promote oxidation of elemental mercury to form mercury-halogen complexes or bind mercury species to particles to form particulate mercury. Each of these mercury forms is easier to capture by APCDs than elemental mercury. Low rank coals typically do not have high enough halogen contents to promote oxidation and capture of elemental mercury. In this case, activated carbon may be injected upstream from the particulate control devices, or halogen-based sorbents may be added to the coal (Kolker and others, 2012; appendix 2, slide 3.2-4). Simple ways to lower mercury emissions include (1) preparing coal to reduce input mercury by removing pyrite-associated elements such as mercury and (2) adjusting power station operating conditions to increase the amount of unburned carbon in the ash, thereby improving mercury capture from the flue gas. The latter may have unwanted effects, though, such as decreasing boiler efficiency and affecting the quality of ash for marketing. Among widely used particulate controls, fabric filters (FFs) generally capture a higher proportion of mercury from the flue gas than electrostatic precipitators (ESPs). Where regulations require reductions in powerplant sulfur dioxide (SO_2) emissions, the addition of FGD to reduce sulfur emissions should have a co-benefit of capturing a high proportion of any gaseous-oxidized mercury present.

In the remainder of this section, a case study of the Kendal and Duvha power stations in South Africa is presented. These stations were sampled in 2010 by the EPA for stack emissions, feed coal, and fly ash in each of the six boiler units for each power station (Scott, 2011; Kolker and others, 2014). Emissions measurements show lower total emissions and a higher fraction of oxidized mercury from three units in the Duvha station equipped with FFs compared to the other three units at Duvha and to all six units at the Kendal station, which are equipped with ESPs. The three Duvha units with FFs have the highest mercury capture efficiency, and USGS results show that fly ash from these units also has the highest mercury content (Kolker and others, 2014; appendix 2, slide 3.2-10). The section concludes by referring to the UNEP guidance document for reducing mercury emissions from coal combustion in powerplants. The UNEP document gives best practices for improving mercury control at a range of costs (UNEP, 2011).

3.3 Ambient Mercury and Fine Particulate Matter

This section gives a brief introduction to sampling ambient mercury and fine particulate matter, based primarily on recent USGS studies. Sampling mercury in the environment relates to coal geochemistry because coal-fired power stations are among the largest point-source emitters of ambient atmospheric mercury (EPA, 2011a, b). Measurement of ambient atmospheric mercury includes three operationally defined species: (1) reactive gaseous mercury (RGM), including all charged gaseous mercury

species; (2) particulate mercury (Hg_p), including all mercury bound to particles; and (3) elemental mercury (Hg°), the dominant form of mercury in the atmosphere. Elemental mercury has a long residence time in the atmosphere and, as a result, can be transported globally, whereas RGM is deposited locally or regionally and has a shorter residence time. Residence time of Hg_p varies depending on particle size, composition, and solubility (Kolker and others, 2007).

The USGS Mobile Mercury Laboratory (Mobile Lab) has been deployed in a variety of settings to investigate ambient mercury species and associated parameters, such as fine particulate ($PM_{2.5}$) mass, and ancillary gases, such as SO_2, NO_x, and ozone (O_3; Kolker and others, 2007, 2008, 2010; Engle and others 2008, 2010). In one such study, the Mobile Lab was deployed to Woods Hole, Massachusetts, for more than a year (Kolker and others, 2013). Mercury species in this northern coastal setting were compared to previous Mobile Lab deployments along the U.S. Gulf Coast and other southern locations to assess controls on atmospheric mercury deposition in coastal environments (Engle and others, 2008, 2010). During the Woods Hole deployment, and in previous studies (Edgerton and others, 2006; Kolker and others, 2008), transient RGM plumes were found to occur together with elevated SO_2 and NO_x, indicating these plumes have coal combustion sources.

During the Woods Hole study, fine particulate matter was collected over several months, using filter-based samplers external to the Mobile Lab (Kolker and others, 2013; appendix 2, slide 3.3-4). Trace elements in $PM_{2.5}$ were determined by extraction of particulate matter from the filters together with analysis by inductively coupled plasma-mass spectrometry (ICP-MS). Sources contributing to the observed trace element distributions were investigated by using a matrix factorization approach together with air mass back trajectories (Kolker and others, 2013). Results of the factorization analysis give weighted proportions of four probable source categories contributing to each element measured and to the total mass of $PM_{2.5}$ collected. Among sources identified, an energy generation source was determined to be the largest contributor to $PM_{2.5}$ mass with lesser contributions from crustal and marine sources and a possible metal smelting source. Elements such as vanadium (V), Cr, Ni, As, Se, molybdenum (Mo), Sb, and Hg are characteristic of coal combustion for energy generation whereas aluminum (Al), titanium (Ti), iron (Fe), yttrium (Y), zirconium (Zr), and the rare earth elements (REE) are characteristic of crustal sources (Duce and others, 1975; Pacyna and Pacyna, 2001; Song and others, 2001; appendix 2, slide 3.3-8). Surprisingly, some crustal-sourced material was contributed by air masses having offshore back trajectories. This determination supports the observed transport of Saharan dust across the Atlantic in the summer months combined with northward transport along the Atlantic coast by clockwise circulation of the summer Bermuda high (Perry and others, 1997; Kolker and others, 2013). These studies demonstrate how sampling and analysis of fine particulate matter can be used for source apportionment and to identify the contribution of energy sources to the ambient environment.

Session 4

This session emphasizes fundamentals of coal combustion products (CCPs) and recent CCP-related USGS research. A recent EPA ruling upholds the designation of CCPs as nonhazardous waste, allowing the continued beneficial use of CCPs in construction materials and in other applications, while eliminating the need for more stringent (and expensive) handling requirements if CCPs were reclassified (EPA, 2014). This session examines the mineralogy of CCPs and mineral transformations that take place during coal combustion, together with trace element variation in CCPs, and between CCPS and coal. Current beneficial use of CCPs is reviewed together with the potential for new uses, such as a source of valuable elements. In the last part of this session, the potential for mobility of coal ash and its trace constituents is considered.

4.1 Introduction to Coal Ash

Coal combustion products primarily include fly ash, bottom ash, and, in plants equipped with FGD, flue-gas desulfurization sludge. The classification of coal ash in ASTM C618 for construction purposes is based on its major element characteristics expressed as the sum of $SiO_2 + Al_2O_3 + Fe_2O_3$ compared to other major constituents. Where $SiO_2 + Al_2O_3 + Fe_2O_3$ is greater than or equal to 50 percent of the total on a weight basis, the ash is called “cementitious” and is classified as Class C. Where $SiO_2 + Al_2O_3 + Fe_2O_3$ is greater than or equal to 70 percent of the total on a weight basis, the ash is called “pozzolanic” and is classified as Class F. Each classification has specific properties for use in concrete.

Common minerals in coal, such as quartz, clays, carbonates and pyrite, either break down, react, or undergo phase transformations at boiler temperatures. Clays, such as illite-smectite and kaolinite, are either replaced in coal fly ash by aluminosilicate minerals, such as mullite ($Al_6Si_2O_{13}$), or they enter the melt, forming aluminosilicate glass upon cooling. Pyrite in coal is oxidized in the boiler to form iron oxides, whereas quartz undergoes a phase transformation to the high-temperature β form (appendix 2, slide 4.1-6). Aluminosilicate glass is the most abundant constituent of coal fly ash, making up about 70 to more than 90 percent of most samples. Unburned carbon in fly ash may be present as various forms of coke or as coal constituents, which have survived the combustion process, such as inertinite (slide 4.1-8). In slides 4.1-9 and 4.1-10, examples show the

use of electron beam methods to characterize constituents of coal ash. Methods shown include BSE and wavelength-dispersive elemental mapping. These methods are discussed further in section 5.1

4.2 Trace Elements in Coal Ash

The behavior of trace elements in pulverized-coal-fired boilers is highly dependent on relative element volatilities (Ratafia-Brown, 1994; appendix 2, slide 4.2-3). Elements such as selenium. mercury, and the halogens are extremely volatile, leading to concerns over emission of these constituents. Conversely, elements such as manganese (Mn), rubidium (Rb), Zr, and the REE, are highly retained in the ash fraction and, as a result, are considered to be potential resources if they can be effectively recovered (see the following section). Most elements have more intermediate behavior and are both emitted and retained to some degree. Elements such as Be, Cr, Ni, As, Sb, and Pb fall into this category. However, concern over their emission is sufficient for them to be included with elements whose emissions are limited under the EPA MATS regulations (EPA, 2011a). Retention or partial retention of elements of environmental interest in coal ash results in pronounced overall enrichment in these elements relative to concentrations present in coal, because the mass fraction of ash is much smaller than that of the feed coal (Deonarine and others, 2015; appendix 2, slide 4.2-5). In addition to a general enrichment of trace elements in fly ash relative to coal, fly ash trace element contents vary by location within APCDs as flue-gas temperature and particle size decrease downstream from the boiler, resulting in greater element capture. As a result, concentrations of elements such as arsenic, mercury, and lead tend to be higher in the back rows of ESPs where the finest size fractions are collected (Mardon and Hower, 2004; James Hower, unpub. data, 2004; appendix 2, slides 4.2-7, 4.2-8).

4.3 Beneficial Uses of Coal Ash

The affirmation of nonhazardous waste status by the EPA allows the continued beneficial use of CCPs, with specified procedures for proper handling, transport, and storage of these materials. In 2016, the rate of CCP re-use in the United States reached 52 percent, an all-time high (American Coal Ash Association, not dated; appendix 2, slide 4.3-3). The increased rate of re-use is important because CCPs that are not re-used must be stored in landfills or impoundments, which is costly and could release coal ash into the environment in the event of a catastrophic failure (see the following section). Primary uses of coal ash and FGD sludge include raw material in concrete products, feedstock in the production of cement, waste stabilization, and road construction. FGD sludge is a component of synthetic gypsum for use in construction and agriculture.

The U.S. Department of Energy (DOE) is supporting a range of promising research approaches to recover REE from coal and coal-related materials. These materials include coal itself, coal fly ash, and even acid mine drainage from past coal mining (DOE, 2017a, b). This effort resulted from the need for REE in a wide range of modern applications ranging from cell phones to rare earth magnets used in wind-powered electric generation (Van Gosen and others, 2014). The need for REE is also reflected in the fact that one country, China, provides much of the REE commodity supplied to the world (Gambogi, 2017; slide 4.3-5).

The USGS is currently investigating the distribution of REE in coal fly ash as an alternative source of REE to conventional mining. REE are strongly retained in the coal ash after coal combustion, leading to enrichment relative to their concentrations in coal and shale (appendix 2, slide 4.3-8). Normalization of REE concentrations to chondritic meteorites (chondrite normalization) is a convenient way to compare REE results for different samples and to compensate for the Oddo-Harkins effect, apparent in REE, in which even-numbered elements are more abundant than odd-numbered elements (appendix 2, slide 4.3-9). Although discrete REE-bearing trace mineral phases are apparent in coal (appendix 2, slides 4.3-11 and 4.3-12), these minerals are much less common in coal ash (Hower and others, 2013).

Using an ion microprobe (section 5.1; https://shrimprg.stanford.edu/), REE distribution within constituents of coal ash was investigated on a grain scale (Kolker and others, 2017a). Results indicate that glasses formed at boiler temperatures have similar REE distributions as the bulk ash samples. REE are also contained in iron oxide-glass intergrowths but are much less abundant in quartz, which constitutes a small portion of some samples. Results for bulk REE distribution in a larger group of samples (Taggart and others, 2016) show a good correlation of REE content with Al_2O_3, consistent with USGS findings on a grain scale that REE are partitioned into aluminosilicate glasses in coal fly ash (appendix 2, slide 4.3-14).

4.4 Coal Ash Environmental Issues

The continued designation of coal ash as nonhazardous waste (EPA, 2014) has allowed a wide range of beneficial uses of coal ash to continue and has eliminated the need to store a large portion of ash in U.S. landfills and impoundments. For ash that is stored, standard tests, such as the EPA Toxicity Characteristic Leaching Procedure (TCLP), help ensure that harmful elements are not readily mobilized (EPA, 1992). Recently, several large releases of stored coal ash into the environment occurred in the

United States, including ash stored at Kingston, Tennessee, in December 2008 and Eden, North Carolina, in February 2014 (appendix 2, slide 4.4-3). The Kingston spill resulted in the transport of harmful constituents, such as arsenic and mercury, from coal ash to river sediments, and these sediments continued to be affected by the spill even after concentrations of trace metals in river water returned to normal levels (Ruhl and others, 2010; Deonarine and others, 2015).

Leaching tests, such as the TCLP, assume that coal ash is stored at the land surface or in surface impoundments, under oxic conditions, where oxygen is available. This is not always the case in landfills and impoundments, especially at depth, where oxygen may be unavailable and, thus, conditions may be anoxic. Fly ash leaching experiments by Deonarine and others (2015, 2016), conducted under controlled conditions, show that leaching behavior of elements, such as chromium and arsenic, can be much different depending on the availability of oxygen. Although arsenic was leachable in all cases studied, in one sample, it was more leachable under anoxic conditions than if oxygen had been available (appendix 2, slide 4.4-6). These experiments show that additional leaching tests that more accurately reflect the conditions where coal ash is stored are needed to ascertain the potential for mobility of trace constituents from coal ash into the environment. The design of ash storage facilities is also an important factor. Lined landfills are much less likely to release constituents to the environment than unlined landfills (Deonarine and others, 2015; appendix 2, slide 4.4-5).

Session 5

In this session, analytical methods used to study trace elements in coal are reviewed, including bulk analytical methods and methods for microanalysis. Each method is discussed from the standpoint of its advantages and common pitfalls. This discussion is followed in section 5.2 by the examination of data affected by common analytical problems, especially bulk analysis by ICP-MS. The short course concludes by introducing, in section 5.3, mathematical concepts underlying compositional data analysis. The purpose of this section is to help data users avoid potential problems, such as spurious correlation and contradictory results, encountered when statistical approaches are applied to data that sum to a constant as in results expressed as a percentage and (or) parts per million. Section 5.3 describes tools needed to avoid these problems.

5.1 Laboratory Methods

This section gives methods for bulk analysis and microanalysis of coal, in large part from the authors' experience with all but transmission electron microscopy (TEM) and instrumental neutron activation analysis (INAA). Some approaches, such as X-ray diffraction (XRD), are used to identify which minerals are present in the whole (bulk) coal sample, whereas microanalysis generally provides compositional information for individual grains within a sample (slide 5.1-2). Bulk analysis is used to determine the element distribution in a whole sample. Methods for bulk chemical analysis include ICP-MS, INAA, X-ray fluorescence, and isotope dilution. Advantages and disadvantages of each method are shown in appendix 2, slide 5.1-3. ICP-MS is the most common multi-element bulk analytical method currently in use but requires that a solid sample be digested to get it into solution. Prior to sample digestion, coal samples are "ashed" in a laboratory furnace to consume the organic fraction, leaving behind all but the most volatile elements in the inorganic fraction. Volatile elements such as mercury and selenium should be run on whole coal samples rather than on laboratory ash. Care should be taken in ICP-MS analysis to avoid or correct for interferences for the elements of interest. An example is given in section 5.2 showing how one or more isotopes having the same mass as the element of interest can interfere with the determination and how to avoid or correct for these isobaric interferences. Here and previously in section 2.1, the importance of accurately determining moisture contents, especially for low-rank coals, is emphasized to express elemental concentrations in coal. To eliminate variability resulting from differences in moisture content and the proportion of ash present in coal, expression of concentrations on a moisture-free whole coal basis is recommended, requiring accurate determination of moisture in coal together with bulk analysis and knowledge of the proportion of ash present (slide 5.1-5). National Institute of Standards and Technology (NIST) standard reference material (SRM) 1632d (Trace Elements in Bituminous Coal) and SRM 1633c (Trace Elements in Coal Fly Ash) are useful for analysis of coal and coal ash. NIST SRMs are produced in batches having expiration dates, and values with three levels of certainty are given: certified, reference, and informational. Where certified values are unavailable, reference and informational values may be useful, but generally, these two values should not be used for primary instrument calibration (slide 5.1-6).

In appendix 2, slide 5.1-7, methods for bulk mercury analysis are compared. The most widely used methods are (1) thermal decomposition together with amalgamation and measurement by atomic absorption spectrophotometry, an EPA method also known as direct mercury analysis (DMA; EPA, 2007); (2) cold vapor atomic absorption (CVAA); and (3) cold vapor atomic fluorescence (CVAFS). DMA is the most common method currently in use because of its flexibility to run solid or liquid samples

and the availability of relatively inexpensive, ready-to-use analyzers. CVAA has a similar range of determination as DMA but requires solid samples to be brought into solution. CVAFS has lower detection limits than either DMA or CVAA but is used primarily in studies of low-level ambient mercury rather than mercury in coal. Portable atomic absorption units with Zeeman background corrections are useful in field applications to measure real-time vapor phase mercury, especially in areas where sources of mercury emissions are nearby.

In the next part of section 5.1, microanalysis methods used in the characterization of coal and coal combustion products are discussed, including methods that are useful in determining major constituents, such as scanning electron microscopy (SEM), electron microprobe, and TEM, and methods specific to trace element microanalysis, such as LA-ICP-MS, ion microprobe, and synchrotron-based approaches (slides 5.1-8 to 5.1-20). Examples showing laboratory setups and results generated by micro-beam instruments, such as SEM, electron microprobe, and TEM, are given in slides 5.1-9 to 5.1-13. Electron beam instruments are useful in imaging samples using secondary electrons, obtaining combined imaging and compositional data using BSE, and obtaining compositional data and element mapping using wavelength dispersive or energy dispersive analysis (slides 5.1-9 to 5.1-12). Examples illustrating trace element microanalysis using LA-ICP-MS, ion microprobe, and synchrotron-based methods are shown in slides 5.1-15 to 5.1-20. Laser ablation and ion microprobe analysis primarily offer point analyses at much lower detection limits than electron beam instruments. Both methods offer concentration and isotopic determination on the same spots. Sychrotron-based methods are primarily used for bulk sample determinations of element speciation but have been adapted to do combined concentration mapping and element speciation of the same sample areas (slides 5.1-14 and 5.1-20). TEM analysis is especially useful in revealing characteristics of particle surfaces (slide 5.1-13) and in determining sample mineralogy on a nanometer scale, which in many cases has proven to be very different than micro- or macromineralogy.

5.2 Laboratory Quality Assurance

Increasingly, laboratories such as the USGS are adopting formal quality management procedures, requiring written standard operating procedures (SOPs) for analysis methods, and enhanced review and record keeping for laboratory data. Although this process is an important aspect of laboratory operation, it is not covered in this short course. Instead, this section emphasizes common problems with bulk trace element analysis using ICP-MS and how to recognize them from ICP-MS results. As noted in section 5.1, ICP-MS is the most widely used method of bulk sample analysis, including laboratories at the SGC.

Incomplete sample digestion, especially for insoluble minerals such as zircon and monazite, is a common problem in ICP-MS if acid digestion is used. Using a sinter digestion, where sample material is mixed with sodium peroxide and sintered in a crucible at high temperature, generally gives a more complete sample digestion (appendix 2, slide 5.2-3), but acid digestion is commonly used in metals analysis, where trace phase digestion is not critical. In the example shown in appendix 2, slide 5.2-5, REE analysis of USGS standard GXR-4 after sinter digestion and acid digestion, performed by the same commercial laboratory, is compared. Results by acid digestion give much lower material recoveries for the REE, suggesting some REE-bearing phases were not dissolved. In the next example, REE analysis of NIST SRM 1633c in two sinter digestions by two laboratories is compared. Whereas there are no certified values for the REE in this SRM, it is difficult to assess the quality of the two analyses. If the results are plotted on a chondrite-normalized plot, however, the result from Lab 1 gives a smooth pattern whereas the result for Lab 2 has a kinked pattern for the heavy rare earth elements, especially ytterbium, suggesting there may be a problem with the result. Because of their low abundance, analysis of odd-numbered heavy REE such as holmium, thulium, and lutetium can often be problematic, although not in this example. Plotting results on a chondrite-normalized plot can help distinguish possible analytical problems for the REE.

In the next series of slides (appendix 2, slides 5.2-10 to 5.2-13), the problem of ICP-MS isobaric interferences is discussed and an example is given showing a correction for isobaric interferences for ^{75}As, the only isotope of arsenic. This correction uses the polyatomic species $^{37}Cl^{40}Ar$ to determine the interference of $^{35}Cl^{40}Ar$, after correcting for an interference by ^{77}Se at mass 77 with any selenium present (appendix 2, slide 5.2-13). A newer approach to arsenic and selenium determination by ICP-MS uses a collision/reaction cell to minimize spectral interferences (Li and others, 2014).

Other potential problems with ICP-MS include extrapolation of results beyond the calibrated range and carryover from a previous high-concentration sample if wash time is insufficient. Internal checks on data quality include running standards as unknowns, running total analytical blanks, and, for major elements, determining if the analysis sum is near 100 percent. For coal, sulfur is a major element and should be included in the summation. For rare earth elements, results plotted on a chondrite-normalized plot should give a smooth pattern. If not, there may be a problem. And finally, as a check, can you replicate results obtained previously or in another laboratory? The section concludes with a mercury analysis example where the same sample materials were determined at USGS laboratories in Reston, Virginia, and Denver, Colorado. Agreement generally was good, but a few samples needed multiple runs by the two laboratories for values to converge (appendix 2, slide 5.2-16; Kolker and others, 2014). This difference is a result of the concentration of mercury in pyrite contributing to variability of mercury analysis.

5.3 Introduction to Compositional Data Analysis

This section introduces basic concepts of compositional data analysis, a mathematical approach to compositional data analysis, and data interpretation. The approach is gaining acceptance in the geosciences with recognition that spurious correlations (and misinterpretation) can result from the application of conventional statistics to compositional data that are constrained to a constant sum (Aitchison and Pawlowsky-Glahn, 1997; Filzmoser and Hron, 2008; Pawlowsky-Glahn and others, 2015). Examples where compositional data are constrained to a constant sum include major element data expressed in percent and trace element data expressed in parts per million. Together, these are the primary datasets used by geochemists.

The section begins by comparing data that are mathematically limited to a constant sum, such as percent, and data that are inherently unconstrained, such as speed and molar concentrations. Closure of constrained compositional data requires that proportions of the whole must be positive or zero. This constraint sets compositional data apart from variables with absolute scales such as speed, mass, and time. In a given dataset, mathematical covariance of results can lead to spurious correlations, giving misleading or contradictory results. An example is given that is an analogue to proximate analysis of coal expressed in moisture-containing and dry states. In the moist state, there is an apparent correlation between components X_1 and X_2. However, moisture (X_4) expressed in percent is constrained to be no more than 100 percent. When this variable is removed by drying, the sign of the covariation between components X_1 and X_2 is reversed (appendix 2, slide 5.3-5). Problems with compositionally constrained data apply even where only a few of many components are measured, such as in trace element data, where values add up to be much less than the total.

To avoid problems inherent in constrained compositional data, a series of approaches is given whereby these data are converted into forms that can be used in unconstrained space where conventional statistical approaches are applicable. The first step is to compute ratios of variables and determine the logarithms of the ratios (log ratios; appendix 2, slide 5.3-8). As shown in appendix 2, slide 5.3-9, log ratios are then mathematically transformed to give calculated variables that include isometric log-ratio transformations (ilr) and centered log-ratio transformations (clr). These transformed variables can then be used to explore controlling dependencies of the dataset. One such approach is to use a two-dimensional biplot showing principal components and transformed log-ratio variables of the dataset in an unconstrained space (Otero and others, 2005; Thió-Henestrosa and Comas, 2016; appendix 2, slide 5.3-10). Log-ratio transformations can also be mapped to display transformed data in a geospatial context as shown in appendix 2, slide 5.3-11; Olea and Luppens, 2015). Both the biplot and the map show that among a range of coal parameters for the dataset examined, ash yield exerts the greatest overall control on the distribution of values obtained. Once constraints are removed, as shown in appendix 2, slide 5.1-13, compositional data can be used to test or describe processes such as variation of constituents with time, as shown, and (or) other geologically relevant processes.

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Appendix 1. Short Course Slide Descriptions

Session 1

1.1 Global Coal Production and Use

1.1-1 Title slide Session 1, Topic 1: Global Coal Production and Use

1.1-2 Global Coal Production and Export. Compilation showing top ranking global coal producers and exporters based on IEA (2016) data. Colombia is highlighted as the #11 producer and the #4 coal exporter.

1.1-3 World Coal Proved Reserves. World Energy Council (2013) compilation showing the top 15 countries listed in order of proved coal reserves. The United States is #1 and Colombia is #12.

1.1-4 Electricity from Coal. Plot showing World Bank (2013) data for relative dependence on coal for electric power generation. France is lowest due to reliance on nuclear power. Poland and South Africa are among the highest. The United States is slightly below the world average coal dependence.

1.1-5 Colombian Coal Production. Plots showing increasing production of Colombian coal and coal produced for export. The two trends are nearly identical because most coal in Colombia is produced for export (IEA, 2016). Plot at right shows the proportion of coal produced in Guajira and Cesar Departments of Colombia, where the largest mines are located, relative to other parts of the country (World Coal, 2011).

1.1-6 Coal Fields of Colombia. Map at left showing the administrative Departments of Colombia and the locations of coal fields. Map at right shows simplified geologic base (from Tewalt and others, 2006).

1.1-7 Colombia—Power Generation by Source. Plot showing electric power generation in Colombia over time and that hydroelectric power generation predominates. Coal use constitutes a relatively small portion of electric power generation and this proportion has been fairly constant.

1.1-8 U.S. Coal Production (1980–2015). Graph showing declining U.S. coal production starting in about 2010. This is the first in a series of slides comparing the U.S. energy mix to that of Colombia (EIA, 2016).

1.1-9 U.S. Coal Basins. Map showing the distribution of U.S. coal basins and the location of the Appalachian Basin, Powder River Basin, and Illinois Basin discussed in slide 1.1-10 (from East, 2013).

1.1-10 U.S. Coal Production by Coal Basin. Plot showing production data, with time, of major coal producers—the Appalachian Basin, Powder River Basin, and Illinois Basin.

1.1-11 U.S. Electric Power Sector (1980–2015). Plot showing long-term U.S. trends in electric power generation by energy source. Plot shows decrease in the proportion of coal used for power generation beginning about 2010 and a corresponding increase in natural gas-fired power generation. Data are from EIA (2016).

1.1-12 U.S. Electric Power Generation (1990–2040). Plot showing current and projected trends in U.S. electric power generation by source. In current (2015) energy mix, coal- and gas-fired power generation are each 33 percent of net electric generation. Projected trends show increase in renewables and continued increase in gas-fired power generation and a decrease in the proportion of coal used for power generation. The extent of reduction in coal use depends on whether the proposed EPA Clean Power Plan (CPP) is adopted. Data are from EIA (2016).

1.1-13 U.S. Power Generation by Region. Map showing differences in the U.S. energy mix for electric power generation by region in 2015 and projected variation to 2030. Proportion of coal used for power generation is lowest in California and the Northeastern States and highest in the Northern Plains region. U.S. average from slide 1.1-13 is shown as inset in lower left. Data are from EIA (2016).

1.1-14 U.S. Shale Gas Production (2007–2014). Plot showing U.S. production of shale gas since 2007. Increasing gas production has compensated for the decline in coal production as U.S. coal-fired powerplants have increasingly adopted gas-fired power generation. Data are from EIA (2016).

1.1-15 USGS Shale Gas Studies. Summary slide listing ongoing USGS shale gas research and projection from EIA (2016) that U.S. shale gas production is expected to continue to increase between 2020 and 2040. USGS research topics include studies of pore structure in shales to understand gas distribution, sampling of produced water, and testing of produced water for constituents added in hydraulic fracturing.

1.1-16 Carbon Capture and Storage. Summary slide describing a recent USGS study of the capacity for geologic carbon dioxide (CO_2) storage in underground saline reservoirs. The largest capacity is in the Gulf Coast, Rocky Mountains, northern Great Plains, and Alaska. The study does not address how to capture and store CO_2. The study shows that the largest storage capacity for CO_2 is not near the greatest concentration of U.S. coal-fired power stations in the Midwestern States. Results are from USGS (2013).

1.1-17 Summary—Topic 1: Global Coal Production and Use. Summary of Topic 1.1 with emphasis on Colombian coal production, the energy mix in Colombia, and characteristics of Colombian coals.

1.1-18 Summary—Topic 1: Global Coal Production and Use (Continued). Summary of Topic 1.1 with emphasis on U.S. coal production, the energy mix in the United States, growth of U.S. shale gas production, and USGS work on assessing the underground storage capacity for CO_2 in the United States.

1.1-19 References—Topic 1: Global Coal Production and Use.

1.2 Review of Basic Coal Data

1.2-1 Title slide Session 1, Topic 2: Review of Basic Coal Data

1.2-2 Some Basic Points About Coal. Review slide defining basic properties of coal such as rank, heating value, moisture, and ash.

1.2-3 Coal–A Complex Natural Resource. Slide showing USGS Circular 1143 (Schweinfurth, 2003), which is an introduction to coal quality and coal science.

1.2-4 Important ASTM Methods for Coal. Summary slide showing commonly used ASTM International methods for characterizing coal, including the name for each method and what it does.

1.2-5 ASTM Coal Rank (ASTM D388). Plot showing coal rank as defined by ASTM D388, based on variation in heating (calorific) value and percent fixed carbon. Figure is from East, (2013).

1.2-6 Example of ASTM D388 Rank Classification. Example showing application of ASTM D388 formulae for fixed carbon and heating value used to determine rank classification for four Colombian coal samples using results in Tewalt and others (2006).

1.2-7 Coal Sampling. Summary slide showing ASTM methods for coal sampling and what each method is used for.

1.2-8 Sampling Coal Ash. Summary slide showing recommendations for sampling coal ash at a power station. There are no ASTM methods for geochemical sampling of coal ash.

1.2-9 Forms of Sulfur (ASTM D2492). Summary slide showing what goes into ASTM D2492 (sulfur forms), what these forms are, and how they are determined.

1.2-10 Examples of Sulfur Forms (ASTM D4239 + D2492). Slide showing three examples of sulfur forms determinations using ASTM methods. South African example is low sulfur, un-weathered; Illinois Basin example is high sulfur with corresponding sulfur reduction and increase in heating value by coal preparation. Ukraine example is moderate sulfur with sulfate fraction contributed by weathering.

1.2-11 Summary—Topic 2: Review of Basic Coal Data. Review listing of basic coal parameters and variation in coal characteristics with these parameters.

1.2-12 References—Topic 2: Review of Basic Coal Data.

1.3 Toward Global Emissions Standards

1.3-1 Title slide Session 1, Topic 3: Toward Global Emissions Standards.

1.3-2 Paris Agreement on Climate Change. Summary slide showing basic elements of the Paris Agreement to reduce carbon emissions adopted on December 12, 2015.

1.3-3 Limiting U.S. Carbon Emissions. Summary slide showing elements of the EPA CPP to limit U.S. carbon emissions.

1.3-4 Minamata Convention on Mercury. Summary slide showing elements of the United Nations Minamata Convention to limit, regulate, and phase out global mercury use, including controls on air emissions of mercury.

1.3-5 U.S. EPA Mercury and Air Toxics Standards (MATS). Slide showing basic elements of the EPA for U.S. coal- and oil-fired generating units.

1.3-6 Rationale for U.S. EPA MATS. Slide showing rationale for implementing EPA MATS in the United States and their projected health benefits. EPA estimates that 50 percent of U.S. atmospheric mercury is derived from emissions from U.S. coal-fired power stations (EPA, 2011b).

1.3-7 Rationale for U.S. EPA MATS. Further rationale for EPA MATS is shown in a map of U.S. fish consumption advisories for mercury and in a table showing reduction in mercury emissions in industrial sectors that have become regulated versus coal-fired utility powerplants, which were unregulated prior to implementation of MATS in 2016.

1.3-8 Summary—Topic 3: Global Emissions Standards.

1.3-9 References—Topic 3: Global Emissions Standards.

Session 2

2.1 Trace Elements in Coal

2.1-1 Title slide Session 2, Topic 1: Trace Elements in Coal.

2.1-2 Why Study Trace Elements in Coal? Slide summarizing rationale for understanding trace element distribution in coal. Reasons include effects on power station operation, prediction of emissions, prediction of element behavior in coal preparation, control of metals release for coal and coal combustion products to groundwater, and minimizing health consequences.

2.1-3 Effects of Inorganic Constituents on Coal Utilization. Summary slide showing inorganic constituents that affect power station operations and their effects.

2.1-4 Mode of Occurrence Concept. Introduction to the concept that the form of a chemical element in coal determines its behavior during coal combustion and other characteristics, including its environmental effect. Mode of occurrence is a function of geologic setting and can provide information on the geologic history of a sample.

2.1-5 Element Modes of Occurrence. Slide summarizing primary organic and inorganic associations of trace elements in coal.

2.1-6 Generalized Mineral Matter in Coal. Compilation of the mineral constituents of coal including major constituents such as clay minerals and trace constituents such as lead selenide. Compilation also shows trace elements substituting in major constituents, such as chromium in illite-smectite. From Finkelman, 1981; Kolker and Finkelman, 1998; Finkelman and others, 2018.

2.1-7 Minor/Trace Phases. Compilation of minor and trace mineral phases in coal and their constituents.

2.1-8 Metals in Coal. Compilation of potentially toxic metals in coal and their modes of occurrence.

2.1-9 How to Study Trace Elements in Coal. Compilation of analytical methods used to study the distribution of trace elements in coal on a bulk sample basis and in microanalysis. These methods are discussed in greater detail in section 5.1.

2.1-10 About Moisture. Slide emphasizing the importance of determining the moisture content of coal samples and the effect of moisture in determining the concentration of elements in coal.

2.1-11 Arsenic in Coal. Summary slide on the distribution and behavior of arsenic in coal, referring to Kolker and others (2006a).

2.1-12 Leaching Procedure for Coal Samples. Diagram showing selective chemical leaching of coal samples used in past USGS studies to indirectly determine the mode of occurrence of elements in coal (from Palmer and others, 1998).

2.1-13 Selective Leaching of Arsenic in U.S. Coals. Slide showing selective leaching results for arsenic in 13 U.S. coal samples, including 11 bituminous samples and 2 subbituminous coals. Plot shows a predominant pyritic (nitric-acid leached) association in the bituminous samples and a less pronounced pyritic association for arsenic in lower rank coals.

2.1-14 Arsenic Oxidation. Slide describing Kolker and Huggins (2007) study of coals with different extents of arsenic substitution in pyrite to see if this substitution affects the rate of formation of arsenate, the oxidized form of arsenic.

2.1-15 Spontaneous Arsenic Oxidation in Coal. Slide showing results of Kolker and Huggins (2007) study in which arsenic oxidation was monitored using arsenic X-ray absorption near-edge structure (XANES). Results show progressive arsenic oxidation under dry conditions regardless of starting pyritic arsenic. In samples that were wetted, arsenic oxidation was much more rapid, leading to nearly 100 percent arsenate by the end of the experiment.

2.1-16 Selective Leaching vs. X-Ray Absorption Fine Structure (XAFS) for Arsenic Species. Slide describing Huggins and others (2002) study comparing USGS selective leaching results for arsenic forms versus XANES, an XAFS approach, as a monitor for progressive arsenic oxidation in coal. Both methods give similar proportions of arsenate, but the leaching approach is indirect and requires interpretation that arsenate is removed in both the hydrochloric (HCl) and hydrofluoric (HF) acid leaching fractions.

2.1-17 Selective Leaching of Arsenic in U.S. Coals. Repeat of slide 2.2-13 included here to show combined results for the HF and HCl acid leaching fractions interpreted to represent the arsenate fraction in coal.

2.1-18 Summary—Topic 1: Trace Elements in Coal.

2.1-19 Summary—Topic 1: Trace Elements in Coal (Continued).

2.1-20 References—Topic 1: Trace Elements in Coal.

2.2 Trace Elements in Fe-Disulfides in Coal

2.2-1 Title slide Session 2, Topic 2: Trace Elements in Fe-Disulfides in Coal.

2.2-2 Why Study Fe-Disulfides (FeS_2) in Coal? Slide stating the benefits of studying pyrite and marcasite in coal. Benefits include understanding the source of air and water pollutants in coal use, reducing harmful constituents in coal preparation, showing diagenetic history, and predicting the formation of acid mine drainage (AMD).

2.2-3 Compilation of Minor Elements in Fe-disulfides in Coal. Compilation showing extents of minor and trace element substitution in pyrite and marcasite in coal. Compilation from various sources included in Kolker (2012).

2.2-4 Substitution of Minor Elements in FeS_2. Compilation from Deditius and others (2008) showing elements that substitute for iron and those that substitute for sulfur in iron disulfides (FeS_2).

2.2-5 Generations of Iron Disulfides in Coal. Slide stating that iron disulfides can be present in multiple generations in coal and that framboidal pyrite is earliest and cleat- or vein-filling pyrite is latest.

2.2-6 Framboids and their Overgrowths. Scanning electron microscope backscattered electron (BSE) images from Kolker (2012), showing framboidal pyrite overgrown by a later pyrite generation. Similar textures are found in widely dispersed coals.

2.2-7 Alabama, USA Warrior Basin Coal. Examples from Warrior Basin coal samples, showing differences in arsenic contents in different generations of pyrite in coal (Goldhaber and others, 2003).

2.2-8 Donetsk-Makeevka District, Ukraine. BSE image and wavelength-dispersive elemental maps showing arsenic-enriched pyrite overgrowths on arsenic-poor framboids in coal from Ukraine. Texture and genesis are very similar to that shown in slide

2.2-9 Arsenic and Selenium Enrichment in Iron Disulfides. Enrichment of arsenic and selenium in iron disulfides in coal, shown by wavelength-dispersive electron microprobe elemental maps for coal samples from the United States and Ukraine. From Kolker (2012).

2.2-10 Nickel Enrichment in Framboids. Wavelength-dispersive electron microprobe elemental maps for nickel in coal samples from the United States and Ukraine, showing preferential concentration of nickel at the core or mantle of pyrite framboids. From Kolker (2012).

2.2-11 Summary—Topic 2: Trace Elements in Fe-Disulfides in Coal.

2.2-12 References—Topic 2: Trace Elements in FeS_2.

2.3 Introduction to Mercury in Coal

2.3-1 Title slide Session 2, Topic 3: Introduction to Mercury in Coal.

2.3-2 Mercury in Coal. Summary slide listing the most common forms of mercury occurrence in coal and how we know that pyrite is the most common form of mercury occurrence in bituminous coals.

2.3-3 U.S. Coal Databases: Mercury Results. Comparison of mercury results in USGS and EPA U.S. coal databases. USGS COALQUAL database represents coal in the ground and has a higher mean mercury content than what is included in EPA databases, which contain data on coal delivered to power stations. This difference is a function of coal preparation prior to delivery and a greater proportion of low-mercury western coals included in the EPA databases. From Kolker and others (2012).

2.3-4 Mercury in World Export Coals. Plots of mercury and arsenic concentrations in coals imported to the Netherlands from various sources. Slide gives world averages for mercury and arsenic in coal and shows that Colombian export coals are well below the world averages for these elements. From Meij and te Winkel (2009).

2.3-5 Mercury in Iron Disulfides. Summary slide showing how it is known that mercury resides in iron disulfides in coal.

2.3-6 Mercury-Rich Coals in Ukraine versus U.S. Illinois Basin Coals. Plots of mercury and pyritic sulfur, comparing mercury-rich coals in Ukraine with U.S. Illinois Basin coals, each group having similar pyritic sulfur contents. The trend for active mines in Ukraine is shown in the upper plot (from Kolker and others, 2009). Ukraine data are shown in the lower plot together with the trend for U.S. Illinois Basin coals (Bragg and others, 1997). The lower plot shows that mercury content of the whole coal is a function of both the amount of pyrite and the mercury content of that pyrite.

2.3-7 Summary—Topic 3: Introduction to Mercury in Coal.

2.3-8 References—Topic 3: Introduction to Mercury in Coal.

Session 3

3.1 Mercury and Halogens in Coal

3.1-1 Title slide Session 3, Topic 1: Mercury and Halogens in Coal.

3.1-2 Mercury in Coal—Session 2 Review. Review of key points noted in previous session introducing the topic of mercury in coal.

3.1-3 Halogens in Coal—Cl, F, Br, I. Summary slide listing positive effects of halogens in coal to promote mercury capture and negative effects on boiler operation if the concentration of halogens, especially chlorine, is too high.

3.1-4 Mercury and Halogens in Coal. Slide listing major points about mercury and halogens in coal given in Kolker and others (2012).

3.1-5 Halogens in U.S. Coals. Plot of chlorine versus bromine contents of U.S. coals averaged by county. Plot shows that bromine content of U.S. coals typically is 1–4 percent of chlorine content on a mass basis. Plot is from Kolker and others (2012), modified from Vosteen and others (2010).

3.1-6 Rank Dependence of Halogens. Plots showing county-average distribution of chlorine and bromine contents in U.S. coals as a function of ASTM coal rank. Plots show depletion of halogens in low-rank coals. From Kolker and Quick (2015).

3.1-7 Mode of Occurrence of Halogens in Coal. Investigation by Huggins and Huffman (1995), using XANES for chlorine and bromine. Their results show association of halogens in coal with organic fraction but not bound as organohalogen complexes. Huggins and Huffman (1995) concluded that chlorine and bromine are present in coal moisture and are loosely bound to maceral surfaces or retained in pore spaces.

3.1-8 Geologic Factors Influencing Coal Halogen Contents. Summary slide listing geologic factors determining halogen content of coals. Factors include rank, depth of burial or paleodepth, chemistry of associated formation waters, and proximity to geologic structures.

3.1-9 Chlorine in U.S. Coal. Map showing the distribution of chlorine in U.S. coal by county average, used as an introduction to the case study of chlorine in coal in the U.S. Illinois Basin (example 1). Map from Quick and others (2005).

3.1-10 Example 1: U.S. Illinois Basin. Study describing the progressive increase of chlorine in formation water with depth in the Illinois Basin and a corresponding increase in the chlorine content of coal associated with those waters. From Gluskoter and Rees (1964).

3.1-11 Chlorine in U.S. Coal. Map showing distribution of chlorine in U.S. coal by county average, used as an introduction to the case study of chlorine in coal in the U.S Appalachian Basin (example 2). Map from Quick and others (2005).

3.1-12 Example 2: Chlorine Variation with Depth. Example 2 showing controls of chlorine variation in coal. Compilation from Bragg and others (1991) showing variation in chlorine content of Appalachian Basin coals with stratigraphic depth.

3.1-13 Mercury in South African Feed Coals. Introduction to the case study by Kolker and others (2014) for mercury in South African coals used in power generation.

3.1-14 Mercury Distribution by Power Station. Plot of mercury content for 13 coal-fired utility power stations operating in South Africa. The mean value for these coals is compared to U.S. feed coals from EPA databases and South African coals prepared for export. The mean mercury content of coals used for domestic power generation in South Africa is about four times the mercury content of South African export coals. From Kolker and others (2014).

3.1-15 Impact of Coal Preparation on Mercury. Summary slide showing benefits of coal preparation to improve coal quality on mercury reduction.

3.1-16 South African Highveld #4 Coal. Introduction to the case study on tests of density separates of South African Highveld #4 coal as a source of export coal (Kolker and others, 2017b).

3.1-17 Density Separates. Plots showing variation in pyritic sulfur with mercury and ash contents for density separates of South African Highveld #4 coal. Plots show correspondence of pyrite contents with ash and mercury. Results show the lowest ash and mercury contents are in the low density separates that approximate export coals (Kolker and others, 2017b).

3.1-18 Pyrite by Laser Ablation ICP-MS. In situ determination of arsenic and mercury in pyrite from density separates of South African Highveld #4 coal. Results show enrichment of both elements in pyrite relative to the whole coal and a large extent of grain-scale variation in mercury and arsenic contents within individual pyrite grains (Kolker and others, 2017b).

3.1-19 Coal Products Predicted from Density Separates. Table showing ash, mercury, arsenic, and selenium contents predicted in coal products used in South Africa, exported, or discarded, based on simple combinations of results for density separates from Highveld #4 coal. Mercury contents would be expected to vary by about a factor of 8 in these materials (Kolker and others, 2017b).

3.1-20 Summary—Topic 1: Mercury and Halogens in Coal.

3.1-21 References—Topic 1: Mercury and Halogens in Coal.

3.2 Improving Mercury Capture

3.2-1 Title Slide Session 3, Topic 2: Improving Mercury Capture.

3.2-2 Factors that Influence Mercury Capture. Summary slide listing coal quality factors and plant operation factors influencing mercury capture in coal-fired powerplants. From United Nations Environment Programme (UNEP; 2011) and Senior (2015).

3.2-3 Impact of Chlorine on Mercury Capture. Plot showing extent of mercury capture in coal-fired utility power stations equipped with various conventional air pollution control devices (APCDs). Results show the optimal range for chlorine to promote mercury capture, above which additional halogen contents are less beneficial. Results are based on U.S. county averages and available best-fit equations for each control technology. Plot is from Kolker and others (2006b), using county averages from Quick and others (2005).

3.2-4 Role of Halogens in Mercury Capture. Diagram showing gas phase and gas-particle reactions in the boiler involving mercury, halogens, and particulate matter. Halogens promote mercury oxidation to form mercury-halogen complexes or mercury bound to particles. These forms are easier to capture than gaseous elemental mercury. Diagram is from Kolker and others (2012).

3.2-5 Improving Mercury Capture. Plot showing mercury removal across an electrostatic precipitator (ESP) as a function of unburned carbon content (represented by loss on ignition [LOI]) of the ash. Results from Senior and Johnson (2005).

3.2-6 Improving Mercury Capture. Slide listing other options for improving mercury capture in coal-fired power stations equipped with conventional air pollution controls. These options include the addition of fabric filters (FFs) and the use of sorbents with an affinity for mercury.

3.2-7 Improving Mercury Capture. Slide showing addition of flue-gas desulfurization (FGD) as an option for improving mercury capture. FGD is a more expensive option, and its primary use would be to reduce sulfur emissions. If FGD is added, these devices can remove mercury in its gaseous oxidized form with high efficiency.

3.2-8 Kendal and Duvha Power Stations, South Africa. Introduction to the UNEP, Eskom, EPA, and USGS collaborative study (Scott, 2011; Kolker and others, 2014) of feed coal and fly ash from the Kendal and Duvha power stations.

3.2-9 Kendal and Duvha Power Stations, South Africa. Table showing total mercury emissions and proportion of oxidized mercury emitted from each boiler unit at Kendal and Duvha power stations. Measurements are from 2010 EPA field visit (Scott, 2011). Also shown is the concentration of mercury in fly ash as a function of the air pollution controls present. Results show that mercury oxidation is higher and more mercury is captured in the fly ash in units equipped with fabric filters (Kolker and others, 2014).

3.2-10 Kendal and Duvha Power Stations, South Africa. Plots showing that the extent of mercury capture and mercury content of fly ash is higher in Duvha boiler units equipped with fabric filters relative to Duvha and Kendal units equipped with electrostatic precipitators (ESPs). Coal and fly ash samples shown in the left plot were collected in duplicate with total sampling and analytical variation as shown (Kolker and others, 2014).

3.2-11 Kendal and Duvha Power Stations, South Africa. Summary slide showing findings with respect to variation in mercury capture in Kendal and Duvha boiler units equipped with ESPs versus FFs.

3.2-12 Improving Mercury Capture. Slide showing UNEP guidance document giving best practices for mercury emissions reduction and improving mercury capture without mercury-specific controls.

3.2-13 Summary—Topic 2: Improving Mercury Capture.

3.2-14 References—Topic 2: Improving Mercury Capture.

3.3 Measuring Ambient Mercury and Fine Particulate Matter

3.3-1 Title slide Session 3, Topic 3: Measuring Ambient Mercury and Fine Particulate Matter.

3.3-2 Speciation of Ambient Mercury. Summary slide defining measurable mercury species in the atmosphere, including elemental mercury (Hg^0), reactive gaseous mercury (RGM), and particulate mercury (Hg_p), and the characteristics of each.

3.3-3 USGS Mobile Mercury Laboratory. Slide showing USGS Mobile Mercury Laboratory and its capabilities for measuring mercury species; ancillary gases such as sulfur dioxide (SO_2), nitrous oxides (NO_x), and ozone (O_3); and fine particulate mass ($PM_{2.5}$). From Kolker and others (2007).

3.3-4 Ambient Mercury and Fine Particulate Matter. View of the interior of the USGS Mobile Mercury Laboratory showing instrument controls and view of the particulate sampler external to the Mobile Laboratory deployed to collect fine particulate matter for trace element analysis.

3.3-5 Ambient Mercury, Woods Hole, Massachusetts. Results of study by Kolker and others (2013), showing correspondence of RGM peaks with transient elevation of SO_2 and NO_x. Correspondence of all three parameters is indicative of plumes from coal-burning emission sources such as coal-fired powerplants.

3.3-6 Mercury Species and Other Gases, Woods Hole. Plots showing longer term correspondence between mercury species and ancillary gas concentrations, Woods Hole, Mass. (Kolker and others, 2013).

3.3-7 Distinguishing Sources of Ambient Mercury. Summary slide for distinguishing plumes from coal combustion versus other mercury sources such as chlor-alkali plants and the use of mercury in small-scale gold mining. Results are based on studies by Edgerton and others (2006) and by Kolker and others (2008 and 2010).

3.3-8 Trace Elements in $PM_{2.5}$. Summary slide showing generalized source categories of element groupings in fine particulate matter. From Duce and others (1975); Pacyna and Pacyna (2001); and Song and others (2001).

3.3-9 Trace Elements in $PM_{2.5}$. Results from the Kolker and others (2013) study of fine particulate matter at Woods Hole, Mass., showing crustal, marine, smelter, and energy- source categories and the calculated proportions of each.

3.3-10 Summary—Topic 3: Measuring Ambient Mercury and Fine Particulate Matter.

3.3-11 References—Topic 3: Measuring Ambient Mercury and Fine Particulate Matter.

Session 4

4.1 Introduction to Coal Ash

4.1-1 Title Slide Session 4, Topic 1: Introduction to Coal Ash.

4.1-2 Coal Combustion Products (CCPs). Summary slide with background information and definitions for coal combustion products.

4.1-3 Coal Combustion Products (CCPs). Diagram showing the range of coal combustion products produced in power generation and where in the plant they are generated. Diagram is from Deonarine and others (2015).

4.1-4 ASTM C618 Fly Ash Classification. Slide showing characteristics of ASTM Class C (“cementitious”) and Class F (“pozzolanic”) fly ash based on major element chemistry. From ASTM C618-17.

4.1-5 In the Boiler. Plot showing the range of temperature conditions in the boiler during coal combustion. From Senior (2015).

4.1-6 Mineral Transformations in Powerplants. Slide showing the mineralogical differences between coal and fly ash produced during coal combustion.

4.1-7 Examples of Fly Ash Constituents. SEM and microscopic images of coal fly ash showing constituents of the ash, including glass cenospheres, mullite ($Al_6Si_2O_{13}$), magnetite (Fe_3O_4), and partially combusted coal. Images courtesy of James Hower, University of Kentucky.

4.1-8 Fly Ash Petrography. Summary of organic and inorganic constituents of fly ash that are newly formed in the boiler (neoformed), such as glassy material, and those that are inherited from the feed coal, such as quartz and inertinite.

4.1-9 Fly Ash Microanalysis. Electron microprobe BSE images and wavelength dispersive elemental maps of iron oxide particle in glass and skeletal iron oxides with interstitial glass in fly ash. Nickel maps suggest an association of nickel with the iron oxide phase.

4.1-10 Fly Ash Microanalysis. Electron microprobe BSE and wavelength dispersive elemental maps of Fe, Ca, Al, and Si distribution in a coal fly ash sample. Images show glassy aluminosilicate cenospheres, iron oxides, and calcium-enriched zones in this sample area.

4.1-11 Summary—Topic 1: Introduction to Coal Ash.

4.1-12 References—Topic 1: Introduction to Coal Ash.

4.2 Trace Elements in Coal Ash

4.2-1 Title Slide Session 4, Topic 2: Trace Elements in Coal Ash.

4.2-2 Trace Elements in Coal Ash. Summary slide listing generalized behavior of trace elements in coal fly ash including volatile elements such as mercury that are emitted during coal combustion and refractory elements such as the rare earths that are retained in the ash fraction.

4.2-3 Behavior of Elements During Coal Combustion. Diagram showing relative volatility of elements during coal combustion. Volatile elements are emitted whereas refractory (not volatile) elements are retained in a smaller mass fraction. From Ratafia-Brown (1994).

4.2-4 From the Flue Gas. Slide summarizing the capture of volatile elements from the flue gas.

4.2-5 Element Enrichment in Coal Ash. Plot showing trace element enrichment in three U.S. coal fly ash samples relative to mean concentrations for these elements in U.S. coal from Bragg and others (1997). Plot is from Deonarine and others (2015).

4.2-6 Variation in Fly Ash Chemistry. Slide summarizing the variation in trace element content of fly ash within the ash collection system as a function of decreasing particle size and temperature.

4.2-7 Fly Ash Chemistry—Arsenic. The variation of arsenic content from front to rear in ESP hoppers in a Kentucky powerplant. From James Hower, University of Kentucky (unpub. data, 2004).

4.2-8 Fly Ash Chemistry—Mercury. The variation of mercury content from front to rear and from side to side in ESP hoppers in a Kentucky powerplant. From Mardon and Hower (2004).

4.2-9 Mercury Capture. Summary of the status of mercury capture in U.S. coal-fired utility power stations. Outline of factors that influence the process and extent of mercury capture in power stations that burn coal.

4.2-10 Summary—Topic 2: Trace Elements in Coal Ash.

4.2-11 References—Topic 2: Trace Elements in Coal Ash.

4.3 Beneficial Uses of Coal Ash

4.3-1 Title Slide Session 4, Topic 3: Beneficial Uses of Coal Ash.

4.3-2 Beneficial Use of Coal Combustion Products. Summary slide giving the status of EPA regulation of coal ash for beneficial use and the status of the use of coal combustion products in the United States. Sources: EPA (2014); American Coal Ash Association (not dated).

4.3-3 Use of U.S. Coal Combustion Products (CCPs). Plot showing amounts of CCPs produced and used by year and proportion used as a percentage. In 2016, proportion used exceeded 50 percent for the first time. Source: American Coal Ash Association (not dated).

4.3-4 Some Current Use of Coal Ash and FGD. Summary slide listing primary uses of coal ash and FGD materials. Source: American Coal Ash Association (not dated).

4.3-5 Recovery of Rare Earth Elements from Coal Ash? Summary slide listing the need for alternative sources of rare earth elements (REE), characteristics of coal ash that make it a possible source of REE, and the potential for REE recovery from coal ash.

4.3-6 Advantages of Coal Ash as a Source of REE. Summary of the advantages of coal ash as a potential source of REE, continued from previous slide.

4.3-7 Behavior of Elements During Coal Combustion. Slide emphasizing the nonvolatile behavior of REE during coal combustion. Slide is repeated from slide 4.2-3, which emphasized very volatile behavior of elements such as mercury and is the opposite of the behavior of REE during coal combustion. From Ratafia-Brown (1994).

4.3-8 REE in Coal Ash vs. Coal and Upper Continental Crust. Slide comparing REE enrichment of U.S. average coal (Bragg and others, 1997, Palmer and others, 2015; Upper Continental Crust (Taylor and McLennan, 1985), and a series of coal fly ash samples (Kolker and others, 2017a). Plot illustrates relative REE enrichment in fly ash relative to other materials. Chondrite-normalized plot, with normalizing values from from Korotev (2009).

4.3-9 Oddo-Harkins Effect. Slide illustrating the Oddo-Harkins effect in which even-numbered elements are more abundant than odd-numbered elements. Normalization to chondrites eliminates the appearance of a sawtooth abundance pattern resulting from the Oddo-Harkins effect.

4.3-10 Possible Modes of Occurrence of REE in Coal Ash. Summary slide explaining the uncertainty in mode of occurrence of REE in coal ash and giving possibilities that have been proposed for this occurrence.

4.3-11 REE-Bearing Trace Phases in Coal. Table listing REE-bearing trace phases found in coal and their melting temperatures as pure phases. These melting temperatures are similar to or exceed peak temperatures attained in coal-fired utility boilers.

4.3-12 REE-Bearing Trace Phases in Coal. Additional forms of REE occurrence in coal. Some are present only in mineralized coals.

4.3-13 Investigation of Fly Ash for REE. Outline of ongoing USGS studies of fly ash to determine the distribution of REE and preliminary results using ion microprobe analysis described in Session 5 of this short course.

4.3-14 REE in Coal Fly Ash. Results from Kolker and others (2017a) showing the distribution on a chondrite-normalized plot of REE in two bulk fly ash samples and their constituents.

4.3-15 Summary—Topic 3: Beneficial Uses of Coal Ash.

4.3-16 References—Topic 3: Beneficial Uses of Coal Ash.

4.3-17 References (Continued)—Topic 3: Beneficial Uses of Coal Ash.

4.4 Coal Ash Environmental Issues

4.4-1 Title Slide Session 4, Topic 4: Coal Ash Environmental Issues.

4.4-2 Mobility of Constituents from Coal Ash? Diagram showing possible pathways of migration of leachates from a coal ash impoundment where the impoundment is unlined. Slide also lists EPA TCLP leaching protocol used for testing potential element mobility from coal ash.

4.4-3 Mobility of Constituents From Coal Ash? Description of recent U.S. coal ash spills in Kingston, Tenn., and Eden, N.C., and the magnitudes of each spill.

4.4-4 Mobility of Constituents From Coal Ash? Photograph and map of the area affected by the 2009 Kingston, Tenn., coal ash spill. From Ruhl and others (2010), EPA (2014), and Deonarine and others (2015, 2016).

4.4-5 Potential for Mobility of Trace Elements. Slide showing USGS Fact Sheet 2015–3037 (Deonarine and others, 2015) and list of key findings: (1) Potential mobility of trace elements from coal ash differs by element; (2) Degree of oxygenation affects extent of element mobility; and (3) Standardized leaching tests only consider case where oxygen is available.

4.4-6 Leaching Experiments for Arsenic and Chromium in Fly Ash. Results from Deonarine and others (2015, 2016), showing leaching behavior of arsenic and chromium from two coal fly ash samples under oxic (with oxygen present) and anoxic (little or no oxygen present) conditions. Results show that arsenic is leachable under all conditions whereas chromium is partly leachable in one sample under oxic conditions and not leachable in the other cases.

4.4-7 Summary—Topic 4: Coal Ash Environmental Issues.

4.4-8 References—Topic 4: Coal Ash Environmental Issues.

Session 5

5.1 Laboratory Methods

5.1-1 Title Slide Session 5, Topic 1: Laboratory Methods.

5.1-2 How to Study Trace Elements in Coal. Summary slide comparing whole sample (bulk) analysis methods versus microanalysis methods for selective analysis of individual minerals or constituents in coal.

5.1-3 Common Methods for Bulk Trace Element Analysis. Table listing bulk analysis method from slide 5.2-2 and giving advantages and disadvantages of each method. Methods include inductively coupled plasma-mass spectrometry (ICP-MS), instrumental neutron activation analysis (INAA), X-ray fluorescence, and isotope dilution. Compilation is based on experience by the author with each method except for INAA.

5.1-4 About Moisture. Slide emphasizing the importance of moisture determination for coal in bulk analysis on a whole-coal basis and on a dry basis.

5.1-5 Whole Coal versus Ash Basis. Slide explaining the difference between whole-coal and ash basis for bulk analysis of coal. Slide showing sources of variation in results expressed on an ash basis and how these can be eliminated by expressing results for bulk coal samples on a dry, whole-coal basis.

5.1-6 Standards for Coal and Coal Ash Analysis. Slide listing U.S. National Institute for Standards and Technology (NIST) standard reference materials (SRMs) for coal and coal ash analysis, including SRM 1632d, Trace Elements in Bituminous Coal, and SRM 1633c, Trace Elements in Coal Fly Ash. Also, the difference between certified, reference, and informational values in NIST SRMs is explained.

5.1-7 Common Methods for Bulk Mercury Analysis. Table listing bulk analysis methods for mercury giving advantages and disadvantages of each method. Compilation is based on experience by the author with the direct mercury analysis (DMA) method.

5.1-8 Microanalysis Methods. Table listing microanalysis methods and giving advantages and disadvantages of each method, including scanning electron microscopy (SEM) with energy dispersive X-ray (EDX) analyzer, electron microprobe, and transmission electron microscopy (TEM) or high resolution (HR) TEM. Compilation is based on experience by the author with each method except for TEM.

5.1-9 Scanning Electron Microscope SEM/EDX. Photographs of an SEM equipped with EDX analyzer and an SEM image of a fly ash particle.

5.1-10 Electron Microprobe. Photograph of an electron microprobe and diagram showing the cross section of a wavelength-dispersive spectrometer used to measure characteristic X-rays of elements generated by interaction of the sample with the electron beam.

5.1-11 Electron-beam Instruments. Diagram showing interaction of sample with the electron beam and source regions for secondary electrons used in SEM, backscattered electrons used in BSE, and characteristic X-rays used for compositional analysis.

5.1-12 Microanalysis. Images showing microanalysis of a fly ash sample including wavelength-dispersive elemental maps for Fe, Ca, Al, and Si, and BSE map of the same image area.

5.1-13 Transmission Electron Microscopy (TEM). Example of high-resolution TEM image of fly ash particle surfaces showing surface coating at nanometer scale. From Deonarine and others (2015).

5.1-14 Trace Element Microanalysis Methods. Table listing microanalysis methods capable of determining trace elements and advantages and disadvantages of each method. Methods include laser ablation ICP-MS (LA-ICP-MS), ion microprobe, and synchrotron-based microprobe. Compilation is based on experience by the author with each method.

5.1-15 Laser Ablation ICP-MS. Slide showing an LA-ICP-MS instrument and its characteristics.

5.1-16 Pyrite Analysis by Laser Ablation ICP-MS. Example of LA-ICP-MS analysis of arsenic and mercury in pyrite in South Africa Highveld #4 coal density separate. From Kolker and others (2017b).

5.1-17 Ion Microprobe. Summary slide for Stanford/USGS SHRIMP-RG ion microprobe used for USGS REE studies in coal fly ash.

5.1-18 SHRIMP-RG Ion Microprobe. Photograph showing Stanford/USGS SHRIMP-RG ion microprobe and additional information on its uses. This instrument is used to determine elements present at concentrations below detection by electron beam instruments, such as the REE (Bacon and others, 2012; Stanford University, not dated).

5.1-19 Ion Microprobe Data for the REE. Preliminary REE data for selective constituents of coal fly ash determined using the SHRIMP-RG ion microprobe. Concentrations are shown on a chondrite-normalized plot together with data for bulk sample from separate bulk analysis.

5.1-20 Synchrotron Methods. Example in coal fly ash showing arsenic composition map determined by synchrotron microanalysis and corresponding arsenic species (forms of arsenic) using X-ray absorption near-edge structure (XANES). Synchrotron source has the advantage of giving bulk trace element microanalysis together with element speciation. Example is from Deonarine and others (2015).

5.1-21 Summary—Topic 1: Laboratory Methods.

5.1-22 References—Topic 1: Laboratory Methods.

5.2 Laboratory Quality Assurance

5.2-1 Title Slide Session 5, Topic 2: Laboratory Quality Assurance.

5.2-2 Common Problems in ICP-MS Analysis. Summary slide listing common problems that can affect bulk trace element analysis by ICP-MS.

5.2-3 Sample Digestion for ICP-MS. Summary slide listing approaches to digestion of solid samples for ICP-MS analysis and the requirements and limitations of each method.

5.2-4 REE-Bearing Trace Phases in Coal. Summary slide showing common REE-bearing trace phases in coal that may not be fully digested in acid digestion for REE analysis by ICP-MS.

5.2-5 Fusion Digestion vs. 4-Acid Digestion for REE. Comparison of measured and certified values for USGS standard GXR-4 in two separate ICP-MS runs by the same commercial laboratory. Using acid digestion, in most cases, recovery is only about 50 to 70 percent of the certified values. Using fusion digestion, recovery is near 100 percent.

5.2-6 Two Sinter Digestions for NIST SRM 1633c. Table showing separate ICP-MS runs for REE in NIST SRM 1633c, from two different laboratories, both using a sinter digestion procedure. Results obtained are similar in each case to available certified, reference, and informational values. Based on the values alone, it is not possible to determine which is the better analysis.

5.2-7 Chondrite Normalization. Chondrite normalization shows a smooth pattern for REE data subject to the Oddo-Harkins effect.

5.2-8 Data Comparison using Chondrite Normalization. Comparison of REE data from slide 5.2-6, using chondrite normalization. Data from Lab 1 give a smooth pattern whereas data from Lab 2 have a kinked pattern in Er and Yb, suggestive of analytical problems for the heavy REE.

5.2-9 Chondrite Normalization. Comparison of chondrite normalization approaches presented by Korotev (2009). Korotev suggests an approach using Anders and Grevesse (1989) x 1.36 to give Sm = 0.200 ppm. That approach has been adopted in this short course.

5.2-10 ICP-MS Isobaric Interferences. Summary slide showing potential isobaric interferences affecting trace element analysis by ICP-MS and ways to avoid, correct for, or eliminate them (Li and others, 2014).

5.2-11 IUPAC Periodic Table of the Isotopes. Table of the isotopes showing isotopic variation for arsenic and selenium discussed in the next slide.

5.2-12 Isotopes of Arsenic and Selenium. Table showing isotopes of arsenic and selenium needed to correct for isobaric interferences at ^{75}As, the only isotope of arsenic, in ICP-MS determination of arsenic.

5.2-13 Example of Interference Correction for ^{75}As. Example showing isobaric interferences for ^{75}As and procedure to correct for these interferences.

5.2-14 Other Common Problems with ICP-MS. Summary slide describing calibration and carryover problems inherent in ICP-MS analysis.

5.2-15 Internal Checks on Data Quality. Summary slide listing internal checks on data quality in bulk analysis. Checks include running standards, blanks, and replicates, and, for major elements, summing to near 100 percent. For REE analyses, data should define a smooth pattern on a chondrite-normalized plot. If the checks are unsatisfactory, rerun the sample.

5.2-16 Run it Over Again. Example comparing DMA mercury analyses for the same samples run in USGS laboratories in Denver, Colo., and Reston, Va. Overall, results show good agreement between the two laboratories, with a few problem samples. Rerunning the problem samples resulted in convergence of initially disparate results for the two laboratories. Results from Kolker and others (2014).

5.2-17 Summary—Topic 2: Laboratory Quality Assurance.

5.2-18 References—Topic 2: Laboratory Quality Assurance.

5.3 Introduction to Compositional Data Analysis

5.3-1 Title Slide Session 5, Topic 3: Introduction to Compositional Data Analysis.

5.3-2 Compositional Data. Common examples where compositional data are constrained to a constant sum, such as values expressed in percent and parts per million, compared to unconstrained results, such as concentrations measured in milligrams per liter, micrograms per cubic meter, or molar concentrations.

5.3-3 Closure. Closure of compositional data means that proportions of a whole must be positive or zero. This sets compositional data apart from variables using absolute scales such as speed, mass, and time.

5.3-4 Correlations. In a given sample set, mathematical covariance of results can lead to misleading or contradictory results.

5.3-5 Subcompositional Incoherence. Correlations of components are compared in case A, a sample that contains moisture, and case B, where the sample material has been dried. The sign of the covariation between components X_1 *and* X_2 is reversed by drying. This example is similar to a coal proximate analysis expressed on a moisture-containing basis and on a dry basis.

5.3-6 Simplex. This example shows a set of values in D-dimensional noncompositional space where statistical techniques are valid and a set of values in (D-1)-dimensional space (a simplex) where compositional values add to a constant. The triangular D-1 simplex is a section within D-dimensional space.

5.3-7 Warnings. Some common fallacies pertaining to compositional data are given.

5.3-8 Solutions. An approach is given whereby compositional data constrained to a constant sum can be converted for use in unconstrained space where statistical approaches are applicable. This approach includes computing rations of variables and taking the logarithms of the ratios (log ratios).

5.3-9 Log-Ratio Transformations using Geometric Means. Variable log ratios can be further transformed as shown and expressed as isometric log-ratio transformations (ilr) or centered log-ratio transformations (clr) These transformed variables can then be used to explore controlling dependencies of the dataset.

5.3-10 The Biplot: A Tool for Exploring Dependencies. Example using available software (Thió-Henestrosa and Comas, 2016) to generate plot showing principal components and variable log ratios in unconstrained space. Plot is useful in evaluating controls on data variability. Plot shows that the centered log ratio representing the ash (clr A) exerts the greatest control on the dataset.

5.3-11 Mapping. Log-ratio transformations can also be mapped to show data in a geospatial context. Here the data from the previous slide are mapped. The map also shows that where ash is highest, everything else is lower, as indicated in the previous slide.

5.3-12 Modeling of Compositional Processes. A process analogue is shown where each component has a different rate of change. This process can be applicable in cases where characterizing time series data is appropriate, such as production from different wells.

5.3-13 Summary—Topic 3: Compositional Data Analysis.

5.3-14 References—Topic 3: Compositional Data Analysis.

Appendix 2. Short Course Slides

Short course material, presented in PDF as a series of PowerPoint slides, is available at https://doi.org/10.3133/ofr20181145.

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Document 33

U.S. Geological Survey, Short Course: Modes of Occurrence of Trace Elements in Coal.

SHORT COURSE C

Modes of Occurrence of Trace Elements in Coal:

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MODES OF OCCURRENCE OF TRACE ELEMENTS IN COAL

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Introduction

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Impact of Trace Metals

Understanding of trace-metal distribution is needed to:

- Develop models for power plant emissions.
- Predict coal behavior upon cleaning.
- Control release of metals from coal and coal combustion materials to ground water.
- Minimize health consequences of coal use in domestic settings.

Effects of Inorganic Components on Coal Utilization

Element	Effects
• Sodium	• Boiler Fouling
• Iron	• Boiler Slagging
• Chlorine	• Corrosion; Hg capture
• Si (Quartz)	• Erosion of Combustors

Trace Element Averages

Element	Mean Value (ppm)	Standard deviation	Maximum value	Number of samples
Beryllium	2.2	4.1	330	7,484
Chromium	15	15	250	7,847
Manganese	43	84	2,500	7,796
Cobalt	6.1	10	500	7,800
Nickel	14	15	340	7,900
Arsenic	24	60	2,200	7,676
Selenium	2.8	3.0	150	7,563
Cadmium	0.47	4.6	170	6,150
Antimony	1.2	1.6	35	7,473
Mercury	0.17	0.24	10	7,649
Lead	11	37	1,900	7,469
Thorium	3.2	3.0	79	6,866
Uranium	2.1	16	1,300	6,923

Average concentrations of elements of environmental interest in U. S. Coals (results from USGS COALQUAL database, Bragg et al., 1998; after Finkelman, 1993; Kolker and Finkelman, 1998).

About Moisture

- Generally, calorific value increases and moisture decreases with increasing rank. Need to know moisture content to accurately express elemental concentrations in coal.
- Moisture contents range from about 2% in bituminous coals to as much as 30% in low rank coals. Perfect analyses determined on a dry basis can be off by as much as 30% if moisture is not taken into account.

Mode of Occurrence Concept

- Definition- Understanding the chemical form of an element present in coal.
- Importance- Determines element behavior during coal combustion and potential for removal. Determines environmental impact, technological behavior and byproduct potential. Can provide information on geologic history.

Element Modes of Occurrence

Organic Association (Maceral)	Inorganic Association (Mineral)
• Ionic bound to maceral • Covalent bound to maceral • Moisture	• Solid solution (e.g As for S in pyrite; Cr in illite/smectite; Cd in sphalerite) • Essential Structural Constituent (e.g. Galena - PbS)

Results for Elements of Environmental/Human Health Interest

Element	Mode of Occurrence	Confidence*
Antimony	Pyrite; accessory sulfides	Moderate
Arsenic	Pyrite	High
Beryllium	Organic association; silicates	Low/moderate
Cadmium	Sphalerite	High
Chromium	Illlite; organic association; chromite	Moderate/high
Cobalt	Pyrite; accessory sulfides	Moderate
Lead	Galena; selenides	High
Mercury	Pyrite	Moderate/high
Manganese	Carbonates, illite	High
Nickel	Pyrite; organic; other	Moderate
Selenium	Organic; pyrite; selenides	High

* Interpretative index assigned by the authors; i.e. "High" indicates a high confidence in the results by the authors for the specified element mode of occurence.

Geologic Factors Influencing Coal Chemistry

- Burial and diagenetic changes.
- Stratigraphic and lateral variation.
- Interaction with mineralizing fluids (e.g. Alabama, China, western Washington).
- Movement of fluids along fractures.
- Cleat (fracture-filling) mineralization during coal formation.

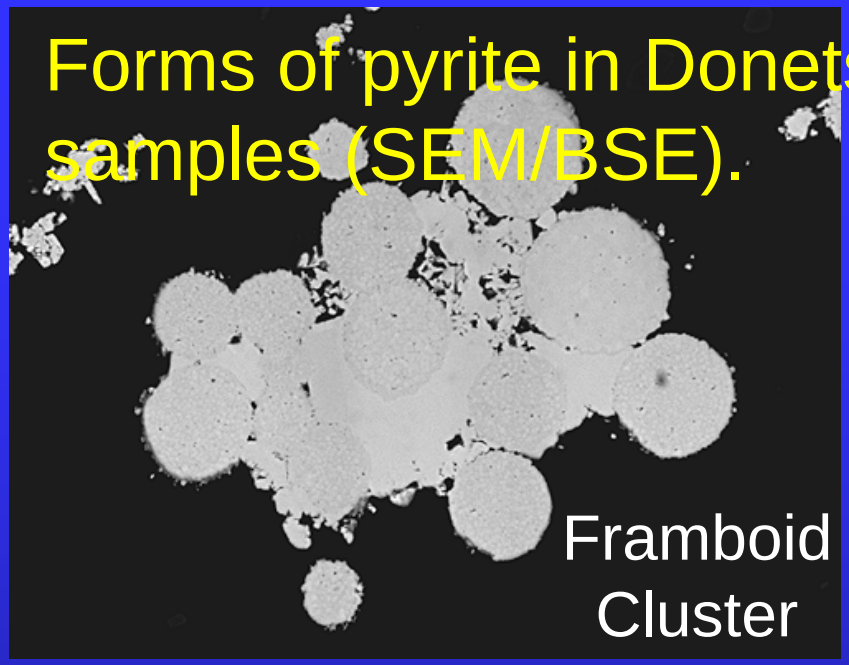
Coal Mineralogy and Mineral Chemistry

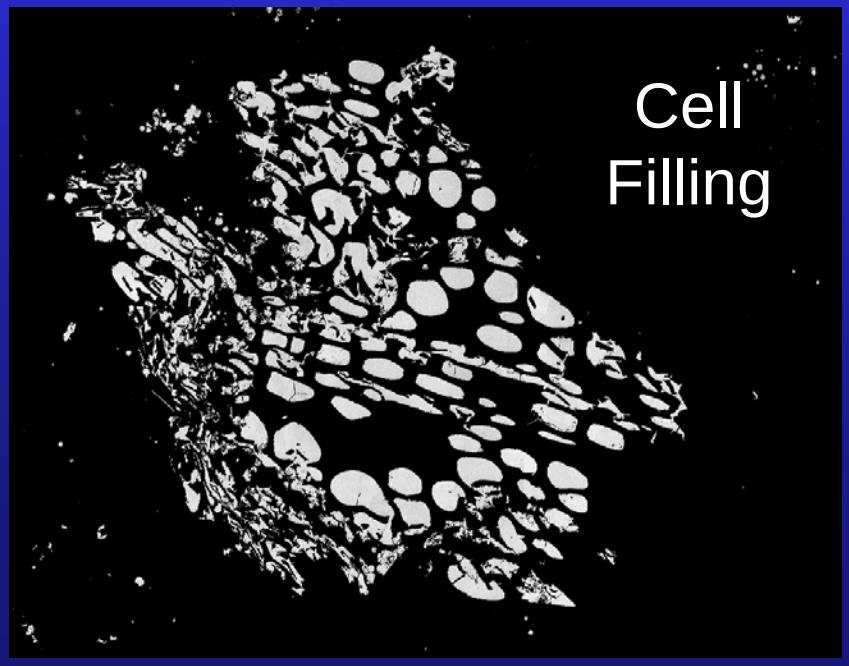
Allan Kolker

Coal Mineralogy

Mineral	Minor Elements
Quartz (SiO_2)	Negligible
Clays	
Illite/Illite-smectite	Fe,Cr,Mn,V,
Kaolinite $Al_4(Si_4O_{10})(OH_8)$	Negligible (?)
Carbonates	
Calcite ($CaCO_3$)	Sr, Mn
Siderite ($FeCO_3$)	Mn
Ankerite $Ca(Mg,Fe,Mn)(CO_3)_2$	Sr
Pyrite (Marcasite) (FeS_2)	As,Hg,Co,Ni

Forms of pyrite in Donets Basin (Ukraine) coal samples (SEM/BSE).





Minor/Trace Phases

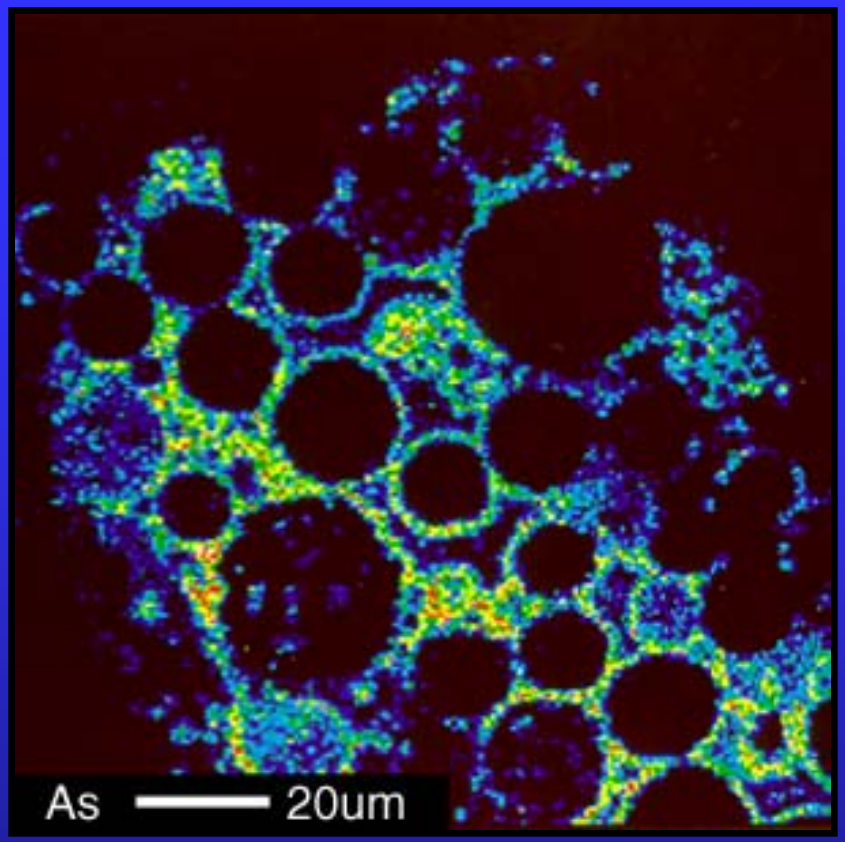
Mineral	Formula or Major Components	Minor Elements
Galena	(PbS)	
Sphalerite	(ZnS)	Cd
Chalcopyrite	($CuFeS_2$)	
Clausthalite	(PbSe)	
Crandallite Group	(Ca, Al, P)	Ba, Sr, REE
Monazite	(REE, P)	Th
Xenotime	(YPO_4)	REE
Apatite	(Ca, P)	REE
Zircon	($ZrSiO_4$)	U, Pb, Th
Rutile	(TiO_2)	
Barite	($BaSO_4$)	
Feldspars	(Ca, Na, K, Al, Si)	
Micas	(K, Fe, Mg, Ti, Al, Si)	
Zeolites	(Ca, Na, K, Al, Si)	

Low Temperature Ashing/XRD

- Method for determining coal mineralogy.
- Concentrate mineral matter by slowly consuming organic matter at 175°C.
- Mineral I.D. by X-Ray diffraction of LTA.
- Mixture of minerals solved by computer.
- Computer-controlled SEM is an alternate approach. Both techniques are semi-quantitative.

Arsenic in Coal

- Pyrite is primary host of arsenic in bituminous coals; Arsenopyrite is rare
- Arsenic contents vary widely within and between pyrite grains.
- In low rank coals, pyrite is a less important host of arsenic.



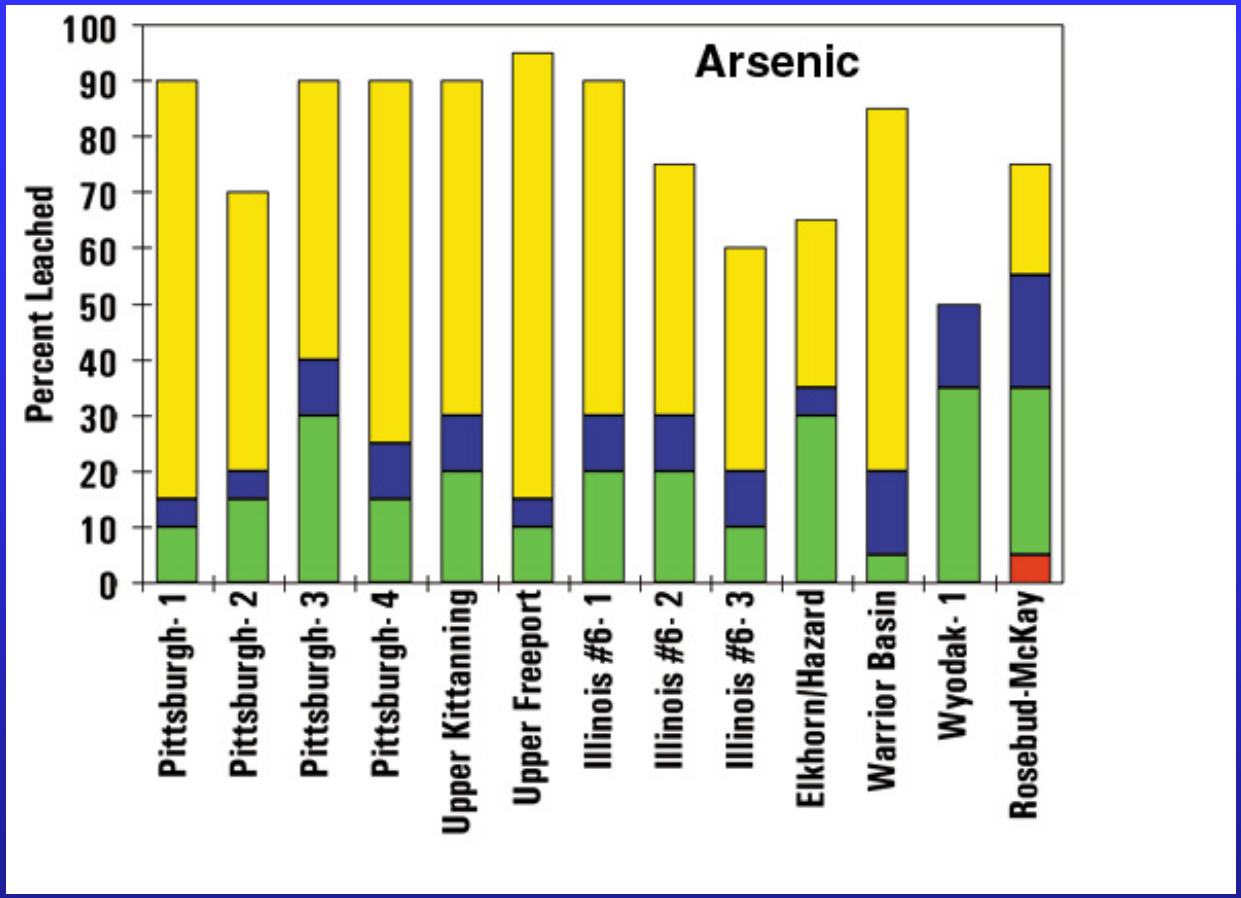
Arsenic-rich pyrite overgrowths on pyrite framboids in an Alabama bituminous coal.

Source: Goldhaber et al., 2003

Arsenic in Coal - continued

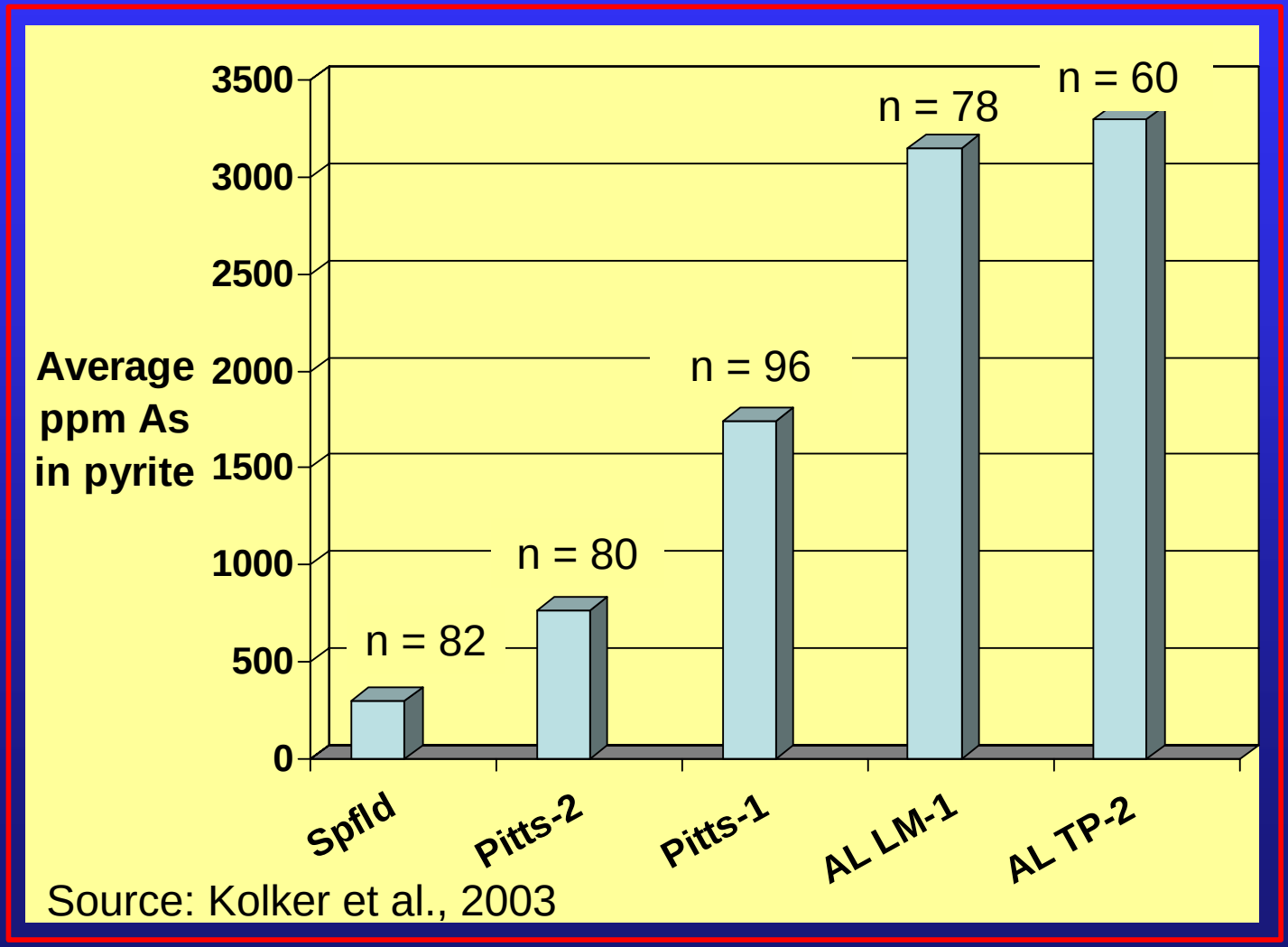
- Coal cleaning reduces pyrite content, but framboids may remain in organic fraction.
- Pyrite oxidation releases arsenic to the environment and changes arsenic oxidation state.
- Documented health effects from arsenic are rare: 1) Guizhou, Province, China: Domestic use of ultra-high-arsenic coals (up to 30,000 ppm). 2) Central Slovakia, 1970's: Arsenic toxicity from use of local coals in power plant.

Arsenic selective leaching results for 13 coal samples showing pyrite association (yellow) for 11 bituminous samples.

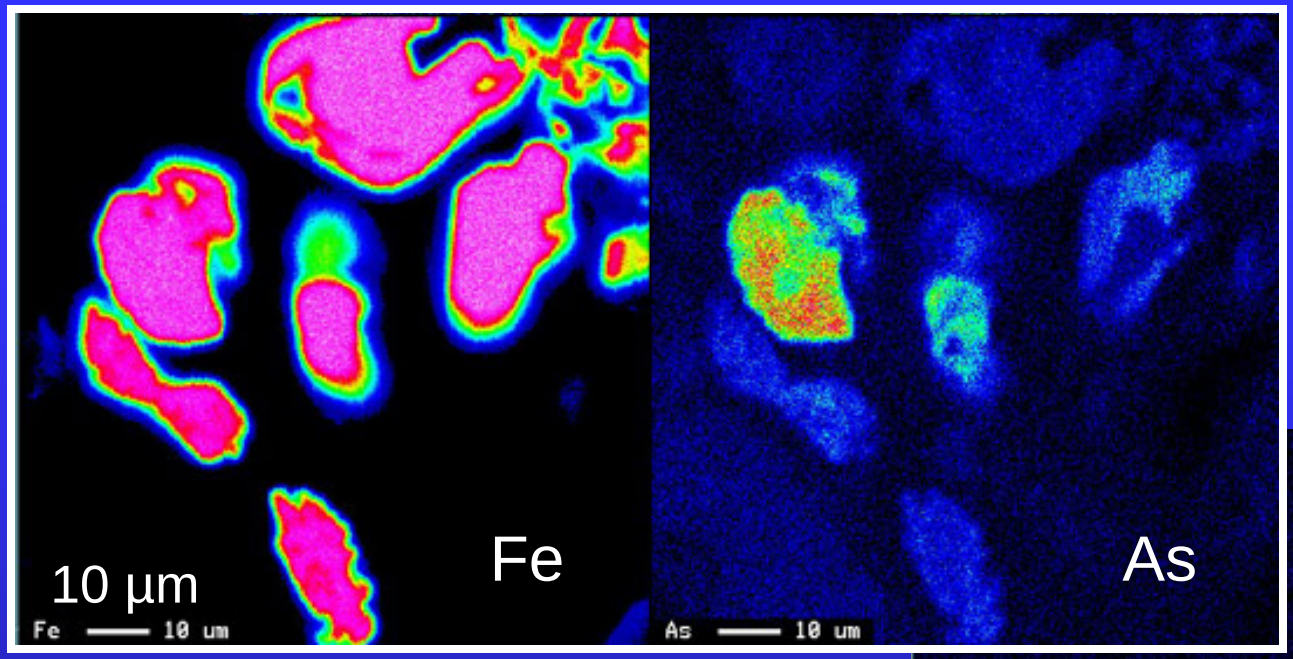


Source: Palmer et al., 1998

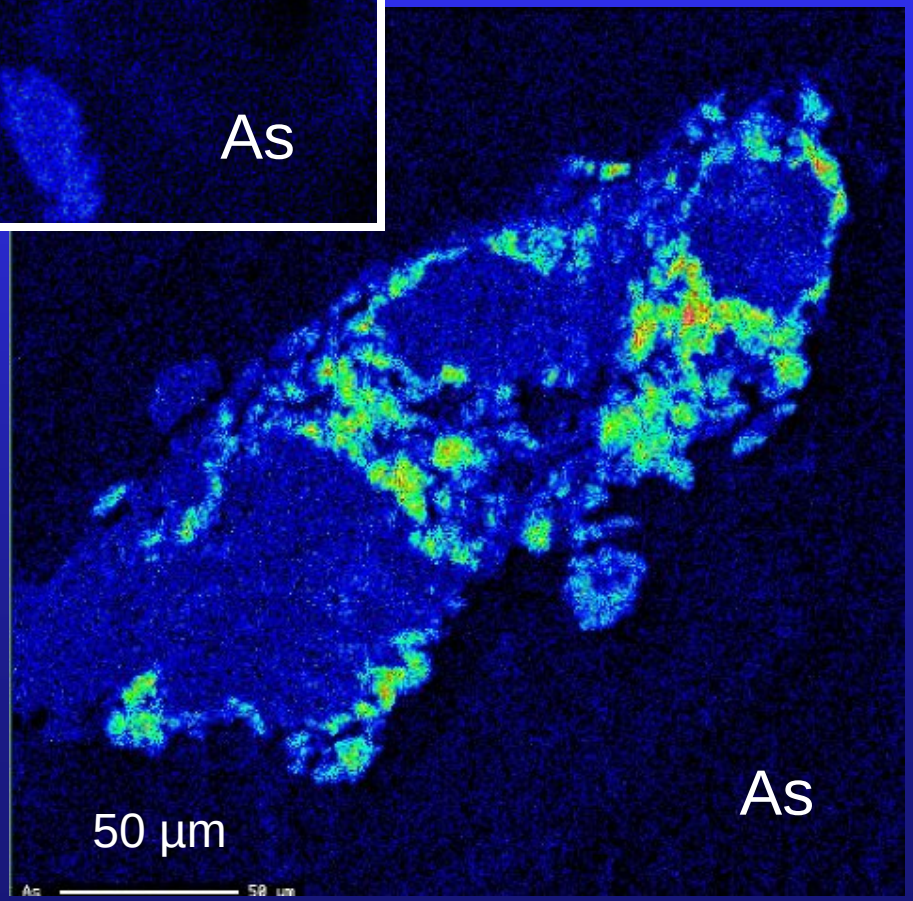
Relative Concentration of As in Pyrite



Source: Kolker et al., 2003



Wavelength-dispersive electron microprobe elemental maps of pyrite in Alabama samples LM-1 (above) and TP-1 (right) showing arsenic-enriched domains.



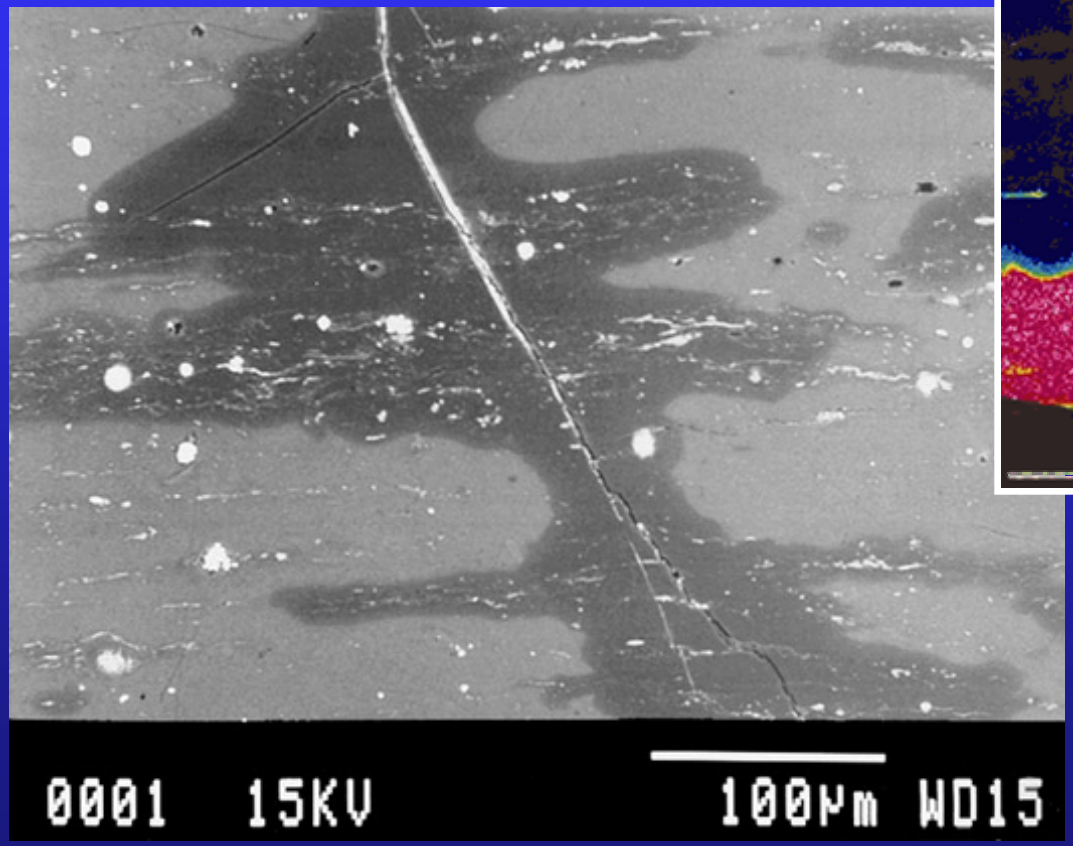
Coals used domestically in areas of pervasive arsenic poisoning, southwest Guizhou Province, China (Belkin et al.).

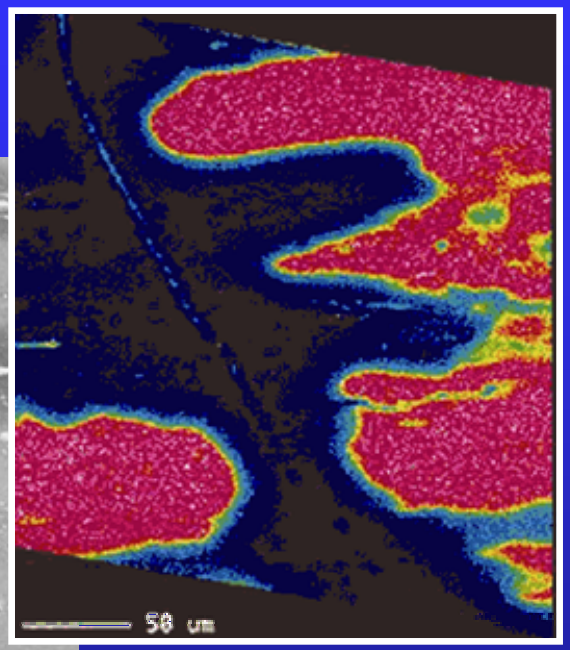
Jiaole Township				Haizi Township				Xingyi City-Dadi area			
Sample	As	Sb	Hg	Sample	As	Sb	Hg	Sample	As	Sb	Hg
A	2223	55	14	A	35037	209	4.1	A	5.2	0.4	0.1
B	1591	132	45	B	32316	140	5.8	B	274	0.7	0.48
C	7391	165	8.5	C	48	8	0.32	C	386	0.5	0.41
D	607	40	29	D	318	13	0.48	D	1100	1.6	0.26
E	405	29	2.0	E	53	16	0.9	E	5.5	0.4	0.7
F	419	22	6.9	F	22	16	0.32	F	925	0.6	0.24
G	239	38	17.6	G	7817	364	5.2	G	26	0.4	0.18
H	313	68	46	H	85	5	0.53	H	4.8	0.6	0.34
I	2286	142	30.2	I	315	16	1.4				

As and Sb by INAA, Hg by Cold-Vapor AA (USGS Labs, Denver). Values are in ppm.

Guizhou (China) Coal Samples

Back-Scattered Electron Image

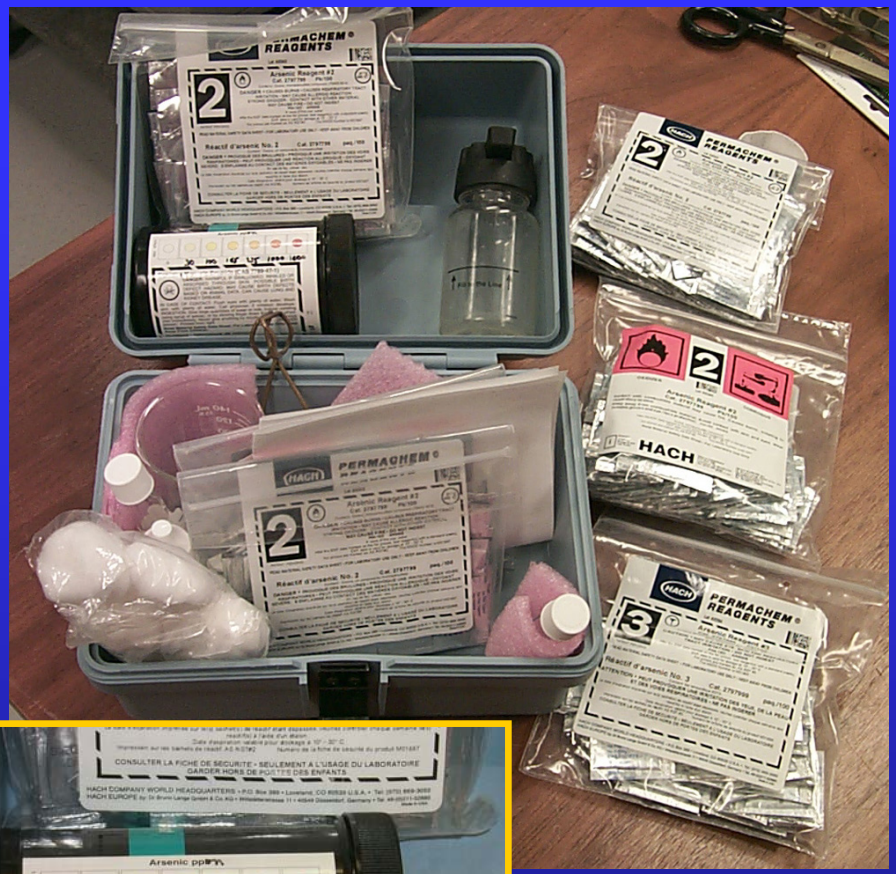




Arsenic Microprobe Map

Images from Belkin et al.

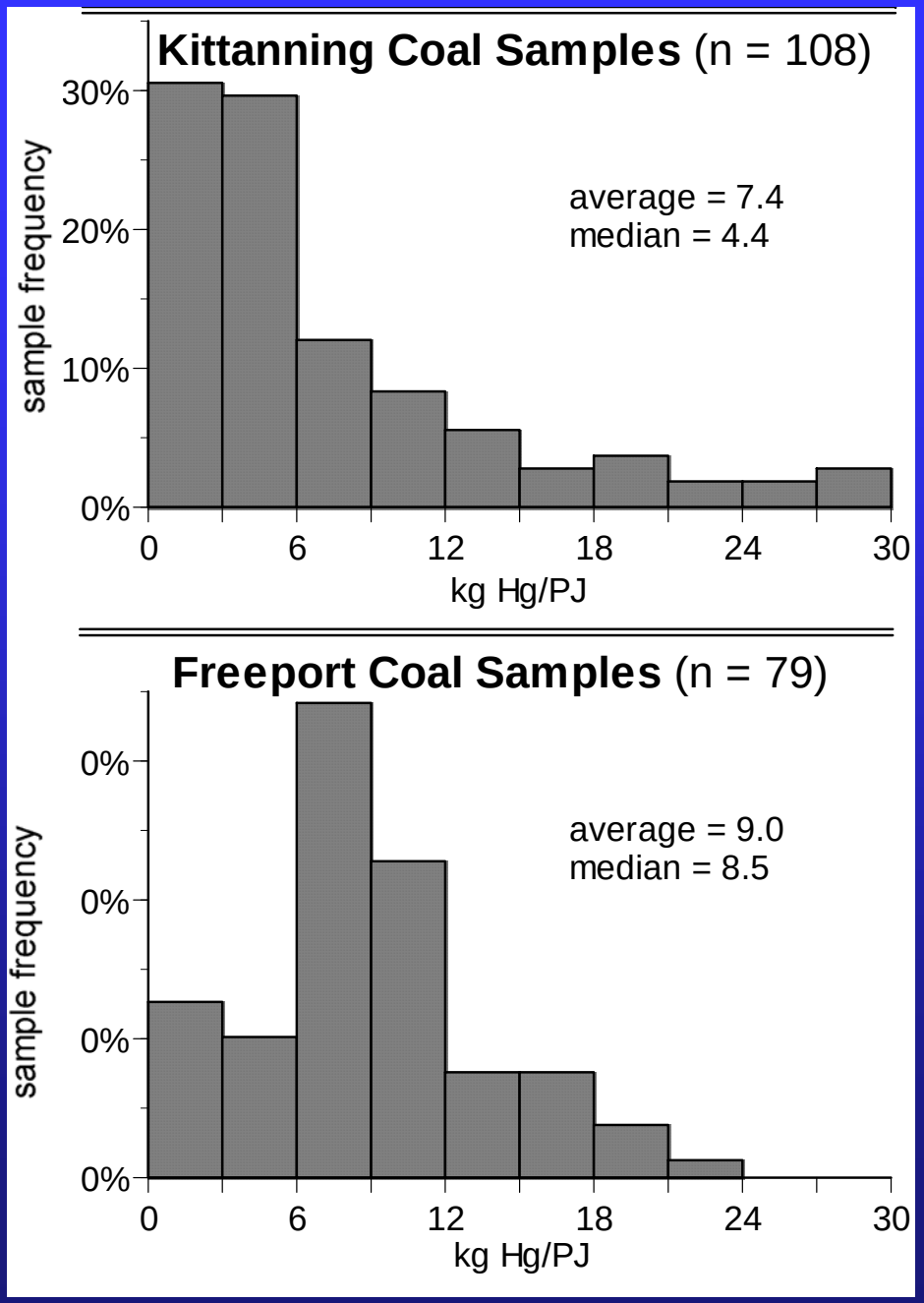
Arsenic Field Tests



- Test kit developed in China to identify arsenic-rich coals in the field.
- Commercial version (left) being introduced by U.S. manufacturer.
- Testing has resulted in closure of “mines” with highest As coal.

Mercury in Coal

- Pyrite (FeS_2) is the most common mercury association in bituminous coals.
- Mercury content of pyrite is variable and can be correlated with arsenic and other air toxics.
- In low rank coals, an organic association is common.
- In very mercury-rich coals, HgSe, HgS (cinnabar), and/or native mercury may be present.

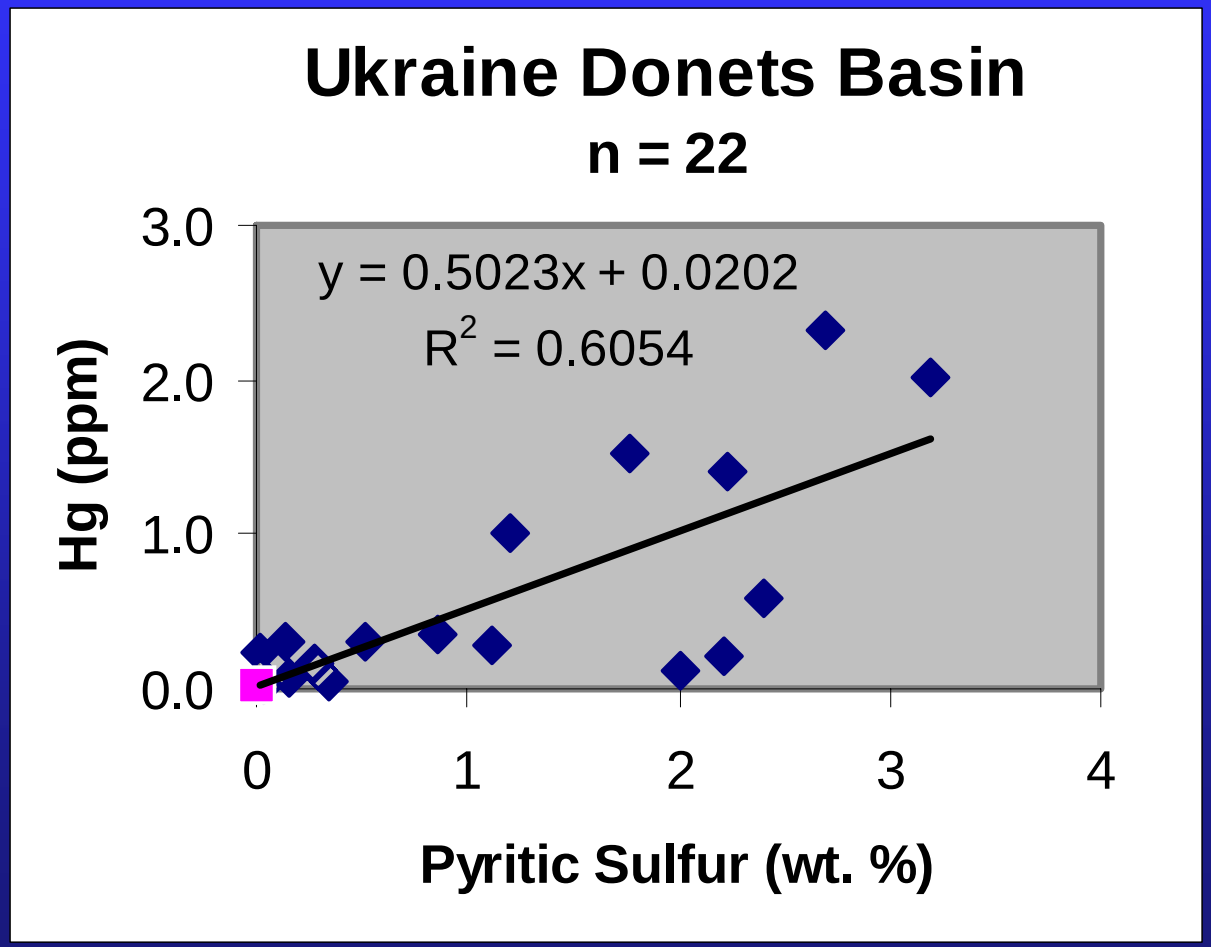


Comparison of mercury distribution in Kittanning and Freeport Coals.

From: Quick et al. , *2003, Environmental Geology*

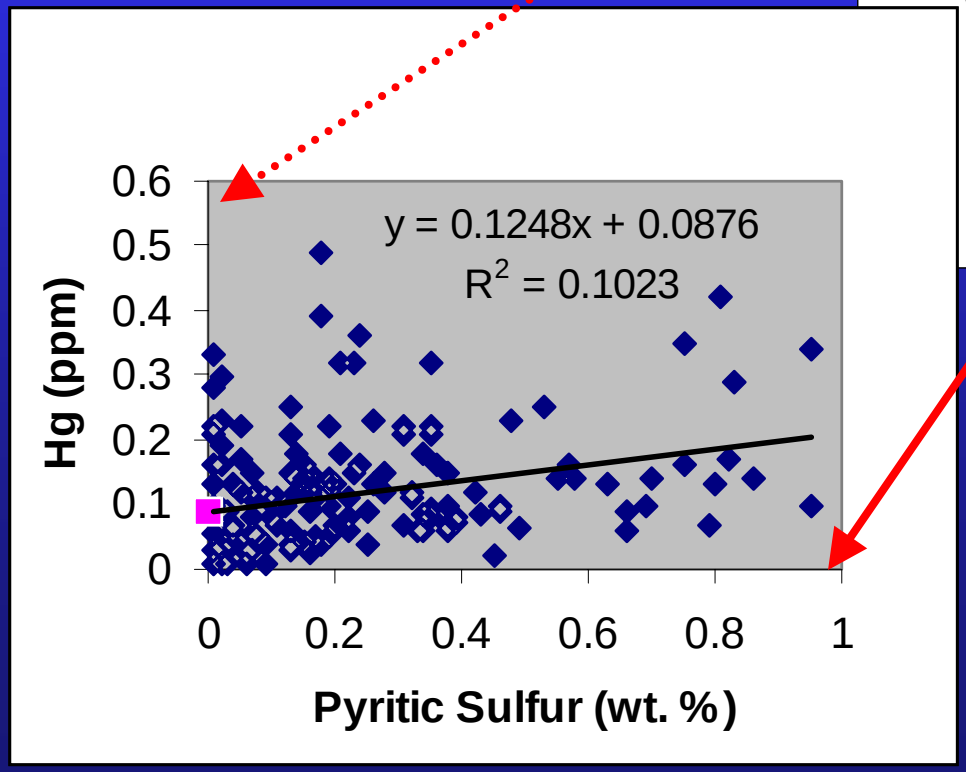
Example of Hg variation controlled by pyrite

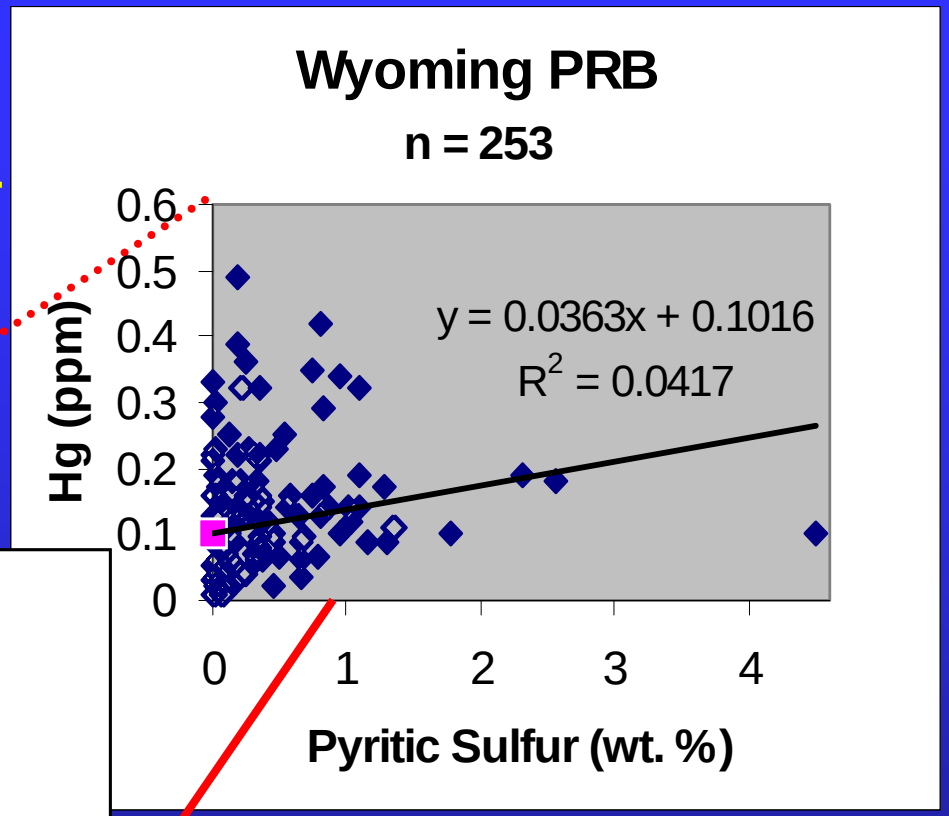
One outlier (Hg = 4.5 ppm) removed



Source: Modified from Kolker et al., 2002

Example of poor correlation between Hg and pyrite, Powder River Basin, Wyoming. Organic affinity indicated by positive Hg intercept.





Two high-Hg points excluded (1.1 and 0.74 ppm); Data from Bragg et al., 1998

Selenium in Coal

- Important organic association indicated by most studies.
- Measurable Se in some pyrite; May contribute Se to ground water upon pyrite oxidation.
- Selenides (eg. PbSe) common in coal, unlike other sediments.
- Sensitive to in-situ oxidation, but less so than As.

Chromium in Coal

- Silicate (illite) and organic-hosted forms are dominant.
- Cr may also occur in Fe-Ti-Cr oxide minerals, if present.
- Not prone to in-situ oxidation in coal, unlike Fe, As, Se.

Source: Huggins et al., 2002

Chlorine in Coal

- Chlorine content is an important parameter because of corrosive effects of HCl and Hg-Cl complexing in coal-fired power plants.
- Chlorine contents are strongly influenced by salinity or paleo-salinity.
- Salinity increases with depth or paleo-depth.

Chlorine in Appalachian Coal

Basin	Average Cl in Coal (ppm)*
Northern Appalachian	850
Central Appalachian	950
Southern Appalachian	310

*Results for Bragg et al., 1991

Chlorine Stratigraphic Variation

Age	Formation	Number of Samples	Mean Cl (ppm)
Lower Permian (?)	Dunkard Group	44	162
Upper Pennsylvanian	Monongahela Formation	73	477
Upper Pennsylvanian	Conemaugh Formation	41	828
Middle Pennsylvanian	Allegheny Formation	709	1097
Middle Pennsylvanian	Kanawha Formation	36	1408
Lower Pennsylvanian	New River Formation	56	1503

Results for Bragg et al., 1991

Trace Metals in Coal Macerals

- Limited number of determinations, in-situ or on maceral separates.
- Information on vitrinite, liptinite and inertinite groups.
- Large variation within and between coals:
  sub-ppm: Hg
  sub-ppm to few ppm: Sb, Th, U
  ppm to 10's ppm: Cr, Ni, As, V
  ppm to 100's ppm: Fe, Mn

Source: Kolker and Finkelman, 1998

Summary - Trace Metals in Coal

- Arsenic:
  - Arsenic-bearing pyrite is dominant form in fresh bituminous coals.
  - Oxidized form (arsenate) is a function of the degree of pyrite oxidation.
  - Greater organic fraction in low-rank coals.
- Chromium:
  - Illite and organic forms are dominant.
  - Oxidation state all Cr(III) in coal; rare Cr(VI) in ash.
- Mercury:
  - Pyrite is most significant host of Hg.
  - Organic fraction is greater in low-rank coals.

Trace Metals in Coal- continued

- Selenium:
  - Exhibits multiple forms; common to have a significant organic fraction, even in bituminous coals.
  - Oxidation state changes with pyrite decomposition, but less so that Fe, As.
- Chlorine:
  - Chlorine content variable; controlled by salinity or paleo-salinity.
  - Affects Hg emissions by Hg-Cl complexing.
- Macerals:
  - Largest fraction of trace elements in low-rank coals.
  - May be a significant host of transition metals.

USGS
science for a changing world
Coal Formation and Diagenesis
Geologic Controls on Coal Chemistry
The Society for Organic Petrology
Trace Elements in Coal
September 21, 2003

Conclusions

The concentration, variation (both laterally and vertically), and modes of occurrence of trace elements are controlled by geologic and geochemical processes that begin in the peat stage of coalification and continue thru coalification and exploitation.

If we understand the processes that control elements we have a good chance of predicting: 1) where elements are; 2) how they are bound; and 3) what will happen to elements during coal utilization.

What controls coal quality?

Allogenic controls

Climate
Tectonism
Eustasy

Autogenic controls

Depositional environment
Hydrology
Sediment influx
Alteration within peat body
Diagenetic reactions
Rank
Weathering

Allogenic Control 1

Climate

Controls the type of peat, the type and rate of vegetation, and sediment input into the mire or peat swamp.

Allogenic Control 1

Domed (convex upward) peat:

- *Ever-wet, tropical climates* - domed, rain-fed (ombrogenous) peat bodies. (Sumatra foreland basin, L. Mississippian to mid-Middle Pennsylvanian Central Appalachian Basin coals: includes Pocahontas, Fire Clay, Winifred/Stockton coals.)

Doming, radial drainage, flushing.
Low in nutrients: eolian input, dissolved solids minimal.
Limited buffering capacity, rapid peat development.
Minimal degradation of organic matter.
Upland soils anchored

Allogenic Control 1

Planar (flat-lying) peats

Seasonally-wet, more temperate climates –planar, ground-water and rainwater-fed (rheotrophic) peat bodies. (U.S. coastal swamps; late Middle to U. Pennsylvanian Appalachian basin coals).

High sediment/nutrient input – eolian, fluvial, and groundwater.
Leaching can be high.
Relatively high pH (>4); organics degraded.

Allogenic Control 2

Tectonism

Controls rate of base level change – climatic fluctuations may raise or lower water table but need base level rise to build up thick peat.

Fluctuations in base level dependent on tectonic subsidence, eustasy, and compaction.

For the preservation of economic coals need a continuous rise in groundwater (subsidence) and relatively low relief of hinterlands to restrict sediment influx. These conditions occur in foreland basins.

Model for Cretaceous coals of western U.S.

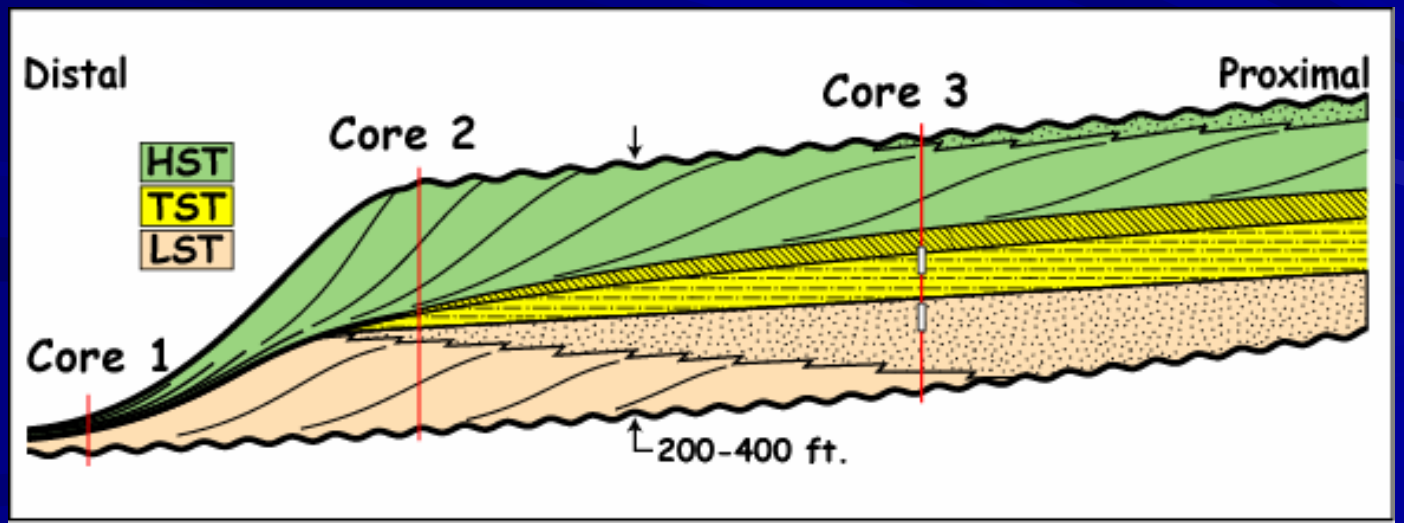
Allogenic Control 3

Eustasy

Increased water depths with marine flooding elevates water tables in non-marine and continental settings.

Elevated fresh water tables allow for plant growth, peat development, and coal preservation in the accommodation space.

Sequence stratigraphy concepts.



What controls coal chemistry?

Autogenic controls

Depositional environment
Hydrology
Sediment influx
Burial
Alteration within peat body
Diagenetic reactions
Rank
Weathering

Depositional Environment & Geologic Setting

Affects geometry, extent, and boundaries of peat bodies.

Affects bed and dissolved load of streams and peat swamp.

Controls underlying substrate.

Exerts a control on ground-water chemistry.

Hydrology

CONTROLS, TO A LARGE EXTENT, GEOMETRY

Ombrotrophic peats (rainwater-fed)

Low in ash – few dissolved solids.
Often domed – limits detrital influx.
Sediment input-eolian volcanics and dust.
Highly acidic.
Low diversity of plants, stunted in middle.

Rheotrophic peats – (groundwater-fed)

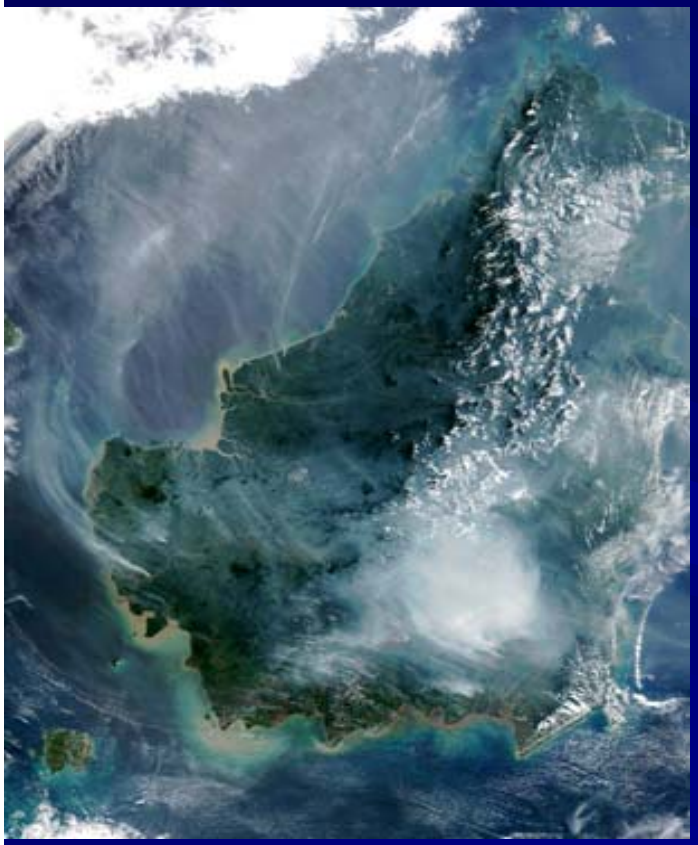
High in dissolved solids.
Often planar.
Sediment-rich.

Mesotrophic peats (ground-and rainwater)

Intermediate in ash.

Autogenic Controls

Sediment Input



www.noaa.gov

Eolian Sources (domed and planar)

Dust

Volcanic ash-fall material – amphibole, pyroxene, quartz, feldspar, glass, etc.

Cosmic dust

Sea-spray

Water-born sources (predominantly planar, edges of domes)

Dependent on geologic setting

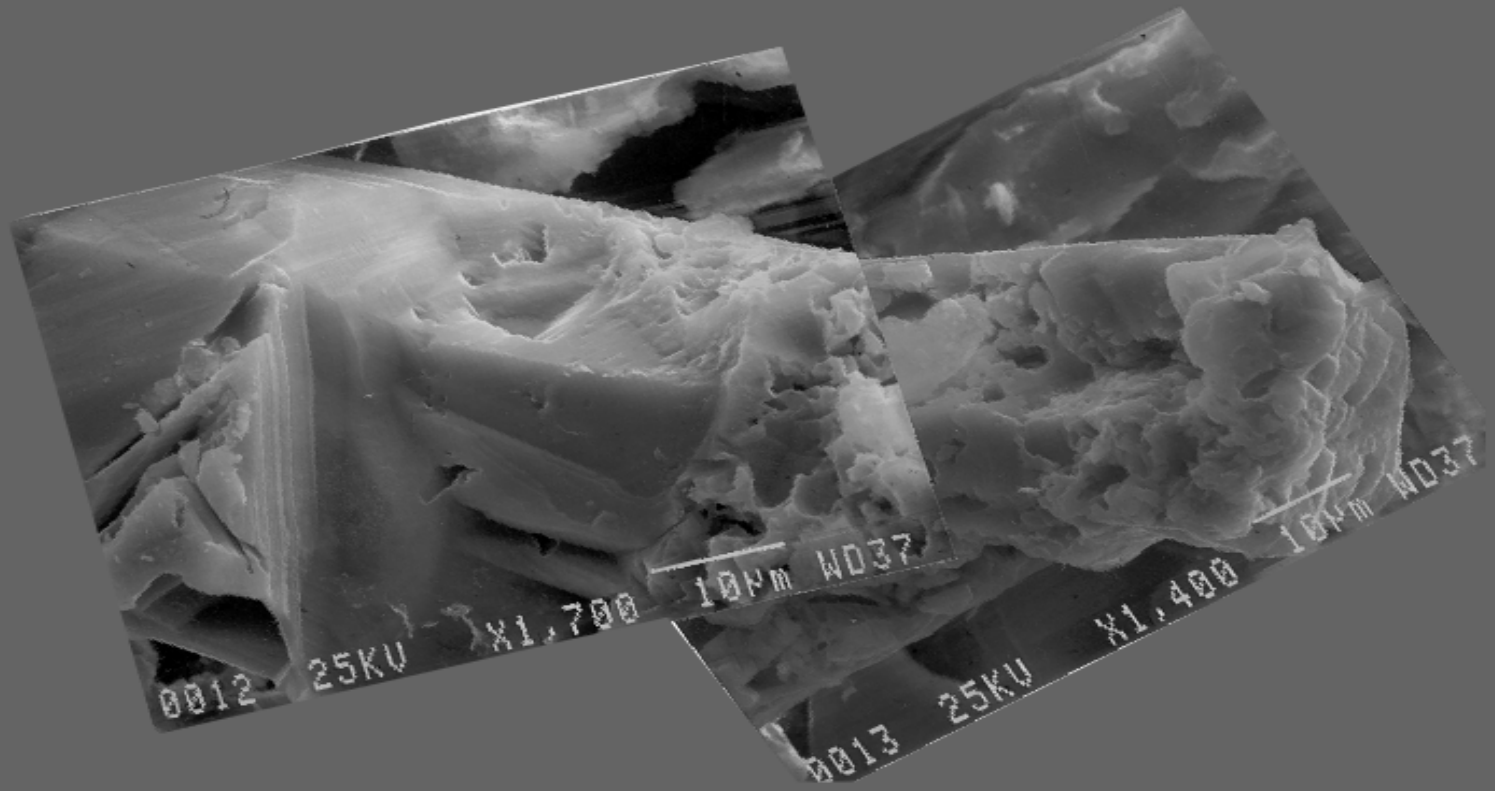
Rate and amount must be low

What gets into the peat doesn't necessarily stay there:

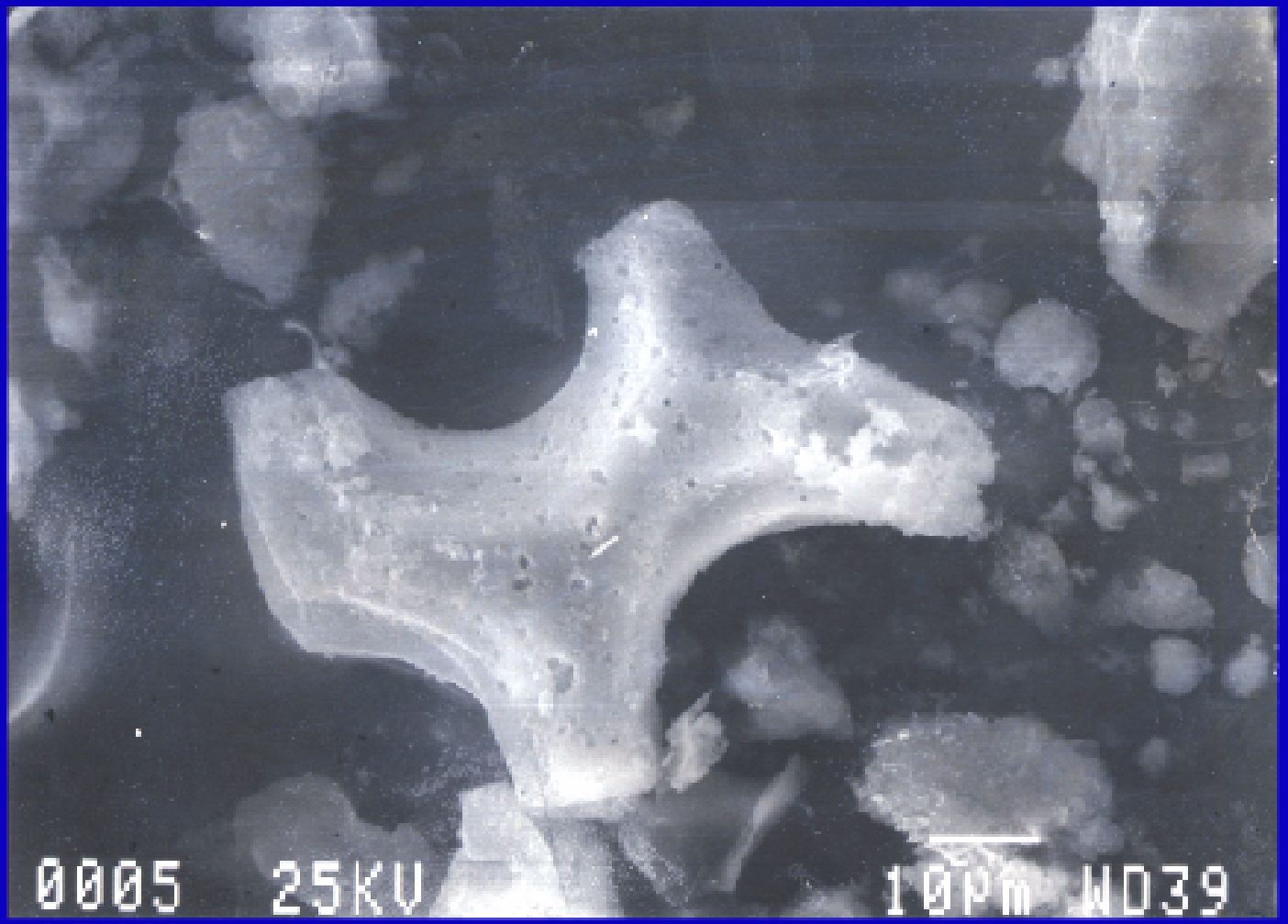
With production of multiple organic acids:

- Dissolution and alteration of mineral matter.
- Loosely bonded organic and inorganic complexes can break.
- Inorganic elements can bond with different organic complexes or become incorporated in syngenetic mineral phases.
- Ions available from ground and surface waters can be incorporated in minerals.

* Organically-associated elements are the most likely to be mobilized during diagenesis. These elements can be leached from the system or re-precipitated into epigenetic mineral phases. *



Etching of an eolian, volcanic quartz grain from a domed Indonesian peat by organic acids.



Disassociated elements can recombine into other authigenic phases, be flushed from the system, or bond to organics.

Peat Preservation and Burial

To preserve peat you need:

Anoxic conditions - control the rate and degree of humification (decay within peat profile).

Very acidic conditions - generation of humic acid from organics.

Burial must be rapid.

Subsidence must be rapid.

What gets into the peat doesn't necessarily stay there:

After burial:

As rank increases, organic bonds weaken, releasing elements.

Elements continue to be moved around.

Elements added, subtracted, and moved within the system.

Epigenetic mineral phases form.

Leaching continues.

Cleat

Two types of cleating:

1 – Moisture/volatile loss – occurs once moisture falls below about 20% (sub-bituminous range).

2 – Tectonic forces/differential compaction.

Cleats can be coated with minerals, then further infilled.

Cleat infilling – pyrite, kaolinite, sphalerite, calcite, gypsum, etc.

Multi-generational cleat infilling not uncommon.

Faults

Faults can act as conduits for fluid flow in coals and coal basins.

Example – Warrior Basin, Alabama

Weathering

Atmospheric weathering and action of ground waters effect the elemental and mineral composition of coal beds.

Development of new suites of minerals
- oxidation (pyrite to sulfate);
- inclusion of water in clay lattice – (allophane)

Removal of some remaining organically-bound minerals.

Removal of some organics concentrating inorganic elements.

Conclusions:

1 – Coal quality results from a continuum of processes that start in the peat stage and continue through coalification.

2 – Geometry of a peat body (planar vs. domed) factors heavily in the quality of the resulting coal.

The concentration, variation (both laterally and vertically), and mode of occurrence of elements are controlled by geologic and chemical processes that start during peat development and continue through coalification. Understanding those processes will allow us to predict coal quality trends before mining.

Overview of Bulk Analytical Methods and USGS Selective Leaching Procedure

Curtis Palmer

U.S. Geological Survey

Bulk Analytical Methods: Coal Quality Characterization

- ASTM Procedures
  - USGS uses contract labs such as Geochemical Testing and Wyoming Analytical Laboratories
- Major and Trace Elements
  - Uses procedures developed by USGS some of these are included in ASTM procedures and are preformed by USGS personnel

ASTM Procedures

- Ultimate analysis:
  - ASTM D3176-D3179
  - Moisture, C, H, O, N, total S
- Proximate analysis
  - ASTM D3172-D3175
  - Moisture, volatile matter, fixed carbon and ash
- Other techniques
  - Sulfur forms, calorific values,
  - Hardgrove grindability free swelling index, ash fusability,
  - Specific gravity, equilibrium moisture

Analytical Methods Overview and Relative Merits

- Methods to be covered (Elemental Analysis)
  - Routine Methods
    - Multi-Element Techniques
      - Inductively Coupled Plasma- Atomic Emission Spectroscopy (ICP-AES)
      - Inductively Coupled Plasma- Mass Spectroscopy (ICP-MS)
    - Single Element Techniques
      - Cold Vapor Atomic Absorption (CVAA; Hg)
      - Hydride Generation Atomic Absorption (HGAA; Se)
  - Non-Routine Methods
    - Instrumental Neutron Activation analysis (INAA)

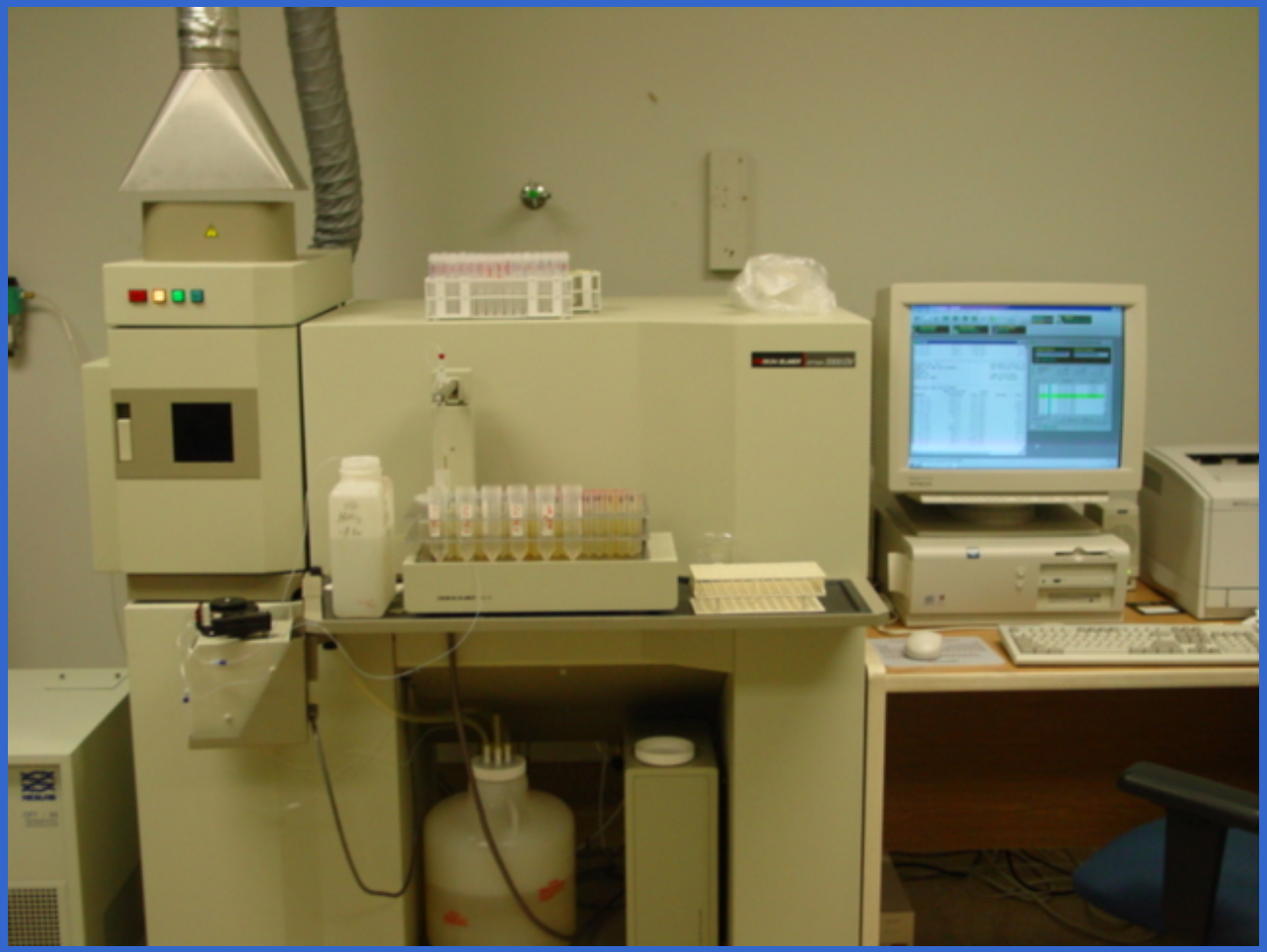
- Sample Preparation:To Ash or Not to Ash
  - Advantages of Ashing
    - Increases concentration and apparent detection limits
    - Makes it easier to place many elements into solution
    - Ash is more stable for long term storage (Archiving)
    - Can improve homogeneity

- Disadvantages of Ashing
  - Some elements may volatilize
    - Volatility may be matrix dependent
    - Amounts volatilized may be different for each sample and element
    - Occasionally elements not normally considered volatile are volatile for a given sample
    - Potential of cross-contamination of volatile components
  - Larger sample needed
  - Additional steps and time
    - Elements may need to be recalculated to a whole coal basis
    - Care must be taken to ensure ashing is complete
  - Mechanical losses can effect results

- Ashing Procedure– USGS – Similar to ASTM
  - Samples heated from 25 ^{o}C to 200 ^{o}C in about 1 hour
  - Samples heated at 200 ^{o}C for 1.5 hrs
  - Temperature increased to 350 ^{o}C and held 2 hrs
  - Temperature increased to 525 ^{o}C and held 36 hrs
  - Samples slowly cooled (1-2 hr)
  - Samples examined and re-ignited at 525 ^{o}C if necessary
  - Samples homogenized

- Methods requiring ashing
  - ICP-AES
    - Advantages
      - Rapid
      - Low Cost
      - Multi-element
    - Disadvantages
      - Requires dissolution of ash
      - Moderate sensitivity

USGS ICP-AES



- Two dissolution procedures (sinter and acid digest)
  - Sinter (Ash fused at 445 ^{o}C with Na_2O_2)
    - » Advantages
      - -- Dissolves species difficult by acid dissolution
      - -- Conserves volatile elements during acid dissolution
    - » Disadvantages
      - -- High dissolution ratio reduces sensitivity
      - -- High salt content can cause instrument problems
    - » Elements Determined
      - -- Major elements in ash except Na
      - -- Trace elements: B, Ba, Zr

- Acid Digest
  - » Advantages
    - --Low dissolution ratio--Higher sensitivity
    - --Low salt content no Na contamination
  - » Disadvantages
    - --Some elements are volatile, eg. B, Se, Cl
    - --Some elements are associated with insoluble minerals, eg. Zr, Ba
  - » Elements Determined
    - -- Major element: Na_2O
    - -- Trace elements: Be, Co Cr, Cu, Li, Mn, Ni, Sc, Sr, Th, V, Y, Zn

– ICP-MS

- Much higher sensitivity (10 to 1000 times)
- Higher cost instrument
- Some elements have interferences– poorer results than ICP-AES; Others similar results to ICP-AES
- Same dissolutions as ICP-AES but sinter dissolution is not routinely analyzed because the use of the highly ionic solution requires special setup and require additional maintenance
- Acid digest: Ag, As, Au, Bi, Cd, Cs, Ga, Ge, Mo, Nb, Pb, Rb, Sb, Sn, Te, Tl, U
- Sinter: 13 Rare earth elements, Hf, Ta and W

USGS ICP-MS

- Whole Coal Techniques
  - Cold Vapor Atomic Absorption (CVAA)
    - Single element (Hg)
    - Requires dissolution
    - 5 to 10 percent of coals below detection limit of 0.02 ppm
    - Reliable and accurate (ASTM method)
  - Ion Chromotography
    - Single element Cl
    - Requires dissolution
    - Less than 5 percent of coals below detection limit of 150 ppm
    - Reliable and acurate

USGS Ion chromotragraph

- Hydride generation atomic absorption (HGAA)
  - Single element (Se)
  - Requires dissolution
  - Several elements (especially heavy and transition metals) in high concentrations can interfere with results
- Instrumental neutron activation analysis (INAA)
  - Time consuming multi-element technique
  - Highly linear—few interferences
  - Small sample size
  - No ashing or dissolution required
  - High sensitivity
  - High cost– requires nuclear reactor
  - Elements include: Na, K, Fe, Sc, Cr, Co, Ni, Zn, As, Se, Br, Rb, Sr, Mo, Sb, Cs, Ba, La, Ce, Nd, Sm, Eu, Tb, Yb, Lu, Hf, Ta, W, Th, U
  - Other elements possible Al, Ca, Mg, Ti, S, V, Cl, I, Mn, Dy, Hg

Quality Control and Quality Assurance

- Accuracy – degree of agreement between the measured value to the “true” or proposed value
- Standard Reference Materials
  1. CLB-1 – coal
  2. NIST 1632b – coal (bituminous)
  3. NIST 1633a – coal fly ash
- Certified Calibration Standards
- Precision – degree of agreement between measured values under repetitive testing of a sample; reproducibility of results
- Duplicate samples

- References
  - Visit our web site: energy.er.usgs.gov/products/papers
    - Click Palmer, C.A., 1997, The chemical analysis of Argonne Premium Coals: U.S. Geological Survey Bulletin 2144 or enter energy.er.usgs.gov/products/papers/B2144
    - Click Golightly, D.W., and Simon, F.O., 1989, Methods for Sampling and Inorganic Analysis of Coal: USGS Bulletin 1823 or enter energy.er.usgs.gov/products/papers/B1893
    - Click Swanson, V.E. and Huffman, C., Jr. 1976, Guidelines for sample collecting and analytical methods used in the U.S. Geological Survey for determining chemical composition of coal: United States Geological Survey Circular 735 or enter energy.er.usgs.gov/products/papers/C735

Summary

- Multi-element techniques provide methods to obtain a large and varied amount of data in a relatively short time.
- Cost of instruments for multi-element techniques can be very high.
- Some elements in coal can not be determined using multi-element techniques due to volatility and problem matrices.

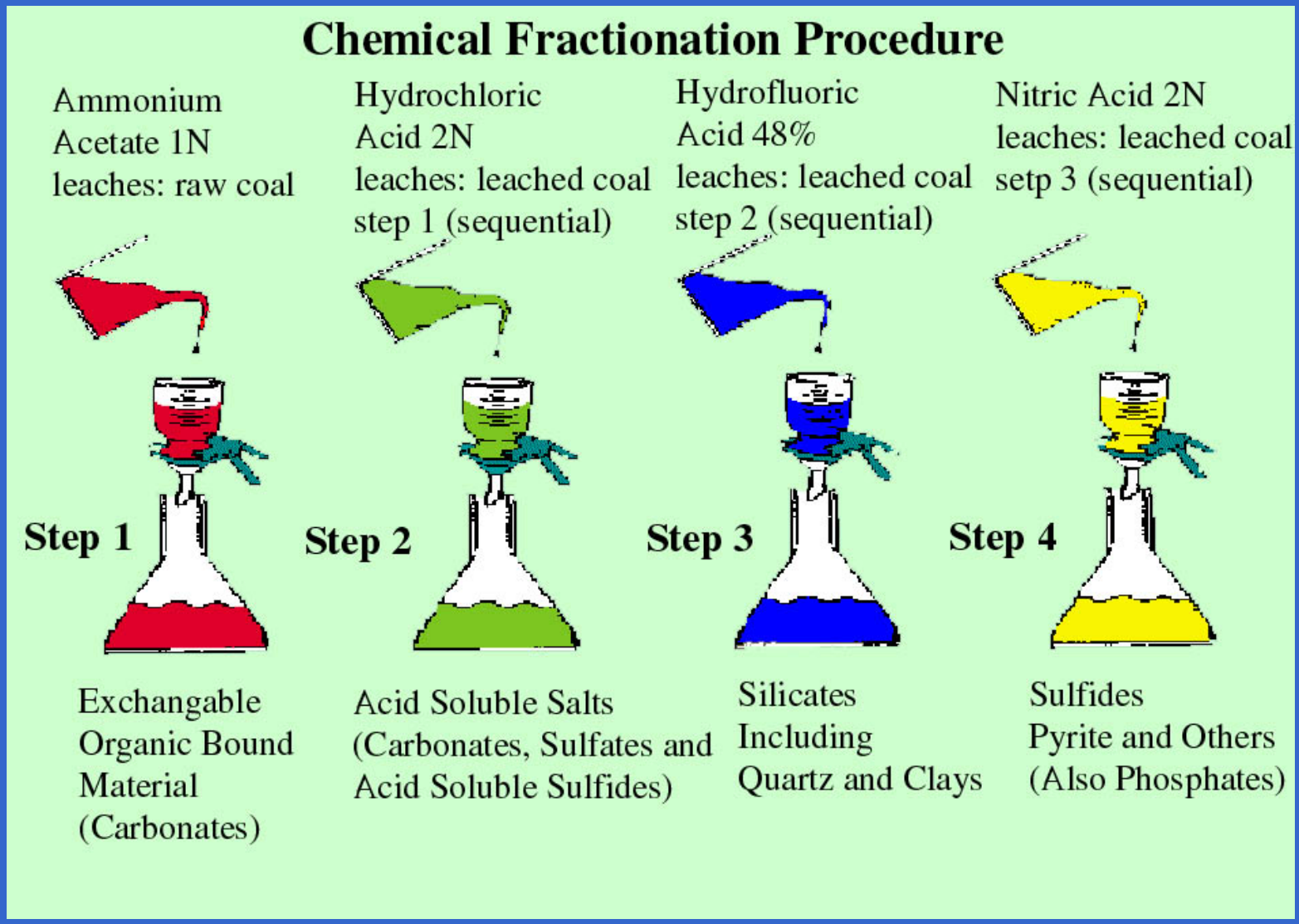
Modes of Occurrence of Elements in Coal

- Selective leaching
- Scanning electron microscopy
- Microprobe Analysis

Overview of Leaching Procedure

- A Multi-Element Semi-Quantitative Approach
  - Semi-Quantitative Leaching Results
  - Microprobe Analysis– Concentration of elements in minerals
  - Qualitative SEM– Mineral identification in whole samples and leached residues
  - Semi-quantitative XRD– Concentration of minerals in coal

Leaching Procedure



Sequential Leaching

- Duplicate, 5 gram 60 mesh samples are shaken in a centrifuge tube with 35 ml of Ammonium Acetate for 18 hrs
  - The resulting solution is saved for analysis by ICP-AES and ICP-MS
  - A 300 mg split of the resulting solid is analyzed by INAA and a 200 mg split is analyzed by CVAA for Hg. Additional splits may be taken for specialized experiments (XAFS, SEM, etc)

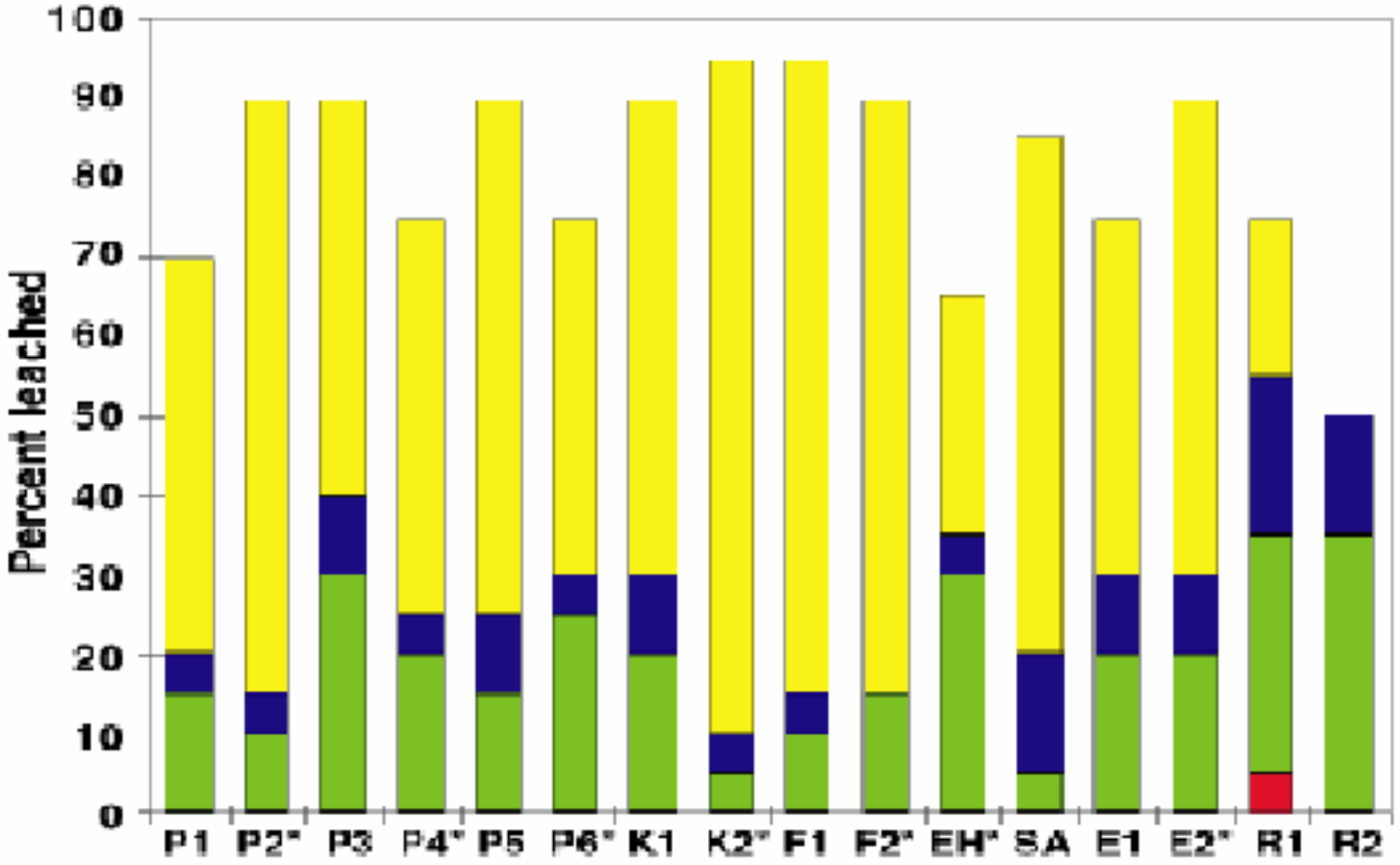
Sequential Leaching

- The remaining solid from each sample is leached in the same manner with hydrochloric acid (HCl) and subsequently with hydrofluoric acid (HF) with splits taken
- The remaining solid after leaching with HF is leached in a flask with nitric acid (HNO_3)
  - Procedure is similar to ASTM method for determining pyritic sulfur
  - Solutions and solid samples are analyzed as in other steps

Results

- Several Elements Are mainly associated with Pyrite as demonstrated by a large percentage of the element leached by HNO_3 (nitric acid)

Arsenic

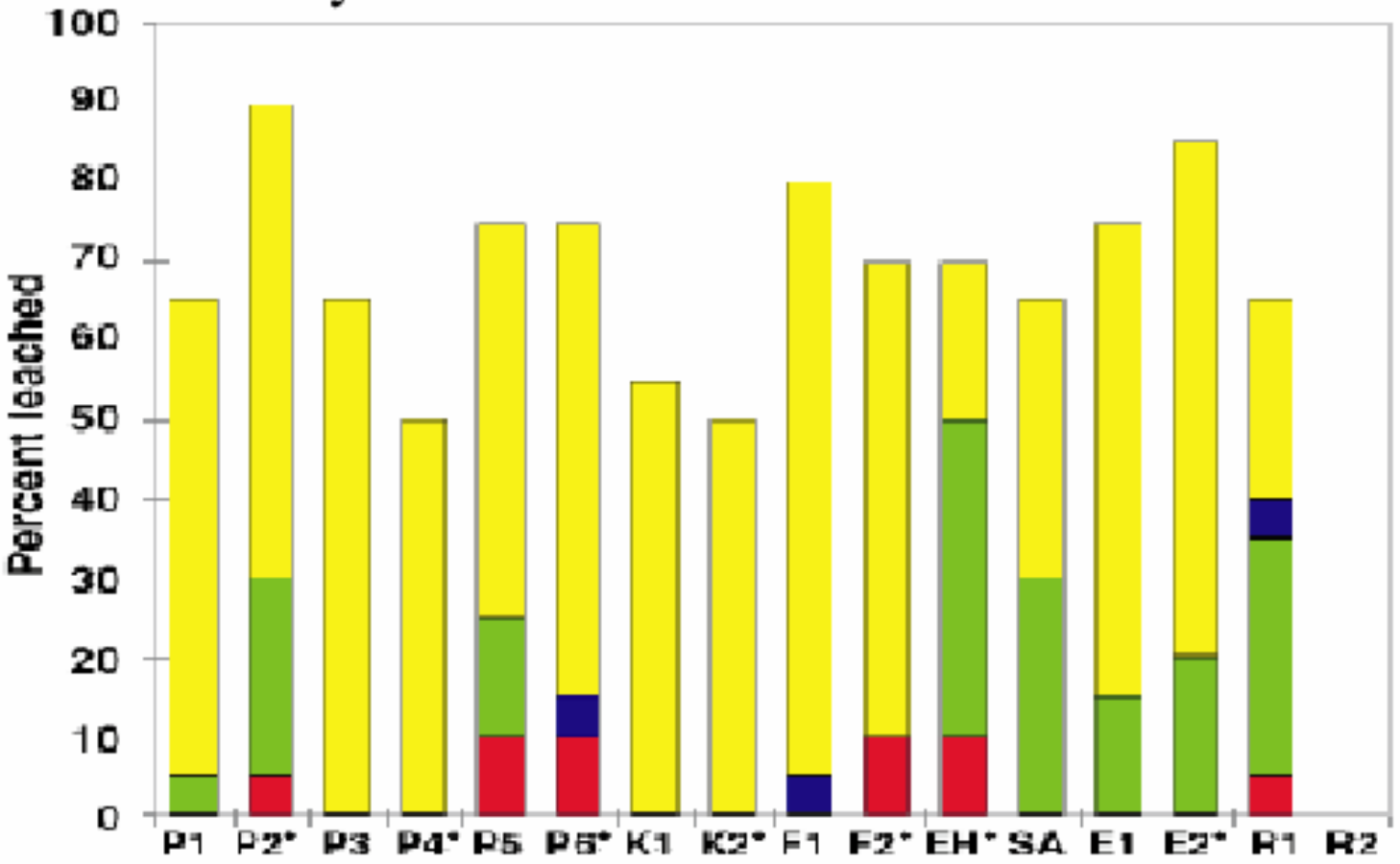


Ammonium Acetate
Hydrochloric Acid
Hydrofluoric Acid
Nitric Acid

Concentrations of As in the original coal samples in parts per million

P1	7.4	P5	13	F1	45	E1	7.2
P2	4	P6	4.5	F2	2	E2	2.3
P3	10	K1	13	EH	4.4	R1	1.5
P4	3.5	K2	4.7	SA	20	R2	1.2

Mercury



Ammonium Acetate
Hydrochloric Acid
Hydrofluoric Acid
Nitric Acid

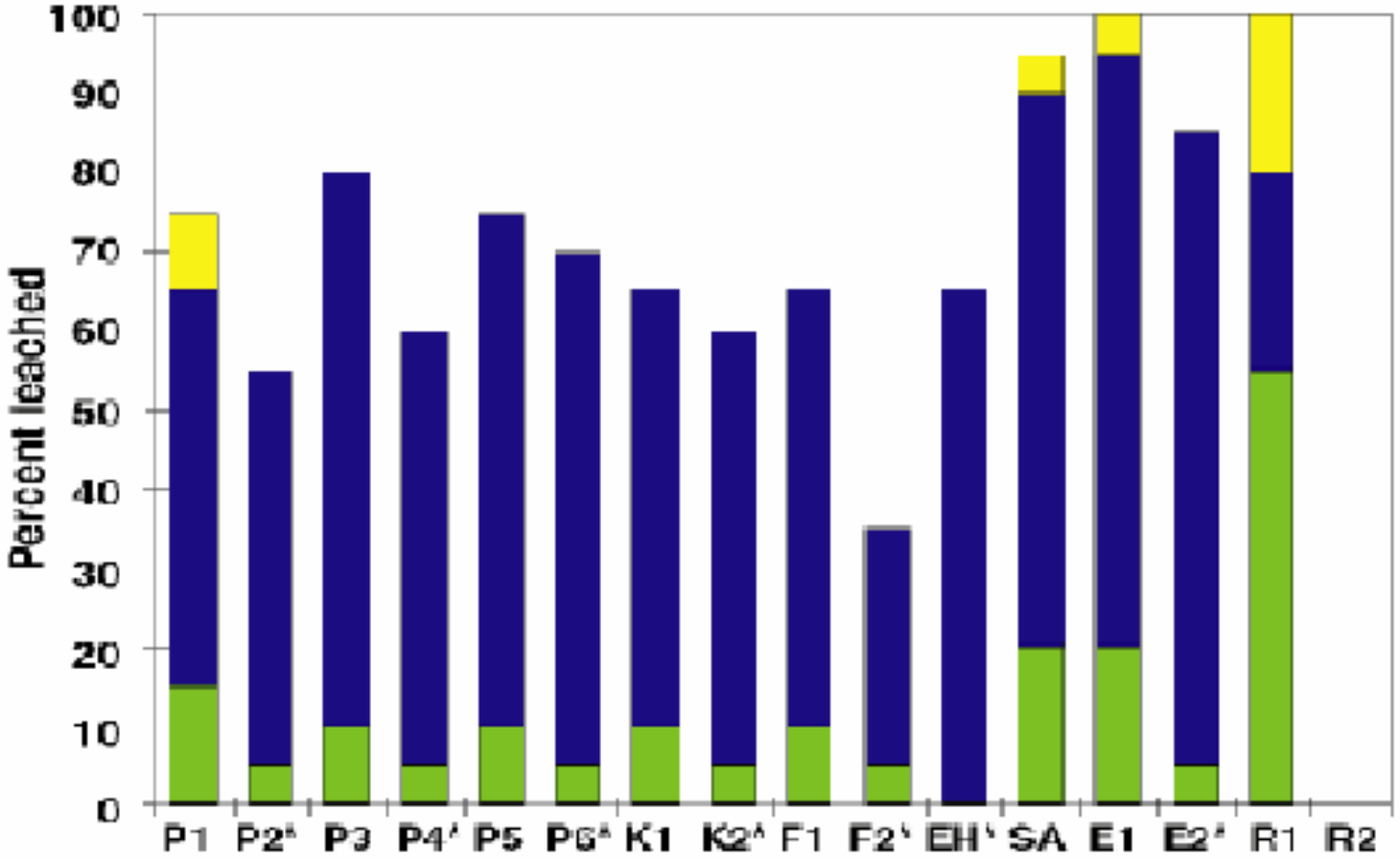
Concentrations of Hg in the original coal samples in parts per million

P1	0.09	P5	0.15	F1	0.5	E1	0.09
P2	0.09	P6	0.08	F2	0.4	E2	0.06
P3	0.13	K1	0.25	EH	0.05	R1	0.07
P4	0.06	K2	0.16	SA	0.1	R2	0.08

Results

- Other elements are mainly associated with silicates as demonstrated by a large percentage of the element leached by Hydrofluoric Acid.

Beryllium

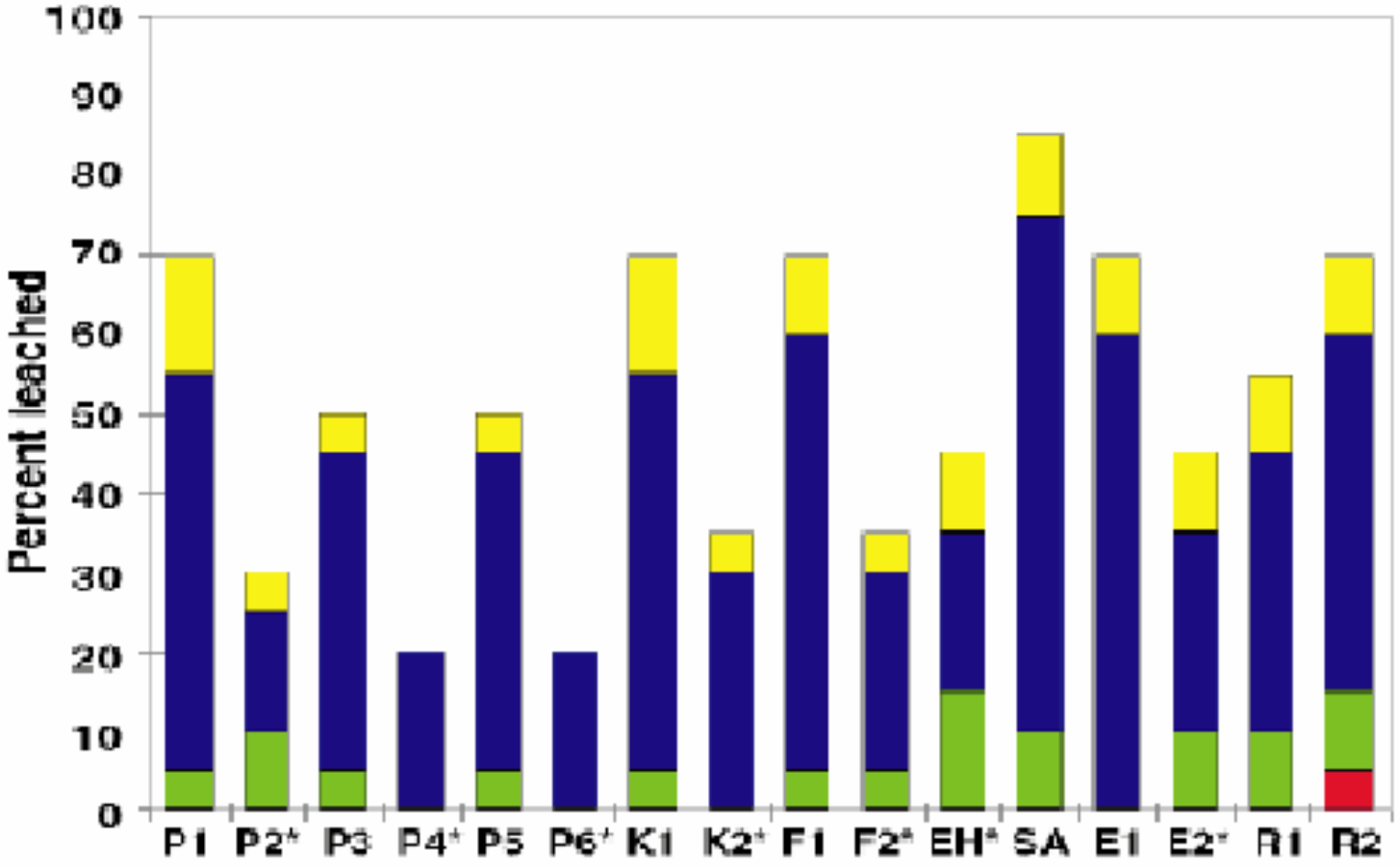


Ammonium Acetate
Hydrochloric Acid
Hydrofluoric Acid
Nitric Acid

Concentrations of Be in the original coal samples in parts per million

P1	1	P5	0.7	F1	3	E1	1
P2	0.6	P6	0.7	F2	2	E2	1
P3	0.9	K1	2	EH	12	R1	0.5
P4	0.8	K2	2	SA	31	R2	0.4

Chromium



Ammonium Acetate
Hydrochloric Acid
Hydrofluoric Acid
Nitric Acid

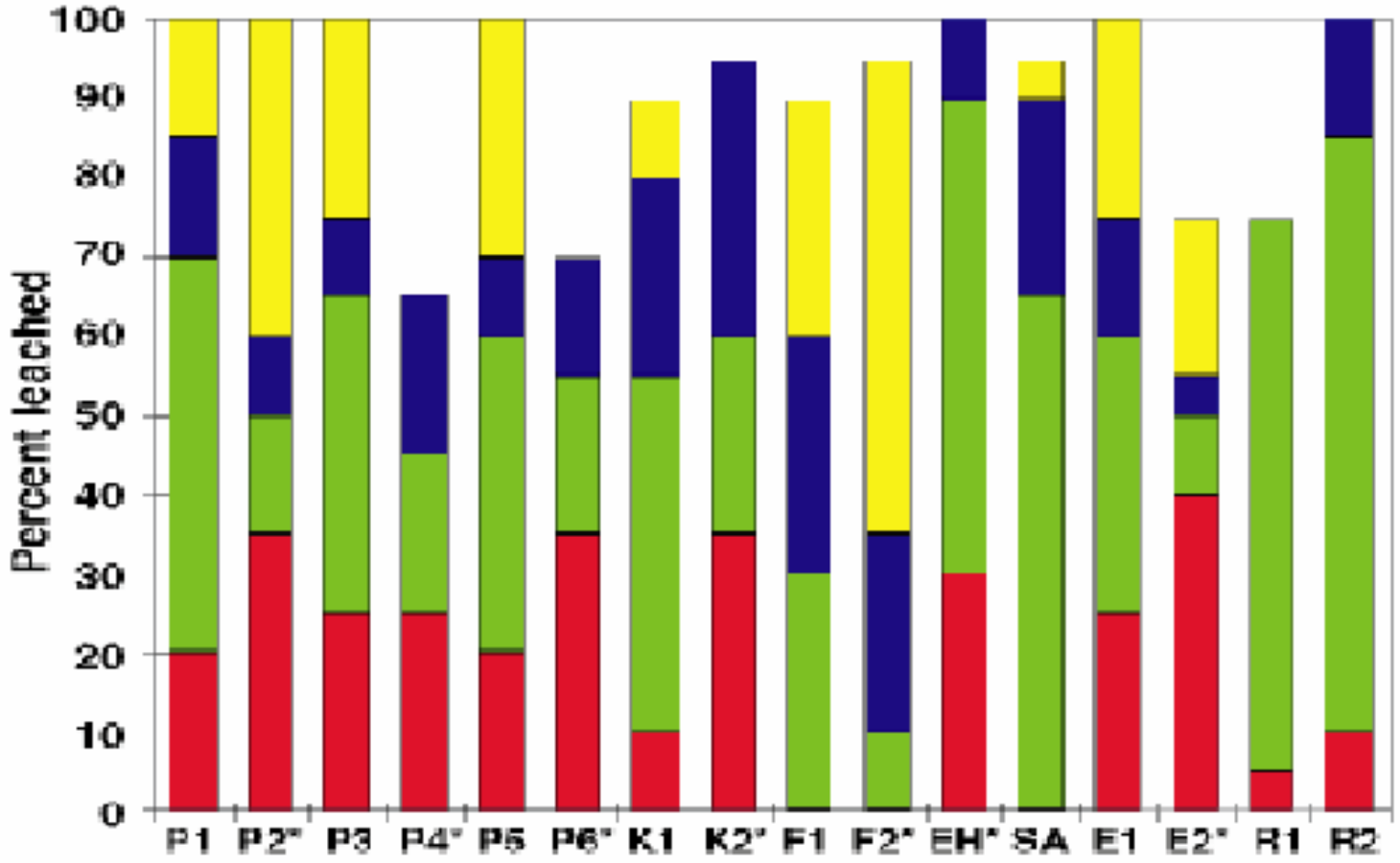
Concentrations of Cr in the original coal samples in parts per million

P1	31	P5	17	F1	33	E1	97
P2	9.7	P6	12	F2	15	E2	23
P3	20	K1	54	EH	18	R1	3.9
P4	12	K2	25	SA	62	R2	6

Results

- When the majority of a element is soluble with HCl then the element is likely associated with carbonates or monosulfides.
- Elements associated with calcite are partially soluble in ammonium acetate.

Manganese

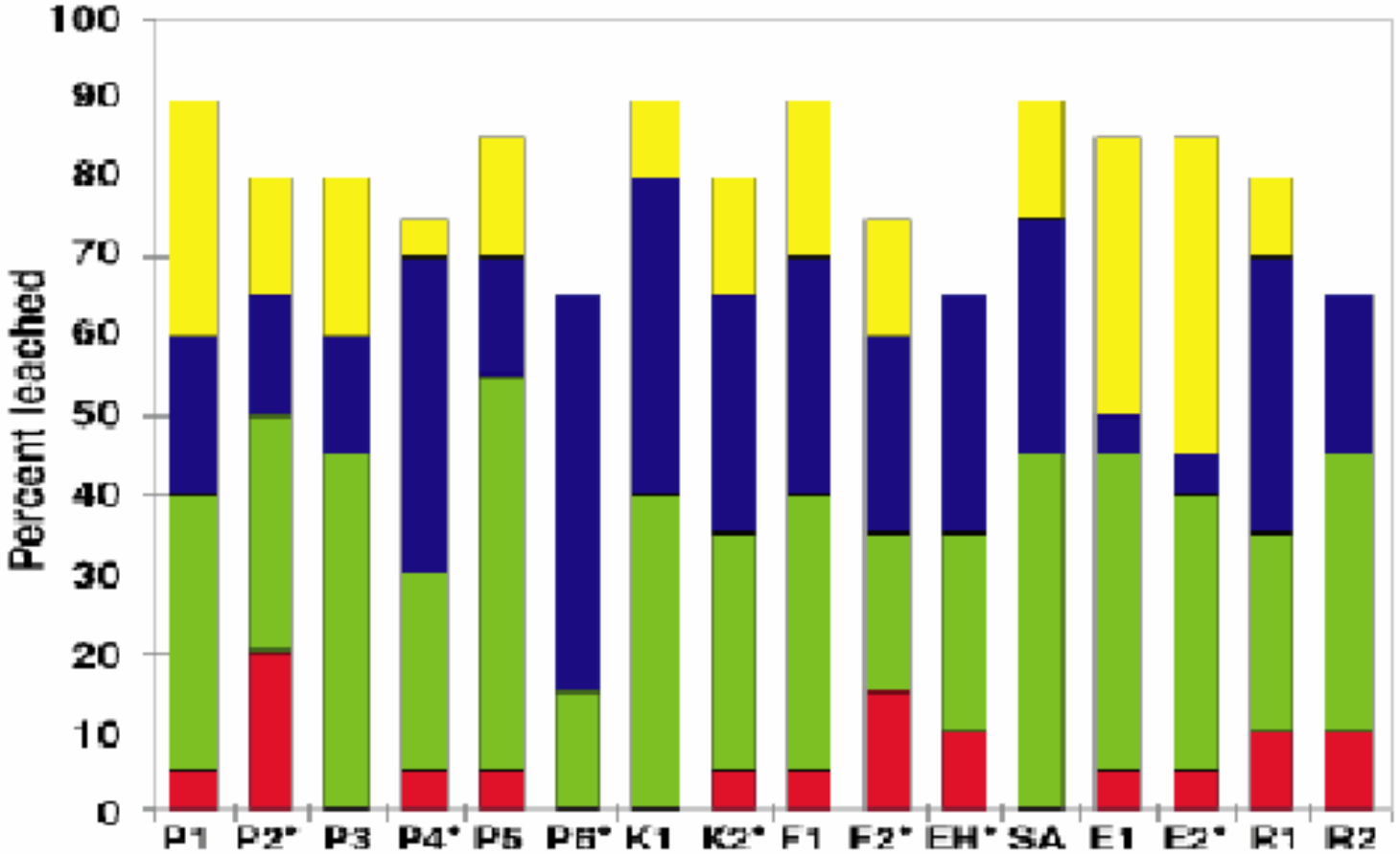


Ammonium Acetate
Hydrochloric Acid
Hydrofluoric Acid
Nitric Acid

Concentrations of Mn in the original coal samples in parts per million

P1	29	P5	35	F1	39	E1	94
P2	13	P6	16	F2	10	E2	37
P3	23	K1	57	EH	14	R1	150
P4	8.1	K2	7.4	SA	230	R2	8.7

Zinc



- Ammonium Acetate
- Hydrochloric Acid
- Hydrofluoric Acid
- Nitric Acid

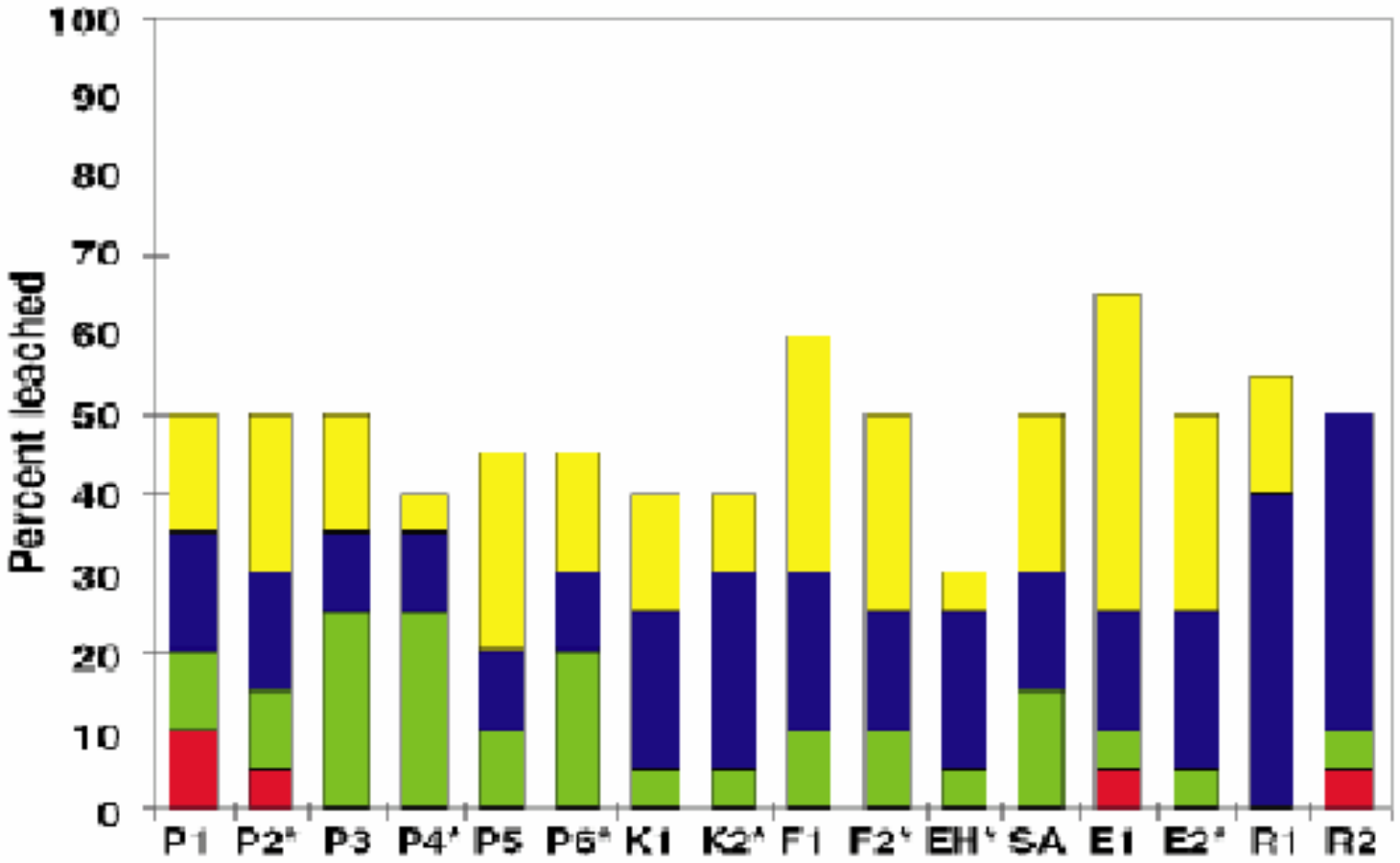
Concentrations of Zn in the original coal samples in parts per million

P1	25	P5	18	F1	34	E1	190
P2	9.3	P6	5.1	F2	13	E2	70
P3	18	K1	52	EH	6.6	R1	6.8
P4	7.6	K2	15	SA	60	R2	8.1

Results

- For some elements a significant fraction is unleached indicating that the element is organically associated
- In some cases mineral species are encapsulated or insoluble.
  - Examination by SEM can usually be used to determine encapsulated or insoluble species.

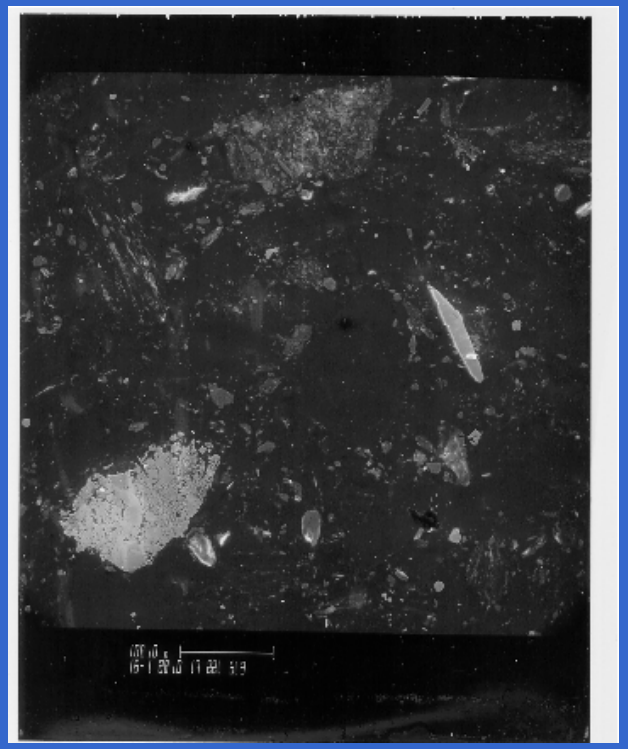
Antimony



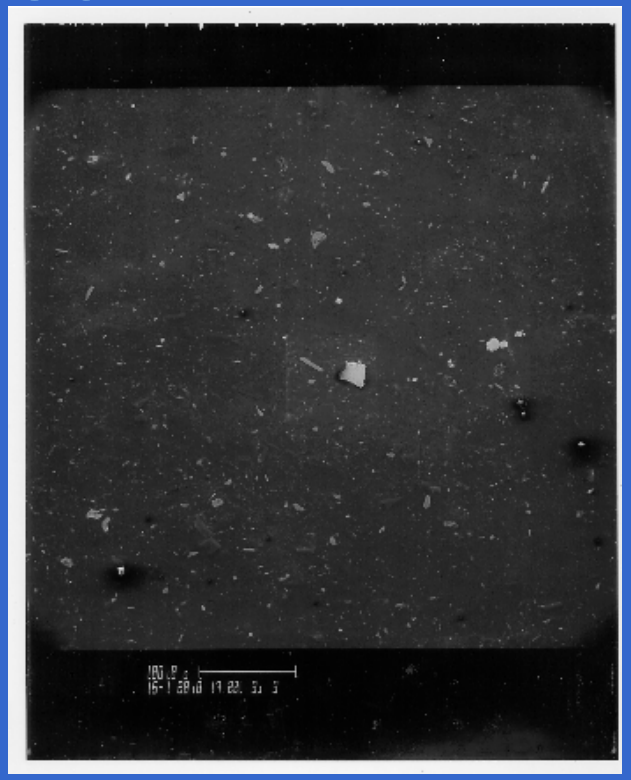
Concentrations of Sb in the original coal samples in parts per million

P1	0.72	P5	0.56	F1	0.62	E1	1.2
P2	0.29	P6	0.26	F2	0.48	E2	0.44
P3	0.49	K1	1.8	EH	1.1	R1	0.31
P4	0.31	K2	2.1	SA	1.6	R2	0.24

SEM comparison of original coal to leached coal



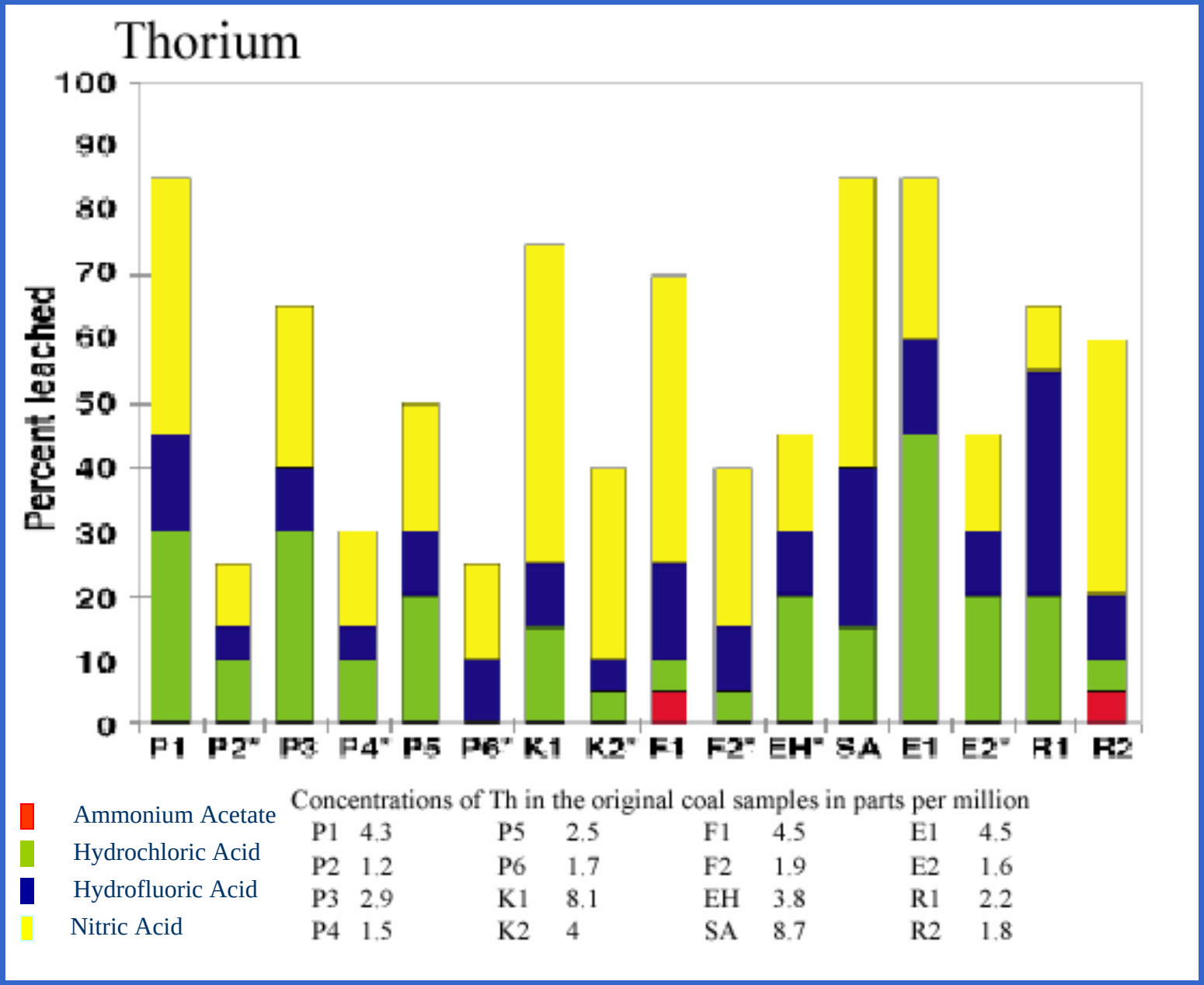
- Raw
- Minerals of all sizes



Demineralized
Small mineral grains
(mostly grinding compound)

Results

- Phosphates are also soluble in HCl
- Some elements can be in mineral forms especially phosphates encapsulated by silicates.
  - Produces significant amounts of element leached by HNO_3
  - Can be tested by leaching with HCl after HF leach

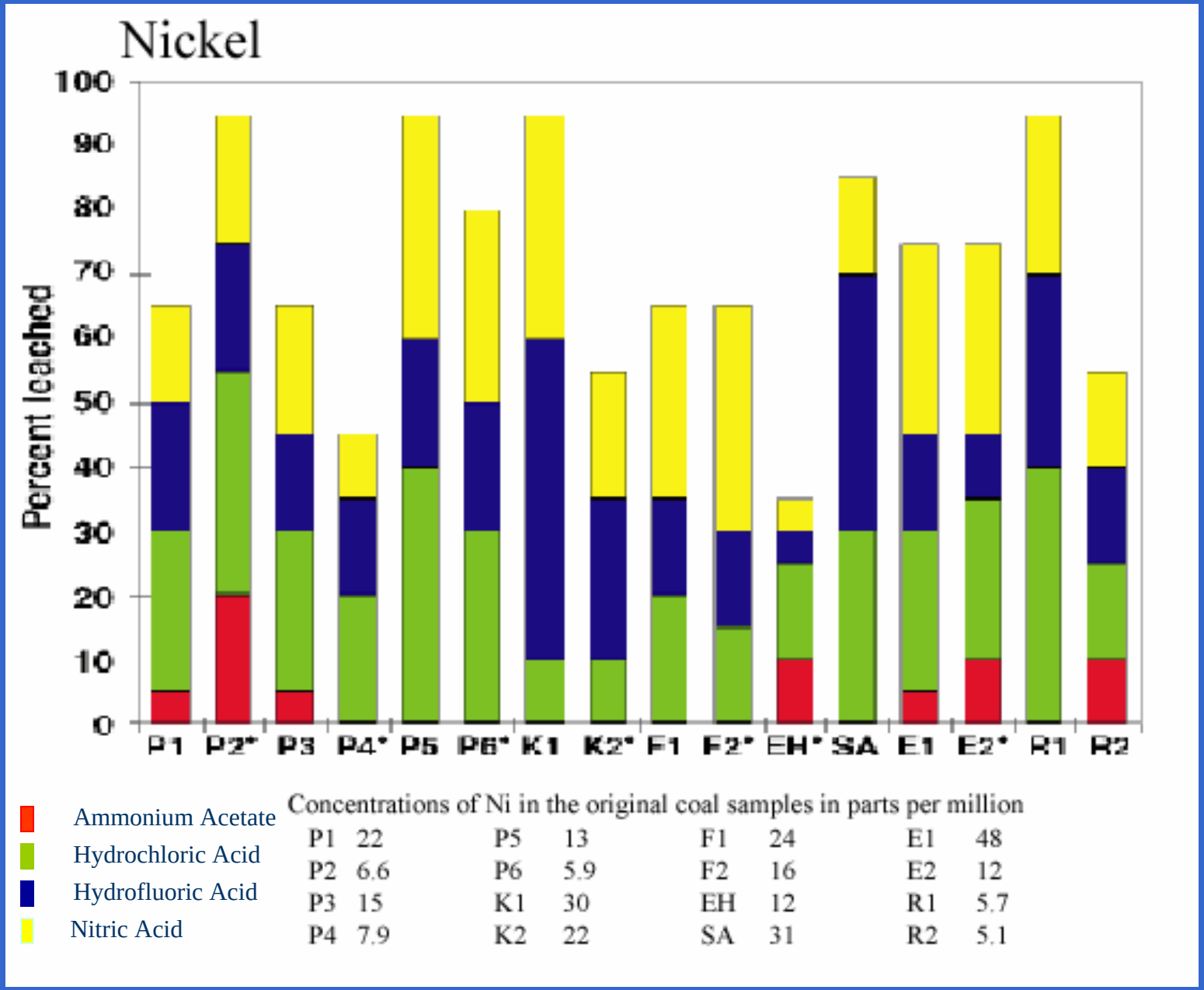


Concentrations of Th in the original coal samples in parts per million

P1	4.3	P5	2.5	F1	4.5	E1	4.5
P2	1.2	P6	1.7	F2	1.9	E2	1.6
P3	2.9	K1	8.1	EH	3.8	R1	2.2
P4	1.5	K2	4	SA	8.7	R2	1.8

Results

- Leaching of some elements are not dominated by a single solvent
  - Multiple modes of occurrence
  - Said to by mixed modes of occurrence



Concentrations of Ni in the original coal samples in parts per million

P1	22	P5	13	F1	24	E1	48
P2	6.6	P6	5.9	F2	16	E2	12
P3	15	K1	30	EH	12	R1	5.7
P4	7.9	K2	22	SA	31	R2	5.1

Conclusions

- The mode of occurrence can be semi-quantitatively determined by selective leaching
- Since each solvent dissolves more than one species supporting techniques (SEM, Microprobe etc.) are needed to determine exact mode of occurrence
- There is a great deal of consistency within a given rank of coal

Microanalysis and Spectroscopic Methods

Allan Kolker

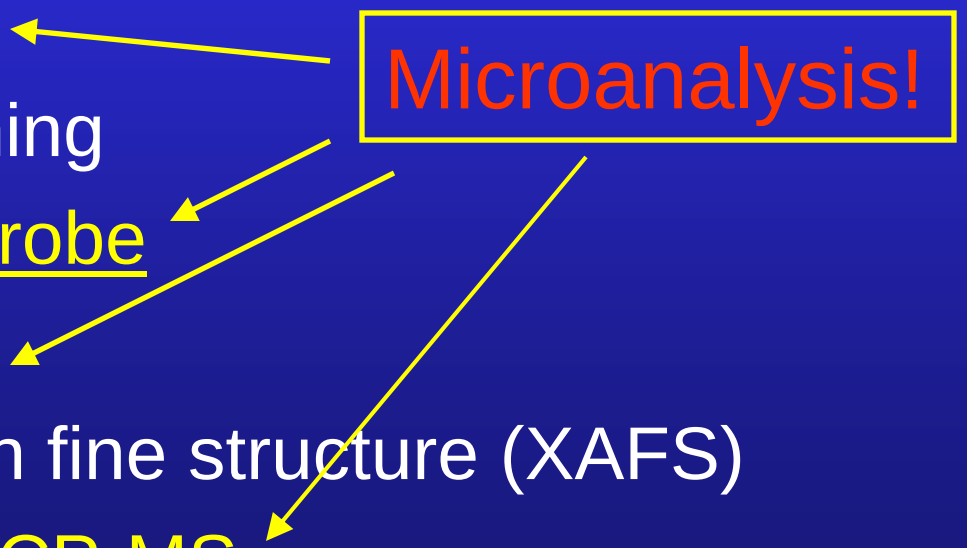
Leaching vs. Microanalysis

- Selective leaching is a bulk multi-element method.
- Interpretation is based on known or inferred leaching behavior.
- Leaching is constrained by element mass-balance.

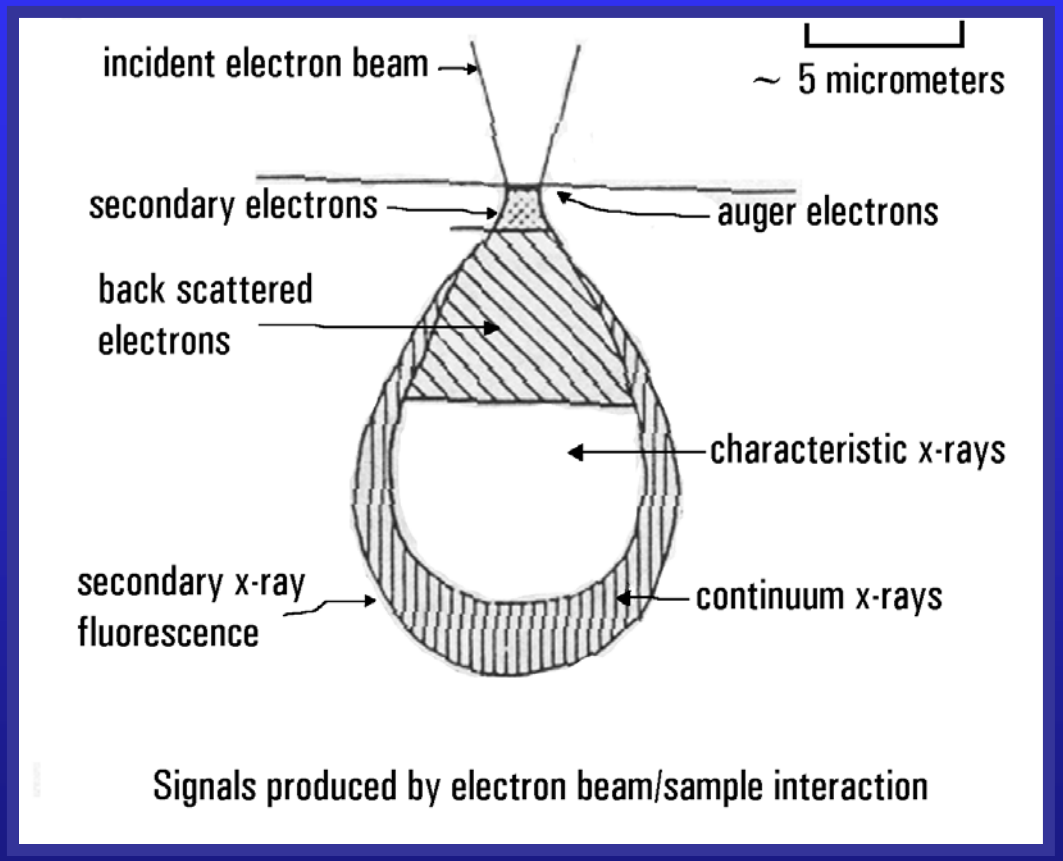
- Microanalysis selects phases of interest on a microns scale.
- Microanalysis gives a direct analysis, where an appropriate method can be found.
- Not intended to achieve a mass balance.

Methods of Determining Element Associations in Coal

- XRD Mineralogy
- Bulk Chemical Testing (INAA, ICP-AES, ICP-MS, XRF, etc.)
- SEM with BSE
- Selective Leaching
- Electron Microprobe
- Ion Microprobe
- X-ray absorption fine structure (XAFS)
- Laser Ablation ICP-MS



Electron-beam Instruments (SEM and Electron Microprobe)



Secondary Electrons

(imaging)

Back Scattered Electrons

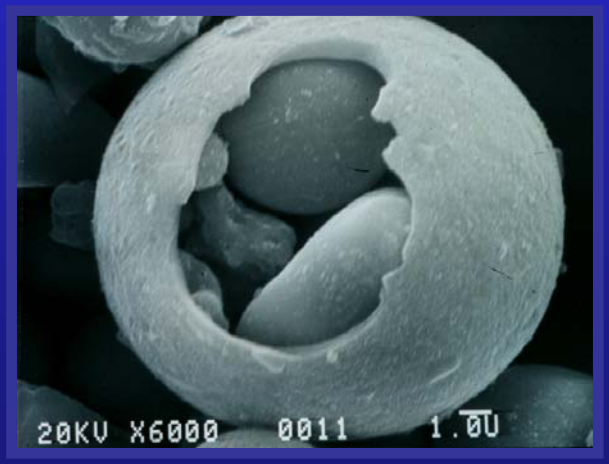
(imaging + comp.)

Characteristic X-rays

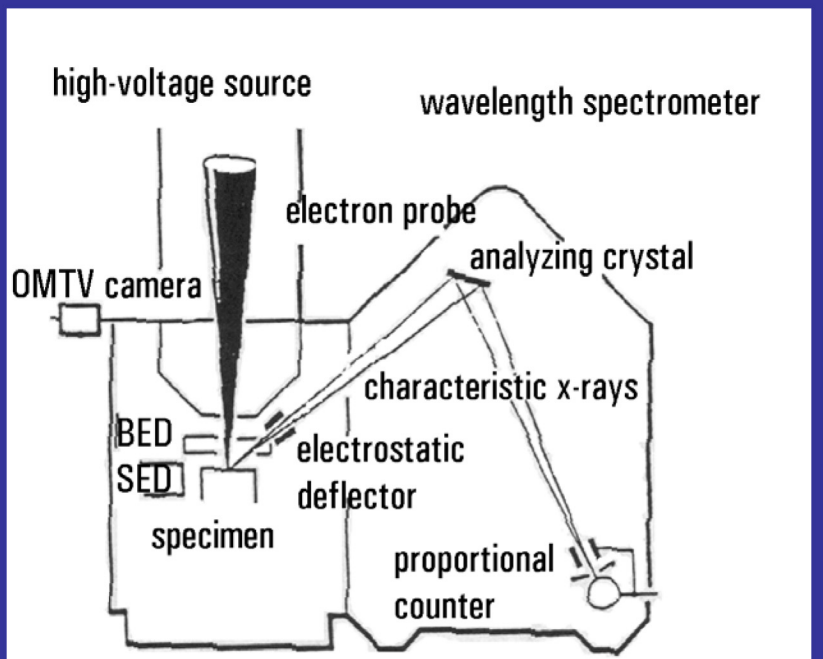
(elemental composition)

Scanning Electron Microscope

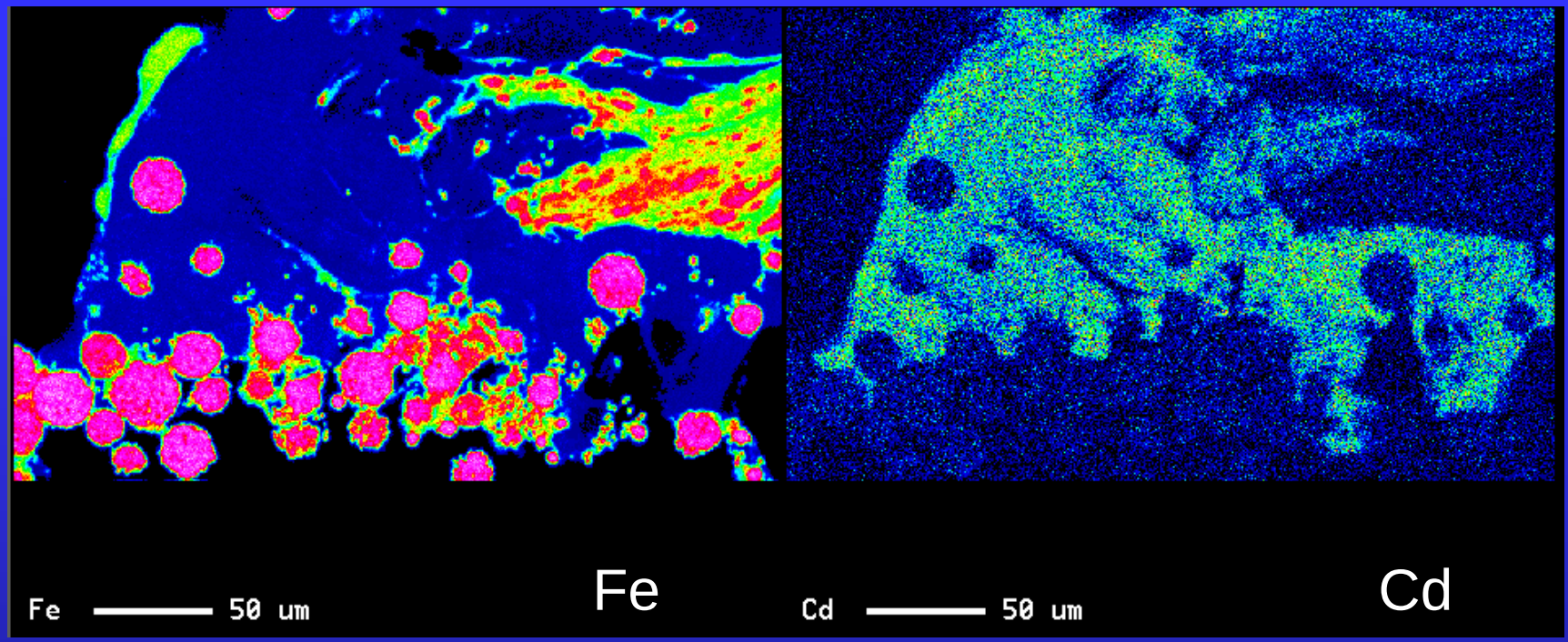
SEM Image of Fly Ash Particle



Electron Microprobe



Microprobe schematic
SED = secondary electron detector
BED = backscattered electron detector
OMTV = optical microscope viewer/camera



Electron microprobe elemental maps of Fe (left) and Cd (right) showing Cd-bearing sphalerite enclosing pyrite framboids, 458.2' WV#7 core. Host is sandstone above coal-bearing interval in Allegheny Formation. Scale bar is 50 micrometers.

Source: Kolker et al., 2001

Stanford/USGS

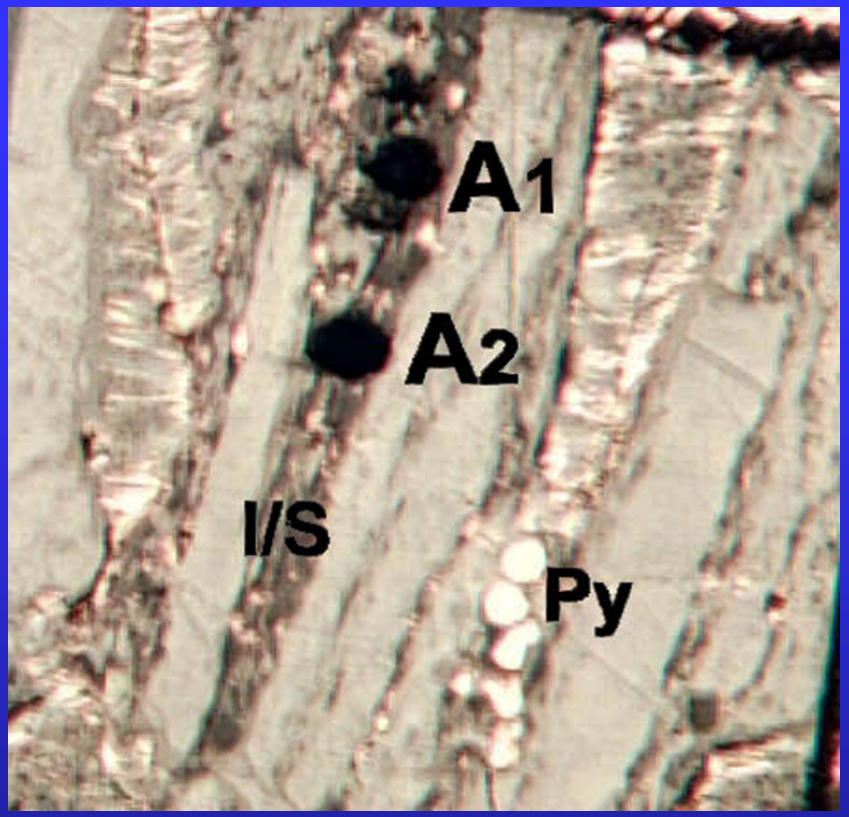
SHRIMP-RG Ion Microprobe

Sensitive High-Resolution Ion Microprobe Reverse Geometry

- Primary beam of O_2^- or Cs^+ ions
- Detection in the ppm range
- 10-15 micron spot size
- Determine isotope ratios

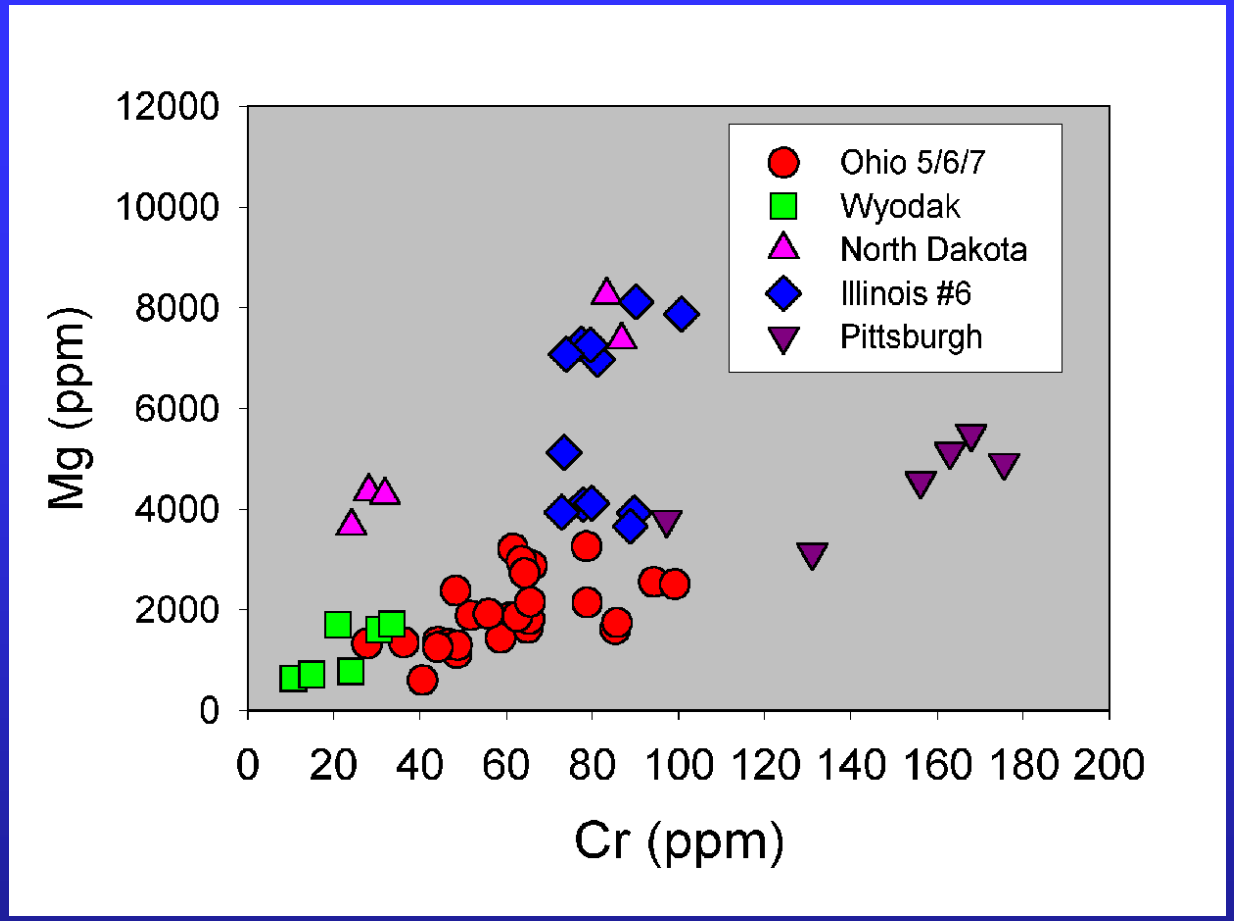
Cr in Coal

- Silicate and organic hosted forms.
- Quantitative results for illite/smectite using Stanford-USGS SHRIMP-RG ion microprobe.
- Concentrations in illite:
  Cr = 11 to 176 ppm
  Mn = 2 to 149 ppm
  V = 23 to 248 ppm
- Confirms leaching results and electron microprobe data.



Reflected-light image of illite-smectite band in Illinois coal and two 15 μm SHRIMP-RG analysis points.

SHRIMP-RG results for chromium in illite-smectite in 5 U.S. coal samples. Results confirm selective leaching studies commonly indicating a silicate association for Cr.

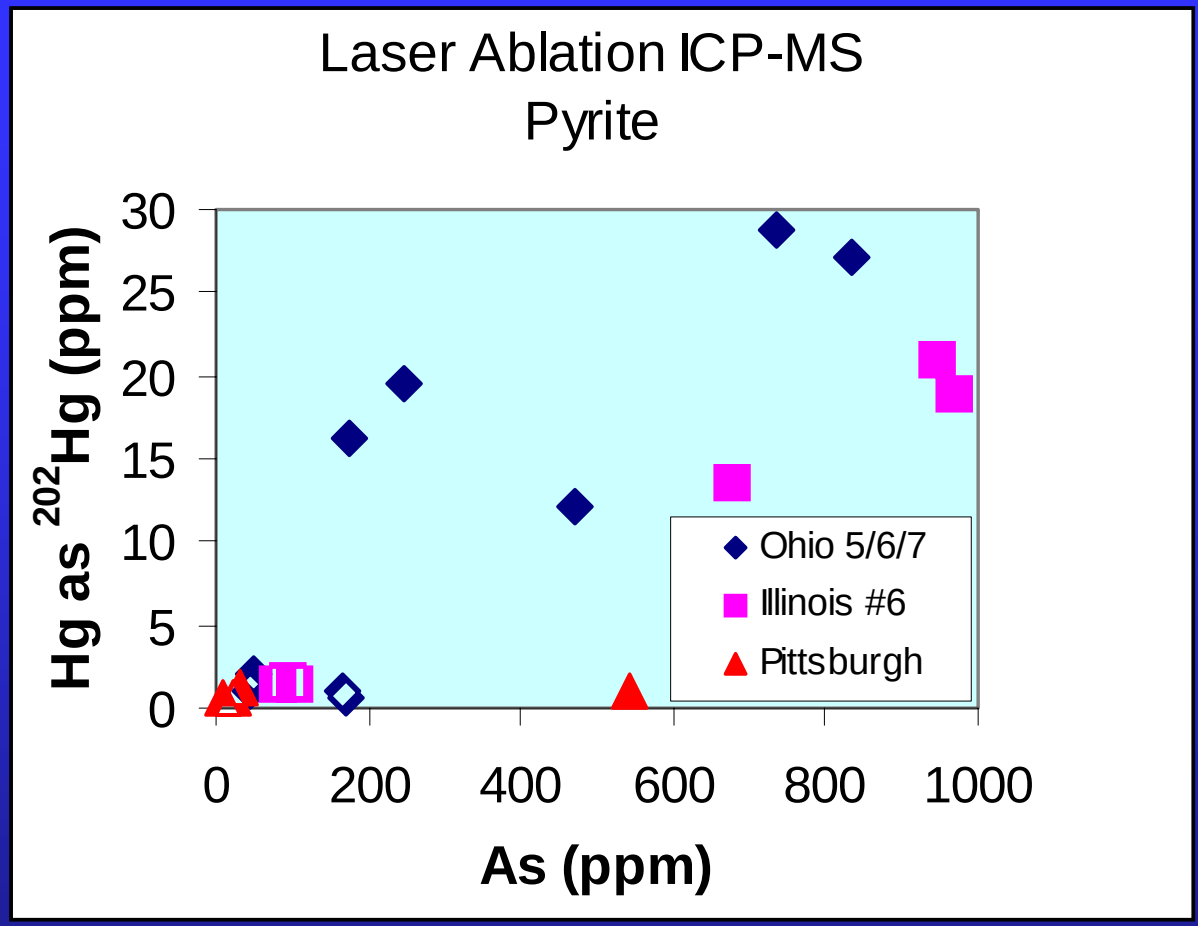


Source: Kolker et al., 2000

Laser Ablation ICP-MS

- Pulsed Nd (YAG) laser coupled to dedicated ICP-MS. Excavation rate is about 3 μm/sec.
- Results for Cr, Mn, Co, Ni, Cu, Zn, As, Se, Mo, Cd, Sb, Tl, Pb, and Hg, in pyrite.
- Sample/standard matrix match not critical as both are introduced into ICP-MS in an argon plasma.
- Best results for Hg with 50 μm beam (about 3 times that of SHRIMP-RG).

Laser ablation ICP-MS confirms mercury association with pyrite in selected bituminous coal samples.



Source: Kolker et al., 2002.

Element Speciation

- Different forms of an element can have very different behavior.

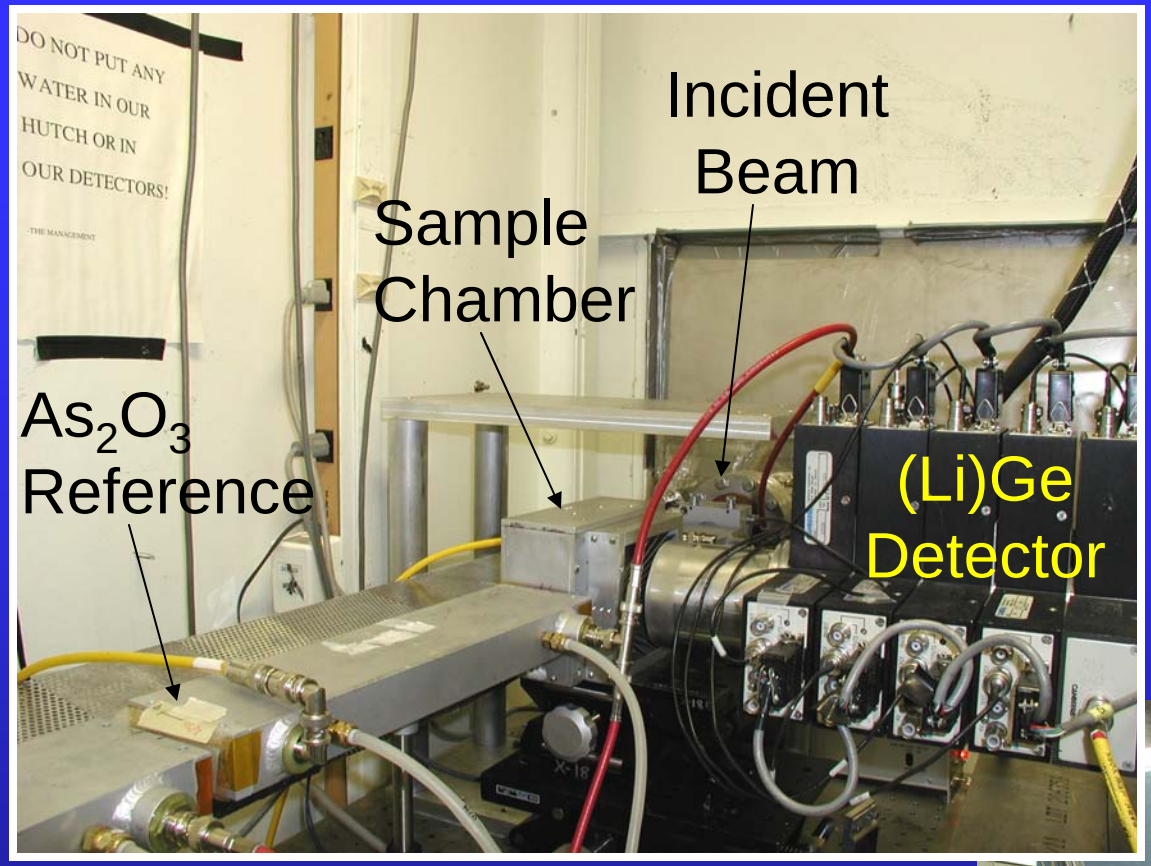
  Examples:
- Trivalent chromium is an essential nutrient; hexavalent chromium is a carcinogen.
- Trivalent arsenic (arsenite) is more toxic than pentavalent arsenic (arsenate).

Approaches to Speciation Determinations

- Classical approach using ion-exchange column chemistry.
- Spectroscopic methods such as X-ray absorption fine structure (XAFS) and ^{57}Fe Mössbauer analysis (primarily solids)
- Selective leaching, where leached form of an element corresponds to a particular species.
- Coupled ion-chromatography-ICP/MS.

XAFS

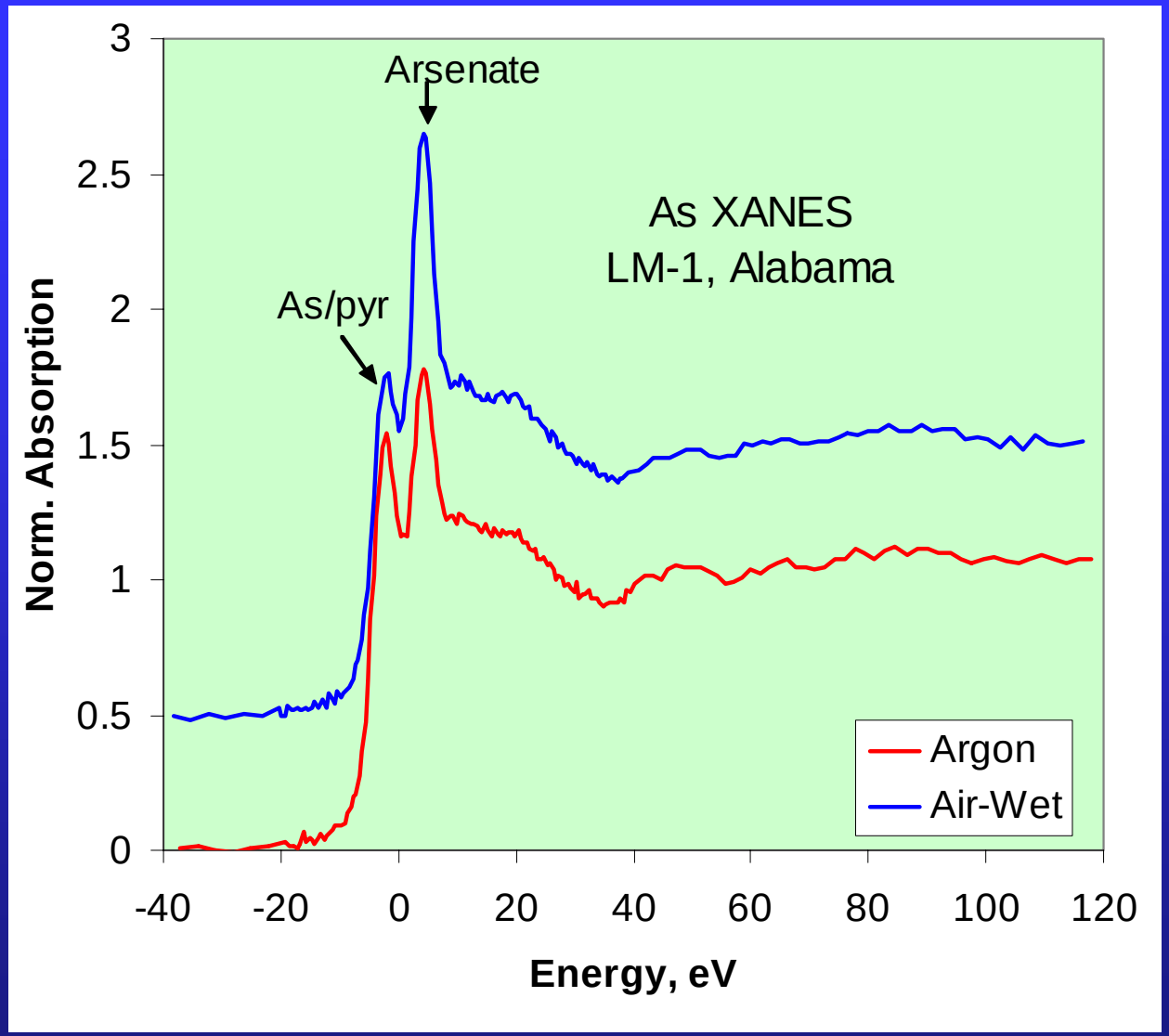
- Can determine elemental species in powdered coal samples using high-energy synchrotron radiation.
- Need samples with several ppm of an element; limited atomic number range, best for transition metals, As, Se.
- To be quantitative, need to do least-squares fitting of spectra for unknowns to spectra of calibration standards.



NSLS
Beamline
X23 A2

XAFS
Experiment

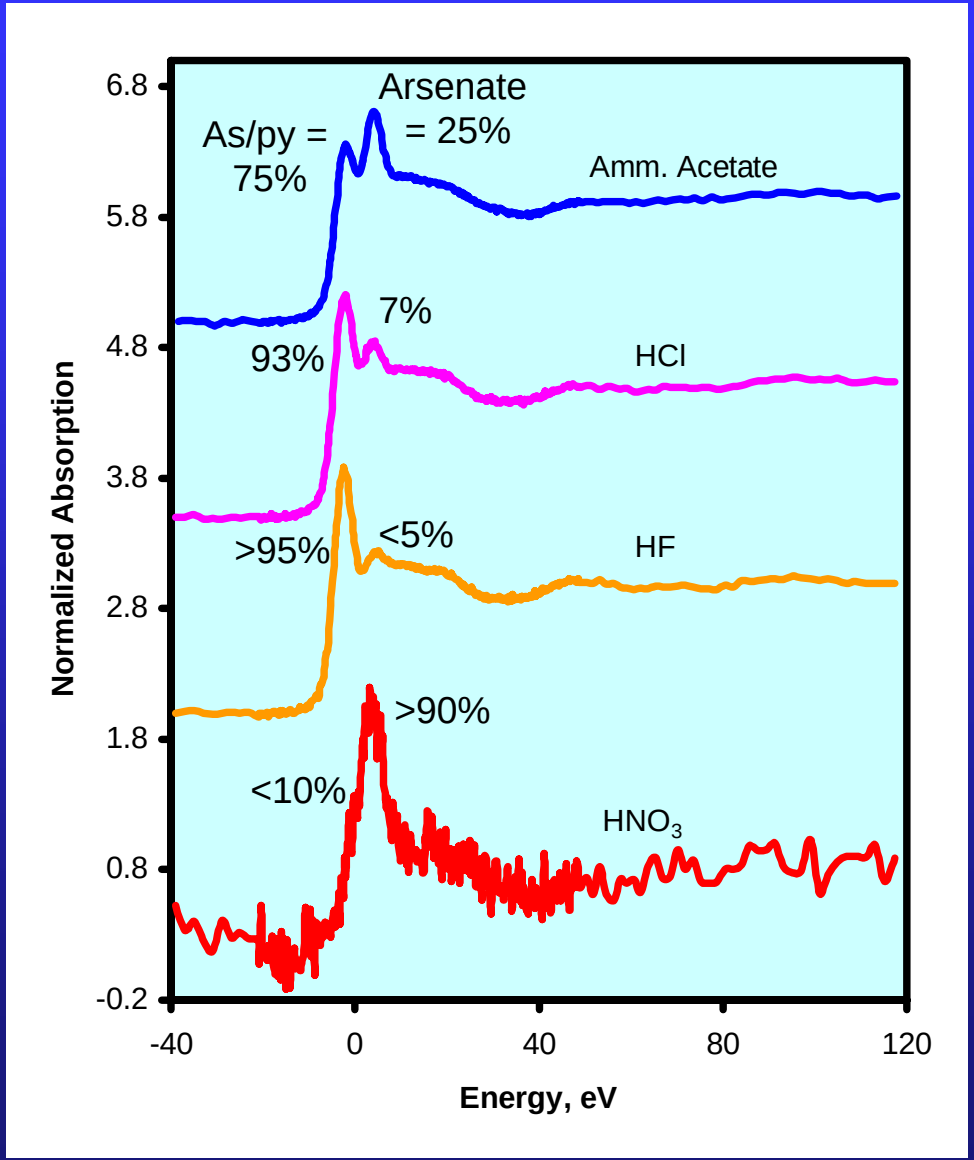
XAFS spectra of Alabama coal sample showing pyritic arsenic and arsenate forms.



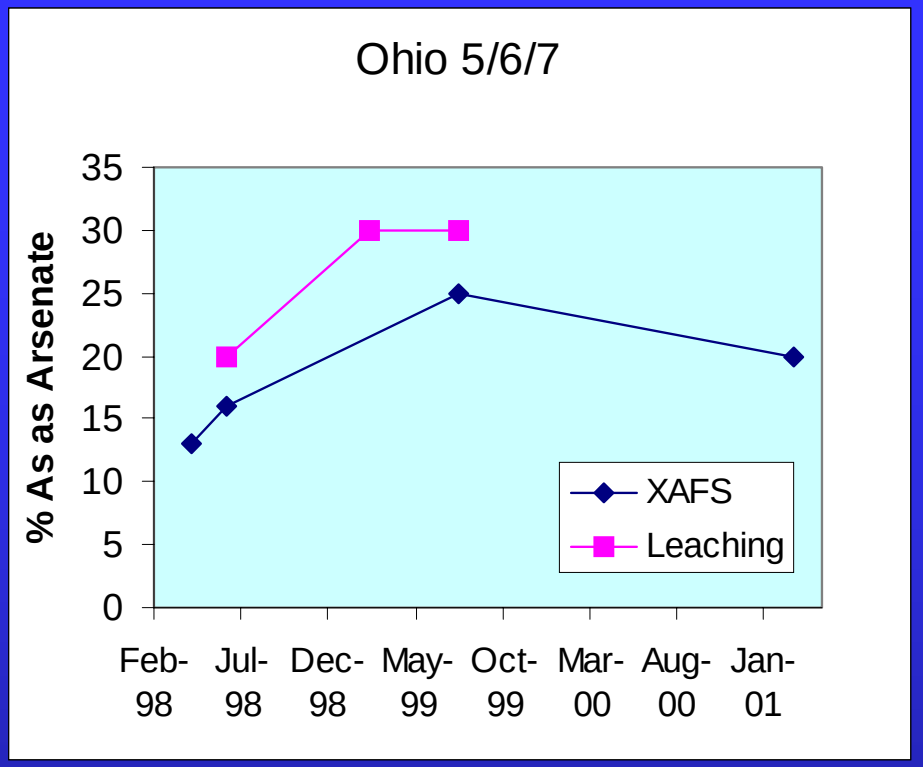
As XAFS of Leached Residues

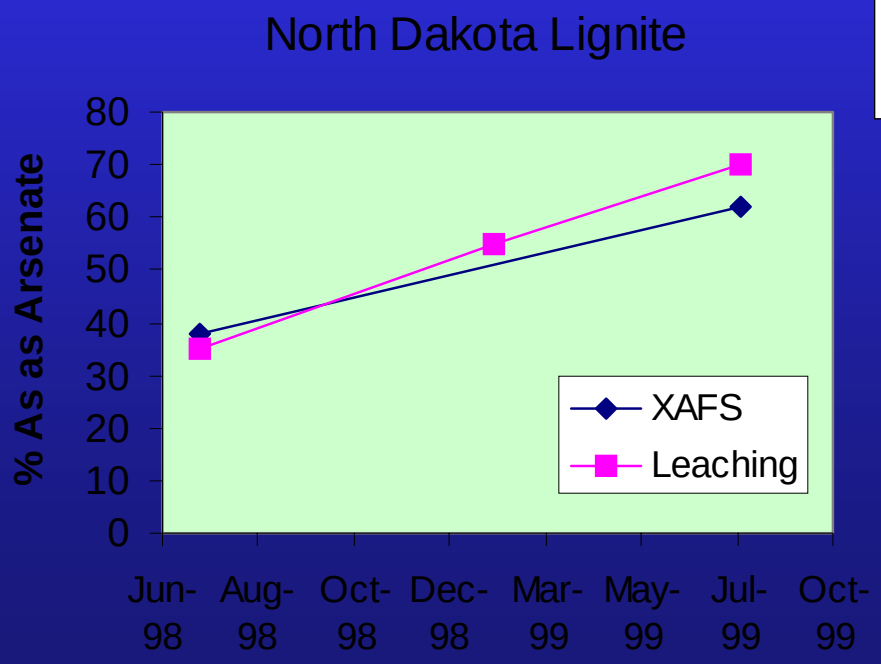
- Pyrite and arsenate are main forms of arsenic in Ohio5/6/7 (bituminous) coal.
- HCl removes arsenate but does not remove significant pyritic arsenic.
- HF removes arsenate not removed by HCl (no As-bearing silicates).
- Fraction of arsenate is primarily a function of pyrite oxidation.

Source: Huggins et al., 2002



Comparison of XAFS and leaching results for Ohio (bituminous) and North Dakota (lignite) coal samples. Determinations show formation of arsenate from As/pyrite over time.





Leaching results are sum of arsenic leached by HCl and HF. Data from Huggins et al., 2002.

XAFS Summary

Arsenic

- Pyrite and arsenate (equivalent to HCl + HF-leached As) are main forms in bituminous coals.
- Arsenate and As (III) are main forms in low rank coals.
- Fraction of arsenate is primarily a function of pyrite oxidation.

Chromium

- Two major forms identified:
  - Cr^{3+}/illite
  - Org. associated Cr (Amorph. CrOOH)
- Chromite- Common only in coals unusually rich in Cr.
- Oxidation State- Always Cr^{3+} in coal (rare Cr $^{6+}$ in some fly ash)

Coal-use Issues and Case Studies

Allan Kolker

Trace elements and coal use

- Mercury emissions balance potential health effects vs. multi-billions cost of controls.
- Fine particulate matter ($PM_{2.5}$) concentrate trace metals relative to coarser ash fractions, and are more readily inhaled.
- Water quality issues:
  - Acid mine drainage (AMD).
  - Disposal of coal preparation wastes.
  - Use of coal combustion products- considered non-hazardous under RCRA.

Pyrite Oxidation

- Oxidation of pyrite results in acid mine drainage and releases metals such as arsenic into the environment.
- Oxidation of pyrite in coal occurs spontaneously over time. Arsenic oxidation proceeds more rapidly than iron oxidation.
- Pyrite oxidation has important implications for coal transport and handling, potentially resulting in leaching of metals from coal piles.

Background- Coal Oxidation Experiments

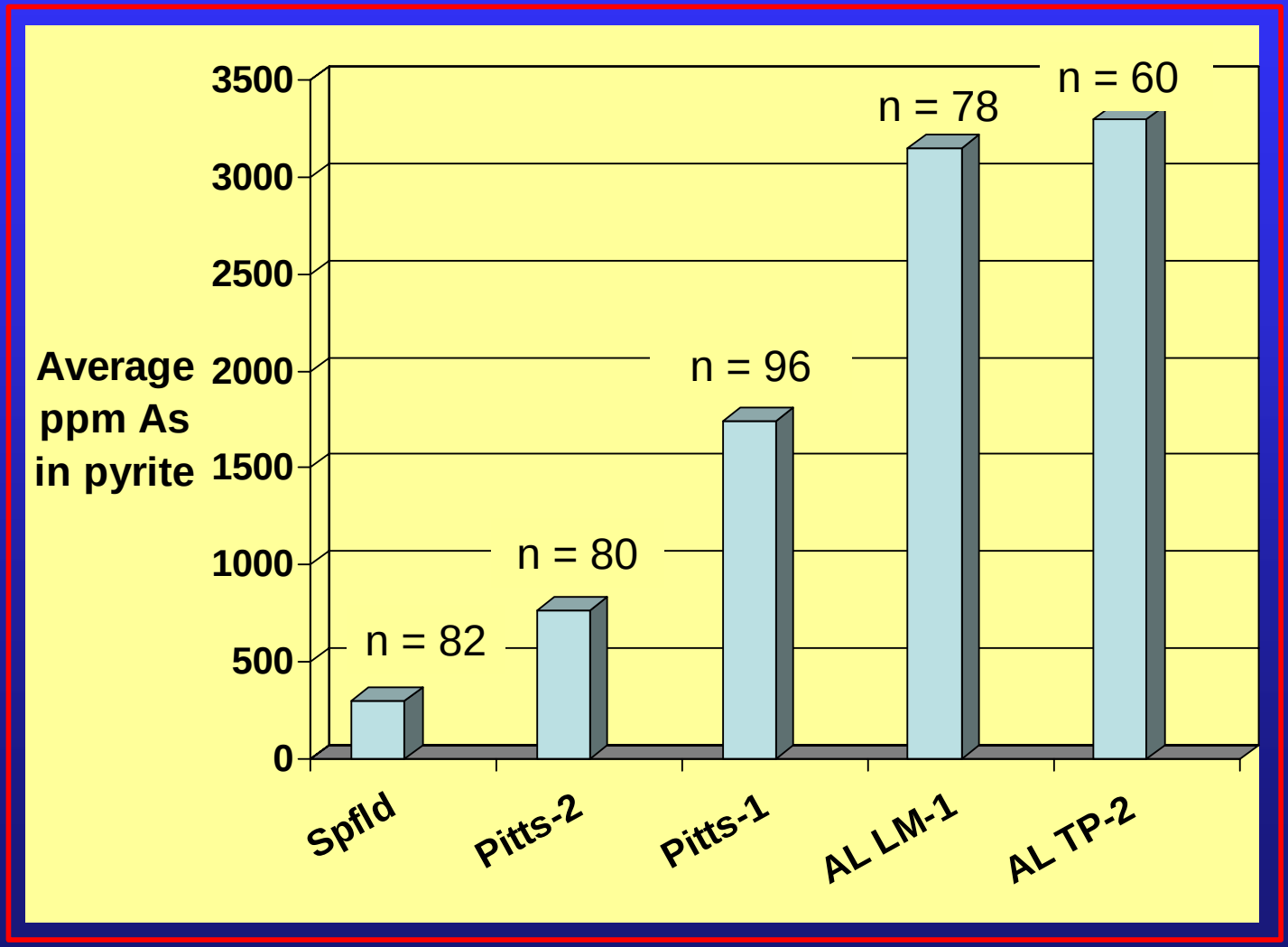
- Huggins et al. (2002), using As XANES showed that arsenate forms from pyritic arsenic in coal samples over time.
- We use As XANES and Fe-Mössbauer analysis to monitor pyrite oxidation in coal under controlled conditions.
- Experiments test the hypothesis that arsenic-rich pyrite is more susceptible to oxidation than pyrite with little or no arsenic.

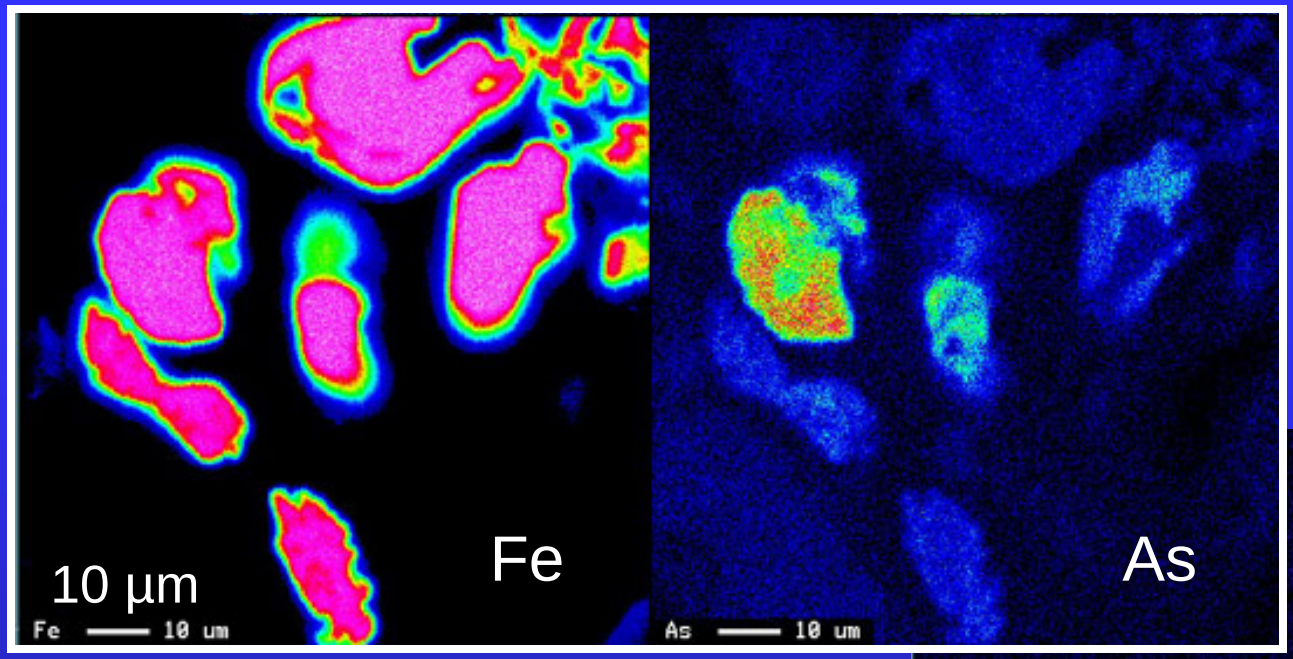
Comparison of Coal Samples Investigated

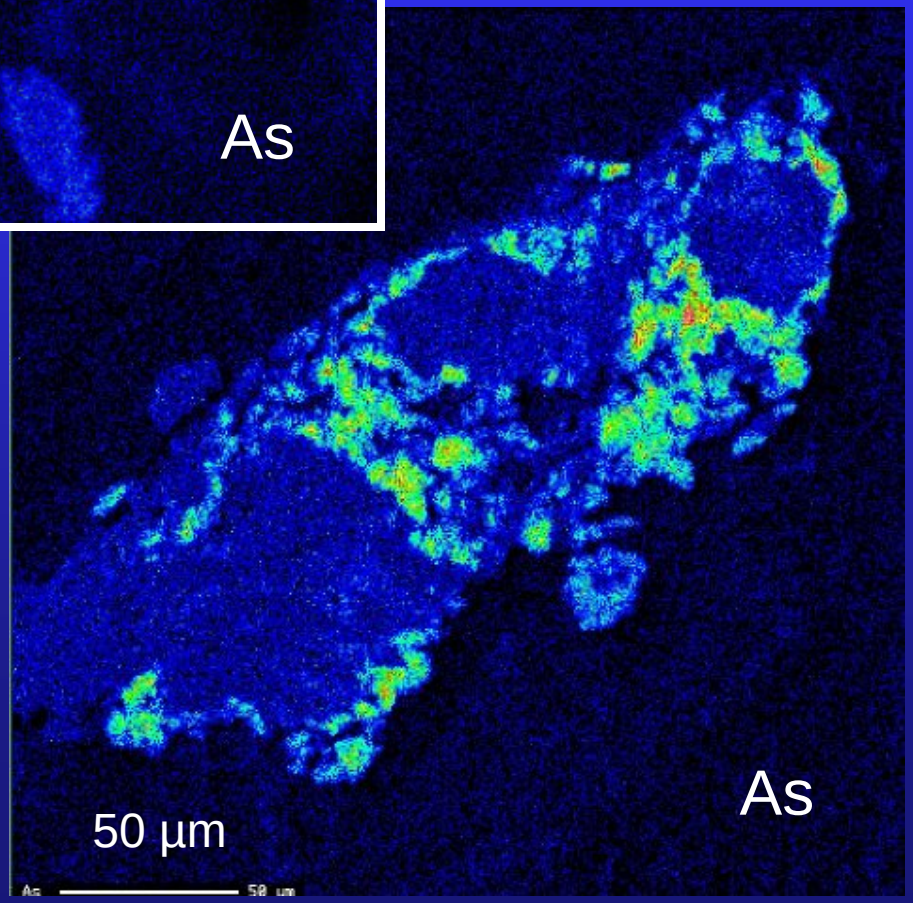
Sample	Coal Bed	Location	Arsenic Content (ppm)	Pyritic Sulfur[1] (wt. %)	Arsenic in Pyrite (wt. %)
Pitts #1	Pittsburgh	West Virginia	23.0	1.32	d.l.[2] to 0.34
Pitts #2	Pittsburgh	West Virginia	12.0	1.58	d.l to 0.14
Spfd	Springfield	Indiana	6.5	2.13	d.l. to 0.06
TP1-1.0	Warrior	Alabama	8.2	0.26	d.l. to 2.46
LM1-2.0	Warrior	Alabama	8.9	0.27	d.l. to 2.72

[1]Dry Basis; [2]Microprobe detection limit approximately 0.01 weight percent.

Relative Concentration of As in Pyrite







Wavelength-dispersive electron microprobe elemental maps of pyrite in Alabama samples LM-1 (above) and TP-1 (right) showing arsenic-enriched domains.

Controlled Atmosphere Experiment
(Argon, Oxygen, Air)

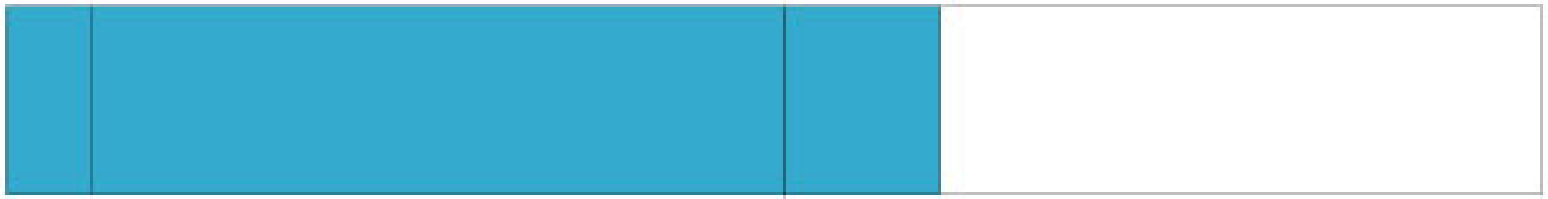
Air-wet Experiment

XAFS PROJECT TIMELINE

Stage 1
November, 2002

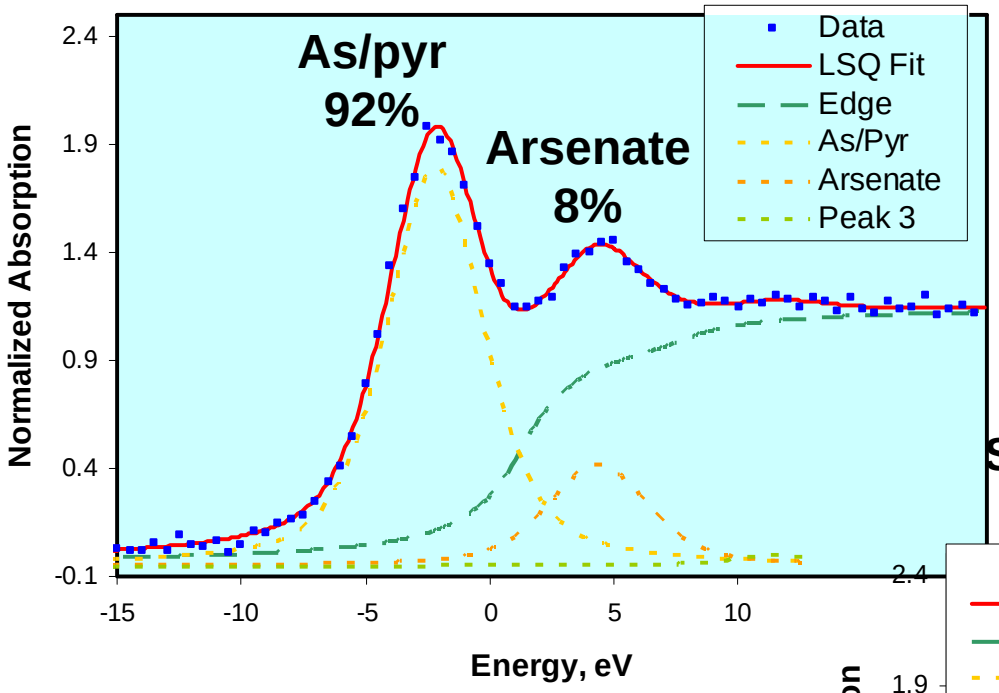
Stage 2
July 2003

Stage 3
April 2004



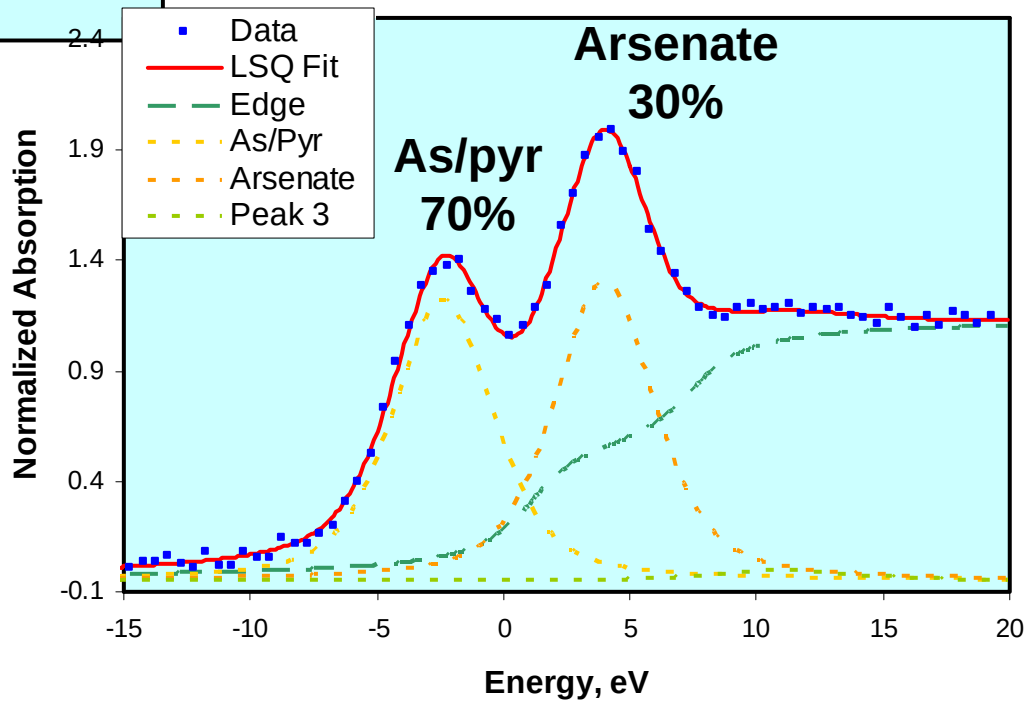
Start
October, 2002

Springfield No. 2 Indiana Argon



Results of least-squares fitting of As XANES spectra

Springfield No. 2 Indiana Air-Wet



Examples from Stage 1 XAFS November, 2002

Results of least-squares fitting of As XANES spectra, Stage 1 analysis, November, 2002

Sample	Ala. LM-1		Ala. TP-1		Springfield		Pitts #1		Pitts #2	
	Pyrite	Arsenate	Pyrite	Arsenate	Pyrite	Arsenate	Pyrite	Arsenate	Pyrite	Arsenate
Argon	77	23	82	18	92	8	93	7	92	8
Oxygen	76	24	81	19	91	9	92	8	91	9
Air Dry	75	25	81	19	91	9	93	7	91	9
Air Wet	61	39	69	31	70	30	81	19	77	23

Data are %As of total As in sample that is associated with pyrite or arsenate
Estimated error ±3%

Comparison of As XANES and ^{57}Fe Mössbauer Results (Stage 1 Data)

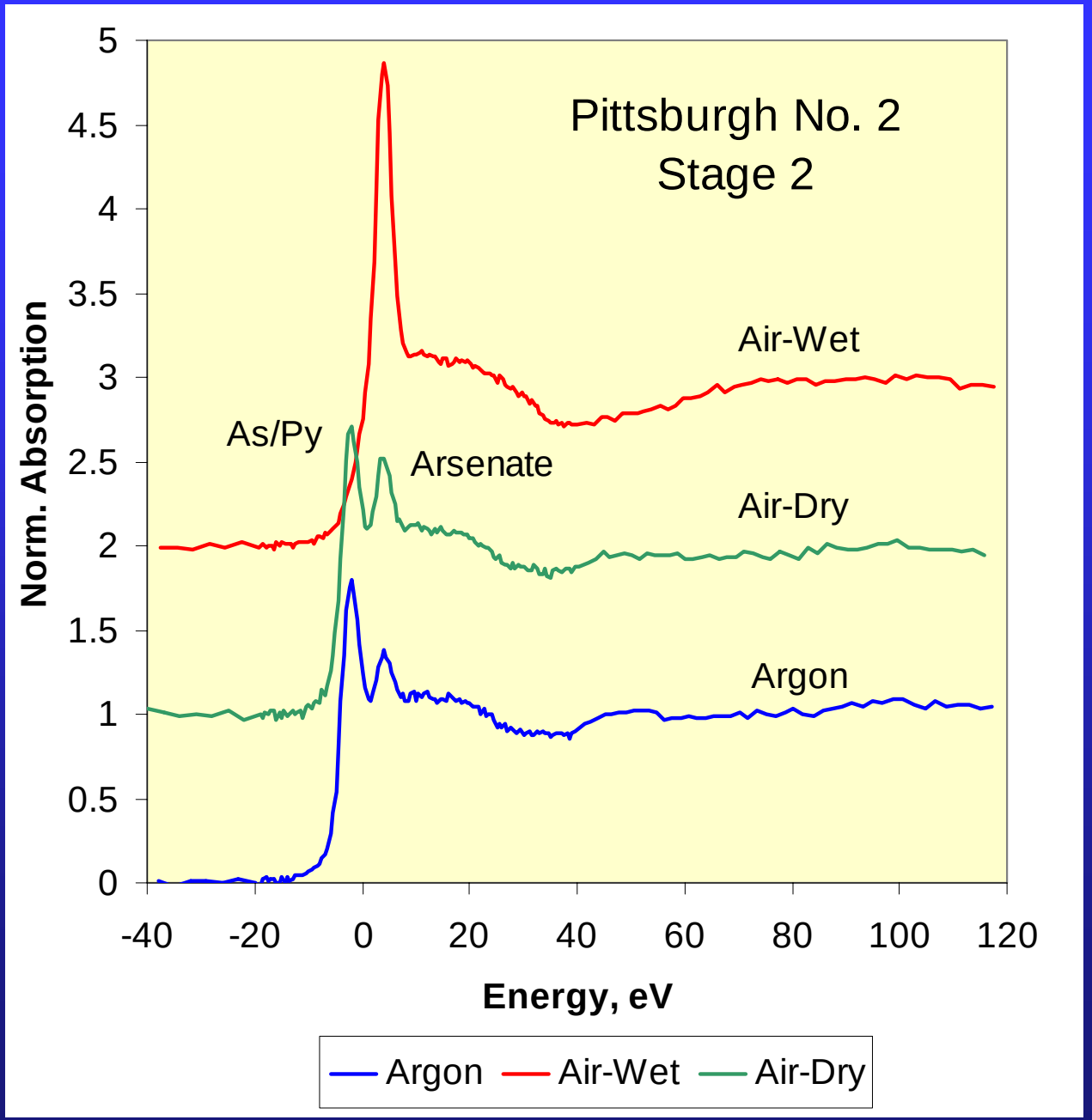
	Springfield			
	Arsenic		Iron	
	Pyrite	Arsenate	Pyrite	Jarosite
Argon	92	8	91	8
Air Wet	70	30	82	16
	Pittsburgh #1			
Argon	93	7	98	2
Air Wet	81	19	86	14

Stage 2 Experiments

- Little or no difference between samples stored under dry gasses (argon & oxygen).
- Unlike Stage 1, samples stored in air are more oxidized than those kept in dry gas.
- Air-wet samples:

  Pitts #2 and Ala TP-1 (no As/py (<5%) remaining); Ala LM-1, Springfield, Pitts #1, 10 to 50% As/py remaining (estimated).

Example of Stage 2 XAFS Results, July, 2003



Summary- Coal Oxidation Experiments

- Nearly complete range of arsenic oxidation is produced by experimental conditions. Arsenic and iron show parallel oxidation.
- Humidity and/or presence of water, and oxygen availability are most important factors controlling oxidation state.
- Complete results are needed to evaluate rates of pyrite oxidation as a function of pyrite arsenic content.

Mercury Emissions from Coal-Fired Power Plants

- December, 2000, EPA determines to limit mercury emissions from coal-fired power plants; timetable superceded by Clear Skies.
- Clear Skies*- Multi-pollutant plan links Hg, SO2 and NOx. Reduces 1999 Hg emissions (48 tons) to 26 tons by 2010 and 15 tons by 2018.
- Boiler MACT- Multi-pollutant plan for industrial/commercial boilers. Limits new boilers to 3 lbs Hg/trillion BTU and existing plants to 7 lbs/trillion BTU. Legislation sought by early 2004 and compliance in 3 years.

*http://www.epa.gov/clearskies/

Estimates of U.S. Point-Source Mercury Emission Rates (1994-1995*)

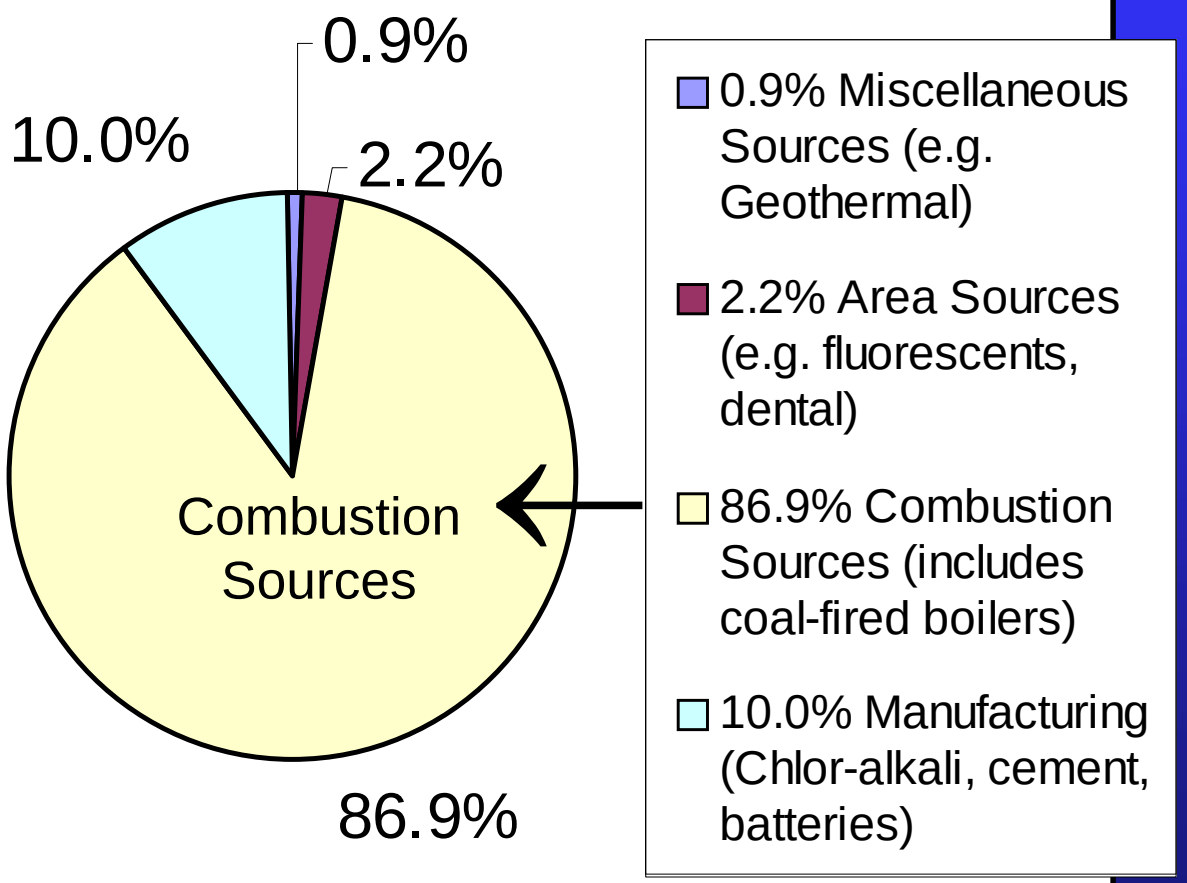
Regulated or Proposed Regulations

Medical Waste
Municipal Waste
Hazardous Waste
Non-Utility Boilers

Not Regulated:

Coal-Fired Utilities (about 33% of U.S. emissions)

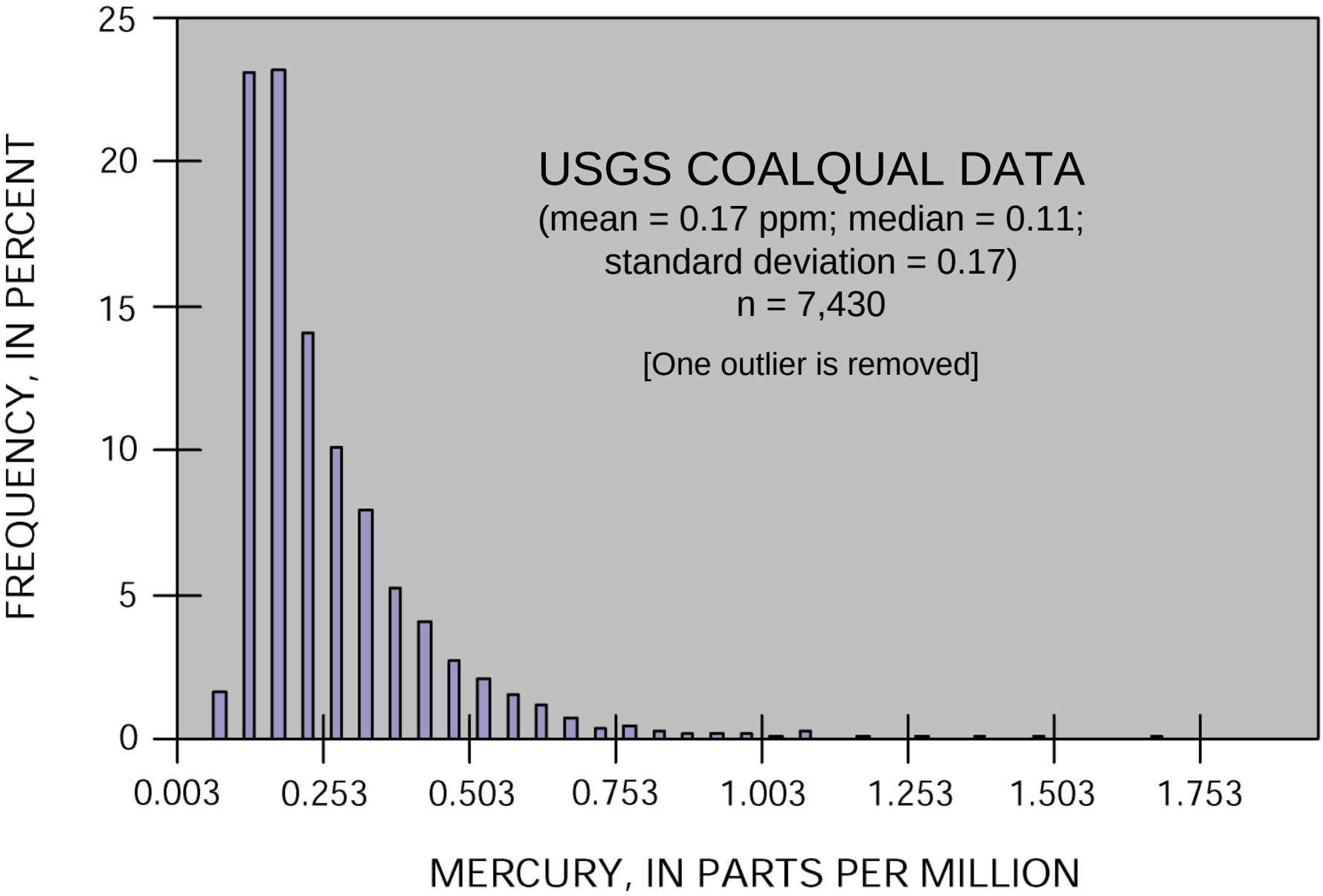
Source: EPA-PB98-124738



*Latest Figures Available

Health Risks from Mercury

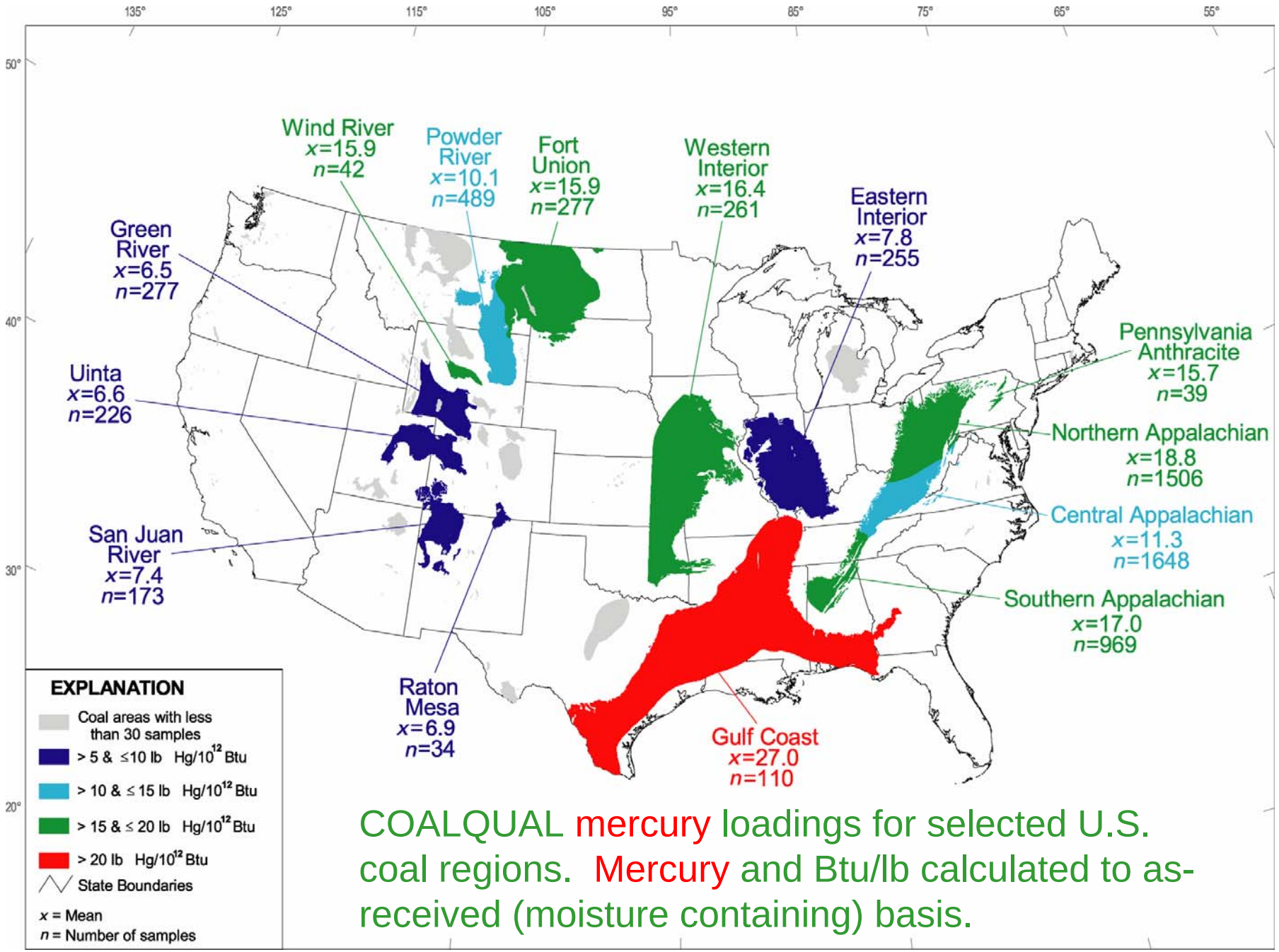
- Exposure due to consumption of methyl-mercury in fish.
- Nervous system effects and developmental disorders. Documented effects of chronic exposure at low levels. Risk to fetuses and infants is greatest.
- Strong association with kidney damage and disease.
- Likely association with increases in lung cancer, and possible cardiovascular effects.


USGS COALQUAL DATA
(mean = 0.17 ppm; median = 0.11;
standard deviation = 0.17)
n = 7,430
[One outlier is removed]
FREQUENCY, IN PERCENT
25
20
15
10
5
0
0.003
0.253
0.503
0.753
1.003
1.253
1.503
1.753
MERCURY, IN PARTS PER MILLION

Comparison of USGS and EPA ICR Data Sets

- EPA ICR database reflects mercury content of commercial coals delivered in 1999 to U.S. power plants ≥ 25 MW.
- USGS database includes data for about 40 elements and many coal-use parameters.
- Subsets[1] give averages of 0.10 ppm for ICR and 0.17 ppm for COALQUAL. Difference reflects cleaned vs. in-ground values, and increased use of low-S western coals.

[1] Quick et al. , *2003, Environmental Geology*



COALQUAL mercury loadings for selected U.S. coal regions. Mercury and Btu/lb calculated to as-received (moisture containing) basis.

Average Mercury Loadings Appalachian Coal Regions

Coal Region	**Mean Hg** (ppm)	**Mean Calorific Value** (Btu/lb)	**Mean Hg Loading*** (lbs Hg/10^{12} Btu)
Northern Appalachian	0.24	12,440	18.8
Central Appalachian	0.15	13,210	11.3
Southern Appalachian	0.21	12,760	17.0

*as-received basis

USGS Results from Tewalt et al., 2001

Calculating Mercury Loading

Example:

High-volatile B Bituminous Coal

Calorific value = 13,500 Btu/lb

Hg = 0.1 ppm Hg (equivalent basis)

$$\frac{1 \text{ lb Hg}}{10^7 \text{ lb coal}} \times \frac{1 \text{ lb coal}}{1.35 \times 10^5 \text{ Btu}} = \frac{7.4 \text{ lbs Hg}}{10^{12} \text{ Btu}}$$

Benefit of Coal Cleaning

Table shows calorific value and mercury contents for raw and cleaned coal averages for 24 eastern bituminous coal samples (dry, equal-energy basis).

Calorific value raw coal (Btu/lb)	Hg content raw coal (ppm)	Calorific value cleaned coal (Btu/lb)	Hg content cleaned coal (ppm)	Percent Hg reduction (equal energy basis)
10,704	0.23	13,730	0.16	37

Results from B. Toole-O'Neil et al., *Fuel*, v. 78, p. 47-54, 1999.

Reducing Mercury Loading

- Example- Coal Cleaning for average Central Appalachian coal:

Raw Coal (lbs $Hg/10^{12}$ Btu)	**Estimated Cleaned Coal** (37% reduction)	**MACT** (existing boilers)
11.3	7.1	7.0

Other Ways To Reduce Hg:

- Selective Mining
- Increase Hg capture with ESP, FGD, etc.
- Unburned Carbon

Eastern coal producers practice coal cleaning and selective mining; Delivered Hg contents are lower than USGS in-ground averages.

Estimating Yearly Mercury Loading to U.S. Power Plants

- Need to accurately know tonnages and moisture contents of coals having a particular mercury content.
- Estimates:

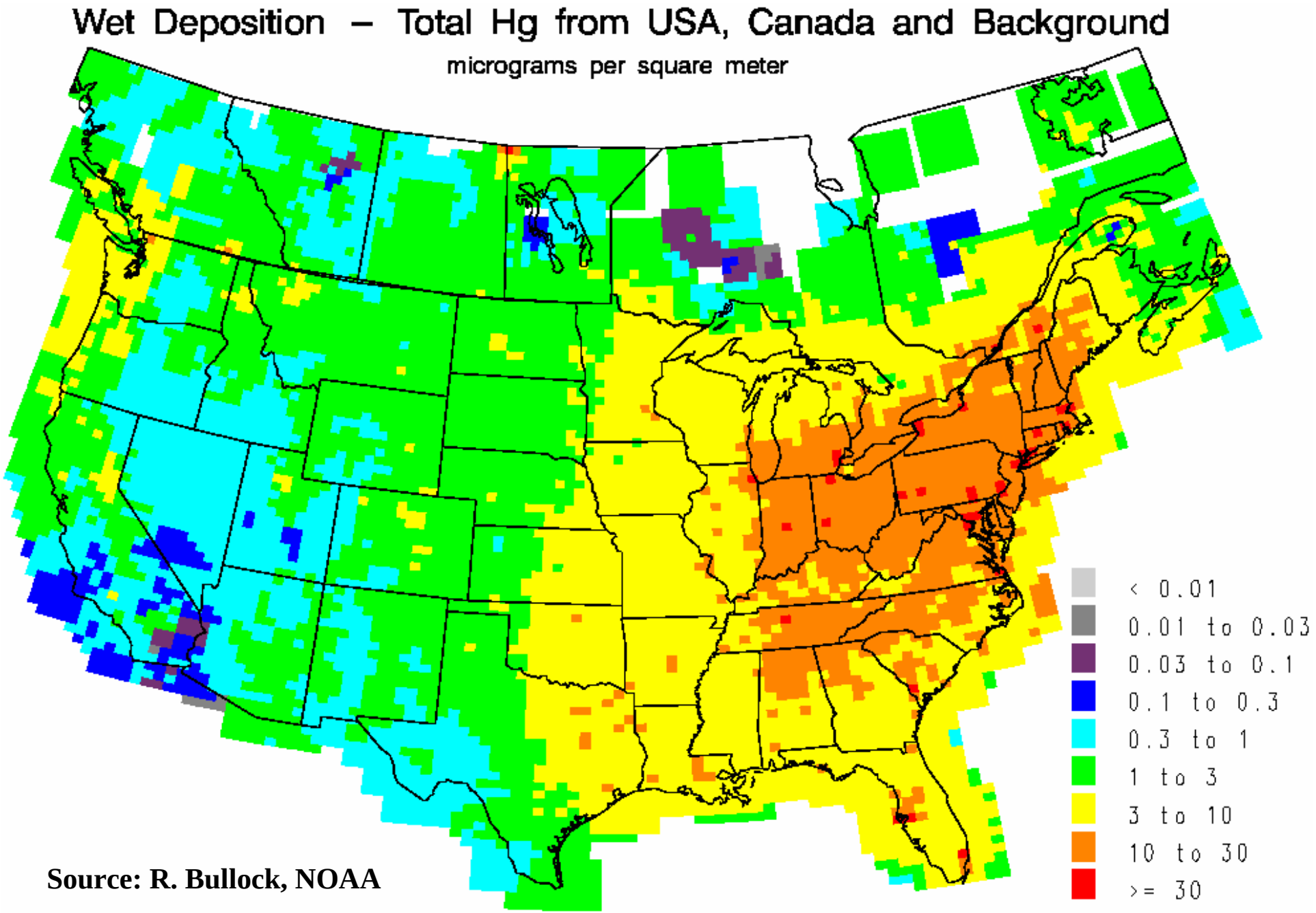
  1) 63 [1]Mg, based on ICR state averages, EIA tonnage data, for power plants ≥ 50 MW only (Quick et al.).

  2) 68 Mg, based entirely on ICR data ([2]Kilgroe et al.).

  3) 111 Mg, based on COALQUAL state averages (Quick et al.). Reduced to about 70 Mg with estimated 37% reduction by cleaning (equal energy basis).

[1]Mg is one metric ton; 1 metric ton = 1.1023 U.S. tons

[2]EPA-600/R-01-109, April 2002



Source: R. Bullock, NOAA

Mercury Deposition Network

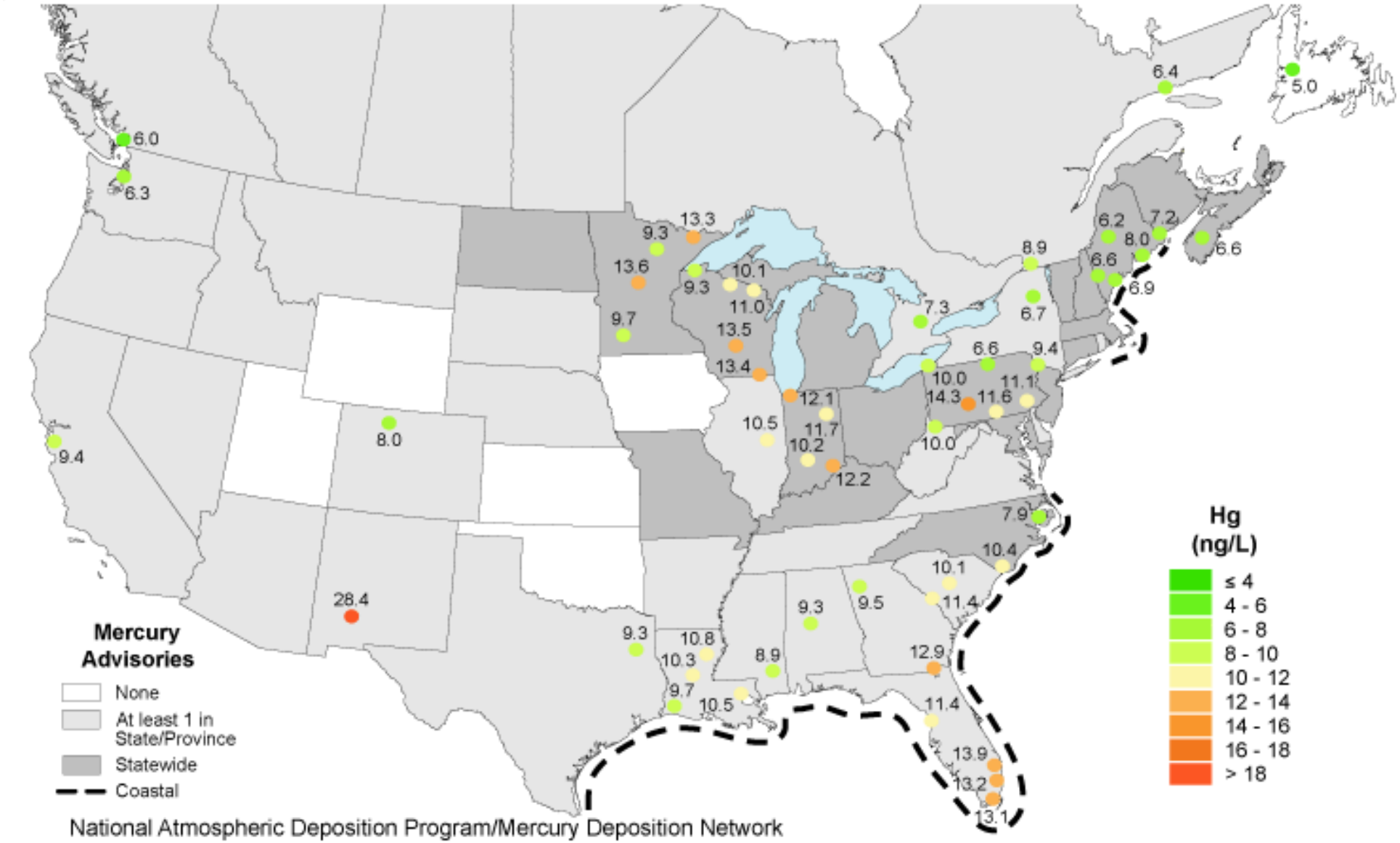
- Subprogram of National Atmospheric Deposition Program initiated in 1995 to monitor mercury levels in precipitation.
- Current network consists of about 80 standardized sites in U.S. and Canada.
- Weekly wet deposition samples are determined by cold vapor atomic fluorescence at Frontier Geosciences, Inc.
- Data distribution and program management by Illinois State Water Survey.

Data available at: http//:nadp.sws.uiuc.edu

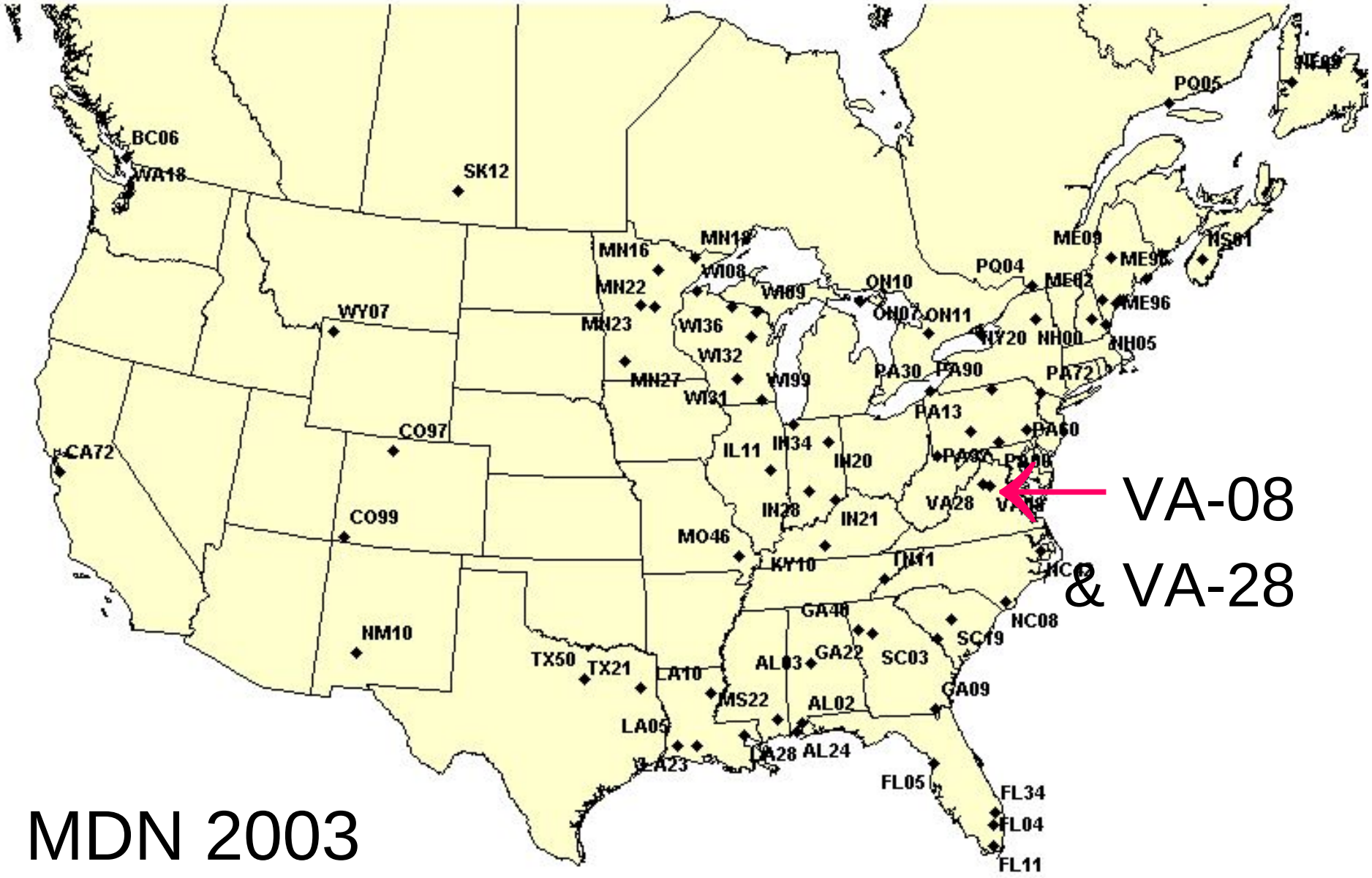
Background

- Highest projected rates of mercury deposition in the eastern third of U.S.
- Nonetheless, no operating MDN sites in DE, MD, VA, or WV as of 2002 (2 inactive sites).
- VA-08 Culpeper (USGS/GMU) and VA-28 SNP Big Meadows (National Park Service) started in Oct./Nov. 2002 to help fill the void.
- VA-28: Reference for ecological and water quality studies in Shenandoah National Park.
- VA-08 and VA-28: Regional background for mercury emissions prior to mandated changes.

Total Mercury Concentration, 2001



National Atmospheric Deposition Program
Mercury Deposition Network



Views of new MDN stations

Preliminary results- Quarterly volume-averaged mercury concentrations, VA-08, VA-28 and nearest active sites.

Site	*VA-08*	*VA-28*	*PA-37*	*PA-13*	*PA-00*	*PA-47*
Name	Culpeper	SNP Big Meadows	Holbrook	Allegheny Portage NHS	Arendtsville	Millersville
Latitude	38.42	38.52	39.82	40.50	39.92	39.99
Longitude	-78.10	-78.44	-80.29	-78.55	-77.31	-76.39
Elevation (m)	163	1074	1140	739	269	85
Dist. VA-08 (km)	----	31	245	235	180	229
1 Qtr 2003	**4.25**	**2.76**	**6.31**	**5.09**	**5.43**	**4.05**
2 Qtr 2003	**7.02**	**6.37**	**10.58**	**7.98**	**8.79**	**7.16**

Document 34

Willman, H.B., J.C. Frye, J.A. Simon, K.E. Clegg, D.H. Swann, E. Atherton, C. Collinson, J.A. Lineback, T.C. Buschbach, and H.B. Willman, 1967. Geologic Map of Illinois: Illinois State Geological Survey map, scale 1:500,000.

ILLINOIS STATE GEOLOGICAL SURVEY

JOHN C. FRYE, Chief
Urbana

GEOLOGIC MAP OF ILLINOIS

COMPILED BY
H. B. WILLMAN AND OTHERS

Quaternary, Tertiary, Cretaceous geology by H. B. WILLMAN and JOHN C. FRYE
Pennsylvanian geology by JACK A. SIMON and KENNETH E. CLEGG
Mississippian, Devonian, Silurian geology by D. H. SWANN, ELWOOD ATHERTON, CHARLES COLLINSON, and JERRY A. LINEBACK
Ordovician, Cambrian geology by T. C. BUSCHBACH and H. B. WILLMAN
With the collaboration of other members of the staff

1967

SOUTHERN

NORTHERN

STRUCTURE ON TOP OF GALENA GROUP AND INDEX TO CROSS-SECTIONS

GLACIAL MAP

THICKNESS OF SURFICIAL DEPOSITS
(Glacial drift, loess, and alluvium)

EXPLANATION

SUB-ST. PETER GEOLOGIC MAP

SUB-MIDDLE AND UPPER DEVONIAN GEOLOGIC MAP

SUB-PENNSYLVANIAN GEOLOGIC MAP

C-C' EAST-WEST CROSS-SECTION BELLEVILLE TO CARMI

A-A' NORTH-SOUTH CROSS-SECTION CAIRO TO ROCKFORD

Base map by U.S. Geological Survey

Document 35

Natural Resource Technology, an OBG Company (NRT/ OBG), 2017. Hydrogeologic Monitoring Plan, Newton Primary Ash Pond – CCR Unit ID 501, Newton Landfill 2 – CCR Unit ID 502, Newton Power Station, Canton, Illinois, Illinois Power Generating Company. October 17, 2017.

OBG

Hydrogeologic Monitoring Plan

Newton Primary Ash Pond – CCR Unit ID 501
Newton Landfill 2 – CCR Unit ID 502

Newton Power Station
Canton, Illinois

Illinois Power Generating Company

October 17, 2017

Natural Resource Technology
AN OBG COMPANY

OCTOBER 17, 2017 | PROJECT #2285

Hydrogeologic Monitoring Plan

Newton Primary Ash Pond – CCR Unit ID 501
Newton Landfill 2 – CCR Unit ID 502

Newton Power Station
Canton, Illinois

Prepared for:
Illinois Power Generating Company

STUART J. CRAVENS, PG
Principal Hydrogeologist

ROBERT J KARNAUSKAS, PG, PH
Principal Hydrogeologist

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Appendix B Geotechnical Exploration Locations and Laboratory Test Results
Appendix C Hydraulic Conductivity/Slug Test Results
Appendix D Groundwater Elevation Contour Maps

ACRONYMS AND ABBREVIATIONS

bgs	below ground surface
CCR	coal combustion residual
CFR	Code of Federal Regulations
cm/s	centimeters per second
CPT	Cone Penetrometer Test
ft	feet
ft/ft	feet per feet
ft MSL	feet above Mean Sea Level
HMP	Hydrogeologic Monitoring Plan
ID	Identification number
IEPA	Illinois Environmental Protection Agency
IPGC	Illinois Power Generating Company
ISGS	Illinois State Geological Survey
NPS	Newton Power Station
NRT	Natural Resource Technology, an OBG Company
PWS	Public Water Supply
RCRA	Resource Conservation and Recovery Act
SAP	Sampling and Analysis Plan
USEPA	United States Environmental Protection Agency

1 INTRODUCTION

1.1 OVERVIEW

This Hydrogeologic Monitoring Plan (HMP) has been prepared by Natural Resource Technology, an OBG Company (NRT) to provide background information necessary to support the monitoring well network established for development of the Sampling and Analysis Plan (SAP) requirements of the United States Environmental Protection Agency (USEPA) Final Rule to regulate the disposal of Coal Combustion Residual (CCR) as solid waste under Subtitle D of the Resource Conservation and Recovery Act (RCRA) [40 CFR 257 Subpart D; published in 80 FR 21302-21501, April 17, 2015] for the Newton Power Station, Jasper County, Illinois. The Newton Power Station is owned by Illinois Power Generating Company (IPGC). This HMP will apply specifically to the following CCR Units: Newton Primary Ash Pond (CCR Unit ID 501) and Newton Landfill 2 (CCR Unit ID 502), as defined further below.

1.2 PREVIOUS INVESTIGATIONS AND REPORTS

Numerous hydrogeologic investigations have been performed concerning the CCR Units located at the Newton Power Station. The information presented in this HMP includes data collected in support of the monitoring well network established for development of the Sampling and Analysis Plan (SAP) and supplements comprehensive data collection and evaluations from prior hydrogeologic investigation reports (most recent to oldest), including, but not limited to, the following:

- ***Rapps Engineering and Applied Science, April 10 2013, Phase I Hydrogeological Assessment Report, Coal Combustion Product Impoundment, Ameren Energy Generating Company, Newton Energy Center, Jasper County, Illinois.*** A hydrogeologic study to assess the potential for constituent migration from this impoundment. Report includes: water well survey, development of a groundwater monitoring plan, and an initial groundwater quality assessment. This report summarizes hydrogeologic information pertinent to the site, evaluates groundwater quality data to determine if operation of the impoundment has adversely affected groundwater, and makes recommendations for future actions related to groundwater quality management.
- ***Geotechnology, Inc., February 8, 2011, Initiation of Monitoring Report, Ameren, Newton Power Station, Newton, Illinois.*** This report documents the results of the monitoring well installation and groundwater monitoring activities performed at the site. Three wells were installed, developed and sampled.
- ***Rapps Engineering and Applied Science, November 2009, Site Characterization and Groundwater Monitoring Plan for CCP Impoundment, Ameren Energy Generating Company, Newton Power Station, Jasper County, Illinois.*** Hydrogeologic study and groundwater monitoring plan to assess the potential for constituent migration from this impoundment. Includes an assessment of subsurface hydrogeologic conditions at the site, identification of private, potable water wells and oil and gas wells within 2,500 feet of the facility, public water supply (PWS) wells within 10 miles of the facility, and plans for a groundwater monitoring well network designed to characterize and monitor groundwater quality.
- ***Rapps Engineering and Applied Science, 1997, Hydrogeologic Investigation and Groundwater Monitoring Program, Newton Power Station, Jasper County, Illinois.*** Investigation presents site-specific data obtained through the completion of approximately 40 borings, 20 monitoring wells, and review of regional information and an evaluation of subsurface data from nearby residential wells. Part of Application for Landfill Permit – Rapps 1997.

The HMP supports the monitoring well network established for development of the SAP and provides the following background information:

- Site Geology and Hydrogeology
- Aquifer Properties
- Monitoring Network Placement and Rationale

1.3 SITE LOCATION AND DESCRIPTION

The Newton Power Station (NPS) is located in Jasper County in the southeastern part of central Illinois, approximately 7 miles southwest of the town of Newton (Figure 1). The plant is located on the north side of Newton Lake and has one active CCR impoundment (Newton Primary Ash Pond) located in Section 26 and the western half of Section 25, Township 6 North, Range 8 East. The site also contains the Newton Landfill 2, located in the western half of Section 26 and eastern half of Section 27, Township 6 North, Range 8 East. The area is also bounded by agricultural land and Newton Lake to the west, south, and east. Beyond the lake is additional agricultural land.

1.4 DESCRIPTION OF CCR MANAGEMENT UNITS

The CCR Units at the Newton Power Station, including the Newton Primary Ash Pond (CCR Unit ID 501) and the Newton Landfill 2 (CCR Unit ID 502), will hereafter be referred to as the 'Site'.

1.4.1 Newton Primary Ash Pond (CCR Unit ID 501)

The NPS's sole CCR impoundment, consisting of a Primary Ash Pond, was constructed in 1977 and has a design capacity of approximately 9,715 acre-feet for the primary pond. There is also a non-CCR 83.6 acre-feet Secondary Pond. The Primary Ash Pond has a surface area of 400 acres and a height of approximately 71 feet above grade. The Secondary Pond has an area of 9.3 acres and a height of approximately 29 feet above grade. The Primary Ash Pond currently receives bottom ash, fly ash, and low-volume wastewater (LVW) from the plant's two coal-fired boilers. The CCR impoundment is operated per NPDES Permit IL0049191, Outfall 001. The impoundment was not excavated during construction except for native materials used to build the containment berms.

1.4.2 Newton Landfill 2 (CCR Unit ID 502)

Newton Landfill 2 includes two cells, Phase I (west) cell and Phase II (east) cell. The Phase I cell, built around 1977, was unlined, and accepted sodium-based flue gas desulfurization (FGD) wastes. Phase I was closed in 1999 with a 40-millimeter thick geomembrane cap and currently has a Groundwater Management Zone (GMZ) established. Following a switch by the NPS to western coal in 1997, the Phase II cell began receiving coal ash that same year; a portion of the Phase II cell is still operational. The Phase II cell has a geomembrane liner with a leachate collection system.

2 GEOLOGY AND HYDROGEOLOGY

The results of the site characterization activities performed at the Site are discussed below.

2.1 GEOLOGY

Geologic units present at the Site include fill, ash generated at the site, unlithified alluvial sediments, unlithified glacial deposits, and Pennsylvanian-age bedrock.

2.1.1 Regional Setting

Illinois is situated in the south-central part of the great Central Lowland Province near the confluence of two major lines of drainage, the Mississippi and Ohio Rivers (Leighton et al., 1948). The NPS lies at the southeastern portion of the Springfield Plain of the Till Plains section, the largest physiographic division in Illinois, covering approximately four-fifths of the state. It is characterized by its flatness and shallowly entrenched drainage. Drainage systems are well developed, and the district is in a late youthful stage of dissection.

The unlithified geologic deposits in the region range from 100 to 120 feet (ft) thick and are derived from recent river deposition (alluvium), glacial outwash, and glacial till deposits. The unlithified deposits directly overly Pennsylvanian Mattoon Formation bedrock. The Mattoon Formation is the youngest formation in the Pennsylvanian System in Illinois. It is underlain by the Bond Formation, while the top is mostly an erosional surface overlain by Pleistocene glacial deposits. The Mattoon Formation has a maximum thickness of more than 600 feet in the central part of the Illinois Basin in Jasper County. It is characterized by a complex sequence of thin limestones, coals, black fissile shales, underclays, thick gray shales, and several well developed sandstones. The lateral extent of many of the named units has not been determined due to widely scattered outcrops and scarce subsurface data. However, coals and limestone units are considered to be as persistent as those in the underlying Bond Formation.

Borings advanced at the NPS as part of a hydrogeologic site investigation for a CCP landfill indicate that the elevation of the top of the bedrock surface at the site is approximately 400 to 450 ft MSL. The depth to bedrock varies widely in the area owing to the undulatory nature of the eroded upper bedrock surface and ranges from approximately 90 to 120 ft. Logs indicate that the lithology of the uppermost bedrock is mostly shale.

2.1.2 Site Geology

The geology has been evaluated during previous hydrogeologic investigations and groundwater quality assessments since the first borings and monitoring wells were installed. Quaternary deposits in the Newton area consist mainly of diamictons and outwash deposits that were deposited during Illinoian and Pre-Illinoian glaciations. The unconsolidated deposits which occur at Newton Power Station include the following units (beginning at the ground surface):

- Ash/Fill Units – CCR and fill within the various CCR Units
- Upper Confining Unit – Low permeability clays and silts, including the Peoria Silt (Loess Unit) in upland areas and the Cahokia Formation in the flood plain and channel areas to the south and east, underlain by the Sangamon Soil, and the predominantly clay diamictons of the Hagarstown (Till) Member of the Pearl Formation and the Vandalia (Till) Member of the Glasford Formation
- Uppermost Aquifer (Groundwater Monitoring Zone) – Thin to moderately thick (3 to 17 ft), moderate to high permeability sand, silty sand, and sandy silt/clay units of the Mulberry Grove Member of the Glasford Formation
- Lower Confining Unit – Thick, very low permeability silty clay diamicton of the Smithboro (Till) Member of the Glasford Formation and the silty clay diamictons of the Banner Formation
- Bedrock – Pennsylvanian-age Mattoon Formation that is mostly shale near the bedrock surface, but is characterized at depth by a complex sequence of shales, thin limestones, coals, underclays, and several

sandstones. The erosional surface of the Pennsylvanian-age Mattoon Formation bedrock ranges widely in depth in the vicinity of the site, but is typically encountered at 90 to 120 ft below ground surface (bgs).

The major unconsolidated materials present at the site are discussed in greater detail below:

2.1.2.1 Ash/Fill Units

Ash is present within the Newton Primary Ash Pond as well as the Newton Landfill 2. The majority of ash fill at the Newton Primary Ash Pond lies on top of the loess and clay.

2.1.2.2 Cahokia Formation

The Cahokia Formation of the Holocene Stage consists of deposits in floodplains and channels of modern rivers and streams and consists of mostly poorly sorted sand, silt, and clay with wood and shell fragments and local deposits of sandy gravel. The Cahokia is likely present in the Big Muddy Creek valley west of the site and along the bottom of Newton Lake to the east, which used to be the bottomland for Law Creek (Lineback, 1979; Berg and Kempton, 1987).

2.1.2.3 Peoria Silt (Loess Unit)

The Peoria Silt is a Loess Unit which extends from beneath the topsoil, derived from the loess, to the top of the Hagarstown Member. The loess, ranging in thickness from 3 to 9 ft where present, has been described as silt, clayey silt, and silty clay. The Loess Unit is generally considered unsaturated.

2.1.2.4 Sangamon Soil

The Sangamon Soil formed between the interglacial period between the Illinoian and Wisconsinan stages of glaciation as a result of weathering of the upper portion of the Illinoian drift. This layer occurs throughout the site and consists of approximately 2 to 6 ft of light brown to light gray silty clay

2.1.2.5 Hagarstown (Till) Member

The Hagarstown Member (also referred to as Hagarstown Beds) of the Pearl Formation, consists of clay till with varying amounts of sand and gravel. Where present at the site, the clay till ranges in thickness from 3 to over 24 ft. Where present, the sandy portion of the Hagarstown is generally less than 5 ft thick. The composition of the sandy portion of the Hagarstown unit varies across the site and was classified as gravelly till, poorly sorted gravel, well sorted gravel, sand and silty sand.

2.1.2.6 Vandalia (Till) Member

The Vandalia Member is a sandy/silty till with thin, discontinuous lenses of silt, sand, and gravel. The Vandalia Till was encountered in all borings advanced at the site. The Vandalia Till typically ranges in thickness from 20 to 60 ft. Results from laboratory tests completed for vertical hydraulic conductivity indicate the Vandalia unit has a very low vertical hydraulic conductivity.

2.1.2.7 Mulberry Grove Member

As described by Willman et al. (1975), the Mulberry Grove Member of the Glasford Formation typically consists of a thin, lenticular unit of gray sandy silt (Willman et al., 1975). It represents the interval between the retreat of the glacier that deposited the Smithboro Member and the advance of the glacier that deposited the Vandalia Member. At the site, the Mulberry Grove Member consists of fine to coarse sand with varying amounts of silt and small to large gravel. The portion of the Mulberry Grove Member at the site that is defined as a sand layer ranges in thickness from 3 to 17 ft with an average thickness of 8 ft. This unit generally occurs across the site at depths between 55 and 88 ft bgs.

2.1.2.8 Smithboro (Till) Member

The Smithboro Member is described as a gray, compact, silty-clay diamicton. The Smithboro Member typically ranges in thickness from 10 to 20 ft.

2.1.2.9 Banner Formation

The Banner Formation consists of pre-Illinoian undifferentiated diamictons and intercalated sand and gravel outwash that generally rest directly on bedrock. The Banner Formation is approximately 20 to 30 ft thick at the site and consist of greenish-gray silty clay with traces of sand.

Name	Age	Description
Cahokia	Holocene	poorly sorted sand, silt, and clay (alluvial)
Peoria Silt	Wisconsinan	sandy silt along bluffs to clayey silt away from bluffs; local lenses of fine to med grained sand; 3-9 ft thick
Sangamon Soil	Sangamonian	light brown to light gray silty clay; weathered upper portion of Illinoisan drift; 2.5-5.5 ft thick
Hagarstown Member	Illinoisan	gravel, sand, and gravelly diamicton; 3-24' thick where present; reddish-brown silty clay with some sand and gravel; surface at 510 to 532 ft; can also be gravelly till with poorly sorted gravel, well sorted gravel, and sand
Vandalia Member	Illinoisan	gray silty to sandy clay diamicton with traces sand and gravel; thin lenses of silt, sand, and gravel; 20-60 ft thick
Mulberry Grove	Illinoisan	fine to coarse sand with varying amounts of silt and fine to coarse gravel; 3 - 17 ft thick; may contain lenses of silt, sand and gravel
Smithboro Member	Illinoisan	gray, silty clay diamicton w/ traces sand and gravel; 10-20 ft thick
Banner Formation	pre-Illinoisan	undifferentiated diamictons; greenish-gray moist silty clay with traces of sand; 20-30 ft thick

2.2 HYDROGEOLOGY

The information used to describe the hydrogeology is based on the local geology obtained from published sources, hydrogeologic investigation data, and boring data collected during monitoring well installation.

2.2.1 Uppermost Aquifer

The uppermost aquifer is the Mulberry Grove Member, typically consisting of fine to coarse sand with varying amounts of clay, silt and fine to coarse gravel. The portion of the Mulberry Grove Member at the site that is defined as a sand layer ranges in thickness from 3 to 17 ft. with an average thickness of 8 ft and with only a few exceptions occurs between depths of 55 to 88 ft bgs.

2.2.2 Lower Limit of Aquifer

The lower hydrostratigaphic units consist of the Smithboro Member and the Banner Formation, both of which are predominantly low permeability clay diamictons with varying amounts of silt, sand and gravel. The lower unlithified confining unit is 30 to more than 50 ft thick above the underlying bedrock.

2.2.3 Hydraulic Conductivity

Hydraulic conductivity/slug tests were completed in wells screened in the unlithified material during prior site investigations and by NRT in April 2017. The hydraulic conductivity values determined from 15 individual monitoring wells (Appendix C) within the uppermost aquifer (Mulberry Grove Member) ranged from 3.9×10^{-8} to 3.6×10^{-2} centimeters per second (cm/s). The geometric mean of the hydraulic conductivity for NRT tested monitoring wells in the Uppermost Aquifer, excluding one outlier, is 2.5×10^{-4} cm/s. Monitoring wells around the Primary Ash Pond had a geometric mean hydraulic conductivity of 1.2×10^{-3} cm/s and those around Landfill 2, excluding one outlier, had a geometric mean hydraulic conductivity of 7.4×10^{-5} cm/s. Field hydraulic conductivity test results reported by Rapps (1997) for six locations near Landfill 1 ranged from 2.5×10^{-6} to 6.0×10^{-3} cm/s with a geometric mean of 9.8×10^{-4} cm/s.

The uppermost unit intercepted in the area of the Primary Ash Pond and Landfill 2 is the silty to sandy clay of the "Upper Drift", or aquitard, as identified in the Rapp's 1997 landfill investigation and consists of Peoria Silt, Sangamon Soil, and/or Hagarstown Member. The hydraulic conductivity of this unit, as tested at monitoring wells near the landfill with screen depths between 8 and 36 ft bgs (Rapps, 1997), ranged from 2.4 x 10^{-6} to 6.1 x 10^{-5} cm/s with a geometric mean of 1.7 x 10^{-5} cm/s. Three in-situ tests conducted by NRT of the uppermost materials near the Primary Ash Pond, on wells screened between 7 and 20 ft bgs, had a geometric mean hydraulic conductivity of 1.3 x 10^{-5} cm/s. Laboratory testing results for five soil samples collected from depths of 20 to 32 ft bgs in the underlying Vandalia Member (Rapps, 1997) ranged from 6.3 x 10^{-9} to 2.1 x 10^{-8} cm/s with a geometric mean hydraulic conductivity of 1.1 x 10^{-8} cm/s.

The hydraulic conductivity value determined from one field (i.e. in-situ) test of the upper part of the Lower Confining Unit by Rapps (1997), at a depth of 79 to 87 ft bgs, was 1.4 x 10^{-7} cm/s.

2.2.4 Groundwater Elevations, Flow Direction and Velocity

Seasonal variation of groundwater levels and flow direction at the Landfill is indicated in the series of 2015-2017 groundwater elevation contour maps (Appendix D). Groundwater elevations across Landfill 2 ranged from approximately 441 to 520 ft MSL (NAVD88) from 2015 to 2017. Overall groundwater flow beneath the two phases of Landfill 2 within the uppermost aquifer is southward toward Newton Lake, but with predominantly eastward flow under Phase I (west phase of Landfill 2) and an east and south component of flow under Phase II (east phase of Landfill 2). Horizontal hydraulic gradients (Table 1) were moderate at 0.016 ft/ft. Calculated groundwater flow velocity based on the January and June 2017 groundwater contour maps was 1.42 ft per day (ft/day).

Seasonal variation of groundwater levels and flow direction at the Primary Ash Pond is indicated in the series of 2015-2017 groundwater elevation contour maps (Appendix D). Groundwater elevations across the GMF Pond ranged from approximately 492 to 508 ft MSL. Groundwater flow across Primary Ash Pond within the uppermost aquifer is consistently in a south to southwest direction toward Newton Lake. Horizontal hydraulic gradients (Table 1) were low at 0.007 ft/ft. Calculated groundwater flow velocity based on the January and June 2017 groundwater contour maps was 0.12 ft/day.

Vertical hydraulic gradients as measured between shallow water table wells and uppermost aquifer monitoring wells was consistently downward at both the Landfill 2 and the Primary Ash Pond (Table 1).

3 GROUNDWATER MONITORING

In August 2015, NRT began an assessment of the existing monitoring well network(s) at the Newton Power Station with respect to the existing CCR units. Included in the assessment was a review of the current placement and number of monitoring wells with respect to individual and contiguous CCR units as well as potential locations for new monitoring wells, as appropriate. The discussion below summarizes the results of this assessment and the supplemental well installations.

3.1 CCR Monitoring Well Network

The 40 CFR Part 257 well network consists of seventeen monitoring wells installed in the uppermost aquifer and adjacent to the Newton Landfill 2 (G06D, G48MG, G201, G202, G203, G208, G217D, G220, G222, G223, G224) and the Newton Primary Ash Pond (APW5, APW6, APW7, APW8, APW9, APW10). The Site utilizes four upgradient (or background) monitoring wells (APW5, APW6, G201, and G48MG) as part of their CCR monitoring well network. The boring logs, well construction forms and other related monitoring well forms are available in the Operating Records as required by Title 40 CFR Part 257 Section 257.91 for each monitored CCR Unit. Sampling of these wells commenced December 2015. The 40 CFR Part 257 groundwater monitoring network well locations are shown on Figure 1. Details on the procedures and techniques used to fulfill the groundwater sampling and analysis program requirements are found in the SAPs for Newton Power Station. The well depths, well screen intervals, depth to groundwater and monitored units at the 40 CFR Part 257 monitoring well network locations are summarized below:

Table 3: CCR Groundwater Monitoring Well Information

Primary Ash Pond Monitoring Well Information (Unit ID: 501)					
Well Number	Well Depth (ft bgs)	Well Screen Interval (ft bgs)	Depth to Water (ft bgs)	Unit Monitored	Screened Interval Lithology
APW5	68	63-68	13.89	Upgradient Shallow Unlithified	Sand
APW6	74	68-73	19.21	Upgradient Shallow Unlithified	Sand
APW7	83	78-83	45.05	Downgradient Shallow Unlithified	Sand
APW8	82	71-81	35.29	Downgradient Shallow Unlithified	Sand
APW9	62	56-61	26.00	Downgradient Shallow Unlithified	Sand
APW10	46	41-46	16.98	Downgradient Shallow Unlithified	Sand

Landfill 2 Monitoring Well Information (Unit ID: 502)					
Well Number	Well Depth (ft bgs)	Well Screen Interval (ft bgs)	Depth to Water (ft bgs)	Unit Monitored	Screened Interval Lithology
G06D	96	74-94	30.12	Downgradient Shallow Unlithified	Clay
G48MG	77	71.5-76.5	18.59	Upgradient Shallow Unlithified	Sand
G201	69	59-69	18.54	Upgradient Shallow Unlithified	Sand
G202	74	64-74	43.21	Downgradient Shallow Unlithified	Clay/Gravel
G203	73	63-73	37.60	Downgradient Shallow Unlithified	Sand/Silt
G208	95	74-94	19.13	Downgradient Shallow Unlithified	Silty Clay
G217D	69.3	* - 69.3	16.14	Downgradient Shallow Unlithified	N/A*
G220	87	76-86	16.59	Downgradient Shallow Unlithified	Silt/Sand
G222	80	64-79	14.09	Downgradient Shallow Unlithified	Silty Clay/Sand
G223	89	79-89	33.64	Downgradient Shallow Unlithified	Silty/ Clay/Silty Sand
G224	74	63-73	41.73	Downgradient Shallow Unlithified	Silty Sand/Sand

Notes:
Groundwater depth measurements were collected June 12, 2017.
NM indicates groundwater depth was not measured.
*boring log not available for review

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Tables

Table 1. Vertical Gradients
Newton Power Station
January 2017 and June 2017
Hydrogeologic Monitoring Plan

Date	06/12/2017					
	Groundwater Elevation	Reference Elevation	Head Change (dH)	Dist. Change (dL)	Vertical Hydraulic Gradient (dH/dL)*	
APW-7	493.32	455.92	2.10	7.55	0.278	down
G203	495.42	463.47				
APW-9	505.52	469.76	18.85	44.04	0.428	down
APW-3	524.37	513.80				
APW-10	507.27	478.84	2.54	30.06	0.084	down
APW-4	509.81	508.90				

Date	01/16/2017					
	Groundwater Elevation	Reference Elevation	Head Change (dH)	Dist. Change (dL)	Vertical Hydraulic Gradient (dH/dL)*	
APW-7	492.98	455.92	0.04	7.55	0.005	down
G203	493.02	463.47				
APW-9	505.67	469.76	20.93	44.04	0.475	down
APW-3	526.60	513.80				
APW-10	506.96	478.84	14.05	30.06	0.467	down
APW-4	521.01	508.90				

Notes:
1. The reference point is equal to the water elevation when the water table intersects the screen, or the screen midpoint if the screen is submerged.
*: Vertical gradients less than ±0.0015 are considered flat, and they typically have less than 0.02 foot difference between wells

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Table 2. Groundwater Flow Velocities
Newton Power Station
January 2017 and June 2017
Hydrogeologic Monitoring Plan

6/12/2017 (Round 8)				
	Average Hydraulic Conductivity (cm/s)	**Horizontal Hydraulic Gradient***	**Effective Porosity**	**Velocity (ft/day)**
Newton Primary Ash Pond	1.2E-03	0.007	0.2	0.12
Newton Landfill 2	7.4E-05	0.016	0.2	1.42
1/16/2017 (Round 6)				
	Average Hydraulic Conductivity (cm/s)	**Horizontal Hydraulic Gradient***	**Effective Porosity**	**Velocity (ft/day)**
Newton Primary Ash Pond	1.2E-03	0.007	0.2	0.12
Newton Landfill 2	7.4E-05	0.016	0.2	1.42

Note:

1) cm/sec x 2,835 = feet/day

2) Source of hydraulic conductivity values is the geometric mean value for the aquifer unit.

3) The effective porosity of the clayey sand/silty sand aquifer (20%) was estimated from literature values (Sanders, 1998)

* Horizontal hydraulic gradient calculated from water levels in CCR wells near the primary ash pond and landfill 2

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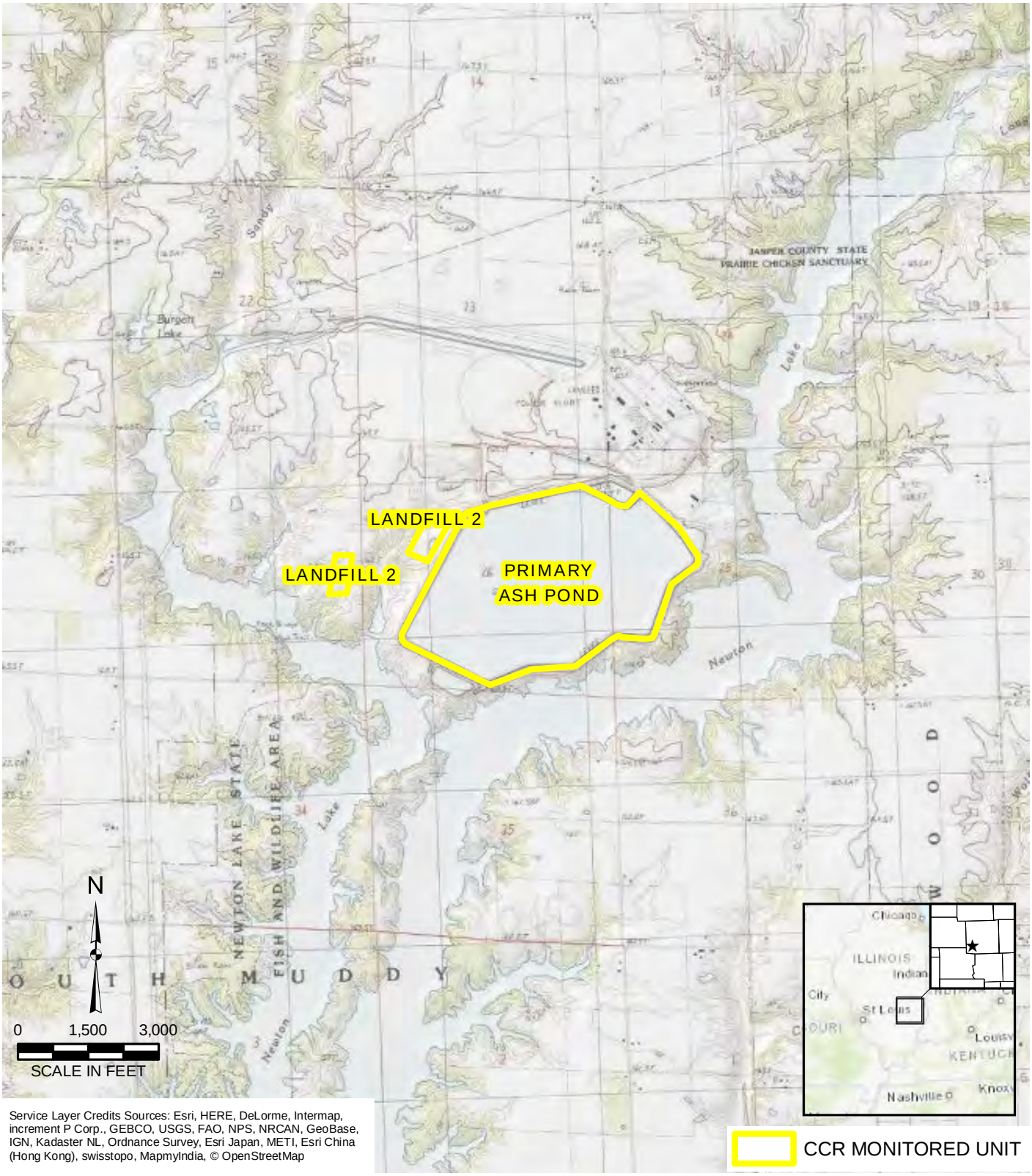
Figures



Service Layer Credits Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap

DRAWN BY/DATE:
SDS 7/27/17
REVIEWED BY/DATE:
TBN 10/2/17
APPROVED BY/DATE:
SJC 10/3/17

SITE LOCATION MAP

HYDROGEOLOGIC MONITORING PLAN
NEWTON POWER PLANT
NEWTON, ILLINOIS

PROJECT NO: 2285

FIGURE NO: 1

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Y:\Mapping\Projects\2212285\MXD\Newton_HGMP\Figure 1_Topo Vicinity Map.mxd Author: stolzsd; Date/Time: 10/3/2017, 2:30:47 PM

Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

GROUNDWATER SAMPLING WELL LOCATION MAP

HYDROGEOLOGIC MONITORING PLAN
NEWTON POWER PLANT
NEWTON, ILLINOIS

DRAWN BY/DATE:
SDS 7/27/17
REVIEWED BY/DATE:
TBN 10/2/17
APPROVED BY/DATE:
SJC 10/3/17

PROJECT NO: 2285

FIGURE NO: 2

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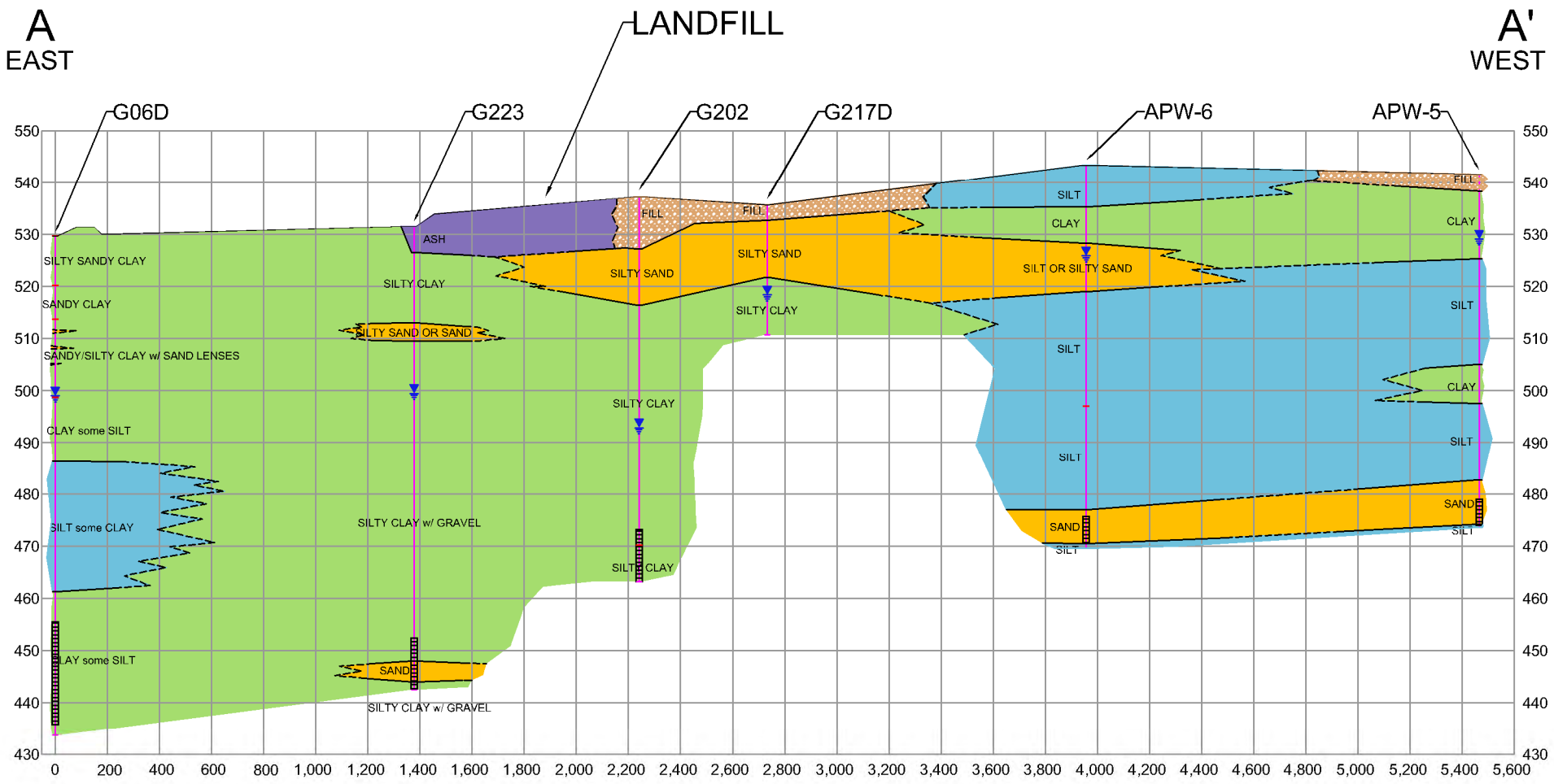
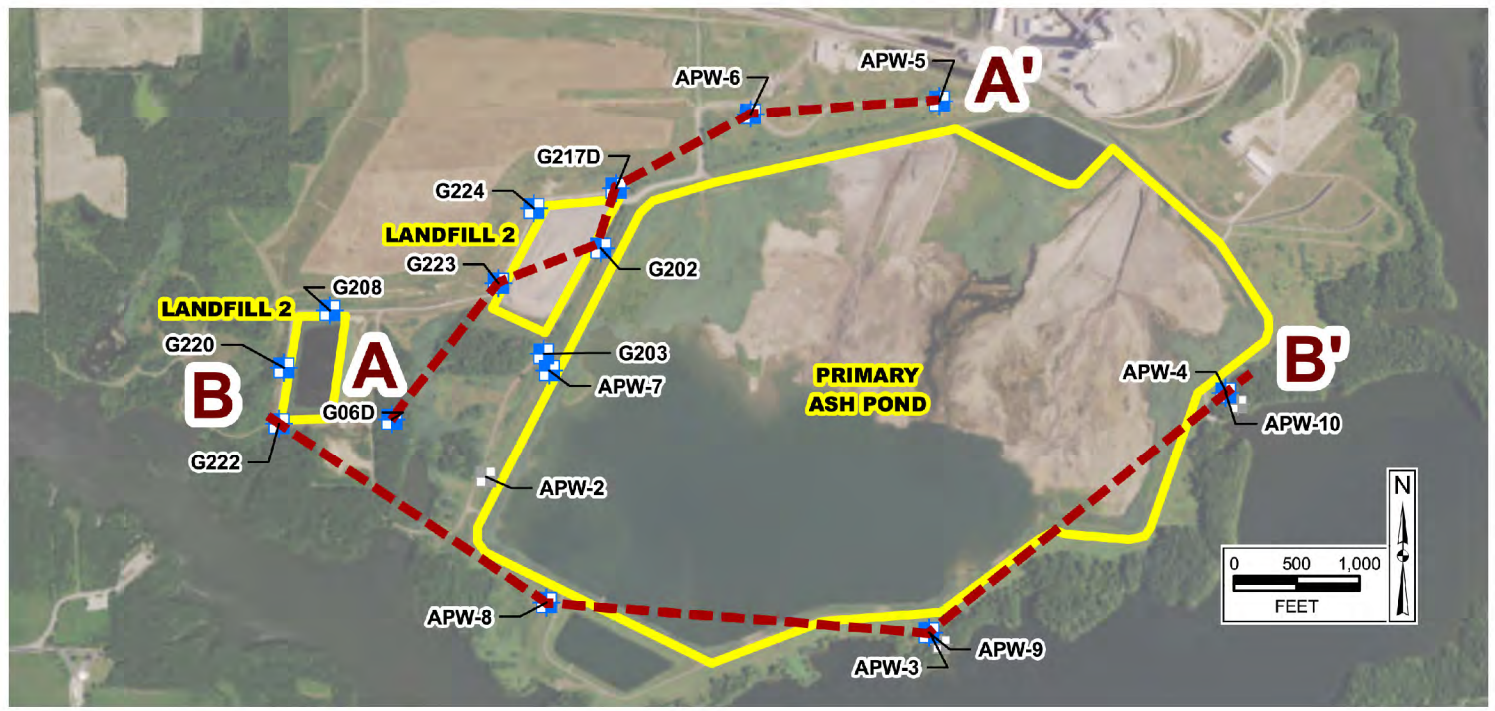
Y:\Mapping\Projects\22\2285\MXD\Newton_HGMP\Figure 2_Well Location Map - Newton.mxd Author: stolzsd Date/Time: 10/4/2017, 5:03:47 PM

Appendix A

Geologic Cross Sections





FILL
ASH
CLAY
SILT
SAND
WELL SCREEN
GROUNDWATER ELEVATION

VERTICAL SCALE IN FEET
30
600
HORIZONTAL SCALE IN FEET

VERTICAL EXAGGERATION =20

GEOLOGIC CROSS-SECTION A-A'

HYDROGEOLOGIC MONITORING PLAN

NEWTON POWER STATION
NEWTON, ILLINOIS

DRAWN BY:	JMO	DATE: 08/29/2017
CHECKED BY:	TBN	DATE: 10/2/2017
APPROVED BY:	SJC	DATE: 10/2/2017
DRAWING NO:	Fig A - Geologic Cross-Section A-A'	
REFERENCE:	.	

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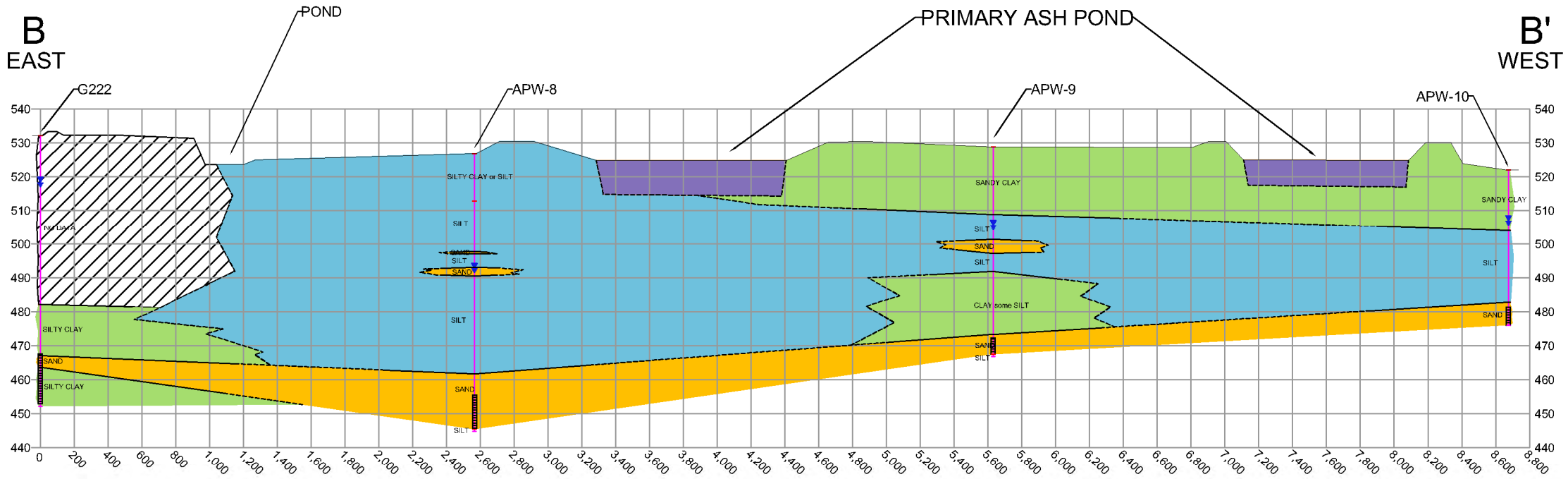
PROJECT NO.
2285

FIGURE NO.
APPENDIX A-1

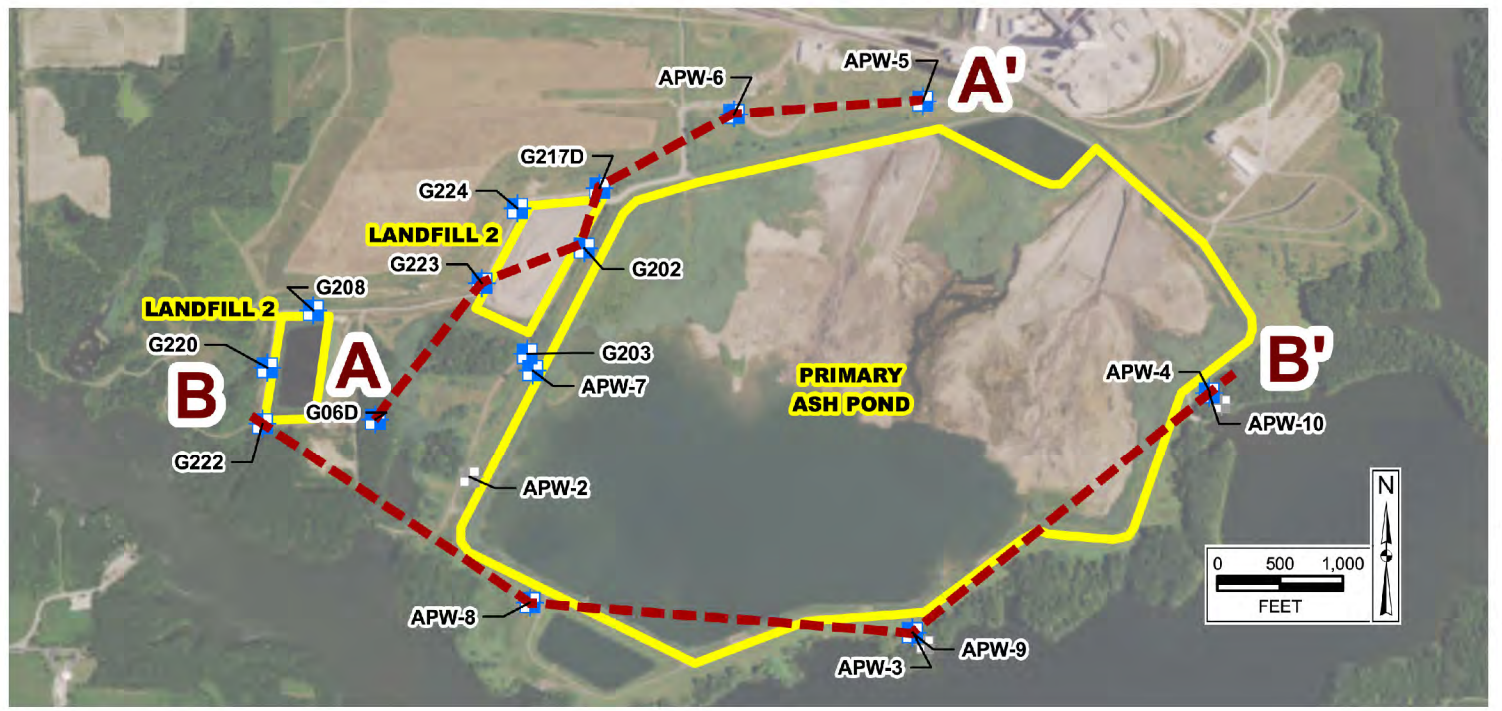


NO DATA
ASH
CLAY
SILT
SAND
WELL SCREEN
GROUNDWATER ELEVATION

NOTE THAT THE DEPTH OF THE ASH IN THE ASH POND IS APPROXIMATE.

VERTICAL SCALE IN FEET: 40
HORIZONTAL SCALE IN FEET: 800

VERTICAL EXAGGERATION =20



GEOLOGIC CROSS-SECTION B-B'

HYDROGEOLOGIC MONITORING PLAN

NEWTON POWER STATION
NEWTON, ILLINOIS

DRAWN BY:	JMO	DATE: 08/29/2017
CHECKED BY:	TBN	DATE: 10/2/2017
APPROVED BY:	SJC	DATE: 10/2/2017
DRAWING NO:	Fig X_Geologic Cross-Section A-A'	
REFERENCE:	.	

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2285

FIGURE NO.
APPENDIX A-2

Appendix B

Geotechnical Exploration Locations and Laboratory Test Results

Appendix B From:
AECOM, 2015, Dynegy CCR-Newton Investigation

Q:\Projects\DOE\0 Projects\Dynegy\Newton\09_Data\GIS\Mxds\Newton_Exporation_Locations.mxd

Legend

- AECOM Boring Location
- AECOM CPT Location

N
W E
S

0.1 0 0.1 0.2
Miles

DYNEGY

AECOM

Figure D-01
Exploration Locations
Newton Power Station
Jasper County, Illinois

AECOM #60428794-108
Dynegy CCR - Newton
LABORATORY TESTING DATA SUMMARY

BORING	SAMPLE	DEPTH	IDENTIFICATION TESTS									PERMEABILITY	STRENGTH			CONSOLIDATION		REMARKS
			WATER	LIQUID	PLASTIC	PLAS.	USCS	SIEVE	HYDRO.	TOTAL	DRY		TEST	PEAK	STRAIN	INITIAL CONDITIONS		
NO.	NO.		CONTENT	LIMIT	LIMIT	INDEX	SYMB. (1)	MINUS NO. 200	% MINUS 2 μm	UNIT WEIGHT	UNIT WEIGHT		TYPE @STRESS	SHEAR STRESS	@ PEAK STRESS	VOID RATIO	SATUR-ATION	
		(ft)	(%)	(-)	(-)	(-)		(%)	(%)	(pcf)	(pcf)	(cm/sec)	(ksf)	(ksf)	(%)	(-)	(%)	
NEW-B001	ST-5	10-12								125.4								
NEW-B001	ST-5	10.55	19.3															
NEW-B001	ST-5B	10.75	18.1	50	14	36	CH	79.1		132.6	112.3		CIU@1.5	2.3	21.3			T3937
NEW-B001	ST-7	20-22								130.1								
NEW-B001	ST-7	20.3	22.8															
NEW-B001	ST-7	20.85	18.4															
NEW-B001	ST-7B	21.1	16.2	49	13	36	CL	59.9		134.5	115.7		CIU@3.0	2.6	20.6			T3939
NEW-B001	S-8	25-27	17.1				CL	65.3										
NEW-B001	S-10	35-37	15.8	25	14	11	CL	55.6	17									
NEW-B001	S-11	40-41	14.6	22	13	9	CL	57.0	11									
NEW-B001	S-13	45-47	11.8															
NEW-B001	S-15	50-52	12.3	27	18	9	CL											
NEW-B001	S-16	55-57	11.5	30	13	17	CL	63.3	16									
NEW-B001	S-18	65-67	12.8	33	14	19	CL	64.6	18									
NEW-B001	S-19	70-70.92	12.4	24	15	9	CL											
NEW-B001	S-20	75-77	13.0															
NEW-B001	S-23	90-92	12.8	28	14	14	CL											
NEW-B001	S-24	95-97	11.0				SM	13.4	2									
NEW-B003	S-3	9-11	16.1															
NEW-B003	ST-1	14-15.9								129.5								
NEW-B003	ST-1	14.55	16.3															
NEW-B003	ST-1	15.1	23.7															
NEW-B003	ST-1C	15.35	20.9	59	15	44	CH	77.3		129.5	107.1		CIU@2.5	1.7	15.7			T3940
NEW-B003	S-4	20-22	17.7															
NEW-B003	ST-2	23-24.6								130.6								
NEW-B003	ST-2	23.35	16.6															
NEW-B003	ST-2	23.9	19.5															
NEW-B003	ST-2B	24.15	19.4	43	17	26	CL	82.7		130.9	109.7		UU@4	2.5	15.0			UU296a
NEW-B003	S-5	25-27	19.2															
NEW-B003	ST-3	27.5-29.5								128.1								
NEW-B003	ST-3	28.05	19.7															
NEW-B003	ST-3B	28.3	21.2				CH			126.4	104.3	9.6E-8						P10611
NEW-B003	ST-3	28.6	22.8															
NEW-B003	ST-3C	28.8	21.1	55	16	39	CH			129.2	106.7		UU@3	3.0	15.0			UU296b

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BORING	SAMPLE	DEPTH	IDENTIFICATION TESTS									PERMEABILITY	STRENGTH			CONSOLIDATION		REMARKS
			WATER	LIQUID	PLASTIC	PLAS.	USCS	SIEVE	HYDRO.	TOTAL	DRY		TEST	PEAK	STRAIN	INITIAL CONDITIONS		
NO.	NO.		CONTENT	LIMIT	LIMIT	INDEX	SYMB. (1)	MINUS NO. 200	% MINUS 2 μm	UNIT WEIGHT	UNIT WEIGHT		TYPE @STRESS	SHEAR STRESS	@ PEAK STRESS	VOID RATIO	SATUR-ATION	
		(ft)	(%)	(-)	(-)	(-)		(%)	(%)	(pcf)	(pcf)	(cm/sec)	(ksf)	(ksf)	(%)	(-)	(%)	
NEW-B003	S-6	30-32	19.6	42	14	28	CL	69.8	23									
NEW-B003	S-7	35-37	17.0	41	15	26	CL											
NEW-B003	S-8	40-42	22.9	50	18	32	CH	88.2	25									
NEW-B003	S-9B	46-47	11.7															
NEW-B003	S-12	60-62	13.3	32	35	17	CL											
NEW-B003	S-13	65-67	12.7				CL	67.6	19									
NEW-B004	S-3	5-7	13.9				CL	64.2										
NEW-B004	ST-4	8-10								132.3								
NEW-B004	ST-4	8.15	16.1															
NEW-B004	ST-4	8.7	18.5															
NEW-B004	ST-4	9.25	17.9															
NEW-B004	ST-4C	9.5	18.5	50	13	37	CH	83.9	28	131.3	110.9		CIU@0.5	1.4	17.9			T3936
NEW-B004	S-5	10-12	20.0															
NEW-B004	S-6	15-17	20.3				CL	79.3										
NEW-B004	ST-7	18-20								126.9								
NEW-B004	ST-7	18.55	18.1															
NEW-B004	ST-7	19.1	16.7															
NEW-B004	ST-7C	19.35	18.3	52	15	37	CH			128.5	108.7		CIU@3.0	2.4	20.5			T3941
NEW-B004	S-8	20-22	20.3															
NEW-B004	S-9	25-27	20.7															
NEW-B004	S-10	27.5-29.5	17.7	37	14	23	CL	61.7	25									
NEW-B004	ST-12	33-33.5								106.5								
NEW-B004	ST-12A	33.2	9.7	24	13	11	CL			136.2	124.2	6.4E-6						P10610
NEW-B004	ST-12	33.5	10.2															
NEW-B004	S-13	33.5-35.5	9.0				CL	52.8	16									
NEW-B004	S-14	36-37.92	8.9	26	13	13	CL											
NEW-B004A	S-1	45-46	10.4				CL	63.2	13									
NEW-B004A	S-2	50-52	11.3	29	15	14	CL											
NEW-B004A	S-3	55-57	10.0															
NEW-B004A	S-4	60-62	11.4				CL	68.1										
NEW-B004A	S-6	70-72	16.8	32	14	18	CL											
NEW-B004A	S-8	80-82	12.5	31	14	17	CL											
NEW-B004A	S-10	90-92	10.9															
NEW-B004A	S-11	95-97	11.1				SW-SM	11.2	3									

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BORING	SAMPLE	DEPTH	IDENTIFICATION TESTS									PERMEABILITY	STRENGTH			CONSOLIDATION		REMARKS
			WATER	LIQUID	PLASTIC	PLAS.	USCS	SIEVE	HYDRO.	TOTAL	DRY		TEST	PEAK	STRAIN	INITIAL CONDITIONS		
NO.	NO.		CONTENT	LIMIT	LIMIT	INDEX	SYMB. (1)	MINUS NO. 200	% MINUS 2 μm	UNIT WEIGHT	UNIT WEIGHT		TYPE @STRESS	SHEAR STRESS	@ PEAK STRESS	VOID RATIO	SATUR-ATION	
		(ft)	(%)	(-)	(-)	(-)		(%)	(%)	(pcf)	(pcf)	(cm/sec)	(ksf)	(ksf)	(%)	(-)	(%)	
NEW-B005	S-3	5-7	17.9	47	15	32	CL											
NEW-B005	S-5	10-12	9.8	24	13	11	CL											
NEW-B005	S-6	15-16.5	9.4	27	12	15	CL	54.6	16									
NEW-B005	S-7	20-20.92	10.8	26	13	13	CL											
NEW-B005	S-8	25-26	11.6				CL	54.6	18									
NEW-B005	S-10	35-37	11.3				ML	66.4										
NEW-B005	S-11	40-42	14.0															
NEW-B005	S-12	45-47	13.1	33	15	18	CL	70.2	19									
NEW-B006	S-3	10-12	21.2	66	14	52	CH	88.2	36									
NEW-B006	ST-1	20-22								128.0								
NEW-B006	ST-1	20.4	21.6															
NEW-B006	ST-1	20.95	16.4															
NEW-B006	ST-1B	21.2	18.2	40	17	23	CL	78.4	22	130.8	110.6		UU@3.5	2.3	8.7			UU301f
NEW-B006	ST-2	25-27								140.1								
NEW-B006	ST-2	25.4	17.9															
NEW-B006	ST-2	25.95	18.2															
NEW-B006	ST-2	26.5	18.6															
NEW-B006	ST-2C	26.75	19.7	44	12	32	CL	65.6	28	128.8	107.6		CIU@7.5	3.0	12.8			T3945
NEW-B006	S-6	27-29	19.4	54	13	41	CH											
NEW-B006	ST-3	30-32								133.0								
NEW-B006	ST-3	30.45	29.1															
NEW-B006	ST-3	31.0	20.4															
NEW-B006	ST-3B	31.25	20.7				CL			130.6	108.1	1.6E-7						P10597
NEW-B006	ST-3	31.55	18.5															
NEW-B006	ST-3C	31.8	18.3	37	15	22	CL	52.1	21	133.3	112.8		CIU@7.2	4.0	14.8			T3915
NEW-B006	S-7	32-34	17.5															
NEW-B006	ST-4	35-35.8		30	13	17	CL	58.3	20	148.8								
NEW-B006	ST-4	35.4	11.1				CL			140.2	126.2		DS@9	6.6				DS1619
NEW-B006	ST-4	35.6	15.8				CL			147.4	127.2		DS@18	11.5				DS1617
NEW-B006	ST-4	35.7	11.2															
NEW-B006	S-9	40-42	13.0															
NEW-C006	ST-1	10-12								115.2								
NEW-C006	ST-1	10.5	26.7															
NEW-C006	ST-1	11.05	27.1															

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BORING	SAMPLE	DEPTH	IDENTIFICATION TESTS									PERMEABILITY	STRENGTH			CONSOLIDATION		REMARKS
			WATER CONTENT	LIQUID LIMIT	PLASTIC LIMIT	PLAS. INDEX	USCS SYMB. (1)	SIEVE MINUS NO. 200	HYDRO. % MINUS 2 μm	TOTAL UNIT WEIGHT	DRY UNIT WEIGHT		TEST TYPE @STRESS	PEAK SHEAR STRESS	STRAIN @ PEAK STRESS	INITIAL CONDITIONS		
NO.	NO.															VOID RATIO	SATUR-ATION	
		(ft)	(%)	(-)	(-)	(-)		(%)	(%)	(pcf)	(pcf)	(cm/sec)	(ksf)	(ksf)	(%)	(-)	(%)	
NEW-C006	ST-1B	11.3	25.2	54	16	38	CH			124.1	99.2		CIU@1.5	1.2	13.7			T3916
NEW-C006	ST-2	12-14								121.4								
NEW-C006	ST-2	12.75	19.3															
NEW-C006	ST-2B	13.0	18.9	53	14	39	CH			131.5	110.6		CIU@2.0	2.4	16.7			T3917
NEW-B007	S-4	7.5-9.5	13.2															
NEW-B007	ST-1	10-12								131.6								
NEW-B007	ST-1	10.75	16.5															
NEW-B007	ST-1	11.3	17.3															
NEW-B007	ST-1C	11.55	15.4	38	14	24	CL			135.1	117.1		CIU@1.0	2.3	21.5			T3933
NEW-B007	ST-2	20-22								143.6								
NEW-B007	ST-2	20.25	10.1															
NEW-B007	ST-2	20.8	12.7															
NEW-B007	ST-2B	21.0	12.1	30	13	17	CL	52.3		140.5	125.4		CIU@2.5	3.7	21.1			T3934
NEW-B007	S-6	25-27	16.3															
NEW-B007	ST-3	30-32								131.1								
NEW-B007	ST-3	30.35	17.8															
NEW-B007	ST-3	30.9	20.1															
NEW-B007	ST-3	31.45	19.2															
NEW-B007	ST-3C	31.7	21.5	52	12	40	CH	71.5	29	132.0	108.6		UU@6.0	2.6	11.7			UU288d
NEW-B007	S-7	35-37	14.8															
NEW-B007	ST-4	40-42																
NEW-B007	ST-4	40.85	25.1															
NEW-B007	ST-4B	41.0	17.5	57	13	44	CH			129.9	110.5		DS@5	2.7				DS1620
NEW-B007	ST-4C	41.3	14.7				CH			128.7	112.2		DS@10	5.4				DS1621
NEW-B007	ST-4B	41.5	16.1				CH			132.6	114.2		DS@15	7.6				DS1622
NEW-B007	ST-5	50-51.5								131.5								
NEW-B007	ST-5A	50.3	16.3				CH			137.1	117.9	5.1E-9						P10598
NEW-B007	ST-5	50.8	14.0															
NEW-B007	ST-5B	51.05	13.9	32	16	16	CL			136.1	119.5		DSS@7.6	3.5	5.6			DSS855
NEW-B008	ST-1	15-17								132.9								
NEW-B008	ST-1	15.85	11.1															
NEW-B008	ST-1	16.4	16.9															
NEW-B008	ST-1C	16.65	16.7	50	13	37	CH	74.4		136.3	116.8		UU@2.5	3.1	15.0			UU288e
NEW-B008	S-4	20-22	20.1															

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BORING	SAMPLE	DEPTH	IDENTIFICATION TESTS									PERMEABILITY	STRENGTH			CONSOLIDATION		REMARKS
			WATER CONTENT	LIQUID LIMIT	PLASTIC LIMIT	PLAS. INDEX	USCS SYMB. (1)	SIEVE MINUS NO. 200	HYDRO. % MINUS 2 μm	TOTAL UNIT WEIGHT	DRY UNIT WEIGHT		TEST TYPE @STRESS	PEAK SHEAR STRESS	STRAIN @ PEAK STRESS	INITIAL CONDITIONS		
NO.	NO.															VOID RATIO	SATUR-ATION	
		(ft)	(%)	(-)	(-)	(-)		(%)	(%)	(pcf)	(pcf)	(cm/sec)	(ksf)	(ksf)	(%)	(-)	(%)	
NEW-B008	S-5	22.5-24.5	22.6															
NEW-B008	S-6	25-27	23.2															
NEW-B008	ST-2	27.5-28.75								130.3								
NEW-B008	ST-2A	27.7	20.3				CL			122.5	101.8		DS@2	1.2				DS1624
NEW-B008	ST-2B	28	14.4	49	14	35	CL			133.8	117.0		DS@4	2.9				DS1626
NEW-B008	ST-2C	28.4	16.4				CL			133.2	114.5		DS@8	4.4				DS1628
NEW-B008	S-7	35-37	13.8															
NEW-B008	S-8	40-42	14.6				SC	46.9	9									
NEW-B008	S-10	50-51.5	15.4	32	16	16	CL	65.4	20									
NEW-B009	ST-1	9-11								131.1								
NEW-B009	ST-1	9.5	20.0															
NEW-B009	ST-1B	9.75	19.0	47	15	32	CL			132.3	111.2		UU@2.0	2.5	15.0			UU288f
NEW-B009	S-3	14-16	15.3															
NEW-B009	S-4	19-21	18.3															
NEW-B009	ST-2	29-31.3								128.8								
NEW-B009	ST-2B	30.0	16.7	31	14	17	CL			132.6	113.6		CIU@4.0	2.9	10.5			T3942
NEW-B009	ST-2	30.35	19.5															
NEW-B009	S-6	34-35.5	8.6	24	12	12	CL	51.6										
NEW-B009	S-7	37.5-38	16.9		19	NP	ML											
NEW-B009	S-9	42.5-44.5	15.0															
NEW-B009	S-10	50-52	13.7				CL	74.0	21									
NEW-B009	S-11	55-57	14.6															
NEW-B009	S-12	60-62	13.5	24	16	8	CL	66.4	18									
NEW-B009	S-14	70-71.42	12.2				CL	51.5	12									
NEW-B010	ST-1	5-7								137.3								
NEW-B010	ST-1	5.55	10.9															
NEW-B010	ST-1	6.1	15.8															
NEW-B010	ST-1C	6.3	10.2	24	13	11	CL			140.5	127.5		CIU@1.0	4.4	21.3			T3943
NEW-B010	S-4	10-12	13.7															
NEW-B010	ST-2	15-17								137.9								
NEW-B010	ST-2	15.7	13.9															
NEW-B010	ST-2	16.25	12.7															
NEW-B010	ST-2C	16.5	13.8	33	13	20	CL			137.3	120.6		CIU@2	3.5	20.9			T3944
NEW-B010	S-5	20-22	16.1															

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BORING	SAMPLE	DEPTH	IDENTIFICATION TESTS									PERMEABILITY	STRENGTH			CONSOLIDATION		REMARKS
			WATER	LIQUID	PLASTIC	PLAS.	USCS	SIEVE	HYDRO.	TOTAL	DRY		TEST	PEAK	STRAIN	INITIAL CONDITIONS		
NO.	NO.		CONTENT	LIMIT	LIMIT	INDEX	SYMB. (1)	MINUS NO. 200	% MINUS 2 μm	UNIT WEIGHT	UNIT WEIGHT		TYPE @STRESS	SHEAR STRESS	@ PEAK STRESS	VOID RATIO	SATUR-ATION	
		(ft)	(%)	(-)	(-)	(-)		(%)	(%)	(pcf)	(pcf)	(cm/sec)	(ksf)	(ksf)	(%)	(-)	(%)	
NEW-B010	S-6	25-27	19.1															
NEW-B010	S-7	30-32	21.0	49	16	33	CL	62.3	24									
NEW-B010	S-8	35-37	8.5	23	12	11	CL											
NEW-B010	S-12	47.5-48.2	13.5															
NEW-B010	S-13	50-50.8	10.1				SC	22.3	6									
NEW-B010	S-16	65-67	15.0				CL	70.6										
NEW-B010	S-18	75-77	14.5	28	15	13	CL											
NEW-B010	S-19	80-82	14.7	25	15	10	CL											
NEW-B012	ST-4	8-10								134.0								
NEW-B012	ST-4	8.65	15.5															
NEW-B012	ST-4	9.2	14.9															
NEW-B012	ST-4C	9.45	12.6	34	13	21	CL			139.6	123.9		UU@1.5	4.1	15.0			UU296d
NEW-B012	ST-7	20-21.7								135.0								
NEW-B012	ST-7	20.35	14.8															
NEW-B012	ST-7A	20.6	13.3				CL			137.1	121.0	7.8E-9						P10609
NEW-B012	ST-7	20.9	16.7															
NEW-B012	ST-7B	21.15	13.3	35	13	22	CL	52.1		138.4	122.1		CIU@2.5	3.2	21.8			T3938
NEW-B012	S-8	25-27	15.2	36	13	23	CL											
NEW-B012	S-9	30-32	12.9															
NEW-B012	S-10	35-37	16.8	40	15	25	CL											
NEW-B012	S-11	40-42	9.9				CL	55.9	17									
NEW-B012	ST-12	45-47								131.7								
NEW-B012	ST-12	45.55	19.8															
NEW-B012	ST-12	46.15	14.3															
NEW-B012	ST-12C	46.4	17.5	43	14	29	CL	62.1	30	133.6	113.8		CIU@6	3.4	23.3			T3883
NEW-B012	S-13	50-52	20.0															
NEW-B012	S-14	55-57	15.8	41	13	28	CL											
NEW-B012	ST-15	60-62								136.2								
NEW-B012	ST-15	60.65	18.7															
NEW-B012	ST-15	61.2	14.1															
NEW-B012	ST-15C	61.45	12.8	42	14	28	CL			132.5	117.6		DSS@7.2	2.8	7.1			DSS849
NEW-B012	S-17	70-72	10.9															
NEW-B012	S-18	75-77	11.8	29	13	16	CL	53.3	17									
NEW-B012	ST-19	80-82								139.7								

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BORING	SAMPLE	DEPTH	IDENTIFICATION TESTS									PERMEABILITY	STRENGTH			CONSOLIDATION		REMARKS
			WATER CONTENT	LIQUID LIMIT	PLASTIC LIMIT	PLAS. INDEX	USCS SYMB. (1)	SIEVE MINUS NO. 200	HYDRO. % MINUS 2 μm	TOTAL UNIT WEIGHT	DRY UNIT WEIGHT		TEST TYPE @STRESS	PEAK SHEAR STRESS	STRAIN @ PEAK STRESS	INITIAL CONDITIONS		
NO.	NO.															VOID RATIO	SATUR-ATION	
		(ft)	(%)	(-)	(-)	(-)		(%)	(%)	(pcf)	(pcf)	(cm/sec)	(ksf)	(ksf)	(%)	(-)	(%)	
NEW-B012	ST-19	80.85	12.2															
NEW-B012	ST-19	80.95	11.7															
NEW-B012	ST-19	81.1	11.2	25	14	11	SC			136.8	122.9		DS@6	4.2				DS1611
NEW-B012	ST-19	81.5	10.5				SC			139.2	126.0		DS@24	15.1				DS1612
NEW-B012	ST-19	81.8	16.9				SC			130.5	111.7		DS@12	7.2				DS1613
NEW-B012	S-20	85-87	16.2	34	14	20	CL											
NEW-B012	S-22	95-97	15.7															
NEW-B014	ST-1	2.5-4.1								140.5								
NEW-B014	ST-1A	2.95																
NEW-B014	ST-1	3.25	13.5															
NEW-B014	ST-1B	3.5	9.5	28	13	15	SC	46.2	16	142.7	130.3		UU@0.5	5.8	8.4			UU260f
NEW-B014	S-3	7.5-9.5	13.7	41	14	27	CL											
NEW-B014	S-4	10-12	18.7	42	15	27	CL											
NEW-B014	ST-2	15-16.9								133.8								
NEW-B014	ST-2	15.6	11.6															
NEW-B014	ST-2B	15.85	12.2	31	14	17	CL			139.2	124.1		EXT CIU	-1.6	-8.4			TE15001
NEW-B014	ST-2	16.15	10.2															
NEW-B014	S-5	20-22	9.6				SC	49.8										
NEW-B014	S-6	25-27	16.1	40	15	25	CL	59.0										
NEW-B014	S-7	30-31.33	16.7															
NEW-B014	S-7A	31.33-32	17.5				CL	60.4										
NEW-B014	ST-3	35-37								135.0								
NEW-B014	ST-3	35.3	19.7															
NEW-B014	ST-3	35.85	15.9															
NEW-B014	ST-3	36.4	12.6															
NEW-B014	ST-3C	36.65	16.3	38	13	25	SC	13.5	4	132.6	114.0		CIU@3	4.2	12.9			T3884
NEW-B014	S-8	40-42	16.2	39	14	25	CL											
NEW-B014	S-10	48-50	17.5															
NEW-B015	ST-1	10-12								130.3								
NEW-B015	ST-1A	10.4																
NEW-B015	ST-1	10.7	20.7															
NEW-B015	ST-1B	10.95	23.0	59	15	44	CH			126.0	102.5		CIU@1.5	1.3	18.0			T3885
NEW-B015	S-5	15-17	18.4															
NEW-B015	S-6	20-22	18.2															

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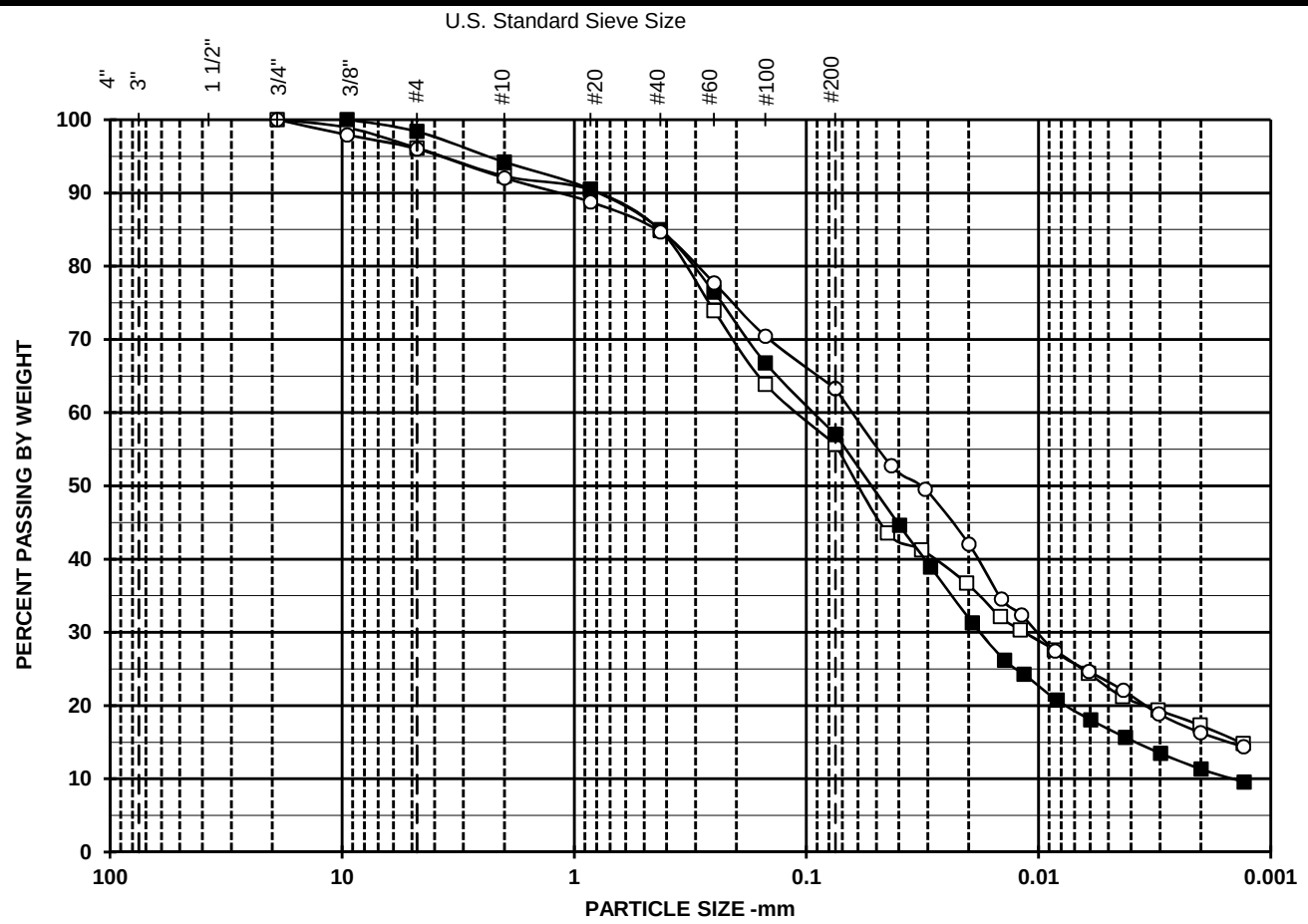
LABORATORY TESTING DATA SUMMARY

BORING	SAMPLE	DEPTH	IDENTIFICATION TESTS									PERMEABILITY	STRENGTH			CONSOLIDATION		REMARKS
			WATER CONTENT	LIQUID LIMIT	PLASTIC LIMIT	PLAS. INDEX	USCS SYMB. (1)	SIEVE MINUS NO. 200	HYDRO. % MINUS 2 μm	TOTAL UNIT WEIGHT	DRY UNIT WEIGHT		TEST TYPE @STRESS	PEAK SHEAR STRESS	STRAIN @ PEAK STRESS	INITIAL CONDITIONS		
NO.	NO.															VOID RATIO	SATUR-ATION	
		(ft)	(%)	(-)	(-)	(-)		(%)	(%)	(pcf)	(pcf)	(cm/sec)	(ksf)	(ksf)	(%)	(-)	(%)	
NEW-B015	ST-2	25-27								130.2								
NEW-B015	ST-2	25.2	15.6															
NEW-B015	ST-2A	25.45	24.0				CH			126.1	101.7	1.8E-9						P10608
NEW-B015	ST-2	25.75	24.7															
NEW-B015	ST-2B	26.0	19.5	52	15	37	CH			131.4	110.0		CIU@5	3.1	13.2			T3935
NEW-B015	S-7	30-32	16.3	37	13	24	CL											
NEW-B015	S-8	35-37	21.5	46	14	32	CL	84.5	36									
NEW-B015	S-9	40-42	8.1															
NEW-B015	S-11	50-52	14.1															
NEW-B015	ST-3	60-61.3								137.7								
NEW-B015	ST-3	60.15	11.7															
NEW-B015	ST-3	60.35	11.2				CL			139.6	125.5		DS@3.75	3.2				DS1623
NEW-B015	ST-3	60.75	11.9	30	15	15	CL			140.2	125.3		DS@7.5	5.4				DS1625
NEW-B015	ST-3	61.05	12.7				CL			139.8	124.1		DS@15	9.1				DS1627
NEW-B015	ST-4	70-70.3																no tests
NEW-B016	S-3A	5-6	16.4	35	13	22	CL											
NEW-B016	S-3B	6.5-7					SM	13.2	7									
NEW-B016	S-4B	8-9	11.3															
NEW-B016	S-5	10-12	12.1				ML	62.6										
NEW-B016	S-6	15-17	11.1	52	14	38	CH	73.0	20									
NEW-B016	S-7	20-22	14.5															
NEW-B016	S-9	30-32	11.6	29	15	14	CL											
NEW-B016	S-10	35-37	13.2															

Note: (1) USCS symbol based on visual observation and Sieve and Atterberg limits reported.

COBBLES	GRAVEL		SAND			SILT OR CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	



Symbol	□	■	○
Boring	NEW-B001	NEW-B001	NEW-B001
Sample	S-10	S-11	S-16
Depth	35-37	40-41	55-57
% +3"	0.0	0.0	0.0
% Gravel	3.9	1.6	4.0
% SAND	40.5	41.4	32.7
%C SAND	3.9	4.2	4.0
%M SAND	7.5	9.2	7.4
%F SAND	29.2	28.0	21.4
% FINES	55.6	57.0	63.3
% -2μ	17	11	16
D_{100} (mm)	19.00	9.50	19.00
D_{60} (mm)	0.11	0.10	0.07
D_{30} (mm)	0.01	0.02	0.01
D_{10} (mm)			
Cc			
Cu			

Particle Size	PERCENT FINER		
(Sieve #)	□	■	○
4"			
3"			
1 1/2"			
3/4"	100.0		100.0
3/8"	98.9	100.0	97.9
4	96.1	98.4	96.0
10	92.3	94.2	92.0
20	90.4	90.5	88.8
40	84.8	85.0	84.7
60	73.9	76.4	77.7
100	63.9	66.8	70.4
200	55.6	57.0	63.3

SYMBOL	w (%)	LL	PL	PI	USCS	DESCRIPTION AND REMARKS	Date Tested
□	15.8	25	14	11	CL	Brown, Sandy lean clay	9/2/2015
■	14.6	22	13	9	CL	Brown, Sandy lean clay	9/2/2015
○	11.5	30	13	17	CL	Dark brown, Sandy lean clay	9/2/2015

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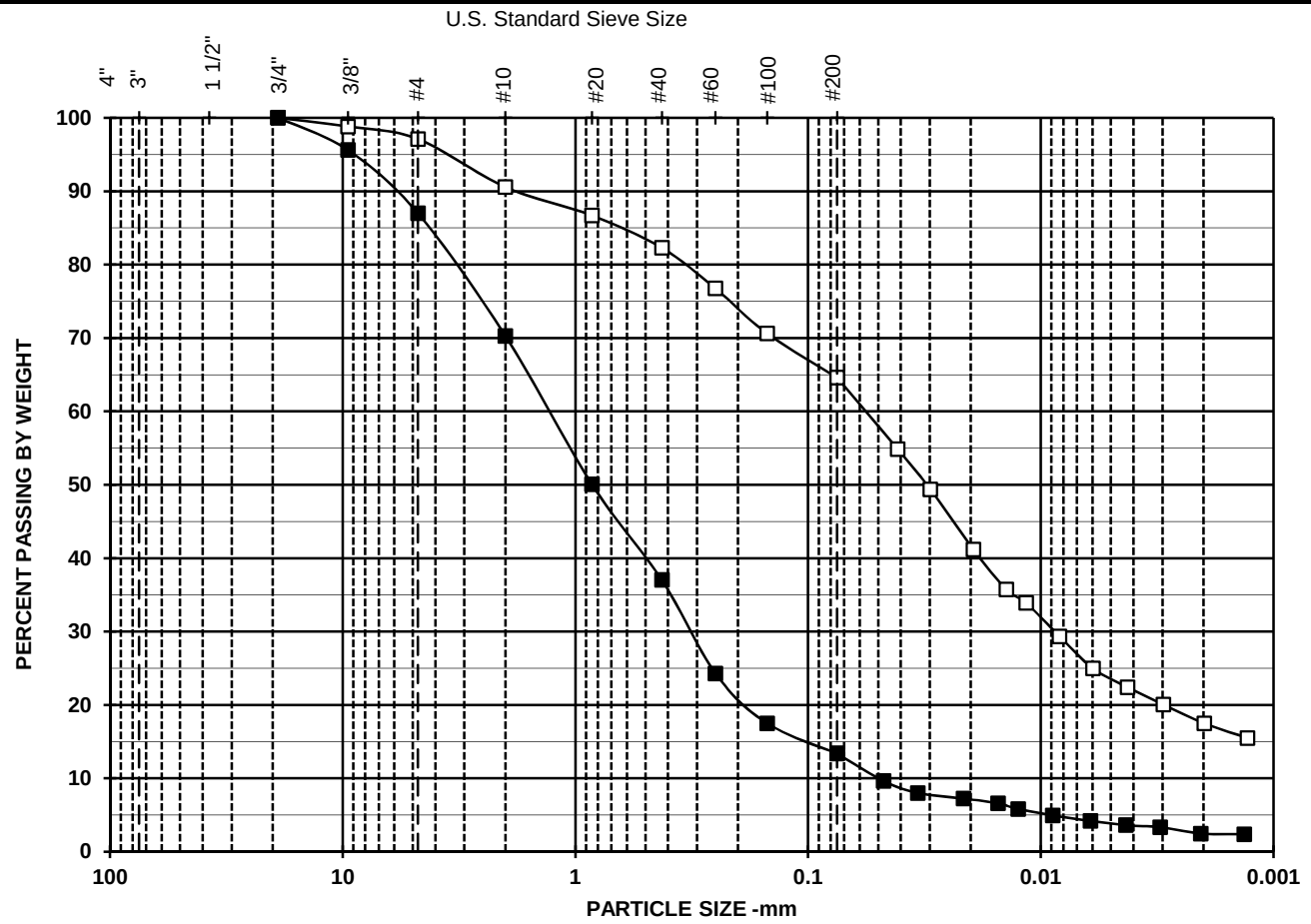
COBBLES	GRAVEL		SAND			SILT OR CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	



Symbol	□	■	○
Boring	NEW-B001	NEW-B001	
Sample	S-18	S-24	
Depth	65-67	95-97	
% +3"	0.0	0.0	
% Gravel	2.9	13.0	
% SAND	32.5	73.6	
%C SAND	6.6	16.7	
%M SAND	8.3	33.3	
%F SAND	17.7	23.6	
% FINES	64.6	13.4	
% -2μ	18	2	
D_{100} (mm)	19.00	19.00	
D_{60} (mm)	0.06	1.41	
D_{30} (mm)	0.01	0.33	
D_{10} (mm)			
Cc			
Cu			

Particle Size	PERCENT FINER		
(Sieve #)	□	■	○
4"			
3"			
1 1/2"			
3/4"	100.0	100.0	
3/8"	98.8	95.6	
4	97.1	87.0	
10	90.6	70.3	
20	86.7	50.1	
40	82.3	37.0	
60	76.7	24.3	
100	70.6	17.5	
200	64.6	13.4	

SYMBOL	w (%)	LL	PL	PI	USCS	DESCRIPTION AND REMARKS	Date Tested
□	12.8	33	14	19	CL	Dark brown, Sandy lean clay	9/2/2015
■	11.0				SM	Brown, Silty sand	9/2/2015
○							

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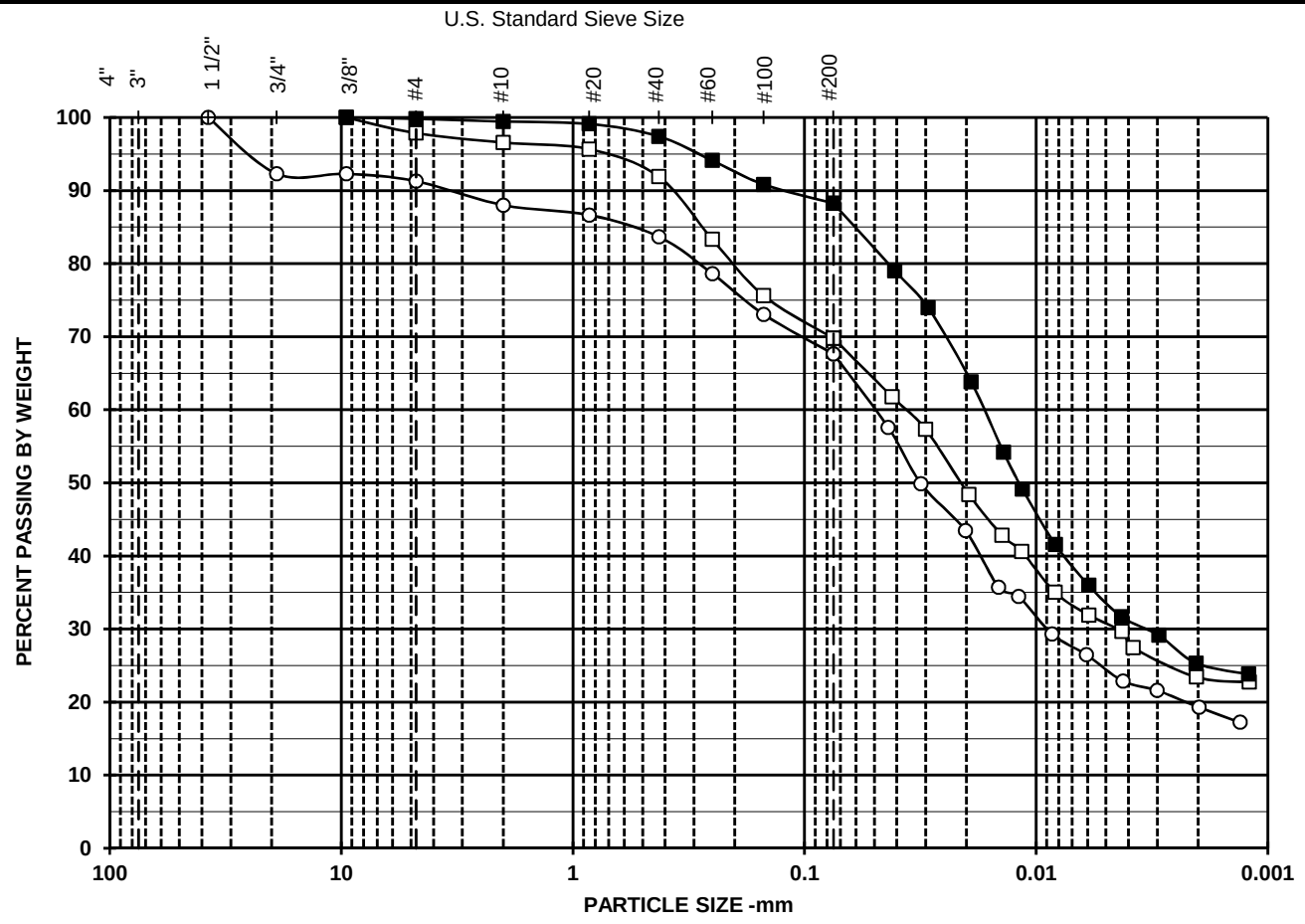
COBBLES	GRAVEL		SAND			SILT OR CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	



SYMBOL	w (%)	LL	PL	PI	USCS	DESCRIPTION AND REMARKS	Date Tested
□	19.6	42	14	28	CL	Brown , Sandy lean clay	9/3/2015
■	22.9	50	18	32	CH	Brown, Fat clay	9/3/2015
○	12.7				CL	Brown, Sandy lean clay	8/31/2015

Symbol	□	■	○
Boring	NEW-B003	NEW-B003	NEW-B003
Sample	S-6	S-8	S-13
Depth	30-32	40-42	65-67
% +3"	0.0	0.0	0.0
% Gravel	2.1	0.2	8.7
% SAND	28.1	11.6	23.7
%C SAND	1.3	0.4	3.3
%M SAND	4.7	2.0	4.3
%F SAND	22.1	9.2	16.0
% FINES	69.8	88.2	67.6
% -2μ	23	25	19
D_{100} (mm)	9.50	9.50	37.50
D_{60} (mm)	0.04	0.02	0.05
D_{30} (mm)	0.00	0.00	0.01
D_{10} (mm)			
Cc			
Cu			

Particle Size	PERCENT FINER		
(Sieve #)	□	■	○
4"			
3"			
1 1/2"			100.0
3/4"			92.3
3/8"	100.0	100.0	92.3
4	97.9	99.8	91.3
10	96.6	99.4	88.0
20	95.7	99.1	86.6
40	91.9	97.4	83.7
60	83.3	94.1	78.6
100	75.6	90.8	73.0
200	69.8	88.2	67.6

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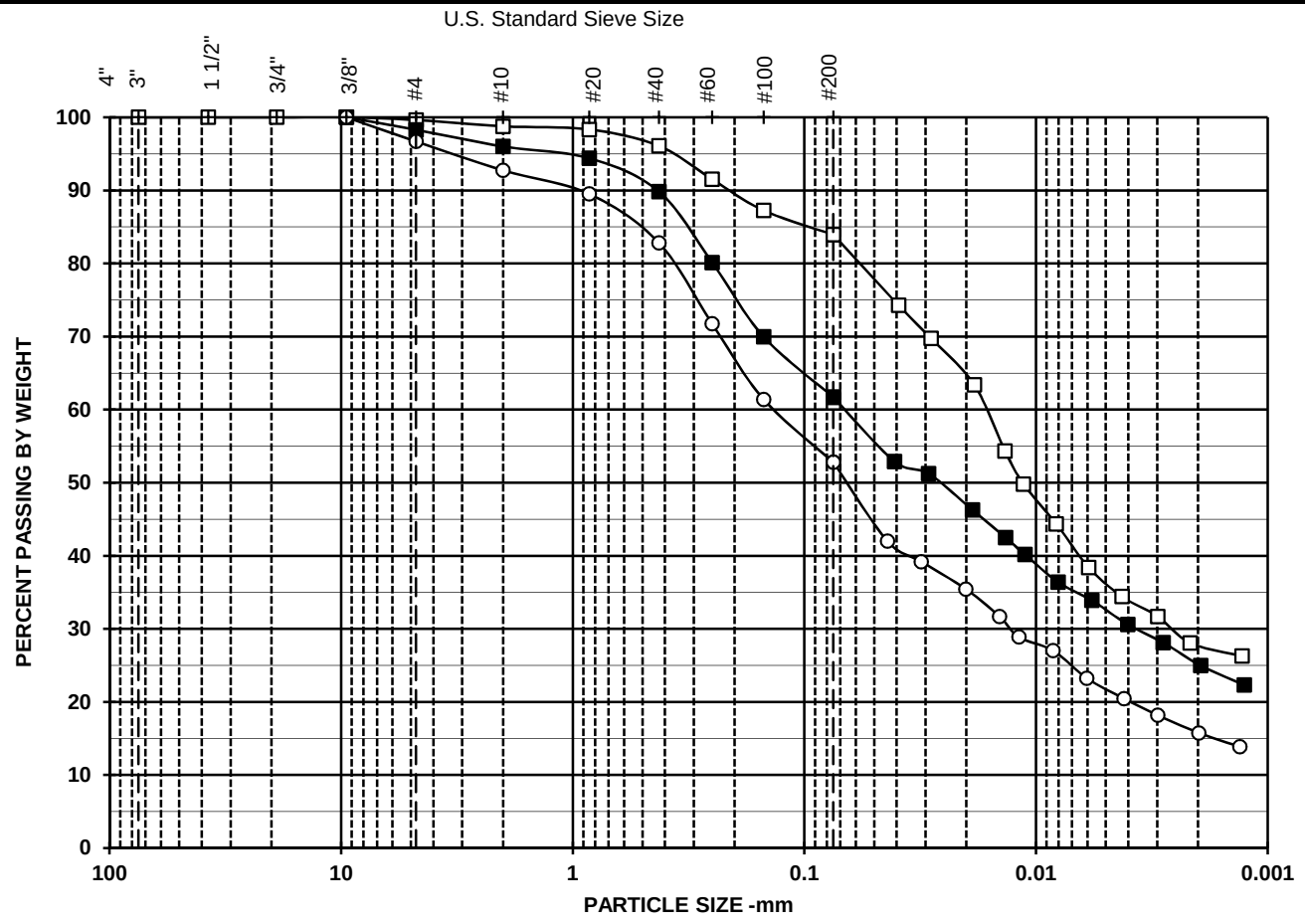
COBBLES	GRAVEL		SAND			SILT OR CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	



SYMBOL	w (%)	LL	PL	PI	USCS	DESCRIPTION AND REMARKS	Date Tested
□		50	13	37	CH	Gray brown , Fat clay with sand	10/27/2015
■	17.7	37	14	23	CL	Brown, Sandy lean clay	9/2/2015
○	9.0				CL	Light brown, Sandy lean clay	8/31/2015

Symbol	□	■	○
Boring	NEW-B004	NEW-B004	NEW-B004
Sample	ST-4C	S-10	S-13
Depth	9.5	27.5-29.5	33.5-35.5
% +3"	0.0	0.0	0.0
% Gravel	0.4	1.7	3.3
% SAND	15.7	36.6	43.9
%C SAND	0.9	2.3	4.0
%M SAND	2.7	6.2	9.9
%F SAND	12.1	28.1	30.0
% FINES	83.9	61.7	52.8
% -2μ	28	25	16
D_{100} (mm)	9.50	9.50	9.50
D_{60} (mm)	0.02	0.07	0.14
D_{30} (mm)	0.00	0.00	0.01
D_{10} (mm)			
Cc			
Cu			

Particle Size	PERCENT FINER		
(Sieve #)	□	■	○
4"	100.0		
3"	100.0		
1 1/2"	100.0		
3/4"	100.0		
3/8"	100.0	100.0	100.0
4	99.6	98.3	96.7
10	98.8	96.0	92.7
20	98.3	94.4	89.5
40	96.1	89.8	82.8
60	91.5	80.1	71.7
100	87.2	70.0	61.4
200	83.9	61.7	52.8

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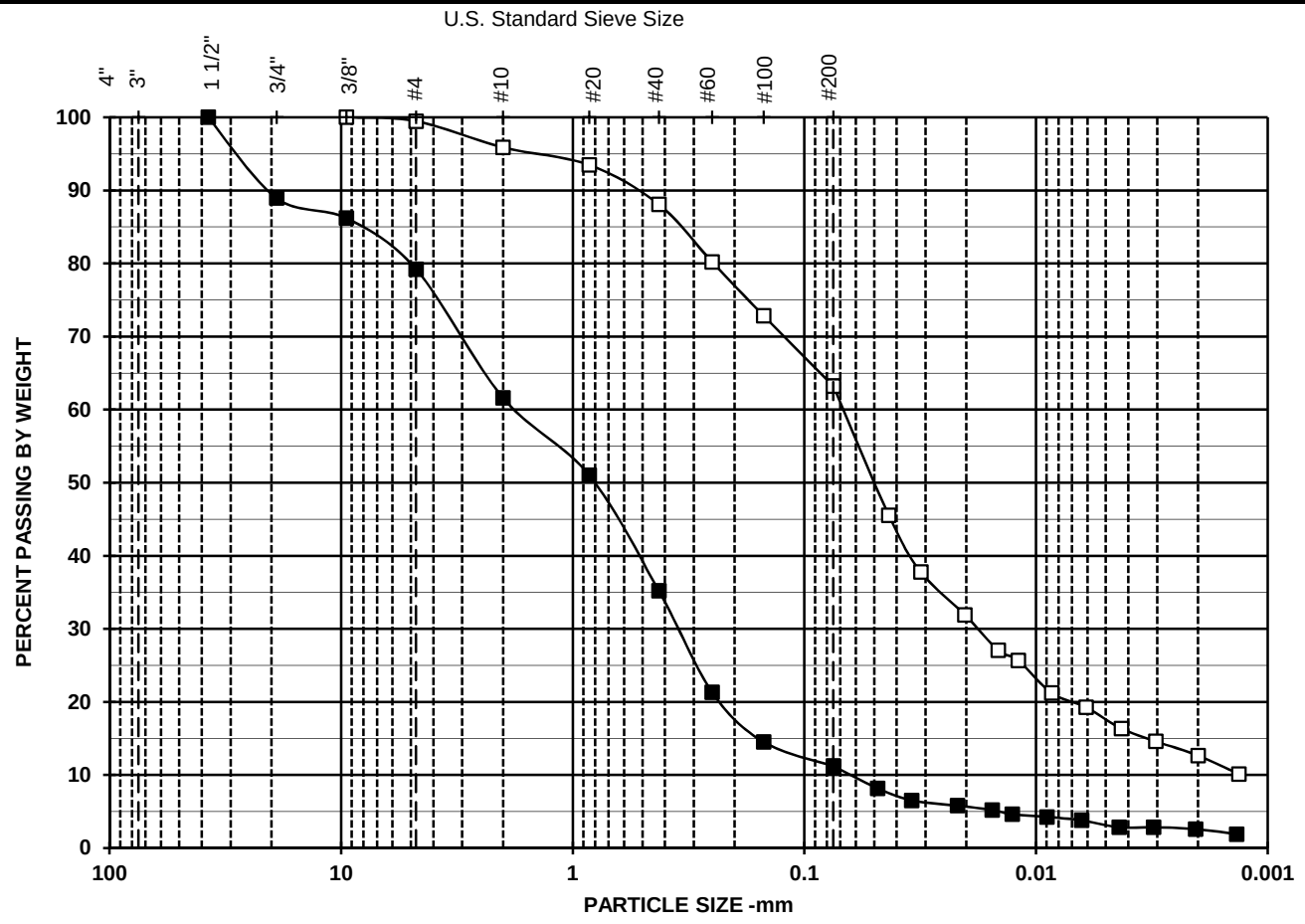
COBBLES	GRAVEL		SAND			SILT OR CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	



Symbol	□	■	○
Boring	NEW-B004A	NEW-B004A	
Sample	S-1	S-11	
Depth	45-46	95-96.5	
% +3"	0.0	0.0	
% Gravel	0.5	20.8	
% SAND	36.3	68.0	
%C SAND	3.6	17.6	
%M SAND	7.8	26.4	
%F SAND	24.9	24.0	
% FINES	63.2	11.2	
% -2μ	13	3	
D_{100} (mm)	9.50	37.50	
D_{60} (mm)	0.07	1.82	
D_{30} (mm)	0.02	0.36	
D_{10} (mm)		0.06	
Cc		1.1	
Cu		28.4	

Particle Size	PERCENT FINER		
(Sieve #)	□	■	○
4"			
3"			
1 1/2"		100.0	
3/4"		88.9	
3/8"	100.0	86.2	
4	99.5	79.2	
10	95.9	61.6	
20	93.5	51.0	
40	88.1	35.2	
60	80.2	21.3	
100	72.8	14.5	
200	63.2	11.2	

SYMBOL	w (%)	LL	PL	PI	USCS	DESCRIPTION AND REMARKS	Date Tested
□	10.4				CL	Brown, Sandy lean clay	8/31/2015
■	11.1				SW-SM	Brown, Well-graded sand with silt and gravel	8/31/2015
○							

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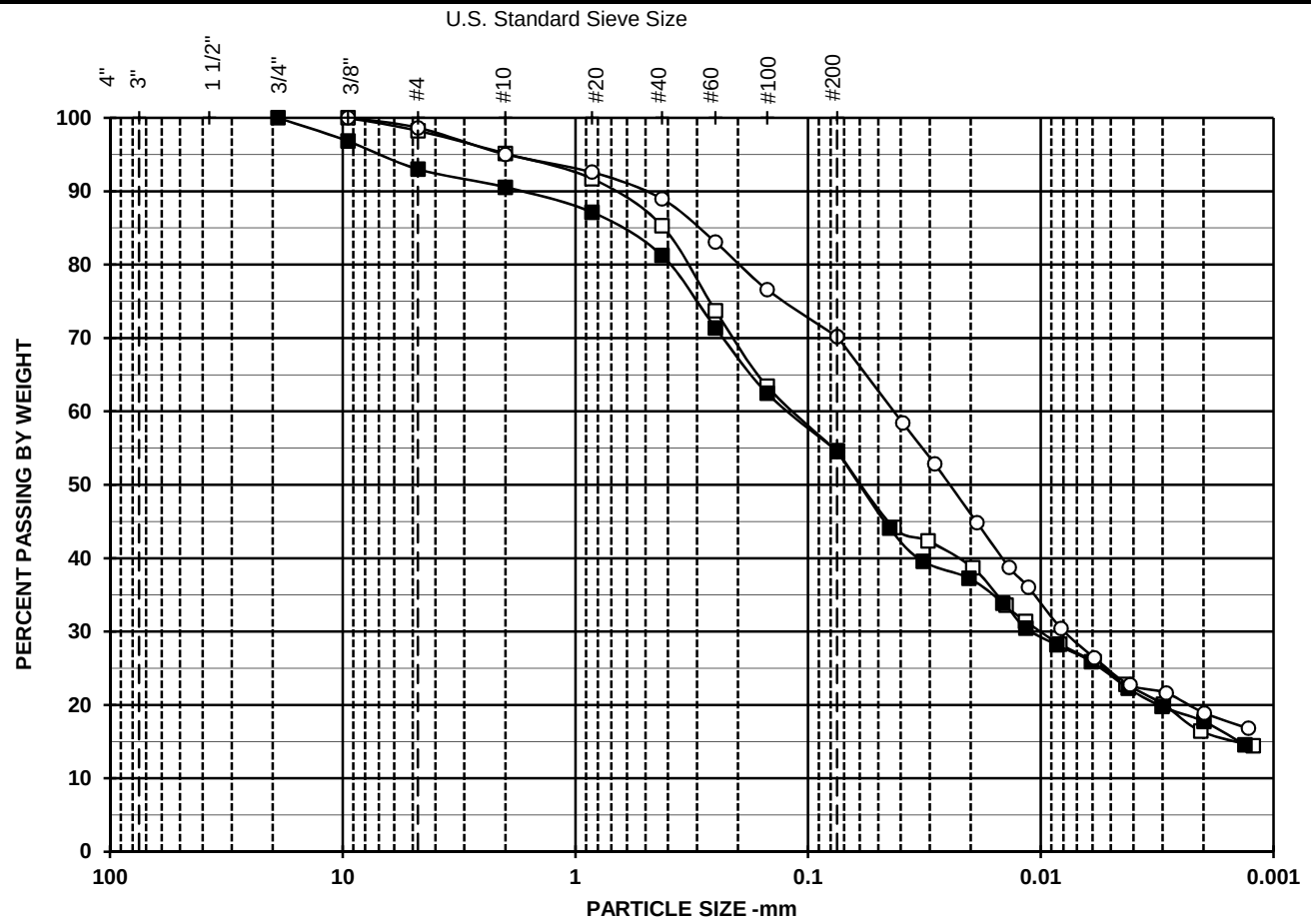
COBBLES	GRAVEL		SAND			SILT OR CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	



Symbol	□	■	○
Boring	NEW-B005	NEW-B005	NEW-B005
Sample	S-6	S-8	S-12
Depth	15-16.5	25-26	45-47
% +3"	0.0	0.0	0.0
% Gravel	1.8	7.0	1.4
% SAND	43.6	38.4	28.4
%C SAND	3.1	2.5	3.6
%M SAND	9.8	9.3	6.1
%F SAND	30.7	26.7	18.8
% FINES	54.6	54.6	70.2
% -2μ	16	18	19
D_{100} (mm)	9.50	19.00	9.50
D_{60} (mm)	0.12	0.13	0.04
D_{30} (mm)	0.01	0.01	0.01
D_{10} (mm)			
Cc			
Cu			

Particle Size	PERCENT FINER		
(Sieve #)	□	■	○
4"			
3"			
1 1/2"			
3/4"		100.0	
3/8"	100.0	96.8	100.0
4	98.2	93.0	98.6
10	95.1	90.5	95.0
20	91.7	87.1	92.6
40	85.3	81.2	89.0
60	73.7	71.4	83.1
100	63.4	62.5	76.6
200	54.6	54.6	70.2

SYMBOL	w (%)	LL	PL	PI	USCS	DESCRIPTION AND REMARKS	Date Tested
□	9.4	27	12	15	CL	Brown, Sandy lean clay	9/3/2015
■	11.6				CL	Brown, Sandy lean clay	8/31/2015
○	13.1	33	15	18	CL	Dark brown, Lean clay with sand	9/2/2015

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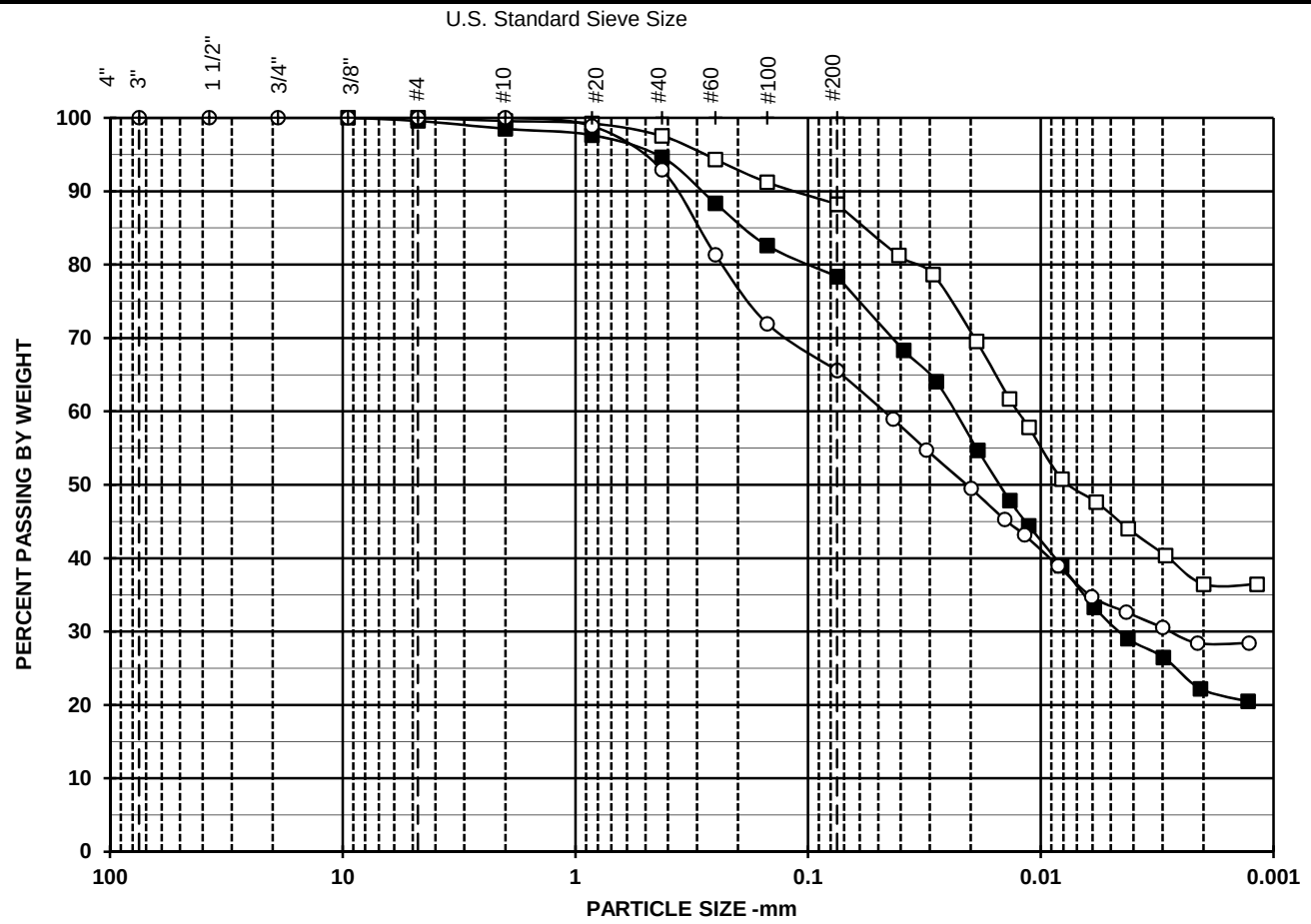
COBBLES	GRAVEL		SAND			SILT OR CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	



SYMBOL	w (%)	LL	PL	PI	USCS	DESCRIPTION AND REMARKS	Date Tested
□	21.2	66	14	52	CH	Brown, Fat clay	9/3/2015
■	18.2	40	17	23	CL	Brown, Lean clay with sand	10/29/2015
○		44	12	32	CL	Brown, Sandy lean clay	11/5/2015

Symbol	□	■	○
Boring	NEW-B006	NEW-B006	NEW-B006
Sample	S-3	ST-1B	ST-2
Depth	10-12	21.20	26.75
% +3"	0.0	0.0	0.0
% Gravel	0.0	0.4	0.0
% SAND	11.8	21.2	34.4
%C SAND	0.4	1.1	0.0
%M SAND	2.0	3.9	7.1
%F SAND	9.3	16.3	27.4
% FINES	88.2	78.4	65.6
% -2μ	36	22	28
D_{100} (mm)	4.75	9.50	2.00
D_{60} (mm)	0.01	0.02	0.05
D_{30} (mm)	0.00	0.00	0.00
D_{10} (mm)			
Cc			
Cu			

Particle Size	PERCENT FINER		
(Sieve #)	□	■	○
4"			100.0
3"			100.0
1 1/2"			100.0
3/4"			100.0
3/8"		100.0	100.0
4	100.0	99.6	100.0
10	99.6	98.5	100.0
20	99.2	97.6	98.9
40	97.5	94.6	92.9
60	94.3	88.3	81.3
100	91.2	82.6	71.9
200	88.2	78.4	65.6

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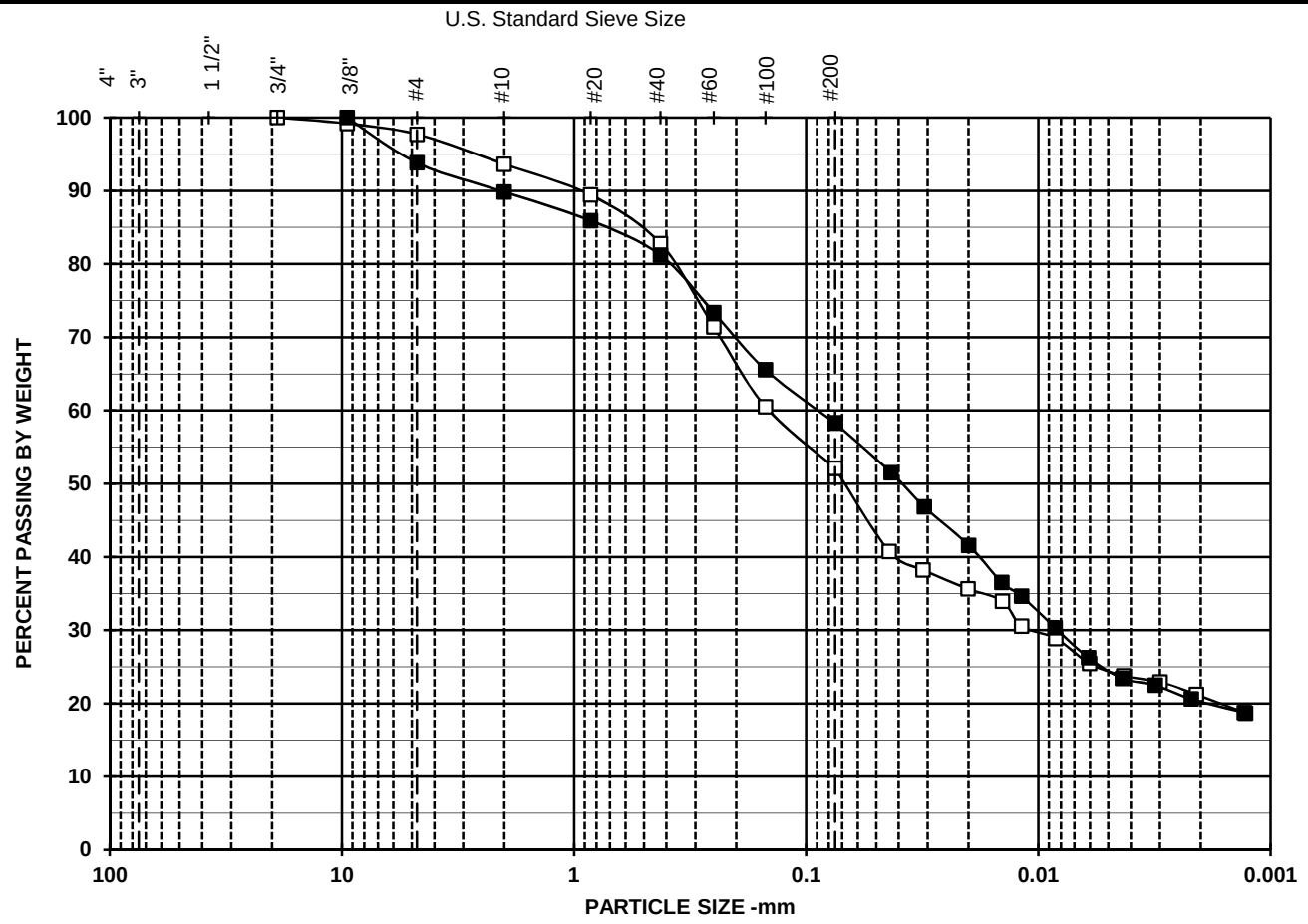
PARTICLE SIZE DISTRIBUTION

Dynegy CCR - Newton

COBBLES	GRAVEL		SAND			SILT OR CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	



Symbol	□	■	○
Boring	NEW-B006	NEW-B006	
Sample	ST-3C	ST-4	
Depth	31.8	35-35.8	
% +3"	0.0	0.0	
% Gravel	2.3	6.2	
% SAND	45.6	35.5	
%C SAND	4.1	4.0	
%M SAND	10.8	8.6	
%F SAND	30.7	22.9	
% FINES	52.1	58.3	
% -2μ	21	20	
D_{100} (mm)	19.00	9.50	
D_{60} (mm)	0.15	0.09	
D_{30} (mm)	0.01	0.01	
D_{10} (mm)			
Cc			
Cu			

Particle Size	PERCENT FINER		
(Sieve #)	□	■	○
4"			
3"			
1 1/2"			
3/4"	100.0		
3/8"	99.2	100.0	
4	97.7	93.8	
10	93.6	89.8	
20	89.4	85.9	
40	82.8	81.2	
60	71.4	73.4	
100	60.5	65.6	
200	52.1	58.3	

SYMBOL	w (%)	LL	PL	PI	USCS	DESCRIPTION AND REMARKS	Date Tested
□		37	15	22	CL	Dark brown, Sandy lean clay	10/13/2015
■		30	13	17	CL	Light brown, Sandy lean clay	9/28/2015
○							

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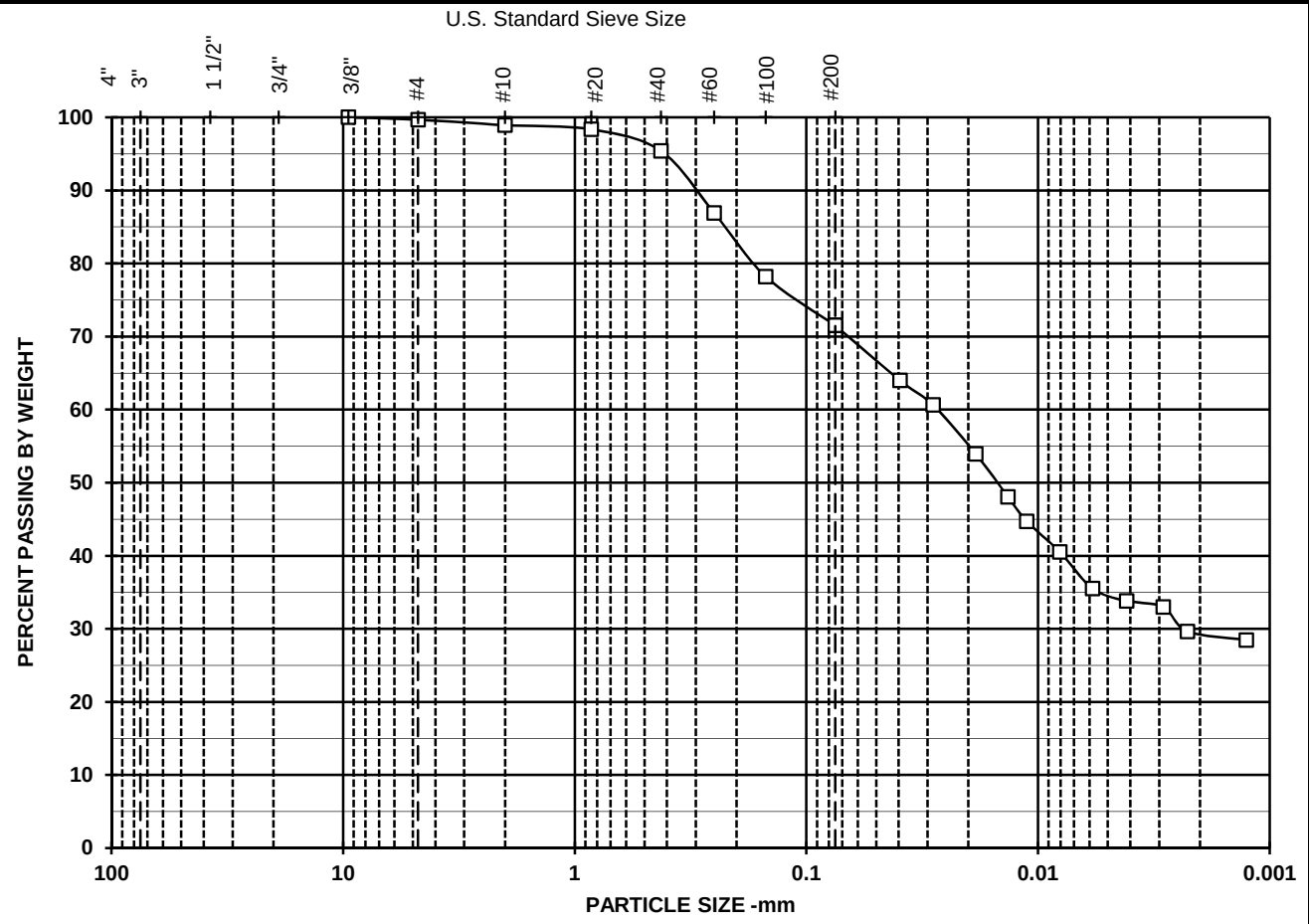
PARTICLE SIZE DISTRIBUTION
Dynegy CCR - Newton

COBBLES	GRAVEL		SAND			SILT OR CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	



SYMBOL	w (%)	LL	PL	PI	USCS	DESCRIPTION AND REMARKS	Date Tested
□	21.5	52	12	40	CH	Brown , Fat clay with sand	10/19/2015
■							
○							

Symbol	□	■	○
Boring	NEW-B007		
Sample	ST-3C		
Depth	31.7		
% +3"	0.0		
% Gravel	0.3		
% SAND	28.2		
%C SAND	0.7		
%M SAND	3.5		
%F SAND	23.9		
% FINES	71.5		
% -2μ	29		
D_{100} (mm)	9.50		
D_{60} (mm)	0.03		
D_{30} (mm)	0.00		
D_{10} (mm)			
Cc			
Cu			

Particle Size	PERCENT FINER		
(Sieve #)	□	■	○
4"			
3"			
1 1/2"			
3/4"			
3/8"	100.0		
4	99.7		
10	98.9		
20	98.4		
40	95.4		
60	86.9		
100	78.2		
200	71.5		

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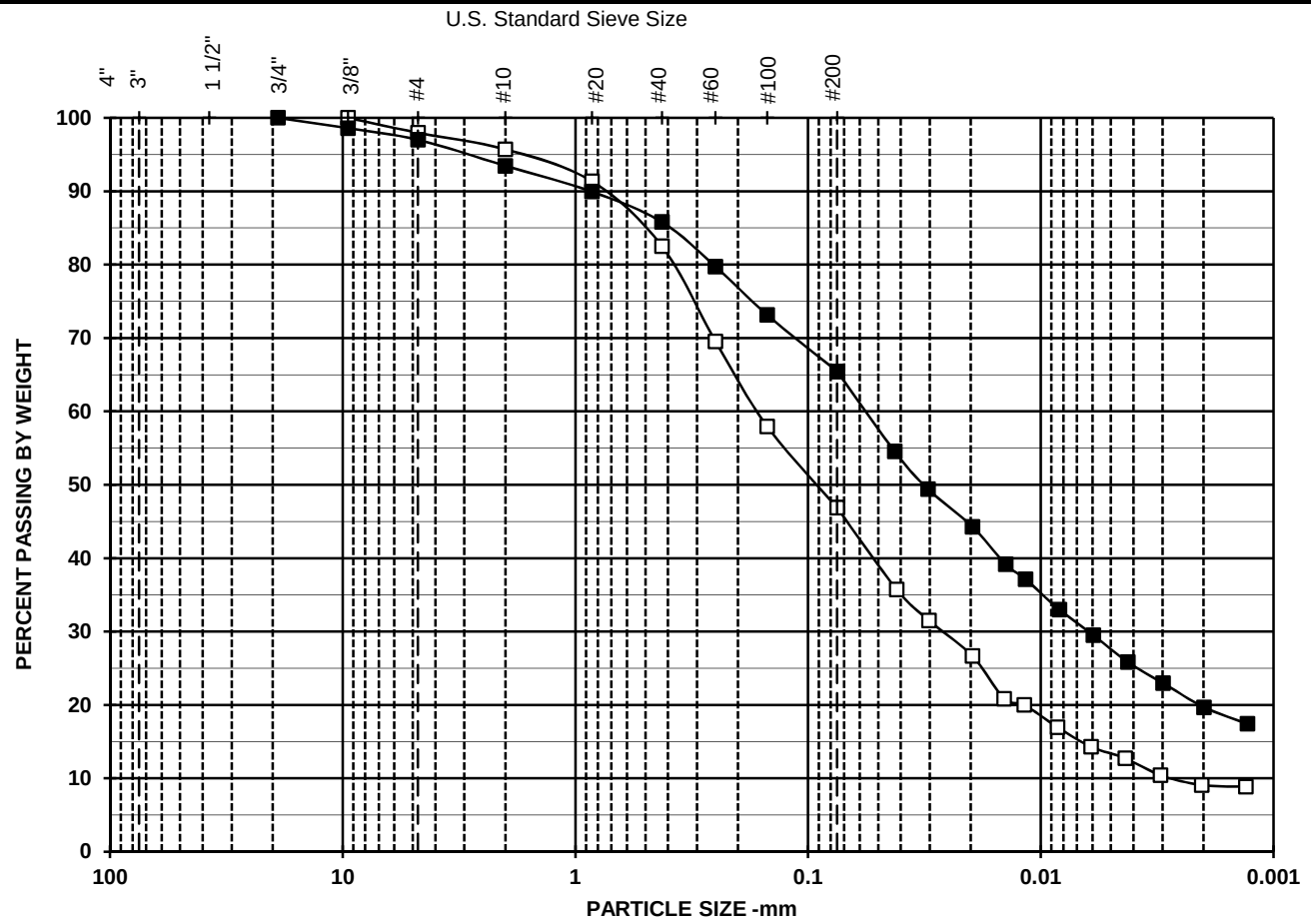
PARTICLE SIZE DISTRIBUTION
Dynegy CCR - Newton

COBBLES	GRAVEL		SAND			SILT OR CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	



SYMBOL	w (%)	LL	PL	PI	USCS	DESCRIPTION AND REMARKS	Date Tested
□	14.6				SC	Brown , Clayey sand	9/2/2015
■	15.4	32	16	16	CL	Brown, Sandy lean clay	9/2/2015
○							

Symbol	□	■	○
Boring	NEW-B008	NEW-B008	
Sample	S-8	S-10	
Depth	40-42	50-51.5	
% +3"	0.0	0.0	
% Gravel	2.0	3.0	
% SAND	51.1	31.6	
%C SAND	2.3	3.5	
%M SAND	13.2	7.7	
%F SAND	35.7	20.4	
% FINES	46.9	65.4	
% -2μ	9	20	
D_{100} (mm)	9.50	19.00	
D_{60} (mm)	0.17	0.06	
D_{30} (mm)	0.03	0.01	
D_{10} (mm)			
Cc			
Cu			

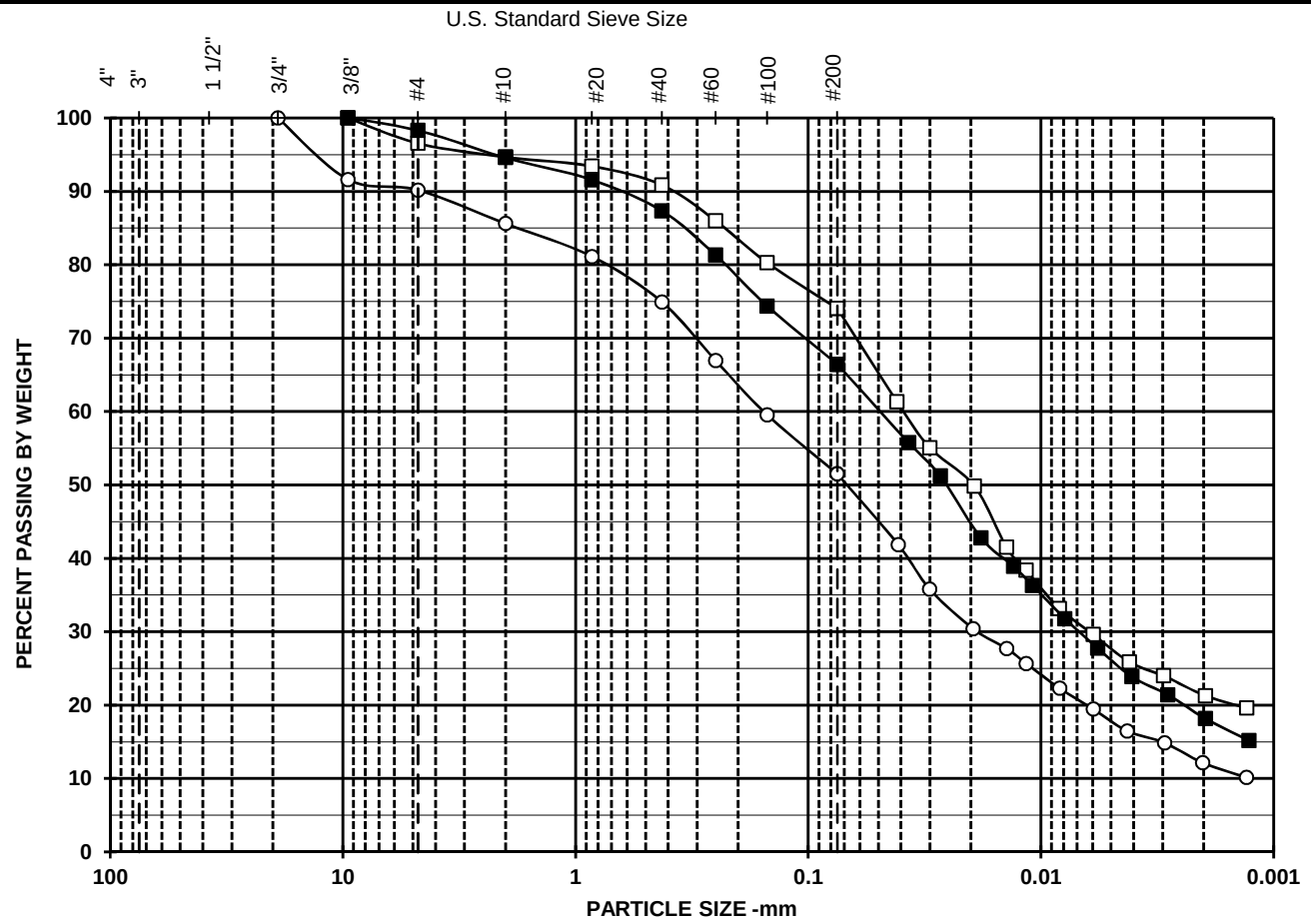
Particle Size	PERCENT FINER		
(Sieve #)	□	■	○
4"			
3"			
1 1/2"			
3/4"		100.0	
3/8"	100.0	98.6	
4	98.0	97.0	
10	95.7	93.5	
20	91.4	89.9	
40	82.5	85.8	
60	69.5	79.7	
100	58.0	73.1	
200	46.9	65.4	

TerraSense, LLC	AECOM
T60428794	60428794-108

PARTICLE SIZE DISTRIBUTION

Dynegy CCR - Newton

COBBLES	GRAVEL		SAND			SILT OR CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	



Symbol	□	■	○
Boring	NEW-B009	NEW-B009	NEW-B009
Sample	S-10	S-12	S-14
Depth	50-52	60-62	70-71.4
% +3"	0.0	0.0	0.0
% Gravel	3.5	1.7	9.8
% SAND	22.5	31.9	38.7
%C SAND	1.9	3.7	4.6
%M SAND	3.8	7.3	10.7
%F SAND	16.8	20.9	23.4
% FINES	74.0	66.4	51.5
% -2μ	21	18	12
D_{100} (mm)	9.50	9.50	19.00
D_{60} (mm)	0.04	0.05	0.16
D_{30} (mm)	0.01	0.01	0.02
D_{10} (mm)			
Cc			
Cu			

Particle Size	PERCENT FINER		
(Sieve #)	□	■	○
4"			
3"			
1 1/2"			
3/4"			100.0
3/8"	100.0	100.0	91.6
4	96.5	98.3	90.2
10	94.7	94.6	85.6
20	93.4	91.6	81.1
40	90.9	87.3	74.9
60	86.0	81.3	67.0
100	80.3	74.4	59.5
200	74.0	66.4	51.5

SYMBOL	w (%)	LL	PL	PI	USCS	DESCRIPTION AND REMARKS	Date Tested
□	13.7				CL	Brown, Lean clay with sand	8/31/2015
■	13.5	24	16	8	CL	Brown, Sandy lean clay	9/2/2015
○	12.2				CL	Brown, Sandy lean clay	9/2/2015

TerraSense, LLC	AECOM
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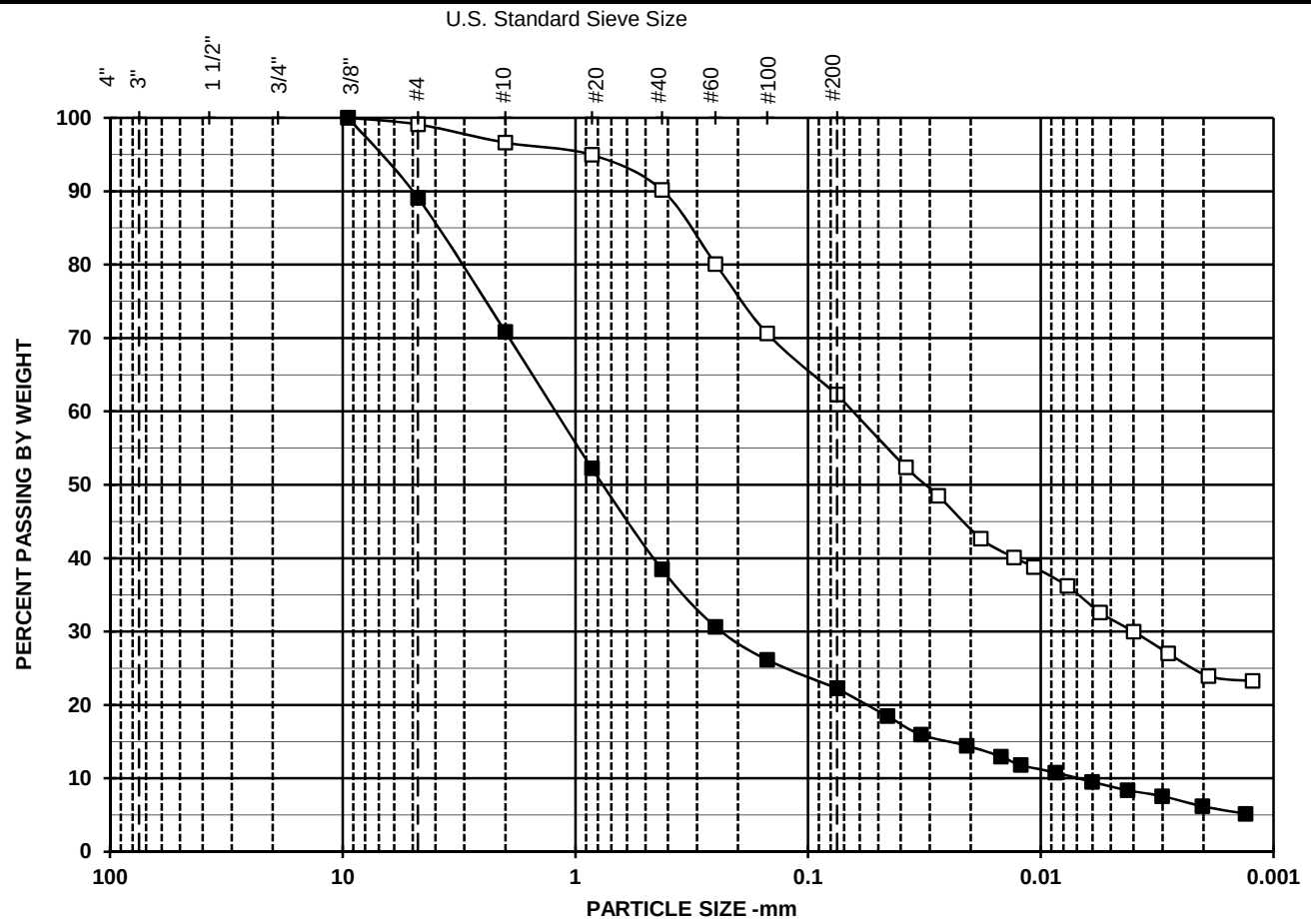
PARTICLE SIZE DISTRIBUTION

Dynegy CCR - Newton

COBBLES	GRAVEL		SAND			SILT OR CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	



Symbol	□	■	○
Boring	NEW-B010	NEW-B010	
Sample	S-7	S-13	
Depth	30-32	50-50.8	
% +3"	0.0	0.0	
% Gravel	0.9	10.9	
% SAND	36.8	66.8	
%C SAND	2.5	18.3	
%M SAND	6.5	32.3	
%F SAND	27.9	16.2	
% FINES	62.3	22.3	
% -2μ	24	6	
D_{100} (mm)	9.50	9.50	
D_{60} (mm)	0.07	1.33	
D_{30} (mm)	0.00	0.24	
D_{10} (mm)			
Cc			
Cu			

Particle Size	PERCENT FINER		
(Sieve #)	□	■	○
4"			
3"			
1 1/2"			
3/4"			
3/8"	100.0	100.0	
4	99.1	89.1	
10	96.6	70.8	
20	95.0	52.2	
40	90.2	38.5	
60	80.1	30.6	
100	70.6	26.1	
200	62.3	22.3	

SYMBOL	w (%)	LL	PL	PI	USCS	DESCRIPTION AND REMARKS	Date Tested
□	21.0	49	16	33	CL	Brown , Sandy lean clay	9/2/2015
■	10.1				SC	Brown, Clayey sand	9/2/2015
○							

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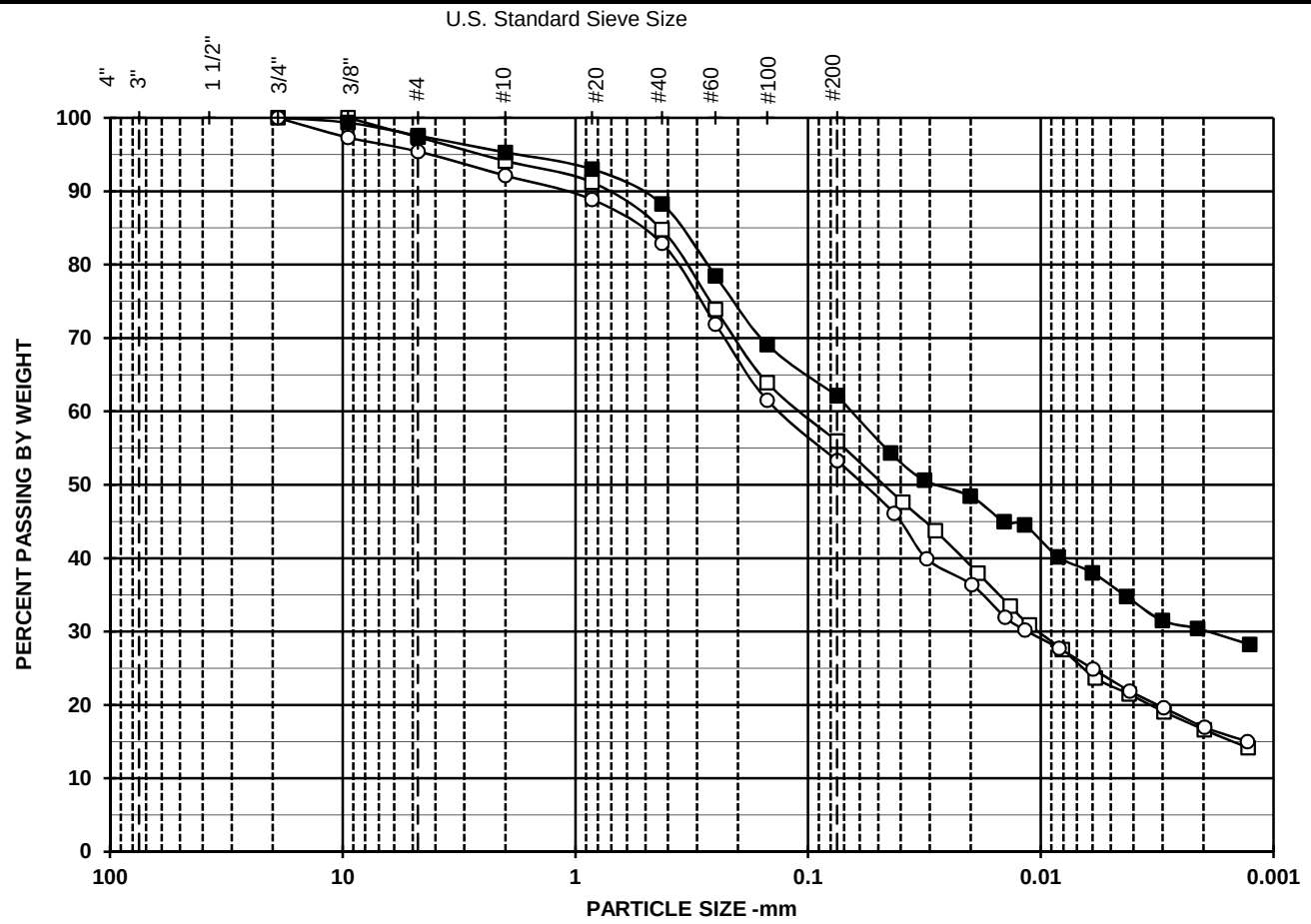
PARTICLE SIZE DISTRIBUTION
Dynegy CCR - Newton

COBBLES	GRAVEL		SAND			SILT OR CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	



SYMBOL	w (%)	LL	PL	PI	USCS	DESCRIPTION AND REMARKS	Date Tested
□	9.9				CL	Brown , Sandy lean clay	9/2/2015
■		43	14	29	CL	Brown, Sandy lean clay	9/23/2015
○	11.8	29	13	16	CL	Brown, Sandy lean clay	9/2/2015

Symbol	□	■	○
Boring	NEW-B012	NEW-B012	NEW-B012
Sample	S-11	ST-12C	S-18
Depth	40-42	46.4	75-77
% +3"	0.0	0.0	0.0
% Gravel	2.6	2.4	4.6
% SAND	41.5	35.5	42.1
%C SAND	3.3	2.3	3.3
%M SAND	9.3	7.0	9.2
%F SAND	28.8	26.1	29.6
% FINES	55.9	62.1	53.3
% -2μ	17	30	17
D_{100} (mm)	9.50	19.00	19.00
D_{60} (mm)	0.11	0.07	0.14
D_{30} (mm)	0.01	0.00	0.01
D_{10} (mm)			
Cc			
Cu			

Particle Size	PERCENT FINER		
(Sieve #)	□	■	○
4"			
3"			
1 1/2"			
3/4"		100.0	100.0
3/8"	100.0	99.4	97.3
4	97.4	97.6	95.4
10	94.1	95.3	92.1
20	91.2	93.0	88.9
40	84.8	88.3	82.9
60	73.9	78.5	71.9
100	63.9	69.1	61.5
200	55.9	62.1	53.3

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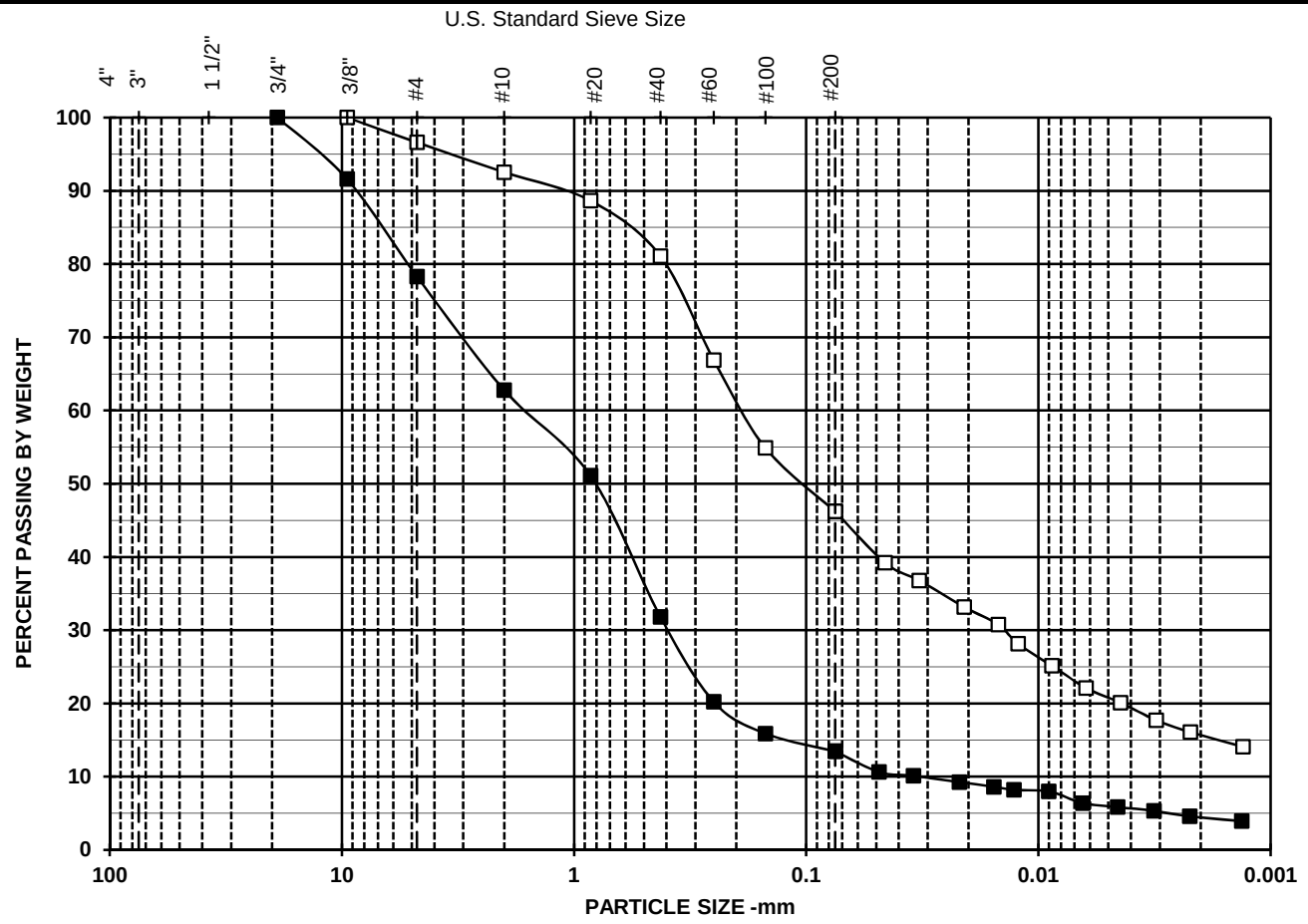
PARTICLE SIZE DISTRIBUTION

Dynegy CCR - Newton

COBBLES	GRAVEL		SAND			SILT OR CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	



Symbol	□	■	○
Boring	NEW-B014	NEW-B014	
Sample	ST-1B	ST-3C	
Depth	3.5	36.65	
% +3"	0.0	0.0	
% Gravel	3.4	21.7	
% SAND	50.4	64.8	
%C SAND	4.1	15.5	
%M SAND	11.5	31.0	
%F SAND	34.9	18.3	
% FINES	46.2	13.5	
% -2μ	16	4	
D_{100} (mm)	9.50	19.00	
D_{60} (mm)	0.19	1.73	
D_{30} (mm)	0.01	0.40	
D_{10} (mm)			
Cc			
Cu			

Particle Size	PERCENT FINER		
(Sieve #)	□	■	○
4"			
3"			
1 1/2"			
3/4"		100.0	
3/8"	100.0	91.6	
4	96.6	78.3	
10	92.5	62.8	
20	88.7	51.1	
40	81.1	31.8	
60	66.9	20.2	
100	54.9	15.9	
200	46.2	13.5	

SYMBOL	w (%)	LL	PL	PI	USCS	DESCRIPTION AND REMARKS	Date Tested
□	9.5	28	13	15	SC	Orange brown, Clayey sand	9/18/2015
■		38	13	25	SC	Brown, Clayey sand with gravel	9/23/2015
○							

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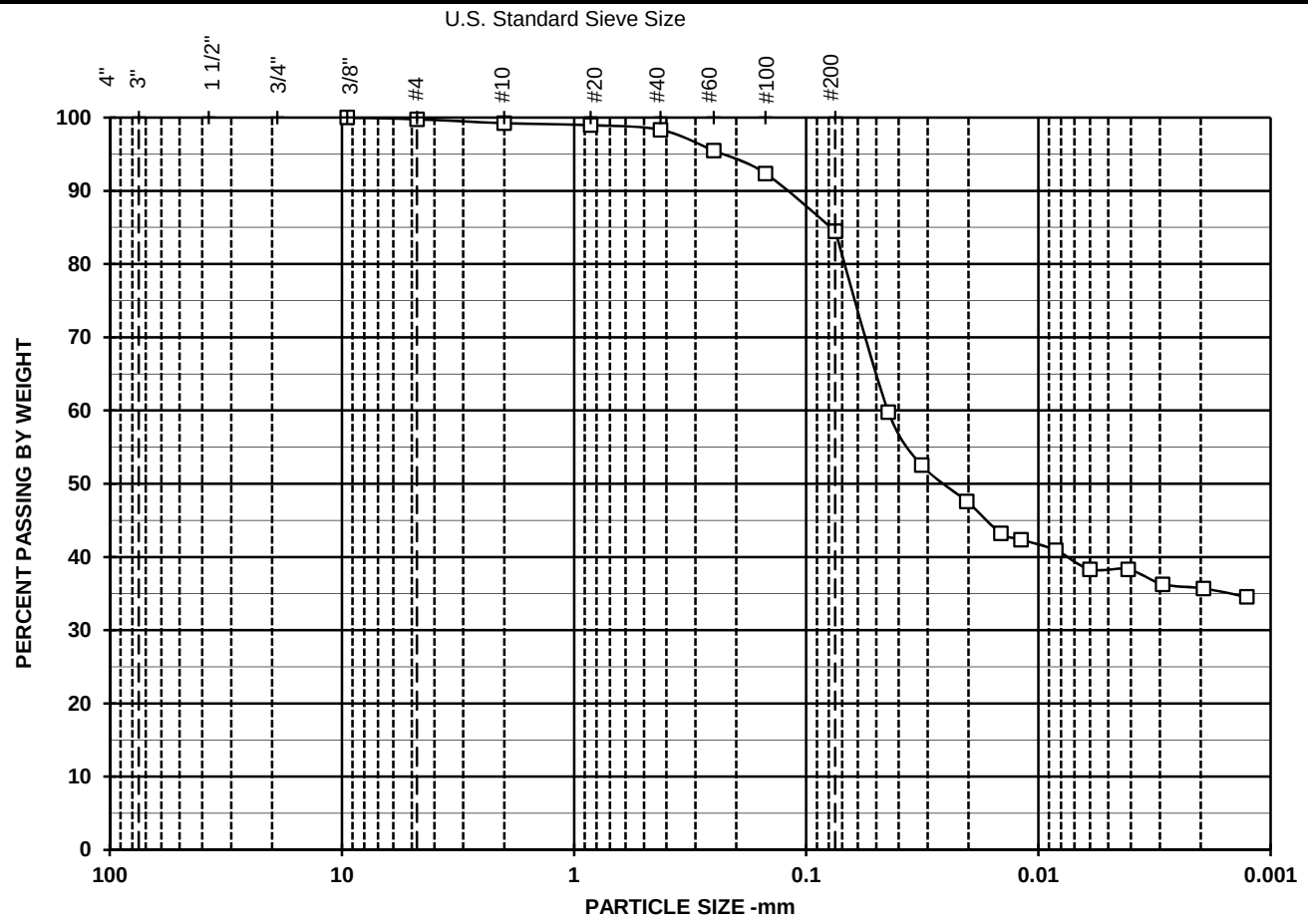
PARTICLE SIZE DISTRIBUTION

Dynegy CCR - Newton

COBBLES	GRAVEL		SAND			SILT OR CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	



SYMBOL	w (%)	LL	PL	PI	USCS	DESCRIPTION AND REMARKS	Date Tested
□	21.5	46	14	32	CL	Brown , Lean clay with sand	9/2/2015
■							
○							

Symbol	□	■	○
Boring	NEW-B015		
Sample	S-8		
Depth	35-37		
% +3"	0.0		
% Gravel	0.2		
% SAND	15.3		
%C SAND	0.5		
%M SAND	0.9		
%F SAND	13.8		
% FINES	84.5		
% -2μ	36		
D_{100} (mm)	9.50		
D_{60} (mm)	0.04		
D_{30} (mm)	0.00		
D_{10} (mm)			
Cc			
Cu			

Particle Size	PERCENT FINER		
(Sieve #)	□	■	○
4"			
3"			
1 1/2"			
3/4"			
3/8"	100.0		
4	99.8		
10	99.2		
20	99.0		
40	98.3		
60	95.5		
100	92.4		
200	84.5		

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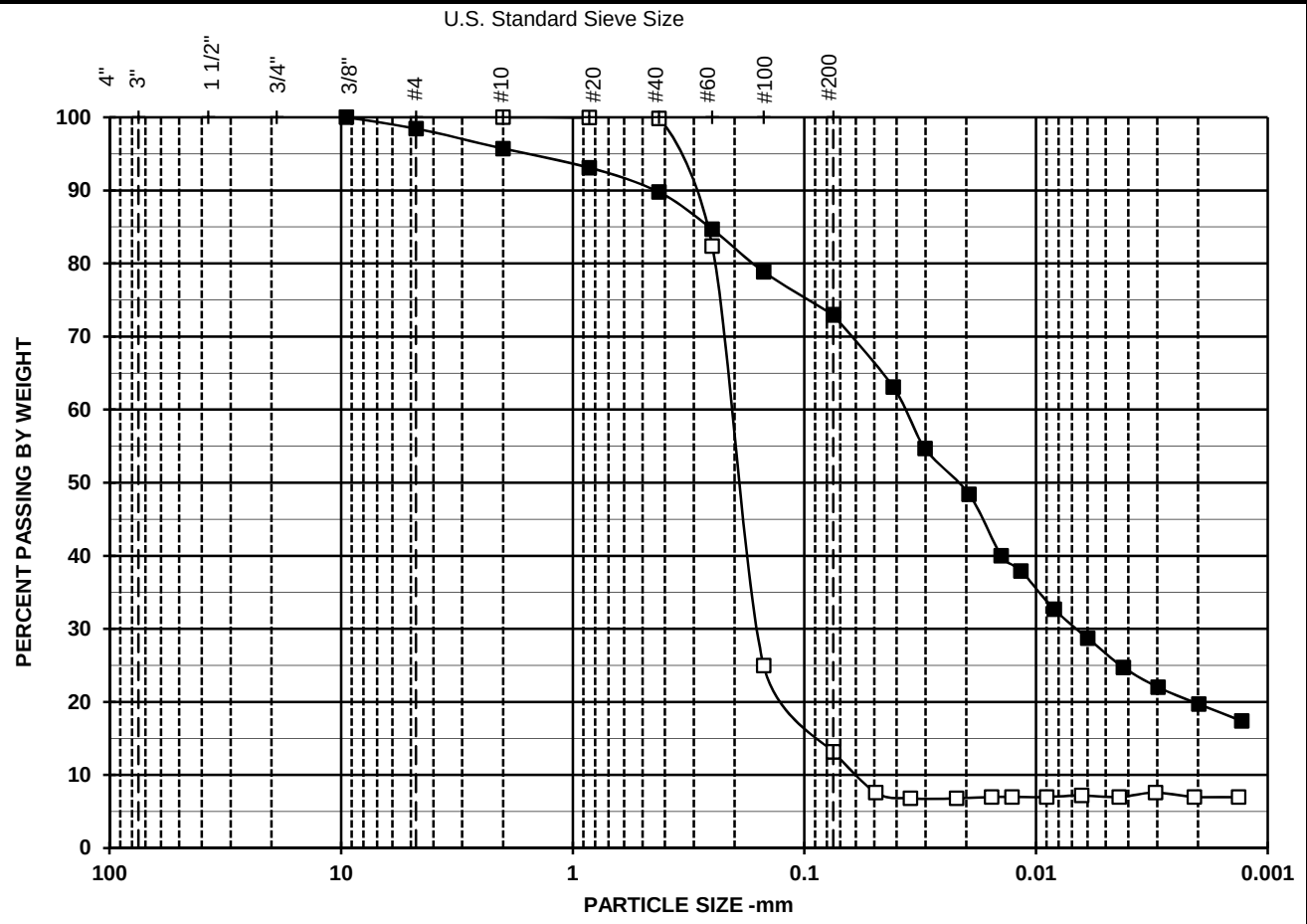
PARTICLE SIZE DISTRIBUTION
Dynegy CCR - Newton

COBBLES	GRAVEL		SAND			SILT OR CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	



SYMBOL	w (%)	LL	PL	PI	USCS	DESCRIPTION AND REMARKS	Date Tested
□					SM	Brown, Silty sand	9/1/2015
■	11.1	52	14	38	CH	Dark brown, Fat clay with sand	9/2/2015
○							

Symbol	□	■	○
Boring	NEW-B016	NEW-B016	
Sample	S-3B	S-6	
Depth	6.5-7	15-17	
% +3"	0.0	0.0	
% Gravel	0.0	1.6	
% SAND	86.8	25.4	
%C SAND	0.0	2.7	
%M SAND	0.2	5.9	
%F SAND	86.7	16.8	
% FINES	13.2	73.0	
% -2μ	7	20	
D_{100} (mm)	2.00	9.50	
D_{60} (mm)	0.21	0.04	
D_{30} (mm)	0.16	0.01	
D_{10} (mm)			
Cc			
Cu			

Particle Size	PERCENT FINER		
(Sieve #)	□	■	○
4"			
3"			
1 1/2"			
3/4"			
3/8"		100.0	
4		98.4	
10	100.0	95.7	
20	100.0	93.1	
40	99.8	89.8	
60	82.4	84.7	
100	25.0	78.9	
200	13.2	73.0	

TerraSense, LLC	AECOM
T60428794	60428794-108

PARTICLE SIZE DISTRIBUTION
Dynegy CCR - Newton

PERMEABILITY TEST: FALLING HEAD - CONSTANT VOLUME U-TUBE

ASTM D 5084 - Method F

Project No.: T60428794 | BORING: NEW-B003 | Test No.: P10611

Project Name: Dynegy CCR - Newton | SAMPLE: ST-3 | DEPTH (ft): 28.3

Specimen - Apparatus set-up - Test Information | Cell No. D | Apparatus No. 2 | Stage No.: 4

Preliminary Length/Area Calculations

Lo =	4.021	in	Lo=	10.212	cm
dLc=	0.057	in	Ao =	42.07	cm^2
Lc=	3.964	in	Vo =	429.65	cm^3
			Lc=	10.068	cm
dVc = 3 Vo * (dLc/Lo)			dVc=	18.27	cm^3
			Vc =	411.38	cm^3
Sc =	0.246	cm^{-1}	Ac=	40.862	cm^2

1) Specimen Tested in :	x	Triaxial Cell or		Compaction Mold or		
	x	with stones or		Stones with filter paper or		top + bottom
2) Specimen orientation for:	x	Vertical or		Horizontal permeability determination		
3) During saturation: Water flushed up sides of specimen to remove air			x	No		Yes
4) During consolidation:	x	Top and bottom drainage or		Top		Bottom only
5) Direction of permeant :	x	Up during or		Down during permeation		
6) Permeant: water used	x	Tap		Distilled		
or		Demineralized		0.005 N calcium sulfate (CaSO4)		Permeability

Equations Used

Kt = - 0.0000746 * Sc/dT(min) * ln (ho/hf)

RT = (-0.02452*(ave. temp in C) + 1.495)

K @ 20 ºC = RT * Kt TubeC= 1.3214

Consol Stage-Trial No.	Temp. ºC	Date	Time hr	Time min	Time sec	Initial σ_c psi	Initial Ub psi	U-tube Reading Head (cm) (cc)	U-tube Reading Tail (cm) (cc)	Flow in/out gradient	Preliminary Final at 20ºC cm/sec Dev. from Ave.
initial	21.0	10/27/15	09	13	00	120.8	100.0	60.70	42.60	1.01	9.84E-08
final	21.2	10/27/15	09	51	00			58.18	43.40		9.51E-08
1	RT = 0.978	dT =		38.00 min		σ'_c =	3.0 ksf	0.187	0.185	io= 22.6	-1%
initial	21.2	10/27/15	09	52	00	120.8	100.0	59.07	43.10	1.05	1.01E-07
final	21.5	10/27/15	10	30	00			56.79	43.80		9.72E-08
2	RT = 0.971	dT =		38.00 min		σ'_c =	3.0 ksf	0.170	0.162	io= 19.9	1%
initial	21.5	10/27/15	10	31	00	120.8	100.0	58.80	43.20	1.00	1.03E-07
final	21.8	10/27/15	11	15	00			56.22	44.03		9.82E-08
3	RT = 0.964	dT =		44.00 min		σ'_c =	3.0 ksf	0.192	0.192	io= 19.5	2%
initial	21.8	10/27/15	11	16	00	120.8	100.0	58.70	43.23	1.00	1.01E-07
final	22.3	10/27/15	12	07	00			55.84	44.15		9.53E-08
4	RT = 0.954	dT =		51.00 min		σ'_c =	3.0 ksf	0.213	0.213	io= 19.3	-1%
initial											
final											
5											
initial											
final											
6											

TEST SUMMARY

Final Specimen and Test Conditions

Lc = 10.068 cm ε_{axial} = 1.4%

Ac = 41.331 cm^2

Vc= 416.10 cm^3 ε_{vol} = 3.2%

Sc = 0.244 cm^{-1} Sc = Lc / Ac , final

	w (%)	γ_τ (pcf)	γ_d (pcf)	S (%)
Initial	21.21	126.4	104.3	91.3
PreTest	21.34	130.7	107.7	100.0

HYDRAULIC CONDUCTIVITY SUMMARY

Averages for trials: 1-4

ave K @ 20 ºC: **9.64E-08** cm/sec

(i_o)ave = 20.3

Tested By: BB Reviewed By: G. Thomas

PERMEABILITY TEST: FALLING HEAD - CONSTANT VOLUME U-TUBE

ASTM D 5084 - Method F

Project No.: T60428794 | BORING: NEW-B004 | Test No.: P10610

Project Name: Dynegy CCR - Newton | SAMPLE: ST-12 | DEPTH (ft): 33.2

Specimen - Apparatus set-up - Test Information | Cell No. 6 | Apparatus No. 3 | Stage No.: 5

Preliminary Length/Area Calculations

Lo =	3.994	in	Lo=	10.145	cm
dLc=	0.058	in	Ao =	42.13	cm^2
Lc=	3.936	in	Vo =	427.40	cm^3
			Lc=	9.997	cm
dVc = 3 Vo * (dLc/Lo)			dVc=	18.62	cm^3
			Vc =	408.78	cm^3
Sc =	0.245	cm^{-1}	Ac=	40.889	cm^2

1) Specimen Tested in :	x	Triaxial Cell or		Compaction Mold or			
	x	with stones or		Stones with filter paper or			top + bottom
2) Specimen orientation for:	x	Vertical or		Horizontal permeability determination			
3) During saturation: Water flushed up sides of specimen to remove air			x	No		Yes	
4) During consolidation:	x	Top and bottom drainage or		Top		Bottom only	
5) Direction of permeant :	x	Up during or		Down during permeation			
6) Permeant: water used	x	Tap		Distilled			
or		Demineralized		0.005 N calcium sulfate (CaSO4)			

Equations Used

Kt = - 0.0000755 * Sc/dT(min) * ln (ho/hf)

RT = (-0.02452*(ave. temp in C) + 1.495)

K @ 20 ºC = RT * Kt TubeC= 1.3132

Consol Stage-Trial No.	Temp. ºC	Date	Time hr	Time min	Time sec	Initial σ_c psi	Initial Ub psi	U-tube Reading Head (cm) (cc)	U-tube Reading Tail (cm) (cc)	Flow in/out gradient	Permeability Preliminary Final at 20ºC cm/sec Dev. from Ave.
initial	21.0	10/27/15	09	06	00	131.3	100.0	58.00	49.20	1.02	6.64E-06
final	21.0	10/27/15	09	08	00			54.56	50.26		6.41E-06
1	RT = 0.980	dT =		2.00 min		σ'_c =	4.5 ksf	0.257	0.253	io= 11.1	0%
initial	21.0	10/27/15	09	09	00	131.3	100.0	58.00	49.20	0.99	6.63E-06
final	21.0	10/27/15	09	12	00			53.58	50.60		6.40E-06
2	RT = 0.980	dT =		3.00 min		σ'_c =	4.5 ksf	0.330	0.334	io= 11.1	-1%
initial	21.0	10/27/15	09	13	00	131.3	100.0	58.00	49.20	1.00	6.65E-06
final	21.0	10/27/15	09	14	30			55.20	50.08		6.42E-06
3	RT = 0.980	dT =		1.50 min		σ'_c =	4.5 ksf	0.209	0.210	io= 11.1	0%
initial	21.0	10/27/15	09	16	00	131.3	100.0	58.00	49.20	0.97	6.76E-06
final	21.0	10/27/15	09	18	30			53.98	50.50		6.52E-06
4	RT = 0.980	dT =		2.50 min		σ'_c =	4.5 ksf	0.300	0.310	io= 11.1	1%
initial											
final											
5											
initial											
final											
6											

TEST SUMMARY

Final Specimen and Test Conditions

Lc =	9.997	cm	ε_{axial} =	1.5%	
Ac =	41.520	cm^2			
Vc=	415.09	cm^3	ε_{vol} =	2.9%	
Sc =	0.241	cm^{-1}	Sc = Lc / Ac , final		

	w (%)	γ_τ (pcf)	γ_d (pcf)	S (%)
Initial	9.67	136.2	124.2	70.9
PreTest	12.18	143.5	127.9	100.0

HYDRAULIC CONDUCTIVITY SUMMARY

Averages for trials: 1-4

ave K @ 20 ºC: **6.44E-06** cm/sec

(i_o)ave = 11.1

Tested By: BB Reviewed By: G. Thomas

PERMEABILITY TEST: FALLING HEAD - CONSTANT VOLUME U-TUBE

ASTM D 5084 - Method F

Project No.: T60428794 | BORING: NEW-B006 | Test No.: P10597

Project Name: Dynegy CCR - Newton | SAMPLE: ST-3 | DEPTH (ft): 31.25

Specimen - Apparatus set-up - Test Information | Cell No. D | Apparatus No. 1 | Stage No.: 5

Preliminary Length/Area Calculations

Lo =	3.986	in	Lo=	10.124	cm
dLc=	0.132	in	Ao =	41.97	cm^2
Lc=	3.854	in	Vo =	424.87	cm^3
			Lc=	9.789	cm
dVc = 3 Vo * (dLc/Lo)			dVc=	42.21	cm^3
			Vc =	382.66	cm^3
Sc =	0.250	cm^{-1}	Ac=	39.091	cm^2

1) Specimen Tested in :	x	Triaxial Cell or		Compaction Mold or			
	x	with stones or		Stones with filter paper or			top + bottom
2) Specimen orientation for:	x	Vertical or		Horizontal permeability determination			
3) During saturation: Water flushed up sides of specimen to remove air			x	No		Yes	
4) During consolidation:	x	Top and bottom drainage or		Top		Bottom only	
5) Direction of permeant :	x	Up during or		Down during permeation			
6) Permeant: water used	x	Tap		Distilled			
or		Demineralized		0.005 N calcium sulfate (CaSO4)			

Equations Used

Kt = - 0.0000757 * Sc/dT(min) * ln (ho/hf)

RT = (-0.02452*(ave. temp in C) + 1.495)

K @ 20 ºC = RT * Kt TubeC= 1.3127

Consol Stage-Trial No.	Temp. ºC	Date	Time hr	Time min	Time sec	Initial σ_c psi	Initial Ub psi	U-tube Reading Head (cm) (cc)	U-tube Reading Tail (cm) (cc)	Flow in/out gradient	Preliminary Final at 20ºC cm/sec Dev. from Ave.
initial	22.7	10/7/15	09	32	00	130.0	80.0	55.90	38.12	0.98	1.95E-07
final	22.5	10/7/15	10	57	00			48.00	40.65		1.70E-07
1	RT = 0.941	dT =		85.00 min		σ'_c =	7.2 ksf	0.592	0.606	io= 22.8	5%
initial	22.6	10/7/15	11	52	00	130.0	80.0	55.90	38.10	0.99	1.86E-07
final	22.5	10/7/15	13	37	00			47.18	40.85		1.62E-07
2	RT = 0.942	dT =		105.00 min		σ'_c =	7.2 ksf	0.653	0.659	io= 22.9	0%
initial	22.5	10/7/15	13	39	00	130.0	80.0	56.20	38.00	1.01	1.82E-07
final	22.7	10/7/15	14	44	00			49.75	40.00		1.59E-07
3	RT = 0.941	dT =		65.00 min		σ'_c =	7.2 ksf	0.483	0.479	io= 23.4	-2%
initial	22.7	10/7/15	14	48	00	130.0	80.0	55.80	38.12	0.99	1.78E-07
final	22.8	10/7/15	17	24	00			45.44	41.40		1.55E-07
4	RT = 0.937	dT =		156.00 min		σ'_c =	7.2 ksf	0.776	0.786	io= 22.7	-4%
initial											
final											
5		dT =				σ'_c =					
initial											
final											
6		dT =				σ'_c =					

TEST SUMMARY

Final Specimen and Test Conditions

Lc =	9.789	cm	ε_{axial} =	3.3%	
Ac =	42.154	cm^2			
Vc=	412.65	cm^3	ε_{vol} =	2.9%	
Sc =	0.232	cm^{-1}	Sc = Lc / Ac , final		

	w (%)	γ_τ (pcf)	γ_d (pcf)	S (%)
Initial	20.74	130.6	108.1	98.3
PreTest	19.44	133.0	111.3	100.0

HYDRAULIC CONDUCTIVITY SUMMARY

Averages for trials: 1-4

ave K @ 20 ºC: **1.62E-07** cm/sec

(i_o)ave = 22.9

Tested By: BB Reviewed By: G. Thomas

PERMEABILITY TEST: FALLING HEAD - CONSTANT VOLUME U-TUBE

ASTM D 5084 - Method F

Project No.: T60428794 | BORING: NEW-B007 | Test No.: P10598

Project Name: Dynegy CCR - Newton | SAMPLE: ST-5A | DEPTH (ft): 50.3

Specimen - Apparatus set-up - Test Information | Cell No. 6 | Apparatus No. 2 | Stage No.: 5

Preliminary Length/Area Calculations

Lo =	3.981	in	Lo=	10.112	cm
dLc=	0.088	in	Ao =	42.06	cm^2
Lc=	3.893	in	Vo =	425.32	cm^3
			Lc=	9.888	cm
dVc = 3 Vo * (dLc/Lo)			dVc=	28.21	cm^3
			Vc =	397.12	cm^3
Sc =	0.246	cm^{-1}	Ac=	40.161	cm^2

1) Specimen Tested in :	x	Triaxial Cell or		Compaction Mold or		
	x	with stones or		Stones with filter paper or		top + bottom
2) Specimen orientation for:	x	Vertical or		Horizontal permeability determination		
3) During saturation: Water flushed up sides of specimen to remove air			x	No		Yes
4) During consolidation:	x	Top and bottom drainage or		Top		Bottom only
5) Direction of permeant :	x	Up during or		Down during permeation		
6) Permeant: water used	x	Tap		Distilled		
or		Demineralized		0.005 N calcium sulfate (CaSO4)		Permeability

Equations Used

Kt = - 0.0000746 * Sc/dT(min) * ln (ho/hf)

RT = (-0.02452*(ave. temp in C) + 1.495)

K @ 20 ºC = RT * Kt TubeC= 1.3214

Consol Stage- Trial No.	Temp. ºC	Date	Time hr	Time min	Time sec	Initial σ_c psi	Initial Ub psi	U-tube Reading Head (cm) (cc)	U-tube Reading Tail (cm) (cc)	Flow in/out gradient	Preliminary Final at 20ºC cm/sec Dev. from Ave.
initial	22.8	10/8/15	09	06	00	132.0	80.0	60.40	42.75	1.02	4.30E-09
final	22.3	10/9/15	08	55	00			56.60	43.95		3.90E-09
1	RT = 0.942	dT =	1429.00 min			σ'_c =	7.5 ksf	0.283	0.278	io= 22.4	-24%
initial	22.3	10/9/15	08	59	00	132.0	80.0	60.75	42.65	0.99	5.83E-09
final	22.7	10/9/15	19	26	00			58.28	43.45		5.28E-09
2	RT = 0.943	dT =	627.00 min			σ'_c =	7.5 ksf	0.184	0.185	io= 23.0	3%
initial	22.7	10/9/15	19	31	00	132.0	80.0	60.30	42.80	1.02	5.81E-09
final	23.0	10/10/15	11	41	00			56.80	43.90		5.22E-09
3	RT = 0.935	dT =	970.00 min			σ'_c =	7.5 ksf	0.260	0.255	io= 22.2	2%
initial	23.1	10/10/15	12	10	00	132.0	80.0	60.35	42.70	0.98	5.99E-09
final	22.0	10/11/15	11	33	00			55.45	44.30		5.42E-09
4	RT = 0.942	dT =	1403.00 min			σ'_c =	7.5 ksf	0.365	0.370	io= 22.4	6%
initial	23.2	10/11/15	19	17	00	132.0	80.0	60.13	42.50	0.86	4.99E-09
final	22.9	10/13/15	16	42	00			53.15	45.10		4.46E-09
5	RT = 0.930	dT =	2725.00 min			σ'_c =	7.5 ksf	0.519	0.602	io= 22.4	-13%
initial	22.9	10/13/15	16	53	00	132.0	80.0	60.05	42.87	1.00	5.93E-09
final	22.4	10/14/15	08	45	00			56.61	43.98		5.36E-09
6	RT = 0.940	dT =	952.00 min			σ'_c =	7.5 ksf	0.256	0.257	io= 21.8	5%

TEST SUMMARY

Final Specimen and Test Conditions

Lc =	9.888	cm	ε_{axial} =	2.2%	
Ac =	41.793	cm^2			
Vc=	413.25	cm^3	ε_{vol} =	2.8%	
Sc =	0.237	cm^{-1}	Sc = Lc / Ac , final		

	w (%)	γ_τ (pcf)	γ_d (pcf)	S (%)
Initial	16.26	137.1	117.9	99.6
PreTest	14.82	139.3	121.3	100.0

HYDRAULIC CONDUCTIVITY SUMMARY

Averages for trials: 2-6

ave K @ 20 ºC: **5.11E-09** cm/sec

(i_o)ave = 22.2

Tested By: BB Reviewed By: G. Thomas

PERMEABILITY TEST: FALLING HEAD - CONSTANT VOLUME U-TUBE
ASTM D 5084 - Method F

Project No.: T60428794 | BORING: NEW-B012 | Test No.: P10609
Project Name: Dynegy CCR - Newton | SAMPLE: ST-7 | DEPTH (ft): 20.6

Specimen - Apparatus set-up - Test Information | Cell No. C | Apparatus No. 1 | Stage No.: 5

Preliminary Length/Area Calculations

Lo =	4.004	in	Lo=	10.171	cm
dLc=	0.045	in	Ao =	41.88	cm^2
Lc=	3.959	in	Vo =	425.95	cm^3
			Lc=	10.057	cm
dVc = 3 Vo * (dLc/Lo)			dVc=	14.36	cm^3
			Vc =	411.59	cm^3
Sc =	0.246	cm^{-1}	Ac=	40.926	cm^2

1) Specimen Tested in :	x	Triaxial Cell or		Compaction Mold or			
	x	with stones or		Stones with filter paper or			top + bottom
2) Specimen orientation for:	x	Vertical or		Horizontal permeability determination			
3) During saturation: Water flushed up sides of specimen to remove ai			x	No		Yes	
4) During consolidation:	x	Top and bottom drainage or		Top		Bottom only	
5) Direction of permeant :	x	Up during or		Down during permeation			
6) Permeant: water used	x	Tap		Distilled			
or		Demineralized		0.005 N calcium sulfate (CaSO4)			

Equations Used
Kt = - 0.0000757 * Sc/dT(min) * ln (ho/hf)
RT = (-0.02452*(ave. temp in C) + 1.495)
K @ 20 ºC = RT * Kt TubeC= 1.3127

TEST SUMMARY

Final Specimen and Test Conditions

Lc =	10.057	cm	ε_{axial} =	1.1%		
Ac =	41.598	cm^2				
Vc=	418.35	cm^3	ε_{vol} =	1.8%		
Sc =	0.242	cm^{-1}	Sc = Lc / Ac , final			

	w (%)	γ_τ (pcf)	γ_d (pcf)	S (%)
Initial	13.28	137.1	121.0	88.9
PreTest	14.02	140.5	123.2	100.0

HYDRAULIC CONDUCTIVITY SUMMARY
Averages for trials: 1-4
ave K @ 20 ºC: **7.77E-09** cm/sec
(i_o)ave = 26.8

Tested By: BB Reviewed By: G. Thomas

Consol Stage-Trial No.	Temp. ºC	Date	Time hr	Time min	Time sec	Initial σ_c psi	Initial Ub psi	U-tube Reading Head (cm) (cc)	U-tube Reading Tail (cm) (cc)	Flow in/out gradient	Preliminary Final at 20ºC cm/sec Dev. from Ave.
initial	21.6	10/26/15	09	43	00	117.4	100.0	58.25	37.33	0.97	8.93E-09
final	22.5	10/26/15	12	19	00			57.10	37.70		8.38E-09
1	RT = 0.954	dT =		156.00 min		σ'_c =	2.5 ksf	0.086	0.089	io= 26.2	8%
initial	22.5	10/26/15	12	20	00	117.4	100.0	58.63	37.24	1.04	8.86E-09
final	23.6	10/26/15	14	37	00			57.60	37.55		8.11E-09
2	RT = 0.930	dT =		137.00 min		σ'_c =	2.5 ksf	0.077	0.074	io= 26.7	4%
initial	23.6	10/26/15	14	38	00	117.4	100.0	58.85	37.16	0.99	8.15E-09
final	23.5	10/26/15	18	00	00			57.45	37.60		7.36E-09
3	RT = 0.918	dT =		202.00 min		σ'_c =	2.5 ksf	0.105	0.105	io= 27.1	-5%
initial	23.5	10/26/15	18	03	00	117.4	100.0	59.00	37.19	1.02	7.74E-09
final	21.0	10/27/15	08	44	00			53.90	38.75		7.23E-09
4	RT = 0.949	dT =		881.00 min		σ'_c =	2.5 ksf	0.382	0.374	io= 27.3	-7%
initial											
final											
5											
initial											
final											
6											

PERMEABILITY TEST: FALLING HEAD - CONSTANT VOLUME U-TUBE

ASTM D 5084 - Method F

Project No.: T60428794 | BORING: NEW-B015 | Test No.: P10608

Project Name: Dynegy CCR - Newton | SAMPLE: ST-2A | DEPTH (ft): 25.45

Specimen - Apparatus set-up - Test Information | Cell No. C | Apparatus No. 3 | Stage No.: 2

Preliminary Length/Area Calculations

Lo =	4.012	in	Lo=	10.191	cm
dLc=	0.025	in	Ao =	42.03	cm^2
Lc=	3.987	in	Vo =	428.31	cm^3
			Lc=	10.127	cm
dVc = 3 Vo * (dLc/Lo)			dVc=	8.01	cm^3
			Vc =	420.30	cm^3
Sc =	0.244	cm^{-1}	Ac=	41.501	cm^2

1) Specimen Tested in :	x	Triaxial Cell or		Compaction Mold or			
	x	with stones or		Stones with filter paper or			top + bottom
2) Specimen orientation for:	x	Vertical or		Horizontal permeability determination			
3) During saturation: Water flushed up sides of specimen to remove air			x	No		Yes	
4) During consolidation:	x	Top and bottom drainage or		Top		Bottom only	
5) Direction of permeant :	x	Up during or		Down during permeation			
6) Permeant: water used	x	Tap		Distilled			
or		Demineralized		0.005 N calcium sulfate (CaSO4)			Permeability

Equations Used

Kt = - 0.0000755 * Sc/dT(min) * ln (ho/hf)

RT = (-0.02452*(ave. temp in C) + 1.495)

K @ 20 ºC = RT * Kt TubeC= 1.3132

Consol Stage-Trial No.	Temp. ºC	Date	Time hr	Time min	Time sec	Initial σ_c psi	Initial Ub psi	U-tube Reading Head (cm) (cc)	U-tube Reading Tail (cm) (cc)	Flow in/out gradient	Preliminary Final at 20ºC cm/sec Dev. from Ave.
initial	22.5	10/16/15	09	48	00	106.9	100.0	63.45	47.50	0.86	3.95E-09
final	24.0	10/16/15	16	24	00			62.46	47.86		3.57E-09
1	RT = 0.925	dT =		396.00 min		σ'_c =	1.0 ksf	0.074	0.086	io= 19.8	95%
initial	21.0	10/19/15	09	42	00	106.9	100.0	64.94	47.00	0.80	2.38E-09
final	22.5	10/19/15	17	53	00			64.10	47.33		2.24E-09
2	RT = 0.962	dT =		491.00 min		σ'_c =	1.0 ksf	0.063	0.079	io= 22.3	22%
initial	22.5	10/19/15	17	54	00	106.9	100.0	66.26	46.67	0.87	2.07E-09
final	22.0	10/20/15	08	42	00			64.84	47.18		1.92E-09
3	RT = 0.949	dT =		888.00 min		σ'_c =	1.0 ksf	0.106	0.122	io= 24.3	5%
initial	22.0	10/20/15	08	45	00	106.9	100.0	66.70	46.50	0.89	1.67E-09
final	23.1	10/20/15	17	04	00			66.02	46.74		1.54E-09
4	RT = 0.942	dT =		499.00 min		σ'_c =	1.0 ksf	0.051	0.057	io= 25.1	-16%
initial	23.1	10/20/15	17	07	00	106.9	100.0	66.82	46.46	1.02	1.76E-09
final	21.5	10/21/15	08	45	00			65.49	46.87		1.63E-09
5	RT = 0.948	dT =		938.00 min		σ'_c =	1.0 ksf	0.099	0.098	io= 25.3	-11%
initial											
final											
6		dT =				σ'_c =					

TEST SUMMARY

Final Specimen and Test Conditions

Lc =	10.127	cm	ε_{axial} =	0.6%	
Ac =	42.456	cm^2			
Vc=	429.98	cm^3	ε_{vol} =	-0.4%	
Sc =	0.239	cm^{-1}	Sc = Lc / Ac , final		

	w (%)	γ_τ (pcf)	γ_d (pcf)	S (%)
Initial	23.96	126.1	101.7	96.8
PreTest	24.99	126.6	101.3	100.0

HYDRAULIC CONDUCTIVITY SUMMARY

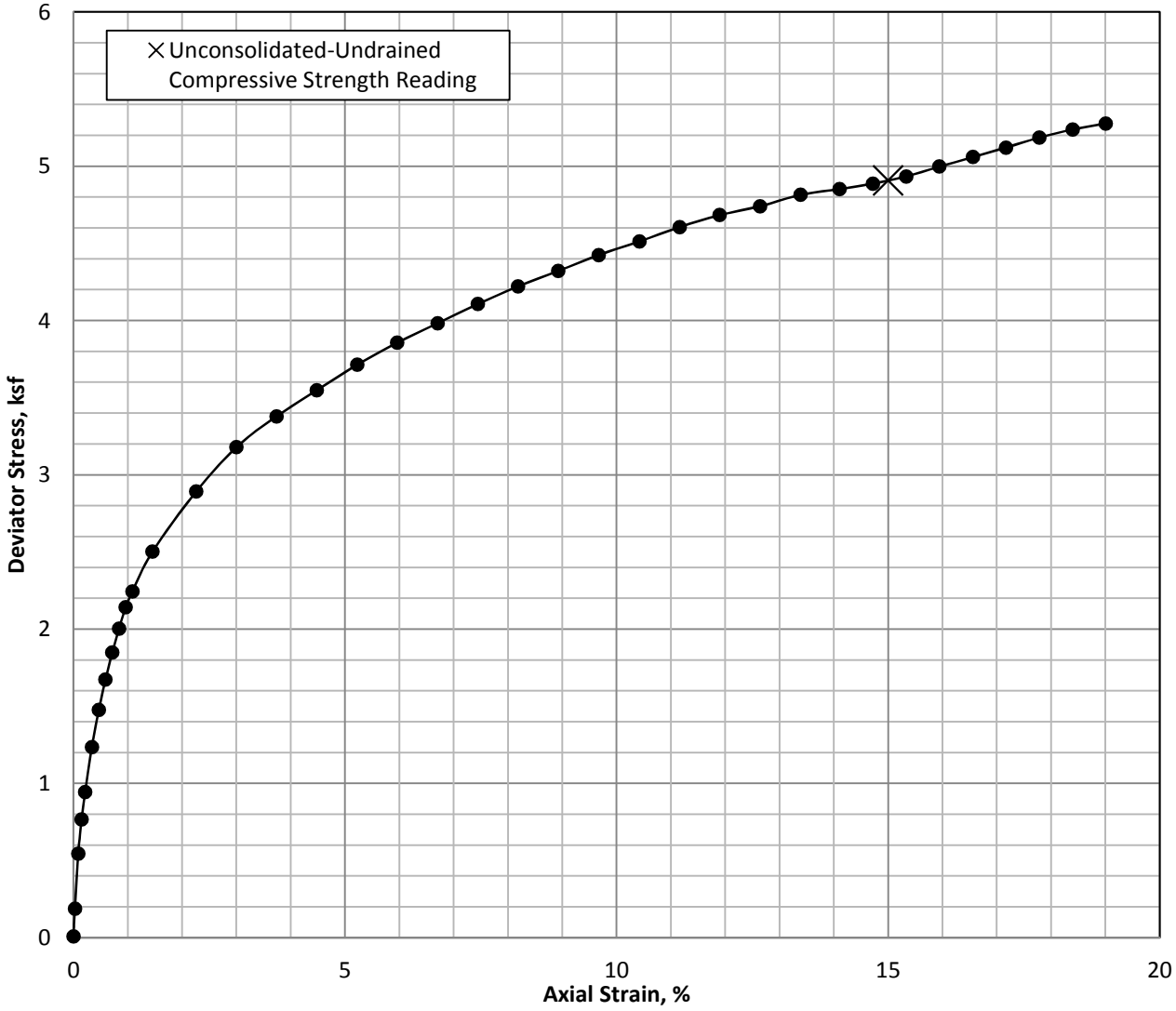
Averages for trials: 2-5

ave K @ 20 ºC: **1.83E-09** cm/sec

(i_o)ave = 24.2

Tested By: BB Reviewed By: G. Thomas

UNCONSOLIDATED-UNDRAINED COMPRESSIVE STRENGTH TEST, ASTM METHOD D2850



Specimen and Material Property Information

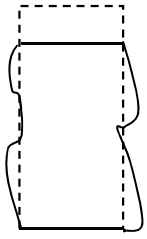
Sample Type: Intact tube sample

Description and/or Classification: CL, brown lean clay

Cell Pressure (ksf)	Water [1] Content (%)	Wet Unit Weight (pcf)	Dry Unit [1] Weight (pcf)	Void Ratio (-)	Saturation [2] (%)	Length (inch)	Diameter (inch)	L/D (-)	LL/ PL (-)	PI (-)	Specific [2] Gravity (-)
0 (Initial)	19.4	130.9	109.7	0.56	94.8	5.999	2.880	2.1	43	26	2.74
4.0	19.4	132.2	110.8	0.54	97.5	5.979	2.870	2.1	17		

Failure Summary

U-U Compressive Strength (ksf)	U-U Shear Strength, s_u (ksf)	Strain to to Peak (%)	Strain Rate (%/min)
4.91	2.455	15.0	0.74



FAILURE SKETCH

Remarks and Notes:

(1) Water Content determined after shear from partial specimen.

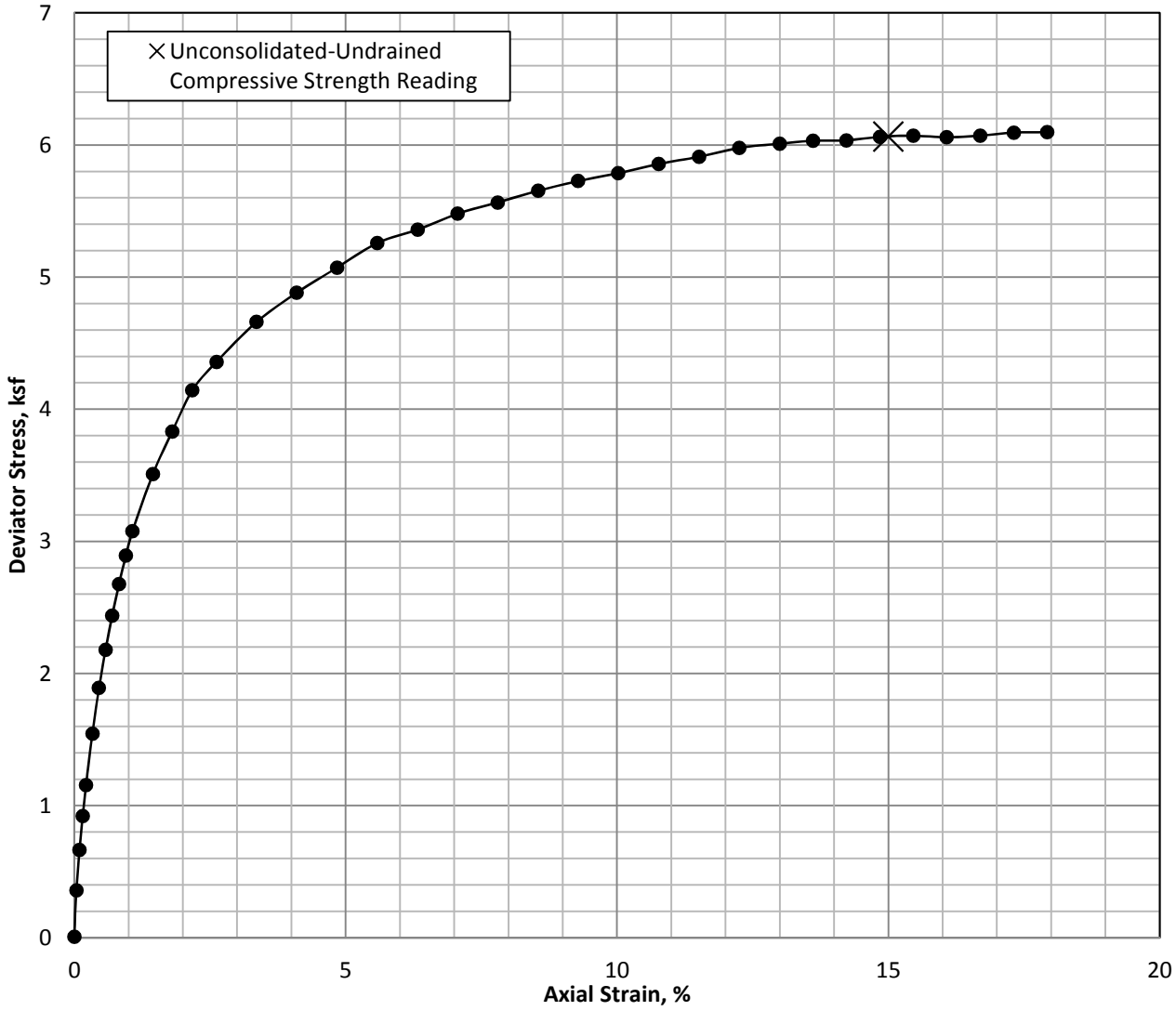
(2) Assumed specific gravity

Tested by: BB Reviewed by: GET

Test Date: 10/23/2015 Review Date: 10/27/2015

AECOM **Project # 60428794-108**	**Dynegy CCR - Newton**	**UNCONSOLIDATED-UNDRAINED COMPRESSION TEST**
TerraSense, LLC **Project # T60428794**		**Boring: NEW-B003 Sample: ST-2** **Section: B Depth: 24.15 ft.**

UNCONSOLIDATED-UNDRAINED COMPRESSIVE STRENGTH TEST, ASTM METHOD D2850



Specimen and Material Property Information

Sample Type: Intact tube sample

Description and/or Classification: CH, brown fat clay

Cell Pressure (ksf)	Water (1) Content (%)	Wet Unit Weight (pcf)	Dry Unit (1) Weight (pcf)	Void Ratio (-)	Saturation (2) (%)	Length (inch)	Diameter (inch)	L/D (-)	LL/ PL (-)	PI (-)	Specific (2) Gravity (-)
0 (Initial)	21.1	129.2	106.7	0.60	96.0	6.014	2.881	2.1	55	39	2.74
3.0	21.1	130.0	107.3	0.59	97.5	6.002	2.875	2.1	16		

Failure Summary

U-U Compressive Strength (ksf)	U-U Shear Strength, s_u (ksf)	Strain to to Peak (%)	Strain Rate (%/min)
6.06	3.03	15.0	0.74

FAILURE SKETCH

Remarks and Notes:

(1) Water Content determined after shear from partial specimen.

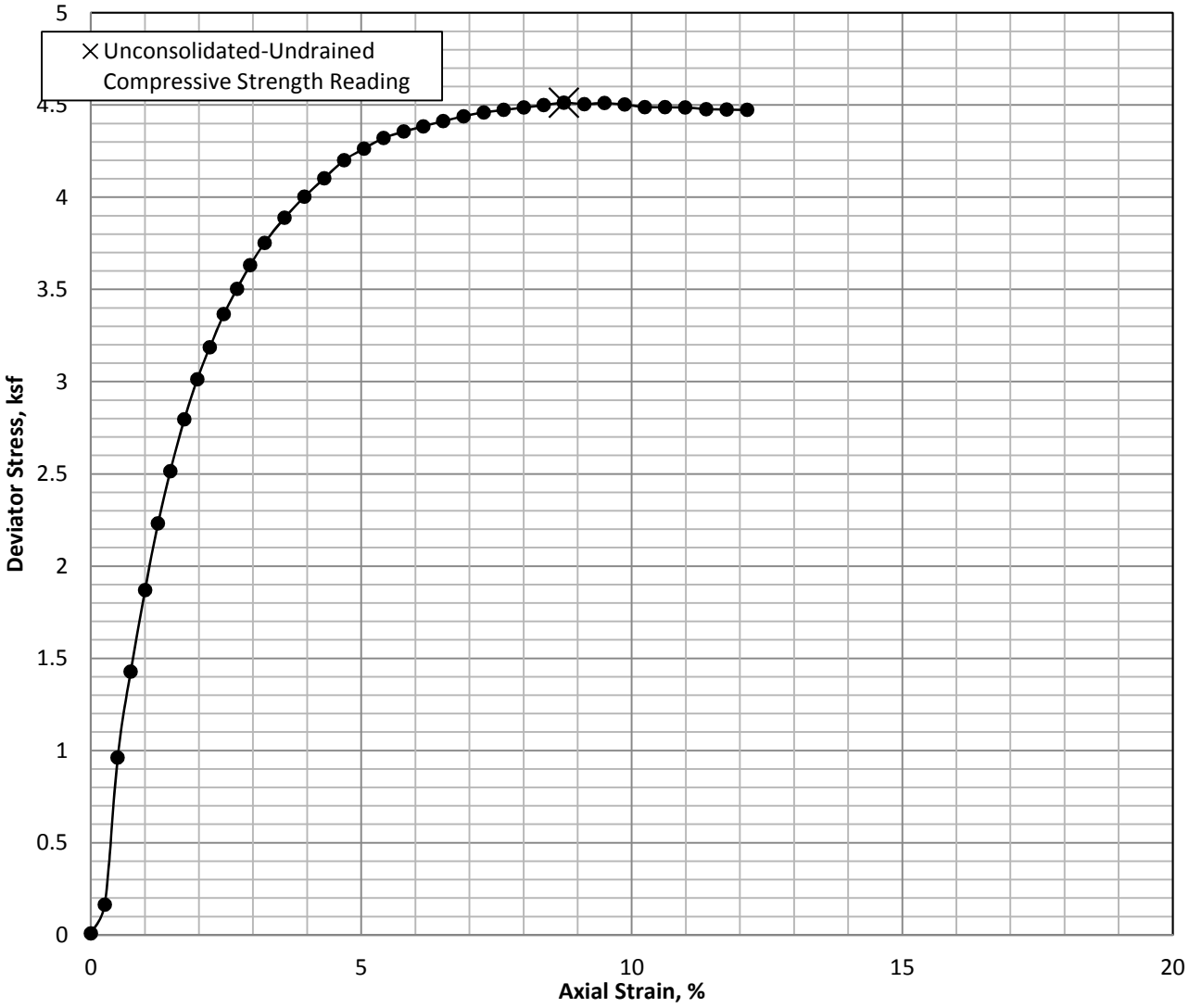
(2) Assumed specific gravity

Tested by: BB Reviewed by: GET

Test Date: 10/23/2015 Review Date: 10/27/2015

AECOM **Project # 60428794-108**	**Dynegy CCR - Newton**	**UNCONSOLIDATED-UNDRAINED COMPRESSION TEST**
TerraSense, LLC **Project # T60428794**		**Boring: NEW-B003 Sample: ST-3** **Section: C Depth: 28.8 ft.**

UNCONSOLIDATED-UNDRAINED COMPRESSIVE STRENGTH TEST, ASTM METHOD D2850



Specimen and Material Property Information

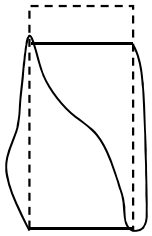
Sample Type: Intact tube sample

Description and/or Classification: CL, orange-brown clay

Cell Pressure (ksf)	Water [1] Content (%)	Wet Unit Weight (pcf)	Dry Unit [1] Weight (pcf)	Void Ratio (-)	Saturation [2] (%)	Length (inch)	Diameter (inch)	L/D (-)	LL/ PL (-)	PI (-)	Specific [2] Gravity (-)
0 (Initial)	18.2	130.8	110.6	0.54	92.0	5.996	2.879	2.1	40	23	2.73
3.5	18.2	131.8	111.5	0.53	94.2	5.980	2.871	2.1	17		

Failure Summary

U-U Compressive Strength (ksf)	U-U Shear Strength, s_u (ksf)	Strain to to Peak (%)	Strain Rate (%/min)
4.51	2.255	8.7	0.74



FAILURE SKETCH

Remarks and Notes:

(1) Water Content determined after shear from partial specimen.

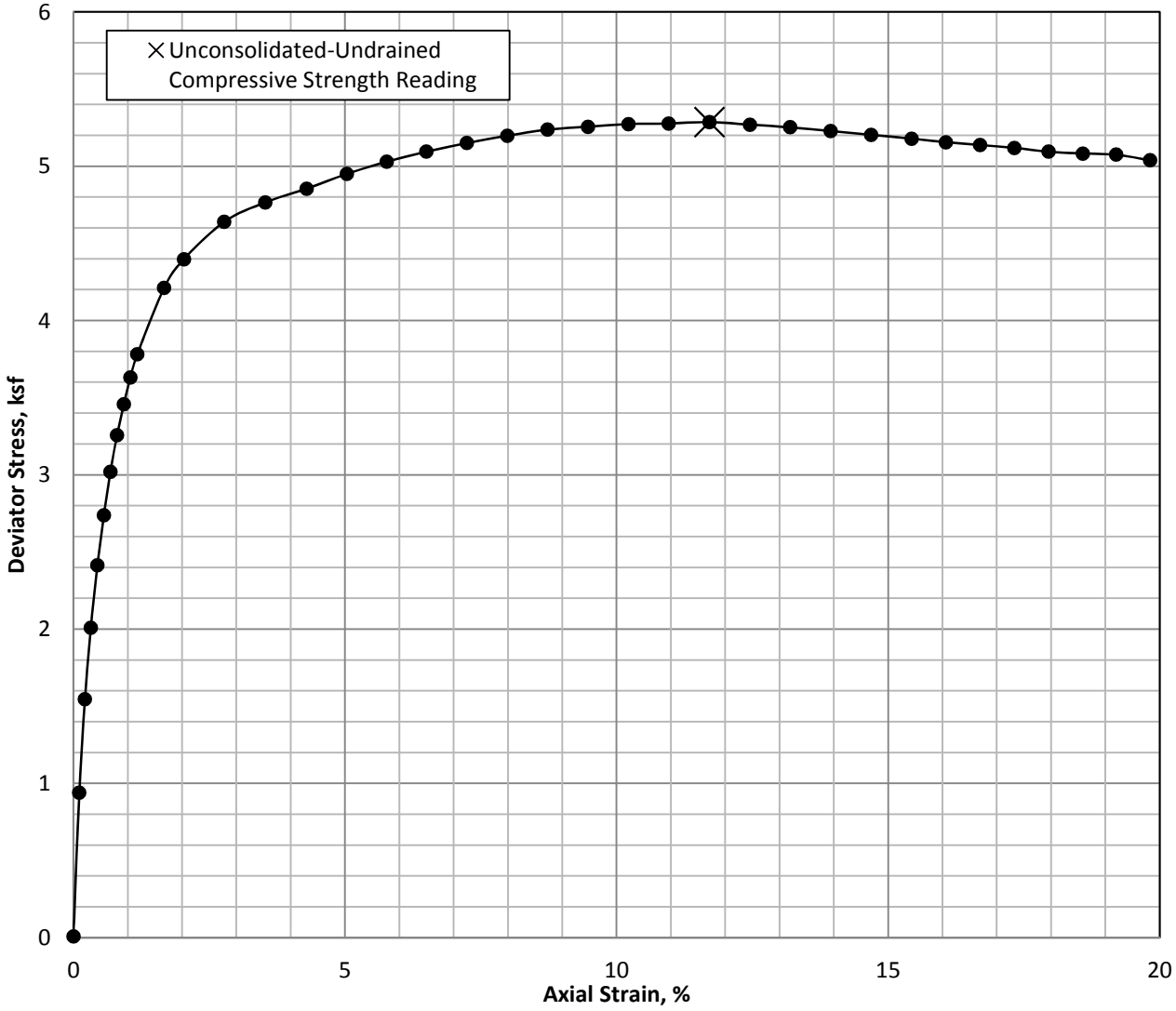
(2) Assumed specific gravity

Tested by: BB Reviewed by: GET

Test Date: 10/28/2015 Review Date: 11/2/2015

AECOM **Project # 60428794-108**	**Dynegy CCR - Newton**	**UNCONSOLIDATED-UNDRAINED COMPRESSION TEST**
TerraSense, LLC **Project # T60428794**		**Boring: NEW-B006 Sample: ST-1** **Section: B Depth: 21.20 ft.**

UNCONSOLIDATED-UNDRAINED COMPRESSIVE STRENGTH TEST, ASTM METHOD D2850



Specimen and Material Property Information

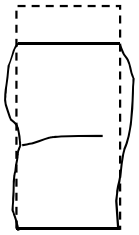
Sample Type: Intact tube sample

Description and/or Classification: CH, brown fat clay

Cell Pressure (ksf)	Water (1) Content (%)	Wet Unit Weight (pcf)	Dry Unit (1) Weight (pcf)	Void Ratio (-)	Saturation (2) (%)	Length (inch)	Diameter (inch)	L/D (-)	LL/ PL (-)	PI (-)	Specific (2) Gravity (-)
0 (Initial)	21.5	132.0	108.6	0.61	98.9	5.987	2.877	2.1	52	40	2.80
6.0	21.5	133.0	109.4	0.60	100.9	5.972	2.870	2.1	12		

Failure Summary

U-U Compressive Strength (ksf)	U-U Shear Strength, s_u (ksf)	Strain to to Peak (%)	Strain Rate (%/min)
5.29	2.645	11.7	0.74



FAILURE SKETCH

Remarks and Notes:

(1) Water Content determined after shear from partial specimen.

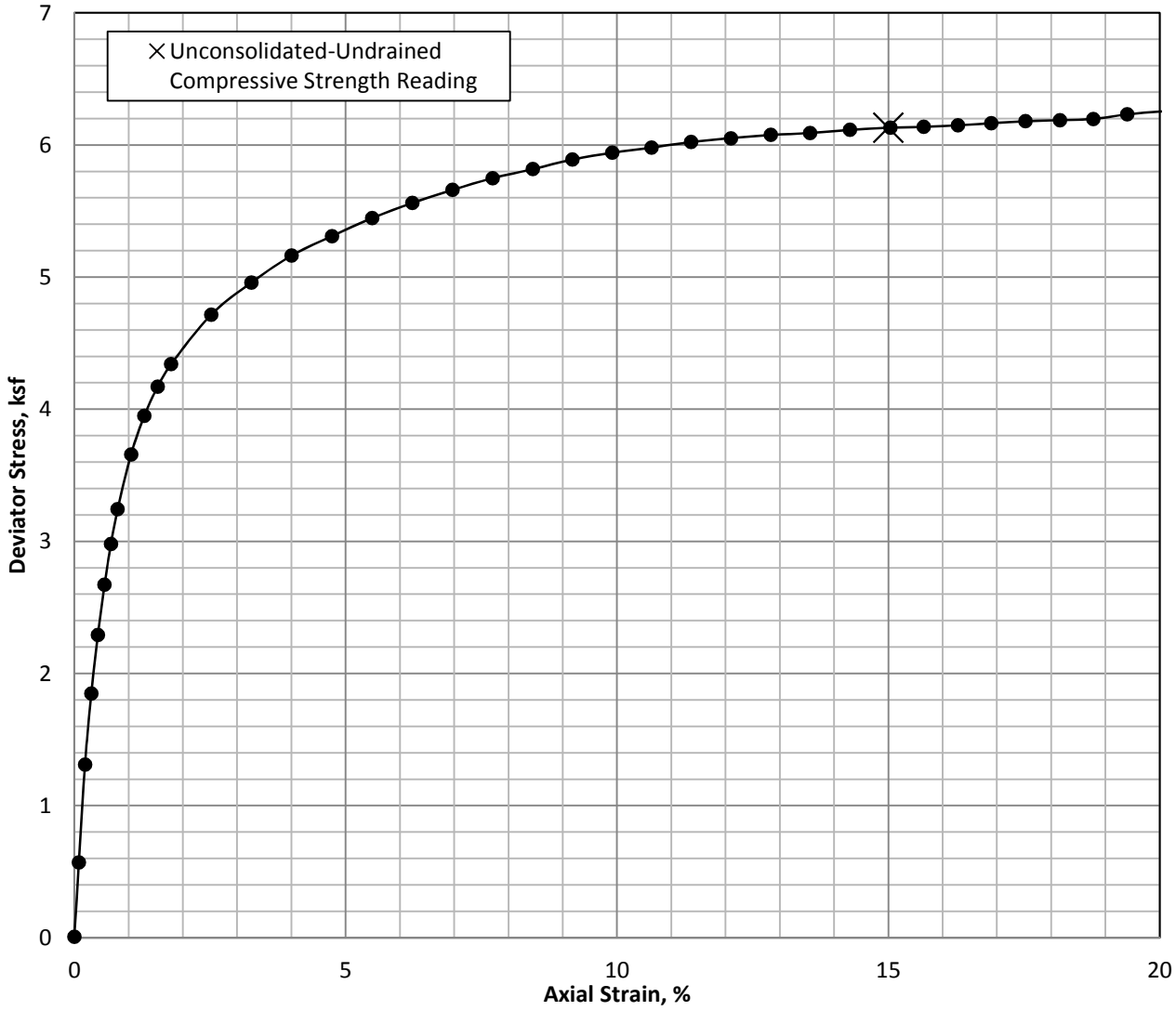
(2) Assumed specific gravity

Tested by: BB Reviewed by: CMJ

Test Date: 10/15/2015 Review Date: 10/26/2015

AECOM **Project # 60428794-108**	**Dynegy CCR - Newton**	**UNCONSOLIDATED-UNDRAINED COMPRESSION TEST**
TerraSense, LLC **Project # T60428794**		**Boring: NEW-B007 Sample: ST-3C** **Section: Depth: 31.70 ft.**

UNCONSOLIDATED-UNDRAINED COMPRESSIVE STRENGTH TEST, ASTM METHOD D2850



Specimen and Material Property Information

Sample Type: Intact tube sample

Description and/or Classification: CH, brown fat clay

Cell Pressure (ksf)	Water (1) Content (%)	Wet Unit Weight (pcf)	Dry Unit (1) Weight (pcf)	Void Ratio (-)	Saturation (2) (%)	Length (inch)	Diameter (inch)	L/D (-)	LL/ PL (-)	PI (-)	Specific (2) Gravity (-)
0 (Initial)	16.7	136.3	116.8	0.46	98.2	5.986	2.882	2.1	50	37	2.74
2.5	16.7	136.7	117.2	0.46	99.3	5.979	2.878	2.1	13		

Failure Summary

U-U Compressive Strength (ksf)	U-U Shear Strength, s_u (ksf)	Strain to to Peak (%)	Strain Rate (%/min)
6.13	3.065	15.0	0.74

FAILURE SKETCH

Remarks and Notes:

(1) Water Content determined after shear from partial specimen.

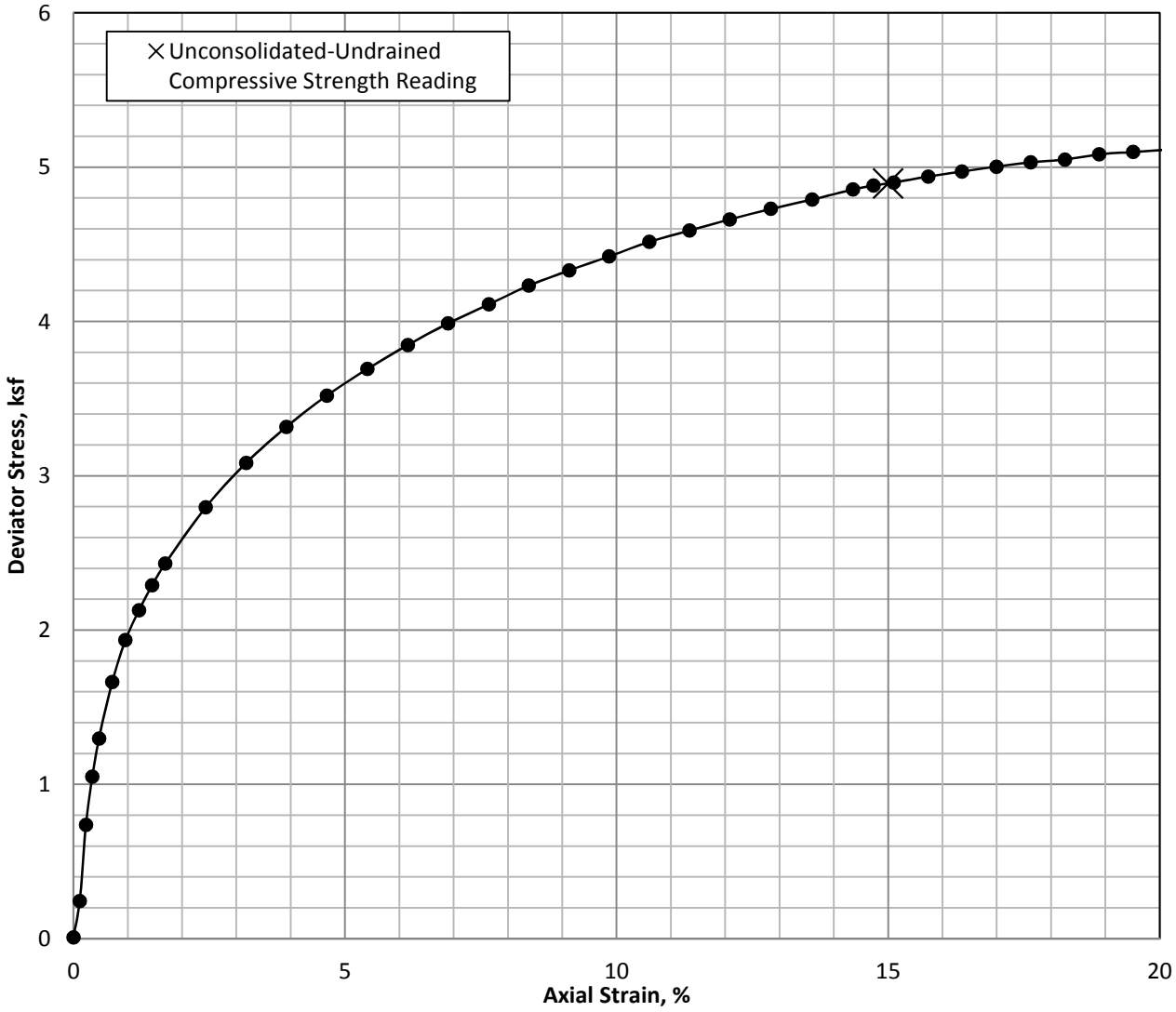
(2) Assumed specific gravity

Tested by: BB Reviewed by: CMJ

Test Date: 10/15/2015 Review Date: 10/26/2015

AECOM **Project # 60428794-108** **TerraSense, LLC** **Project # T60428794**	**Dynegy CCR - Newton**	**UNCONSOLIDATED-UNDRAINED COMPRESSION TEST** **Boring: NEW-B008 Sample: ST-1C** **Section: Depth: 16.65 ft.**

UNCONSOLIDATED-UNDRAINED COMPRESSIVE STRENGTH TEST, ASTM METHOD D2850



Specimen and Material Property Information

Sample Type: Intact tube sample

Description and/or Classification: CL, brown lean clay

Cell Pressure (ksf)	Water [1] Content (%)	Wet Unit Weight (pcf)	Dry Unit [1] Weight (pcf)	Void Ratio (-)	Saturation [2] (%)	Length (inch)	Diameter (inch)	L/D (-)	LL/ PL (-)	PI (-)	Specific [2] Gravity (-)
0 (Initial)	19.0	132.3	111.2	0.52	98.6	5.982	2.874	2.1	47	32	2.71
2.0	19.0	132.7	111.6	0.52	99.6	5.975	2.870	2.1	15		

Failure Summary

U-U Compressive Strength (ksf)	U-U Shear Strength, s_u (ksf)	Strain to to Peak (%)	Strain Rate (%/min)
4.9	2.45	15.0	0.75

FAILURE SKETCH

Remarks and Notes:

(1) Water Content determined after shear from partial specimen.

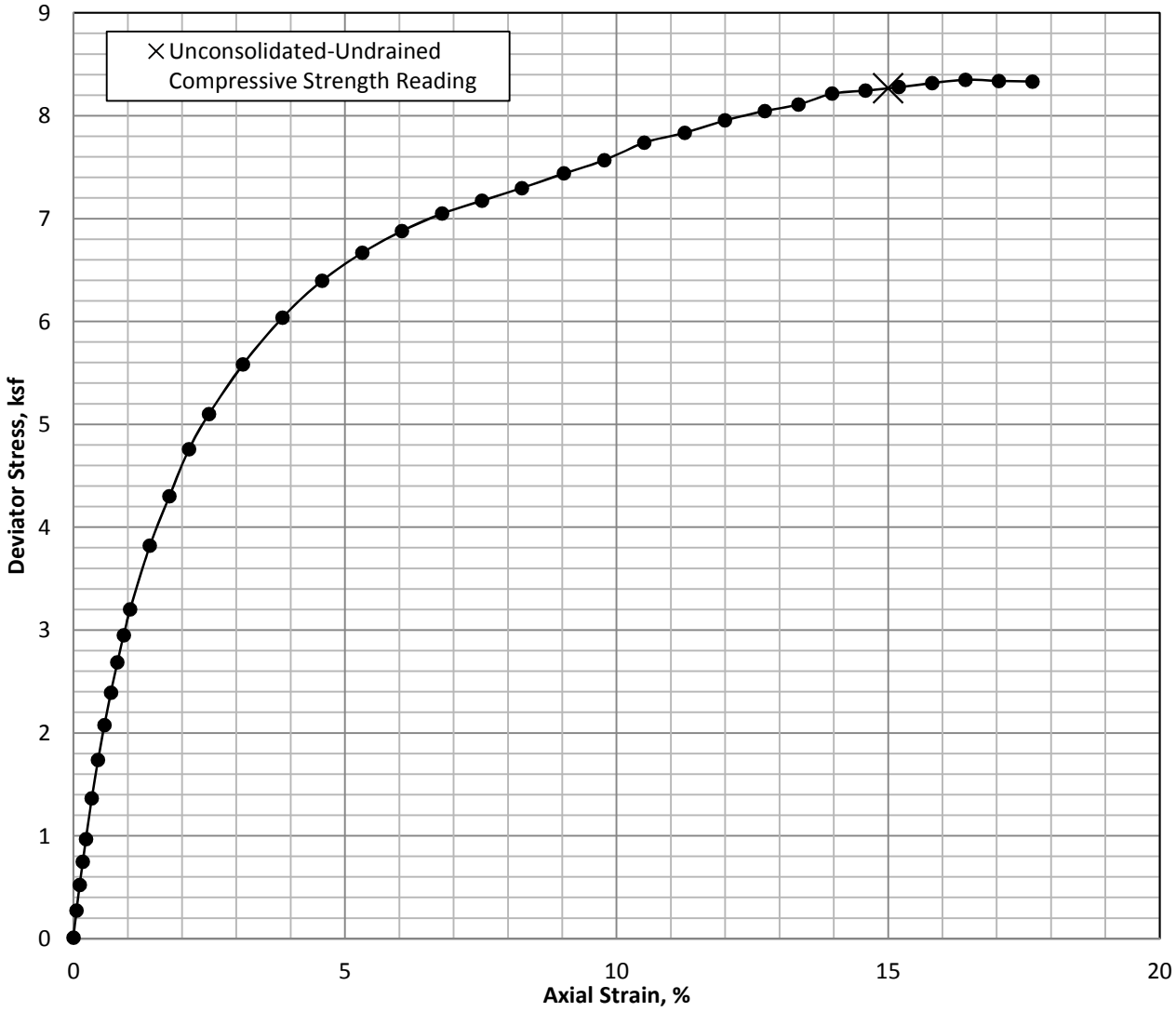
(2) Assumed specific gravity

Tested by: BB Reviewed by: CMJ

Test Date: 10/15/2015 Review Date: 10/26/2015

AECOM **Project # 60428794-108**	**Dynegy CCR - Newton**	**UNCONSOLIDATED-UNDRAINED COMPRESSION TEST**
TerraSense, LLC **Project # T60428794**		**Boring: NEW-B009 Sample: ST-1B** **Section: Depth: 9.75 ft.**

UNCONSOLIDATED-UNDRAINED COMPRESSIVE STRENGTH TEST, ASTM METHOD D2850



Specimen and Material Property Information

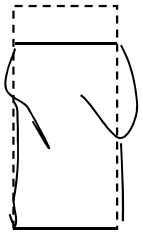
Sample Type: Intact tube sample

Description and/or Classification: CL, brown sandy clay, trace gravel

Cell Pressure (ksf)	Water (1) Content (%)	Wet Unit Weight (pcf)	Dry Unit (1) Weight (pcf)	Void Ratio (-)	Saturation (2) (%)	Length (inch)	Diameter (inch)	L/D (-)	LL/ PL (-)	PI (-)	Specific (2) Gravity (-)
0 (Initial)	12.6	139.6	123.9	0.38	91.1	6.033	2.883	2.1	34	21	2.74
1.5	12.6	140.3	124.5	0.37	92.7	6.023	2.878	2.1	13		

Failure Summary

U-U Compressive Strength (ksf)	U-U Shear Strength, s_u (ksf)	Strain to to Peak (%)	Strain Rate (%/min)
8.27	4.135	15.0	0.74



FAILURE SKETCH

Remarks and Notes:

(1) Water Content determined after shear from partial specimen.

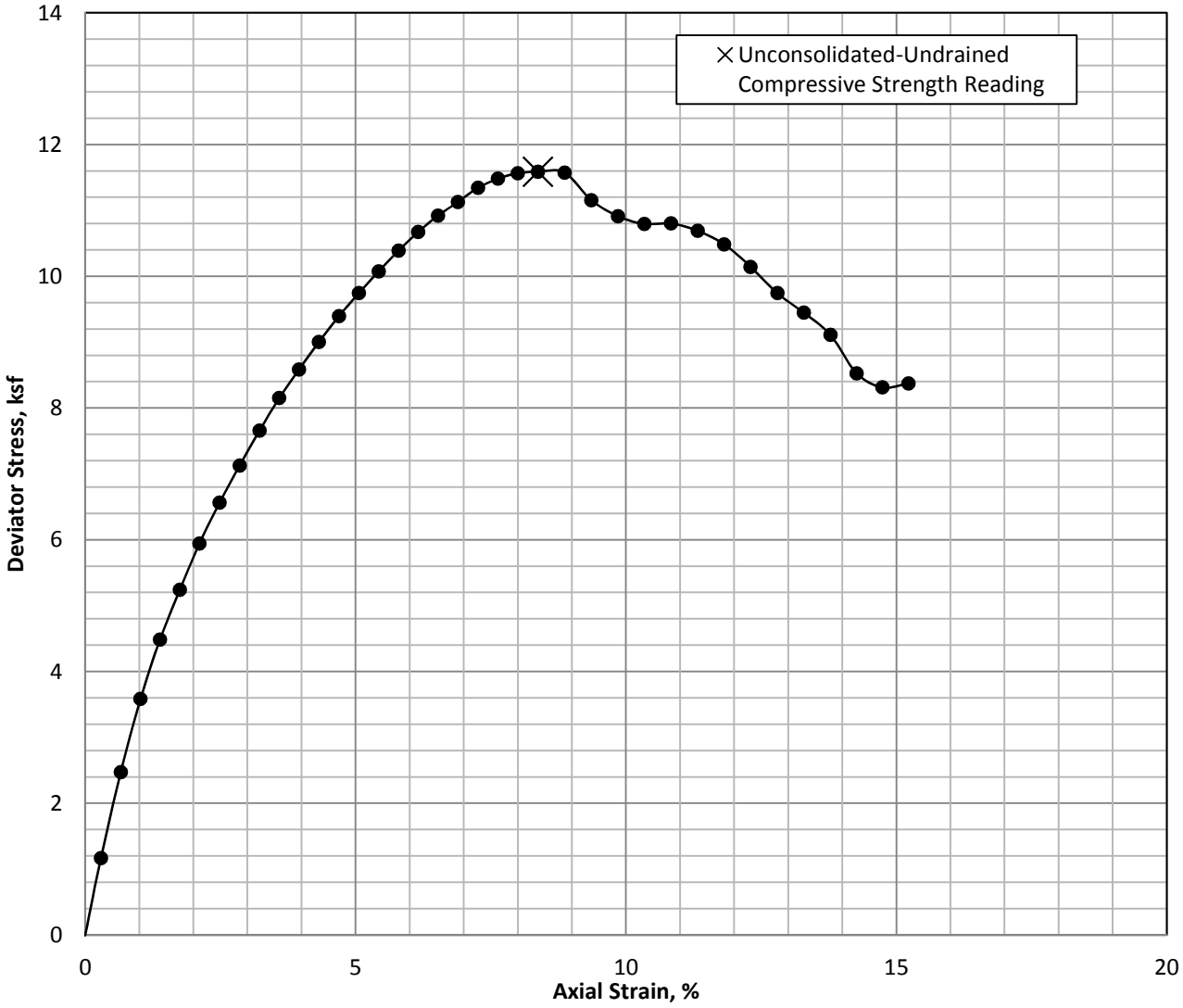
(2) Assumed specific gravity

Tested by: BB Reviewed by: GET

Test Date: 10/23/2015 Review Date: 10/29/2015

AECOM **Project # 60428794-108**	**Dynegy CCR - Newton**	**UNCONSOLIDATED-UNDRAINED COMPRESSION TEST**
TerraSense, LLC **Project # T60428794**		**Boring: NEW-B012 Sample: ST-4** **Section: C Depth: 9.45 ft.**

UNCONSOLIDATED-UNDRAINED COMPRESSIVE STRENGTH TEST, ASTM METHOD D2850



Specimen and Material Property Information

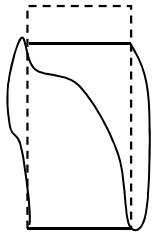
Sample Type: Intact tube sample

Description and/or Classification: SC, orange brown clayey sand

Cell Pressure (ksf)	Water (1) Content (%)	Wet Unit Weight (pcf)	Dry Unit (1) Weight (pcf)	Void Ratio (-)	Saturation (2) (%)	Length (inch)	Diameter (inch)	L/D (-)	LL/ PL (-)	PI (-)	Specific (2) Gravity (-)
0 (Initial)	9.5	142.7	130.3	0.31	84.3	6.025	2.886	2.1	28	15	2.73
0.5	9.5	142.9	130.4	0.31	84.7	6.023	2.885	2.1	13		

Failure Summary

U-U Compressive Strength (ksf)	U-U Shear Strength, s_u (ksf)	Strain to to Peak (%)	Strain Rate (%/min)
11.6	5.8	8.4	0.73



FAILURE SKETCH

Remarks and Notes:

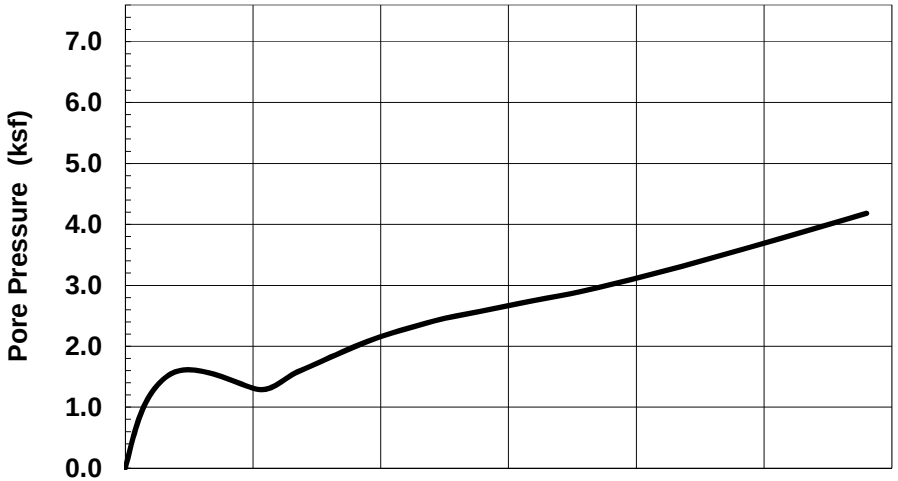
(1) Water Content determined after shear from partial specimen.

(2) Assumed specific gravity

Tested by: BB Reviewed by: GET

Test Date: 9/17/2015 Review Date: 10/27/2015

AECOM **Project # 60428794-108**	**Dynegy CCR - Newton**	**UNCONSOLIDATED-UNDRAINED COMPRESSION TEST**
TerraSense, LLC **Project # T60428794**		**Boring: NEW-B014 Sample: ST-1** **Section: B Depth: 3.50 ft.**



SAMPLE INFORMATION

Boring: NEW-B007 Sample: ST-5 Depth: 51.05 feet
Type: Intact tube sample
Description: CL, stiff brown clay, trace c-f sand, fine gravel
LL = 32 PL = 16 PI = 16

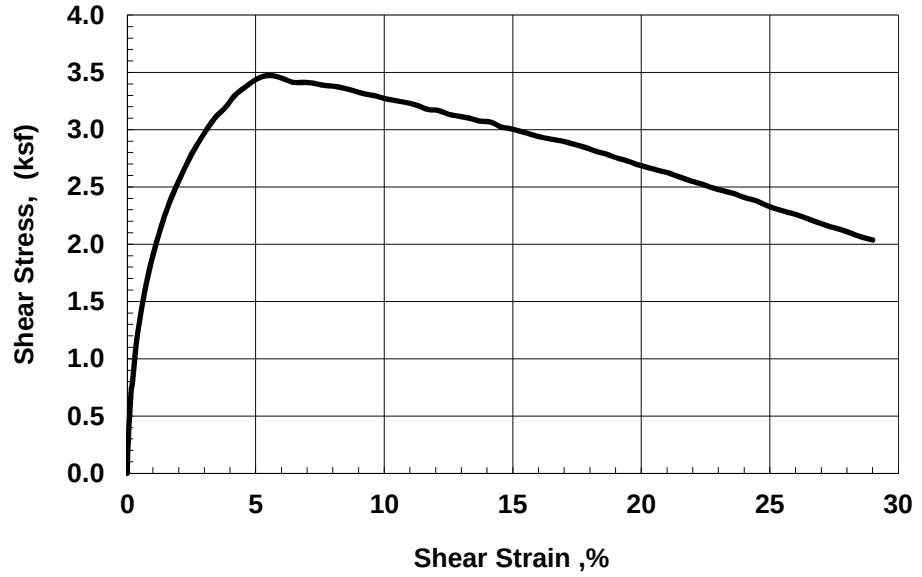
SPECIMEN INFORMATION (Initial)

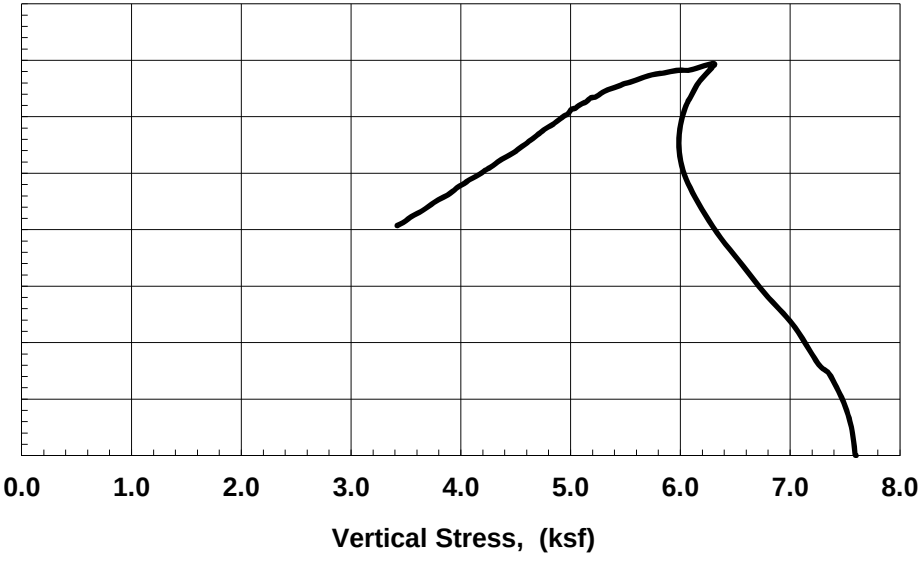
Height: 0.72 Diameter: 2.63 inch Area: 5.42 in²
Water Content: 13.9 % Total Unit Weight: 136.1 pcf

TEST SUMMARY

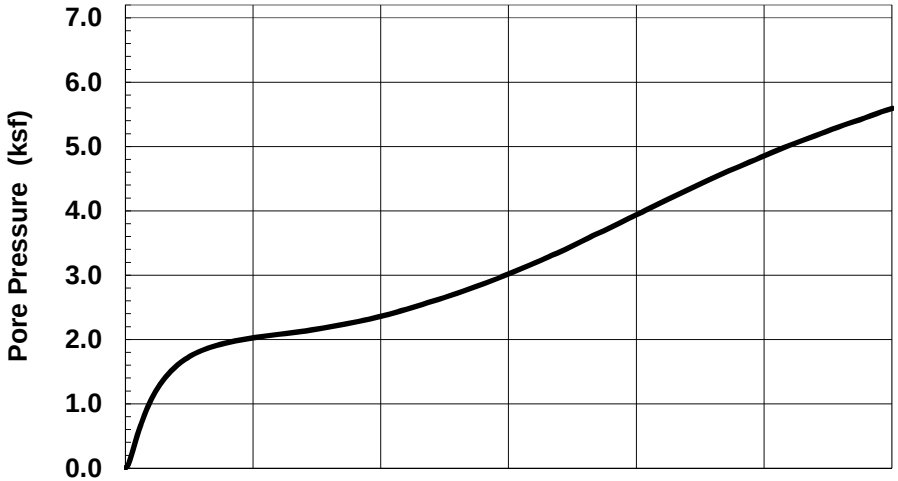
Vertical Consolidation Stress: 7.60 ksf OCR = 1.0
Water Content: 14.8 % Total Unit Weight: 139.9 pcf
Peak Shear Strength: 3.47 ksf @ 5.6 % Strain
Strain Rate: 0.064 %/min

REMARKS:





Test by: D Tso	Project No. T60428794	AECOM #60428794 Dynegy CCR - Newton	CONSTANT VOLUME	
Checked by: GET	**TerraSense, LLC**		DIRECT SIMPLE SHEAR Boring NEW-B007 Sample ST-5	October-15



SAMPLE INFORMATION

Boring: NEW-B012 Sample: ST-15 Depth: 61.45 feet
Type: Intact tube sample
Description: CL, brown clay
LL = 42 PL = 14 PI = 28

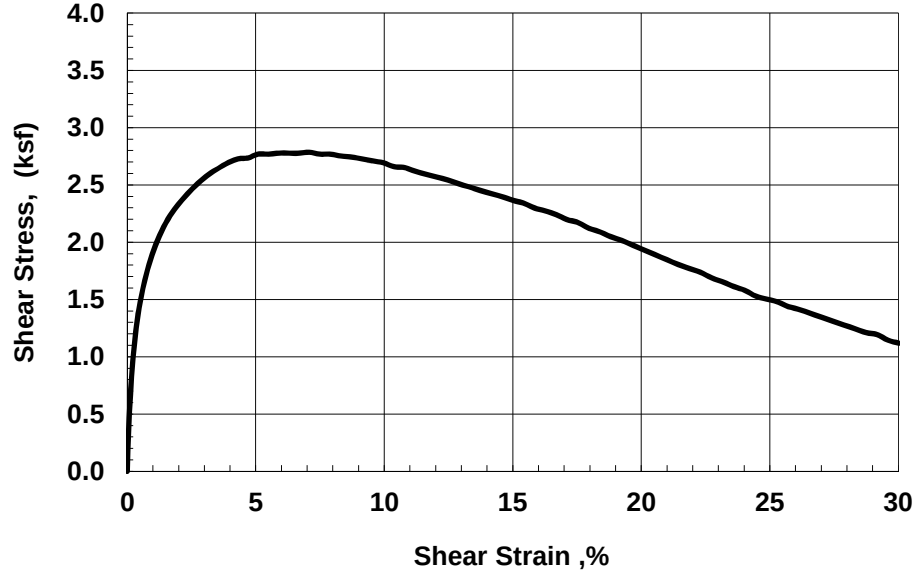
SPECIMEN INFORMATION (Initial)

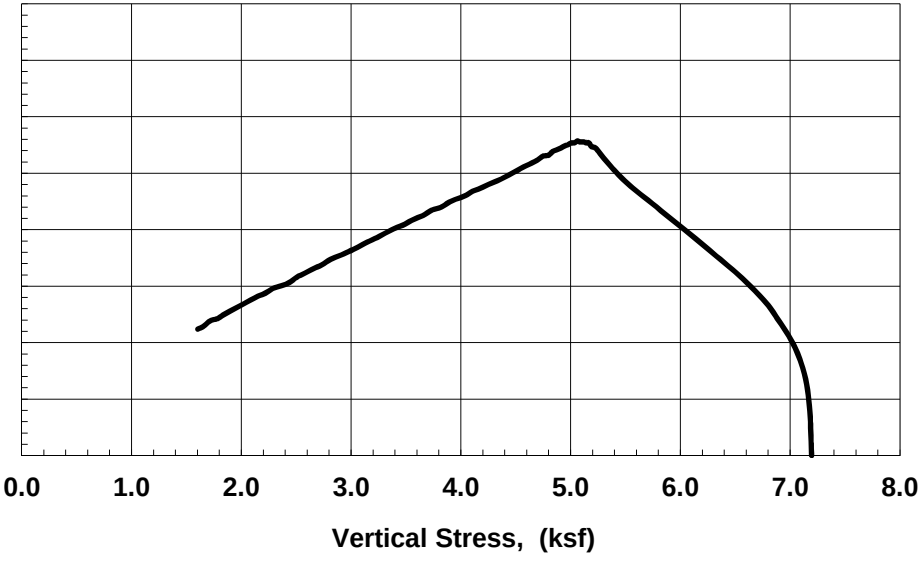
Height: 0.72 Diameter: 2.63 inch Area: 5.45 in²
Water Content: 12.8 % Total Unit Weight: 132.5 pcf

TEST SUMMARY

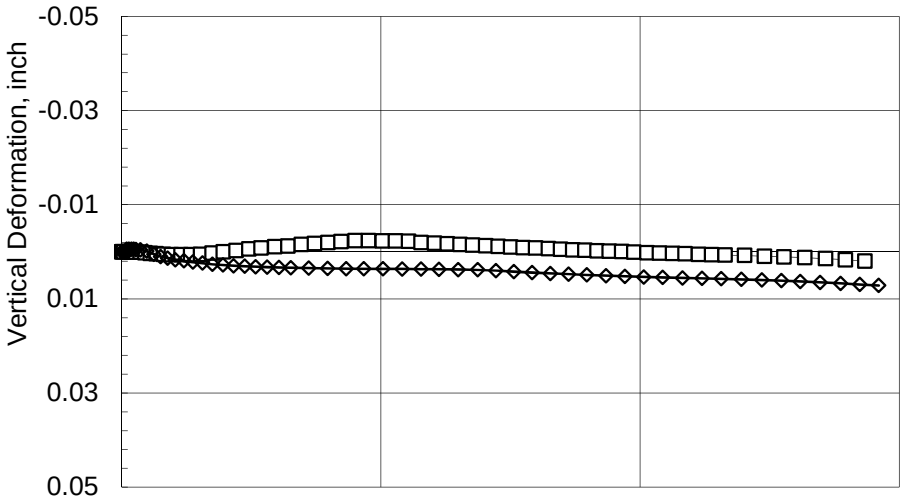
Vertical Consolidation Stress: 7.20 ksf OCR = 1.0
Water Content: 13.6 % Total Unit Weight: 138.6 pcf
Peak Shear Strength: 2.79 ksf @ 7.1 % Strain
Strain Rate: 0.067 %/min

REMARKS:





Test by: G. Thomas	Project No. T60428794	AECOM #60428794 Dynegy CCR - Newton	CONSTANT VOLUME	
Checked by: GET	**TerraSense, LLC**		DIRECT SIMPLE SHEAR Boring NEW-B012 Sample ST-15	October-15



SAMPLE INFORMATION

Boring: NEW-B006 Sample: ST- 4 Depth: 35-35.8 feet
Type: Intact tube sample
Description: CL, brown sandy clay

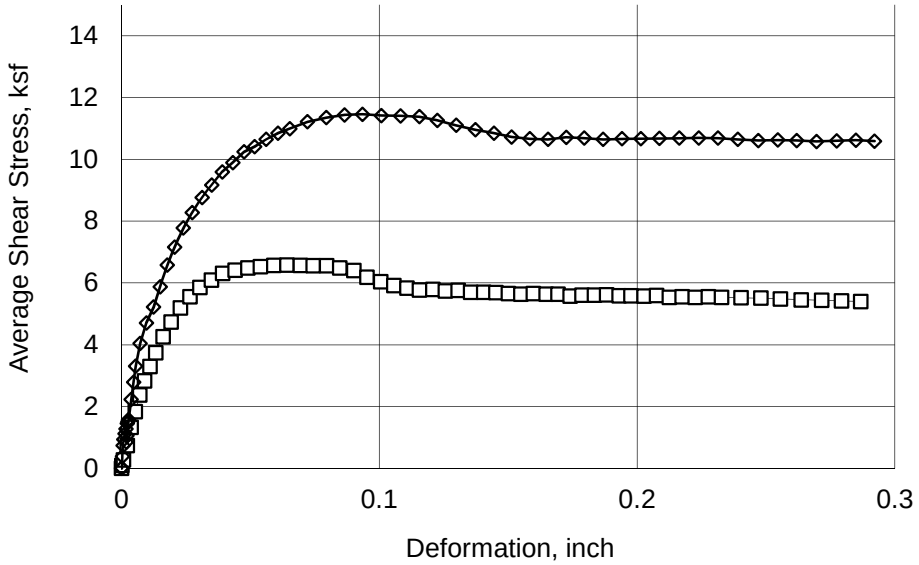
TEST INFORMATION

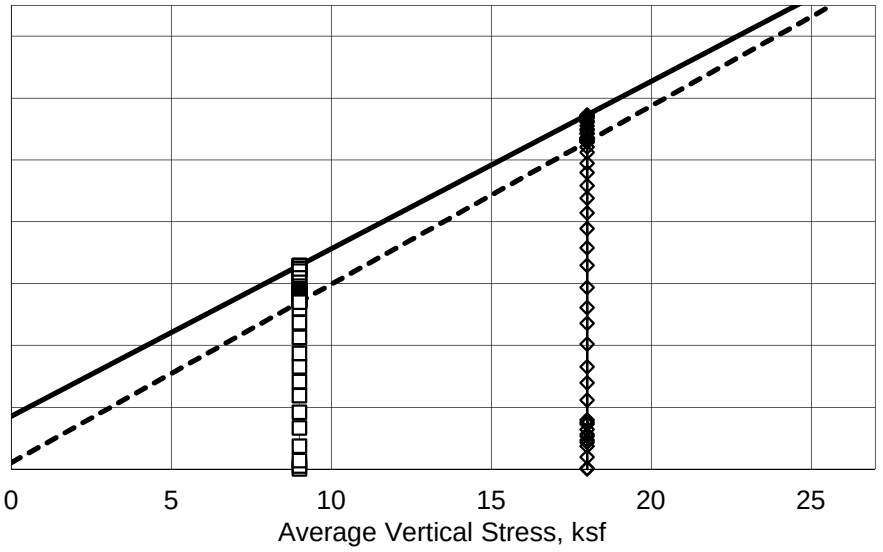
Test	Symbol	Vertical Stress (ksf)	Deformation Rate (inch/min.)
DS1619	□	9.0	0.0022
DS1617	◊	18.0	0.0020

TEST SUMMARY

Peak Effective Friction Angle: 28.4°, cohesion = 1.7ksf
Final Effective Friction Angle: 30.0°, cohesion = 0.2ksf

REMARKS:





Prepared by: MHC Checked by: GET	AECOM #60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR** **SERIES SUMMARY**	
	TerraSense, LLC	T60428794	Boring: NEW-B006 Sample: ST- 4 Depth: 35-35.8	November 2015

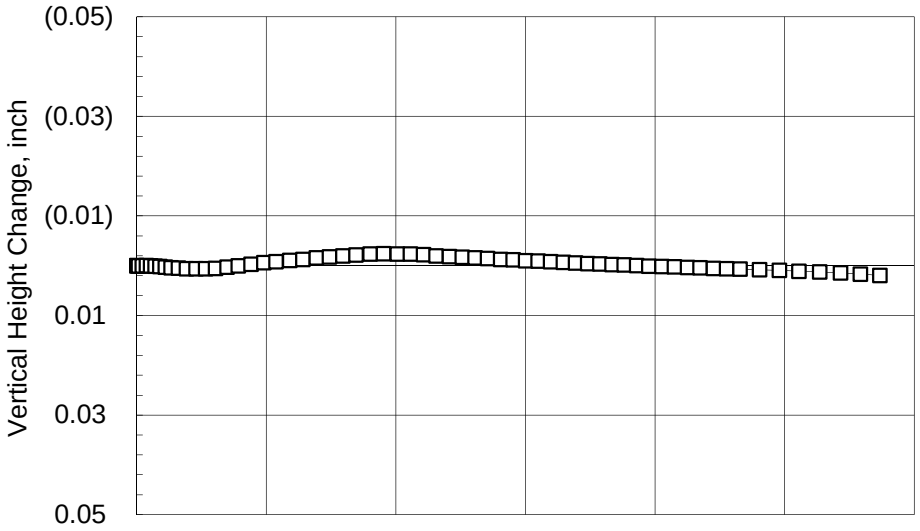
STAGED DRAINED DIRECT SHEAR TEST SERIES

Boring No	Depth (ft)	w_o	γ_{to}	γ_{do}	$\sigma'_{v,c}$ (ksf)	Deformation rate (inch/min)	at Peak Shear Stress at High Deformation				Remarks
Sample/ Specimen	Test ID	w_c (estimated) (%)	γ_{tc} (estimated) (pcf)	γ_{dc} (estimated) (pcf)	$\varepsilon_{v,c}$ (%)	t_c (days)	ΔL (inch)	τ_h (ksf)	ε_v (%)	Φ' for c'=0	
NEW-B006	35.4	11.1	140.2	126.2	9.00	2.2E-3	0.06	6.58	-0.12	36.2	
ST- 4	DS1619	12.7	142.9	126.9	2.4	0.05	0.29	5.39	0.19	30.9	
NEW-B006	35.6	15.8	147.4	127.2	18.00	2.0E-3	0.09	11.46	0.36	32.5	
ST- 4	DS1617	12.4	148.1	131.7	27.0	0.16	0.29	10.59	0.71	30.5	

Description of Material Tested and Remarks	
DS1619	CL, brown sandy clay
DS1617	CL, brown sandy clay

Strength Envelope Summary			
Test Series	Failure Criterion	Φ' (degree)	c' (ksf)
1	1	28.4	1.7
	2	30.0	0.2
Failure Criterion		1. Peak shear stress 2. High deformation	

	AECOM #60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR SERIES SUMMARY**
Prepared by: MHC Checked by: GET	**TerraSense, LLC**	T60428794	Boring: NEW-B006 Sample: ST- 4 Depth: 35-35.8 ft



SAMPLE INFORMATION

Boring: NEW-B006 Sample: ST- 4 Specimen: B Depth: 35.4 ft
Type: Intact tube sample

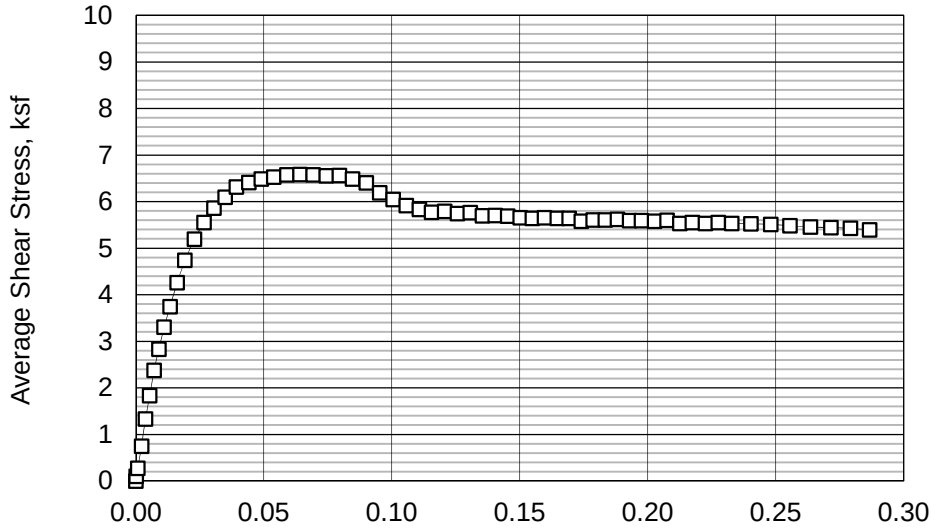
SPECIMEN INFORMATION (Initial)

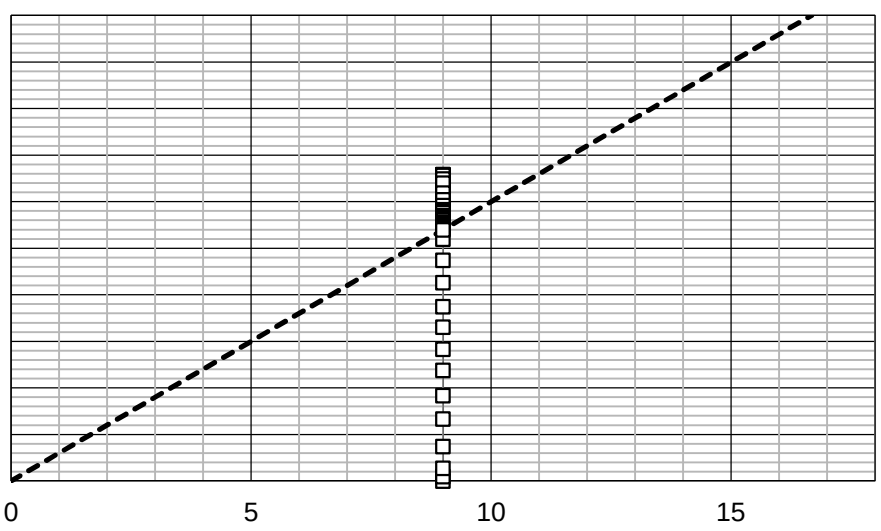
Description: CL, brown sandy clay
Height: 1.01 inch Diameter: 2.50 inch Area: 4.91 in²
Water Content: 11.1 % Dry Unit Weight: 126.2 pcf

TEST SUMMARY

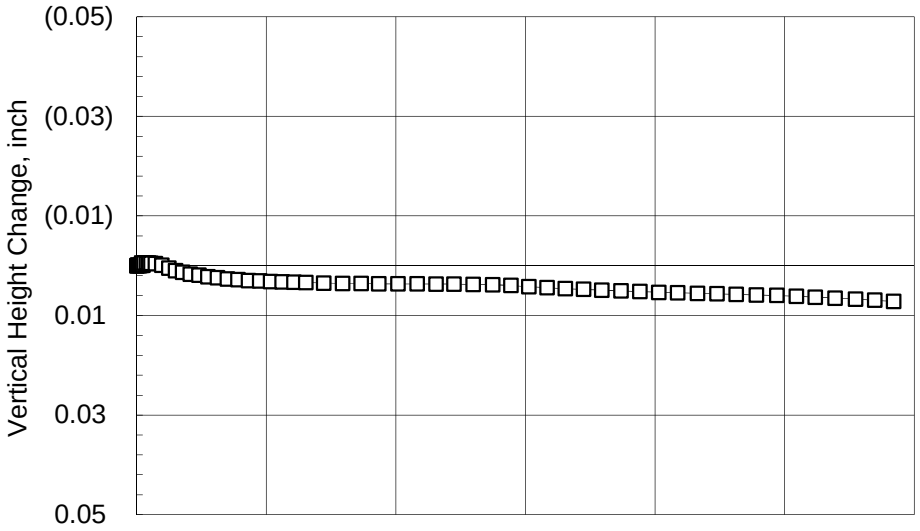
Vertical Consolidation Stress: 9.00 ksf
Water Content: 12.7 % Dry Unit Weight: 126.9 pcf
Deformation Rate: 0.00224 inch/min.
Peak Shear Strength: 6.58 ksf @ 0.06 inch deformation
Peak Effective Friction Angle: 36.2°, cohesion = 0.0ksf
Final Shear Strength: 5.39 ksf @ 0.29 inch deformation
Final Effective Friction Angle: 30.9° (Shown)

REMARKS:





	AECOM 60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR** **TEST SUMMARY**	
Prepared by: MHC Checked by: GET	**TerraSense, LLC**	T60428794	Boring: NEW-B006 Sample: ST- 4 Specimen: B Depth: 35.4 ft	November 15



SAMPLE INFORMATION

Boring: NEW-B006 Sample: ST- 4 Specimen: A Depth: 35.55 ft
Type: Intact tube sample

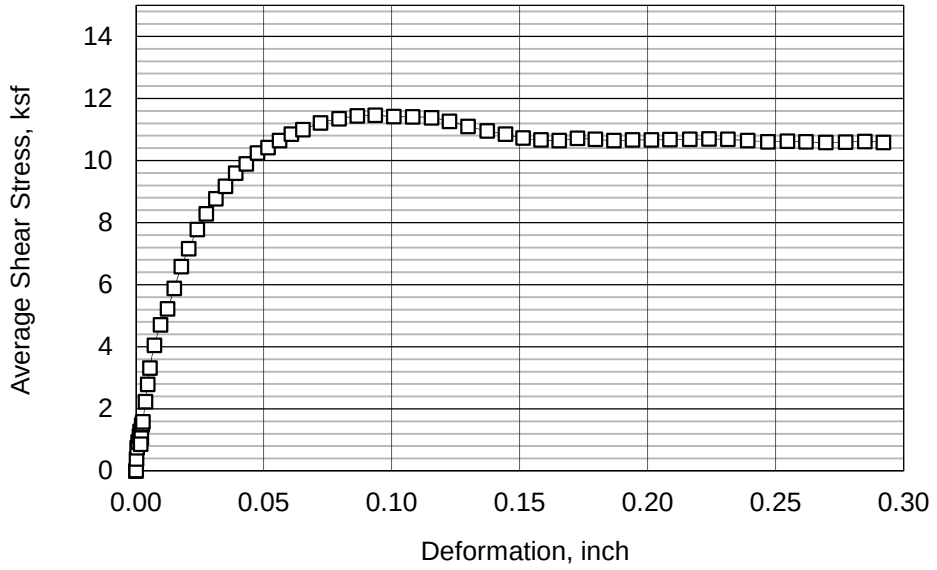
SPECIMEN INFORMATION (Initial)

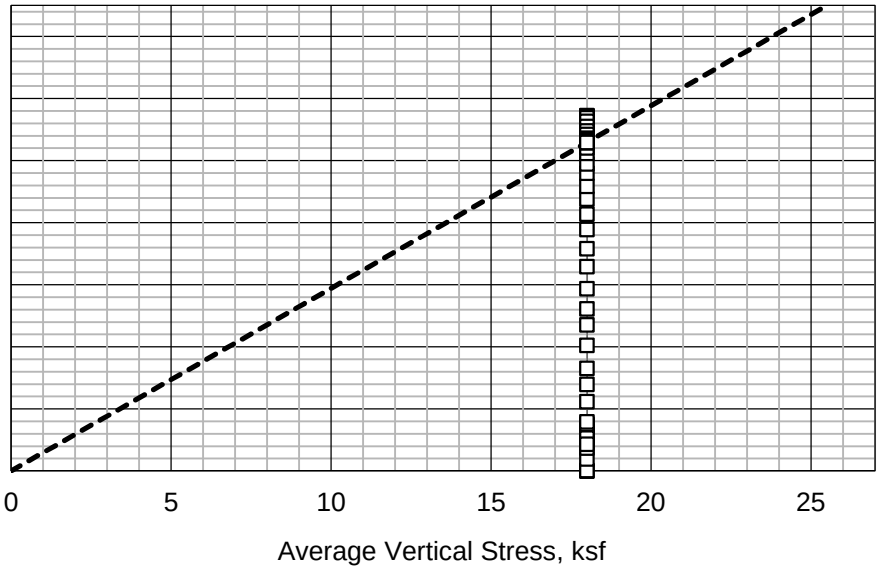
Description: CL, brown sandy clay
Height: 1.01 inch Diameter: 2.50 inch Area: 4.91 in²
Water Content: 15.8 % Dry Unit Weight: 127.2 pcf

TEST SUMMARY

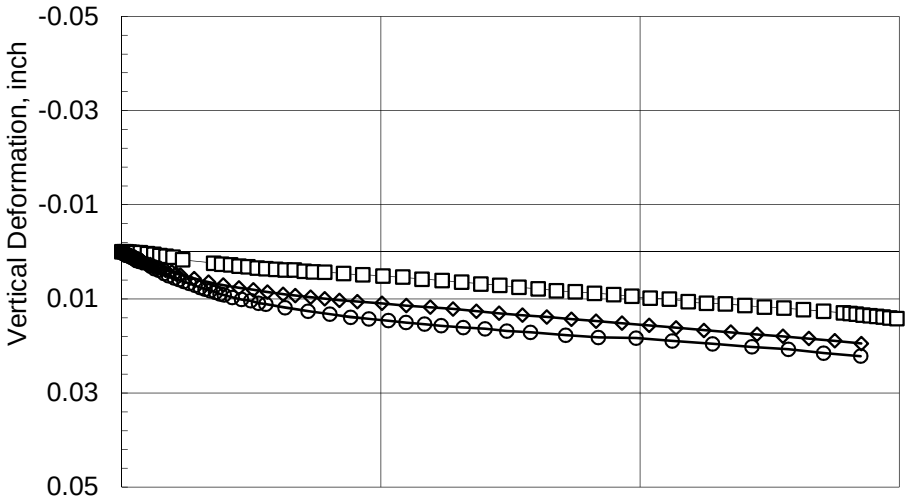
Vertical Consolidation Stress: 18.00 ksf
Water Content: 12.4 % Dry Unit Weight: 131.7 pcf
Deformation Rate: 0.00200 inch/min.
Peak Shear Strength: 11.46 ksf @ 0.09 inch deformation
Peak Effective Friction Angle: 32.5°, cohesion = 0.0ksf
Final Shear Strength: 10.59 ksf @ 0.29 inch deformation
Final Effective Friction Angle: 30.5° (Shown)

REMARKS:





	AECOM 60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR** **TEST SUMMARY**	
Prepared by: MHC Checked by: GET	**TerraSense, LLC**	T60428794	Boring: NEW-B006 Sample: ST- 4 Specimen: A Depth: 35.55 ft	November 15



SAMPLE INFORMATION

Boring: NEW-B007 Sample: ST-4 Depth: 40-42 feet
Type: Intact tube sample
Description: CH, brown clay with sand

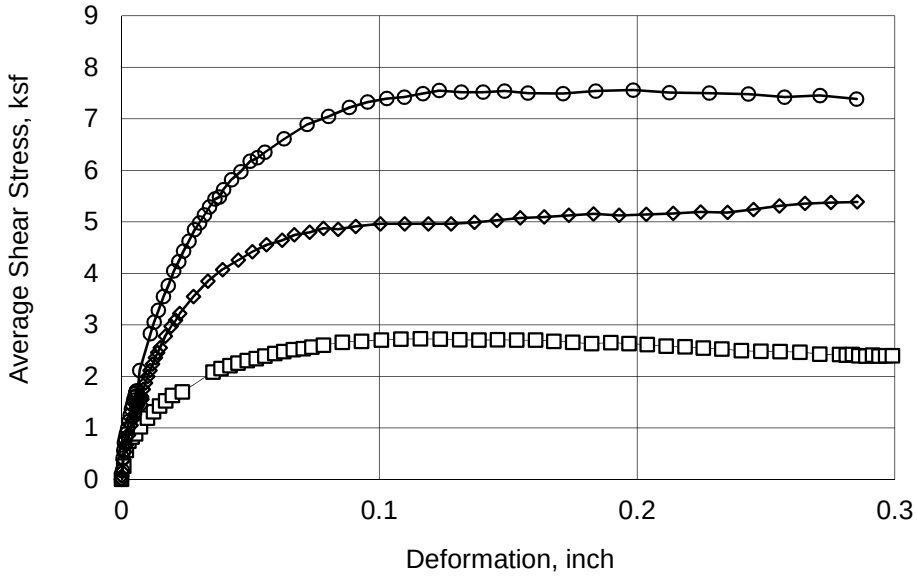
TEST INFORMATION

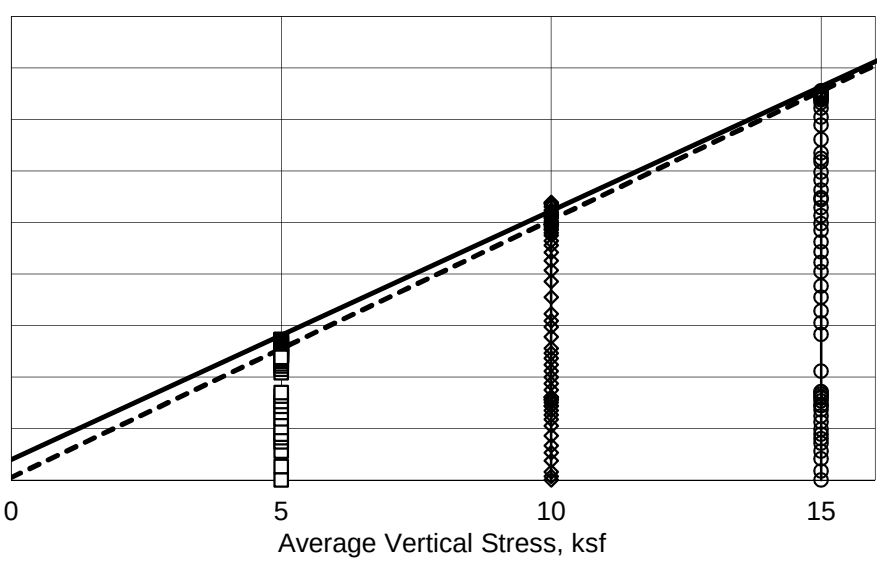
Test	Symbol	Vertical Stress (ksf)	Deformation Rate (inch/min.)
DS1620	□	5.0	0.0022
DS1621	◊	10.0	0.0002
DS1622	○	15.0	0.0001

TEST SUMMARY

Peak Effective Friction Angle: 25.8°, cohesion = 0.4ksf
Final Effective Friction Angle: 26.6°, cohesion = 0.1ksf

REMARKS:





Prepared by: MHC Checked by: GET	AECOM #60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR** **SERIES SUMMARY** Boring: NEW-B007 Sample: ST-4 Depth: 40-42	
	TerraSense, LLC	T60428794		November 2015

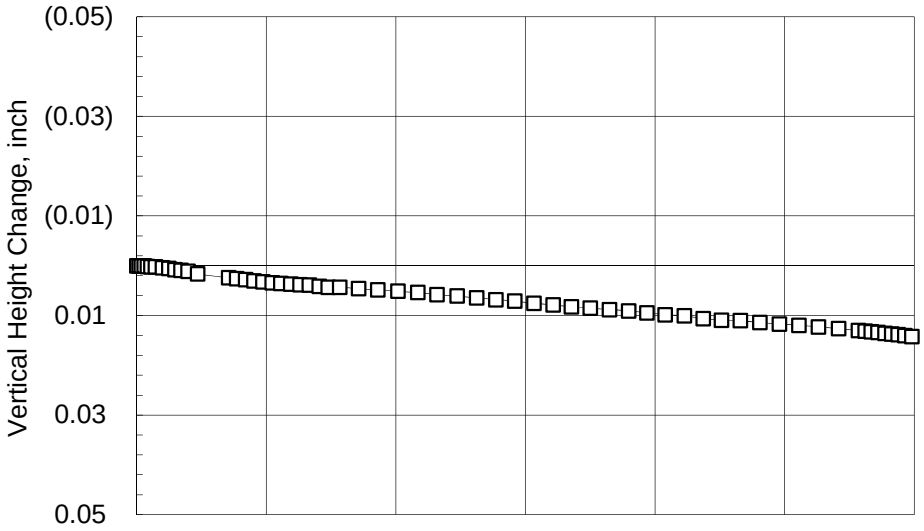
STAGED DRAINED DIRECT SHEAR TEST SERIES

Boring No	Depth (ft)	w_o	γ_{to}	γ_{do}	$\sigma'_{v,c}$ (ksf)	Deformation rate (inch/min)	at Peak Shear Stress at High Deformation				Remarks
Sample/ Specimen	Test ID	w_c (estimated) (%)	γ_{tc} (estimated) (pcf)	γ_{dc} (estimated) (pcf)	$\varepsilon_{v,c}$ (%)	t_c (days)	ΔL (inch)	τ_h (ksf)	ε_v (%)	Φ' for c'=0	
NEW-B007	41.0	17.5	129.9	110.5	5.00	2.2E-3	0.12	2.73	0.58	28.6	
ST-4	DS1620	18.6	131.8	111.1	2.9	1.69	0.30	2.38	1.45	25.5	
NEW-B007	41.3	14.7	128.7	112.2	10.00	1.8E-4	0.29	5.39	1.91	28.3	
ST- 4	DS1621	16.3	132.9	114.2	4.7	0.71	0.29	5.39	1.91	28.3	
NEW-B007	41.5	16.1	132.6	114.2	15.00	1.3E-4	0.20	7.56	1.83	26.7	
ST- 4	DS1622	14.8	138.9	121.0	8.5	0.78	0.29	7.38	2.21	26.2	

Description of Material Tested and Remarks	
DS1620	CH, brown clay with sand
DS1621	CH, brown clay with sand
DS1622	CH, brown clay with sand

Strength Envelope Summary			
Test Series	Failure Criterion	Φ' (degree)	c' (ksf)
1	1	25.8	0.4
	2	26.6	0.1
Failure Criterion		1. Peak shear stress 2. High deformation	

	AECOM #60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR SERIES SUMMARY**
Prepared by: MHC Checked by: GET	**TerraSense, LLC**	T60428794	Boring: NEW-B007 Sample: ST-4 Depth: 40-42 ft



SAMPLE INFORMATION

Boring: NEW-B007 Sample: ST-4 Specimen: B Depth: 41 ft
Type: Intact tube sample

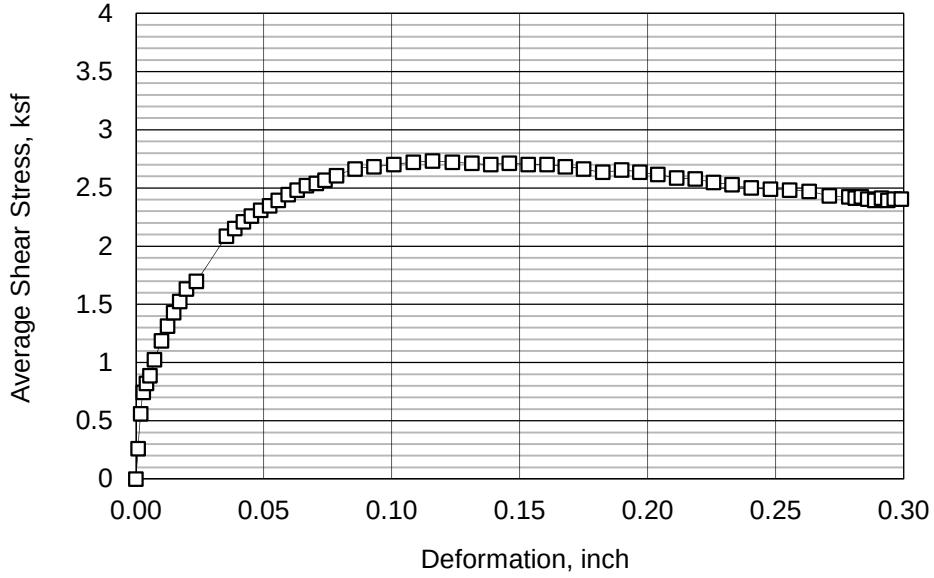
SPECIMEN INFORMATION (Initial)

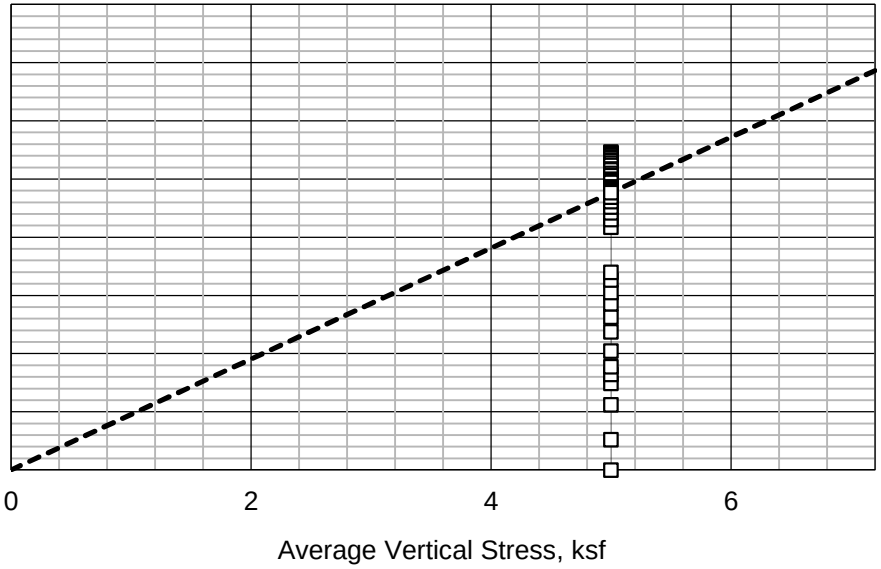
Description: CH, brown clay with sand
Height: 1.00 inch Diameter: 2.50 inch Area: 4.91 in²
Water Content: 17.5 % Dry Unit Weight: 110.5 pcf

TEST SUMMARY

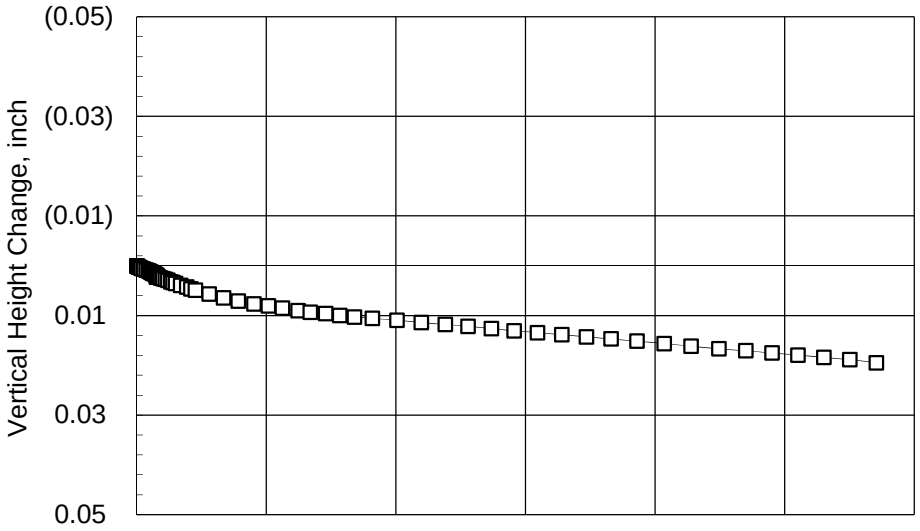
Vertical Consolidation Stress: 5.00 ksf
Water Content: 18.6 % Dry Unit Weight: 111.1 pcf
Deformation Rate: 0.00222 inch/min.
Peak Shear Strength: 2.73 ksf @ 0.12 inch deformation
Peak Effective Friction Angle: 28.6°, cohesion = 0.0ksf
Final Shear Strength: 2.38 ksf @ 0.30 inch deformation
Final Effective Friction Angle: 25.5° (Shown)

REMARKS:





	AECOM 60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR** **TEST SUMMARY**	
Prepared by: MHC Checked by: GET	**TerraSense, LLC**	T60428794	Boring: NEW-B007 Sample: ST-4 Specimen: B Depth: 41 ft	November 15



SAMPLE INFORMATION

Boring: NEW-B007 Sample: ST- 4 Specimen: C Depth: 41.25 ft
Type: Intact tube sample

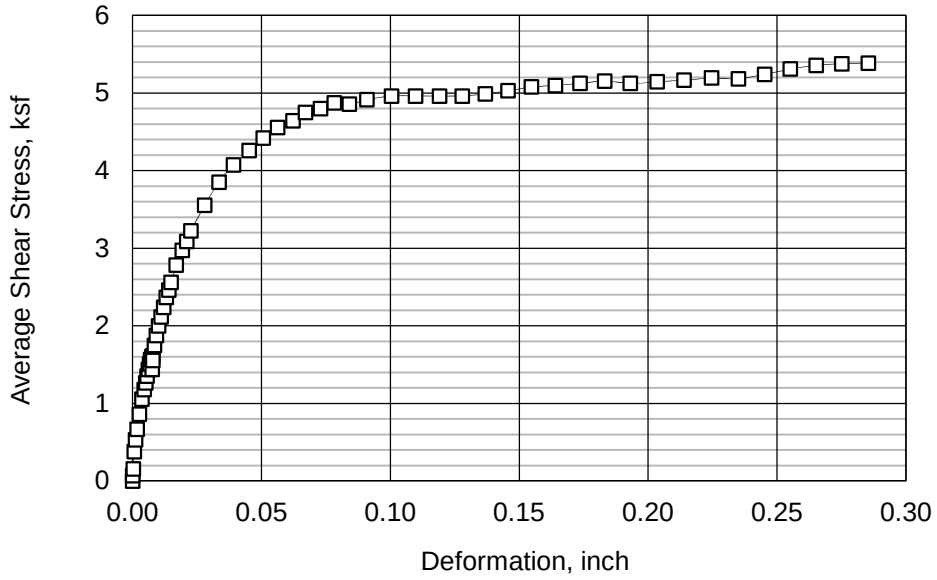
SPECIMEN INFORMATION (Initial)

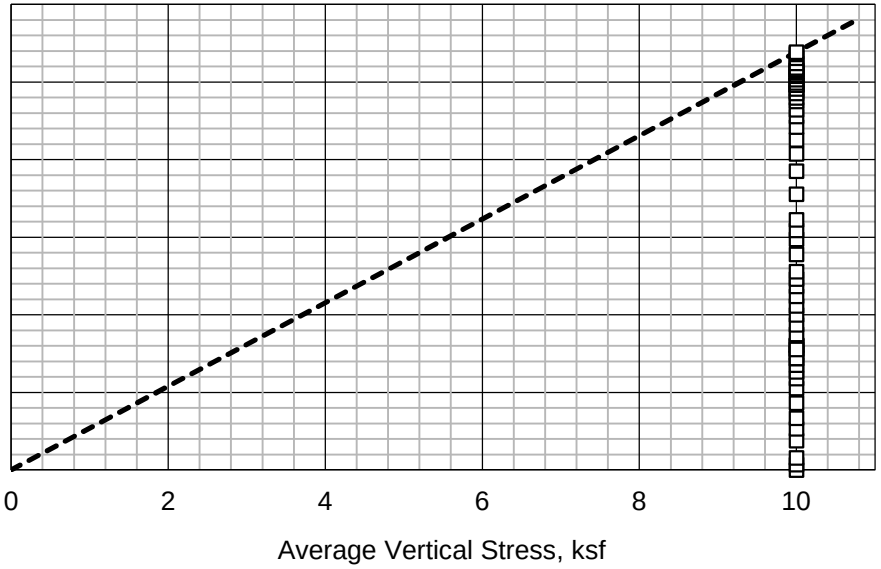
Description: CH, brown clay with sand
Height: 1.02 inch Diameter: 2.50 inch Area: 4.91 in²
Water Content: 14.7 % Dry Unit Weight: 112.2 pcf

TEST SUMMARY

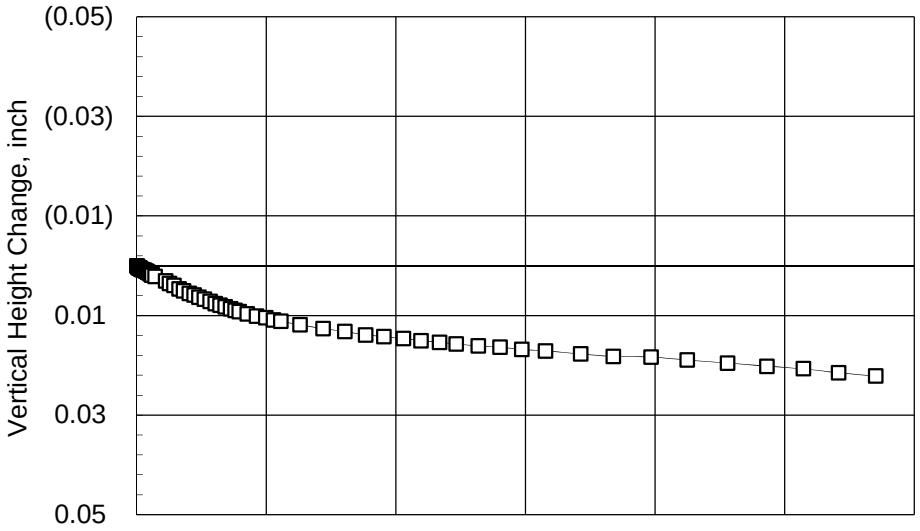
Vertical Consolidation Stress: 10.00 ksf
Water Content: 16.3 % Dry Unit Weight: 114.2 pcf
Deformation Rate: 0.00018 inch/min.
Peak Shear Strength: 5.39 ksf @ 0.29 inch deformation
Peak Effective Friction Angle: 28.3°, cohesion = 0.0ksf
Final Shear Strength: 5.39 ksf @ 0.29 inch deformation
Final Effective Friction Angle: 28.3° (Shown)

REMARKS:





	AECOM 60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR** **TEST SUMMARY**	
Prepared by: MHC Checked by: GET	**TerraSense, LLC**	T60428794	Boring: NEW-B007 Sample: ST- 4 Specimen: C Depth: 41.25 ft	November 15



SAMPLE INFORMATION

Boring: NEW-B007 Sample: ST- 4 Specimen: D Depth: 41.45 ft
Type: Intact tube sample

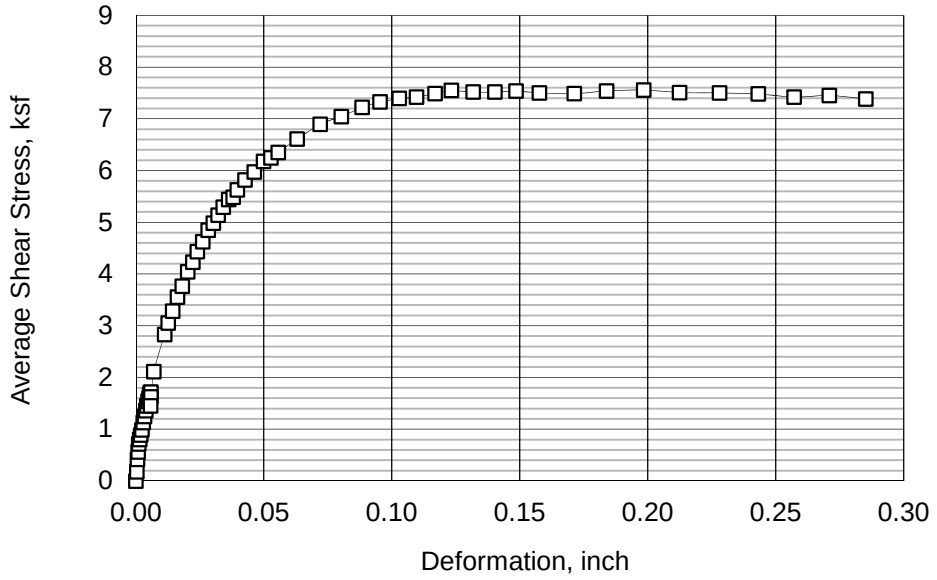
SPECIMEN INFORMATION (Initial)

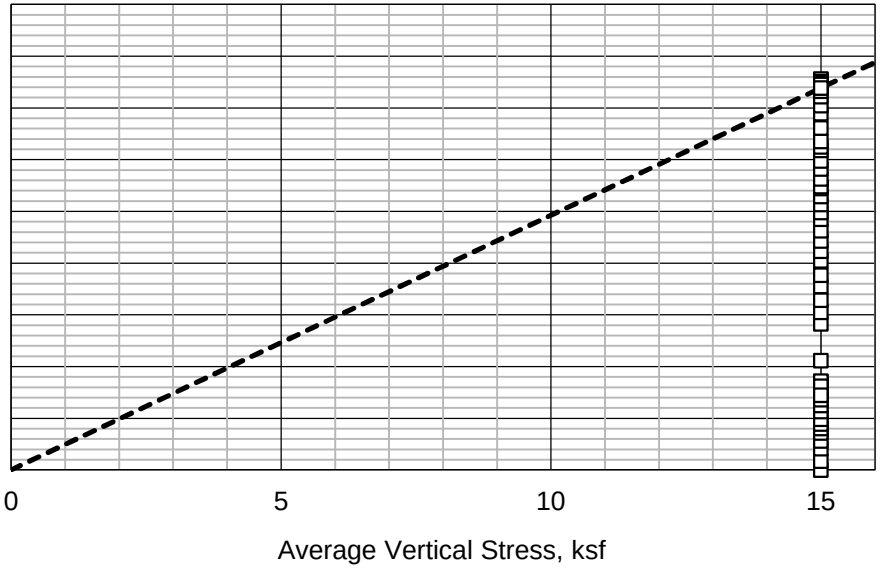
Description: CH, brown clay with sand
Height: 1.00 inch Diameter: 2.50 inch Area: 4.91 in²
Water Content: 16.1 % Dry Unit Weight: 114.2 pcf

TEST SUMMARY

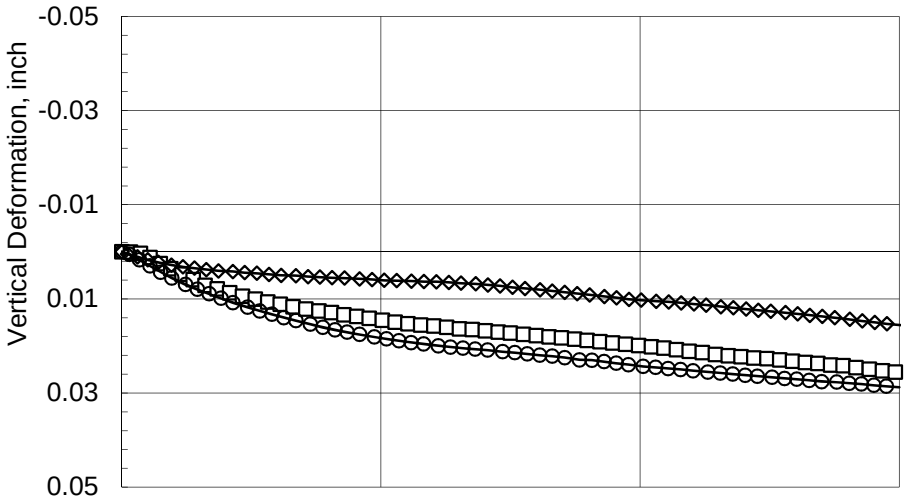
Vertical Consolidation Stress: 15.00 ksf
Water Content: 14.8 % Dry Unit Weight: 121.0 pcf
Deformation Rate: 0.00013 inch/min.
Peak Shear Strength: 7.56 ksf @ 0.20 inch deformation
Peak Effective Friction Angle: 26.7°, cohesion = 0.0ksf
Final Shear Strength: 7.38 ksf @ 0.29 inch deformation
Final Effective Friction Angle: 26.2° (Shown)

REMARKS:





	AECOM 60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR** **TEST SUMMARY**	
Prepared by: MHC Checked by: GET	**TerraSense, LLC**	T60428794	Boring: NEW-B007 Sample: ST- 4 Specimen: D Depth: 41.45 ft	November 15



SAMPLE INFORMATION

Boring: NEW-B008 Sample: ST-2 Depth: 27.5-28.75 feet
Type: Intact tube sample
Description: CL, dark brown sandy clay with gravel

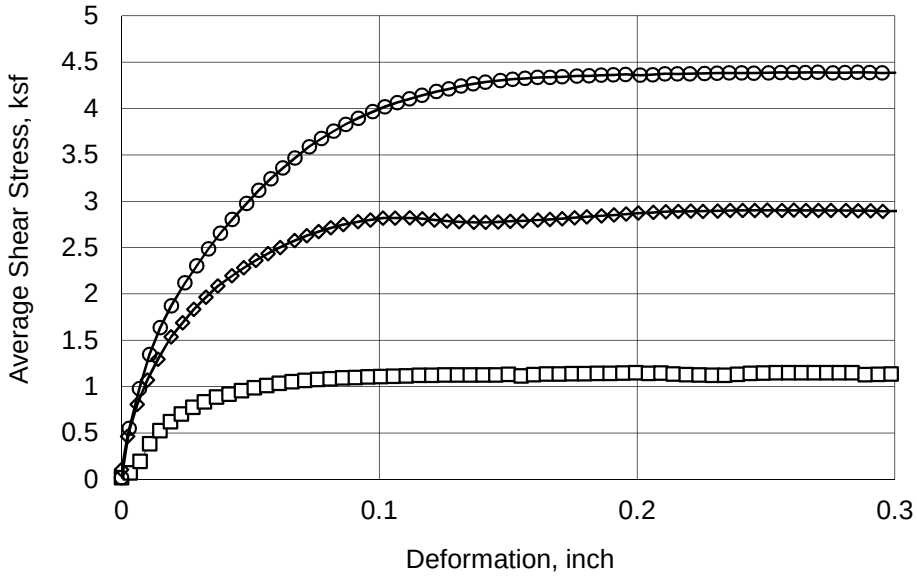
TEST INFORMATION

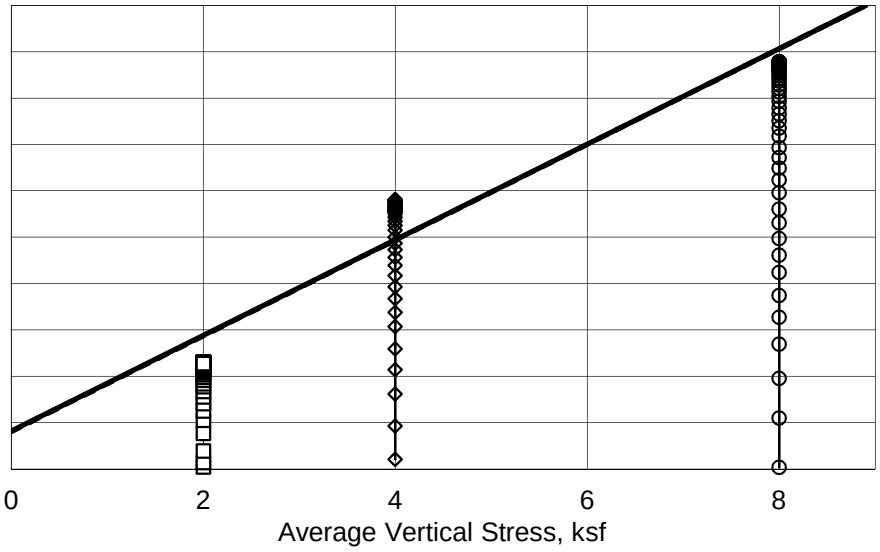
Test	Symbol	Vertical Stress (ksf)	Deformation Rate (inch/min.)
DS1624	□	2.0	0.0002
DS1626	◊	4.0	0.0002
DS1628	○	8.0	0.0002

TEST SUMMARY

Peak Effective Friction Angle: 27.3°, cohesion = 0.4ksf
Final Effective Friction Angle: 27.3°, cohesion = 0.4ksf

REMARKS:





Prepared by: MHC Checked by: GET	AECOM #60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR** **SERIES SUMMARY**	
	TerraSense, LLC	T60428794	Boring: NEW-B008 Sample: ST-2 Depth: 27.5-28.75	November 2015

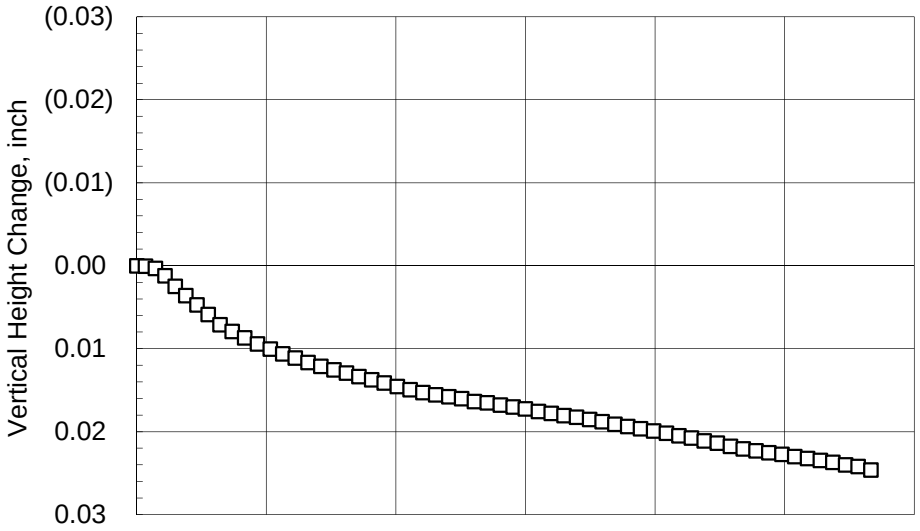
STAGED DRAINED DIRECT SHEAR TEST SERIES

Boring No	Depth (ft)	w_o	γ_{to}	γ_{do}	$\sigma'_{v,c}$ (ksf)	Deformation rate (inch/min)	at Peak Shear Stress at High Deformation				Remarks
Sample/ Specimen	Test ID	w_c (estimated) (%)	γ_{tc} (estimated) (pcf)	γ_{dc} (estimated) (pcf)	$\varepsilon_{v,c}$ (%)	t_c (days)	ΔL (inch)	τ_h (ksf)	ε_v (%)	Φ' for c'=0	
NEW-B008	27.7	20.3	122.5	101.8	2.00	1.9E-4	0.27	1.15	2.29	29.9	
ST-2	DS1624	20.9	126.7	104.8	4.0	0.33	0.28	1.15	2.34	29.9	
NEW-B008	28.0	14.4	133.8	117.0	4.00	1.9E-4	0.25	2.90	1.26	36.0	
ST-2	DS1626	19.3	143.5	120.3	4.4	0.67	0.29	2.90	1.46	35.9	
NEW-B008	28.4	16.4	133.2	114.5	8.00	1.9E-4	0.29	4.39	2.79	28.8	
ST-2	DS1628	18.2	141.6	119.9	7.2	0.67	0.29	4.39	2.79	28.8	

Description of Material Tested and Remarks	
DS1624	CL, dark brown sandy clay with gravel
DS1626	CL, dark brown sandy clay with gravel
DS1628	CL, dark brown clay with sand and gravel

Strength Envelope Summary			
Test Series	Failure Criterion	Φ' (degree)	c' (ksf)
1	1	27.3	0.4
	2	27.3	0.4
Failure Criterion		1. Peak shear stress 2. High deformation	

	AECOM #60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR SERIES SUMMARY**
Prepared by: MCH Checked by: GET	**TerraSense, LLC**	T60428794	Boring: NEW-B008 Sample: ST-2 Depth: 27.5-28.75 ft



SAMPLE INFORMATION

Boring: NEW-B008 Sample: ST-2 Specimen: A Depth: 27.7 ft
Type: Intact tube sample

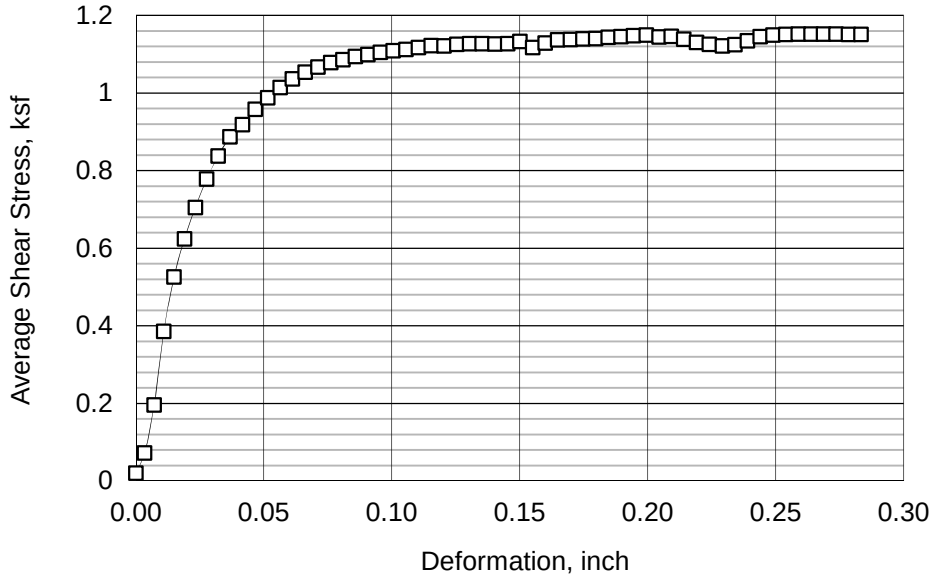
SPECIMEN INFORMATION (Initial)

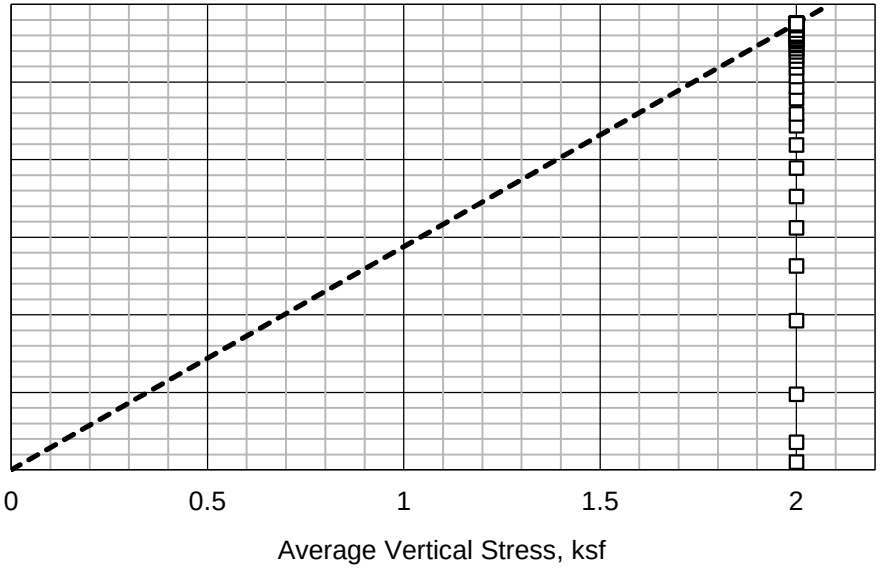
Description: CL, dark brown clay with sand and gravel
Height: 1.05 inch Diameter: 2.50 inch Area: 4.91 in²
Water Content: 20.3 % Dry Unit Weight: 101.8 pcf

TEST SUMMARY

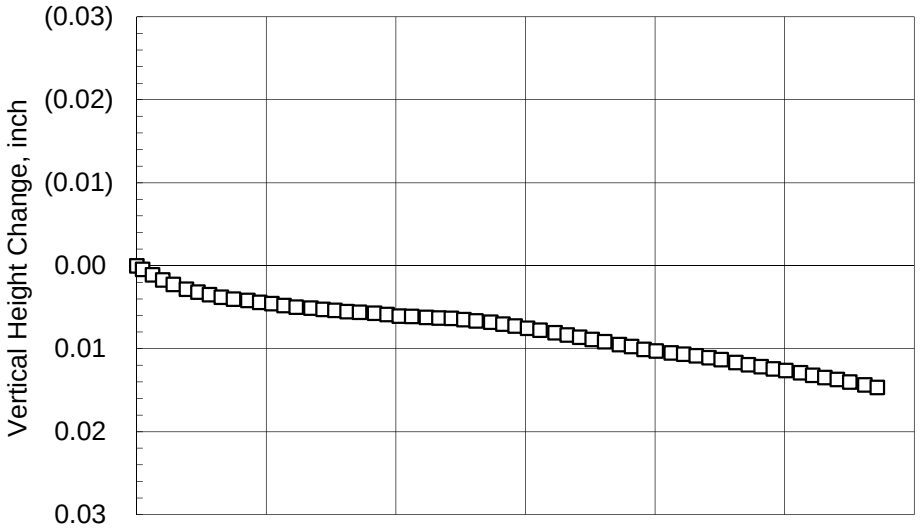
Vertical Consolidation Stress: 2.00 ksf
Water Content: 20.9 % Dry Unit Weight: 104.8 pcf
Deformation Rate: 0.00019 inch/min.
Peak Shear Strength: 1.15 ksf @ 0.27 inch deformation
Peak Effective Friction Angle: 29.9°, cohesion = 0.0 ksf
Final Shear Strength: 1.15 ksf @ 0.28 inch deformation
Final Effective Friction Angle: 29.9° (Shown)

REMARKS:





	AECOM 60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR** **TEST SUMMARY**	
Prepared by: MCH Checked by: GET	**TerraSense, LLC**	T60428794	Boring: NEW-B008 Sample: ST-2 Specimen: A Depth: 27.7 ft	November 15



SAMPLE INFORMATION

Boring: NEW-B008 Sample: ST-2 Specimen: B Depth: 28 ft
Type: Intact tube sample

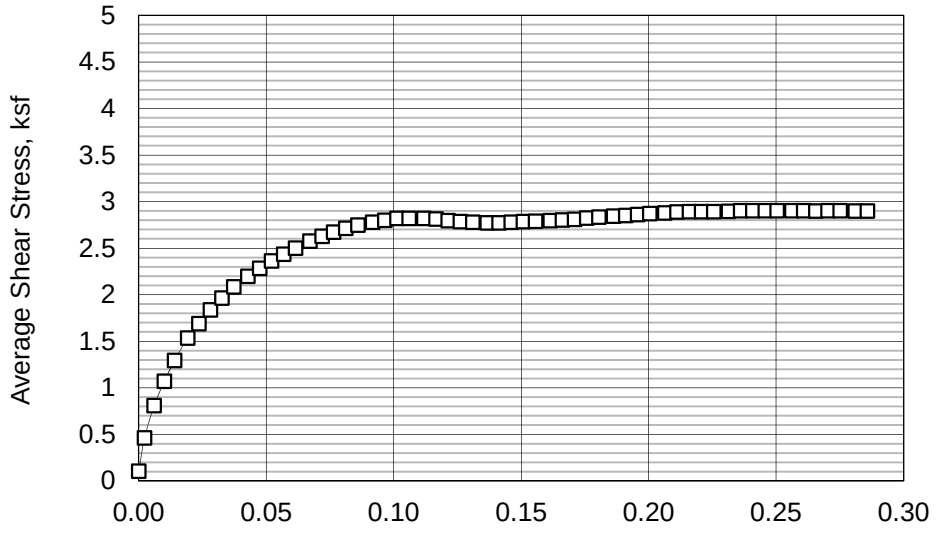
SPECIMEN INFORMATION (Initial)

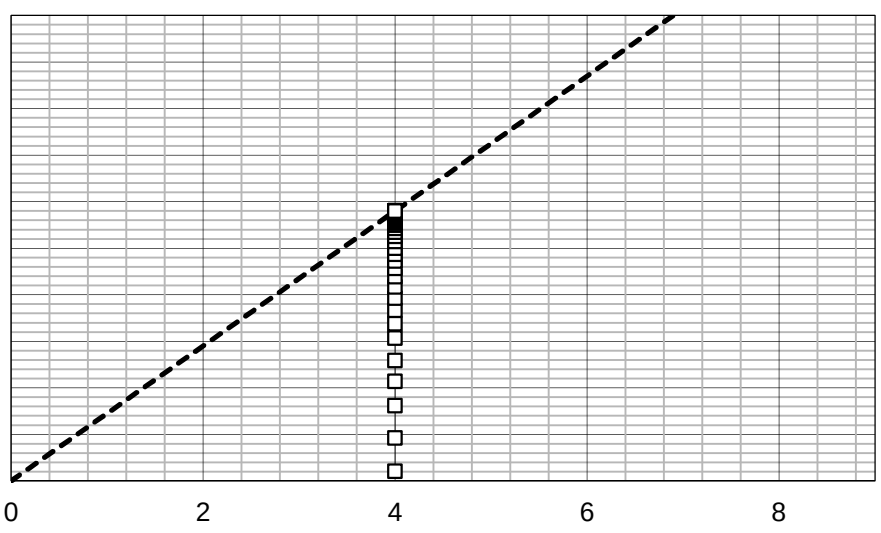
Description: CL, dark brown sandy clay with gravel
Height: 1.00 inch Diameter: 2.50 inch Area: 4.91 in²
Water Content: 14.4 % Dry Unit Weight: 117.0 pcf

TEST SUMMARY

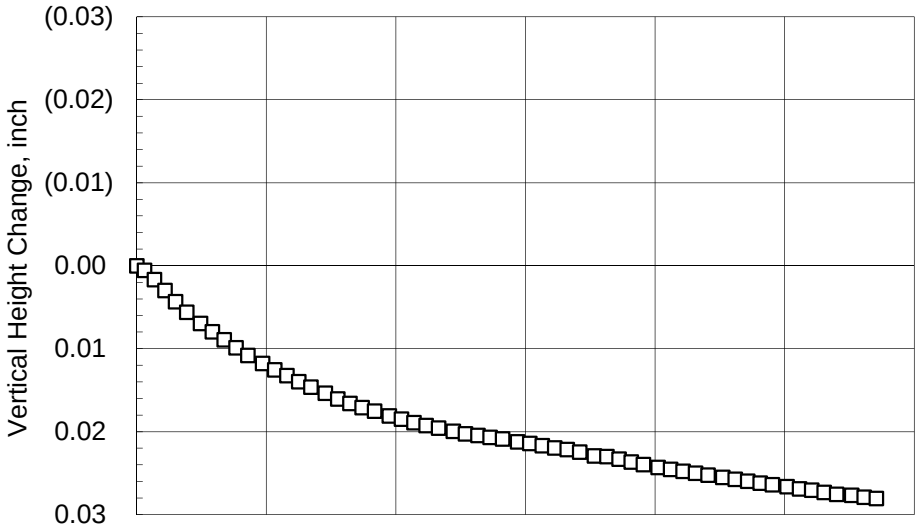
Vertical Consolidation Stress: 4.00 ksf
Water Content: 19.3 % Dry Unit Weight: 120.3 pcf
Deformation Rate: 0.00019 inch/min.
Peak Shear Strength: 2.90 ksf @ 0.25 inch deformation
Peak Effective Friction Angle: 36.0°, cohesion = 0.0 ksf
Final Shear Strength: 2.90 ksf @ 0.29 inch deformation
Final Effective Friction Angle: 35.9° (Shown)

REMARKS:





	AECOM 60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR** **TEST SUMMARY**	
Prepared by: MCH Checked by: GET	**TerraSense, LLC**	T60428794	Boring: NEW-B008 Sample: ST-2 Specimen: B Depth: 28 ft	November 15



SAMPLE INFORMATION

Boring: NEW-B008 Sample: ST-2 Specimen: C Depth: 28.4 ft
Type: Intact tube sample

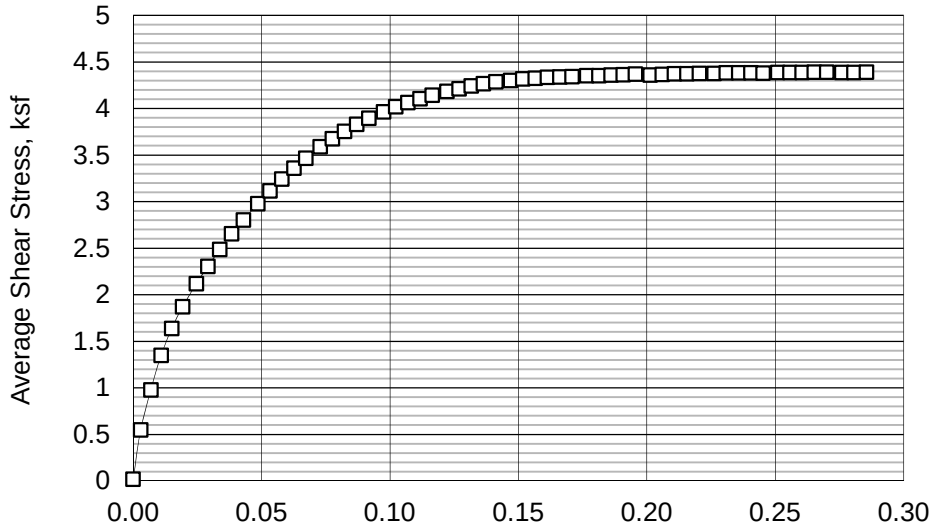
SPECIMEN INFORMATION (Initial)

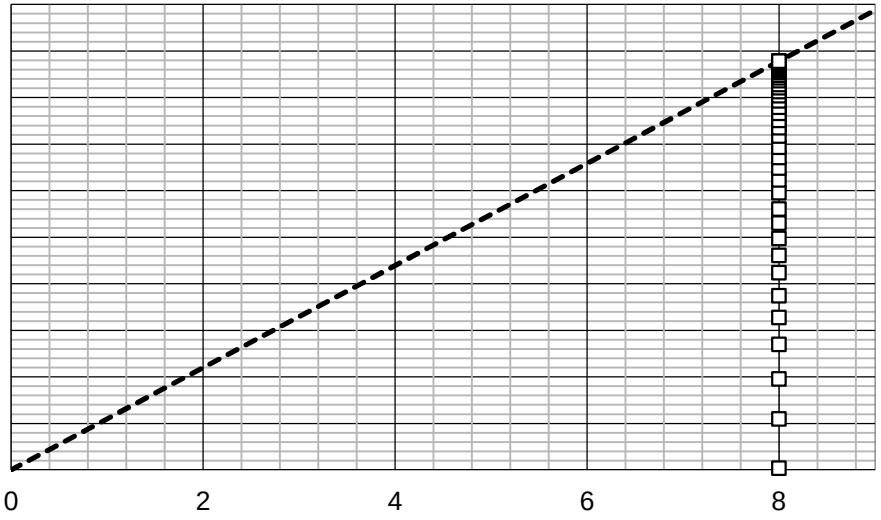
Description: CL, dark brown sandy clay with gravel
Height: 1.01 inch Diameter: 2.50 inch Area: 4.91 in²
Water Content: 16.4 % Dry Unit Weight: 114.5 pcf

TEST SUMMARY

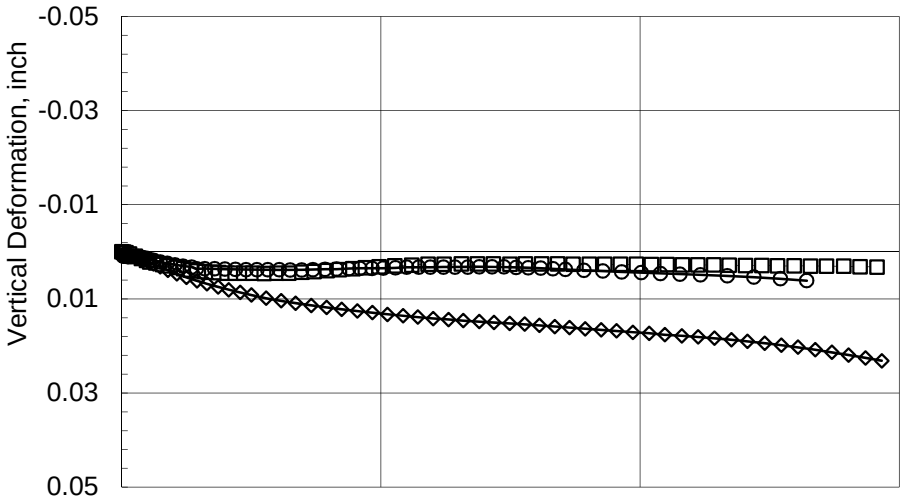
Vertical Consolidation Stress: 8.00 ksf
Water Content: 18.2 % Dry Unit Weight: 119.9 pcf
Deformation Rate: 0.00019 inch/min.
Peak Shear Strength: 4.39 ksf @ 0.29 inch deformation
Peak Effective Friction Angle: 28.8°, cohesion = 0.0 ksf
Final Shear Strength: 4.39 ksf @ 0.29 inch deformation
Final Effective Friction Angle: 28.8° (Shown)

REMARKS:





	AECOM 60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR** **TEST SUMMARY**	
Prepared by: MCH Checked by: GET	**TerraSense, LLC**	T60428794	Boring: NEW-B008 Sample: ST-2 Specimen: C Depth: 28.4 ft	November 15



SAMPLE INFORMATION

Boring: NEW-B012 Sample: ST-19 A Depth: 80-82 feet
Type: Intact tube sample
Description: SC, brown clayey sand

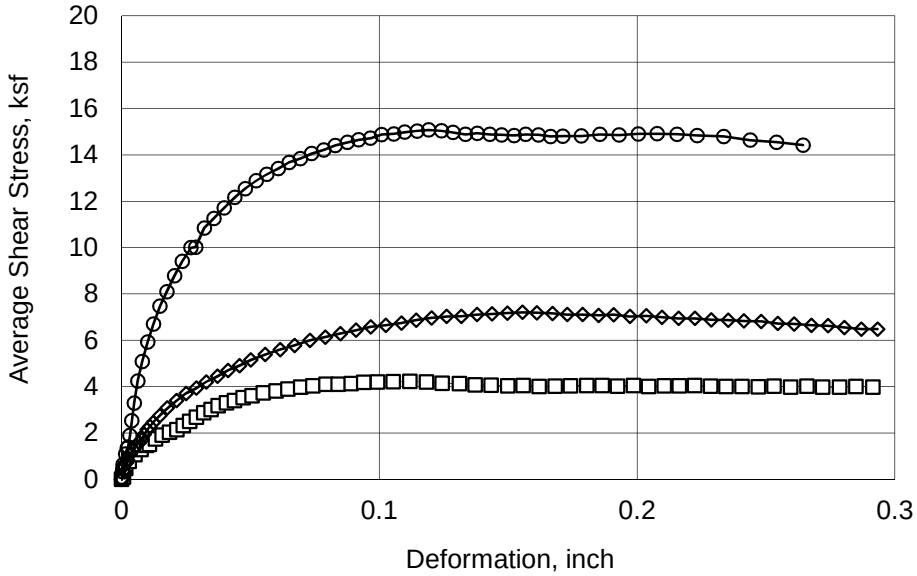
TEST INFORMATION

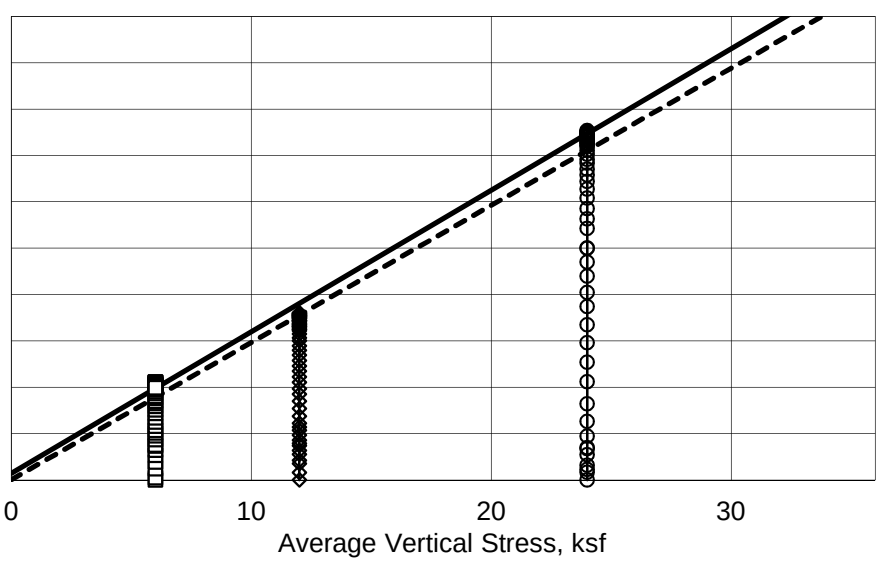
Test	Symbol	Vertical Stress (ksf)	Deformation Rate (inch/min.)
DS1611	□	6.0	0.0022
DS1613	◊	12.0	0.0021
DS1612	○	24.0	0.0017

TEST SUMMARY

Peak Effective Friction Angle: 31.4°, cohesion = 0.3ksf
Final Effective Friction Angle: 30.6°, cohesion = 0.0ksf

REMARKS:





Prepared by: MHC Checked by: GET	AECOM #60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR** **SERIES SUMMARY**	
	TerraSense, LLC	T60428794	Boring: NEW-B012 Sample: ST-19 A Depth: 80-82	November 2015

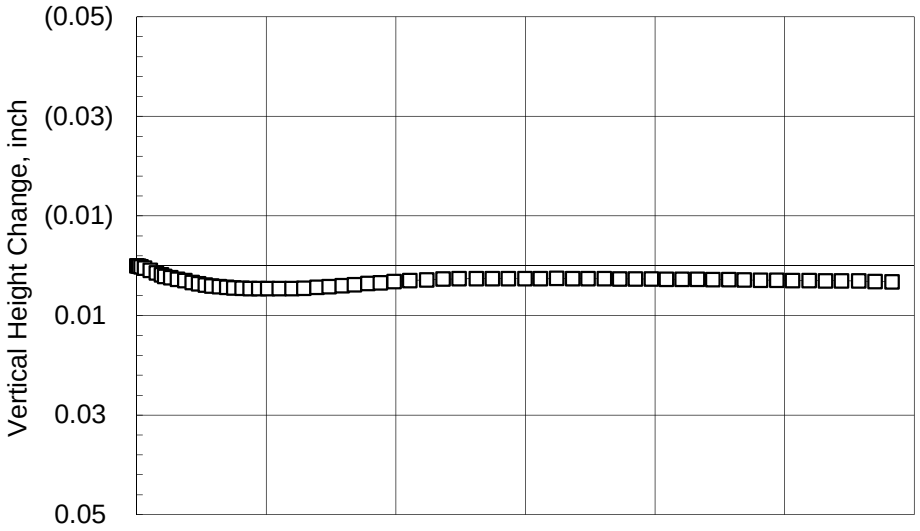
STAGED DRAINED DIRECT SHEAR TEST SERIES

Boring No	Depth (ft)	w_o	γ_{to}	γ_{do}	$\sigma'_{v,c}$ (ksf)	Deformation rate (inch/min)	at Peak Shear Stress at High Deformation				Remarks
Sample/ Specimen	Test ID	w_c (estimated) (%)	γ_{tc} (estimated) (pcf)	γ_{dc} (estimated) (pcf)	$\varepsilon_{v,c}$ (%)	t_c (days)	ΔL (inch)	τ_h (ksf)	ε_v (%)	Φ' for c'=0	
NEW-B012	81.1	11.2	136.8	122.9	6.00	2.2E-3	0.11	4.23	0.28	35.2	
ST-19 A	DS1611	12.1	140.7	125.5	4.4	0.06	0.29	3.98	0.32	33.5	
NEW-B012	81.8	16.9	130.5	111.7	12.00	2.1E-3	0.16	7.21	1.54	31.0	
ST-19	DS1613	16.7	136.2	116.7	8.6	1.81	0.29	6.49	2.32	28.4	
NEW-B012	81.5	10.5	139.2	126.0	24.00	1.7E-3	0.12	15.08	0.33	32.1	
ST-19	DS1612	10.9	145.6	131.3	14.6	0.13	0.26	14.42	0.61	31.0	

Description of Material Tested and Remarks	
DS1611	SC, brown clayey sand
DS1613	SC, brown clayey sand
DS1612	SC, brown clayey sand

Strength Envelope Summary			
Test Series	Failure Criterion	Φ' (degree)	c' (ksf)
1	1	31.4	0.3
	2	30.6	0.0
Failure Criterion		1. Peak shear stress 2. High deformation	

	AECOM #60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR SERIES SUMMARY**
Prepared by: MHC Checked by: GET	**TerraSense, LLC**	T60428794	Boring: NEW-B012 Sample: ST-19 A Depth: 80-82 ft



SAMPLE INFORMATION

Boring: NEW-B012 Sample: ST-19 A Specimen: 1 Depth: 81.1 ft
Type: Intact tube sample

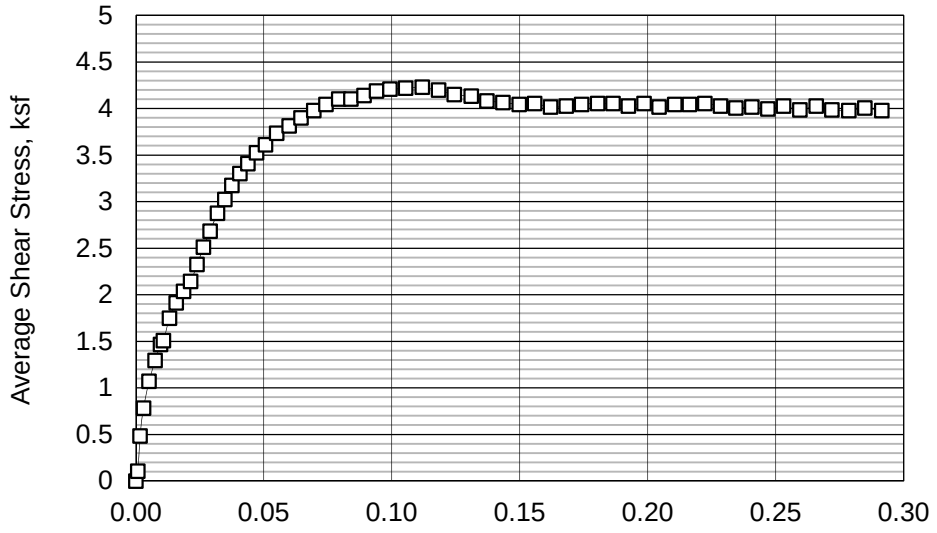
SPECIMEN INFORMATION (Initial)

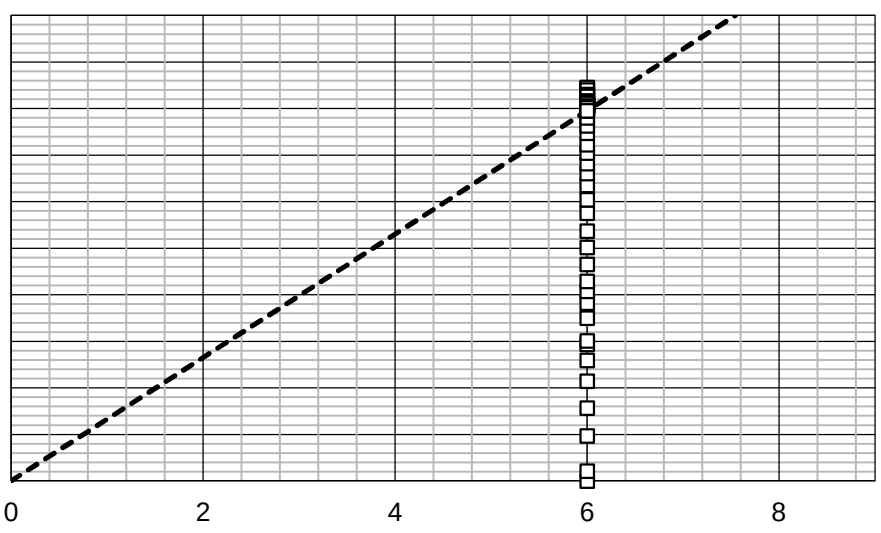
Description: SC, brown clayey sand
Height: 1.00 inch Diameter: 2.50 inch Area: 4.91 in²
Water Content: 11.2 % Dry Unit Weight: 122.9 pcf

TEST SUMMARY

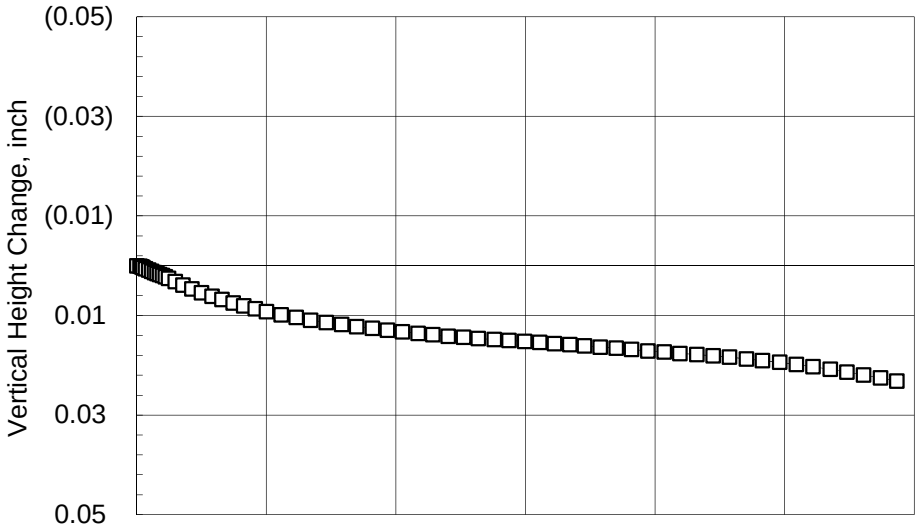
Vertical Consolidation Stress: 6.00 ksf
Water Content: 12.1 % Dry Unit Weight: 125.5 pcf
Deformation Rate: 0.00222 inch/min.
Peak Shear Strength: 4.23 ksf @ 0.11 inch deformation
Peak Effective Friction Angle: 35.2°, cohesion = 0.0ksf
Final Shear Strength: 3.98 ksf @ 0.29 inch deformation
Final Effective Friction Angle: 33.5° (Shown)

REMARKS:





	AECOM 60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR** **TEST SUMMARY**	
Prepared by: MHC Checked by: GET	**TerraSense, LLC**	T60428794	Boring: NEW-B012 Sample: ST-19 A Specimen: 1 Depth: 81.1 ft	November 15



SAMPLE INFORMATION

Boring: NEW-B012 Sample: ST-19 Specimen: C Depth: 81.8 ft
Type: Intact tube sample

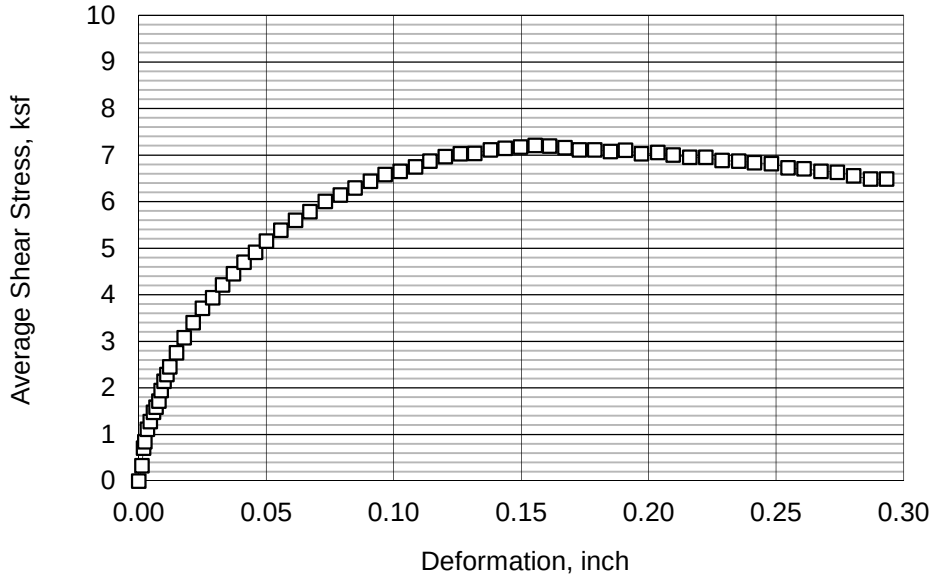
SPECIMEN INFORMATION (Initial)

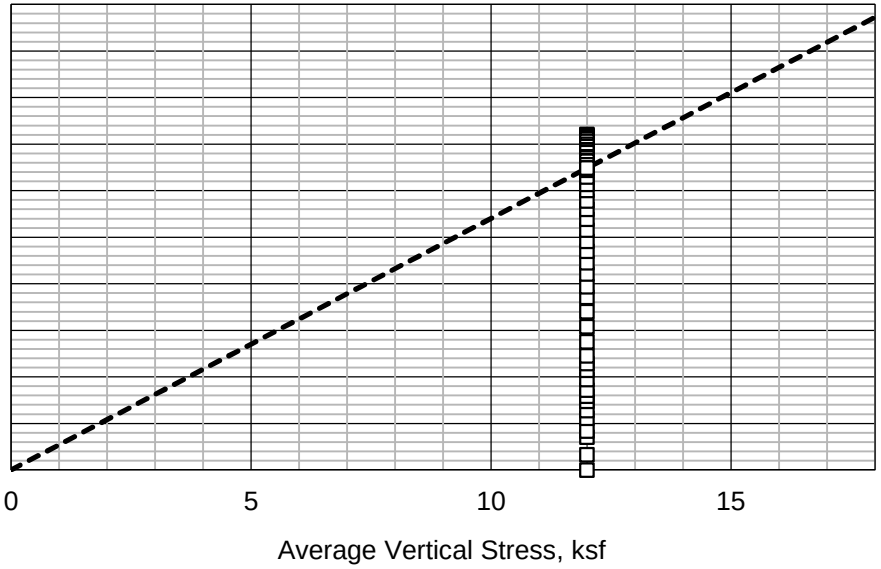
Description: SC, brown clayey sand
Height: 1.00 inch Diameter: 2.50 inch Area: 4.91 in²
Water Content: 16.9 % Dry Unit Weight: 111.7 pcf

TEST SUMMARY

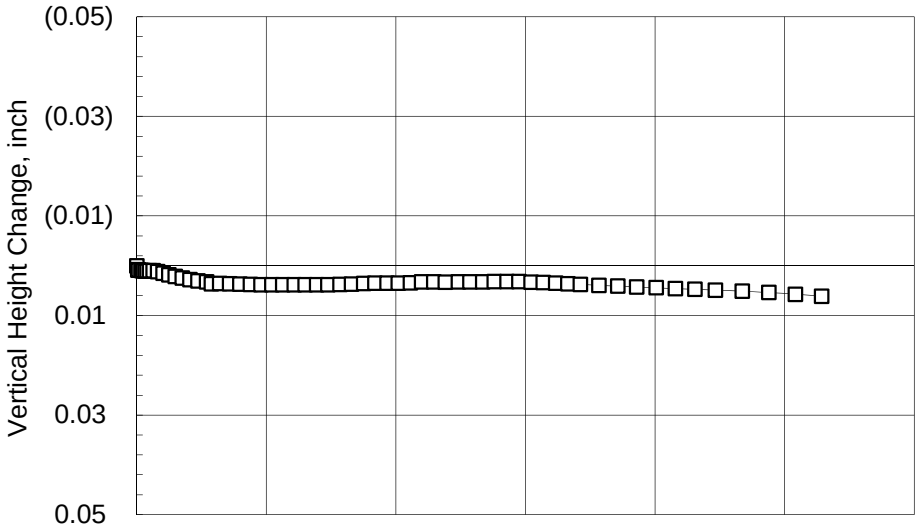
Vertical Consolidation Stress: 12.00 ksf
Water Content: 16.7 % Dry Unit Weight: 116.7 pcf
Deformation Rate: 0.00211 inch/min.
Peak Shear Strength: 7.21 ksf @ 0.16 inch deformation
Peak Effective Friction Angle: 31.0°, cohesion = 0.0ksf
Final Shear Strength: 6.49 ksf @ 0.29 inch deformation
Final Effective Friction Angle: 28.4° (Shown)

REMARKS:





	AECOM 60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR** **TEST SUMMARY**	
Prepared by: MHC Checked by: GET	**TerraSense, LLC**	T60428794	Boring: NEW-B012 Sample: ST-19 Specimen: C Depth: 81.8 ft	November 15



SAMPLE INFORMATION

Boring: NEW-B012 Sample: ST-19 Specimen: B Depth: 81.5 ft
Type: Intact tube sample

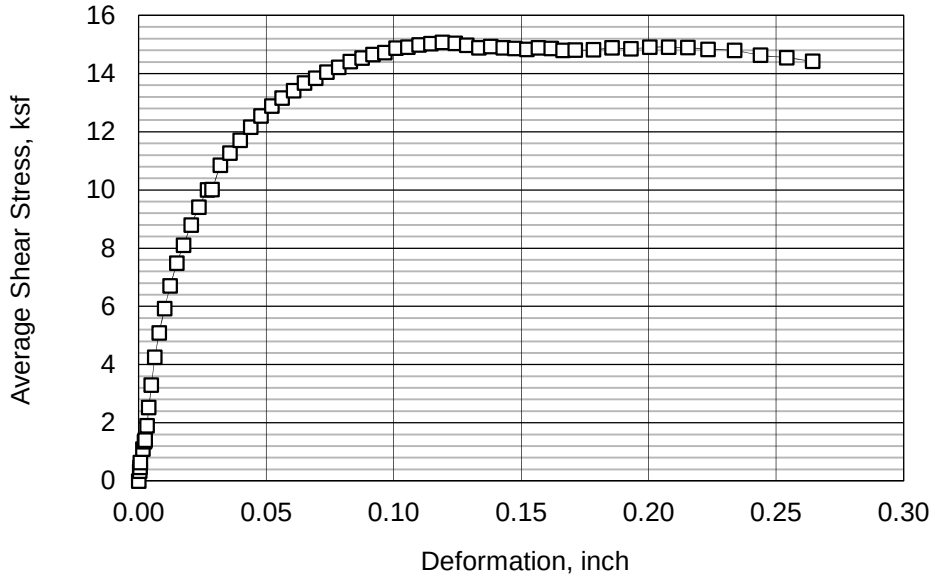
SPECIMEN INFORMATION (Initial)

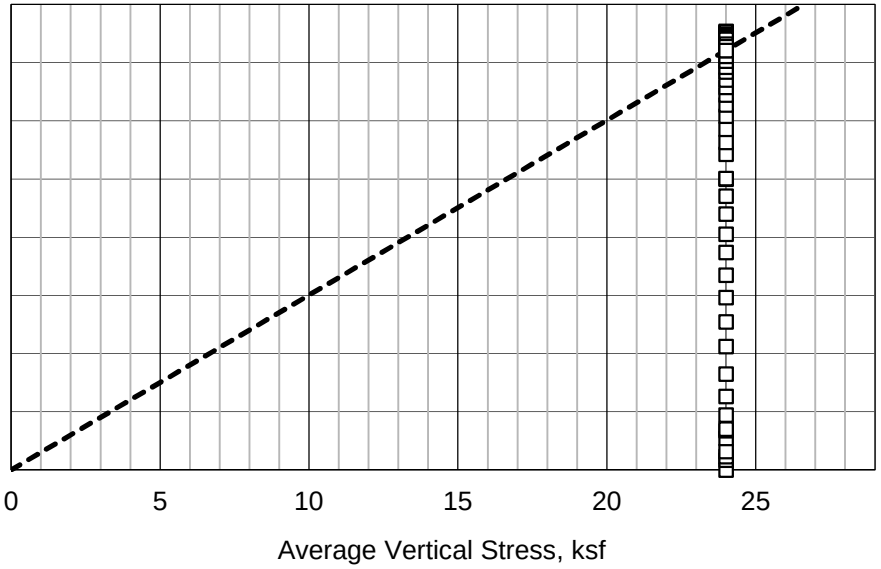
Description: SC, brown clayey sand
Height: 1.00 inch Diameter: 2.50 inch Area: 4.91 in²
Water Content: 10.5 % Dry Unit Weight: 126.0 pcf

TEST SUMMARY

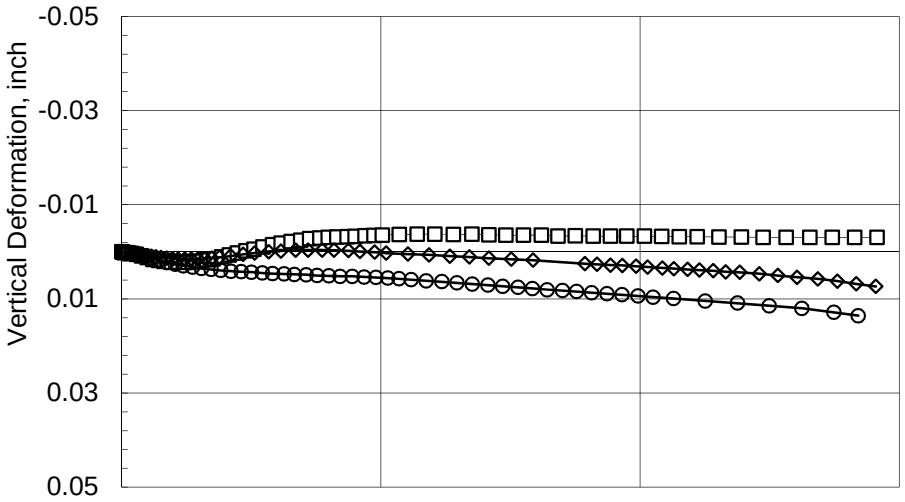
Vertical Consolidation Stress: 24.00 ksf
Water Content: 10.9 % Dry Unit Weight: 131.3 pcf
Deformation Rate: 0.00171 inch/min.
Peak Shear Strength: 15.08 ksf @ 0.12 inch deformation
Peak Effective Friction Angle: 32.1°, cohesion = 0.0ksf
Final Shear Strength: 14.42 ksf @ 0.26 inch deformation
Final Effective Friction Angle: 31.0° (Shown)

REMARKS:





	AECOM 60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR** **TEST SUMMARY**	
Prepared by: MHC Checked by: GET	**TerraSense, LLC**	T60428794	Boring: NEW-B012 Sample: ST-19 Specimen: B Depth: 81.5 ft	November 15



SAMPLE INFORMATION

Boring: NEW-B015 Sample: ST-3 Depth: 60-61.3 feet
Type: Intact tube sample
Description: CL, brown clay with sand and gravel

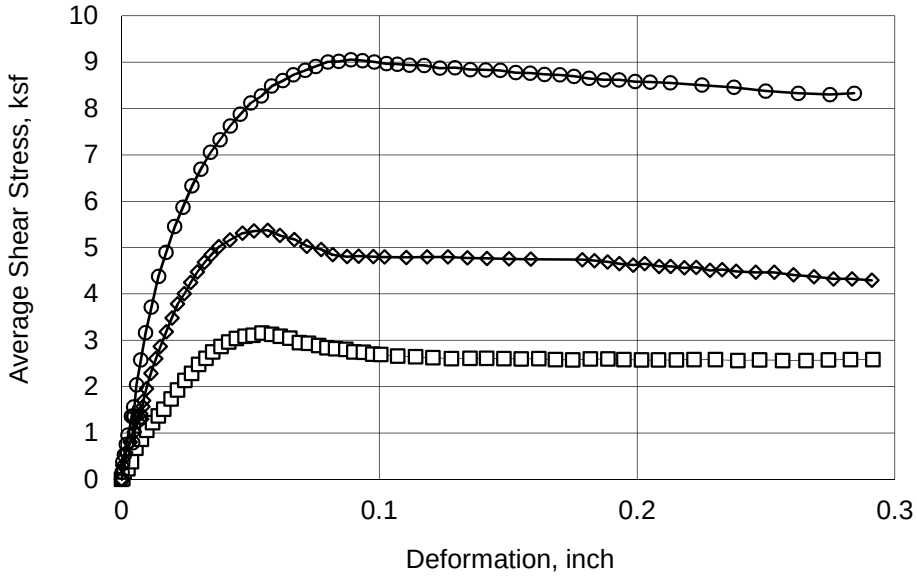
TEST INFORMATION

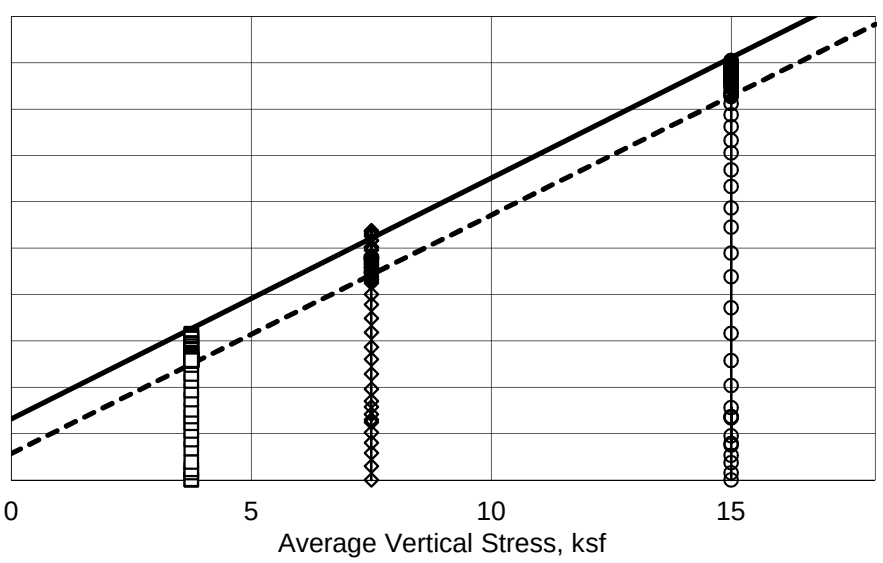
Test	Symbol	Vertical Stress (ksf)	Deformation Rate (inch/min.)
DS1623	□	3.8	0.0008
DS1625	◊	7.5	0.0008
DS1627	○	15.0	0.0007

TEST SUMMARY

Peak Effective Friction Angle: 27.4°, cohesion = 1.3ksf
Final Effective Friction Angle: 27.2°, cohesion = 0.6ksf

REMARKS:





Prepared by: MHC Checked by: GET	AECOM #60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR** **SERIES SUMMARY**	
	TerraSense, LLC	T60428794	Boring: NEW-B015 Sample: ST-3 Depth: 60-61.3	November 2015

STAGED DRAINED DIRECT SHEAR TEST SERIES

Boring No	Depth (ft)	w_o	γ_{to}	γ_{do}	$\sigma'_{v,c}$ (ksf)	Deformation rate (inch/min)	at Peak Shear Stress at High Deformation				Remarks
Sample/ Specimen	Test ID	w_c (estimated) (%)	γ_{tc} (estimated) (pcf)	γ_{dc} (estimated) (pcf)	$\varepsilon_{v,c}$ (%)	t_c (days)	ΔL (inch)	τ_h (ksf)	ε_v (%)	Φ' for c'=0	
NEW-B015	60.4	11.2	139.6	125.5	3.75	8.2E-4	0.05	3.16	-0.10	40.1	
ST-3	DS1623	12.0	141.2	126.1	2.8	0.63	0.29	2.59	-0.30	34.6	
NEW-B015	60.8	11.9	140.2	125.3	7.50	7.8E-4	0.06	5.38	0.00	35.6	
ST-3	DS1625	13.3	142.1	125.5	2.7	0.24	0.29	4.29	0.73	29.8	
NEW-B015	61.1	12.7	139.8	124.1	15.00	6.6E-4	0.09	9.05	0.51	31.1	
ST-3	DS1627	12.0	141.4	126.2	4.9	1.08	0.28	8.33	1.33	29.0	

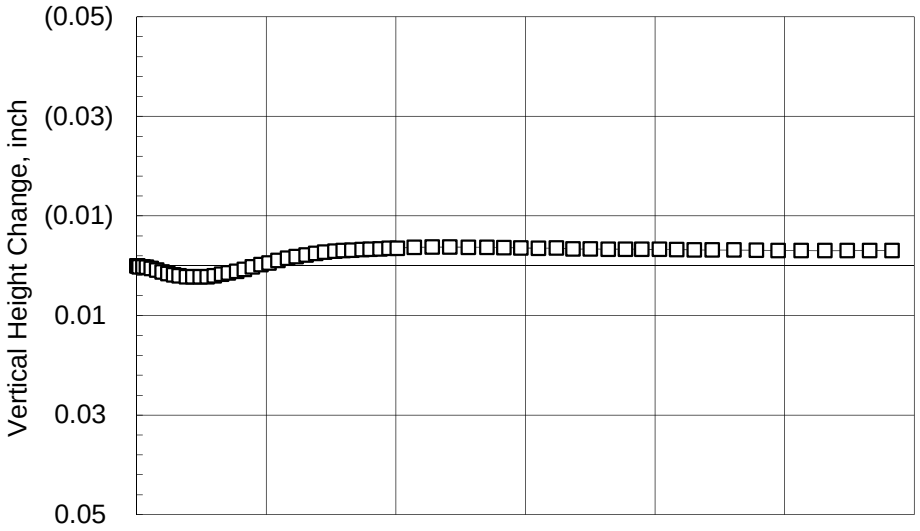
Description of Material Tested and Remarks	
DS1623	CL, brown clay with sand and gravel
DS1625	CL, brown clay with sand
DS1627	CL, brown clay with sand

Strength Envelope Summary

Test Series	Failure Criterion	Φ' (degree)	c' (ksf)
1	1	27.4	1.3
	2	27.2	0.6

Failure Criterion: 1. Peak shear stress; 2. High deformation

	AECOM #60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR SERIES SUMMARY**
Prepared by: MHC Checked by: GET	**TerraSense, LLC**	T60428794	Boring: NEW-B015 Sample: ST-3 Depth: 60-61.3 ft



SAMPLE INFORMATION

Boring: NEW-B015 Sample: ST-3 Specimen: B Depth: 60.35 ft
Type: Intact tube sample

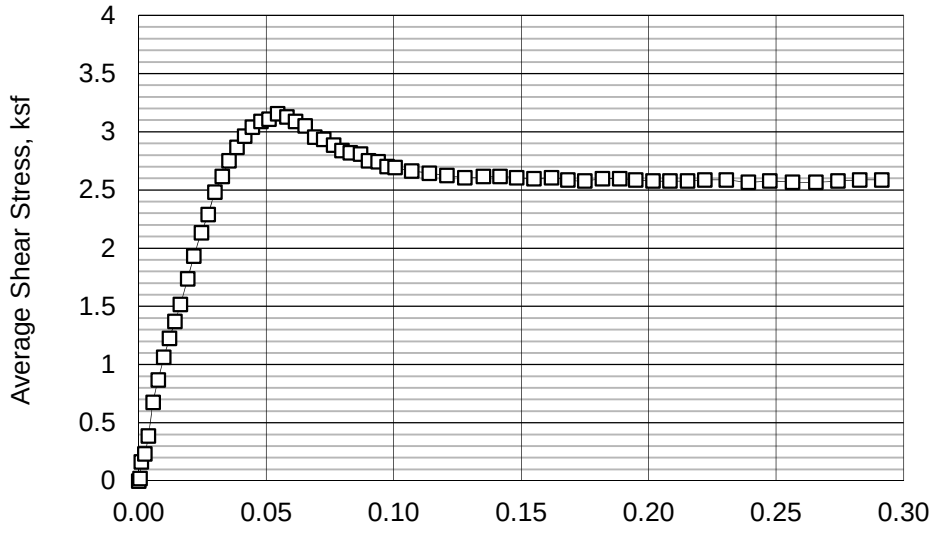
SPECIMEN INFORMATION (Initial)

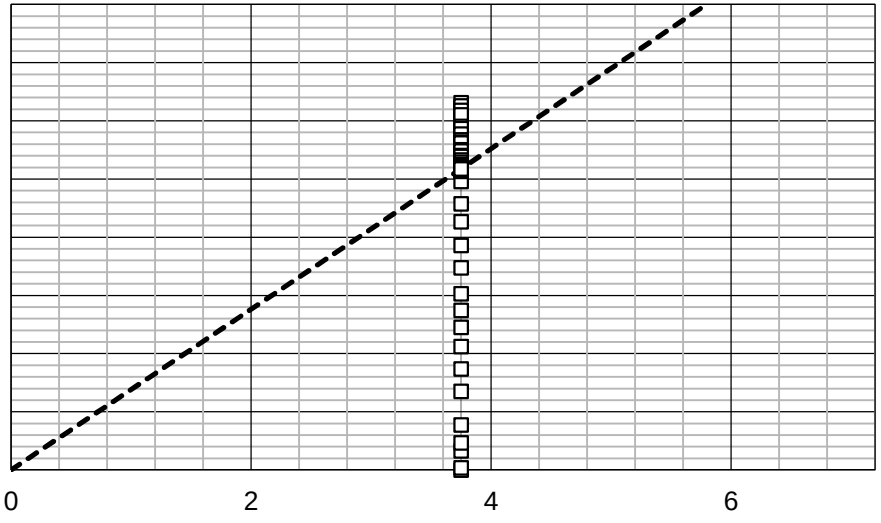
Description: CL, brown clay with sand and gravel
Height: 1.01 inch Diameter: 2.50 inch Area: 4.91 in²
Water Content: 11.2 % Dry Unit Weight: 125.5 pcf

TEST SUMMARY

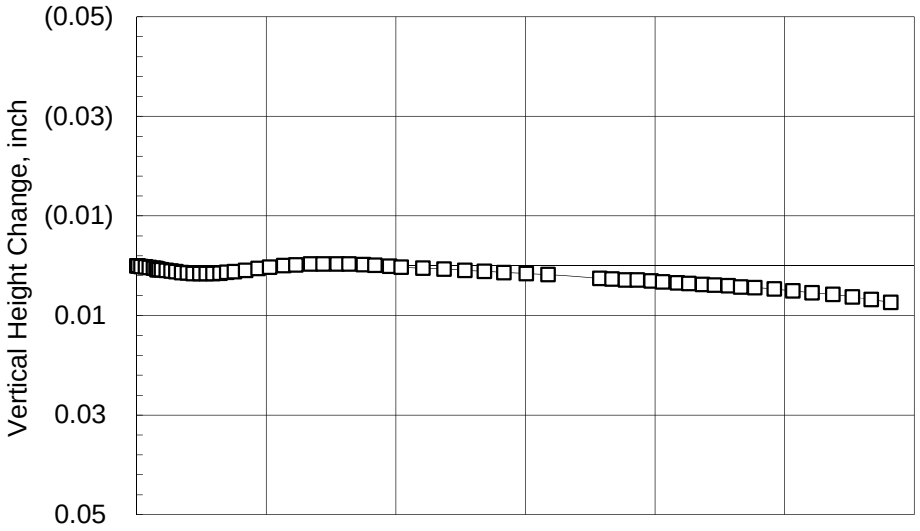
Vertical Consolidation Stress: 3.75 ksf
Water Content: 12.0 % Dry Unit Weight: 126.1 pcf
Deformation Rate: 0.00082 inch/min.
Peak Shear Strength: 3.16 ksf @ 0.05 inch deformation
Peak Effective Friction Angle: 40.1°, cohesion = 0.0ksf
Final Shear Strength: 2.59 ksf @ 0.29 inch deformation
Final Effective Friction Angle: 34.6° (Shown)

REMARKS:





	AECOM 60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR** **TEST SUMMARY**	
Prepared by: MHC Checked by: GET	**TerraSense, LLC**	T60428794	Boring: NEW-B015 Sample: ST-3 Specimen: B Depth: 60.35 ft	November 15



SAMPLE INFORMATION

Boring: NEW-B015 Sample: ST-3 Specimen: C Depth: 60.75 ft
Type: Intact tube sample

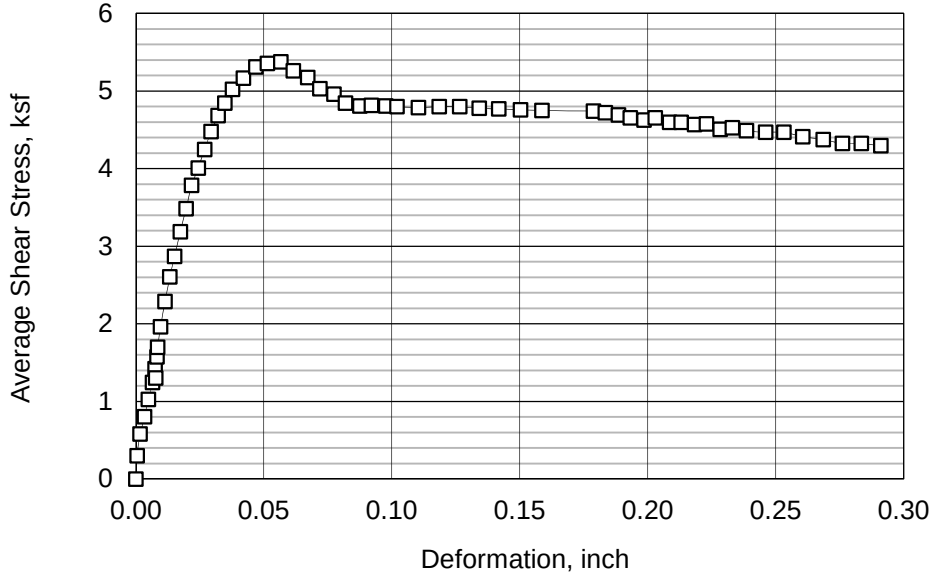
SPECIMEN INFORMATION (Initial)

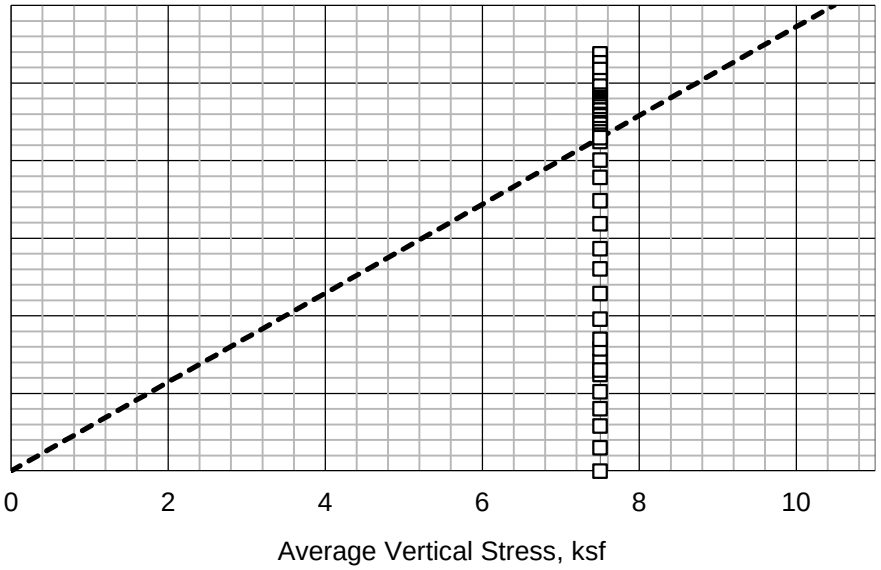
Description: CL, brown clay with sand
Height: 1.00 inch Diameter: 2.50 inch Area: 4.91 in²
Water Content: 11.9 % Dry Unit Weight: 125.3 pcf

TEST SUMMARY

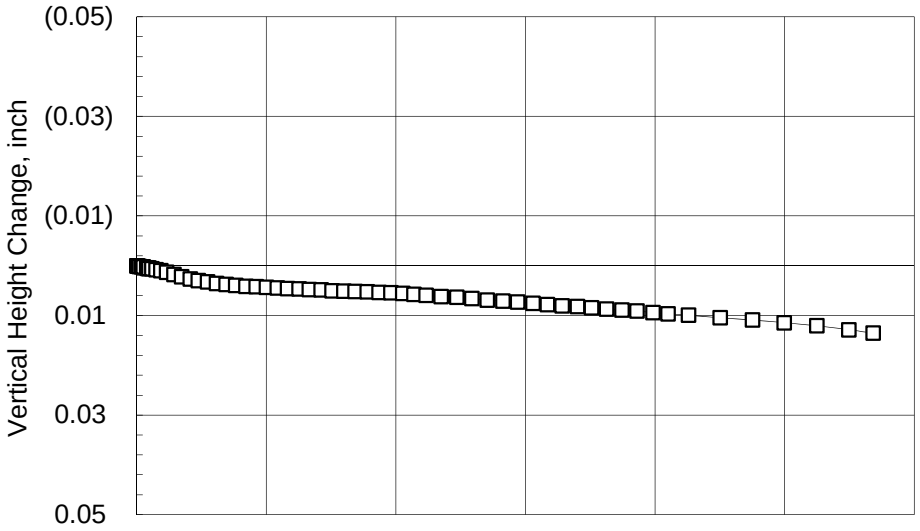
Vertical Consolidation Stress: 7.50 ksf
Water Content: 13.3 % Dry Unit Weight: 125.5 pcf
Deformation Rate: 0.00078 inch/min.
Peak Shear Strength: 5.38 ksf @ 0.06 inch deformation
Peak Effective Friction Angle: 35.6°, cohesion = 0.0ksf
Final Shear Strength: 4.29 ksf @ 0.29 inch deformation
Final Effective Friction Angle: 29.8° (Shown)

REMARKS:





	AECOM 60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR** **TEST SUMMARY**	
Prepared by: MHC Checked by: GET	**TerraSense, LLC**	T60428794	Boring: NEW-B015 Sample: ST-3 Specimen: C Depth: 60.75 ft	November 15



SAMPLE INFORMATION

Boring: NEW-B015 Sample: ST-3 Specimen: D Depth: 61.05 ft
Type: Intact tube sample

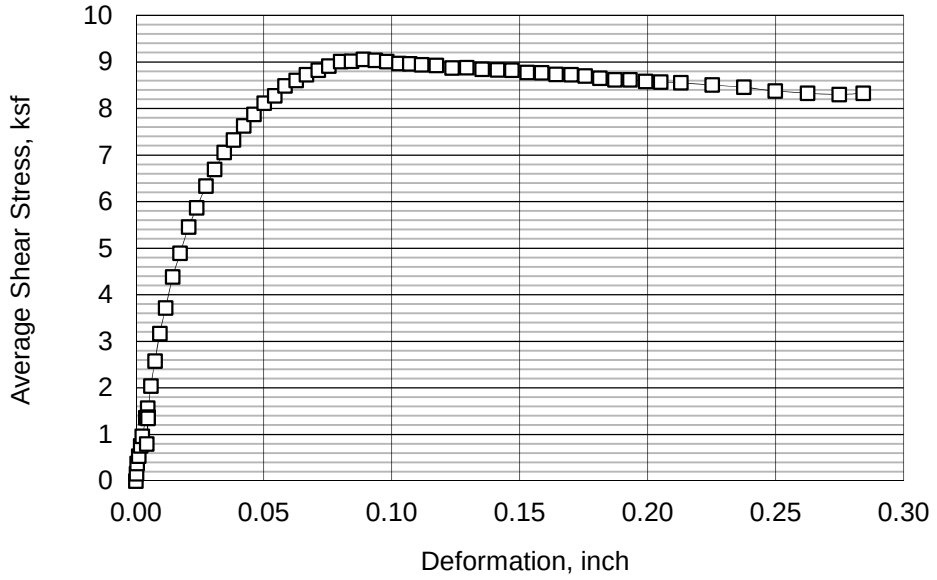
SPECIMEN INFORMATION (Initial)

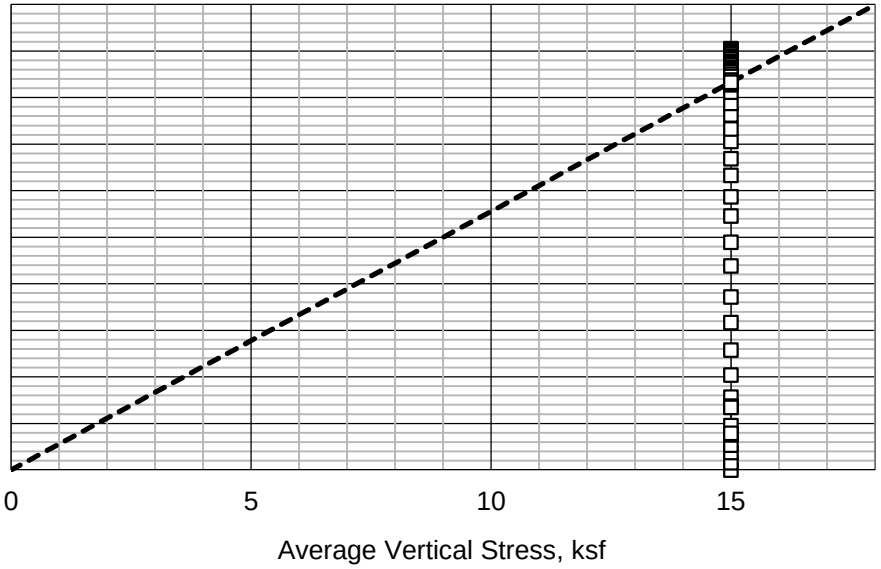
Description: CL, brown clay with sand
Height: 1.02 inch Diameter: 2.50 inch Area: 4.91 in²
Water Content: 12.7 % Dry Unit Weight: 124.1 pcf

TEST SUMMARY

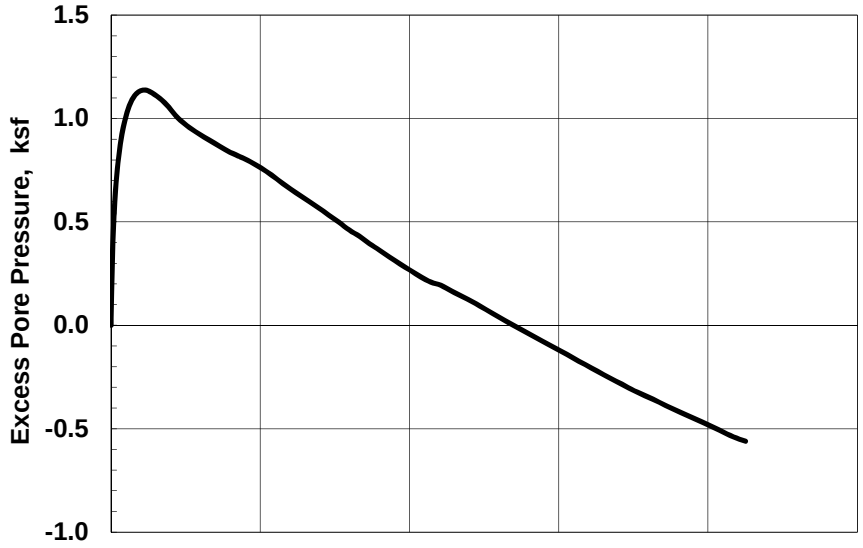
Vertical Consolidation Stress: 15.00 ksf
Water Content: 12.0 % Dry Unit Weight: 126.2 pcf
Deformation Rate: 0.00066 inch/min.
Peak Shear Strength: 9.05 ksf @ 0.09 inch deformation
Peak Effective Friction Angle: 31.1°, cohesion = 0.0ksf
Final Shear Strength: 8.33 ksf @ 0.28 inch deformation
Final Effective Friction Angle: 29.0° (Shown)

REMARKS:





	AECOM 60428794	Dynegy CCR - Newton	**DRAINED DIRECT SHEAR** **TEST SUMMARY**	
Prepared by: MHC Checked by: GET	**TerraSense, LLC**	T60428794	Boring: NEW-B015 Sample: ST-3 Specimen: D Depth: 61.05 ft	November 15

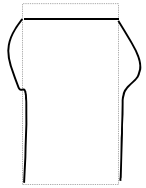


SAMPLE INFORMATION

Boring: NEW-B001 Sample: ST-5 Depth: 10.75 ft
Type: Intact tube sample
Description: CH, gray fat clay
LL = 50 PL = 14 PI = 36

SPECIMEN INFORMATION (Initial)

Height: 6.00 inch Diameter: 2.88 inch Area: 6.51 in²
Water Content: 18.1 % Total Unit Weight: 132.6 pcf

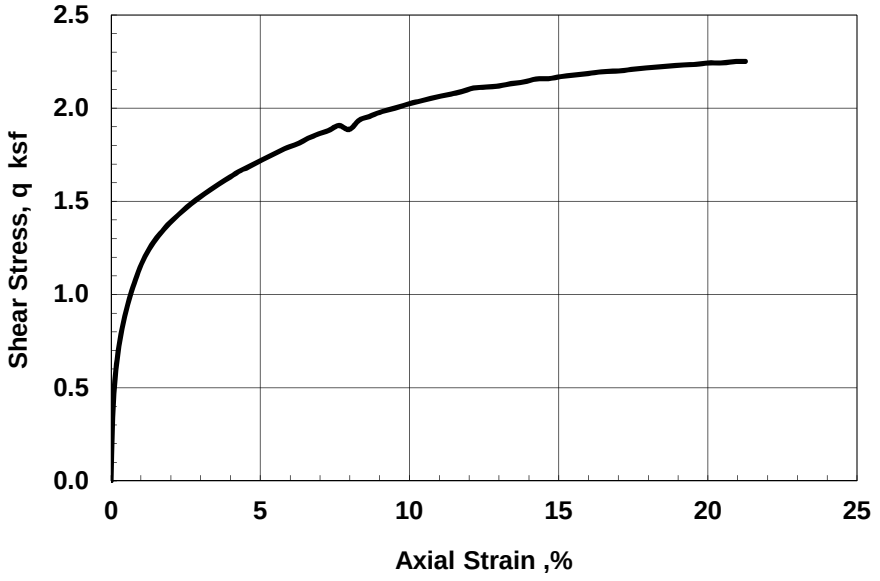


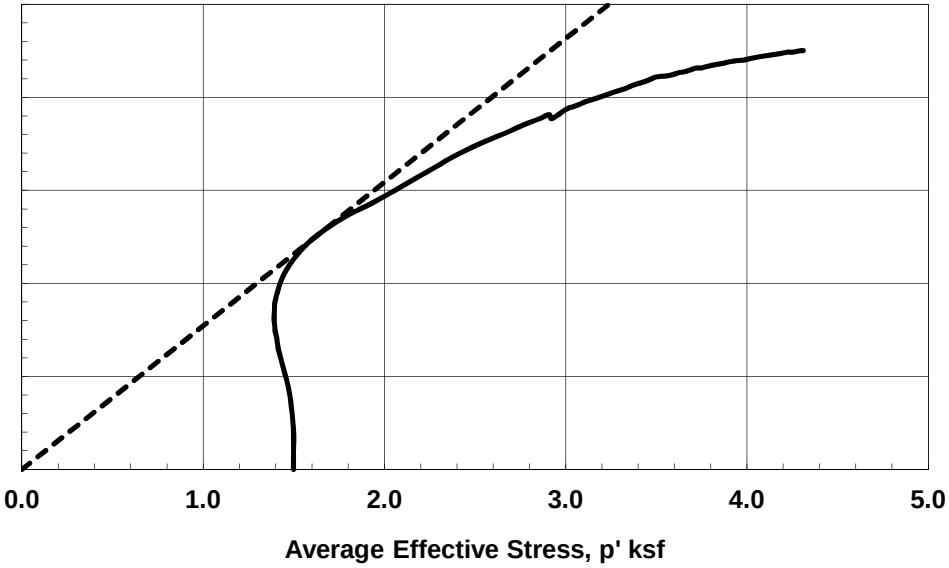
Failure Sketch

TEST SUMMARY

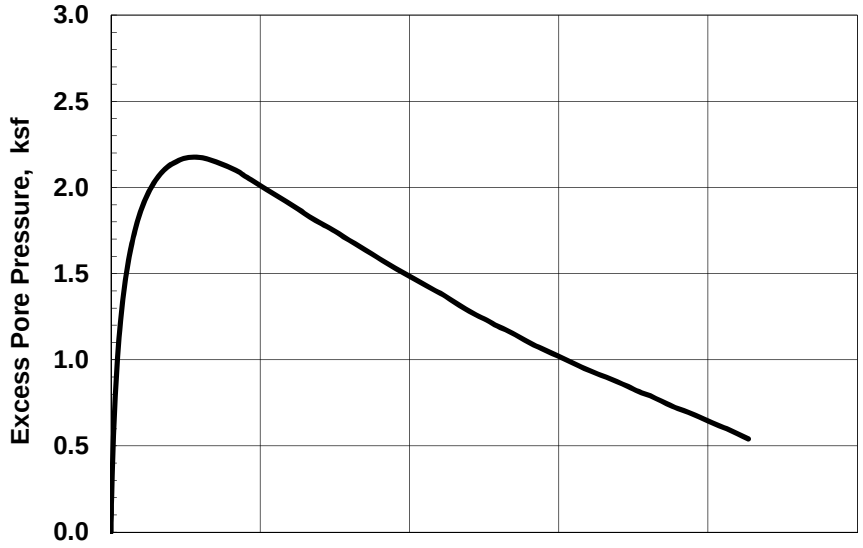
Consolidation Stresses: 1.50 ksf vertical, 1.50 ksf lateral
Water Content: 19.1 % Total Unit Weight: 133.4 pcf
B Coefficient: 99.6 Strain Rate: 0.021 %/min
Peak Shear Strength: 2.25 ksf @ 21.3 % Strain
Peak Effective Friction Angle: 50.5°

REMARKS:





Test by: BB	Project No. T60428794	AECOM Dynegy CCR - Newton	CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION with Pore Pressure Measurements
Checked by: GET	**TerraSense, LLC**		Boring: NEW-B001 Sample: ST-5 — November-15



SAMPLE INFORMATION

Boring: NEW-B001 Sample: ST-7B Depth: 21.1 ft
Type: Intact tube sample
Description: CL, gray brown sandy lean clay
LL = 49 PL = 13 PI = 36

SPECIMEN INFORMATION (Initial)

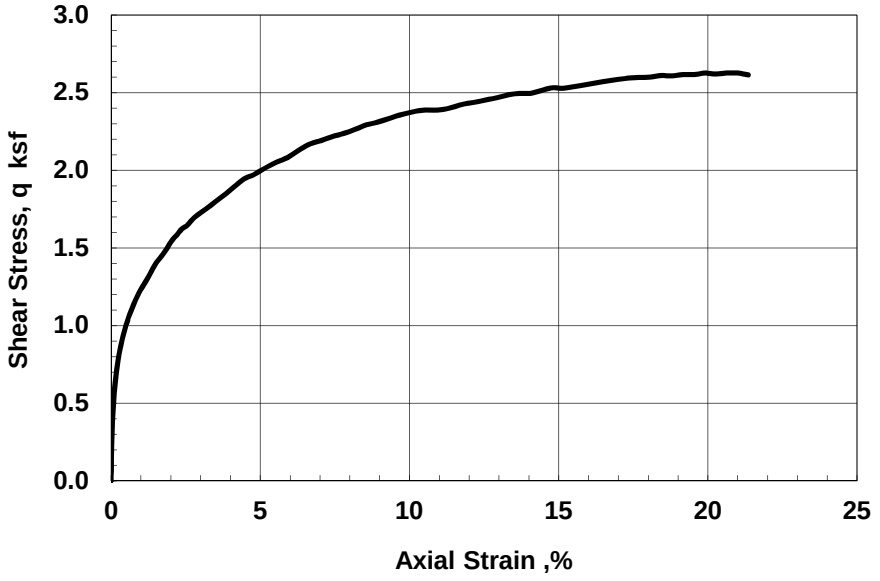
Height: 6.00 inch Diameter: 2.88 inch Area: 6.51 in²
Water Content: 16.2 % Total Unit Weight: 134.5 pcf

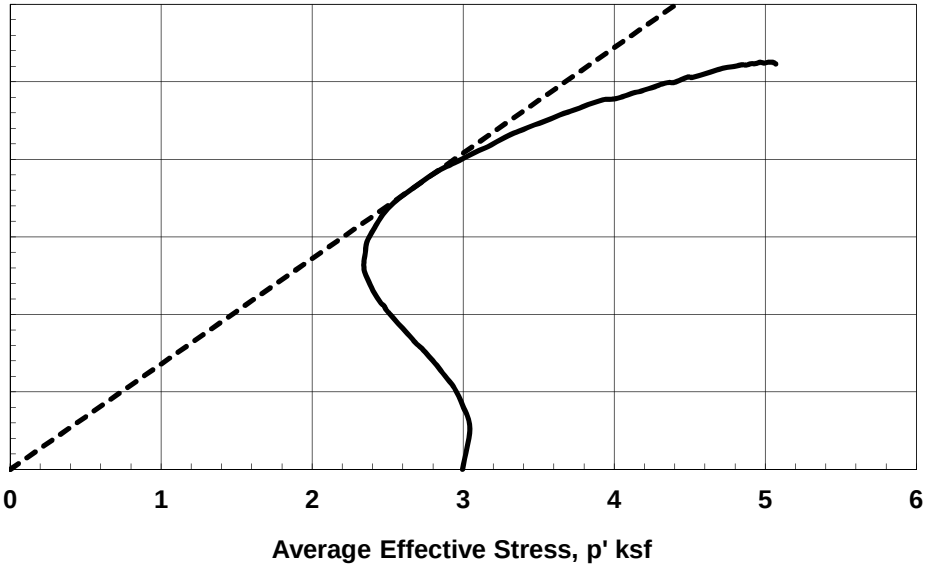
TEST SUMMARY

Consolidation Stresses: 3.00 ksf vertical, 3.00 ksf lateral
Water Content: 17.0 % Total Unit Weight: 136.5 pcf
B Coefficient: 99.14 Strain Rate: 0.023 %/min
Peak Shear Strength: 2.63 ksf @ 20.6 % Strain
Peak Effective Friction Angle: 42.9°

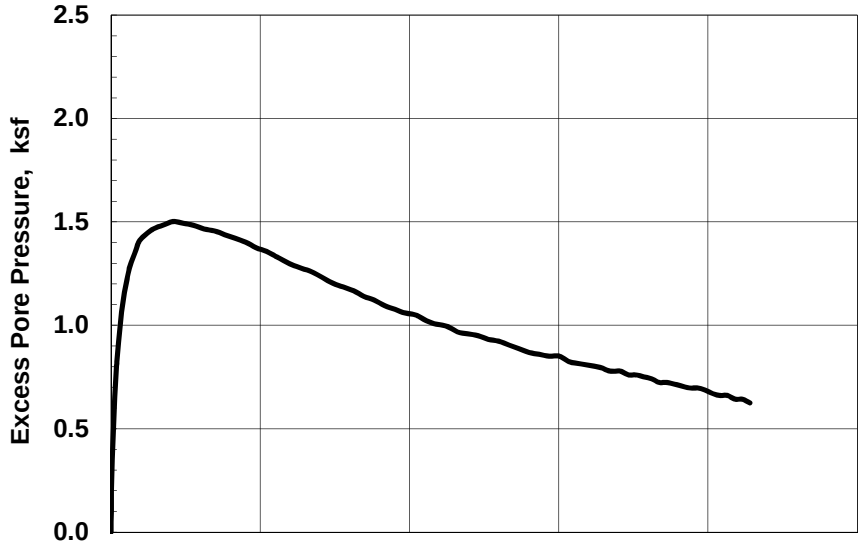
Failure Sketch

REMARKS:





Test by: BB	Project No. T60428794	AECOM Dynegy CCR - Newton	CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION with Pore Pressure Measurements	
Checked by: GET	**TerraSense, LLC**		Boring: NEW-B001 Sample: ST-7B	November-15

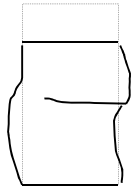


SAMPLE INFORMATION

Boring: NEW-B003 Sample: ST-1C Depth: 15.35 ft
Type: Intact tube sample
Description: CH, gray brown fat clay with sand
LL = 59 PL = 15 PI = 44

SPECIMEN INFORMATION (Initial)

Height: 6.00 inch Diameter: 2.87 inch Area: 6.49 in²
Water Content: 20.9 % Total Unit Weight: 129.5 pcf

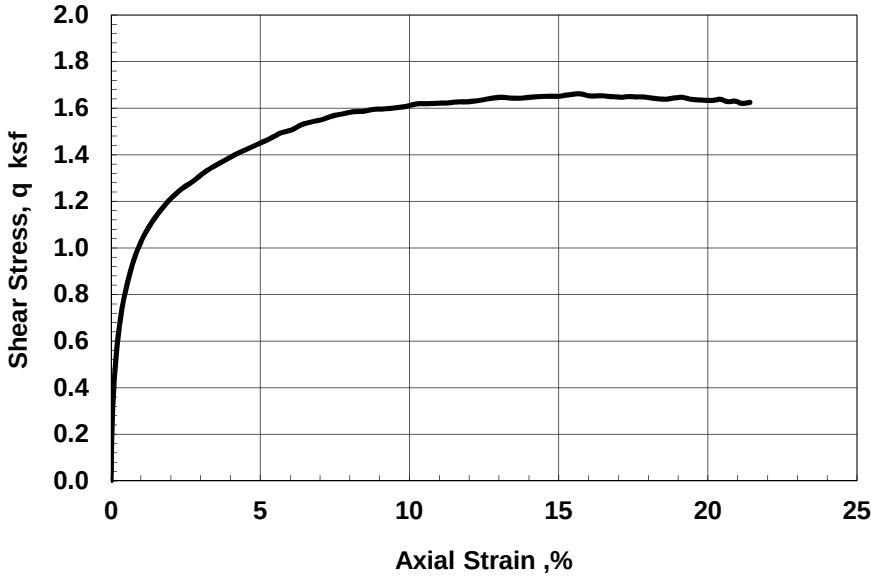


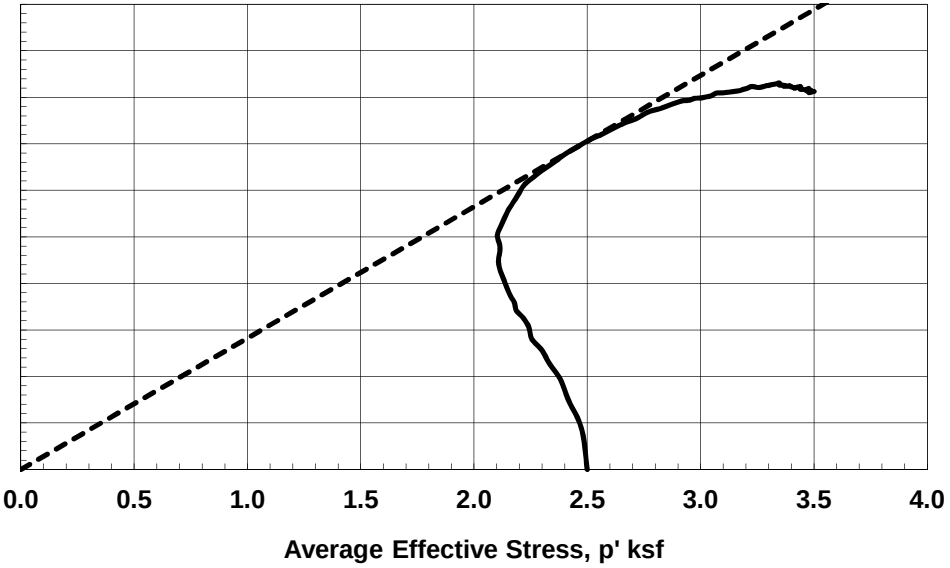
Failure Sketch

TEST SUMMARY

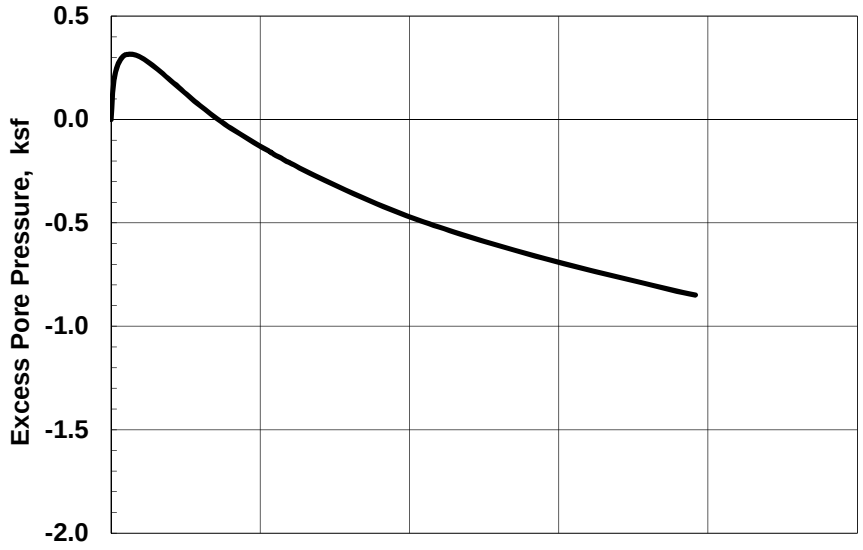
Consolidation Stresses: 2.50 ksf vertical, 2.50 ksf lateral
Water Content: 21.1 % Total Unit Weight: 131.8 pcf
B Coefficient: 99.52 Strain Rate: 0.021 %/min
Peak Shear Strength: 1.66 ksf @ 15.7 % Strain
Peak Effective Friction Angle: 34.4°

REMARKS:





Test by: BB	Project No. T60428794	AECOM Dynegy CCR - Newton	CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION with Pore Pressure Measurements	
Checked by: GET	**TerraSense, LLC**		Boring: NEW-B003 Sample: ST-1C	November-15



SAMPLE INFORMATION

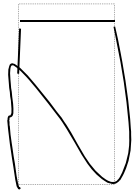
Boring: NEW-B004 Sample: ST-4 Depth: 9.5 ft
Type: Intact tube sample
Description: CH, gray fat clay with sand
LL = 50 PL = 13 PI = 37

SPECIMEN INFORMATION (Initial)

Height: 6.00 inch Diameter: 2.88 inch Area: 6.52 in²
Water Content: 18.5 % Total Unit Weight: 131.3 pcf

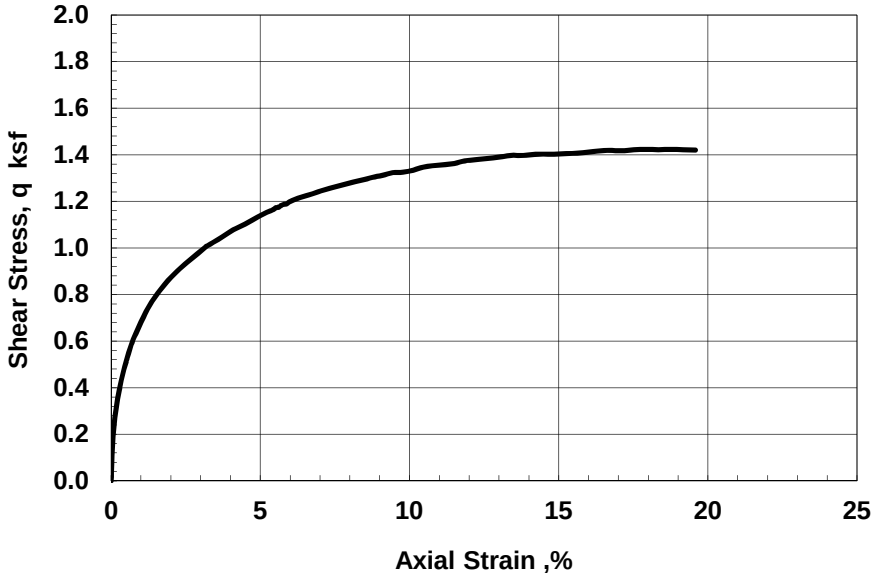
TEST SUMMARY

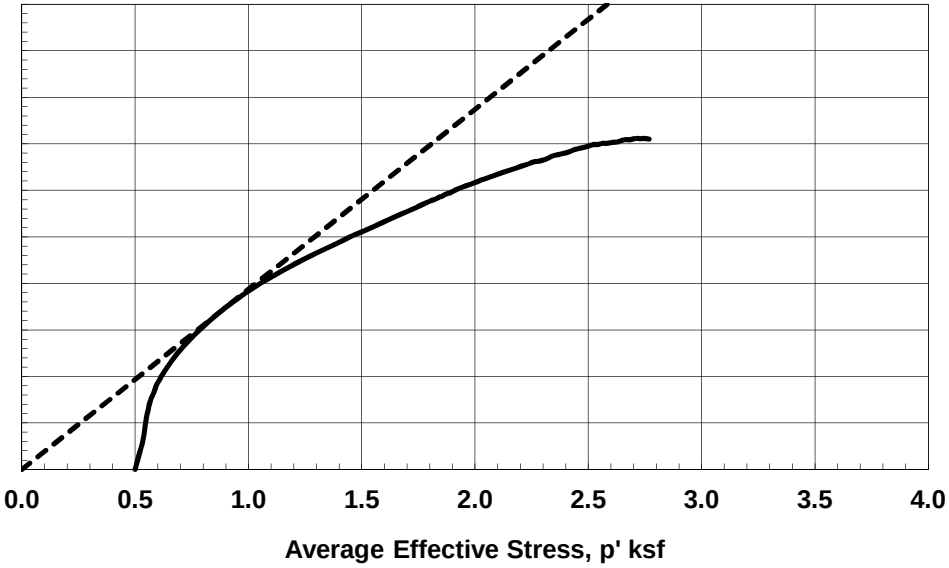
Consolidation Stresses: 0.50 ksf vertical, 0.50 ksf lateral
Water Content: 19.7 % Total Unit Weight: 132.6 pcf
B Coefficient: 99 Strain Rate: 0.022 %/min
Peak Shear Strength: 1.42 ksf @ 17.9 % Strain
Peak Effective Friction Angle: 50.7°



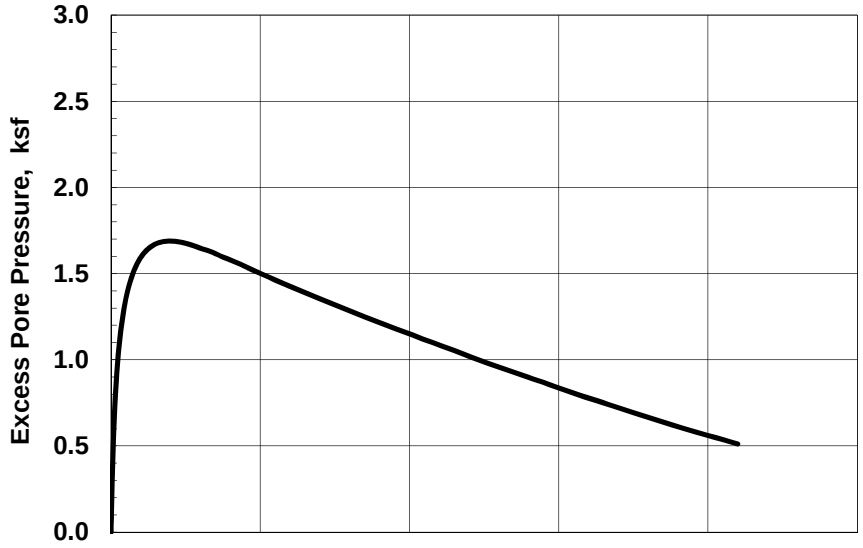
Failure Sketch

REMARKS:





Test by: BB	Project No. T60428794	AECOM Dynegy CCR - Newton	CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION with Pore Pressure Measurements
Checked by: GET	**TerraSense, LLC**		Boring: NEW-B004 Sample: ST-4
			November-15

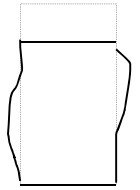


SAMPLE INFORMATION

Boring: NEW-B004 Sample: ST-7C Depth: 19.35 ft
Type: Intact tube sample
Description: CH, gray brown fat clay with sand
LL = 52 PL = 15 PI = 37

SPECIMEN INFORMATION (Initial)

Height: 6.01 inch Diameter: 2.88 inch Area: 6.50 in²
Water Content: 18.3 % Total Unit Weight: 128.5 pcf

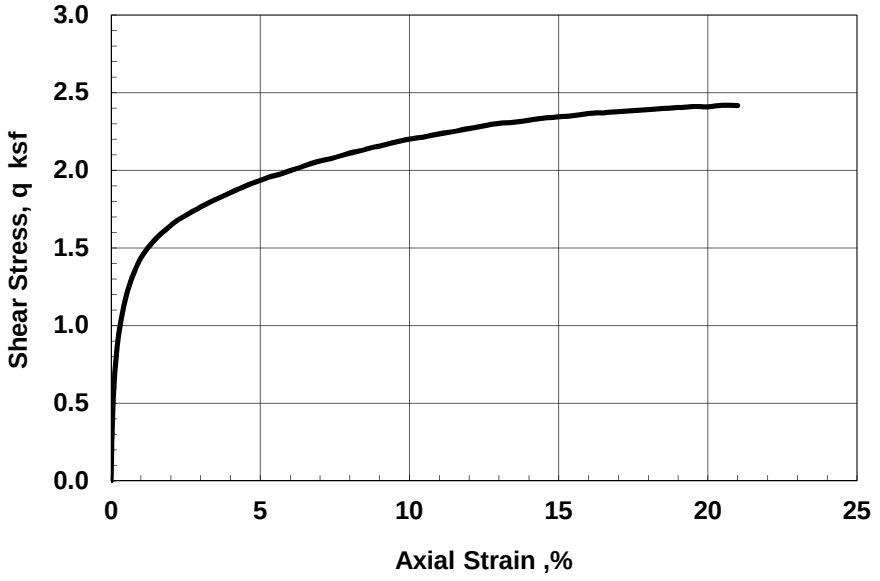


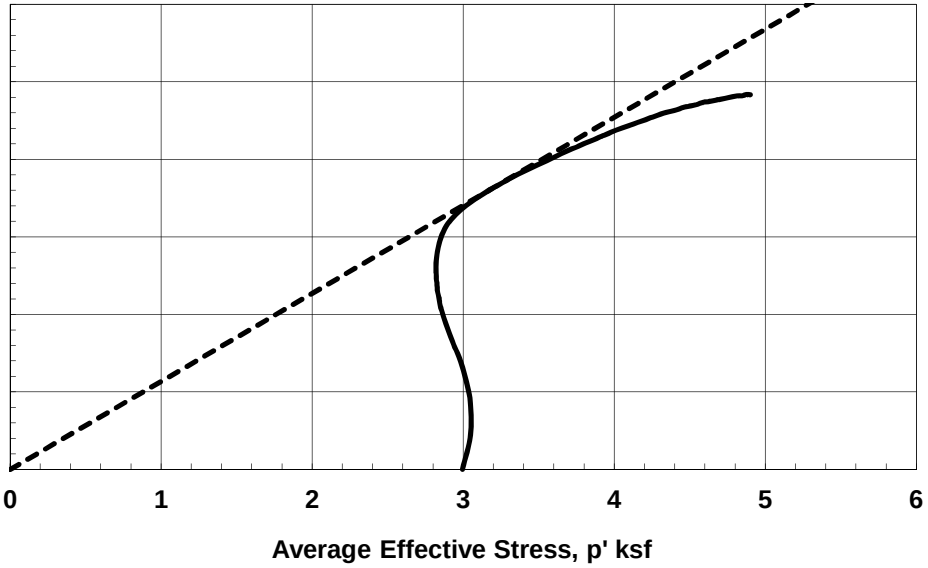
Failure Sketch

TEST SUMMARY

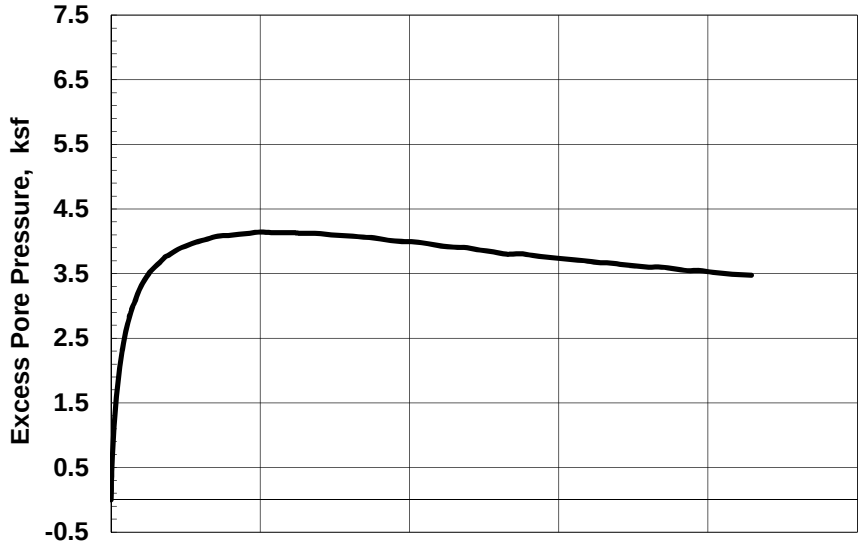
Consolidation Stresses: 3.00 ksf vertical, 3.00 ksf lateral
Water Content: 19.6 % Total Unit Weight: 133.7 pcf
B Coefficient: 99.56 Strain Rate: 0.021 %/min
Peak Shear Strength: 2.42 ksf @ 20.5 % Strain
Peak Effective Friction Angle: 34.6°

REMARKS:





Test by: BB	Project No. T60428794	AECOM Dynegy CCR - Newton	CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION with Pore Pressure Measurements
Checked by: GET	**TerraSense, LLC**		Boring: NEW-B004 Sample: ST-7C
			November-15



SAMPLE INFORMATION

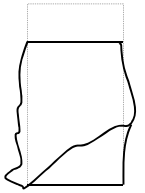
Boring: NEW-B006 Sample: ST-2 Depth: 26.75 ft
Type: Intact tube sample
Description: CL, gray sandy clay
LL = 44 PL = 12 PI = 32

SPECIMEN INFORMATION (Initial)

Height: 6.01 inch Diameter: 2.88 inch Area: 6.52 in²
Water Content: 19.7 % Total Unit Weight: 128.8 pcf

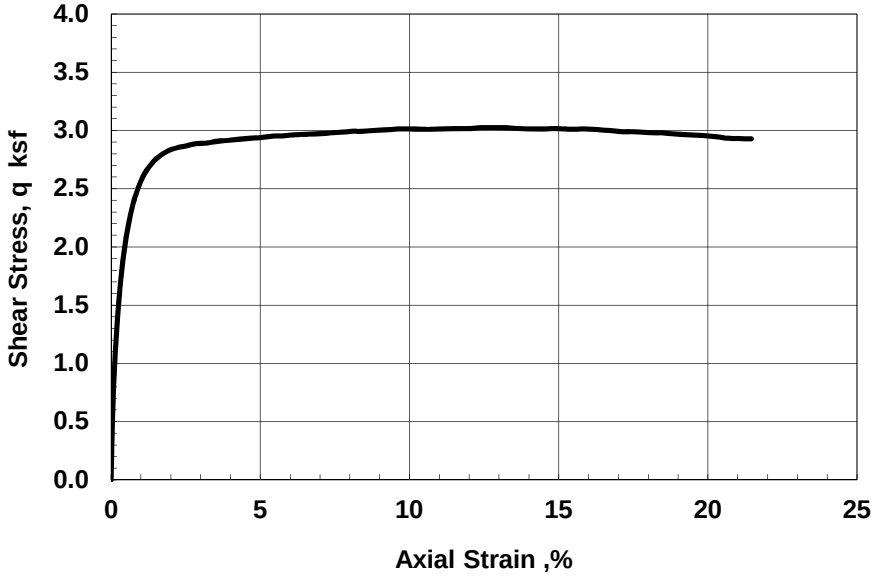
TEST SUMMARY

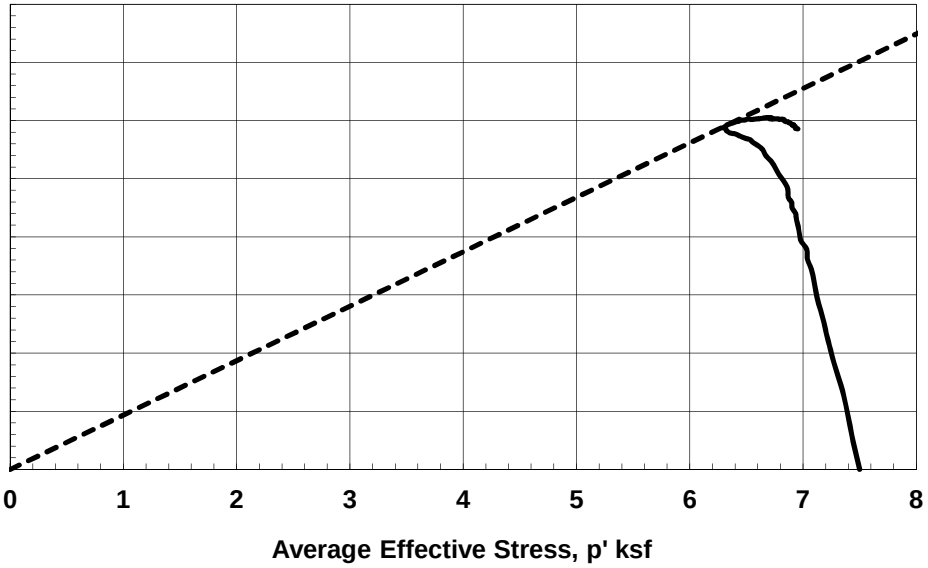
Consolidation Stresses: 7.50 ksf vertical, 7.50 ksf lateral
Water Content: 18.2 % Total Unit Weight: 134.6 pcf
B Coefficient: 97.7 Strain Rate: 0.022 %/min
Peak Shear Strength: 3.03 ksf @ 12.8 % Strain
Peak Effective Friction Angle: 27.9°



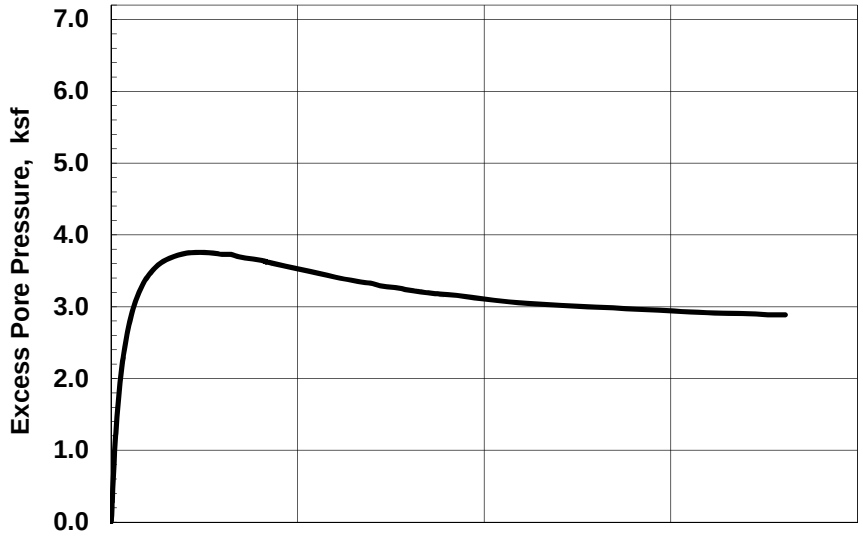
Failure Sketch

REMARKS:





Test by: BB	Project No. T60428794	AECOM Dynegy CCR - Newton	CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION with Pore Pressure Measurements
Checked by: GET	**TerraSense, LLC**		Boring: NEW-B006 Sample: ST-2 November-15



SAMPLE INFORMATION

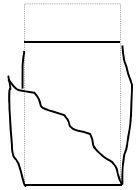
Boring: NEW-B006 Sample: ST-3C Depth: 31.8 ft
Type: Intact tube sample
Description: CL, dark brown sandy lean clay
LL = 37 PL = 15 PI = 22

SPECIMEN INFORMATION (Initial)

Height: 6.00 inch Diameter: 2.88 inch Area: 6.52 in²
Water Content: 18.3 % Total Unit Weight: 133.3 pcf

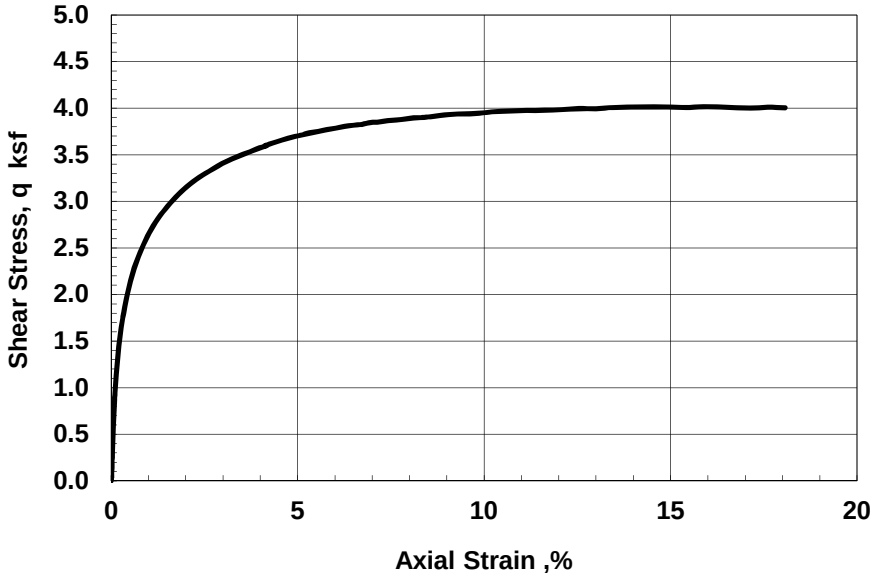
TEST SUMMARY

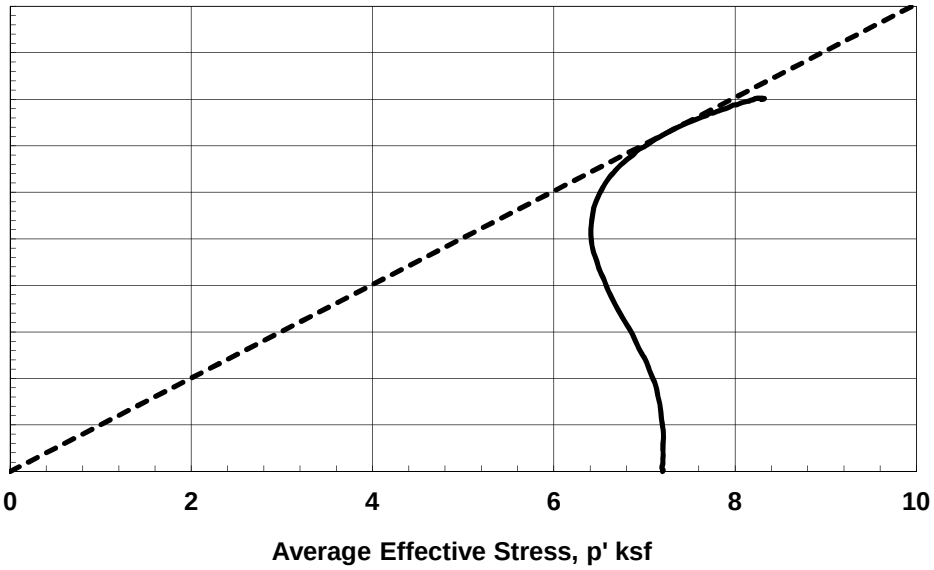
Consolidation Stresses: 7.20 ksf vertical, 7.20 ksf lateral
Water Content: 17.0 % Total Unit Weight: 138.2 pcf
B Coefficient: Strain Rate: 0.019 %/min
Peak Shear Strength: 4.01 ksf @ 14.8 % Strain
Peak Effective Friction Angle: 30.2°



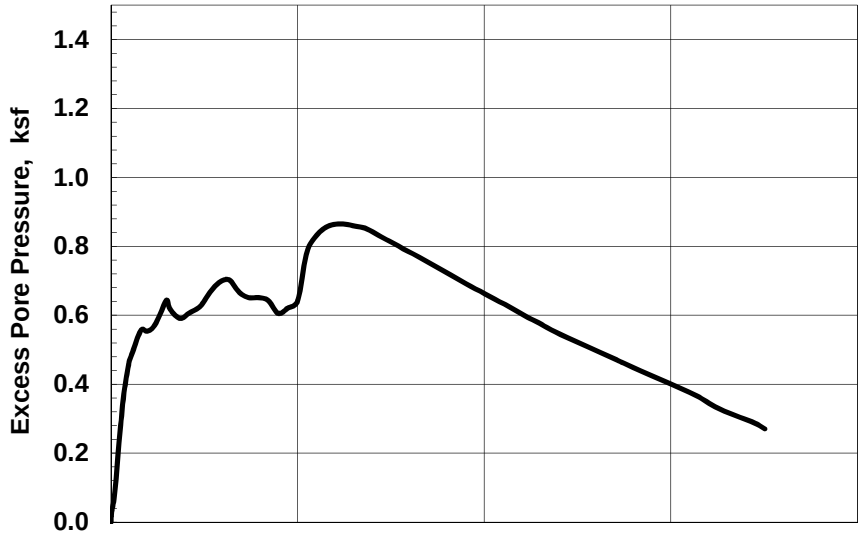
Failure Sketch

REMARKS:





Test by: BB	Project No. T60428794	AECOM Dynegy CCR - Newton	CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION with Pore Pressure Measurements	
Checked by: GET	**TerraSense, LLC**		Boring: NEW-B006 Sample: ST-3C	November-15

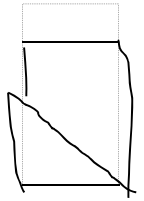


SAMPLE INFORMATION

Boring: NEW-C006 Sample: ST-1B Depth: 11.3 ft
Type: Intact tube sample
Description: CH, brown fat clay with sand
LL = 54 PL = 16 PI = 38

SPECIMEN INFORMATION (Initial)

Height: 6.03 inch Diameter: 2.87 inch Area: 6.48 in²
Water Content: 25.2 % Total Unit Weight: 124.1 pcf

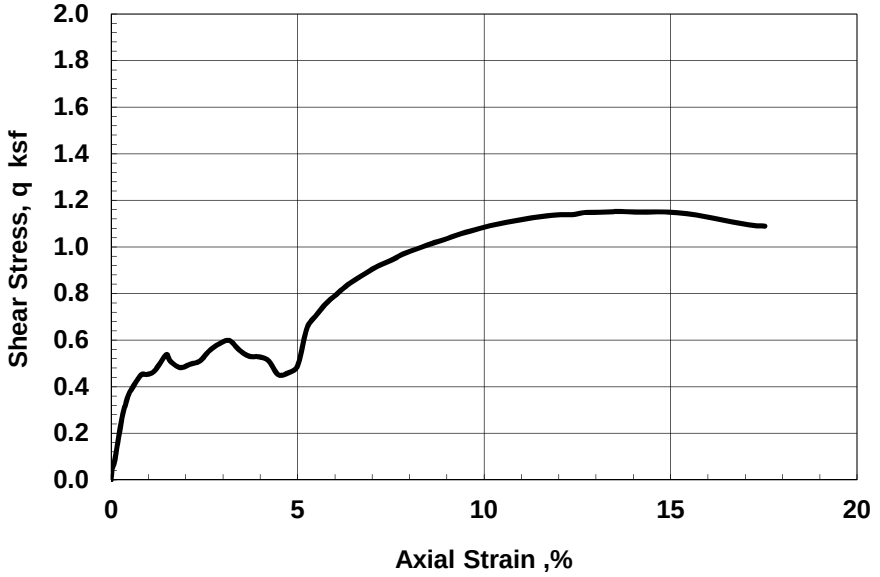


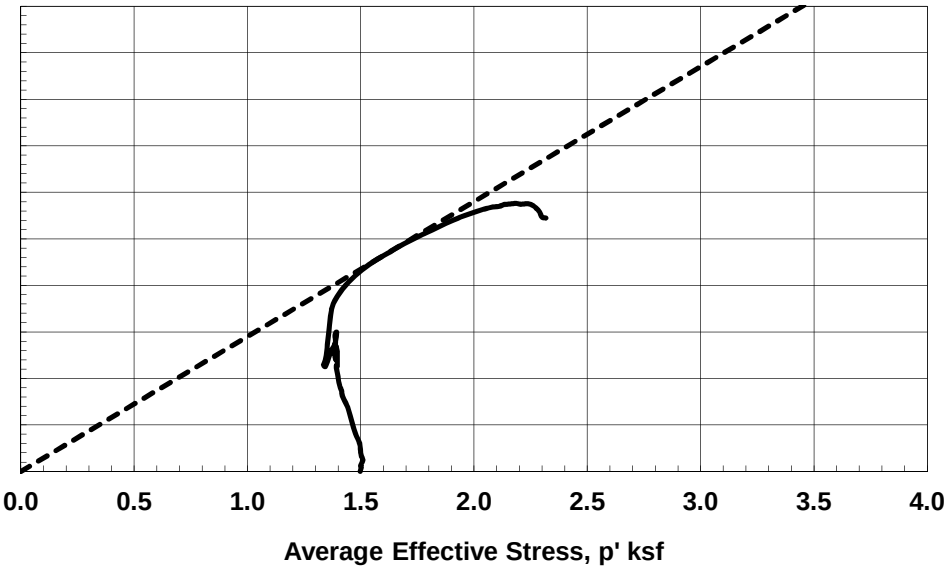
Failure Sketch

TEST SUMMARY

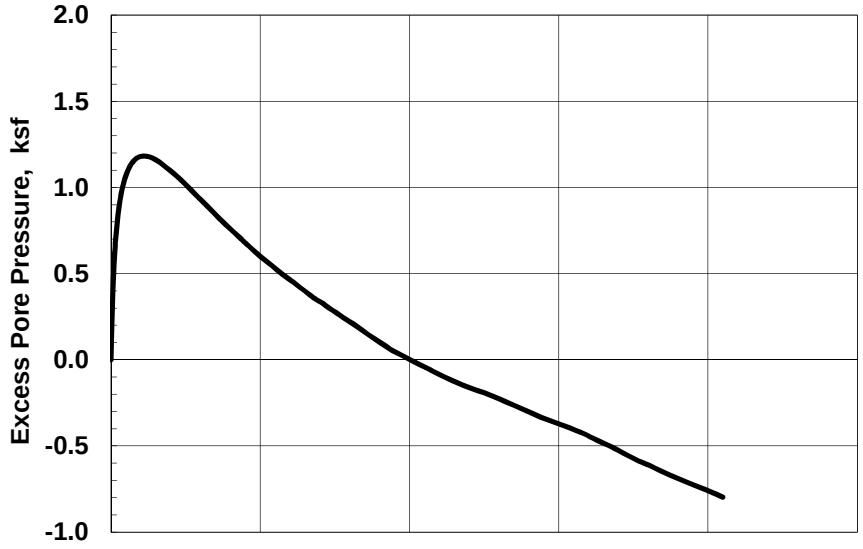
Consolidation Stresses: 1.50 ksf vertical, 1.50 ksf lateral
Water Content: 25.0 % Total Unit Weight: 127.5 pcf
B Coefficient: Strain Rate: 0.021 %/min
Peak Shear Strength: 1.15 ksf @ 13.7 % Strain
Peak Effective Friction Angle: 35.5°

REMARKS:





Test by: BB	Project No. T60428794	AECOM Dynegy CCR - Newton	CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION with Pore Pressure Measurements
Checked by: GET	**TerraSense, LLC**		Boring: NEW-C006 Sample: ST-1B
			November-15



SAMPLE INFORMATION

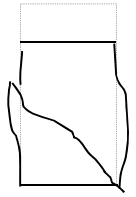
Boring: NEW-C006 Sample: ST-2B Depth: 13 ft
Type: Intact tube sample
Description: CH, brown fat clay
LL = 53 PL = 14 PI = 39

SPECIMEN INFORMATION (Initial)

Height: 6.02 inch Diameter: 2.88 inch Area: 6.49 in²
Water Content: 18.9 % Total Unit Weight: 131.5 pcf

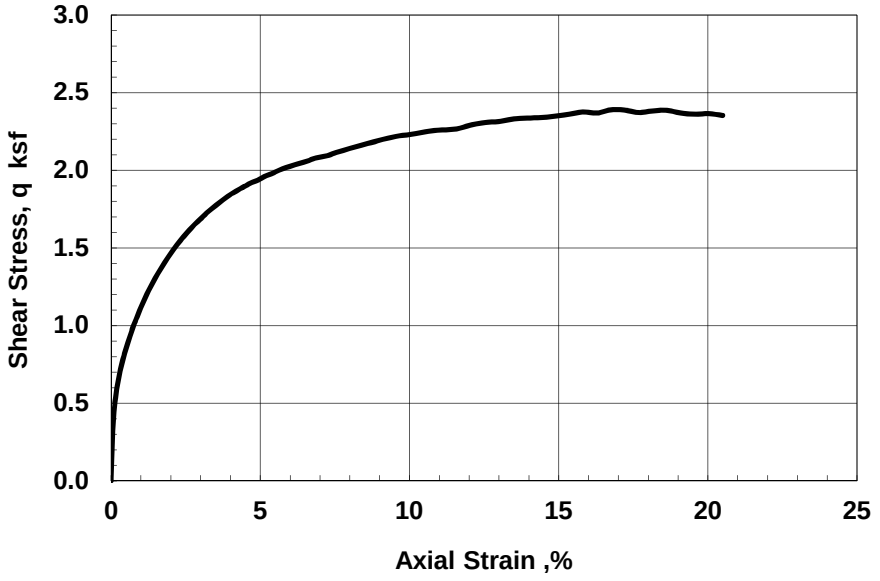
TEST SUMMARY

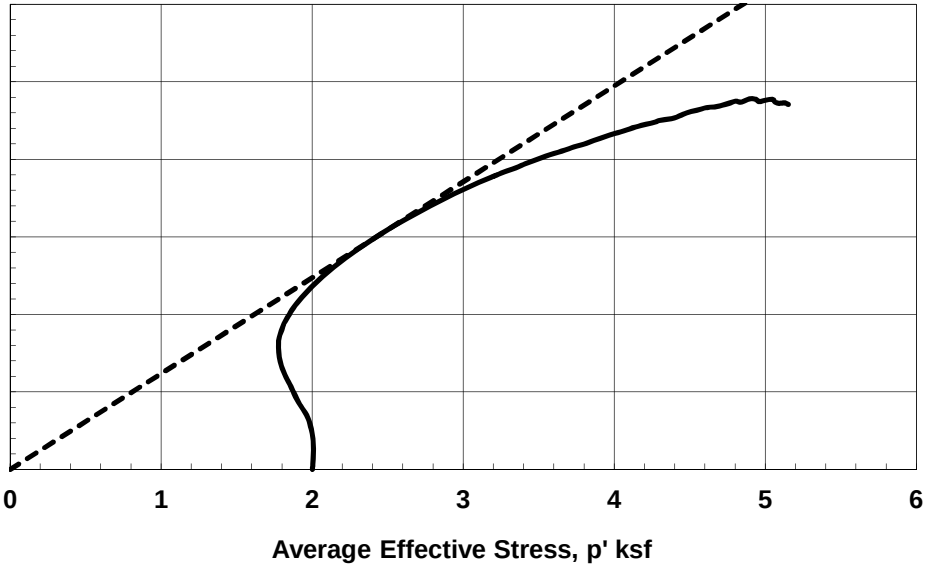
Consolidation Stresses: 2.00 ksf vertical, 2.00 ksf lateral
Water Content: 19.4 % Total Unit Weight: 134.0 pcf
B Coefficient: Strain Rate: 0.020 %/min
Peak Shear Strength: 2.39 ksf @ 16.7 % Strain
Peak Effective Friction Angle: 38.2°



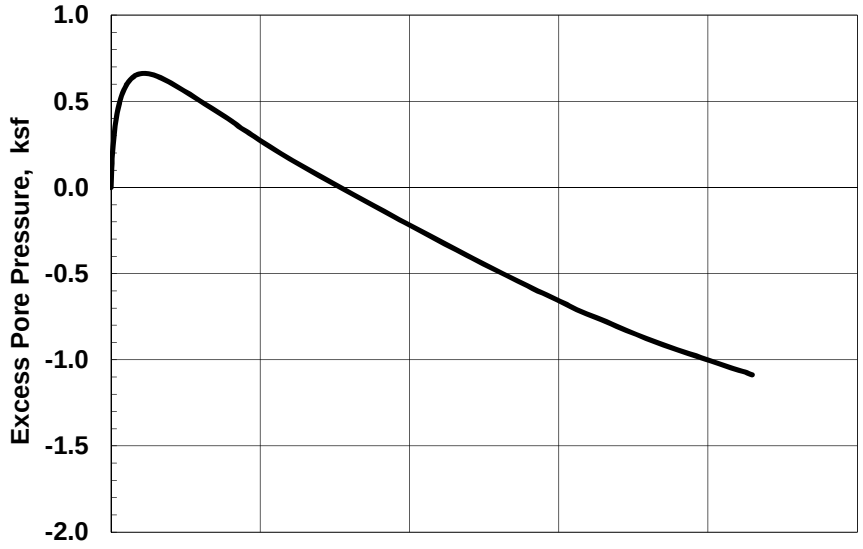
Failure Sketch

REMARKS:





Test by: BB	Project No. T60428794	AECOM Dynegy CCR - Newton	CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION with Pore Pressure Measurements	
Checked by: GET	**TerraSense, LLC**		Boring: NEW-C006 Sample: ST-2B	November-15



SAMPLE INFORMATION

Boring: NEW-B007 Sample: ST-1C Depth: 11.55 ft
Type: Intact tube sample
Description: CL, brown lean clay with sand
LL = 38 PL = 14 PI = 24

SPECIMEN INFORMATION (Initial)

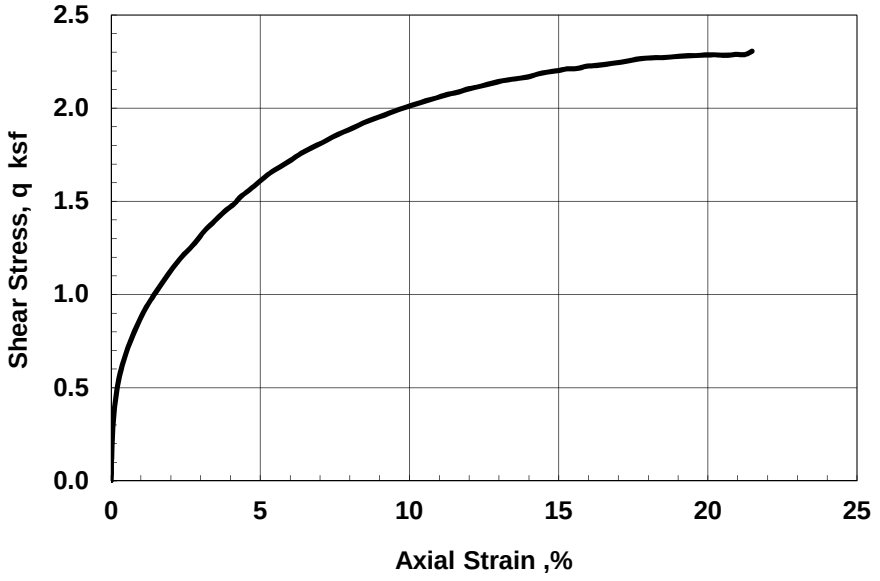
Height: 6.01 inch Diameter: 2.88 inch Area: 6.51 in²
Water Content: 15.4 % Total Unit Weight: 135.1 pcf

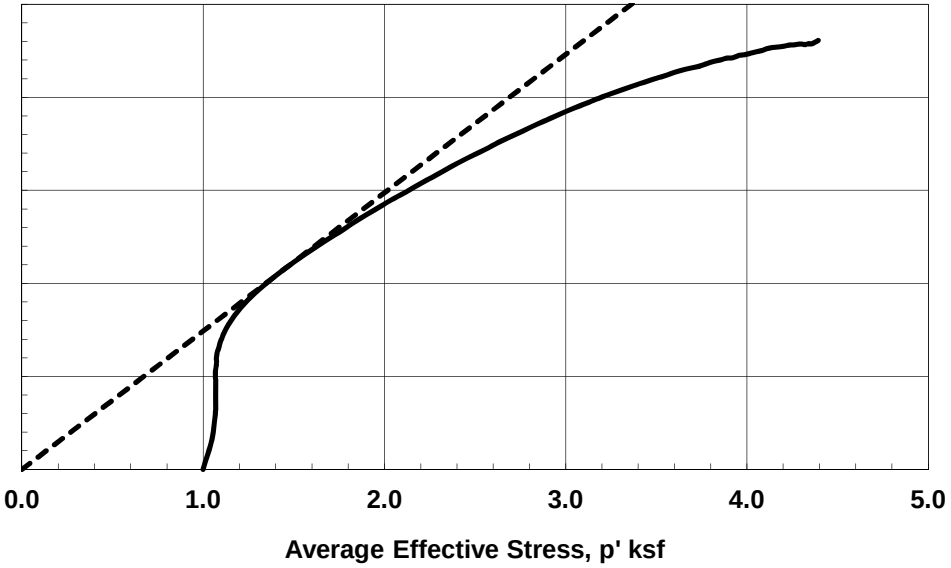
TEST SUMMARY

Consolidation Stresses: 1.00 ksf vertical, 1.00 ksf lateral
Water Content: 15.9 % Total Unit Weight: 137.7 pcf
B Coefficient: 99.2 Strain Rate: 0.021 %/min
Peak Shear Strength: 2.31 ksf @ 21.5 % Strain
Peak Effective Friction Angle: 48.0°

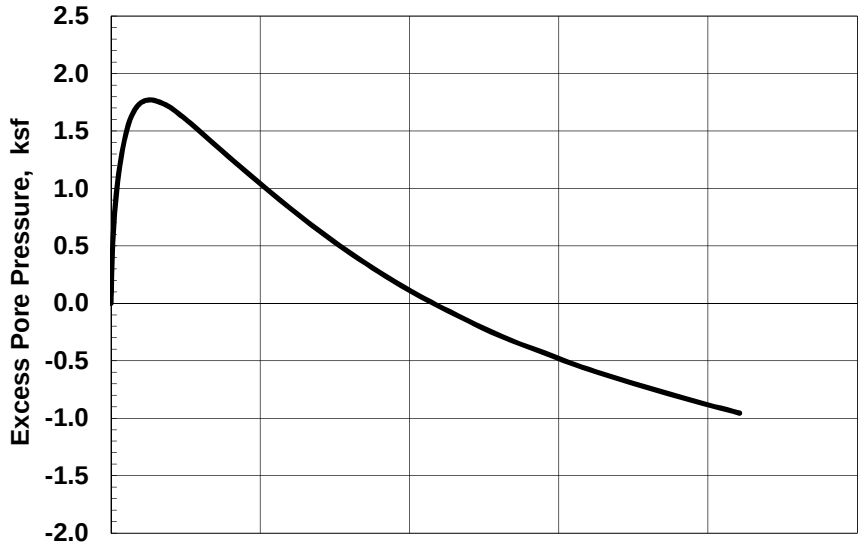
Failure Sketch

REMARKS:





Test by: BB	Project No. T60428794	AECOM Dynegy CCR - Newton	CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION with Pore Pressure Measurements
Checked by: GET	**TerraSense, LLC**		Boring: NEW-B007 Sample: ST-1C
			November-15



SAMPLE INFORMATION

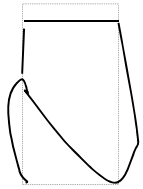
Boring: NEW-B007 Sample: ST-2 Depth: 21 ft
Type: Intact tube sample
Description: CL, brown sandy lean clay
LL = 30 PL = 13 PI = 17

SPECIMEN INFORMATION (Initial)

Height: 5.99 inch Diameter: 2.88 inch Area: 6.50 in²
Water Content: 12.1 % Total Unit Weight: 140.5 pcf

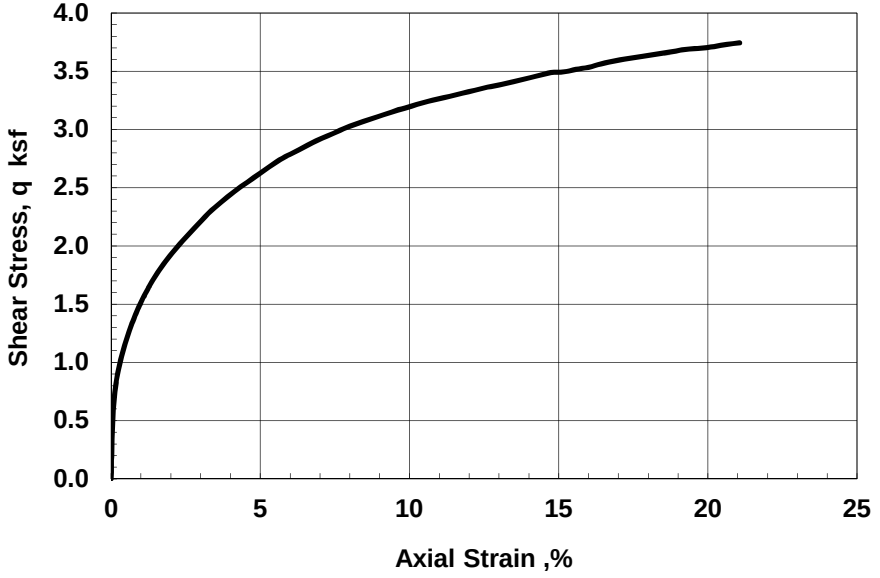
TEST SUMMARY

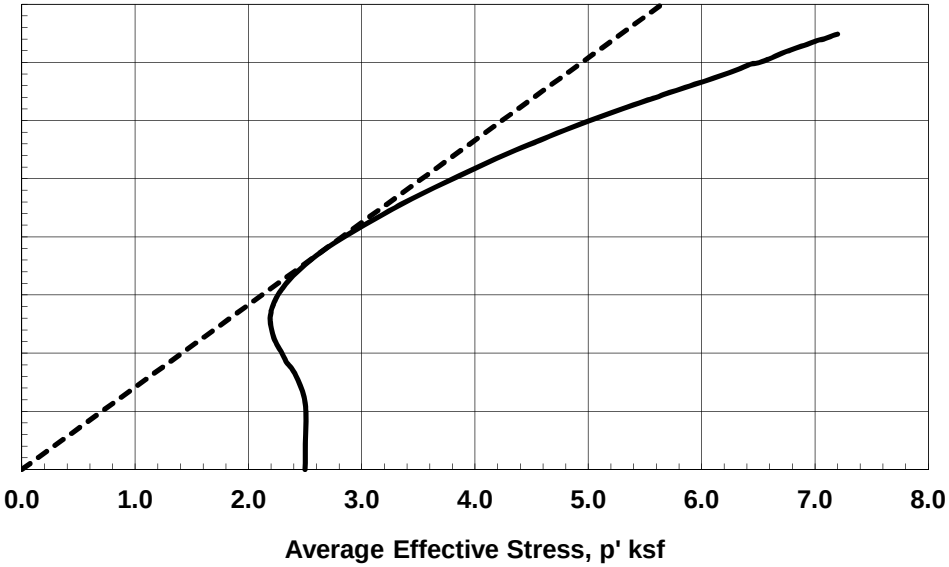
Consolidation Stresses: 2.50 ksf vertical, 2.50 ksf lateral
Water Content: 12.5 % Total Unit Weight: 142.9 pcf
B Coefficient: 99.62 Strain Rate: 0.021 %/min
Peak Shear Strength: 3.74 ksf @ 21.1 % Strain
Peak Effective Friction Angle: 45.1°



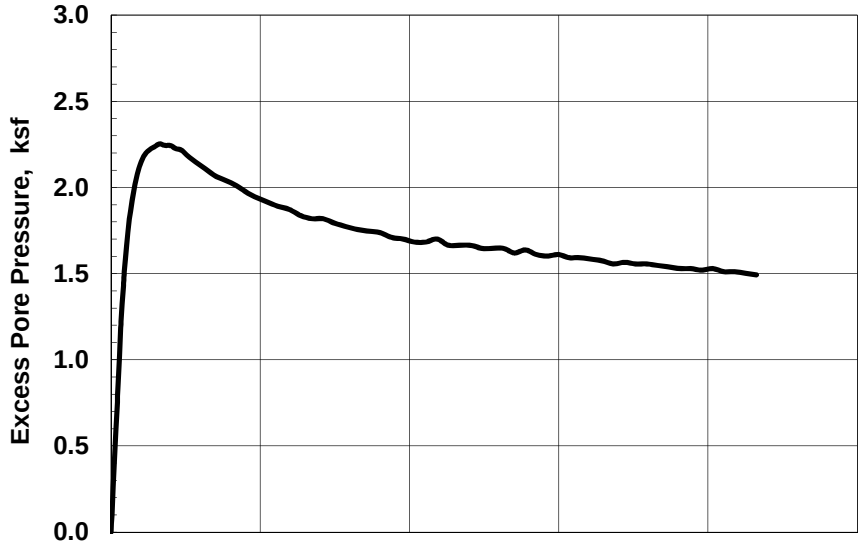
Failure Sketch

REMARKS:





Test by: BB	Project No. T60428794	AECOM Dynegy CCR - Newton	CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION with Pore Pressure Measurements
Checked by: GET	**TerraSense, LLC**		Boring: NEW-B007 Sample: ST-2 November-15

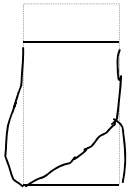


SAMPLE INFORMATION

Boring: NEW-B009 Sample: ST-2B Depth: 30 ft
Type: Intact tube sample
Description: CL, yellowish brown lean clay with sand
LL = 31 PL = 14 PI = 17

SPECIMEN INFORMATION (Initial)

Height: 5.96 inch Diameter: 2.89 inch Area: 6.55 in²
Water Content: 16.7 % Total Unit Weight: 132.6 pcf

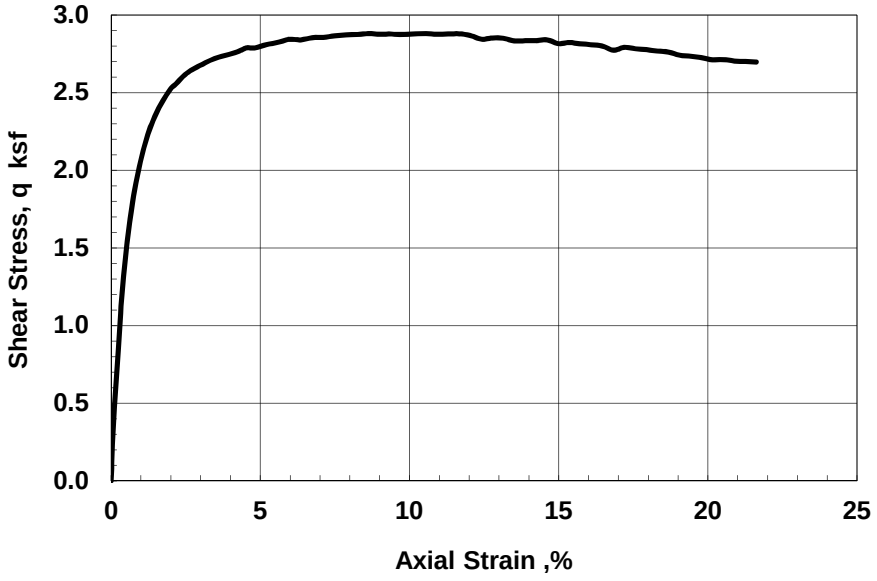


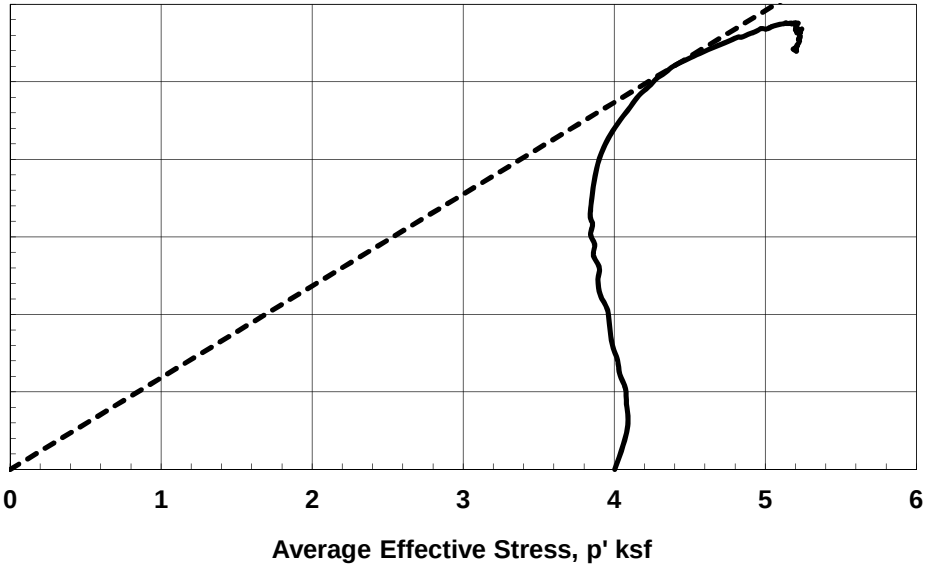
Failure Sketch

TEST SUMMARY

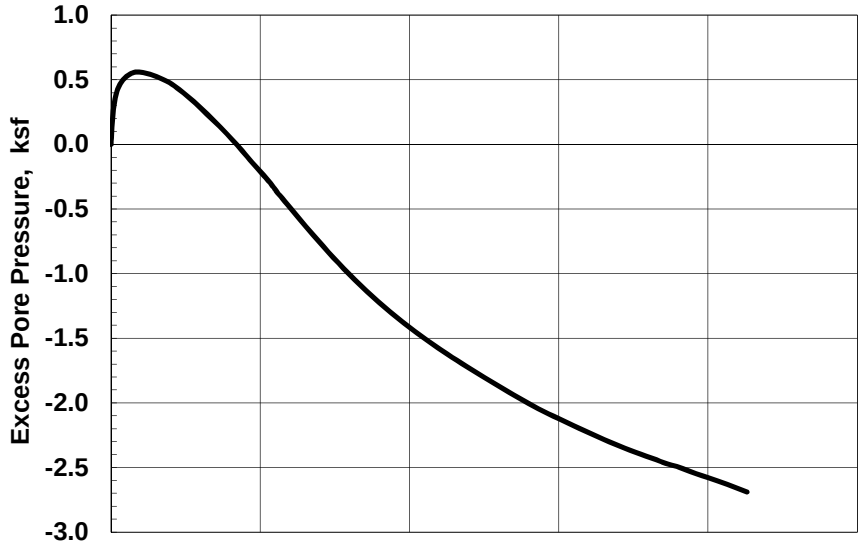
Consolidation Stresses: 4.00 ksf vertical, 4.00 ksf lateral
Water Content: 17.1 % Total Unit Weight: 136.8 pcf
B Coefficient: 98.02 Strain Rate: 0.023 %/min
Peak Shear Strength: 2.88 ksf @ 10.5 % Strain
Peak Effective Friction Angle: 36.3°

REMARKS:





Test by: BB	Project No. T60428794	AECOM Dynegy CCR - Newton	CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION with Pore Pressure Measurements	
Checked by: GET	**TerraSense, LLC**		Boring: NEW-B009 Sample: ST-2B	November-15



SAMPLE INFORMATION

Boring: NEW-B010 Sample: ST-1C Depth: 6.3 ft
Type: Intact tube sample
Description: CL, brown lean clay with sand
LL = 24 PL = 13 PI = 11

SPECIMEN INFORMATION (Initial)

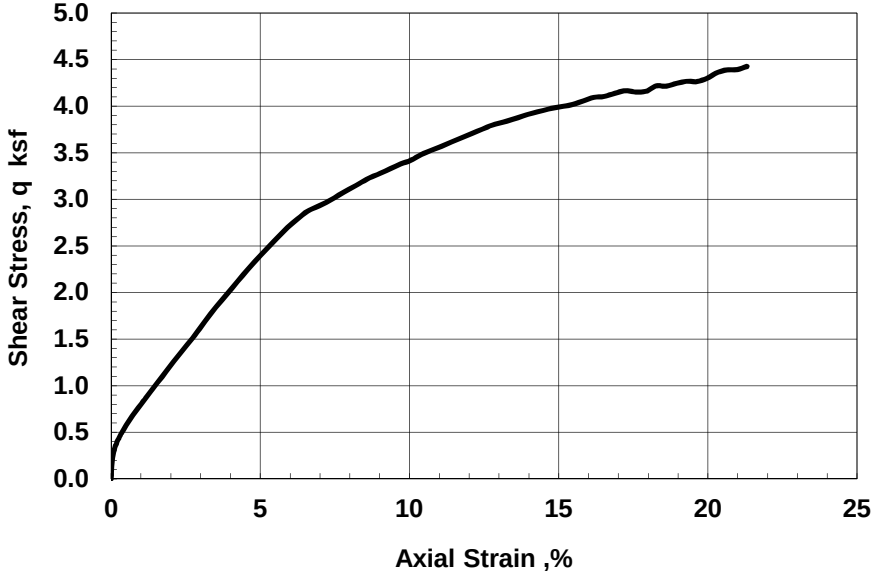
Height: 6.05 inch Diameter: 2.88 inch Area: 6.51 in²
Water Content: 10.2 % Total Unit Weight: 140.5 pcf

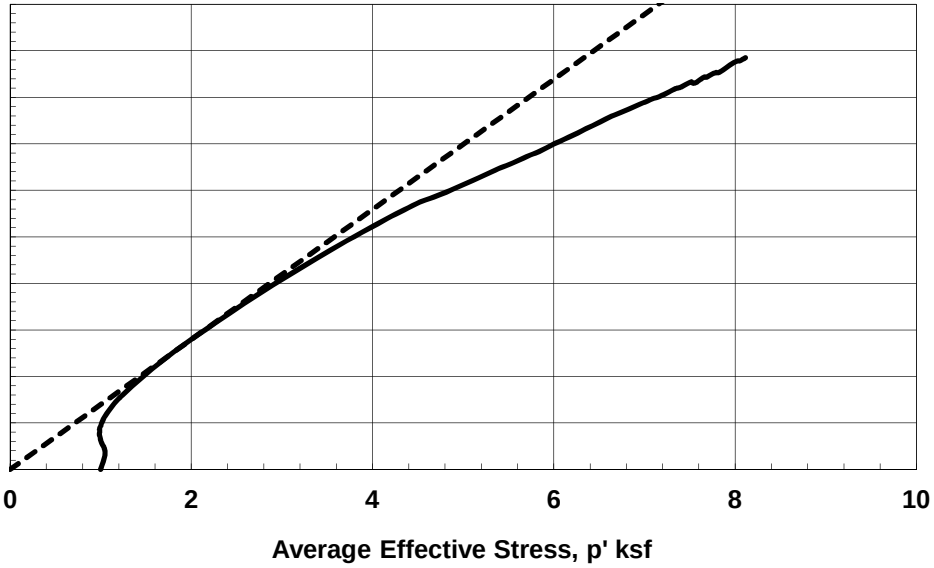
TEST SUMMARY

Consolidation Stresses: 1.00 ksf vertical, 1.00 ksf lateral
Water Content: 11.6 % Total Unit Weight: 145.2 pcf
B Coefficient: 98.32 Strain Rate: 0.021 %/min
Peak Shear Strength: 4.43 ksf @ 21.3 % Strain
Peak Effective Friction Angle: 44.4°

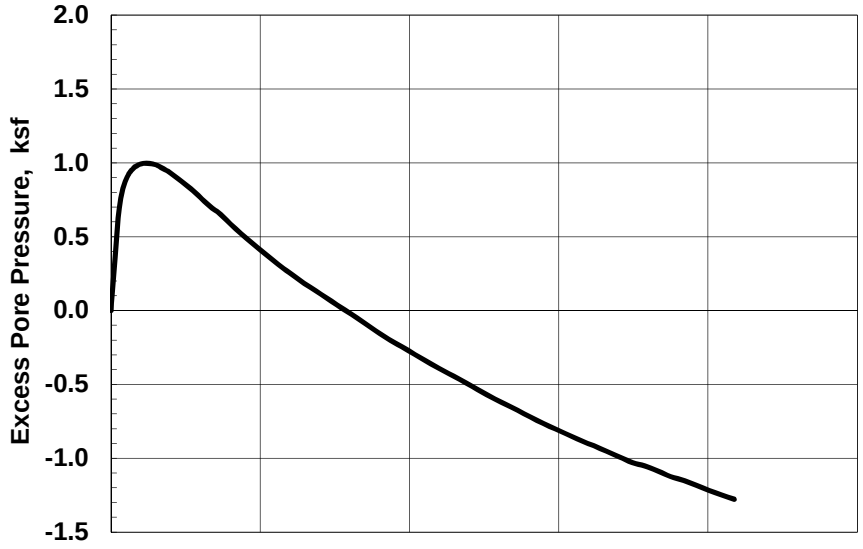
Failure Sketch

REMARKS:





Test by: BB	Project No. T60428794	AECOM Dynegy CCR - Newton	CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION with Pore Pressure Measurements	
Checked by: GET	**TerraSense, LLC**		Boring: NEW-B010 Sample: ST-1C	November-15

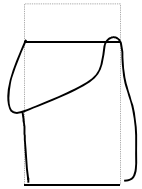


SAMPLE INFORMATION

Boring: NEW-B010 Sample: ST-2 Depth: 16.5 ft
Type: Intact tube sample
Description: CL, yellowish brown lean clay with sand, some m-f gravel
LL = 33 PL = 13 PI = 20

SPECIMEN INFORMATION (Initial)

Height: 6.02 inch Diameter: 2.88 inch Area: 6.53 in²
Water Content: 13.8 % Total Unit Weight: 137.3 pcf

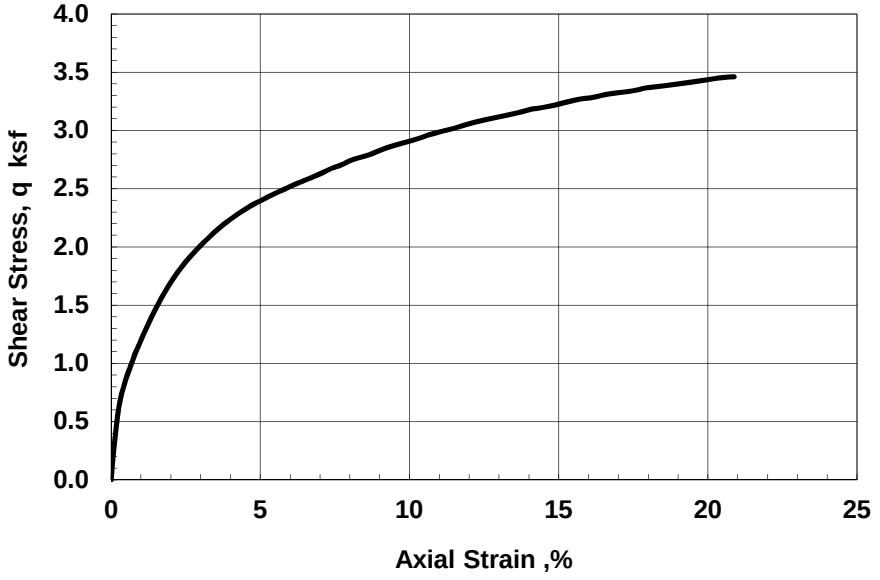


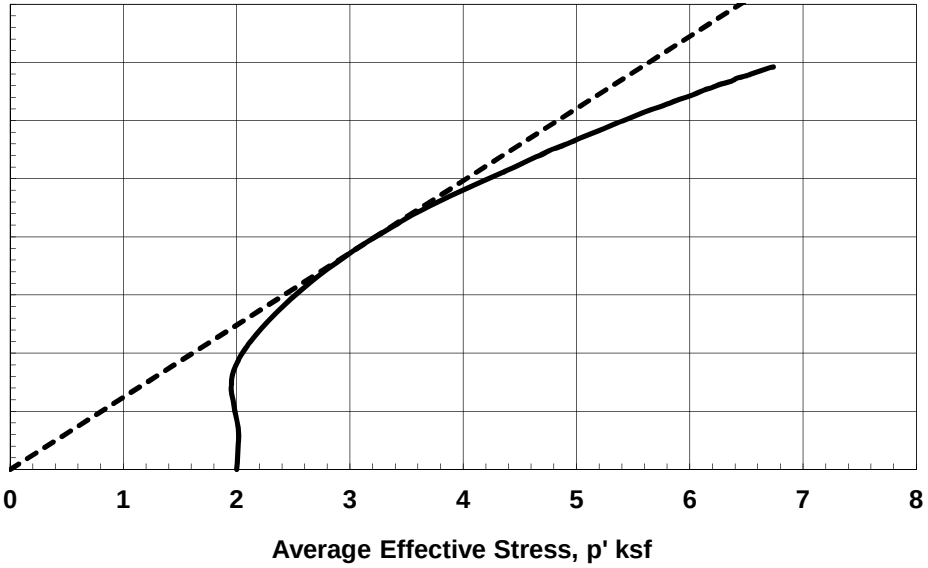
Failure Sketch

TEST SUMMARY

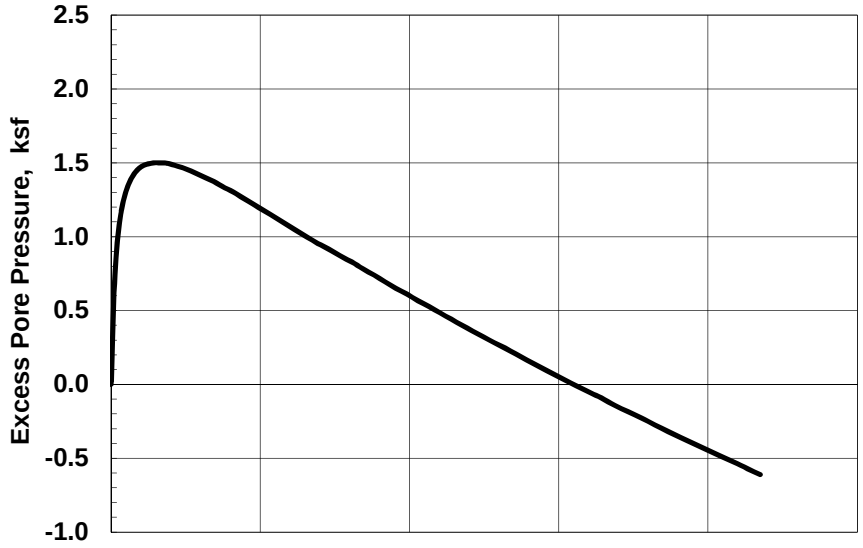
Consolidation Stresses: 2.00 ksf vertical, 2.00 ksf lateral
Water Content: 14.7 % Total Unit Weight: 139.5 pcf
B Coefficient: 99.6 Strain Rate: 0.022 %/min
Peak Shear Strength: 3.46 ksf @ 20.9 % Strain
Peak Effective Friction Angle: 38.4°

REMARKS:





Test by: BB	Project No. T60428794	AECOM Dynegy CCR - Newton	CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION with Pore Pressure Measurements
Checked by: GET	**TerraSense, LLC**		Boring: NEW-B010 Sample: ST-2 November-15



SAMPLE INFORMATION

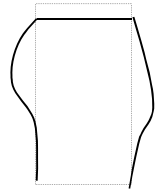
Boring: NEW-B012 Sample: ST-7 Depth: 21.15 ft
Type: Intact tube sample
Description: CL, brown sandy clay
LL = 35 PL = 13 PI = 22

SPECIMEN INFORMATION (Initial)

Height: 6.00 inch Diameter: 2.88 inch Area: 6.52 in²
Water Content: 13.3 % Total Unit Weight: 138.4 pcf

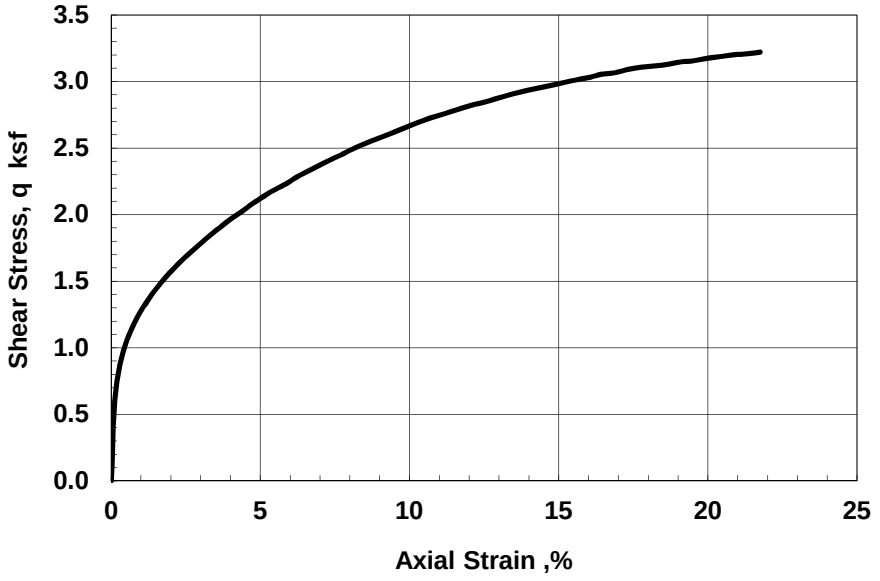
TEST SUMMARY

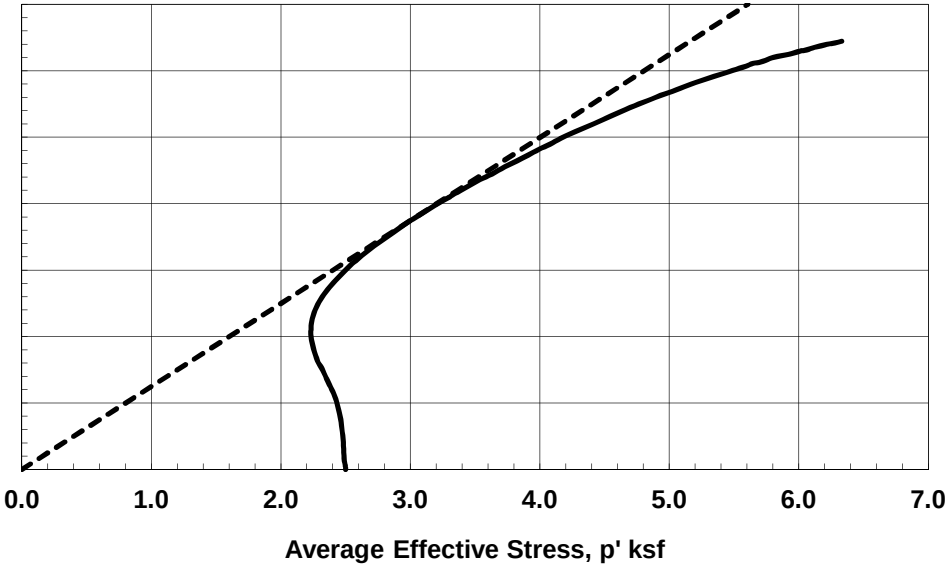
Consolidation Stresses: 2.50 ksf vertical, 2.50 ksf lateral
Water Content: 14.0 % Total Unit Weight: 140.6 pcf
B Coefficient: 97.9 Strain Rate: 0.023 %/min
Peak Shear Strength: 3.22 ksf @ 21.8 % Strain
Peak Effective Friction Angle: 38.6°



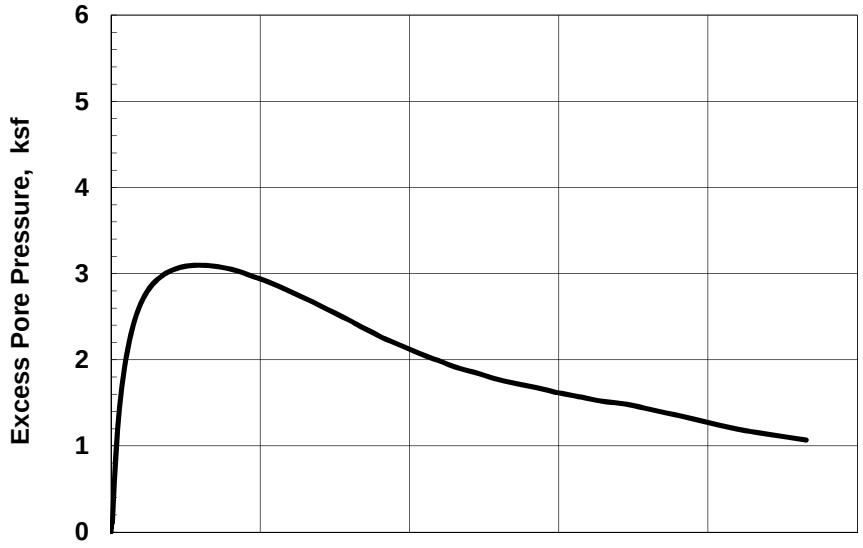
Failure Sketch

REMARKS:





Test by: BB	Project No. T60428794	AECOM Dynegy CCR - Newton	CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION with Pore Pressure Measurements
Checked by: GET	**TerraSense, LLC**		Boring: NEW-B012 Sample: ST-7 — November-15

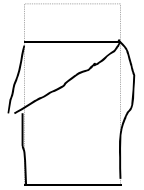


SAMPLE INFORMATION

Boring: NEW-B012 Sample: ST-12C Depth: 46.4 ft
Type: Intact tube sample
Description: CL, brown sandy lean clay
LL = 43 PL = 14 PI = 29

SPECIMEN INFORMATION (Initial)

Height: 6.04 inch Diameter: 2.88 inch Area: 6.52 in²
Water Content: 17.5 % Total Unit Weight: 133.6 pcf

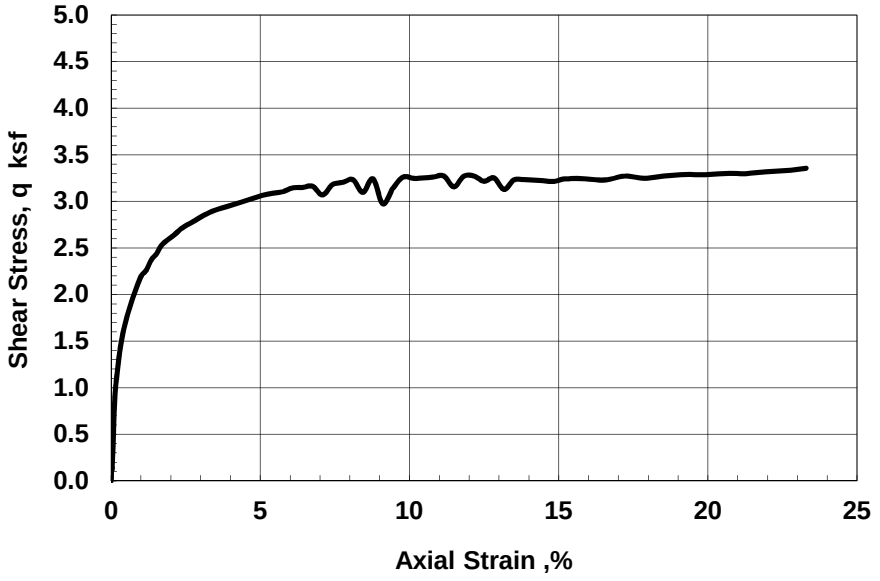


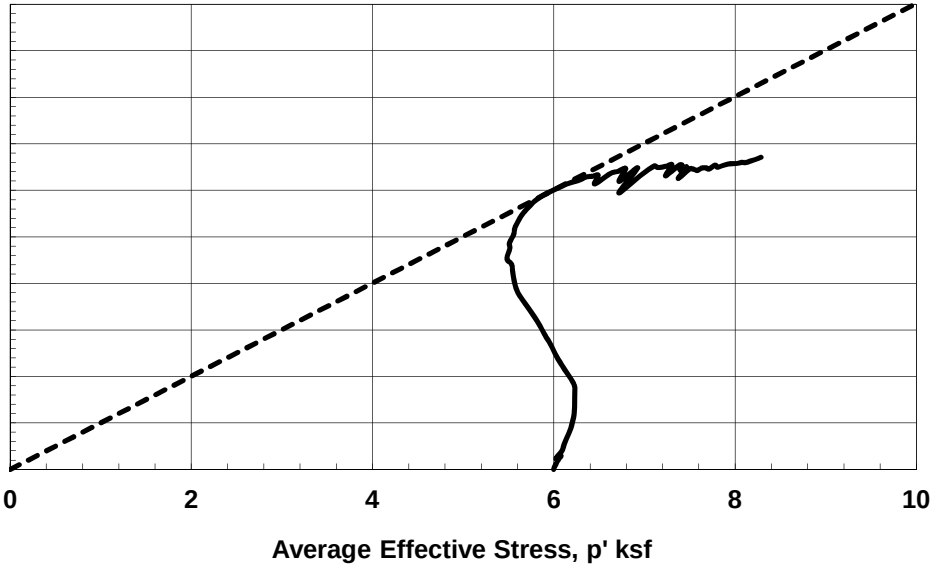
Failure Sketch

TEST SUMMARY

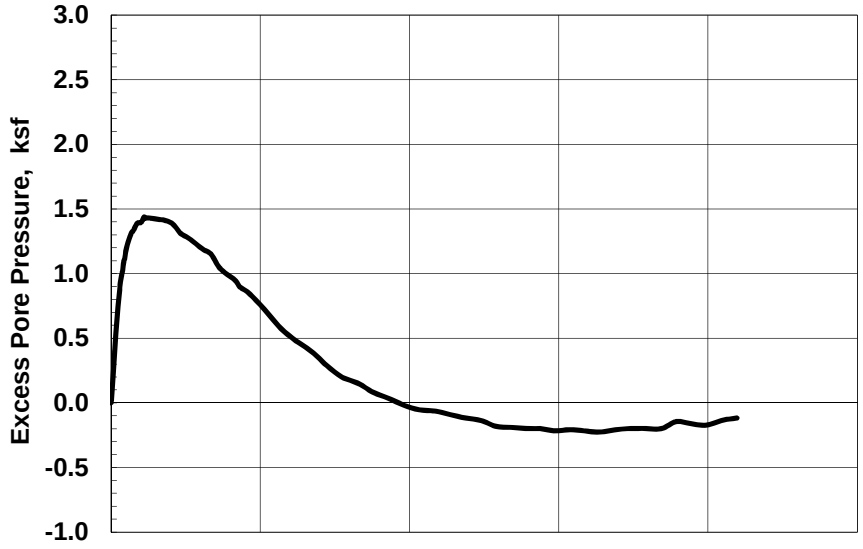
Consolidation Stresses: 6.00 ksf vertical, 6.00 ksf lateral
Water Content: 17.2 % Total Unit Weight: 137.3 pcf
B Coefficient: 96.31 Strain Rate: 0.021 %/min
Peak Shear Strength: 3.36 ksf @ 23.3 % Strain
Peak Effective Friction Angle: 30.1°

REMARKS:





Test by: BB	Project No. T60428794	AECOM Dynegy CCR - Newton	CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION with Pore Pressure Measurements	
Checked by: GET	**TerraSense, LLC**		Boring: NEW-B012 Sample: ST-12C	November-15



SAMPLE INFORMATION

Boring: NEW-B014 Sample: ST-3C Depth: 36.65 ft
Type: Intact tube sample
Description: SC, brown clayey sand with gravel
LL = 38 PL = 13 PI = 25

SPECIMEN INFORMATION (Initial)

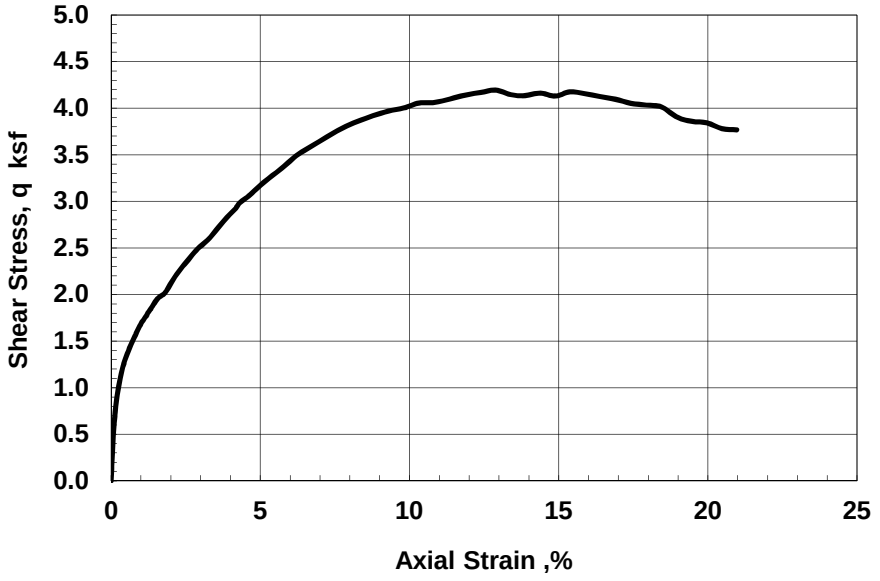
Height: 6.06 inch Diameter: 2.90 inch Area: 6.62 in²
Water Content: 16.3 % Total Unit Weight: 132.6 pcf

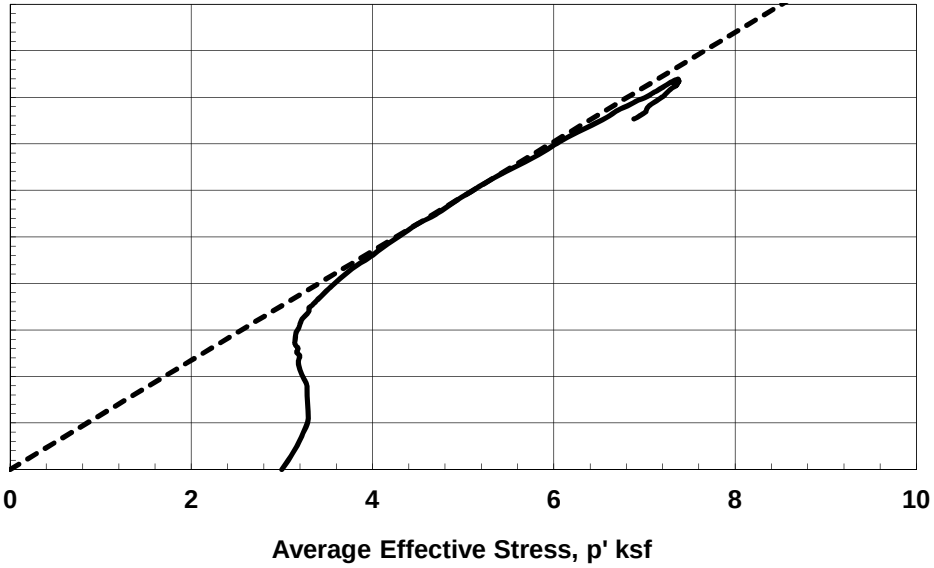
TEST SUMMARY

Consolidation Stresses: 3.00 ksf vertical, 3.00 ksf lateral
Water Content: 15.1 % Total Unit Weight: 134.8 pcf
B Coefficient: Strain Rate: 0.021 %/min
Peak Shear Strength: 4.19 ksf @ 12.9 % Strain
Peak Effective Friction Angle: 36.0°

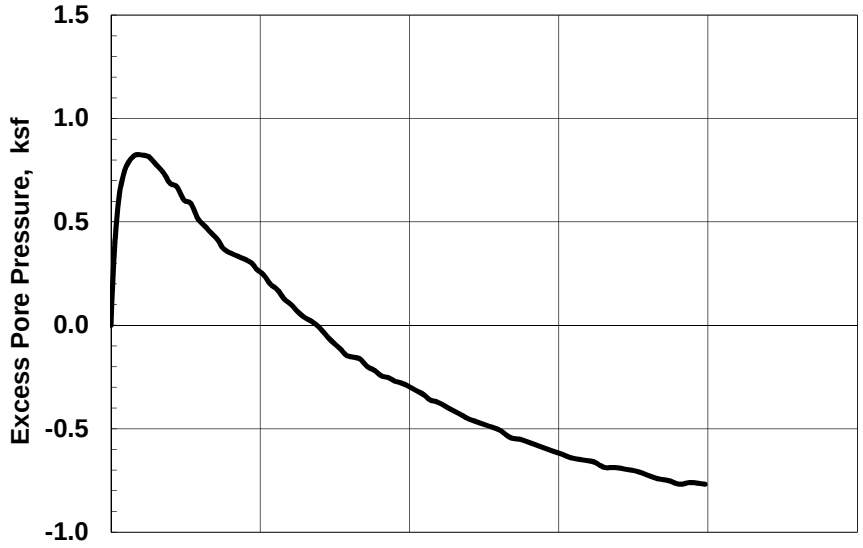
Failure Sketch

REMARKS:





Test by: BB	Project No. T60428794	AECOM Dynegy CCR - Newton	CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION with Pore Pressure Measurements
Checked by: GET	**TerraSense, LLC**		Boring: NEW-B014 Sample: ST-3C
			November-15



SAMPLE INFORMATION

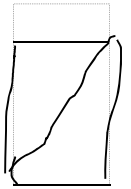
Boring: NEW-B015 Sample: ST-1B Depth: 10.95 ft
Type: Intact tube sample
Description: CH, gray brown fat clay
LL = 59 PL = 15 PI = 44

SPECIMEN INFORMATION (Initial)

Height: 6.02 inch Diameter: 2.89 inch Area: 6.56 in²
Water Content: 23.0 % Total Unit Weight: 126.0 pcf

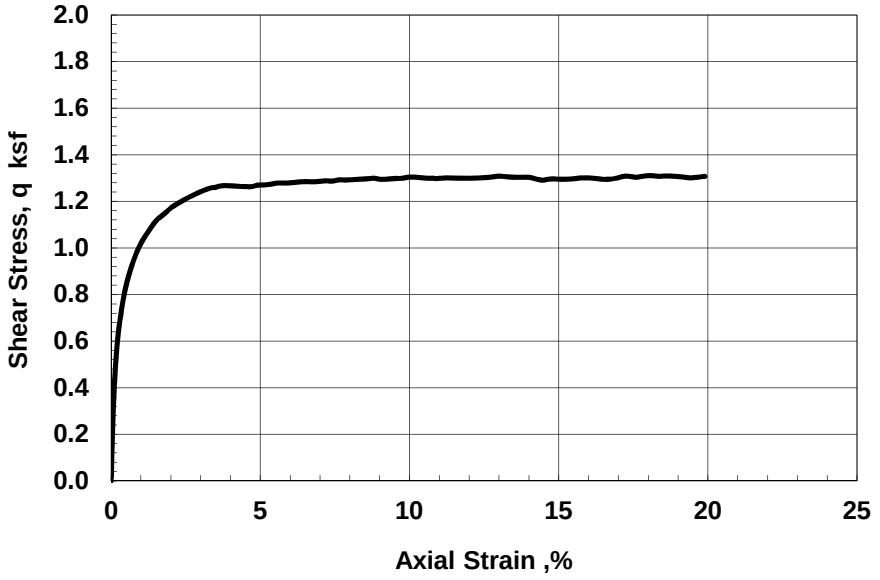
TEST SUMMARY

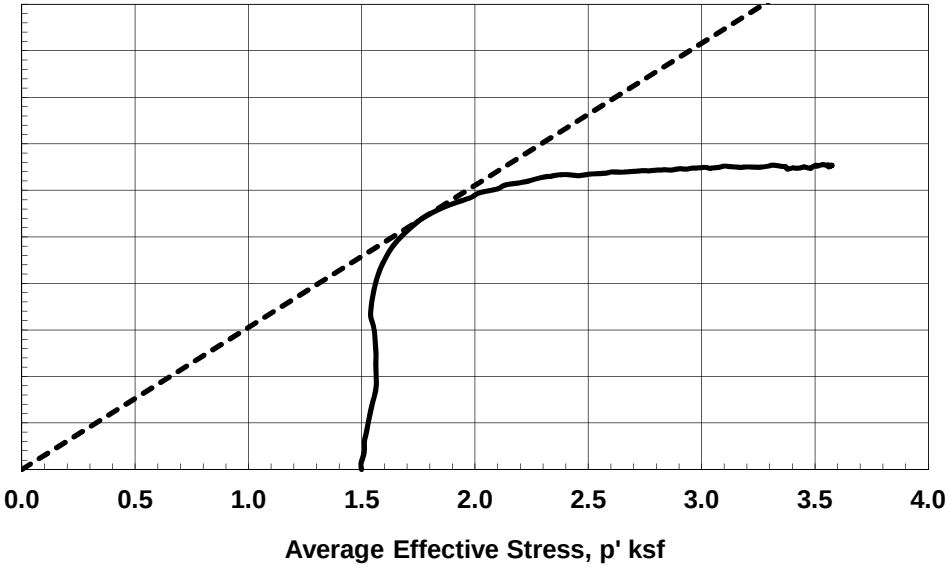
Consolidation Stresses: 1.50 ksf vertical, 1.50 ksf lateral
Water Content: 23.6 % Total Unit Weight: 128.1 pcf
B Coefficient: Strain Rate: 0.020 %/min
Peak Shear Strength: 1.31 ksf @ 18.0 % Strain
Peak Effective Friction Angle: 37.7°



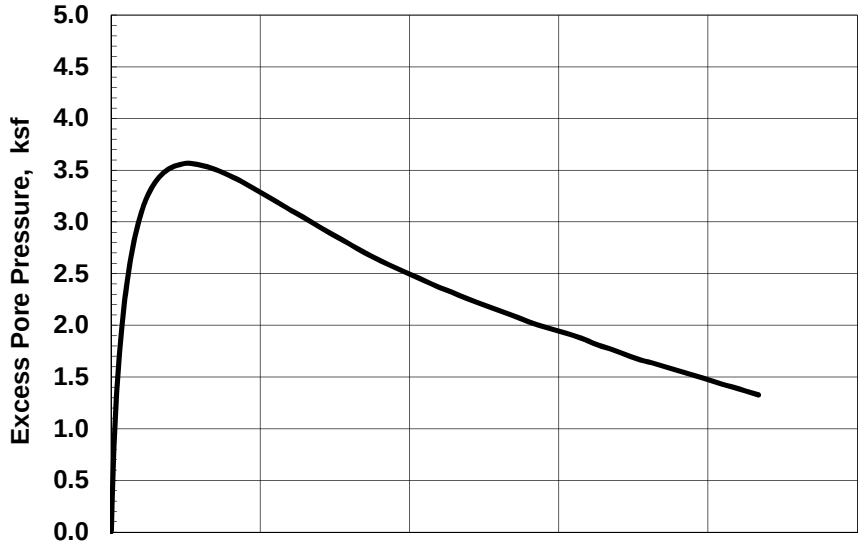
Failure Sketch

REMARKS:





Test by: BB	Project No. T60428794	AECOM Dynegy CCR - Newton	CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION with Pore Pressure Measurements
Checked by: GET	**TerraSense, LLC**		Boring: NEW-B015 Sample: ST-1B
			November-15

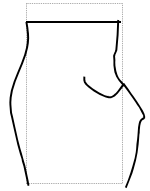


SAMPLE INFORMATION

Boring: NEW-B015 Sample: ST-2 Depth: 26 ft
Type: Intact tube sample
Description: CH, gray fat clay
LL = 52 PL = 15 PI = 37

SPECIMEN INFORMATION (Initial)

Height: 6.00 inch Diameter: 2.88 inch Area: 6.50 in²
Water Content: 19.5 % Total Unit Weight: 131.4 pcf

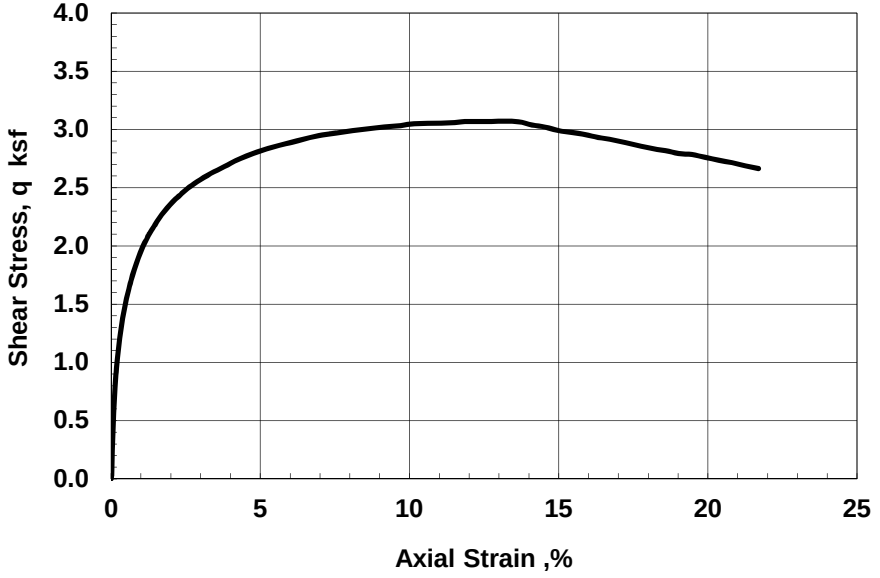


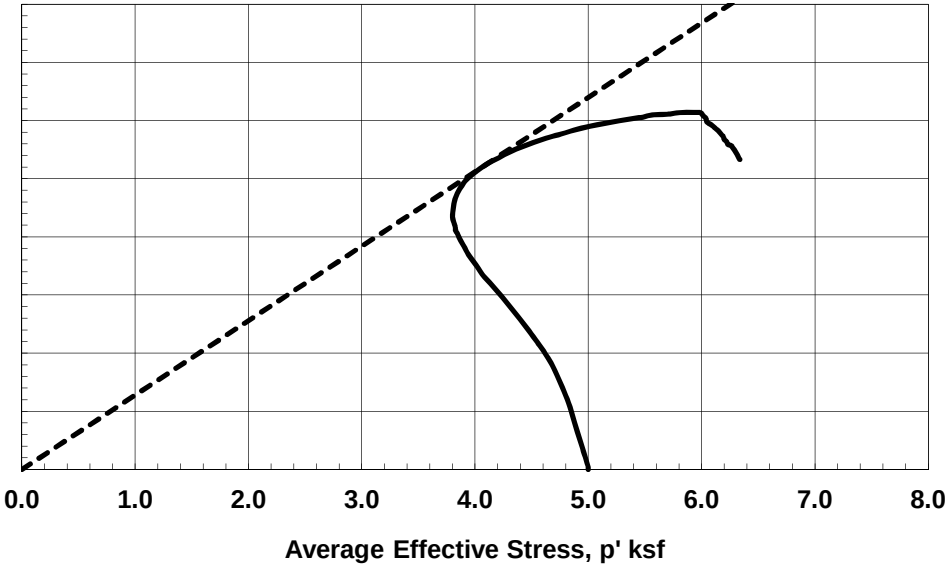
Failure Sketch

TEST SUMMARY

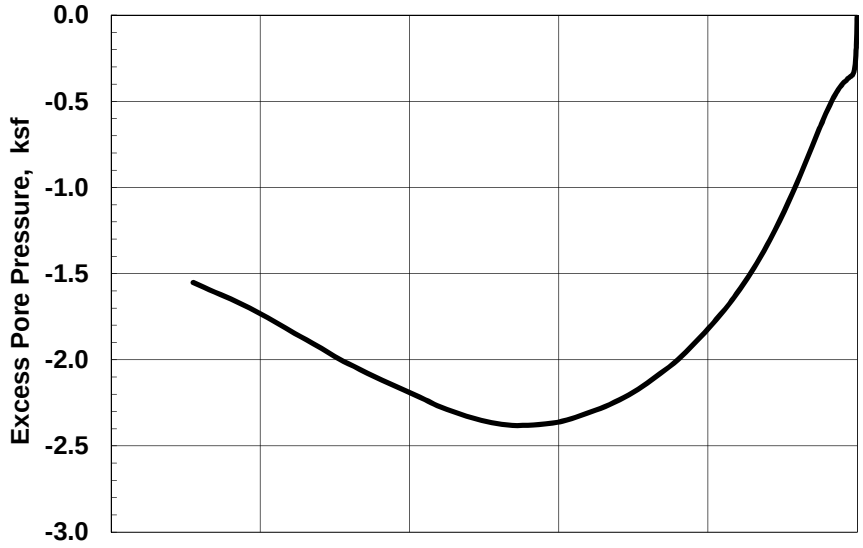
Consolidation Stresses: 5.00 ksf vertical, 5.00 ksf lateral
Water Content: 19.6 % Total Unit Weight: 132.8 pcf
B Coefficient: 99.27 Strain Rate: 0.023 %/min
Peak Shear Strength: 3.07 ksf @ 13.2 % Strain
Peak Effective Friction Angle: 39.8°

REMARKS:





Test by: BB	Project No. T60428794	AECOM Dynegy CCR - Newton	CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION with Pore Pressure Measurements
Checked by: GET	**TerraSense, LLC**		Boring: NEW-B015 Sample: ST-2 November-15



SAMPLE INFORMATION

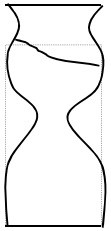
Boring: NEW-B014 Sample: ST-2 Depth: 15.85 ft
Type: Intact tube sample
Description: CL, gray clay, some f-c sand, trace gravel
LL = 31 PL = 14 PI = 17

SPECIMEN INFORMATION (Initial)

Height: 6.03 inch Diameter: 2.88 inch Area: 6.50 in²
Water Content: 12.2 % Total Unit Weight: 139.2 pcf

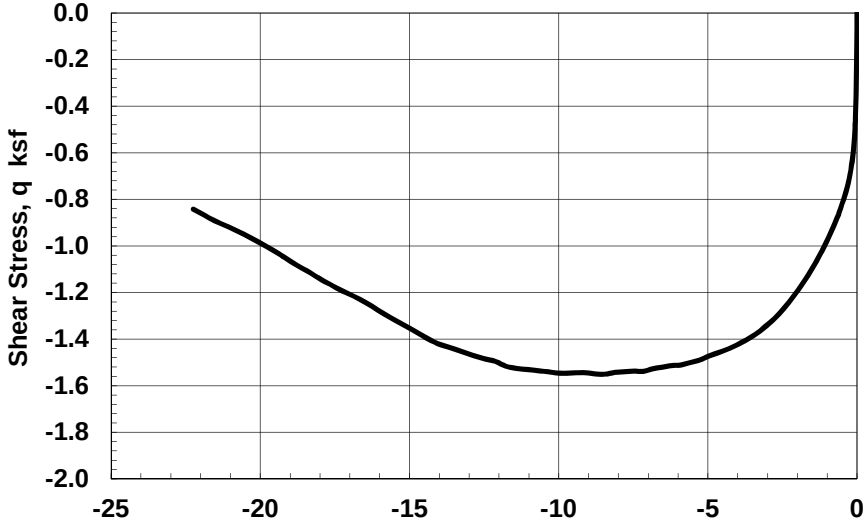
TEST SUMMARY

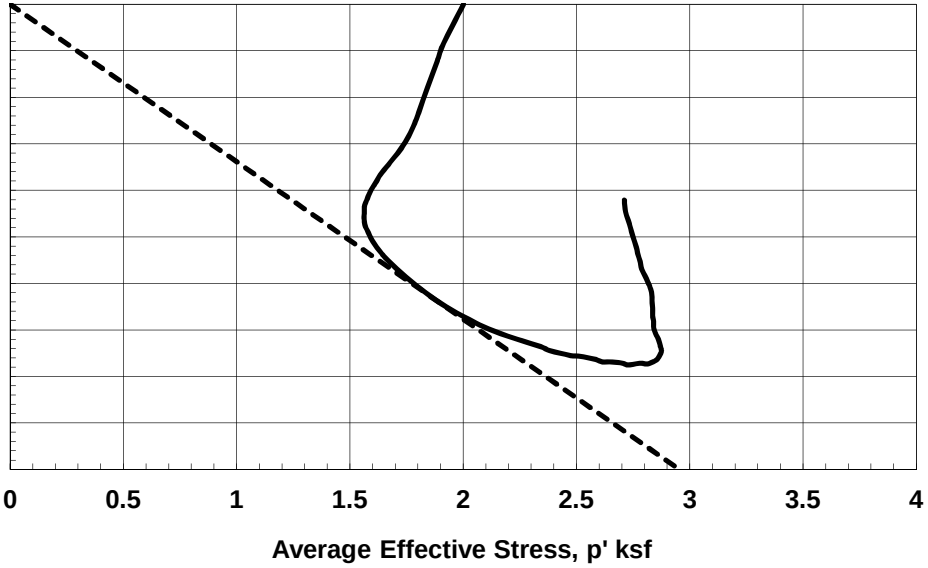
Consolidation Stresses: 2.00 ksf vertical, 2.00 ksf lateral
Water Content: 12.8 % Total Unit Weight: 142.5 pcf
B Coefficient: 98 Strain Rate: -0.020 %/min
Peak Shear Strength: -1.55 ksf @ -8.4 % Strain
Peak Effective Friction Angle: 42.6°



Failure Sketch

REMARKS:





Test by: GT	Project No. T60428794	AECOM Dynegy CCR - Newton	CONSOLIDATED UNDRAINED TRIAXIAL EXTENSION with Pore Pressure Measurements
Checked by: GET	**TerraSense, LLC**		Boring: NEW-B014 Sample: ST-2
			November-15

Appendix C

Hydraulic Conductivity/Slug Test Results

Appendix C - Table 1
Newton Power Station
Slug Test Results - Primary Ash Pond Wells (ID 501)
Hydrogeologic Monitoring Plan

Well ID	Slug In 1	Slug In 2	Slug In 3	Slug Out 1	Slug Out 2	Slug Out 3	Slug Out 4	MIN	MAX	GEOMEAN	Solution
APW2		4.41E-05		4.52E-05		3.45E-05		3.45E-05	4.52E-05	4.1E-05	Bouwer-Rice
APW3	8.44E-06			8.61E-06				8.44E-06	8.61E-06	8.5E-06	Bouwer-Rice
APW4	6.66E-06			5.14E-06				5.14E-06	6.66E-06	5.8E-06	Bouwer-Rice
APW5	5.66E-04	1.42E-03		1.54E-04	2.74E-04	2.56E-04		1.54E-04	1.42E-03	3.9E-04	Bouwer-Rice
APW6	1.64E-03	2.18E-03			2.09E-03	1.98E-03		1.64E-03	2.18E-03	2.0E-03	Bouwer-Rice
APW7	2.25E-03				3.24E-03	2.99E-03	2.75E-03	2.25E-03	3.24E-03	2.8E-03	Bouwer-Rice
APW8	6.60E-04	1.31E-03			1.06E-03	7.89E-04		6.60E-04	1.31E-03	9.2E-04	Bouwer-Rice
APW9	3.21E-03	3.28E-03		3.40E-03	3.00E-03			3.00E-03	3.40E-03	3.2E-03	Bouwer-Rice
APW10	5.27E-04	5.49E-04			5.73E-04	5.60E-04		5.27E-04	5.73E-04	5.5E-04	Bouwer-Rice

All slug test (i.e. hydraulic conductivity) results are in centimeters per second
Not Applicable

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Appendix C - Table 2
Newton Power Station
Slug Test Results - Landfill 2 CCR Wells (ID 502)
Hydrogeologic Monitoring Plan

Well ID	Slug In 1	Slug In 2	Slug In 3	Slug Out 1	Slug Out 2	Slug Out 3	MIN	MAX	GEOMEAN	Solution
G06D				3.92E-08			3.92E-08	3.92E-08	3.9E-08	Bouwer-Rice
G202	1.70E-02	1.43E-02			2.87E-02	2.33E-02	1.43E-02	2.87E-02	2.0E-02	Bouwer-Rice
G203	2.53E-02			2.42E-02	3.47E-02		2.42E-02	3.47E-02	2.8E-02	Bouwer-Rice
G208				1.32E-08			1.32E-08	1.32E-08	1.3E-08	Bouwer-Rice
G217D	2.27E-04	2.92E-04				3.03E-04	2.27E-04	3.03E-04	2.7E-04	Bouwer-Rice
G220				3.51E-07			3.51E-07	3.51E-07	3.5E-07	Bouwer-Rice
G222				1.54E-06			1.54E-06	1.54E-06	1.5E-06	Bouwer-Rice
G223	5.19E-05	2.50E-05		1.37E-05	1.79E-05		1.37E-05	5.19E-05	2.4E-05	Bouwer-Rice
G224	5.15E-02	1.90E-02	4.64E-02	4.31E-02		2.97E-02	1.90E-02	5.15E-02	3.6E-02	Bouwer-Rice

All slug test (i.e. hydraulic conductivity) results are in centimeters per second
Not Applicable

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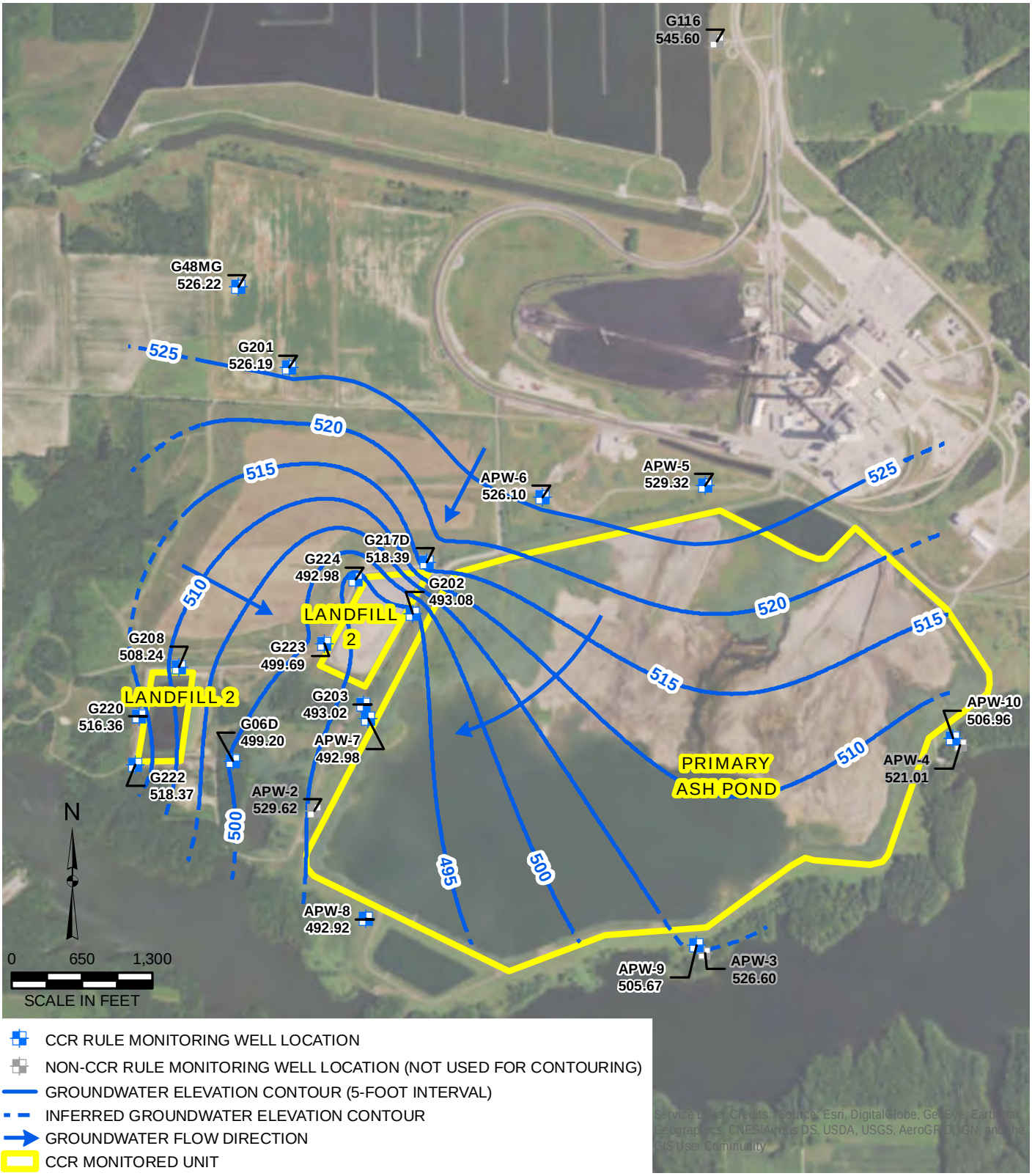
Appendix D

Groundwater Elevation Contour Maps



DRAWN BY/DATE:
SDS 10/3/17
REVIEWED BY/DATE:
TBN 10/3/17
APPROVED BY/DATE:
SJC 10/3/17

GROUNDWATER ELEVATION CONTOUR MAP
ROUND 6: JANUARY 16, 2017

HYDROGEOLOGIC MONITORING PLAN
NEWTON POWER STATION
NEWTON, ILLINOIS

PROJECT NO: 2285

FIGURE NO: 1

Natural Resource Technology
AN OBG COMPANY

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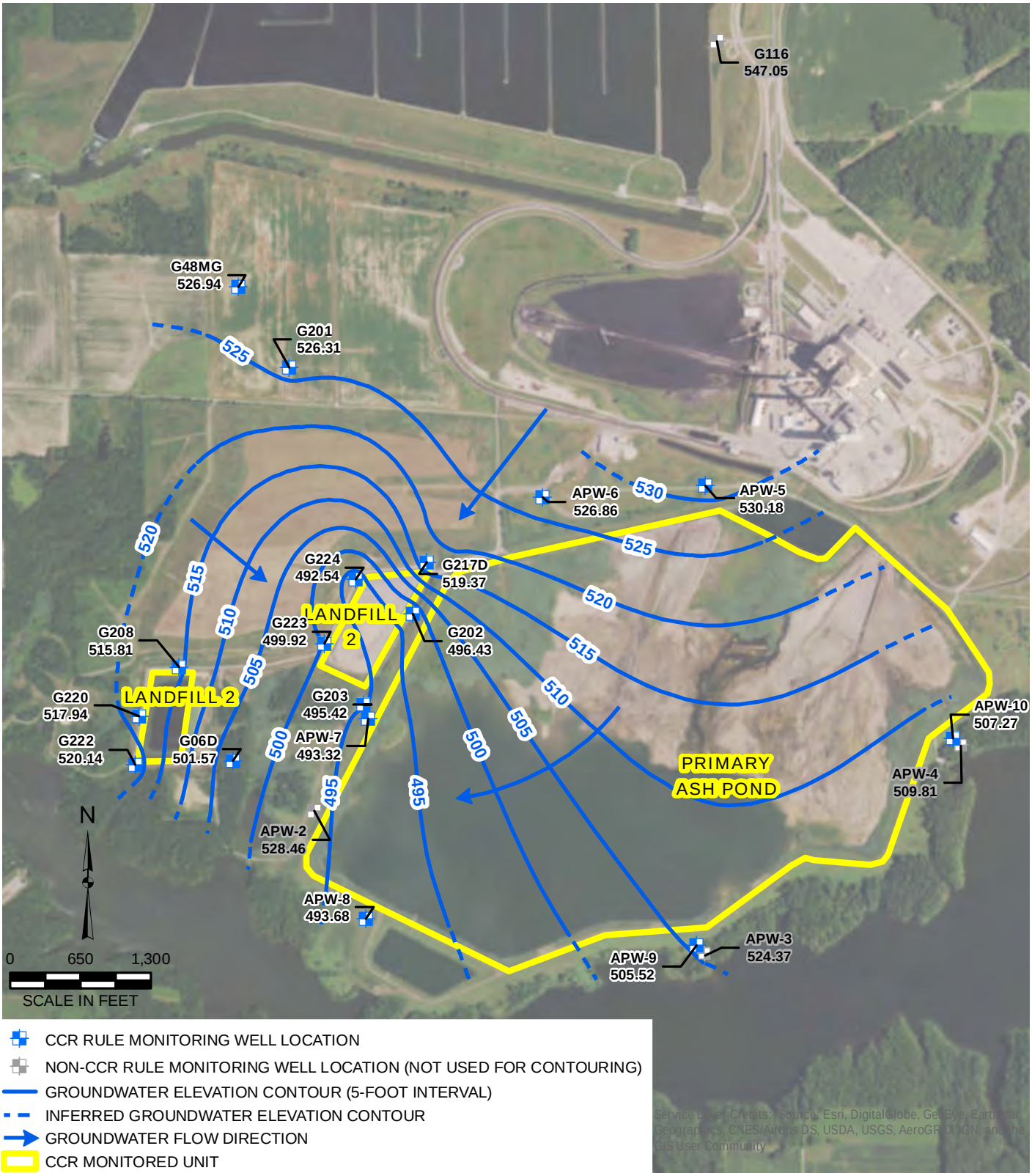

DRAWN BY/DATE:
SDS 8/12/17
REVIEWED BY/DATE:
TBN 8/12/17
APPROVED BY/DATE:
JJW 8/30/17

GROUNDWATER ELEVATION CONTOUR MAP
ROUND 8: JUNE 12, 2017

HYDROGEOLOGIC MONITORING PLAN
NEWTON POWER STATION
NEWTON, ILLINOIS

PROJECT NO: 2285

FIGURE NO: 1

Natural Resource Technology
AN OBG COMPANY

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OBG

THERE'S A WAY

Document 37

**Lineback, J., 1979. Quaternary Deposits of Illinois:
Illinois State Geological Survey map, scale 1:500,000**

INSTITUTE OF NATURAL RESOURCES
STATE OF ILLINOIS
ILLINOIS STATE GEOLOGICAL SURVEY
Jack A. Simon, Chief
Urbana, 1979

QUATERNARY DEPOSITS OF ILLINOIS

Compiled by Jerry A. Lineback

From maps prepared in 1975 by Paul B. DuMontelle, Leon R. Follmer, David L. Gross, Alan M. Jacobs, John P. Kempton, Jerry A. Lineback, E. Donald McKay, and Philip C. Reed, with the assistance of Herbert D. Glass, W. Arthur White, and Harold B. Willman.

EXPLANATION

Because many of the areas mapped are small, the conventional symbols for Quaternary units are abbreviated. Q for Quaternary is omitted.

SYSTEM	SERIES	STAGE	SUBSTAGE
QUATERNARY	HOLOCENE	WISCONSINAN and HOLOCENE	WOODFORDIAN, TWOCREEKAN, VALDERAN, and younger
	PLEISTOCENE	WISCONSINAN	WOODFORDIAN, TWOCREEKAN, VALDERAN, and younger
			ALTONIAN, FARMDALIAN, WOODFORDIAN, TWOCREEKAN, and VALDERAN
		ILLINOIAN	LIMAN, MONICAN, and JUBILEEAN
		KANSAN	LIMAN
	PLIOCENE-PLEISTOCENE		
TERTIARY-QUATERNARY			

Surface Mines — sm

Includes coal strip mines; rock quarries; clay, sand, or gravel pits; and other excavated areas, including those where the mixed fill of bedrock or Quaternary deposits was replaced or disturbed. Also includes areas of man-made fill in areas formerly covered by Lake Michigan or Lake Calumet in northeastern Illinois and by causeways in Rend Lake and Carlyle Lake in southern Illinois. Many small areas are not shown.

Cahokia Alluvium — c

Deposits in floodplains and channels of modern rivers and streams; mostly poorly sorted sand, silt, or clay containing local deposits of sandy gravel; in many places overlies well-sorted glacial outwash of the Henry Formation.

Alluvial-fan facies of Cahokia Alluvium — c-f

Fan-shaped deposits of poorly sorted sand and silt at the mouths of tributary streams along the Illinois and Mississippi Rivers.

Lake Michigan Formation — lmr

Lacustrine sediments and beach deposits of modern lakes.

Ravinia Sand Member of Lake Michigan Formation — py

Sand on modern beaches; map shows only areas along major beaches of Lake Michigan such as those near Illinois Beach State Park.

Peyton Colluvium — pl

Narrow deposits of largely unsorted debris that resulted from creep and slopewash and accumulated on and at the base of river bluffs. May include some areas where materials were deposited by slumps or landslides (Lacon Formation).

Parkland Sand — gl

Windblown sand; well-sorted, medium-grained sand in dunes and thick sheet deposits between dunes.

Grayslake Peat

Peat, muck, and marl; dominantly organic deposits that are interbedded with silt and clay in some places. Mostly found in glacial lake basins; locally in lake basins on floodplains of major rivers.

Equality Formation — ec

Lake deposits; offshore deposits of silt and clay; sand facies near shorelines. Deposits in older lakes have a thin to medium cover of silt (Richland Loess or Peoria Loess).

Carmi Member of Equality Formation

Largely quiet-water lake sediments dominated by well-bedded silt and some clay; includes sediment of proglacial lakes and slack-water lakes in valleys tributary to major river valleys. Where thin and discontinuous, generally covers more than 25 percent of the area mapped.

Dolton Member of Equality Formation — ed

Largely shallow-water, nearshore lake sediments in beaches, bars, spits, and deltas; includes some former lakes that contain coarse-grained deposits; dominantly medium-grained sand; some gravel along beaches; contains beds of silt where gradational with the Carmi Member.

Henry Formation

Sand and gravel; generally well sorted; local minor beds of silt; glacial outwash in outwash plains, valley trains, and ice-contact deposits; generally has a thin cover of silt (Richland Loess or Peoria Loess).

Mackinaw Member of Henry Formation — hm

Sand and gravel; generally well sorted and well bedded; deposits in valleys; mostly glacial outwash in former valley trains and terrace remnants of former valley trains.

Batavia Member of Henry Formation — hb

Sand and gravel; well-sorted deposits of glacial meltwater in outwash plains and fans on uplands.

Wasco Member of Henry Formation — hw

Sand and gravel, unevenly sorted, irregularly bedded lenses of silt and till; glacial ice-contact deposits in kames, eskers, and kame terraces.

Peoria Loess and Roxana Silt — pr

Windblown silt more than 20 feet (6 m) thick on uplands; local lenses of fine-grained sand. Combined thickness of Peoria and Roxana (outside the limit of Wisconsinan glaciation) shown by 15-foot (4.5-m), 10-foot (3.0-m), and 5-foot (1.5-m) contour lines. Thicknesses are averages for undisturbed uplands. The thickness of the Peoria Loess on Altonian drift and the thickness of the Richland Loess within the areas of Woodfordian drift are also shown by the contours.

Peyton Colluvium, Peoria Loess, and Roxana Silt — ppr

A complex deposit of silt more than 20 feet (6 m) thick on steep slopes along the bluffs of the Mississippi River in the St. Louis area. A colluvial mixture of Peoria and Roxana formed by creep and slopewash.

Wedron Formation

Mostly glacial till with lenses and beds of sand, gravel, and silt; includes all tills of Woodfordian age in the Lake Michigan and Green Bay Lobes; surface often mantled with silt (Richland Loess).

Ground moraine

Solid colors indicate ground moraine, including areas of generally low relief underlain by tills that lie between the moranic ridges.

Moraine

Overprinted pattern indicates moraines associated with the till members; generally continuous curvilinear areas that have elevated hummocky topography and local deposits of sand, gravel, and peat in addition to till.

Wadsworth Till Member of Wedron Formation · Yorkville Till Member of Wedron Formation · Snider Till Member of Wedron Formation — ww wy ws

Mostly gray clayey and silty clayey till. The Wadsworth contains few pebbles and cobbles and is more clayey near Lake Michigan than till to the south and west. Local lenses of sand and silt. Where the intervening Haeger Till Member is absent, the Wadsworth is separated from the Yorkville, and the boundary is placed at the front of the Valparaiso Moranic System. The Yorkville is a gray or greenish-gray, very clayey till overlain in some places by extensive glacial lake deposits. The Snider is a gray silty clayey till that has a coarse blocky structure.

Haeger Till Member of Wedron Formation — wh

Sandy and gravelly till, commonly thin, over thick deposits of sand and gravel outwash that are included in the member; present only in northeastern Illinois.

Malden Till Member of Wedron Formation · Batestown Till Member of Wedron Formation · Piatt Till Member of Wedron Formation — wm wb wp

Gray silty till that oxidizes to olive brown; some sandy till and lenses of sand and gravel. The Malden is a gray silty till that oxidizes to olive brown; local lenses of sand and gravel. The Batestown is a gray silty till that oxidizes to olive brown; recognized in east-central Illinois only. The Piatt includes sandy and silty gray till.

Continued in next column

Tiskilwa Till Member of Wedron Formation · Ablation drift of Tiskilwa Till Member · Delavan Till Member of Wedron Formation · Fairgrange Till Member of Wedron Formation — wt wd wt-a wf

Pink, pinkish-gray, gray, brown, and reddish-brown silty and sandy till; lenses of silt, sand, and gravel in some places. The Tiskilwa is generally sandy and silty till that is pinkish- or reddish-brown; includes yellow-gray to pinkish-gray sandy ablation drift (Gilberts Drift) in a small area in northeastern Illinois. The Delavan is gray to pinkish-gray sandy to silty till. The Fairgrange is pink, reddish-brown, and brownish-gray sandy till in east-central Illinois.

Lee Center Till Member of Wedron Formation · Esmond Till Member of Wedron Formation — w/c we

Gray silty to clayey till in the Green River Sublobe of the Lake Michigan Lobe in northwestern Illinois; generally thin and discontinuous; includes some lenses of ice-contact drift. The Lee Center is a gray clayey till. The Esmond is a gray till, silty in the upper part and silty clay till in the lower part.

Trafalgar Formation (of Indiana)

Mostly till; some associated sand and gravel. An extension of Erie or Saginaw Lobe drift into Illinois; overlies part of the Yorkville Till Member of the Wedron Formation.

Unnamed till member of Trafalgar Formation (of Indiana) — tr

Mostly yellow-gray sandy and silty till; the Iroquois Drift.

Winnebago Formation

Till with interbedded silt, peat, and gravel; present at surface in northwestern and central northern Illinois; separated from the Wedron Formation by the Robein Silt and Morton Loess. Generally covered by thin to medium layers of silt (Peoria Loess).

Capron Till Member of Winnebago Formation — wic

Pink sandy till in upper part, silty in lower part; mapped in central northern Illinois only.

Argyle Till Member of Winnebago Formation — wia

A very sandy, gravelly, pinkish-tan or salmon till; may include older tills with similar composition; present in central northern Illinois.

Teneriffe Silt — t

Mostly silt and clayey silt with beds of sand or clay deposited in large proglacial lakes associated with several Illinoian glaciers; may contain some outwash, sheetwash, and eolian deposits. Generally has prominent Sangamon Soil at top of deposits and is overlain by a moderate thickness of silt (Peoria Loess and Roxana Silt).

Pearl Formation — pe

Sand, gravel, and some silt in outwash plains and valley-train deposits of Illinoian glaciers; largely preserved as small terrace remnants along major drainageways in central and western Illinois and as extensive remnants along the lower Kaskaskia River Valley in southern Illinois. Generally has prominent Sangamon Soil at top of deposits and is overlain by moderate to thick silt (Peoria Loess and Roxana Silt).

Glasford Formation

Till with interbedded sand and gravel and surficial clay, silt, sand, and gravel deposits. The Glasford is the most widespread glacial formation in Illinois. The Glasford is divided into several members; generally has prominent Sangamon Soil at top of deposits and is overlain by moderate to great thickness of silt (Peoria Loess and Roxana Silt).

Ground moraine

Solid colors indicate Illinoian ground moraine.

Moraine

Small moraines of the Illinoian present in some places are indicated by the overprint pattern. The moraines consist of subdued, rounded ridges of till and some outwash sands and gravels.

Hagarstown Member of Glasford Formation — gha

Mostly well-sorted and well-bedded sand and gravel, cemented in some places; till in places; in kames, eskers, and crevasse fillings; kames may contain large thrust blocks of older till or bedrock. Includes the Vandalia Till Member, but overlay deposits overlying older and younger tills are mapped as the Hagarstown Member also; includes the "ridged drift" of the Kaskaskia Basin, elongate sand-and-gravel-cored ridges in south-central Illinois.

Radnor Till Member of Glasford Formation · Sterling Till Member of Glasford Formation — gr gs

Mostly gray compact silty till with a little gravel, sand, and silt in some places.

Winslow Till Member of Glasford Formation · Ogle Till Member of Glasford Formation · Vandalia Till Member of Glasford Formation · Hulick Till Member of Glasford Formation — gw gv go gh

Compact, hard, silty, sandy, and clayey till and intercalated sand and gravel. The Winslow is dark-gray clayey till in northwestern Illinois, related to the Ogle, but more clayey; thin with many small outcrops of underlying bedrock included. The Ogle is thin and discontinuous, tan to grayish-brown, sandy till; many small outcrops of underlying bedrock or areas of bedrock controlled. The Hulick and Vandalia are related to the Hulick. The Hulick and Vandalia are hard, compact sandy till with sand and gravel; mapped as Hulick west of the Illinois River and Vandalia east of the Illinois River; gradational to silty till in southern Illinois.

Kellerville Till Member of Glasford Formation — gk

Brown and gray silty till with discontinuous sand and gravel beds; mineralogically intermediate between western Banner Formation tills and the Vandalia-Hulick; may include some older tills of similar composition in extreme western Illinois; mapped only west of the Illinois River; small areas of stratigraphically equivalent Smithboro Till Member in southern Illinois may be included in the Vandalia.

Banner Formation · Banner Formation outwash facies — b b-o

Mostly till, but includes small areas of outwash sands and gravels and lacustrine silt and clay. Sand and gravel facies (b-o) in terrace remnants along tributaries to the Mississippi. Mapped where not overlain by Illinoian deposits in western Illinois and in other scattered locations where it crops out from under Illinoian drift; generally has Yarmouth Soil or combined Yarmouth and Sangamon Soil at the top of deposit and is overlain by thick deposits of silt (Peoria Loess and Roxana Silt). As mapped, Banner Formation may actually include deposits of several pre-Illinoian glaciations.

Mounds Gravel — mg

Mostly gravel on uplands; brown chert pebbles; high remnants of former terrace levels believed to be of Pliocene-Pleistocene age; does not contain materials characteristic of glacial deposits; mapped only in extreme southern Illinois. Similar gravel, the Grover Gravel, is present in areas too small to map in western Illinois (Calhoun County); generally overlain by moderate to thick silt (Peoria Loess and Roxana Silt).

White areas on map indicate that rocks older than Pliocene are present at or near the surface; for bedrock units, see inset bedrock map or refer to Willman and others (1967), *Geologic Map of Illinois* (1:500,000).

5 — Thickness of loess; contour interval, 5 feet (1.5 m)

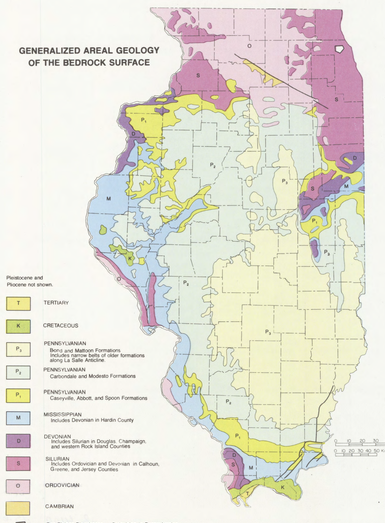
Inferred limit of glaciation

Scale 1:500,000
1 inch equals approximately 8 miles

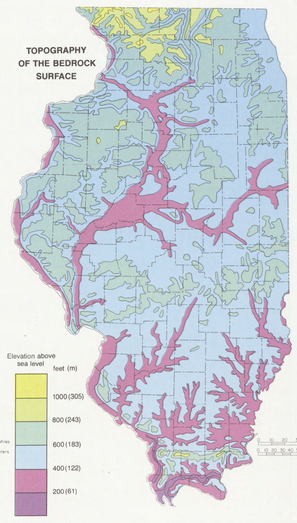
Lambert conformal conic projection based on standard parallels 33° and 45°

BASE MAP
BY U. S. GEOLOGICAL SURVEY

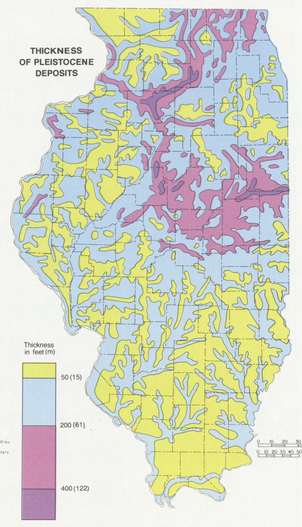
GENERALIZED AREAL GEOLOGY OF THE BEDROCK SURFACE



TOPOGRAPHY OF THE BEDROCK SURFACE



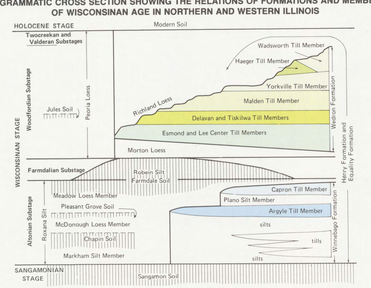
THICKNESS OF PLEISTOCENE DEPOSITS



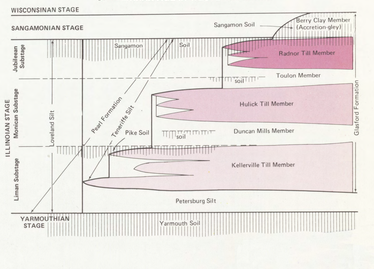
STRATIGRAPHIC CLASSIFICATIONS OF THE PLEISTOCENE DEPOSITS OF ILLINOIS

TIME STRATIGRAPHY			ROCK STRATIGRAPHY										SOIL STRATIGRAPHY
QUATERNARY SYSTEM	HOLOCENE STAGE												Modern Soil
	PLEISTOCENE SERIES	WISCONSINAN STAGE	VALDERAN SUBSTAGE										
			TWOCREEKAN SUBSTAGE										
			WOODFORDIAN SUBSTAGE	Peoria Loess	Richland Loess	Lake Michigan Fm.	Ravinia Sand Member; Waukegan M.; Lake Forest M.; Winnetka M.; Sheboygan M.; Wilmette Bed; South Haven M.	Cahokia Alluvium	Parkland Sand	Grayslake Peat	Lacon Formation	Peyton Colluvium	Jules Soil
						Wedron Fm.	Wadsworth Till Member; Haeger Till Member; Yorkville Till Member; Malden Till Member	Trafalgar Fm.	Snider Till M.	Batestown T.M.	Piatt Till Member	Fairgrange T.M.	
							Tiskilwa Till Member; Delavan Till Member; Lee Center Till Member; Esmond Till Member		Oakland Till M.				Farmdale Soil
			FARMDALIAN SUBSTAGE		Morton Loess		Peddicord Formation						
			ALTONIAN SUBSTAGE	Roxana Silt	Meadow Loess M.; McDonough Loess M.; Markham Silt M.	Winnebago Fm.	Capron Till Member; Piano Silt Member; Argyle Till Member						Pleasant Grove Soil
								Equality Formation — Carmi and Dolton Members		Henry Formation — Batavia, Mackinaw, and Wasco Members			Chapin Soil
			SANGAMONIAN STAGE				Berry Clay Member						Sangamon Soil
		ILLINOIAN STAGE	JUBILEEAN SUBSTAGE				Radnor T.M. Sterling T.M. Hagarstown M.						
			MONICAN SUBSTAGE	Loveland Silt	Teneriffe Silt	Glasford Formation	Toulon M. Roby Silt M. Winslow T.M.						Pike Soil
			LIMAN SUBSTAGE				Hulick T.M. Ogle T.M. Vandalia T.M. Duncan Mills M. Kellerville T.M. Mulberry Grove M. Smithboro T.M.				Pearl Fm.		
					Petersburg Silt								Yarmouth Soil
			YARMOUTHIAN STAGE			Banner Fm.	Liele Clay Member: Tilton T.M., Hillery T.M., Harmattan T.M., Belgium Member, Hegeler T.M., Harkness Silt M., Sankoty Sand M., Mahomet Sand M.						
			KANSAN STAGE										Afton Soil
			AFTONIAN STAGE										
			NEBRASKAN STAGE				Enion Formation	Mounds Gravel	Grover Gravel				

DIAGRAMMATIC CROSS SECTION SHOWING THE RELATIONS OF FORMATIONS AND MEMBERS OF WISCONSINAN AGE IN NORTHERN AND WESTERN ILLINOIS



DIAGRAMMATIC CROSS SECTION SHOWING THE RELATIONS OF FORMATIONS AND MEMBERS OF ILLINOIAN AGE IN WESTERN ILLINOIS



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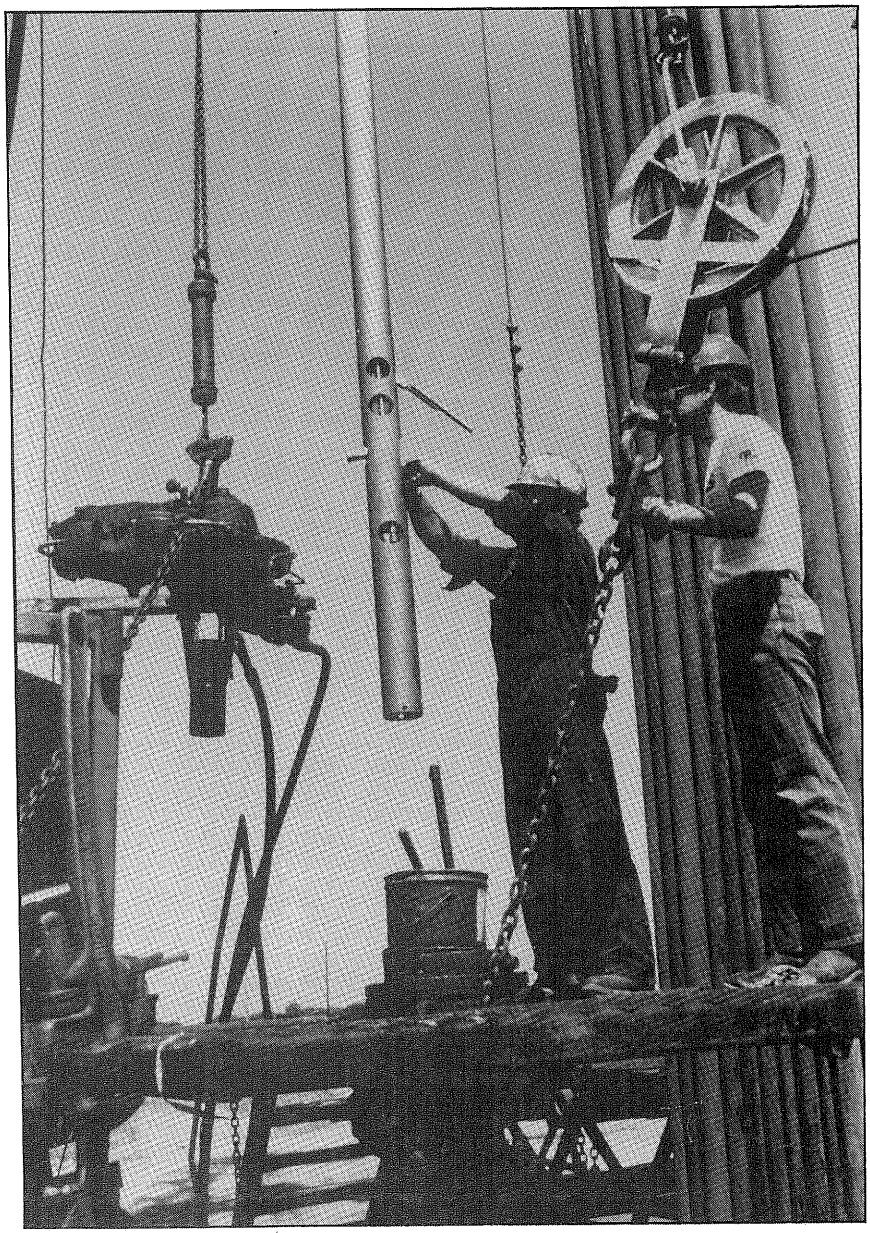
INVESTIGATION OF THE HYDRAULIC EFFECTS OF DEEP-WELL INJECTION OF INDUSTRIAL WASTES

Edward Mehnert, Craig R. Gendron, and Ross D. Brower



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Department of Energy and Natural Resources
Illinois State Geological Survey
Hazardous Waste Research and Information Center

INVESTIGATION OF THE HYDRAULIC EFFECTS OF DEEP-WELL INJECTION OF INDUSTRIAL WASTES

Edward Mehnert, Craig R. Gendron, and Ross D. Brower
Illinois State Geological Survey

Final Report

Prepared for

United States Environmental Protection Agency
Office of Drinking Water
David Morganwalp, Project Officer
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Department of Energy and Natural Resources
Jacqueline Peden, Project Officer
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ABSTRACT

A numerical modeling study was conducted to investigate the hydraulic effects of liquid waste injection on an injection system. The site investigated was a chemical refinery with an operational Class I well and an observation well, both completed in Devonian limestone. Input data for the model were obtained from available records and field investigations.

The regional geologic investigation indicated that the injection system (defined here as the injection zone and its associated confining units) was laterally continuous. The hydraulic response of the injection system was numerically modeled under two injection scenarios: average historical injection rate and maximum average permitted rate. For both scenarios, pressure buildup from waste injection during the simulated 30-year injection and 30-year postinjection periods did not approach the pressure calculated to be necessary to initiate or propagate fractures in the injection system. Therefore, injected waste would be contained, and waste injection at this site and for the scenarios modeled would not endanger human health or the environment.

This analysis assumes that hydraulic conductivity remains constant; however, the formation of brucite within the injection zone may invalidate this assumption and the preceding analysis. Brucite formation within the injection zone requires additional study.

The model was also used to investigate the response of the injection system when a hypothetical conduit was introduced. This hypothetical conduit connected the uppermost injection zone with an overlying aquifer. Differences in head buildup were not monitorable in the injection well or in an observation well completed in the injection zone. Monitorable head differences were observed only in the overlying aquifer, when the hydraulic conductivity of the hypothetical conduit was greater than or equal to 1×10^{-10} m^2.

EXECUTIVE SUMMARY

Concern over the potential for groundwater contamination from waste injection prompted a multi-faceted research effort funded by the U.S. Environmental Protection Agency (USEPA) and industry. The research will provide the USEPA with data needed to determine if underground injection of hazardous waste endangers human health or the environment. One facet of this research effort was an investigation of the hydraulic effects of deep-well injection on the injection system.

The injection system includes the geologic units constituting the injection zone and the upper and lower confining units. The site of this investigation was a chemical refinery in Illinois that has an operational injection well and an observation well completed in Devonian limestone.

Data Collection and Analysis

Before numerical modeling could be conducted, a hydrogeologic description of the site was developed from available records and geophysical logs. Numerous records and logs were available from oil- and gas-related tests and wells within a 10-mile radius of the site. Logs and records for on-site wells were also used.

In addition, hydraulic tests and geophysical logs were run to obtain detailed hydrogeologic data on the injection system. Two hydraulic tests were run in the injection well: a continuous spinner flowmeter survey and a 15-day injection test. Sidewall cores were also retrieved from the injection well. The following geophysical logs were run in the observation well: Compensated Neutron Log, Borehole Compensated Sonic Log, Minilog, Dual Induction Spherically Focused Log, and Gamma Ray Log.

Although analyses of the data from these logs and tests yielded much information concerning the hydrogeologic character of the injection system, there was one discrepancy—the results of the spinner flowmeter indicated that the waste was flowing through different zones of the injection system than had been theorized from the results of geophysical logging. To clarify this discrepancy, we conducted additional analyses (x-ray diffraction and scanning electron microscopy). The discrepancy can be explained briefly as follows. Because of its high pH, the injected wastewater reacts with the Mg^{2+} present in the injection zones or in solution, forming brucite ($Mg[OH]_2$). Brucite accumulation reduces the permeability of the injection zone. Greater amounts of brucite apparently formed in the injection zones where the flow of fluid was greater; thus the zones with higher permeability were affected first. Additional work beyond the scope of this project is needed to verify the brucite-formation hypothesis. Also, the long-term effect of this decrease in permeability on injectivity needs to be investigated.

Numerical Modeling

Site Analysis

A description of the regional and site-specific stratigraphy, structural geology, and hydrogeology of the injection system was generated from a review of available data and the field work conducted during this project. This description formed the basis of input for the numerical model. Model input also included data on the physical and chemical characteristics of the injected wastewater and the native brine in the injection system.

These data were employed as input data for a three-dimensional groundwater flow model (HST3D). Before the effects of various injection scenarios were evaluated, HST3D was verified with respect to two analytical solutions and calibrated by the use of data collected during a 2-week injection test. Both verification and calibration were considered satisfactory.

Once calibrated, the model was used to predict the effects of various injection scenarios. The effect of long-term injection was investigated at two constant injection rates—the average historical rate (1.15×10^{-2} m^3/sec) and the maximum average rate permitted under Class I regulations (2.21×10^{-2} m^3/sec). With both scenarios, significant head buildup was observed at the injection well and radially from it. During the simulated 30-year injection period, steady state was approached but not obtained for both injection scenarios. During the subsequent 30-year postinjection period, dropoff in head buildup was fairly rapid, falling to half in less than 2,000 hours for both scenarios. The maximum hydraulic pressures at the bottom of the well and at the base of the upper confining unit were significantly lower than the pressures calculated to initiate hydraulic fracturing. A fracture gradient of 1.5×10^4 Pa/m (Pascals/meter) (0.65 psi/ft) was used to calculate the hydraulic fracture pressures.

The regional and site-specific geological analysis revealed the continuity of the stratigraphy and qualitative permeability on a regional basis. The numerical modeling indicated that injection pressures were lower than calculated pressures required to initiate hydraulic fracturing. Therefore, from a hydraulic viewpoint, waste injected into this injection system would be contained, and waste injection at this site and for the scenarios modeled would be considered protective of human health and the environment.

These results were based on an assumption that the permeability remains constant. If the hypothesis concerning the formation of brucite is correct, its formation may reduce the permeability of the injection zones and invalidate this analysis. Any reduction in permeability of the injection zones will probably increase the hydraulic pressure resulting from waste injection if the injection rate remains constant. In such a situation, hydraulic fracturing may be of concern. Because of the potential ramifications, formation of brucite within the injection zone requires additional geochemical analysis.

Effects of Hypothetical Conduit

The model was also used to investigate the hydraulic response of the injection system to the introduction of a hypothetical conduit. The conduit, a microannulus (0.01 m wide) at the injection well, hydraulically connects the uppermost injection zone and an aquifer immediately overlying the upper confining unit. To determine the impact of the microannulus, the head buildup with the microannulus present was compared with the buildup from runs with the microannulus not present. Differences in head buildup at selected positions and for certain times were computed. Differences in the head buildup were considered unmonitorable at the injection well and the observation well. The difference in head buildup in the overlying aquifer was monitorable only when the microannulus had a hydraulic conductivity greater than or equal to 1.00×10^{-10} m^2. The head buildup in the overlying aquifer is a function of its hydraulic conductivity, the hydraulic conductivity of the microannulus, and the radial distance from the microannulus. Thus for the scenario modeled, leakage via a microannulus could not be hydraulically monitored by use of the injection well or an observation well completed within the injection zone. This leakage was monitorable only through the use of an observation well in the overlying aquifer.

GLOSSARY

AIF	aquifer influence boundary
b	thickness
DOW	Devonian Observation Well
GL	ground level
HST3D	Heat and Solute Transport Model
ISGS	Illinois State Geological Survey
k	permeability
K	hydraulic conductivity
KB	Kelly Bushing
m	modulus of shear for the medium
Pa	Pascals
POR	porosity
psi	pounds per square inch
q	pumping rate
S	storativity
SEM	scanning electron microscopy
SWIFT	Sandia Waste Isolation Flow and Transport Model
SWIP	Survey Waste Isolation Program
T	transmissivity
TDS	total dissolved solids
USDW	underground sources of drinking water
USEPA	United States Environmental Protection Agency
WDW2	Waste Disposal Well 2
α	matrix compressibility
β	fluid compressibility
Δh	head buildup
ρ	fluid density
μ	fluid viscosity

1. INTRODUCTION

Background

Liquid waste is disposed of through underground injection by pumping the waste into or allowing it to flow through a specially designed and monitored well. Developed by the petroleum industry in the 1930s as a method for brine disposal, the technique was adapted by other industries in the 1950s for the disposal of industrial waste streams. As regulations for the disposal of waste into landfills and surface waters became more stringent, the volume of waste disposed of by underground injection increased.

Regulatory agencies have classified injection wells according to the purpose of the wells and the proximity of injection reservoirs to the lowermost underground source of drinking water (USDW). The five classes of injection wells are:

Class I — wells used to inject hazardous and nonhazardous wastes below the lowermost USDW (this report is concerned with this class of wells).

Class II — wells associated with the production and storage of oil and gas below the lowermost USDW.

Class III — wells used in special process (mining) operations to inject fluid above, into, or below an USDW.

Class IV — wells used to inject hazardous waste into or above an USDW (this class of wells is currently banned).

Class V — wells used to inject all other wastes into or above an USDW.

According to the U.S. Environmental Protection Agency (USEPA), there were 429 Class I injection wells active in 1986 (USEPA 1986). Although the volume of waste disposed of nationwide via these wells is difficult to estimate, accurate figures are available from some states. In Illinois, nine Class I wells were used in 1984 to dispose of 310 million gallons of waste (Brower et al. 1989).

With the promulgation of the Hazardous and Solid Waste Amendments of 1984, the level of interest in underground injection increased tremendously. Provisions of the act mandated that the administrator of USEPA determine if underground injection is a threat to human health and the environment for the period the waste remains hazardous. If underground injection is found to be hazardous to human health and the environment, or if the determination is not made by the Congressionally mandated date, all underground injection will be banned. Some environmental groups want situations detailed in which underground injection has endangered or may endanger human health or the environment.

The USEPA developed an extensive research agenda to examine pertinent issues. The USEPA has funded to date one or more projects in each of the following areas: identification and classification of Class I well failures; techniques to detect abandoned wells; monitoring of various aspects of the well; flow and transport modeling of various injection scenarios; geochemical modeling of injected waste, injection formation, and brine; and hydrogeologic characterization of important injection formations and associated confining formations. Industry also has conducted research into pertinent topics of underground injection.

In this project, a numerical model was used to investigate the hydraulic effects of waste injection on the geologic reservoir. The site of the investigation is a chemical refinery located near Marshall, Illinois, in north-central Clark County (fig. 1). The chemical company used the injection well

to dispose of alkaline (pH>12) waste. An observation well, which is completed in the same formation as the injection well, is located 506 meters north of the injection well.

Purpose

The primary purpose of this project was to investigate the pressure response (flow modeling) of an actual injection formation and its associated confining formations due to waste injection via a Class I well. Modeling of solute transport was not investigated here but was addressed by other researchers sponsored by USEPA and industry. Flow modeling requires detailed characterization of the site hydrogeology, so this project bridged two areas of concern—flow modeling and hydrogeologic characterization. In addition, the effectiveness of pressure-monitoring systems to detect movement of fluid beyond the injection formation was evaluated.

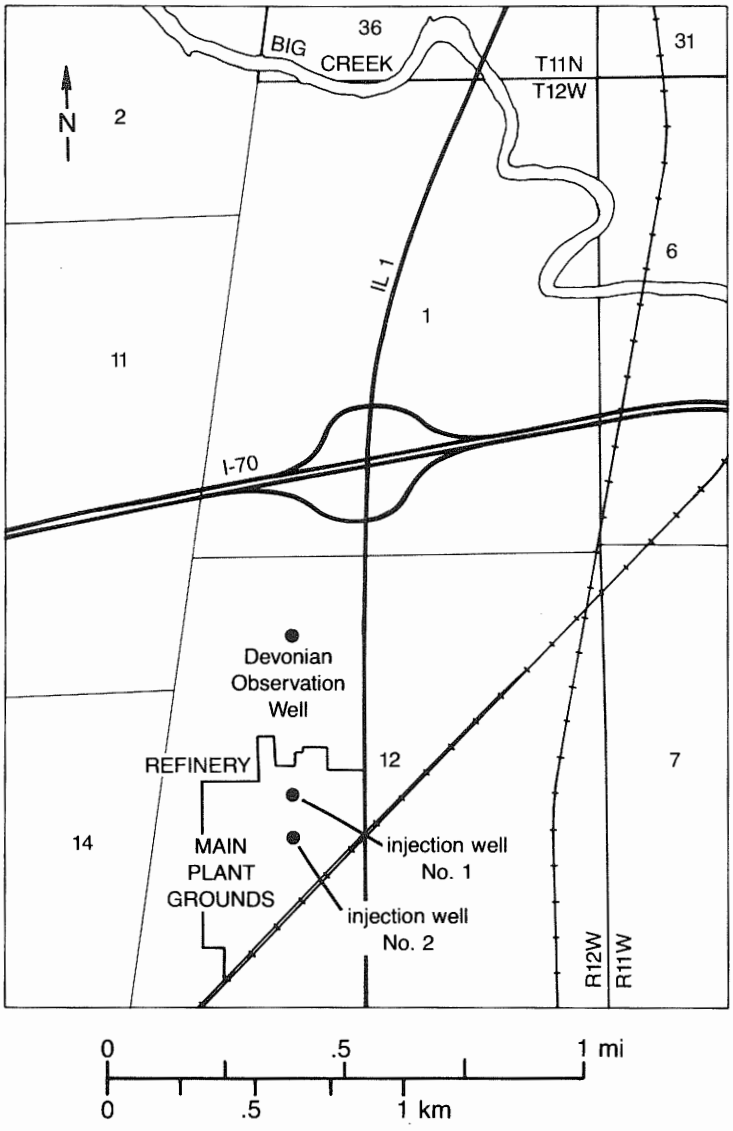


Figure 1 Location of investigation site.

2. GEOLOGY OF THE INJECTION SYSTEM

The geologic environment of an injection well site controls many aspects of the disposal operation and the fate of the injected wastes. This section includes a summary of the regional geology and hydrogeology of the units involved with the deep-well injection operation. The geologic setting is described within the context of the regional geology to show regional trends and the degree of uniformity in geologic conditions.

Only those aspects of geology pertinent to underground injection are described. The major emphasis is on the hydrogeology of the confining units and the injection interval, specifically, the hydrogeology of the upper confining unit (New Albany Group), the lower confining unit (Maquoketa Group), and the injection interval (Hunton Supergroup). The Borden Siltstone, which overlies the New Albany Group, acts as an additional confining zone.

Overview of Geologic Conditions Affecting Waste Injection

The principal geologic factors for the regional evaluation are those affecting (1) the capacity of geologic units in the injection system to accept and confine injected waste, (2) the chemical interaction of the waste with injection system components, (3) the generation of dislocations that developed during the forming of structural features or seismic events, and (4) the use of subsurface space and commercial grade resources in the area of disposal influence.

In this section we have focused on the broader regional issues that relate to local geologic conditions. Broadly defined lithologic units form a key component of the regional discussion. These units have been described in the literature, and the uniformity of their general geologic conditions and structural trends have been established by oil, gas, water, and mineral resource exploration activities in the region.

The character and trends of the regional geology have been determined from data gathered from key well records, reports, and publications. This information reveals the distribution of aquifers that meet regulatory requirements for Class I injection, i.e., aquifers that contain saline water (>10,000 mg/L total dissolved solids [TDS]) and that have confining intervals capable of protecting all USDW from contamination by injection activities. Injection is limited to selected aquifers in the southern two-thirds of Illinois, including the Hunton Supergroup and the Salem Limestone, which have been used for disposal at the study site. Injection system response to waste injection is primarily controlled by porosity and permeability characteristics, which can be directly related regionally to specific geologic units.

Porosity and permeability develop during sedimentation processes and are modified by other geologic processes. Thus porosity and permeability have a general relationship with specific lithologies. Each geologic unit in the region exhibits a range of values and areal trends. The sedimentary geologic units in east-central Illinois exhibit relatively uniform characteristics over large areas; however, both vertical and radial trends are noted within each unit. Similar patterns can also be expected within the subdivisions of each unit, but determining this would require a detailed study of subsurface records.

The lithology of the geologic units forming the injection system plays an important role in the chemical interaction between the injected waste and injection system. Chemical interaction between injected waste and the injection system can affect flow conditions (porosity and permeability) and under certain disposal conditions can compromise the integrity of the confining intervals. However, beneficial interactions may also occur that would improve flow conditions, involve retention of some waste components near the well, and provide treatment for selected, undesirable components in the waste.

This discussion focuses on the general regional characteristics of principal geologic units and relates these characteristics to hydrogeologic parameters for characterizing flow in the injection system. An effective evaluation by numerical modeling requires that the hydrogeologic character of the geologic units accepting and retaining injected waste be predictable and relatively uniform throughout the area influenced by injection. A more detailed description of the character and radial uniformity of the units in the injection system is presented in chapter 3.

General Geologic Setting

The geologic framework of Illinois in which deep-well disposal is practiced can be described as a sequence of areally extensive sedimentary rock units deposited in a large midcontinent basin known as the Illinois Basin. The study site, in the east-central part of the basin, is immediately east of the axis of the Marshall-Sidell Syncline and about 14 miles east of the La Salle Anticlinal Belt, the most dominant structural feature in the area. Figure 2 shows the generalized geology of the bedrock surface in Illinois. Generalized geologic cross sections of Illinois are depicted in figure 3. Figure 4 provides a generalized geologic column and comments on the stratigraphy, lithology, hydrogeology, and groundwater geochemistry of the geologic units associated with or protected from waste injection. Additional details on geologic units covered in this report are available in the *Handbook for Illinois Stratigraphy* (Willman et al. 1975), the *Bibliography of Illinois Geology* (Willman et al. 1968) and reports prepared by Brower et al. (1989), Cluff et al. (1981), Gray et al. (1979), and Piskin and Bergstrom (1975).

In Illinois, lithologies range from very fine- to coarse-grained clastics, a variety of carbonates, and a few evaporites and organics. Relatively uniform lithologic characteristics exist on a regional basis within individual units as a whole and within the subdivisions of each unit.

Many processes have been involved in forming, altering, and structurally readjusting these units from the time of deposition to the present day. Sedimentary deposition began early in the Paleozoic Era on the eroded surface of igneous and metamorphic rock of the Precambrian basement complex. Deposition and some erosion continued throughout the Paleozoic. Several episodes of deposition in the Mesozoic and Cenozoic Eras produced nonlithified sedimentary units. The present-day landscape has developed principally on these nonlithified sediments. Marine carbonate and clastic lithologies are dominant in the Paleozoic units, but terrestrial clastics and some organic deposits are present in the upper part of the Paleozoic (Mississippian and Pennsylvanian Systems).

The thickness of the sedimentary sequence in Illinois ranges from approximately 2,000 feet northwest of Rockford to more than 20,000 feet in the southeastern corner of the state, the deepest part of the Illinois Basin (Sargent and Buschbach 1985). In the project area, the total thickness of the sedimentary units is approximately 8,500 feet. Lithologies include dolomite, limestone, sandstone, siltstone, shale, and some coal and evaporite. The stratigraphic column in figure 4 provides a summary of the typical sedimentary sequence in the Illinois Basin. Widespread carbonate lithologies are dominant in the lower part of the Paleozoic, and a few sandstones and some shales are interbedded with these carbonates. Most of the carbonates become sandy to the north, and a few grade into sandstones in the far northern part of the state. Greater variations in regional lithology exist in the upper part of the Devonian through the middle part of the Mississippian. Cyclic deposits of fine-grained clastics (shales and siltstones), some carbonates, and some coarse-grained clastics (sandstones) accumulated in the upper part of the Mississippian and in all of the Pennsylvanian as numerous sea-level oscillations shifted shorelines across shallow-marine and flat-lowland terrestrial environments.

The study site is in the Marshall-Sidell Syncline (see fig. 5), a broad structural feature of low relief between the La Salle Anticlinal Belt, about 14 miles to the west, and the Kankakee Arch more than 90 miles to the northeast. These two structures are reflected in the distribution of the boundaries of the geologic units exposed at the bedrock surface (fig. 2). The regional dip of the units in the study area is to the southwest from the Kankakee Arch and into the Illinois Basin, but

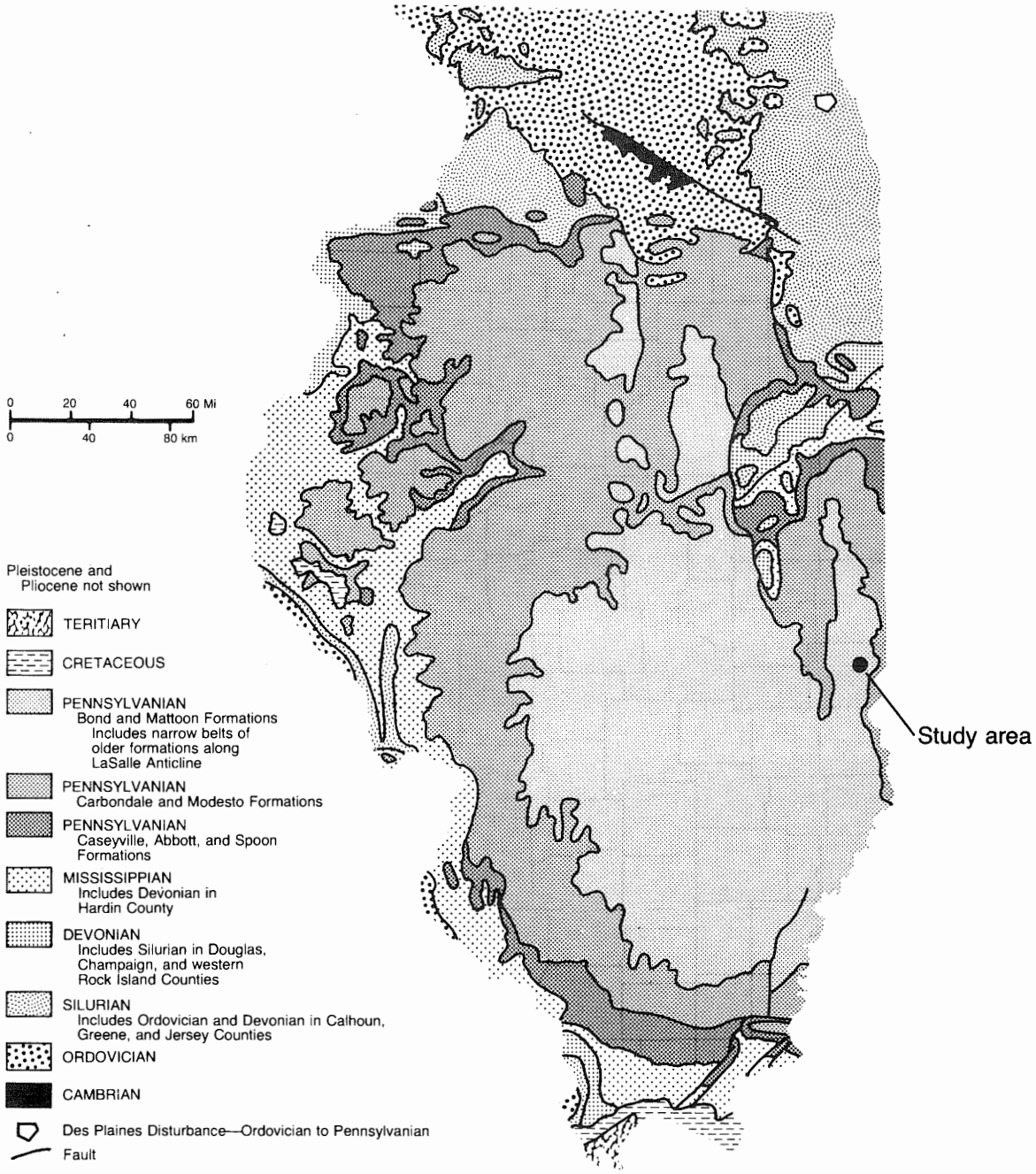


Figure 2 Generalized areal geology of the bedrock surface (from Willman and Frye 1970).

boundaries of the geologic units exposed at the bedrock surface (fig. 2). The regional dip of the units in the study area is to the southwest from the Kankakee Arch and into the Illinois Basin, but locally the units dip gently in a south-to-southwesterly direction toward the axial trend of the Marshall-Sidell Syncline.

Waste Injection Potential in Illinois

Some sequences of Paleozoic units possess sufficient porosity, permeability, and confinement to accept and retain wastes injected at moderate to high injection rates. Criteria for acceptable injec-

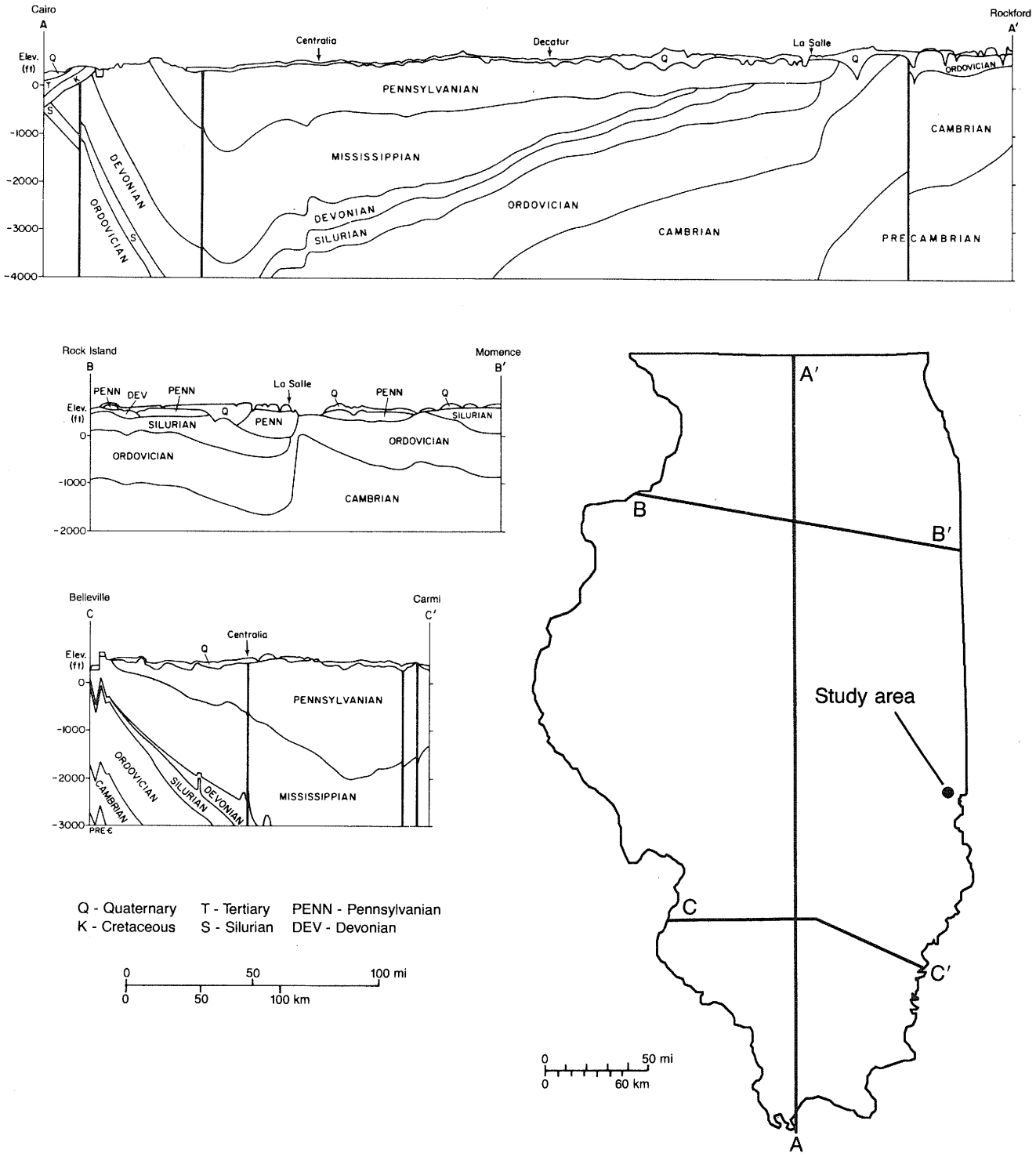


Figure 3 Generalized statewide cross sections of Illinois (from Willman et al. 1975).

Protection Act (Title 35, Illinois Administrative Code). Within Illinois, the base of the USDW ranges in depth from 500 to slightly more than 3,000 feet. All units below the lowermost USDW contain groundwater with a TDS content exceeding 10,000 mg/L (milligrams/liter). Injection is feasible only in portions of Cambrian through basal Pennsylvanian units that meet the criteria for waste injection established in the Illinois Environmental Protection Act.

In the study area, the base of the USDW has been established at a depth of about 500 feet (Piskin 1986). In the immediate vicinity of the study site, significant injection potential for the Salem and Hunton carbonate units has been proved by oil exploration and waste-injection testing conducted to a depth of 6,000 feet. Recently, injection has been limited to the Devonian portion of the Hunton. Very limited groundwater supplies have been obtained from the uppermost part of the Pennsylvanian bedrock. The City of Marshall obtains a moderate to large water supply from a shallow sand and gravel aquifer in the nearby valley of Big Creek.

Seismic Activity in Illinois

Earthquake waves traveling through earth materials can affect deep-well disposal systems. Earthquakes are infrequent in Illinois, and most have been low to moderate in magnitude and intensity (fig. 7). Several earthquakes of low-to-moderate magnitude recently occurred in the vicinity of the Wabash Valley Fault System, which extends northward into Edwards and Wabash Counties from southeastern Illinois (fig. 5). The largest earthquakes affecting Illinois in recorded history occurred near New Madrid, Missouri, in 1811 and 1812 (Heigold 1968, 1972). Although faulting is reported in other areas of Illinois, field studies and drilling records available to the Illinois State Geological Survey indicate that no faults are mapped at the surface or known to have occurred in the subsurface in the vicinity of the study area.

The greatest likelihood for major damage from earthquakes exists in 14 southern Illinois counties (figs. 6 and 7). This region of the state is in Area 3 on the Seismic Risk Map (fig. 6) compiled by Algermissen (1969). The project site is near the southern margin of Area 1, the area in which the damage expectancy from potential earthquakes is rated as minor.

Subsurface Resources

Subsurface resources in Illinois exclusive of groundwater resources include mineral deposits, hydrocarbon deposits, and subsurface storage space. Many of the geologic units containing subsurface resources also qualify as potential disposal horizons. The regulations for deep-well disposal require a review of all subsurface resources of commercial value in order to reduce the potential for conflicts between injection and resource extraction.

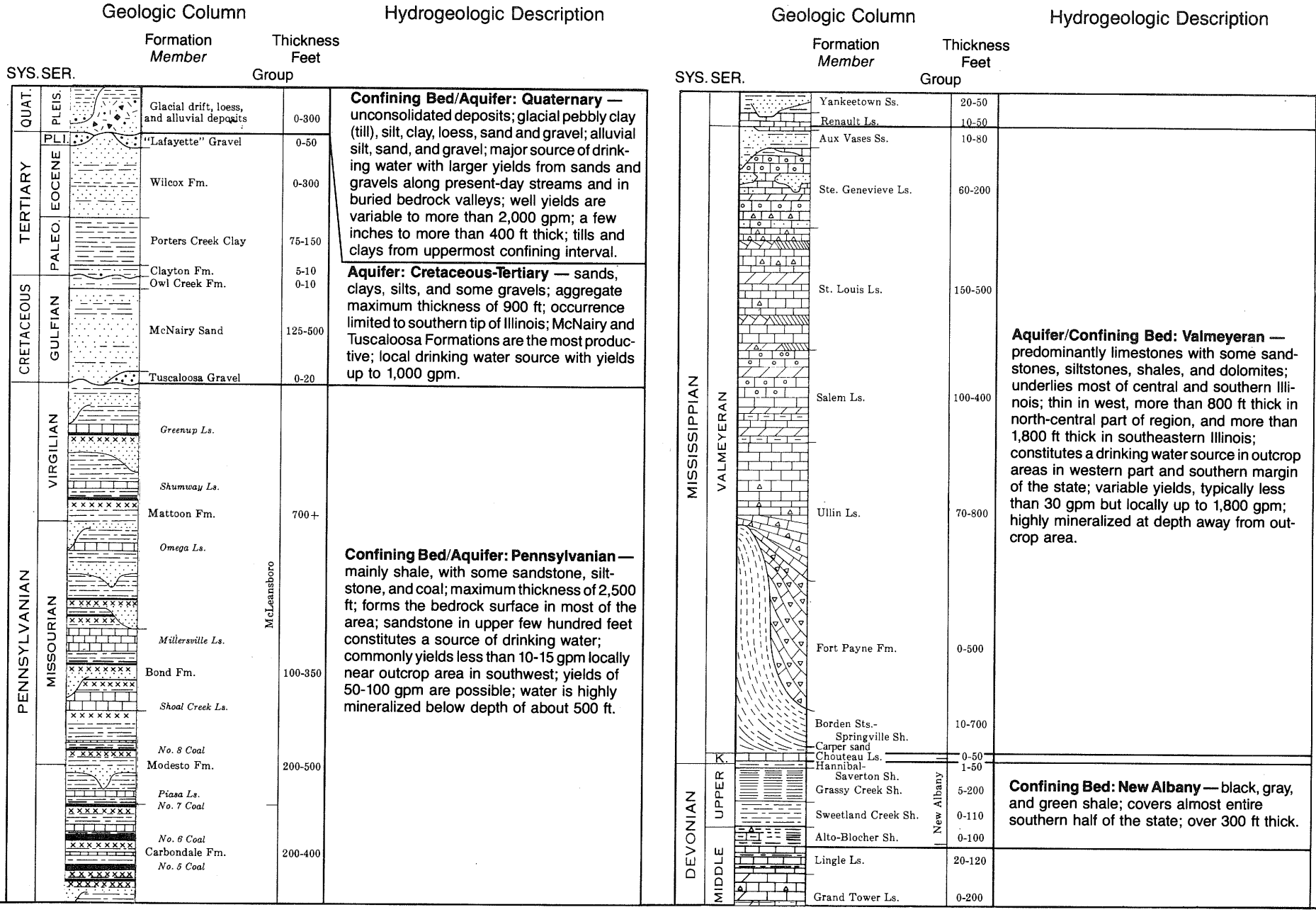
Oil and limited natural gas resources have been exploited in numerous permeable units above the St. Peter Sandstone. Oil production is mainly associated with Mississippian units; however, significant production has come from other Paleozoic units. The petroleum-producing regions in Illinois are confined to the Illinois Basin (fig. 8). Wells drilled for production provide valuable information about subsurface conditions; however, if not properly sealed, these wells can be potential avenues for fluid movement into overlying geologic units.

Oil has been produced in the Weaver Field about 9 miles to the east-southeast of the study area and in several small fields on the La Salle Anticlinal Belt, more than 14 miles to the west. Exploratory wells have been drilled throughout the vicinity of the study site; a few of these wells are within the 2.5-mile area of review of the disposal well. No commercial oil pools have been reported in the Marshall-Sidell Syncline in the vicinity of the study site.

Coal deposits are more widespread than petroleum deposits in the Pennsylvanian units, and multiple coal deposits are often found where Pennsylvanian units are present. Although more than 50 potential coal horizons have been found in Illinois, only a few are thick enough for commercial development. The coals in the project area tend to be relatively thin and deeply buried. Most coal deposits mined in Illinois are shallow (less than 500 ft) and lie within units designated as USDW.

Rock Units and Their Hydrogeologic Roles

Southern Illinois



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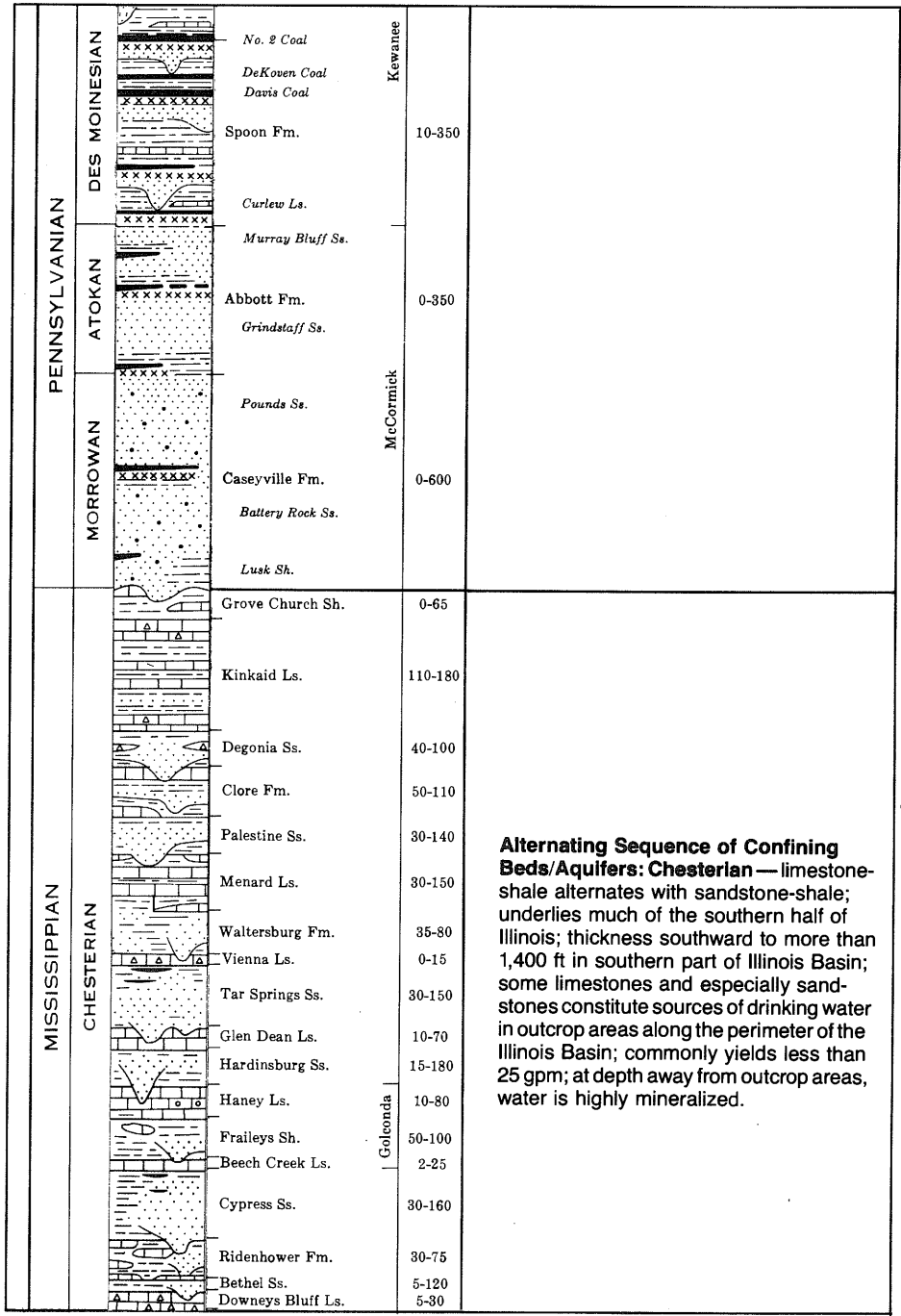

Alternating Sequence of Confining Beds/Aquifers: Chesterian — limestone-shale alternates with sandstone-shale; underlies much of the southern half of Illinois; thickness southward to more than 1,400 ft in southern part of Illinois Basin; some limestones and especially sandstones constitute sources of drinking water in outcrop areas along the perimeter of the Illinois Basin; commonly yields less than 25 gpm; at depth away from outcrop areas, water is highly mineralized.

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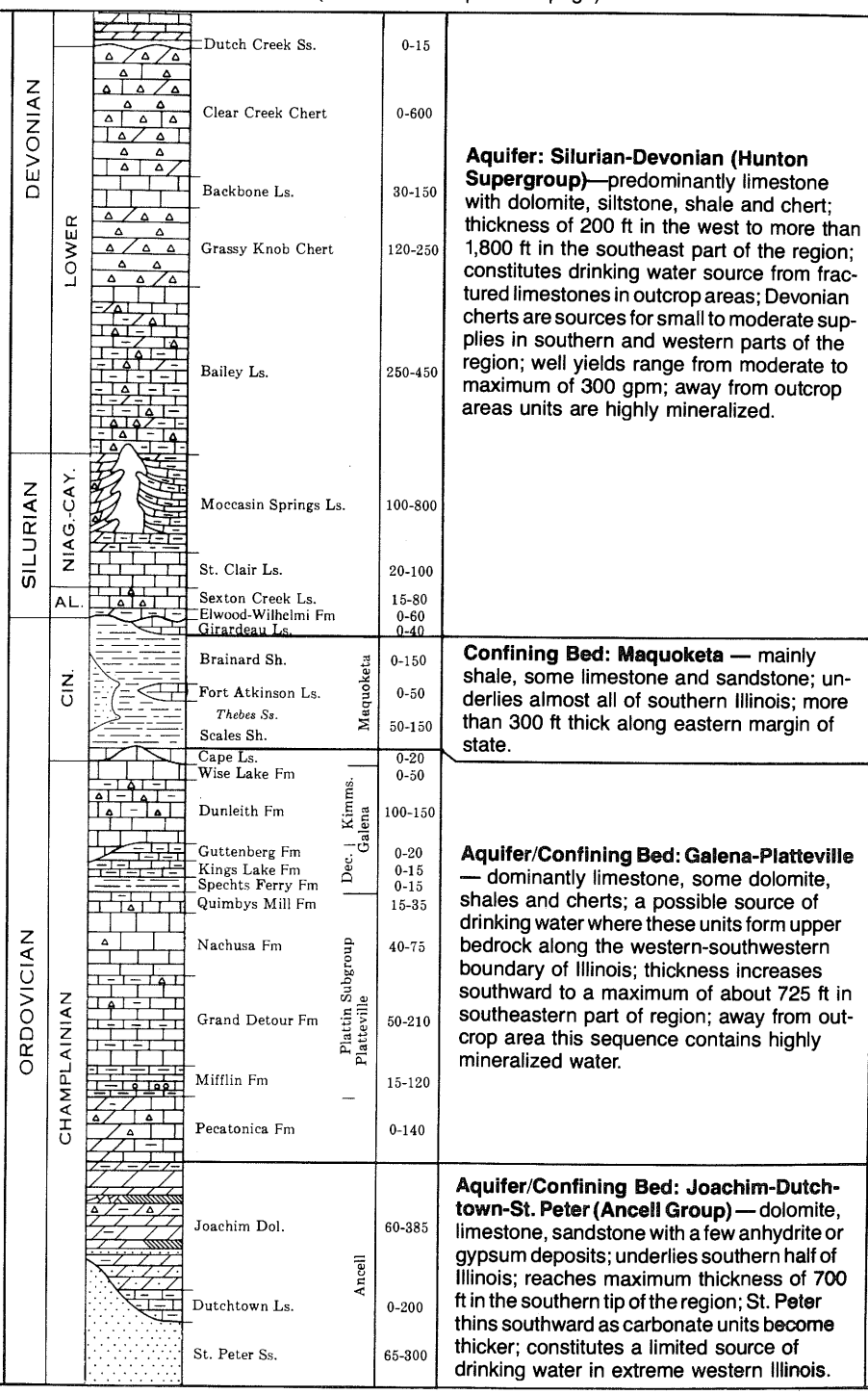


Aquifer: Silurian-Devonian (Hunton Supergroup)—predominantly limestone with dolomite, siltstone, shale and chert; thickness of 200 ft in the west to more than 1,800 ft in the southeast part of the region; constitutes drinking water source from fractured limestones in outcrop areas; Devonian cherts are sources for small to moderate supplies in southern and western parts of the region; well yields range from moderate to maximum of 300 gpm; away from outcrop areas units are highly mineralized.

Confining Bed: Maquoketa — mainly shale, some limestone and sandstone; underlies almost all of southern Illinois; more than 300 ft thick along eastern margin of state.

Aquifer/Confining Bed: Galena-Platteville — dominantly limestone, some dolomite, shales and cherts; a possible source of drinking water where these units form upper bedrock along the western-southwestern boundary of Illinois; thickness increases southward to a maximum of about 725 ft in southeastern part of region; away from outcrop area this sequence contains highly mineralized water.

Aquifer/Confining Bed: Joachim-Dutchtown-St. Peter (Ancell Group) — dolomite, limestone, sandstone with a few anhydrite or gypsum deposits; underlies southern half of Illinois; reaches maximum thickness of 700 ft in the southern tip of the region; St. Peter thins southward as carbonate units become thicker; constitutes a limited source of drinking water in extreme western Illinois.

Figure 4 Description of rock units and their hydrogeologic roles (Brower et al 1989).

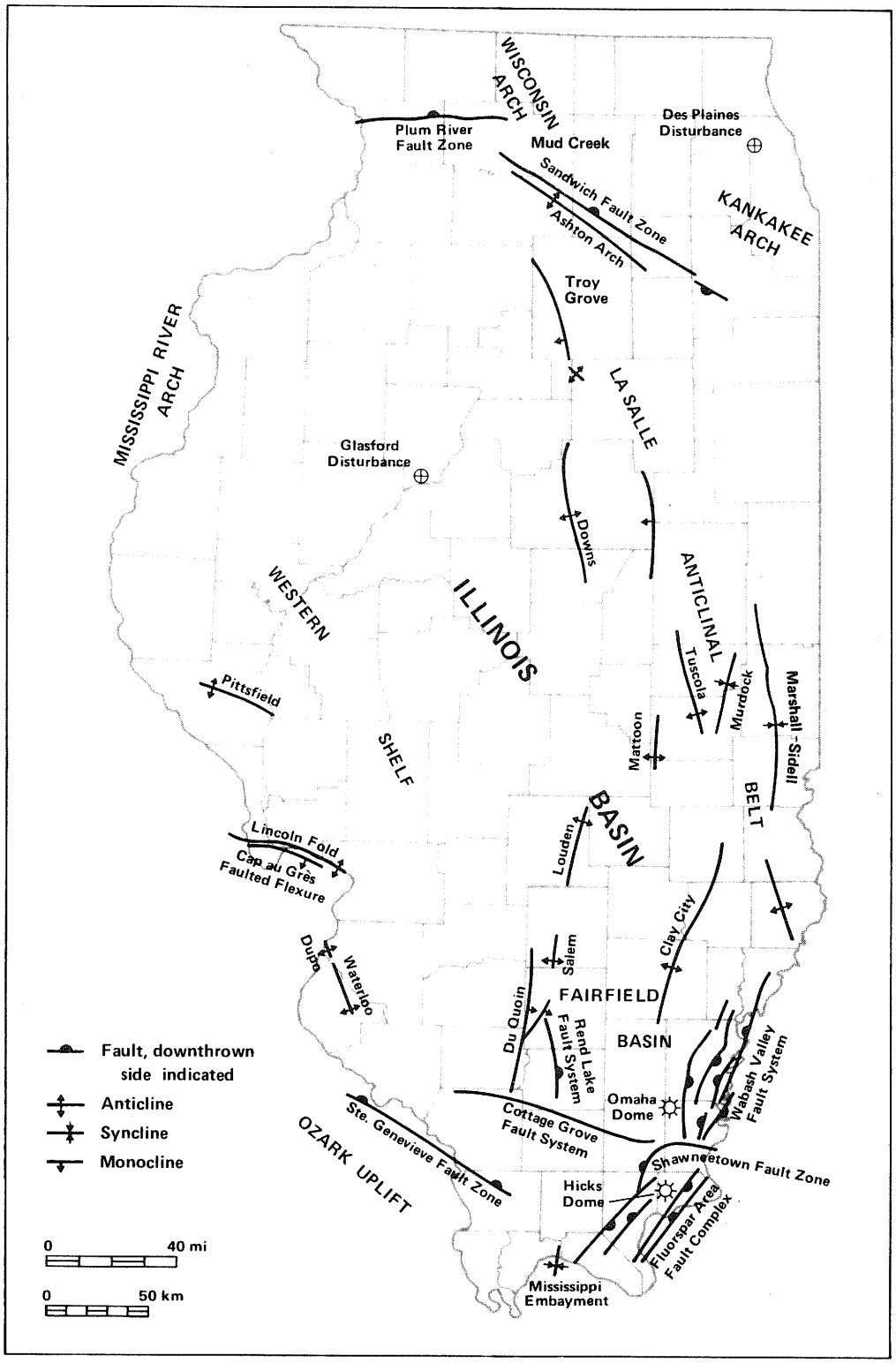


Figure 5 Geologic structures in Illinois (compiled by J. Treworgy 1979).

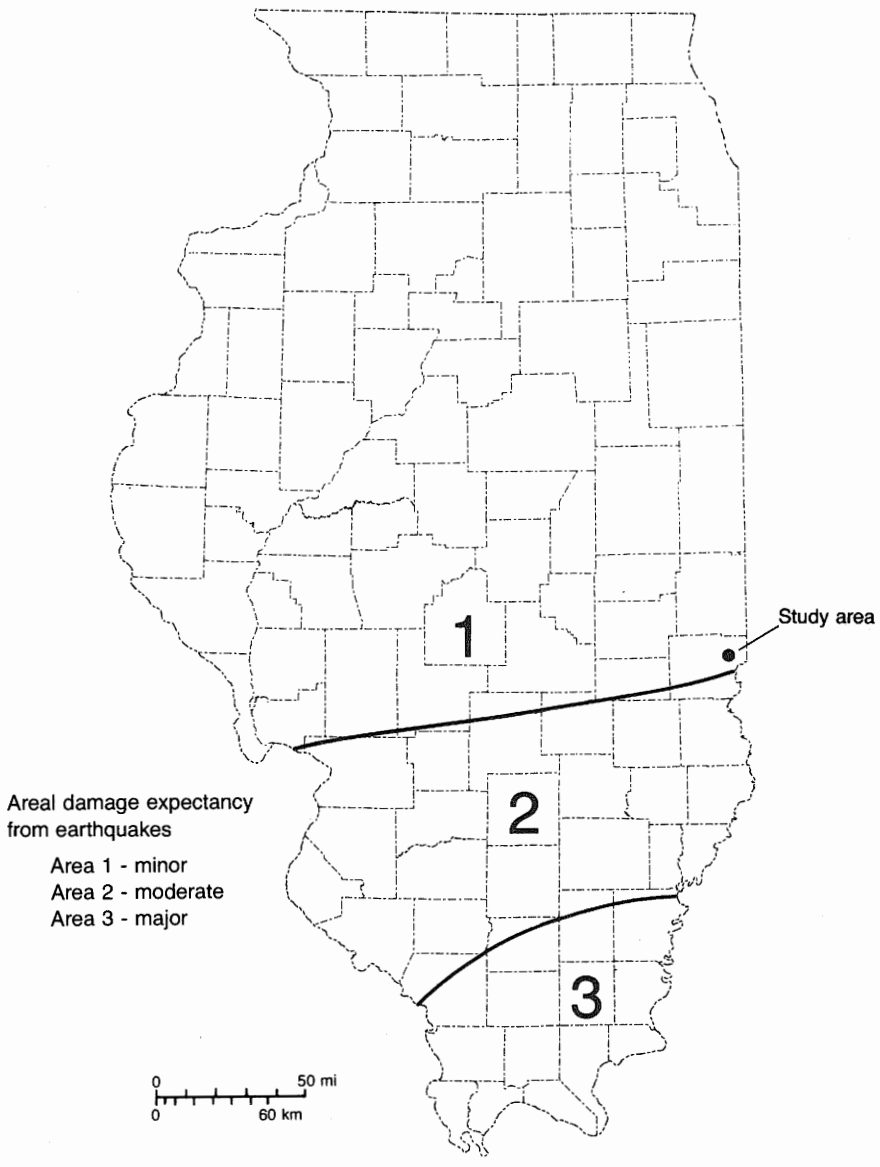


Figure 6 Seismic risk map for Illinois (after Algermissen 1969).

Other mineral resources, including building stone, agricultural lime, clay, sand, sand and gravel, metals, fluorite, barite, and tripoli, have been mined commercially throughout Illinois (Samson 1983, 1989). Most of the mining operations are at or near the land surface. Only limited surface mining (for aggregate and stone) has been done near the study area, and apparently neither the mining nor the injection operations have affected each other.

Natural gas storage fields in aquifers having localized structural closure features are scattered throughout the state. Three storage fields are located about 10 miles north and northeast of the study site (fig. 9). Aquifers of sandstone and limestone strata of Cambrian through Pennsylvanian age have been used for storage. Drilling and testing records from the Nevins, State Line, and Elbridge storage facilities have provided much useful information about subsurface geologic and

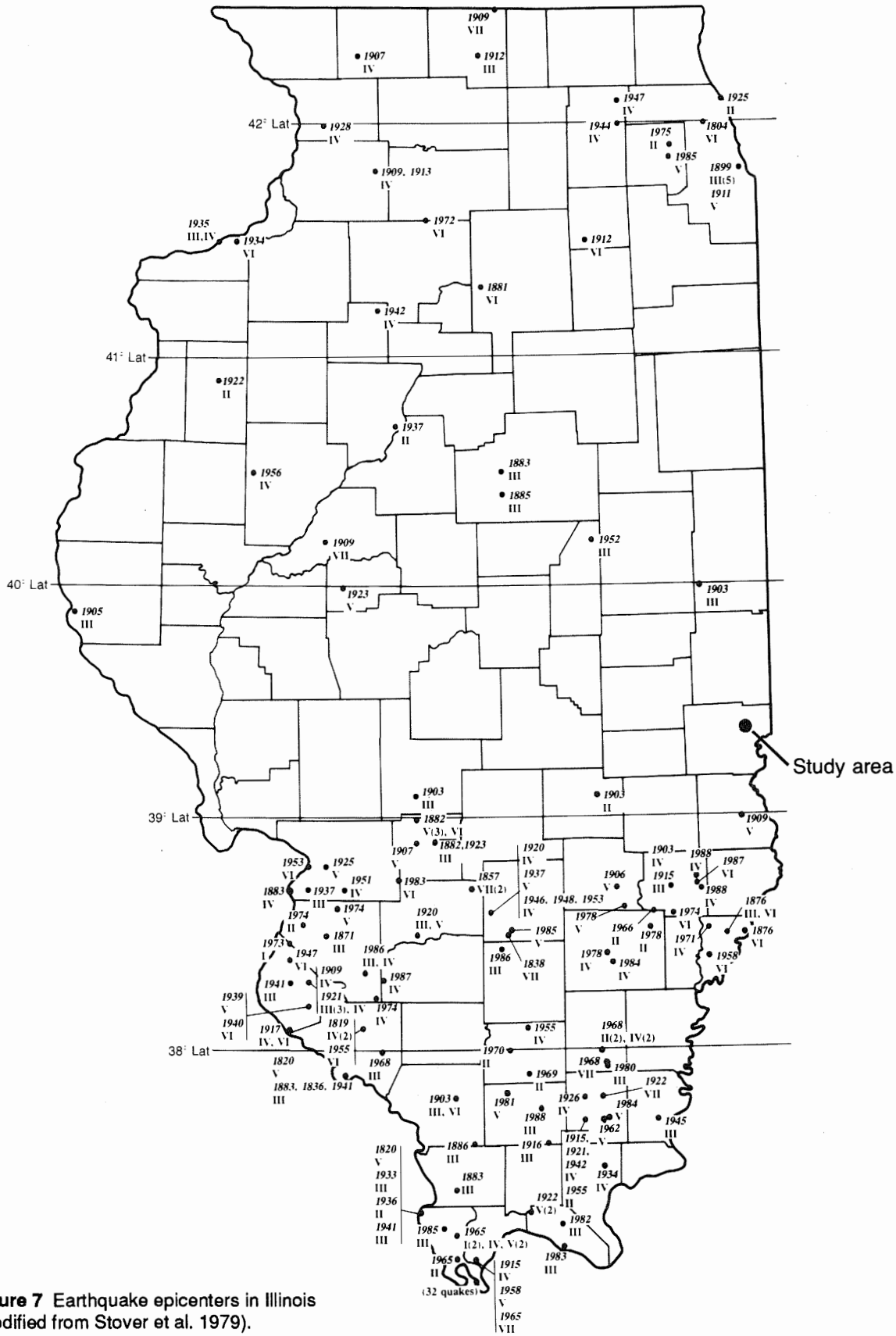


Figure 7 Earthquake epicenters in Illinois (modified from Stover et al. 1979).

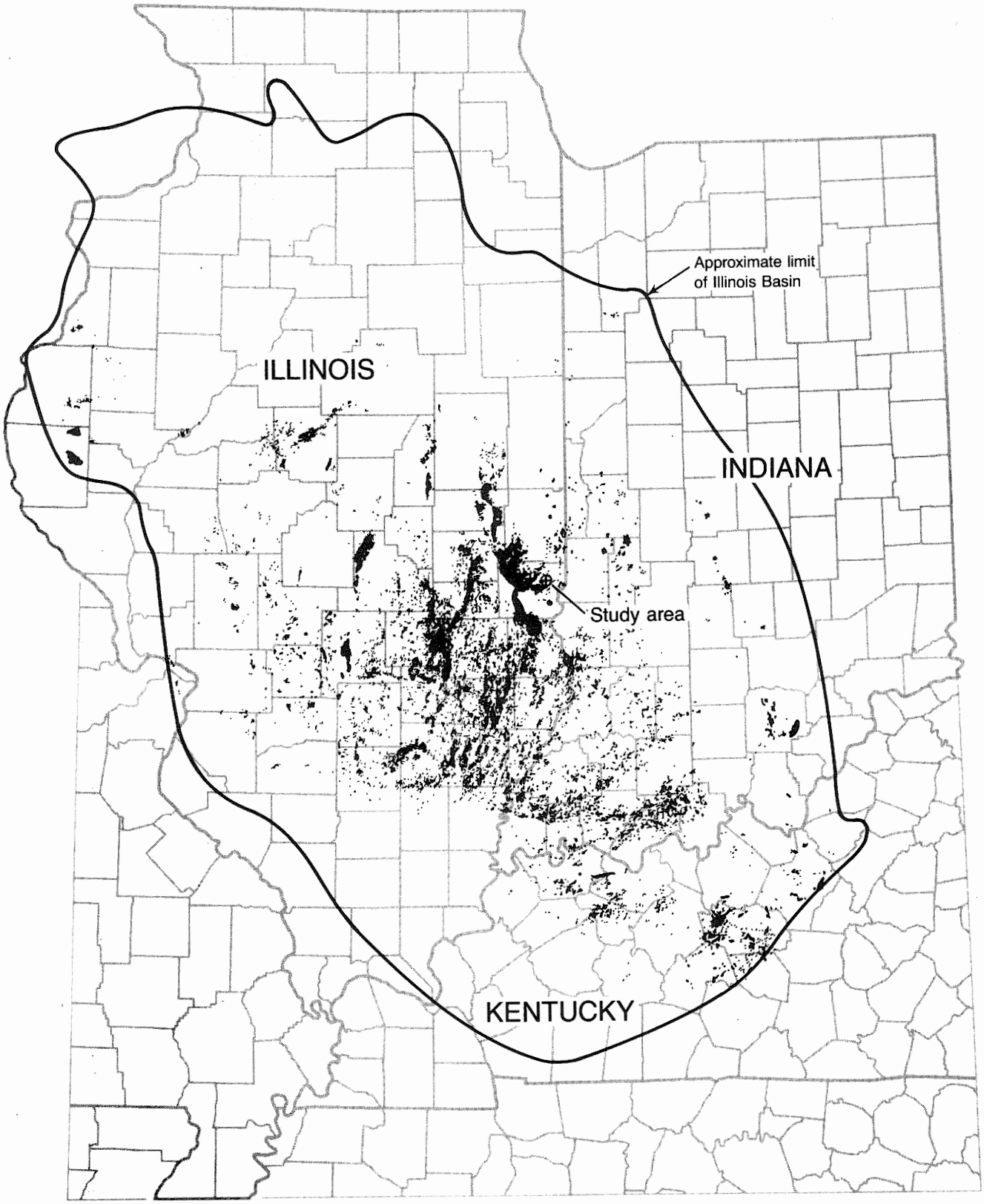


Figure 8 Oil and gas fields of the Illinois Basin (from Leighton et al. in press).

hydrogeologic conditions at the study site. Injection activities in the nearby natural gas storage fields and at the study site do not appear to affect each other significantly, although both utilize the same units of the Hunton.

Regional Geology and Hydrogeology

The units that are part of the injection system and are penetrated by the disposal well include the basal confining interval (Maquoketa Group), the injection interval (Hunton carbonate sequence), and the upper confining interval (New Albany shale sequence). Additional impermeable units and some aquifers lie between the upper confining interval and land surface. The first significant aquifer above the injection interval is the Salem Limestone.

Waste Disposal Well 2 (WDW2) was originally drilled to 6,000 feet (Eminence-Potosi Dolomites). It was plugged back into the uppermost unit of the Silurian limestone part of the Hunton because the immediately overlying Devonian limestone was the deepest, most receptive injection interval available.

Ordovician System

Ordovician strata (fig. 4) range in thickness from 700 feet (in northern Illinois) to more than 6,000 feet (in southern Illinois). The thickness increases gradually toward the south. Dolomites and limestones are the predominant lithologies; however, several distinct sandstones are found in the lower (Gunter and New Richmond Sandstones) and middle (St. Peter Sandstone) parts of the Ordovician. A thick shale-shaly carbonate sequence (Maquoketa Group) forms the upper part of the Ordovician. Many of the units below the Maquoketa are relatively impermeable and act as aquitards. The St. Peter Sandstone, a thin (50-ft), fine-grained, low-permeability sandstone in Clark County, is the first significant aquifer below the Hunton injection interval.

Maquoketa Group (Lower Confining Unit)

The Maquoketa Group (fig. 4) consists of two shale units and an interbedded shaly limestone-dolomite unit. The thickness of the Maquoketa ranges from approximately 150 feet in the western part of the state, where the top is eroded, to nearly 300 feet along the eastern edge of the state (fig. 10). In the vicinity of Marshall, the Maquoketa is less than 300 feet thick.

Hydrologic Characteristics of the Ordovician System

In northern Illinois, carbonate units of the Ordovician that are at or near land surface have moderate to relatively low permeabilities. As the burial depth of these units increases toward the south, the permeabilities of the units generally decrease. Carbonate units lying below freshwater zones (groundwater with less than 10,000 mg/L TDS) are essentially aquitards. Figure 11 shows the basal position of USDW in a north-south cross section from Rockford to Cairo. The southward-pointing tongue of USDW in the Ordovician lies in the St. Peter Sandstone. The TDS level of the St. Peter in the Marshall area is greater than 50,000 mg/L (Meents 1952).

Porosities in carbonate units in the southern half of the state are generally less than 10 percent; permeabilities in the more permeable units rarely exceed 1 to 30 millidarcys (Ford et al. 1981, Mast 1967). Porosities and permeabilities across vertical sections of the St. Peter are quite variable. The more permeable horizons measured in northern Illinois had porosities ranging from 12 to 17 percent and permeabilities ranging from 25 to 250 millidarcys. In the south, where the St. Peter is thinner, finer-grained, and more shaly, porosity and permeability values can be expected to be smaller. The shale units in the Maquoketa Group are expected to be very tight (<1 millidarcy).

Hunton Supergroup (Injection Interval)

The limestone and dolomite units of the Silurian and Devonian Systems have similar lithologic and hydrogeologic characteristics and thus are considered one large unit, the Hunton Supergroup. The thickness of the Hunton ranges from a featheredge along the Mississippi River to more than 1,800 feet near the southern tip of the state. Figure 12 shows the thickness and dis-

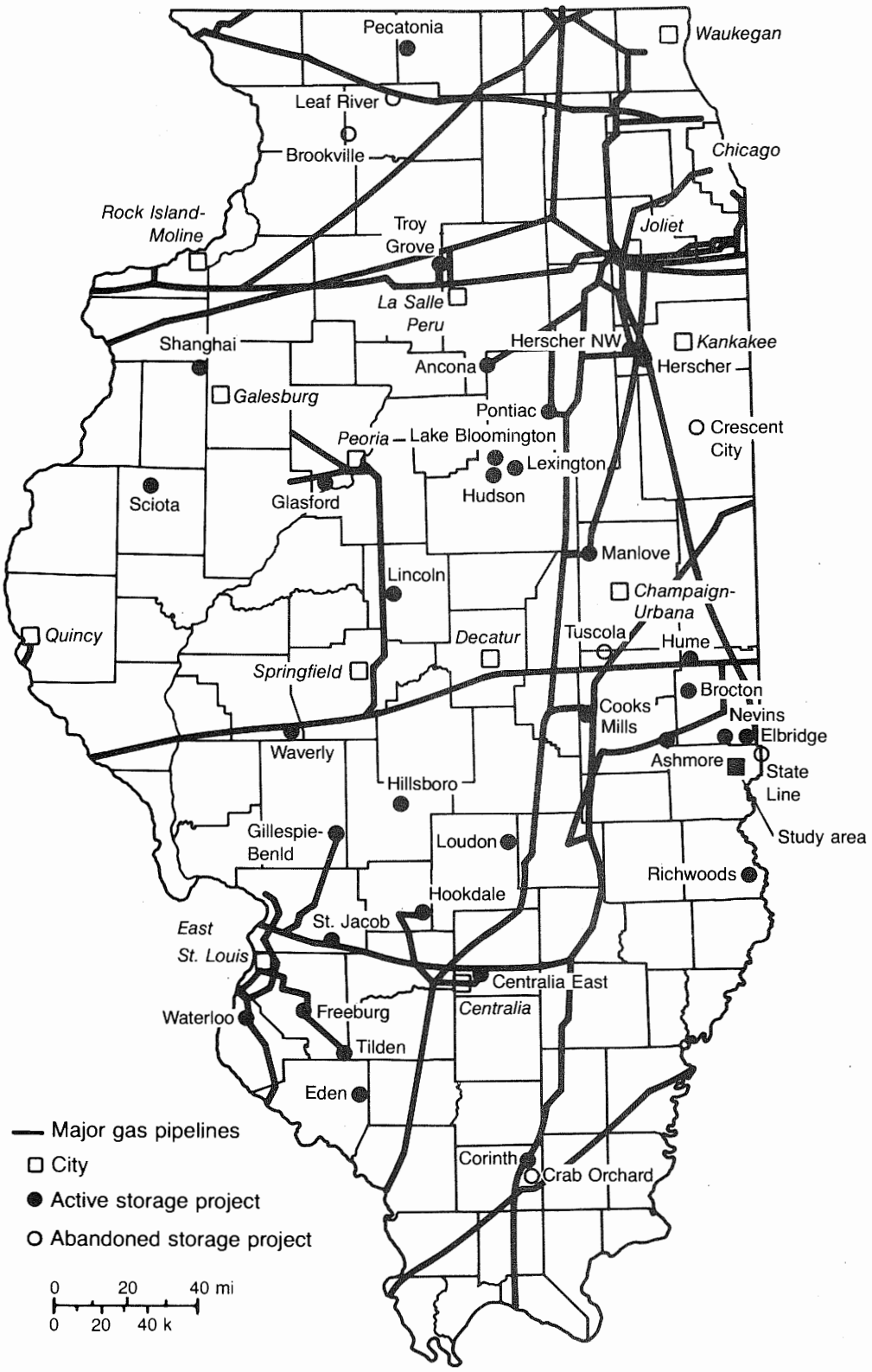


Figure 9 Location of underground gas storage projects in Illinois (after Buschbach and Bond 1974).

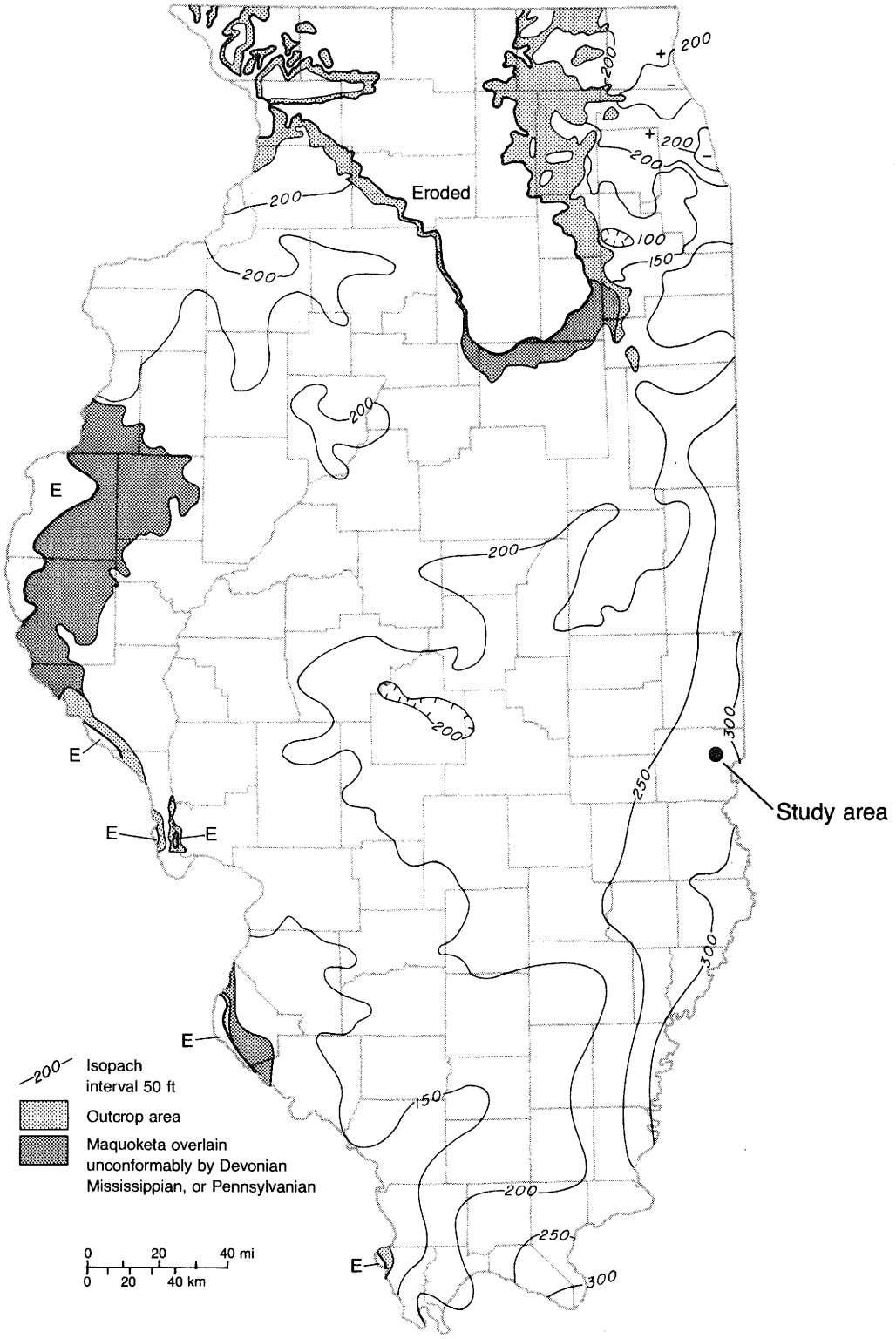


Figure 10 Generalized thickness and distribution of the Maquoketa Group (after Willman et al. 1975).

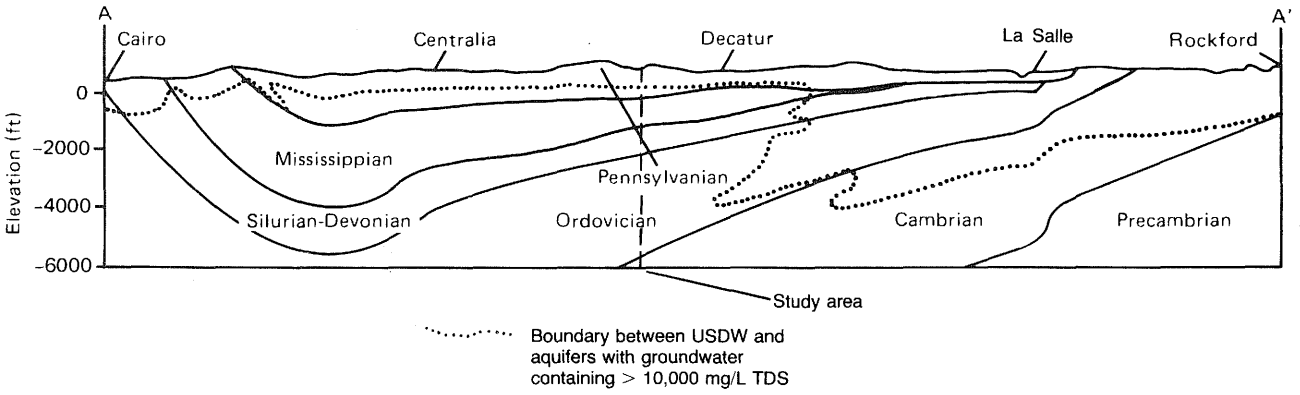


Figure 11 Cross section from Cairo to Rockford (see fig. 3) showing the position of base of the USDW (Brower et al. 1989).

tribution of this unit. Note that erosion has truncated the Hunton in a large area in the northern third of the state. Near the project site the Hunton is about 800 feet; its upper 350 feet includes units of the Devonian System.

Silurian Part of Hunton Supergroup

The Silurian consists of Alexandrian (lower part) and Niagaran (middle part) units and thickens eastward from an erosional featheredge in western Illinois to more than 700 feet in the east-central part of the state. In places, pinnacle reefs may increase the thickness to 1,000 feet. Units of the Cayugan (upper part) are thin or missing in Illinois. The Niagaran, the principal unit of the Silurian, consists of three dominant carbonate facies: shaly dolomite in the south, intermediate-purity carbonate in the north-central and northeast, and relatively high-purity carbonate in the northwest. Reefs are found throughout the Silurian units, and those in the southern part of the state (particularly in the southwestern part) may be oil-bearing (Whitaker 1988).

The uppermost Silurian unit in the study area is the Moccasin Springs Formation (fig. 4). The Moccasin Springs consists mostly of red (or red-and-gray-mottled), very silty, argillaceous limestone and calcareous siltstone; shale is common near the top. The Moccasin Springs contains numerous reefs, dominantly limestone, which have well-defined flank structures. The Moccasin Springs is commonly 160 to 200 feet thick and is more than 160 feet thick in the study area.

Devonian Part of the Hunton Supergroup

The Devonian part of the Hunton is composed of a basal sequence of four cherty limestones (including the Bailey Limestone) and an upper sequence of two limestones (the Grand Tower Limestone and the Lingle Formation). The Bailey Limestone is a silty, cherty, thin-bedded, hard limestone that begins along a southwesterly trending featheredge in central Illinois. Southeast of Marshall, additional cherty carbonate units were successively deposited above the Bailey. The combined thickness of these units reaches 1,200 feet in the southern part of the state. The Bailey is 144 feet thick in the Marshall area. The overlying Grand Tower Limestone and Lingle Formation begin along a southwesterly trending featheredge 75 miles northwest of Marshall and thicken southward to more than 400 feet in Gallatin County. Near Marshall, these two units have a total thickness of 96 feet; the Lingle is 22 feet thick.

Hydrogeology of the Hunton Supergroup

Fresh water is found at or near the surface in the Hunton in the northern half of the state and along the margins of the Illinois Basin. Well yields vary, depending mostly on the degree of fracture development. Variations in primary porosity and permeability can be related to lithology, which exerts some control on the degree of fracture development. Fracture development is greatest near the surface and generally decreases as depth of burial increases, particularly where the Hunton is overlain by impermeable shale units of the New Albany and Pennsylvanian.

The boundary marking the base of USDW in the Hunton is shown in figure 12. Typically, groundwater mineralization increases rapidly southward from this boundary. However, in Clark County the rate of increase in the TDS of the brine is relatively lower southwest of the USDW boundary, resulting in a TDS content of approximately 16,000 mg/L in the permeable Devonian units. Increased groundwater circulation in units with higher permeabilities allows less mineralized water to advance greater distances downdip (Brower et al. 1989). Other examples of this phenomenon are shown in figure 11; tongues of fresher water in the St. Peter Sandstone (Ordovician), the Ironton-Galesville Sandstone (Cambrian), and in certain shallow units (Silurian through basal Pennsylvanian near Cairo) move downdip into the Illinois Basin (Student et al. 1981). In the deeper parts of the basin, the mineral content of groundwater in the Hunton may reach from 150,000 to more than 200,000 mg/L TDS (Graf et al. 1966).

Drilling records and testing for the region show that the Lingle, portions of the Grand Tower, and a major part of the Silurian are relatively tight. The Bailey and several horizons in the Grand Tower and the Silurian have significant zones of permeability. Selected intervals of higher permeability in the Bailey have been used for disposal at the study site.

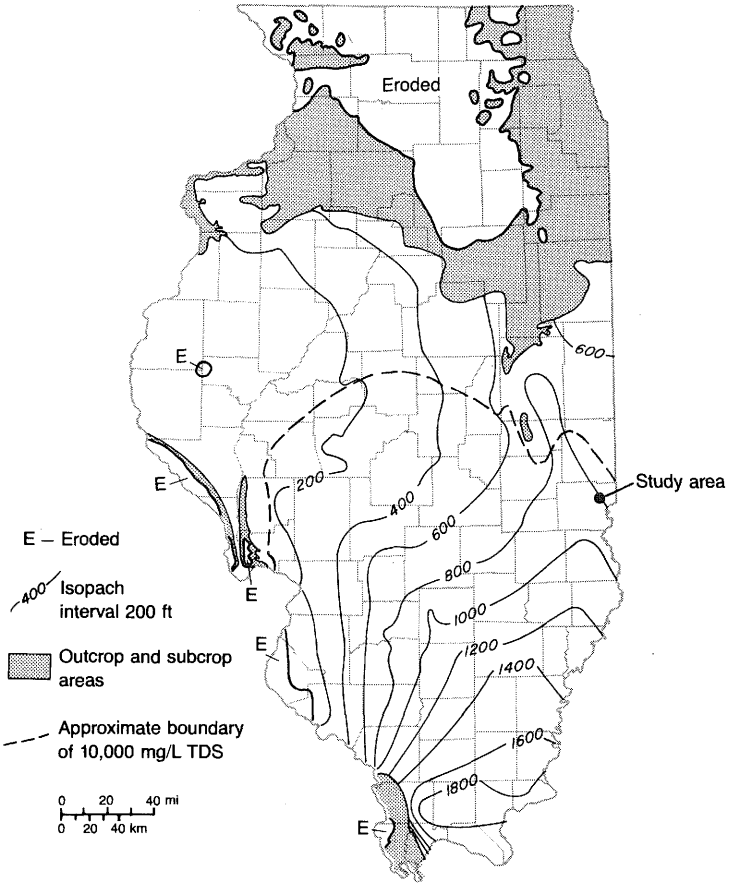


Figure 12 Generalized thickness and distribution of the Hunton Supergroup (after Willman et al. 1975) and the TDS boundary for USDW (Brower et al. 1989).

Porosity and permeability data obtained from tests run on samples collected from oil exploratory and gas storage wells scattered around the state show a mean porosity of 13 percent and a mean permeability of 40 millidarcys (Mast 1967). These data included values obtained from units in the Galena Group. Ford et al. (1981) reported porosity values of 12 to 19.5 percent and permeability values of 50 to 300 millidarcys for 269 wells completed in Devonian carbonate reservoirs of Illinois.

Evaluation of geophysical logs and sample cuttings conducted during the course of this study and for related studies of the disposal wells indicated that discrete, areally extensive horizons having high, moderate, and low permeabilities occur in the Bailey. Pore sizes range from 5 microns (μm) to over 300 (average range, 10 to 25 μm), and the pores have a fair degree of interconnection.

New Albany Group

Sedimentation during Late Devonian and Kinderhookian (Mississippian) time produced widespread accumulation of black, gray, and green shales and some limestones and siltstones. The rock units that accumulated during this time attained a total thickness of 100 to 450 feet through central and southeastern Illinois (fig. 13). Cluff et al. (1981) identified three formations present in east-central Illinois. The Blocher Shale, the basal unit, appears several miles west of the study area and thickens toward the southeast. The Blocher consists of calcareous-to-dolomitic, pyritic shale that is rich in organic matter. The Blocher is overlain with the Sweetland Creek Shale, which thickens from about 50 feet at an erosional cutoff in the central part of the state to more than 350 feet in Hardin County in southern Illinois. The Sweetland Creek is dark gray (in some places, green) and has poorly developed, laminated bedding. The unit is similar in

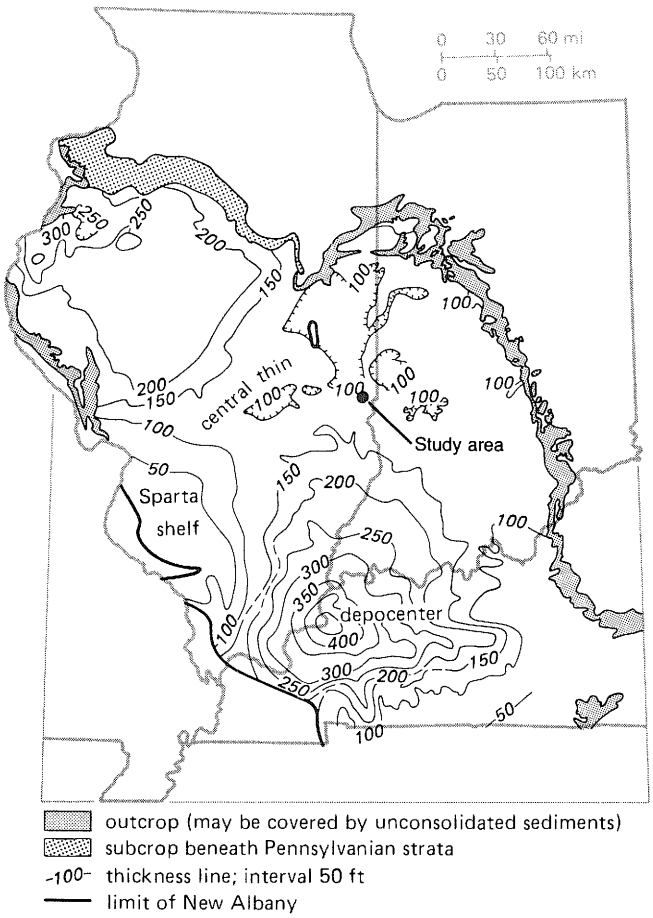


Figure 13 Generalized thickness and distribution of the New Albany Group (after Cluff et al. 1981).

appearance to both the Blocher and the overlying Hannibal Shale, but has widely traceable key beds. The overlying Hannibal Shale or its equivalent is less than 10 feet thick and indistinctly bedded. These formations are not differentiated at the study site.

Hydrogeology of the New Albany Group

The units of this group are very tight and therefore serve as an upper confining interval for the Hunton Supergroup. Natural gas storage fields completed in the Hunton utilize the low porosity and very low permeability of these units to retain gas in the underlying storage reservoirs (Buschbach and Bond 1974). The shale units in this group have essentially no water- or oil-yielding potential.

Mississippian Units

Mississippian units cover the southern two-thirds of the state and reach a maximum thickness of 3,300 feet in Williamson and Saline Counties (fig. 14). The widespread, thin, irregularly bedded Chouteau Limestone (Buschbach 1952) rests on the top of the New Albany and marks the base of three simultaneously deposited units: (1) the deltaic, tongue-shaped Borden Siltstone trending southwesterly across the state from the west-central part of Indiana; (2) the Burlington-Keokuk Limestones to the northwest; and (3) the Fort Payne Formation and Ullin Limestone to the southeast. The Borden consists of siltstone, some silty shale, and a few beds of fine sandstone and coarse siltstone. The "Carper sand" is present in places near the base of the Borden. The Ullin or its equivalent overlaps the top of the Borden with 150 feet of limestone and some shale in the Marshall area. Widespread limestone units, including the Salem, St. Louis, and Ste. Genevieve Limestones, accumulated between the Borden and the overlying alternating sequences of shale-limestone and shale-sandstone units that were deposited during Chesterian time.

The Mississippian section above the Chouteau is approximately 1,200 feet thick in the Marshall area and includes 450 feet of Borden Siltstone. The "Carper sand" is approximately 20 feet thick and lies very near the base of the Borden.

Hydrogeologic Conditions in the Mississippian

Mississippian units are used extensively for small (and some moderate) water supplies in and near outcrop areas. Most wells are finished at shallow depths, typically less than 300 to 500 feet. Groundwater mineralization increases rapidly with increasing depth of burial and in a down-dip direction toward the Illinois Basin (Meents 1952).

The Borden Siltstone is a thick unit of very low-permeability material that provides confinement in addition to the New Albany Group, the primary confining unit of the Hunton injection interval. The "Carper sand" provides the first somewhat permeable horizon above the top of the Hunton. Several thin, fine-grained sandstones also lie near the top of the Borden. Available porosity logs suggest that porosities of about 8 to 12 percent can be expected in these sandstones. At the study site, the Salem Limestone is the first overlying aquifer having significant permeability; it has been used for waste injection in the past. The measured static water level in the Salem is about 50 feet lower than the water level in the Bailey. The mineral content of the Salem and the Bailey in the Marshall area is similar (about 15,000 to 16,000 mg/L TDS). The groundwater in these units has an anomalously low mineral content, which appears to be related to the relatively high porosity and permeability of these units. Figures 12 and 14 show the location of the USDW boundary in Hunton and Mississippian units. The less permeable units of the Mississippian, particularly those in the upper part, contain groundwater with a much higher mineral content.

Pennsylvanian Units

The bedrock surface in the southern two-thirds of the state has been formed on Pennsylvanian units. Shale and clay units (more than 50% of the total thickness), sandstones and siltstones (more than 25%), limestones (less than 10%), and coals comprise more than 500 distinguishable units. Pennsylvanian strata reach a maximum thickness of 2,500 feet in the south-central part of the basin. Sandstones are interbedded with the shale throughout the Pennsylvanian but are most

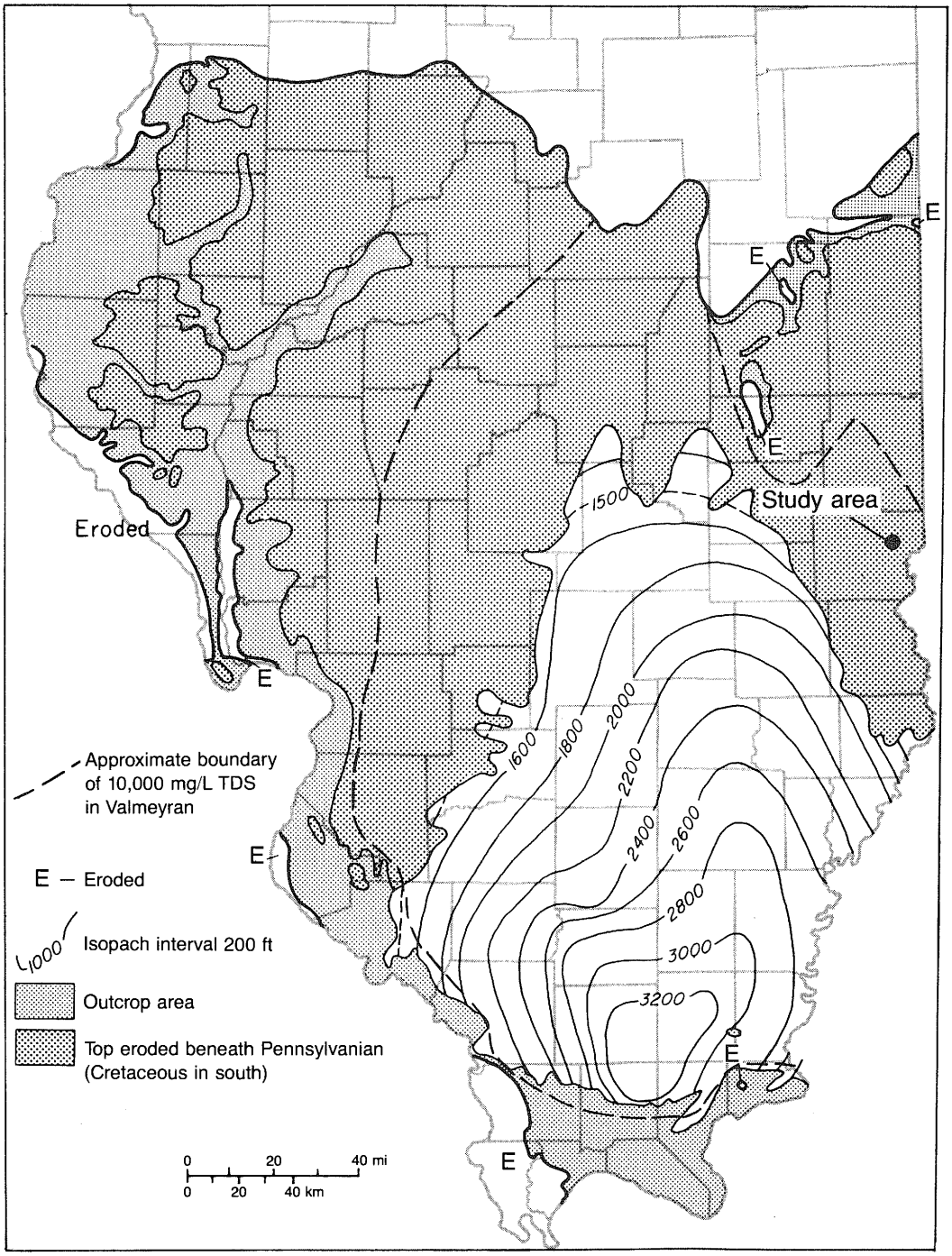


Figure 14 Generalized thickness and distribution of the Mississippian System (after Willman et al. 1975) and the TDS boundary for USDW (Brower et al. 1989).

abundant in the lower two of seven formations. Limestones are more abundant in the second formation from the top, and the most well-developed coal units are in the middle (fourth) formation.

In the Marshall area, the Pennsylvanian is about 1,050 feet thick. The thicker sandstones are found near the base of the Pennsylvanian. Coal units are present but thin. The more prominent coals occur below a depth of 400 feet.

Hydrogeologic Conditions in the Pennsylvanian Units

Fresh water exists in the upper 300 to 500 feet of the Pennsylvanian units and is a principal source for low-volume water supplies where no potential for supply exists in overlying glacial deposits. Near the margins of the basal formations, the more permeable sandstones contain fresh water to depths of more than 1,000 feet. In the Marshall area, mineralization of groundwater increases rapidly below depths of 50 to 75 feet, and water wells rarely penetrate to depths below 100 to 200 feet. The base of USDW is estimated from geophysical logs to lie about 500 feet below the surface (Piskin 1986).

Sandstones in the upper three-fourths of the Pennsylvanian are thin and widely spaced and yield very little water. The basal sandstones in the Marshall area may yield up to 20 gpm; however, water from these sandstones has a very high mineral content (38,000 mg/L TDS) (ISGS UIC files).

Porosity and permeability values measured from cores and wells collected from or finished in all types of Pennsylvanian units range from 9 to 25 percent and 10 to 10,000 millidarcys (Ford et al. 1981). Porosities measured in oil-producing sandstones are relatively uniform, averaging 17 to 20 percent (Whiting et al. 1964). Whiting also reported permeabilities of 100 to 400 millidarcys, which decrease as depth of burial increases.

Quaternary System

Glacial deposits consisting of loess, silt, clay, till, sand, and gravel cover a large part of the bedrock surface of Illinois. In the Marshall area, the drift is less than 10 to 50 feet thick in the upland areas and up to 30 to 100 feet thick in the larger stream valleys. Peoria Loess (2 to 6 ft thick) and Roxana Silt (0 to 3 ft thick) mantle the Glasford Formation (clay, sand, and till, 0 to >21 ft thick) on the upland. The Banner Formation (clay and till 0 to >20 ft) underlies Glasford Formation till where thicker drift is present in the upland areas (ISGS UIC files 1981). Cahokia Alluvium (silt, sand, and clay) overlies Henry Formation (outwash sand and gravel up to 70 ft thick) in the valley of Big Creek. Very limited to small water supplies are available from the upland glacial deposits. Moderate to large water supplies are available along some segments of Big Creek valley. Marshall obtains its water supply from the Henry Formation, about 2.25 miles east of the study site.

3. HYDROGEOLOGIC INVESTIGATION OF THE INJECTION SYSTEM

This chapter briefly discusses techniques used to collect and analyze hydrogeologic data. Details of the techniques and analyses are in appendices A and B. Specifically, stratigraphic correlations within the injection system from regional (5 to 10 miles) and local (3 miles) perspectives are discussed, along with methods used to collect additional data from the site of the injection well. These methods include geophysical logging, sidewall coring and associated analysis, and hydraulic testing. A hydrogeologic description of the injection system at the site is also given.

Stratigraphic and Structural Definition of the Injection System

The injection system consists of the geologic materials constituting the injection zone and its associated upper and lower confining units. To evaluate the confining and injection potential for the Devonian injection system, data were collected from wells in three gas storage fields (Nevins, Elbridge, and State Line), wells within 5 to 10 miles from the project site, and wells within 3 miles of the site (see figure 15 and table 1). The gas storage fields are approximately 9 miles northeast of Velsicol's Waste Disposal Well 2 (WDW2). Data from these wells were used to correlate hydrogeologic units within the injection system and to construct a structure map of the top of the Lingle Formation. The injection interval for WDW2 lies within the Devonian limestone sequence, immediately below the Lingle and Grand Tower Formations.

Each of the three gas storage fields utilizes a domal structure with closure to concentrate and store the gas. Each domal structure was formed by the deposition of Devonian- and Silurian-age shelf facies sediments over Silurian-age reef facies sediments.

Although this type of structure is not present in the area immediately surrounding the Velsicol plant, the general stratigraphic relationship of the rock units near the storage fields and those near the disposal well was shown to be consistent. Inferences were then made regarding data from the gas storage fields to the disposal well at Velsicol.

Geophysical logs from wells at a 5- to 10-mile radius from the plant were used to correlate stratigraphy and to give a regional picture of the configuration of the injection system. Geophysical logs from wells within 3 miles of the injection well were used to construct a structure map consistent with regional data.

Stratigraphic Description of the Injection System

The stratigraphy of the injection system includes the Silurian-age Moccasin Springs Formation at the base through the Grassy Creek Shale, the uppermost Devonian unit of the New Albany Group. Figure 16 is a geologic column showing the stratigraphic position and hydrogeologic characteristics of these units at the waste disposal well studied. Much of the strata information is from Willman et al. (1975). Additional data were obtained for the Middle Devonian strata from North (1969) and for the strata of the New Albany Group from Cluff et al. (1981).

The Devonian strata comprise three series—the Lower, Middle, and Upper. The Bailey Limestone, basal unit of the Lower Devonian Series, is dominantly gray to greenish gray, silty, cherty, thin-bedded, very hard limestone. Some beds are argillaceous. The chert, black to dark gray, occurs in bands up to 2 feet thick. An upper zone, 0 to 100 feet thick, is limestone that is pure, white, coarsely crystalline, and only slightly cherty.

A major unconformity occurs at the Lower and Middle Devonian interface. The basal formation of the Middle Devonian Series is the Grand Tower Limestone, which is mostly coarse-grained, light gray, medium- to thick-bedded, cross-bedded, pure, fossiliferous limestone. It also contains lithographic limestone, which becomes more abundant upward. One member differentiated at the study site is the Tioga Bentonite Bed, which is found 10 to 30 feet from the top of the Grand

Table 1 Wells used in study

Well No.	Name	Location
3	Richard Lindley #1	29-11N-10W
4	Thomas Coats #2	31-10N-13W
5	C. A. Pence #1	31-10N-13W
6	Burger #1	23-10N-13W
7	H. O. Coldren #1	4-11N-11W
8	A. Kannmacher #1	24-10N-13W
9	Clifford I Morgan, et al. #1	4-11N-11W
10	Gus Birchfield #1	24-10N-13W
12	Frank Morgan, et. al. #1	19-10N-13W
13	S. M. Scholfield #1	6-11N-11W
14	Birchfield-Shumaker Comm. #1	34-11N-11W
15	Boyd #1	5-11N-14W
17	Smitley #1	7-11N-11W
19	F. Kuhn #1	8-11N-11W
21	D. M. Davison #1	8-11N-11W
23	Eugene Chenowith #1-A	9-11N-11W
25	Alfred Seidel #1	15-10N-11W
26	Russel Higginbottom, et. al. #1	34-10N-12W
27	E. P. Daly #1	8-11N-14W
28	E. F. Newman, et. al. #1	30-10N-13W
29	Ella Mae Young #1	19-10N-13W
30	Ormal Higginbotham #1	22-11N-13W
33	Fraker #1	16-11N-11W
35	Lickert #1	16-11N-11W
36	Guinnip-Keyes Comm. #1	10-11N-12W
37	Southerland Comm. #1	16-11N-11W
39	Southerland #2	16-11N-11W
43	Gunder #1	19-11N-11W
45	Monk #1	21-11N-11W
48	WDW1	12-11N-12W
49	DOW	12-11N-12W
50	Redman #1	5-11N-14W
51	Mary E. Kendall #1	22-11N-11W
52	G. and E. Herrington #1	8-11N-10W
53	Frank Morgan #2	24-10N-14W
54	WDW2	12-11N-12W
55	J. C. Yeley #1	27-12N-11W
56	Elbridge #1 (gas storage)	2-12N-11W
57	Nevins #6 (gas storage)	5-12N-11W
58	State Line #1 (gas storage)	28-12N-10W
61	Hall #1	1-11N-12W
69	Alton Blankenship #1	16-11N-12W
77	Bays #1	21-11N-12W
79	Anna Brosman #1	21-11N-12W
81	Minnie L. Jackson #1	21-11N-12W
85	John W. Dawson #1	22-11N-12W
87	Frahm-Cole-Lee Comm. #1	28-11N-12W
103	Glen Morgan #1	21-11N-12W
111	Waller Comm. #1	21-11N-11W

Tower. The Tioga is a greenish to brownish gray shale that contains biotite flakes and an abundance of silicate minerals that distinguish it from other shales. The Tioga generally is only 1 to 2 inches thick, but it may be 6 to 8 inches thick.

The Lingle Formation overlies the Grand Tower and is more argillaceous, darker, and finer-grained than the Grand Tower. At the study site, the Lingle is composed of two members, the Howardton Limestone Member and the Tripp Limestone Member. Howardton, the basal member, is gray, fine-grained, slightly silty, argillaceous limestone, most of which has thin, shaly partings. The Tripp is heterogeneous, containing limestone, dolomite, chert, siltstone, and shale. It is largely cherty, argillaceous, silty limestone, but beds of shale are abundant near its base and top.
The New Albany Group overlies the Lingle Formation. The Devonian portion of this group includes the Blocher, Selmier (Sweetland Creek), and Grassy Creek Shales. These units were not

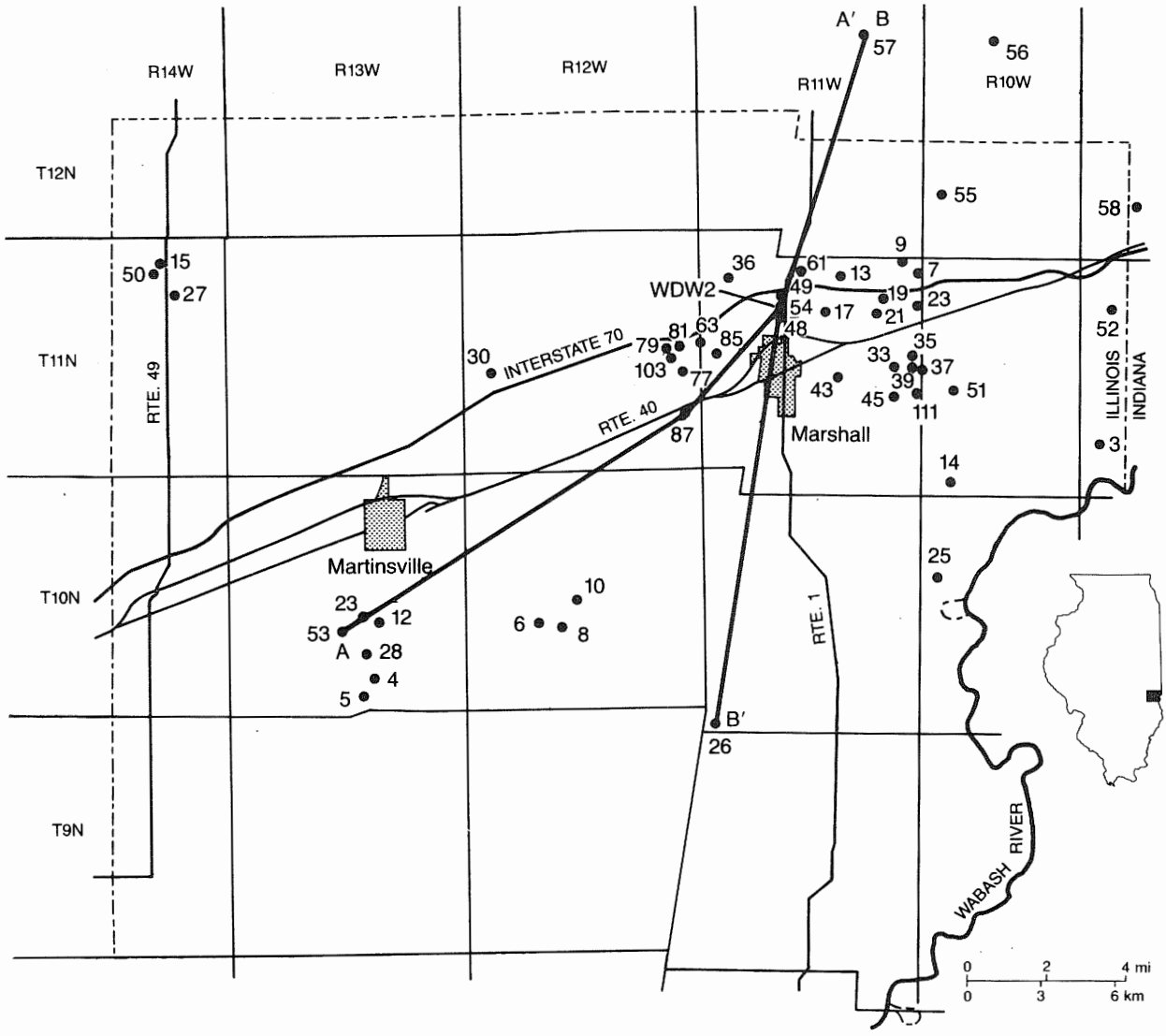


Figure 15 Well locations. Cross sections for A-A′ and B-B′ appear in figures 17, 18, and 19.

differentiated at the study site. The Blocher is the basal formation of the New Albany Group and is a calcareous or dolomitic black shale. The Blocher is the only shale in the New Albany containing much calcite.

The Selmier Shale Member overlies the Blocher and consists of greenish gray, dolomitic, bioturbated mudstone at the top that grades downward through an interbedded zone to black dolomitic laminated shale at the base. North (1969) placed these same units in the Sweetland Creek Member. The Selmier is conformably overlain by the Grassy Creek Shale Member.

The Grassy Creek is the uppermost Devonian unit of the New Albany Group and consists of brownish black to grayish black, finely laminated, pyritic, carbonaceous shale.

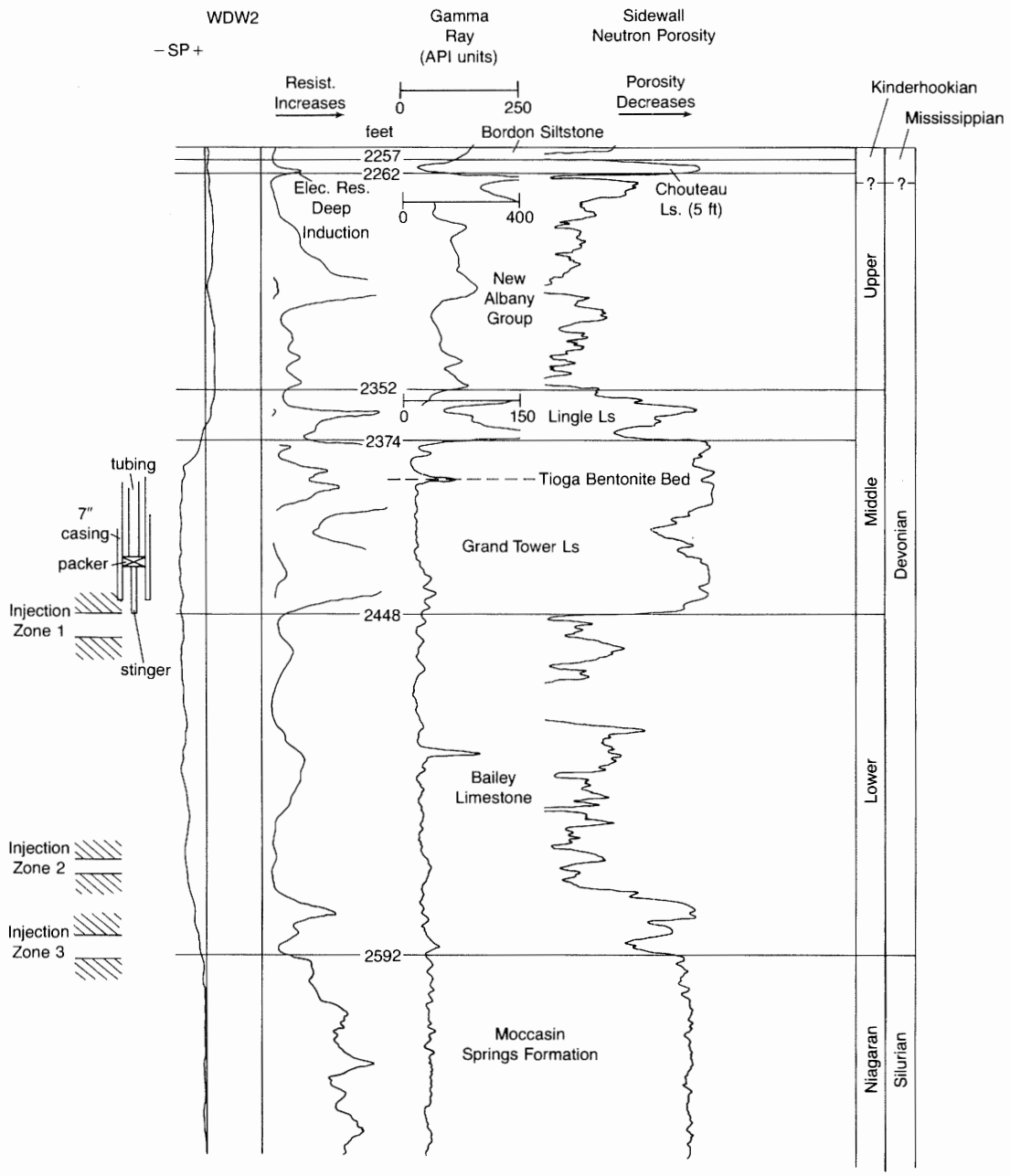


Figure 16 Geologic column for the injection system at Waste Disposal Well 2 (WDW2).

Geophysical Log Correlations

Figures 17, 18, and 19 illustrate the stratigraphic continuity of the hydrogeologic units within the injection system and the base of the New Albany Group within a 10-mile radius of WDW2. Figure 17 shows a southwest-northeast cross section based on resistivity logs, Induction Electric Logs (IEL), and Electric Logs (EL). Figure 18 is also a southwest-northeast cross section, but it is based on qualitative permeability log (Minilog) responses. Figure 19 shows a north-south cross section that is based on resistivity logs. Qualitative permeability logs were not available for all wells along this cross section.

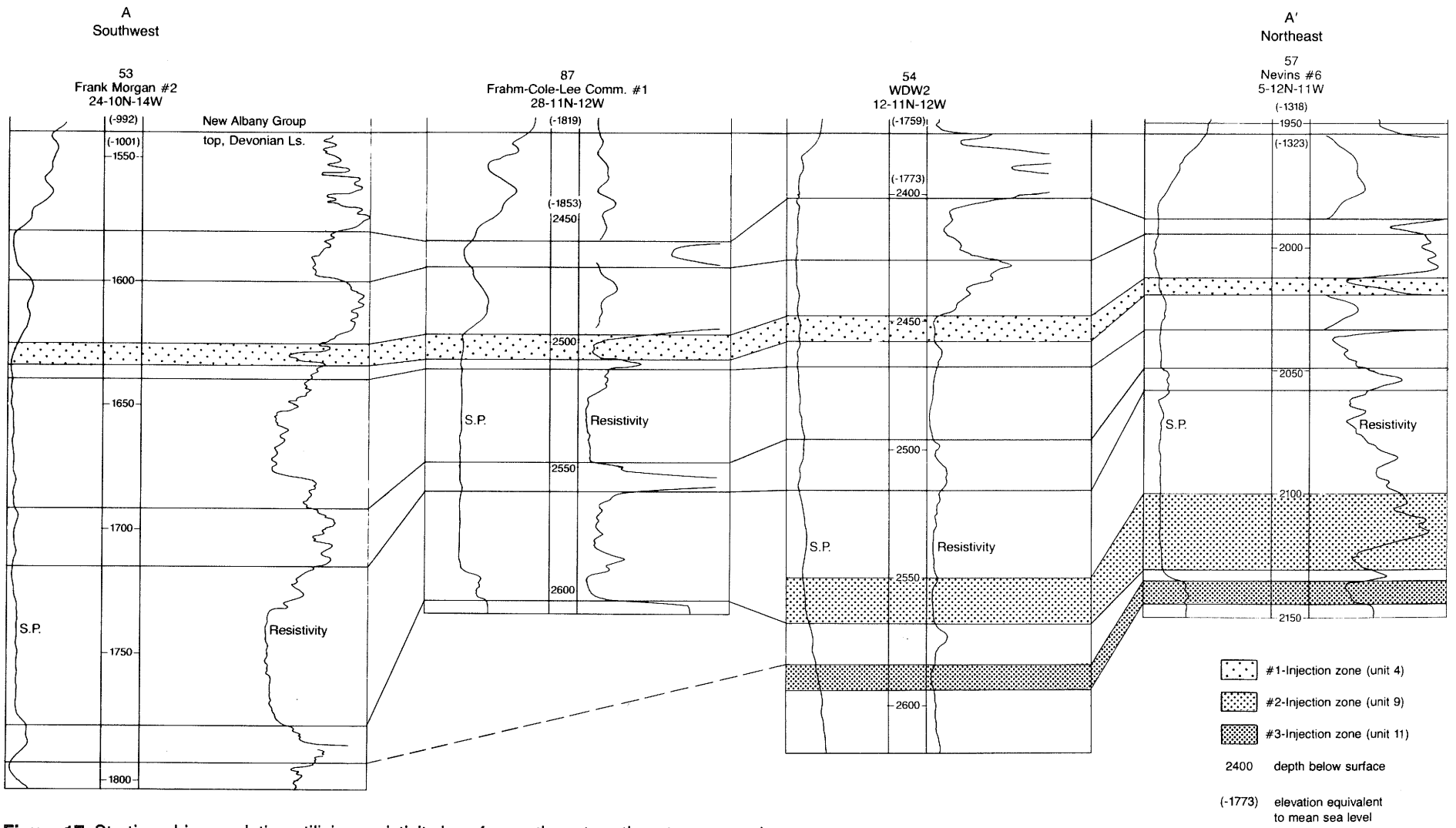


Figure 17 Stratigraphic correlation utilizing resistivity logs for southwest-northeast cross section.

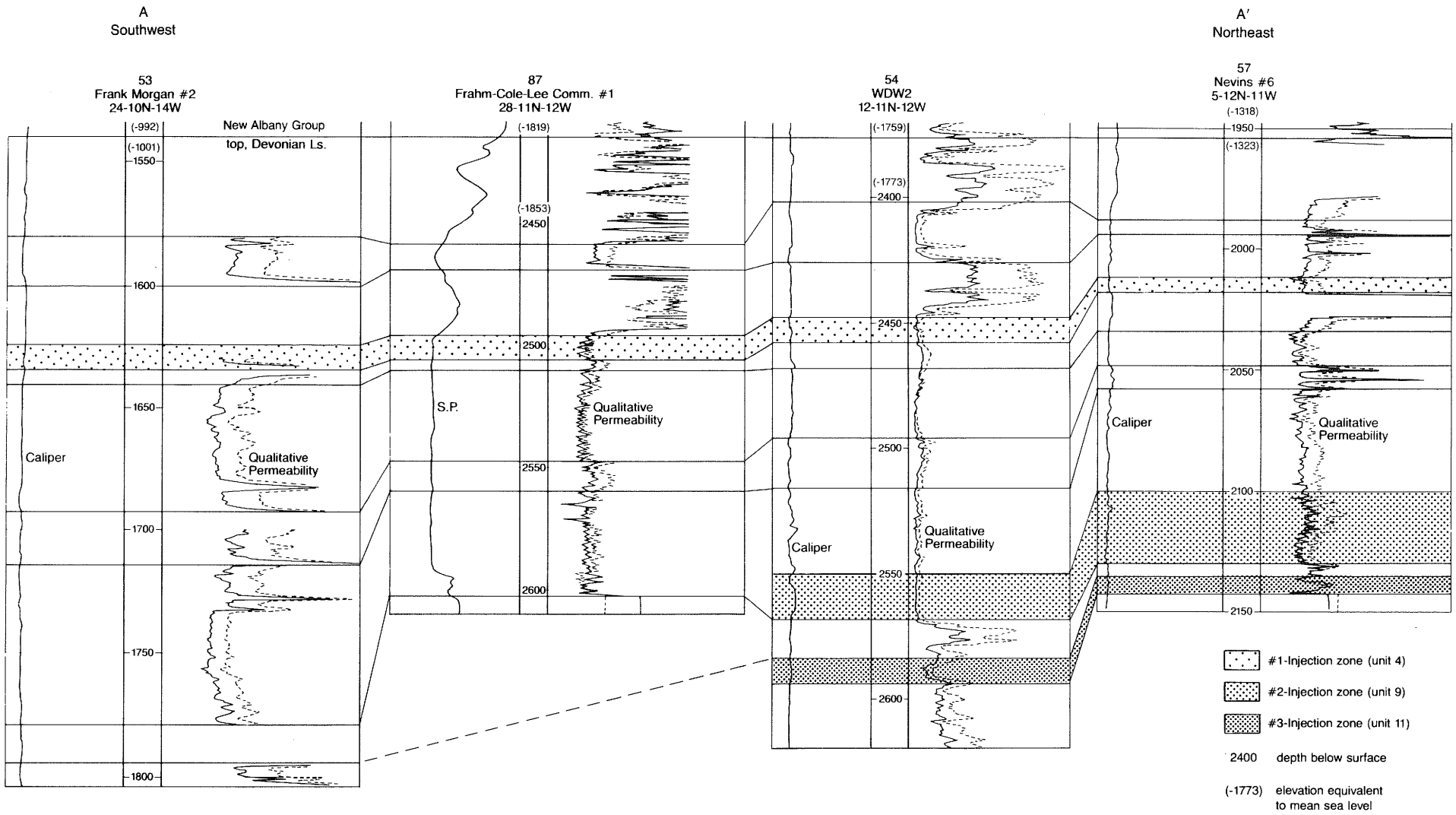


Figure 18 Qualitative permeability correlation utilizing permeability indicator logs for southwest-northeast cross section.

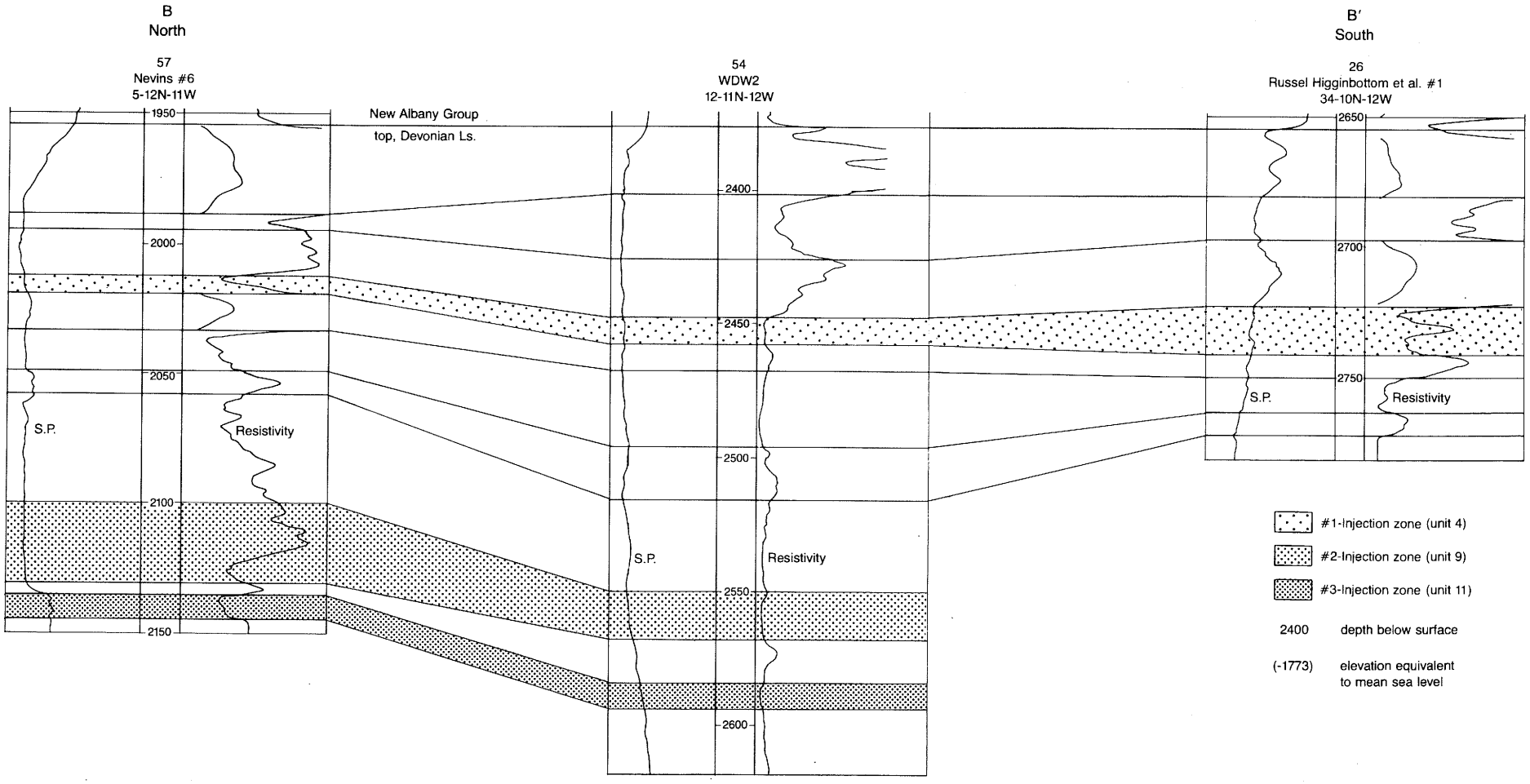


Figure 19 Stratigraphic correlation utilizing resistivity logs for north-south cross section.

The data presented in figures 17 and 19 show the hydrogeologic units within the injection system to be laterally continuous across the study area with one exception. Likewise, the continuity of the qualitative permeability of these units is inferred from figure 18. On the basis of resistivity and qualitative permeability logs, injection zone no. 2 could not be differentiated from the overlying unit in some wells in the study area. These unit designations are not included in these cross sections.

Nevertheless, the stratigraphic and qualitative permeability continuity of the Devonian limestone and the New Albany shale between the wells at Velsicol and the wells in the gas storage fields can be inferred; thus, continuity of quantitative permeability can be inferred. Analysis of core retrieved from WDW2 provided quantitative permeability data for the various hydrogeologic units. The quantitative permeability data obtained from wells at the three gas storage field wells are summarized later in this chapter (see Hydrogeology of the Site, p. 40).

A structure map of the top of the Lingle Formation was constructed (fig. 20) using information from wells within a 3-mile radius of Velsicol.

Stratigraphic and Structural Characterization

On the basis of correlations between the disposal well at Velsicol and the wells within a 5- to 10-mile radius of the plant, both the upper and lower confining units and the injection zones appear to be continuous across the study area. Although information about the thickness of the lower confining unit is limited, figures 17, 18, and 19 clearly show its stratigraphic location.

The analysis of available geophysical logs for regional hydrogeology of the injection system is summarized in figure 21. A confining unit is distinguished from an "impermeable" unit by its position with respect to the permeable units. Confining units lie directly above the uppermost perme-

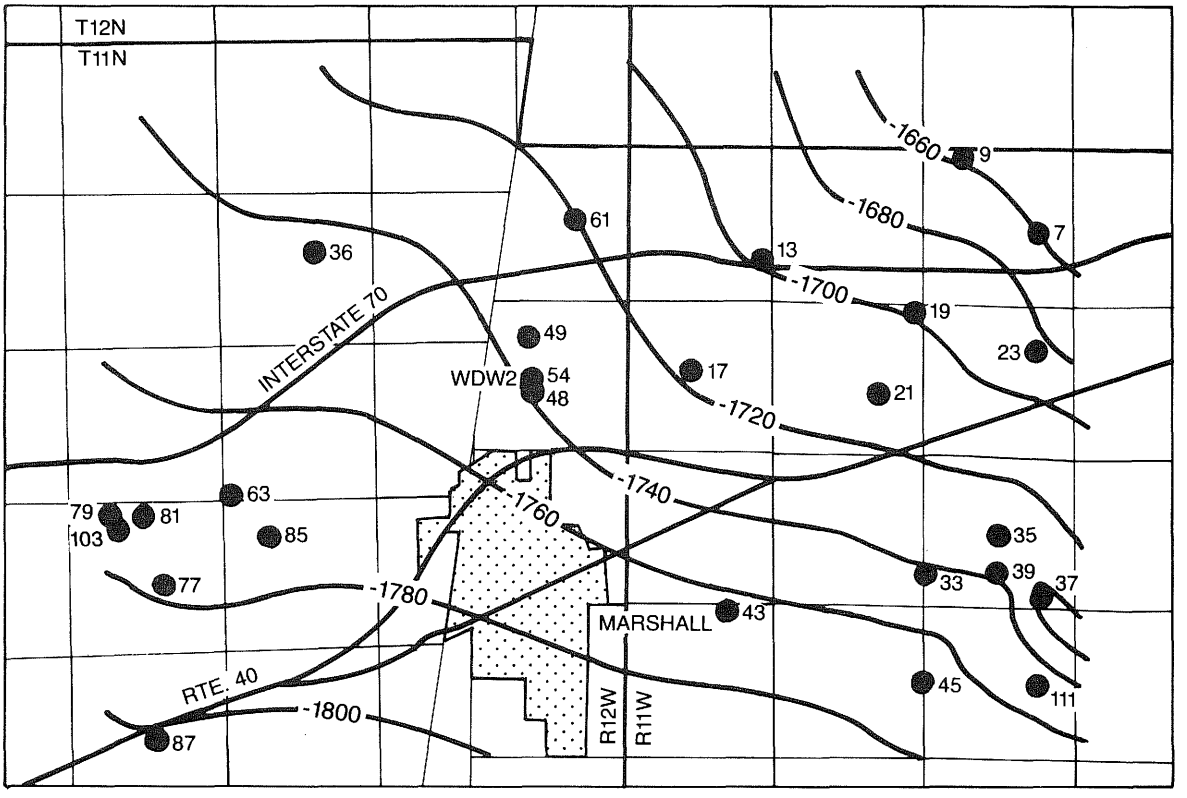


Figure 20 Structure contour map of the top of the Lingle Formation in the vicinity of the Velsicol plant.

able unit or directly below the lowermost permeable unit; impermeable units lie between permeable units. For permitting purposes, the upper confining unit includes the base of the New Albany shale and 26 feet of the Lingle Formation and Grand Tower Formation. Thickness variations for this section of the upper Devonian limestone are limited to about ±8 feet over the 10-mile region of investigation. In terms of the hydraulic confinement of the injection interval, the upper confining unit is composed of Grand Tower Limestone. Its thickness is approximately 74 feet at WDW2.

For permitting purposes, the Maquoketa shale is considered the lower confining unit. In terms of hydraulic confinement, the lower confining unit consists of the Moccasin Springs Limestone. Its total thickness could not be determined in this study because of limited data, but it is at least 160 feet thick at WDW2, based on available geophysical log data.

It is evident from figure 20 that the structure in the Velsicol plant area is generally flat with a gradual inclination of about 25 feet/mile to the northeast.

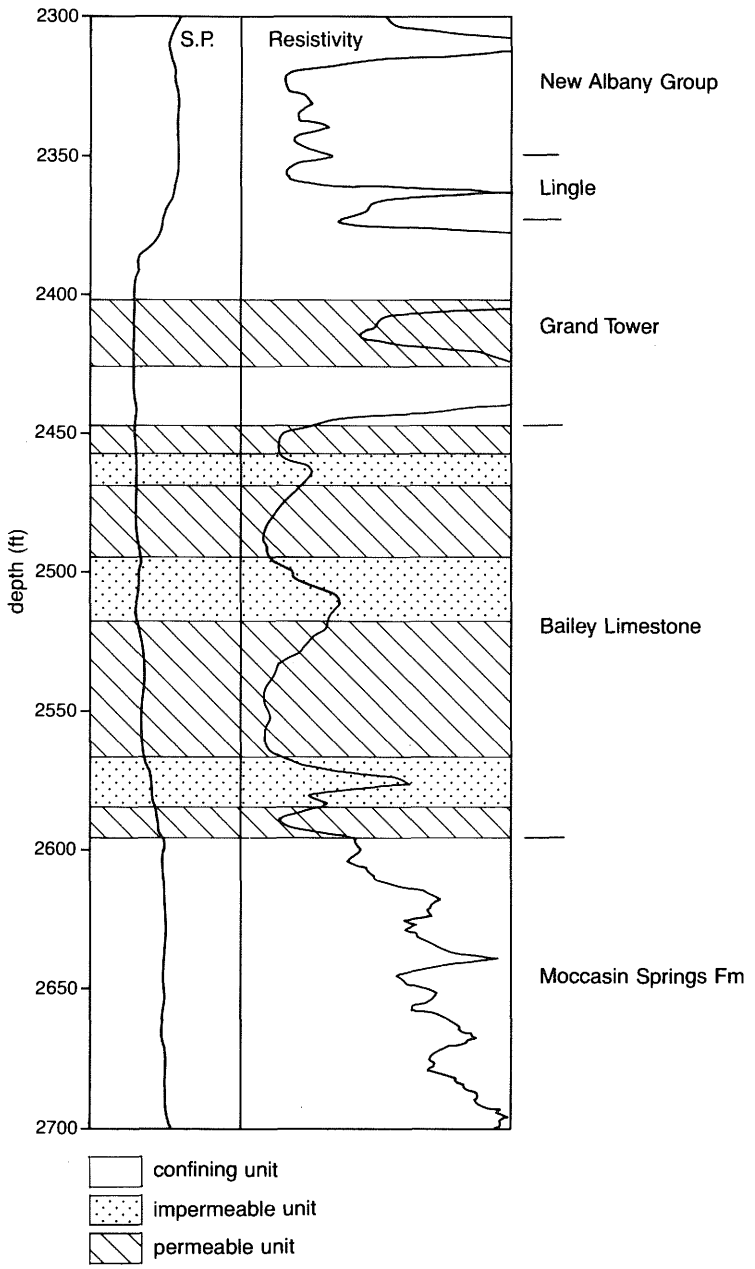


Figure 21 Injection system in WDW2 indicating permeable and impermeable zones delineated with available geophysical logging.

Determination of Horizontal Hydraulic Gradient

If the horizontal gradient is to be properly calculated, the hydraulic head within the injection system must be known for various locations. The initial reservoir pressure, obtainable from drill stem tests (DSTs), would be an excellent source of data. For initial reservoir pressure calculations, the pressure versus time chart from the DST is needed. This chart, however, was not available for wells in this area. Final flow and final closed-in pressures, as well as static water levels, were used to calculate the horizontal gradient. According to limited, high-quality data, the greatest horizontal gradient existed between wells 54 (WDW2) and 57. The hydraulic gradient (dh/dl) has a magnitude of 3.5×10^{-4} in a general direction of north to south.

Field Investigations

Two phases of geophysical logging were performed at the Velsicol site. During phase I, data on porosity and qualitative permeability, stratigraphic orientation, and the lithology of the rock units within the disposal zone were obtained from the Devonian Observation Well (DOW), Well 49. Data reduction indicated the units most favorable for fluid infiltration. Phase II was a detailed study based on information obtained from phase I. Results from phase II included quantitative data on permeability (air and water), bulk compressibility, hydraulic conductivity, specific discharge, and specific storage of the injection horizon. Those units with the greatest injection potential were further characterized for thickness, storativity, and transmissivity. In addition, hydraulic testing (flowmeter and injection testing) of the injection system was conducted.

Phase I Investigations

Records (well logs, drilling records, and other data) provided a general overview of the structure and regional continuity of stratigraphic units particularly important to waste injection and confinement. These data, however, were only one aspect of the overall integrated approach used to characterize the injection system. Additional data were needed to precisely define the character of possible confining and injection intervals. The methods and techniques used to characterize the disposal zone are discussed briefly and considered in detail in appendix A.

Existing geophysical logs. After a review of the historical records, a preliminary estimate was made of the stratigraphic location of the potential confining units (upper and lower) and the impermeable units associated with the operational waste disposal well (WDW2). These hydrogeologic units were delineated using four principal downhole geophysical logs, which were run during initial well (WDW2) construction in 1971. The logs were the Sidewall Neutron Log (SNL), Induction Electric Log (IEL), Gamma Ray Log (GRL), and Microlog (MIL). The hydrogeologic units determined from analysis of these logs are presented in figure 22. Consideration of all four logs was necessary to fully evaluate porosity, qualitative permeability, shale percentage, and lithology of the geologic materials. Interpretation methods used in the evaluation of these logs are discussed in appendix B.

Additional existing geophysical logs include the Temperature/Salinometer and GR/Neutron Logs run in the DOW in 1981 and 1973, respectively, and a Sonic Log (SL) run in WDW1 in 1965.

However, since logging instrument technology has progressed dramatically and subsequent equations and modeling of formation characteristics have advanced since these logs were run, a new suite of logs was run. Use of these geophysical logs enabled further delineation of the hydrogeologic characteristics of the injection system.

Phase I geophysical logging. A suite of logs was selected on the basis of the considerations discussed above and the physical dimensions of the casing and tubing in the three wells at Velsicol. The only well suitable for study during phase I was the DOW. Dresser Atlas performed the logging. The two types of porosity logs run were the Compensated Neutron Log (CNL) and the Borehole Compensated Sonic Log (BCS). The Minilog (MIL) was run to qualitatively determine permeability. Resistivity parameters were determined by the Dual Induction Spherically Focused

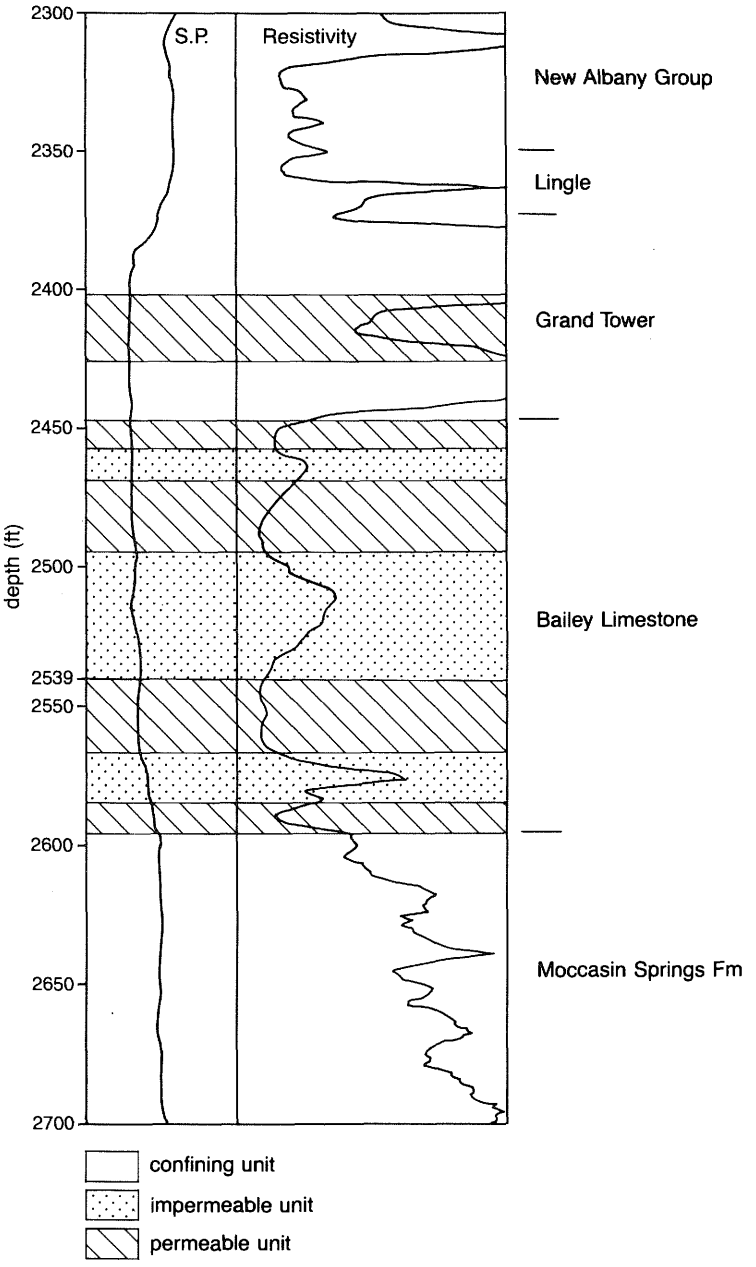


Figure 22 Injection system in WDW2 indicating permeable and impermeable zones delineated after phase I logging.

Log (DISFL). Finally, to provide the best stratigraphic correlation between the three wells at Velsicol, the Gamma Ray Log (GR) was run. (See appendix A for a discussion of the theory and general application of these logs.)

The techniques used to reduce the geophysical log data are discussed in appendix B. The data from these logs, analyzed and reported in 2-foot intervals, are presented in table 2. With the use of these modern logging tools and incorporation of improved analytical techniques, it was possible to obtain more accurate hydrogeologic data of the geologic materials constituting the injection interval. These data consisted of the formation's matrix-corrected CNL porosity ([POR]Ncor), matrix-corrected BCS porosity ([POR]BCScor), cross-plotted porosity ([POR]xp), secondary porosity ([POR]sec), true resistivity (Rt), matrix lithology (MA), water saturation (SW), shale volume (Vsh), and qualitative permeability (k). The same data were obtained from existing logs for WDW2 and are reported in table 3. Important parameters from these tables are summarized in table 4.

Table 2 Data from geophysical logs run in the DOW

DEPTH GL (ft)	GR (API)	(POR) Nls (%)	(POR) Ncor (%)	t (sec)	(POR) BCScor (%)	(POR) xp (%)	(POR) sec (%)	RT (ohm-m)	MA	SW (%)	Vsh (%)	k
2434	28	4.3	4.3	53	3.8	4.3	0.5	50.0	LS	100	6.2	N
36	40	5.0	5.0	53	3.8	5.0	1.2	65.0	LS	100	15.4	N
38	35	12.0	12.0	60	8.8	10.0	3.2	20.0	LS	100	11.5	N
40	25	18.0	18.0	69	15.1	16.4	2.9	11.0	LS	100	3.8	N
42	30	19.0	19.0	69	15.1	16.7	3.9	7.0	LS	100	7.7	Y
44	25	23.8	23.8	77	20.8	21.7	3.0	5.0	LS	100	3.8	Y
46	22	22.6	22.6	76	20.1	21.1	2.5	4.8	LS	100	1.5	Y
48	23	23.0	17.0	70	18.2	18.2	0.0	7.0	DOL	100	2.3	N
50	30	16.0	10.0	62	12.7	12.0	0.0	10.0	DOL	100	7.7	N
52	30	17.5	11.5	57	9.3	9.7	2.2	16.0	DOL	100	7.7	N
54	22	19.0	13.0	60	11.3	11.7	1.7	13.0	DOL	100	1.5	N
56	17	22.0	16.0	62	12.7	13.3	3.3	9.0	DOL	100	0.0	N
58	20	20.6	14.6	63	13.4	13.6	1.2	10.0	DOL	100	0.0	N
60	28	21.8	15.8	61	12.0	12.7	3.8	9.0	DOL	100	6.2	N
62	27	24.6	18.6	65	14.8	15.6	3.8	7.0	DOL	100	5.4	Y
64	32	24.0	18.0	66	15.5	16.0	2.5	5.5	DOL	100	9.2	Y
66	22	25.5	19.5	70	18.2	18.5	1.3	4.8	DOL	100	1.5	Y
68	23	28.5	22.5	78	23.7	23.5	0.0	4.0	DOL	100	2.3	Y
70	17	29.2	23.2	82	26.5	26.0	0.0	3.3	DOL	100	0.0	Y
72	18	28.0	28.0	82	24.3	25.7	3.7	3.0	LS	100	0.0	Y
74	17	30.0	30.0	87	27.9	28.8	2.1	3.2	LS	100	0.0	Y
76	17	28.0	28.0	83	25.0	26.3	3.0	3.5	LS	100	0.0	Y
78	19	26.8	20.8	78	23.7	23.2	0.0	3.9	DOL	100	0.0	Y
80	17	26.3	20.3	77	23.0	22.6	0.0	4.4	DOL	100	0.0	Y
82	20	29.0	23.0	74	21.0	21.4	2.0	4.0	DOL	100	0.0	Y
84	24	23.5	17.5	71	18.9	18.5	0.0	4.6	DOL	100	3.1	Y
86	26	21.3	15.3	63	13.4	13.7	1.9	7.1	DOL	100	4.6	N
88	23	22.3	16.3	64	14.1	14.5	2.2	10.0	DOL	100	2.3	N
90	23	16.5	10.5	60	11.3	11.1	0.0	11.0	DOL	100	2.3	N
92	30	16.4	10.4	56	8.6	8.9	1.8	16.0	DOL	100	7.7	N
94	29	19.8	13.8	57	9.3	10.2	4.5	21.0	DOL	100	6.9	N
96	60	19.0	13.0	60	11.3	11.6	1.7	20.0	DOL	100	30.8	N
98	84	18.5	12.5	60	11.3	11.5	1.2	15.0	DOL	100	49.2	N
2500	52	19.3	13.3	62	12.7	12.7	0.6	14.0	DOL	100	24.6	N
2	37	18.2	12.2	57	9.3	9.8	2.9	14.0	DOL	100	13.1	N
4	33	22.0	16.0	59	10.7	11.8	5.3	11.0	DOL	100	10.0	N
6	45	23.0	17.0	64	14.1	15.1	2.9	8.0	DOL	100	19.2	N
8	30	19.8	13.8	60	11.3	12.1	2.5	9.0	DOL	100	7.7	N
10	23	20.0	14.0	58	10.0	11.3	4.0	8.5	DOL	100	13.1	N
12	20	22.8	16.8	60	11.3	13.2	5.5	8.2	DOL	100	0.0	N
14	32	20.7	14.7	64	14.1	14.4	0.6	9.0	DOL	100	9.2	N
16	30	20.1	14.1	60	11.3	12.4	2.8	10.5	DOL	100	7.7	N
18	42	20.8	14.8	62	12.7	13.6	2.1	8.5	DOL	100	16.9	N
20	38	19.0	13.0	60	11.3	12.1	1.7	10.0	DOL	100	13.8	N
22	30	20.3	14.3	56	8.6	10.4	5.7	11.0	DOL	100	15.4	N
24	23	21.7	15.7	61	12.0	13.3	3.7	10.0	DOL	100	2.3	N
26	24	20.0	14.0	60	11.3	12.2	2.7	8.0	DOL	100	3.1	N
28	23	16.0	10.0	57	9.3	9.7	0.7	9.0	DOL	100	2.3	N
30	23	19.0	13.0	61	12.0	12.5	1.0	10.0	DOL	100	2.3	N
32	21	20.4	14.4	63	13.4	13.8	1.0	12.0	DOL	100	0.8	Y

Table 2 Continued

DEPTH GL (ft)	GR (API)	(POR) Nls (%)	(POR) Ncor (%)	t (sec)	(POR) BCScor (%)	(POR) xp (%)	(POR) sec (%)	RT (ohm-m)	MA	SW (%)	Vsh (%)	k
2534	33	22.5	16.5	60	11.3	12.2	5.2	10.0	DOL	100	10.0	Y
36	27	22.0	16.0	63	13.4	13.9	2.6	7.5	DOL	100	5.4	Y
38	28	24.3	18.3	65	14.8	15.5	3.5	6.5	DOL	100	6.2	Y
40	29	24.0	18.0	63	13.4	14.2	4.6	5.8	DOL	100	6.9	Y
42	35	17.3	11.3	61	12.0	11.8	0.0	7.1	DOL	100	11.5	N
44	40	16.5	10.5	59	10.7	10.6	0.0	9.0	DOL	100	15.4	N
46	42	21.3	15.3	63	13.4	13.7	1.9	8.5	DOL	100	16.9	Y
48	40	22.5	16.5	70	18.2	17.7	0.0	6.7	DOL	100	15.4	Y
50	40	20.6	14.6	66	15.5	15.1	0.0	6.7	DOL	100	15.4	Y
52	38	15.6	15.6	65	12.3	13.3	3.3	10.0	LS	100	13.8	N
54	29	8.6	8.6	57	6.6	7.4	2.0	20.0	LS	100	6.9	N

Table 3 Data from existing geophysical logs run in WDW2[1]

DEPTH GL (ft)	GR (API)	(POR) Nls (%)	(POR) Ncor (%)	t (sec)	(POR) BCScor (%)	(POR) xp (%)	(POR) sec (%)	RT (ohm-m)	MA	SW (%)	Vsh (%)	k
2582	26	8.1	8.1	63	10.9	10.1	0.0	30.0	LS	90	4.6	N
84	30	10.0	10.0	66	13.0	12.2	0.0	28.0	LS	77	7.7	N
86	34	15.0	15.0	71	16.5	16.3	0.0	17.0	LS	74	10.8	N
88	38	14.7	14.7	73	18.0	17.1	0.0	13.0	LS	81	13.8	Y
90	37	13.5	13.5	73	18.0	16.9	0.0	13.0	LS	82	13.1	Y
92	26	7.8	11.1	68	8.8	10.0	2.3	20.0	SS	100	4.6	Y
94	29	6.1	9.3	65	7.1	8.2	2.2	38.0	SS	98	6.9	N

1 All logs used for study were from WDW2 (run during well installation), except the Sonic Log (SL), which was from WDW1 (run during well installation). The methods of analysis used were the same as above. All depths measured are from Kelly Bushing (KB), which is 12 feet above GL.

From the data (see appendix B) it appeared that the host formation, the Bailey Limestone, was composed mainly of a clean dolomite with less than 20 percent shale throughout most of the interval logged. Since the Bailey Limestone is predominantly a dolomite, secondary porosity is always a consideration. A comparison of CNL and BCSL data suggested that secondary porosity may account for up to 10 percent of the total porosity. The intervals with higher relative permeability have a slightly higher secondary porosity and, in turn, total porosity.

Also, the entire interval is primarily 100 percent water saturated with a fluid resistance of approximately 0.247 ohm-m. At a formation temperature of about 80°F and depth of 2,460 feet GL, the fluid composition was estimated to be approximately 24,000 ppm NaCl.

Phase I log analysis provided qualitative data of the disposal horizon. On the basis of this analysis, an additional section of the disposal horizon (2,518 to 2,539 ft KB [Kelly Bushing]) was eliminated as a possible injection zone (fig. 23).

Table 4 Summary of important formation characteristics

(POR)xp,ave = 16%	(POR)xp,max= 28.8	%(POR)xp, min = 8.9%
(POR)sec,ave = 1.98%	(POR)sec,max= 5.7%	
tave = $66.7x10^{-6}$ sec/ft		
tmax = $87x10^{-6}$ sec/ft		
tmin = $56x10^{-6}$ sec/ft		
Rt,ave = 8.6 ohm-m	Rt,max= 21 ohm-m	Rt,min= 3 ohm-m
Vsh,ave = 8.05%	Vsh,max= 49.2%	Vsh,min= 0.0%

Formation lithology (based on 98 feet of "higher permeability, higher porosity" unit), 61.0% dolomite, 35.0% limestone, and 4.0% sandstone.

Phase II Geophysical Logging

Phase II analysis consisted of a detailed site-specific evaluation of the injection/confining interval. Continuous Spinner Flowmeter logging (CSFL) and core analysis formed the basis of the study. Scanning Electron Microscope (SEM) analysis and formation brine/wastewater analysis were also conducted.

Continuous spinner flowmeter logging. The foregoing data were obtained exclusively from a static environment, i.e., no fluid injection into the well. For a quantitative evaluation of the response of the formation to "normal" or near-normal injection rates, a Continuous Spinner Flowmeter Log (CSFL) was run in WDW2. (An X-Y Caliper Log run prior to the CSFL provided borehole volumetric data to be used in conjunction with the CSFL data.) Again, as with the previous set of geophysical logs, borehole conditions in WDW2 restricted the interval available for logging. But work-over operations subsequent to the WDW2 logging permitted coverage of all anticipated injection zones as delineated by historical and phase I logging (fig. 23).

The CSFL data were used in two ways. First, the data enabled the delineation of specific injection zones and the calculation of the percentage of total flow into each zone. Second, the data were used to identify the lower boundary of fluid infiltration (i.e., the upper limit of the basal confining unit).

To evaluate the effect of varying injection rates, we recorded flow rates at three surficial injection rates: 75 gallons per minute (gpm), 100 gpm, and 150 gpm. The results are reported in table 5. Fluid loss is the percentage, on a volumetric basis, of fluid moving into a particular unit. For example, on average, 14 percent of the fluid flows into injection zone 1. The 150-gpm rate is the closest to the "average" waste injection rate (182 gpm) for WDW2 (see p. 58).

The repeatability of the flowmeter was verified by taking measurements as the flowmeter moved both up and down the borehole. With the flowmeter stationary, data were collected adjacent to suspected high permeability units and below the base of the anticipated injection horizon (2,594 ft KB from the other geophysical surveys). The validity of the results was checked by obtaining data with a stationary flowmeter in the 7-inch casing. At surficial injection rates of 75 gpm, 100 gpm,

Table 5 Fluid loss percentage calculated from CSFL

Injection zone no.	Depth (ft below KB)	Fluid Loss (%) injection rates (gpm)			
		75	100	150	Average
1	2448-2458	11	15	17	14
2	2552-2558	40	38	29	36
3	2584-2594	49	47	54	50

and 150 gpm, calculated flow rates in the 7-inch casing were 81 gpm, 107 gpm, and 163 gpm, respectively (margin of error less than 10%).

The effective interval of injection at the time of logging the CSFL (from the base of the 7-inch casing to the deepest depth of penetration of the logging tool) was from 2,437 to 2,614 feet KB. If conditions remain stable, fluid should infiltrate exclusively into the zones listed in table 5 and shown on figure 23. No flow was detected below 2,614 feet.

As shown on figure 23, data from the CSFL were not consistent with the interpretation of the geophysical logs. First, the interval from 2,468 to 2,496 feet was identified from both the historical and phase I logging as a potential injection zone, but the CSFL indicated an absence of flow into this interval. Second, data from the CSFL indicated that only a portion of the potential injection interval from 2,538 to 2,568 feet allowed substantial fluid infiltration. And third, on the basis solely of porosity and permeability data, zone 3 should have accepted less fluid than either zones 1 or 2;

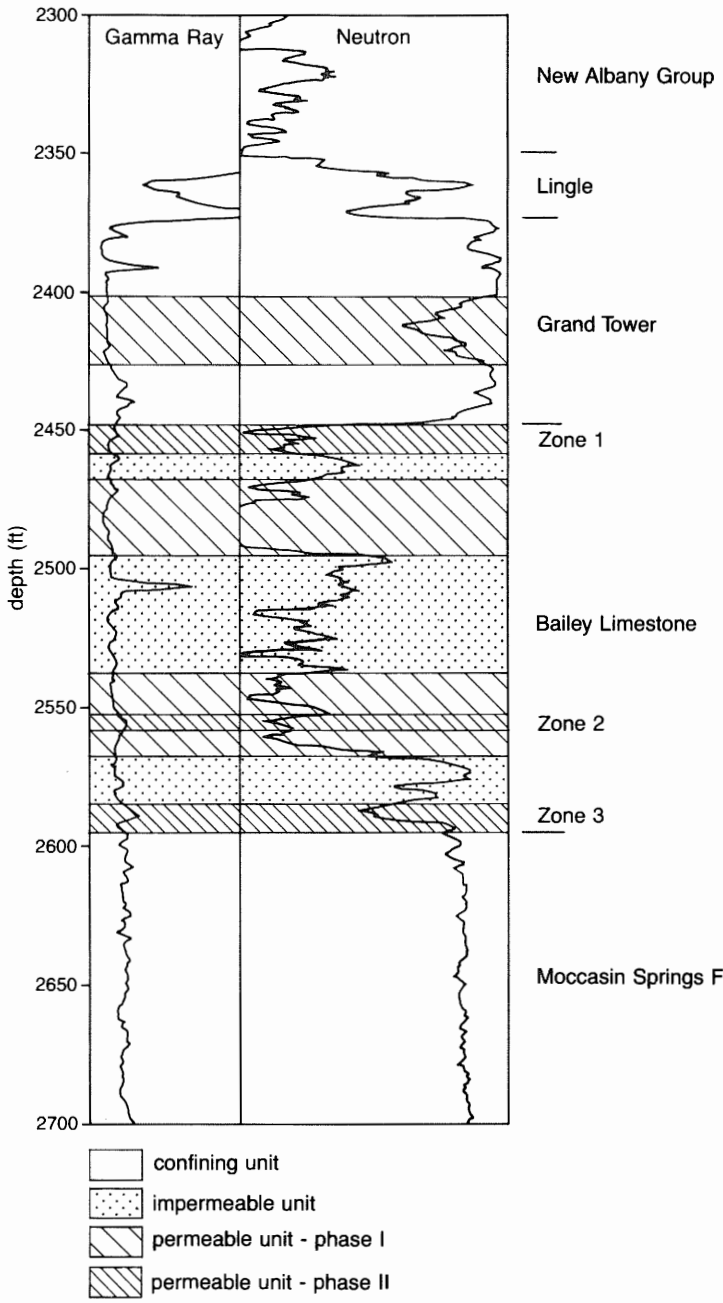


Figure 23 Injection system in WDW2 indicating permeable and impermeable units delinated after phase II logging.

however, this scenario was not supported by the CSFL data. In an effort to resolve these discrepancies and to obtain two additional parameters (quantitative permeability and bulk compressibility) essential to injection-interval evaluation, we conducted lab testing of sidewall cores.

Core retrieval and analysis. Several criteria were used to choose the coring zones. In order of decreasing priority, the selection criteria were to (1) cover all possible injection zones determined from the historical and phase I logging, (2) obtain cores from the anticipated lower confining unit indicated by logging data, and (3) cover a range of permeabilities and other physical properties present in the disposal horizon. Core depths are indicated in figure 24 and table 6.

Twenty-nine sidewall cores were retrieved with Gearhart's Hard Rock Coring tool. Gearhart Industry Inc. Corelab performed the core analysis. Additional core study was done at the ISGS. The core analysis provided data on quantitative permeability, bulk compressibility, and mineralogic composition, and provided a means to evaluate the accuracy of the downhole geophysical methods employed. The results of the core analysis are reported in table 7 and figures 25 and 26.

Table 6 Core location and analysis

Core no.	Core depth	kw[1] (Y,N)	Strength[2] test (Y,N)	Comments[3]
1	2663.0	N	N	No ka
2	2622.0	Y	Y	
3	2620.0	Y	N	
4	2617.5	N	N	No ka
5	2606.0	N	N	
6	2605.0	Y	Y	
7	2588.5	Y	N	
8	2573.5	Y	N	
9	2572.5	N	N	No ka
10	2560.5	N	N	
11	2556.5	N	N	No ka
12	2555.0	Y	Y	
13	2551.5	N	N	No ka
14	2539.5	N	N	
15	2509.5	Y	Y	
16	2508.5	N	N	
17	2491.5	N	N	
18	2490.5	N	N	
19	2484.5	Y	Y	
20	2482.5	N	N	No ka
21	2481.0	N	N	
22	2479.5	N	N	
23	2478.5	N	N	No ka
24	2463.5	N	N	
25	2462.5	N	N	
26	2457.5	N	N	No ka
27	2456.5	N	N	
28	2451.5	Y	Y	
29	2450.5	N	N	No ka

1 Water permeabilities (kw) derived from air permeabilities (ka) by applying a Klinkenburg correction.
2 Separate test which yields Poisson's ratio, Young's modulus, and bulk compressibility (corrected for in situ pore and confining pressures).
3 Basic analysis and x-ray diffraction performed on all cores. Basic analysis consists of ka, total porosity, water saturation (Sw), and fluorescence. X-ray diffraction identifies all minerals that have an abundance of 1% or more by weight and the total clay percentage.

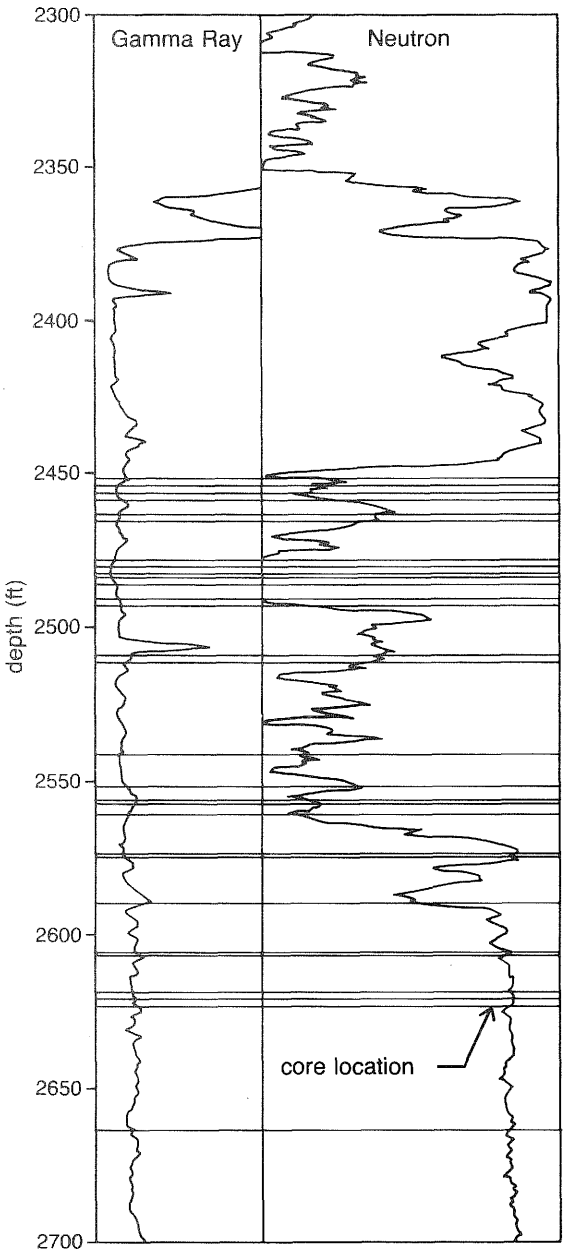


Figure 24 Core locations for WDW2.

Available data indicate that the discrepancies between the injection zones identified from phase I and phase II are due to the presence of brucite ($Mg[OH]_2$). The supporting data used to develop the brucite-formation hypothesis are summarized below and more fully described in appendix C.

Mineralogic analysis of sidewall cores identified brucite (up to 45% by weight) to be present in potential injection zones, as identified from phase I logging. Brucite, not present in the injection system prior to well operation, forms during waste injection. Brucite apparently formed in zones having the highest potential for fluid flow, as identified from phase I logging. Brucite formation does not reduce porosity (as identified from geophysical logs) but does reduce the permeability significantly. Flow rates in the different injection zones appear from CSFL results to be proportional to the brucite concentration within that zone, i.e., zones with higher brucite concentrations have lower flow rates.

Table 7 Results of core analysis

Depth (ft KB)	POR (%)	ka (md)	kw (md)	Compress x10^{-12} (cm sec^2/gm)
2450.5		24.2		
51.5	26.1	0.640	0.476	15.5
56.5	27.7	62.54		
62.5	13.2	0.0076		
63.5	11.5	0.0087		
79.5	26.4	0.178		
81.0	24.8	0.017		
82.5	56.1			
84.5	30.8	14.97	12.940	8.70
90.5	29.4	2.292		
91.5	24.2	0.457		
2508.5	9.9	0.0089		
09.5	11.4	0.017	0.001	3.36
39.5	17.7	0.203		
51.5	8.9			
55	18.0	0.060	0.017	8.41
60.5	17.1	0.095		
73.5	5.2	0.0050	0.00013	
88.5	16.6	0.021	0.004	11.9
2605	3.1	0.0055	0.00042	4.71
06	4.6	0.0029		
17.5	4.8			
20	4.6	0.0034		
22	3.8	0.0038		
63	6.7			

The source of ions for brucite formation is not clear. The source of OH^- is the injected waste (pH > 12), but the source of Mg^{2+} is unclear. Two possible sources are the waste fluid or the dolomite within the injection zones.

Hydrogeology of the site. Having developed a hypothesis to explain brucite formation, we quantified the hydrogeologic characteristics of the injection system, which allowed the data to be used as parameter input for the numerical model. The disposal interval was divided into 12 units based on hydrogeologic characteristics (fig. 27 and table 8), using data derived from figure 23. These 12 units were used for differentiating the stratigraphic cross sections (figs. 17, 18, and 19). Local and regional stratigraphic/structural studies, presented in Stratigraphic and Structural Definition of the Injection System, page 23, were also considered to ensure that the units chosen were not localized anomalies (i.e., noncontinuous).

Table 8 lists the units and their associated characteristics. Permeability, air (ka) and water (kw), and bulk compressibility data were obtained from core analysis. Hydraulic conductivity (K) and specific storage (Ss) measurements were derived from these results. The porosity measurements (POR) were taken from table 2 (geophysical logging results) and core analysis results. Storativity (S) and transmissivity (T) data were calculated only for the three injection zones delineated previously (table 9). Units 2, 9, and 11 in table 8 correspond to injection zones 1, 2, and 3, respectively. The thicknesses (b) for units 2, 9, and 11 were determined from figure 27.

The three gas-storage field wells mentioned in Stratigraphic and Structural Definition of the Injection System, page 24, provided additional permeability data for the intervals corresponding to unit 1 and the overlying strata (above 2,402 feet KB). Values for vertical water permeabilities of

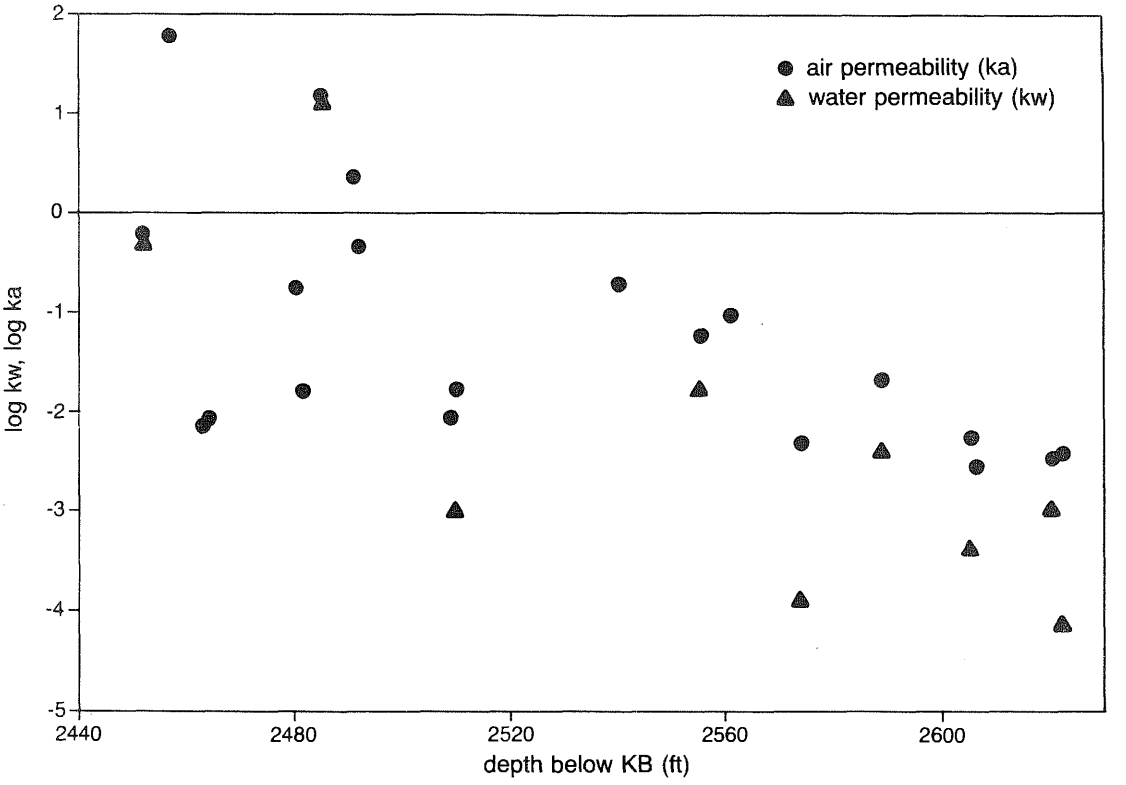


Figure 25 Core permeabilities (air and water) versus depth for WDW2.

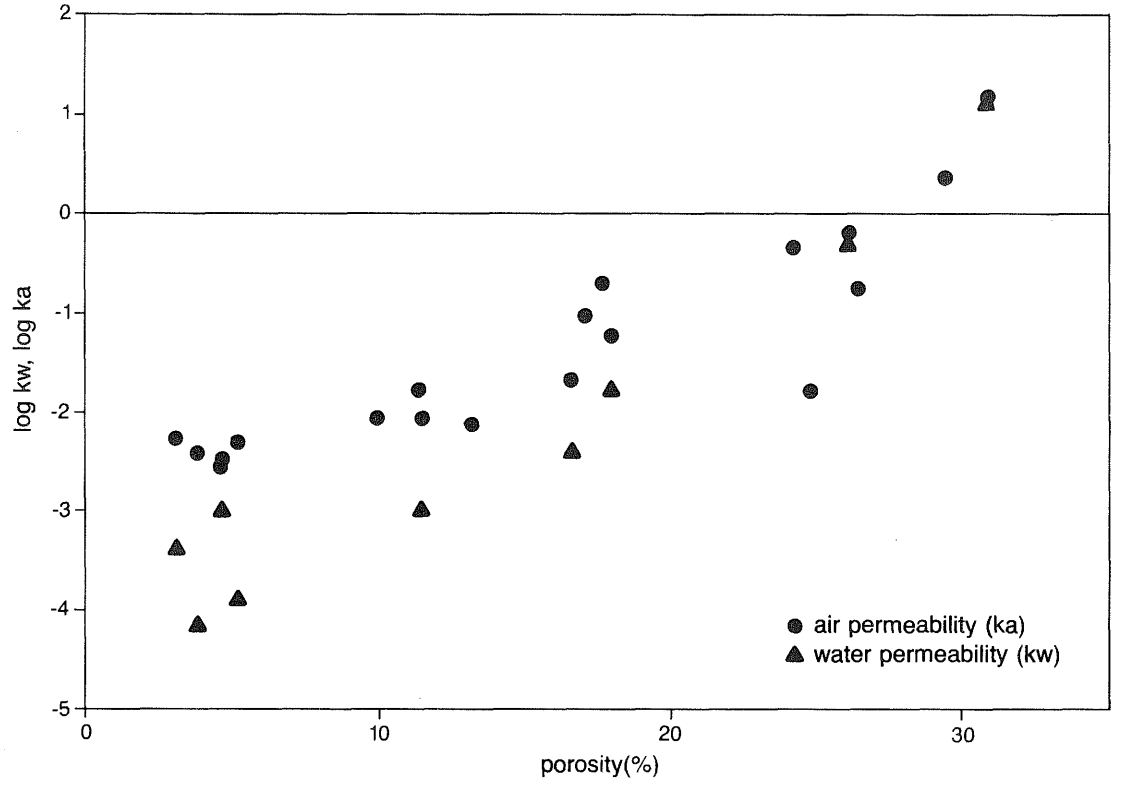


Figure 26 Core permeabilities versus core porosities for WDW2.

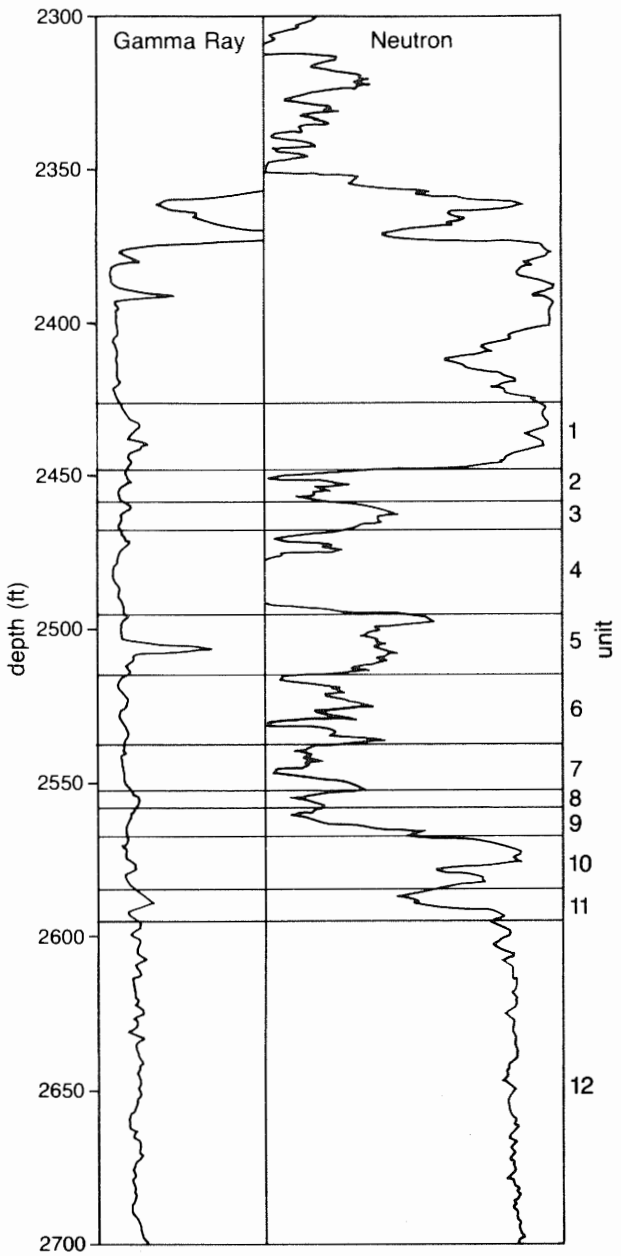


Figure 27 Unit locations for WDW2.

7.85×10^{-5} md (millidarcys) for the interval corresponding to unit 1 and 3.51×10^{-5} md for the overlying strata were obtained.

Long-Term Injection Test

A long-term injection test was conducted to obtain T and S values for the injection formation. An injection test is similar to a standard pump test except that water is injected into the well instead of being withdrawn from it.

The injection test started at 10 a.m., July 9, 1987, and was completed at 7 a.m., July 24, 1987. The test ended at this time because of a power outage scheduled by the power company. Velsicol

Table 8 Summary of hydrogeological data for a portion of the disposal system

Depth (ft KB)	POR (%)	ka (md)	kw (md)	Compressx10^{-12} (cm sec^2/gm)	K[a]x10^{-8} cm/sec	Ss[b]x10^{-8} cm^{-1}	Unit
2432	2.0						1
34.5	2.0						1
36	4.0						1
38	2.0						1
40	7.8	7.85x10^{-5}**					1
42	4.0						1
44	4.3						1
46	5.0						1
48	10.0						1
50	21.7						1
50.5	24.2						1
51.5	26.1	.640	.476	15.5	52.73	2.67	2
52	21.1						2
54	18.2						2
56	18.2						2
56.5	27.7	62.54					2
57.5	18.2						2
58	15.0						2
60	12.0						3
62	9.7						3
62.5	13.2	.0076					3
63.5	11.5	.0087					3
64	11.7						3
66	13.3						3
68	13.3						3
70	15.6						4
72	16.0						4
74	18.5						4
76	18.5						4
78	23.5						4
79.5	26.4	.178					4
80	26.0						4
81	24.8	.017					4
82	25.7						4
82.5	56.1						4
84	28.8						4
84.5	30.8	14.97	12.940	8.70	1434	2.21	4
86	26.3						4
88	23.2						4
90	22.6						4
90.5	29.4	2.292					4
91.5	24.2	.457					4
92	21.4						4
94	18.5						4
96	13.7						5
98	14.5						5
2500	11.1						5
02	8.9						5
04	10.2						5
06	11.6						5
08	11.5						5
08.5	9.9	.0089					5
09.5	11.4	.017	.001	3.36	.111	.831	5
10	12.7						5
12	9.8						5
14	11.8						5
16	15.3						6
18	11.0						6
20	11.0						6

Table 8 Continued

Depth (ft KB)	POR (%)	ka (md)	kw (md)	Compressx10^{-12} (cm sec^2/gm)	$K^a x10^{-8}$ cm/sec	$Ss^b x10^{-8}$ cm^{-1}	Unit
22	14.3						6
24	9.5						6
26	9.5						6
28	12.2						6
30	14.2						6
32	14.2						6
34	11.9						6
36	9.3						6
38	12.0						6
39.5	17.7	.203					7
40	14.1						7
42	12.2						7
44	13.9						7
46	15.5						7
48	14.2						7
50	11.8						7
51.5	8.9						7
52	10.6						8
54	13.7						8
55	18.0	.060	.017	8.41	1.88	1.62	8
56	17.7						8
56.5	17.0						8
58	15.1						8
60	13.3						9
60.5	17.1	.095					9
62	17.8						9
64	14.5						9
66	7.0						9
68	6.2						9
70	4.0						10
72	1.0						10
73.5	5.2	.0050	.00013		.0144		10
74	1.0						10
76	1.0						10
78	6.2						10
80	5.0						10
82	5.0						10
84	5.5						11
86	8.9						11
88	9.8						11
88.5	16.6	.021	.004	11.9	.443	1.90	11
90	7.0						11
92	4.0						11
94	4.0						11
96	4.0						12
98	4.0						12
2600	4.0						12
02	4.2						12
04	4.4						12
05	3.1	.0055	.00042	4.71	.0465	.597	12
06	4.6	.0029					12
17.5	4.8						12
20	4.6	.0034					12
22	3.8	.0038					12
63	6.7						12

** Average vertical water permeability (kaw) and POR from three gas injection wells in the study area.

Table 9 Additional hydrogeological data for primary injection zones

Section	b (ft)	$S^c \times 10^{-6}$ (-)	$T^d \times 10^{-6}$ (cm^2 / sec)
2	10	8.14	161
8	6	2.96	3.44
10	10	5.79	1.35

Explanation for tables 8 and 9:

(a) $K = kw\rho g / \mu$

where

K = hydraulic conductivity
kw = water permeability (Klinkenburg corrected air permeability)
ρ = water density = 0.997 gm/cm^3*
g = acceleration due to gravity = 980 cm/sec^2
μ = water viscosity = 0.008705 gm/cm sec*

* temperature used to determine ρ and μ was taken to be 26°C. This came from Temperature Log run in WDW2 assuming the cooling effect due to past injection was extremely localized (see appendix A).

(b) $Ss = \rho g (\alpha + n\beta)$

where

Ss = specific storage
α = matrix bulk compressibility
β = fluid bulk compressibility* = 4.513×10^{-11} $cm\text{-}sec^2/g$
n= porosity

* temperature used to determine β was taken to be 26°C (see note above).

(c) $S = Ssb$

where

S = storativity
Ss = specific storage
b = zone thickness

(d) $T = Kb$

where

T = transmissivity
K = hydraulic conductivity
b = zone thickness

injected water from its stormwater retention ponds during the test. Table 10 shows the physical and chemical properties of the fluid injected during the in injection test (Velsicol, 1987). Table 11 shows the volume and rate of fluid injected. The average injection rate was 288.4 gpm.

Head data were collected at the DOW using a Stevens water level recorder (fig. 28). The water level recorder was set with a 1:1 gearing and an 8-day chart.

Data obtained from the DOW were analyzed by two techniques: Theis analysis and Cooper-Jacob analysis (see Todd 1980 or Freeze and Cherry 1979 for a detailed explanation of these techniques). Theis analysis is a curve-fitting technique; therefore, the T and S values obtained from this method depend on the analyst's judgment. The Cooper-Jacob technique is somewhat less subjective since the data plot is a straight line on semilog paper.

Table 10 Selected chemical and physical properties of water injected during injection test (Velsicol 1987)

Suspended solids	29 mg/L
Dissolved solids	1205 mg/L
Sodium chloride	794 mg/L
Sodium hydroxide	235 mg/L
pH	8.0
Specific gravity	1.004
Sample temperature	58°F

Table 11 Volume injected into WDW2 during injection test

Reporting date	Hours operated	Volume injected (gallons)	Injection rate (gpm)
7/10/87	21	340,673	270.4
7/11	24	414,607	287.9
7/12	24	422,409	293.3
7/13	24	419,684	291.2
7/14	24	423,836	294.2
7/15	24	419,042	290.8
7/16	24	401,760	278.8
7/17	24	418,939	290.8
7/18	24	411,973	285.9
7/19	24	413,270	286.9
7/20	24	411,616	285.7
7/21	24	410,420	284.9
7/22	24	424,717	294.8
7/23	24	424,211	294.4
7/24	24	419,352	291.0
Average		411,767	288.4

Table 12 Analysis of injection test

Method	S (-)	Transmissivity (m^2/min)
Theis	2.75×10^{-4}	0.385
Cooper-Jacob (r = 0.960)	2.47×10^{-4}	0.386

r = correlation coefficient for the linear regression

For the Cooper-Jacob technique, head buildup was plotted versus log time (fig. 29). Linear regression was used to calculate the parameters (S and t_o) for this method. An iterative approach was taken since the data used in the analysis depend on the outcome of the analysis. For the Cooper-Jacob method, u ($u = r^2S / (4Tt)$) must be less than to 0.01. From the definition of u and the value of T and S, a minimum time can be determined (i.e., only field data where $t > t_{min}$ can be used). Thus, an iterative technique was necessary to calculate T and S. Table 12 shows the results of the analyses (only the values for the final iteration of the Cooper-Jacob analysis are presented). Note the good agreement between the Theis and Cooper-Jacob analyses. The values obtained by the Cooper-Jacob technique are considered to be the more accurate since this technique is less subjective.

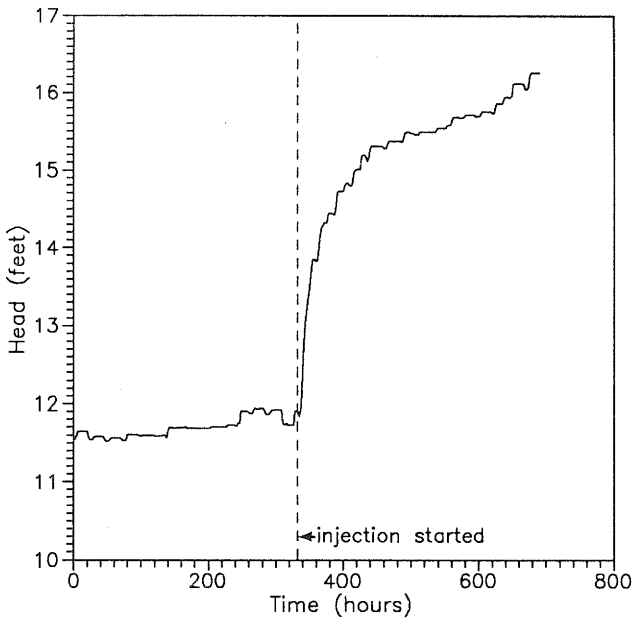


Figure 28 Water level record for DOW, including data from injection test.

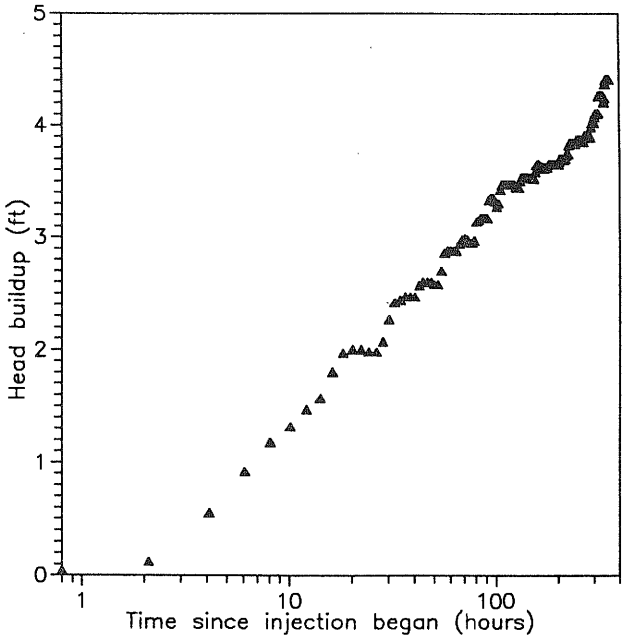


Figure 29 Plot of data used for Cooper-Jacob analysis.

4. NUMERICAL MODELING

Model Selection

Model selection is an important step in conducting a modeling investigation of a groundwater flow problem. The model should be able to handle all significant physical processes of the groundwater flow system. If the model does not incorporate these processes, it cannot be expected to simulate the field situation with any degree of accuracy.

The literature contains descriptions of many general and specialized numerical models. At the outset of this project, it was thought that a model capable of simulating three-dimensional (3D) flow and flow through complex hydrogeologic regimes would be required. Several 3D groundwater flow models have been developed, including the Sandia Waste Isolation Flow and Transport Model (SWIFT) (Reeves and Cranwell, 1981) and the Heat and Solute Transport Program (HST3D) (Kipp 1987). SWIFT and HST3D are finite difference groundwater flow and transport models that are independent modifications of SWIP (INTERCOMP, 1976). This original model, developed to model the effects of deep-well waste injection, includes sophisticated well functions rarely incorporated into other models. Although SWIFT and HST3D have a more general focus than does their predecessor, both models retain these well functions, and either model could be used for this project. Since a version of HST3D compatible with the Prime 9650 computer used in this project was available before a similar version of SWIFT (II), HST3D was selected.

Model Description

HST3D is a descendent of the Survey Waste Isolation Program (SWIP) written for the U.S. Geological Survey by INTERCOMP Resource Development and Engineering Consultants. HST3D represents a complete rewrite of SWIP with many major and minor modifications, improvements, and corrections.

Overview of Model

HST3D simulates saturated groundwater flow and associated heat and solute transport in three dimensions. The following equations are solved numerically: the saturated groundwater flow equation, formed from combining the conservation of total fluid mass and Darcy's Law for flow through porous media; the heat transport equation from the conservation of enthalpy for the fluid and porous medium; and the solute transport equation from the conservation of mass for a single solute, which may adsorb onto the porous medium and/or decay (Kipp 1987). These equations are coupled through the dependence of advective transport on the interstitial fluid velocity field, fluid viscosity on temperature and solute concentration, and fluid density on pressure, temperature, and solute concentration.

For the dependent variables of pressure, temperature, and mass fraction, numerical solutions are obtained successively using a set of modified equations that more directly link the original equations through the velocity, density, and viscosity coupling terms. Finite difference techniques are used for the spatial and temporal discretization of the equations. When supplied with appropriate boundary and initial conditions and system-parameter distributions, a wide variety of heat and solute transport simulations can be performed (Kipp 1987).

The basic source-sink term represents wells. A complex well-flow model may be used to simulate specified flow rate and pressure conditions at the land surface or within the aquifer, with or without pressure constraints. Types of boundary conditions include specified value, specified flux, leakage, heat conduction, an approximate free surface, and two types of aquifer influence functions. All boundary conditions may be functions of time (Kipp 1987).

Assumptions Incorporated into the Model

Since this project was concerned with simulation of fluid flow and not heat and/or contaminant transport, only the assumptions incorporated into the flow model will be discussed. Kipp (1987) incorporated the following assumptions into the partial differential equation describing groundwater flow:

- Groundwater fully saturates the porous medium within the region of groundwater flow.
- Groundwater flow is described by Darcy's Law.
- The porous medium and the fluid are compressible.
- The porosity and permeability are functions of space.
- The coordinate system is chosen to be aligned with the principal directions of permeability tensor so that this tensor is diagonal for anisotropic media.
- The coordinate system and the principal directions of the permeability tensor are orthogonal.
- The coordinate system is right-handed with the z-axis pointing vertically upward.
- The fluid viscosity is a function of space and time through dependence on temperature and solute concentration.
- Density-gradient diffusive fluxes of the bulk fluid are neglected relative to advective-mass fluxes.
- Dispersive-mass fluxes of the bulk fluid from spatial-velocity fluctuations are excluded.

Input Data

Input data required by HST3D for modeling fluid movement may be categorized as follows: hydrogeologic properties of the aquifer, physical dimensions of the aquifer, physical dimensions of the well(s), hydraulic properties of the well(s), and physical and chemical properties of the fluid. Additional input data are required for any attempts to model solute and/or heat transport.

Physical Configuration of the Injection System

As defined here, the injection system refers to the geologic deposits that constitute the injection zone and its associated confining units. The hydrogeology of the site is described in chapter 3. The physical dimensions and hydrogeologic properties of the injection system used as model input will be described where appropriate in each section.

Description of the Injection and Observation Wells

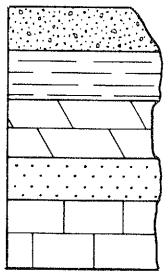
Waste Disposal Well 2 (WDW2) at the Velsicol Chemical Corporation's Marshall Plant was modeled. WDW2 is a packer-annulus-type well completed in Devonian limestone (fig. 30). Originally, the well was drilled to a total depth of 6,007 feet and was completed open-hole from 2,440 to 2,737 feet. Preceding the phase II field testing of the well, Velsicol completed extensive well workover procedures to remove debris, which had partially filled the well. These procedures included a high-pressure jet wash of the well bore. In addition to suspending and removing the debris in the well, the tool scoured the well bore. Thus it is assumed that the skin effect for this well would be negligible. Access for geophysical tools to total depth was blocked at 2,610 feet, presumably due to bridging of materials sloughed from the well face. However, the bridging probably did not plug the well from a hydraulic standpoint.

Located 506 meters due north of WDW2 is the Devonian Observation Well (DOW), which was completed open-hole starting near the top of the Devonian limestone (fig. 31). Total depth for this well is 2,580 feet. Water-level data were collected from this well during this project.

Physical and Chemical Properties of the Fluids

HST3D requires input of various physical properties of the fluids, including density, temperature, viscosity, and compressibility. These data are required for the fluid injected and the native fluid in the formation (brine). Fluid-compressibility data for injected wastes and/or brines were generally not available but were estimated on the basis of the chemical composition of these fluids. Much of these required input data were available from a database compiled by the ISGS.

Lithology



Unconsolidated

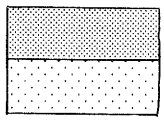
Shale

Dolomite

Sandstone

Limestone

Aquifers (USDW)



Primary freshwater aquifer (0-2,500 mg/l)

Secondary aquifer (2,500-10,000 mg/l)

Stratigraphic Units

Q	Quaternary
P	Pennsylvanian
M	Mississippian
Mc	Chesterian sandstone
Msg, sl	Ste. Genevieve Limestone
	St. Louis Limestone
Msa	Salem Limestone
Mb	Borden Siltstone
Mch	Chouteau Limestone
M/D	Mississippian/Devonian
M/Dna	New Albany Group
D	Devonian
Dlgb	Lingle Limestone
	Grand Tower Limestone
	Bailey Limestone
S	Silurian
Sm	Moccasin Springs Fm
Su	Undifferentiated dolomite
O	Ordovician
Om	Maquoketa Shale
Ogp	Galena-Platteville dolomite
Osp	St. Peter Sandstone
Opdc	Prairie du Chien dolomite
Є	Cambrian
Єep	Eminence-Potosi dolomite

Injection System Components

M/Dna	Upper confining unit
Dlgb	Injection unit
Sm	Lower confining unit

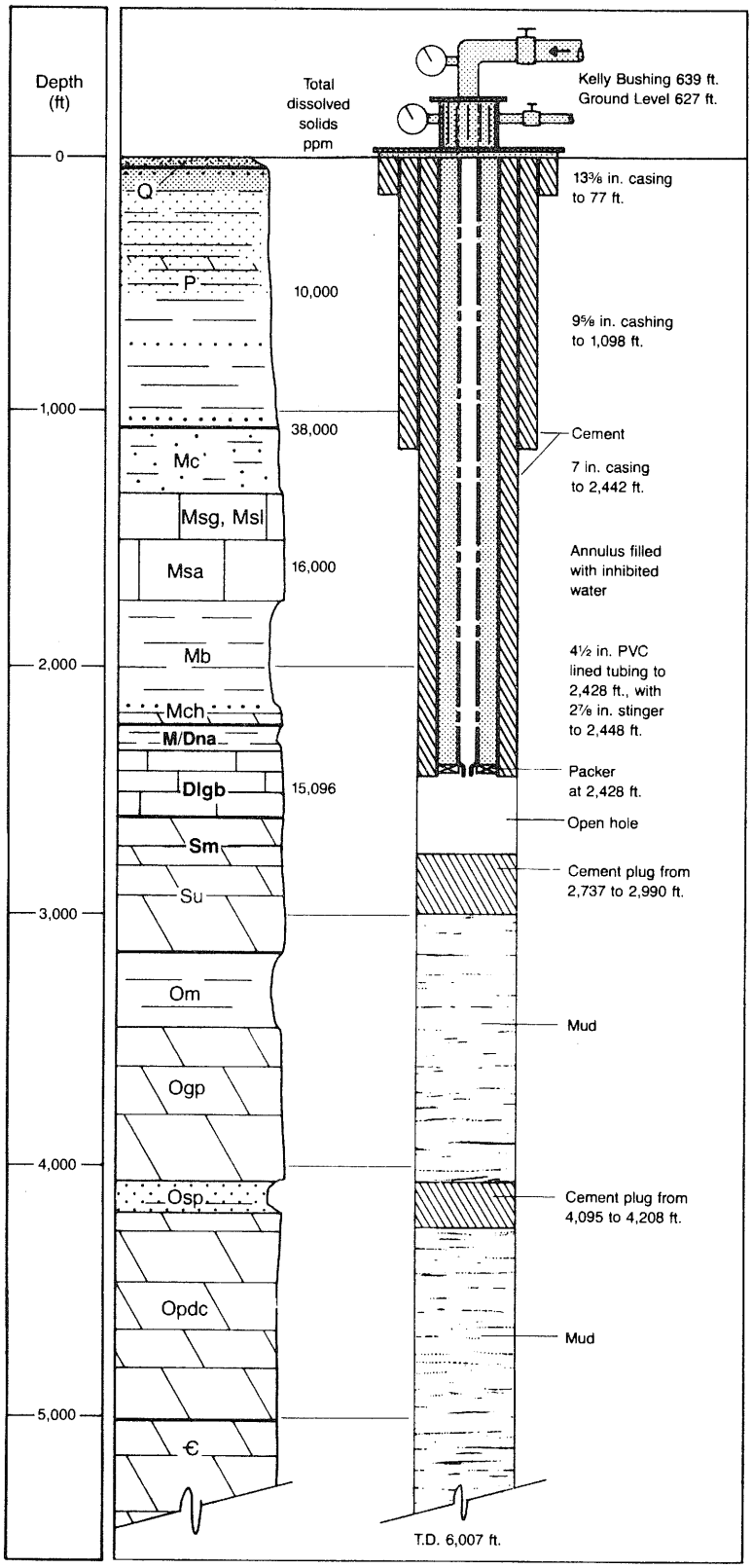


Figure 30 Schematic for WDW2 (modified from Brower et al. 1989).

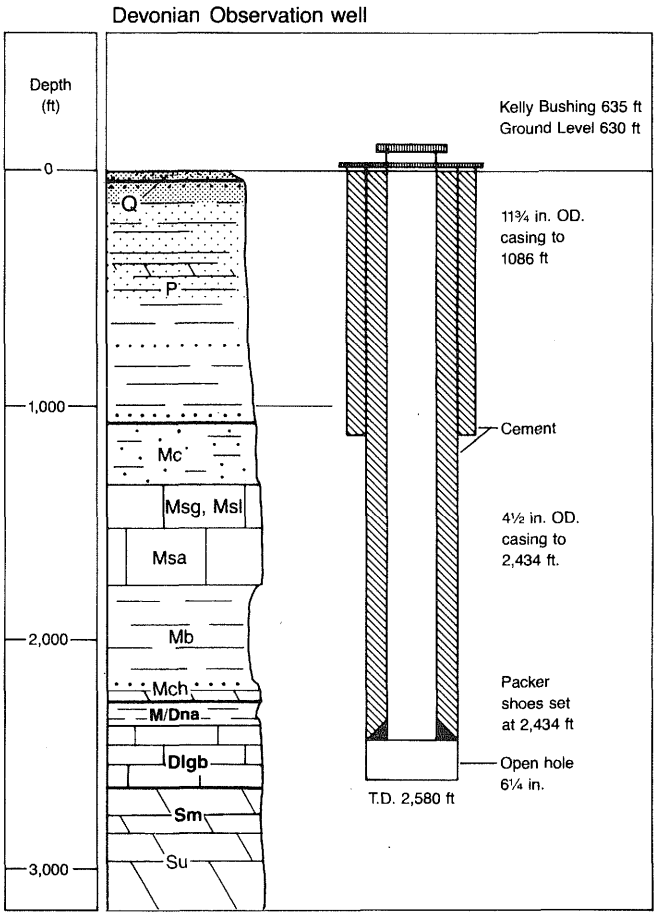


Figure 31 Schematic for DOW (Velsicol 1984).

General Parameters

Velsicol injected hazardous waste consisting of production wastewater and surface runoff water from on-site process areas. Chlorinated pesticides were produced at this site. The waste was highly alkaline (pH > 12) and contained pesticides and other chlorinated hydrocarbons. The relative concentrations of constituents in the waste were NaCl > NaOH > hexachlorocyclopentadiene (hex) > chlordane.

Velsicol has been required by permit to sample and analyze the waste injected into WDW2 and the brine from the DOW. Thus an extensive database of physical and chemical properties of the injected fluid and brine is available. This database was compiled by the ISGS and used extensively in this project. For WDW2, available data date back to early 1973, when operating reports were first required. Data for dissolved solids, specific gravity, and viscosity are presented in table 13.

Table 13 Selected parameters for fluids injected via WDW2

Parameter (unit)	Range	Average	Standard deviation	Number
Dissolved solids (mg/L)	200 - 254,000	38,346	35,388	671
Specific gravity (-)	0.9948 - 1.14	1.027	0.025	538
Viscosity (centipoise)	0.7161 - 0.9822	0.7857	0.0700	33

Data for dissolved solids in table 13 show the variability of the injected fluid, which is predominantly storm water runoff. Brower et al. (1989) attributed this variation in dissolved solids to variation of precipitation frequency and intensity.

A relationship between specific gravity and viscosity seems to exist (fig. 32). Linear regression of these variables produced a correlation coefficient of 0.873. If additional viscosity data had been available, this correlation might have improved.

The mean value for specific gravity of the waste was used as input for the numerical model. For comparison, Devonian brine sampled during construction of WDW2 had a specific gravity of 1.011. The linear relationship between viscosity and specific gravity was assumed to be valid; thus, viscosity was determined using the mean specific gravity of the waste (fig. 32).

All modeling was conducted under isothermal conditions. Although the temperature of the injected fluid varied throughout the year, it was assumed that the temperature of the formation would not change significantly from its mean temperature because of injection. The formation temperature was determined from a temperature log run down the DOW on December 18, 1986. The mean formation temperature was 34.4°C (94°F).

Compressibility of the Fluids

Lab-determined values for the compressibility of the waste and brine were not available; however, compressibility values for common saline solutions were available in the literature. Millero et al. (1974) published compressibility values for NaCl, $MgCl_2$, $NaSO_4$, and $MgSO_4$ as a function of temperature and molality. Figure 33 depicts the fluid compressibility in relation to temperature and molality for NaCl solutions.

Roy et al. (1989) characterized the brine and waste as predominantly NaCl solutions. Table 14 shows the chemical analysis of the Velsicol waste, Velsicol dilute waste, and Devonian brine. In this context, waste refers only to the fluids from the plant processes. Dilute waste, typically the fluid injected, comprises fluids from the plant processes and surface runoff. The sample of Devonian brine was obtained from the DOW in June 1987.

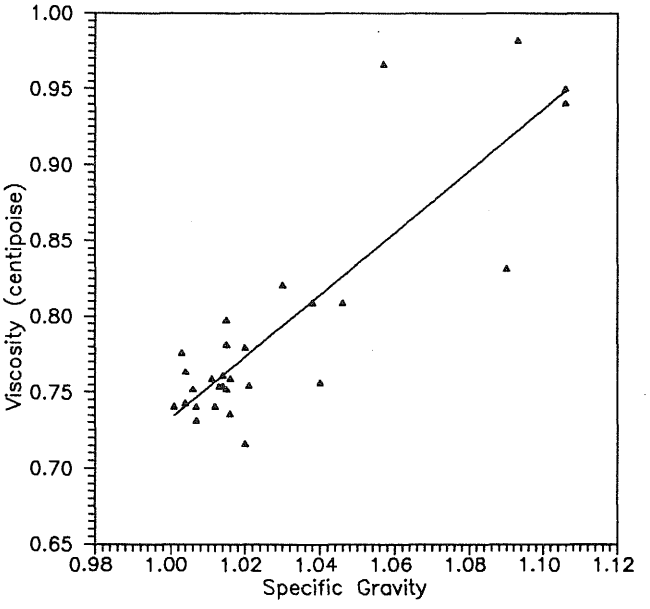


Figure 32 Relationship between waste viscosity and specific gravity.

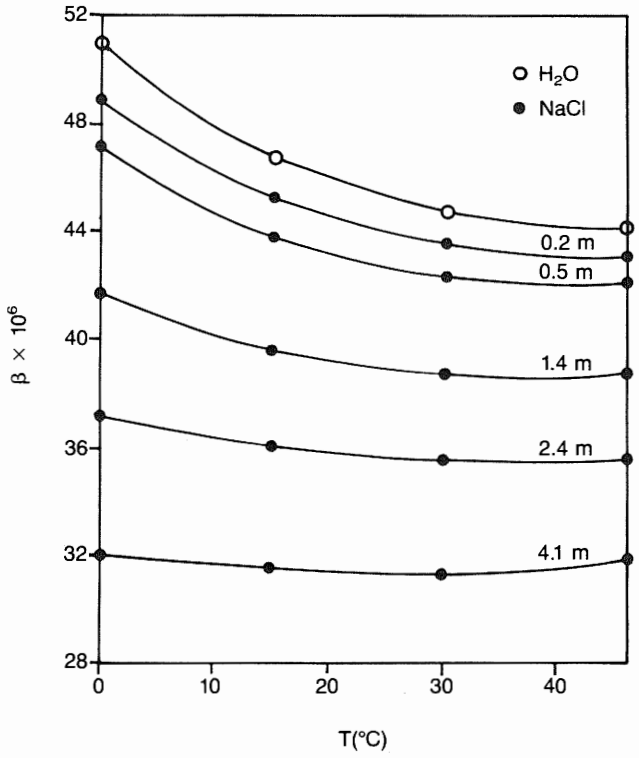


Figure 33 The compressibility of water and NaCl solutions versus temperature (Millero et al. 1974).

Table 14 Chemical analysis of waste and brine

Parameter (unit)	Waste	Dilute waste	Brine
pH	12.92	12.85	9.07
Eh (mV)[a]	+572	+572	-154
EC (mmhos @ 25°C)	403	56[b]	22
TDS (mg/L)	215,900[b]	37,300[b]	—
Cl (mg/L)	112,664	15,400	12,700
F (mg/L)	151	—	20.1
Na (mg/L)	86,350	—	8,370
SO_4 (mg/L)	61.5	—	182
NO_3 (mg/L)	274	—	25.1
Mg (mg/L)	<0.07	—	117.0

a: relative to a standard ZoBell solution
b: Mravik (1987)
from Roy (1987)

Concentrations of the major anion and cation were used to determine the molality of each fluid. Compressibility of each fluid was determined on the basis of the molality and two assumptions: (1) that the temperature was 34.4°C and (2) that the fluids could be considered NaCl solutions. Table 15 shows the molality and compressibility of the three fluids.

Review of the TDS data for the waste and dilute waste indicated that the "average" waste injected into WDW2 (TDS = 38,346 mg/L) had a slightly higher TDS concentration than the dilute waste. Thus the compressibility of the "average" waste should be close to, but slightly lower than, the compressibility of the dilute waste. (See table 18 for the value used.)

Table 15 Compressibility of waste and brine

Fluid	Molality (moles/kg)	Compressibility (1/Pa)
Waste	3.76	3.185×10^{-10}
Dilute waste	0.799	4.105×10^{-10}
Brine	0.703	4.145×10^{-10}
Waste	—	4.46×10^{-10}

Volume of Injected Waste

Since waste injection began in March 1972, Velsicol (1987) reported that 1.4623×10^9 gallons of fluid have been injected via WDW2. Simple volumetric equations were used to determine the extent to which these fluids have moved within the injection zone.

Cross-plotted analysis of geophysical logs indicated that the thickness-averaged porosity of the injection zone is 12.5 percent. Assuming that waste has flowed through the entire thickness (174 ft) of the injection zone and radially from the well, the pore volume of the injection zone from WDW2 to the DOW (1,660 ft) is 1.406×10^9 gallons. Thus the cumulative volume of injected fluid is equivalent to 1.04 pore volumes. To account for this fact, model input of fluid data was based on the physical properties of the waste. In this project, only groundwater flow was simulated; thus, the properties of the fluid must be homogeneous throughout the injection system. To consider nonhomogeneous fluids, one would need to model solute transport.

Modeling Results

Most numerical modeling studies of groundwater flow include several modeling phases, which have also been followed in this study. First, verification of the model is conducted. In this stage, the model is used to simulate known analytical solutions. This phase is typically followed by history matching or model calibration. Here, the model was used to simulate field data, usually collected during a pump test. Sensitivity analysis generally follows model calibration. During this phase, the effect of pertinent parameters is quantified. The final stage is the prediction stage, which is an exercise in "what if." For example, what will the pressure buildup be at the well if a certain flow rate is continued for 30 years. The following discussion describes each of these phases for this project.

Model Verification

Model verification was necessary since HST3D was a new code. Verification allowed the modeler a chance to become familiar with this new model and to check the model accuracy versus analytical solutions. HST3D was verified using two analytical solutions: unsteady radial flow in a confined aquifer with constant pumping rate (Theis 1935), and unsteady radial flow in leaky systems with no storage in the semipervious layer at a constant pumping rate (Hantush 1964).

Theis Solution. Theis solution is an analytical solution for unsteady radial flow in confined aquifers. This solution is readily available in any groundwater text and is not repeated here. Input data for the analytical solution and HST3D are listed in table 16.

A radial coordinate system was used to discretize the groundwater flow domain: 50 nodes in the r-direction and 20 nodes in the z-direction. The radius of the aquifer simulated was 24,960 m. No-flow conditions were applied at all boundaries.

Figure 34 shows the drawdown at a point 100 m from the pumping well determined by numerical and analytical methods. The two solutions are identical.

Leaky Aquifer Solution . HST3D was also verified against an analytical solution for wells in leaky systems without storage in the semipervious layer (no storage in the semipervious is an as-

Table 16 Input data for the Theis solution

HST3D	Analytical solution
aquifer thickness, b = 3.05 m hydraulic conductivity, K = 3.29 x 10^{-4} m/sec porosity, n = 0.20 matrix compressibility, α = 3.34 x 10^{-8} Pa^{-1} fluid compressibility, β = 4.53 x 10^{-10} Pa^{-1} viscosity, μ = 0.001 kg/m-sec fluid density, ρ = 999.5 kg/m^3 pumping rate, q = 3.00 x 10^{-3} m^3/sec	transmissivity, T = 0.001 m^2/sec storativity, S = 0.001 pumping rate, q = 3.0 x 10^{-3} m^3/sec

sumption inherent to HST3D) (Hantush 1964). A radial coordinate system was used to discretize the aquifer: 50 nodes in the r-direction and 5 nodes in the z-direction. No-flow conditions were applied at the lower and radial boundaries. A leaky aquifer boundary condition is applied at the top boundary. The remaining input data for this simulation are listed in table 17.

The drawdown for a well 20 m from the pumping well was determined using the analytical and numerical solutions (fig. 35). The numerical solution tends to slightly underestimate the drawdown. These results are closer to the analytical solution than those reported by Ward et al. (1984) and are considered to be acceptable.

Model Calibration

Data used for model calibration (history matching) were obtained from the long-term injection test described in chapter 3 (p. 42). and plotted on figure 28. The conceptual model for the injection system was based on data presented in Long-Term Injection Test (p. 42) and is shown on figure 36. The hydraulic conductivity and physical dimensions in the vertical direction are also depicted on this figure. Other pertinent input data are listed in table 18. The injection system was discretized with radial coordinates: 60 nodes in the r-direction and 22 nodes in the z-direction.

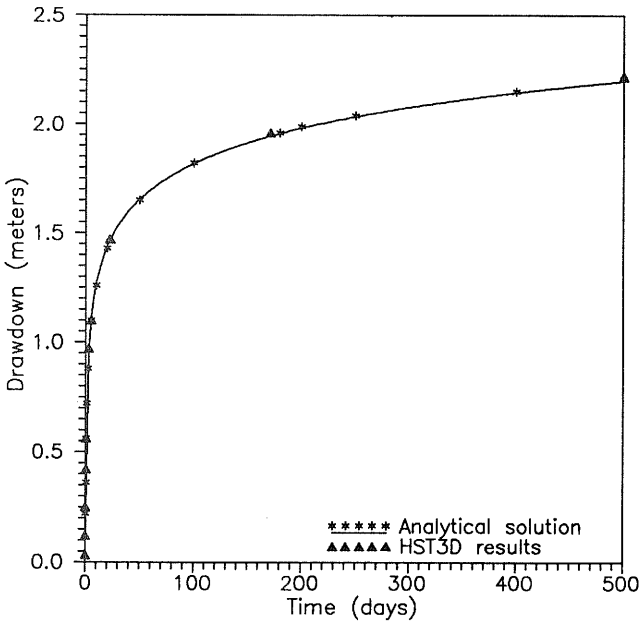


Figure 34 (left) Comparison of model-predicted drawdowns with results from Theis Analysis.

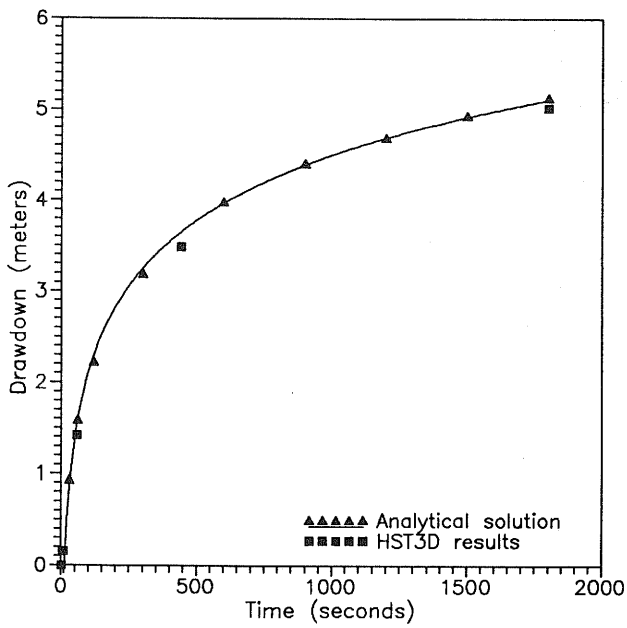


Figure 35 Comparison of model-predicted drawdowns in relation to time with Hantush Analysis.

Table 17 Input data for leaky aquifer simulation

HST3D	Analytical solution
aquifer thickness, b = 3.05 m	transmissivity, $T = 10^{-3}$ m^2/sec
aquifer intrinsic hydraulic conductivity, $K = 3.35 \times 10^{-11}$ m^2	storativity, $S = 10^{-4}$
matrix compressibility, $\alpha = 3.34 \times 10^{-8}$ Pa^{-1}	aquitard hydraulic conductivity, $K' = 3 \times 10^{-10}$ m/sec
fluid compressibility, $\beta = 4.53 \times 10^{-10}$ Pa^{-1}	aquitard thickness, b′ = 0.30 m
fluid density, $\rho = 999.5$ kg/m^3	pumping rate, q = 0.014 m^3/sec
viscosity, $m = 1.00 \times 10^{-3}$ kg/m-sec	
aquitard intrinsic hydraulic conductivity, $K = 3.06 \times 10^{-17}$ m^2	
aquitard thickness, b′ = 0.30 m	
pumping rate, q = 0.014 m^3/sec	

Table 18 Selected input data for model calibration

radius, r = 15870.90 m
$\beta = 4.00 \times 10^{-10}$ Pa^{-1}
$\alpha = 4.50 \times 10^{-10}$ Pa^{-1}
$\rho = 1020$ kg/m^3
$\mu = 7.87 \times 10^{-4}$ kg/m-sec

No-flow conditions were applied at the top and bottom boundaries, while an aquifer influence was applied at the radial boundary.

Kipp (1986) describes the use of aquifer influence boundary conditions (AIF BC) as a simple, but approximate, method for embedding an inner region of groundwater simulation within a larger region where groundwater flow may be treated in an approximate fashion. The use of aquifer influence functions reduces the size of the computational grid with a corresponding reduction in computer storage and execution time.

The natural hydraulic gradient of the Devonian limestone is very low (see p. 32); thus, the hydraulics of the injection well will dominate the groundwater hydraulics in the area surrounding the well. The flow rate across an AIF boundary is a function of the potentiometric head and hydrogeologic characteristics of the aquifer. The use of the AIF BC was favored over a specified head or flow-type BC, since the AIF is a more accurate representation of the hydraulics of the injection system.

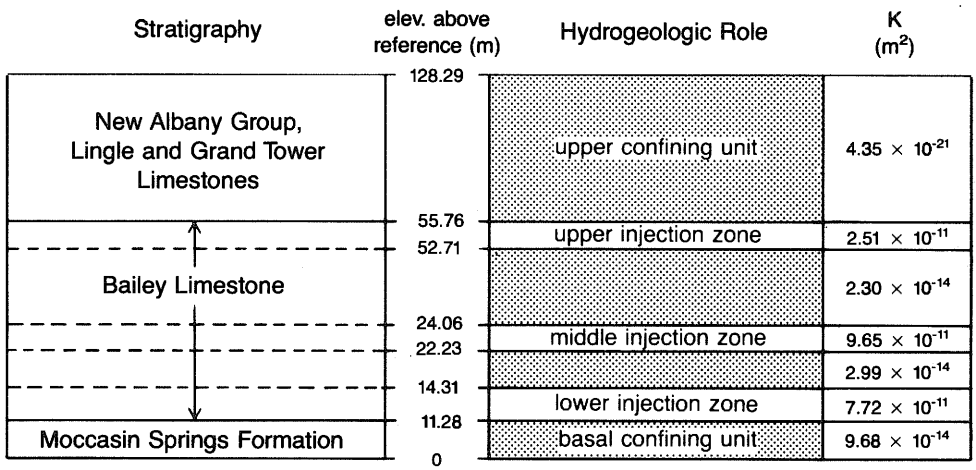


Figure 36 Conceptual model 1 of the injection system.

The T and S values calculated on the basis of input data, as well as the values determined from field testing, are presented in table 19. The input data and field data match reasonably well. Closer agreement of the field and model T and S values probably could have been obtained with minor adjustments to the input data (chiefly K, α, and β); however, the T and S values used were considered satisfactory.

The model values for T and S were even more satisfactory considering that two of the chief input parameters, α and β, are consistent with published values. Fluid compressibility (β) has been previously discussed (p. 52).

Table 19 Comparison of transmissivity (T) and storativity (S) values

	Field test	**HST3D**
T (m^2/min)	0.386	0.373
S (-)	2.47×10^{-4}	2.65×10^{-4}

Our rock compressibility (α) values also agreed with values in the literature. Birch (1966) reports that $\alpha = 1.22 \times 10^{-11}$ Pa^{-1} for dolomite. Domenico and Mifflin (1965) report α for sound rock ranges from 10^{-9} to 10^{-10} Pa^{-1}, while α for jointed rock ranges from 10^{-8} to 10^{-10} Pa^{-1}. Since secondary porosity was present in the cores retrieved, one would have expected that α for the dolomite at the study site would be slightly greater than $\alpha = 1.22 \times 10^{-11}$ Pa^{-1}. In fact, the values of the cores tested range from 1.55×10^{-10} to 3.26×10^{-11} Pa^{-1}. Thus the use of $\alpha = 4.50 \times 10^{-10}$ Pa^{-1} for model calibration seemed reasonable. As discussed in appendix C, the scanning electron microscopy (SEM) work indicated that secondary porosity was present, primarily in the form of vugginess and some localized microfractures. The microfractures were very small and tended to be interconnected. Because of the close spacing and size of the microfractures, modeling flow through this geologic material as flow through porous media was considered to be a valid assumption.

The intrinsic permeability values for the three injection zones ranged from 2.5×10^{-11} to 9.7×10^{-11} m^2 (25.4 to 97.8 darcys). Schmoker et al. (1985) summarized data for limestone and dolomite petroleum reservoirs throughout the United States. These authors report that only 11 percent of all dolomite reservoirs exceed 0.1 darcy. Freeze and Cherry (1979) list 0.2 darcy as an upper permeability limit for limestone and dolomite. Clearly, the permeability values for the injection zones seem to be quite high. The permeabilities used as model input were based on the results of the injection test and were higher than the laboratory-determined permeabilities. There appear to be two explanations for the apparent high permeability values. First, the permeability values were actually calculated from transmissivity values and thickness of "permeable" units of the aquifer. The thickness of these units could have been underestimated. Another possibility was that the cores may not be representative of the overall injection system. Greater emphasis was placed on the results of the injection test, since this is an in situ measurement of the system.

In addition to aquifer transmissivity, another control on specifying intrinsic permeability was the results of the flowmeter survey conducted during phase II of the field experiments. The intrinsic permeability of the three injection zones was adjusted so that the flow into each of these three zones matched the flow profile defined by the flowmeter. Thus in the model, 48.1 percent of the injected fluid flowed into the lower injection zone, 36.2 percent into the middle zone, and 15.7 percent into the upper zone.

Figure 37 depicts the head build-up at the DOW during the injection test and the buildup predicted by HST3D versus time. The model overpredicted the head buildup at times by less than 20 hours; however, the results at later times are very close. Oscillation of the head buildup (field data) is also evident in figure 37. This oscillation is believed to be a manifestation of earth tides and not a variation in the pumping rate.

Matching model results with the later field results was considered more important because the main use of the model was to predict long-term effects of injection. The input data were reasonable, and the predicted head buildup matched reasonably well the head buildup observed in the field; therefore, model calibration was deemed successful.

Sensitivity Analysis

A rigorous sensitivity analysis as described by Yeh (1986) was not conducted. The sensitivity analysis conducted here involved varying significant parameters and noting the effect of this variation on head buildup (Δh) at the DOW, the parameter of interest. The significance of various parameters (i.e., injection rate, hydraulic conductivity) was observed during the two previous stages of this project. Based on these observations, sensitivity analysis was conducted for the following parameters: boundary conditions, injection rate, rock compressibility, fluid compressibility, hydraulic conductivity, and anisotropy. The sensitivity analysis is summarized here and described in detail in appendix D.

Injection rate and hydraulic conductivity were the most sensitive input parameters. That is, a given change in injection rate or hydraulic conductivity would produce the largest change in Δh observed at the DOW. The type of boundary condition and the location of the boundary could also significantly affect the head buildup predicted by the model. In decreasing order, the most sensitive parameters were injection rate and hydraulic conductivity, rock compressibility, anisotropy, and fluid compressibility.

Model Projections for Long-Term Injection

Using the conceptual model developed during the model calibration phase, we investigated the effects of long-term, continuous injection at two rates: 1.150×10^{-2} and 2.208×10^{-2} m^3/sec. The first injection rate is the "average" rate at which the company injected waste during the life of the well. This was calculated by dividing the cumulative volume of waste injected by the length of operation for WDW2. The second injection rate is the maximum average injection rate permitted by the Illinois Environmental Protection Agency (IEPA 1987).

Embedded in this calculation of the "average" injection rate is the assumption that the well was operated on a continual basis; however, WDW2 was not in operation continually. A larger head buildup in the injection system would be produced by assuming continuous (24-hour) operation because pressure in the injection system would never bleed off.

HST3D was used to predict the head buildup in the injection system over a 30-year period. The decline in head was also modeled for an additional 30-year postinjection period. Thirty years was chosen since this is typically the length of service for an injection well. Because of problems experienced with HST3D, the injection rate during the postinjection period could not be set to zero. During the postinjection period, the injection rate was set as low as possible, $q = 1.82 \times 10^{-4}$ m^3/sec. Figure 38 shows the head buildup in relation to radial distance from the injection well after 10,927 days (30 years). At the DOW, Δh after this time is 0.03 m. Thus, use of $q = 1.82 \times 10^{-4}$ m^3/sec during the postinjection period did not significantly impact the pressure decline during the postinjection period.

Injection Scenario 1

Injection scenario 1 is injection for 30 years at a rate of 1.150×10^{-2} m^3/sec, followed by a postinjection period in which $q = 1.82 \times 10^{-4}$ m^3/sec. Figure 39 shows the response of the injection system during both 30-year periods (262,980 hours each). Head buildup at the DOW increases exponentially. After 30 years of injection, $\Delta h = 1.61$ m at the DOW. In terms of Δh, steady state was approached but not reached. The head buildup at the DOW also dropped exponentially. Approximately 900 hours after the change in the injection rate, the head buildup was approximately half of its maximum value. Nearly 7.5 years (66,000 hours) after the change in the injection rate,

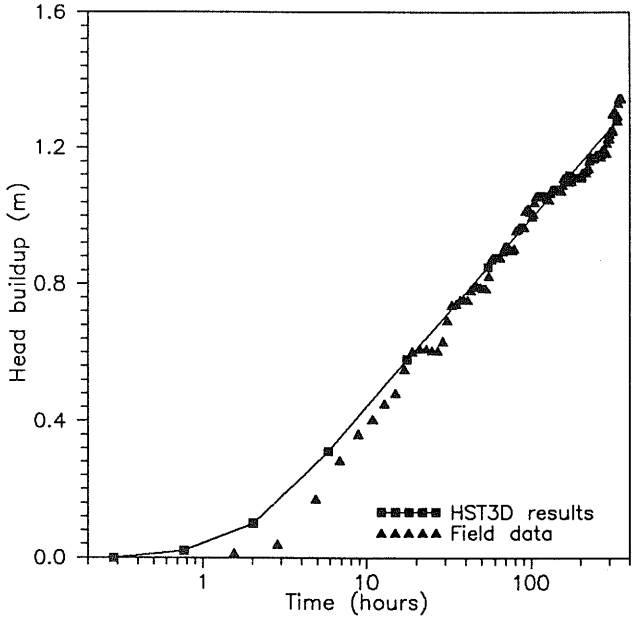


Figure 37 (left) Comparison of model-predicted Δh versus field data for DOW.

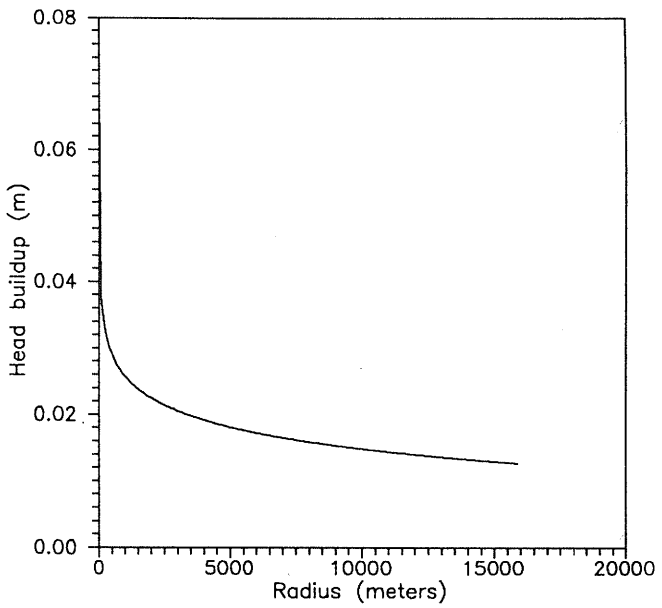


Figure 38 Head buildup versus radial distance from WDW2 $q = 1.82 \times 10^{-4}$ m^3/sec.

the head buildup was only 0.01 m, after correcting for Δh due to injection at $q = 1.82 \times 10^{-4}$ m^3/sec. During the 30-year postinjection period, the head buildup did not reduce to 0.00 m.

Injection Scenario 2

During the second injection scenario, the effects of injection for 30 years at $q = 2.208 \times 10^{-2}$ m^3/sec were investigated. A postinjection period followed during which $q = 1.82 \times 10^{-4}$ m^3/sec. Figure 40 shows the head buildup at the DOW. The results were similar to the results for injection scenario 1. The head buildup increased exponentially to a maximum Δh = 3.20 m after 30 years of injection. Also, after the injection rate was reduced, the head fell exponentially. The head buildup approached but did not go to 0.00 m during the postinjection period.

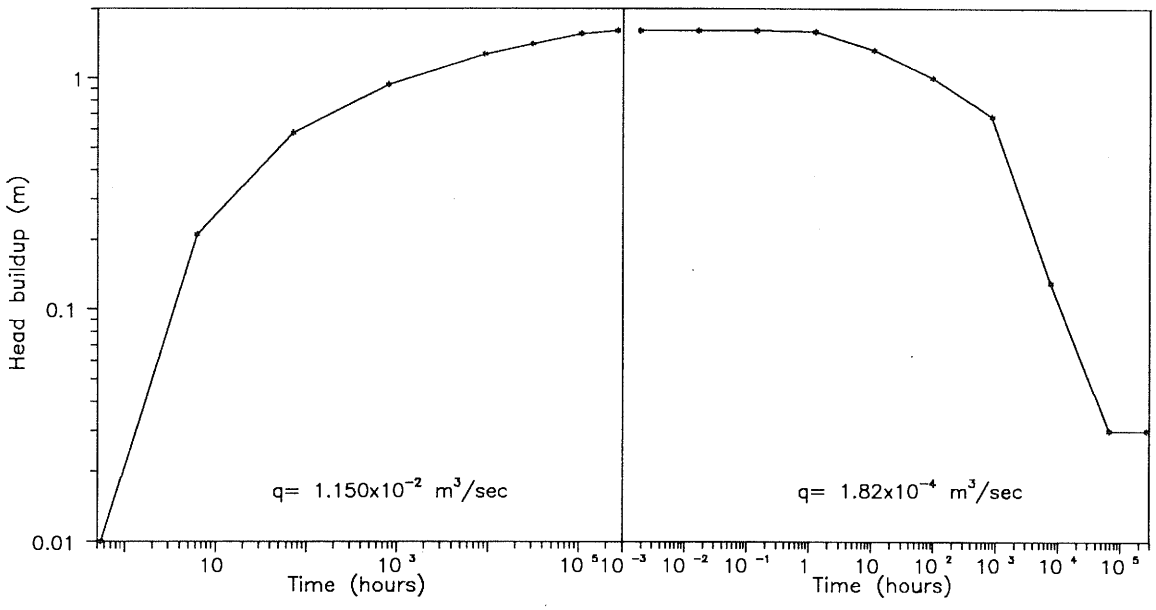


Figure 39 Injection scenario 1: head buildup and decline with time at the DOW.

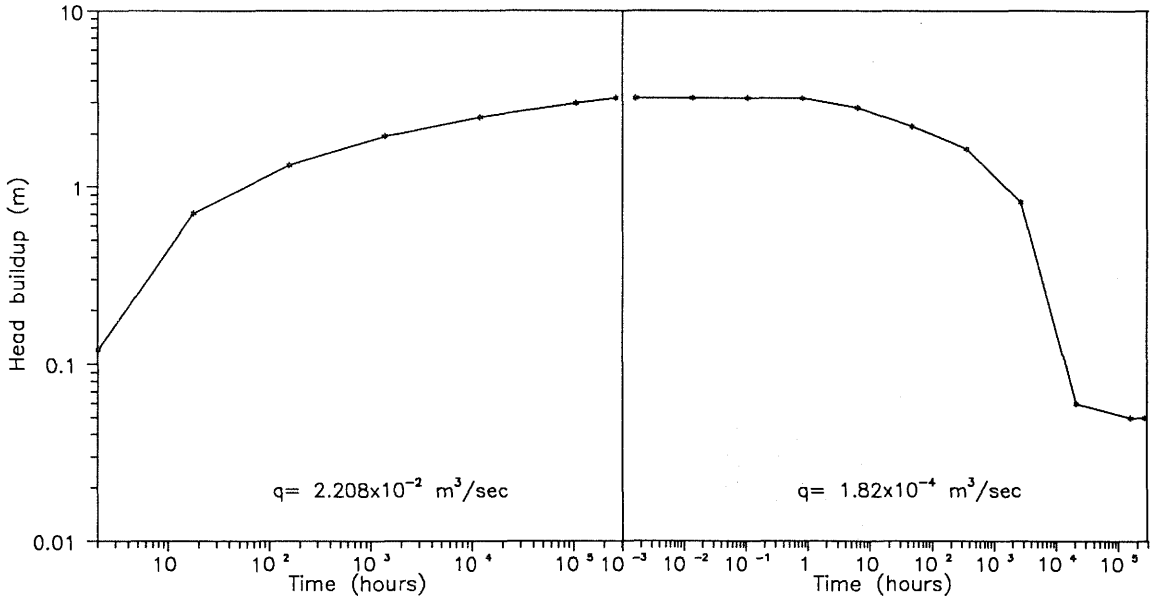


Figure 40 Injection scenario 2: head buildup and decline with time at the DOW.

Figure 41 shows the head buildup at the WDW2 during the injection and postinjection periods. The results were similar to the results shown in figure 40 except the magnitude of the head buildup was greater at the injection well. After 30 years of injection, Δh at WDW2 was 7.88 m. For comparison, Δh at WDW2 for injection scenario 1 was 4.22 m.

Maximum hydraulic pressure was 7.081x10^6 Pa (1,027 psi) and occurred at the bottom of the well after 30 years of injection under injection scenario 2. The pressure at the base of the confining layer equaled 6.687x10^6 Pa (970 psi). The pressure increase due to 30 years of injection was 7.73x10^4 and 6.69x10^4 Pa at the bottom of the well and the base of the confining unit, respectively. The pressures resulting from injection scenario 1 (q = 1.150x10^{-2} m^3/sec) were slightly lower than those listed here.

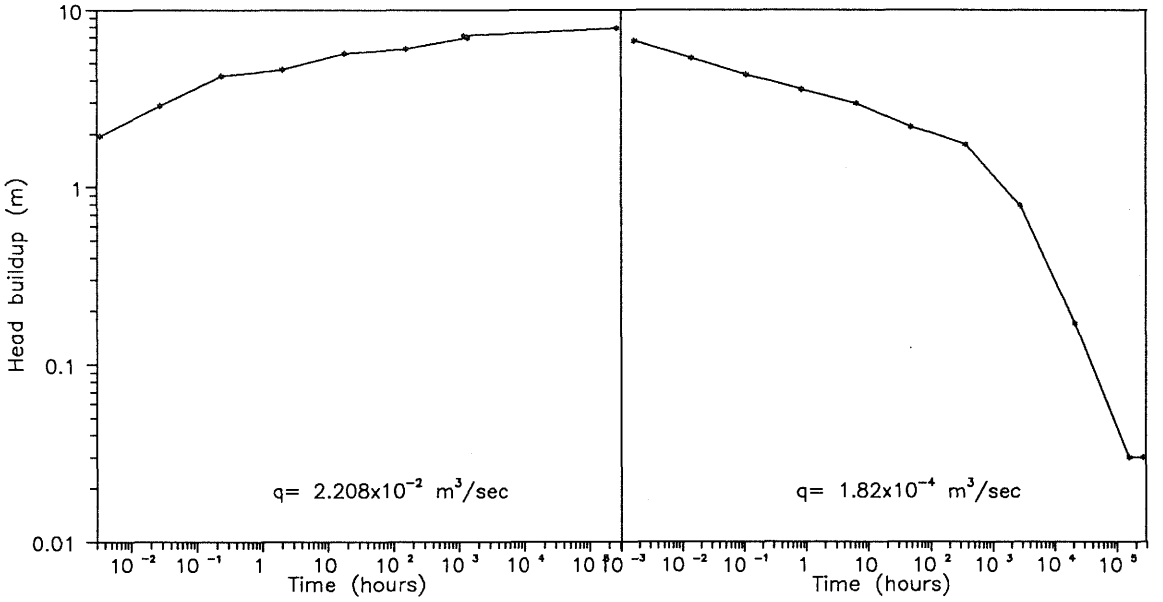


Figure 41 Injection scenario 2: head buildup and decline with time at WDW2.

In Illinois, the hydraulic fracture gradient is generally considered to be equal to $1.5x10^4$ Pa/m (0.65 psi/ft). Using this value, the hydraulic pressure necessary to initiate fractures was calculated as 1.19×10^7 Pa (1,694 psi) for the bottom of the well (depth = 794.3 m) and as $1.12x10^7$ Pa (1,591 psi) for the base of the confining unit (746.2 m). Thus pressures due to 30 years of continuous injection at the maximum permitted injection rate were much less than the pressure calculated to initiate hydraulic fracturing.

Hypothetical Conduits

During this final phase of modeling, the hydraulic response due to the presence of hypothetical conduits was investigated throughout the injection system. Jones and Haimson (1986) describe some hypothetical conduits pertinent to underground injection. These conduits, which allow fluid movement from the injection zone, include abandoned wells, microannuli at the injection well, and permeable fault zones. Time constraints restricted the investigation to the effect of a microannulus at the injection well. Accomplishing this task required numerical modeling to evaluate whether the pressure response in the injection system or in an overlying unit could be used to identify fluid movement from the injection zone. Three monitoring strategies were evaluated: monitoring at the injection well (WDW2), at the observation well (DOW), and in the overlying aquifer.

A new conceptual model of the site hydrogeology was developed for this task (fig. 42). A thicker sequence of geologic materials than that previously used included the Devonian limestones, the overlying New Albany Shale (a confining unit), the "Carper sand" (a permeable unit), and the Borden Siltstone (another confining unit). Since "Carper sand" lies near the base of Borden Siltstone, for purposes of modeling, it is considered the basal horizon of this formation. Hydrogeologic characteristics for these units appear on figure 42.

For this conceptual model, the head buildups at the injection and monitoring wells were slightly lower than the buildups used in the original model; however, the results were considered acceptable. The slight decrease (0.03 m at the DOW) was probably due to the greater thickness of compressible geologic materials for the conceptual model.

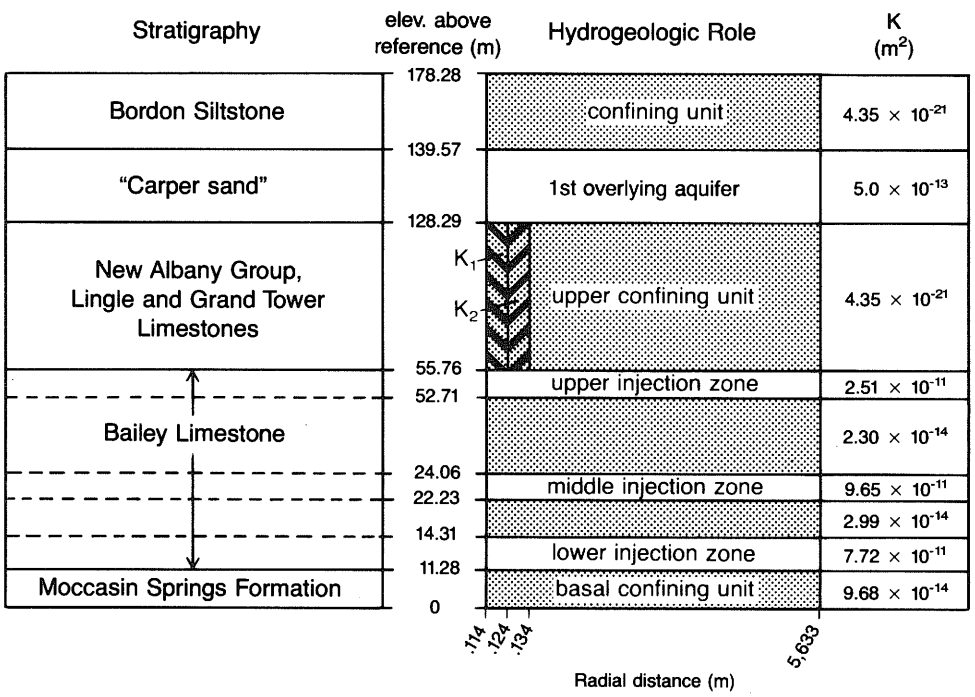


Figure 42 Conceptual model 2 of the injection system

Modeling Results: Hypothetical Conduit Scenario

In this scenario, a microannulus was assumed to have developed at the injection well. Extending from the top of the uppermost injection zone to the base of the Carper, the microannulus connected these two permeable units (fig. 42) and was input into the model as two zones. The first zone was considered the microannulus, and the second zone, a transition between the microannulus and the New Albany Shale. Both zones were 0.01 m thick and discretized using three nodes. Several runs were made, with different zone permeabilities (table 20). CT3DB1 was the baseline run used for comparison.

Table 20 Permeability (m^2) of the microannulus

Run	Microannulus (K1)	Transition zone (K2)
CT3DB1	4.35×10^{-21}	4.35×10^{-21}*
CT3DB2	1.00×10^{-12}	1.00×10^{-14}
CT3DB3	1.00×10^{-10}	1.00×10^{-12}
CT3DB5	1.00×10^{-9}	1.00×10^{-11}
CT3DB4	1.00×10^{-8}	1.00×10^{-10}

* same permeability as New Albany shale.

For this series of model runs, the maximum permitted injection rate ($q = 2.208 \times 10^{-2}$ m^3/sec) was used to maximize the pressure gradients in the injection system. Injection continued at this rate for 365 days. Because the "Carper sand" does not produce water or hydrocarbons, hydrogeologic data for this unit are rare. On the basis of interpretations of geophysical logs from wells near Marshall, which indicated that the Carper is a permeable sandstone, permeability was assumed to be 5.0×10^{-13} m^2.

For analysis of results, a head difference of 0.05 m, when compared with results of CT3DB1, was considered monitorable. Differences of less than 0.05 m were not considered sufficient to be monitored because of errors in measurement, head fluctuations due to earth and/or barometric tides, and related factors.

Head buildup in relation to time is shown for WDW2 (fig. 43), DOW (fig. 44), and the base of the Carper at WDW2 (fig. 45). As the permeability of the microannulus increased, the head buildup at WDW2 decreased slightly. For CT3DB4 ($K1 = 1.00 \times 10^{-8}$ m^2), difference in head buildup was -0.23 m after 1 year. Head buildup for the other cases were lower— for instance, Δh = -0.10 m when $K1 = 1.00 \times 10^{-10}$ m^2. A change in the head build-up of this magnitude at an operating injection well might not be monitorable because of head buildup associated with other factors, such as wellbore plugging and pipe friction increases.

For the five cases investigated, no monitorable difference in head buildup was observed at the DOW (fig. 44). For CT3DB4 ($K1 = 1.00 \times 10^{-8}$), head buildup was lower than the other cases by just 0.01 m after 365 days. Thus monitoring the DOW would not detect the leak at the microannulus. Monitorable differences in head buildup were predicted at the base of the Carper in three of the four cases. For CT3DB3, the difference after 365 days was 0.08 m. The differences after 365 days were greater for CT3DB5 (0.77 m) and CT3DB4 (3.98 m). The radial extent of head buildup at the base of the Carper varied for each of the cases. For CT3DB5, it was approximately 100 m, and for CT3DB4, more than 6,000 m (fig. 46).

In summary, monitoring the DOW would not reveal the presence of a leaky microannulus, in part because of the distance between the injection and observation wells. Monitoring the injection well might reveal a leaky microannulus, but the differences in head buildup for the cases investigated might be masked by well bore plugging, corrosion buildup in the tubing, and other related factors. Finally, monitoring in the overlying aquifer appears to be the best alternative, but it depends on the hydraulic conductivity of the microannulus. As the hydraulic conductivity of the hypothetical

conduit increases, the volume of fluid moving into the overlying aquifer and the head buildup also increases. The head buildup observed in the Carper is also a function of its hydraulic conductivity. Lower Δh would be observed if the Carper were more permeable. On the other hand, higher Δh would be observed over a smaller area if the Carper had a lower hydraulic conductivity.

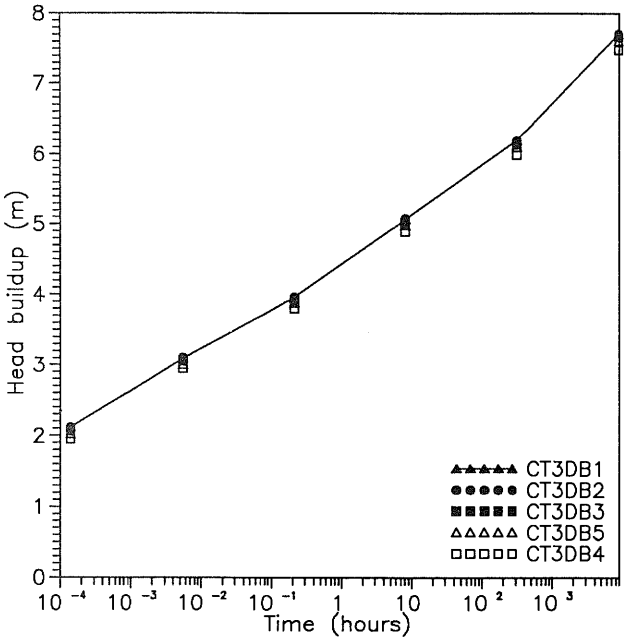


Figure 43 Effect of microannulus on the head buildup at the WDW2.

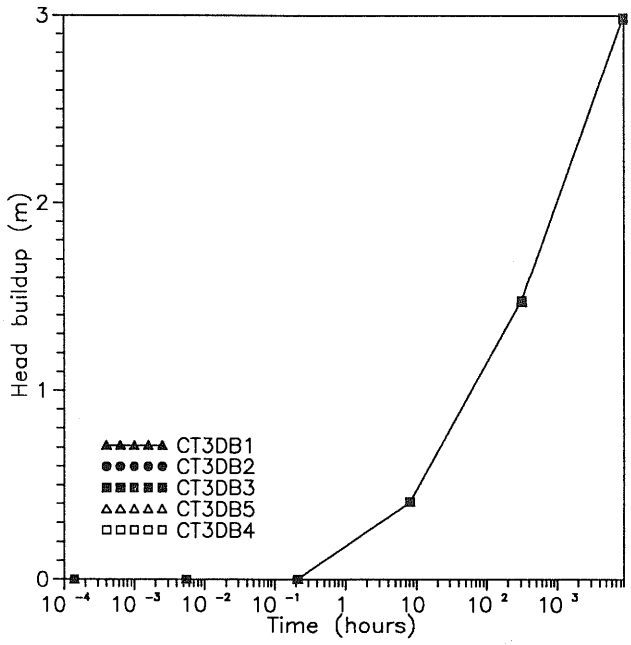


Figure 44 Effect of microannulus on the head buildup at the DOW.

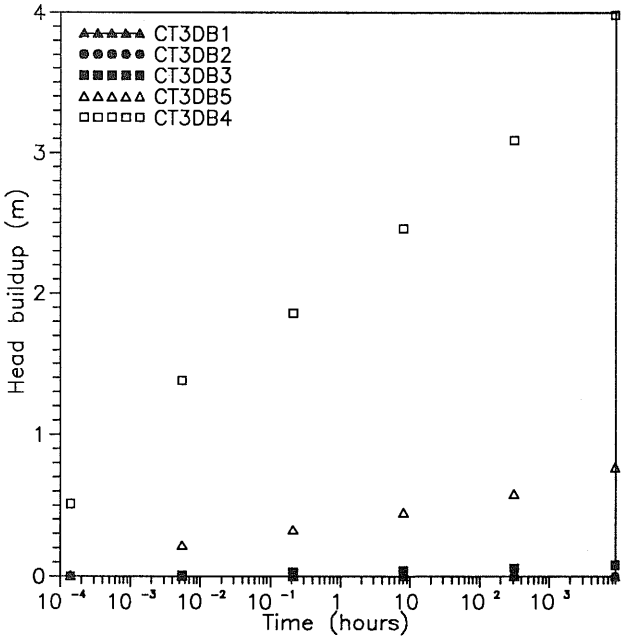


Figure 45 Effect of microannulus on the head buildup in the "Carper sand."

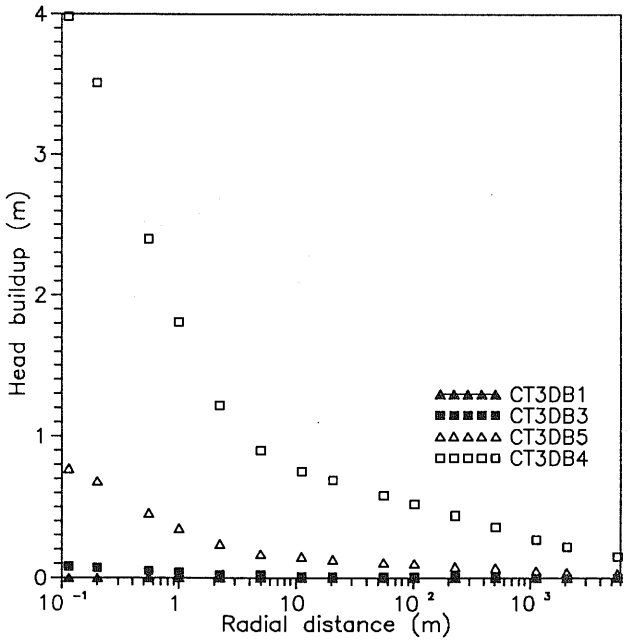


Figure 46 Head buildup in the "Carper sand" versus radial distance from WDW2.

5. SUMMARY AND CONCLUSIONS

Evaluation of Injection Scenarios

Available records and logs pertinent to the injection system were studied, hydraulic tests were conducted, geophysical logs were run, and other tests were conducted on-site to determine the hydrogeologic characteristics of the injection system. Regional and site-specific descriptions of the system's stratigraphy, structural geology, and hydrogeology were generated from analyses of these logs and test results. These descriptions formed the basis of input for the numerical groundwater flow model (HST3D) used to investigate the hydraulic effects of injection upon the injection system. Other input included data on the physical and chemical characteristics of the injected wastewater and the native brine in the injection system.

Before the effects of various injection scenarios were investigated, HST3D was verified with respect to two analytical solutions (figs. 34 and 35) and calibrated with respect to data collected during an injection test (fig. 37). Both verification and calibration were considered satisfactory.

Once calibrated, the model was used to predict the effects of various injection scenarios. The effect of long-term injection was investigated at two constant injection rates: the average historical rate (1.150×10^{-2} m^3/sec) and the maximum average permitted rate (2.208×10^{-2} m^3/sec). Under both scenarios, significant head buildup was observed at the injection well and radially from it. During the simulated 30-year injection period, steady state was approached but not obtained during either injection scenario. During the subsequent 30-year postinjection period, decrease in head buildup was fairly rapid—dropping to half in less than 2,000 hours for both scenarios. The maximum hydraulic pressures at the bottom of the well and at the base of the upper confining unit were significantly lower than the pressures calculated to initiate hydraulic fracturing.

The continuity of the regional stratigraphy and its qualitative permeability were determined from the regional and site-specific study. Numerical modeling indicated that the pressures resulting from waste injection were lower than pressures calculated to initiate hydraulic fracturing; thus new fractures would not be initiated. From a hydraulic viewpoint, therefore, waste injected within this injection system would be contained and would be considered protective of human health and the environment for the two injection scenarios investigated.

These results are based on an assumption that hydraulic conductivity remains constant. However, from available data it appears that the high pH of the injected wastewater causes it to react with the dolomite present in the injection zones, forming brucite ($Mg[OH]_2$), which reduces the hydraulic conductivity of the injection zone. Apparently, greater amounts of brucite formed in the zones where there was a greater flow of fluids; thus the zones with higher permeability were affected first. This hypothesis must be verified by additional work, which is beyond the scope of this project. At the study site, the long-term effect of this decrease in permeability on injectivity needs to be investigated. Any further decrease in the hydraulic conductivity of the injection zones will invalidate the results of the numerical modeling conducted for this study. In addition, any reduction in hydraulic conductivity of the injection zones will most likely cause an increase in hydraulic pressure if the injection rate remains constant. In such a case, hydraulic fracturing may be of concern.

Evaluation of Monitoring Strategies

The model was also used to investigate the hydraulic response throughout the injection system when a hypothetical conduit was introduced. In this scenario, a microannulus at the injection well was introduced, hydraulically connecting the uppermost injection zone and an aquifer immediately overlying the upper confining unit.

Model results were reported in terms of difference in head build-up when the microannulus was and was not present. At the WDW2, Δh (-0.23 m) was greatest for the scenario with the greatest microannulus permeability ($1x10^{-8}$ m^2). A difference of this magnitude at an operating well would be considered unmonitorable because of interferences such as increased Δh resulting from well bore plugging or tubing corrosion. At the DOW, Δh was considered too low to be monitorable. The difference in the overlying aquifer (Carper sand) was considered monitorable for the microannulus permeability greater than or equal to $1x10^{-10}$ m^2. The head buildup in the Carper is a function of its hydraulic conductivity, the hydraulic conductivity of the microannulus, and the radial distance from the microannulus. Thus from a practical standpoint and for the scenario modeled, the overlying aquifer is the only viable location for hydraulically monitoring leakage via the microannulus.

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APPENDIX A. THEORY AND PRACTICAL APPLICATION OF GEOPHYSICAL LOGGING INSTRUMENTS

Geophysical logging was used in this study to investigate the site and regional hydrogeology, and this section briefly explains the basic operational theory and applications of the geophysical tools used. Comprehensive coverage of every aspect of tool theory or all possible applications is beyond the scope of this project. These tools and their many applications are discussed in greater detail in Bateman 1985a, Bateman 1985b, Helander 1983, Leach et al. 1974, Curtis 1966, Peebler, Hallenburg 1984, Dobrin 1976, Kovacs and Associates 1981, Pickett 1977, Hilchie 1977, Brock 1984a, Brock 1984b, Rider 1986, Gearhart, Gearhart 1983, Dresser Atlas 1981, Schlumberger 1984, Schlumberger 1985, Dresser Atlas 1985a, Dresser Atlas 1985b, Dresser Atlas 1985c, Prasada Rao 1985, Keys and MacCary 1971, and Martin 1982. The discussion below draws liberally from these references.

Caliper Log (CL)

The Caliper Log tool is a theoretically uncomplicated instrument. Most tools still rely on a single or a series of potentiometers (fig. A-1). The potentiometers respond to a number of arms (caliper arms), which transmit information about the borehole environment to the potentiometer actuator. This information is relayed as a series of pulses to the surface recording equipment, which then processes the data.

There are a number of different arm configurations with the CL tool. For the purposes of injection/confining interval evaluation, the one- and four-arm tools are appropriate.

For applications that utilize the numerical CL data, such as calculations involving the Flowmeter Log (FL), the more sensitive four-arm CL tool is employed. For other applications, such as mudcake and washout location and general borehole conditions, a one-arm CL tool (usually run in mechanical combination with another device, such as an Neutron Log, Density Log, or Permeability Log) is utilized almost invariably.

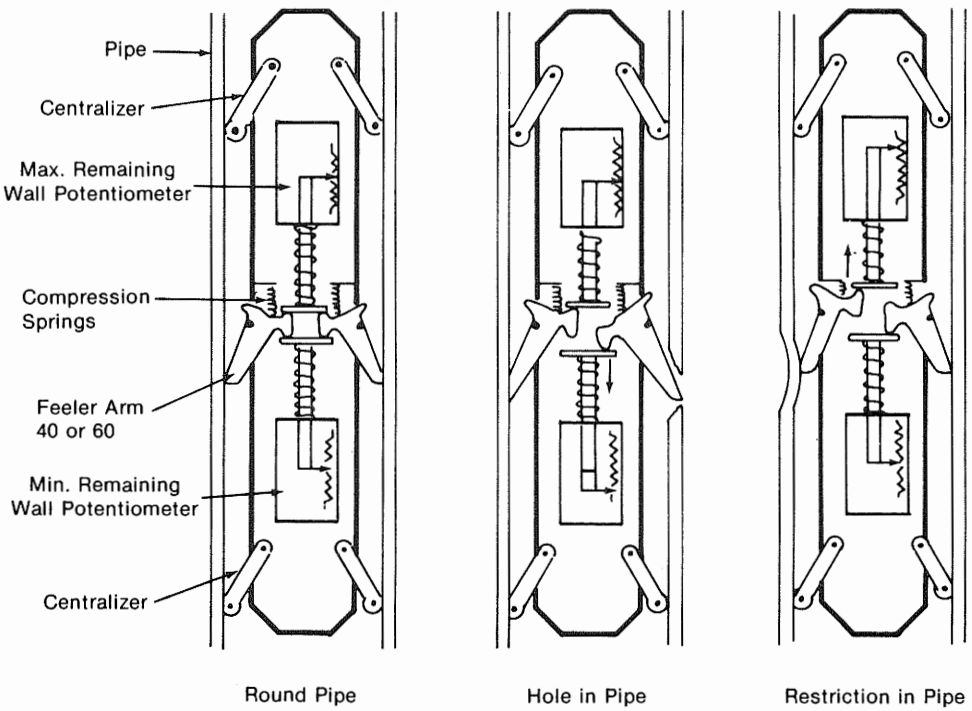

Figure A-1 Caliper Log tool that utilizes a dual potentiometer configuration (from Dresser Atlas 1985c)

Flowmeter Log (FL)

Several types of Flowmeter Log tools are available, and they all operate in a similar fashion. The tool considered in this report is the continuous variety, which would be the most appropriate at the high flow rates often encountered in waste-disposal wells.

The Continuous Spinner Flowmeter Log (CSFL) tool, shown in figure A-2, incorporates an impeller into its design. The impeller rotates in response to fluid movement. This rotation generates a series of electrical pulses that are transmitted uphole to the surface equipment for computer processing. The number of pulses generated is proportional to the number of revolutions per second of the impeller, which can be related to flow velocity. The volumetric flow rate, the measurement of most interest, can be calculated from borehole diameter data obtained from the four-arm CL tool.

The CSFL tool measures fluid velocity very satisfactorily in turbulent fluid flow. Although this flow regime is encountered most often, it nonetheless requires verification. One method of defining whether a flow regime is turbulent is to use the Reynold's Number (Re). Re is defined as

$$Re = vD\rho/\mu \qquad [A\text{-}1]$$

where ρ = fluid density, g/cm^3
v = average fluid velocity, cm/sec
D = hole diameter, cm
μ = fluid viscosity, poise

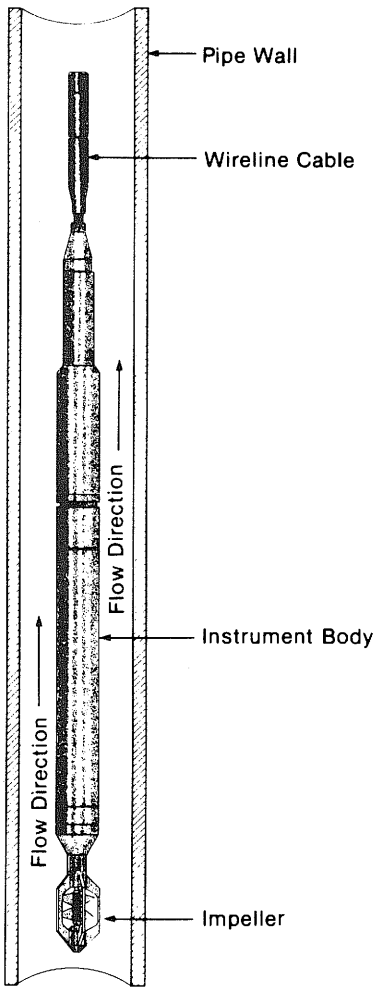

Figure A-2 Continuous Spinner Flowmeter Log tool (from Dresser Atlas 1981).

Re values of 3,000 or greater are used to represent turbulent flow in most literature dealing with fluid flow. For most applications of the CSFL tool in injection/confining interval evaluation, fluid will be injected at the surface to initiate impeller movement. A useful conversion in Re calculations is

$$v = (0.3637)Q/D^2 \qquad [A\text{-}2]$$

where v = average fluid velocity, cm/sec
D = hole diameter, cm
Q = flowrate, barrels per day

This conversion is combined with the definition of the Reynold's Number to yield

$$Re = (0.3637)Q\rho/\mu D \qquad [A\text{-}3]$$

Gamma Ray Log (GRL)

As its name suggests, the GRL detects gamma rays—random, high-energy electromagnetic waves emitted during the decay of unstable radioisotopes. The radioisotopes normally found in rocks are ^{40}K and the daughter products of the uranium and thorium decay series. The GRL discussed here is unable to differentiate the contribution of each individual radioisotope to the total intensity of gamma radiation.

The detector of the tool normally consists of a sodium iodide (NaI) crystal optically coupled to a photomultiplier tube. Atoms of the NaI crystal absorb gamma ray collision energy, which places the electrons of the atoms in a higher energy state. When the excited electrons lose this acquired energy and fall back into their original state, they give off light that is converted to a voltage pulse through the photomultiplier tube. These pulses are transmitted uphole and converted, on the appropriate scale, to a measure of the gamma ray intensity.

Because of the high natural concentration of ^{40}K in clay minerals, shales generally exhibit a high gamma ray intensity. On the other hand, sandstones and carbonates generally produce a lower gamma ray count because of their relatively low concentration of clays and other highly radioactive constituents. Because of this difference in gamma ray intensity, various lithologies can easily be identified (allowing correlation of lithologic units), and a rock unit's shale volume can be determined.

During phase I logging, a GRL that used a Geiger Mueller type of detector was run. The Geiger Mueller replaced the Scintillation type of detector employed in the previous GRL. This change results in a smoother, less fluctuating GR, which provides a better estimate of the formation's natural gamma ray activity (GR, measured in API units).

Sonic Log (SL)

The Sonic Log is an acoustic device that generates acoustic waves and measures reflected acoustic waves. The measurements taken from the SL tool are the direct result of the propagation of acoustic (elastic) waves through the borehole environment. The two important waves to the SL tool are the compressional (longitudinal) and the shear (transverse) waves.

The initial energy to produce the sound (acoustic) waves is generated by the transmitter (T) portion of the tool (fig. A-3). The velocity of a shear wave (Vs) is given by:

$$Vs = (\mu/\rho)^{0.5} \qquad [A\text{-}4]$$

where μ = modulus of shear for the medium
ρ = density of the medium

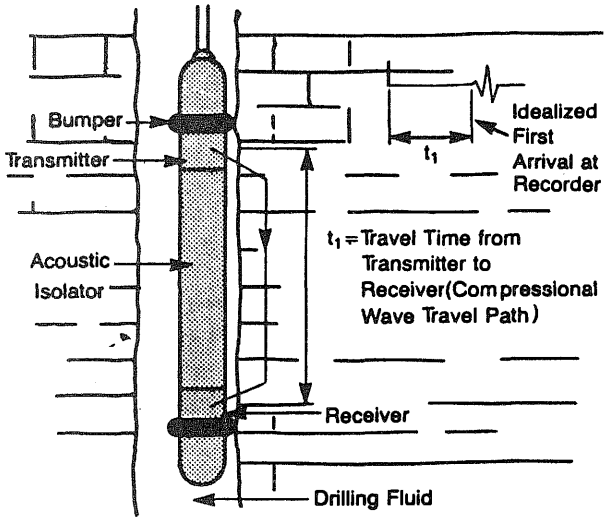

Figure A-3 (left) Generalized Sonic Log tool (from Helander 1983).

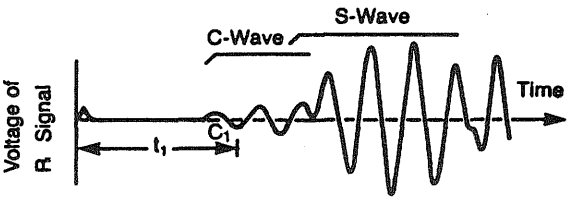

Figure A-4 Idealized schematic of receiver (R) signal (from Helander 1983).

Since the incident energy generated by the SL transmitter must first traverse a liquid medium in the borehole (where $\mu = 0$), it would appear that no shear wave would be generated, and subsequently received, by the SL tool. However, the occurrence of both shear and compressional waves in the response from the tool (fig. A-4) is a curious and useful anomaly. This apparent discrepancy can be resolved by noting that as the compressional wave strikes an interface or simply an adjacent medium with different elastic properties, a shear wave is produced. Therefore, as the compressional wave traverses from the transmitter (T) to the receiver (R) on the tool, the wave generates a shear wave that can, in this manner, be detected by the receiver circuitry. Shear waves generally are of a larger amplitude and about half as fast as compressional waves.

The transmitter-receiver array is chosen to account for abnormalities present in the borehole environment, i.e., washouts and tool tilting. The standard transmitter-receiver (T-R) arrangement is shown in figure A-5. Although other T-R configurations are available, this configuration is most nearly suited to the needs of injection/confining interval evaluation. The specific SL tool that incorporates this T-R array into its design is the Borehole Compensated Sonic Log (BCSL) tool. The main benefit of this type of T-R spacing is the compensation for washouts and tool tilting effects on travel time measurements.

Since the compressional wave has the fastest velocity of propagation, it is the one of most concern with the BCSL. If t_{fl} is the time taken to travel through the pore space (fluid travel time) and t_{ma} is the time taken to travel through the matrix, the total travel time will be t (the travel time recorded by the BCSL tool). The porosity (POR)BCS (Borehole Compensated Sonic) can be represented be the Wyllie time-average equation,

$$(POR)BCS = (t - t_{ma})/(t_{fl} - t_{ma}) \qquad [A\text{-}5]$$

The compressional wave (p-wave, also called C-wave) takes the path of least resistance. Areas of isolated (not interconnected) pockets of porosity, which would normally be found in the case of secondary porosity, will not have a pronounced effect on the travel time of the p-wave. By comparing the BCSL data with data from a tool that is influenced by the total porosity (primary and secondary), the amount of secondary porosity present can be estimated. The following equation applies to this situation,

$$(POR)tot = (POR)sec + (POR)prim \qquad [A\text{-}6]$$

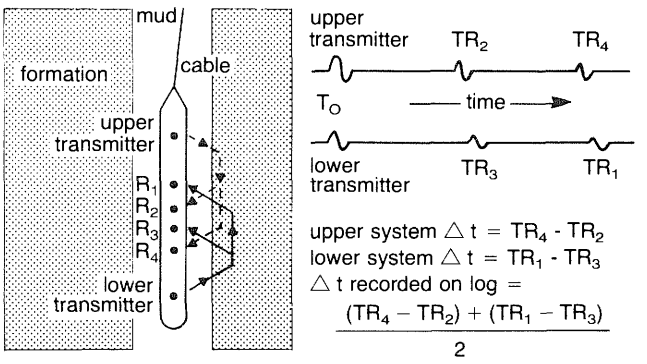

Figure A-5 Generalized Borehole Compensated Sonic Log tool (from Bateman 1985b).

During phase I logging, the BCSL was run in place of the SL. A more advanced detection system in the BCSL allows compensation for environmental factors that affect the signal transit time (t) used by the BCSL to make porosity determinations. A more accurate porosity profile results with the use of the BCSL.

One other SL tool that should be mentioned is the Long Spaced Sonic Log (LSSL) tool. It incorporates a longer T-R spacing than does the BCSL tool. In this manner, the LSSL tool is affected by a zone farther away and less disturbed by drilling operations than the zone at the borehole interface. This tool has been used for shear wave analysis, which when combined with compressional wave data results in an evaluation of some of the formation's strength characteristics, such as the pressure required to fracture the formation and the formation's elastic properties. If a hole has a large potential for washouts, this tool may be the best SL tool to use.

Neutron Log (NL)

The neutron is a fundamental particle found in the nucleus of all atoms except hydrogen, which contains only a proton. The neutron is a chargeless particle with about the same mass as the proton. The NL tool exploits these two properties of the neutron particle. The neutron source is usually a mixture of americium and beryllium, which react together to continuously emit neutrons.

Since the neutron is a small and electrically neutral particle, it passes with ease through most matter. During its passage, the neutron particle loses energy by colliding with other atoms. When the neutron's energy is reduced to a level equal to the surrounding matter (a function of absolute temperature), the neutron is called a thermal neutron. The energy of a thermal neutron is in the range of 0.025 eV.

Simple force relationships reveal that the maximum energy loss in the collision of two balls occurs when the two balls are of equal mass. Since the neutron and the hydrogen atom's proton have nearly equal masses, hydrogen dominates the behavior of neutrons and, in turn, the response of the NL tools. The thermal neutron flux is therefore controlled by the hydrogen content of the formation. Since hydrogen is found in the water molecules filling the pore space, the thermal neutron flux is a direct indication of the porosity of the formation.

Environmental factors such as hole size and mud weight influence the response of the NL tool. This influence can be corrected by taking two readings of thermal neutron flux at different spacings and using them to define the slope of the response line of the tool. This slope is relatively unaltered by environmental effects. The Compensated Neutron Log (CNL) tool utilizes this concept. The primary measurement of the CNL tool is therefore a ratio of the two count rates, far and near. Figure A-6 shows a CNL tool schematic.

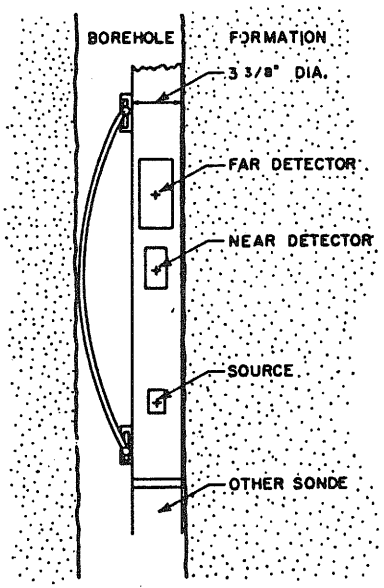

Figure A-6 Generalized Compensated Neutron Log tool (from Bateman 1985b).

The CNL displays a measurement of total porosity. Thus, it can be combined with the BCSL to provide an estimate of secondary porosity. Along with another porosity device, usually the BCSL or the Compensated Density Log (CDL), a lithologic determination may be made in addition to an accurate estimate of total porosity (cross-plotted porosity).

The CNL has replaced the Sidewall Neutron Log (SNL). The CNL utilizes a dual detector while the SNL has only one. The second detector enables the CNL to compensate effectively for environmental factors not taken into account with the SNL, such as salinity and temperature of the borehole fluid and diameter of the borehole. Accounting for these factors results in a more accurate determination of porosity with the CNL, ([POR]NIs).

Density Log (DL)

The DL utilizes a focused gamma ray source, normally cesium-137, which emits gamma rays into the formation from a pad assembly that is forced against the borehole wall via a back-up arm. The gamma rays interact with the electrons in the material opposite the focused source mainly through Compton scattering. This results in the gamma ray losing energy at each collision. The intensity of the back-scattered gamma ray is then measured by the gamma ray detectors (usually two) (fig. A-7). The measured gamma ray intensity is a function of the electron density of the formation. As the electron density of the formation increases, the probability of collision increases, resulting in reduced gamma ray intensity measured by the gamma ray detectors. The electron density, ρ_e, has been related to the bulk density, ρ_b, by the following equation,

$$\rho_e = \rho_b(2Z/A) \qquad [A\text{-}7]$$

where Z = atomic number or the number of electrons per atom
A = atomic weight

In most cases, the ratio, 2Z/A, is approximately equal to 1.0. Therefore $\rho_e = \rho_b$, and the apparent bulk density response of the tool is a response to the bulk density, ρ_b, of the formation material opposite the tool.

A two-detector DL or Compensated Density Log (CDL), which was used for phase I logging, allows for the compensation of the mudcake's effect on CDL tool response. In this way, an accurate

total porosity measurement is obtained. CDL response can be compared to BCSL porosity to estimate secondary porosity or cross-plotted with the BCSL or CNL to produce lithologic and total porosity determinations.

Resistivity Log (RL)

The property of a material that opposes the flow of an electrical current is called electrical resistance. Resistivity is a measure of the resistance of a volume of material. Several authors have noted that formation resistivity can be determined by,

$$R = KV/I \qquad [A\text{-}8]$$

where R = resistivity
K = geometric factor specific for a particular tool
V = potential across current path
I = current.

Since the RL tool measures the potential, and K and I are known, R can be calculated. The calculated resistivity is dependent on the amount of porosity and fluid contained in the pores.

RL tools have a number of applications. For this study, the resistivity device was needed for two purposes: to determine an accurate, true formation resistivity for fluid saturation calculations, cementation factor determinations, and stratigraphic correlations; and to estimate the invasion of borehole fluids into the formation, which may affect the RL tool's response.

Two appropriate resistivity logging systems are available: the Dual Laterolog Microspherically Focused Log tool and the Dual Induction Laterolog (Spherically Focused Log) tool. Although both systems will provide the necessary results, specific borehole conditions dictate which one is appropriate. The former is used when sea water or brine mud fills the borehole and the latter when fresh or oil-based mud is present. For this discussion, the Dual Induction Laterolog (DIL) tool will be considered. (The Dual Induction Spherically Focused Log [DISFL] tool is similar in principle to the DIL.)

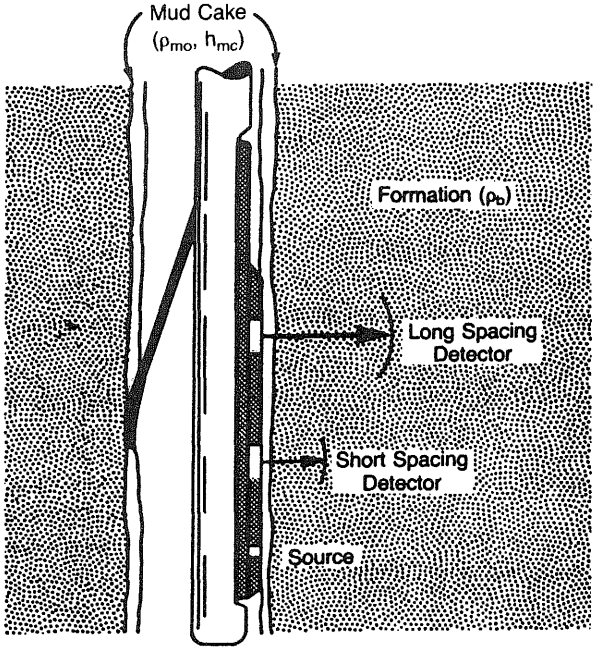

Figure A-7 Generalized two-detector Density Log tool (from Helander 1983).

The DIL tool comprises two sections: the induction and the lateral. The induction section produces two measurements, the "induction log deep" and the "induction log medium"; the lateral section yields one, the "laterolog."

The induction section, shown in schematic in figure A-8, is equipped with transmitter-receiver (T-R) coil pairs. An alternating current is applied to the transmitter, which generates a magnetic field around the tool, thereby inducing current flow in the surrounding formation. The current flow generates a magnetic field in the formation which, in turn, induces a voltage in the receiver coils. The measured voltage is proportional to the formation conductivity, which is inversely related to the formation resistivity.

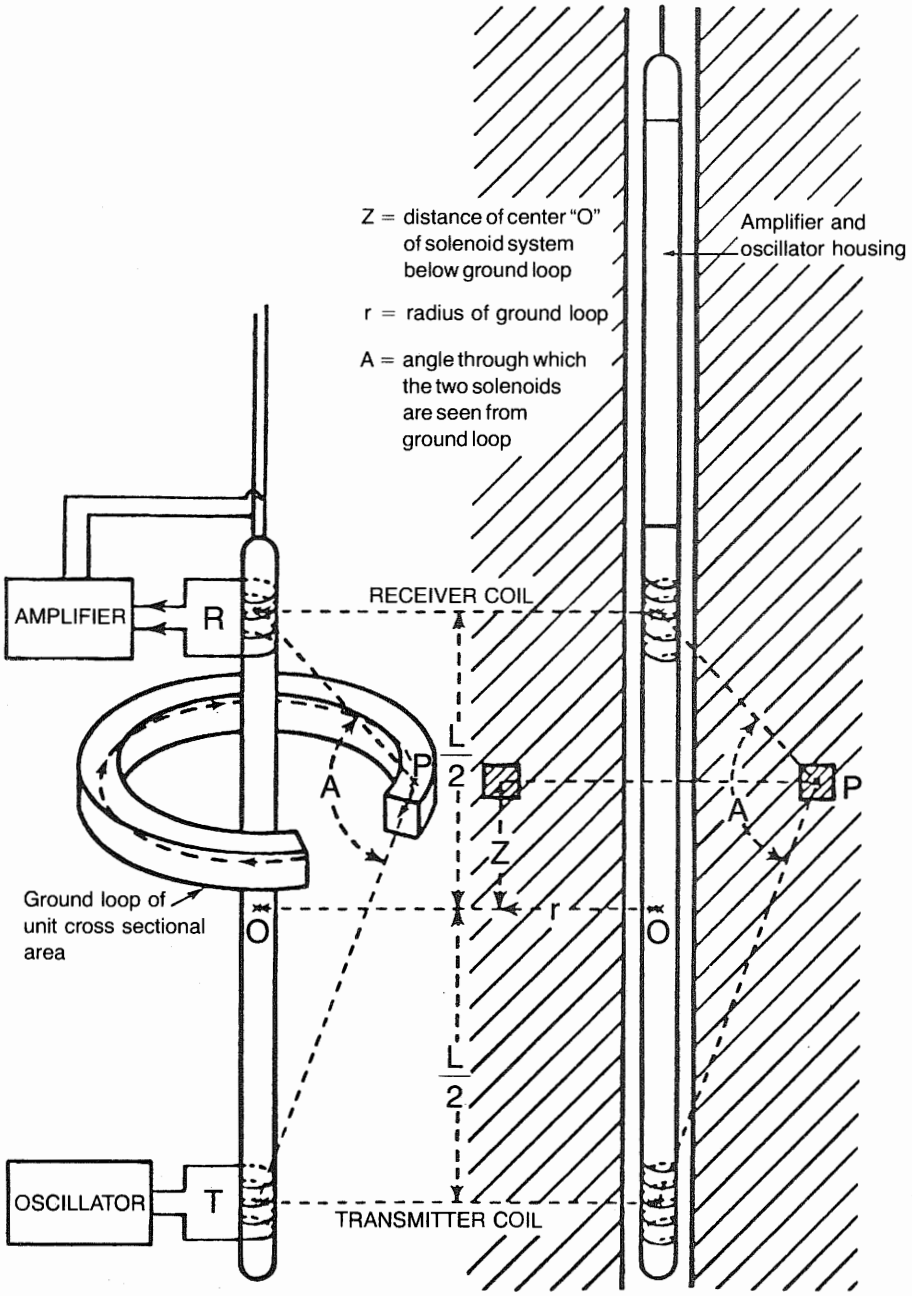

Figure A-8 Schematic diagram of induction log principles (from Hallenburg 1984).

Lateral devices pass a current of constant intensity from the tool into the formation (fig. A-9). This current flow creates equipotential spheres around the source electrode (A). Potential measuring electrodes (M, N) record the potential created by the current flow. The potential measured is then converted to formation resistivity.

The three curves generated have different depths of investigation into the formation, because of T-R spacing on the induction section and A-M,N spacing on the laterolog section. In this way, an evaluation of the amount of invasion is made, which is used to correct the deepest measurement (induction log deep) for invasion effects to produce an accurate, true formation resistivity. This resistivity can be used to obtain the cementation factor and fluid saturation of the formation.

The DISFL has replaced the Induction Electric Log (IEL). With the addition of one more resistivity curve to the output of the DISFL, the Induction Log Medium resistivity, and a deeper reading Induction Log Deep resistivity, factors that affected the resistivity response of the DISFL can be taken into account. These factors include the depth of invasion of the borehole fluids and the effect of this invasion on the determination of a true resistivity for the formation. The result is an Induction Log Deep resistivity corrected for invasion effects, which is considered more accurate than the formation's true resistivity determined by the IEL.

Permeability Log (PL)

The Permeability Log tool used most frequently today is the Minilog (MIL) tool. The MIL replaced the Microlog. Advanced electronics have increased the sensitivity of the Minilog as compared with the Microlog. Use of the Minilog results in more accurate information on permeability, mud (Rm), mud filtrate (Rmf), and mudcake (Rmc) resistivities.

The MIL, which utilizes the same resistivity theory discussed for the RL, is not discussed in detail here. The output of the MIL tool consists of two measurements: normal and lateral resistivities. The lateral configuration is described above. The normal measurement utilizes a slightly different system, shown in general schematic in figure A-10. The two arrays are housed in a nonconductive, fluid-filled rubber pad that is forced against the borehole wall by a back-up arm. This configuration is necessary to prevent the borehole fluid from short-circuiting the closely spaced current electrodes.

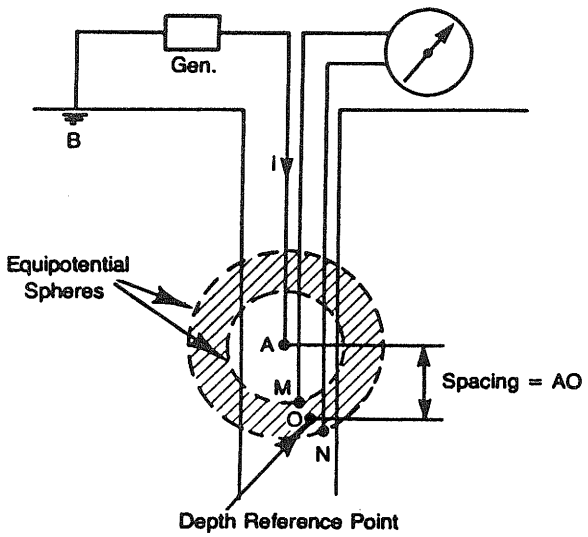

Figure A-9 (left) Schematic diagram of lateral logging system (from Helander 1983).

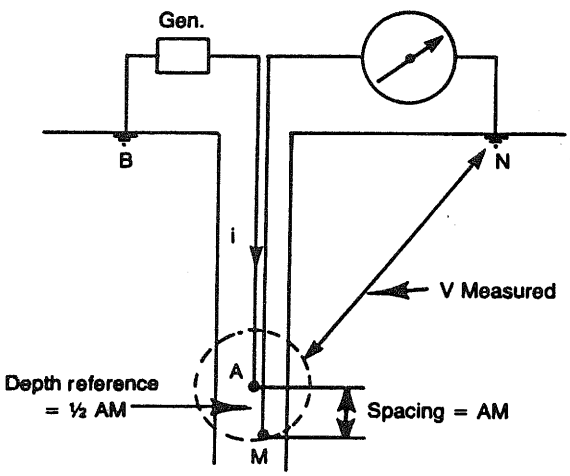

Figure A-10 Schematic diagram of normal logging system (from Helander 1983)

By utilizing two different configurations, MIL can produce varying depths of investigation. A comparison of the curves indicates the presence and magnitude of invasion of the borehole fluids into the formation. This enables a qualitative determination of the presence of permeability.

Spontaneous Potential Log (SPL)

Although the SPL system has one of the simplest physical configurations (fig. A-11), it is the result of many different factors. The SPL system records the change in naturally occurring potentials as a function of depth in the borehole. Two types of potential may contribute to the total Spontaneous Potential (E_{sp}): electrochemical (E_c) and electrokinetic (E_k). In well log analysis it is assumed that the measured SP response is due solely to the electrochemical component; therefore, $E_{sp} = E_c$.

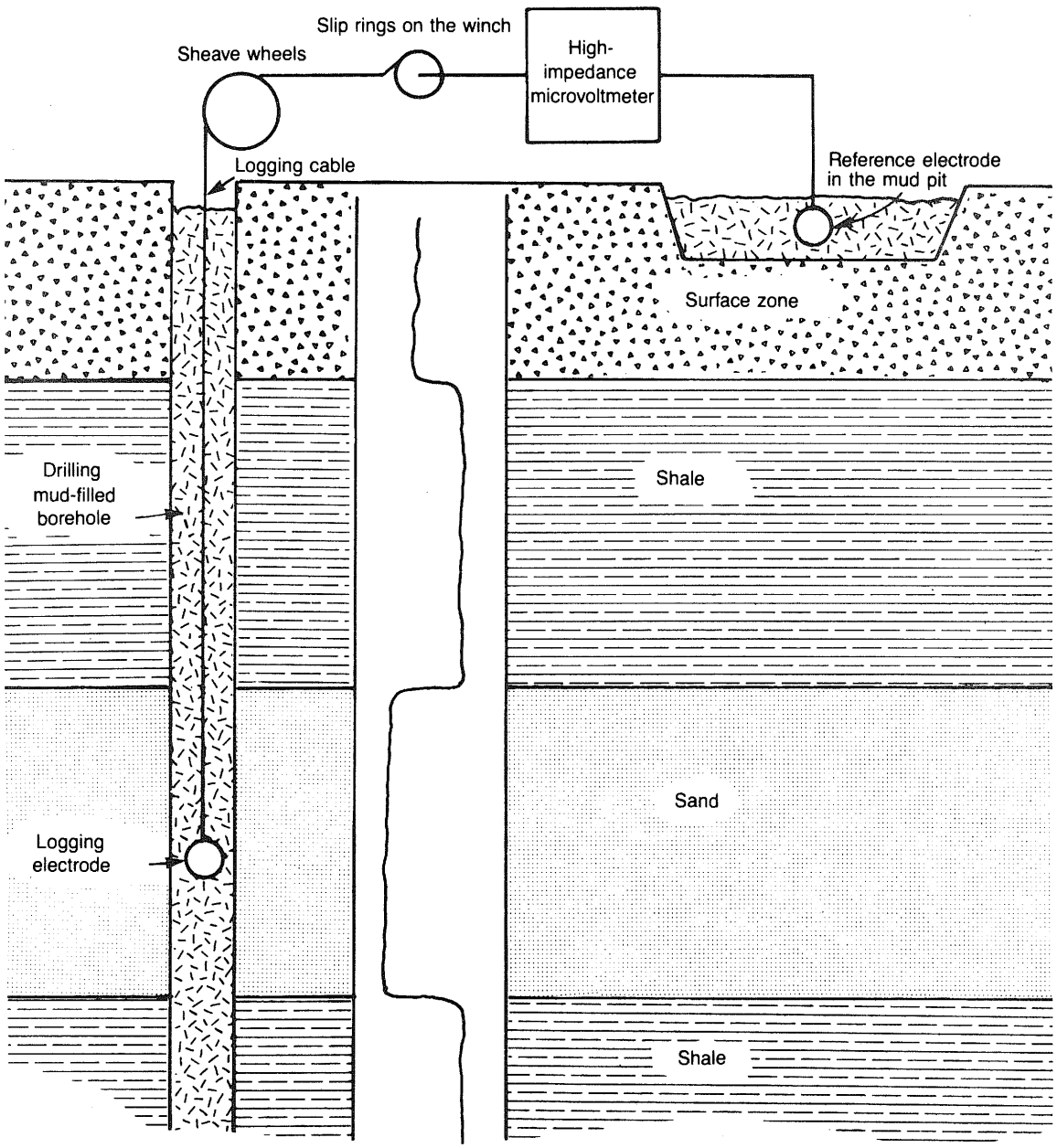

Figure A-11 Schematic diagram of spontaneous potential circuit.

The electrochemical potential is composed of the membrane potential (E_m) and the liquid junction potential (E_j). The membrane potential is caused by the separation of two fluids of different activity by a permeable, charged membrane. An analogy might be mud and formation water separated by shale. The liquid junction potential is the result of the contact of two solutions of differing activity, such as mud filtrate and formation water.

The E_{sp} is commonly written as

$$E_{sp} = -K_c \log(R_{mf}/R_w) \qquad [A\text{-}9]$$

where $K_c = 61 + 0.133T(°F)$
R_{mf} = mud filtrate resistivity
R_w = formation water resistivity.

This equation illustrates one application of the SPL system, namely R_w determination. The other applications relevant to this study are stratigraphic correlation and qualitative permeability estimation. The latter two are available through a consideration of the fluids and formation materials that give rise to the membrane and liquid junction potentials.

Temperature Log (TL)

The TL tool is simply a device that records the magnitude of the subsurface temperature. This is accomplished by incorporating into the tool's design a sensor element that provides ultrasensitive, stable readings over a suitable temperature range. A temperature probe in contact with the borehole environment transmits the thermal energy to the sensor, which converts the energy to a signal coverted by the surface equipment to absolute and differential temperature. These data can be useful to injection/confining interval evaluation in several ways. First, in many injection wells the temperature of the injection fluid is anomalously cooler than the native formation temperature. This anomaly can often be detected by the TL, providing another method, along with the CSFL, for delineating the location of fluid infiltration into a formation. Also, data from the TL provide temperature values to be used in the selection of appropriate temperature-corrected fluid and formation parameters (such as fluid density and water compressibility) necessary in many calculations.

Radioactive Tracer Log (RATL)

The Radioactive Tracer Log tool "traces" the movement of a radioactive source. This is accomplished by injecting a short-lived, radioactive isotope (usually ^{131}I) from one section of the tool and recording its movement with a detection gamma ray package housed in another section of the tool. As the radioactive isotope decays, it emits gamma rays that are detected by the gamma ray apparatus. It is in this way that the position of the radioactive "slug" can be monitored as it makes its way through the cased and uncased borehole. Thus it is another technique for delineating fluid flow within the injection zone.

APPENDIX B. REDUCTION AND ANALYSIS OF GEOPHYSICAL LOG DATA

Improved modeling techniques (correction charts) were used to interpret the advanced suite of logs run during phase I and II. Use of these charts generally improved the accuracy of data obtained from the phase I and II logs, compared with logs run during WDW2 construction. Figures B-1, B-2, and B-3 are examples of the correction charts used. By using these modern logging tools and incorporating improved analytical techniques, we were able to determine more accurately the following hydrogeologic data on geologic materials constituting the injection interval: the forma-tion's matrix-corrected CNL porosity ([POR]Ncor), matrix corrected BCS porosity ([POR]BCScor), cross-plotted porosity ([POR]xp), secondary porosity ([POR]sec), true resistivity (Rt), matrix lithology (MA), water saturation (SW), shale volume (Vsh), and qualitative permeability (k). These values, computed at 2-foot intervals throughout the injection zone, are reported in table B-1. The same parameters for geophysical logs run down WDW2 are reported in table B-2.

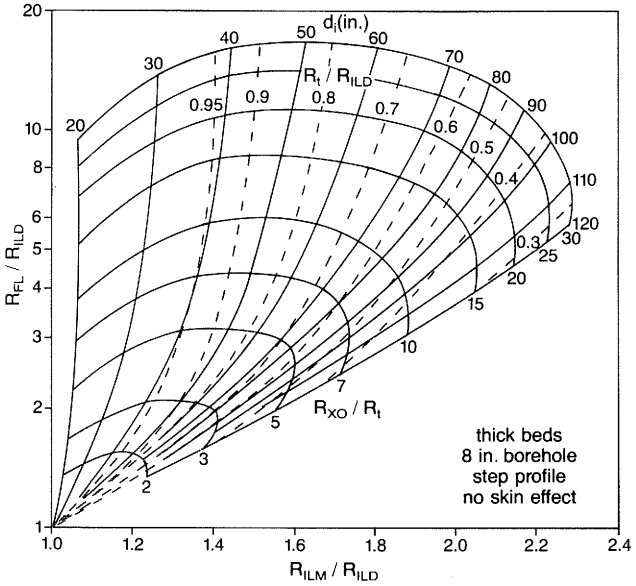

Figure B-1 (left) "Tornado" chart for Dual Induction-Focused Log analysis (Dresser Atlas 1981).

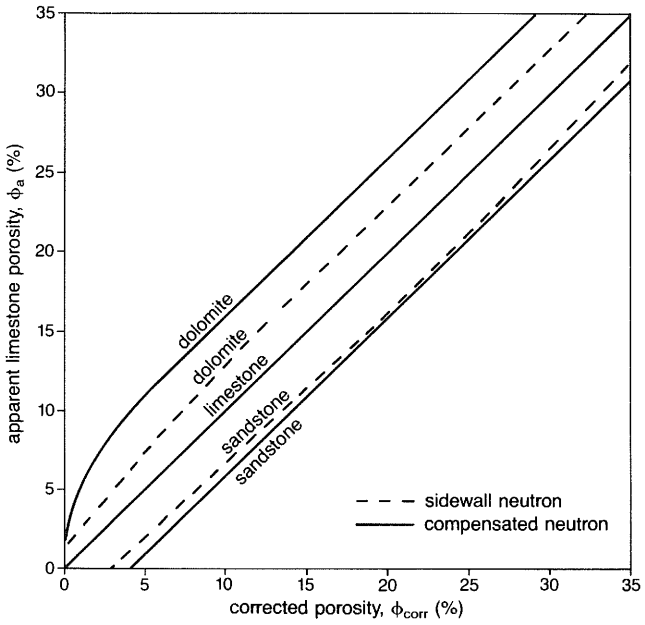

Figure B-2 Neutron porosity lithologic correction chart (Dresser Atlas 1981).

Table B-1 Data from geophysical logs run in the Devonian Observation Well

Depth GL (ft)	GR (API)	(POR) Nls (%)	(POR)[1] Ncor (%)	t (sec)	(POR)[2] BCScor (%)	(POR)[3] xp (%)	(POR)[4] sec (%)	RT[5] (ohm-m)	MA[6]	SW[7] (%)	Vsh[8] (%)	k[9]
2,434	28	4.3	4.3	53	3.8	4.3	0.5	50.0	LS	100	6.2	N
36	40	5.0	5.0	53	3.8	5.0	1.2	65.0	LS	100	15.4	N
38	35	12.0	12.0	60	8.8	10.0	3.2	20.0	LS	100	11.5	N
40	25	18.0	18.0	69	15.1	16.4	2.9	11.0	LS	100	3.8	N
42	30	19.0	19.0	69	15.1	16.7	3.9	7.0	LS	100	7.7	Y
44	25	23.8	23.8	77	20.8	21.7	3.0	5.0	LS	100	3.8	Y
46	22	22.6	22.6	76	20.1	21.1	2.5	4.8	LS	100	1.5	Y
48	23	23.0	17.0	70	18.2	18.2	0.0	7.0	DOL	100	2.3	N
50	30	16.0	10.0	62	12.7	12.0	0.0	10.0	DOL	100	7.7	N
52	30	17.5	11.5	57	9.3	9.7	2.2	16.0	DOL	100	7.7	N

Table B-1 *continued*

Depth GL (ft)	GR (API)	(POR) Nls (%)	(POR)[1] Ncor (%)	t (sec)	(POR)[2] BCScor (%)	(POR)[3] xp (%)	(POR)[4] sec (%)	RT[5] (ohm-m)	MA[6]	SW[7] (%)	Vsh[8] (%)	k[9]
54	22	19.0	13.0	60	11.3	11.7	1.7	13.0	DOL	100	1.5	N
56	17	22.0	16.0	62	12.7	13.3	3.3	9.0	DOL	100	0.0	N
58	20	20.6	14.6	63	13.4	13.6	1.2	10.0	DOL	100	0.0	N
60	28	21.8	15.8	61	12.0	12.7	3.8	9.0	DOL	100	6.2	N
62	27	24.6	18.6	65	14.8	15.6	3.8	7.0	DOL	100	5.4	Y
64	32	24.0	18.0	66	15.5	16.0	2.5	5.5	DOL	100	9.2	Y
66	22	25.5	19.5	70	18.2	18.5	1.3	4.8	DOL	100	1.5	Y
68	23	28.5	22.5	78	23.7	23.5	0.0	4.0	DOL	100	2.3	Y
70	17	29.2	23.2	82	26.5	26.0	0.0	3.3	DOL	100	0.0	Y
72	18	28.0	28.0	82	24.3	25.7	3.7	3.0	LS	100	0.0	Y
74	17	30.0	30.0	87	27.9	28.8	2.1	3.2	LS	100	0.0	Y
76	17	28.0	28.0	83	25.0	26.3	3.0	3.5	LS	100	0.0	Y
78	19	26.8	20.8	78	23.7	23.2	0.0	3.9	DOL	100	0.0	Y
80	17	26.3	20.3	77	23.0	22.6	0.0	4.4	DOL	100	0.0	Y
82	20	29.0	23.0	74	21.0	21.4	2.0	4.0	DOL	100	0.0	Y
84	24	23.5	17.5	71	18.9	18.5	0.0	4.6	DOL	100	3.1	Y
86	26	21.3	15.3	63	13.4	13.7	1.9	7.1	DOL	100	4.6	N
88	23	22.3	16.3	64	14.1	14.5	2.2	10.0	DOL	100	2.3	N
90	23	16.5	10.5	60	11.3	11.1	0.0	11.0	DOL	100	2.3	N
92	30	16.4	10.4	56	8.6	8.9	1.8	16.0	DOL	100	7.7	N
94	29	19.8	13.8	57	9.3	10.2	4.5	21.0	DOL	100	6.9	N
96	60	19.0	13.0	60	11.3	11.6	1.7	20.0	DOL	100	30.8	N
98	84	18.5	12.5	60	11.3	11.5	1.2	15.0	DOL	100	49.2	N
50	52	19.3	13.3	62	12.7	12.7	0.6	14.0	DOL	100	24.6	N
2	37	18.2	12.2	57	9.3	9.8	2.9	14.0	DOL	100	13.1	N
4	33	22.0	16.0	59	10.7	11.8	5.3	11.0	DOL	100	10.0	N
6	45	23.0	17.0	64	14.1	15.1	2.9	8.0	DOL	100	19.2	N
8	30	19.8	13.8	60	11.3	12.1	2.5	9.0	DOL	100	7.7	N
10	23	20.0	14.0	58	10.0	11.3	4.0	8.5	DOL	100	13.1	N
12	20	22.8	16.8	60	11.3	13.2	5.5	8.2	DOL	100	0.0	N
14	32	20.7	14.7	64	14.1	14.4	0.6	9.0	DOL	100	9.2	N
16	30	20.1	14.1	60	11.3	12.4	2.8	10.5	DOL	100	7.7	N
18	42	20.8	14.8	62	12.7	13.6	2.1	8.5	DOL	100	16.9	N
20	38	19.0	13.0	60	11.3	12.1	1.7	10.0	DOL	100	13.8	N
22	30	20.3	14.3	56	8.6	10.4	5.7	11.0	DOL	100	15.4	N
24	23	21.7	15.7	61	12.0	13.3	3.7	10.0	DOL	100	2.3	N
26	24	20.0	14.0	60	11.3	12.2	2.7	8.0	DOL	100	3.1	N
28	23	16.0	10.0	57	9.3	9.7	0.7	9.0	DOL	100	2.3	N
30	23	19.0	13.0	61	12.0	12.5	1.0	10.0	DOL	100	2.3	N
32	21	20.4	14.4	63	13.4	13.8	1.0	12.0	DOL	100	0.8	Y
2,534	33	22.5	16.5	60	11.3	12.2	5.2	10.0	DOL	100	10.0	Y
36	27	22.0	16.0	63	13.4	13.9	2.6	7.5	DOL	100	5.4	Y
38	28	24.3	18.3	65	14.8	15.5	3.5	6.5	DOL	100	6.2	Y
40	29	24.0	18.0	63	13.4	14.2	4.6	5.8	DOL	100	6.9	Y
42	35	17.3	11.3	61	12.0	11.8	0.0	7.1	DOL	100	11.5	N
44	40	16.5	10.5	59	10.7	10.6	0.0	9.0	DOL	100	15.4	N
46	42	21.3	15.3	63	13.4	13.7	1.9	8.5	DOL	100	16.9	Y
48	40	22.5	16.5	70	18.2	17.7	0.0	6.7	DOL	100	15.4	Y
50	40	20.6	14.6	66	15.5	15.1	0.0	6.7	DOL	100	15.4	Y
52	38	15.6	15.6	65	12.3	13.3	3.3	10.0	LS	100	13.8	N
54	29	8.6	8.6	57	6.6	7.4	2.0	20.0	LS	100	6.9	N

Notes for table B-1

1. Matrix corrected using figure B-2.
2. Matrix corrected using (POR)BCScor = (tlog - tma)/(tf1 - tma) x 1/Cp,
   where tma = 47.6×10^{-6} sec/ft for limestone
   tma = 43.5×10^{-6} sec/ft for dolomite
   tf1 = 189×10^{-6} sec/ft
   tlog = transit time from log
   tma = transit time of the matrix
   Cp = constant for shale correction
   assume Cp = 1, since no shale correction is needed
3. See figure B-3
4. (POR)sec = (POR)Ncor - (POR)BCScor
5. Since Rilm and Rild are approximately equal, a correction for invasion was not necessary; see figure B-1
6. Taken from (POR)N versus t crossplot, figure B-3
7. Using SW^2 = Ro/Rt = FRw/Rt = Rw/$(por)^2$Rt = Rw/(por)xp^2Rt, from this, all zones were 100% water saturated.
8. Using Vsh = (GRlog - GRc1)/(GRsh - GRc1),
   where GRlog = GR reading taken off log.
   GRcl = GR reading from the zone with the lowest GR (10 @ 2,474 ft).
   GRsh = GR reading from nearest shale zone (140 @ 2,242 ft).
9. Based on interpretation of MIL, Y denotes zone interpreted as having "significant" permeability. N denotes zone interpreted as not having "significant" permeability. MIL response is adversely affected by unevenness of borehole. A 4-arm caliper run indicated a very even borehole: 6.3-inch diameter from 2,424 to 2,524 ft, 6.2-inch diameter from 2,525 to 2,556 ft, and 5.8-inch diameter from 2,557 to 2,560 ft.

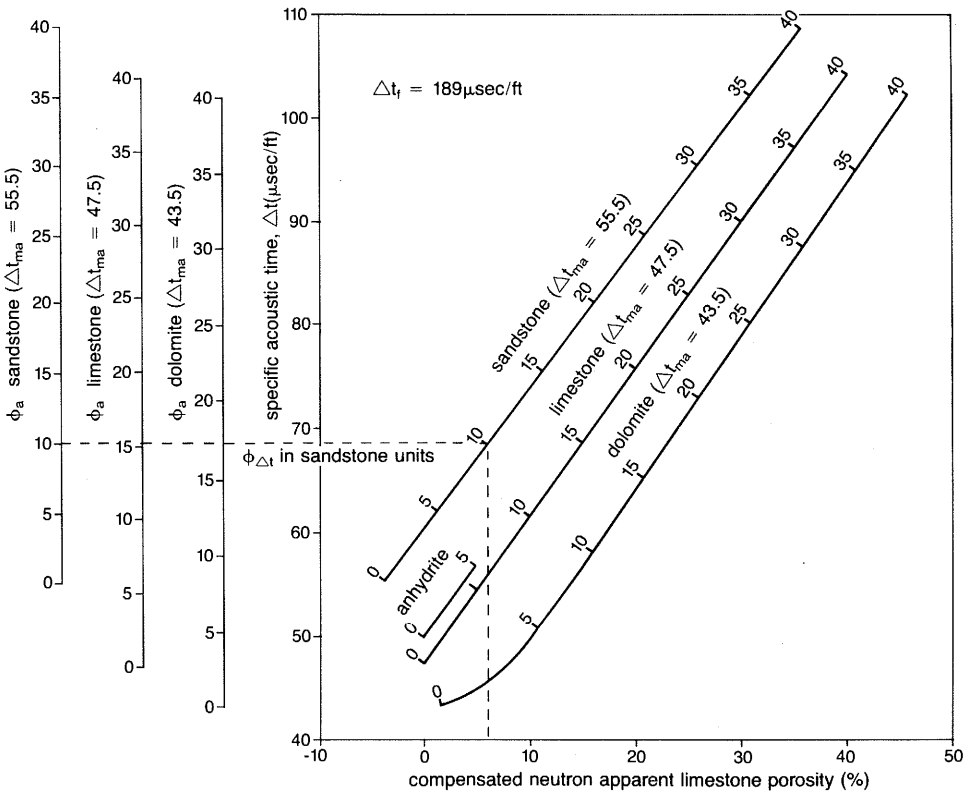

Figure B-3 Compensated Neutron Log and Borehole Compensated Acoustilog porosity crossplot (Dresser Atlas 1983).

Table B-2* Data from existing geophysical logs run in WDW2**

DEPTH GL (ft)	GR (API)	(POR) Nls (%)	(POR) Ncor (%)	t (sec)	(POR) BCScor (%)	(POR) xp (%)	(POR) sec (%)	RT (ohm-m)	MA	SW (%)	Vsh (%)	k
2582	26	8.1	8.1	63	10.9	10.1	0.0	30.0	LS	90	4.6	N
84	30	10.0	10.0	66	13.0	12.2	0.0	28.0	LS	77	7.7	N
86	34	15.0	15.0	71	16.5	16.3	0.0	17.0	LS	74	10.8	N
88	38	14.7	14.7	73	18.0	17.1	0.0	13.0	LW	81	13.8	Y
90	37	13.5	13.5	73	18.0	16.9	0.0	13.0	LS	82	13.1	Y
92	26	7.8	11.1	68	8.8	10.0	2.3	20.0	SS	100	4.6	Y
94	29	6.1	9.3	65	7.1	8.2	2.2	38.0	SS	98	6.9	N

* For explanation of column headings, see table B-1.

** All logs used for study were run during well installation, and all were from WDW2 except the sonic log (SL), which was from WDW1. Analysis methods used were those described in table B-1. All depths measured are from Kelly Bushing (KB), which is 12 ft above ground level.

A brief discussion of the computation of the correction factors and assumptions used to analyze the logging data follows. The analysis focused on data from intervals with higher relative permeabilities (as displayed by the Minilog and higher porosities from the CNL). These zones were 2,440 to 2,506 ft GL, 2,532 to 2,552 ft GL, and 2,572 to 2,582 ft GL as logged in DOW.

From figure B-4:

m = 1.54 or 1.76; this value is in close agreement with an assumed value of m = 2 for limestone (Ls) and dolomite (Dol).

From Minilog:

Rm = 0.30 ohm-m

Therefore, from figure B-5,

Rmf = 0.23 ohm-m and

Rmc= 0.41 ohm-m

From temperature log on WDW2,

Temperature @ 2,460 ft = 75.6° F.

Determine Rw:

Using Archie's Equation:

$F = a/(por)^2 = Ro/Rw$ and

$SW^n = Ro/Rt$

where F = formation factor

Ro= true resistivity of the formation at 100% water saturation (when SW = 100%)

n = saturation exponent

a = constant

For limestone and dolomite,

Assume a = 1, m = n = 2

Therefore,

$F = 1/(por)^2$

$SW^2 = Ro/Rt$

@ 2473 ft assume SW = 100%

$SW^2 = Ro/Rt$

Ro = Rt

Assume Rt = Rildcorr

Correct Rild for invasion, figure B-1
Rildcorr = 3 ohm-m
Rt = 3 ohm-m
Ro = 3 ohm-m
Ro = F x Rw = Rw/(por)^2
Rw = Ro x (por)^2
Porosity is needed; assume por = porxp of Sonic vs CNS
porxp = 28.7%

Therefore,

Rw = 0.247 ohm-m

These factors were used to analyze the logging data reported in tables B-1 and B-2. Important hydrogeologic parameters of the injection zones are summarized in table B-3.

Table B-3 Summary of important formation characteristics

(POR)xp,ave = 16%	(POR)xp,max = 28.8%	(POR)xp,min = 8.9%
(POR)sec,ave = 1.98%	(POR)sec,max = 5.7%	
tave = 66.7x10^{-6} sec/ft		
tmax = 87x10^{-6} sec/ft		
tmin = 56x10^{-6} sec/ft		
Rt,ave = 8.6 ohm-m	Rt,max = 21 ohm-m	Rt,min = 3 ohm-m
Vsh,ave = 8.05%	Vsh,max = 49.2%	Vsh,min = 0.0%

Formation lithology (based on 98 ft of "higher permeability, higher porosity" zone), 61.0% dolomite, 35.0% limestone, and 4.0% sandstone.

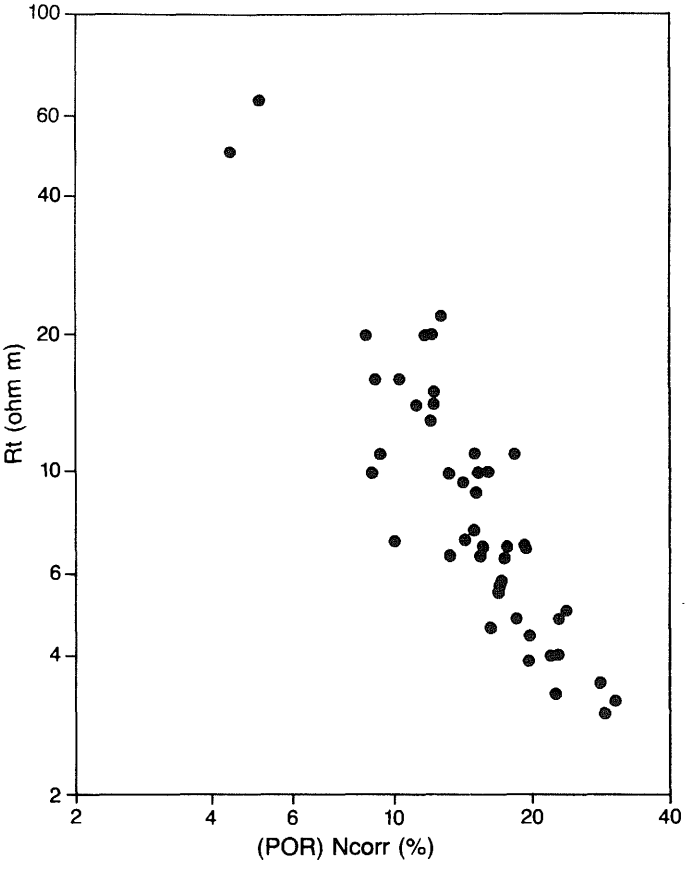

Figure B-4 Determination of the cementation factor.

After reviewing the data, we concluded that the host formation, the Bailey Limestone, is composed mainly of a clean dolomite with less than 20 percent shale throughout most of the interval logged. Since the Bailey Limestone is predominantly a dolomite, secondary porosity is always a consideration. A comparison of CNL and BCSL data suggests that secondary porosity may account for up to 10 percent of the total porosity. The intervals with higher relative permeability have a slightly higher secondary porosity and therefore a higher total porosity.

The entire interval is primarily 100 percent water saturated and has a fluid resistance of approximately 0.247 ohm-m. At a formation temperature of about 80°F and depth of 2,460 feet GL, the fluid composition is estimated to be approximately 24,000 ppm NaCl (fig. B-6).

As stated in chapter 3, one use of the core data was to verify data obtained from the geophysical logs. Figure B-7 shows good agreement between the two methods for porosity data. Figure B-8 indicates a close correlation between the two methods for true formation resistivity values (Rt); this correlation becomes more apparent when the equation used to derive water saturation (Sw) is reviewed,

$$S_w^2 = \frac{Rw}{(por) \times \frac{2}{p}} \quad (1/R_t)$$

S_w is shown to be indirectly proportional to the square root of R_t.

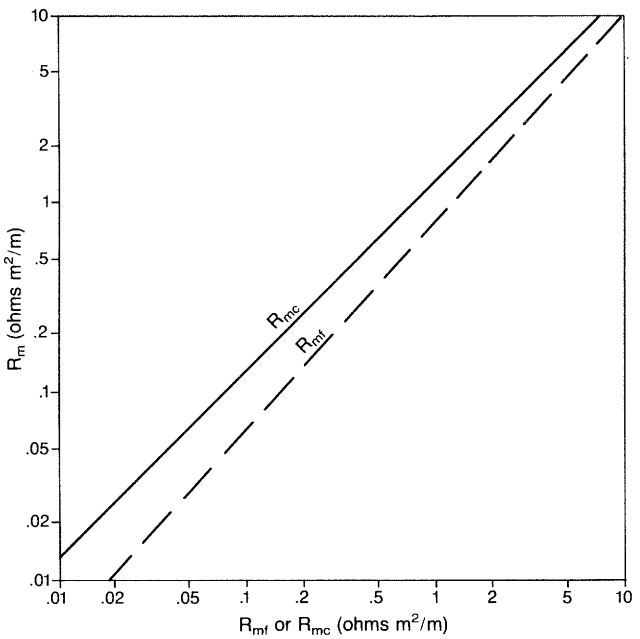

Figure B-5 Rm-Rmf-Rmc relationships (Gearhart).

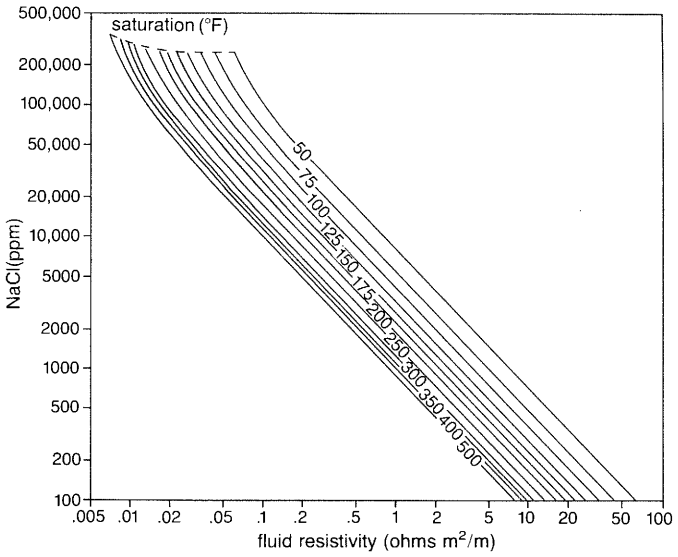

Figure B-6 NaCl concentration for different temperatures and fluid resistivities (Gearhart).

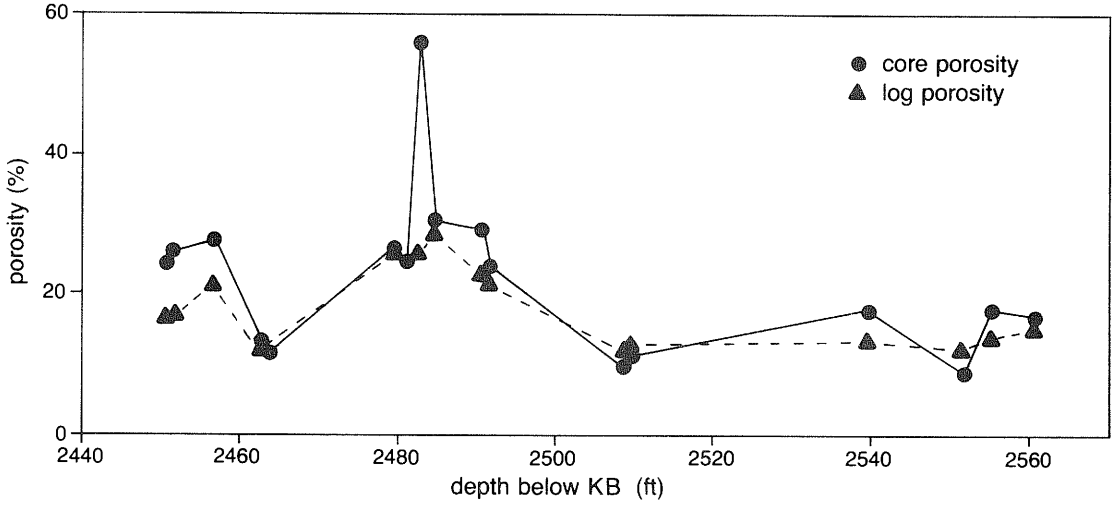

Figure B-7 Core porosity versus log porosity (phase I, cross-plotted porosity) for WDW2.

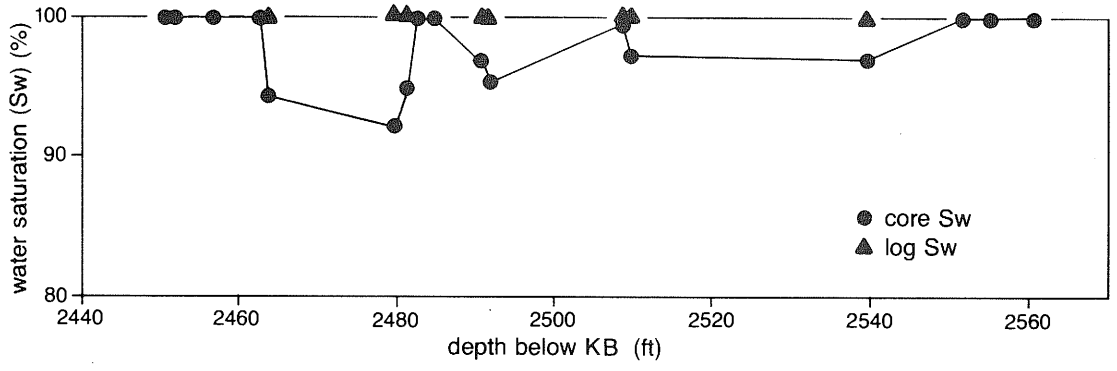

Figure B-8 Core water saturation versus log water saturation for WDW2 at designated depths. Log Sw obtained from phase I logging on the DOW.

APPENDIX C. BRUCITE FORMATION: PROPOSED MECHANISM OF FORMATION

The hydrogeologic site descriptions developed from phase I and phase II data (see chapter 3) differed from each other significantly; however, the reason for these differences was not readily apparent. To develop a hypothesis to explain the results and increase our understanding of the site hydrogeology, we conducted additional analyses.

Core Analysis

Analysis of sidewall core obtained during phase II was critical to the development of a hypothesis to explain the discrepancies described in chapter 3. Our core analysis included hydraulic testing, mineralogic analysis, and scanning electron microscope (SEM) investigation.

Hydraulic Testing

Hydraulic testing provided no hard evidence to resolve the discrepancies between phase I and phase II data. Injection zones 1, 2, and 3 (fig. C-1) had abnormally high porosities and permeabilities, but core analysis data did not agree with the results from the CSFL. First, the zone from 2,468 to 2,496 feet KB showed some injection potential. Core analysis indicated that at least some portions of this zone (e.g., 2,481.0 ft KB) were not permeable enough to allow fluid flow; however, most of this zone appeared to have sufficient permeability. Second, the core from 2539.5 feet KB seemed to have sufficient porosity and permeability to allow fluid flow, but the CSFL did not show any flow at this location. On the basis of CSFL results, zone 3 should have had the highest porosity and permeability, zone 2 the next highest, and zone 1 the lowest; however, core analysis indicated just the opposite. Therefore, the same discrepancies were encountered with core analysis as with geophysical logging.

Mineralogic Analysis

Cores were also analyzed for their mineralogical content. Brucite was found in the anomalous zones, and its presence was confirmed by x-ray diffraction (XRD) analysis. Brucite was not expected to be present in the injection system environment of WDW2. Brucite is normally found in veins in serpentine and basic rocks and as flakes scattered through some marbles (Pough 1953). Roy et al. (1989) analyzed a sample of the native formation brine taken from the DOW. The sample was vastly undersaturated with respect to brucite, $Mg(OH)_2$. The ion activity product of Mg^{2+} and OH^- (brucite) in the sample was 3 percent of that predicted by the solubility of brucite determined by thermodynamic modeling (Roy 1987).

Mineralogical analysis conducted on a few representative samples of the original well cuttings collected during the drilling of WDW2 indicated that none of these samples contained brucite. Downhole geophysical data (table 2) also confirmed the absence of brucite and indicated that prior to injection, the disposal horizon was predominantly dolomitic.

Apparently the injected waste, which consisted of a number of organics in a very alkaline (pH>12), brinelike solution, created an environment in the injection system that promoted the formation of brucite. Although the waste had a component of Mg^{2+}, dolomite (from injection zone rock) was the most likely source of Mg^{2+} for two reasons. First, an increase in the brucite concentration accompanied a corresponding decrease in the dolomite concentration (fig. C-2). Second, the porosity throughout the injection zone subsequent to brucite precipitation should have been lower than the original (pre-injection) porosity if the brine was the source of the Mg^{2+}. Data from log analysis did not indicate a decrease in porosity. Therefore, on the basis of available data, the most plausible hypothesis is that dissolution of dolomite from injection zone rock released magnesium, which then combined with the OH^- in the waste stream to form brucite.

If this hypothesis is correct, the zones that originally had the highest porosities and permeabilities would accept the greatest volume of waste fluid and thus would show the highest brucite con-

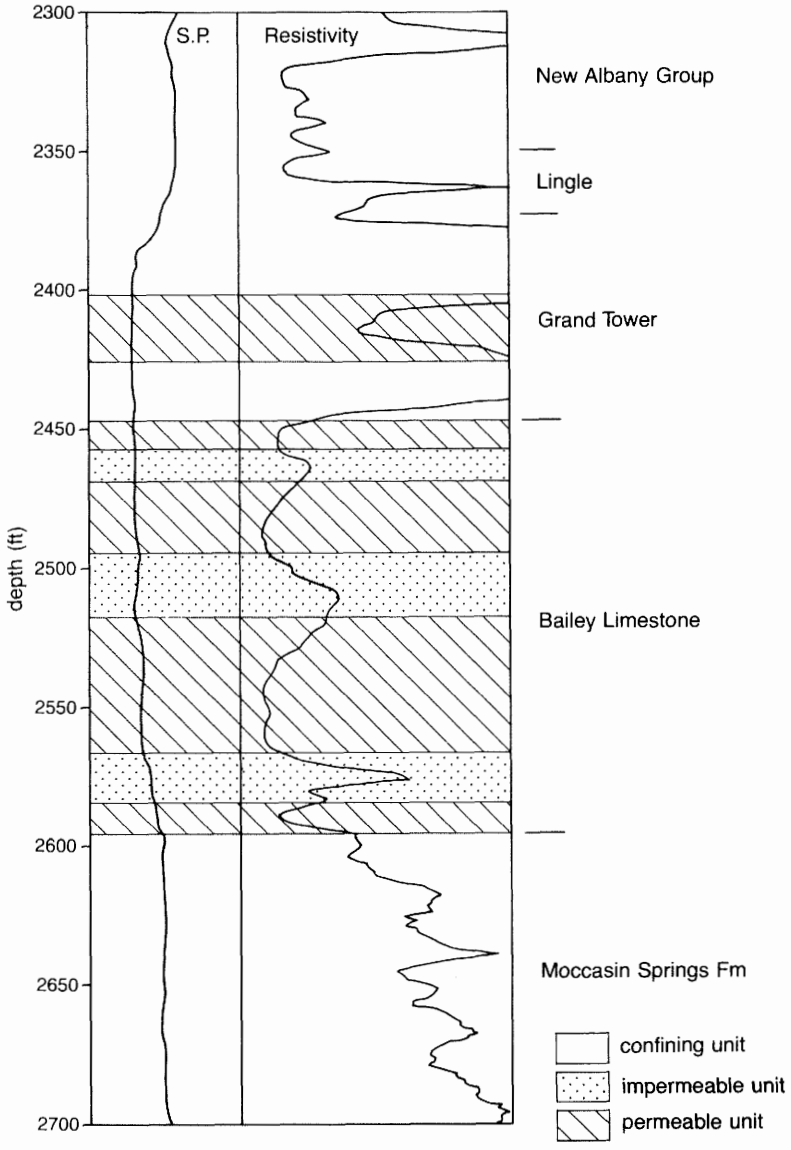

Figure C1 Injection system in WDW2 indicating permeable and nonpermeable zones delineated with the aid of geophysical logging.

centrations. Table C-1 gives porosity and brucite percentages for the cored intervals. For comparison, the Sidewall Neutron Log run during well construction was used to obtain original porosity data. Five intervals were identified and ranked on the basis of porosity characteristics. Zones with higher average porosity were given a higher porosity ranking.

Table C-2 shows the five highest ranked zones with their corresponding average brucite concentrations, air permeabilities (ka), and percentages of total flow (from the CSFL). These data indicate that the presence of brucite has a profound effect on fluid movement. However, laboratory permeability values for zones with higher brucite concentrations were greater than the values for zones with lower brucite concentrations, and laboratory porosity values for zones with higher brucite concentrations were similar to the pre-injection porosities.

In an attempt to explain this finding, we reviewed the analytical procedure used to determine permeability. Laboratory permeabilities were performed on dried samples. If the cations (Na+) that may have been lodged between the brucite layers were lost during drying, a volume reduction in brucite would occur. Therefore, in samples with high brucite concentrations, abnormally high permeability measurements could be encountered, and the cores at 2,479.5, 2,481.0, 2,490.5, 2,491.5, 2,439.5, and 2,560.5 ft KB should have higher permeabilities than expected. These depths corresponded to the zones in which discrepancies were noted between core and CSFL analysis. The anomalously high core permeabilities appeared to be the result of a volume reduction of the brucite upon drying.

Table C-1 Core porosities and brucite concentrations

Depth (KB) (ft)	Original porosity (%)	Porosity ranking	Brucite (wt %)
2450.5	23	3	9
2451.5	25	3	21
2456.5	24	3	0
2462.5	17	-	18
2463.5	19	-	22
2479.5	30+	1	45
2481	30+	1	45
2484.5	30+	1	12
2490.5	30+	1	39
2491.5	30	1	31
2508.5	18	-	26
2509.5	19	-	35
2539.5	27	2	41
2551.5	20	2	38
2555	24	4	7
2556.5	28	2	45
2560.5	28	2	45
2572.5	4	-	2
2573.5	5	-	0
2588.5	15	5	0
2605	6	-	0
2606	6	-	0

Table C-2 Effect of brucite concentration on total flow

Porosity ranking	Brucite (wt %)	Ave ka (md)	Total Flow (vol %)
1	40	1	0
2	42.3	0.1	0
3	10	0.6	14
4	7	0.06	36
5	0	0.02	50

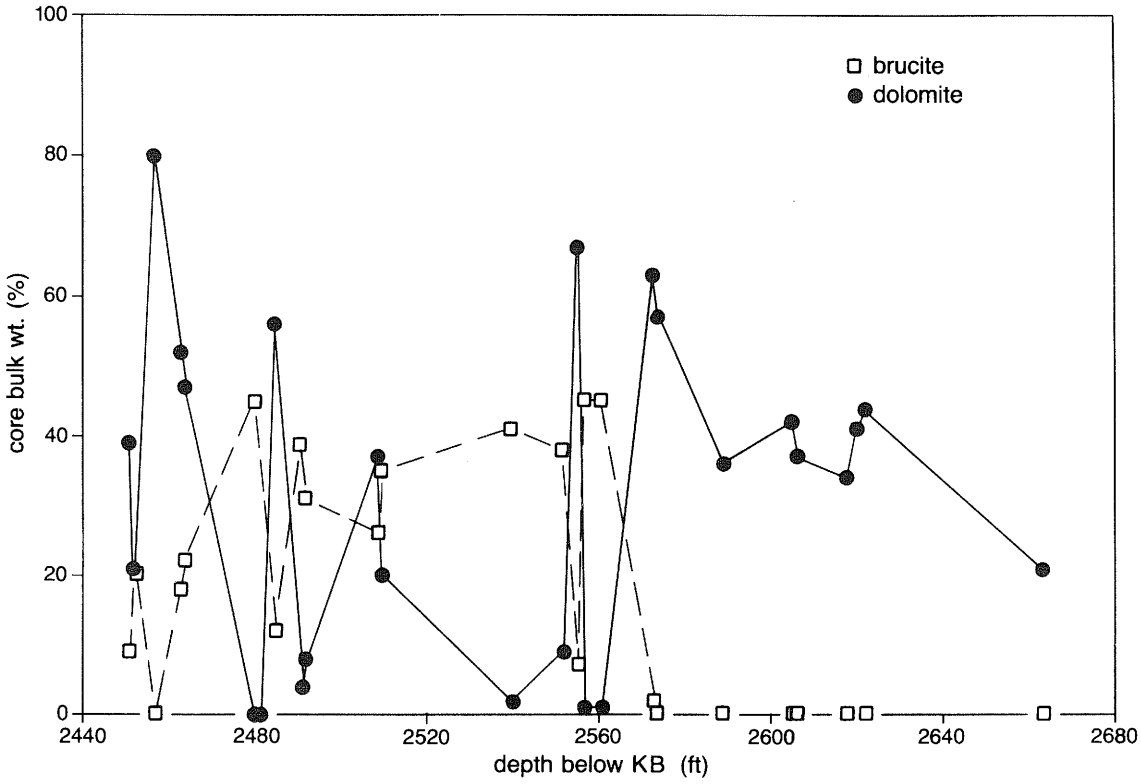

Figure C-2 Core composition: dolomite and brucite in WDW2.

On the basis of available data, this explanation appeared to be reasonable, but two problems with the results remained unresolved: (1) the cores at 2,462.5, 2,463.5, 2,508.5, and 2,509.5 ft KB showed slightly higher than expected brucite concentrations (approximately 25% brucite), and (2) the core at 2,484.5 ft KB had an extremely high core permeability (ka = 14.97 md) but a relatively low concentration of brucite (12%). Scanning Electron Microscope (SEM) analysis was performed on selected core samples in an attempt to resolve these discrepancies, gain additional information on the factors affecting fluid flow, and confirm some of the assumptions inherent in the previous discussion.

SEM Analysis

Eight cores chosen for analysis represented the three injection zones and the major areas where anomalous results were encountered by various analytical procedures (e.g., core analysis, CSFL, and standard geophysical logging). Generally, two magnifications were used per sample: approximately 100x to show the general porosity type and any large-scale features such as fracturing, and 1,000x to show the pore geometry and other small-scale features. Although a detailed discussion of SEM analysis results is beyond the scope of this project, a few generalizations can be made to help resolve the discrepancies noted.

SEM analysis was performed on dried samples; therefore, the effect of cation adsorption into the crystal lattice of brucite was assumed to be unrecognizable.

Data from historical and phase I logging indicated that the core at 2,484.5 ft KB should have had a high injection potential. When the CSFL indicated a lack of fluid flow into this zone, we reasoned—on the basis of core analysis—that the lack of flow into this zone could have been due to the presence of brucite in the sample. However, only 12 percent brucite was found in this core,

compared with an average of 40 percent in the other adjacent samples. Another explanation for the lack of flow was obviously needed. Figures C-3 and C-4 indicate that the predominant type of porosity in this sample is fracture porosity. Figure C-3 shows that the fracturing is discontinuous on a large scale. Figure C-4 is a close-up of the fracture depicted in figure C-3. The platy material on the fracture walls was interpreted to be brucite.

Another sample selected was the core at 2,479.5 feet KB, which is from the same zone as the previous sample. No fractures can be seen in figures C-5 and C-6, and the crystals and matrix of the sample are coated. Core analysis indicated that this sample was 45 percent brucite, so this coating was assumed to be brucite. With such a widespread occurrence of brucite, the decrease in permeability seems reasonable.

A sample from the uppermost injection zone (2,456.5 ft KB) (figs. C-7 and C-8) is free of the coating present in the previous samples. Core analysis indicated that this sample had no brucite, which agrees with SEM analysis and the supposition that brucite has not affected fluid flow in the uppermost injection zone.

The hypothesis used to resolve the brucite formation explains the available data and was confirmed to some extent by SEM analysis. But to evaluate this hypothesis more fully, additional work beyond the scope of this project is necessary.

Additional Research

To support the hypothesis developed regarding brucite formation, the following work should be done. A hydrogeochemical investigation of the Velsicol waste stream and the Devonian limestone, similar to that of Roy et al. (1989), should be conducted. Core from the DOW could be used in this type of investigation. This type of work would help define the conditions favorable for brucite formation.

Figure C-3 SEM photograph of core at 2,484.5 feet KB (x58.5).

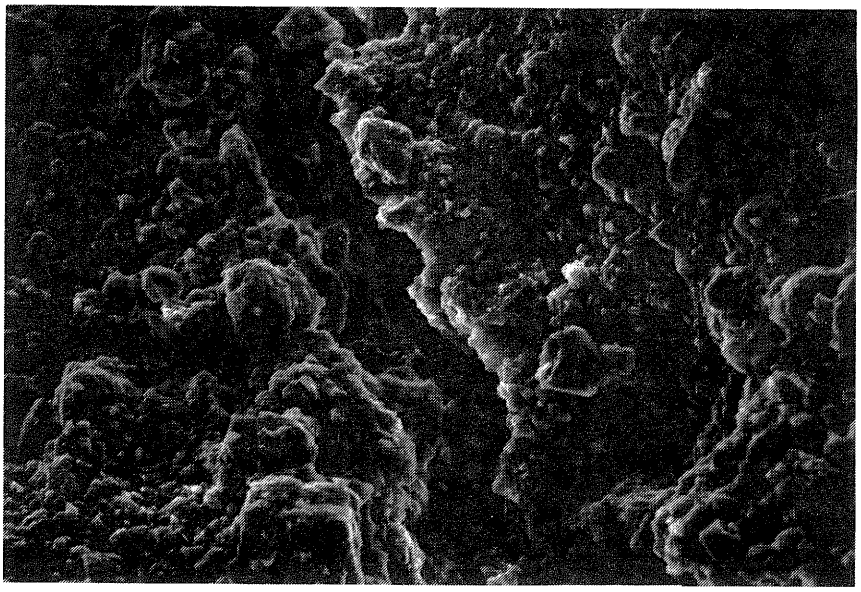

Figure C-4 SEM photograph of core at 2,484.5 ft KB (x 1,050).

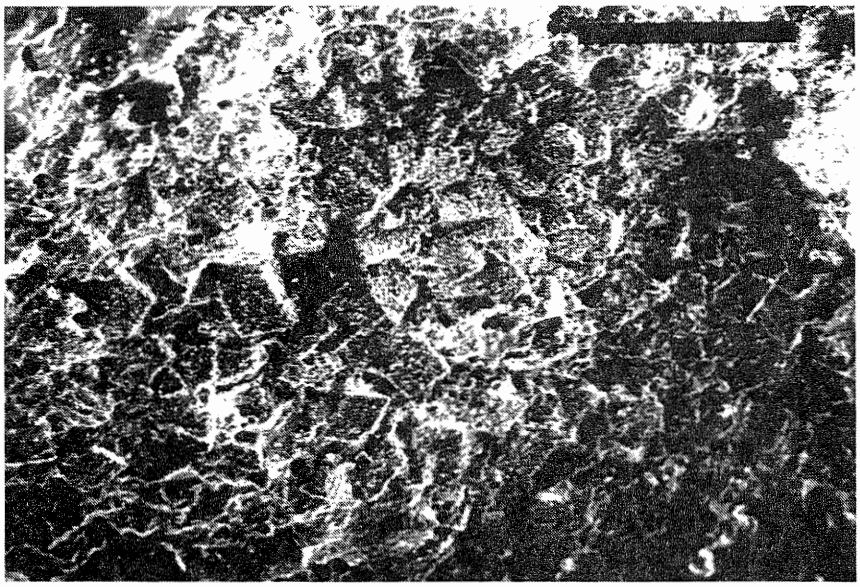

Figure C-5 SEM photograph of core at 2,479.5 KB (x80).

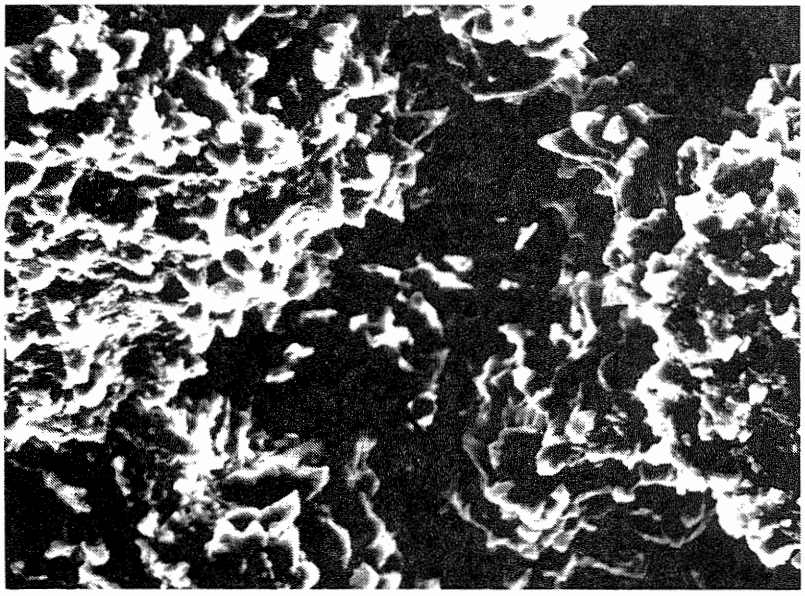

Figure C-6 SEM photograph of core at 2,479.5 KB (x1,080).

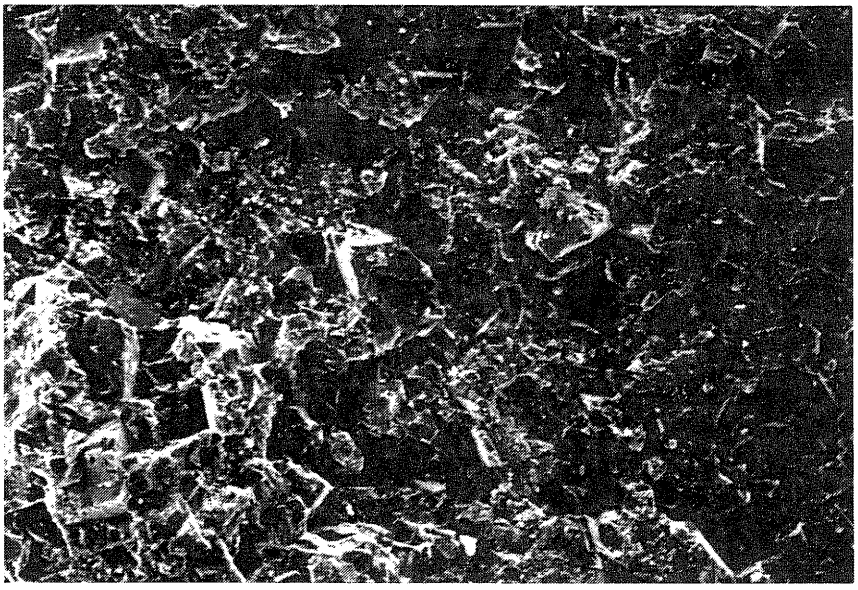

Figure C-7 SEM photograph of core at 2,456.5 KB (x113).

Figure C-8 SEM photograph of core at 2,456.5 feet KB (x1,160).

APPENDIX D. SENSITIVITY ANALYSIS

A rigorous sensitivity analysis as described by Yeh (1986) was not conducted. The sensitivity analysis conducted for this project involves the variation of significant parameters and the effect of this variation on head buildup (Δh) at the DOW, the parameter of interest. The significance of various parameters (injection rate, hydraulic conductivity, etc.) was observed during the validation and calibration stages of modeling. On the basis of these observations, sensitivity analysis was conducted for the following parameters: boundary conditions, injection rate, rock compressibility, fluid compressibility, hydraulic conductivity, and anisotropy.

Throughout this phase of the project, the same conceptual model as depicted in figure D-1 was used unless otherwise noted. The injection system was modeled using cylindrical coordinates with 60 nodes in the r-direction and 22 nodes in the z-direction. A no-flow boundary condition was applied at the upper and lower boundaries, while an aquifer influence function (AIF) condition was applied at the radial boundary.

Boundary Conditions

Boundary conditions (BC) are the most difficult and critical issue in the development of a conceptual model for a numerical modeling study and must be selected carefully (Franke and Reilly 1987). In all cases, the upper and lower boundaries were modeled as no-flow boundaries.

The type and distance of the radial boundary from the injection well were varied. For the purposes of comparison, VELS14I was considered the baseline run. Five other runs were made in order to note the effect of the boundary condition on head buildup at various locations within the injection system. Table D-1 summarizes the types of boundary conditions and results.

The results of VELS14G2 indicate that the no-flow boundary condition did not cause an increase in head buildup at the DOW during the 14-day period investigated, but a slight increase in Δh occurred at the radial boundary. For VELS14H, the radial boundary is located farther from the injection well than in VELS14G2; no Δh was observed at the radial boundary. These two runs and the other runs of the VELS14 series show that the radial boundary exerted no real influence on the head buildup at the DOW (r = 505.95 m) during the time period investigated.

VELS14I and VELS14I2 indicate the effect of the intrinsic permeability of the aquifer influence region (k_{AIF}). A reduction in k_{AIF} may increase the Δh observed at the radial boundary. Although

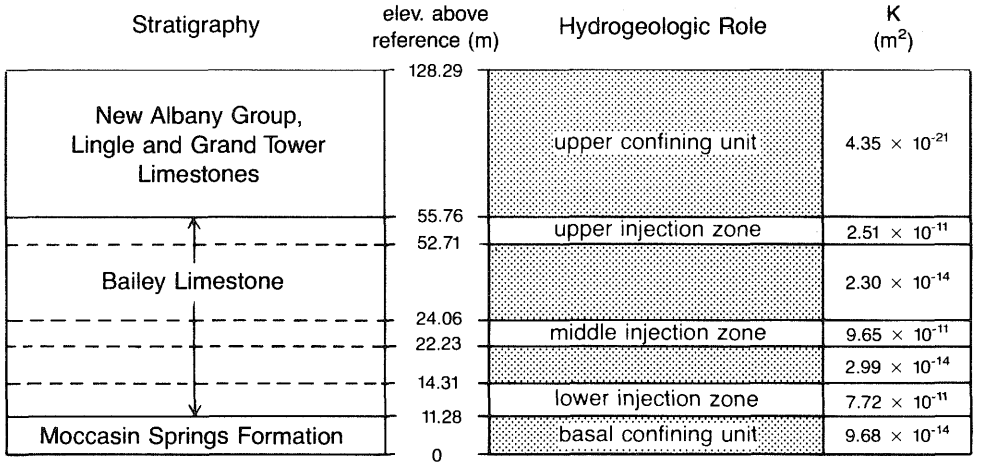

Figure D-1 Conceptual model 1 of the injection system.

Table D-1 Effect of boundary conditions on head buildup

Run	No. of r-nodes	Radius (m)	Type[1] of BC	k_{AIF}[2] (m^2)	Δh @ DOW[3] (m)	Δh @ radial boundary (m)
VELS14I	60	15870.9	AIF	1.00×10^{-11}	1.28	0.01 t = 14.0 days
VELS14G2	60	15870.9	NF	—	1.28	0.02 t = 7.16 days
VELS14H	60	35703.0	NF	—	1.28	0.00 t < 14.0 days
VELS14I2	60	15870.9	AIF	1.00×10^{-12}	1.28	0.02 t = 14.0 days
VELS18H2	60	15870.9	AIF	1.00×10^{-11}	1.25	—
VELS18J	50	2090.8	AIF	1.00×10^{-11}	0.75	—

Notes: (1) AIF = aquifer influence boundary condition; NF = no-flow boundary condition; (2) k_{AIF} = intrinsic permeability of aquifer influence region; (3) all values given at t = 14.00 days.

not shown in Table D-1, if k_{AIF} were reduced, the cumulative fluid outflow via the AIF boundary also would be reduced. In this case, the cumulative fluid outflow across the radial boundary, in terms of the total volume of fluid injected, was reduced from 3.0 percent (VELS14I) to 0.69 percent (VELS14I2) when k_{AIF} was reduced one order of magnitude.

Over longer periods, the radial boundary would certainly influence the head buildup at the DOW. Thus the use of an AIF BC appeared to be a better choice for the radial boundary, especially when the model is used as a tool to predict long-term (30-year) effects of injection upon the system. In addition, the regional hydrogeologic investigation covered a 10-mile (16,000-m) radius from the well; thus use of a radius larger than 10 miles was considered speculative.

Two runs from the VELS18 series are included to show the effect of the position of the AIF BC. The conceptual model for the VELS18 series is more complex than the VELS14 series and includes a thicker sequence of geologic materials (fig. D-2). The results from VELS18H2 are in agreement with VELS14I, allowing for a slightly lower head buildup for VELS18H2 due to the greater thickness of compressible geologic materials. For VELS18J, distance to the radial

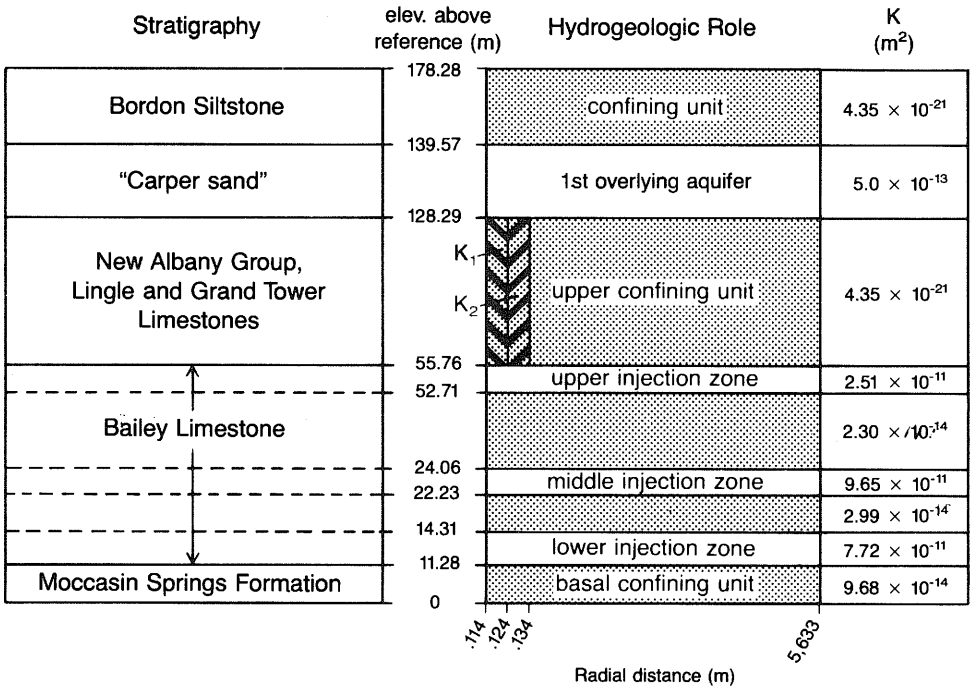

Figure D-2 Conceptual model 2 of the injection system.

boundary was much closer than for VELS18H2. In addition, the head buildup at the DOW was much lower, although k_{AIF} is the same for both runs. For both VELS18H2 and VELS18J, the AIF zone is more transmissive than the inner discretized zone; therefore, decreasing the radial distance of this zone from the injection well allows fluid to move more readily and with less head buildup. The results of VELS18H2 and VELS18J indicate the effect of the location of the boundary and the need to properly define the intrinsic permeability of the aquifer influence region.

Injection Rate

Three runs were made to investigate the effect of the injection rate upon head buildup at the DOW. VELS14I ($q = 1.820 \times 10^{-2}$ m^3/sec) is the baseline run. For VELS15A, the injection rate was increased 10 percent, $q = 2.00\ 2 \times 10^{-2}$ m^3/sec. For VELS15B, the injection rate was decreased 10 percent to 1.638×10^{-2} m^3/sec. Figure D-3 shows the Δh at the DOW with time. Increasing the q by 10 percent resulted in a 10.2-percent increase in Δh. The increase in Δh was noticeable after several hours of injection. In a similar fashion, a 10-percent reduction in the injection rate resulted in a 9.4-percent decrease in Δh. This decrease was also noticeable after several hours of injection. Round-off error for the percentage increase/decrease of Δh was responsible for these values not being equal and the deviation of these values from 10 percent as predicted by Darcy's Law.

Rock Compressibility

Storativity may be defined according to the following equation (Lohman 1972).

$$S = n\gamma b(\beta + \alpha/n) \qquad [D\text{-}1]$$

where S = storativity (-)
n = porosity (-)
γ = unit weight of fluid (kg/m^3)
b = aquifer thickness (m)
β = fluid compressibility (Pa^{-1})
α = rock compressibility (Pa^{-1})

Rock compressibility (α) is one of two major components of storativity. For HST3D, Kipp (1987) indicated that it is more convenient to use rock and fluid compressibility than a storativity term, since fluid density (i.e., unit weight) may be variable.

Three runs were used to investigate the effects of rock compressibility. VELS14I was the baseline run with $\alpha = 4.50 \times 10^{-10}$ Pa^{-1}. For VELS15C, rock compressibility was reduced 10 percent to $\alpha = 4.05 \times 10^{-10}$. For VELS15D, α was increased 10 percent, $\alpha = 4.95 \times 10^{-10}$. Figure D-4 shows the results of the runs. Decreasing α by 10 percent resulted in a 1.6-percent increase in Δh at the DOW. Similarly, a 10-percent increase in α resulted in a 1.6-percent decrease in Δh. The increase and decrease in Δh were evident after several hours of injection.

Fluid Compressibility

Fluid compressibility (β) is the other major component of storativity. VELS14I, VELS15G, and VELS15H were used to investigate the effect of varying fluid compressibility on the head buildup at the DOW. For VELS14I, $\beta = 4.00 \times 10^{-10}$ Pa^{-1}. A 10-percent reduction in β was used for VELS15G, $\beta = 3.60 \times 10^{-10}$. For VELS15H, β was increased to $\beta = 4.40 \times 10^{-10}$.

Figure D-5 shows the results from these runs. Decreasing β did not cause any change in Δh. Increasing β produced a negligible change in Δh, which was probably due to round-off error. The lack of sensitivity of Δh to β can easily be explained. Referring back to equation D-1, one can see that S is proportional to the quantity $(\beta + \alpha/n)$. For the situation investigated here, α/n was approximately 8 times larger than β; thus minor changes in β did not affect S and did not affect Δh.

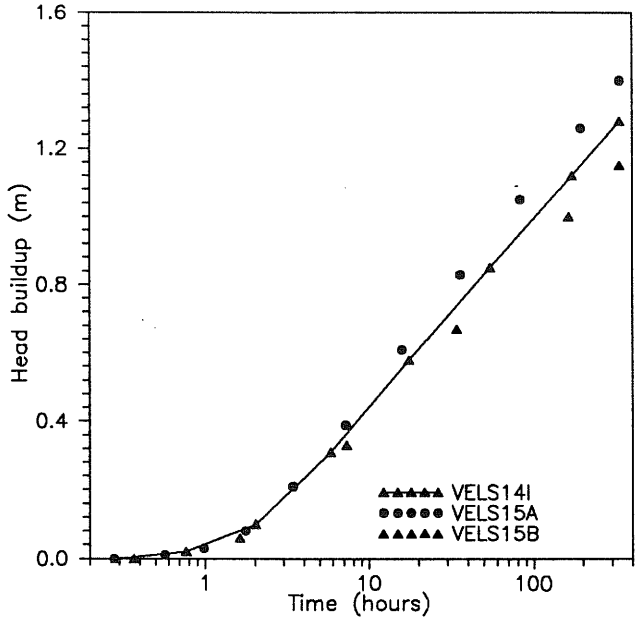

Figure D-3 (left) Sensitivity analysis: effect of injection rate.

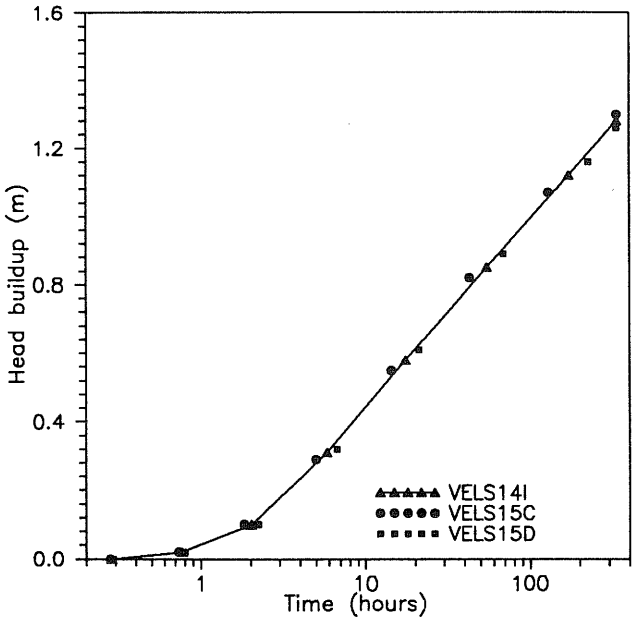

Figure D-4 Sensitivity analysis: effect of rock compressibility.

Hydraulic Conductivity

The results from VELS14I, VELS15I, and VELS15J were used to demonstrate the effect of hydraulic conductivity on Δh. For VELS15I, the hydraulic conductivity of each of the 7 layers was reduced by 10 percent, compared with the hydraulic conductivity values used for VELS14I. Similarly, the hydraulic conductivity values used in VELS15J were all increased by 10 percent.

Figure D-6 shows the results for all runs. As expected, decreasing the hydraulic conductivity resulted in an increase in Δh observed at the DOW. A 10-percent decrease in hydraulic conductivity resulted in a 9.4-percent increase (within round-off error of 10 percent) in Δh at the DOW. Increasing the hydraulic conductivity by 10 percent caused only a 7-percent decrease in Δh at the DOW. The deviation of this value from 10 percent, as predicted by Darcy's Law, is due to the K_{AIF}. The K_{AIF} for VELS15J was not increased from the value used for VELS14I, causing the head build-up within the inner aquifer region to be higher than anticipated.

Anisotropic Conditions

To this point, isotropic conditions have been assumed. On the basis of the hydrogeologic and geophysical tests conducted at the site during the project, it was not possible to establish the predominance of isotropic or anisotropic conditions. Thus, this series of runs was conducted to investigate the effect of this assumption.

Two runs were used to investigate this effect, VELS14I and VELS15K. Isotropic conditions (i.e., $k_r/k_z = 1$) were assumed for VELS14I. For VELS15K, k_z was decreased so that k was 10 times greater in the radial direction than in the vertical direction (i.e. $k_r/k_z = 10$). Figure D-7 indicates that under anisotropic conditions, Δh observed at the DOW was lower by approximately 2 percent than under isotropic conditions. Thus, if the assumption of isotropic conditions is not correct, the hydraulic conductivity of the geologic materials determined during model calibration may need to be reduced by nearly 2 percent.

Summary of Sensitivity Analysis

On the basis of the preceding sensitivity analysis, injection rate and hydraulic conductivity were the most sensitive input parameters. That is, a given change in injection rate or hydraulic conductivity produced the largest change in Δh observed at the DOW. The type of boundary condition and the location of the boundary can also have a significant effect on the head buildup predicted by the model. In decreasing order, the most sensitive parameters were injection rate and hydraulic conductivity, rock compressibility, anisotropy, and fluid compressibility.

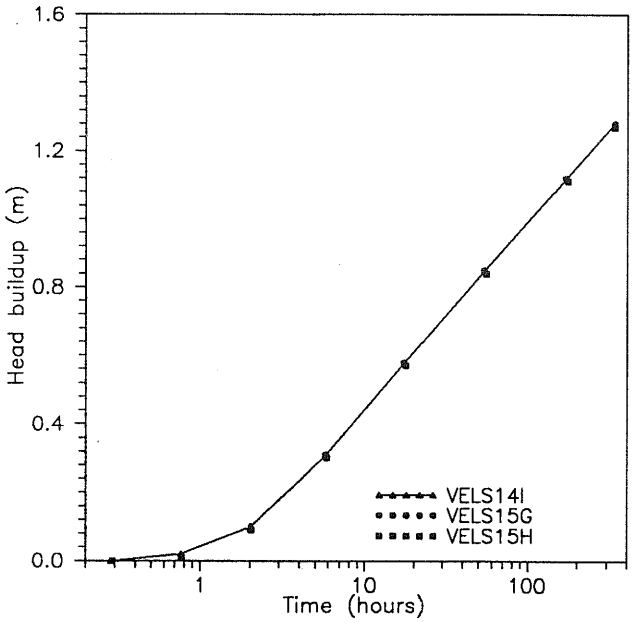

Figure D-5 (left) Sensitivity analysis: effect of fluid compressibility.

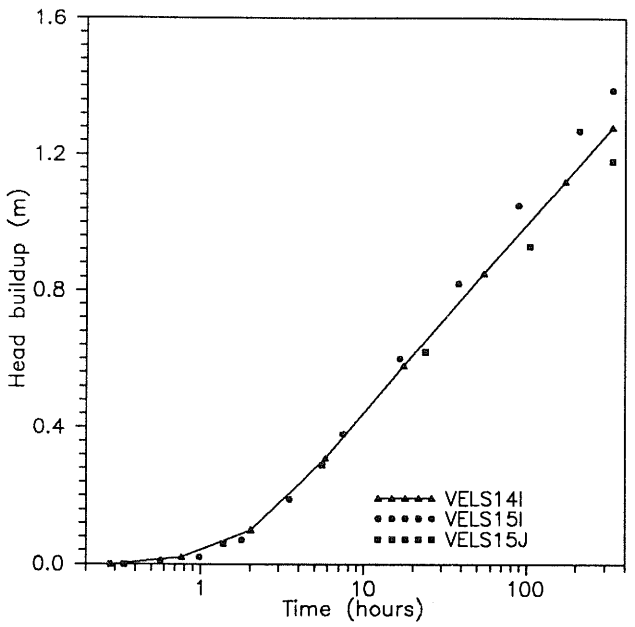

Figure D-6 Sensitivity analysis: effect of hydraulic conductivity.

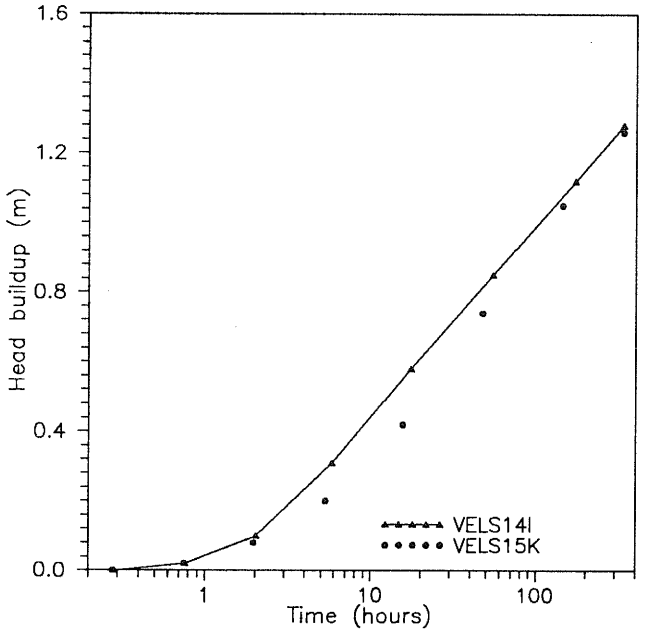

Figure D-7 Sensitivity analysis: effect of anisotropy.